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# 5 YEAR OPERATION OF RIKEN SUPER-CONDUCTING LINAC

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*Abstract*

The RIKEN superconducting (SC) heavy-ion linear accelerator (SRILAC) has been supplying beams supply for super-heavy elements synthesis experiments since its commissioning in January 2020. The SRILAC has been successfully operating for nearly five years, with both minor and major hardware issues being resolved. A broken coupler in the early stage of operation, together with several years of service, led to increased X-ray emission levels in several SC cavities; these were successfully mitigated by High Power Processing (HPP). Owing to fine tunings of the LLRF control system and cryogenic system, an availability of more than 99% has been achieved. This talk will share the experiences and lessons learned from five-year operation with low beta SC-cavities.

## INTRODUCTION

RIKEN has a long tradition of nuclear-science research pioneered by Yoshio Nishina [1], who constructed the first cyclotron (26-inch) in 1937 outside the United States (second in the world). In 1975, the RIKEN linear accelerator (RILAC) was designed and built to extend the research activities by providing ions heavier than Ne [2]. RILAC was later followed by a series of cyclotron constructions, forming an accelerator complex capable of providing Uranium (U)-ions up to 345 MeV/u at RIBF [3]. The super-heavy element (SHE) synthesis program was initiated in 2002 using RILAC. To satisfy the energy requirement for the SHE experiment, a booster linac, called charge-state-multiplier (CSM) system [4] comprising drift-tube tanks was constructed. Over ten years of experiments ultimately led to the synthesis of Nihonium through the cold fusion reaction$^{209}$Bi +$^{70}$ Zn $\rightarrow^{278}$ Nh + $n$. A $^{70}$Zn beam with energy of 5.04 MeV/u and intensity of 0.5 pμA was continuously provided, enabling the successful synthesis and observation of element 113 [5–7].

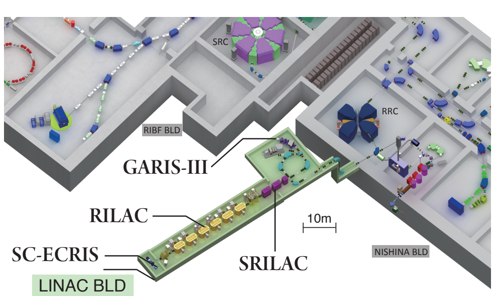


Figure 1: Birds-eye view of the RILAC.

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In 2016, the RNC commenced a new comprehensive SHE research program [8]. Its main objective was to expand the periodic table of elements by synthesizing new SHE. After the discovery of oganesson (Z = 118) [9], the program's aim of the SHE project became discovering an elements beyond Z= 118. Thus, the primary focus the project was on upgrading RILAC by introducing a SC linear accelerator to increase the final beam energy from 5.5 to 6.5 MeV/u and a SC electron-cyclotron-resonance ion source (SC-ECRIS) [10] to increase beam intensity by a factor of five (see Fig. 1).

In 2020, beam commissioning of SRILAC was successfully conducted [11], and user beam service subsequently began [12]. Argon and vanadium beams have since been provided for the experiments, with energies ranging between 4.2 and 6.3 MeV/u. Owing to the newly constructed SC-ECRIS [13] and the improvements in RILAC transmission efficiency [14], the maximum beam intensity of 5.2 pμA (duty 100%) exceeded the project's initial target.

In this presentation, we report on five-year of SRILAC operation since 2020, in conjunction with the nearly 50-year-old RILAC facility.

## SRILAC OVERVIEW

Since we had no prior experience with SC cavities, their design work was carried out cautiously, with careful consideration given not only to RF performance but also long-term operational reliability. The SRILAC design was based on that of the U accelerator, with an energy of 11 MeV/u and a current of 1 mA [15]. Research and development were conducted under the Fujita ImPACT program, funded by the Japan Science and Technology Agency, which involved constructing and commissioning a low-$\beta$ cryomodule operating at a frequency of 80 MHz [16]. This prototype effort, conducted in close collaboration with the KEK SRF group and successfully achieved the target gap voltage ($V_g$) of 1.6 MV and demonstrated stable 24-hour operation without field emission.

The design specification of superconducting cavity for SRILAC are listed in Table 1. SRILAC is based on ten SC-QWRs, with an amplitude and phase of the accelerating field adjustable independently for each cavity. The independent RF system enables seamless tuning of the beam energy. The gap length was optimized for $\beta$ = 0.078, with a operating frequency of 73 MHz. The operating temperature was 4.5 K. The SC-QWRs were fabricated from high-purity Nb sheets (RRR= 250). The inner surfaces underwent standard processing method as follows: (i) bulk etching via buffered chemical polishing (BCP), (ii) annealing at 750 °C for 3 hours in a vacuum furnace, (iii) light etching via BCP, (iv) high-pressure rinsing (HPR) with ultrapure water, and (v)

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# EIC CRAB CAVITY RF SYSTEMS*

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*Abstract*

The Electron-Ion Collider (EIC) is being implemented at Brookhaven National Laboratory (BNL) in a special partnership with Thomas Jefferson National Accelerator Facility. EIC is designed to collide electrons and protons/Heavy Ions with energies of 5-18 GeV, 2.5 A in the Electron Storage Ring (ESR) and 41-275 GeV/u, 1 A in the Hadron Storage Ring (HSR). The interaction region with a crossing angle of 25 mrad requires several Crabbing Cavity RF Systems operating at 197 MHz and 394 MHz. All the crabbing systems are designed with superconducting RF-dipole type cavities, where the HSR will include both 197 MHz and 394 MHz crabbing cavities, while ESR will include only 394 MHz crabbing cavities. In this paper, we will review the EIC crabbing system design, its complexities, and the challenges it presents.

## INTRODUCTION

The Electron Ion Collider, currently under construction at BNL, is a high-luminosity electron-hadron collider that will be the next major research facility for fundamental nuclear physics research [1]. The EIC will modify the existing RHIC machine, which will become the HSR, and will add a new high-current ESR [2]. The EIC comprises multiple RF subsystems, as shown in Fig. 1, including both superconducting and normal-conducting cavities that operate over a range of RF frequencies [3]. The ESR 591 MHz 1-cell accelerating cavity and the HSR 197 MHz crab cavity are identified as the most complex RF systems in the EIC.

Crab cavity systems are required to meet the target integrated luminosity goal of ~$10^{34}$ $cm^{-2}s^{-1}$ due to the large geometric crossing angle of 25 mrad [4]. The electron-ion collisions occur in the Interaction Region – IR6 following a local crabbing scheme. The crab cavity RF systems consist of a 394 MHz single cavity cryomodule system in the ESR and a 197 MHz 2-cavity cryomodule with an additional second harmonic of 394 MHz 2-cavity cryomodule systems in the HSR. The total transverse kick and total number of crab cavities required at IR6 are listed in Table 1, which includes the cavities that crab and uncrab the beams after the collisions.

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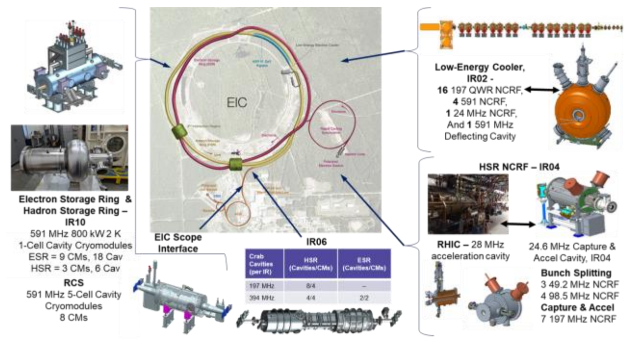


Figure 1: RF subsystems of the EIC.

Table 1: Crabbing Systems of EIC

| | $V_t$ [MV] | | No. of cavities | |
|---|---|---|---|---|
| **System** | **HSR** | **ESR** | **HSR** | **ESR** |
| 197 MHz | 33.83 | – | 8 | – |
| 394 MHz | 4.75 | 2.90 | 4 | 2 |

The lower operational frequency of 197 MHz leads to a large cavity, including the higher order mode (HOM) couplers. The large cavity increases the complexities in fabrication and cavity processing, limiting the available facilities for RF testing. In this paper, we will present the status of the different crab cavity designs, including the challenges of the 197 MHz crab cavity.

## SRF DESIGN APPROACH

The 197 MHz crab cavity is designed based on the RF-Dipole geometry [5, 6]. The cavity is designed to meet the following system requirements.

- Nominal operational voltage per cavity = 8.5 MV
- Maximum operational voltage per cavity = 11.5 MV
- Peak fields at 11.5 MV: $E_p < 45$ MV/m & $B_p < 80$ mT
- Dimensional constraints:
  - Beam pipe aperture = 100 mm
  - Cavity length (flange-to-flange) < 1.5 m
  - Beam line space per side for HSR < 12.5 m
- Impedance thresholds per cavity (considering simultaneous operation of both interaction regions):
  - Longitudinal < 10 kΩ
  - Transverse-H < 0.132 MΩ
  - Transverse-V < 0.66 MΩ
- Multipole components at 33.8 MV, per side [7, 8]:
  - Quadrupole component ($b_2$) < 0.008 T

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# COMMISSIONING EXPERIENCE OF ESS SUPERCONDUCTING LINAC

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*Abstract*

The ESS superconducting linac is an in-kind contribution by IJCLAB (Spoke cavities and Cryomodules), INFN (Medium Beta Cavities), STFC (High beta cavities) and CEA (all elliptical cryomodule assembly). Spoke cryomodules have been tested at the FREIA Facility in Uppsala and at the elliptical at the ESS Test Stand 2 in Lund. In the talk we summarize the first phase experience of cryomodules commissioning in the ESS linac.

## INTRODUCTION

The installation of 27 cryomodules (13 spoke, 9 medium beta elliptical and 5 high beta elliptical) was completed in summer 2024, providing a 2 MW beam power capability on the neutron production target for the first operation phase of the facility. The ESS superconducting linac [1] cool down to 4K started in late November 2024, followed by the non-resonant cold conditioning of all 82 superconducting cavity couplers (26 spokes, 56 elliptical of which 36 medium beta and 20 high beta).

Stable 2 K conditions were reached in January 2025, followed by the tuning to resonance and the start of the cavity conditioning process to nominal operation parameters.

The preparation of cavities for stable beam operation then started, interrupted by the need to recover from several infrastructure outages that resulted in cryoplant failures. Beam operation was achieved on April 9$^{th}$, with the first proton bunches to the temporary beam dump.

### *Cryomodule Test Prior to Installation*

All cryomodules are tested prior to their installation, both to assess whether the performance requirements are met and to build the linac configuration based on the collected data and according to beam physics requirements. Spoke cryomodules were tested at FREIA laboratory in Uppsala and all the spoke cavities reached the nominal design gradient of 9 MV/m [2]. All elliptical modules are being tested in the ESS test facility TS2 [3,4], where a single bunker is available for elliptical cryomodule (CM) tests, two klystrons are used to power 4 cavities (power is directed to the specific cavity under test using a variable power divider) and where only one timing system is available (the pulse length and repetition rate are fixed for the whole module and we can't operate independently different cavities). Even given the test stand limitations listed above an average of 60 test calendar days has been steadily reached (see Fig. 1). Data resulting from the acceptance test is routinely correlated with measurements provided by in-kind partners during the cavity qualification vertical tests. Figure 2 shows the overall correlation between the gradients achieved in vertical tests and the performance obtained at TS2.

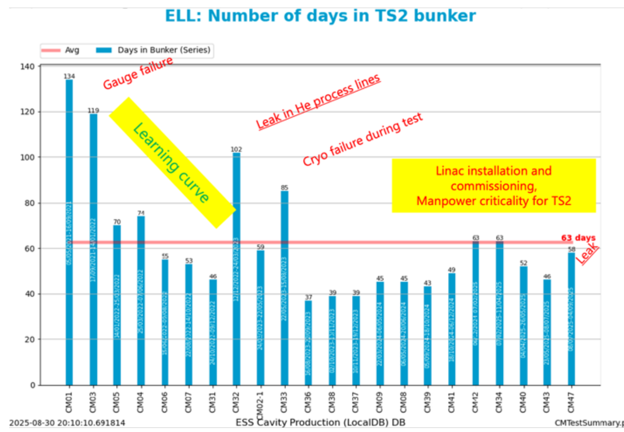


Figure 1: Statistics of elliptical cryomodule test duration in bunker.

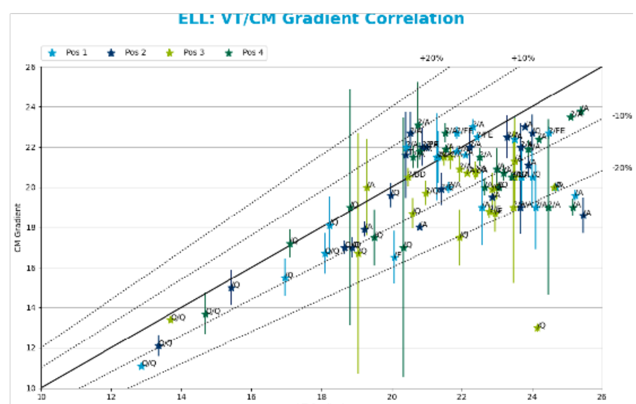


Figure 2: Comparison between maximum gradient reached in CM vs maximum gradient measured during VT. If perfect agreement happens all points should fit on a diagonal slope.

Most data falls within ±10% of the ideal correlation, until a gradient of about 20 MV/m. An administrative power limit of 300 kW and 400 kW for medium and high beta respectively is set at TS2 to avoid coupler breakdowns in standing wave regime. This leads to the flattening of the correlation curve at higher fields. The administrative limit corresponds approximately to the power needed to establish a gradient of 20 MV/m at the nominal loaded Q-factors. A further analysis on limiting mechanism and comparison between vertical qualification and cryomodule tests can be found in [3,4].

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# FRIB OPERATION, STATUS OF POWER RAMP UP, AND R&D FOR ENERGY UPGRADE*

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*Abstract*

FRIB is the first heavy-ion accelerator facility to deploy a large number of Half-Wave Resonators (220 HWRs) and operate at 2 K in its superconducting drive linac. As of today, FRIB delivered the world's highest uranium beam power (>20 kW) on target and will continue its power ramp-up in the next few years in parallel to support user science program. The technologies that have sustained the establishment of the FRIB facility and beam power ramp-up include large-scale superconducting RF, superconducting magnets, liquid metal charge stripping, and high-power targetry. This talk summarizes the current operational experience with these technologies, the plan to ramp up power to the full design power of 400 kW, and the R&D activities preparing for linac energy upgrade in the near future.

## INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) at Michigan State University is a U.S. Department of Energy Office of Science (DOE-SC) scientific user facility [1]. Since starting user operations in May 2022, FRIB has entered its fourth year of supporting nuclear science experiments. The facility consists of a driven linac, targetry, fragment separator and experiment beam lines as shown in Fig. 1 [2–4]. The facility is designed to accelerate a broad range of ion species, up to $U^{238}$, delivering energies of <200 MeV/u and up to 400 kW beam power for rare isotope production. The science program covers four main areas: structure and properties of atomic nuclei, nuclear astrophysics, fundamental symmetric, and isotope applications.

## SRF LINAC OPERATIONS

FRIB's superconducting radio-frequency (SRF) linac is the largest low $\beta$ SRF accelerator in operation [6]. It consists of 46 cryomodules that house 324 cavities (QWR and HWR) and 69 focusing solenoids. The linac consists of three segments: 100 QWRs in LS1, 144 HWRs in LS2, and 48 HWRs in LS3 as shown in Fig. 1. Installation and commissioning occurred in phases between 2018–2021 [7, 8], with the majority cryomodules cold for

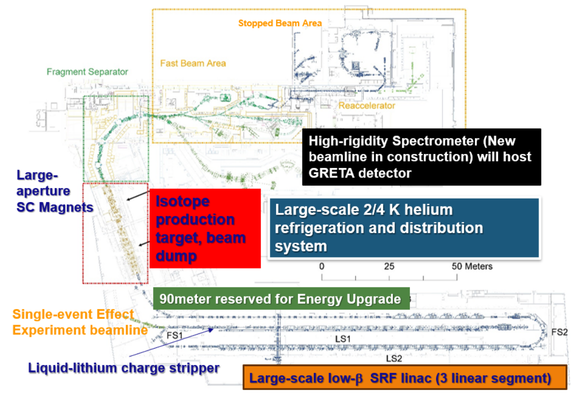


Figure 1: Lay out of FRIB facility including on-going new high-rigidity spectrometer HRS [5] beamline.

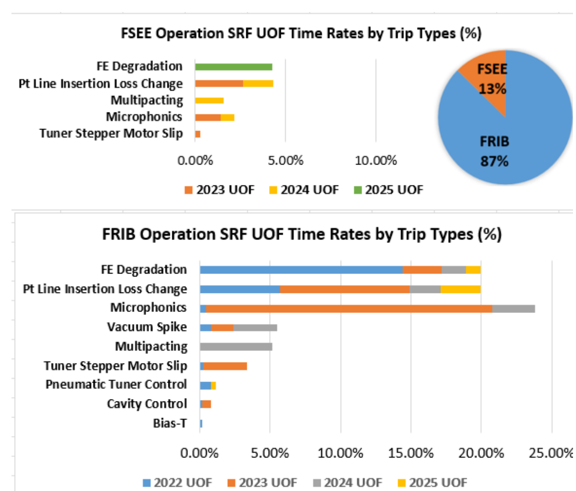


Figure 2: Breakdown of SRF system trips during beam operation. Top, FSEE operation (LS1) and bottom FRIB operation.

more than five years. In 2020, linac was warmed up: LS1 to room temperature and LS2-3 to ~200 K to support the connection of the cryogenic system to cryogenic loads in the target and fragment separator areas. A more recent full warm-up of LS2-3 in summer 2025 to support tuner maintenance work. In 2024, QWR cryomodule SCM801 has been replaced as part of the preventive maintenance program.

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# STATUS OF SRF ACTIVITIES FOR THE SHINE PROJECT*

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*Abstract*

Recently, the SHINE Linac layout has been modified to use fewer cryomodules (CMs) to reach 8 GeV, benefiting from the higher performance of high-Q cavities and CMs. The mass production of SHINE cavities and CMs is currently underway. To date, more than 100 mid-T baked cavities and 100 N-doped cavities have been vertically tested. Most of them have been assembled into cryomodules, achieving high Q and quite high gradient in horizontal test. These high-Q CMs are being gradually installed into the Linac section. Two 3.9 GHz CMs have been assembled and tested, demonstrating excellent RF performance. This paper will report the progress in the production and performance of the cavities and CMs.

## INTRODUCTION

Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE) is designed to accelerate electron beam up to 8 GeV using cryomodules (CMs) equipped with superconducting radio frequency (SRF) cavities [1]. SHINE accelerator consists of a VHF gun, an injector, and four linac sections separated by three bunch compressors, designated as BC1 to BC3.

The injector employs a symmetric design, which includes a single-cavity CM (i1CM) with twin fundamental power couplers (FPCs) and an 8-cavity CM (i8CM) with ABBA orientation of FPCs, in order to minimize the RF kick effect [2]. Two 3.9 GHz CMs are used to linearize the longitudinal phase space in the L1 section before the first bunch compressor. Power couplers for 3.9 GHz cavities alternate sides to compensate dipole kicks.

Due to performance improvements in SHINE 1.3 GHz high-Q cavities in recent years, the specifications for high-Q cavities and CMs were updated in October, 2024, as shown in Table 1. With a higher average gradient at 20 MV/m per cavity in the CMs, the designed beam energy of 8.0 GeV can be achieved using fewer CMs.

Recently, the SHINE linear accelerator is modified to accelerate the beam to 8 GeV using 54 high-Q CMs, instead of 75 in the original design that operates at a gradient of 16 MV/m. In the L1 section, one of the three CMs was replaced with a pipe-CM— a copper pipe in the beam line that contains no cavity but retains a cold beam position monitor (BPM) and a superconducting quadruple magnet. In the L3 and L4 sections, 14 and 6 CMs are removed, respectively. Furthermore, a bypass line is added after L3 section to extract beam energy ranging from 3.5 to 4.5 GeV for FEL-2 experiments. The modified layout of SHINE linear accelerator is shown in Figure 1.

Table 1: Updated specifications for the SHINE High-Q 1.3 GHz Cavities and Cryomodules

| | **1.3 GHz cavity** | **1.3 GHz CM** |
|---|---|---|
| **$Q_0$ ($10^{10}$) at 20 MV/m** | ≥ 3.0 | ≥ 3.0 |
| **Max $E_{acc}$ (MV/m)** | ≥ 22 | 26 (adm. limit*) |
| **FE onset (MV/m)** | ≥ 22 | |
| **Vtot (MV)** | | ≥ 166 |

The SRF infrastructures including the cavity surface-treatment platform in Wuxi, the CM assembly and test platforms in Shanghai, began construction in 2018 and have been commissioned and operational since 2021. At the same time, the CM component prototypes were developed, including SRF cavities, power couplers, tuners, BPMs, superconducting quadruple magnets, cryostats and so on. Two prototype CMs were assembled and tested in order to break through key technologies of CM. Degaussing and fast cooling of CM were also studied to preserve high-Q in horizontal test [2-4].

Based on the competence and experience gained during pre-research period, the two special CMs for the injector were developed, reached their design specifications in horizontal test, and were installed in tunnel in the first half of 2024. Beam commissioning of injector section was performed and reached its designed energy of 100 MeV in October 2024. The two 3.9 GHz CMs were assembled and tested successively before January 2025. Together with 2 high-Q CMs and a pipe-CM installed in L1 section, beam commissioning of L1 to BC1 section began in August 2025. For the L2 section, 9 out of 18 high-Q CMs have been installed. CM installation is conducted during the day, and beam commissioning takes place at night.

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# 5 YEARS OF SPIRAL2 LINAC OPERATION: CRYOGENIC AND SUPERCONDUCTING RF ASPECTS

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*Abstract*

The superconducting linear accelerator LINAC of SPIRAL2 at the GANIL facility has been in operation since October 2019. The 26 superconducting quarter-wave resonators (QWR) of the LINAC are integrated into 19 cryostats and cooled to 4 K using a dedicated refrigeration system. These superconducting cavities are operated at a nominal gradient of 6.5 MV/m but most cavities can be run up to 8 MV/m. One of the 26 cavities showed abnormal energy dissipation at medium and high RF gradients. This paper reports on five years of operational experience, with particular emphasis on cryogenic and RF challenges, outlining the issues encountered and the improvements implemented to reduce beam downtime.

## INTRODUCTION

The SPIRAL2 facility at GANIL (Grand Accélérateur National d'Ions Lourds) is dedicated to producing rare isotope beams with some of the highest intensities worldwide [1]. SPIRAL2 accelerator is engineered to deliver protons, deuterons, and heavy ions over a broad spectrum of energies and beam intensities. Table 1 summarises the range of beams available at the SPIRAL2 facility. The fourth column lists the parameters of a new future injector (NEWGAIN project) being built for heavier ions [2].

Table 1: SPIRAL2 Beam Specifications

| Parameter | $H^+$ | $D^+$ | $A/Q \leq 3$ | $A/Q \leq 7$ |
|---|---|---|---|---|
| A/Q | 1 | 2 | 3 | 7 |
| Max I(mA) | 5 | 5 | 1 | 1 |
| Max E (Mev/A) | 33 | 20 | 14.5 | 7 |
| Beam power (kW) | 165 | 200 | 45 | 16 |

These wide ranges of particles, intensities and energies are possible thanks to 26 bulk niobium, superconducting (SC), independently phased resonators. These cavities are assembled in two families of cryomodules (CM). The first family, called type A, is composed of 12 CM and contains 12 quarter-wave resonators (QWRs) optimized for $\beta = 0.07$ (one cavity/CM). The second family, called type B, is composed of 7 CM that integrate a total of 14 QWRs optimized for $\beta = 0.12$ (two cavities/CM) (Fig. 1). The 26 cavities are operated at the same temperature (liquid helium temperature close to atmospheric pressure around 4.2 Kelvin) and at the same frequency of 88.0525 MHz.

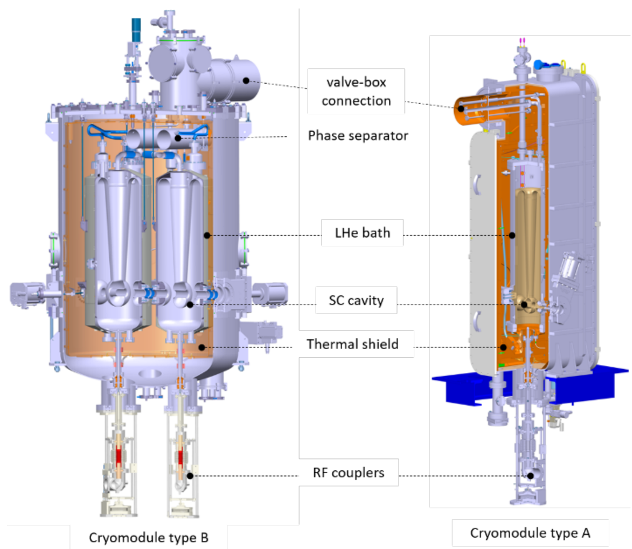


Figure 1: 3D representations of the two cryomodules families (A and B) with their main components.

The operation of the SC cavities requires two main conditions: The first is to maintain the cavities at a stable temperature below the transition temperature (between 8.5 and 9.2 K). To achieve this, all cavities are completely immersed in liquid helium at 4.2 K. Partially emerged cavities suffer from poor thermal dissipation at the exposed region which can induce a quench, resulting in a partial or total loss of its SC state. The second operating condition is related to external perturbations that may affect the cavity operating frequency. As niobium is not perfectly rigid, pressure oscillations of the liquid helium bath induce vibrating mechanical deformations resulting in resonance RF frequency shifts. Other sources can induce this type of perturbation and may include: the Lorentz force, helium pressure/level cross-coupling (including between different CM), cryogenic operation setpoint, thermoaccoustic oscillations (TAO), vacuum pumps, vibrations, helium turbulence, and other sources of external mechanical vibrations [3].

For slow pressure oscillations (< 1 Hz), cavity frequency deviations are compensated by the Frequency Tuning System (FTS). For fast oscillations (> 100 Hz), the low-level

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# CEPC SUPERCONDUCTING RF SYSTEM EDR DESIGN AND R&D

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*Abstract*

CEPC (Circular Electron-Positron Collider) is a 100-kilometer circular collider designed to operate at center-of-mass energies ranging from 90 GeV to 360 GeV, with the primary physics program targeting Z and W bosons, Higgs bosons, and top-quark pair (ttbar) production. Following the publication of its Technical Design Report (TDR) in 2024, the project has now entered the Engineering Design Report (EDR) phase. This contribution outlines the EDR design of the CEPC's Superconducting Radiofrequency (SRF) system, along with the associated R&D challenges and recent progress. During the EDR phase, the SRF system's primary objective is to develop SRF cryomodules for the first operational stage of the CEPC. A key milestone will be a full-scale 650 MHz cryomodule prototype for the collider ring to validate the stable operation using an 800 kW continuous-wave (CW) klystron and the Low-Level Radio Frequency (LLRF) control system. Additionally, preparations for mass-production of 650 MHz and 1.3 GHz cavities and cryomodules are underway aligned with China's ongoing large-scale SRF projects.

## INTRODUCTION

CEPC [1] and FCC-ee [2] are the two proposed future circular electron positron colliders as Higgs, W, Z-pole and top factory. They are both designed as a double-ring collider with a full energy booster, operating in four different modes (H, W, Z and ttbar) with a wide range of beam parameters. The collider beam energy ranges from 45 to 180 GeV with a beam current of 1.3 A to 5 mA , RF voltage of 0.1 to 10 GV, and synchrotron radiation (SR) power of 30 to 50 MW per beam. The booster beam energy ranges from 20 or 30 GeV to the top-off injection energy of each mode, with the beam current ranging from 0.1 to 30 mA. RF system design should fulfil all of these requirements and consider the operation sequence and flexibility of the energy staging. The RF challenges are significant in terms of high RF voltage, high power, high current, wide parameter range and mode switching. High gradient and high Q cavities, very high input power couplers, high higher-order-mode (HOM) power couplers and absorbers are required. Especially for Z-pole mode, the low energy and high current beam in a large ring will result in severe fundamental mode and HOM instability and gap transient effects.

With the release of its Technical Design Report (TDR) in 2024 [1], the CEPC project has now entered the Engineering Design Report (EDR) phase. This paper discusses the design evolution, baseline, and alternatives for the CEPC SRF system and presents the latest R&D progress.

## CEPC SRF SYSTEM DESIGN

### *Evolution of CEPC RF System Design*

In the Pre-CDR [3] published in 2015, CEPC is designed as a 54 km single-ring collider with pretzel scheme only operating in Higgs mode. The RF system will use 384 5-cell 650 MHz cavities for the collider (main ring) and 256 9-cell 1.3 GHz cavities for the booster to provide 6.87 and 5.12 GV RF voltage respectively. The SR power per beam of the collider is 52 MW.

In the CDR [4] published in 2018, CEPC collider changed to a 100 km double-ring with shared cavities for Higgs operation and separate cavities for W and Z operations. The maximum RF voltage of both the collider and the booster reduced to around 2 GV for Higgs, requiring 240 2-cell 650 MHz cavities and 96 9-cell 1.3 GHz cavities. The SR power per beam of the first phase is 30 MW for Higgs / W, and 16.5 MW for Z.

In the TDR [1] published in 2024, 50 MW Higgs/W operation, 30 / 50 MW high luminosity Z operation and ttbar operation are included as power and energy upgrade of CEPC. The SRF system for both the collider and the booster is optimized for the Higgs mode of 30 MW SR power per beam of the collider, and upgradable to higher power and/or energy by adding cavities and/or RF power sources. Mode switching is required between the operation modes, especially Z, W, and Higgs.

### *TDR Design of CEPC SRF Syste*

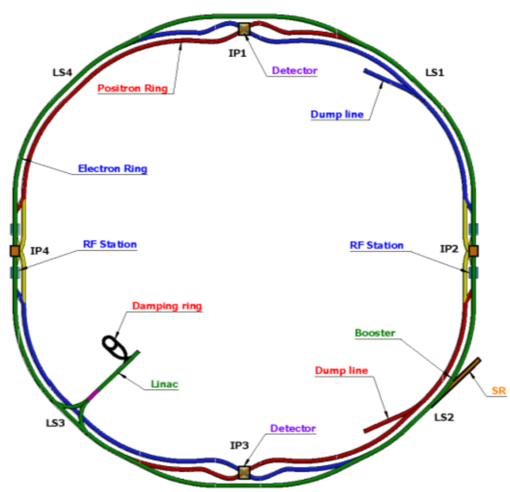


Figure 1: CEPC layout with two RF sections.

There are two RF sections located at two symmetric long straight sections (IP2 and IP4 in Fig. 1). The collider 650 MHz cryomodules will be mounted on the tunnel floor, and the booster 1.3 GHz cryomodules will be hung from

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# OPERATIONAL STATUS AND EXPERIENCE OF THE TLS CESR-B TYPE SRF MODULE

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*Abstract*

Taiwan Light Source (TLS) is a third-generation synchrotron light source located at NSRRC in Taiwan, operating at an electron energy of 1.5 GeV. The original RF system of TLS utilized two normal-conducting Doris cavities. In 2005, these were replaced with a single CESR-B type superconducting RF (SRF) module, which significantly improved the system's stability and enabled an increase in the operating beam current to 360 mA. This report describes the operational performance of the SRF module over more than 20 years, including statistical records, performance monitoring, and major operational issues along with their solutions. The status of the spare SRF module is also discussed in this report.

## INTRODUCTION

The Taiwan Light Source (TLS) is a third-generation synchrotron light source located at NSRRC in Taiwan. It operates at an electron energy of 1.5 GeV and has been open to users since 1993 [1]. Several key parameters of TLS are listed in Table 1. The RF system of the TLS storage ring initially employed two normal-conducting Doris cavities. At the 2005, these cavities were upgraded to a CESR-B type superconducting module [2, 3], which improved beam stability and enabled an increase in operating current to 360 mA [4]. Currently, the superconducting module operates at a RF voltage of 1.3 MV. Under top-up mode at 360 mA during user operation periods, the RF system delivers approximately 70 kW of output power.

At TLS, we have two SRF modules: one currently in operation, designated as S1, and the other serving as a spare, designated as S2. S1 has been continuously operating since its installation, while S2 has been stored at room temperature since passing its high-power acceptance test. The following report provides a comprehensive overview of the status and performance of both S1 and S2.

## OPERATION STATISTICS

Since 2005, the superconducting module S1 has been in operation for nearly 20 years. Figure 1 shows the statistics of SRF-related trip events from 2006 to the present. In the early years, SRF-related trips mainly fell into three categories, while in recent years, they have been reduced to two main types. Only a small number of trips were caused by component failures. The three early types of trips included: unexplained phase fast change, phase oscillations, and window arc events. Most window arc events were false alarms, which ceased after improvements in shielding (e.g., lead wrapping) and the implementation of a voting mechanism. In later years, the main SRF-related trips were due to unidentified quenches and vacuum bursts. Additionally, many early trip events could not be clearly diagnosed due to the lack of diagnostic components at the time.

Table 1: Key Parameters of the TLS

| Main parameter | Value |
|---|---|
| Circumference | 120 m |
| Beam Energy | 1.5 GeV |
| Beam Current | 360 mA |
| Natural Emittance $\varepsilon_x$ | 22 nm-rad |
| Harmonic Number | 200 |
| RF Frequency | 499.65 MHz |
| Energy Spread | $7.56 \times 10^{-4}$ |
| Energy Loss per turn (dipole) | 128 keV |

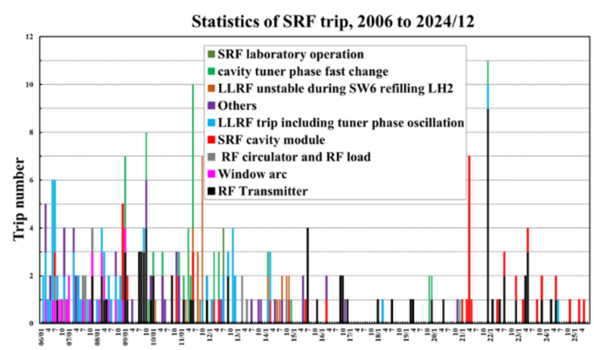


Figure 1: Statistics of TLS SRF trip events.

In early phase oscillation events, a typical phenomenon involved a phase shift caused by unknown factors, followed by RF voltage oscillation that led to system trips, as shown in Fig. 2. Depending on the operating conditions, different oscillation frequencies were observed. This behavior was attributed to insufficient overall system stability under heavy beam loading. By adjusting the loading angle toward more negative values, such oscillations could be avoided. Using a control model, we calculated the oscillation angle and frequency, and the results were consistent with experimental observations, confirming that the phenomenon was indeed caused by interactions among the beam, cavity, and LLRF system [5].

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# UPGRADE OF THE ELETTRA 2.0 CRYOGENIC PLANT

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*Abstract*

On July 2nd 2025 started the removal of the Italian third generation synchrotron light source Elettra (www.elettra.eu) to be replaced by Elettra 2.0 a fourth-generation one. The replacement project also includes the upgrade and expansion of the helium liquefaction plant.

The current cryogenic system is based on a Kaeser He compressor and a Helial 1000 cold box liquefier/refrigerator, with a Siemens S7-00 PLC-based control system, currently connected exclusively to the superconducting third harmonic cavity (S3HC). The upgraded system will continue to provide cooling for the S3HC, but will also supply liquid helium to users and provide cryogenic support for the superconducting wiggler (SCW). A complete renewal of the control system is underway, transitioning from the obsolete and unsupported Siemens S7-300 PLC to the S7-1500 series. A helium recovery and re-liquefaction system is planned both for the SCW and for the beamlines that require liquid helium for experimental activities.

## ELETTRA 2.0 LIQUID HE REQUEST

The new light source Elettra 2.0 [1] requires a consumption of 10000 liters of liquid helium. 7440 of which are dedicated to the beam lines, with the remainder for the superconducting components of the storage ring. In particular, the beamlines require a total of 150lt /week (Table 1).

The SC components of the storage ring which require liquid helium are: SCW [2] and S3HC [3]. The SCW is housed in a zero boil-off cryostat, utilizing recondensers cooled by 4K cold heads and it requires liquid helium only for cooldown (once every 18 months). S3HC has a consumption of 35 l/h in addition, two warm-up sessions per year are included for routine maintenance, the S3HC cryomodule is connected to an Air Liquide 1000 refrigerator with a control system based on Siemens 7 PLC. The capacity of the Air Liquid 1000 with Kaeser compressor is 100 l/h in pure liquefaction and 35 lt/h in liquefaction and refrigeration power of 105 W. Therefore, our cryogenic plant, which is currently connected only to the S3HC, can cover the liquid helium demand of Elettra 2.0 with an upgrade of the cryogenic lines and a renewal of the control system, also because the SCW cooldown is done during scheduled shutdowns with the machine turned off.

Table 1: Liquid Helium Foreseen Request from Beamline

| **Beam line** | **LHe request [lt/y]** |
|---|---|
| APE | 250 |
| BaDelPh | 1500 |
| NanoESCA | 100-300 |
| Spectromiscroscopy | 1200 |
| SuperEsca | 1200 |
| SISSI-Mat | 300 |
| SISSI-Bio | 600-1000 |
| CDI(new beamline) | 2000 |
| **Total** | **6200** |

Figure 1 shows the positions of the beam lines that will use liquid helium in E2.0.

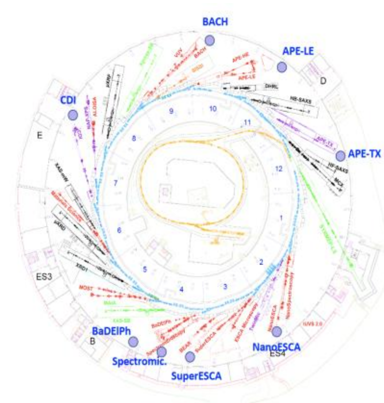


Figure 1: Beamlines requiring LHe in E2.0.

## THE NEWCRYOGENIC PIPING LINES

The conceptual diagram (Fig. 2) below shows the cryogenic and recovery lines for SCW and S3HC and the He refill line for users with 250-litre Dewars. All parts are already installed and tested, see Figs. 3 and 4, except 3 which consists of recompressing the gas to 200 bar with a booster stage up to 15 bar and a final compression from 15 bar to 200 bar. The gas circuit is closed and clean, so no filter is required.

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# BEAM DYNAMICS STUDIES OF CAVITY FAILURES FOR THE INITIAL OPERATION PHASE OF THE ESS SUPERCONDUCTING LINAC

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*Abstract*

The European Spallation Source (ESS) superconducting proton linac is currently undergoing commissioning. During the initial operation phase, the final beam energy will be about 800 MeV, reaching a 2 MW power. High reliability and availability are crucial for the success of the ESS science programs and thus operations will be maintained even with failures of main linac components such as cavities and quadrupoles, as long as 50% of the intended power can be achieved. To this end, we developed beam optics strategies to address failures in the cavities of the superconducting linac. Due to the constraints in the RF cavity amplitudes, we implemented a modified version of standard cavity compensation techniques. The results indicated that this strategy enables beam recovery that meets the beam quality specifications, thereby enhancing the availability of the ESS linac.

## INTRODUCTION

The European Spallation Source (ESS) will be a world-leading facility featuring a high-intensity superconducting proton linear accelerator (linac) to provide neutrons via a spallation process for neutron science experiments [1]. The ESS linac accelerates a proton beam of 62.5 mA in pulse mode, with a duty cycle of 4%, reaching a final energy of 2 GeV, which results in a beam power of 5 MW [2]. In the initial phase of operation, the linac will utilize only the first five cryomodules of the final superconducting section to accelerate the beam [3]. As a result, the maximum final energy will be limited to approximately 800 MeV, and the maximum beam power will reach 2 MW.

Figure 1 illustrates the schematic design of the ESS linac. Additionally, Table 1 presents the main linac parameters for both the baseline and initial operation phase of the ESS.

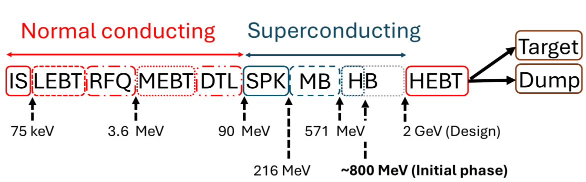


Figure 1: Schematic design of the ESS linac.

Reliability and availability are becoming essential features in accelerators to achieve their operational goals [4]. In recent years, there has been a renewed interest in Accelerator-Driven Systems (ADS) linacs [5], leading many high-beam power linacs [6–8] to explore new optical strategies aimed at increasing availability by minimizing beam downtime. Availability assessments [9, 10] indicate that the reliability of RF cavities is lower than that of magnets. Moreover, since the number of RF cavities is greater than that of other components and considering the flexibility of the superconducting linac to function with some RF cavities non-operational, this work presents optical beam compensations for RF cavity failures. These compensations are designed to meet the ESS linac specifications and constraints, ensuring high availability during operation.

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Table 1: ESS Main Linac Parameters

| **Parameter** | |
|---|---|
| Particle | Proton |
| Peak current (mA) | 62.5 |
| Proton beam energy (GeV) | 2.0 (Design)/ 0.8 (Initial phase) |
| Repetition rate (Hz) | 14 |
| Beam pulser (ms) | 2.86 |
| Duty factor (%) | 4 |
| Beam power (MW) | 5 (Design)/ 2 (Initial phase) |

## ESS RELIABILITY AND AVAILABILITY CONSIDERATIONS

The reliability and availability requirements for the ESS were presented in a previous paper [11]. The requirements focus on the needs of neutron beam users. For example, a beam power greater than 50% of the nominal power is demanded to conduct their experiments; therefore, if the beam meets this condition, this reduced beam power operation is not considered a beam trip. This specification is less stringent than that of ADS linacs, which require full beam power recovery. Furthermore, the compensation time for ADS systems is a few seconds, while for the ESS, the compensation time can be longer.

Fast cavity compensation [12] is pursued for high-power superconducting linacs [6–8, 13] as a fast way to recover beam operation after a failure of a RF cavity, increasing the availability. When a failure in a RF cavity occurs, the beam will be stopped and at the same time the faulty RF cavity will be fast detuned and the neighbors RF cavities will be rapidly rephased by adjusting, synchronous phase ($\phi_s$) and accelerating gradient ($E_{acc}$), to compensate the effect of the

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# OPTIMIZATION OF SEVERAL OPERATING PARAMETERS TO INCREASE THE BEAM DELIVERY TIME AT THE EUROPEAN XFEL

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*Abstract*

The pulsed linac at EuXFEL, operated by DESY, is designed to deliver up to 2700 electron bunches during a beam delivery time of 600 µs within an RF flat-top time of 650 µs. The user community would like to have more photon pulses. This can be done only by increasing RF flat-top length. The whole RF pulse length at the linac is limited by several factors, primarily the RF pulse length in the existing photoinjector. The new RF photoinjector, currently under development and testing, will enable beam pulses of up to 800 µs. The second limiting factor could be the stability of the RF power sources, the klystrons, which must handle longer high-voltage and RF pulses. Other very important parts are the accelerating cavities and RF fundamental couplers, which must handle higher power during cavity filling and a longer RF flat-top time. Initial investigations into extending the RF flat-top length began in 2022. Recently, various measures have been developed and implemented to increase the RF flat-top length while keeping power consumption low without compromising linac performance. These include optimizing the klystron high-voltage (HV) waveform, the high-power RF pulse shape, and the coupling factors of the accelerating cavities. The latest results from the tests of several RF stations with a beam delivery time of 800 µs are presented.

## INTRODUCTION

As initially designed, the EuXFEL [1] high voltage (HV) pulse has a length of 1.7 ms and the RF pulse has a length of 1.4 ms, 0.75 ms from that is used for cavities filling and the remaining 0.65 ms for the flat-top out of which only 0.6 ms can be used for the beam acceleration [2]. The level of klystron output power at the stage of cavities filling, should be at least 15% below the saturated power to provide a margin for feedback regulation. All EuXFEL RF power sources, the multibeam klystrons, were tested at 10 MW output power and rectangular RF pulse length of 1.5 ms [3]. Since the beginning of EuXFEL regular operation several operational improvements have been proposed, some of them have already been implemented and some are in the testing phase. All of them will be very important for increasing the beam delivery time without affecting other parameters of the accelerator, namely:

- Dynamic frequency shift (DFS) [4] during filling time enables the klystron frequency follow the cavity frequency, which is changing during cavity filling time according to the Lorenz force detuning [5] which is proportional to the accelerating field squared.
- Using part of the HV pulse rising and falling-edge times to produce RF power, we have already got a reduction of HV pulse length that we are using now for energy saving, but this can be used for increasing beam delivery time as well. The RF pulse starts at the time when the HV level reaches 70%-80% of nominal and stops when the HV drops to 85%. Due to this we need only 1.58 ms HV pulse length instead 1.7ms keeping the same beam time length. The phase change and power reduction during the rising and falling of the HV can be easily compensated [6].
- The drop of 15-20% in HV waveform during second part of the pulse, where the required RF output power is lower than at first and can be reached with lower cathode voltage. The drop introduces strong variation in the amplitude gain and phase at the klystron output, but because these variations are stable, for given HV pulse shape, they can be compensated [7].
- Increasing of coupling factor to the accelerating cavities, helps to reduce the RF power requirement during cavities filling time and, as a result, to decrease the klystron cathode voltage.
- Transferring the klystron to a mode in which it operates very close to saturation, but only during the first part of the filling time, and using the rest of the filling time to stabilize the field by feedback for a given power reserve [8], also enables a reduction of HV.

## TECHICAL LIMITATION

The main factors, though not the only ones, limiting the HV pulse duration at the klystron cathode and, consequently, the beam delivery time, are the magnetization factor of the high voltage transformers and the average power dissipated in the klystron collectors. It is important to note that the klystrons and the HV transformers are located inside the underground tunnel of the EuXFEL.

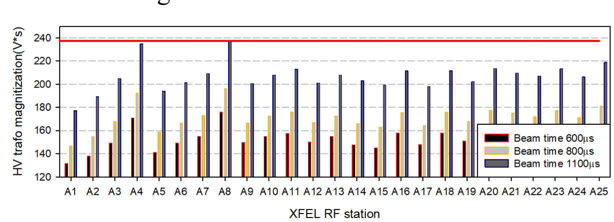


Figure 1: Magnetization factor for EuXFEL RF stations.

After energy consumption optimization, including all the aforementioned steps, the HV values were determined for each klystron depending on the maximum energy of the station with some reserve required for feedback regulation. As a result, by reducing the average HV value, it has

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# FRANCE-JAPAN COLLABORATION FOR HIGH-Q / HIGH-G SRF CAVITIES

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*Abstract*

High-performance SRF cavities are of central importance for many future projects and can only be realized through international collaboration. A key challenge is the standardization of parameters for chemical etching, heat treatment, and vertical testing. We have observed small but significant differences in the parameters defined locally across laboratories. In parallel with collaborative initiatives within European laboratories and between American and French institutions, we are consolidating the partnership between France and Japan. At present, we are developing a 1-cell 1.3 GHz cavity to systematically compare the vacuum furnaces at IJCLab and KEK, as well as the vertical testing procedures at CEA and KEK. Our investigations include mid-T baking, high-temperature annealing, low-temperature baking, and studies of magnetic field sensitivity. In this contribution, we present the global scope of the collaboration, the comparative analysis of furnaces, and the results of vertical tests.

## INTRODUCTION

Bulk niobium cavities are the standard technology for continuous-wave particle accelerators in use today and in the near future. The surface treatment process has been studied intensively for decades, and standard procedures are now established, yielding results in multiple accelerator projects [1, 2]. A subtle but decisive factor affecting cavity performance is heat treatment at various temperatures [3]. Although practical guidelines for heat treatments are available, the fundamental physics behind them remains unclear despite several plausible hypotheses that have been proposed. Some explanations are microscopic, while others are more phenomenological; the community has reached a qualitative consensus, but direct experimental evidence is still lacking. In addition to these limited theoretical insights, heat treatment and doping processes have been the subject of experimental studies, particularly concerning their reproducibility across laboratories worldwide [4]. It is therefore essential to establish international collaborative efforts to systematically analyze experimental conditions, including potential nuisance parameters that may have been overlooked in current recipes. In this work, French and Japanese laboratories join forces to advance the understanding of heat treatment processes, with support from partner institutions in Germany, Italy, the United States, Canada, China, and elsewhere.

## HEAT TREATMENT IN CLEAN VACUUM FURNACES

A clean vacuum furnace with cryogenic pumping is an essential facility for the study of high-$Q$/high-$G$ SRF cavities. Figure 1 shows the vacuum furnaces at IJCLab and KEK. The IJCLab furnace was previously used for hydrogen degassing through 600 °C annealing of spoke resonators in earlier projects [5]. These cavities were annealed with titanium helium jackets and ConFlat flanges made of stainless steel. The KEK furnace, in contrast, has been primarily dedicated to R&D on heat treatments [3]. One of the objectives of this study is to validate the IJCLab furnace for advanced heat treatments, such as medium-temperature baking (mid-$T$ bake).

Each furnace and laboratory exhibits different behavior due to variations in parameters and local definitions. Traditionally, only the flat-top temperature and the duration of the heat treatment are reported; however, parameters such as ramping speed and temperature homogeneity are often overlooked. For example, a statement such as “300 °C baking for 3 hours” does not specify how these terms are defined in different laboratories. To enable systematic comparison of furnaces and to establish unified conventions and terminology, we propose three parameters: the area, the ramping-up time constant $\tau_h$, and the ramping-down time constant $\tau_c$, in addition to the flat-top temperature $T$ and its duration $\Delta t$. Figure 2 shows the temperature profile measured by a sensor mounted directly on the cavity. Although the furnace control was set to 300 °C, the cavity temperature rose to 316 °C, leading to an underestimation of the actual heating temperature. In contrast, the KEK furnace appears to overestimate the temperature, so that the true cavity temperature is slightly lower than the control target. This investigation is ongoing with additional datasets from DESY and JLAB. The complete results will be published elsewhere.

## VERTICAL TESTS

Heat treatments were investigated on a single-cell 1.3 GHz cavity, which was previously electropolished (EPed) aannealed at 800°C and then at 600 °C. Multiple vertical tests were carried out in 2024 and 2025. Since the cryostat at IJCLab has been dedicated to jacketed spoke cavities and its

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# EARLY EXPLORATION OF ZIRCONIUM DOPING SRF CAVITIES WITH CHEMICAL VAPOR DEPOSITION*

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*Abstract*

The introduction of zirconium to niobium SRF cavities suggests a promising alloy with lower RF losses, higher critical magnetic fields, and a higher endurance to gradients. However, difficulties in fabrication of a ZrNb alloy, especially on the irregular surface of SRF cavities, have slowed the applicatory study of this potential improvement. We utilize a newly commissioned chemical vapor deposition system to fabricate this alloy with minimal surface defects on irregular surfaces. We present the initial results of this method's effectiveness with surface characterization methods.

## INTRODUCTION

With bulk niobium cavities approaching their fundamental limits, recent years' studies have been dedicated to exploring alternate materials for SRF cavities. A Zr-Nb alloy surpasses the abilities of bulk niobium in the predicted superheating field, $B_{SH}$, which determines the maximum accelerating gradient, of up to 400 mT [1] compared to Nb $B_{SH}$ of ~220 mT [2] and a critical temperature, $T_C$, of approximately 13 K [3] compared to niobium's $T_C$ of 9.2 K [4], allowing for similar quality factors at higher temperatures or higher quality factors at similar temperatures that would be used for bulk niobium.

## COMPARISON TO $Nb_3Sn$

### *Critical Temperature*

The Jahn-Teller-Peierls limit suggests that Zr-Nb alloys can have critical temperatures up to 17.7 K [1]. Both Zr and Nb contribute d-band electrons near the Fermi level (e. g. the system is Jahn-Teller active) and, in an ordered structure of ZrNb, the density of states is enhanced via band degeneracy and orbital overlap increase. This is because the $\beta$-phase of ZrNb (Fig. 1) [5] allows for symmetry-adapted distortions – crystal distortion without breaking fundamental symmetry rules whilst allowing for the emergence of new physical behaviors, like electron-phonon coupling enhancement.

Considering conventional BCS theory:

$$T_C = 1.14\Theta Dexp(-1/N(0)V) , \tag{1}$$

where $\Theta_D$ is the Debeye temperature, N(0) is the density of states at the Fermi level, and V is the effective electron-phonon coupling constant, increasing the density of states at the Fermi level yields a higher $T_C$. Zr-Nb alloys in the $\beta$-phase, a continuous bcc structure, can have a varying composition without forming secondary phases, so the electronic structure evolves smoothly, and $T_C$ changes gradually. $Nb_3Sn$ has a sharp density of states, therefore a $T_C$ that is stoichiometrically sensitive. Small deviations from the 3:1 stoichiometry can easily disrupt its A15 phase and cause sudden drops in $T_C$ [6]. As can be seen in Fig. 2, a similar difference in critical temperature occurs at only a 4 percent composition difference for $Nb_3Sn$ and a 25 percent composition difference for ZrNb.

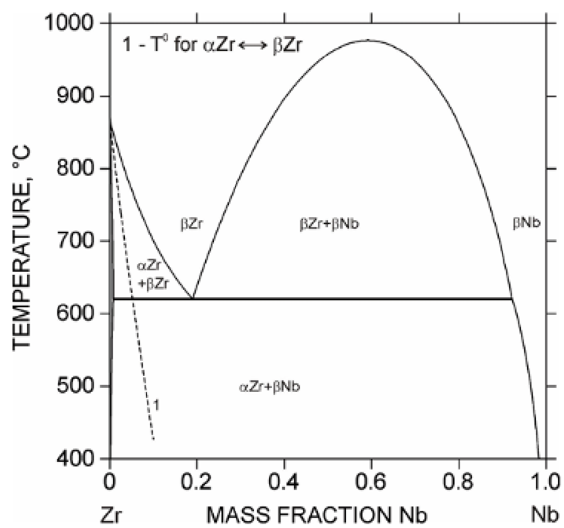


Figure 1: Phase diagram of ZrNb.

### *Quench Fields*

$Nb_3Sn$ has a thermal conductivity significantly lower than bulk Nb at cryogenic temperatures [7].$Nb_3Sn$ cavities are particularly prone to thermal instabilities under high fields due to the impairment of heat dissipation from the surface. Defects such as grain boundaries can act as hot spots that cause reduced quench fields and premature breakdown. Although Zr-Nb alloys have thermal conductivities less than bulk Nb [8], Zr-Nb alloys have smoother interfaces due to their continuous phase, which reduces the risk of thermal quench.

### *Coherence Length*

$Nb_3Sn$ has a very short coherence length, the average distance over which the electrons in a Cooper pair remain correlated, of 2–3 nm [9]. Short coherence lengths enhance sensitivity to local defects because when a defect is larger

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# HIGH Q – HIGH G STUDY ON SINGLE CELL MEDIUM GRAIN NIOBIUM CAVITIES

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*Abstract*

Medium Grain Niobium (MG Nb) is a cost-effective material compared to Fine grain Nb (FG Nb) that has isotropic mechanical properties and can clear the high-pressure gas safety criteria for a 1.3 GHz 9-Cell jacketed Tesla cavity. At KEK, various high Q – high G surface treatments have been applied to the 1-Cell MG Nb cavities, and its performance has been measured via vertical tests, with and without trapped flux. It has been observed that the performance of these cavities are on par with FG Nb cavities for standard, 2-step and Mid-T furnace baking. Moreover, the flux expulsion of the single cell MG Nb cavity has been studied at 800 and 900 °C annealing, and the subsequent performance improvement has been confirmed with 900 °C annealing.

## INTRODUCTION

R&D is conducted on direct-sliced medium grain (MG) Nb material, for jacketed SRF cavities, as a part of the cost-reduction studies for the ILC [1-3]. This material is cheaper to mass produce with respect to conventional fine grain (FG) Nb due to its manufacturing process. It has an average grain size of 200 – 300 µm with occasional grains of few mm, compared to FG Nb average grain size of 50 µm, which is widely used and industry standard. Extensive mechanical tests of the MG Nb from room temperature to liquid helium temperatures (4.2 K) have proven to be a viable cost-effective alternative to FG Nb, for a jacketed 1.3 GHz 9-Cell SRF cavity, in terms of high-pressure gas safety regulations [2, 3].

To determine the performance of the MG Nb compared to FG Nb, two single-cell 1.3 GHz SRF cavities were manufactured in-house at Cavity Fabrication Facility (CFF), KEK, as shown in Fig. 1 [3]. Due to the larger average grain size of MG Nb, orange peel effect was observed on the surface of the cavities, which can degrade the performance of SRF cavities. These cavities were tested with standard surface treatment of bulk electropolishing (Pre EP – 5 µm + EP1 - 100 µm), annealing at 800 °C * 3 h, another round of electropolishing (EP2 - 20 µm), and baking at 120 °C * 48 h. The performance of the MG Nb cavities exceeded ILC requirement of accelerating gradient (Eacc) ≥ 35 MV/m with a quality factor ($Q_0$) ≥ $1\times10^{10}$, on par with FG Nb cavities [2,3].

## PURPOSE OF THE STUDY

The performance of the MG Nb 1-Cell cavities is currently unknown for various high-gradient (high G) and high-quality factor (Q) surface treatments. In this paper, the performance of these cavities is determined for various high Q - high G surface treatments, such as two-step baking and medium temperature furnace baking (mid-T FB). Moreover, the flux expulsion of these cavities is measured with 800 °C and 900 °C, and the subsequent performance improvement is confirmed with 900 °C annealing. Also, the performance of the MG Nb 1-Cell cavities is further compared with 1-cell FG Nb cavities.

The high - G surface treatments refer to techniques that can generate Eacc > 35 MV/m with $Q_0 \geq 1\times10^{10}$. These surface treatments are important for future SRF cavity-based particle accelerators operating in pulse mode, especially for ILC. High-Q surface treatments refer to techniques that enable the SRF cavity to operate at higher $Q_0 > 3\times10^{10}$ and have a distinct anti-Q slope. Notable surface treatments are nitrogen-doping (applied for LCLS-II, SLAC) [4, 5] and mid-T furnace baking (oxygen diffusion) [6]. Recently, mid-T FB has been gaining traction due to its ability to produce both high G and high Q, by controlling the amount of oxygen diffusion in the bulk Nb.

## METHODOLOGY

A systematic study is conducted with specific surface treatments that are known to be reproducible with FG Nb 1-cell cavities at KEK, to determine the performance of the 1-cell MG Nb cavities for various high Q – high G surface treatments via vertical tests (VTs), its setup is shown in Fig. 2. For each surface treatment, a set of VTs were performed, with temperature scan (T-scan) from 2.0 K to 1.6 K in steps of 0.1 K. The experimental condition of the two VT's is:

- VT with flux expulsion: The maximum possible flux expulsion (at KEK) is achieved using a beam pipe (BMP) heater and fast cooldown, to create a $\Delta T$ of > 1 K between equator and iris of the single cell cavity. Solenoid coil surrounding maintains < 1 mG magnetic field around the cavity.
- VT with trapped flux: This VT is performed by applying 20 mG of magnetic field to the SRF cavity during superconducting transition. To ensure maximum trapped flux condition, the cavity is cooled down slowly during the superconducting transition, without BMP heater, to keep the flux expulsion < 1 mG.

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# SUPPRESSING Nb OXIDATION VIA NOBLE-METAL CAPS AND OXIDE REPLACEMENT: AB INITIO GUIDANCE

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*Abstract*

Niobium surfaces form native oxides that degrade superconducting radio-frequency (SRF) performance and coherence in superconducting circuits. We develop a unified *ab initio* framework that couples density functional theory (DFT), machine-learning (ML) sampling of amorphous-like oxides, and strong-coupling superconductivity calculations to design ultrathin passivation coatings on Nb. Interfacial and surface energies yield a spreading parameter that captures wetting on realistic Nb(110) microstructures, including vicinal steps and interfacial oxygen. This identifies a thin wetting/adhesion underlayer of Cu that enables continuous noble-metal caps at few-monolayer thickness. Adsorption energies show that protection against O/N/H saturates by ~2 ML for noble metals and their Au-rich alloys (AuPd, AuPt), so thicker caps provide little additional chemical benefit. An Eliashberg bilayer analysis then constrains the normal-metal thickness to preserve superconductivity, with $d_N/d_{\mathrm{Nb}} \lesssim 0.1$ maintaining $T_c/T_c^{\mathrm{bulk}} \geq 0.8$. Complementary ML screening of oxide chemistry highlights $Al_2O_3$ as substantially more resistant to H/N/O interstitials than native niobium oxides, with $ZrO_2$ showing similar but slightly weaker behavior. Together, these results provide practical stacks such as Au or Au-rich alloys (2–3 ML)/Cu(1–2 ML)/Nb and $Al_2O_3$ or $ZrO_2$/Nb to reduce residual surface resistance while maintaining superconducting performance.

## INTRODUCTION

Niobium has been widely used in SRF cavities and superconducting qubit substrates, yet native oxides and interstitial impurities (O, N, H) introduce loss and two-level systems (TLSs) that degrade its performance [1–3]. Metallic encapsulation for oxide passivation is an attractive solution, but three coupled constraints must be solved simultaneously: (i) chemical passivation against O/N/H, (ii) continuity (wetting and adhesion) on realistic Nb surfaces with steps and residual oxygen, and (iii) preservation of superconductivity in the presence of proximity-coupled normal overlayers. Here we formulate and apply a single *ab initio* framework for Nb that distills practical design rules for ultrathin encapsulation. We introduce a *wetting/adhesion underlayer (WAL)* to decouple adhesion from passivation (Fig. 1) and connect to recent demonstrations of noble-metal capping on Nb [4–10]. In addition to metallic capping layers, and following recent experimental trends [3, 11], we study replacing the native Nb oxide with a less lossy oxide by using machine-learning (ML) models to generate thousands of oxide unit cells and calculate interstitial formation energies of different contaminants—effectively sampling amorphous-like oxides that would be impractical with traditional DFT alone.

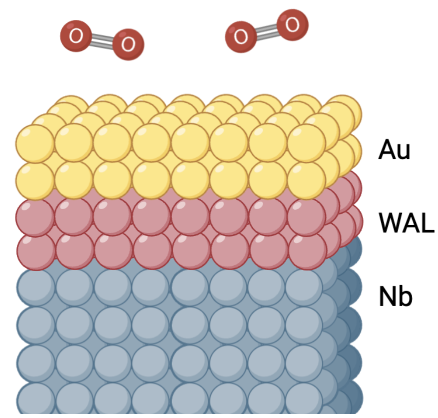


Figure 1: Illustration of Au capping layer, wetting/adhesion underlayer (WAL), and Nb substrate.

## METHODS

*DFT energetics.* Interstitial formation energies, surface energies, and interface formation energies were computed with plane-wave density-functional theory (PBEsol, norm-conserving pseudopotentials) using JDFTx [12–16]. Bulk calculations employed a 12×12×12 $k$-mesh; surface calculations used 12-layer bcc Nb(110) slabs with truncated Coulomb interactions in the surface-normal direction. Interface energies $\gamma_{\mathrm{int}}$ and epitaxial overlayer free-surface energies $\gamma_{\mathrm{cap}}$ (at the substrate lattice) were combined with the Nb(110) surface energy $\gamma_{\mathrm{sub}}$ to form the spreading parameter $S = \gamma_{\mathrm{sub}} - (\gamma_{\mathrm{int}} + \gamma_{\mathrm{cap}})$; $S > 0$ indicates wetting. To assess microstructure sensitivity and identify a suitable WAL under realistic conditions, we considered clean terraces, vicinal 3×1 stepped surfaces, and O-decorated (110) surfaces (1 ML O at hollow sites) for the interface-energy calculations.

*Modeling amorphous oxides.* By definition, amorphous oxides cannot be represented by a single periodic unit cell and are thus challenging to treat *ab initio*. We address this with two ML models [17, 18]: one generative (thousands of candidate oxide cells at a specified composition) and one predictive (fast energy/relaxation to filter stable structures within 0.01 eV of the convex hull). From the resulting stable set (~1000 unit cells per oxide), we computed interstitial formation energies for {O, N, H}, using a universal ML potential [18] to identify the most stable interstitial sites.

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# ELBE SRF GUN – THE MOST ADVANCED SOURCE OF ITS KIND

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*Abstract*

At the electron accelerator for beams with high brilliance and low emittance (ELBE) [1, 2], the second version of a superconducting radio-frequency (SRF) photoinjector was brought into operation in 2014. After a period of commissioning, a gradual transfer to routine operation took place in 2017, so that now up to 1800 h of user beam are provided every year [3]. In addition to the regular operation mode at 10 µA average current, the possibility of generating 1 mA at 13 MHz has recently been demonstrated. High average current is required to drive the IR-FELs at ELBE and therefore a CW beam from the SRF gun was accelerated to 30 MeV, after which lasing was readily achieved and even a sensitive user experiment could be conducted. This is particularly important with regard to the successor of the ELBE accelerator called DALI [4], which is planned to be fed by a similar SRF gun delivering 1mA average current.

## MOTIVATION

It is widely accepted that superconducting radio frequency photoinjectors (or SRF guns) offer highest flexibility and highest potential for continuous wave (CW) linear accelerators (LINAC) [5]. Although highest fields and, consequently, the best peak brightness are typically associated with pulsed normal-conducting RF (NCRF) electron sources, the situation changes once a quasi-continuous electron beam (repetition rates from MHz to GHz) becomes essential. Due to the inherent CW operation of superconducting cavities with simultaneously high field strength and high energy gain, which is the key for space charge compensation, best brightness can only be expected from SRF guns (Table 1). Furthermore, they enable very compact and efficient beam generation, especially for SRF LINACs where a LHe refrigerator already exists, as neither additional booster nor buncher cavities are required. For completeness, it should be noted that direct current (DC) photoinjectors are naturally running in CW as well, but as their energy gain is significantly limited by the breakdown voltage of the used insulators, peak brightness is limited to a medium level.

Table 1: General Comparison of Common Types of Electron Sources Based on Some Key Characteristics

| injector | NCRF | NCRF | DC | SRF |
|---|---|---|---|---|
| limitation | diss. power ~H² | | HV discharge | particulates |
| operation mode | pulsed | CW | CW | CW |
| cathode field | highest | med | med | high |
| energy gain | high | low | low | high |
| peak brightness | highest | med | med | high |

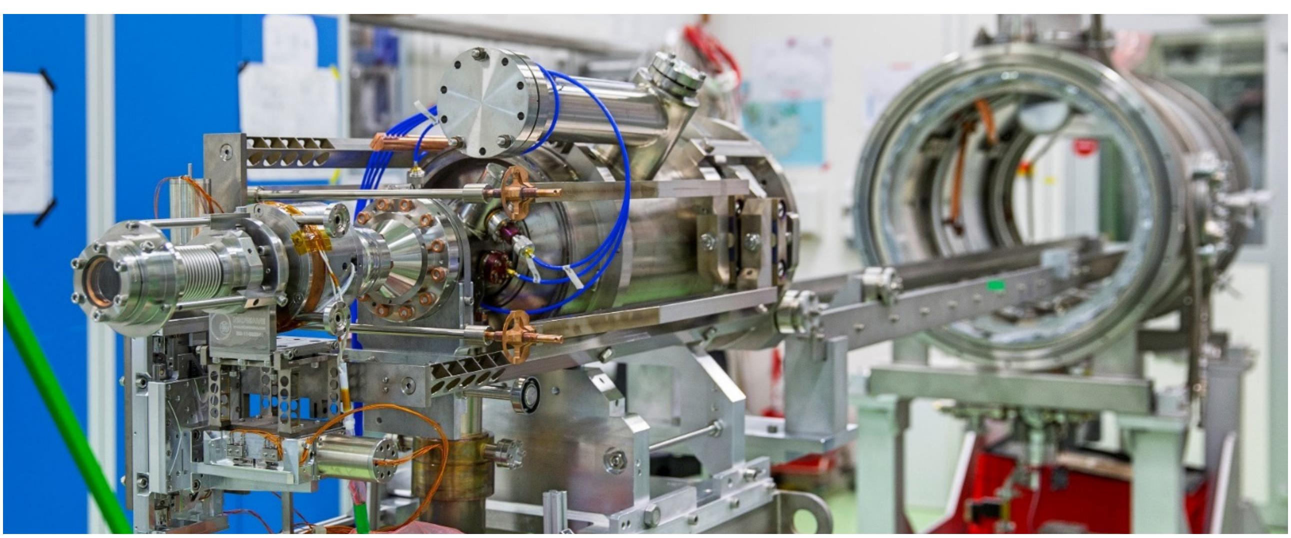

Figure 1: Photograph of SRF gun II during final assembly of the cold mass (front) into the cryomodule (background).

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# INITIAL RESULTS FOR CVD BASED GROWTH OF $Nb_3Sn$*

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*Abstract*

Niobium-3 tin Nb3Sn is a promising material for next-generation superconducting RF cavities due to its high critical temperature and high theoretical field limit. There is currently significant worldwide effort aiming to improve Nb3Sn growth to push this material to its ultimate performance limits. In this paper, we present the first results of deposition of Sn on different Nb samples in different orientations in our Chemical Vapor Deposition (CVD) system. We discuss imaging results for Sn on Nb substrates. We discuss CFD flow simulations and how they may be relevant to formulating a recipe for coating cavities. We describe the parameters used in the film deposition and future steps towards coating a 2.6 GHz cavity in our CVD system. We also discuss potential alternative tin precursors to improve coating uniformity and stoichiometry.

## INTRODUCTION

Niobium-3 tin ($Nb_3Sn$) is one of the most promising alternative materials to niobium for the future of SRF accelerator cavities. The material could in principle double accelerating gradients and operating temperatures of SRF cavities, decreasing costs and increasing efficiency of future accelerators [1–5].

The Sn vapor diffusion growth process is currently the most effective at creating films of good quality [4], leading to quench fields of up to 24 MV/m. Still, defects and surface roughness have hindered the performance of these films [3]. Exploring alternative $Nb_3Sn$ growth methods is important as some offer fundamentally different growth processes and allow for better control of the $Nb_3Sn$ growth mechanism, which should lead to improved RF performance. In this paper we will focus on the first Sn coating on Nb samples using the Chemical Vapor Deposition (CVD) system developed at Cornell.

## CHEMICAL VAPOR DEPOSITION (CVD) SYSTEM

The Chemical vapor deposition system at Cornell is described in detail in the references [6–9].

Figure 1 shows the sample holder with 4 Nb samples loaded into the furnace for a CVD coating using a $SnCl_2$ and $H_2$ as precursors to deposit Sn.

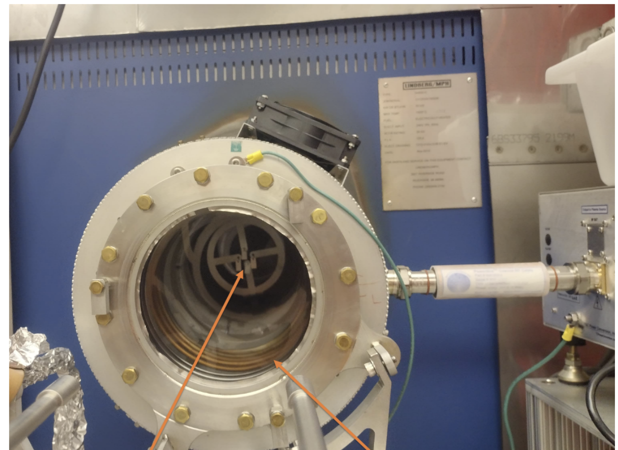


Figure 1: Sample holder inside deposition chamber of the CVD system.

## RUN FOR Sn DEPOSITION ON Nb SAMPLES

Here we describe the initial plan for the first Sn deposition run, and then then actual parameters for the CVD run. For the first run, we limited the HCl sensor reading on the CVD exhaust to 5 ppm, which necessitated process modifications during the actual run.

### *Initial Plan for First Sn Run*

- $SnCl_2$ Bubbler Temperature: 190 °C
- Heat Tape Temperature: 200 °C
- Furnace Temperature: 300 °C
- Time: 1hr
- Initial Target Pressure: 1 Torr
- Initial flow rates:
  - $H_2$/Ar: 500 sccm
  - Ar Carrier + Precursor: 500 sccm

For the actual run, we reduced the flow to 300 sscm for both the Ar gas (that carries $SnCl_2$) and the $H_2$/Ar gas mixture. The target pressure in the system was also raised to 3 Torr. After 30 minutes, the pressure was raised to around 5 Torr and that was maintained till the end of the run to keep the exhaust HCl sensor under 5 ppm.

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# COMMISSIONING OF A CHEMICAL VAPOR DEPOSITION SYSTEM FOR SUPERCONDUCTING THIN FILMS*

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*Abstract*

Next-generation, thin-film surfaces employing $Nb_3Sn$, ZrNb, or other compound superconductors are essential for reaching enhanced RF performance levels in SRF cavities. However, optimized and advanced deposition processes are required to enable high-quality films of such materials on large and complex-shaped cavities. For this purpose, Cornell University has developed and commissioned a chemical vapor deposition (CVD) system that facilitates coating on complicated geometries with a high deposition rate. This system is based on a high temperature tube furnace with high vacuum abilities and a gas and precursor delivery system. Here, we present the commissioned system with the control aspects and safety considerations addressed and the materials we are interested in growing.

## INTRODUCTION

Chemical vapor deposition is a powerful deposition technique that allows for uniform coating of high-quality films on irregular geometries. Isotropic distribution of gas-phase precursors in chemical vapor deposition is a superior technique for improved conformity and uniformity on surfaces compared to line-of-sight techniques such as sputter or evaporation for SRF technology [1].

With niobium cavities approaching fundamental limits of their material, alternative materials for SRF cavities are being explored. With the ability to improve performance while simultaneously lowering cost, this is an attractive option. $Nb_3Sn$, for example, with a critical temperature of 18 K and theoretical superheating fields nearly twice that of bulk niobium [2], is the forerunning alternative for SRF cavities. While the pursuit of alternative materials for SRF cavities has the realistic potential to lower both the length and cost of accelerators [3], the manufacturing of these cavities quickly becomes complicated due to requirements of near-perfect stoichiometric and surface requirements.

Chemical vapor deposition allows for precise tuning of partial pressures, substrate temperature, flow rates, and reaction kinetics, promising high control over material composition. Chemical vapor deposition also promises efficient control of film thickness with substrate temperature, flow rates, and deposition time control, as well as crystallinity control with substrate temperature and chamber pressure control. Over the past 5 years, design and assembly of a chemical vapor deposition system for SRF technology, initially conceptualized by Z. Sun. Past developments are detailed in Refs. [4–6]. Now, we have a functional chemical vapor deposition system with precise control for a broad exploration of alternative materials for SRF cavities, like $Nb_3Sn$ and ZrNb.

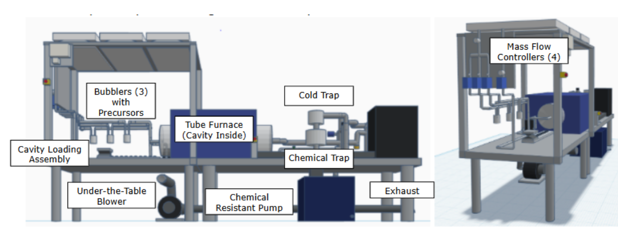


Figure 1: Three-dimensional chemical vapor deposition system model.

## CHEMICAL VAPOR DEPOSITION (CVD) SYSTEM

The chemical vapor deposition system at Cornell begins with carrier and reactant gases, Ar (g) and a 96.9:3.1 Ar:$H_2$ (g) mixture, whose flow rates are controlled via MKS mass flow controllers. The carrier gas flows through heated bubblers made of hastelloy. These bubblers containing precursor material are heated up to achieve an appropriate vapor pressure for deposition. The carrier gas caries these precursors in vapor form via the stainless steel tubing into the quartz tube furnace where the substrate/sample is located. The chemical vapor deposition system has a specialized loading system for sample study coupons and 2.6 GHz sized cavities inside a clean room. Inside the tube, the reactant gas yields the following example reactions of interest with precursors $SnCl_2$ and $Zr_4$, respectively:

$$SnCl_2(s) + H_2(g) \rightarrow Sn(s) + 2HCl(g) \qquad (1)$$

$$ZrCl_4(s) + 2H_2(g) \rightarrow Zr(s) + 4HCl(g). \qquad (2)$$

Throughout this process, the system, while able to achieve high vacuum pressures with its Pfeiffer HiPace 80 turbopump and Varian ion pump, maintains a controlled pressure via a VAT butterfly valve while pumping through a Ebara chemical-resistant pump. Once the chemical vapor deposition process is complete, any gaseous waste product is pumped through a Pfeiffer cold and Ancorp activated charcoal chemical trap to adsorb hazardous material before being

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# IMPEDANCE MEASUREMENT SETUP DESIGN OF A SILICON CARBIDE BEAMLINE HIGHER-ORDER-MODE ABSORBER*

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*Abstract*

Cylindrical shell silicon carbide (SiC) higher-order-mode (HOM) beamline absorbers (BLA) were developed and high-power tested for the 591 MHz single-cell superconducting radio frequency (SRF) cavities in the Electron Storage Ring (ESR) of the Electron-Ion Collider (EIC). The material properties of the BLA are crucial for HOM damping and wakefield performance. However, discrepancies were observed between the material parameters measured from small SiC samples and those of the full SiC cylinder used in the BLA, which has an inner diameter of 274 mm. To address this, a coaxial-type test setup was designed to measure the transmission characteristics and extract the material parameters of SiC. These parameters will support more accurate HOM analyses in the design of the 591 MHz SRF cavity string.

## INTRODUCTION

The Electron-Ion Collider (EIC) [1], currently under construction at Brookhaven National Laboratory (BNL) in partnership with Thomas Jefferson National Accelerator Facility, is designed to provide high-luminosity collisions of polarized electrons and ions. In the Electron Storage Ring (ESR), eighteen single-cell 591 MHz superconducting RF (SRF) cavities are employed to compensate synchrotron radiation losses of up to 10 MW.

To ensure beam stability, effective higher-order-mode (HOM) damping is essential. The maximum HOM power reaches 73 kW under the conditions of a 10 GeV beam energy, a bunch length of 7.7 mm, and a beam current of 2.5 A. To address this, a cylindrical-shell silicon carbide (SiC) beamline absorber (BLA) prototype with an inner diameter of 308 mm was developed and tested, demonstrating stable performance at surface power densities exceeding 0.44 W/mm$^2$ without damage [2]. The latest 591 MHz SRF cryomodule layout is shown in Fig. 1, which incorporates a room-temperature SiC BLA with an inner diameter of 274 mm placed between two single-cell cavities [3]. Figure 2 shows the BLA design, consisting of 14 mm thick SiC shells and oxygen-free copper water-cooling channels, with a total length of 240 mm.

However, discrepancies were observed in the dielectric parameters, both among small SiC samples from different vendors and between small samples and the full-size SiC shells. Such variations can significantly affect wakefield performance and the estimation of HOM power. To resolve this, a coaxial-type impedance measurement setup was designed to directly characterize the dielectric properties of the SiC cylinders used in the BLAs. The extracted parameters will enable more accurate HOM analyses in cavity string simulations and provide guidance for future BLA production.

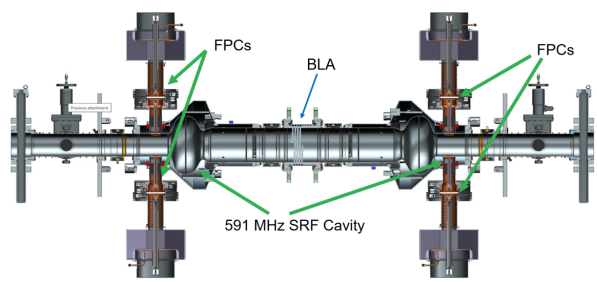


Figure 1: 591 MHz SRF cryomodule layout.

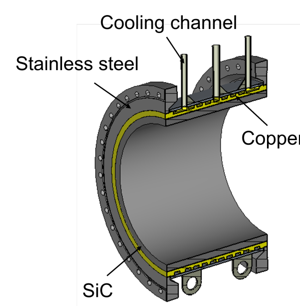


Figure 2: The design of BLA of 591 MHz cryomodule.

## MEASUREMENT SETUP DESIGN

Taking the Φ308 mm BLA prototype as an example, the measurement setup design is shown in Fig. 3. The system adopts a coaxial structure, where the ratio of the inner to outer conductors ensures a characteristic impedance of 50 Ω. On both sides of the BLA, tapered transitions are employed to connect to the existing 1-5/8” EIA to Type-N adapters. The vector network analyzer (VNA) is connected through the Type-N ports to measure the transmission coefficient $S_{21}$, from which the dielectric properties of the SiC material can be extracted. The impact of these parameters is discussed in the following section.

The taper length between the BLA and the adapters was optimized and chosen to be 400 mm. Figure 4 illustrates

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# RF PERFORMANCE RESULTS OF RF DOUBLE QUARTER WAVE RESONATORS FOR THE HIGH LUMINOSITY LHC PROJECT*

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*Abstract*

Double Quarter Wave (DQW) superconducting crab cavities will be employed to compensate for the vertical crossing angle in the High-Luminosity LHC (HL-LHC). Four DQW series cavities were manufactured and tested at the CERN vertical test facility. Each cavity undergoes a sequence of cold tests, starting from the bare cavity and progressing to the cavity in its final configuration, with all higher-order mode (HOM) couplers and the field antenna installed. This document presents the experience gained from RF cold test measurements of the first batch of DQW series cavities, with particular emphasis on measurements involving the HOM couplers. Challenges encountered during testing, such as limited field reach and the onset of field emission in two cavities equipped with HOM couplers, are also discussed.

## INTRODUCTION

The crab cavities are designed to apply an appropriate transverse kick to the head and tail of each bunch, effectively deflecting them to restore near head-on collisions at the LHC interaction points (IPs). This correction enhances the overlap of the colliding bunches, resulting in a significant increase in peak luminosity. To accommodate the different crossing angle planes, two cavity designs were selected: the Radio-frequency Dipole (RFD) crab cavity at IP1 for the horizontal crossing angle and the Double Quarter Wave (DQW) at IP5 to provide compensation for the vertical crossing angle [1,2]. Each cavity is made from high-purity bulk niobium sheets, operates at 2 K and provides a nominal transverse kick voltage of 3.4 MV at 400.79 MHz. Both cavity designs incorporate multiple HOM couplers to mitigate beam instabilities and reduce heat loads caused by the high proton current in the HL-LHC [3].

There are a total of 10 DQW cavities for HL-LHC: eight manufactured by Research Instruments GmbH (RI) in Germany and two by CERN. Among the eight cavities produced by RI, two have already been equipped with helium tanks and tested in their final dressed configuration, including HOM couplers and a field antenna. The remaining six cavities are undergoing cold tests at CERN in bare configuration, with helium tank integration scheduled to follow. Two additional DQW cavities were produced in-house at CERN [4] and prepared for testing with titanium helium tanks and RF ancillaries. Their performance was assessed at the CERN SM18 facility through cryogenic vertical tests of the bare, jacketed, and dressed configurations. Each cavity underwent

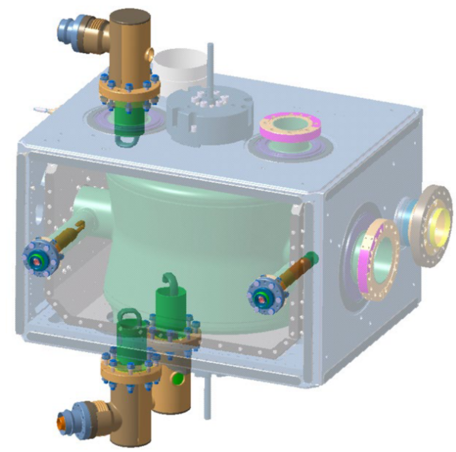

Figure 1: 3D view of the DQW dressed crab cavity with RF couplers and antennas [5].

a minimum of three RF tests at 2 K to establish compliance with HL-LHC requirements. In the bare cavity configuration, two antennas were installed, one used as the input with critical coupling or stronger and the other used as a pickup with weak coupling. The jacketed setup included a cold magnetic shield and a helium vessel around the bare cavity. The dressed configuration incorporated final components, such as HOM couplers and a field antenna, into the jacketed assembly, as shown in Fig. 1.

This paper discusses the main challenges encountered during the preparation, processing, and cryogenic testing of the four dressed DQW cavities. The results of the bare and jacketed cold tests for these cavities were previously reported [6]. Recent results from the remaining series production of the bare cavities will also be presented.

## RF TEST PREPARATION

After fabrication, the DQW cavities underwent a surface preparation program that included buffered chemical polishing (BCP) [7], high-temperature treatment at 650 °C for 24 h in an ultra-high vacuum furnace at RI, light BCP and rinsing with ultra-pure water at high pressure (HPR) for several hours [6]. Two vertical cryostats (V3 and V4) are used to perform the RF cold test, at 2 K, in the SM18 test facility. The outer surface of the cavity is equipped with contact CERNOX® temperature sensors and three single-axis magnetic flux probes. The cryostats are also equipped with radiation monitors for X-ray measurements and magnetic compensation coils to keep the ambient field around 0.5 µT during the cold test of bare crab cavities. The position of the

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# RFD CRAB CAVITY HOM EVOLUTION: DRESSED CAVITIES THROUGH TO CRYOMODULE TESTING AT 2 K*

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*Abstract*

As part of the High Luminosity Large Hadron Collider (HL-LHC) project, crab cavities will be installed around the CMS and ATLAS experiments of the LHC to accommodate the different crossing angle planes. Two cavity designs will be used: the RF Dipole (RFD) for the horizontal plane and the Double Quarter Wave resonator (DQW), for the vertical. A requirement for both crab cavity designs is strong Higher Order Mode (HOM) damping.

Two prototype RFD cavities, herewithin referred to as RFD1 & RFD2, were fabricated and successfully tested at CERN in the SM18 cryogenic test facility. Subsequently, the cavities were integrated into a cryomodule at STFC Daresbury Laboratory in the UK within the scope of the HL-LHC-UK collaboration. After transporting the cryomodule back to CERN, it was tested at 2 K to validate RF, mechanical, and cryogenic performance.

This analysis presents the HOM evolution for the two RFD cavities, including measurement results from vertical tests and cryomodule tests at 2 K. The measured results are compared with simulation data and used to qualify the HOM couplers and their performance across test environments.

## INTRODUCTION

For the High-Luminosity LHC (HL-LHC), Radio Frequency Dipole (RFD) cryomodules will be installed at Point 1 (ATLAS), deflecting in the horizontal plane [1]. The cryomodule discussed in this paper is currently installed in the Super Proton Synchotron (SPS), being the prototype cryomodule. The RFD cavities were successfully tested in their dressed configuration at CERN, wherein a dressed cavity test is a cavity integrated into its Helium tank with Higher Order Mode (HOM) couplers installed. Following successful validation, cryostating was carried out by UK-STFC. The cryomodule, containing two cavities, was then returned to CERN for final validation at 2 K prior to installation in the SPS.

As a critical component of the HL-LHC upgrade, the RFD crab cavity must meet the strict requirements related to beam stability and cryogenic heat loads, of particular significance here is the impedance contributions due to HOMs [1]. Therefore, HOM measurements form a critical part of the cryomodule validation process, providing direct insight into the damping performance in the cryostat environment.

To suppress the HOMs, the RFD cavity design employs two superconducting HOM couplers per cavity: one in the vertical plane (VHOM) and one in the horizontal plane (HHOM), as illustrated in Fig. 1. As well as effectively damping, the HOM couplers should not couple to the fundamental mode of the cavity at a frequency of ≈ 400.79 MHz. This is achieved by mounting the couplers into waveguide sections with cut-off frequencies above 400 MHz [2].

For the RFD cavity to be HL-LHC compatible the impedance limits are 200 k and 1 M/m for the longitudinal and transverse modes respectively [3]. The impedance spectra of the RFD geometry were simulated during the design phase to confirm compliance with HL-LHC impedance limits and to identify potential ‘detrimental modes’. The critical HOMs are those which result in high impedance or produce excess power. For RFD, these modes are summarised in Table 1 and will be tracked with additional attention [2].

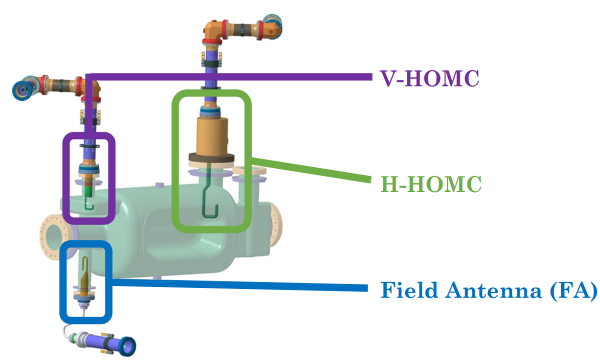


Figure 1: RFD Bare Cavity with HOM Couplers & Field Antenna.

Table 1: RFD Dressed Cavity: Critical HOMs

| Freq (MHz) | $Q_e$ | $R_{\perp v}$ ($k\Omega$/m) | $R_{\perp h}$ ($k\Omega$/m) | $R_{\parallel}$ ($k\Omega$) |
|---|---|---|---|---|
| 635 | 1121 | 0 | 573 | 0 |
| 752 | 192 | 0 | 0 | 17 |
| 1322 | 2974 | 0 | 625 | 0 |
| 1470 | 38208 | 0 | 348 | 0 |
| 1629 | 10404 | 1 | 758 | 0 |
| 1646 | 10742 | 2 | 63 | 8 |
| 1726 | 39216 | 11 | 355 | 0 |
| 1808 | 7574 | 2 | 389 | 0 |

Additional boundaries were placed upon the RFD's 750 MHz longitudinal mode which has the potential for interaction with the $19^{th}$ bunch spacing harmonic of HL-LHC type beam. Consequently, it is classified as a *high power*

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# ELECTROMAGNETIC DESIGN OF A QUADRUPOLE RESONATOR FOR SRF MATERIALS AT IMP *

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*Abstract*

The Quadrupole Resonator (QPR) is a dedicated radio-frequency characterization equipment for evaluating superconducting material. It employs the calorimetric compensation technique and has a surface resistance resolution of less than 1 nOhm, operating over a wide range of parameters, including temperature, resonant frequency, and magnetic field. As a part of R&D work of superconducting material for SRF application in particle accelerators, a QPR with an operating frequency of 325 MHz has been developed at Institute of Modern Physics (IMP), CAS. In this paper, we compared the electromagnetic properties of different loop shapes. The simulation results showed that adding certain chamfers to the edges of the loop is beneficial for increasing the peak magnetic field on the sample surface ($B_{sample}/B_{pk}$). Additionally, we optimized the edge leakage field of the sample by adjusting the geometric parameters of the loop, thereby reducing measurement error. Finally, the cavity is in the processing stage.

## INTRODUCTION

Superconducting radio frequency (SRF) technology is widely applied in modern particle accelerators, with SRF cavities serving as their core components. Currently, the SRF team is dedicated to developing new materials that go beyond the theoretical performance limit of niobium, such as thin films and multilayers. All these efforts are aimed at achieving a higher operational accelerating gradient ($E_{acc}$) and quality factor ($Q_0$) in the SRF cavity application. It is essential to characterize the materials' RF properties for the research of new surface treatment technology and new materials. Thus, a QPR test system has been developed since 2024 at IMP.

The Quadrupole Resonator (QPR), a dedicated sample testing apparatus originally developed by CERN in the late 1990s [1]. QPR is a four-transmission-line half-wave resonator using TE21-like mode, capable of measuring a wide range of magnetic fields, temperatures, and frequencies. The QPR system employs the RF-DC calorimetric compensation method to determine the surface resistance of samples, which has a high measurement resolution of less than 1 nOhm. As illustrated in Fig. 1, the RF loss is quantitatively determined by the difference in DC heater power ($P_{DC1}$-$P_{DC2}$). The average surface resistance is given by equation (1) [2].

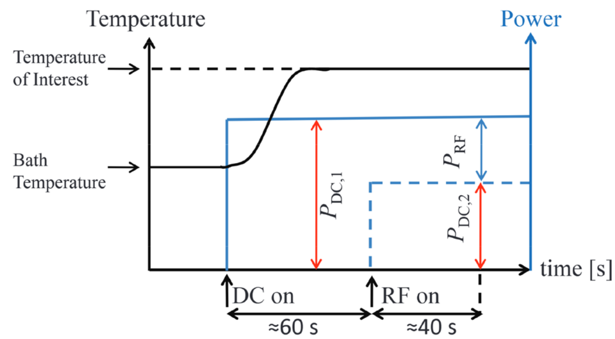


Figure 1: Measurement principle of RF-DC calorimetric system [2].

$$R_s = \frac{2\mu_0^2}{P_L \tau} \cdot \frac{c_1}{c_2} \cdot (P_{DC1} - P_{DC2}) \qquad (1)$$

Significant advances in material evaluations have been made possible through QPR systems at CERN, HZB, and UHH&DESY, including studies on Nb/Cu, $Nb_3Sn$ and NbTiN-AlN-Nb multilayers. However, several challenges may still hinder the achievement of theoretical performance benchmarks, such as mode overlapping, multipacting and the leak field. This paper investigates the RF properties of various loops.

p geometries and presents an improvement in leak field management of IMP's 325 MHz QPR, with a focus on enhancing measurement performance.

## RF DESIGN

### *Parametric Model*

The schematic view of IMP's QPR is given in Fig. 2, and the critical geometrical parameters are shown in Fig. 3. The system is designed to operate at a baseline frequency of 325 MHz, and the higher harmonic modes at 650 MHz, 975 MHz and 1300 MHz are also available for excitation. The lowest operating frequency (i.e., 325 MHz) offers the highest measurement resolution of residual resistance, due to the comparatively low level of BCS resistance contribution (as described in Eq. 2). This frequency range covers

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# VERTICAL TEST RESULTS FOR ITN SINGLE CELL CAVITIES

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*Abstract*

To support the ILC Technology Network (ITN) Cryomodule project at KEK, we have constructed and assembled six single cell cavities, four fine grain (FG) and two medium grain (MG) for vertical testing (VT). A series of surface treatment were applied to the cavities using the proposed recipe for the construction of the International Linear Collider (ILC). This recipe consists of four steps: bulk electropolishing (EP), annealing, cold EP, and finally two step baking. Using this recipe, we can consistently exceed the ILC specifications. We analyze the performance and characteristics of these cavities using Q vs E and temperature mapping measurements. One of the cavities was treated with a special recipe which skips the cold EP step to simplify the cavity preparation process. We find that this modified recipe is also able to exceed the ILC specification, however the quality factor was negatively affected.

## INTRODUCTION

The ITN project aims to develop high-performance SRF technology suitable for future accelerator facilities (see invited talk MOA04) [1]. As part of this effort, six single-cell cavities were fabricated and tested to prove our capability to achieve the ILC SRF cavity specification, quality factor of $10^{10}$ at 31.5 $\mathrm{MV\,m^{-1}}$ accelerating gradient. The ITN cavity processing recipe utilizes annealing, cold-EP, HPR, and 2-step baking to achieve high Q high gradient without field emission. The cavity batch includes both MG and FG niobium material types to investigate the performance of different niobium material types.

## CAVITY OVERVIEW AND PROCESSING

### *Cavity Types*

The six tested cavities are summarised as follows:

- **Medium Grain (MG):** 2 cavities
  R1MC01
  R1MC02
- **Fine Grain (FG):** 4 cavities
  R1FC01
  R1FC02
  R1FC03
  R1FC04

All cavities share the same single-cell geometry designed for 1.3 GHz operation.

### *Processing Procedures*

The cavity preparation procedure for the ITN cryomodule uses a combination of electropolishing (EP), high pressure water rinsing (HPR), 900 °C annealing, and 2-step baking to achieve high gradient and high quality factor. The steps are performed in the following order:

1. **Inspection:** Cavity inner surface is inspected and any defects are removed by manual grinding
2. **EP-1:** Bulk electropolishing to remove 5 µm by pre-EP and ∼150 µm of material by EP-1
3. **HPR:** High-pressure ultrapure water rinse
4. **Annealing:** Heat treatment at 900 °C for 3 hours
5. **EP-2:** Cold electropolishing (∼15 µm)
6. **HPR:** High-pressure ultrapure water rinse
7. **Assembly:** Power coupler, pumping port, and pick up antenna are attached and cavity is sealed
8. **2-Step Bake:** 75 °C for 4 hours followed by 120 °C for 48 hours
9. **Vertical Testing:** Cavity performance is measured

After cavities are received for processing the inside surface is inspected using a camera to look for defects. These inspection images are also used to compare with later inspections to see the effects of EP.

Electropolishing is performed in the STF EP facility using the horizontal cathode method. For EP-1 the cavities are polished using air cooling resulting in a cavity temperature of 26 °C. The polishing voltage for EP-1 is 41 V. For EP-2 the cavities are cooled by water from the outside, often referred to as cold-EP. The cavity temperature is maintained at 14 °C and a 16 V polishing voltage is used.

After each electropolishing the cavity is rinsed using ultrasonic cleaning for 30 min and then cleaned with HPR for 30 min. After EP-2 the cavity is thoroughly cleaned using HPR for 3 h and dried over night in a class 10 clean room before assembly. Assembly is performed in a class 10 cleanroom.

Annealing is performed in a high vacuum furnace at 900 °C for 3 h to outgas hydrogen from the cavity.

The ITN cavity preparation utilizes 2-step baking to be able to reach the high field required for the ILC specification. This process consists of two steps, a short 4 h heat treatment at 75 °C followed immediately by a 48 h heat treatment at 120 °C [2, 3]. A slow pumping system is used to minimize the turbulence in the cavity during pumping. This has been shown to reduce particulate contamination. Once the vacuum is below $1 \times 10^{-3}$ Pa the temperature increase to 75 °C is started. The temperature of the cavity is measured using thermocouples placed at 0 °, 90 °, 180 °, and 270 ° to give a

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# THE FABRICATION OF THE 1.3 GHz SINGLE-CELL CAVITIES BY NIOBIUM MATERIALS WITH FINE AND MEDIUM GRAIN SIZES

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*Abstract*

The collaboration research is conducted according to the ITN (ILC Technology Network). As a part of research into the manufacturing methods for SRF cavities used in ILC (International Linear Collider), two 1.3 GHz single-cell cavities were fabricated by utilizing fine and medium grain size niobium materials, respectively. Those cavities are manufactured by KAT Co., Ltd. in Korea under the research collaboration for ILC SRF cavity between KEK and KU (Korea University). Both cavities are fabricated with the same process and toolings including the pressing dies, machining jigs, and welding jigs. They have been tested in KEK and satisfied the required specification in the vertical test. This presentation shows lesson learn during the fabrication process of both cavities.

## INTRODUCTION

The International Linear Collider (ILC) requires high-performance superconducting radio-frequency (SRF) cavities with reliable manufacturing methods. In order to evaluate fabrication feasibility and potential material dependence, single-cell 1.3 GHz SRF cavities were produced using fine grain (FG) and medium grain (MG) niobium sheets. Fine gain high-purity niobium sheet has traditionally been the baseline material due to its well-established fabrication history and consistent mechanical properties. In parallel, medium grain niobium sheet, directly sliced form ingots, has been investigated as an alternative, offering potential advantages such as reduced lower costs. The focus is placed on the fabrication experience, the issues that were encountered, and the methods adopted to resolve them. The lessons learned here are expected to inform future multi-cell cavity fabrication efforts.

## FABRICATION PROCESS AND ISSUES

In the present work, two 1.3 GHz single-cell cavities were fabricated using FG niobium sheets and MG niobium sheets. The overall fabrication sequence was carried out using KAT equipment, following standard procedures for SRF cavity manufacturing. The main steps comprised: (i) Cutting a central hole in the niobium discs, (ii) press-forming into half-cell shapes, (iii) machining the iris and equator edges using a lathe, (iv) buffered chemical polishing (BCP) of each part, (v) electron beam welding (EBW) of each part. [1, 2] The fabrication of SRF cavities requires careful control of each step, as minor deviations during forming, machining, or welding can significantly affect the cavity final performance. In this section, we describe the fabrication procedures employed for both fine-grain and medium-grain niobium cavities, with focus on the difficulties encountered and the corrective actions applied.

### *Deep Drawing of Half-Cells*

Deep drawing is the first step in shaping niobium sheets into half-cells. Deep drawing requires optimization of process parameters to minimize defects such as wrinkling, tearing, galling and cracking. No particular issues occurred during deep drawing of the half-cell using the FG niobium sheet. However, during deep drawing of the MG niobium sheet, a crack occurred in the iris region of the half-cell. Both FG and MG half-cells were processed under the same die set and pressure conditions. To resolve this issue, the inner hole diameter of the sheet was increased from 55 mm to 60 mm, reducing stress concentration [3]. Additionally, a light buffered chemical polishing of 5 µm was applied to remove surface contaminants. After enlarging the inner hole diameter of the sheet, three MG half-cell were formed without any crack. Figure 1 shows the crack in the iris region of MG half-cell during deep drawing, and Figure 2 shows its elimination through sheet inner hole enlargement.

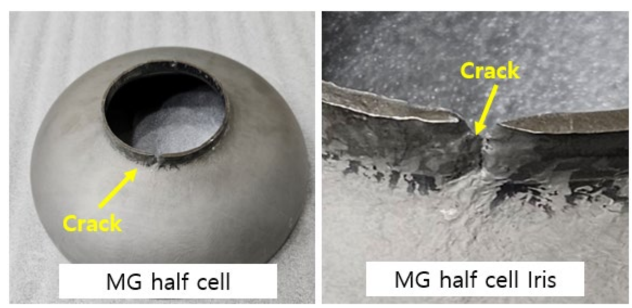

Figure 1: MG half-cell with a crack in the iris region.

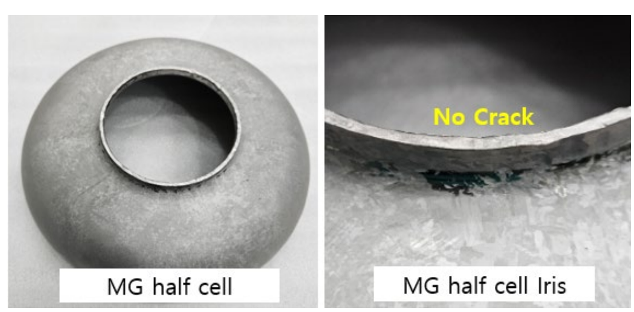

Figure 2: MG half-cell with sheet inner hole enlargement applied.

### *Beam Tube Machining and Grinding*

Niobium is a soft and ductile metal, and burrs are easily occurred during machining. While machining the niobium

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# STRENGTH EVALUATION OF LARGE-GRAIN NIOBIUM SHEETS AND DERIVATION OF ALLOWABLE STRESS

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*Abstract*

The high-purity niobium material used in superconducting cavities is an ingot produced via electron beam melting; it is a polycrystalline with a grain size of 10–200 µm. Niobium sheets sliced from ingots contain large grains (LGs). Superconducting cavities created from LG niobium have the advantages of a high maximum acceleration gradient, large Q value, and low manufacturing costs. Large-numbered tensile testing at room temperature using two types of LG niobium sheets with RRR392 and RRR189 was conducted; the tensile strengths were 79.2 and 83.3 MPa, respectively, about half that of ordinary fine grain (FG) niobium. The variation in strength was significant owing to crystal orientation. The minimum tensile strength was estimated based on material strength studies to apply the LG cavity to the High-Pressure Gas Safety Act, and the allowable stress for vessel design was derived, which was 12 and 15 MPa, respectively, less than half that of FG niobium. The strength estimation method described here can be applied with approximately 50 tensile testing results; it is also simple and versatile, and does not require crystal orientation measurement.

## INTRODUCTION

High-purity niobium used for superconducting cavities is an ingot produced via electron beam melting; it is a polycrystalline with a grain size of 10–200 µm. The central cell part of the 1.3 GHz superconducting cavity [1] shown in Fig. 1 is produced by pressing a niobium plate with a thickness of about 3 mm. The niobium plate is often produced by forging and rolling an ingot [2]. The crystals are finely divided, with a grain size of about 0.01 to 0.1 mm. These crystals are called fine grain (FG). In contrast, in another method, a cylindrical ingot is sliced to make cell material, which is then pressed to produce the cavity. The sliced disk contains large crystal grains, which are called large grains (LGs). An LG cavity has characteristics such as a higher maximum acceleration gradient and Q value than an FG cavity [1, 3, 4]. Furthermore, the slicing process is simpler than forging and rolling processes; therefore, it is effective in reducing the secondary processing costs of the material.

The superconducting cavity is installed in a helium tank, where it is immersed and cooled with liquid helium. These are subject to the High Pressure Gas Safety Act [5]. If the materials used or the soundness of the welds are different from the example standards, a prior evaluation by the High Pressure Gas Safety Institute is required. The allowable material stress to be referenced in the design is specified in the JIS standard [6]. For commonly used steel materials and non-ferrous metals such as copper and aluminum, an appendix is provided, and the values in the table are used. Materials not included in the appendix are called specially certified materials, and users must obtain and submit the mechanical property values of those materials. The FG cavity passed the prior evaluation using the property values submitted by the material manufacturer. However, no application for application of the High Pressure Gas Safety Act to the LG cavity has been submitted in Japan.

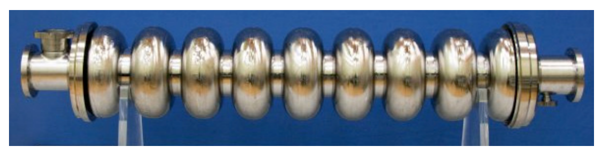

Figure 1: 1.3 GHz SRF cavity made by LG niobium (KEK-2) [1].

Reports have been published on the tensile strength of LG niobium at room temperature [7, 8], but the number of tests and ingots is small. Therefore, in this study, two types of niobium ingots were subjected to multiple tensile tests at room temperature to evaluate their strength. From the results, we attempted to derive the allowable stress of the material to be used in the design of the LG niobium cavity. Furthermore, we considered whether the LG niobium cavity can be applied to the High Pressure Gas Safety Act.

## PREPARATION OF TEST SPECIMENS

Two types of niobium ingots manufactured by Tokyo Denkai with different residual resistance ratios (RRRs) were used in the experiment. These ingots were sliced with a multi-wire saw to produce LG disks. Because the LG disks used in other experiments were reused, the diameters of the niobium ingots and the thicknesses of the disks for LG1 and LG2 were different, 290/2.55 mm, and 240/2.8 mm, respectively. Tensile test specimens were cut from the LG disks through wire cutting for the crystal

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# SRF R&D ACTIVITIES AT INFN-LASA

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*Abstract*

Sustainability and cost reduction are key factors for the development of future large particle accelerators. This has led INFN LASA to start an INFN-funded R&D program dedicated to studying and improving the performance of SRF Nb cavities in terms of quality factor (High-Q) and accelerating gradient (High-G). Moreover, the R&D program is also pushed by the INFN LASA contribution to international projects such as PIP-II and by the participation on the international collaboration ILC Technology Network (ITN). The strategy of the R&D program consists of studying and optimizing different surface treatments on 1.3 GHz single-cell cavities that will later be applied to 9-cell cavities in view of the industrialization process needed for large scale production. A key activity of this program is the upgrade of our experimental vertical cold test facility needed to enable the qualification of such high-performance cavities. Ongoing activities include a new dedicated cryostat designed to minimize the liquid helium inventory consumption, the implementation of an active magnetic field compensation for the reduction of trapped magnetic flux, and the usage of a wide range of diagnostics for quench, field emission, etc. This paper presents the current status of the facility and its key features, an overview of the cavities currently in production, and the experimental results obtained to date.

## INTRODUCTION

The future machines – such as lepton colliders and advanced light sources – require high-performance accelerators to push energy and beam quality beyond the present state-of-the-art. To achieve this, sustainability and cost reduction are mandatory.

Within the accelerator components, one of the key players to reduce footprint and cost are the improvement of the accelerating components, namely the Superconducting Radio Frequency cavities. The role of SC cavities has been also highlighted in the 2020 European Strategy for Particle Physics (ESSP) [1]. Therefore, R&D programs focused on the optimization of cavity surface and thermal treatments to achieve High-Q and High-Gradient (HG) performance are of strategic importance.

The SRF group of INFN Milano - LASA has extensive experience in designing, prototyping and producing with industry of niobium (Nb) superconducting (SC) cavities and related accessories. This includes significant research and development activities aimed at the industrialization of related technologies. The success of our approach is represented by the results we have obtained in our In-Kind contributions to major international projects, namely the European-XFEL, the European Spallation Source (ESS) and, recently, Proton Improvement Plan-II (PIP-II) at Fermilab in the framework of the DUNE experiment [2-5].

Maintaining and reinforcing this excellence and expertise is vital in view of future high-performance accelerators. In 2023, INFN initiated a 3-4 year program to support these activities (with a focus on future initiatives like the ILC, Muon Collider, FCC, etc.). The global relevance of this approach is supported by similar programs in different countries but also by international collaborations. One notable example is the ILC Technology Network (ITN) headed by Japan, which aims to achieve high gradient (High-G) while maintaining good $Q_0$, in line with ILC design goals [6]. Specifically, ILC targets 31.5 MV/m with $\geq 1\times10^{10}$ in pulsed operation while, for example, FCC aims for 20 MV/m with $3\times10^{10}$ in CW operation.

## OUR R&D STRATEGY

The strategy we have developed consists of a first R&D phase based on 1.3 GHz single cells cavities (the reference frequency for these activities) for the development of cavity processes that should allow extending the high $Q_0$ range towards the high gradient region. Once these treatments are consolidated, the second phase consists in transferring the processes to multicell cavities and, an essential step, make it industrially feasible in view of a possible future large-scale production. This strategy is synergic with our other current programs dedicated to future colliders (ILC, Muon Collider, FCC, etc.) as previously briefly discussed.

Moreover, the R&D activities here described, in particular the High-Q part, will benefit and take advantage of the on-going developments and studies we are developing in the framework of the optimization of the 650 MHz ($1^{st}$ sub harmonic of 1.3 GHz) PIP-II cavity treatments [7], given the very high $Q_0$ requested by the project but at modest accelerating gradient being the operation CW.

Within the reference time frame (3-4 years) of this activity, the plan for the activities we propose, based on 1.3 GHz technology, can be summarized as follows:

- **High-Q/High-Gradient process development** on two single-cell cavities, beginning with a baseline European XFEL-like treatment (150 µm bulk EP, 900 °C annealing, 10-20 µm final cold EP, 120 °C baking), and then including other advanced techniques such as mid-temperature baking (mid-T) and two-step baking. Performance validation will occur both at LASA and at partner labs (e.g. CEA) to enable cross-comparison and process validation.

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# ITN IN EUROPE: A COORDINATED EFFORT FOR ILC TECHNOLOGY DEVELOPMENT

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*Abstract*

The ILC Technology Network (ITN) in Europe, in close collaboration with KEK and key institutions including CEA, CERN, and INFN, is actively driving the development of advanced superconducting radiofrequency (SRF) technologies to support the realization of the International Linear Collider (ILC). The ITN-EU initiative focuses on developing and validating cost-effective, high-performance cavity production processes, transitioning from single-cell research and development to the industrialization of 9-cell cavities. Activities include optimizing surface treatment protocols, rigorous quality control of niobium materials, harmonization with Japanese High Pressure Gas Safety (HPGS) regulations, and preparing technical specifications for cavity jacketing and testing. As part of this program, Europe will contribute fully qualified SRF cavities to a globally designed ILC-type cryomodule for testing at KEK. The collaboration fosters knowledge exchange across laboratories and industry, supports advanced diagnostics development, and benefits from wider initiatives such as the Marie Skłodowska-Curie EAJADE network. These collective efforts not only support ILC realization but also reinforce Europe's strategic capabilities in SRF technology for future accelerators.

## INTRODUCTION

Superconducting radiofrequency (SRF) technology has reached a high level of maturity through large-scale accelerator projects such as the European XFEL and LCLS-II, and continues to evolve toward higher performance and cost-effective production.

Within this context, the realization of the International Linear Collider (ILC), a proposed 20 km electron–positron collider designed to reach 250 GeV center of mass energy and a luminosity of $1.35 \times 10^{34}$ $cm^{-2}s^{-1}$, relies on three key technologies: SRF cavities for beam acceleration, electron and positron sources, and nano-beam focusing [1]. To address the technological and organizational challenges associated with these components, the International Development Team (IDT) established in 2023 the ILC Technology Network (ITN), structured around time-critical Work Package-Primes (WPPs) covering SRF, sources, and nanobeams [2, 3].

Europe contributes unique expertise to the ITN through its experience with large-scale SRF projects such as the European XFEL and ESS, where extensive industrial partnerships, quality control procedures, and infrastructure for cavity fabrication and testing have already been established. Building on this foundation, Europe is well positioned to play a strategic role in advancing ILC technologies and ensuring the industrial readiness required for a globally coordinated construction effort.

Within this framework, the ITN-EU consortium, coordinated by CERN with the support of CEA-Saclay and INFN-LASA, plays a leading role in advancing SRF technology in close collaboration with KEK.

Its strategy focuses on developing an optimized, industrially viable production chain for high-gradient SRF cavities, beginning with single-cell prototypes to refine surface preparation "recipes" and progressing toward the industrialization of 9- cell cavities. Material procurement and qualification, including eddy current scanning of fine- and medium-grain niobium sheets and discs, have already been completed, and two single-cell cavities are currently under fabrication to validate the preparation strategies. In parallel, activities concentrate on harmonizing European production with Japanese High Pressure Gas Safety (HPGS) regulations, defining technical specifications for jacketing, and qualifying industries for large-scale manufacturing. A key milestone of the collaboration will be the assembly and testing at KEK of an ILC-type cryomodule equipped with eight 9- cell cavities—six procured by KEK and two delivered by ITN-EU—providing a comprehensive validation of the European contribution.

Through this integrated approach, ITN-EU not only contributes directly to the preparation for ILC construction but also strengthens Europe's strategic role in SRF technology. The activities support international collaboration on critical technologies, foster knowledge exchange between laboratories and industries, and lay the groundwork for future globally coordinated accelerator projects [4].

In this context, the four-year EAJADE EU Marie Curie program [5] plays a key role in supporting these activities. By funding staff exchanges between early-career European researchers and leading laboratories and universities in the US and Japan, EAJADE fosters valuable knowledge transfer and advances in the SRF field.

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# STATUS OF PIP-II HB650 CAVITIES PRODUCTION

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*Abstract*

The production of High-Beta 650 MHz (HB650) superconducting radio-frequency cavities for the PIP-II accelerator project has reached significant milestones, combining industrial manufacturing demands with advanced processing techniques to meet ambitious performance criteria. This paper describes the procurement, fabrication, testing, and process adaptations that have enabled world-record performance in these cavities, alongside challenges encountered and resolved during production.

## INTRODUCTION

The United Kingdom Research and Innovation Science and Technology Facilities Council (UKRI STFC) Daresbury Laboratory is responsible for procuring and testing 20 High-Beta 650 MHz (HB650) cavities for the Proton Improvement Plan II (PIP-II) accelerator project at Fermi National Accelerator Laboratory (FNAL, Fermilab). These cavities must meet stringent performance requirements (Table 1), including a gradient of 18.8 MV/m at a quality factor ($Q_0$) exceeding $4\times10^{10}$ which is achieved through electropolishing (EP) and nitrogen doping.

To date 7 High-Beta cavities, shown in Figure 1 have been fabricated in industry by Zanon Research and Innovation (Zanon) in Italy and delivered to Daresbury Laboratory and FNAL for qualification testing.

Table 1: PIP-II High-Beta 650 MHz Cavity

| Parameter | Value |
|---|---|
| Cavity type | Elliptical |
| No. of cells | 5 |
| Length, flange-to-flange (mm) | 1400.2 |
| Geometrical β | 0.92 |
| Frequency (MHz) | 650.00 |
| Nominal accelerating gradient (MV/m) | 18.8 |
| $Q_0$ at nominal gradient | $4 \times 10^{10}$ |

### *Procurement and Fabrication*

The HB650 cavity procurement strategy was focused on setting clear expectations and engaging vendors early in the process through a comprehensive market survey.

STFC's manufacturing specifications and requirements for the key steps such as surface treatments, High-Pressure Rinse (HPR), and final assembly were originally largely based on the collaboration's extensive experience and success of 1.3 GHz EU-XFEL-style cavities, incorporating lessons learned from other projects, PIP-II prototype experiences, and further refined utilizing potential vendors' feedback from the market survey.

Partner laboratories, STFC and Fermilab, closely collaborated with the vendor from the start to develop procedures, drawings, and quality control (QC) documentation. Collaborative vendor support has been continuously provided for the duration of the contract.

Pre-series cavities were subject to very detailed and involved quality control at every manufacturing stage to qualify vendor's processes, including additional hold points. The experience and QC refinements gained during the pre-series phase are now being leveraged to control series manufacturing, minimizing production interruptions and optimizing data review while maintaining the end-product quality.

Figure 1: Jacketed PIP-II High-Beta 650 MHz cavity.

### *Test Facility*

Qualification testing of the 2 pre-series cavities, B92M-ZRI-301 and B92M-ZRI-302, was performed initially at FNAL, for the bare cavities and then for jacketed, at STFC, as part of the fundamental verification of the industrial cavity manufacturing process. Jacketed cavities are being tested in the Test Facility (VTF) at the UKRI-STFC Daresbury Laboratory.

In conventional facilities such as FNAL and DESY, bare and jacketed cavities are mounted in the test stand vertically, immersed in a bulk Liquid Helium (LHe) bath. By contrast, the STFC VTF tests cavities after jacketing;

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# UPGRADES TO THE DARESBURY LABORATORY VERTICAL TEST FACILITY AND TESTING OF PIP-II HB650 CAVITIES

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*Abstract*

A novel vertical test facility (VTF) has been in operation at the UKRI-STFC Daresbury Laboratory since 2019. This VTF tests jacketed SRF cavities in a horizontal configuration at 2 K. Originally designed and operated for 704 MHz high-beta cavities for ESS, the facility has now been upgraded and expanded to test 650 MHz high-beta cavities for PIP-II, including fast cooldown capability (>20 K/min) for magnetic flux expulsion. This paper reports on the new design, commissioning, and operation of the facility.

## INTRODUCTION

The Proton Improvement Plan II (PIP-II) project is an essential upgrade to Fermilab's accelerator complex to enable the world's most intense high-energy beam of neutrinos for the international Deep Underground Neutrino Experiment (DUNE), and a broad physics program, powering new discoveries for many decades to come [1]. The UK's in-kind contribution to PIP-II includes work at the Daresbury Laboratory to supply and qualify twenty 650 MHz high-beta (HB650) cavities, followed by integration of eighteen of them into three superconducting accelerator cryomodules.

A companion paper [2] submitted to this conference details the cavity production, with this paper separately covering the upgrades to the cavity test facility at Daresbury.

The conventional method for vertical testing of SRF cavities is to fully immerse them in a large liquid helium (LHe) bath, and then cool to 2 K using vacuum pumps or cold compressors to reduce the vapour pressure over the bath. RF testing is then carried out with the cavities held at 2 K. This approach has been used successfully for many programs, including Eu-XFEL cavity testing at DESY [3]. However, whilst well-proven, this technique requires both a large LHe inventory and a large cryoplant (and, accordingly, large electricity draw).

With environmental sustainability in mind, an alternative Vertical Test Facility (VTF) cryostat architecture was developed for vertical testing of jacketed SRF cavities at Daresbury, requiring significantly less LHe and a much smaller cryoplant throughput. Originally designed, commissioned, and operated in the Superconducting RF Lab (SuRF Lab) at Daresbury between 2019 and 2024 for the 704 MHz high-beta cavities for the European Spallation Source (ESS) [4], this VTF has now been upgraded to meet the requirements for testing HB650 cavities for PIP-II.

The cryostat is based on a cavity support insert (CSI), where jacketed cavities are mounted horizontally below a header tank, fed by a common fill/pumping line. The insert is mounted into a cryostat vessel which comprises the outer vacuum chamber, magnetic shielding, and thermal radiation shields. The cryostat was manufactured by Criotec[1]. Sub-atmospheric pumps provide cooldown of the liquid to 2 K. Helium is recovered from the CSI cooling circuits, returned to an ALAT[2] Hélial ML cryoplant, which stores, purifies, and then reliquefies the He, providing a completely closed-loop system. Details of the VTF in its ESS configuration and of the cryoplant infrastructure have previously been reported elsewhere; the interested reader is directed to Refs. [5–7].

## PIP-II HB650 CAVITY TESTING REQUIREMENTS

The requirements on the UK facility for testing PIP-II HB650 cavities were set out and agreed with Fermilab [8]. Notable areas of upgrade undertaken to the existing facility are listed below and are detailed along with their respective commissioning and validation in the following sections.

- Mechanical changes to the insert to accommodate the larger cavity size and different port positions relative to the ESS cavities, and to direct the flow of LHe to enable fast cooldown (>20 K/min)
- Changes to the RF system to enable testing at 650 MHz rather than the previous 704 MHz for ESS cavities
- Changes to improve the magnetic hygiene at the cavity (requirement to be <0.5 µT for PIP-II rather than <1.0 µT for ESS)

## MECHANICAL AND CRYOGENIC UPGRADES

As has previously been reported [5–7], two identical inserts were built and commissioned for the ESS testing program at Daresbury. One of these (CSI-A) has been retained in the ESS configuration, whilst the second (CSI-B), has been modified for PIP-II. These two inserts are shown in Figs. 1 and 2 respectively.

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# FIRST RESULTS ON PLASMA CLEANING TESTS IN A SSR1-TYPE SPOKE RESONATOR FOR PIP-II PROJECT AT IJCLAB*

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*Abstract*

Plasma ignition studies have been initiated at IJCLab since 2022. These are focusing on "in situ" plasma decontamination of SRF cavities with complex geometries as Quarter Wave Resonator (QWR) and Single Spoke Resonators (SSR). IJCLab being strongly involved in PIP-II project and in particular in the qualification test of SSR1- and SSR2-type resonators, the vertical cryostat has been upgraded to implement plasma decontamination capabilities. With the support of Fermilab and Eurolabs project, the impact of plasma ignition on the performance of a prototype SSR1 cavity has been assessed. This paper will give an overview on the upgrade work done on the cryostat, on the plasma decontamination process and on the comparative analysis of the 2 vertical tests (before and after plasma process).

## INTRODUCTION

Plasma cleaning has been applied to Superconducting Radiofrequency (SRF) accelerating cavities since the 2010s. The pioneering works took place at SNS and was aiming at recovering initial performances of cavities which were degraded during their operation on the linac [1]. Acting as cryopumps, surface contamination was accumulated on the surface triggering lower field emission onset and thus increased X-rays emission level at nominal gradient. Plasma cleaning is offering a cost- and time-effective solution to mitigate field emission and potentially recover initial cavity performance without any cryomodule disassembly. Plasma cleaning requires cavity warming up at room temperature and injection of a gas mixture (a noble gas and oxygen) at a pressure level below 0.1 mbar. Plasma ignition is achieved by exciting the accelerating mode or an Higher Order Mode (HOM) thanks to the installed RF couplers (power coupler or HOM couplers) depending on their coupling at room temperature.

The plasma generates ions (Ar+, O-) and excited atoms (O*) which can break chemical bounds and desorb surface contamination. CO, CO2 and H2O are produced and evacuated thanks to the constant gas flow. At the sight of energy levels (few tens of eV), only carbon base contamination can be treated. Sputtering of other type of contamination like metallic compounds would require more energetic ions (several hundreds of eV).

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Plasma cleaning studies have been initiated at IJCLab in 2022 and are focusing on low beta cavities as Quarter-wave resonators (QWR) and single resonators Spoke (SSR). The goals were first to develop a plasma cleaning process to recover Spiral2 cryomodule and secondly to characterize plasma parameters by using plasma diagnostics [2]. Finally, in the framework of CNRS/IN2P3 contribution to PIP-II project [3], the capability of plasma cleaning to mitigate field emission and multipacting during cavity qualification in vertical cryostat was studied. This paper will summarize all activities and results obtained for this last study. This will cover the facility upgrades performed, the optimization of plasma cleaning procedure on a dedicated plasma test stand, measurements done during plasma treatment in the vertical cryostat and finally the impact on the cavity RF performances. The cavity used in this study is a prototype of a single spoke resonator SSR1 for PIP-II project [4].

## UPGRADE OF FACILITIES

In order to apply the plasma cleaning procedure during vertical testing, the vertical cryostat in operation on Supratech platform [5] at IJCLab required to be upgraded. All vacuum system and lines had to be modified to:

- Allow standard operation during vertical testing
- Simulate plasma cleaning in same condition as in cryomodule
- Allow plasma treatment of cavity in-situ without removal of insert from cryostat.
- Allow RGA analysis during standard operation (vacuum level 1E-8 mbar) and plasma treatment (vacuum level 1E-1 mbar).
- Ensure clean injection of gas and avoid particulate migration

Figure 1 depicts the schematic and Fig. 2 the pictures of the new vacuum system. All components of this line have been degreased in ultrasonic bath with detergent and assembled in ISO4 clean-room. After full assembly on the cryostat insert, the full system has been baked at 100 °C ensuring a vacuum level below 5E-9 mbar.

Gas is injected through a filter (0.5 um) and controlled by a flowmeter. Two independent vacuum systems are installed. The main, composed of a turbo molecular pump and a dry primary pump, evacuates the vacuum line and maintain vacuum level of cavity below 5E-8 mbar during normal operations. The second, with same composition, allows to maintain RGA at a vacuum level below 1E-4 mbar

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# CNRS CONTRIBUTION TO PIP-II PROJECT: OVERVIEW AND LESSONS LEARNED FROM SSR2 CAVITIES PROTOTYPING*

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*Abstract*

Since 2018, IJCLab is involved in PIP-II project on the design, development and qualification of accelerator components for the SSR2 (Single Spoke Resonator type 2) section of the superconducting linac. All pre-production components (cavity, coupler and tuner) have been fabricated and qualified either at IJCLab (tuner and cavity) and/or at Fermilab (coupler and cavity). This paper will summarize all tests done during this prototyping phase at IJCLab.

## INTRODUCTION

Since 2018, IJCLab [1] has been contributing in-kind to the Proton Improvement Plan-II project [2]. PIP-II encompasses a set of upgrades and improvements to the Fermilab accelerator complex. In particular, PIP-II project is aiming at constructing a new superconducting linac for which Fermilab benefits from a strong commitment as in-kind contributions of international partners.

The technical contribution of CNRS/IN2P3 is focused on the second Spoke section (SSR2 cryomodules) of the superconducting linac and covers from the preliminary design phase up to delivery phase of production components as described in detail here [3].

The contribution focuses on the three main components composing the so-called SSR2 dressed cavity meaning the cavity, tuner and power coupler (see Fig. 1).

This paper will give a summary of all activities and results obtained during the SSR2 prototyping phase terminated end of 2025.

Figure 1: Pictures of the three types of components: a SSR2 resonator (left), a power coupler (center) and a tuner (right).

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## TEST RESULTS

### SSR Power Coupler

Four couplers have been procured by IJCLab to the French company PMB [4] based on Fermilab design. All couplers have been delivered "ready for RF test" to Fermilab. Two couplers out of the four have the ceramic window coated with TiN to evaluate whether this multi-pacting mitigation coating was required to ensure safe operation and easier conditioning. From [5], couplers surpassed nominal power requirements of 12 kW and TiN-coated coupler didn't show improved behaviour during power conditioning. More technical details could be found here [6].

### SSR2 Frequency Tuner

Five tuners have been procured to the French PSI company [7] and delivered at IJCLab for cryogenic qualification. More technical details about tuners could be find here [8].

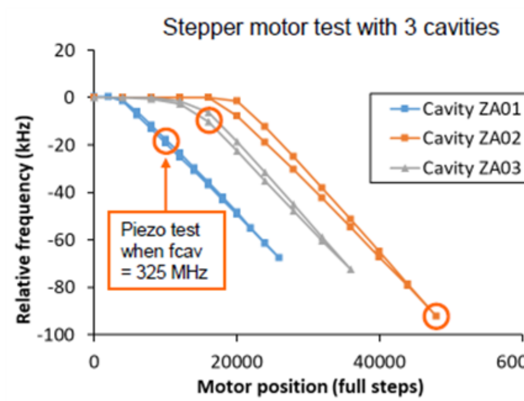


Figure 2: Plots of frequency detuning versus stepper motor position during three different cold tests of three different cavities and tuners.

Qualification tests consisted in tuning the cavity down to the frequency target of 325 MHz and assessing the frequency sensitivity, the mechanical hysteresis (in Hz/step) as well as the maximal detuning achieved by the piezo actuators when polarized at 100 V. Results are summarized in Table 1.

Four of them have been fully tested on a prototype cavity during vertical test and all of them show sound and reproducible mechanical behaviours (see Fig. 2).

Additional testing results could be found here [8].

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# INFN LASA ACTIVITIES TOWARD THE PIP-II LB650 CAVITY PRODUCTION

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*Abstract*

This contribution outlines the current status and recent progresses of INFN LASA's in-kind contribution to the PIP-II project at Fermilab.

It focuses on key manufacturing activities, on preliminary inspection results on sub-components and on upgrades to cavity testing infrastructures.

The production of the 38, 5-cell, β = 0.61 SRF cavities designed by INFN LASA for the LB650 section of the linac is underway, starting with two pre-series units aimed at validating the full manufacturing and processing workflow. The series production is being carried out by industry, with cavities also undergoing most of surface treatments as well as final cleaning and preparation at vendor's premises.

Final experimental qualification, to verify that cavities meet the challenging performance specifications required by the project, will be conducted through vertical cold tests at the DESY AMTF (Germany) facility before being delivered at CEA Saclay (France) as ready for string-assembly.

## THE INFN LB650 CAVITY FOR THE PIP-II LB650 SECTION

The *Fermilab* (USA) Proton Improvement Plan II (PIP-II) Linac is engineered to deliver a 1.2 MW $H^-$ beam, with future scalability to multi-megawatt operations, in support of the LBNF and DUNE neutrino research programs [1]. The 800 MeV beam is directed to the upgraded Booster Ring via a dedicated linac-to-booster transfer line and subsequently injected into the Main Injector Ring.

The PIP-II linac is designed with a flexible time structure for its 0.55 ms, 2 mA beam pulse, allowing adaptability to various experimental requirements. Its radiofrequency (RF) systems are capable of continuous-wave (CW) operation.

A critical portion of the linac is the 650 MHz superconducting section with a geometric beta of 0.61 (LB650), comprising 36 five-cell elliptical cavities housed in 9 cryomodules. This section accelerates the beam from 177 MeV to 516 MeV.

The target working point for the LB650 cavities, once in operation in the cryomodules, is set at a challenging and unprecedented 2.4 $10^{10}$ quality factor at the accelerating gradient of 16.9 MV/m [2]. Even higher targets are set for the qualification of cavities alone in the vertical cold test configuration.

All 38 superconducting cavities (36 series and 2 pre-series) will be delivered to the project by INFN after successful vertical cold testing [3]. They will arrive in a ready-for-string-assembly state: jacketed, fully equipped, and kept under ultra-high vacuum.

INFN LASA developed both the electromagnetic and mechanical design of the LB650 resonator, ensuring full compatibility with the performance requirements and technical interfaces defined by the project (Table 1). These include all cavity ports and flanges, the fundamental mode power coupler, the tuner, the helium vessel and all the interconnections with cryomodule environment in general.

Table 1: Design Parameters and Operational Performance Requirements of LB650 Cavity

| Parameter | Value |
|---:|---|
| $\beta_{geometric}$ | 0.61 |
| Frequency | 650 MHz |
| Number of cells | 5 |
| Cell-to-cell coupling, $k_{cc}$ | 0.95 % |
| Optimum beta $\beta_{opt}$ | 0.65 |
| $E_{peak}/E_{acc}$ @ $\beta_{opt}$ | 2.40 |
| $B_{peak}/E_{acc}$ @ $\beta_{opt}$ | 4.48 mT/(MV/m) |
| R/Q @ $\beta_{opt}$ | 340 Ω |
| G @ $\beta_{opt}$ | 193 Ω |
| Target acc. Gradient in CM | 16.9 MV/m |
| Target Quality factor in CM | 2.4 $10^{10}$ |
| Qualification gradient in VT* | 19.4 MV/m |
| Target Q0 in VT – naked | 2.9 $10^{10}$ |
| Target Q0 in VT – jacketed | 2.6 $10^{10}$ |
| Max. admissible radiation | 1 mSv/h |
| Multipacting-free range | 15.2 -18.6 MV/m |

## BASELINE TREATMENT RECIPE AND PREPARATION SEQUENCE

Through a preliminary R&D activity, also exploiting single and multi-cell cavity prototypes, the reference surface processing baseline recipe and the final preparation sequence has been defined, jointly by INFN and FNAL.

The key points of this sequence are briefly described below and visually summarized in the flow-chart in Fig. 1.

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# UPDATE ON INFN LASA IN-KIND CONTRIBUTION TO ESS ERIC SUPERCONDUCTING LINAC

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*Abstract*

INFN-LASA has successfully completed its in-kind contribution to the European Spallation Source Eric, delivering 36 superconducting medium beta cavities for the ESS Linac. These cavities are designed to increase the energy of the proton beam from 216 MeV to 571 MeV. In addition, four spare cavities are being fabricated. This article outlines the performance of the cavities delivered so far and updates on the production status of the latest cavities.

## INTRODUCTION

INFN Milano - LASA has taken on the responsibility of the Italian In-Kind contribution to the European Spallation Source (ESS) ERIC, specifically in the development of the Superconducting (SC) Medium Beta Cavities.

In the SC linac (see Fig. 1), the Medium Beta ($\beta$=0.67) cavities will intercept the 62.5 mA proton beam from the Spoke section at 256 MeV and accelerate it to 571 MeV, before the injection into the High Beta cryomodules. These modules will then boost the beam to its final energy of 2 GeV.

The 5 MW average power proton beam will operate in pulse mode at 14 Hz, with each pulse lasting 2.86 ms. The long beam pulse operation was a significant factor in the project decision to use superconducting cavities, as they allow achieving the project parameters while maintaining cost-effectiveness. Furthermore, there is a pressing need to operate the cavities at a high accelerating gradient to attain higher energy within the projected accelerator footprint.

Upon reaching the target station, the proton beam will generate a neutron beam through the spallation process [1]. Once operational, the European Spallation Source ERIC is set to become the world's most intense neutron source [2]. In March 2025, the SC Linac in a configuration that includes only five High Beta Cryomodule has been commissioned and the first proton beam has been successfully transported to dump [3].

As initial part of our contribution, we have developed the electromagnetic design for these cavities, optimizing it within the boundaries of mechanical requirements, industrial feasibility, and adherence to the ESS interface requirements. The importance of this last point should not be underestimated, as it has been instrumental in ensuring a seamless assembly of the cavities in their cryomodule at CEA Saclay.

The key parameters of the INFN Medium Beta cavities are summarized in Table 1.

Table 1: ESS Medium Beta Cavity Main Parameters

| Parameter | Value |
|---|---|
| $R_{iris}$ | 50 mm |
| Geometrical $\beta$ | 0.67 |
| $\pi$-mode Frequency | 704.42 MHz |
| Acc. length | 0.855 m |
| Cell-to-cell coupling k | 1.55% |
| $\pi$-$5\pi/6$ mode sep. | 0.70 MHz |
| Geometrical factor G | 198.8 Ω |
| Optimum beta, $\beta_{opt}$ | 0.705 |
| Max R/Q at $\beta_{opt}$ | 374 Ω |
| $E_{acc}$ at $\beta_{opt}$ | 16.7 MV/m |
| $E_{peak}/E_{acc}$ | 2.55 |
| $E_{peak}$ | 42.6 MV/m |
| $B_{peak}/E_{acc}$ | 4.95 $\frac{mT}{MV/m}$ |
| $Q_0$ at nominal gradient | $>5 \times 10^9$ |
| $Q_{ext}$ | $7.8 \times 10^5$ |

The designed was validated by a prototype cavity that outperformed the ESS project specifications. This set the base for starting the series production. We firstly procured the Niobiun materials and selected a qualified cavity producer by a public tender. The cavity vendor delivered then cavities fully treated, integrated and ready for qualification test. These tests have been done at DESY AMTF, a qualified infrastructure able to withstand the high throughput required by the ESS scheduling.

This paper provides a brief review on the cavity production, with a particular focus on the recovery actions undertaken to qualify cavities that were initially performing below expectations, incorporating lessons learned during the recovery process. Moreover, we present here also an update on the fabrication of four additional cavities that will be delivered next year to ESS as spares.

## CAVITY PRODUCTION

The ESS Medium Beta cavities production is based on the "build to print" scheme inherited from our previous work for European XFEL SRF cavities [4, 5]. To ensure high quality, strict guidelines for cavity production and a comprehensive Quality Control and Quality Assurance plan are enforced during the entire cavity production cycle [6].

Based on the ESS requirements, we have chosen to treat the cavities using a Buffered Chemical Polishing (BCP) process, both for the bulk treatment as well as as a final treatment.

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# DEVELOPMENT OF HIGH-PRESSURE RINSING (HPR) SIMULATION FOR SSR CAVITIES AT RAON*

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*Abstract*

High-Pressure Rinsing (HPR) is one of the most important processes in achieving high performance of SRF cavities. The geometry of SSR cavities differs significantly from that of HWR and QWR cavities. To upgrade the HPR process of SSR cavities, it is important to understand how much of the inner surface area can be effectively reached by the waterjet from HPR nozzles. HPR simulation software was developed to evaluate waterjet coverage based on parameters such as nozzle hole orientation, rotation speed, and translation speed of the nozzle rod. Two types of nozzles were fabricated for SSR1 and SSR2 cavities to improve rinsing performance. Prototype testing of SSR1 and SSR2 cavities using these new nozzles is currently underway at IRIS. The nozzle design is being optimized based on simulation and experimental results.

## INTRODUCTION

The SCL3 of the RAON accelerator was completed in 2023, and pre-production for SCL2 is currently in progress. The SCL2 linac consists of two sections: the first section includes SSR1 cryomodules, while the second section contains SSR2 cryomodules. Prototype SSR1 and SSR2 cavities have already been fabricated and tested. To enhance the performance of the cavities, many approaches are being considered. High pressure rinsing is one of such endeavours.

High-pressure rinsing (HPR) is one of the final processes that a cavity must undergo. It employs ultra-pure water (UPW) to remove particles and chemical residues remaining from the buffered chemical polishing (BCP) process. Advances in HPR, both in hardware and software, have been made at several institutes [1, 2]. In particular, software for calculating HPR coverage was developed at Fermilab [1]. Using this tool, it is possible to identify shadowed regions not reached by the waterjet, thereby providing valuable insight into the effectiveness of the HPR process for our cavities. Building upon this concept, we have developed our own simulation code that calculates the surface coverage of waterjets emitted from the HPR nozzle as it moves along a prescribed path while rotating.

## COVERAGE CALCULAION

We have developed codes to calculate the hit coverage by the virtual waterjet. We used MATLAB, Python, and C code for GPU computation. Matlab was used to verify algorithms and to generate the input datasets composed of the direction vectors of the virtual waterjet and nozzle position vectors along the HPR path and the post-processing or visualization of the results. GPU-accelerated C code was used to reduce computation time. Python was used to automate the batch processing of GPU computations.

### *Intersection Checking Code*

At first ray-triangle intersection algorithm was tested. There are many algorithms that calculate the intersection status of a vector to the triangle [3]. In our HPR simulation code, Barycentric coordinates were used to calculate the intersection status. Barycentric coordinates take values that sum to unity when a point lies within the plane of a triangle.

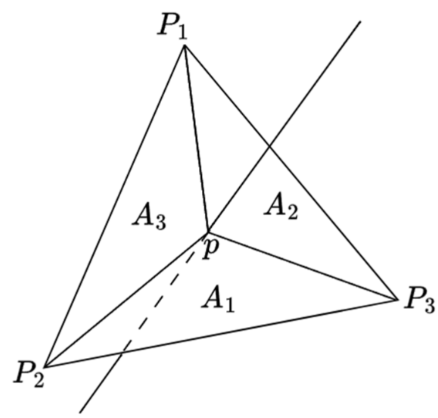


Figure 1: Barycentric coordinates.

In Fig. 1, $A_1, A_2, and\ A_3$ are the areas of the inner triangle that is made by point p and each pair of vertices of the triangle (P1, P2, and P3). If we define u, v, and w as follows:

$$u = \frac{A_1}{A_1+A_2+A_3}, v = \frac{A_2}{A_1+A_2+A_3}, w = \frac{A_3}{A_1+A_2+A_3} \quad (1)$$

The sum of u, v, and w becomes 1 when the point p is within the triangle or on the edge or on the vertex of the triangle. If the sum is larger than 1, it is outside of the triangle.

### *MATLAB and C Code for GPU Computation*

MATLAB code was used to prepare the dataset for the GPU computation for the intersection check of the waterjet vectors and to verify the algorithms and to visualize the results. MATLAB code first loads STL(Stereolithography) file which contains vertex and face information of the cavity. The vertex and face information can be easily extracted using MATLAB function. STL file format is one of the most widely used mesh file formats. Vertex and face information for SSR1 and SSR2 was generated by ANSYS Mechanical. The mesh counts were approximately 250,000 for

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# RF AND MECHANICAL DESIGN OF A 1.3 GHz 7-CELL HIGH-CURRENT SUPERCONDUCTING CAVITY

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*Abstract*

To meet the stringent requirements of high-current energy recovery linacs (ERLs), a 1.3 GHz 7-cell superconducting cavity was designed and optimized. The RF design employed multi-objective optimization to balance accelerating mode performance with higher-order mode (HOM) damping, achieving effective HOM suppression without compromising the fundamental mode performance. Key RF components, including the fundamental power coupler antenna and HOM absorbers, were optimized. Based on the optimized geometry, mechanical analysis was conducted to evaluate structural strength, pressure and tuning sensitivities, and modal behavior. Optimization of the stiffening ring radius further enhanced mechanical stability and reduced frequency variation. The integrated RF and mechanical studies demonstrate that the proposed cavity fulfills the performance and reliability demands of high-current ERL applications.

## INTRODUCTION

With the rapid development of accelerator-based light sources, such as synchrotron radiation and free-electron lasers (FELs), the demand for high-brightness and high-power beams continues to increase. Energy recovery linacs (ERLs) have emerged as promising candidates for next-generation light sources, combining the high average current of storage rings with the superior beam quality of linacs. By recycling beam energy after acceleration, ERLs can significantly reduce RF power consumption, lower beam dump radiation, and improve cost efficiency [1, 2].

In recent years, several ERL facilities, such as CBETA, cERL, KEK-EUV, bERLinPro, and S-DALINAC, have demonstrated the feasibility of ERL technology. Although significant progress has been achieved, reliable high-current operation still places stringent demands on the accelerating cavity. It must combine efficient acceleration with effective HOM damping while ensuring mechanical stability under operating conditions. To address these challenges, this work presents the RF and mechanical design of a 1.3 GHz 7-cell superconducting cavity optimized for ERL applications.

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## RF DESIGN

### *Cavity Optimization Strategy*

The optimization of the superconducting cavity was carried out in a hierarchical workflow, as illustrated in Fig. 1. The procedure consists of three stages: (i) optimization of the fundamental accelerating mode, (ii) evaluation and suppression of higher-order modes (HOMs), and (iii) verification after the inclusion of the input coupler.

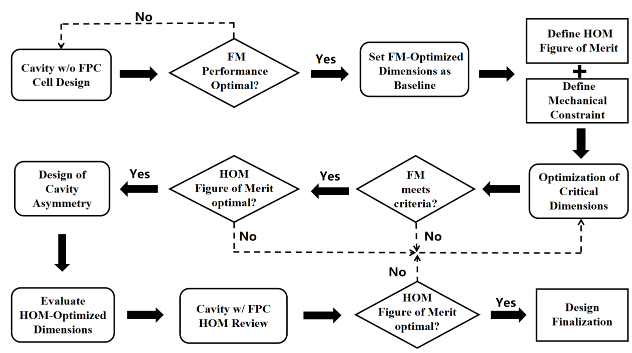


Figure 1: Hierarchical workflow of cavity geometry optimization, including fundamental mode optimization, higher-order mode evaluation, and verification after coupler design.

The RF design of the accelerating mode was guided by three objectives: (1) maximize the geometrical shunt impedance ($R/Q$) for efficient beam acceleration (e.g., Cornell 7-cell cavity achieves $R/Q = 774\,\Omega$); (2) limit the surface electric field to $E_{pk}/E_{acc} < 2.1$ to suppress field emission; (3) constrain the magnetic field to $B_{pk}/E_{acc} < 4.25\,\mathrm{mT/(MV/m)}$ to avoid thermal load and quench [3, 4].

The center cells adopt the TESLA geometry [5], while the end cells and transition regions were optimized using SUPERFISH. As shown in Fig. 2, nine parameters define the end-cell and transition geometry, with the half-cell length $L$ tuned for frequency and field flatness. The iris radius $R_i$ plays a critical role: a smaller value enhances accelerating efficiency but hinders HOM propagation.

Using the multi-objective optimization algorithm described in Ref. [6], an initial geometry was obtained that achieves optimal accelerating mode performance. The resulting cavity provides $R/Q = 784.8\,\Omega$, $E_{pk}/E_{acc} = 2.03$, $B_{pk}/E_{acc} = 4.23\,\mathrm{mT/(MV/m)}$, and 98.1% field flatness. This geometry serves as the baseline for the higher-order mode optimization presented in the following section.

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# CAVITIES MASS PRODUCTION FOR SHINE AT HERT

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*Abstract*

Beijing HE-Racing Technology Co., ltd. (HERT) is totally owned by IHEP, which has 120 employees. HERT started to produce SRF cavities in 2013. In 2018, HERT began to produce 1.3 GHz 9-cell cavities for Shanghai High Repetition Rate X-ray FEL and Extreme Light Facility (SHINE). To date, there have been more than 100 1.3 GHz 9-cell cavities made by HERT, which were purchased by SHINE, DALS, IHEP, etc. Moreover, the first 1.3 GHz high Q cryomodule was developed jointly by IHEP and HERT, which was the first mid-T baking cryomodule all over the world. The 1.3 GHz 9-cell cavities in the cryomodule achieved an unprecedented high average intrinsic quality factor (Q0) of $3.8 \times 10^{10}$ at 16 MV/m and $3.6 \times 10^{10}$ at 21 MV/m during the horizontal test. The cryomodule can operate stably up to a total CW RF voltage greater than 193 MV, with an average cavity usable accelerating gradient of more than 23 MV/m.

## INTRODUCTION

The main accelerator of SHINE is an 8 GeV CW SRF linac, which consists of 54 standard 1.3 GHz cryomodules, as shown in Figure 1. Each cryomodule is made up of 8 1.3 GHz 9-cell cavities and other components.

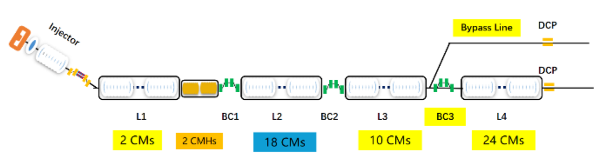

Figure 1: Accelerator layout.

The average gradient of cavity is 20 MV/m with $Q0 > 3.0 \times 10^{10}$.

Since 2013, HERT has been the leading vendor of 1.3 GHz TESLA cavities in China. To date, SHINE has ordered 152 (136+16) 1.3 GHz 9-cell cavities from HERT.

## CAVITY PROCESS

To meet the requirements of batch production, several innovations have been implemented, such as Multi Station Welding Fixture (3 sets), Semi-automatic Frequency Measurement, CNC Polishing Machine, Laser welding machine with a robotic arm, etc.

All production process is stable now, including machining, Surface Treatment, EBW, and test after EBW etc.

Figure 2 shows part of the production process.


Figure 2: Machining and EBW of cavities.


Figure 3: RF test and leak check.

After EBW, we check the Mechanical dimension, vacuum, frequency of bare cavity, etc., as shown in Figure 3.

The qualified cavities are shipped to Shanghai for post process and vertical test.

## HELIUM VESSEL ASSEMBLY

Laser welding machine, as shown in Figure 4, is applied to weld the seam of the helium vessel. And the structure is adjusted to fulfill the welding requirement. Figure 5 shows the welding structure of helium vessel.


Figure 4: Laser welding machine.

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# HOM ANALYSIS OF THE 1.3 GHz 3-CELL CAVITY FOR HIGH-CURRENT BEAM ACCELERATION*

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*Abstract*

Recently, 1.3 GHz 3-cell superconducting cavities were proposed for the injector of the high-brightness free electron laser based on the energy recovery linac scheme. In the injector section, three cavities are required to accelerate a 10 mA electron beam to 10 MeV. The diameter of the beam pipe is increased to 100 mm to damp higher order modes (HOMs), which may lead to beam quality degradation or beam instability. The results of HOM simulations and measurements will be presented in this paper.

## INTRODUCTION

Free electron lasers (FELs), as fourth-generation light sources, have wide applications in biology, medicine, and materials science. To achieve higher average power, ERL-based FELs are among the most promising next-generation options [1], where SRF technology enables high-current, high-quality beams in continuous-wave operation [2–4]. In the past two decades, several SRF-based ERL facilities, such as cERL [5], EUV-FEL [6], CBETA [7], and bERLinpro [8], have been constructed, with cERL operating for nearly a decade and CBETA demonstrating multipass energy recovery.

Recently, a high-brightness ERL-FEL injector was proposed in Shanghai [9], employing a 216.667 MHz VHF gun and three 1.3 GHz 3-cell cavities to accelerate a 10 mA beam to 10 MeV. The first bare cavity achieved $Q_0 = 2.0 \times 10^{10}$ at 12 MV/m and maximum $E_{acc} = 25.6$ MV/m after conditioning at 2 K, exceeding design goals [10]. This paper reports the higher order modes (HOMs) simulations and measurements of the 3-cell cavity.

## RF DESIGN OF THE CAVITY

Based on a multiobjective genetic algorithm, a 1.3 GHz 3-cell cavity design was proposed to meet 10 mA high-current operation [11]. The first version adopted the TESLA middle-cell shape [12], with optimized end-groups for HOM damping. To shorten fabrication time and maximize the use of existing techniques, a modified version also adopted the TESLA end-cell shape. A 100 mm beam pipe was introduced for HOM damping, and about 33 kW RF power is coupled through twin FPCs in continuous-wave mode. More details are given in Refs. [10, 11]. The schematic and fundamental mode field distribution are shown in Fig. 1.

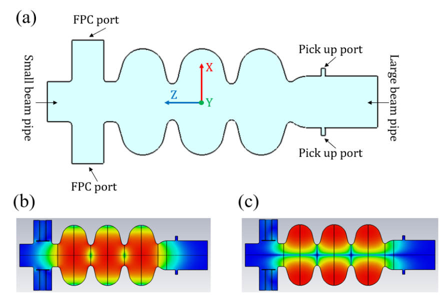


Figure 1: (a) Schematic of 1.3 GHz 3-cell cavity design, (b) electric and (c) magnetic field distribution of the fundamental mode.

## HOM SIMULATIONS

HOMs are a major concern for high-current operation, as beam–cavity interactions can cause power loss, emittance growth, or instabilities. To enhance HOM damping, the beam pipe diameter on one side of the cavity is enlarged to 100 mm. The cutoff frequencies of the 100 mm round pipe are 1756.8 MHz (TE11) and 2295 MHz (TM01). HOMs above cutoff propagate to the beam line absorber. A larger diameter could further suppress HOMs [11], but requires longer pipes to limit fundamental-mode loss and increases longitudinal space. Thus, 100 mm represents a compromise.

HOM impedances are calculated using the CST [13] Eigenmode solver with the lossy method, yielding longitudinal $R_\parallel/Q$, transverse $R_\perp/Q$, and $Q_e$. The longitudinal impedance is defined as [14]:

$$\frac{R_\parallel}{Q} = \frac{\left|\int_{-\infty}^{\infty} E_z(\rho = 0) e^{ik_n z}, dz\right|^2}{\omega_n U}, \quad (1)$$

and the transverse as:

$$\frac{R_\perp}{Q} = \frac{R_d}{Q} \cdot k_n, \quad (2)$$

where $R_d/Q = \left|\int_{-\infty}^{\infty} E_z(\rho = r) e^{ik_n z}, dz\right|^2 / (r^2 k_n^2 \omega_n U)$ [14]. Here $E_z$ is the longitudinal electric field at radius $\rho$, $U$ the stored energy, $\omega_n$ the resonant frequency, $k_n = \omega_n/c$, and $c$ the speed of light. Units are $\Omega$ for $R_d/Q$ and $\Omega$/cm for $R_\perp/Q$ [15], evaluated at $r = 1$ mm.

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# THE DESIGN OF A COMPACT CONDUCTION-COOLING SYSTEM FOR SRF CHARACTERIZATION

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*Abstract*

The precise and efficient testing of the RF performance of superconducting radio frequency (SRF) samples under superconducting conditions serves as the fundamental support for developing new SRF materials. The traditional SRF material RF performance testing systems have technical bottlenecks such as strong dependence on liquid helium, long testing cycles, and high operating costs. In this paper, a conduction-cooling RF performance testing system for SRF materials is presented. Without liquid helium (LHe) cooling, the system can achieve high-field and high-resolution measurements of surface resistance. The system is designed based on an optimized mushroom-type sample host cavity, which mainly works at 3.9 GHz TE011 mode. The sample has a diameter of 66 mm Coating the inner surface of the cavity with niobium-tin ($Nb_3Sn$) can reduce the microwave surface loss of the cavity, and the conduction-cooling structure of the system is also well-designed. In this study, the resolution and measurement range of surface resistance ($R_s$) are analysed via multiphysics simulation.

## INTRODUCTION

SRF technology is crucial for modern particle accelerators, owing to the ultra-low power dissipation and capability for Continuous Wave (CW) operation of SRF cavities. To further advance SRF performance and reduce operating costs, superconducting thin-film materials (e.g., $Nb_3Sn$, $MgB_2$) have emerged as promising candidates. Compared with bulk niobium, these materials exhibit higher transition temperatures, higher superheating fields, and other superior properties [1]. Research and development efforts are ongoing to develop methods for fabricating SRF films with stable and excellent RF performance. For the development of new materials, devices for SRF sample characterization, rather than experiments on actual cavities, are more economical and effective.

Early SRF testing platforms can date back to the 1970s [2]. Due to limitations in niobium cavity performance and temperature control precision, it was once challenging to simultaneously achieve a sample surface peak magnetic field exceeding 50 mT and nΩ-level $R_s$ resolution [3]. Recent designs have focused on three priorities: increasing the sample surface magnetic field for a wider measurement range, reducing sample size to facilitate mass fabrication, and adjusting the cavity resonant frequency to match the actual operating frequency of SRF accelerators. These platforms generally used sample-loaded resonant cavities, including sapphire-loaded impedance characterization (SIC) systems, quadrupole resonators (QPR), choked cavities, and mushroom cavities [4]. The 7.4 GHz SIC system is developed at Jefferson Lab (JLAB), which achieves $R_s$ resolution better than 1 nΩ but operates at a frequency far from practical SRF cavity applications [5]. The QPR systems are developed by CERN and Helmholtz-Zentrum Berlin (HZB), can achieve sub-nanohms level of $R_s$ resolution and a peak magnetic field exceeding 120 mT [6], but their sample replacement procedure is complicated. Research on mushroom cavities has been conducted by SLAC, Cornell University, the Institute of Modern Physics (IMP), and the Shanghai Advanced Research Institute (SARI) [7-10]. Systems based on mushroom cavities are capable of generating a peak magnetic field exceeding 100 mT on samples while maintaining nΩ-level $R_s$ resolution [9], allowing easy sample replacement. Nevertheless, most of these platforms rely on LHe cooling, which increases both the complexity and cost of experiments.

The aim is to address the challenges of high-resolution testing and LHe-free operation for SRF material performance platforms. $Nb_3Sn$ coated cavities received large efforts and have been demonstrated to enable conduction-cooled operation [11], showing great potential for application in such SRF test platforms. By introducing $Nb_3Sn$ coating, optimizing cavity geometry, and adopting conduction cooling, a comprehensive design scheme for an SRF material performance testing platform will be proposed. In this paper the electromagnetic optimization of the sample host cavity will be presented, and the design of the conduction cooling cryostat will also be discussed.

## CAVITY DESIGN

The core RF component is an axisymmetric mushroom-type cavity optimized for $TE_{011}$ -like mode at 3.9 GHz. A replaceable sample plate is affixed to the bottom of the mushroom cavity and directly exposed to RF field. In TE011-like mode, the magnetic field at the connection between the sample and the cavity is very small, with almost no RF leak. Meanwhile, the electric field lines form closed loops around the cavity axis, and the electric field is very small at the cavity wall and the sample. There is no electric field component perpendicular to the cavity surface, which prevents issues like electron multipacting and field emission.

The cavity's resonant frequency is set to 3.9 GHz, which is the 3rd harmonic frequency of the commonly used 1.3 GHz SRF cavities. The design target for the peak

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# DESIGN OF A 915 MHz CONDUCTION-COOLED CRYOMODULE*

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*Abstract*

High-power, compact, continuous-wave (CW) linear electron accelerators with beam energies of up to 10 MeV are being considered for possible industrial applications. Conduction-cooled, superconducting radio-frequency (SRF) technology allows operating such machines at high electrical efficiency, thereby reducing the operating cost significantly. A prototype conduction-cooled SRF cryomodule has been designed and components are currently being manufactured. The cryomodule features a two-cell, 915 MHz SRF cavity, two cryocoolers, a fundamental power coupler, two magnetic shields, a thermal shield and warm-to-cold transitions. The cryomodule has been designed to be able to provide an energy gain of 3.5 MeV to a CW electron beam with a current of 5 mA. This contribution focuses on thermal and mechanical design aspects of the cryomodule.

## INTRODUCTION

The progress made in the development of thin-film $Nb_3Sn$ superconducting radio-frequency (SRF) cavities along with the development of commercial closed-cycle refrigerators (CCR), also known as cryocoolers, with increasing cooling capacity at 4 K enabled the design of compact SRF accelerators for industrial applications [1, 2]. Applications such as the treatment of biosolids or wastewater [3], medical device sterilization [4] and phytosanitary treatment [5] would benefit from the availability of high-power, continuous-wave (CW) linear electron accelerators with beam energies of up to 10 MeV.

The use of the SRF technology would allow for a significant increase in the efficiency of the RF-to-beam power conversion, therefore reducing the operating expense of the accelerator. A beam power in the range 200 kW - 1 MW would allow a higher throughput of material being treated, for the same dose, therefore reducing the unit cost of treatment.

The requirement of high beam power results in the high-power RF source being a significant factor in the overall capital and operating cost of the accelerator. Commercially available, high-power 915 MHz magnetrons used for industrial heating are the most efficient high-power RF sources with the lowest cost per watt.

Jefferson Lab is leading a project aiming at producing a 915 MHz conduction-cooled cryomodule designed to be able to accelerate a 5 mA CW electron beam with initial energy of 1 MeV up to 4.5 MeV . The cryomodule is planned to be assembled and tested at General Atomics, without beam, with up to 20 kW RF power provided by a magnetron.

The cryomodule consists of a 2-cell 915 MHz Nb cavity with a $Nb_3Sn$ thin-film formed on the inner surface. A "low-loss" coaxial fundamental power coupler (FPC) is used to couple RF power into the cavity. Two CCRs, a Gifford-McMahon (GM) type with nominal capacity of 2 W at 4 K (model RDE-418D4, Sumitomo Cryogenics of America) and a pulse-tube (PT) type with a nominal capacity of 5 W at 4 K (model Cryomech PT450, BLUEFORS), respectively, are used to cool the cavity through flexible thermal links. Two layers of magnetic shields are used to minimize the residual magnetic field at the cavity surface. A thermal shield connects the higher temperature, 1$^{st}$ stages of the CCRs to a thermal intercept ring on the FPC through multiple thermal straps. Two warm-to-cold beamline transitions, each with two bellows sections, are connected between the cavity beamline flanges and the vacuum vessel. This contribution presents the design of the different cryomodule components, which was guided by finite-element engineering analysis.

## COLD-MASS ASSEMBLY

Figure 1 shows a 3D computer aided design (CAD) model of the cold-mass assembly, which consists of the 2-cell cavity, the warm-to-cold transitions, the FPC and the thermal links. The design of the 2-cell cavity is described in Ref. [6] and that of the FPC is described in Ref. [7]. Two types of cavities have been designed, with different thermal connections to the 2$^{nd}$ (4 K) stage of the CCRs. One cavity has a 4 mm thick Nb ring electron-beam welded at the equator of each cell, which will be thickened by 5 mm thick high-purity Cu layers, electroplated on both sides of each ring. A Cu electroplated layer will also be formed on sections of the beam tubes closer to the cells and on the Nb cooling plates electron-beam welded between the irises and the beam tubes.

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# CONDUCTION-COOLED OPERATION OF AN SRF MULTI-CELL CAVITY*

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*Abstract*

The development of compact, SRF-based accelerators for applications beyond research is experiencing notable advancements due to the use of cryocoolers for conduction cooling instead of traditional liquid cryogens. Following the successful demonstration of a single-cell cavity operated through conduction cooling with three two-stage cryocoolers, Jefferson Lab (JLab) has made strides in the operation of a multi-cell resonator. This milestone paves the way for high-energy applications of compact, conduction-cooled SRF machines. The demonstration, carried out in collaboration with General Atomics, will take place in a dedicated horizontal test cryostat (HTC) at their San Diego facility. This presentation will highlight the technological developments, the latest results, and valuable lessons learned.

## MOTIVATION

JLab continues to advance the development of compact irradiation systems utilizing conduction-cooled SRF cavities. The core components of such an accelerator system include an injector, an initial normal-conducting booster, a single cryomodule housing a conduction-cooled $Nb_3Sn$ cavity, and a beam delivery system (BDS) tailored to the specific application. A key design challenge is maintaining a compact footprint – ideally within the dimensions of a standard shipping container. This constraint also applies to auxiliary systems such as RF sources and cryocooler compressors, which must be similarly compact.

Following the initial design of a 1 MeV linear accelerator (linac) in 2018 [1], efforts have shifted toward achieving higher beam energies, up to 10 MeV. This progression is primarily enabled by transitioning from a single-cell to a multi-cell cavity within the cryomodule. The associated design and simulation work has been detailed in Ref. [2]. Figure 1 presents a CAD rendering of the latest design iteration, while Fig. 2 illustrates the beam energy progression along the beamline, as determined through beam dynamics simulations.

To support this design initiative, a hardware demonstration is underway to validate the conduction-cooled operation of a multi-cell cavity. Building on the previously demonstrated single-cell cavity operation, this test uses the same HTC located at General Atomics in San Diego, a key collaboration partner [3]. The cooling system comprises three Sumitomo RDE-418D GM-type cryocoolers, each offering a nominal cooling capacity of 2 W at 4 K [4].

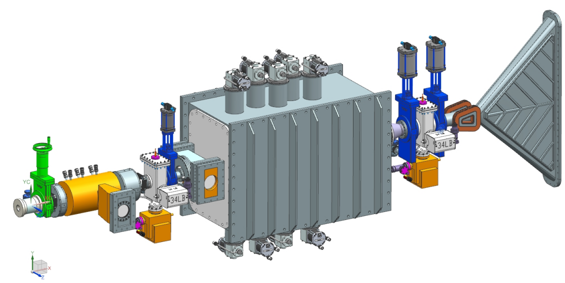

Figure 1: Design of a compact 10 MeV linac with injector, booster, five-cell 915 MHz cryomodule with nine 2 W cryocoolers and a beam delivery system.

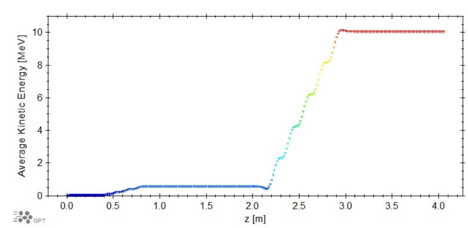


Figure 2: Result for the energy evolution along the above depicted beamline for a 109.3 pC electron bunch.

## MULTI-CELL CAVITY

While the 10 MeV compact linac design shown above is based on a 915 MHz five-cell cavity [2], the hardware demonstration was constrained by the physical limitations of the existing HTC. Due to space restrictions, a smaller multi-cell cavity was selected for testing. To further reduce costs, a hydroformed 1.3 GHz three-cell cavity – originally manufactured at DESY and previously used in other JLab experiments [5] – was repurposed for this demonstration. The cavity in its initial state is shown in Fig. 3. To adapt it for conduction-cooled operation, niobium rings were electron beam welded to each equator and subsequently plated with copper. This approach replicates the cooling strategy developed for the five-cell cavity used in the 10 MeV linac design [2].

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# INITIAL CONDITIONING OF THE 1.5 GHz PROTOTYPE COUPLERS FOR VSR DEMO*

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*Abstract*

Two prototype 1.5 GHz fundamental power couplers for the VSR (Variable pulse length Storage Ring) DEMO project at Helmholtz Zentrum Berlin (HZB) were produced by Research Instruments (RI) and Thales, with the aim of reaching 16 kW continuous wave (CW). To allow for conditioning of the couplers, a dedicated coupler test stand was designed, installed, and commissioned. The couplers were delivered March 2023 after substantial reworking; however, due to a vacuum leak during mounting, further reworking was required and were installed on the test stand June 2024. Such levels of rework dictated a more cautious testing plan. After a 120 C baking, an initial short conditioning run was performed in August 2024, followed by a longer run from April to May 2025. Here, we present the first conditioning results.

## INTRODUCTION

VSR DEMO is a feasibility study of a 3rd harmonic (1.5 GHz) SRF system for 500 MHz high current storage rings. Several 1.5 GHz components have been designed and manufactured and are now being tested at HZB including HOM damped multicell 1.5 GHz SRF cavities [1, 2]. These cavities require fundamental power couplers to provide 16 kW CW RF power. The 1.5 GHz VSR couplers are a scaled version of the Cornell ERL couplers [3, 4] with modifications to meet the VSR DEMO requirements.
The initial design and subsequent development is found in [5–8]. Prototype production by Research Instruments (RI) and Thales began in 2021; however, manufacturing challenges prompted design changes, including a significant change to the RF and vacuum seal between the warm part of the coupler and the waveguide. (Full details [9].) These modifications during production led to significant reworking, which, along with insufficient protection during welding and brazing, led to concerns about prototype quality and the implementation of a more cautious testing plan.

## CONDITIONING SET-UP

Couplers must be conditioned to process away contaminants and minimize the conditions for multipacting, ensuring reliability and good performance. To condition the couplers a dedicated RF testing set-up was designed and built ( cf.

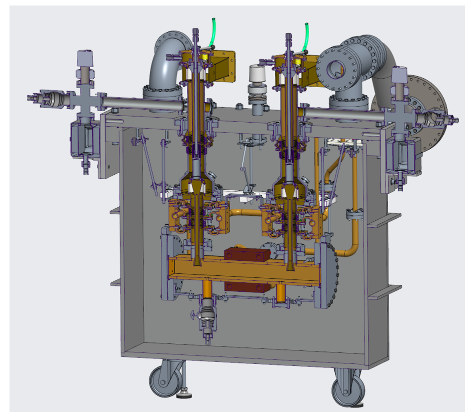

Figure 1: A cut through of the testing setup showing base RF testbox and couplers suspended in the vacuum of a cryostat.

Fig. 1), comprising of a base RF testbox designed specifically for these couplers, with 1.5 GHz cut off frequency and a separation between the couplers that ensures good transmission. The couplers are mounted onto the RF testbox and suspended in a vacuum cryostat up to the 300 K flange, to prevent icing and condensation when cooled. The system is cooled using gaseous helium at ≈90 K, with direct cooling on the base RF testbox and thermal strips on the coupler cold bellows, creating an environment that mimics module conditions. Additional cooling is provided with air and water cooling circuits. The couplers are equipped with a DC bias to combat possible multipacting, allowing for a voltage to be applied to the warm inner conductors.

### *Diagnostics and Monitoring*

For diagnostics and monitoring, the testing setup is split into three parts shown in Fig. 2. The upstream coupler, is defined as the warm part of the coupler connected to the RF input. The cold part, is the largest area and encompasses the cold parts of both couplers and the base RF testbox. Finally, the downstream coupler is defined as the warm part of the coupler connected to the RF output (a load). Each part is carefully monitored using the following sensors;

- Two arc detectors, one per coupler.
- Four vacuum gauges and getter pump readouts, one per region and one for the cryostat vacuum.

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# DESIGN AND CONDITIONING OF A LOW THERMAL LOAD COUPLER FOR CONDUCTION-COOLED ACCELERATORS

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*Abstract*

Thermal management of high-power input couplers is a critical challenge in conduction-cooled superconducting accelerators. This work presents a low thermal load input coupler design featuring a detachable electromagnetic shield , effectively directing microwave-induced heat toward the 50 K region. RF and thermal simulations confirm its efficient power transmission and reduced heat load at cryogenic temperatures around 4 K. Experimental tests validate the electromagnetic shielding performance. High-power conditioning demonstrates stable 70 kW CW power transmission, meeting the dual requirements of low thermal load and high RF power handling for conduction-cooled accelerators.

## INTRODUCTION

Conduction-cooled superconducting accelerators have attracted increasing interest due to their compact structure and reduced operational cost. Unlike traditional systems that rely on liquid helium, these accelerators use cryocoolers to maintain the superconducting state of radio frequency (RF) cavities, eliminating the need for complex cryogenic infrastructure [1].

However, the limited cooling capacity of cryocoolers—especially at temperatures below 4 K—poses a major challenge. Only a small fraction of it can be allocated to auxiliary components such as the input coupler. Most existing couplers, originally designed for helium-bath-cooled systems, exhibit relatively high thermal loads at the cold end and are thus incompatible with conduction-cooled environments.

To meet the stringent thermal requirements of conduction-cooled systems, several laboratories have proposed lower thermal load coupler designs. While these efforts have shown progress, challenges such as complex geometry, manufacturing difficulty, and insufficient power handling remain.

This work presents the design and fabrication of a high-power, low-thermal-load input coupler specifically developed for conduction-cooled superconducting accelerators. The coupler features a detachable electromagnetic shield, which effectively redirect microwave-induced heat toward high-temperature thermal anchors. This structure significantly reduces the thermal load at the cold end while maintaining excellent RF performance. The design also emphasizes engineering simplicity and ease of assembly, improving overall manufacturability and system reliability.

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Two prototype couplers have successfully passed a 70 kW continuous wave (CW) power conditioning test at room temperature, and they are planned to serve as the RF input components for the conduction-cooled electron gun at Peking University. This paper presents the couplers' electromagnetic design and key thermal management strategies in detail.

## ELECTROMAGNETIC DESIGN

In the design of a low-thermal-load RF coupler, we aim to support CW power of 50 kW while keeping the thermal loads below approximately 1.5 W at the 4 K stage and 35 W at the 50 K stage. Building on the coupler developed for the DC-SRF-II electron gun at Peking University [2], several modifications were introduced to reduce both conductive heat transfer and RF-induced thermal dissipation. Notably, the cold-end ceramic window was removed, as it contributed significant RF heating at cryogenic temperatures. Unlike liquid-helium-cooled systems that require a double-window structure to prevent helium leaks, conduction-cooled systems allow for a safe and practical single-window design. An electromagnetic shielding structure was incorporated via an impedance transformation section to suppress RF leakage and associated thermal loads.

The electromagnetic shield is a key component for thermal management. It concentrates most of the microwave-induced heating within itself and guides the thermal energy to the first-stage cold head of the cryocooler via thermal anchors. At the same time, it avoids direct thermal contact with the superconducting cavity, helping to reduce the thermal load on the 4 K region.A schematic illustration of the shielding structure and the intended heat flow path is shown in Fig.1.

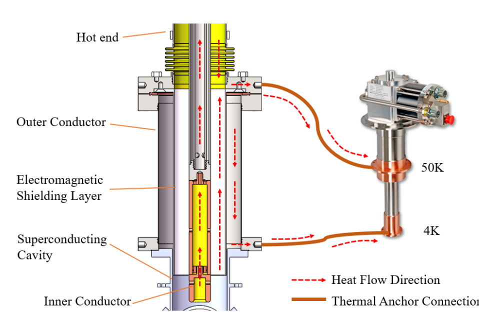


Figure 1: Schematic illustration of the electromagnetic shielding structure and the intended heat flow path in the coupler.

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# STATUS OF THE POWER COUPLER FOR THE HALF WAVE RESONATOR IN INSTITUTE FOR RARE ISOTOPE SCIENCE

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*Abstract*

A heavy-ion accelerator facility, RAON (Rare Isotope Accelerator for Online experiments), was constructed for the Rare Isotope Science Project (RISP) at the Institute for Rare Isotope Science (IRIS) in Daejeon, Korea. The cryomodule with quarter-wave resonators (QWRs) and half-wave resonators (HWRs) was installed in the SCL (Superconducting Linac) 3 tunnel, and the beam commissioning (Beam energy = 16.4 MeV/u, $^{40}Ar^{8+}$) has been completed. The geometry of the fundamental power coupler (FPC) for the HWRs is a coaxial capacitive type based on a conventional 1-5/8inch Electronic Industries Alliance (EIA) 50 Ω coaxial transmission line with a single ceramic window. The multi-physics analysis, which includes electromagnetic, thermal, and mechanical analysis, was performed by ANSYS to evaluate the thermal expansion of the power couplers. In this paper, we present the analysis results and revised design of the power coupler for HWRs.

## INTRODUCTION

The RAON is a heavy-ion research facility under construction in Korea for the study of rare isotopes. The supoerconducting linac 3 (SCL3), completed in 2022, consists of QWRs ($f$ = 81.25 MHz, $\beta$ = 0.049) and HWRs ($f$ = 162.5 MHz, $\beta$ = 0.13) for beam acceleration. During the beam commissioning in 2023, instability in the low-level RF (LLRF) control system was frequently observed. Post-analysis revealed that the source of instability was frequency drift in the HWRs, directly connected to the thermal expansion of the FPC. Since the fabricated FPC design lacked sufficient thermal loads, especially in the unplated stainless steel bellows, heat accumulation during RF operation resulted in mechanical deformation. To understand and mitigate this problem, we performed multi-physics simulations and installed temperature sensors to measure real-time temperature changes during beam operation. These efforts led to a revised FPC design, which is currently under fabrication.

## STATUS OF THE POWER COUPLERS

### *Design*

The FPC for HWRs at IRIS employs a coaxial capacitive coupling scheme utilizing a 1-5/8 inch EIA 50 Ω transmission line with a single ceramic RF window. Figure 1 shows the design of the fabricated model for HWRs. The brown-colored intercept and the inner conductor are both made of copper, while the outer conductor is made of stainless steel. The static heat load applied to the cavity is reduced through the 4.5 K and 40 K thermal intercepts. The FPC consists of two bellows: A cryomodule bellows to compensate for mechanical misalignment during assembly, and a vacuum section bellows to allow fine-tuning of the antenna penetration depth. The vacuum section bellows were fixed in place by four stud bolts to prevent shrinkage during vacuum pumping of the HWRs. The vacuum section bellows were initially fabricated without copper plating. This led to higher RF losses due to increased surface resistance. The main parameters of the FPC for HWRs are listed in the Table 1 [1].

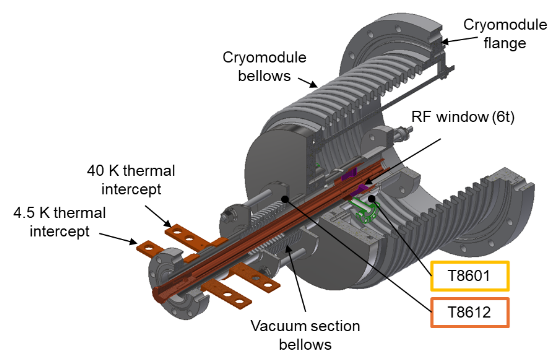


Figure 1: Design of the fabricated model.

Table 1: Main Parameter of the FPC

| Parameter | Value |
|---|---|
| Operating frequency | 162.5 MHz |
| Reflection coefficient (FPC only at 162.5 MHz) | < -20 dB |
| Operating power (Nominal) | 1.8 kW |
| Operating power (SSPA) | 4 kW |
| External quality factor | 1.1-1.8 ×10$^6$ |
| Impedance of the vacuum section | 48.2 Ω |
| Impedance of the air section | 50 Ω |
| TiN coating on the window | Not-Applied |
| Copper plating on outer conductors | Not-Applied |
| DC-bias | Applied |

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# HIGHER ORDER MODES COUPLERS TUNING OPTIMIZATION OF 1.3 GHz 9 CELL SRF CAVITIES FOR SHINE PROJECT*

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*Abstract*

The Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE) project has entered its construction phase. This state-of-the-art facility includes an 8 GeV electron linear accelerator, which utilizes superconducting radio frequency (SRF) cavities. Each cryomodule within the accelerator comprises eight standard TESLA 1.3 GHz 9-cell superconducting cavities with two Higher Order Modes (HOM) couplers. Effective suppression of HOM is crucial to maintain beam quality and stability.This paper discusses the performance and adjustment experiences related to the HOM couplers integrated within SHINE's 1.3 GHz cryomodules. We present detailed results from vertical and horizontal tests, emphasizing the successful HOM notch filter tuning to maintain the fundamental mode HOM Qext above 3.0E+11 at 2 K.Optimization strategies and revised specifications for HOM tuning have been established and formally approved.

## INTRODUCTION

The Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE) is an advanced X-ray Free Electron Laser (XFEL) facility under construction in Shanghai, China, designed to support advanced research in physics, materials science, and life sciences [1, 2]. The facility employs a superconducting radio-frequency (SRF) linear accelerator, operating in continuous-wave (CW) mode, to achieve high repetition rates and ensure stable beam performance necessary for precision experiments.

However, the high beam current and repetition rates inevitably give rise to the generation of HOM within the cavities [3, 4]. To mitigate these issues, the stored energy associated with the HOM must be efficiently extracted. This is achieved through the use of HOM couplers, which are strategically mounted on the beam pipe sections of standard TESLA 1.3 GHz 9-cell superconducting cavities [5]. Effective suppression of HOM is vital to maintaining beam quality and stability, particularly in high-repetition-rate XFEL facilities like SHINE. As shown in Table 1. the specifications of HOM damping were updated in October, 2024 [6, 7].

This paper focuses on the performance and adjustment experiences associated with the HOM couplers integrated within SHINE's 1.3 GHz cryomodules. It presents detailed results from both vertical and horizontal tests, highlighting the successful tuning of HOM notch filters. The findings contribute to the development of optimization strategies and revised specifications for HOM tuning, which have been formally approved as part of SHINE's operational plan. This paper provides valuable insights into the ongoing efforts to optimize HOM damping techniques, ensuring the stability and high performance of the accelerator.

Table 1: HOM Qualification Parameters in Horizontal Tests

| Qualification Parameter | Acceptance Condition |
|---|---|
| HOM antenna coupling in operating mode (Qext) | ≥ 3.0E+11 |
| HOM coupler emitted power (P_HOM) at Eacc = 20 MV/m | ≤ 1.4 W |
| HOM antenna coupling in HOM mode (Qext,hom) | ≤ 1.0E+6 |

## HOM COUPLERS TUNING AND CHALLENGES

Each 1.3 GHz 9-cell TESLA-type cavity is equipped with two HOM couplers. The HOM coupler located near the fundamental power coupler (FPC) is referred to as HOMc, while the one near the pickup side is designated as HOMpu, as shown in Fig. 1. Proper tuning of HOM filters is crucial, as it is essential to minimize RF transmission on the operating mode [8].

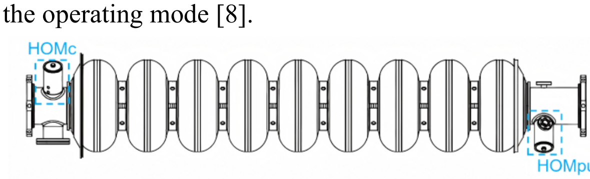


Figure 1: Side view of the 1.3 GHz 9cell cavity with two HOM couplers for SHINE Project.

Due to fabrication tolerances, surface treatment, cavity assembly in the cleanroom environment, and the slow vacuum pumping process, the HOM coupler's notch fre-

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# HIGH-POWER RF CONDITIONING OF MYRRHA PROTOTYPE POWER COUPLERS AT IJCLAB

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*Abstract*

The Multi-purpose hYbrid Research Reactor for High-tech Applications (MYRRHA) is an experimental accelerator-driven system currently being developed at SCK CEN. Its objectives include advanced fuel qualification, material investigations for Generation IV nuclear systems, studies on fusion reactor components, and the large-scale production of medical and industrial radioisotopes.

Within the French contribution to the MYRRHA project, IJCLab is responsible for industrial monitoring, quality control, and the RF conditioning of power couplers, which are designed to operate up to 60 kW at 352 MHz for the spoke cavity cryomodules.

This paper reports on the RF conditioning campaigns performed on prototype couplers in both full transmission and full reflection modes. The results provide insights into vacuum behavior, multipacting processing, and thermal stability under high RF power, highlighting the robustness of the couplers and the efficiency of the conditioning procedures.

Preliminary results from the prototype conditioning stage were partially presented in a previous publication. Here, we expand on those findings, highlight lessons learned, and discuss their implications for the qualification and preparation of the series couplers.

## INTRODUCTION

MYRRHA [1] aims to build an accelerator-driven system (ADS) in Mol, Belgium, powered by a 600 MeV, 4 mA superconducting linac. The front section uses 352 MHz single-spoke cavities in compact 2 K cryomodules and RF couplers rated up to 80 kW CW at 352 MHz**.**

Over the past fifteen years, IJCLab has built end-to-end expertise in high-power RF couplers (mechanical design, RF simulation, vacuum, clean-room assembly, RF conditioning) [2]. This was demonstrated with TTF3 couplers at FLASH, the industrialization and preparation of ≈800 couplers for European XFEL [3], and the conditioning of 30 couplers for **ESS** [4]. MYRRHA leverages this legacy and infrastructure to ensure reliable conditioning and qualification of its high-power couplers— a key milestone toward realizing this strategic ADS facility.

### *From Prototype Conditioning to Series Couplers*

After conditioning prototype couplers in transmitted-wave mode, a second campaign in full-reflection mode qualified RF behavior under the most demanding conditions and refined understanding of multipacting barriers**,** vacuum stability, and thermal response.

Next, a pre-series of four couplers will validate manufacturing choices, optimize assembly, and standardize conditioning protocols while establishing throughput and schedule for series production. Based on prototype results**,** a single design is retained for both pre-series and series, with TiN-coated ceramic windows to ensure stable conditioning and improved long-term reliability.

## COUPLERS CONDITIONING

The RF power coupler (CPLR), illustrated in Fig. 1, was designed by LPSC in collaboration with IJCLab, combining their complementary expertise in RF design and high-power coupler development. The design process included electromagnetic simulations to optimize impedance matching and minimize RF losses, as well as mechanical studies and thermal analysis to ensure safe operation up to 80 kW CW at 352 MHz.

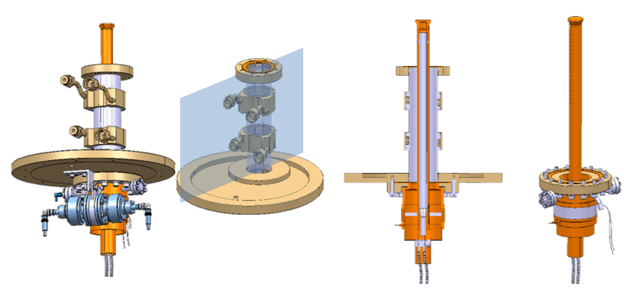

Figure 1: CAD views of the MYRRHA RF power coupler.

The different CAD views highlight the main functional parts of the coupler, including the ceramic window, the external cooling circuits, and the mechanical interfaces to the cryomodule, which are critical to guaranteeing reliable performance under continuous high-power operation. The detailed design methodology and associated results have been reported in previous publications [5].

### *Conditioning in Full Transmission Mode*

Figure 2 presents the RF power evolution during the conditioning of prototype couplers 2 and 3 in full transmission mode. In this configuration, the RF line is terminated by a matched load, and the conditioning was carried out progressively up to the maximum available power of 80 kW.

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# THE HIGHER ORDER MODE STUDY OF CSNS-II SUPERCONDUCTING LINAC*

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*Abstract*

The study of higher order modes (HOM) excited in the pulse mode superconducting Linac of CSNS-II is presented in this paper. The effects of cryogenic losses and influences on beam dynamics caused by the HOMs have been investigated.

## INTRODUCTION

As the only spallation neutron source in China, the China Spallation Neutron Source (CSNS) target beam power has been stably maintained above 100 kW, providing high-intensity neutron beam support for multidisciplinary research. The core goal of CSNS-II is to further increase the target beam power to 500 kW [1]. To this end, an additional superconducting acceleration section has been added to the linear accelerator.

The superconducting section comprises two parts: one featuring 324 MHz double-spoke cavities with a beta value of 0.5, and another consisting of 648 MHz elliptical cavities with a beta value of 0.62. Table 1 summarizes the 44 superconducting cavities to be installed in the CSNS-II Linac.

Table 1: Superconducting Cavities for the CSNS-II Linac

| Section | No. | Max $E_{acc}$ (MV/m) | $Q_{ext}$ |
|---|---|---|---|
| 0.1 | 4.59 | 4.48 | 4.01 |
| 1 | 4.93 | 4.82 | 4.29 |

Large number of cavities in CSNS-II SRF linac can result to resonance excitation of some high order modes with high shunt impedance. The main issues related to higher-order modes (HOMs) include cryogenic losses and beam instabilities, such as emittance degradation, energy spread, klystron-type instability, and the threshold current limit for beam breakup. The primary objective of HOM analyses is to determine whether HOM couplers or dampers are required for the elliptical cavities of CSNS-II.

## HOMS IN CSNS-II LINAC

HOM losses are primarily attributed to two types of modes: those with the highest impedance, and those whose frequencies are in close proximity to the main lines of the beam current spectrum. Spectrum calculations have been done for both type of cavities with CST code and PEC boundary conditions at the beam pipe end are used for non-propagating monopole and dipole modes, which impedance is defined as [2]:

$$\left(\frac{R}{Q}\right)_{\parallel,n} = \frac{V_{\parallel,n}^2}{\omega_n U_n} = \frac{\left|\int_{-\infty}^{+\infty} E_{z,n}^{(0)}\Big|_{r=0} e^{i\omega_n z/\beta c} dz\right|^2}{\omega_n U_n}. \quad (1)$$

$$\left(\frac{R}{Q}\right)_{\perp,n} = \frac{V_{\perp,n}^2}{\omega_n U_n} = \frac{\left|\int_{-\infty}^{+\infty} \frac{\partial E_{z,n}^{(1)}(r,\varphi,z)}{\partial r}\Big|_{r=0} e^{i\omega_n z/\beta c} dz\right|^2}{k_n^2 \omega_n U_n}. \quad (2)$$

### *HOMs in DSR Cavities*

The impedances of HOMs and corresponding $Q_L$ versus frequency are presented in Fig. 1. The beam pipe diameter is 50 mm, thus leads to a cutoff frequency of 797 MHz for TM01 mode and 610 MHz for TE11 mode through the beam pipe. 6 monopole modes and 12 dipole modes up to 900 MHz were calculated in the CST eigenmode solver.

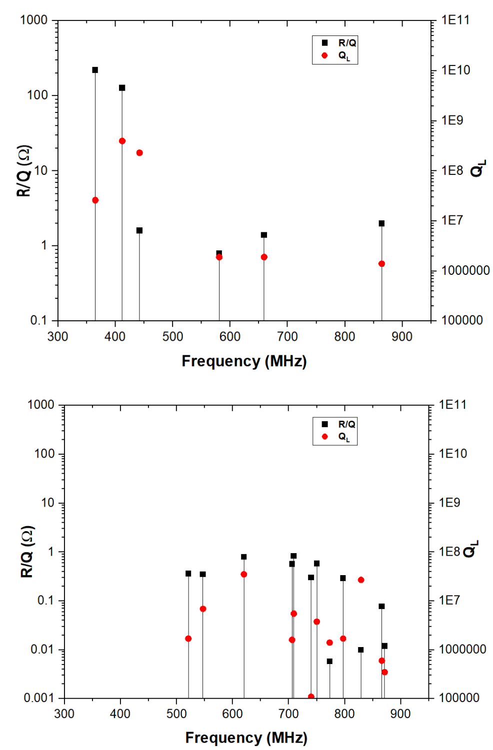


Figure 1: Calculated R/Q and Qext of monopoles (upper) and dipoles (lower) for CSNS-II DSR cavities.

As can be seen from Fig. 1, the spectral distribution of DSR cavities is fairly sparse and the impedances fall

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# FIRST ESS LINAC COOLDOWN USING THE MASTER AUTOMATIC CONTROL SEQUENCE

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*Abstract*

This paper presents the key aspects of cryogenic integrated controls system for the ESS superconducting linear accelerator and its importance during the first operational experience in a LINAC configuration, enabling for 2 MW beam power and beyond. This unified system is controlled by a master PLC (Programmable Logic Controller) managing the complete CMDS (Cryomodules and Cryogenic distribution System) consisting of 43 cells, each comprising a Cryomodule with 352.21 MHz Double-Spoke or 704.42 MHz Elliptical SRF cavities, and valve box, which in turn are controlled by their own dedicated PLC.

A key aspect of this integrated control system is the Master Automatic Control Sequence (MACS) that allows for the simultaneous cryogenic operation of the entire LINAC, managing and coordinating the different phases required for cryogenic operation, while handling failure response protocols, and operator interface requirements. The paper also highlights lessons learned during the operation, identifies areas for improvement, and proposes strategies for optimizing SRF cryogenic controls in the upcoming phases of the ESS project.

## INTRODUCTION

### *The ESS Superconducting Linear Accelerator*

The superconducting linear accelerator (LINAC) of the European Spallation Source (ESS) is currently being built in Lund, Sweden. Initial operations started in November 2024, with Beam on Dump achieved in May 2025. During this phase, 27 cryomodules (CMs) containing 82 superconducting (SRF) cavities were immersed in a superfluid helium bath at a temperature of 2K, enabling the proton beam to be accelerated up to 870 MeV and 2 MW [1]. Once completed, the accelerator will include a total of 43 CM, allowing it to achieve a beam energy of 2 GeV and a beam power of 5 MW [2].

### *The Master Automatic Control Sequence*

Manual operation of the full LINAC cryogenic system would require a large operations team, including several risks for the system: High workload, risk of human error by having to track many variables, un-synchronised cryomodule processes, and inconsistencies between modules [3]. To mitigate this issue, an Automatic Control Sequence (ACS) was designed, following the typical sequencer structure used in automated fluid processes [4]. This design was later extended with the incorporation of a Master PLC to orchestrate the entire Cryomodule and Cryogenic Distribution System (CMDS) which would host the Master ACS, taking care of the orchestration of each individual controls sequence so all cryomodules go through the states and operation modes at the same time. The Operator Panel Interface (OPI) showing the MACS can be seen in Fig. 1.

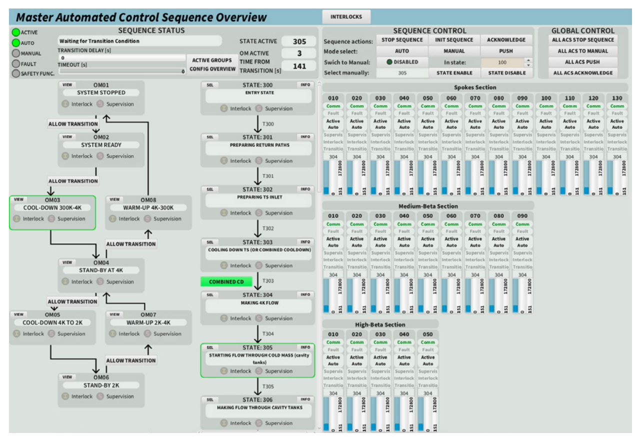


Figure 1: OPI Overview of the MACS orchestrating the entire Cryogenics for the LINAC in 2 MW configuration.

## INTEGRATION WORK

The Cryogenic Control System for the ESS LINAC is split in two levels: a dedicated Controls System for each Cryomodule + Valvebox system, and a Master Control System dedicated to organizing all the modules for the unified operation of the machine, including overall safety functions and interlocks [5]. This division helps to isolate a Cryomodule in case of repairs or dedicated work and simplifies the Control System replicability for new Cryomodules to be installed.

One of the additions to each individual Control System is a Local version Automatic Control Sequence (LACS). The LACS employs Finite State Machine (FSM) logic to rigorously define operational states, permissible transitions, and corresponding actions for each cryomodule. Transitions are executed exclusively upon satisfaction of predefined conditions, frequently incorporating programmed delays to ensure dynamic stability [6]. Embedded safety interlocks and supervisory mechanisms provide continuous validation of operating conditions, enforcing controlled progression and immediate interruption of sequences in the event of detected faults. It is important to note that Safety Functions and Interlocks (SFI) remain

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# GAMMA-BASED DIAGNOSTICS OF FIELD EMISSION IN SRF CAVITIES AND CRYOMODULES USING PLASTIC SCINTILLATORS: A JOINT STUDY AT ESS TS2

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*Abstract*

Field emission is a major parasitic phenomenon that limits the performance of superconducting RF (SRF) cavities. It leads to the generation of dark currents and bremsstrahlung gamma rays, which in turn cause increased cryogenic load, local heating, and in severe cases, cavity quench. Moreover, the high dose rates produced in the proximity of the cavity can result in material damage and activation, posing additional challenges for maintenance and safe operation. The maturity of plastic scintillator technology, combined with recent advances in fast digital acquisition systems, enables the development of compact and sensitive diagnostics for these emissions. We present a modular gamma detection system based on plastic scintillators with various geometries, designed for temporally and spatially resolved measurements. Different prototypes have been deployed at the TS2 facility of the European Spallation Source (ESS) to monitor gamma radiation during RF tests. Preliminary results confirm its ability to detect field emission onset and localize emission regions, offering a promising tool for understanding emission mechanisms and improving SRF cavity performance and reliability.

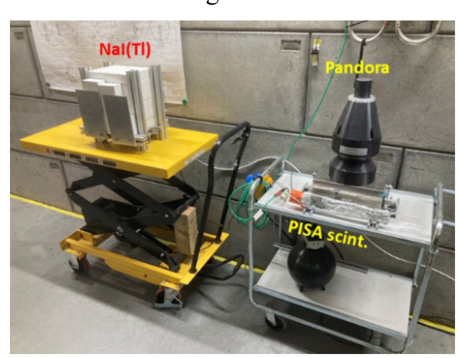
## INTRODUCTION AND MOTIVATION

Field emission remains one of the main limitations to the performance and reliability of superconducting RF (SRF) cavities [1,2]. The emission of dark currents and bremsstrahlung gamma rays not only increases the cryogenic load but could also trigger cavity quenches under severe conditions. In addition, the high radiation dose rates in the vicinity of the cavities may lead to material degradation and activation, as well as false triggering of cryomodule diagnostics, thereby complicating maintenance and safe operation. To address these challenges [3], there is a strong need for sensitive diagnostics capable of detecting the onset of field emission and providing spatial and temporal information on its development. Recent progress in plastic scintillator technology, combined with fast digital acquisition systems, offers new opportunities for compact and flexible gamma diagnostics tailored to SRF applications.

## EXPERIMENTAL SET-UP

At CEA-Saclay, a suite of plastic scintillator detectors has been developed since the beginning of the ESS project to provide time-resolved gamma diagnostics during cryomodule testing [4–6]. Figures 1 and 2 show a typical detector setup in the Test Stand 2 (TS2) facility at ESS [7], while Fig. 3 represents a schematic of the detectors setup. Two plastic scintillator blocks (1.5m length) were positioned beneath the cryomodule, in proximity to cavities 1 and 4. Each scintillator was coupled to a photomultiplier tube, and the signals were read out through the Local Protection System (LPS) and recorded with a digital oscilloscope. On the side of the cryomodule, additional detectors were installed to complement the plastic scintillators positioned beneath it. These included a NaI(Tl) gamma spectrometer, protected by a lead shield, a PANDORA detector [8], and a shorter plastic scintillator block (30 cm in length) referred to as PISA (Pandora Integrated Scintillator Assembly). The PISA detector was connected in the same manner as the scintillators placed below the cryomodule, using a photomultiplier for signal collection and the same readout chain. The PISA detector was positioned in proximity to the PANDORA system to enable a direct comparison of its signal with a reference dose rate


Figure 1: Two plastic scintillator blocks are placed on the ground close to cavities 1 and 4. The detectors in the red insert are described in the figure below.

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# INSIGHTS INTO THE CRYOGENIC OPERATION OF THE ESS SUPERCONDUCTING CRYOMODULES DURING THE FIRST COMMISSIONING PHASE

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*Abstract*

The first commissioning run of the superconducting cryomodules at the European Spallation Source (ESS) provided important insights into the performance of the cryogenic systems. This paper reviews the cryogenic operations, with a focus on cooldown processes, pressure control, temperature stability, and overall system reliability.

The effectiveness of individual helium bath pressure regulation in managing pressure transients during cavity quenches and RF trips is demonstrated. The response of the system to cryoplant trip events is also analyzed. In addition, results from automated heat load measurements are presented, confirming that the thermal performance meets expectations. These findings demonstrate the robustness of the ESS cryogenic systems.

## INTRODUCTION

The European Spallation Source (ESS) [1] is designed to be the world's most powerful neutron source, driven by a high-power 5 MW proton linear accelerator. The superconducting linac (SCL) is the heart of this accelerator, responsible for efficiently accelerating the proton beam to its final energy of 2.0 GeV. Upon completion, the SCL will comprise a chain of 43 superconducting radio-frequency (SRF) cryomodules: 13 Spoke Resonators (SPK), 9 Medium-Beta Elliptical Resonators (MB), and 21 High-Beta Elliptical Resonators (HB) [2, 3].

As of June 2025, the ESS SCL has successfully concluded a major commissioning phase with a partially installed cavity chain. This initial cold section consisted of 13 SPK, 9 MB, and 5 HB cryomodules, providing a total accelerating energy of 870 MeV (Fig.1).

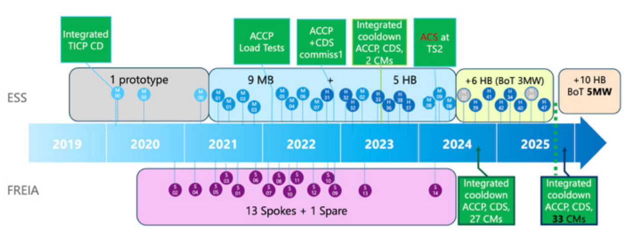


Figure 1: Timeline of the preparation of the ESS linac [3].

Throughout this phase, the cryomodules were operated at a repetition rate of 1 Hz with a pulse length of 1 ms. This demonstrated stable cryogenic performance but is well below the final design goals of 14 Hz and 3.2 ms. A key success of this phase was the first accelerated beam on the dump (BoD), which marked the first integrated operation of the cryogenic plant, the cryomodules, and the RF systems at ESS. This milestone not only validated the individual component designs but also the complex interplay between these systems under cryogenic conditions.

Currently, six additional HB cryomodules are being installed during the summer 2025 shutdown. This will provide the capability for a 3 MW proton beam (Fig. 2). Following this, the next commissioning run will start in November 2025 with the milestone of reaching the first beam on target (BoT).


Figure 2: ESS linac configuration for 3 MW capability.

## OVERVIEW OF THE SCL CRYOGENIC SYSTEM

The SCL cryogenic system has two key components: the accelerator cryoplant (ACCP) and the cryogenic distribution system (CDS). The ACCP is the largest cryoplant at ESS, providing 2 K helium for the SRF cavities, 4.5 K for power coupler intercepts, and 40-50 K for the thermal shields. Its architecture includes a cold compressor station and a single coldbox. The CDS connects the ACCP to the linac cryomodules via a Cryogenic Transfer Line (CTL) that runs through the accelerator tunnel. U-shaped jumper connections with vacuum-insulated valve boxes link each cryomodule to the CTL (Fig. 3).

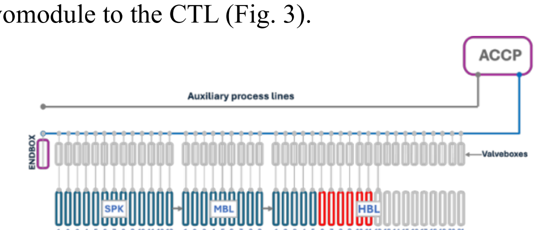


Figure 3: Cryogenic system overview.

This setup enables the independent warm-up, cooldown, and maintenance of individual cryomodules without affecting their neighbors. These valve boxes contain multiple cryogenic valves to precisely control the flow, creating an effectively modular system [4].

## CRYOMODULE QUALIFICATION AND INSTALLATION

The successful cryogenic commissioning of the ESS linac was dependent on an extensive pre-operational phase.

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# 591 MHz SINGLE-CELL CAVITY OPTIMIZATION USING EVOLUTIONARY ALGORITHMS

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*Abstract*

The Electron Storage Ring (ESR) of the Electron Ion Collider (EIC) will host up to 2.5 A, 18 GeV electron beam. To restore the energy primary lost through synchrotron radiation, 18 identical single-cell 591 MHz superconducting RF cavities each will provide an accelerating voltage of up to 4 MV. Here we applied evolutionary algorithm to accelerate the cavity parameter optimization of the fundamental mode electromagnetic properties in the design process.

## MOTIVATION

The EIC is a next-generation experimental facility dedicated to polarized electron–proton and electron–ion collisions, aiming at advancing the fundamental theory of strong interactions—quantum chromodynamics—at the subatomic scale [1]. It will provide a luminosity of up to $10^{34}$ $cm^{-2}s^{-1}$ by upgrading the current Relativistic Heavy Ion Collider (RHIC) facility as Hadron Storage Ring (HSR) and the addition of an Electron Storage Ring (ESR). In the EIC ESR, the electron beam will operate with currents ranging from 0.23 to 2.5 A and energies from 5 to 18 GeV. To compensate for synchrotron radiation and higher-order mode (HOM) losses, the RF system must supply up to 10 MW of beam power, achieved through an array of 18 single-cell 591 MHz SRF elliptical cavities [2, 3].

The design of the 591 MHz SRF cavity begins with fundamental-mode optimization. In traditional approaches, geometry parameters are manually swept to satisfy design requirements, a process that is time-consuming. Given the large number of identical cavities, even modest improvements can have a significant impact.

## REQUIREMENT

This optimization study intends to optimize four key electromagnetic properties associated to the fundamental mode of the 591 MHz single-cell elliptical cavity:

1. The fundamental frequency must be 591 ± 0.1 MHz.
2. The R/Q of the mode (591 MHz) should be less than 80 Ω (accelerator definition) for Robinson stability.
3. To avoid field emission and secondary electron emission, the maximum peak surface electric field E must be below 40 MV/m.
4. The superconducting material has a critical magnetic field above which it quenches, so the maximum peak surface magnetic field B must be below 80 mT.

These optimization objectives are summarized in Table 1.

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Table 1: 591 MHz Cavity Requirment [3]

| Parameter | Requirement |
|---|---|
| Fundamental Frequency | 591 ± 0.1 MHz |
| Fundamental mode's R/Q | < 80 Ω |
| Maximum peak surface electric field, E | < 40 MV/m @ 4 MV |
| Maximum peak surface magnetic field, B | < 80 mT @ 4 MV |

The elliptical cavity is axially symmetrical. Its cross-section is defined by elliptical arcs and straight lines that are tangentially connected, as shown in Fig. 1. In total, the cavity geometry is defined by 17 independent geometry parameters. This constitutes a four-objective optimization problem, which is challenging to visualize.

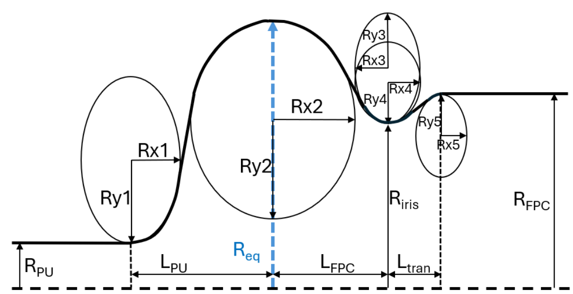


Figure 1: Schematic of the half cross-section the cavity.

The multi-objective optimization algorithm Non-dominated Sorting Genetic Algorithm III (NSGA-III) is a reference-point-based evolutionary method designed for many-objective problems [4, 5]. The NSGA-III has been successfully applied to benchmark test cases involving three to fifteen objectives. Compared to its predecessor NSGA-II, the used version introduces a set of well-distributed reference points to better maintain diversity in high-dimensional objective spaces. This is particularly effective for problems where trade-offs among conflicting objectives must be systematically explored, making it well suited to the cavity design optimization studied here. For example, the simultaneous optimizations of both peak electric field and peak magnetic field are often in conflict.

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# TRAPPED MODE AND WAKEFIELD EVALUATION OF BELLOWS FOR 197 MHz SUPERCONDUCTING CRAB CAVITIES*

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*Abstract*

Stainless steel bellows are designed to connect between the 197 MHz superconducting crab cavities and beampipes in the Hardon Storage Ring (HSR) in the Electron-Ion Collider (EIC). Their purpose is to compensate for cavity displacements caused by cryogenic temperature variations. The impedance of the bellows is evaluated with respect to both potential trapped high order modes and short-range wakefield effects.

## INTRODUCTION

The EIC's design seeks to achieve luminosity up to $10^{34}$ cm$^{-2}$s$^{-1}$ to understand the strong nuclear force and the role of quarks and gluons [1]. The crab cavities are designed to facilitate head-on collisions between electron and proton beams, thereby increasing the luminosity at the interaction point [2, 3]. These cavities are superconducting and operate at 2 Kelvin. During cooling down and warming up, deformation occurs between the cavity mechanical connections. This deformation must be compensated by bellows structures.

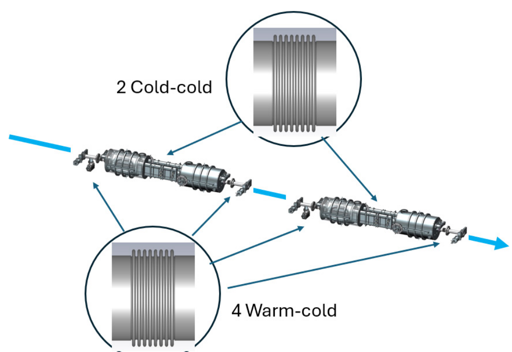


Figure 1: Schemics of the bellow positions for two cryomodules on one side of the interaction point (IP) in the HSR (the other side cryomodules are not show).

There are two crab cavities inside one cryomodules. The HSR contains four cryomodules with a total of eight crab cavities. Four cold–cold bellows are required to connect the cavities inside the cryomodules, and eight warm–cold bellows are needed to connect the beam pipe to the crab cavities (Figure 1). So far, we assume the same design will be used for both cold–cold and warm–cold bellows, since the cold–cold bellows require a larger deformation range, which is also sufficient to meet the warm–cold connection requirements. For each bellows, the expected deformation range is ±10 mm longitudinally and ±0.7 mm transversely.

## DESIGN AND SIMULATIONS

### *High Order Modes (HOMs)*

Cutoff frequencies of the beam pipe with diameter of 100 mm are 1757 MHz for TE11 mode and 2294.83 MHz for the TM01 mode. Initially a trapped longitudinal mode is found at about 2252.02 MHz by high frequency eigen solver in CST studio [4]. The frequency sensitivity was studied by importing the displacement of the compressed and extended results from its mechanical solver as perturbation field. These two deformation states push the trapped mode frequencies beyond the range of the two neighbour harmonic lines of the beam spectrum (Figure 2), which lead to nearly 1 W dissipation over the bellows due to their possible transient overlapping.

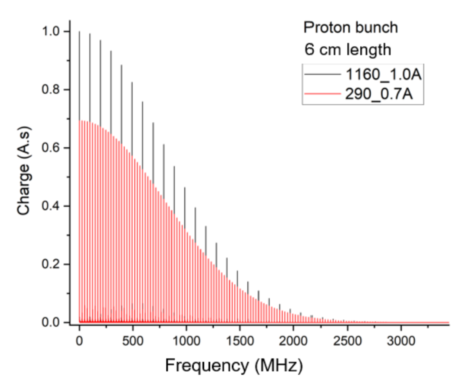


Figure 2: Proton beam spectrums:1160 bunch with an average current 1.0 A (black lines) and 290 bunch with an average current 0.7 A (red lines), here the RMS length of the Gaussian beam bunch is 6 cm.

As is depicted in Figures 3, 4, and 5, we optimized the dimensions of the bellows by iterating between mechanical solver and the high frequency solver. The results are following:

- At neutral position, the resonate frequency is centered at 2253.89 MHz.
- Both extended and compressed status, the resonant frequency is kept 1 MHz minimum, by design, from beam spectrum lines. The maximum dissipated power is about 0.10 W.

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# THE PATH TO HIGH DUTY CYCLE AT EUROPEAN XFEL: CRYOMODULE DEVELOPMENTS

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*Abstract*

The European XFEL is in operation since 2017 with a maximum energy of 17.5 GeV in short-pulse (SP) mode, consisting of 0.65-ms long bunch trains at 10 Hz repetition rate. The accelerator can deliver up to 2700 electron bunches every 100 ms, with a spacing between bunches of 220 ns. After eight years of successful operation the accelerator team, with strong support from the EuXFEL strategy process, is working to define an accelerator upgrade scenario for possible implementation in the next decade. The main goal of the upgrade is to facilitate more bunches per second with larger bunch spacing while maintaining the high energy of the beam, a world record amongst FEL machines. Possible scenarios include continuous-wave (CW) and long-pulse operating modes, collectively referred to as high duty cycle (HDC). This paper describes the different operating modes under investigation and the R&D activities ongoing at DESY to support the upgrade. The main focus of the paper is on the cryomodule and cavity design modifications, while also giving a brief introduction of the other challenging aspects connected to the upgrade.

## HIGH DUTY CYCLE (HDC) AT EuXFEL

The current EuXFEL 'burst mode' (or 'short pulse', SP) provides up to a 600 μs beam pulse with a maximum electron beam energy of 17.3 GeV, at a pulse repetition rate of 10 Hz, corresponding to a beam duty cycle of 0.6%. With a bunch repetition rate of up to 4.5 MHz, the EuXFEL is currently capable of producing up to 27000 bunches per second. A more detailed description of the EuXFEL linac and its operation can be found in [1]. As a possible future upgrade to the facility, the potential of higher average bunch rates from running at higher duty cycles, up to and including 100% (continuous wave, CW), is actively being studied. A cost-effective proposal which reuses the existing SRF linac cryomodules was already proposed in [2] and still forms the basis of the current approach: The cryomodules in the injector and bunch compressor linacs (L1, L2) will be replaced with new CW-optimised cryomodules, with the originals being relocated to the end of the main accelerating linac (L3) to boost the energy reach. The upgrade also foresees a new SRF CW 1-MHz photoinjector, the installation of low-power CW RF sources, new LLRF systems, and an additional cryoplant, effectively doubling the current 2 K cooling capacity.

A primary constraint on the maximum beam energy is the increased cryogenic 2 K dynamic load associated with the higher duty cycle. The upgraded cryogenic infrastructure will provide a total of 5 kW cooling capacity at 2 K, approximately half of which will be available for the main linac (L3). Figure 1 shows how the beam energy can be traded for duty cycle assuming a fixed (L3) cryogenic load.

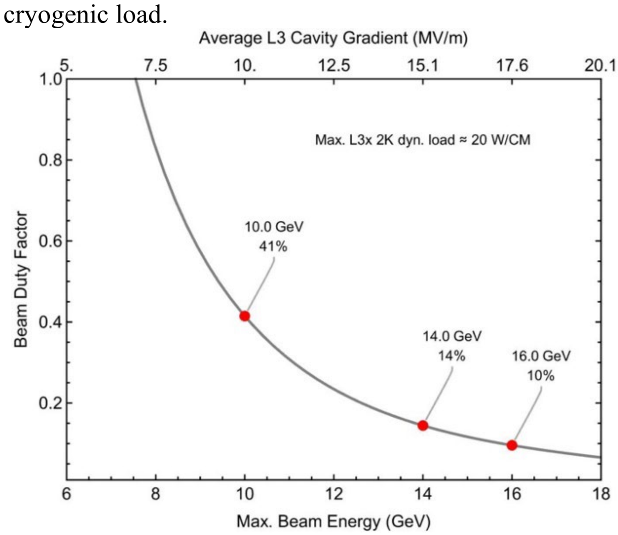


Figure 1: Beam duty cycle versus maximum beam energy assuming a constant (maximum) 2 K dynamic load in the L3 linac. The top horizontal axis gives the average required accelerating gradient. The three highlighted working points were identified as use cases for further study. Full CW operation is possible below 7.5 GeV.

Table 1 gives the top-level parameters corresponding to the operation points shown in Fig. 1. Running with duty cycles of $D < 100\%$ requires pulsing the RF. A 1-Hz pulse repetition rate is currently considered with RF (beam) pulses ranging from 100-430 ms, so-called Long Pulse (LP) mode. The choice of LP pulse lengths and low repetition rate is primarily driven by the much longer fill times required for the very narrow bandwidth cavities (typically tens of milliseconds).

The reduction in dynamic cryogenic load is achieved by reducing the average gradient to about 8 MV/m in the L3 linac, where the maximum load is constrained by the design of the existing cryomodules (in particular the diameter of the two-phase pipe). For the bunch compressor linacs, the accelerating gradients are fixed by the compression parameters and do not change with the maximum beam energy. Hence new CW-optimised cryomodules capable of CW operation at higher accelerating gradients must be installed. Table 2 gives the main top-level requirements for these new modules.

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# STUDIES OF *IN-SITU* BAKING OF SRF NIOBIUM CAVITIES WITHOUT A FURNACE AT HZB*

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*Abstract*

Vacuum thermal treatments (baking) are a well-established method to improve the superconducting properties of niobium cavities by enhancing their intrinsic quality factor $Q_0$. We demonstrate a novel baking approach in which an evacuated cavity is annealed with local heaters mounted on its outer surface inside a cryostat. This setup maintains exterior vacuum conditions, protects the cavity surface from oxidation, and enables *in situ* RF testing immediately after treatment. It eliminates the need for flange cooling, avoids reoxidation from air exposure, and simplifies the procedure compared to conventional furnace baking. A single-cell 1.3 GHz niobium cavity baked at 230 °C for 24 h showed a twofold increase in $Q_0$ at $E_{acc}$=10 MV m$^{-1}$ (from $1.20 \times 10^{10}$ to $2.4 \times 10^{10}$) while preserving a maximum accelerating field of 35 MV m$^{-1}$. Guided by XPS studies, the treatment ensures partial reduction of $Nb_2O_5$, limiting contamination. We propose extending this method to cryomodules, offering a practical route to performance gains in operational accelerators.

## INTRODUCTION

Superconducting radiofrequency (SRF) cavities are at the heart of state-of-the-art particle accelerators and free-electron lasers, enabling progress across physics, medicine, and industrial technologies. Their performance is governed by the intrinsic quality factor, $Q_0$, and its dependence on the accelerating gradient, $E_{acc}$. A high $Q_0$ corresponds to low dissipative losses and reduced demand on cryogenic power. Since cryogenic systems operating at 2 K typically run at efficiencies of only a few tenths of a percent, even modest improvements in $Q_0$ can substantially lower AC power consumption and simplify cryoplant design.

The value of $Q_0$ is directly linked to the surface resistance of a thin layer, about 40 nm deep, that interacts with the RF field under cryogenic operation. Over the past decades, worldwide efforts have focused on tailoring this surface region through various heat treatments. Approaches include vacuum annealing at different temperatures and times (e.g., mild or medium-temperature baking [1–7]) as well as treatments involving controlled gas atmospheres, sometimes combined with chemical processing (e.g., nitrogen doping and infusion [8–11]). In all cases, the objective is to raise $Q_0$ by adjusting point defect concentrations within the RF penetration depth and tuning the chemical composition of the surface layer.

The mechanisms behind $Q_0$ enhancement are multifaceted. Reducing the mean free path of normal-conducting electrons lowers the Bardeen–Cooper–Schrieffer (BCS) resistance, $R_{BCS}$ [12]. Under certain conditions, the residual resistance $R_{res}$ can also be diminished, likely due to optimized flux pinning [13–15]. Point defects may further suppress the nucleation of lossy niobium hydrides that form upon cooldown and degrade RF performance [16–19].

In recent years, medium-temperature (mid-T) baking has gained prominence as a straightforward method to boost $Q_0$. Conventionally, cavities are heated in a vacuum furnace, but this procedure has notable drawbacks. Exposure of the inner cavity surface to the furnace environment risks contamination, particularly if the protective $Nb_2O_5$ layer is fully reduced [20]. While protective caps have been employed to mitigate this effect [6, 7], the risk of contamination persists. In addition, reoxidation upon air exposure after treatment can offset the benefits of baking [5]. To overcome these issues, alternative strategies have been developed, such as isolating the cavity volume and coupling it to an external pumping system during annealing [5]. This requires protecting vacuum seals from thermal damage using additional cooling on the cavity flanges. Although effective, such approaches remain costly and technically demanding, relying on dedicated furnaces, cooling systems, and lengthy preparation.

In this paper, we summarize the results of [21], which presents a simplified vacuum annealing procedure for niobium cavities that enhances their RF performance. For more details, the reader is referred to the original work. The method eliminates the need for conventional furnace setups and flange cooling, while also preventing reoxidation of the cavity surface prior to RF testing. Additionally, here we present the $Q_0(E)$ performance of the cavity after 1.5 years of storage with closed flanges, during which the internal pressure remained close to $1 \times 10^{-1}$ mbar.

## EXPERIMENTAL SETUP AND METHODS

### *Mid-T Baking of Nb Samples*

**Synchrotron XPS study** As the first step of our investigation, we performed an *in – situ* synchrotron X-ray photoelectron spectroscopy (XPS) study of fine-grain niobium samples subjected to baking between 200 °C to 400 °C in ultra-high vacuum (UHV, from $1 \times 10^{-9}$ mbar to $5.2 \times 10^{-9}$ mbar). This approach enabled monitoring, with high temporal and chemical resolution, the evolution of nio-

* Part of this work was supported by the BONSAI Project as part of the Helmholtz Innovation Fund INNOPOOL.
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# ENHANCEMENT OF MEDIUM-TEMPERATURE HEAT-TREATED SRF CAVITIES FOR HIGH QUALITY AND HIGH GRADIENT*

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*Abstract*

Improving the quality factor and the gradient of superconducting radio frequency (SRF) cavities, which are an essential component of modern particle accelerators, remains a challenge. While mid-T heat treatments (240 °C to 350 °C) generally improves the quality factor $Q_0$ at moderate fields, it often limits the gradient due to quenches at around 20 MV/m to 30 MV/m. We demonstrate here that this limitation can be overcome by applying a newly developed combination of mid- and low-temperature heat treatment to cavities. After such treatment, quality factors of up to $4 \cdot 10^{10}$ and acceleration gradients of up to 40 MV/m can be achieved, which are well suited for cavities for a possible European XFEL upgrade. Furthermore, advanced investigations of the surface resistance and calculated diffusion lengths of our mid-T data revealed correlations consistent with those previously reported in the literature.

## INTRODUCTION

The heat treatment of SRF cavities at medium temperature (240°C to 350°C), also known as “mid-T heat treatment”, is one of the R&D activities at DESY towards a high-duty-cycle (HDC) upgrade of the European XFEL (EuXFEL). Such treated cavities exhibit an improvement in the quality factor $Q_0$ at a moderate accelerating electric field strength $E_{acc}$ compared to EuXFEL cavities. In fact, cavities treated with a mid-T heat treatment quench at 20 MV/m to 30 MV/m, i.e. they cannot be operated at gradients above this limit. However, we have found that with a heat treatment consisting of a combination of mid-T and low temperature (low-T: 120°C to 130°C) treatment not only high $Q_0$-values were measured, but additionally high gradients of up to 40 MV/m could be achieved. This offers great potential for upgrading modern LINACs with new high usable performance not only in $Q_0$ but also in the gradient.

This work builds on the DESY mid-T campaign and expands the results of [1] with new considerations concerning the $R_{BCS}$, new measurements and a treatment impact overview. Also the the results after an additional low-T treatment following a mid-T treatment will be subject of this paper, with some of the results already published on a preprint server [2].

## EXPERIMENTAL OVERVIEW

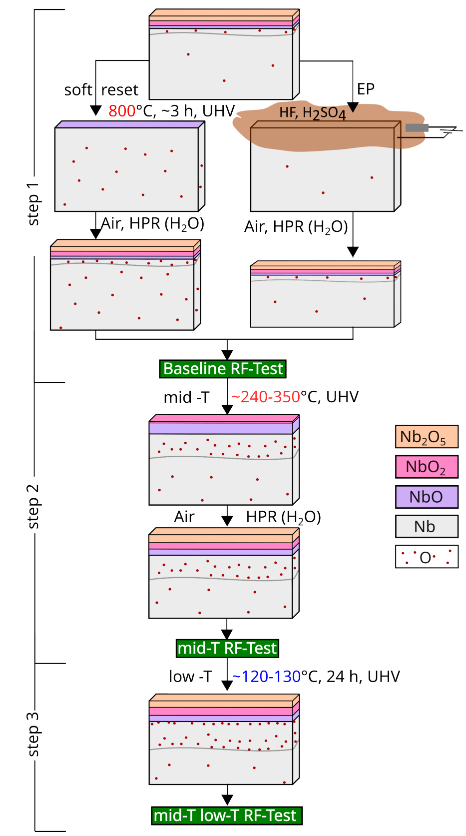


Figure 1: The schematic of the cavity preparation. The rectangular bulk Nb represents the cavity. Furthermore the colors depict the different oxide layers on the Nb surface while the red dots represent oxygen atoms. The arrows stand for the treatments and the blocks the states afterwards.

**Furnace and Heating Setups** The DESY furnace infrastructure used for the so-called “soft resets” (800 °C / 900 °C for approx. 3 hours) and for mid-T heat treatments of the cavities, together with the related workflow (pre- and post treatment of a cavity), are described in detail in [1, 3]. A different heating set-up was used for the low-T heat treatment (120 °C to 130 °C for approx. 24 hours), in which the cavities are kept under UHV conditions during and after heating (*in-situ*). However, there was one exception, where the cavity was low-T treated in an argon atmosphere during heating and subsequently evacuated. Details can be found in [2].

**Cavity Preparation** Information about the cavities and their pre-treatment (after manufacturing) can be found in [1] as well. The schematic of the cavity preparation is shown in Fig. 1. The starting point (step 1) before a mid-T treat-

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# PLASMA ELECTROLYTIC POLISHING OF 1.3 GHz CAVITIES*

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*Abstract*

The performance of Superconducting Radio Frequency (SRF) cavities strongly depends on surface preparation. Traditionally, Electropolishing (EP) has been used to achieve clean, low-roughness surfaces on both niobium (Nb) and copper (Cu) substrates, although this technique relies on harsh and corrosive acids. Since 2019, research at LNL has explored an alternative approach: Plasma Electrolytic Polishing (PEP). This method employs low-conductivity (often diluted salt) solutions and offers several advantages over EP, including higher removal rates (2 – 8 μm/min for Nb and 3–30 μm/min for Cu) and surface roughness (Ra) values below a few tens of nanometres. Moreover, the experimental setup has been simplified by using only external cathodes, eliminating the need for electrodes inside the elliptical cavity. In 2022, we established the first optimized PEP recipes, four of which were patented in 2023. Initial successful applications included Cu 6 GHz elliptical cavities, Quadrupole Resonators (QPRs), and 3D-printed devices. In August 2024, the process was successfully scaled to a 1.3 GHz Cu elliptical cavity. A collaboration with CERN and KEK is currently ongoing to validate the impact of PEP on the RF performance of a hydroformed seamless cavity produced at KEK and subsequently Nb-coated at CERN. This contribution presents the first demonstration of PEP applied to 1.3 GHz cavities.

## INTRODUCTION

Plasma Electrolytic Polishing (PEP) is a powerful method for polishing metallic surfaces and has already been industrialized in several fields, such as medical implants, stainless steel polishing, and deburring. Since 2019, INFN has been investigating PEP as an innovative and promising treatment for the preparation of SRF cavities [1-5], which demand exceptionally smooth and clean surfaces. As a result of this research, PEP has emerged as one of the most promising alternatives to conventional polishing technologies for both thin-film and bulk Nb applications [6,7].

State-of-the-art research demonstrates the applicability of PEP to both niobium and copper, in bulk and thin-film approaches. However, PEP of Nb still requires further optimization to address challenges associated with medium-sized or complex elliptical samples. By contrast, PEP of copper has consistently shown reproducible and positive results on samples of various dimensions and geometries, including those with elliptical shapes.

Beyond SRF cavities, PEP is also being applied to other accelerator components. In particular, the growing interest in additively manufactured structures opens new opportunities for this technology. Further details on these applications are provided in [8].

## PEP OF ELLIPTICAL GEOMETRY

The feasibility of PEP for Cu 6 GHz cavities was first demonstrated in earlier studies [2], [9]. Since 2023, LNL has updated the workflow for preparing such cavities by replacing the conventional electropolishing + SUBU standard protocol with a streamlined two-step PEP treatment performed prior to superconductive layer deposition. To date, more than ten cavities have been successfully prepared using this method.

The process is carried out in a plastic bath containing approximately 30 L of electrolyte. The cathode is a 2 mm niobium sheet placed along the perimeter of the PVC bath. No internal cathode is required—an improvement that both simplifies the procedure and avoids obstructing the electrolyte mass flow and the vapor-gas layer generated inside the elliptical geometry of the 6 GHz cavity. It was also observed that the PEP process inside the elliptical geometry could only be initiated if the outer surface of the cavity was covered with heat-shrinking material. Following successive iterations, the final cavity assembly and adapters for anodic polarization were successfully implemented [8].

## LNL'S EXPERIENCE

As of 2025, the PEP process has been extensively studied at LNL for a wide range of applications, including metals that are often underrepresented in the literature. Our expertise covers copper and its alloys, as well as niobium, tantalum, titanium, silver, and stainless steels.

Successfully polished prototypes include 6 GHz elliptical cavities, Split cavities, Haloscopes, Spiral geometries, Quadrupole Resonator (QPR) samples, 3D cavities for qubit applications, and other substrates. Building on this research, INFN has patented several original electrolyte solutions [10-12] and actively welcomes collaborations with both industrial and research partners.

## PEP SCALING

In general, the PEP process is inherently scalable, provided that an appropriate ratio between the electrolyte

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# TEST STAND FOR HELIAC CRYOMODULES AT GSI

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*Abstract*

The Helmholtz Linear Accelerator (HELIAC) is a superconducting continuous-wave linear accelerator for heavy ions, developed at GSI in Darmstadt and the Helmholtz Institute Mainz. The main acceleration will be provided by four cryomodules, each about 5 m long, equipped with superconducting CH cavities, solenoids, and a spoke resonator used longitudinal bunching. For testing these modules, a new experimental area with cryogenic infrastructure, RF systems, and a beamline connected to the existing HLI injector was set up inside a radiation protection shelter at GSI.

Since 2021, the first cryomodule (CM1) has undergone several commissioning steps. Initial tests validated the cryostat performance and confirmed the functionality of the superconducting solenoids. In 2023, the first RF operation and acceleration of ion beams with the targeted energy gain were achieved. This contribution reports on the new test area as well as on the features of the first cryomodule. Its integration in the test stand and lessons learned from cryogenic operation are discussed.

## INTRODUCTION

The HELIAC (Helmholtz Linear Accelerator) [1–3] is a superconducting (sc) continuous-wave (cw) linear accelerator for heavy ions, currently under development at GSI Darmstadt and the Helmholtz Institute Mainz (HIM). Its main objective is to deliver higher beam intensities for superheavy element research (SHE) [4], though it also supports other experiments in the low-energy domain. Figure 1 provides a schematic layout of the accelerator, and the key machine parameters are summarized in Table 1.

After the ion source and a normal-conducting (nc) injector linac [5, 6], the main acceleration is achieved with superconducting multigap crossbar H-mode (CH) cavities [7, 8] operated at 217 MHz. Three of these cavities [9, 10] are installed in each of four cryomodules [11, 12], which operate at 4 K. Every cryomodule also houses two sc 9 T solenoids [12] for transverse beam focusing and one sc single spoke resonator (SSR) [13] for longitudinal bunching. The HELIAC will provide continuously adjustable beam energies from 1.4 MeV/u up to 7.6 MeV/u for ions with mass-to-charge ratios up to 6.

Table 1: General Characteristics of the HELIAC

| **Characteristic** | **Value** |
|---|---|
| Frequency (nc-section) | 108.4 MHz |
| Frequency (sc-section) | 216.8 MHz |
| Mass-to-charge ratio (A/q) | ≤ 6 |
| Repetition rate | Continuous wave |
| Beam current | ≤ 1 mA |
| Injector energy | 1.4 MeV/u |
| Output energy | 1.4 MeV/u to 7.6 MeV/u |
| LHe operation | 4.2 K |
| Total length | Approx. 30 m |

Following the successful 2017 demonstration of a superconducting CH cavity with ion beam [14], the HELIAC project advanced to its next development phase. Alongside work on the nc pre-accelerator, the new focus was the construction and test of the first cryomodule for the superconducting section. To support this, the existing test area at GSI required extensive upgrades, particularly in the liquid helium supply and control systems [12].

## HELIAC CRYOMODULE CM1

Figure 2 shows a photograph of the module during assembly in Mainz [15]. It features two rectangular service doors on each side, which allow work on the cavity tuners, sensors, power couplers, insulations and magnetic shielding to be performed without removing the entire string. The string components are suspended within a support frame with eight tie rods each (Fig. 3). The 50 K thermal shielding is also part of the support frame and can be easily

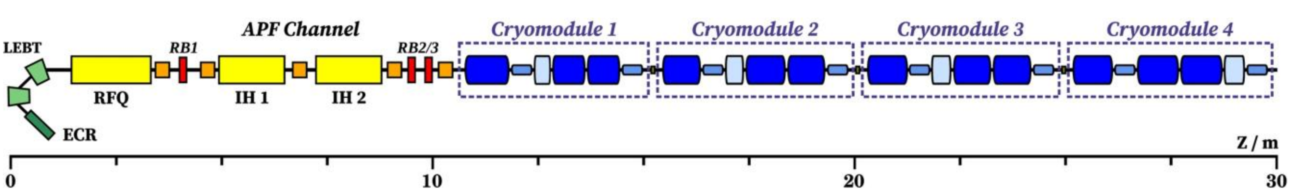


Figure 1: Schematic layout of the HELIAC. The ion source to the left, followed up by a normal conducting section (yellow) and the superconducting part (blue).

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# CAVITY COMPENSATION STUDIES IN THE JAEA-ADS SUPERCONDUCTING LINAC USING LIGHTWIN

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*Abstract*

High-intensity accelerators, particularly Accelerator-Driven Systems (ADS), require high availability and reliability for proper operation. For superconducting linear accelerators, the ability to continue operating even when one of the RF cavities fails is key to achieving the required availability, known as cavity compensation. Beam dynamics studies of the JAEA-ADS linear accelerator have demonstrated the possibility of operating with multiple RF cavities disabled with acceptable beam quality. Several other superconducting linear accelerator laboratories have adopted similar methods and developed their procedures. Among these efforts, the LightWin tool has proven to be an effective tool for automatically and systematically identifying compensation settings for each cavity failure in any linear accelerator. This software has been successfully utilized on the MINERVA linac, as well as on the high-energy part of the JAEA-ADS linac. It has currently been tested and improved to ease SPIRAL2 operation. This work presents an analysis of cavity compensation in the JAEA-ADS superconducting linear accelerator using the LightWin tool and compares the results with previous studies.

## INTRODUCTION

To address the challenges caused by the high radio-toxicity and long lifetime of nuclear waste, the Japan Atomic Energy Agency (JAEA) is designing an accelerator-driven system (ADS) focused on the transmutation of minor actinides. JAEA envisages to accelerates a 30 −MW proton beam using superconducting linear accelerator (linac) to generate spallation neutrons for an 800 −MWth thermal power subcritical reactor [1]. Table 1 summarizes the main features of the JAEA-ADS linac.

Despite the strict control of beam loss for high-power linacs, the ADS linacs demand a stringent management of both beam duration and the frequency of beam trips to avoid thermal stress on the reactor [2]. To achieve this, the JAEA-ADS linac implements a hybrid redundancy strategy based on hot-standby at the low-energy part and fast element compensation for the high-energy section [3], as shown in Fig. 1.

A previous study [3] showed that cavity compensation can be implemented for fast beam recovery, achieving acceptable quality in case of failure of one or more cavities. However, the compensation process was not automated. For optimal application in beam operations, particularly for ADS

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Table 1: Main Parameters for the JAEA-ADS Linac

| Parameter | | Trip duration |
|---|---|---|
| Beam current (mA) | 20 | |
| Proton beam energy (GeV) | 1.5 | |
| Duty factor (%) | 100 (cw) | |
| RF frequency (MHz) | 162/324/648 | |
| Beam loss (W/m) | <1 | |
| Beam trips per year [2] | $2{\times}10^4$ | ≤10 s |
| | $2{\times}10^3$ | from 10 s to 5 min |
| | 42 | >5 min |

operations, the cavity compensation process must be automated to find the optimal configurations. This work presents results obtained using the LightWin [4] tool for automatic cavity compensation in the JAEA-ADS linac. This research expands on an initial LightWin work presented in another past conference [5] by analyzing the full JAEA-ADS superconducting linac.

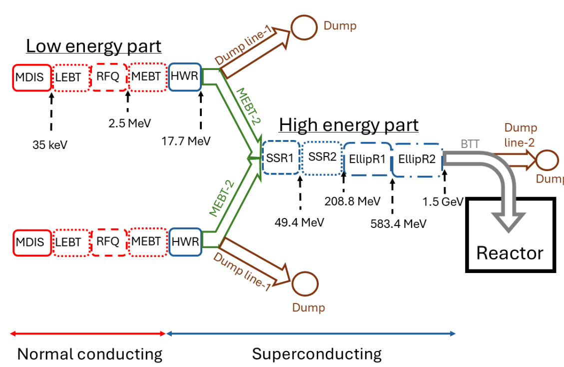


Figure 1: Schematic design of the linac for the JAEA-ADS.

## LIGHTWIN

Cavity retuning for rapid beam recovery after a failure is a strategy pursued by several high-intensity linear accelerators [3,6–9]. To this end, a specialized tool named LightWin was developed for cavity compensation in the MYRRHA linac [10]. LightWin is open source software written primarily in Python and its file formats are compatible with the TraceWin beam dynamics code [11]. The main advantage of LightWin is that it can automatically determine cavity compensation settings for several failure scenarios without requiring direct user intervention. This capability speeds up

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# BEAM CHARACTERIZATION AND LESSONS LEARNED FROM BEAM COMMISSIONING PRIOR TO SRF LINAC INTEGRATION

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*Abstract*

The Linear IFMIF Prototype Accelerator (LIPAc) is a deuteron linear accelerator comprising a radio-frequency quadrupole (RFQ) and a superconducting RF (SRF) linac. It is designed to demonstrate continuous-wave (CW) acceleration of a 125 mA beam up to 9 MeV, as a step toward realizing the IFMIF project. Due to the SRF linac's sensitivity to particle losses, which can cause quenching, component damage, and radioactivation, maintaining stable beam transport with minimal losses is critical. LIPAc has been assembled and commissioned in phases, and the integration of the SRF linac into the beamline is currently in progress. Prior to this integration, the beam commissioning was carried out until June 2024. Despite initial particle losses and discrepancies between measured and simulated beam profiles, iterative optimization enabled the achievement of a matched beam and significantly reduced losses. This paper describes the details of beam tuning, beam characterization, and lessons learned from Phase-B+.

## INTRODUCTION

The accelerator system for the International Fusion Materials Irradiation Facility (IFMIF) is designed to study fusion materials by generating high-intensity neutrons via the interaction of two 125 mA/40 MeV deuteron beams with a flowing liquid lithium target in continuous wave (CW) mode. The resulting neutron spectrum includes high-energy neutrons around 14 MeV, suitable for simulating fusion reactor conditions. The Linear IFMIF Prototype Accelerator (LIPAc), which constitutes the low-energy section of IFMIF, is currently under construction and undergoing stepwise commissioning in Japan in the frame of the Broader Approach agreement between the government of Japan and the European Atomic Energy Community (EURATOM) as part of the IFMIF/EVEDA project [1]. Its goal is to validate the acceleration of a 125 mA deuteron beam up to 9 MeV in CW mode, maintaining particle losses below 1 W/m [1, 2].

The LIPAc beamline comprises a low energy beam transport line (LEBT) equipped with an ECR ion source, followed by a radio frequency quadrupole (RFQ) that accelerates the beam to 5 MeV. This is followed by a medium-energy beam transport line (MEBT) containing five identical quadrupole magnets (quads), a superconducting RF (SRF) linac that further accelerates the beam to 9 MeV, and a high-energy beam transport line (HEBT) with eight quads of three different types and a beam dump.

Beam commissioning was conducted until July 2024 to evaluate beam characteristics and validate diagnostic devices. This stage, referred to as Phase B+, represents an intermediate commissioning phase prior to the installation of the superconducting RF (SRF) linac. As a temporary substitute for the SRF linac, a beam transport line, namely the MEBT extension line (MEL), was constructed using four identical quads. Figure 1 illustrates the beamline configuration for Phase B+.

In the initial phase of Phase B+, conducted with a low duty cycle, beam-based alignment was performed to steer the beam through the magnetic centers of the quads, aiming to reduce particle losses and achieve a matched beam. Subsequently, transverse beam profile measurements in the HEBT section revealed discrepancies between the measured beam sizes and simulation results. To address these issues, the simulation model and the excitation formulas for the quadrupoles, referred to as *gtoI*, were revised. Although this effort resulted in obtaining the matched beam, vacuum degradation in the MEL section due to particle losses was observed when the duty cycle was increased. To mitigate this issue, machine learning techniques were introduced to suppress the increase in vacuum pressure, leading to a significant reduction. A duty cycle of 8.75 % was successfully achieved, constrained possibly by thermal limitations of the RFQ couplers that were temporarily employed. This paper describes the details of beam transport line commissioning conducted to characterize beam properties, along with the lessons learned from Phase B+.

## BEAM-BASED ALIGNMENT

As the first step in the commissioning of the beam transport line, we performed the beam-based alignment (BBA) to ensure that the beam passed through the magnetic centers of each quad. Steering magnet coils are attached to the first and third quads of the triplets, and all doublet quads in the MEBT and HEBT sections are equipped with steering coils. In the MEL section, two steering magnets are placed independently of the MEL quads. Figure 2 shows the beam positions relative to the magnetic centers of the quads before and after the BBA. After the BBA, the beam trajectory was better centered overall. However, residual misalignments were observed in some quads due to the absence of steering magnets for the orbit correction. The horizontal beam orbit

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# IDENTIFYING THE CONNECTIONS BETWEEN GRAIN GROWTH AND FLUX EXPULSION IN LOW RRR NIOBIUM SRF CAVITIES*

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*Abstract*

The SRF community has shown that high temperature annealing can improve the flux expulsion of niobium cavities during cooldown. The required temperature will vary between cavities and different batches of material, typically around 800 °C and up to 1000 °C. However, for niobium with a low residual resistance ratio (RRR), even 1000 °C is not enough to improve its poor flux expulsion. The purpose of this study is to observe the grain growth behavior of low RRR niobium coupons subjected to high temperature annealing to identify the mechanism for improving flux expulsion. We observe that low RRR material experiences less grain growth than high RRR when annealed at the same temperature. We search for the limitations to grain growth in low RRR material and develop a diagnostic based on grain structure to determine the appropriate recipe for good flux expulsion. The results of this study have the potential to unlock a new understanding on SRF materials and enable the next generation of high Q/high gradient surface treatments.

## INTRODUCTION

As we approach the theoretical limit of niobium for superconducting radio-frequency (SRF) cavities, the last decade has brought immense improvements in quality factor ($Q_0$) and accelerating gradients though intentionally added impurities into the niobium surface [1, 2]. Many SRF studies follow a "clean bulk dirty surface" technique by adding impurities to the surface layer of high purity niobium such as nitrogen through N-doping and oxygen through a low temperature bake [3–9]. N-doped cavities are found to have a high sensitivity to trapped flux, so efficient flux expulsion has been an important component for their implementation in accelerators [9–14].

During cavity testing, a fast cooldown is typically performed to prevent trapped magnetic flux, which is known to harm performance by increasing the residual resistance [12–17]. In this process, there is a large thermal gradient across the cavity as it crosses through the superconducting transition temperature $T_c$, as shown in Fig. 1. This allows for a sweeping phase transition to the Meissner state, where the gradients' depinning force is stronger than the attraction of the vortices to the pinning sites, and the flux is effectively expelled [12].

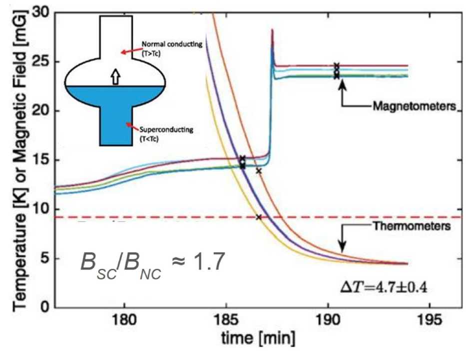


Figure 1: Large thermal gradient and fast cooldown enable flux expulsion, adapted from [12] and [15].

By not following the fast cooldown procedure, flux may be trapped through the incomplete Meissner effect, where there are normal conducting vortices within the superconducting lattice [18]. In this scenario, the cavity's transition to the Meissner state looks more like Fig. 2, where all regions reach $T_c$ simultaneously and the superconducting phase nucleates in multiple locations [12]. If the attraction of the vortices to the pinning sites is more energetically favorable than the onset of superconductivity, this flux becomes trapped [12]. The oscillation of normal conducting vortices during RF operation introduces significant dissipation, limiting the $Q_0$ [19, 20].

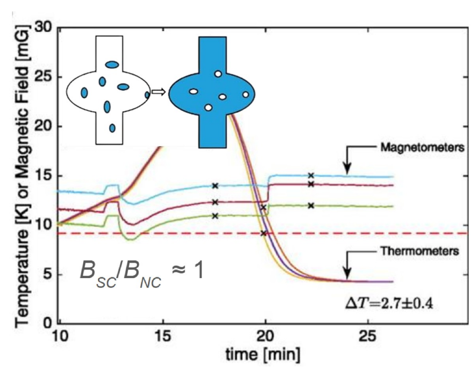


Figure 2: Minimal thermal gradient and slow cooldown impedes flux expulsion, adapted from [12] and [15].

We observe flux expulsion via measurements of fluxgate magnetometers attached to the cavity while cooling down across $T_c$ [15]. Helmholtz coils apply a uniform magnetic field around the cavity. As the cavity transitions to superconducting, the expulsion of flux from the cavity walls increases the magnetic field outside the cavity [12]. We observe a step change in the magnetic field data, which corresponds to the

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# MECHANICALLY POLISHING ELECTROPLATED $Nb_3Sn$ FOR HIGHER ACCELERATING GRADIENTS

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*Abstract*

As the demand for more efficient SRF technology continues to rise, so does the need to improve the performance of $Nb_3Sn$, the most promising alternative to niobium. Leveraging recent breakthroughs in $Nb_3Sn$ research from Cornell University and Fermilab, namely the electrochemical synthesis-based growth of $Nb_3Sn$ and the centrifugal barrel polishing (CBP) technique to smoothen the final $Nb_3Sn$ film, our primary goal is to reduce surface roughness while preserving the film's quality. We present promising RF results from an electroplated cavity that underwent mechanical polishing using the CBP technique, which showed an increase in the maximum accelerating gradient compared to the baseline test. However, contamination-induced Q-slope limited performance. Temperature mapping reveals quench location and heating response before, during and after quench.

## INTRODUCTION

$Nb_3Sn$ is a very promising material for the future of superconducting radio-frequency (SRF) technology, offering significant advantages over conventional niobium used in present-day SRF cavities [1–5]. Its superior superconducting properties, including double the critical temperature of niobium, allow for higher operating temperatures, reduced cooling requirements, and increased operational efficiency. Moreover, $Nb_3Sn$ has a superheating field twice that of Nb [2, 6], allowing for shorter and more powerful accelerators. This material has the potential to contribute to sustainability in accelerator-driven sciences, making SRF technology accessible across a variety of applications, from industrial and medical to quantum computing.

Despite its promise, optimizing $Nb_3Sn$ growth remains an immense challenge. The current state-of-the-art growth method, thermal vapor diffusion, struggles to produce uniform stoichiometric $Nb_3Sn$ layers of the required thickness. Deviations in composition or thickness lead to performance limitations, including lower quality factors and lower accelerating gradients [3, 7–11]. Additionally, surface roughness is believed to also contribute to premature loss of superconductivity due to field enhancement and magnetic flux penetration prior to reaching the superheating field [12]. Notably, the maximum accelerating gradient achieved for $Nb_3Sn$ cavities of 24 MV/m was accomplished at Fermilab using a thinner coating that was significantly smoother than typical coatings [1].

Various chemical and mechanical polishing techniques have been explored to reduce surface roughness in $Nb_3Sn$ cavities. Chemical polishing methods such as electropolishing, buffered chemical polishing, and oxypolishing have been studied [3, 13, 14], however, the different reaction rates of tin and niobium with the chemicals used results in non-stoichiometric $Nb_3Sn$ layers. A recent study from Fermilab optimized a centrifugal barrel polishing (CBP) process, achieving significant surface roughness reduction in vapor-diffused $Nb_3Sn$ [15]. CBP is a mechanical polishing technique that utilizes abrasive media to smooth the cavity surface. In this process, the cavity is filled with a suspension of abrasive media and mounted in a tumbling machine, as shown in Fig. 1. The rotational motion accelerates the polishing media against the inner surface, promoting uniform material removal and resulting in a smoother finish.

However, in addition to causing cracks on the $Nb_3Sn$ film, mechanically polishing the surface can expose tin depleted regions near the Nb-$Nb_3Sn$ interface. Tin depleted regions are problematic for RF performance due to their lower critical temperature and maximum achievable field [7,8]. Exposing these regions poses a significant challenge for surface treatments like CBP.

To address the inhomogeneity of the layer composition accross the thickness of vapor-diffused $Nb_3Sn$ layer, alternative growth methods are being explored. A promising alternative growth method, developed at Cornell University, is electrochemical synthesis based growth [16]. This method involves electrochemically depositing a uniform tin layer onto a niobium substrate, followed by high temperature annealing to form stoichiometric $Nb_3Sn$. Sample studies have shown reduced tin content variation with depth compared to vapor diffused $Nb_3Sn$ [16]. Additionally, cavity results have shown quality factors exceeding $10^{10}$ at 4 K with a quench field of 13 MV/m [17].
By integrating electrochemical synthesis with the mechanical polishing technique of CBP, we aim to address stoichiometric uniformity and surface roughness reduction to increase the accelerating gradients of $Nb_3Sn$ cavities.

## METHODS

Cavity LTE1-9, a 1.3 GHz TESLA elliptical style cavity, was prepared by Z. Sun at Cornell University by electrochemically depositing tin followed by high temperature annealing using the method described in [16]. The cavity was then transported to Fermilab for CBP, where it was tumbled for 4 hours at 120 RPM using 50 nm alumina nanoparticles suspended in water, with 25 mm wool cubes as carrier medium. These parameters were previously optimized at Fermilab for vapor diffused $Nb_3Sn$ cavities. Based on sample studies [15],

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# QUALITY FACTOR ANALYSIS OF SURFACE-PASSIVATED CAVITIES AT LOW GRADIENTS APPLYING TWO LEVEL SYSTEM MODELS

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*Abstract*

The native oxides of niobium cause surface losses during cavity operation arising from two-level systems/defects (TLS). These losses dominate the quality factor at low accelerating gradients ($E_{acc}$ <1 MV/m). In particular, the amorphous $Nb_2O_5$ is identified as a prominent host for TLS. $Nb_2O_5$ dissociates when the material is baked above 200 °C for several hours in vacuum (the so-called Mid-T Bake), allowing for the modification or reduction of these losses. However, due to the inevitable exposure to air after the annealing, the surface reoxidizes and $Nb_2O_5$ regrows. When the cavity is already coated with $Al_2O_3$ and then subjected to the Mid-T Bake, this subsequent reoxidation of the niobium is inhibited. Herein, we studied the quality factor of three superconducting radio frequency cavities in the low gradient range ($E_{acc}$ <1 MV/m) at 1.5 K and analyzed the data using the non-interacting one-species TLS Model.

## INTRODUCTION

Native niobium pentoxide, which forms naturally on niobium surfaces exposed to air, is a defective, off-stochiometric 3-5 nm thick layer which strongly influences the performance of superconducting radio-frequency (SRF) cavities. The impact of the oxide is usually described by two different models applicable for two different ranges of the accelerating field although the microscope origin is the same. In both cases, fields below 5 MV/m or above 20 MV/m, the uncompensated spin of a valence electron the niobium atom within the niobium-pentoxide is the origin of the loss mechanism, but the actual mechanism is of different nature.

For accelerating fields above 20 MV/m, it has been demonstrated that the superconducting density-of-states can be explained best by the Shiba-model, which assumes magnetic impurities in the vicinity of Cooper-Pairs [1]. Furthermore, in Ref. [2] the surface impedance of superconductors in the presence of magnetic impurities were analyzed. This analysis together with the experimental results strongly suggest that the oxide layer, most notably the $Nb_2O_5$, is the host of these magnetic impurities.

At low fields of less than 5 MV/m, there is a strong decrease of the quality factor $Q_0$, the so called low field Q-slope (LFQS) - this range of accelerating field is of interest for the application of cavities in quantum computing. It has been shown that this degradation of the quality factor is increased/enhanced with increasing oxide layer thickness or improved when removing the oxide layer completely [3, 4]. These losses are predominantly from two-level systems (TLS) [5] in the $Nb_2O_5$ layer. Here, it is assumed that the TLS-induced losses emerge from *dangling bonds*, unbound valence electrons of Nb-atoms within the $Nb_2O_5$ layer, coupling to the electric field at the surface of resonators - yet their actual nature and the most accurate model are still under investigation [6]. The loss is then characterized by the dielectric loss tangent $\delta_{TLS}$. Given the strong evidence for TLS in the native niobium oxides and their contribution to the surface losses, manipulating this oxide layer is one of the ways to mitigate TLS losses. With a combination of atomic layer deposition (ALD) to coat a passivating surface, and high-temperature heat treatment to remove the native oxide layer and therefore the TLS, TLS-induced losses are substantially reduced in superconducting niobium resonators, as shown in Ref. [7]. Similar treatments and their results, carried out by our group will be shown here.

## CAVITY PREPARATION

All three cavities used for this study are 1.3 GHz TESLA-shaped single-cell cavities out of high RRR (>300) Niobium.

The first cavity, which serves as baseline cavity, is *1Z13*, a cavity of medium grain. This cavity underwent a coarse electropolishing (EP) of 130 µm. It was then subjected to an UHV anneal at 800 °C for 3 hours and a subsequent fine EP of 20 µm. The cavity was subjected to a final treatment before the test of a low-T bake at 130 °C for 24 hours.

The second cavity is *1DE18*, a single-cell cavity made out of fine grain niobium. This cavity underwent several treatments and tests before. The treatment history is given elsewhere, but the immediate treatment was a coating with 18 nm of $Al_2O_3$ [8]. This cavity then underwent several heat treatments in a single-cell furnace operated in an ISO5 cleanroom [9]. The heat treatment prior to the test was the so-called mid-T heat treatment with 3 h at 300 °C.

The third cavity is *1DE10* and mostly identically to 1DE18 (preparation and treatment), while the last heat treatment prior to the test was a 10 h anneal at 650 °C.

## TEST PROCEDURE

Because of the low energy levels of the TLS, such defects are saturated at high temperature or accelerating field. Hence to be sensitive and capable to study these effects, the material

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# DEVELOPMENT OF A 1.3 GHz LONGITUDINALLY SPLIT RF RESEARCH CAVITY FOR USE IN TESTING OF SUPERCONDUCTING THIN FILMS*

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*Abstract*

RF testing is a key element in the development of superconducting thin film coated cavities. In order to optimize the deposition process, tests initially focussed on flat samples, before moving on to RF cavity tests, however the jump from flat samples to cavities is large and often requires significant changes to the deposition process. In order to develop a multi-step approach to cavity testing, a new 1.3 GHz test cavity has been designed as an intermediary between depositing on flat samples and research cavities. The cavity is split longitudinally, giving it an open-faced design, that enables planar thin film deposition techniques, as well as facilitating easy access for quality control of the deposited surfaces. In addition it has been designed to have a low surface electric field, which allows us to test the superconducting properties due only to the magnetic field, without it being perturbed by field emissions. This paper discusses the design of this novel cavity geometry for use in thin film testing.

## INTRODUCTION

Longitudinally split RF cavities are an answer to several issues that can occur in traditional RF cavities. Most commonly, RF cavities are are produced in two half cells, then electron beam welded together around the equator where the RF surface current is highest. This may result in lowered cavity performance according to research on ISOLDE [1]. In contrast, the 2 halves of the longitudinally split cavity run parallel to the surface current, which allows the introduction of a gap that the fields are unable to couple into. This allows welds to be performed in a space further from the high fields near the cavity equator, which can improve cavity performance. In addition, producing the cavity as two open faced halves allows for planar thin film deposition techniques to be used. A similar concept, but using quadrants is also utilised in the SWELL cavity [2] at CERN for use as an accelerating cavity.

Previously at Daresbury Laboratory, an elliptical, 6 GHz, longitudinally split cavity produced from bulk copper has been used for the testing of Niobium (Nb) thin films [3]. Latest tests with this cavity have achieved surface resistances of 38 μΩ at 4 K, with a residual resistance of 11 μΩ and BCS resistance of 27 μΩ. This is a nearly 15 fold improvement compared to initial results of 532 μΩ at 4 K [4], as a result of improvements in the deposition process, however according to SRIMP [5], the BCS is between 9.5 μΩ and 11.5 μΩ, meaning the measured BCS is still a factor of 2 higher than expected. In order to further optimize the thin film deposition process on RF cavities, a longitudinally split cavity has been developed for use in a test facility.

There are 2 main differences in designing the new cavity compared to a standard cavity optimization process. Firstly, the longitudinally split design introduces potential misalignments between the cavity halves which can result in localised peak fields, so the cavity was designed to minimize the impact of such a misalignment.

Secondly, most existing cavities have been optimised for use as accelerating cavities, where the primary focus is achieving a high accelerating gradient. Therefore, optimising cavity performance often is done by minimizing the peak fields for a given accelerating gradient. In contrast, this cavity design focuses on being able to accurately measure superconducting thin films.

A cavity with this focus has not been designed before, so a new set of optimization parameters had to be defined. The goal was to produce a cavity where there is no field emission by minimizing the peak electric field, while still exposing the superconducting thin film to the highest possible magnetic field at fixed (limited) cryocooler capacity. This allows a stepped approach to be taken, where the material properties can be optimised first.

## LONGITUDINALLY SPLIT CAVITIES

Longitudinally split cavities consist of two open-faced halves, with a geometry such as the one shown in Fig. 1. For both the existing 6 GHz cavity and the new 1.3 GHz cavity, the two halves are bolted together after deposition, allowing for repeated thin film depositions and tests on each cavity.

The 6 GHz split cavity that has been tested previously has a standard elliptical geometry, and is machined from a rectangular block of copper. In contrast, the 1.3 GHz test cavity, features several adaptations to account for the behaviour of the fields at the join between the halves.

In an ideal longitudinally split cavity, the interface between the halves would look the same as in a typical cavity. In reality however, when connecting the two halves a misalignment is likely to be introduced between them, resulting in a sharp step which causes localised peak magnetic fields.

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# DENSITY-FUNCTIONAL THEORY STUDY OF NOVEL RECIPES TO REDUCE $Nb_3Sn$ GRAIN BOUNDARY DISSIPATION*

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*Abstract*

Previous research has shown that $Nb_3Sn$ cavities with tin-rich grain boundaries tend to show significant Q-slope behavior, while cavities with grain boundaries of the "ideal" 25%-tin composition have higher quality factors and reach higher quench fields. In this paper, we make the case that it is possible to improve the properties of $Nb_3Sn$ grain boundaries even further. We use density-functional theory (DFT) to show that the addition of some ternary elements creates $Nb_3Sn$ grain boundaries with more bulk-like electronic structure, potentially making them more resistant to magnetic flux entry and dissipation. We discuss next steps toward introducing ternary elements in a post-processing step compatible with existing state-of-the-art $Nb_3Sn$ cavity recipes.

## INTRODUCTION

The A15 superconductors have been subject to extensive experimental and theoretical studies over the last 70 years [1–4]. Most of these investigations have focused on figures of merit such as superconducting critical temperature $T_c$, critical current $J_c$, and upper critical field $H_c2$, all of which are directly relevant for in-demand applications. Investigations of ternary A15 compounds are no exception; here too the focus has been on demonstrating improved $T_c$, $J_c$, and/or $H_c2$ compared to binary A15 compounds, with significant progress noted in multiple cases [5–7].

In this paper, we consider another relevant property of A15 superconductors which is of particular importance to RF applications: the sensitivity of the superconductor to material defects. While in DC applications the presence of a small volume fraction of disordered, weakly-superconducting material in an A15 wire is inconsequential (or even beneficial depending on how it affects flux pinning), the same defect in an RF device can easily dominate the overall RF dissipation, leading to a degraded quality factor, thermal instability, and quench [8]. Specifically, we choose to focus on grain boundaries as defects responsible for slab-like regions of disorder in the superconductor. While they are not the only source of disorder, they are arguably the largest material defects that are completely impossible to eliminate in any realistic 3-dimensional resonator, and improving their properties is an area of active research for $Nb_3Sn$ SRF applications [9, 10].

In principle, material defects can have an adverse effect on superconducting properties like $T_c$ through a variety of mechanisms [11]. One such mechanism is the broadening of electronic state energy levels; this is a direct quantum-mechanical consequence of short electronic state lifetimes, which in turn result from high rates of electron-defect scattering. This mechanism is particularly relevant for $Nb_3Sn$ and other A15 superconductors because the excellent superconducting properties of well-ordered A15 crystals originate from a narrow peak in the electronic density of states very close to the Fermi level, visualized in Fig. 1. Disorder induced by material defects such as grain boundaries tends to broaden this peak, resulting in a lower density of states at the Fermi level and degraded superconducting properties [12].

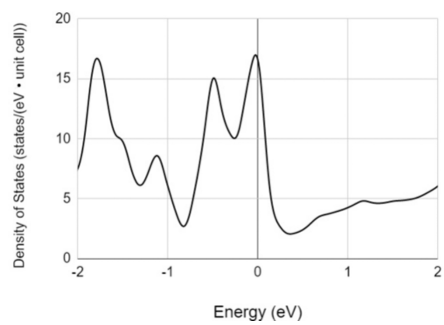


Figure 1: Density of states plot for pure $Nb_3Sn$. The narrow peak at the Fermi level ($E = 0$) is responsible for the high $T_c$ of $Nb_3Sn$ [13].

The effect of disorder on the electronic density of states distribution can be understood as a result of the time-energy uncertainty principle [14]. A higher concentration of defects will result in a higher rate of elastic electron-defect scattering, and shorter electronic state lifetimes. Shorter electronic state lifetimes correspond to broader electronic state energies:

$$\Delta E = \frac{\hbar}{2\tau}. \quad (1)$$

Electronic structure calculations of $Nb_3Sn$ grain boundaries indeed show a significantly lower Fermi-level density of states at the grain boundary core, as we would expect for a region where the electronic state lifetime is likely very short [12]. While the smoothing effect of proximity coupling ensures that the effect of grain boundaries on the superconducting order parameter is less extreme than the effect on the Fermi-level density of states, grain boundaries may still represent weak links in the superconducting surface where magnetic flux can enter more easily than in the surrounding material, possibly explaining Q-slope and quench field limitations of $Nb_3Sn$ cavities.

If grain boundaries are indeed a performance-limiting defect in $Nb_3Sn$ cavities, and if we are unable to eliminate them, then we must consider options to improve the properties of grain boundaries. We will investigate the possibility

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# FIELD EMISSION ANALYSIS IN SRF CAVITIES FOR PIP-II USING GEANT4*

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*Abstract*

Field emission (FE) remains a significant hurdle for achieving optimal performance and reliability in superconducting radiofrequency (SRF) cavities used in accelerator cryomodules. A thorough understanding of the generation and propagation of FE-induced radiation is therefore essential to mitigate this problem. The absence of standardized measurement protocols further complicates the comparison of radiation data across different testing phases and facilities. This highlights the need for a precise quantitative method to diagnose and analyze FE-induced radiation. Such efforts could prove beneficial for improving cavity preparation and cleanroom assembly techniques during the prototype and production stages of Fermilab's Proton Improvement Plan-II (PIP-II) project. This study presents the initial steps of detailed Geant4 simulations aimed at analyzing FE-induced radiation in the low-beta 650 MHz 5-cell elliptical (LB650) cavity. Our goal is to combine these results with radiation diagnostics to enhance diagnostic accuracy and optimize detector positioning. This integrated approach ultimately aims to improve the preparation, assembly, and testing procedures for PIP-II SRF cavities, ensuring the delivery of FE-free cryomodules.

## INTRODUCTION

Superconducting radiofrequency (SRF) cavities are central to modern accelerators, where achieving high accelerating gradients while maintaining low losses is essential for meeting performance goals. Fermilab's Proton Improvement Plan-II (PIP-II) is one such large-scale project, aimed at upgrading the accelerator complex to deliver 1.2 MW of beam power to the Long-Baseline Neutrino Facility (LBNF). The centerpiece of PIP-II is a new superconducting 800 MeV linac that injects beam into the existing 8 GeV Booster. This linac employs 650 MHz, five-cell elliptical cavities to accelerate up to 2 mA peak current of $H^-$ ions in the energy range 185–800 MeV. The low-beta section (LB650, $\beta g = 0.61$) is designed to accelerate the beam from 185 MeV to 500 MeV using 33 dressed cavities distributed across 11 cryomodules [1].

Despite these advances, performance can be limited by field emission (FE), a quantum tunneling process triggered by surface contaminants such as dust, metallic flakes, adsorbed gases, or other impurities. Once emitted, electrons are accelerated by the RF fields, extracting stored energy from the cavity and thereby reducing the intrinsic quality factor ($Q_0$). When these electrons strike the cavity walls, they generate localized heating that increases the cryogenic load and produces Bremsstrahlung radiation in the form of X-rays. Because their trajectories are governed by the time-varying RF fields, the impact locations of electrons may be far from their emission sites. This nonlocal behavior complicates the identification of emitters and makes FE mitigation a persistent challenge.

X-ray detection outside the cryostat has become the standard diagnostic for FE during cavity RF testing. Radiation detectors are simple to operate, can be positioned flexibly, and provide quantitative information about the underlying FE processes. However, external measurements are inherently limited, as the detected radiation strongly depends on the spatial distribution and energy of electrons within the cavity—parameters that cannot be directly observed. Bridging this gap requires detailed simulations to connect measurable radiation signals with the underlying emission phenomena, providing insight that is critical for both diagnostics and mitigation strategies.

This study represents an initial effort to reconstruct FE-induced radiation in the LB650 cavity. The modeling approach is twofold. First, electron trajectories originating from potential emission sites were simulated in CST Microwave Studio [2], which tracked their motion in the RF fields and determined their impact locations and corresponding energies. These results were then used as inputs for Geant4 [3] simulations to model the resulting FE-induced radiation, with particular emphasis on the directionality and propagation of X-rays in Fermilab's Spoke Test Cryostat (STC). Together, these tools provide a systematic framework to identify probable emission sites, guide improvements in cavity cleaning and assembly procedures, and establish a basis for correlating radiation measurements with simulations in future cryomodule tests.

## SOURCE PARTICLE GENERATION

To simulate electron emission from potential sites, CST Microwave Studio was employed. First, the eigenmode solver was used to compute the cavity's electric and magnetic field distributions. These fields were then imported and scaled to the operating gradient of $E_{acc}$=16.4 MV/m (for a fixed RF phase). Using the CST particle tracking (TRK) solver, field-emitted electron trajectories were simulated to determine their motion in the RF fields, along with their impact locations and corresponding energies. The Fowler–Nordheim (F–N) equation, shown in Eq. (1), describes this emission as a quantum tunneling process through the surface potential barrier under a strong electric field.

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# STATISTICAL ANALYSIS OF FIELD EMISSION FOR SHINE PROJECT*

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*Abstract*

Field emission is one of the main problems that is difficult to completely avoid in superconducting accelerator project, and it is usually considered to be caused by particles or chemical residuals. Although careful assembly and cleaning can minimize or eliminate this issue, field emission may still occur to some extent. This report focuses on the field emission problem faced in the SHINE project, including the field emission of bare cavities and of cryomodules. Through statistical analysis, possible correlations between processing and the occurrence of field emission were identified, allowing targeted countermeasures to be implemented and resulting in a noticeable reduction in field emission probability. Ongoing monitoring will be maintained to keep the field emission occurrence rate low in SRF cavities and to further toward field emission-free cryomodules.

## INTRODUCTION

Field emission is one of the main limitations for the achievable accelerating gradient of SRF cavities. The predominant source emitters are microscopic particulates adhering to the inner cavity surface, chemical residuals, and geometrical flaws [1–3]. The particulate contamination could originate from the clean room environment and the generation during the assembly process. Therefore, it is imperative to strictly follow standardized ultra-clean protocols to prevent the deposition of particulates on the inner surface of the cavity during surface treatment and the clean assembly procedure. Field emission remains a persistent challenge throughout the construction of the accelerator, requiring continuous attention and control [4–6]. At present, the SHINE project has entered an intensive phase of construction, with a large number of SRF cavities undergoing surface treatment and testing, and cryomodule assemblies proceeding in parallel. Over the past year, field emission has become one of the primary factors limiting the performance of our SRF cavities. This report presents a statistical analysis of field emission occurrences and outlines effective mitigation strategies to reduce the incidence of field emission in both cavities and cryomodules.

## OVERVIEW OF SHINE CAVITIES

The SHINE project has now entered the mass-production phase, with SRF cavities undergoing surface processing at partner manufacturers, delivered, and subsequently assembled into cryomodules (CMs) [7]. Two surface treatment recipes are employed: mid-T baking recipe for domestically produced cavities and nitrogen doping recipe for those fabricated by international manufacturers [8]. At the time of writing, 252 dressed cavities from both domestic and international manufacturers have completed fabrication, surface treatment, and vertical test. 17 cryomodules have already passed horizontal test, another 10 CMs are under test or assembly, and more CMs are in preparation.

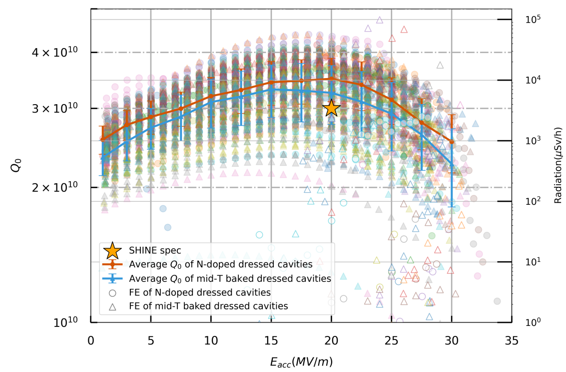


Figure 1: Vertical test results of SHINE cavities.

Table 1 summarizes the present acceptance criteria for SRF cavities and cryomodules at SHINE. For cavities, the accelerating gradient ($E_{acc}$) are required to exceed 22 MV/m, and the intrinsic quality factor ($Q_0$) at 20 MV/m shall be greater than $3 \times 10^{10}$. Cavities with field emission are only accepted if the onset gradient is above 22 MV/m. For cryomodules, the total usable accelerating voltage shall exceed 166 MV, corresponding to an average $E_{acc}$ of approximately 20 MV/m per cavity, with an average $Q_0 \geq 3 \times 10^{10}$. In order to speed up the test and to reduce the risk of field emission at high gradient, the maximum $E_{acc}$ of cavities during horizontal test is capped at 26 MV/m.

A total of 252 dressed cavities have completed vertical test to date, comprising 126 mid-T baked cavities from domestic manufacturers and 126 N-doped cavities from international manufacturers. Figure 1 shows the vertical test results of these dressed cavities. Among these, 192 cavities met the SHINE qualification criteria. Specifically, 152 cavities satisfied the requirements as received, 30 exhibited field emission but were successfully qualified after additional HPR, and 10 showed Q-switch or low $Q_0$ but passed after retest. In addition, 36 substandard cavities were installed concessionally in

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# DESIGN, SIMULATION AND TEST OF 975 MHz SUPERCONDUCTING RADIO FREQUENCY CAVITY*

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*Abstract*

A 975 MHz superconducting radio frequency (SRF) cavity is designed in a new project of China Institute of Atomic Energy to accelerate the H+ ion beam from 500 MeV to 1 GeV. This paper will present the design and simulation, including the multi-parameter electromagnetic design and optimization, multipacting simulations, mechanical and engineering analyses. Prototype cavities were fabricated. The treatment processes of cavities and their vertical test results are also described in this paper.

## CAVITY SHAPE DESIGN FOR 975 MHz SRF CAVITY

Superconducting radio-frequency cavity is one of the key devices of the linear accelerator, the selection of the superconducting cavity is directly related to the accelerated efficiency of the whole accelerated segment. This superconducting radio frequency cavity is designed to accelerate the H+ ion beam in the energy range from 500 MeV to 1000 MeV, we choose elliptical cavity to accelerate proton.

The energy obtained by the particles is only related to the number of charges, the accelerating electric field of the cavity, the time factor (T), the acceleration interval length and the synchronization phase. It is necessary to select the appropriate cavity, which will improve the effective acceleration efficiency of the entire accelerated segment. According to the relationship between T and cavity phase velocity (Fig. 1 (a)) and cavity number (Fig. 1 (b)), the cavity number and cavity phase velocity that need to be balanced TTF and effective acceleration length is required. We choose 5-cell and 0.8 c cavity phase velocity .

(a) (b)

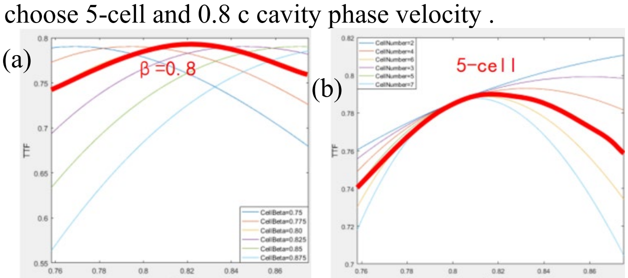


Figure 1:(a) The transition time factor of the same cavity number of different phase velocity;(b): The transition time factor of the same phase velocity of different cavity number.

The first step of a superconducting elliptical cavity RF design is made as a trade-off in the optimization of the cell shape between the region of high electric field and the region of high magnetic field. In practice, the cavity performance may be limited not only by the RF characteristics, but also by detuning due to the Lorentz force, bath pressure fluctuations, or microphonics.

By optimizing the selection of the geometric parameters of the cavity, the theoretically optimized cavity is obtained, and the acceleration gradient is added to the maximum limit, while avoiding several harmful physical effects [1].

To meet the design requirements, several iterations with varying the geometry of the cavity shape were performed.

The equator ellipse ratio has negligible effect on the RF properties of the cavity unless it is too large enough to cause problems on mechanical stability. Therefore it is set to be 1 to make it easy to tune the end cell.

The dependency of the cavity parameters such as peak field ratio, G and r/Q on the iris radius is shown in Fig. 2. The smaller iris radius preferred.

Figure 3 shows the dependency on the wall angle change. The large wall angle makes the surface treatment more convenient. However, the peak surface electric field increases as the wall angle increases.

Figure 4 shows the peak surface electric field increases as the iris ellipse ratio increases. With chosen geometrical parameters through the above considerations, the iris ellipse ratio can be determined to give the lowest surface electric field.

The designed cavity geometry is shown in Fig. 5. As showed in Table 1 and Fig. 6, the field flat of this elliptical cavity was optimized to more than 98% while the Epk/Eacc and Bpk/Eacc reached 2.42 and 5.36, respectively.

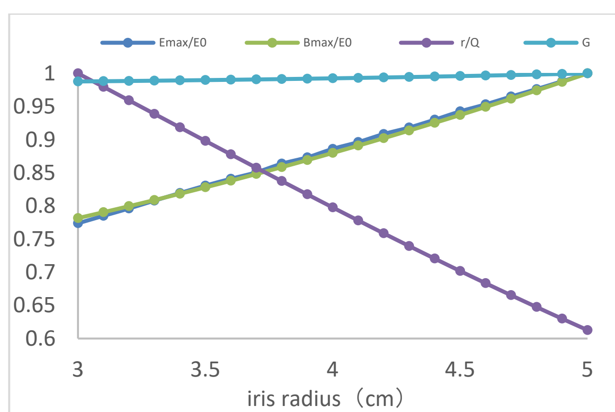


Figure 2: Dependency on iris radius.

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# OPTIMISATION OF $Nb_3Sn$ THIN FILMS FOR SRF APPLICATIONS AT DARESBURY LABORATORY*

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*Abstract*

$Nb_3Sn$ is a promising alternative to bulk niobium (Nb) for superconducting radio-frequency (SRF) cavities due to its higher critical temperature and superheating field. In this study, $Nb_3Sn$ thin films were deposited via DC magnetron sputtering from a stoichiometric Nb:Sn alloy target onto various substrates, including diamond-turned Cu, bulk Nb, and Cu with a Nb bilayer. The influence of magnetron power, film thickness and substrate on the surface resistance ($R_s$) at 7.8 GHz was systematically investigated. Films deposited at lower magnetron powers (50 W) demonstrated significantly lower $R_s$ values, reaching 0.38 μΩ at 4.2 K, whereas higher power led to increased residual resistance, likely due to Cu diffusion and surface defects. Thinner $Nb_3Sn$ films exhibited elevated $R_s$, while $Nb_3Sn$ films on bulk Nb showed variable performance depending on surface preparation, a film with a Nb bilayer on Cu unexpectedly underperformed relative to direct deposition on Cu.

## INTRODUCTION

As the performance of these Nb cavities approaches their intrinsic material limits, research has increasingly focused on enhancing their capabilities through surface engineering techniques, optimized heat treatments, and surface polishing methods [1]. However, as outlined in the European Strategy for Particle Physics Accelerator R&D Roadmap, "increasing the accelerating gradient is an absolute necessity to keep the facility to a reasonable size" [2]. This necessitates the development of alternative superconducting materials that can exceed the performance limitations of bulk Nb.

Thin-film SRF cavities made from alternative superconductors such as $Nb_3Sn$, $V_3Si$, $MgB_2$, and NbTiN coated cavities are promising candidates due to their higher critical temperatures ($T_c$) and superheating field ($H_{sh}$) [3]. These properties could enable SRF cavities to operate at higher temperatures (> 4.2 K) and achieve greater accelerating gradients, thereby reducing cryogenic infrastructure complexity and overall operational costs.

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Among these, $Nb_3Sn$ has seen the most research effort. As a superconducting A15 compound with a $T_c$ = 18 K and $B_{sh}$ = 425 mT, $Nb_3Sn$ has the potential for a significantly lower BCS resistance ($R_{BCS}$) and a higher quality factor ($Q_0$) compared to Nb. However, $Nb_3Sn$ is a brittle material and is therefore only suitable in thin-film form for accelerator applications. Several research programs at various institutions are actively exploring $Nb_3Sn$ film growth via tin (Sn) vapour diffusion. This method involves exposing a Nb cavity to Sn vapour (approximately $10^{-3}$ mbar) at elevated temperatures (> 1000 °C), resulting in the formation of a $Nb_3Sn$ layer on the cavity's inner surface. Cavities produced using this technique have demonstrated $Q_0$ values greater than $1 \times 10^{10}$ at 20 MV/m and 4.4 K, and accelerating gradients up to 24 MV/m [4]. Nonetheless, challenges such as film non-uniformity, surface roughness, Sn residue, and impurity incorporation remain significant hurdles.

This report investigates the optimization of $Nb_3Sn$ thin films (TFs) using physical vapour deposition (PVD) via magnetron sputtering from a stoichiometric Nb:Sn target. A series of films were deposited to study the effects of magnetron power and film thickness, as well as substrate configurations including Nb/Cu bilayers, bulk Cu and bulk Nb. The surface resistance ($R_s$) of the films was evaluated at 7.8 GHz to assess their SRF performance and potential for SRF cavities.

## EXPERIMENTAL

### *Sample Preparation: Magnetron Power*

Four $Nb_3Sn$ TFs were deposited on Cu disks of 100 mm diameter and 3 mm thickness. All Cu disks were mechanically polished at STFC RAL Space via off-axis diamond

Table 1: Typical DC Magnetron Sputtering Deposition Parameters

| Deposition Parameter | | Units |
|---|---|---|
| Base pressure | $10^{-9}$ | [mbar] |
| Substrate temperature | 600 | [°C] |
| Heating duration | 20 | [hrs] |
| Deposition pressure | $3\times10^{-3}$ | [mbar] |
| Sputtering gas | Kr | |

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# DEVELOPMENT OF A NEW SYSTEM FOR $NB_3SN$ THIN FILM DEPOSITION ON 1.3 GHz CAVITIES*

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*Abstract*

Nb3Sn in the form of thin film on copper is one of the most promising routes in the field of superconducting radio-frequency accelerating cavities for future colliders. At INFN – Legnaro National Laboratories, thin films of $Nb_3Sn$ have been successfully deposited on small copper samples via DC magnetron sputtering. The process enabled the production of films with critical temperature ≥ 17 K, at deposition temperatures of 600 °C - 650 °C and with the implementation of a Nb buffer layer of 30 µm thickness. The design and development of a dedicated system to scale this deposition recipe from small samples to a full-size 1.3 GHz copper cavity are presented in this work. The main challenges involve both the high substrate temperatures, requiring careful thermal management and mechanical design, and the need to ensure uniform thin film deposition over a extended and curved surface. Since a planar magnetron is employed, a rotational motion must be maintained during the process, achieved in this case by rotating the cavity itself. The system's core features include substrate heating using four infrared lamps, the insertion of a custom planar magnetron inside the cavity, and a ferrofluidic rotation mechanism compatible with ultra-high vacuum conditions. To this day, the system has been successfully built and tested. The next step will be the deposition of the Nb toward the first RF validation.

## INTRODUCTION

The $Nb_3Sn$ thin films developed at INFN – Legnaro National Laboratories exhibit a critical temperature $T_c > 17$ K and promising surface resistance at $R_s \approx 20$ nΩ at 4.5 K. The deposition recipe [1] used for these films involves a max power density of approximately 250 mW/cm$^2$, a substrate temperature ≥ 600 °C, and a Nb buffer layer between the $Nb_3Sn$ coating and the Cu substrate with a thickness ≥ 30 µm.

Scaling this recipe and its requirements from small samples to a 1.3 GHz cavity requires not only the ability to reproduce an equivalently performing film on a more complex and larger surface, but also the design of a dedicated sputtering chamber. This chamber must ensure that the key conditions driving film formation — such as power density and substrate temperature during deposition — can be accurately achieved.

Given the relatively low power density and the high substrate temperatures required, it is mandatory to design a system capable of withstanding several hours of significant thermal gradients between its components while maintaining ultra-high vacuum conditions. Moreover, it is crucial that the system allows fast and straightforward interchangeability between the two required deposition processes: Nb (for the buffer layer) and $Nb_3Sn$. These two coatings require different power density regimes and deposition techniques: Nb sputtering employs a multilayer approach [2] with a power density approximately two orders of magnitude higher than that used for $Nb_3Sn$.

An innovative system to reach this goal has been designed and the preliminary test result results are presented in this work.

## EXPERIMENTAL PLAN

A cavity made of OFHC Cu, coated with $Nb_3Sn$ using DC magnetron sputtering and featuring a Nb buffer layer with a minimum thickness of 30 µm, requires several intermediate steps to be successfully fabricated:

1. Design of all components required for the cavity operation:
   (a) A vacuum system, designed to meet two simultaneous requirements: ultra-high vacuum (UHV) operability and substrate (cavity) temperatures of at least 700 °C;
   (b) A deposition system compatible with commercially available rectangular $Nb_3Sn$ targets;
   (c) A cavity connection system that avoids the use of brass joints, which could compromise both the UHV conditions and the cleanliness required for the application;
2. Commissioning, testing, and construction of the complete system;
3. Scaling of the recipe with a static configuration, without involving cavity motion. The recipe must be adapted to the new magnetron, taking into account the curvature of the substrate;
4. Scaling of the recipe in dynamic mode, involving the rotational motion of the cavity;
5. Final scaling to a real cavity, followed by RF testing.

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# FIRST 1.3 GHz Nb CAVITY COATED WITH Nb3Sn THIN FILM DEPOSITION BY PVD MAGNETRON SPUTTERING

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*Abstract*

$Nb_3Sn$ thin film cavities are a new generation of superconducting cavities, which have the potential to replace traditional pure niobium cavities owing to their superior theoretical radio frequency (RF) performance. Higher theoretical acceleration gradient and quality factor give $Nb_3Sn$ coated cavities more possibilities in the future. There has been relatively high success in producing such cavities by tin (Sn) diffusion method. The production of such cavities through thin film deposition on copper cavity foresees lower cost of material and at the same time profiting from higher thermal conductance of copper. At Daresbury Laboratory, a new $Nb_3Sn$ deposition facility has been commissioned for depositing a Nb cavity with $Nb_3Sn$. The system is based on using planar magnetron where the optimised parameters for $Nb_3Sn$ on flat surfaces had been well stablished. A cavity was deposited at 620 °C using two special designed 2-inch magnetrons travelling inside cavity simultaneously from each end of the cavity. Prior to cavity deposition a series dummy runs were performed with different magnetron positions inside the cavity to calibrate the film thickness and surface coverage as well as film uniformity. Witness Nb samples showed that the synthesised $Nb_3Sn$ had stoichiometry of 3:1 Nb to Sn ratio and a critical temperature of 17.8 K . The deposition was done at 50 W DC power with a bias of -70 V.

## INTRODUCTION

Niobium (Nb) has been the workhorse material for SRF cavities for decades, powering particle accelerators like LEP, LCLS-II, CEBAF, and the future PIP-II and ILC. However, Nb has fundamental limits: It has a critical temperature of 9.2 K, requiring complex and expensive liquid helium (LHe) cryogenic systems (typically 2 K). Its superheating field $H_{sh} \approx 200$ mT, limits the maximum achievable accelerating gradient. On the other hand, $Nb_3Sn$, an A15 intermetallic compound, offers dramatic improvement. It has a $T_c = 18.3$ K, allowing operation at 4.2 K. This simplifies cryogenics and drastically reduces operating costs. Its theoretical superheating field $H_{sh} \approx 400$ mT, approximately double that of Nb, suggests the potential for much higher accelerating gradients. Furthermore, it has lower surface resistance, especially at higher temperatures (e.g. 4.2 K), leading to higher quality factor ($Q_0$) and hence even lower operating costs.

One of the widely considered methods to fabricate $Nb_3Sn$ on Nb substrates is the Sn vapor diffusion method introduced by Saur and Wurm [1]. In this method, Nb is annealed at high temperature (~1200 °C) with Sn environment. The method was adapted to fabricate $Nb_3Sn$ inside the SRF cavities in 1970s by Siemens AG [2]. Several research groups including Kern Forschungszentrum Karlsruhe, University of Wuppertal, Jefferson Lab, CERN, SLAC, and Cornell University conducted research on $Nb_3Sn$ SRF cavities fabricated by vapor diffusion method during the 1990s [3]. The method is currently adapted at Cornell University, Jefferson Lab and Fermilab to coat single cell and multicell SRF cavities [4, 5]. $Nb_3Sn$/Nb cavities fabricated by the Sn vapor diffusion technique at Jefferson Lab have shown $Q_0 \geq 2\times10^{10}$ at 4 K before quenching at ≥ 15 MV/m for 1.3 GHz single cell cavities [6] and low field $Q_0 \approx 3\times10^{10}$ [7] and maximum accelerating gradient up to 5 MV/m at 4 K for CEBAF 5-cell cavities [8]. Till now, the highest reported accelerating gradient of 24 MV/m at 4 K has been achieved for 1.3 GHz single cell cavities at Fermilab [9]. Several high frequency cavities (2.6 and 3.9 GHz) coated by $Nb_3Sn$ at Cornell University have shown some promising results.

Apart from the conventional Sn vapor diffusion method, several fabrication techniques have been applied to fabricate $Nb_3Sn$ films on flat substrates. $Nb_3Sn$ film was fabricated by co-deposition of Nb and Sn in General Electric Research Laboratory, New York in 1964 [10] where Nb was deposited by evaporation from the molten tip of a Nb rod by electron bombardment and Sn was evaporated by resistance heating. The fabricated films had a superconducting critical temperature Tc up to 16.9 K. At Brookhaven National Laboratory in 1970s [11, 12], $Nb_3Sn$ on Nb was deposited by depositing thin film of Sn on Nb substrate by thermal evaporation then the $Nb_3Sn$ film was formed by thermal diffusion. Perpeet et al. also fabricated $Nb_3Sn$ on sapphire substrate by the Sn vapor diffusion method which is usually considered for Nb substrate [13]. A thick Nb film of ~2 μm thickness was sputtered on the sapphire substrate to provide enough Nb surface for the Sn diffusion. Then the film was transferred to a separate reaction chamber where the samples were annealed at 1100 °C for 5 h with background of Sn and $SnCl_2$. The films showed a critical temperature $T_c = 18.0$ K and a critical current density $J_c$ = 5-6.5 MA/cm$^2$ at 4.2 K. Another approach was used at the National Institute for Nuclear Physics - Legnaro National Lab (INFN-LNL), Italy [14], where Nb was

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# PREPARATION AND TEST OF $Nb_3Sn$ CAVITIES BY TIN VAPOR DIFFUSION METHOD AT PEKING UNIVERSITY

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*Abstract*

Researches on preparation of $Nb_3Sn$ superconducting cavities has been carried at Peking University. $Nb_3Sn$ films were prepared by tin vapor method with a high vacuum furnace. We proposed a coating scheme of 1.3 GHz single cell $Nb_3Sn$ cavity with three tin sources inside. $Nb_3Sn$ films with a tin content of more than 25% were obtained. The vertical tests show the Q of the prepared $Nb_3Sn$ cavities reaches 3.2E10 at low accelerating gradient and larger than 1.0E10@10 MV/m after optimization of the annealing procedure.

## INTRODUCTION

Superconducting radiofrequency (SRF) cavities are widely used in particle accelerators. Traditional niobium cavities have reached outstanding performance levels, which are close to their theoretical limit, in the past half century. $Nb_3Sn$ is known as a novel and potential material for SRF technology, with a higher critical temperature (18.1 K) and higher predicted superheating field (420 mT) than Nb (9.2 K and 240 mT).

The $Nb_3Sn$-coated cavity can contribute to building compact accelerating systems with a much lower cost than that using niobium cavities. The vapor diffusion method is proven to be the most effective method to coat cavities nowadays. In the vapor diffusion method, tin is heated into vapor to be deposited on the inside surface of niobium cavities and forming $Nb_3Sn$ [1]. Recently, more and more institutes have carried out research to improve the performance of $Nb_3Sn$ cavities by the tin vapor diffusion method. The cavity prepared by this method is expected to be applied in a conduction-cooling cryomodule [2]. Nowadays $Nb_3Sn$ cavities have been demonstrated in the stable operation of 4.2 K conduction-cooling compact accelerators, showing their great potentials for practical industrial accelerator applications.

In this work, a new coating design is proposed to apply three tin sources inside a cavity at Peking University (PKU) in order to generate uniform high-pressure tin vapor during the coating process [3]. $Nb_3Sn$ coating experiments are also carried out on 1.3 GHz single-cell cavities and 1.3 GHz 1.5-cell electron gun cavities, detailed analyses is presented in this paper.

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## EXPERIMENT

### *Single-cell Cavity Coating*

The typical temperature profile for single-cell cavity and the vacuum measurements are shown in Fig. 1. A complete coating process includes several stages: degassing, nucleation, coating and annealing. In the nucleation stage, the $SnCl_2$ crucible is heated rapidly to 800 °C and kept for 30 min. The vacuum valve of the molecular pump is closed, and the vacuum is measured during the whole coating process by a film gauge with a measurement range of 0.01 Pa~10 Pa. Then, the $SnCl_2$ crucible cools down to 550 °C for 4.5 h. After nucleation, the cavity temperature is ramped up to 1200 °C and kept for 2 ~3 h, followed by an annealing stage. After the above procedure, the system cools down naturally. This process was proved to coating a uniform $Nb_3Sn$ film with 25%~26% Sn content in previous experiments.

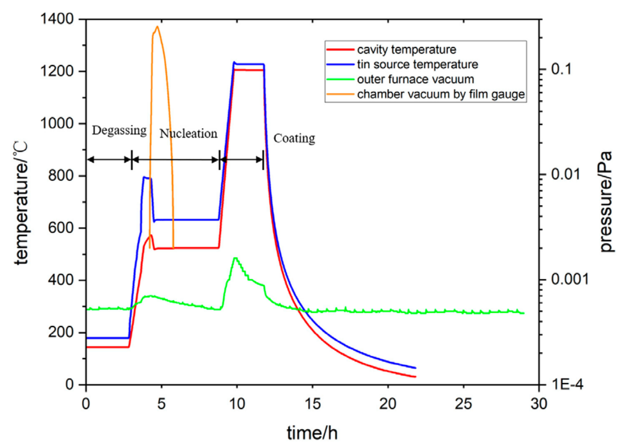


Figure 1: Coating temperature profile.

In previous coating experiments, we frequently observed the Q-slope phenomenon during the RF testing of $Nb_3Sn$ cavities. SEM-EDS and TOF-SIMS analyses of $Nb_3Sn$ films revealed that the depth distribution of Sn within the films is not uniform. Typically, the Sn content of $Nb_3Sn$ thin films fabricated by standard procedure is about 25%, however, the Sn content on the surface of the films exceed 30%, which will have a serious impact on the RF performance. This Sn segregation phenomenon is therefore considered a primary cause of the Q degradation.

Unlike other laboratories, our standard coating procedure does not introduce annealing after the coating stage, because annealing at 1100 °C in our furnace leads to an inhomogeneous Sn distribution between the upper and lower regions of the cavity. Therefore, we performed a

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# AN UPDATE OF THE PLASMA PROCESSING DEVELOPMENTS AT TRIUMF

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## *Abstract*

Superconducting Radio Frequency (SRF) technology is a key component in many particle accelerators operating in a continuous wave, or high duty cycle, mode. The on-line performance of SRF cavities can be negatively impacted by the gradual reduction in the accelerating gradient that can be attained within a reasonable field emission level. Conventional cleaning procedures are both time- and resource-exhaustive as they are done *ex-situ*. Plasma processing is an emerging *in-situ* method of cleaning which chemically removes hydrocarbon-based field emitters through plasma. An R&D program is underway at TRIUMF with the goal to develop fundamental power coupler (FPC) driven plasma processing of the installed 1.3 GHz nine-cell cavities in the ARIEL 30 MeV SRF eLINAC. Processing recipes have been systematically studied in single-cell and multi-cell cavities off-line. The progress on these developments will be reported.

## INTRODUCTION

TRIUMF's Advanced Rare IsotopE Laboratory (ARIEL) is in place to supplement ongoing physics experiments across three experimental locations. The facility includes a 3 mA, 30 MeV SRF electron linear accelerator (eLINAC) that operates in a continuous wave (cw) mode to produce Rare Isotope Beams (RIBs) through the photo-fission process [1, 2]. Electrons accelerated by the eLINAC are incident onto a converter target to generate bremsstrahlung X-rays, which are then used for fission in Actinide targets. The yield of rare isotopes through this process is highly dependent on the incident electron energy, as seen in Fig. 1. Currently, the eLINAC houses three 1.3 GHz 9-cell ARIEL SRF cavities across two cryomodules. Each cavity is specified to operate at a minimum accelerating gradient of 10 MV/m, leaving the final electron energy at the saturation limit of the optimal RIB yield. As such, each cavity must be kept at its designated gradient to avoid decreases in experimental efficiency. Field emission therefore poses a serious concern, as cavity performance can degrade due to the additional power losses introduced by the emitters, limiting the achievable gradient due to high radiation levels and increased cryogenic load.

Plasma processing is a *in-situ* cleaning technique that uses a glow discharge composed of an inert gas and a reactive gas to chemically remove hydrocarbon field emitters from a cavity's surface. Plasma processing has been shown to restore cavity gradients in a number of facilities globally for a fraction of the time required to apply conventional cleaning techniques [4–6]. An R&D program is currently underway at TRIUMF to develop a plasma processing system to prevent field emission from reducing the available gradient within the eLINAC, thereby ensuring that the RIB yield is not compromised. However, the configuration of the eLINAC cryomodules prevents a direct implementation of plasma processing procedures used at other facilities. In particular, the ARIEL cavities are a unique variant of the TESLA design that do not support HOM couplers. HOM dampers are also placed at upstream and downstream beam pipe locations to absorb HOMs [7], restricting the available processing modes. For this reason, FPC driven plasma processing using the $TM_{010}$ and first dipole passbands is being explored. This paper will provide an update on the developments first reported in Ref. [8].

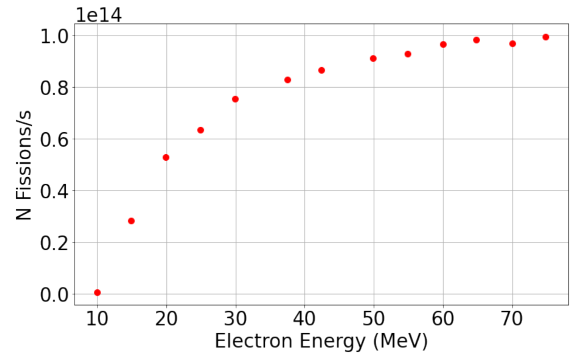


Figure 1: Photo-fission production rates as a function of electron energy for the ARIEL target stations [3]. ARIEL is currently specified to operate at 30 MeV.

## PROCESSING ASSEMBLY

The apparatus used in the processing experiments is illustrated in Fig. 2. Identified by the colored components in Fig. 2, a gas flow and vacuum system is responsible for managing the gas flow into and out of the cavity. Gas injection is done on a port located near the FPC using two gas lines, one for the reactive processing gas (Oxygen) and one for the inert gas (Argon or Helium). One isolation valve and one leak valve are added in series along each gas line to allow manual adjustments to the amount of gas each line is introducing into the cavity. The total cavity pressure used in processing tests is typically kept within the range of 80 mTorr and 200 mTorr. As a result, we employ a CDG-500 capacitance diaphragm gauge to assist in finalizing the cavity pressure by showing the pressure changes due to gas adjustments in real time.

Volatile byproducts formed through the plasma reaction cannot be allowed to resettle onto the cavity surface. To

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# THE PLASMA PROCESSING DEVELOPMENT FOR CSNS-II SUPERCONDUCTING LINAC*

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*Abstract*

As a practical technique to mitigate field emission effect of superconducting cavities on-line, plasma processing has been developed for CSNS-II superconducting Linac. Experimental platform has been set up and experiments of plasma ignited in various cavities with different frequencies have been conducted. The details of the research will be presented in the paper.

## INTRODUCTION

Field emission is one of the main factors that restrict the performance of superconducting cavities used in accelerators. Field emission limits the maximum accelerating field attainable while generating free electrons, which might interact with the beam and cause either damage to the beamline or its activation. In-situ plasma cleaning can be a practical approach to address this problem. CSNS-II comprises 18 superconducting modules (including 44 cavities) [1], and as a user facility it relies on plasma cleaning as the only feasible technical means to achieve on-line rapid treatment of field emission [2, 3].

## PLASMA PROCESSING EFFORTS AT CSNS-II

### *Plasma Processing Experiment Setup*

The scheme of the gas system layout of the plasma processing system for CSNS-II is depicted in Fig. 1, and the plasma ignition experiment was firstly conducted on a 648 MHz single spoke cavity trying to cover the two cavity types of CSNS-II. The gas used in this experiment consists of He/Ne-O2 (90%-10%) mixtures, in which the noble gases function as physical sputtering of the contaminants and oxygen promotes the reaction with hydrocarbon contaminants to produce volatiles that can be easily pumped out.

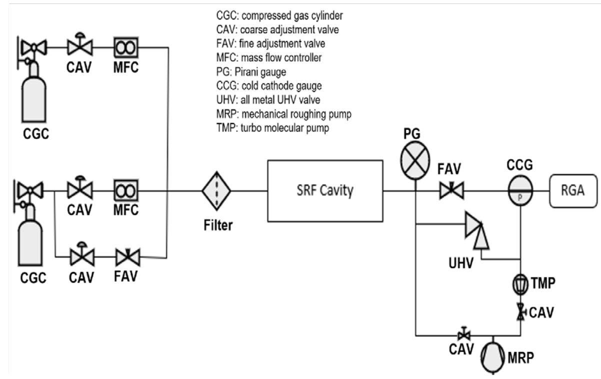


Figure 1: Schematic of gas system of plasma processing.

### *Plasma Ignition Power and Field*

Critical coupling input coupler was firstly used to generate plasma inside the superconducting cavity in a broad range of gas pressure, with the power absorbed into the cavity versus the gas pressure shown in Fig. 2 for both helium and neon. The mechanism of plasma excitation in a superconducting cavity involves plasma being excited in the peak electric field region, followed by the plasma drifting to the low electric field region, and the mathematical relationship between the peak electric field for plasma excitation and gas pressure is fitted as:

$$E_{pk} \sim \frac{100}{\sqrt{P*lnP}}. \quad (1)$$

### *How to Delay Coupler Breakdown*

Plasma coupler breakdown appeared for both helium and neon when some RF power threshold achieved, and this phenomenon is more likely to occur with higher gas pressure (also shown in Fig. 2).

Since the plasma breakdown on coupler has a high risk to cause sputtering of the copper from the antenna onto the cavity or damage of isolating ceramic, it is a tricky problem that remains to be solved. A negative DC bias was attempted onto the input coupler and a significant improvement of the feedforward power to trigger plasma breakdown on coupler has been observed (see Fig. 3) [4].

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# DESIGN AND SIMULATION OF CONDUCTIVE COOLING FOR RADIO FREQUENCY SUPERCONDUCTING CAVITY

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*Abstract*

The RF accelerating module is crucial for imparting kinetic energy to particle beams in accelerators. Superconducting RF (SRF) technology offers key advantages over conventional room-temperature RF systems, including lower operational costs, reduced beam loss, and higher accelerating power. The superconducting cavity, SRF's core component, requires ultra-low temperatures. While liquid helium cooling meets this need, its complex and expensive infrastructure hinders SRF's widespread adoption. Recent advances in cavity manufacturing have improved quality factors (Q-factor) and reduced heat loads to watt levels, enabling alternative cooling methods. This study investigates conduction cooling using compact cryocoolers for a 648 MHz superconducting cavity. Numerical simulations analyzed two cooling structures, focusing on configuration, material choice, and thermal contact resistance. Results show conduction cooling effectively maintains operational temperatures, with high-purity aluminum outperforming oxygen-free copper as a thermal bridge material. Maintaining thermal contact resistance below 10 K·cm²/W is critical. These findings offer valuable guidance for designing more efficient SRF cooling systems.

## INTRODUCTION

In a conduction-cooled superconducting cavity system, the cooling capacity provided by the cold head of a compact cryocooler removes the heat generated by the superconducting cavity through thermal conduction via the conduction cooling structure. As the sole bridge for heat transfer, the conduction cooling structure is crucial within the entire system. Based on the 648 MHz two-cell superconducting cavity designed and manufactured for the China Spallation Neutron Source (CSNS), this paper presents the design and thermal analysis of its conduction cooling structure through heat transfer simulations. The effects of the conduction structure, conduction materials, and contact thermal resistance on the cooling performance were analyzed, resulting in the identification of an appropriate cooling configuration.

## METHOD

The primary methodology of this study involves extracting the electromagnetic loss of the superconducting cavity from ANSYS Workbench HFSS and importing it as a heat source into the Steady-State Thermal module within ANSYS Workbench for analysis and solution. The resulting temperature distribution of the cavity is obtained to evaluate the feasibility of the structural design and to compare the cooling effectiveness.

### *Model Design*

Figure 1 illustrates the geometric configuration of the two superconducting radio-frequency (SRF) cavities designed in this study. The primary design comprises three key components: the equator cooling rings, the beam pipe cooling rings, and the thermal bridges.

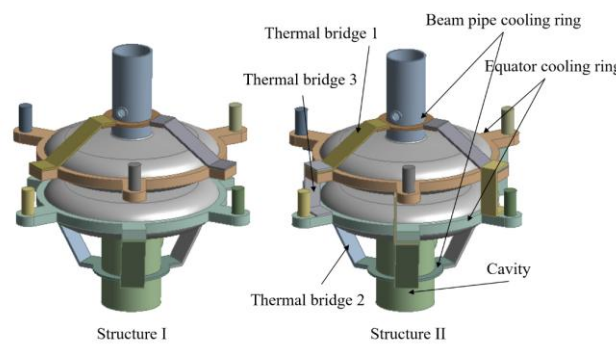


Figure 1: Model of conductive cooling structures.

The equator cooling rings consist of two such rings. They are circumferentially mounted along the equatorial region of the accelerating ellipsoidal cavity of the double-cell superconducting cavity. Their inner surfaces conform to the outer surface of the accelerating ellipsoidal cavity. These rings are connected to the secondary cold source of the refrigerator via flexible cold links. The beam pipe cooling rings also comprise two rings. They are circumferentially arranged along the beam pipe region of the superconducting cavity body, respectively. Their inner surfaces are in close contact with the outer surface of the beam pipe of the superconducting cavity. The thermal bridge structures include thermal bridge 1, used to connect the beam pipe cooling rings to the equator cooling rings, and thermal bridge 2, employed to link the two equator cooling rings together. Structure II, based on structure I, incorporates an additional thermal bridge 3 connecting the two equator cooling rings.

### *Electromagnetic Losses*

The total heat load of a superconducting cavity comprises both the static heat load and the dynamic heat load. The static heat load primarily includes heat leakage from the beam tube and radiation heat. The dynamic heat load is induced by electromagnetic losses within the

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# PLASMA ELECTROLYTIC POLISHING (PEP) AT INFN: A VERSATILE SURFACE TREATMENT TECHNOLOGY FOR ADDITIVELY MANUFACTURED ACCELERATOR COMPONENTS*

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*Abstract*

Over the past decades, advances in surface quality improvement research in superconducting radio-frequency (SRF) technology have led to significant improvements in particle accelerator performance. The degree of surface roughness of SRF cavities remains a key determinant of this performance, driving continuous innovation in surface treatment techniques. At the National Institute of Nuclear Physics, Legnaro Laboratories (INFN–LNL), research has been conducted on advanced polishing methods, including Chemical Polishing (CP), Electrochemical Polishing (EP), and, more recently, Plasma Electrolytic Polishing (PEP). While more energy-intensive than CP and EP, PEP offers distinct advantages such as high-quality surface finishing, faster polishing, lower material costs, reduced risk, and improved environmental sustainability.

To assess the feasibility of PEP for accelerator applications, we treated several additively manufactured components, including a 6 GHz single-cell SRF cavity (a prototype of the standard 1.3 GHz design) and a set of copper AM linear accelerator (linac) parts. The process involved vibrotumbling (for the cavity), polishing with tailored electrolytes, and post-PEP finishing. The results reveal the evolution of surface quality, polishing dynamics, and the potential of PEP as an efficient finishing method for AM-based accelerator components.

## INTRODUCTION

Superconducting radio-frequency (SRF) cavities are a foundational technology for generating high-energy particle beams in modern accelerators. As one of the major applications of low-temperature superconductivity, SRF technology has matured through decades of R&D and now underpins large-scale facilities such as X-ray free-electron lasers, linear colliders, neutrino sources, and energy-recovery linacs [1].

SRF cavities operate by sustaining standing-wave RF fields within their cells, transferring energy to particles through in-phase particle-charge interactions. The efficiency of this process depends strongly on surface resistance, which increases with surface roughness. Even micron-scale roughness raises cryogenic loads and operating costs [2], highlighting the importance of high-quality surface finishing.

Niobium (Nb), cooled with liquid helium, has become the standard SRF material owing to its extremely low surface resistance compared to water-cooled normal-conducting copper (Cu) [3]. However, alternatives such as Nb and $Nb_3Sn$ thin films on copper substrates are being explored to reduce material costs, motivating surface polishing studies on Cu cavities in preparation for Nb-based coatings and RF applications.

Amongst other known polishing techniques, plasma electrolytic polishing (PEP) has emerged as particularly attractive due to its environmental sustainability and efficiency. Since 2019, INFN-LNL has increasingly adopted PEP over conventional CP and EP, consistently obtaining satisfactory results [4]. Encouraged by these outcomes, we extended PEP to accelerator components produced via additive manufacturing (AM). Materials such as Cu, Nb, stainless steel, and Cu–Zr alloys fabricated by LPBF, cold spray, and other AM technologies have been polished in our lab, yielding promising results.

In this paper, we present the application of PEP to an additively manufactured 6 GHz single-cell SRF cavity prototype and several copper AM linear accelerator (linac) components. These applications collectively demonstrate the potential of PEP as a valuable surface-finishing method for advanced accelerator technologies in conjunction with additive manufacturing.

## EXPERIMENTAL METHODS

### *Materials and Methods*

As some particle accelerators operate at 1.3 GHz, evaluating PEP effectiveness requires a representative prototype. To reduce cost and material usage, a 6 GHz single-cell cavity Fig. 1 (a) has emerged as one of the prototype cavities. Since 2021, PEP experiments on this prototype at INFN have focused on improving electrical contacts and confining polishing to the internal surface. Figures 1 (c) & (d) show the improved electrical connection system, which replaces the earlier configuration Fig. 1 (b) that relied on twisted copper wires wound around one end of the cavity in previous polishing iterations. Additionally, external masking with chemically resistant thermo-shrinking material was ap-

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# PLASMA PROCESSING ON LOW BETA SRF ELLIPTICAL CAVITIES

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*Abstract*

Plasma processing has emerged as an effective method for mitigating field emission and recovering the performance of superconducting radiofrequency (SRF) cavities. A collaborative effort involving CEA, ESS, FNAL, and INFN is currently focused on applying this technique to low-beta elliptical cavities for both the ESS and PIP-II linacs. This paper reports on the ongoing work aimed at developing plasma processing for cavities both installed in cryomodules and assembled for the vertical test. For the ESS cavities, a bead-pull setup has been developed, enabling validation of experimental results against electromagnetic simulations. In parallel, FNAL has conducted simulation studies to identify effective modes for plasma ignition in PIP-II cavities, with experimental work expected to start in the coming months.

## INTRODUCTION

One of the main factors limiting the performance of superconducting radio-frequency (SRF) cavities is field emission. To address this issue, plasma processing has gained increasing attention as an effective approach to remove hydrocarbon contaminants - responsible for triggering electron emission - from cavity surfaces. Improving the niobium work function [1], this technique reduces field emission.

Recent investigations [2, 3] have shown that low-pressure reactive plasma discharges, produced with a mixture of a noble gas and oxygen, are highly efficient in cleaning surface impurities. As a result, SRF cavity performance can be improved thanks to the mitigation of field emission.

Within this framework, two parallel paths are being pursued. On the one hand, INFN, CEA, and ESS are jointly developing a plasma processing procedure specifically designed for medium-beta ($\beta = 0.67$) 704.42 MHz 6-cell ESS cavities. On the other hand, INFN, CEA, and FNAL, with the same final goal, are focusing on adapting this process for low-beta ($\beta = 0.61$) 650 MHz 5-cell PIP-II cavities.

Two application scenarios are being pursued: first, plasma treatment of the cavity in a vertical test stand (VTS) prior to cold RF measurements; second, a more advanced solution involving *in-situ* plasma processing of the cavity inside the cryomodule itself. The latter option is particularly attractive, since mitigating field emission without removing the cavities from the cryomodule would significantly cut down on manpower, time, and costs. This step would therefore enhance operational efficiency and cost-effectiveness for large-scale accelerator facilities. Furthermore, reducing field emission translates directly into lower RF power losses within the cryomodule.

The plasma processing method relies on sustaining a room-temperature plasma through an RF induced glow discharge. A noble gas (typically Ar or Ne) with a small fraction of oxygen is injected into the cavity, where free electrons—carrying around 10 eV of kinetic energy—dissociate molecular oxygen into reactive atomic species. These species then attack hydrocarbon contaminants on the niobium surface, decomposing them into volatile compounds such as $CO_2$, $CO$, and $H_2O$ [4]. The process gas removes these byproducts, while a residual gas analyzer (RGA) monitors them in real time [5].

Cleaning the niobium surface in this way not only increases the work function but also decreases the secondary electron emission coefficient, both of which contribute to reducing field emission.

In this paper, we report on electromagnetic simulations and preliminary experimental tests performed on the $MBLG002$ ESS cavity, which at room temperature shows a $Q_0$ of about $10^4$ and a $Q_{ext}$ of approximately $6 \cdot 10^9$. Finally, a section is dedicated to the bead-pull measurements performed on this cavity, along with a brief overview of the simulations carried out on the LB650 PIP-II cavities.

## PLASMA PROCESSING SETUP

Differently from the SRF cavities per electron plasma treated so far, our cavity is not equipped with Higher Order Mode (HOM) couplers, normally used for injecting the RF in the cavity due to their higher coupling factors to HOM modes, and hence the RF power was delivered through the main coupler (MC) port.

The first measurement campaign employed the unity coupler, i.e., the same coupler used during the vertical test that has a $Q_{ext}$ in the $10^{10}$ range. As mentioned earlier, the main objective is to implement plasma processing in the VT configuration. Although at room temperature this coupler provides only weak coupling, the adopted strategy is to select a well-matched mode capable of igniting the glow discharge and then extend it to the remaining cavity cells by means of the plasma bridging technique [6].

Figures 1 and 2 illustrate the experimental configuration: the schematic design of the setup and the apparatus used for the tests, respectively. The RF system consists of a Vector Network Analyzer (VNA), power meter, bidirectional coupler, RF power amplifiers, signal analyzers, spectrum analyzer, camera, and several power splitters/combiners.

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# PERFORMANCE ANALYSIS OF THE ESS SRF CAVITIES FROM QUALIFICATION TO FIRST OPERATION RUN*

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*Abstract*

The 82 SRF cavities of the present 2 MW configuration of the ESS Linac have been operated up to their specification during the first technical commissioning run on the temporary beam dump. Operational experience and comparison of cavity performances between vertical tests at the project in kind members and those measured at the cryomodule test stands and in the tunnel is described.

## THE ESS LINAC

The technical commissioning and first operation run of the ESS Linac were conducted on the temporary beam dump from December 2024 to June 2025. In this phase the linac was configured as illustrated in Figure 2, with the complete NCL front end, followed by 13 cryomodules with 2 double spoke cavities each ($\beta = 0.5$), 9 elliptical cryomodules with 4 cavities each ($\beta_g = 0.67$) and 5 elliptical cryomodules with 4 cavities each ($\beta_g = 0.86$). After completing the coupler and cavity conditioning processes, as well as the phasing of all the linac cavities, successful beam transmission to the beam dump at energies above 800 MeV was achieved in May 2025.

Figure 1 shows the individual cavity maximum performances along the superconducting linac, with the average cavity gradient reached during testing of each cryomodule at the test stands (blue line) and the performances required by the linac design (red line) [1].

All accelerating elements of the ESS accelerator were supplied by the project partners as in-kind contributions. Cavities were provided by IJCLAB in France (spoke [2]), INFN-LASA in Milano (medium beta elliptical [3]) and STFC Daresbury (high beta elliptical [4]). The in-kind partners oversaw the production of cavities by industrial vendors and conducted vertical acceptance tests prior to cryomodule integration. Spoke and elliptical cryomodules were assembled at IJCLAB [5] and at CEA [6] in France, before being sent to the test stands at Uppsala (spoke [7]) and Lund (elliptical [8]), where the site acceptance tests were performed prior to installation.

The handover of cavities from the cavity partners to the cryomodule assembly teams was managed by ESS based on the results of the vertical acceptance tests.

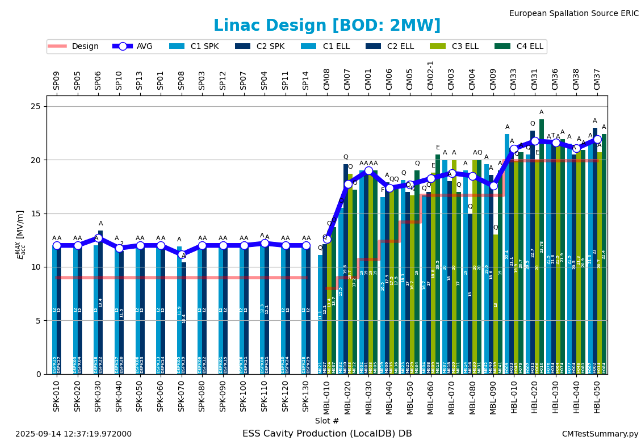


Figure 1: The linac design gradient (red line), the individual maximum gradient of each cavity (bars) and the average max cryomodule gradient (blue line).

## THE ESS CAVITY DATABASE

To streamline the elliptical cavity handover workflow and support the preparation for cryomodule site acceptance tests, as well as their operation in the Linac, a dedicated database for all ESS cavities and cryomodules was established at ESS at the onset of the project [9].

The database stores key information provided by the cavity in-kind partners during fabrication and qualification, including bandwidth measurements, calibration constants, antenna calibration and vertical test results. It tracks both the cavity handover process to cryomodule assembly and the transmission of cryomodule and cavities inspections upon transportation to the test facilities, as well as preparations for installation in the Linac.

When cryomodules arrive at ESS, inspection data and RF test results are added to the database, enabling a comprehensive overview of the cavity lifecycle, from fabrication through cryomodule assembly, transport, and testing, to their operation in the accelerator tunnel. The database also facilitates the identification and documentation of any issues related to transport and handling.

All test data and calibration constants stored in the database were readily accessible during site acceptance testing and commissioning of the accelerator, providing crucial support for efficient testing and operational readiness.

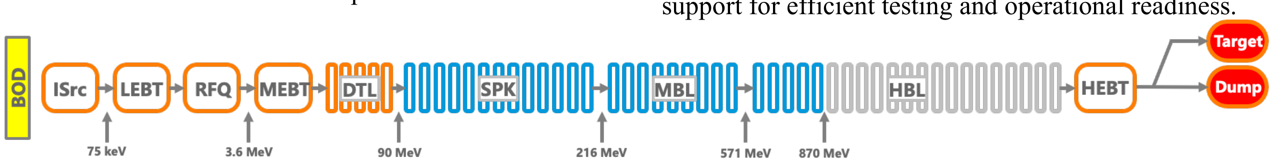


Figure 2: The ESS Linac configuration for the Beam on Dump phase.

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# FABRICATION OF SEAMLESS SINGLE-CELL COPPER ELLIPTICAL CAVITIES THROUGH BULK-MACHINING

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*Abstract*

In the context of future accelerator studies, niobium coating of copper-based cavities plays a key role in achieving an optimal balance between RF performance and cost-effectiveness. Recent advancements have focused on the development of bulk-machined elliptical cavities, featuring a seamless, weld-free equator. By optimizing the design of machining tools, the machining strategy and processing parameters, fabrication of high-quality cavities with excellent shape accuracy and surface finish has been achieved, along with improved repeatability. This contribution presents the current status of fabrication for such seamless cavities, including the design of the specialized cutting tools. It also explores the relationship between cutting tool parameters, machining conditions and surface integrity, providing a deeper insight into the factors that may influence the future success of niobium coatings.

## INTRODUCTION

Traditionally, SRF cavities are fabricated from bulk niobium sheets. However, an alternative approach pioneered at CERN in 1980 is to coat copper cavities with a thin niobium film [1]. This method offers advantages in thermal stability, lower material cost, and potential for improved performance. For more than three decades, research has shown how weld defects can degrade the performance of such niobium coatings [2]. A clear example was seen at CERN during the development of niobium-coated quarter-wave resonators for the HIE-ISOLDE [3]. Performance issues in the produced cavities were traced to fabrication imperfections, notably defects in electron-beam welded regions [4]. Similar performance limitations - due to weld defects - also apply to elliptical niobium-coated copper cavities. Early attempts to eliminate the electron-beam equator weld in elliptical cavities relied on spinning or hydroforming full cells. In the past, machining cavities directly from bulk billets had been considered impractical for thin-shell geometries and consequently set aside [2]. However, setting aside discussions for large-scale production, this approach offers substantial advantages for prototyping and for R&D related to subsequent processes (such as surface treatment), including precise control over RF surface roughness, shape accuracy, consistent local wall thickness and less intensive surface treatment compared to traditional techniques. It also enables the fabrication of highly reproducible reference substrates for coating development, where the additional machining time and material consumption are considered acceptable trade-offs.

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This paper reviews past CERN projects that have employed such seamless cavity approach through bulk machining of elliptical cavities; whereas focus is given on the substrate fabrication perspective. It also presents recent efforts to optimize the machining process and understand its impact on surface integrity, with the ultimate goal of enhancing the RF performance of the Nb-coated cavities.

## FABRICATION OF SEAMLESS BULK-MACHINED CAVITIES AT CERN

### *1.3 GHz Elliptical Cavities*

Direct machining of cavities from bulk copper billets was investigated and successfully implemented at the CERN main workshop [5]. The geometry posed a major challenge: a small aperture relative to the required undercut depth. The solution used indexed turn-mill operations at several machine angles, followed by internal and external semi-finishing and finishing with a custom cavity-conformal toolholder. For internal finishing, a polycrystalline diamond insert was used. This strategy achieved interior profile deviations of ±43 µm, wall-thickness uniformity of ±30 µm, and a surface roughness of $R_a \approx 0.16$ µm.

Cold tests on these bulk-machined cavities coated with Nb showed that they sit amongst the best performing and could comfortably meet RF performance targets, such as those which would be required for the FCC 400 MHz specification at 4.2 K [6, 7]. Nevertheless, comparative tests across different post-machining surface preparations show that removing the machining damage layer prior to coating remains critical for achieving the best performance [7]. Overall, the first ever bulk-machined series demonstrates that precision-machined seamless copper substrates provide robust, reproducible reference platforms for Nb film R&D and support a systematic path to performance improvement.

### *400 MHz Elliptical Cavity*

Building on the success of the bulk-machined 1.3 GHz cavities, the approach was extended to single-cell 400 MHz elliptical cells (Figure 1). Several modifications to the machining sequence and cavity design were made to accommodate the larger size and heavier workpiece.

To improve chip evacuation and minimize distortion, the machining sequence was adjusted so that rough milling was first performed on the outside volume, followed by rough milling of the inner volume. This was then completed with vertical finish turning of the outside surfaces, and finally, multi-axis finish turning of the inner surfaces. This revised sequence mitigates a deformation risk due to constraint relief distortion specific to the larger 400 MHz cavity. Rings were

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# MULTIPACTING ANALYSIS OF THE CONDITIONING BOX OF THE 591 MHz SRF CAVITY FUNDAMENTAL-MODE POWER COUPLER IN EIC*

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*Abstract*

A fundamental-mode power coupler (FPC) for the 591 MHz superconducting RF (SRF) cavities is currently being designed and prototyped for use in the Electron Storage Ring (ESR) of the Electron-Ion Collider (EIC). Due to limitations in power source availability and in consideration of the FPC fabrication schedule, the initial high-power tests of the prototyped FPCs are planned to be conducted using a 704 MHz power source. The conditioning box to be used has been structurally modified based on the existing design. Multipacting simulations have been carried out for both the FPC and the conditioning box under high-power conditions. The simulation results will be compared with subsequent experimental tests to provide references for future high-power testing at 591 MHz.

## INTRODUCTION

The Electron-Ion Collider (EIC) [1] is a high-luminosity collider currently under construction at Brookhaven National Laboratory (BNL), in partnership with Thomas Jefferson National Accelerator Facility. It is designed to achieve an electron–proton luminosity of up to $10^{34}$ cm$^{-2}$s$^{-1}$, enabling precision studies of the structure of matter.

In the electron storage ring (ESR), a total of 18 single-cell 591 MHz superconducting RF (SRF) cavities are employed to provide up to 10 MW of RF power for synchrotron radiation loss compensation [2]. The layout of the 591 MHz SRF cryomodule is shown in Fig. 1. Each cavity is equipped with two continuous-wave (CW) high-power fundamental power couplers (FPCs) [3], installed on the small beam pipe and positioned 180° apart in the horizontal plane. Each FPC is designed to deliver up to 400 kW of RF power, as illustrated in Fig. 2.

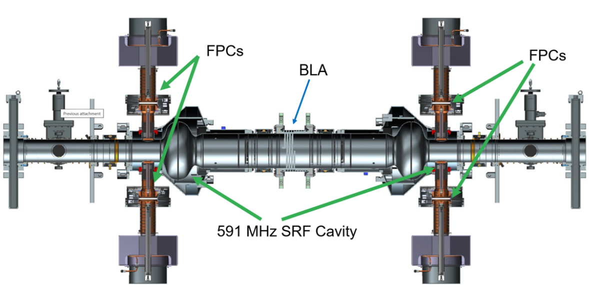


Figure 1: Layout of the 591 MHz SRF cryomodule.

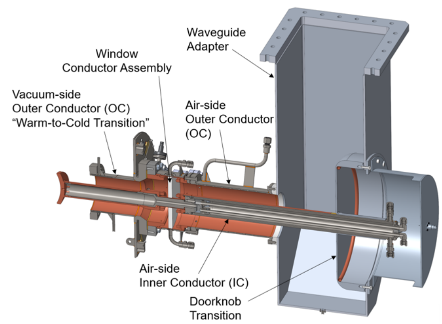


Figure 2: Design of the FPC.

To validate the FPC design and fabrication, high-power RF testing and conditioning will be conducted using the existing 704 MHz klystron, given the development schedule of the 591 MHz klystron. For this purpose, a conditioning box has been structurally adapted from an existing 591 MHz design. Since multipacting can pose critical challenges to both conditioning and long-term operation, comprehensive multipacting simulations have been carried out for the conditioning box and the FPC assembly.

## CONDITIONING BOX DESIGN

The 704 MHz rectangular conditioning box was adapted from the original 591 MHz design by shortening its length, since the operating field mode in the conditioning box is $TE_{103}$. Figure 3 shows the electromagnetic field distribution at 704 MHz in the conditioning box with both FPCs installed. The box accommodates two FPCs, which can be installed and tested simultaneously. Its dimensions were optimized to precisely match the target resonance frequency. The waveguide of one FPC is connected to a movable short-circuit load with an adjustable phase. This enables conditioning and testing under standing-wave conditions at different reflection phases, providing a more comprehensive verification of coupler performance.

The mechanical design of the 704 MHz conditioning box is shown in Fig. 4. The box is fabricated from annealed copper and incorporates internal water-cooling channels to dissipate the heat load. It is divided into upper and lower sections, which allows for frequency tuning during fabrication by trimming excess material, thereby correcting fabrication tolerances.

## MULTIPACTING SIMULATION

The multipacting simulations were performed using SPARK3D under both traveling wave and standing wave conditions, with input power up to 500 kW, covering the

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# DEVELOPMENT OF ORGANIC SOLVENT ELECTROPOLISHING METHOD FOR Nb CAVITY

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*Abstract*

In the fabrication of niobium (Nb) cavities for superconducting accelerators, electropolishing (EP) of the cavity's inner surface via electrochemical reaction is indispensable for achieving high accelerating performance. Conventional EP method of Nb material typically employs a hydrofluoric–sulfuric acid electrolyte. However, this EP protocol presents two major drawbacks: (1) the electrolyte is highly toxic, making the process extremely hazardous and operationally challenging, and (2) water molecules in the electrolyte are incorporated into the Nb surface during EP reaction, which limits the cavity's accelerating performance. To address these issues, an alternative EP method using organic solvents with negligible water content and halide salts has been developed.

## INTRODUCTION

In the construction of superconducting accelerators such as the International Linear Collider (ILC) project and X-ray free-electron lasers, several hundred to several thousand niobium (Nb) cavities are required to attain the desired acceleration performance of charged particles. To achieve optimal cavity performance, the inner surfaces of Nb cavities must be smoothed by electropolishing (EP) method [1]. This necessity stems from the fabrication sequence, in which cavity components pressed from high-purity Nb sheets are joined by electron-beam welding, thereby introducing numerous surface structures, such as weld seams and adsorbed contaminant, on the interior surfac. Under high-power microwave irradiation, these structures act as field-emission sites that critically limit the achievable accelerate gradient. Therefore, it is standard practice to remove approximately the top 100 μm of the cavity's inner surface by EP after fabrication [2].

In conventional EP method of Nb material, a hydrofluoric acid(HF)–sulfuric acid($H_2SO_4$) mixture (1：9 by volume) is typically employed as the electrolyte. In this process, the oxide layer formed on the Nb surface by anodic oxidation is dissolved by HF. Under optimized condition, the polished surface becomes mirror-like. However, the implementation of such procedures is rendered exceedingly challenging by the stringent requirements for chemical-safety management and leak-prevention measures, because of HF is very dangerous in both gaseous and liquid phases. Furthermore, the water content of the mixed acid electrolyte leads to adsorption of water molecules on the freshly exposed Nb surface during EP reaction, with ensuing incorporation of hydrogen atoms into the Nb lattice. These hydrogen atoms precipitate as Nb hydride at cryogenic temperatures, significantly degrading the cavity's accelerating gradient [3].

In the present study, the development of organic liquid EP method for Nb is pursued using halide salts dissolved in common organic solvents as the electrolyte. Candidate solvents were selected to meet all of the following criteria:

1. Non-toxic, ensuring chemical-safety compliance
2. High flash point (≥100 °C) to mitigate fire risk
3. Water-miscible, facilitating post-polish cavity water rinsing
4. Low viscosity, promoting efficient mass transport during EP reaction at room temperature
5. High dielectric constant, enabling dissolution of various salts
6. Low procurement cost

Specific solvents under consideration include ethylene glycol (EG), formamide (FA), dimethylformamide (DMF), and dimethyl sulfoxide (DMSO). Halide salts were chosen for their reactivity with the native Nb oxide layer; $NH_4F$, KF, $NH_4Cl$, and NaCl were evaluated as potential electrolytes. Figure 1 shows the electropolished Nb substrate with a 1 M KF solution in an EG–FA mixed solvent (~15 °C), which yielded a completely mirror-finished single face (polished area: 1 cm²) [4]. The present work extends this approach to larger Nb plates (~14 cm²) and investigates the experimental parameters that achieve uniform, both-side polishing of the plate.

Figure 1: Nb substrate EP treated with 1 M $NH_4F$ in ethylene glycol and formamide (1:1, v/v) [4].

## EXPERIMENTAL SECTION

Organic solvents employed in this study comprised ethylene glycol (EG), formamide (FA), dimethylformamide (DMF), dimethyl sulfoxide (DMSO), and their binary and ternary mixtures. Electrolyte salts $NH_4F$, KF, and NaCl were investigated at concentrations ranging from 0.5 to 2.0 M. As minor additives, water and alcohols (methanol (MeOH), ethanol (EtOH), and propanol) were introduced at 0.1–1.0 vol%. The total electrolyte volume was maintained between 150 and 170 mL. Electrolyte solutions were stirred with a magnetic stirrer, and the optimal agitation rate was determined experimentally. The

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# PRELIMINARY RESULTS OF ELECTROMAGNETIC SIMULATION FOR OPTIMIZING AN SRF GUN CAVITY

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*Abstract*

A high beam brightness is an important requirement for an electron linear accelerator, with the electron source setting the lower limit for the achievable brightness. A superconducting radio-frequency photoelectron injector (SRF gun) stands out as an advanced electron source capable of delivering beams with superior properties compared to other continuous-wave injectors. Currently, SRF guns are being reliably operated at various accelerators. However, the gun cavities are operated below its design gradient due to the field emission. A lower gradient reduces particle energy gain per cell and adversely affects beam quality by deviating from theoretical optima.

To overcome these limitations, a new cavity design is being explored, with the peak on-axis electric field restricted to 30 MV/m, corresponding to the fields that have typically been achieved so far. In the first step, the first short-cell geometry was optimized to maximize the phase at which energy gain is highest, which guarantees the maximum electric field on cathode and the energy gain. Following this, additional full-cells were included in the optimization. This contribution will discuss the initial findings from the electromagnetic study.

## INTRODUCTION

The development of the first SRF gun began in 1989 [1] and a prototype was designed and tested at HZDR, Germany in 2002, becoming the world's first operational SRF gun [2]. Based on this success, a dedicated SRF gun for the electron linear accelerator ELBE (Electron Linac of high Brilliance and low Emittance) was developed and tested in 2007 [3]. In 2014, the injector was replaced with an integrated superconducting solenoid with the on-axis peak field in the short-cell( C0) was increased to 80%. Figure 1 shows the sketch of the gun installed at ELBE, HZDR. As the first one of its kind, this source is in operation at HZDR's free-electron laser FELBE [4], the terahertz source TELBE [5], and the neutron source nELBE [6]. Due to this achievement, several other laboratories across the world have shown strong interest in developing SRF guns to meet the high-brightness electron source demands of future accelerators.

### *Limitations*

Despite significant progress, none of the tested SRF guns have yet reached their design specifications, mostly due to the field emission, arising from contamination during cathode handling and the complexity of cleaning and assembly [7,8]. A reduction in the on-axis $E_{pk}$ not only lowers the energy

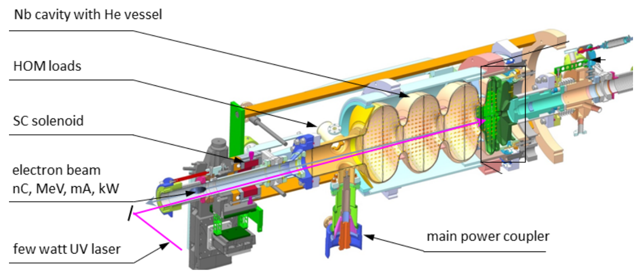


Figure 1: A sketch of the SRF photoelectron injector at ELBE, highlighting the main components of the system.

gain per cell but also lowers the extractable bunch charge. Additionally, operating at lower gradients degrades beam quality, as beam dynamics deviate from the optimal operating conditions. These drawbacks are partially overcome by optimizing the gun operating settings; for example, the laser pulsing phase was reduced to 55° rather than 90° and the cathode was retracted to obtain focussing force. Overall, the achievable performance remains below the intended design goals.

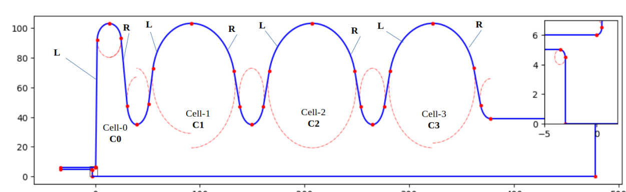


Figure 2: The outline of the gun cavity with the naming convention. The cathode region is zoomed in to show the features.

## OPTIMIZATION FRAMEWORK

Dakota is a versatile optimization software tool that includes a wide range of optimization algorithms, such as gradient-based methods and multi-objective genetic algorithms (MOGA) [9]. It provides a flexible interface to couple with simulation codes for efficient exploration of design parameter spaces. In this work, Dakota is used as the primary optimization framework, while Superfish [10] serves as the electromagnetic field solver.

Dakota runs locally on the machine to generate geometric parameters based on the optimization algorithms. Preprocessing tasks such as input file preparation for the solve, solver execution and post-processing of results are performed on a high-performance computing cluster (HPC). Dakota takes advantage of parallel execution capabilities to speed

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# DEVELOPMENTS FOR THE RF TRANSMISSION SYSTEM OF THE ITN CRYOMODULE*

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*Abstract*

The International Linear Collider (ILC) is a future linear collider that uses superconducting accelerating cavities. In the scope of the ILC Technology Network (ITN), an ILC prototype cryomodule featuring 8 cavities is being developed and built at KEK. The cavities will be driven by a 10 MW multibeam klystron located about 200 m away from the test stand. The WR650 and WR770 are commonly used waveguides for RF transmission at 1.3 GHz. The klystron delivers its power through two WR650 ports, which are combined. The waveguides at the cavity input couplers are also of the type WR650. For efficient transmission of the required RF power over most of the distance, a WR770 type waveguide will be used. An adapter was designed for the interconnection between the WR650 and WR770. WR770 H and E corners were also designed for the transmission line.

## INTRODUCTION

The International Linear Collider (ILC) is a future linear electron-positron collider with a center-of-mass energy of 250 GeV [1, 2]. In the main linacs, TESLA type 9 cell superconducting RF (SRF) cavities are used for the acceleration of the beam. These cavities will be operated at 1.3 GHz using pulsed RF power with a pulse width of 1.65 ms at a repetition rate of 5 Hz. The average accelerating gradient of the cavities is 31.5 MV/m, with a spread of $\pm 20\%$.

The ILC Technology Network (ITN) was jointly initiated by the High Energy Accelerator Research Organization (KEK) and the ILC International Development Team (IDT) to execute high-priority work packages for the ILC prelab proposal [3]. As one of the key work packages, an eight-cavity cryomodule with the necessary infrastructure will be built and tested at KEK in the scope of the MEXT-ATD five-year plan [4]. The center of innovation (COI) building is the test site for the ITN cryomodule. A 10 MW multibeam klystron is employed to drive the cavities of the ITN cryomodule. It was decided to keep the klystron in the superconductivity RF test facility (STF) building. An about 200 m long waveguide (WG) system reaching from STF to COI connects the klystron to the cryomodule.

The eight cavities of the ITN cryomodule are driven by two sub local power distribution system (LPDS). The sub LPDSs are similar to the ILC as shown in Fig. 1. In a sub LPDS variable hybrids are used to deliver the required power to the corresponding cavity [5]. The variable phase shifters are used to compensate the phase shift caused by the variable hybrids while adjusting the coupling ratio [6]. The fixed phase shifters are used to deliver the required RF input phase difference between adjacent cavities. The WG components will be installed in a support frame. The cryomodule integrated with the WG will be installed inside the test bunker [1].

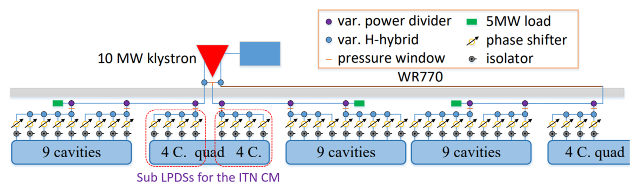


Figure 1: Power distribution system for the ILC [1].

The 10 MW multibeam klystron emits RF power via two ports, with 5 MW from each. The power required for the ITN cryomodule is about 2 MW. Although RF from one output port of the klystron can drive the ITN cryomodule, the power of two ports is combined into a single waveguide for this purpose. The combination of power is chosen to reduce the operating power of the klystron by avoiding dissipation of power to the dummy load. Furthermore, this creates a situation similar to the ILC power distribution system, as shown in Fig. 1. Compared to the WR650, the WR770 has a lower RF loss and a reduced maximum electric field. Therefore, WR770 is proposed for long-range RF transmission in the ILC power distribution system. For the same reason, such a WG is planned to be deployed also for the ITN cryomodule test. The necessary WR770 waveguide components, such as the H-corner, E-corner, and WR650–WR770 adapter, have been designed and are discussed in this contribution.

## POWER COMBINING AND DISTRIBUTION

The RF power emitted via two ports of the klystron can be combined using either an H plane tee or a magic tee. The H plane tee is preferred to combine the power of the same amplitude and phase. However, it is challenging to achieve such a situation, which leads to the upstream propagation of power. In a magic tee, a power resulting from differences in amplitude and phase between the input powers via collinear arms is dissipated in a dummy load connected to the E arm. A folded magic tee was designed, developed, and successfully tested at 5.5 MW at KEK [7]. Therefore, this device

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# REAL-TIME CAVITY SIMULATOR AND TUNER CONTROL SYSTEM FOR THE ITN CRYOMODULE AT KEK

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*Abstract*

At KEK, an International Linear Collider prototype cryomodule containing eight TESLA-type cavities is currently under development and is scheduled for testing in 2028. To evaluate the performance of the low-level RF (LLRF) system, a Red Pitaya-based cavity simulator is being developed. The simulator will also be used at the STF VT stand to support the development of the digital LLRF system, which is necessary for preparation of the Vertical Tests for the ITN CM cavities. Additionally, we are considering utilizing the Red Pitaya hardware platform to control the piezo of the cavity tuners for Lorentz force detuning (LFD) compensation. In this contribution the progress of the cavity simulator and tuner control are reported.

## MOTIVATION

International Linear Collider (ILC) [1] is the next major linear collider project under consideration for construction in Japan. It is designed as an electron-positron collider with an initial collision energy of 250 GeV, with potential future upgrades to 500 GeV and 1 TeV. Initially operating at 250 GeV, ILC250 [2, 3] will serve as a Higgs Boson factory, conducting precise measurements of its properties and offering insights into physics beyond the standard model [4, 5].

At KEK, a five-year project is ongoing to manufacture, construct, and test a prototype cryomodule (CM) that satisfies the ILC specifications. This prototype will feature eight 1.3 GHz Niobium 9-cell, TESLA type superconducting cavities and is scheduled for conduction cooling tests in 2028 without beam acceleration. Figure 1 shows the illustration of the cryomodule and the niobium cavity.

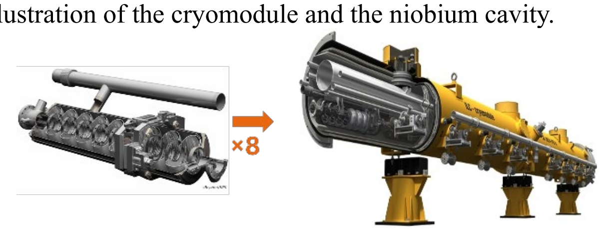


Figure 1: Illustration of the prototype cryomodule and cavity. Credits: R. Hori, KEK.

To control the cavity fields, a MTCA. 4-based LLRF system will be developed, building on the system previously implemented at STF-II [6]. A schematic of this design is shown in Fig. 2. In this configuration, the LLRF system calculates detuning caused by Lorentz Forces, while the piezo controller for LFD compensation is realized by dedicated hardware. In parallel, the Vertical Test (VT) facility at STF is being automated using a digital LLRF system developed in collaboration with DESY.

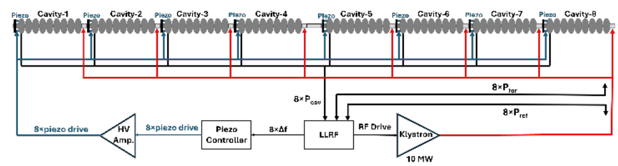


Figure 2: Schematic of the LLRF system [7]. Note that while the LLRF system calculates the detuning, but the piezo controller is independent of the LLRF system.

The issue with the timely development of the LLRF system and tuner piezo controller with automated LFD compensation is the lack of a horizontal cryostat compatible with the prototype cavity at KEK. Furthermore, the STF digital LLRF system can only be tested during the VT of a cavity, which is a bottleneck for faster development of automation. Through this study, we aim to develop a cavity simulator to substitute a real cavity, enabling R&D without the need for actual cavity operation. Such a simulator would accelerate and reduce the cost of R&D, while enabling early testing of the LLRF system and automation algorithms.

## SIMULINK SIMULATOR

Before implementing the real-time cavity simulator on the FPGA, we first developed a simulator in Simulink. This model includes both the electromagnetic (EM) response of the cavity and its mechanical behaviour, as well as the Lorentz Force Detuning (LFD) compensation using a piezo actuator. The schematic of the simulator is shown in Fig. 3. In this section, we present the simulator outputs and briefly explain the role of each component. A more detailed review of the cavity simulator can be found in [8].

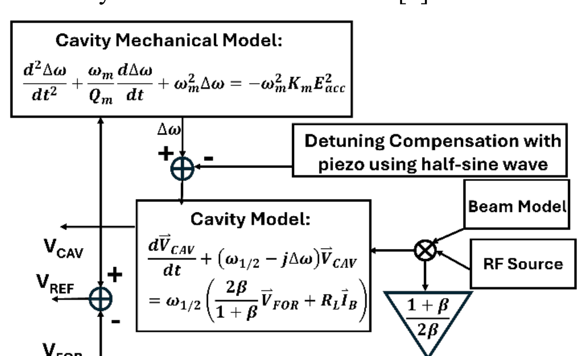


Figure 3: Block diagram of the cavity simulator implemented in Simulink.

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# SPECIFICATION, DESIGN, PRODUCTION INCLUDING QUALITY CHECK AND PREPARATION FOR HIGH-POWER TEST OF INPUT POWER COUPLERS FOR SRF 5-YEAR PLAN (MEXT-ATD) AT KEK BY GLOBAL COLLABORATION FOR ILC TECHNOLOGY NETWORK (ITN)*

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*Abstract*

A five-year project (MEXT advanced Accelerator element Technology Development (MEXT-ATD)) funded by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) began at KEK in FY2023. The goal is to manufacture, construct and test a cryomodule (CM) that satisfies the ILC (International Linear Collider) specifications and conduct cooling tests. The MEXT-ATD program is closely related to the ILC Technology Network (ITN). Based on the KEK-DESY license agreement, a 3D model of European XFEL (E-XFEL) power coupler was provided from IJCLAB, and RF simulations of the power coupler were conducted by KEK and FNAL through the US-Japan science and technology cooperation. In KEK, simulations on static/dynamic heat load was also done. From FY2024, production of four sets of input power couplers began (another four sets to be produced in FY2025). At the same time, quality checks were conducted on brazing, TiN coating, and copper plating. The production of four sets of power couplers were completed by the end of Mar/2025. Currently, preparation for high power test at resonant ring system in STF is under progress. In this presentation, the basic specifications and design of the input power coupler as well as the overall manufacturing/test schedule and recent progress will be reported in detailed.

## INTRODUCTION

Based on the ILC's TDR published in 2013, the input coupler to be used in the MEXT-ATD project [1] was decided to be of the E-XFEL type [2, 3] in Fig. 1. Based on the license agreement concluded between KEK and DESY, we obtained a 3D model of the input coupler and began reviewing the specifications and creating drawings necessary for manufacturing. On the other hand, since the ceramic window material was to be procured domestically [4], quality checks were also required for soldering and titanium nitride coating to suppress secondary electron emission. Additionally, since the copper plating was changed from the previously used pyrophosphate copper plating to sulfuric acid copper plating, quality checks for this were also necessary. The most important difference between E-XFEL and the coupler to be manufactured this time is that the final joint is made by brazing rather than EBW. According to the initial plan, quality checks and prototype manufacturing were to be carried out in FY2024, followed by testing and evaluation, before proceeding to the manufacture of the actual machine. However, due to budget constraints, it was decided to proceed directly to the manufacture of the real power couplers without carrying out prototype manufacturing.

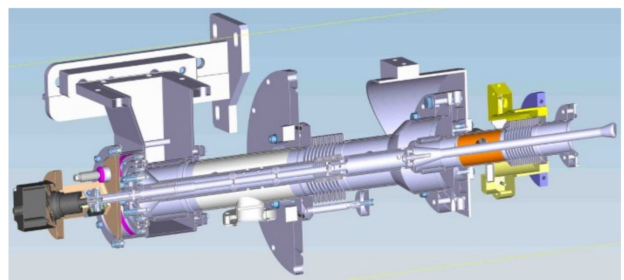

Figure 1: Input power coupler for European XFEL.

## QUALITY CHECK OF EACH TECHNOLOGY

The following three quality checks were performed. Detailed explanations are provided for each.

### *Brazing of Ceramic and Copper Sleeves*

According to the E-XFEL specifications, the tensile stress of the brazing between the ceramic and copper sleeves must be 43 MPa or higher. Therefore, we manufactured and tested several mockups (three cold and one warm) (including the necessary jigs). The first sample failed at 15 MPa because the brazing conditions were not optimized, however the second sample manufactured after improvements met the specification at 73 MPa. The third sample, which had the copper sleeve end face chamfered, reached 97 MPa, further improving the performance. The effect of chamfering the copper sleeve end face had been suggested by simulations. On the other hand, the warm mockup manufactured last failed at the grip end, so the limit value of the brazing joint could not be determined, it was sufficient stress at 128 MPa or higher. Considering the mechanical properties of brazing, the results of warm and the second cold unit should match, however in reality, they do not. There may be an unknown cause for this, since the

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# OVERVIEW OF METAL CATHODE R&D FOR THE CW L-BAND SRF PHOTOINJECTOR AT DESY*

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*Abstract*

Thread-mounted cathode installation directly into the back wall of the SRF gun cavity allows for cavity cleaning following cathode installation, and thus is beneficial for the RF performance of the injector. Recent vertical tests of the CW L-band SRF gun cavity with a Cu cathode installed demonstrated world-record high axial electric fields (up to 50 MV/m).While beneficial for RF performance, the photoemissive performance of Cu degrades quickly following air and water exposure (high-pressure water rinsing followed by a 90 °C bake out). In this work, we provide an overview of metal photocathode R&D activities aimed at addressing a challenging set of requirements with the goal of achieving the top-level parameters of the future continuous-wave / high-duty-cycle upgrade of the European XFEL: bunch charge of 100 pC at 1 MHz repetition rate in the continuous-wave regime.

## INTRODUCTION

The continuous-wave (CW) photoinjector under development at DESY assumes a photocathode insertion method where the cathode is thread-mounted to the cavity back wall [1]. This design assumes exposure of the cathode to the atmosphere during installation. Furthermore, the cathode is directly subjected to high-pressure water rinsing (HPR) during main cavity surface preparation [2]. These operational requirements constrain the material choice to chemically robust noble metals like Cu. The challenge is further amplified by the limited ultraviolet (UV) power for continuous-wave (CW) operation due to the poor conversion rate from infrared to UV. With a fixed maximum laser average power of 2 W at 257 nm from the Light Conversion's PHAROS-based system [3], generating the nominal 100 pC bunch charge at a 1 MHz repetition rate requires a quantum efficiency (QE) of at least $2.5 \times 10^{-4}$.

Atmospheric and water exposure lead to the formation of a chemically undefined oxide layer, which modifies the material's work function (WF) and negatively impacts its QE. This requires a subsequent procedure to achieve a controlled photoemissive surface. The application of an oxide passivation layer and laser ablation for surface cleaning are under consideration to achieve this goal.

Furthermore, efforts on QE enhancement assume considerations beyond standard polycrystalline Cu. One approach proposes single-crystal Cu, as QE is theoretically predicted to be favorably influenced by specific crystallographic orientations and the corresponding WF [1]. A technical challenge for this approach is the large bulk volume of the cathode plug. The practical realization assumes the integration of a dedicated emitting volume made of single-crystal Cu. The primary engineering question is efficient laser-induced heat transfer between the integrated single-crystal part and the bulk cathode volume. Another proposal focuses on the application of novel nano-engineered surfaces to enhance photoemission [4].

While DESY has extensive experience with the preparation and operation of cesium telluride photocathodes, CW SRF photoinjector technology with metal photocathodes presents new challenges requiring specialized infrastructure and expertise. This proceedings presents the research and development activities aimed at addressing these requirements and ensuring the photoinjector design parameters are met.

## CAVITY–CATHODE SEALING INTERFACE

The Cu cathode plug is sealed in air at the back side of the SRF gun cavity using an indium wire. Although the basic technical capability to achieve a leak-tight assembly of the SRF gun cavities with integrated Cu and niobium cathode plugs has been proved by a substantial number of radio-frequency (RF) vertical tests (VT) at DESY [5], robust procedures for multiple assembly cycles would benefit from further development. We prepared a test setup to develop a reproducible Cu cathode integration procedure ensuring leak-tight conditions over multiple cathode integration cycles (see Fig. 1). Initial tests with a 1.5 mm thick indium wire indicated a stable seal under varying thermal conditions (heating up to 90 °C, 26 h in order to remove water residuals

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# COMMISSIONING STATUS OF THE RF POWER SOURCE FOR THE LIPAc SRF LINAC*

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*Abstract*

The Linear IFMIF Prototype Accelerator (LIPAc) is designed as a high-current deuteron linear accelerator (linac) capable of accelerating a 125 mA beam up to 9 MeV in continuous wave (CW) mode. The RFQ linac and subsequent beam transport lines equipped with several diagnostics successfully commissioned a 119 mA deuteron beam with an 8.75 % duty cycle. The superconducting RF (SRF) linac is the remaining critical component to be commissioned in CW to reach the final acceleration target of 9 MeV. The installation of the SRF linac into the beamline is currently underway. In preparation for the integrated commissioning of the SRF linac, the RF station has been commissioned in stand-alone mode. Unlike the synchronized RF control of the RFQ (where 8 RF chains inject in one resonant cavity), the SRF-RF control can be fine-tuned individually and new functionalities specific to the SRF environment, such as quench detection, have been implemented. This report summarizes the features of the LIPAc SRF-RF system and its current commissioning status.

## INTRODUCTION

The Linear IFMIF Prototype Accelerator (LIPAc) is an accelerator designed for the validation facility for the core engineering and technologies of driver accelerator used in the material irradiation facility dedicated for the fusion reactors. The objective of the beam parameter is to achieve a 9 MeV, 125 mA deuteron beam in continuous wave (CW) operation. A key feature of the LIPAc is that the main components are designed and developed by institutes in Europe, and their integration and accelerator operation are being performed by the EU-JA joint team in QST of Japan.

The main challenges of the LIPAc are the validation of the components in the strong space charge environment coming from the 125 mA beam. Accelerating this current level in a single pass is significant challenging in managing heat loads and minimizing beam losses. The RF system, illustrated in Fig. 1, is the main components for the acceleration and the longitudinal manipulation. An interesting aspect of the RF system configuration [1] is the presence of national flags displayed on several components. The RFQ cavity, developed by INFN in Italy, accelerates deuteron from 100 keV unbunched beam to the 5 MeV bunched beam at 175 MHz of the RF frequency. Two rebuncher cavities, developed by CIEMAT in Spain, do not change the kinetic energy but instead rotate the longitudinal phase space, driven by 16 kW solid-state amplifiers. Eight superconducting (SRF) cavities, developed by CEA in France, in one cryomodule accelerate the beam from 5 MeV to 9 MeV.

The RF source of the RFQ and SRF is based on the tetrode amplifier system. The 16 kW level tetrode, called as "driver", and the 200 kW level tetrode, called as "final", are used as the first and the second stage high-power amplifier, respectively. So far, we successfully operated and improved the RF source for the RFQ. For the next commissioning stage, SRF cavities are currently being installed to the LINAC.

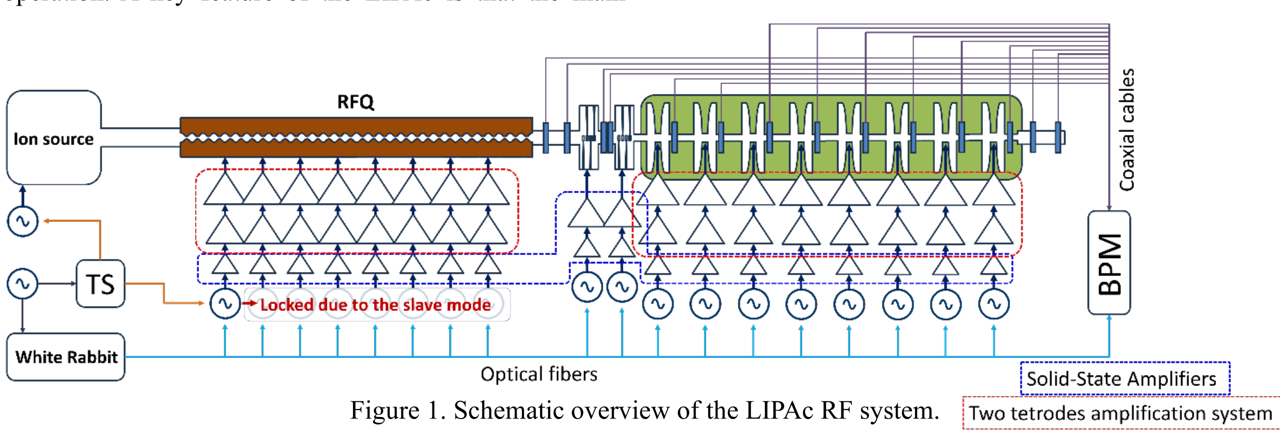


Figure 1. Schematic overview of the LIPAc RF system.

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# IMPLEMENTATION AND INITIAL DEPLOYMENT OF EMBEDDED EPICS FOR MELSEC iQ-R IN THE SRILAC LLRF SYSTEM

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## Abstract

At the Superconducting RIKEN Linear Accelerator (SRILAC), Mitsubishi MELSEC iQ-R series programmable logic controllers (PLCs) are used to manage auxiliary control and monitoring tasks for the RF system, such as RF voltage and power readout, feeder control, and tuner adjustments. These PLCs are directly connected to an FPGA-based LLRF controller to form an integrated system for low-level RF operations. In the conventional configuration, the PLCs communicate with the EPICS via an external Linux computer using the MELSEC communication protocol (MC protocol) over TCP/IP, which often suffers from limited reliability compared to fieldbus-based solutions. To overcome this limitation, we implemented EPICS support directly in the C-language intelligent function module of the iQ-R series. By embedding the EPICS IOC in the PLC module, the need for an external Linux interface was eliminated, and the communication stability was significantly improved. The new system was deployed and tested in the SRILAC LLRF environment. This paper describes the system architecture and embedded EPICS implementation in RD55UP12-V. Because testing during the beam operation was not possible, we implemented the system in a replicated SRILAC environment and reported the results of functional and performance measurements.


## INTRODUCTION

The RIKEN heavy-ion linac (RILAC), which was composed of normal-conducting cavities [1–3], was used to accelerate intense ion beams to synthesize the superheavy element Nh [4]. RILAC has been upgraded to enable further investigation of superheavy elements and the production of radioactive isotopes by introducing a new ECR ion source and superconducting booster linac (SRILAC) [5]. Beam commissioning was completed in January 2020, confirming the stable operation of the 73-MHz quarter-wavelength resonators arranged in three cryomodules. The SRILAC LLRF employs an FPGA-based digital controller with phase-locked field regulation and an automatic tuning scheme that actuates a wire-based port-compression mechanical tuner to compensate for microphonics and slow drifts [6]. During routine operation, a Mitsubishi MELSEC iQ-R programmable logic controller (PLC) is interfaced with the FPGA-based LLRF to supervise the plant-side and auxiliary functions, including the RF voltage and phase readout, feeder control, interlocks, and motor-driven tuner actuation, providing a supervisory path alongside the real-time field-control loop [7]. Historically, these PLC functions were integrated with the Experimental Physics and Industrial Control System (EPICS) using external Linux communication with the PLC over the TCP/IP via the MELSEC communication protocol (MC protocol). However, this TCP/IP-based interface exhibited reliability limitations imposed by NetDev [8, 9]. To improve the reliability, we developed EPICS device support for the iQ-R C-language intelligent function module, embedded the EPICS input/output controller (IOC) in the PLC module, and deployed it during operation.

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## ADVANTAGES OF EMBEDDED EPICS

### Operational Motivation

Our PLC-facing EPICS services run on an external Linux IOC that accesses devices over TCP/IP on Ethernet. Ethernet, which provides physical and data link layers in the OSI reference model, has been widely adopted because it is generic and easy to handle. In our system, the EPICS IOC communicates with TCP/IP-based devices via asynchronous socket connections. Although convenient, it has a practical weakness: following an unexpected power loss or device/switch restarts, the asynchronous TCP socket may be dropped and not automatically reestablished despite apparent network reachability. During user-beam delivery at SRILAC, we observed rare cases after power restoration, where the status shown on the operator interface (OPI) diverged from the actual device state because the asynchronous socket was not automatically reestablished. We encountered this condition during user beam delivery at SRILAC, which delayed the restart of the beam irradiation. To sustain beam availability, it was important to increase the robustness of the IOC-to-device links.

### Embedded System and Field Network at RIBF

To address these issues, the RIBF control system often adopts FA-M3-based embedded EPICS systems, in which a Linux CPU module (F3RP61/F3RP71) hosts the IOC on the same backplane as the PLC, thereby avoiding the reconnection problem at the controller boundary [10]. A similar concept has also been adopted in other accelerator facilities, such as fully embedded EPICS-based LLRF control for SuperKEKB [11].

In addition, the next phase of the magnet power supply control plan uses Ethernet-based field networks for the IOC-to-device links, specifically EtherNet/IP or EtherCAT [12, 13]. In this approach, Ethernet supplies the physical and data-link layers of the OSI, and the field network layer provides a robust deterministic exchange for routine operation.

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# DEVELOPMENT OF FAULT IDENTIFICATION PIPELINE FOR SPIRAL2 LLRF DATA

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*Abstract*

SPIRAL2 is a state-of-the-art superconducting linear accelerator for heavy ions. The radiofrequency operation of the linac can be disrupted by anomalies that affect its reliability. This work leverages fast, multivariate time series postmortem data from the Low-Level Radio Frequency (LLRF) systems to differentiate anomaly groups. However, interpreting these anomalies traditionally relies on expert analysis, with certain behaviours remaining obscure even to experienced observers. By adopting the Time2Feat pipeline, this study explores the interpretability of anomalies through feature selection, paving the way for real-time state observers. Clustering dashboards are presented, allowing the use of multiple clustering algorithms easily configurable and tools to help for visualizing results. A case study on distinguishing electronic quenches and false quench alarms in postmortem data is highlighted. Thereby, a fast and reliable K-Nearest Neighbours (KNN) classifier is proposed.

## INTRODUCTION

Anomalies in time series are the subject of research in many fields. These topics can be divided into subgroups:

- detection: identify behaviours that deviate from nominal operating modes.
- classification: recognize the types of anomalies.
- localization [1]: distinguish the signals causing these malfunctions.

Particle accelerators are no exception to these issues, as they are complex systems that must be kept running for users. During operation, some events such as quenches, multipacting, or microphonics, may occur, leading to beam loss and reduced accelerator availability. Exploring and understanding these events is crucial to enhance the reliability of the accelerator. For CEBAF, work focusing on particle orbit has been carried out [2]. Other work has been directed toward the classification of faults [3]. Similarly, research on this topic has been undertaken for CAFE2 [4]. For EuXFEL, the focus was on identifying quenches [5].

This paper presents the initial efforts to analyse and apply machine learning methods to SPIRAL2 LLRF data, aiming to identify and classify faults. Located at GANIL (Caen, France), this linear accelerator is dedicated to the production of rare and exotic ion beams for nuclear physics research [6]. A cryogenic plant supplies the liquid helium at 4.2 K needed to cool its 26 superconducting niobium cavities (Fig. 1). These are powered by solid-state amplifiers with a maximum power of 10 kW for the low beta ones and 20 kW for all the high beta ones.

In the first section, we introduce the structure of the data, then we present the tools used for its exploration. Next, the main methodology is explicited and a case study on e-quenches [7] events is included. Finally, we suggest some perspectives for this work.

## LLRF & ACQUISITION SYSTEM

Each cavity is associated with a digital LLRF board, based on a Field-Programmable Gate Array (FPGA). These boards are connected to an Experimental Physics and Industrial Control System (EPICS) Input/Output Controller (IOC) for monitoring and control purposes through the local ethernet network (Fig. 2) and are equipped with circular memory. When an alarm is triggered according to predefined criteria, a set of signals is stored in binary or ASCII files. The binary format is preferable because it requires less storage space. Data can also be recorded manually by an operator. The acquisition can be configured in terms of number of samples, sampling frequency, and pre-trigger duration. The sampling of the values can go down to 110 ns but at the expense of the duration of the event. Most of the files contain values recorded every 11 µs and are centred around the moment of manual triggering or the alarm. These faulty events are used in this work.

Historically, postmortem data were processed with a proprietary code and only graphical interpretation from time-domain graphs was possible. In order to progress towards more FAIR (Findable Accessible Interoperable Reproducible) compatible datasets, a different open-source and python compatible preprocessing has been implemented, including metadata management and HDF5 exports.

## DATA STRUCTURE

Each file follows the same structure: a header and multivariate time series, including signals, faults and states.

**The header** The header contains metadata. In particular, it includes the date of the event, the affected cavity, the alarms triggered, the set points, and the calibration values.

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# DESIGN OF AN MTCA.4-BASED LLRF TUNING CONTROLLER FOR CRYOMODULES AT S³FEL*

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*Abstract*

This paper presents the design of an MTCA.4-based low-level radio frequency (LLRF) tuning controller for the Shenzhen Superconducting Soft X-ray Free Electron Laser (S³FEL). A standard 1.3 GHz cryomodule at S³FEL comprises eight superconducting cavities, each requiring one slow tuner motor control, two fast piezoelectric actuator (PZT) controls, and an additional motor control for high-power coupler antenna depth adjustment. To manage these requirements, two pairs of MTCA.4 control boards (each pair consisting of an AMC and an RTM connected via MTCA Zone3 D1.0 interface) are implemented per cryomodule. The controller's core processing utilizes a Kintex UltraScale KU060 FPGA on the AMC, which acquires cavity detuning data from four cavities through backplane peer-to-peer high-speed communication. An FMC mezzanine card interfacing with the AMC provides eight optically isolated motor control channels. The RTM board delivers eight channels of 16-bit high-precision DAC output for PZT control. Preliminary testing confirms that the developed tuning controller meets the operational requirements for S³FEL's standard superconducting cryomodules.

## INTRODUCTION

The Shenzhen Superconducting Soft X-ray Free Electron Laser (S³FEL) is a major scientific facility requiring extremely stable and precise radio frequency (RF) fields within its superconducting accelerator cavities [1]. Maintaining resonance is challenging due to microphonics and Lorentz force detuning. Effective compensation necessitates a sophisticated Low-Level Radio Frequency (LLRF) tuning control system capable of managing both slow mechanical tuners and fast piezoelectric actuators (PZTs) for each cavity. This paper presents the hardware design of an MTCA.4-based controller dedicated to the tuning functions for the S³FEL cryomodules [2]. The Micro Telecommunications Computing Architecture (MTCA.4) standard was chosen for its high-performance, ruggedized form factor, excellent rear I/O capabilities, and strong support for advanced FPGA processing, making it ideal for demanding accelerator controls.

* Work supported by the National Natural Science Foundation of China (Grant No. 12405221).
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## SYSTEM ARCHITECTURE

A standard 1.3 GHz cryomodule at S³FEL contains eight superconducting RF cavities. The tuning control requirements per cavity are: one channel for slow tuner motor control (for coarse frequency adjustment) [3], two channels for fast PZT control (for fine, dynamic compensation of detuning) [4], and one additional channel for motor control of the high-power input coupler's antenna depth. The specific tuner parameters are shown in Table 1. This totals 32 control channels per cryomodule (8 motors + 16 PZTs + 8 coupler motors). The architecture employs two MTCA.4 modules per cryomodule, with each module responsible for four cavities (16 control channels: 4 slow tuners + 8 PZTs + 4 coupler motors), Figure 1 illustrates the composition of the entire system. Each module consists of an Advanced Mezzanine Card (AMC) as the main processing unit and a Rear Transition Module (RTM) for additional I/O, interconnected via the Zone3 connector [5].

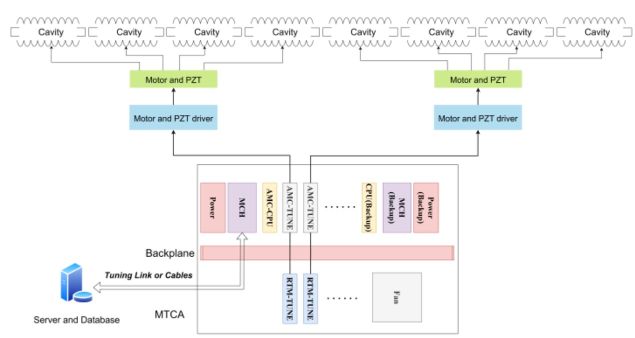


Figure 1: MTCA.4-based LLRF tuning controller for cryomodules.

Table 1: S³FEL Tuner Adjustment Parameters

| Parameter | Value | Unit |
|---|---|---|
| Slow Tuning Frequency Range (Operating / Max) | 250/450 | kHz |
| Slow Tuning Travel Range (Operating / Max) | 0.75/1.3 | mm |
| Slow Tuning Resolution | 1~2 | Hz/step |
| Slow Tuning Stiffness | 30 | N/μm |
| Fast Tuning Bandwidth | 1 | kHz |
| Fast Tuning Travel Range | 3 | μm |
| Fast Tuning Resolution | 1 | Hz |

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# INITIAL RESULTS OF THE ESS CAVITIES PARAMETERS IDENTIFICATION AT THE TS2 TOWARDS FUTURE LLRF OPERATION

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*Abstract*

A dedicated series of tests on the superconducting Medium-$\beta$ and High-$\beta$ cavities has been proposed to determine various parameters critical for future LINAC and LLRF system operation. These studies include measurement of the cavity stiffness coefficient (expressed as the Lorentz Force Detuning factor), evaluation of piezo tuner range and polarity, investigation of piezo capacitance as a function of temperature, and identification of resonator $\pi$-mode frequencies. Additionally, the detection of the main mechanical longitudinal mode and assessment of the field regulation performance are also of interest.

This contribution presents the results from several measurement campaigns conducted at the ESS Test Stand 2 (TS2). It also discusses the development and evaluation of the testing tools, the obtained characterization results, and plans for future implementation in the ESS LINAC environment.

## INTRODUCTION

The qualification of superconducting cavities for the main accelerator installation is based on the test results of these resonators. Studies are performed in the controlled environment of the ESS Test Stand. It is not only the last chance to verify the ready-for-operation assembly of 4 cavities before integration into the linac topology. It is also an opportunity to push the resonator to its limits to estimate future operations boundaries. In addition to the maximum operating gradient or heat load studies, a set of cavity tuning and LLRF operation-related tests is also available. From one side they can show particular resonator limit; on the other they provide data helpful in the given cavity operation.

## PIEZO CAPACITANCE VERSUS TEMPERATURE

### *Measurement*

Piezoelectric properties degrade over time due to aging, material fatigue, mechanical stress, and electrode deterioration. Those property changes are reflected in impedance and capacitance variations, enabling early detection of potential failure and the tunned temperature change (increase). The capacitance at 300 K is 3–4 times higher than at 2 K. At cryogenic temperatures, the crystal properties change and the element contracts, so initial room-temperature displacement must be taken into account for this reduction when designing compensation and, in general, LLRF control systems [1, 2].

The piezo capacitance is the measurement performed in the linac and TS2 environment. The procedure was carried out for several cooldowns and warmups, which allowed the gathering of a sufficient amount of data to calculate dependencies between capacitance and temperature for different types of cryomodules.

The test procedure is carried out by the software module that monitors the temperature from the sensor placed in the cryomodule. Within the user-specified range, it waits for a temperature change (temperature change size is also configured manually). When the target temperature is reached, both piezo tuners are excited with a sine wave and their response is registered. Acquired voltage and current is used to compute FFT and, in results, find impedance and capacitance.

### *Results*

Table 1 illustrates the averaged results of the temperature sensitivity of capacitance for superconducting cavities in the ESS linac. For all types of superconducting cavities, the standard deviation is below 10 %. As expected, the thermal sensitivity of High-$\beta$ and Medium-$\beta$ cryomodules is around 2.5 times smaller than Spokes [3, 4].

Table 1: Capacitance Coefficient for Different Cryomodule Types

| Cavity type | Coeff [nF/K] |
|---|---|
| MBL | 15.97 ± 1.41 |
| HBL | 15.66 ± 1.49 |
| Spokes | 37.96 ± 1.67 |

Table 2 contains capacitance change between extreme temperature points of the accelerator's operation (2 K - 300 K). For MBL and HBL resonators the piezo capacitance in room temperature is around 6.5 $\mu$F while spoke systems exhibits values around 14 $\mu$F. The results follow the measurements described in [4]. That confirms both the measurements' reliability and the applied methodology's consistency.

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# RESULTS FROM A HELIUM FLOWMETER THAT MEASURES SRF CAVITY $Q_0$s IN SITU#

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*Abstract*

We report on the easily accomplished, in situ measurement of individual SRF Cavity power dissipation in cryomodules at the Thomas Jefferson National Accelerator Facility (JLab). A Small Business Innovation Research (SBIR) Grant to Hyperboloid LLC enabled development of a helium gas flow meter that acts as a Watt Meter, enabling calculation of $Q_0$. JLab provided the test bed environment and development of electronics through a cooperative agreement where 14 of the 53 cryomodule positions in CEBAF are now in use. The meter is also adopted as the only method of measuring $Q_0$s of LCLS-II-HE cryomodules built and then tested at JLab and a meter is being evaluated for response at 4 K in JLab's UITF when testing Nb3Sn Cavities. The meter typically measures the helium vapor evaporating from the 2 K helium bath at 1/30 atm, resolving 0.05 g/s = 1 W and has a broad range, measuring from 10 W to 200 W. The meter's sensitivity stems from when a superconductor element changes between conducing states in the presence of cooling from helium gas and heating from a heat source. An Electronics Chassis provides control and data processing of the signals that are presented to JLab's EPICS control system. We present results from CEBAF and LCLS-II-HE cryomodules, the 4 K response in UITF and potential plans for future deployment. The Hyperboloid Flowmeter is now a commercial instrument, available to the SRF community.

## INTRODUCTION

A helium gas flow meter, acting as a power meter (Watt Meter) that generally measures 3 to 7 K helium vapor evaporating from a superfluid, helium bath at 2 K, 1/30 atm was developed over a three-year period. Superconducting Radio Frequency (SRF) Accelerators throughout the world will see this flowmeter as a necessary instrument to assess SRF Cavity health in-situ.

### *The Need - Central Helium Liquefier Limitations at JLab*

The Continuous Electron Beam Acceleration Facility (CEBAF) at Thomas Jefferson National Accelerator Facility (JLab) uses a 2 K, Central Helium Liquefier (CHL) to supply the superfluid helium in which the SRF Cavities are immersed. The refrigerator requires a STEADY Heat Load. Surges tend to "trip" the refrigerator causing hours accelerator-off time. Surges result when cavities are turned off, stopping their heat dissipation and the power from compensating resistive heaters in the cryomodules is not correct. The calculation of the compensating heat stems from $Q_0$s, a lumped term for power dissipations which varies with the cavity's accelerating gradient. The $Q_0$s are out of date and a method of conveniently updating them in situ is not available. The Hyperboloid Flowmeter described in this report fulfils this requirement; it resolves 1 to 2 Watts of cavity dissipation.

## DEVELOPMENT AT JLab

A paper by Japanese researchers [1] indicated they successfully used a delicate, non-industrial, superconducting to non-superconducting transition to generate a strong signal and produce a flowmeter for these conditions.

This report shows the results from a *robust* flowmeter based on this principle that is successful after development and implementation at JLab. The flowmeter was developed under grants awarded by the Office of Nuclear Physics, DOE Office of Science, to Hyperboloid LLC, starting in February of 2022. The Grants utilized a Cooperative Research and Development Agreement (CRADA) with Jefferson Science Associates (JSA), the JLab operating contractor.

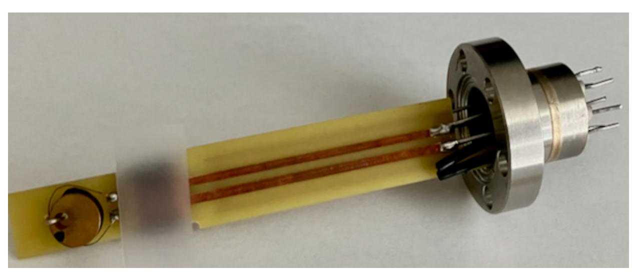

Figure 1: Instrument Head Assembly with Bobbin (obscured for proprietary reasons).

### *How It Works*

The Instrument Head Assembly, where the Bobbin is immersed in the helium stream, is shown in Fig. 1. Cooling from helium vapor flow from the cryomodule is bucked against the heat from a current in a resistive heater wire in the Bobbin. Sandwiched between the wire is a superconductor (SC) that yields a large voltage signal when the heating raises its temperature high enough to go "normal" conducting (Tc ~ 9 K). Increasing flow directly corresponds with increasing Heater Wire Current, the flowmeter's "Signal". The Electronics Chassis (See Fig. 2) designed by JLab with software integration into the Experimental Physics and Industrial Control System (EPICS)

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# COMING CLOSER TO HIGH FREQUENCY GRAVITATIONAL WAVE DETECTION WITH MAGO

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*Abstract*

In the last years, low frequency gravitational waves (GWs) have been consistently measured by the LIGO-Virgo collaboration, but little to no attention has been paid to higher frequencies GWs in the range of 10 kHz to 100 MHz, at which confirmation for current theories or even new physics could be hidden.

The MAGO 2.0 project aims at filling this gap in the parameter space using superconducting radio-frequency (SRF) cavities. Exploiting the excellent Q-factors of these resonators, we plan to detect tiny harmonic deformations induced by GWs which change the boundary conditions of the oscillating electromagnetic field.

We present the results of the first cold tests ran at DESY and FNAL using the cavity prototype built 20 years ago at the end of the MAGO collaboration, characterizing the RF spectrum, Q-factor and surface resistance. Additionally we introduce the mechanical vibration spectrum characterization and the RF response of the cavity with the injection of a "fake GW" signal using piezoelectric actuators.

## INTRODUCTION

Superconducting resonant cavities are a well-established technology in particle accelerator physics, but in the last decade their range of applications has greatly broadened going from dark matter search [1-4] to quantum computing [5-6]. The very high quality factor that these tools offer can be leveraged also in the search for gravitational waves (GWs) in frequency ranges not yet explored by "standard" instruments like for example the earth-based interferometers in the LIGO-VIRGO-KAGRA (LVK) collaboration. Stemming from an idea proposed in the 1970s by Pegoraro *et al.* [7] and Caves [8] the MAGO proposal [9] in the end of 1990s aimed at using SRF cavities to detect gravitational waves in the lower kHz range, since the interferometers had not been built yet. The same concept can be applied to the detection of high frequency GWs in the kHz to MHz, range, where only a small part of the parameter spaces has been covered. This range of frequencies is very interesting because of the absence of known astrophysical sources of GWs, creating an ideal background-free search. Possible sources include primordial black hole mergers (PBH), one of the candidates for dark matter, and superradiance, another exotic phenomenon that would hint at the presence of bosonic dark matter [10].

### Detection Principle

The MAGO proposal uses the so-called heterodyne detection principle: the cavity is designed to have two nearly degenerate EM eigenmodes of which only the lower frequency one (0 mode) is loaded with RF power, while the higher frequency one (π mode) is used as detection mode. The interaction of a GW with the cavity's walls (mechanical interaction[11]) or the EM field in the cavity itself (Gertsenshtein effect[12]) can cause an upconversion of the RF power at a frequency equal to the sum of the 0 mode frequency plus the GW frequency.

$$\omega = \omega_0 + \omega_{GW} \tag{1}$$

The Gertsenshtein effect becomes only relevant in the GHz frequency range for the GW, therefore in this study we will disregard it. The upconversion condition is resonantly enhanced when the resulting frequency coincides with the π mode frequency, resulting in an enhanced sensitivity. This does not mean that the device would be sensitive only on resonance, as it is possible to broaden the read out sensitivity by strongly overcoupling to the cavity [13].

The coupling of a GW to the superconducting cavity's walls can be expressed as [14]:

$$\Gamma_+^l := V_{cav}^{-1/3} \cdot M_{cav}^{-1} \int_{V_{cav}} d^3x\, \rho(\vec{r}) \left( x\vec{\xi}_{l,x}(\vec{r}) - y\vec{\xi}_{l,y}(\vec{r}) \right) \tag{2}$$

$$\Gamma_\times^l := V_{cav}^{-1/3} \cdot M_{cav}^{-1} \int_{V_{cav}} d^3x\, \rho(\vec{r}) \left( x\vec{\xi}_{l,y}(\vec{r}) - y\vec{\xi}_{l,x}(\vec{r}) \right) \tag{3}$$

with $+, \times$ two polarizations of the GW, $V_{cav}, M_{cav}, \rho$ respectively volume, mass and density of the cavity and $\xi_{l,x}$ displacement of the $l$ mechanical eigenmode in the $x$ direction. The second step of coupling between mechanical vibration and EM eigen modes can be then described by the following coupling coefficient:

$$C_{01}^l = \frac{V_{cav}^{1/3}}{2\sqrt{U_0 U_1}} \int_{\partial V_{cav}} d\vec{S} \cdot \vec{\xi}_l(\vec{r}) \left[ \frac{1}{\mu_0} \overrightarrow{B_0}(\vec{r}) \overrightarrow{B_1}(\vec{r}) - \varepsilon_0 \overrightarrow{E_0}(\vec{r}) \overrightarrow{E_1}(\vec{r}) \right] \tag{4}$$

with $U_0, U_1$ energy stored in both modes, $\vec{B}_{0,1}, \vec{E}_{0,1}$ magnetic and electric field distribution respectively in each

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# STATUS OF THE HIGH CURRENT 1.5 GHz SRF CAVITY PROTOTYPES FOR VSR DEMO

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*Abstract*

The BESSY Variable pulse-length Storage Ring (VSR) Demo project is a feasibility study aiming to provide short and long pulses simultaneously in the BESSY II storage Ring. To achieve this goal HZB has developed high current Continuous Wave (CW) Superconducting Radio Frequency (SRF) cavities operating at 1.5 GHz for 300 mA beams with large damping capabilities to cope with the HOM powers expected. This paper presents the current status, fabrication and lessons learned as results from the fabricated prototypes by Reseach Instruments (RI) and the first tests campaign carried on at SupraLab in HZB.

## INTRODUCTION

Elliptical SRF cavities are well established for accelerators but mainly for low-current applications. High-current machines require efficient higher order mode (HOM) damping to avoid instabilities [1]. Standard HOM coupler antennas are limited when dealing with broad-band spectrums and high HOM powers, and beam-pipe absorbers are usually impractical when space is constrained in a synchrotron by the use of anspecific straight section like in BESSY II. Therefore waveguide loaded end-groups represent a practical solution since damping offers broadband performance, high-power capability and results into a compact solution [2].

In this paper the current status of the High current 1.5 GHz waveguide-loaded cavities development is presented. These cavities are being manufactured by Research Instruments (RI). Currently the fabrication of the first prototype is completed to the point of an “undressed” prototype cavity and has been tested for the first time in a Large Vertical Test Stand (LVTS) at HZB’s SupraLab. The results of these tests and lessons learned are presented in this work. A second prototype is currently in the last stages of “undressed” cavity fabrication and is waiting to be tested in the LVTS.

## DESIGN OVERVIEW, MAIN CAVITY ELEMENTS AND MECHANICAL CHALLENGES

The cavity consists of four niobium cells with stiffening rings for pressure stability, two endgroups with HOM waveguide extensions, and a titanium Helium Vessel. Beampipe and Fundamental Power Coupler (FPC) flanges are made from NbTi, prepared for aluminum hexagon gaskets and copper RF lips. Stainless-steel flanges are joined to the Ti-made Lhe tank by by explosive bonding.

There are two end-group configurations, one with three waveguides and the other with two waveguides plus the fundamental power coupler port. In both cases the waveguides are arranged non-symmetrically (60° rotation) to extract the maximum amount of HOM power while minimizing impact on the fundamental mode. The large beampipe cross-section ensures broadband propagation. Waveguide (WG) extensions continue with bends and water-cooled HOM loads dissipating up to 460 W each. To prevent heat transfer back to the cavity, actively cooled flanges connected to the 5–8 K circuit were developed.

Figure 1 depicts the full cavity for illustration with ancillary components attached (Blade tuner, Funda-mental power coupler and HOM loads). For a deeper comprehension, all details on the mechanical design are discussed to the detail in [3] while the electromagnetic design and impedance considerations are discussed in [4].

Tuning is performed by a blade tuner driven by a stepper motor and piezo actuators. The required range of over 1 MHz imposes high forces and frequent operation, demanding robust components. Reliability studies revealed the need for a release mechanism to protect the cavity in case of motor failure. Finite element simulations were carried out for pressure and tuning loads. Safety margins were tight due to niobium’s low yield strength, especially at room temperature. Peak stresses were reduced by design modifications, such as larger radii at critical transitions and optimized stiffening ring positions. Waveguide flanges had to remain leak-tight at 1.8 K while allowing reliable RF contact. Initial designs with rectangular gaskets failed; instead, custom aluminum-copper composite gaskets were developed, achieving vacuum tightness and RF sealing. Integrated cooling channels in the flanges maintain superconductivity in the WG extensions. Tests confirmed stability under pressures well above operating conditions.

## MANUFACTURING AND QUALITY CONTROL

The fabrication process of this cavity has been a four years process in which many compromises and modifications took place. In particular deep drawing of the cavity geometry according to specification required from several iterations. The whole system (with the exception of the presurized cooling of the waveguide flanges) was classified under low-pressure-vessel regulations but subjected to best

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# 591 MHz SRF CAVITY DESIGN FOR THE EIC ESR*

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## *Abstract*

The Electron-Ion Collider (EIC) is a next generation particle accelerator to be built at Brookhaven National Laboratory, in partnership with Thomas Jefferson National Accelerator Facility. The Electron Storage Ring (ESR) of RIC requires a 10 MW RF storage system to restore beam power lost by a 2.5 A electron beam. The RF system will use 18 single-cell 591 MHz Superconducting RF (SRF) cavities. Effective damping of higher-order-modes (HOMs) is critical to ensure beam stability. This paper presents the design of the single-cell 591 MHz cavity, including cavity geometry optimization, multipacting evaluation, and HOM damping analysis.

## INTRODUCTION

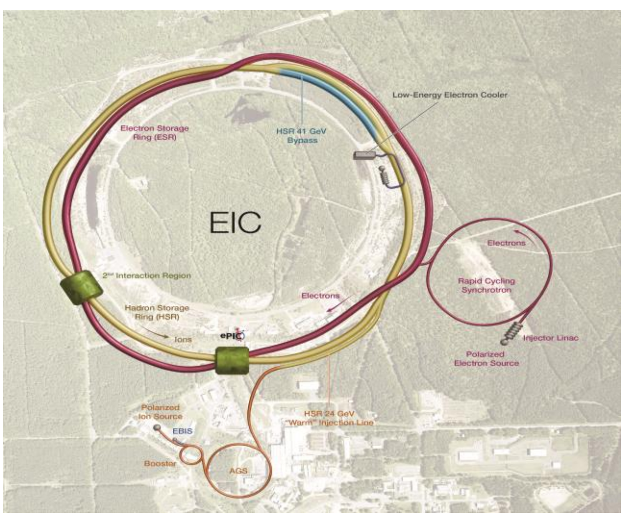


Figure 1: Schematic layout of the EIC.

The EIC [1] to be built at BNL will be a discovery machine, providing answers to long-elusive mysteries of matter related to our understanding of the origin of mass and the spin of the proton, and probing the structure of dense gluon systems in nuclei that make up the entire visible universe. The EIC includes a hadron accelerator that provides hadron beams and an electron accelerator that provide electron beams. The hadron accelerator will use upgraded components and infrastructure of the Relativistic Heavy Ion Collider (RHIC) accelerator system. The electron accelerator chain is new, which includes electron injector, Rapid Cycling Synchrotron (RCS) and Electron Storage Ring (ESR). Figure 1 shows the schematic layout of EIC.

The maximum synchrotron radiation in ESR is up to 10 MW. To compensate such large energy loss, 18x591 MHz single-cell SRF cavities are needed. Since 2021, the cavity design has been evolving, reaching maturity [2]. The first cavity design was presented in [3]. This paper presents the second iteration of the cavity design.

## CAVITY DESIGN

### *Design Requirement*

The EIC ESR SRF cavity has a tight impedance requirement for beam stability and acceptable transient beam loading. The detail requirements are shown in Table 1.

Table 1: ESR SRF Cavity Design Requirement

| Parameters | Requirement |
|---|---|
| Frequency [GHz] | 0.591 |
| R/Q [Ω] | < 80 |
| Max. Voltage [MV] | 4 |
| B [mT] @4 MV | < 80 |
| E[MV/m] @4MV | <40 |
| Longitudinal HOM impedance [Ω-Hz] | < 2.9E12 |
| Transversal HOM impedance [Ω/m] | < 1.3E6 |
| Max. power (2 FPCs) [kW] | 800 |

All the impedance values mentioned in this paper are based on the accelerator definition. The higher-order-mode (HOM) impedance requirements listed above are likely more conservative because it is assumed that all the 18 cavities have the same HOMs.

### *Cavity Geometry*

The SRF cavity geometry optimization follows typical elliptical cavity design recipes, starting from fundamental mode optimization, and then HOM damper optimization. Figure 2 shows the Superfish model of ESR SRF cavity geometry. The radius of the small beampipe is 90 mm, which is 15 mm larger than the first cavity design to reduce impedance and ease the cold-to-warm bellow design. The radius of the larger beampipe stays the same as for the first cavity, i.e., 137 mm, which is enlarged from the cavity's

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# HIGH POWER FPC PROGRESS FOR EIC ESR CAVITIES*

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*Abstract*

Electron-Ion Collider (EIC) is a next generation particle accelerator to be built at Brookhaven National Laboratory, in partnership with Thomas Jefferson National Accelerator Facility. In Electron Storage Ring (ESR), 18 single-cell 591 MHz SRF cavities are required to compensate for up to 10 MW energy loss due to synchronic radiation. Two high power FPCs for each cavity are used to deliver up to 800 kW power to the beam. The high power FPC were designed and reviewed. The FPC prototypes will be ready for high power test around mid-2026. This paper presents the latest development of FPC prototyping and path forward for FPC conditioning.

## INTRODUCTION

The EIC [1] to be built at BNL will be a discovery machine, providing answers to long-elusive mysteries of matter related to our understanding of the origin of mass, structure, and bind of atomic nuclei that make up the entire visible universe. The EIC includes a hadron accelerator that provides hadron beams and an electron accelerator that provide electron beams. The hardon accelerator is based on an upgraded version of the Relativistic Heavy Ion Collider [2] (RHIC) accelerator system. The electron accelerator is a new accelerator system, including electron injector, Rapid Cycling Synchrotron (RCS) and Electron Storage Ring (ESR). Figure 1 shows the schematic layout of EIC.

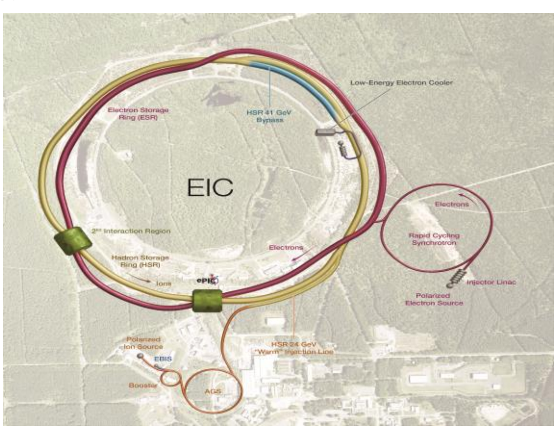


Figure 1: Schematic layout of EIC.

There are 18 single-cell SRF cavities in the ESR for synchronic loss compensation. In each cavity, there are two high power FPCs to deliver up to 800 kW power to the beam. Therefore, a 400 kW CW FPC design is needed for EIC ESR SRF cavity. This paper presents the latest results of FPC prototype and testing plan.

## FPC DESIGN OVERVIEW

### *FPC Design Features*

The EIC FPC is an improved design of KEK/SNS/BNL BeO window FPCs [3-5]. Figure 2 shows ESR SRF cryomodule layout and the design of high-power coupler.

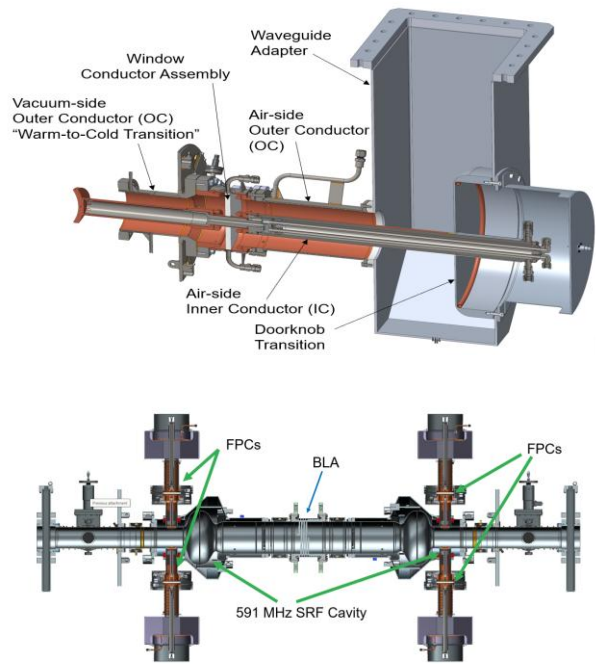


Figure 2: EIC ESR cavity.

There are two FPCs in each cavity, and they are installed horizontally 180 degree apart. With implementing lessons learned from the similar FPC window, there are several features in the EIC FPC[6].

1. RF window material: 99.5% alumina.
2. Broadband window design for multiple frequencies in EIC RF complex.
3. Robust thickness of the RF window: 10.5 mm
4. Large the distance between the window surface to choke tip. This allows visual inspection of the brazing joint and improvement on the uniformity of TiN coating under the choke.
5. FPC coaxial line was optimized for lower RF field, higher coupling factor, and minimize the multipacting zone in the FPC.

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# TOWARDS HIGH POWER TESTS OF AN FE-FRT FOR TRANSIENT DETUNING

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*Abstract*

The design, fabrication and validation progress towards a ferroelectric fast reactive tuner (FE-FRT) as a demonstrator of a high-power tuner for beam loading compensation at LHC injection settings is presented. Such compensation is referred to as transient detuning compensation and involves discrete frequency switching of an LHC cavity configuration on sub-microsecond time scales. The FE-FRT is operated in a two-state mode with a 7 kV bias applied across a $BaTiO_3/SrTiO_3$-Mg ferroelectric material in the tuner stub to provide the required cavity frequency shift. To achieve this, the device has been designed to operate as a coupled resonant tuner that provides an 8 kHz cavity tuning range. As an FE-FRT design, the tuner must tolerate a reactive power load of +/- 226 kVAR and 3 kW of dissipated power. The key design decisions taken are presented along with the specific optimisation of the tuner in terms of the expected performance. Finally, measurements and first results for the tuner demonstrator validation process are discussed.

## INTRODUCTION

The ability to tune an RF cavity's frequency on fast timescales is important for a variety of accelerator applications, including but not limited to: compensation of Lorentz force detuning, transient detuning and microphonics compensation. In recent years the idea of using ferroelectric materials to create fast and high average power tuners has been developed [1, 2], with successful results shown using an FE-FRT prototype to compensate for microphonics [3]. However, despite these results, to date, there has been no experimental validation of an FE-FRT at high reactive power levels (> 10 kW). To address this, this paper details the design and development work leading towards validation of a high power FE-FRT that would be capable of tuning $\pm$ 225 kVAR reactive power.

## FE MATERIAL

At the heart of all FE-FRT designs is the ferroelectric material used to provide real-time tunability of the device, and the designs considered in this paper utilise a commercially available ferroelectric ceramic, developed by Euclid Techlabs [4, 5]. This material is a $BaTiO_3/SrTiO_3$-Mg ceramic, and as a ferroelectric, it changes its permittivity in response to an externally applied electric biasing field. This material is of particular interest as it exhibits low loss for the range of frequencies of interest as well as having a high permittivity tunability: Some of the key material properties at 400 MHz are given in Table 1.

Table 1: FE Material Properties at 400 MHz

| Parameter | Value | Units |
|---|---|---|
| $\epsilon_r$ at 0 V bias and ≈ 25 °C | 160 | - |
| Loss tangent $\delta$ | 1e-3 | - |
| Tunability at 8V/µm | 1.4 | - |
| Thermal conductivity | 7.02 | $Wm^{-1}K^{-1}$ |
| Breakdown strength | 20 | V/µm |

Like all ferroelectric materials, the material permittivity response changes with temperature, with the highest sensitivity just below the material's Curie temperature. For such BST ceramics this temperature limit is typically above 100°C, implying that FE-FRTs operated at or above ambient temperature. Indeed, the choice of operational temperature can be exploited, as by adjusting the operating point, the permittivity and loss tangent of the material can be shifted in order to provide an optimum operating temperature of the material in terms of required tuning range and RF losses. As an example, the temperature dependence on unbiased ferroelectric material is shown in Fig. 1.

## CONCEPT

The FE-FRT presented in this paper was initially designed for a transient detuning use case with the preliminary design reported in Ref. [2]. The tuner is constructed by integrating

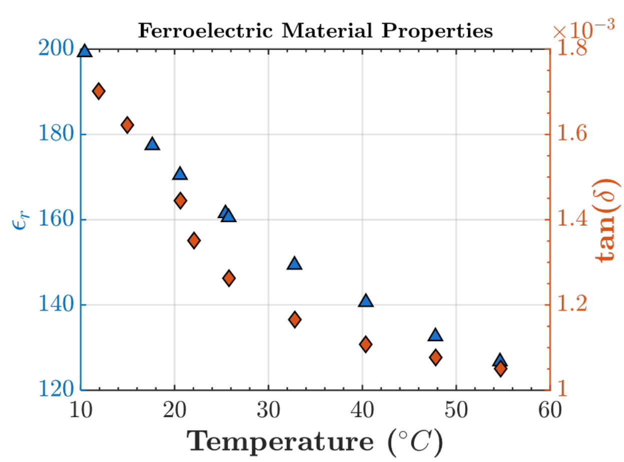


Figure 1: Temperature dependence of Ferroelectric material properties at 400 MHz [6].

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# BEAM ACCELERATION WITH A $Nb_3Sn$ CRYOMODULE AT JLAB*

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*Abstract*

We report on the electron beam acceleration experiment with a $Nb_3Sn$ cryomodule at Thomas Jefferson National Laboratory (JLAB). Two CEBAF-style 5-cell 1.5 GHz $Nb_3Sn$ cavities operated at 4 K, accelerating a 10 μA continuous-wave (CW) electron beam from 200 keV to 5.1 MeV at JLAB's Upgraded Injector Test Facility (UITF). The acceleration gradient capability of each cavity reached 11 MV/m and 7 MV/m, respectively. No field emission was observed. The unloaded quality factors reached $3\sim4\times10^9$ at low fields at 4 K.

## INTRODUCTION

Superconducting radiofrequency (SRF) cavities and cryomodules are essential technologies for particle accelerators that enabled discovery sciences in nuclear and particle physics. Additionally, the SRF technology has become a go-to technology to produce neutrons and photons with unprecedented quality and intensity serving a large community of material sciences.

Existing SRF technology is predominantly based on the SRF cavities made of high-purity bulk niobium (Nb). There is now in the community a growing interest in SRF $Nb_3Sn$ cavities, motivated by its higher critical temperature ($T_c$) and higher superheating magnetic field strength relative to that of Nb [1,2]. The $Nb_3Sn$ cavity development at JLAB started in the early 2010's [3]. Steady progresses have been made over the years, as indicated by the successful demonstration of $E_{acc}$ = 10 MV/m with a 5-cell, 1.5 GHz $Nb_3Sn$ cavity in a cryomodule tested in the Cryomodule Test Facility (CMTF) at JLAB in 2024 [4].

The major objective of the $Nb_3Sn$ technology development at JLAB is to enable 4 K operation of $Nb_3Sn$ cavities with comparable $Q_0$ values of Nb cavities at 2 K. The $Nb_3Sn$ SRF technology holds the promise to improve the energy efficiency of continuous-wave (CW) SRF electron accelerators such as CEBAF [5] and future Energy Recovery Linacs (ERLs), to increase the uptime of future high-power SRF proton linacs for transmutation of used nuclear fuel, and to enable compact SRF accelerators for broader applications in industry [6], material sciences, and biomedical fields.

In this paper, we report on the first electron beam acceleration experiment with the $Nb_3Sn$ cryomodule, named "Gray Enid I" in November 2024. This present work extends our efforts at JLAB from the successful $Nb_3Sn$ component demonstration into an integrated system test in a real accelerator with beam. The beam test was carried out in JLAB's Upgraded Injector Test Facility (UITF).

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## UITF AND CRYOMODULE INTERFACES

UITF is a test bed that can be quickly reconfigured for testing new accelerator technologies such as cryomodules, RF cavities, photocathodes, and polarimeters. It provides a venue to perform low energy physics experiments with polarized electron beam.

Figure 1 shows the $Nb_3Sn$ cryomodule Gray Enid I installed in the accelerator at UITF. The cryomodule is installed in a slot where the accelerator beamlines are connected to the cryomodule at its upstream and downstream isolation gate valves. Rectangular waveguides connect the cavity waveguide couplers with two each 5 kW klystrons upstairs of the accelerator vault. Cryogenic lines connect the cryomodule supply and return end-cans with the Cryogenic Test Facility (CTF). A laser-driven photocathode DC gun produces 200 keV electron bunches at a nominal rep rate of 1497 MHz in CW mode (laser pulse length 35 ps). A buncher cavity further compresses the bunch length before the beam enters the first cavity in Gray Enid I. The accelerated beam is transported to the end of the accelerator, where it is either deflected by a dipole magnet to a spectrometer or is sent directly to the irradiation target area. The overall length of the accelerator from the gun to the target is ~27 meters. The cryomodule length including the supply and return end-cans is ~3.5 meters.

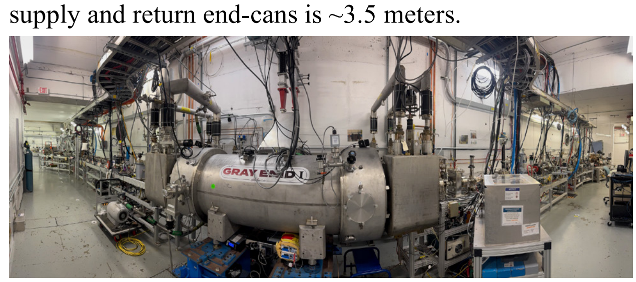


Figure 1: $Nb_3Sn$ cryomodule Gray Enid I installed in the accelerator system at UITF. The laser-driven photocathode DC gun is at the far-right end. The beam spectrometer and the irradiation target area are at the far-left end.

## CAVITY AND CRYOMODULE DESIGN

Existing cavity and cryomodule designs were adopted, allowing the re-use of existing hardware components and permitting plug compatibility with existing infrastructures. The cavity was designed for the CEBAF cryomodule refurbishment effort, aiming at a larger voltage gain relative

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# EFFECTS OF THIN GOLD LAYERS ON PERFORMANCE OF 2.6 GHz SRF CAVITY*

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*Abstract*

SRF cavities are a critical technology both for particle accelerators, where they enable high energies and efficient operation, and superconducting quantum circuits, where they enable large coherence times for qubits. In both applications, the need for better performing cavities with higher quality factors is clear. The native oxide that forms on the surface of niobium may be the source of conductive losses in high-energy accelerator applications and of two level system losses in low-energy quantum applications. Previous work from Cornell University studied the effect of passivating the niobium oxide on an RF sample plate with a thin layer of gold, selected for its properties as a non-oxidizing normal conductor. At sub-nanometer thicknesses, the sample showed an increased quality factor. In this paper, we report first RF results scaling up the treatment for full-scale cavity testing using electrochemical deposition of gold on a 2.6 GHz niobium SRF cavity. We also report sample imaging characterizing the growth of thin gold films on niobium, and DFT calculations on the effect of gold on the presence of oxygen impurities in niobium.

## INTRODUCTION

The interaction of the RF field in an SRF cavity is strongest in the first 40 nm of the niobium surface [1]. Because of this, the surface properties of the cavity are extremely important to its performance, and significant research and development over recent years has focused on this region [2].

When exposed to atmosphere, niobium forms an oxide [3, 4]. The oxide is composed of multiple chemical phases and makes up approximately the first 5-10 nm of the surface, which is a significant portion of the strong RF interaction region. The majority of the oxide is made up of the pentoxide $Nb_2O_5$ phase, followed by the $NbO_2$ phase, then lower-order $NbO_x$ sub-oxide phases. A simplified cartoon of this oxide structure is shown in Fig. 1.

Different phases of the oxide may negatively affect cavity performance in different ways. The lower phases of the oxide may have normal conducting properties, which would inhibit cavity performance during the high-energy operation used in particle accelerator applications [3]. The upper phases of the oxide, including the pentoxide, may have dielectric properties, which would inhibit cavity performance during the low-energy operation used in quantum computing applications [5]. For these reasons, previous work at Cornell University and elsewhere has explored removing the native oxide and replacing it with a thin layer of non-oxidizing normal conductor in order to prevent oxide reformation (see for example [6–8]).

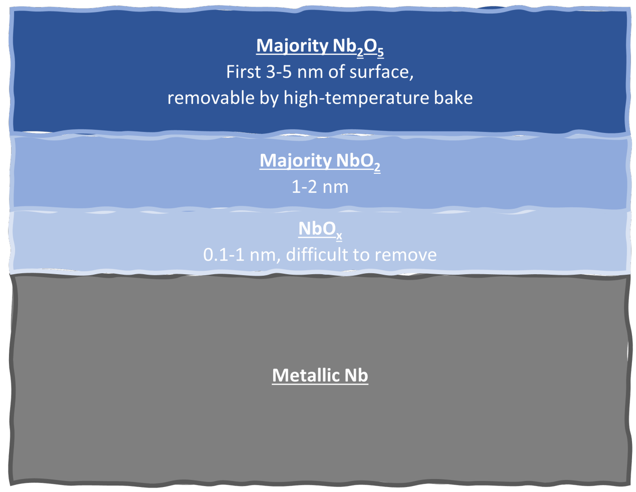


Figure 1: Cartoon of the native niobium oxide structure.

Cornell University performed the first high-field RF study of this technique, using gold to passivate the oxide on a niobium sample and testing the RF performance of that sample [7]. That work found that the quality factor of the sample increased when the oxide was passivated with nominally 0.1 nm of gold. It indicated promise for the technique, and indicated support for the theory that the oxide inhibits cavity performance. That study used electron beam evaporation deposition to deposit the thin film of gold on the niobium surface, which was ideal for sample studies, but is infeasible for full-scale cavity applications due to the size and irregular geometry of a cavity.

Here we present major progress and first results scaling up the technique of oxide passivation with gold on a niobium 2.6 GHz SRF cavity, as well as sample studies and DFT calculations relating to the techniques used.

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# PRODUCTION OF $Nb_3Sn$ FILM ON COPPER SUBSTRATE BY THE BRONZE ROUTE AND THE RF CHARACTERIZATION OF SAMPLES WITH THE QUADRUPOLE RESONATOR

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*Abstract*

Copper-based $Nb_3Sn$ cavity is a promising candidate for next generation accelerator applications in the field of superconducting radio frequency (SRF). It combines the excellent thermal conductivity of copper and the superior superconducting properties of $Nb_3Sn$, and has the potential to greatly improve the performance of the SRF cavity. The electrochemical and thermal synthesis (ETS) bronze route is one of the proven methods to achieve $Nb_3Sn$ coating on copper. Its advantages are low cost, simple operation, suitable for complex cavity types and mass production. In this report, we have prepared a copper-based $Nb_3Sn$ sample specifically for Quadrupole Resonator (QPR) testing. We provide a complete set of QPR sample preparation processes from copper electropolishing, Nb sputtering, electrodeposition and heat treatment to synthesize $Nb_3Sn$. By optimizing the entire preparation process and key parameters, a new Cu-based $Nb_3Sn$ QPR sample was successfully prepared and its RF properties have been characterized by QPR testing system at HZB.

## INTRODUCTION

$Nb_3Sn$ has emerged as a promising alternative for next generation superconducting radio-frequency (SRF) cavities, offering a higher critical temperature ($T_c \sim 18$ K) and significantly lower BCS surface resistance ($R_s$), thereby enabling efficient operation at elevated temperatures such as 4.2 K while maintaining high quality factors ($Q_0$) [1,2]. The most mature $Nb_3Sn$ coating technique for SRF cavities is the tin vapor diffusion (TVD) method [3,4], in which tin vapor reacts with a bulk Nb cavity surface at ~1100 °C to form A15 $Nb_3Sn$ layer. However, this approach fundamentally requires Nb as the substrate and is not applicable to low-melting-point materials, such as copper (melting point: 1085 °C).

Copper offers several intrinsic advantages as an SRF cavity substrate, including superior thermal conductivity, lower material cost, and excellent formability [5]. To enable the use of Cu substrates, several alternative $Nb_3Sn$ film deposition methods have been investigated, including magnetron sputtering [6,7], chemical vapor deposition (CVD) [8], and adaptations of the classical bronze process [9,10]. Among these, the bronze route stands out as a viable and scalable method for synthesizing $Nb_3Sn$ films on Cu surfaces.

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Traditionally developed for multifilamentary $Nb_3Sn$ wire fabrication [11, 12], the bronze route involves solid-state diffusion between Nb and a Cu–Sn alloy at elevated temperatures, forming the superconducting A15 phase within a Cu matrix. Recent work by Barzi *et al.* has adapted this principle to thin-film applications through a modified electrochemical–thermal synthesis (ETS) process [13]. In this method, a high-purity Nb substrate can be replaced by a Cu substrate coated with a Nb diffusion barrier, followed by the electrochemical deposition of a bronze (Cu–Sn) precursor layer. Subsequent vacuum annealing at intermediate temperatures (typically 700 °C) promotes interdiffusion and reaction to form a uniform $Nb_3Sn$ layer on the surface [14]. Finally, the residual bronze layer on the surface can be removed by chemical etching, thereby exposing a clean $Nb_3Sn$ surface suitable for subsequent RF characterization. [14].

In this study, we report the fabrication and RF characterization of the Cu-based $Nb_3Sn$ sample prepared via the bronze route for application in superconducting cavities. The sample was evaluated using the Quadrupole Resonator (QPR) at Helmholtz-Zentrum Berlin (HZB) to determine its surface resistance [15]. Measurements of the surface resistance ($R_s$) were performed as functions of both peak magnetic field and temperature, primarily at a frequency of 412 MHz. This allowed for detailed assessment of how $R_s$ varies under different RF field and temperature. In addition, thermal cycling experiments were conducted by cooling the samples at various rates to study the impact of different cooldown procedures on $R_s$, providing insights into the effects of thermal history and flux trapping on superconducting performance. The critical temperature ($T_c$) of the $Nb_3Sn$ films was also determined from the temperature-dependent resonant frequency measurements. In addition, the $T_c$ was obtained from magnetization measurements using a Physical Property Measurement System (PPMS) and the surface quality was visually inspected using photographic images. Together, these tests contributed to evaluating the film quality and provided guidance for its further improvement.

## EXPERIMENTAL SETUP AND METHODS

The Cu-based $Nb_3Sn$ QPR sample was fabricated through a multi-step bronze route process, as summarized in Fig. 1. The Cu substrate underwent mechanical polishing followed by electrochemical polishing (EP) using a disk-and-belt cathode setup at 2.1 V and 15 °C for one hour, which removed

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# DEVELOPMENT OF $Nb_3Sn$ COATINGS ON COPPER AT INFN-LNL*

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*Abstract*

The successful development of $Nb_3Sn$/Cu coatings for the SRF cavities of next generation particle accelerators would result in the reduction of the needed cryogenic power by a factor 3 with respect to what normally needed for bulk Nb cavities, while maintaining operation at 4.5 K. In the framework of the I.FAST and ISAS collaborations, research activities are carried out at INFN-LNL to develop new technologies for the application of $Nb_3Sn$ on Cu, including seamless spinning of cavity prototypes, surface chemical preparation, cavity coating and testing. At the same time, an optimized recipe for $Nb_3Sn$ films deposited via DCMS has been established on flat samples and is discussed in this work. The recipe delivers films showing a $T_c \simeq 17$ K, at deposition temperatures ≤ 650 °C, on a Cu substrate pre-coated with a 30 µm-thick buffer layer of Nb. The deposition recipe has been validated on bulk Nb by measuring its RF properties on a QPR sample, with the results being also discussed in this work. A surface resistance of 23 nΩ at 4.5 K and 20 mT is measured, which corresponds to a $Q_0$ about 5 times larger than the baseline specification for the LHC Nb/Cu cavities and already fulfills the requirements for the FCC-ee. Finally, updates on the activities toward the scalability of the coating recipe to the 1.3 GHz elliptical cavity prototype are given, and the perspectives for further coating recipe refinement are discussed.

## INTRODUCTION

The development of next-generation particle accelerators, such as the FCC-ee, imposes stringent requirements on energy efficiency [1]. For superconducting RF (SRF) accelerating cavities, the class-A15 intermetallic compound $Nb_3Sn$ is a promising superconducting (SC) material alternative to Nb. Its high critical temperature (18.3 K against 9.2 K of Nb) corresponds to a BCS surface resistance $R_{BCS}$ at 4.5 K comparable to that of Nb at 2 K [2], and lower than that of Nb films on Cu at 4.5 K [3], enabling operation at 4.5 K with significantly reduced cryogenic costs. However, the brittleness of $Nb_3Sn$ makes bulk machining impractical, limiting its application to thin-film coatings.

The state-of-the-art technique for $Nb_3Sn$ cavities is vapour tin diffusion (VTD), whose best performance showed a quality factor $Q_0 \simeq 10^{10}$ at 4.4 K up to 20 MV m$^{-1}$ for 650 MHz cavities [4]. Despite these results, VTD relies on a bulk Nb substrate, much pricier than Cu (RRR = 300 niobium ≈ 100x more expensive than OFHC Cu) [5], making it less appealing, in terms of costs, for large-scale cavity production. The technique is also prone to the formation of sub-stoichiometric phases [6], undesired as they contribute to the degradation of the RF performance. Last, but not least important, the copper substrate introduces several advantages with respect to bulk Nb, in addition to its cost: it has higher thermal conductivity than bulk Nb at 4.5 K, and potentially allows cryocooler-based conduction cooling (9 W cooling power recently demonstrated at 4.2 K [7, 8]). This makes physical vapour deposition (PVD) a technique of high interest for the production of $Nb_3Sn$ films on Cu for SRF cavities. In fact, a successful development of $Nb_3Sn$ coatings on copper would make possible to cover the current baseline requirements for the SRF cavities of FCC-ee [9], for both the main ring and the booster, for which Nb/Cu and bulk Nb cavities are, respectively, currently foreseen.

In this context, a baseline deposition recipe for $Nb_3Sn$ films on copper has been established via direct current magnetron sputtering (DCMS) at INFN-LNL, via a $T_c$-driven study [10]. The experimental methods to pursue this result, to advance the analysis of the morphological, thermal, and superconducting properties of these coatings, and to scale-up the deposition recipe to a 1.3 GHz cavity prototype are described in the Experimental Methods Section. The DCMS deposition recipe will be discussed in Results and Discussion, along with the most recent results in terms of the above-mentioned characterizations, and progress toward the making of the first $Nb_3Sn$/Cu 1.3 GHz cavity.

## EXPERIMENTAL METHODS

### $T_c$-driven DCMS Deposition Recipe Optimization

The production and characterization of the $Nb_3Sn$ film samples produced for the optimization of the DCMS depo-

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# IMPROVING QUENCH FIELDS OF ENHANCED-$T_c$ SURFACES*

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*Abstract*

The sensitivity of compound superconductors to gradient-limiting defects is well established. To overcome this challenge and develop recipes for enhanced-$T_c$ surfaces that approach their fundamental limits, we take a multi-pronged theoretical approach: we identify material systems where low-$T_c$ or normal-conducting defects are less likely to occur, where bulk superconducting properties favor proximity coupling of defects, and where clean interfaces with the niobium substrate allow for thinner films and better thermal stability. We present progress toward growing ultra-thin-film Nb-Zr and $Nb_3Al$ superconductors on niobium with the goal of achieving high quality factors at unprecedented fields.

## INTRODUCTION

Compound superconductors with $T_c$ higher than the 9.2 K $T_c$ of Nb are of interest for superconducting radio-frequency (SRF) applications for two main reasons. First, they offer lower BCS surface resistance, which is especially important at temperatures above 2 K where BCS resistance dominates RF dissipation in modern Nb cavities. Second, they offer the potential for higher superheating fields than Nb [1–5]. Together, these advantages have the potential to make SRF technology for large and small applications far more compact and economical than would be possible with Nb cavities [6].

So far, $Nb_3Sn$ has shown by far the most promise of any compound superconductor. At low fields, state-of-the-art $Nb_3Sn$ cavities have successfully demonstrated quality factors over $10^{10}$ at 4.2 K, fully two orders of magnitude better than Nb cavities of the same geometry. However, even the best $Nb_3Sn$ cavities experience declining Q at higher fields, and quench at fields no more than 24 MV/m, less than $\frac{1}{4}$ of the theoretical superheating field [7].

One possible explanation for the observed Q-slope and premature quench of $Nb_3Sn$ cavities is thermal instability of defects on the $Nb_3Sn$ surface. $Nb_3Sn$ is known to be a poor thermal conductor, and the known trend of thinner $Nb_3Sn$ layers reaching modestly higher fields than thicker layers is qualitatively consistent with the predictions of thermal models (Fig. 1) [8]. In these models, a temperature gradient develops between an energy-dissipating defect on the $Nb_3Sn$ surface and the high-thermal-conductivity substrate, which remains close to the liquid helium bath temperature. Because of the low thermal conductivity of $Nb_3Sn$, this gradient can become large enough that $Nb_3Sn$ near the surface becomes much warmer than the bath temperature, and therefore becomes a significant source of dissipation itself due to its increasing BCS resistance. The overall dissipation concentrated at this location then far exceeds the dissipation of the defect alone, and the resulting positive-feedback loop eventually leads to cavity quench.

While there is some potential to make $Nb_3Sn$ layers thinner still, we may be approaching the lower limit for usable $Nb_3Sn$ layer thickness. This is because an interfacial layer of tin-depleted $Nb_3Sn$ exists between the 25%-Sn surface and the Nb substrate. This tin-depleted layer, with the same crystal structure as $Nb_3Sn$ but a lower tin content of around 18%, has a $T_c$ of only about 6 K, even lower than the $T_c$ of Nb [9]. The BCS resistance of this material is so high that it can easily dominate the overall resistance unless it is covered by several hundred nanometers of $Nb_3Sn$.

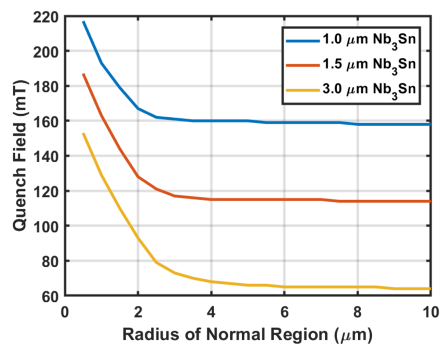


Figure 1: Model of $Nb_3Sn$ thin film thermal stability, showing the potential for thinner films to reach higher fields in the presence of surface defects [8].

In order to overcome this challenge and verify the potential for compound superconductors to reach higher fields, we are motivated to explore material systems that can more easily avoid the formation of low-$T_c$ or normal conducting phases. In particular, if no unfavorable phases exist at the interface of the compound superconductor and the niobium substrate, then arbitrarily thin layers of the compound superconductor could offer lower BCS surface resistance relative to Nb without sacrificing on thermal stability and quench field. We identify the Nb-Zr bcc alloy and the $Nb_3Al$ A15 alloy as candidate materials that satisfy this requirement, and this paper describes our progress toward proof-of-principle RF tests of these materials [10, 11].

## METHODOLOGY

All samples used in this study first received a short buffered chemical polish followed by at least 30 microns of cold electropolishing removal. After electropolishing, the samples are immediately cleaned of residual acid, first in an ultrasonic bath with liquinox detergent and then in an

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# INVESTIGATION OF ANTI-Q-SLOPE AND Q-SLOPE EFFECTS IN SRF CAVITIES: A UNIFIED THEORETICAL FRAMEWORK

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*Abstract*

The discovery of the anti-$Q$-slope effect has represented a major breakthrough in the field of superconducting radio-frequency (SRF) cavities. While properly treated bulk niobium cavities can exhibit an increase in performance with accelerating field, untreated bulk niobium cavities and niobium-coated copper cavities often suffer from the $Q$-slope effect, which limits their performance at medium and high fields. Despite decades of experimental advances—ranging from surface treatments in bulk niobium cavities to deposition techniques in niobium-coated copper cavities—together with extensive theoretical efforts, the origin of both the anti-$Q$-slope and the $Q$-slope effects remains an open question.

In this work, we present a unified theoretical framework based on Eliashberg's nonequilibrium theory, later extended by Chang and Scalapino. By solving the coupled kinetic equations for quasiparticle and phonon distributions under RF/microwave fields, we demonstrate that the reduction of surface resistance with increasing accelerating field can occur in niobium at 1.8 K and 1.3 GHz, provided that the phonon escape lifetime is significantly shorter than the phonon pair-breaking lifetime. This finding may shed light on the origin of the anti-$Q$-slope effect observed in properly treated bulk niobium cavities. In contrast, when the phonon escape lifetime substantially exceeds the phonon pair-breaking lifetime, the reduction of surface resistance is overturned, giving rise instead to a progressive increase with accelerating field. This may explain the $Q$-slope, frequently observed in untreated bulk niobium cavities and in niobium-coated copper cavities. Our model not only explains and unifies two apparently opposite phenomena within a single theoretical framework but also provides insight into how the interplay between RF/microwave fields, quasiparticles, and phonons in superconducting niobium collectively determines the field dependence of the surface resistance in SRF cavities.


## INTRODUCTION

The observation of the anti-$Q$-slope effect has constituted a major advancement in the field of superconducting radio-frequency (SRF) cavities. When the anti-$Q$-slope effect occurs, the quality factor $Q$—which is inversely proportional to the surface resistance—unexpectedly increases with the accelerating field [1–5]. In contrast, the long-standing issue of the medium-field $Q$-slope manifests as a progressive degradation of cavity performance with increasing accelerating field, an effect frequently observed in bulk niobium cavities and particularly pronounced in niobium-coated copper cavities [6–12].

A significant part of the research on bulk niobium cavities has been devoted to the development of surface treatments and processing techniques designed to induce and thereby enhance the anti-$Q$-slope effect. In parallel, considerable effort has also focused on optimizing thin-film deposition methods for niobium-coated copper cavities, with the goal of mitigating the detrimental medium-field $Q$-slope effect and extending the performance limits of this technology. For a detailed overview, the reader is referred to Refs. [2, 5, 7, 9, 12, 13]. Alongside these experimental advances, numerous theoretical investigations [14–21] have been carried out; however, they remain limited in scope and fail to provide a comprehensive overview, thereby hindering the identification of clear optimization strategies. In fact, it would be highly desirable to elucidate how the medium-field $Q$-slope effect can be effectively mitigated in cavities and, if possible, transformed into an anti-$Q$-slope behavior. Despite decades of extensive experimental and theoretical studies, the microscopic origins of both the anti-$Q$-slope and the $Q$-slope effects remain a fundamental open question, continuing to challenge our understanding of cavity performance.

In this work, we present a unified theoretical framework that seeks to explain the microscopic origins of both the anti-$Q$-slope and the $Q$-slope effects in SRF cavities. Building on earlier qualitative ideas, we consider the coupled dynamics of quasiparticles and phonons in superconducting niobium under RF/microwave fields. We show that, under certain conditions, the quasiparticle energy distribution in niobium can be driven out of thermal equilibrium by high-frequency fields, resulting in a reduction of the surface resistance with increasing field strength, in agreement with experimental observations in bulk niobium cavities properly treated to induce the anti-$Q$-slope effect. At the same time, if the phonon escape lifetime is, for some reason, significantly longer than the phonon pair-breaking lifetime, the previously observed reduction in surface resistance is overturned, resulting in a progressive rise with increasing accelerating field. This implies that, rather than the emergence of the anti-$Q$-slope effect, one observes the manifestation of the $Q$-slope effect. By solving the coupled kinetic equations for quasiparticles and phonons, our model offers new insights into the microscopic mechanisms governing the field dependence of cavity performance and suggests possible routes for further optimization.

The paper is organized as follows. After a brief introduction to nonequilibrium superconductivity—an area that was extensively investigated from the 1960s to the 1980s before research focus shifted to high-temperature superconductors following their discovery in the late 1980s—we present the results of our calculations together with the discussion. Finally, conclusions are drawn.

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# SEMI-AUTOMATIC ROBOT ASSISTED, CLEAN ASSEMBLY OF PIP-II LB650 CAVITY STRING AT CEA

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*Abstract*

Achieving optimal performance in SRF (Superconducting Radio Frequency) cavity assembly relies heavily on precise cleanroom processing, where contamination poses significant risks. Human activities, a major source of particle emissions in cleanrooms, not only threaten cavity cleanliness but also contribute to labor intensity and noise exposure. To mitigate these challenges, recent advancements in robotics offer promising solutions for automating critical steps in cavity assembly. In particular, a collaborative robot (cobot) implemented by CEA introduces automated processes such as coupler to cavity assembly, flange and bellows cleaning, and repetitive handling. The cobot, a FANUC CRX-25 6-axis arm mounted on a support frame, can operate independently and at night, significantly reducing assembly duration while ensuring consistent, reproducible results. By eliminating the need for manual operation in noisy, repetitive tasks, this cobot enhances both efficiency and technician safety, supporting higher cleanroom standards. This paper presents an overview of these automated processes, the cobot's implementation, the cavity RF cold test and the technical decisions shaping future developments in SRF cavity assembly.

## COLLABORATIVE ROBOTICS FOR CLEANROOM ASSEMBLY: ADVANCING ACCELERATOR CAVITY INTEGRATION AT CEA SACLAY

Since 2018, CEA's Laboratory for Integration and Development of Cavities and Cryomodules (LIDC2) has pioneered the integration of collaborative robots (cobots) into cleanroom environments to enhance the assembly and cleaning of superconducting accelerator cavities. This initiative, driven by a strategy of continuous innovation, addresses both technical and ergonomic challenges in the production of high-performance cavity strings for projects such as the European Spallation Source (ESS) and the PIP-II linear accelerator at Fermilab.

### *Initial Deployment: Automating Cleaning Processes*

Following feasibility studies and prototyping in 2020–2021, the robotic cleaning process reached Technology Readiness Level (TRL) 7, with successful demonstration in an ISO 4 cleanroom with a cobot DOOSAN M0617.

The first cobot system, deployed between 2021 and 2022, featured a FANUC CRX10 6-axis arm mounted on a mobile cart, equipped with compressed-air tooling, a 2D vision camera, and a 0.3 µm particle counter. This system was designed to replace manual, physically demanding, and noisy cleaning steps—particularly the blowing of flange and bellows holes—during the assembly of ESS cryomodule cavity strings. By applying identical motions in each cycle, the cobot improved reproducibility and enabled unattended overnight operation, significantly boosting throughput.

From May 2022 to February 2025, the cobot was used in production for cleaning cavity flange holes on 24 ESS cryomodules, delivering measurable gains in productivity and operator comfort (see Fig. 7 in Ref. [1]) The automated process ensured consistent cleanliness levels and reproducible motion sequences, minimizing operator-driven variability and reducing exposure to loud noise and awkward postures [2].

### *Technological Evolution: From Cleaning to Assembly*

The original cobot's 10 kg payload limit restricted its use to flange cleaning, as it could not handle heavier components such as power couplers (∼10 kg with flanges). This limitation, combined with the need for precise calibration and motion planning to accommodate component variation, prompted the laboratory to invest in richer sensing solutions and to upskill internal teams in trajectory planning, vision-based positioning, and tooling design. Notably, the team developed 3D-printed end-effectors and other custom tools in-house, fostering technical autonomy and flexibility.

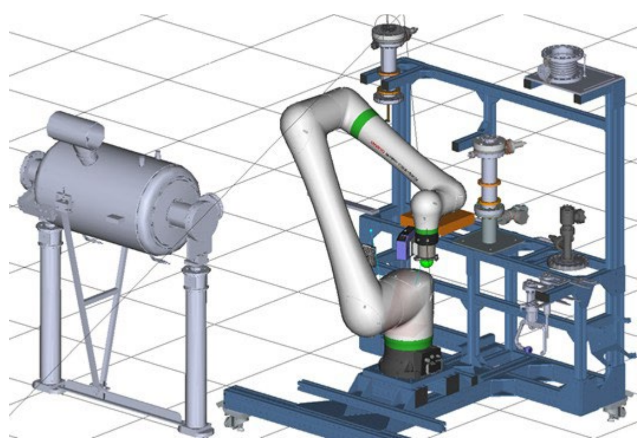

Figure 1: Modeling of the cobot, cavity, and power coupler allows visualization of the processes developed prior to experimentation in real conditions.

In 2024, LIDC2 acquired a new cobot with a 30 kg payload capacity, 3D vision, tool-changing capabilities, and a custom grippers [3, 4]. The overall device was assembled in-house. The programs written in the twin 3D model with cobot, cavity coupler allows visualization of the processes

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# STATUS OF ROBOTICS AND AUTOMATION IN THE SRF COMMUNITY AND REAL APPLICATIONS*

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*Abstract*

The performance of superconducting RF (SRF) cavities is extremely sensitive to contamination by particles on the SRF surface. To mitigate this, high-pressure rinsing (HPR) with ultra-pure water is performed after surface treatment, and cavity assembly is conducted in a cleanroom environment. However, even when cleanroom suits are worn, human involvement in these processes can still introduce particle contamination.

In recent years, significant advancements have been made in the development of work robots across industries such as automotive manufacturing, semiconductor technology, and medical care, leading to increased automation. The SRF community has also embraced this trend. For example, FRIB has implemented robots for HPR, and institutions such as FNAL, KEK, and CEA are exploring robotic solutions for cavity assembly. Looking ahead, the integration of artificial intelligence (AI) is expected to enable cavity assembly that is effectively free from particle contamination while also eliminating the risk of human error. This paper provides an overview of robotic and automated technologies related to superconducting cavities, along with examples of their practical applications.

## MOTIVATION

Recent accelerator projects increasingly employ multiple cavity geometries, including large and complex designs that present significant challenges for cleaning and assembly. The processing and assembly of such cavities within a cleanroom environment constitute a major technical obstacle. Minimizing direct human interaction with critical clean components and cavities provides several benefits, such as reduced particulate contamination, improved repeatability and consistency in assembly processes, decreased reliance on manual labor, shortened production schedules, lower costs, and fewer assembly errors requiring rework. The main objective is the development of contactless technologies that enable particle-free, precise cleaning and assembly of SRF components under cleanroom conditions, while also meeting the scheduling and budgetary constraints characteristic of large-scale production. In response to these requirements, the SRF community is progressively adopting automation to achieve the stringent performance standards demanded by modern accelerator facilities.

## KEYS AREAS OF RESEARCH AND SRF CHALLENGES

Key areas of development within the SRF community toward achieving contactless assembly include the digitalization of components, non-contact measurement of part positions, implementation of computer and camera vision systems, use of collaborative robots (cobots), and industrial robot-assisted positioning and assembly. Additional efforts focus on precision alignment techniques, advanced end-of-arm tooling design, and the deployment of automated guided vehicles (AGVs). Several labs are already combining these technologies to enable automated cleaning and assembly of SRF cavities and components [1].

Cavities are often large and heavy, with complex geometries, multiple ports, and critical flange surfaces that demand careful handling. Fabrication tolerances result in imperfect dimensions, making repeatable tooling setups difficult. Assembly tasks frequently require attention to low-profile flange configurations, gasket and seal retention, and precise alignment of fastener holes. In many cases, specialized tooling is necessary to support cleanroom personnel during assembly. Examples include custom tools for sealing horizontal beamline connections and for the installation of power couplers (Fig. 1).

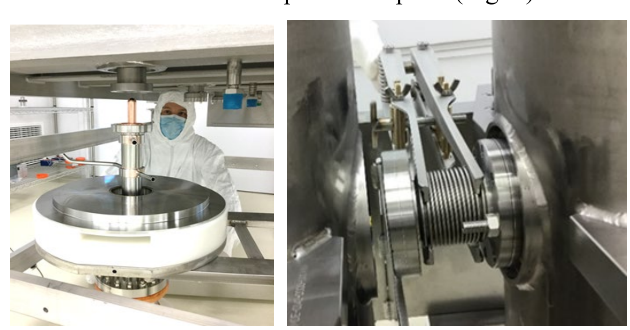

Figure 1: Fundamental power coupler tooling (left) and beamline bellows tooling (right) at FRIB.

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# STATUS OF THE CW SRF GUN DEVELOPMENT AT FRIB FOR LCLS-II-HE*

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*Abstract*

A superconducting radio-frequency photo-injector (SRF-PI) can in principle operate in continuous-wave (CW) mode at high gradients with ultra-high vacuum. Using low mean-transverse-energy photocathodes, SRF-PIs could provide high-brightness, high- repetition-rate beams with long cathode lifetimes. For these reasons, an SRF-PI has been adopted for the proposed Low Emittance Injector (LEI) addition to the SLAC Linac Coherent Light Source II High-Energy (LCLS-II-HE) Upgrade, which would operate in CW with bunch rates of up to 1 MHz. This new injector is a critical part of the effort to extend the photon energy range of this new x-ray laser. A 185.7 MHz quarter-wave gun cavity and cryomodule have been developed by the Facility for Rare Isotope Beam at Michigan State University (FRIB/MSU) in collaboration with HZDR, ANL, and SLAC. A cryomodule test of the first prototype gun cavity and cold tests of a second cavity are underway at FRIB/MSU. The cavities have met the goal of 30 MV/m photocathode field in cold tests in which a photocathode was not installed. All critical cavity parameters fit very well with the simulations and a fully integrated module test with normal conducting cathodes (both metal and semiconductor) are underway.

## LEI OVERVIEW

X-ray free electron lasers (XFELs) are a leading tool in understanding biology, chemistry and materials science on the femtosecond timescale. LCLS-II is one of the premier CW XFELs in the world, and the current upgrade (LCLS-II-HE) will extend its photon energy reach to 13 keV, by doubling the electron beam energy from 4 GeV to 8 GeV. To further improve the machine performance, a new injector (the LEI) is planned, with the goal of reducing the machine emittance to 0.1 µm at 100 pC bunch charge [1]. This will extend the photon energy of the FEL to 20 keV, and significantly improve the x-ray average brightness above 12 keV.

Central to realizing this performance increase is the SRF-PI [2]. The SRF gun will roughly double (to 30 MV/m) the electric field on the cathode compared to the existing LCLS-II injector. Furthermore, the gun vacuum will be significantly improved, which is expected to increase photocathode longevity and enable the use of green-light sensitive photocathodes (alkali antimonides). This will both reduce operational complexity and further improve the beam emittance compared to the UV illuminated $Cs_2Te$ cathodes currently in use. This paper details the testing of two gun cavities that are intended to prove the feasibility of the SRF-PI for the LEI. The first is a "blank" cavity without a cathode port; the second is the full prototype cavity with a cathode insertion capability.

## CAVITY AND CRYOMODULE DESIGN

The SRF gun cavity is a 185.7 MHz quarter-wave resonator (QWR) designed to provide an acceleration field of 30 MV/m on the photocathode [3]. As shown in Fig. 1, the cavity geometry incorporates four ports to enable electropolishing and high-pressure rinsing during fabrication and assembly, and that also serve as interfaces for the fundamental power coupler (FPC), RF pickup, and vacuum pumping during operation. The FPC is based on the ANL 162.5 MHz design used for PIP-II HWR cavities, modified for the QWR geometry and equipped with a DC bias to suppress multipacting in the coupler.

The cryomodule integrates the SRF gun cavity with a superconducting magnet package for emittance compensation (Fig. 2). In addition to the main solenoid doublet, the package incorporates horizontal and vertical dipoles and normal/skew quadrupoles, all wound from NbTi wire and operated in a 4 K liquid-helium environment [4]. These auxiliary corrector coils can be used to correct for field nonuniformity and compensate for misalignments, providing flexible tuning of the emittance-compensation optics. The cavity is further equipped with slow and fast tuners for resonance control and includes provisions for a cathode stalk to support/cool the cathode

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# COLD INTEGRATION OF THE DESY CW L-BAND SRF INJECTOR CAVITY WITH COPPER PHOTOCATHODE*

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*Abstract*

A future upgrade of the European XFEL foresees High-Duty-Cycle (HDC) operation which requires a new electron beam injector. The centerpiece of such a photoinjector is a continuous wave (CW) L-band superconducting radio frequency (SRF) cavity developed at DESY. This cavity demonstrated world record peak axial electric field values of up to 50 MV/m with a copper (Cu) cathode, thread mounted to the cavity backwall. In this contribution, we report on the present status of the cavity design, describe the cold integration of the cavity including the cryostat, tuner and solenoid magnet, and show the plans for a test facility being built to verify the beam quality produced by this SRF injector.

## INTRODUCTION

High gradient photoinjector cavities enable direct electron beam matching into the first SRF L-band accelerating module of light sources like European XFEL and FLASH [1]. Presently, normal conducting (NC) L-band RF injector cavities developed at PITZ are in operation at the European XFEL and FLASH following this scheme. Sufficient cooling of these cavities is only possible at pulsed RF operation. L-band SRF injector technology has the potential of similar high gradients operating CW. It is foreseen for the HDC upgrade of the European XFEL [2, 3], the basic parameters are listed in Table 1.

SRF injector cavities with load lock systems for in situ cathode exchange need to cope with contamination of the cathode channel and the cavity when changing cathodes. The peak on axis gradients of these SRF injector cavities are (still) significantly lower than needed for the European XFEL. An overview on the worldwide SRF injector developments may be found in [4]. Contamination can be avoided by thread-mounting a cathode directly to the cavity backwall [5, 6] in a clean room and performing ultra-pure high-pressure water rinsing (HPR) afterwards. With this setup, the cavity and cathode are both cooled by liquid helium. The SRF injector cavities under development at DESY follow these ideas and demonstrated world record peak field on axis values of up to 50 MV/m with copper cathodes mounted to the cavity backwall. As a disadvantage, only cathodes can be used which are robust against the exposure to air and HPR. Copper cathodes showed a sufficiently high quantum efficiency (QE) at NC injectors at SLAC and SwissFEL [7, 8]. Together with partners, DESY performs R&D on copper cathodes for an SRF injector [9].

The next step is demonstrating electron beam production with this type of SRF cavity and injector. The cryostat and all other cold parts around the cavity are components requiring new designs and constructions. Special requirements are a reasonable distance between the cathode laser mirror and cathode, a superconducting solenoid magnet directly at the SRF cavity exit for beam focusing and the ability to align the cavity and solenoid magnet at cold to optimize the beam properties. About three years ago, first general requirements and concepts on the alignment as well as the assembly of the cold string in the clean room, the module assembly and the connection of the module to a subsequent beam line were elaborated. This includes both the assembly at a test stand as well as the installation in a XFEL injector tunnel in the medium future.

## SRF PERFORMANCE OF THE CAVITIES

The performance of SRF cavities depends extremely on the material and surface properties. Accelerating cavities have relatively large beam ports on both sides which can be used for the surface treatment processes. In contrast, SRF

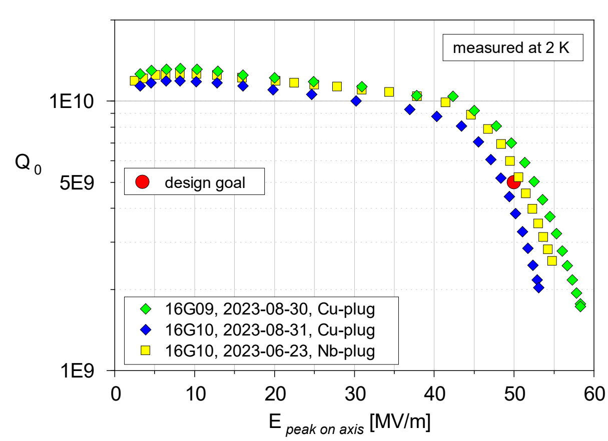


Figure 1: Successful vertical test results of the SRF gun cavities 16G09 and 16G10 with copper cathode plugs and the first test of 16G10 with niobium cathode plug for comparison.

* Work performed in the framework of R&D for future High Duty Cycle (HDC) operation of the European XFEL and financed by the European XFEL GmbH.

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# FIRST BEAM COMMISSIONING OF THE bERLinPro SUPERCONDUCTING RADIO-FREQUENCY (SRF) PHOTOELECTRON GUN*

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*Abstract*

After about a decade of research, development and construction work, the bERLinPro Energy Recovery Linac project at HZB changed over into the commissioning phase and started the operation of the SRF photo-injector with the injection line of the accelerator. This system had already produced beam from a metal photo-cathode in 2018 in a dedicated test environment and was assembled in the accelerator hall after a required refurbishment and repair program. The 1.3 GHz SRF gun successfully generated first photoemission beam from a high quantum efficiency (QE) Na-based multi-alkali photocathode. In this contribution, the results of the first two measurement campaigns will be shown, including a review of the SRF design, the RF commissioning, the cavity performance, especially with respect to dark current, the cathode quantum efficiency and lifetime, as well as the measured beam parameters.

## INTRODUCTION

The SRF cavity based photo-injector [1] at bERLinPro [2] was initially designed to deliver a high power beam of about 2.5 MeV with an average current of 100 mA delivered in bunches of 77 pC filling every RF bucket at 1.3 GHz. This beam would have been transported and further accelerated by the booster module [3] to the injection energy of 6.5 MeV into the recirculator of the single loop high intensity Energy Recovery Linac (ERL). As a design and manufacture of such an high power system was regarded too risky, the injector was developed in several stages, whereas the first prototype featuring an high quantum efficiency photo-cathode in the green wavelength regime was designed to allow a maximum beam current of 5 mA, here limited by the power couplers. Table 1 gives an overview about the original design parameters and the potential performance of the current setup given the prototype SRF gun cavity and the 50 MHz photo-cathode laser for commissioning. An initially successful beam operation with a Cu photo-cathode with a dedicated beamline in a testbunker [4, 5] led finally to a failure of the transfer system with the Cs-K-Sb coated plug in 2018. A repair and refurbishment program was initiated [6], as the replacement cavity experienced a severe damage of the half-cell backwall during HPR assembly at the manufacturer. Following delays by the pandemic in 2020 to 2022, a large cyber-attack on HZB in 2023, shifted the completion of the injector assembly in the bERLinPro accelerator hall towards 2024 with first cooldown and RF operation. This was followed by a first beam trial in December 2024, which caused a failure of a power coupler's warm window, requiring replacement. Finally, first beam was achieved 28$^{th}$ of March 2025, with the first beam time ranging up to beginning of May, followed by a short beam time in July that year. Here, a power outage necessitated an early warm-up of the cryo-module and ended the experiments.

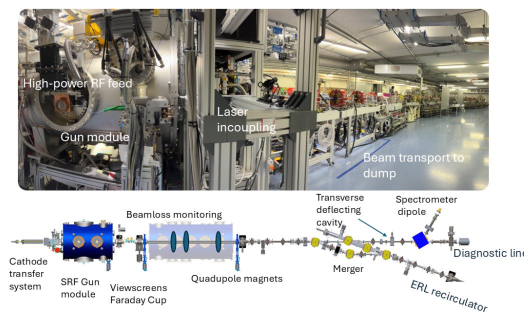


Figure 1: Picture and schematics of the bERLinPro injector. The Booster is here still replaced by quadrupole magnets.

Due to a redirection of HZB's research focus on 4$^{th}$ generation light sources by storage rings, the original goal of an high current ERL got out of reach and the whole bERLinPro facility became an application based accelerator laboratory under the new name SEALAB [7]. Still, ERL related research is as of submission of this manuscript part of SEALAB under the label bERLinPro, e.g. in the framework of the European Particle Accelerator Roadmap for High Energy Physics [8].

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# PROGRESS OF ASSEMBLY AND INSTALLATION OF LIPAc SRF CRYOMODULE UNDER THE EU–JA COLLABORATIVE FRAMEWORK

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*Abstract*

Commissioning of Linear IFMIF Prototype Accelerator (LIPAc) is ongoing for the engineering validation of the high intensity deuteron beam accelerator system. The prototype Superconducting Radio-Frequency linac (SRF) cryomodule has been manufactured, and will be assembled and tested on the LIPAc. During the assembly of the cryomodule, several non-conformities were identified, including vacuum leaks and issues with cryogenic piping. These challenges were resolved through a coordinated effort involving Japanese and European collaborators. The solutions included refabrication and repair of critical components in Japan, in compliance with Japan's High Pressure Gas Safety Act and relevant international standards. Jointly implemented measures encompassed material selection, thermal cycling treatments, magnetization assessments, and regulated welding with non-destructive testing. This paper presents the technical approach taken, highlights the collective efforts of the LIPAc team in overcoming the issues, and reports on progress toward the successful assembly and validation of the LIPAc SRF cryomodule.

## INTRODUCTION

The International Fusion Materials Irradiation Facility (IFMIF) is an accelerator driven neutron source based on deuteron-lithium nuclear reactions, designed to generate high-intensity, high-energy neutrons for the testing of structural materials used in nuclear fusion power reactors [1]. One of the key technological challenges of the IFMIF accelerator is the handling of a 125 mA deuteron beam operated in Continuous Wave (CW) mode. Several SRF cryomodules are required for IFMIF to accelerate deuterons from 5 MeV to 40 MeV. In the EVEDA phase, the validation of the low energy section of the IFMIF accelerator up to 9 MeV is a prerequisite. The construction and commissioning of the Linear IFMIF Prototype Accelerator (LIPAc) is being conducted at Rokkasho Fusion Energy Institute of QST, Japan in collaboration with EU. The LIPAc consists of the injector with ECR ion source and Low Energy Beam Transport (LEBT), Radio-Frequency Quadrupole accelerator (RFQ), Medium Energy Beam Transport (MEBT), one Superconducting Radio-Frequency Linac (SRF) cryomodule, High Energy Beam Transport (HEBT) and Beam Dump (BD) as shown in Figure 1. The first of cryomodule is being assembled and will be installed and tested [2]. In 2019, the deuteron beam operation test of RFQ for 125 mA / 5 MeV at low duty cycle was successfully completed. Following this, the MEBT Extension Line (MEL) was installed in place of the SRF Linac to enable high duty cycle beam operation of the RFQ and facilitate the commissioning of the HEBT and BD. In 2024, the high duty beam operation test of the RFQ and newly installed components was successfully completed [3].

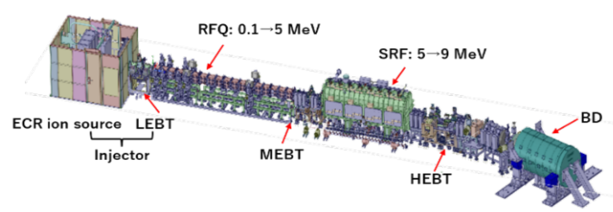


Figure 1: The schematic of the LIPAc.

As shown in Figure 2, the LIPAc SRF cryomodule consists of 8 superconducting Half Wave Resonator (HWR) cavities operating at 4.45 K and 175 MHz, along with RF power couplers and 8 superconducting solenoid coil packages. These components are periodically arranged within the cryostat, accompanied by cryogenic piping, a thermal shield, and a magnetic shield. Table 1 shows the main specification of the LIPAc SRF cryomodule [4]. The string assembly of the cryomodule began at QST, Rokkasho in 2019 and was completed in 2025, after which the unit was transported to the accelerator vault. Installation to the beamline is ongoing [5, 6].

During the assembly, several nonconformities were identified, including vacuum leaks of solenoid coil packages and vacuum manifold of the beam line. Additionally, cryogenic pipe issues were confirmed in the solenoid tank and RF power coupler. Some components were severely damaged and difficult to repair. As a result, the assembly of the cryomodule was delayed due to the

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# THE OPERATION OF ARIEL e-LINAC RF SYSTEM*

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*Abstract*

The 30 MeV section of the Advanced Rare Isotope Laboratory (ARIEL) electron linear accelerator (e-Linac), a 1.3 GHz superconducting SRF system, currently includes the injector cryomodule (EINJ), housing a single nine-cell cavity, and the first accelerator cryomodule (EACA), configured with two cavities. This paper reports recent progress of high-power RF system operation. In 2025, the system achieved stable continuous operation for three consecutive days with a 30 MeV, 1 mA beam, reaching a reliability of approximately 97.9%. EACA, operating in vector sum mode, has demonstrated stable operation for up to eight days.

## INTRODUCTION

ARIEL e-Linac is a continuous-wave (CW) superconducting electron linear accelerator (see Fig. 1). The 'Demonstrator' phase of ARIEL was installed for initial technical and beam tests with successful beam acceleration to 22 MeV [1]. The EACA cryomodule, initially installed with one cavity, was then updated to 2 cavities [2] driven by a single klystron in vector sum. 30 MeV beam has been achieved after EACA which energy gain is about 20.6 MeV [3, 4].

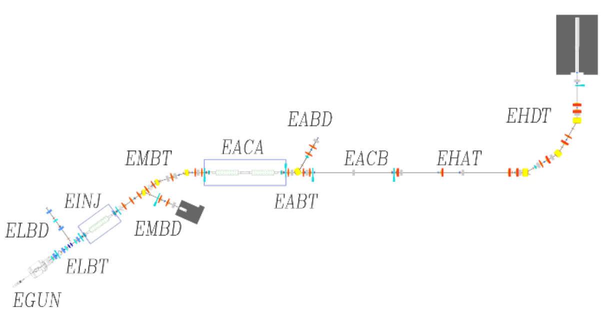


Figure 1: Layout of ARIEL e-Linac 30 MeV section with EINJ and EACA.

In 2021, 10 kW beam operation had been achieved with a 500 µA beam, using an Iterative Learning Controller (ILC) for beam loading compensation [5]. And in 2023 upgraded the E-gun RF tuner [6]. At the beginning of 2024, we successfully maintained three days of continuous operation with 500 µA beam current [6]. To improve beam current stability due to temperature fluctuations, we implemented a PID loop for current regulation using the Alternating Current Transformer (ACCT) signal as feedback [6]. To improve the stability of the e-gun and reduce the impact of temperature fluctuations on beam current [6], the e-gun amplifier was upgraded to a water-cooled version. In 2025, the system achieved stable continuous operation for three consecutive days with a 30 MeV, 1 mA beam, reaching a reliability of approximately 97.9%. EACA, operating in vector sum mode, has demonstrated stable operation for up to eight days.

## TEST PROGRESS

### *Continually Beam Delivery Test in 2024*

To further validate the system's operability and identify potential issues, a continuous beam delivery experiment was conducted at beginning of 2024. During this experiment, the RF system operated stably for five days as shown in Fig. 2. The primary cause of beam trips was EINJ RF flickers which were later confirmed to be due to a bug in the LLRF system. This issue accounted for most of the total downtime, which amounted to 12 hours.

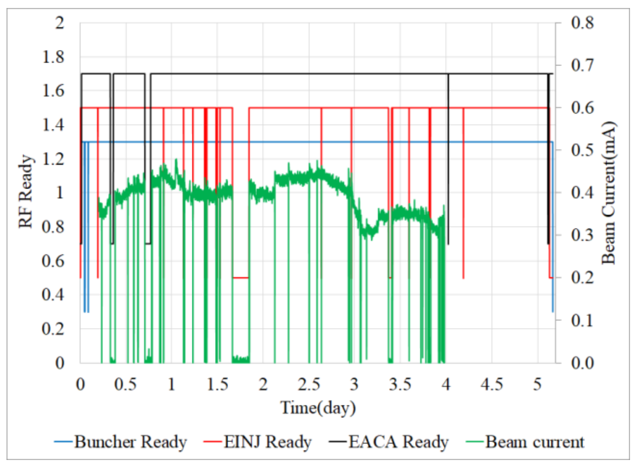


Figure 2: RF cavities status and beam current.

During the test, the beam current fluctuated between 290-480 µA, due to temperature changes in the e-gun RF rack. The e-gun RF system lacked feedback control, making it unable to regulate the output current effectively. This issue was eventually resolved by adding a PID loop, as described in the next section. The EINJ RF flicker problem was addressed through modifications to the LLRF code. The LLRF racks does not have a proper temperature control, resulting in environment temperature instability affecting the stability of the beam energy and result in beam trips.

### *E-gun RF Update*

The performance of the E-gun is significantly affected by external temperatures, especially the temperature of the RF amplifier rack, which can impact the amplifier's performance and, consequently, the E-gun output current strength. To address this, a PID feedback loop based on ACCT signals was designed and tested. The ACCT readings are used

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# Q DEGRADATION IN OPERATION IN ISAC-II SC LINAC*

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*Abstract*

Quality factor (Q) of superconducting RF (SRF) cavities is one of the essential figures of merit in the continuous wave (CW) mode accelerator operation. Q degradation has been observed in the operation of ISAC-II superconducting heavy ion linac. Other than the well-known mechanisms, such as field emission (FE) and the trapped magnetic flux, the operation data reveals that gas molecules in the beam line caused measurable Q drops after a few months' operation. This paper will discuss the observations in ISAC-II linac, propose the hypothesis based on the dielectric loss mechanism, and verify the predication model with a relative demonstration test.

## INTRODUCTION

The Isotope Separator and ACcelerator (ISAC) at TRIUMF uses the Isotope Separation On-Line (ISOL) technique to produce rare-isotope beams (RIB) for studies in astrophysics, nuclear structure and reactions, electroweak interactions and material science [1]. ISAC-II is the high energy section of ISAC. It consists of an S-bend beamline, a superconducting (SC) heavy ion linac and high energy experimental stations. The SC linac accepts RIBs produced in the ISAC target and accelerated by a normal conducting linac in ISAC-I to the beam energy of 1.5 MeV/u and A/q up to 6. The ISAC-II linac provides 40 MV accelerating voltage and boosts the beam energy to 16.5 MeV/u for A/q = 2 and 6.5 MeV/u for A/q = 6 ions.

ISAC-II linac was designed in the early 2000s and commissioned for operation in 2 stages in 2006 and 2010. A SC quarter-wave resonator (QWR) was chosen for the low velocity beam. 40 QWRs are housed in 8 cryomodules (CM). Cavities are designed to two different frequency and three different geometries to accommodate beam velocities from 5.7% to 18.6% of the speed of the light. For 8 low beta and 12 medium beta 106 MHz cavities, each CM consists of 4 cavities. For 20 high beta 141 MHz cavities, there are two CMs with 6 cavities and one CM with 8 cavities. Each CM has a 9 T SC solenoid in the centre. In each CM, cavities are evenly distributed both upstream and downstream to the solenoid. Each cavity operates at 4.5 K and is specified to run in CW mode at the accelerating gradient of 6 MV/m and to provide 1 MV accelerating voltage. The dynamic heat load of each cavity is less than 7 W to satisfy the cryogenics system. The RF power in operation is less than 200 W to provide enough bandwidth for low-level RF (LLRF). Each cavity is equipped with a variable coupler with the adjustment range of $Q_{ext}$ from $10^4$ to $10^9$ to cover the operating, conditioning and performance measurement regimes. In addition, the ISAC-II CM uses a single vacuum design, in which the beam/RF space and the thermal isolation space share the same vacuum. In between CMs, there is a warm section, including beamline, steering magnet and diagnostic box at room temperature.

A typical operation schedule has the ISAC-II linac cooled down to 4.5 K in April and running until December. The cryogenic system is shut down at the end of December and the SC linac is warmed up to the room temperature for a three-month maintenance period. There is a full thermal cycle in the ISAC-II linac every year.

## OBSERVATIONS IN ISAC-II

A common observation is that the ISAC-II cavities experience Q degradations after a few months' operation. The degradations have been assumed to be from trapped flux from the SC solenoids occurring during cavity quenches. A few cases have been studied, and a series of quench tests have been performed to demonstrate the hypothesis, which were discussed in previous reports [2-4]. However, there was no clear evidence of cavity quenches for each degraded cavity in operation and so this issue has remained a mystery for years. In addition, the cavities closer to the solenoid should experience more severe degradations according to the mechanism. But the operation data does not support this inference. Another hypothesis was needed to fully explain Q drops experienced during ISAC-II operation.

Regular Q curve measurements were added to the yearly start-up cycle in 2017. This provides the possibility to compare cavity performance and to investigate cavity degradation over time. However, the measurements are not systematically repeated throughout the year. The measurement may be repeated on a single cavity or CM in the event of an isolated anomalous observation. In the present study104 data points collected over the past 8 years are analysed. Each valid data point consists of at least two Q curves separated by a period of operation in a single cooldown. The surface resistance $R_s$ is calculated from the measured $Q_0$ and the cavity geometry factor, G. Q degradation causes the increase of $R_s$ compared to the measurement taken during start-up. The change of $R_s$, $\Delta R_s$, gives the severity of the degradation. A histogram of the number of cavities with a particular $\Delta R_s$ range is shown with the black curve in Fig. 1. The bin size of the histogram is 2 nΩ. The mode of the statistics is ~ 0, which demonstrates that the cavity Q is stable for most cavities after a period of operation. The negative $\Delta R_s$ is considered as a result of the measurement uncertainty. As a contrast, some cavities have obvious Q degradations with over +10 nΩ resistance increase, and the worst case is a +50 nΩ increase.

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# MAGNETIC FIELD SENSITIVITY OF A QWR UNDER DIFFERENT COOLDOWN DYNAMICS

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*Abstract*

The sensitivity of the surface resistance of SRF cavities depends on several aspects, such as the specific surface and heat treatment of the cavity. The the cooldown dynamics as the cavity transitions into the superconducting (sc) state also influence the performance if there is an external magnetic field. Both temperature gradient across the cavity and speed of the superconducting front have been shown to be impacting the performance. But also the direction of movement of the superconducting front impacts the performance as magnetic fields are pushed by the superconducting front. Quarterwave resonators (QWR) have a complex geometry with their closed inner conductor. Depending on the cooldown dynamics, the magnetic flux could be pushed to either the tip of the inner conductor with low rf surface currents, or to the short plate of the cavity with high rf surface currents. In previous measurements of the TRIUMF multimode QWR the SC front moves from outer conductor to the inner conductor. In the presented paper, the direction has been reversed to show the effects of the direction of movement of the sc front on the cavity performance.

## INTRODUCTION

The performance superconducting radio-frequency (SRF) cavities has been shown to be sensitive to the external magnetic fields. During the transition into the superconducting state magnetic vertices are trapped and cause additional rf losses due to the normal conducting core of these vertices. This is represented by an additional temperature independent surface resistance $R_{\text{mag}}$. It has been shown that the strength of $R_{\text{mag}}$ depends on the surface treatment of the niobium [1], the direction of the external field, the cooldown speed, and the geometry of the cavity [2–4].

In this paper, we explore effect of the cooldown direction in the TRIUMF multi-mode QWR [5], shown in crossection in Fig. 1, using resonant modes at 220 and 650 MHz. Typically this cavity is cooled ‘outside-in’, meaning liquid helium (LHe) is transferred into the bottom of the cryostat holding the cavity, cooling down the bottom of the cavity first. The superconducting front moves up the outer conductor, then across the short plate at the top of the cavity. Finally the inner conductor of the cavity is conductively cooled below $T_c$ from the top to bottom. Magnetic flux is pushed first to the top of the cavity, then down to the tip of the inner conductor [4].

Here we test if cooling down the inner conductor first changes the response to an applied external magnetic field.

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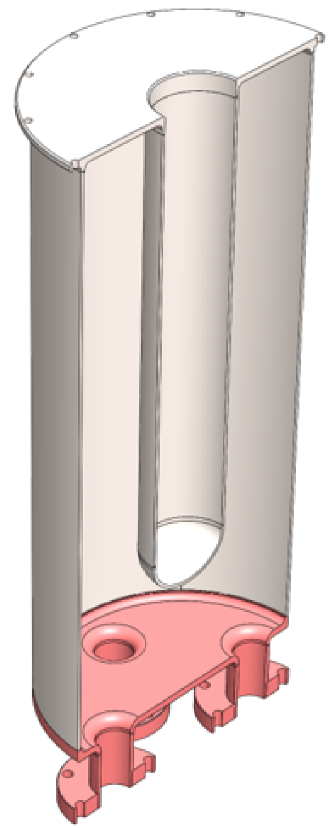

Figure 1: Crossectional view of the multimode QWR. RF ports and vacuum ports are at the bottom of the cavity. This cavity does not have a LHe jacket or beam ports and needs to be put into a bath cryostat. The cavity is about 40 cm in height and its fundamental mode resonantes at 220 MHz.

In this method, flux should be expelled from the inner conductor first, then pushed outwards away from the cavity without trapping inside the niobium.

## SETUP

To accomplish the inverted cooldown dynamics, the helium transfer line is modified to direct the helium flow into the inner conductor, as shown in Fig. 2. A second branch of the transfer line is T-ed off for LHe flow to the bottom of the cryostat to allow a reasonable fill time. The main flow of helium will be into the inner conductor due to the flow inertia. Figure 3 shows temperature sensors at the top and bottom of the cavity during the two cooldown schemes, showing that indeed the inner conductor cools down first in the modified cooldown. Additional temperature sensors were installed in the inner conductor to further show the desired cooldown dynamics. Cooldown speeds $dT/dt$ through the SC transition for the IC first cooldowns were between

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# UNVEILING THE INTERPLAY: COLD WORK, RECRYSTALLIZATION, AND FLUX EXPULSION IN SRF CAVITIES*

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*Abstract*

The fabrication of SRF cavities from sheet materials includes deep-drawing, electron beam welding, chemical and mechanical polishing, high-temperature heat treatment, and material diffusion. The performance of these cavities is frequently limited by magnetic flux trapping giving rise to additional rf loss. In this presentation, we thoroughly examine how recrystallization influences flux expulsion in SRF cavities, using cold-worked niobium sheets from various suppliers. Our findings reveal that cold-worked sheets enhance flux expulsion, especially at lower heat treatment temperatures, by promoting improved recrystallization. In particular, a traditionally fabricated Nb cavity half-cell from an annealed poly-crystalline Nb sheet after an 800 °C heat treatment leads to a bi-modal microstructure that ties in with flux trapping and inefficient flux expulsion. This non-uniform microstructure is related to varying strain profiles along the cavity shape. A novel approach to prevent this non-uniform microstructure is presented by fabricating a 1.3 GHz single cell Nb cavities with a cold-worked sheet and subsequent heat treatment leading to better flux expulsion after 800 °C/3 h.

## INTRODUCTION

Niobium has long been the preferred material for superconducting radio frequency (SRF) cavities, primarily due to its low power loss at the cavity's inner wall and its high ductility, which facilitates the fabrication of complex structures [1]. As an elemental superconductor, niobium has the highest critical temperature ($T_c$ ~ 9.25 K) and the highest critical magnetic field ($H_c$ ~ 200 mT). The performance of these cavities is often quantified using the quality factor ($Q_0$), which is the ratio of the stored energy inside the cavity to the energy dissipated through the inner wall during one RF cycle, as a function of the accelerating gradient ($E_{acc}$).

One of the main factors that degrade the quality factor in SRF cavities is ambient magnetic flux trapping during cooldown. The trapped flux, in the form of vortices, oscillates under the RF field and dissipates energy. The field dependence of RF losses due to trapped vortices is significantly stronger than that of the ohmic-type losses [2]. These flux trapping and RF loss sensitivities are influenced by both extrinsic and intrinsic factors. Flux trapping primarily occurs at material defects, dislocations, impurities, and normal conducting precipitates. For example, during cooldown, flux expulsion can be maximized by generating a large thermal gradient across the cavity surface during the transition from the normal conducting to the superconducting state [3].

On the intrinsic side, flux trapping can be minimized by reducing defects, dislocations, and impurities through various heat treatments, followed by chemical polishing and a high pressure rinse with deionized water. Research has shown that different pinning mechanisms contribute to RF losses due to vortex motion [4]. Moreover, doped cavities are more prone to vortex-induced dissipation due to the presence of dopants on the RF surface [5–8]. Increasing the annealing temperature has been shown to enhance flux expulsion by minimizing pinning centers—removing clusters of dislocations and impurities. Higher annealing temperatures also result in a larger grain size, which affects the cavity's microstructure [9]. For instance, fine-grained, recrystallized microstructures with average grain sizes between 10–50 µm can still lead to flux trapping, even in the absence of dislocation structures within the grains [10]. Thus, careful consideration of niobium's crystallographic structure is crucial both before fabrication and during cavity processing [11].

In this study, we fabricated several single-cell cavities, one from cavity-grade SRF niobium with a grain size specified as ASTM 4-6, and four from cold-worked niobium sheet from different vendors with no specified grain size. All cavities underwent internal surface electropolishing, followed by annealing treatments at 800 °C for 3 hours each. The flux expulsion ratio, flux trapping sensitivity, and $Q_0(B_p)$ at 2.0 K were measured. Furthermore, sample coupons cut out from the sheets and cavity half-cells were analyzed using an electron back-scatter detector (EBSD) to understand the effect of high temperature heat treatments on the microstructure.

## FABRICATION AND SURFACE PREPARATION

Several 1.3 GHz TESLA shaped single cell cavities were fabricated using Nb sheet supplied with different levels of cold work. The standard fabrication process involves deep-

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# DEVELOPMENT OF NIOBIUM 3 GHz SINGLE-CELL CAVITY FOR SUPERCONDUCTING THIN FILM RESEARCH

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*Abstract*

We are developing a compact 3 GHz single-cell elliptical shaped pure bulk niobium radio-frequency cavity to verify the enhancement of the maximum accelerating gradient of superconducting cavities achieved by superconductor-insulator-superconductor structures. As a preliminary step, we established a standard surface treatment process for 3 GHz niobium cavity and measured its cavity performance by a vertical test measurement at 2 K. In the vertical test, an acceleration gradient of up to 22 MV/m was achieved, and the measured $Q_0$ value was approximately 2 x $10^9$.

## INTRODUCTION

Superconductor-Insulator-Superconductor (S'IS) structures is a promising technology for enhancement of the maximum accelerating gradient, Eacc,max, of a superconducting radio-frequency (SRF) cavity. Eacc,max is limited by the effective Hc1 ($H_{c1,eff}$) at which vortex avalanche occurs on the superconducting surface of a SRF cavity. Theoretical studies suggest that S'IS structure at the optimum thicknesses of a top superconducting layer and an insulating layer, typically stacked at appropriate 10-100 nm thicknesses, can realizes significant enhancement of $H_{c1,eff}$. In particular, theoretical calculation predicts that Eacc,max of an elliptical shaped Nb SRF cavity with Nb3Sn-I-Nb structure can reach ~100 MV/m [1].

To experimentally verify these theoretical predictions, it is necessary to construct a superconducting thin-film structure inside a cavity resonator and measure its characteristics in response to RF electromagnetic field. For thin-film deposition methods, we need to control thickness at the nanometer scale. DC-magnetron sputtering [2] and atomic layer deposition [3] are candidates for film-formation techniques of S'IS structure. For any deposition method, we need optimization research to fabricate a reliable S'IS structure on the inner surface of elliptical shape SRF cavities. Therefore, we are developing a compact 3 GHz single-cell elliptical cavity that reduces preparation costs and time compared to 1.3 GHz cavity, enabling a faster progress in optimization research. The 3 GHz cavity has an equator diameter of approximately 9 cm and a cell length of approximately 5 cm, which is smaller and easier to handle compared to the commonly used 1.3 GHz cavities.

This paper describes the surface treatment process for a 3 GHz single-cell elliptical niobium cavity required prior to the film deposition process, and vertical tests to evaluate its performance as a baseline.

## 3 GHz SINGLE-CELL CAVITY

The design and fabrication of the 3 GHz single-cell cavity was advanced through joint research between Jefferson Lab and KEK [4]. Development of the 3 GHz cavity began with copper cavities featuring stainless steel flanges and niobium cavities featuring niobium-titanium flanges. We developed a new niobium cavity with low-RRR niobium flanges to prevent contamination from the flange material during the annealing process required for synthesizing Nb3Sn (Fig. 1). Since niobium flanges are soft and conventional vacuum seals cannot be used, a newly developed pure aluminum hexagon seal was adopted as the vacuum sealing material. In the following sections, we describe the surface treatment and the vertical test result of a 3 GHz cavity with niobium flanges.

Figure 1: Developed 3 GHz single-cell cavities; left: cavity with low-RRR flange, right: cavity with NbTi flange.

## SURFACE TREATMENT

The following treatment including BCP (Buffered Chemical Polishing) and EP (Electro-Polishing) was applied to the 3 GHz niobium cavity.

- BCP (30 μm)
- EP1 (100 μm, < 50 °C)
- Annealing (900 °C, 3 hours)
- EP2 (30 μm, < 20 °C)
- High-pressure rinse
- Assembly in clean room

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# RaSTA 2.0 – DEVELOPMENT OF A COMPACT SAMPLE TEST CAVITY FOR SURFACE RESISTANCE MEASUREMENTS

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*Abstract*

RaSTA, the Rapid Superconductor Test Apparatus, is a sample test cavity project at HZB. It shares the sample geometry and the calorimetric measurement principle with the QPR but is targeted at quicker turnaround times and a more compact footprint at higher operating frequency. RaSTA 2.0 features a niobium coated copper cavity allowing for higher RF field levels and better thermal stability. The outer dimensions have been reduced to fit the system inside a compact cryostat; sample handling and tooling have been revised for reduced overall complexity. RaSTA can be operated without radiation shielding and the entire system is intended to be transferable to labs without extensive SRF infrastructure. We present the design and construction of RaSTA 2.0 together with operating considerations and first data obtained with the new cavity.

## INTRODUCTION AND BACKGROUND

The Quadrupole Resonator (QPR) is a well-established tool for surface resistance ($R_S$) measurements of superconducting materials, particularly in the context of SRF thin films [1]. However, QPR experiments are time-consuming and require a cryogenic and RF infrastructure very similar to vertical tests of single-cell cavities. For SRF material R&D, especially the optimization of thin-film coatings, the number of samples to be tested quickly exceeds the available test slots. Hence, a tool for pre-selection of samples is desired, that ideally even provides enough accuracy for certain applications.

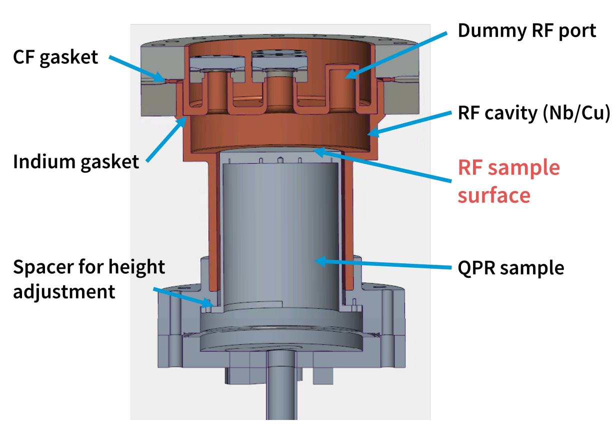


Figure 1: Schematic of the RaSTA 2.0 cavity design. Highlights of the new design are: Dummy RF ports for field symmetry, the separated sealing concept with indium wire and CF gasket, spacers for sample height adjustment.

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To meet this need, the Rapid Superconductor Test Apparatus (RaSTA) was developed [2]. The guiding principle of RaSTA is to retain the QPR sample geometry and the successful calorimetric measurement concept with direct access to $R_S$ vs. $T$ data while making the setup very compact. Most of the complexity and time requirement of QPR tests is closely related to the experimental infrastructure, such as the cryogenic plant operating the LHe bath cryostat and radiation safety measures that are needed for measurements at high RF field levels. In order to fit RaSTA into a small and manually operated LHe cryostat without radiation shielding, its outer diameter is limited to below 200 mm. Furthermore, the RF input power is restricted such, that any occurring radiation is shielded by the cavity itself. This allows for an RF field on the sample surface of up to about 13 mT.

The first version of RaSTA validated the concept of using the QPR sample geometry in a compact pillbox-like host cavity at 4.8 GHz. Its RF performance was limited by thermal quenches of the host cavity at field levels of about 5 mT, due to the construction using stainless steel flanges with a niobium coating together with copper gaskets. Building on this experience, RaSTA 2.0 was designed to address the limitations of RaSTA 1.0 and to improve the usability.

## DESIGN CONSIDERATIONS

A cross section of RaSTA 2.0 is shown in Fig. 1. In terms of the mechanical construction, the design of RaSTA 2.0 was revised in three major aspects:

### *Improved Cooling of RF Surfaces for a Higher RF Field Limit*

The host cavity now uses a bulk copper substrate with reduced thickness, which enhances the thermal conductivity and improves cooling of the RF surfaces. As before, the cavity is demountable to allow the inside to be coated. The sealing concept has been redesigned so that the RF contact between the two cavity parts is ensured with segmented indium wires. At LHe bath temperatures below 3.4 K this results in a fully superconducting Nb/Cu cavity. As before, the high-quality Nb coating is produced at the University of Siegen using HiPIMS with a target thickness of 20 .. 22 µm. The vacuum seal – also to the superfluid LHe bath – is realized with a standard conflat Cu gasket.

### *Reduced Parasitic Losses and RF Field Asymmetry*

Another major aspect of the redesign was the reduction of parasitic losses and RF field asymmetries. These improvements were achieved by introducing dummy RF ports to suppress unwanted dipole components and by implementing

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# STUDY OF MULTILAYER THIN-FILM STRUCTURES IN SUPERCONDUCTING ACCELERATION CAVITIES*

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*Abstract*

We performed a sputtering simulation to design a specialized cathode capable of fabricating Nb-Sn mixed thin-film with Nb:Sn ratio of 3:1, required for $Nb_3Sn$ film formation, on the inner surface of a 3 GHz elliptical superconducting radio-frequency cavity. We successfully simulated DC magnetron sputtering phenomena assuming a rod-shaped cathode made of Nb or Sn, the geometry of film-formation apparatus for 3 GHz cavity at KEK, and realistic film-formation conditions, such as cathode bias voltage of -330 V and Ar gas pressure of 0.8 Pa. In addition, we evaluated the ratio of fluxes emitted from a rod-shaped cathode made of only Nb to that of only Sn at the inner surface of 3 GHz cavity. As a result, Nb-Sn mixed cathode with the target composition ratio of Nb:Sn = 9:1 is required for $Nb_3Sn$ synthesis inside of 3 GHz cavity. Furthermore, we conducted 63 film-formation tests on flat silicon substrates for synthesizing $Nb_3Sn$ films for synthesis of $Nb_3Sn$-I-Nb structures. Finally, we obtained the flux values with consistency, allowing us to identify the good candidates for film-formation condition to synthesize $Nb_3Sn$ films.

## INTRODUCTION

Currently, the maximum accelerating gradient $E_{acc,max}$ of 1.3 GHz elliptical pure bulk niobium superconducting radiofrequency (SRF) cavities is limited to the range from 35 to 45 MV/m. In contrast, theoretical studies predict that $E_{acc,max}$ of Nb SRF cavities with Superconductor-Insulator-Superconductor (S'IS) structures (Fig. 1), when optimized with appropriate S' and I layer thicknesses on their inner surfaces, could reach ≈ 100 MV/m [1,2]. Such an advancement would represent not only a major step forward in particle physics experiments, such as the ILC, but also in industrial applications, including accelerator miniaturization. Therefore, establishing a reliable fabrication method for S'IS structure is of critical importance.

$E_{acc,max}$ is generally determined by the effective Hc1 ($\mathbf{H_{c1,eff}}$), corresponding to the magnetic field at which vortex avalanche occurs on superconducting surface. Our previous studies demonstrated that NbN-SiO2-Nb structure on flat samples significantly enhance $H_{c1,eff}$ [3]. The next step is to develop film-formation techniques for S'IS structures that are applicable to the inner surfaces of cavities. In particular, development of specialized cathodes capable of controlling the elemental ration of alloys created by sputtering is a key technology. Therefore, we perform a sputtering simulation to analyze the film formation speed and film thicknesses distribution for cathode design. Furthermore, several film-formation tests on flat silicon substrates for synthesizing $Nb_3Sn$ films are carried out for creation of $Nb_3Sn$-I-Nb structures.

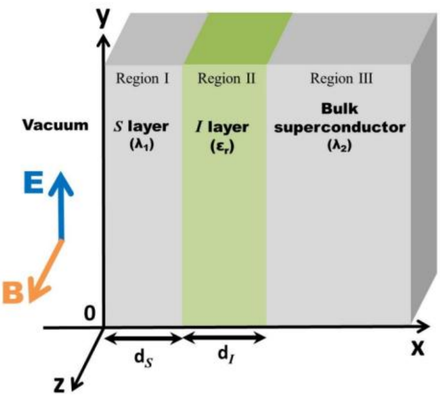


Figure 1: Schema of S'IS structure [4].

We report on the obtained results for these simulations and film-formation tests below.

## FILM FORMATION APPARATUS AT KEK

DC magnetron sputtering apparatus installed at KEK (Fig. 2). This apparatus was based on SH-450 (ULVAC,inc.) with special design according to the obtained results from ULVAC-KEK collaboration research program continuing from 2018 to 2020 for development of

Figure 2: Film deposition apparatus in KEK.

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# A LHE-FREE TEST FACILITY FOR THIN FILM SRF CAVITY TESTING *

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*Abstract*

A new cryogenic facility for the RF testing of thin film coated SRF cavities has been designed and built at Daresbury Laboratory. This facility uses a pulse-tube cryocooler providing 2.7 W of cooling power at 4.2 K and enables cavity tests at: 1.3, 3 and 6 GHz. The cryostat has been constructed and has successfully passed initial vacuum and cryogenic tests. The primary focus of this facility is on testing 1.3 GHz single-cell TESLA cavities. For this, a bespoke conduction cooling system has been engineered to ensure optimal thermal contact to account for slight geometric variations between cavities. A new RF system has also been built that can be used for low power continuous wave and pulsed testing across the full range of test frequencies. With a throughput of at least one cavity per week, the facility provides an efficient platform to pre-select cavities before high-power liquid helium testing at 2 and 4.2 K. Details of the design, commissioning and early performance of the facility are reported.

## INTRODUCTION

The joint ASTeC–Lancaster University team is advancing the UK's capability in thin-film superconducting radio frequency (SRF) cavity research at Daresbury Laboratory. A critical step in developing thin films for accelerator applications is assessing their performance under RF conditions. Until now, RF testing at Daresbury laboratory has been limited to planar samples using a 7.8 GHz Choke Cavity [1] and small 6 GHz split cavities [2–4], with studies focused on thin film niobium (Nb) [5] and $Nb_3Sn$ [6]. This leaves a major gap as no facility exists to evaluate thin film coated 1.3 GHz single-cell TESLA cavities [7].

Although an existing RF stand is being adapted for 1.3 GHz liquid-helium (LHe) tests, its availability is constrained by ESS and PIP-II commitments [8]. Therefore, access must be reserved for cavities already proven to perform well. To support thin film optimisation, a dedicated standalone facility was therefore conceived for quick cryogenic testing of 1.3 GHz single-cell cavities.

A key motivation for this dedicated facility is the growing interest in alternative superconductors such as $Nb_3Sn$ and NbTiN, which offer nearly twice the critical temperature ($T_c$) of Nb. Recent work on $Nb_3Sn$, for example, has lead to the first successful coating of a 1.3 GHz bulk Nb cavity [6, 9]. These materials allow cavity operation at 4.2 K with intrinsic quality factors comparable to Nb at 2 K [10], while maintaining intrinsic quality factors ($Q_0$) comparable to Nb at 2 K [10]. This makes them well suited to cryocooler-based conduction cooling and eliminating the need for liquid cryogens, thus offering safe, push-button operation without the logistical and safety challenges of handling liquid cryogens.

Encouraged by material progress, several groups have demonstrated cryocooler-based SRF test facilities. Fermilab achieved an accelerating gradient $E_{acc}$ = 6.6 MV m$^{-1}$ with a 650 MHz $Nb_3Sn$ on bulk Nb cavity using a 2 W pulse-tube (PT) cryocooler [11], while Jefferson Lab demonstrated similar performance at 1.5 GHz with a 2 W Gifford-McMahon (GM) cryocooler [12]. Cornell University demonstrated gradients up to 10 MV m$^{-1}$ with 2.6 GHz $Nb_3Sn$ on bulk Nb cavities [13], with more recent work on a 1.3 GHz cavity cooled with two cryocoolers providing a combined 4.15 W at 4.2 K [14]. These results confirm the viability of cryocooler-based SRF R&D.

This paper presents the design and initial commissioning of the new LHe-free SRF cavity test facility at Daresbury Laboratory, together with an outlook on planned developments.

## CRYOGENIC FACILITY

The new Daresbury Laboratory facility was designed with simplicity, flexibility, and efficiency in mind. The design approach was informed by experience from the existing cryocooler-based Choke Cavity facility [1], with design criteria emphasising quick turnaround, safe operation by a small team (no more than two people), and compatibility with multiple cavity frequencies (1.3, 3 and 6 GHz). A target was set for cavity installation to require no more than a few hours. Conventional LHe-based systems were ruled out due to their complexity, cost, and safety overheads as well as the continuously increasing cost of LHe. The resulting cryostat design is shown in Fig. 1 which is housed inside a dedicated RF test bunker.

### *Cryostat*

The new cryostat is built around a two-stage PT cryocooler (Cryomech PT425 [15]), providing 2.7 W of cooling power at 4.2 K on the stage 2. This offered the highest available cooling power at 4.2 K at the beginning of 2024 [15]. Notably,

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# EUROPEAN THIN FILM ROADMAP*

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*Abstract*

Superconducting thin film (TF) technology for SRF applications is under intense development in many research centres around the world. TF SRF technology can not only drastically reduce cryogenic costs but also opens the door to simplified alternative cooling schemes with reduced helium inventory. Up to today, TF development have been considered within two High Energy Roadmaps (CERN and Snowmass), without taking into account other possible applications. Within the framework of the European H2020 project IFAST, an "European TF-SRF Roadmap" has been developed that also covers all applications aspects including high-intensity hadron/neutron sources, light sources, cavity detectors, quantum computing or emerging fields like compact accelerators liable to apply to industrial processes and medical diagnostics, and commercial applications. This work proposes a comprehensive approach focused on the expertise and collaborative network that has been built in Europe and in the entire world over the past years. Ten priority topics have been identified on TF development. This paper briefly describes the main features of the roadmap.

## INTRODUCTION

SRF cavities dissipate orders of magnitude less power than copper and support higher duty cycles, but face drawbacks: complex cryogenics, quite inefficient at lower temperatures, costly bulk-Nb cavities, large liquid-helium inventories and non-turnkey deployment. Recent price surges (helium, electricity, Nb) intensify the need for more efficient solutions. Depositing higher-$T_c$ superconducting thin films (TF) on copper offers a practical path forward:

- Thermal efficiency: Cu's superior conductivity improves stability.
- Cost and handling: Cu cavities are cheaper and safer to process.
- Higher-temperature operation: Higher-$T_c$ films can run at or above 4.5 K, even at high frequencies, via TF routes not feasible in bulk.

Operating above 4 K cuts cryogenic load and enables cryocooler-based, compact accelerators that can compete in industrial and medical markets. SRF operates in a different regime than superconductors for magnets. Moving from lab R&D to (quasi-) industrial use demands investment on the scale of 1970s magnet programs.

Required support concerns more than deposition alone:

- Cu cavity fabrication:
- Cu surface preparation.
- Materials science:
- Deposition targets:
- Scaling equipment for larger cavities.
- Cleanrooms, RF tests.

Table 1: List of topics discussed during the Roadmap session at TFSRF2024, and institutions involved in these activities.

| Topic | In Europe | Outside of Europe |
|---|---|---|
| **Thin films development** | | |
| ❶ Niobium on copper | CERN, INFN, LNL, STFC, CEA | JLab, IMP, Peking University, with growing interest in China and India |
| ❷ $Nb_3Sn$ on Cu and Nb | CERN, INFN-LNL, HUH/DESY, STFC/CI, USI, CEA | JLAB, Fermi Lab and Cornell, KEK, IHEP |
| ❸ Other superconductors (other A15, $MgB_2$, other) on Cu and Nb substrate | STFC, USI | Temple University, JLab, LANL, University of Tennessee, KEK |
| ❹ Multilayers (SIS structures) | CEA, DESY/HUH, STFC, USI | JLab, KEK, CAS, FNAL. |
| ❺ Surface functionalisation | HZDR, RTU, CEA, DESY, IJClab | KEK, IHEP |
| **Enabling key activities** | | |
| ❻ Cu cavity production and surface preparation | CERN, INFN-LNL, IJCLab, STFC | KEK |
| ❼ General Characterization / Surface science | HEI with local universities | HEI with local universities |
| ❽ Deposited cavities preparation and RF testing | CEA, CERN, DESY, IJCLab, INFN, HZB, STFC | Jab, FNAL, KEK |
| ❾ Theory | Comenius U., HZB, IJCLab; CERN, INFN, CEA and coll. | ODU, KEK |
| ❿ Industrialisation | CERN, INFN/Picoli | IHEP, Jlab, FNAL, Cornell, PKU |

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# ADDITIVE MANUFACTURING FOR SEAMLESS 6 GHz Nb/Cu CAVITIES*

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*Abstract*

Additive Manufacturing (AM) enables the production of complex components using materials also with high melting points, often challenging to process conventionally. At INFN-LNL and INFN-Padova, seamless 6 GHz copper and bulk Nb cavities were fabricated via AM, aiming to eliminate internal supports while ensuring compatibility with ultra-high vacuum (UHV), superconducting coatings and cryogenic conditions. In this study those factors are evaluated, including chemical treatment using Plasma Electrolytic Polishing (PEP). On the Cu cavity, a 3 µm niobium (Nb) film was then deposited at ~300 °C, but delaminated during High Pressure Rinsing (HPR), preventing RF testing. A new deposition run is planned with higher temperature and thicker coating to improve adhesion. The bulk Nb cavity underwent chemical process and was measured at 4.2 K having a ($Q_0$) of approx. $1.3 \times 10^5$.

## INTRODUCTION

Laser Powder Bed Fusion (LPBF) enables rapid fabrication of complex components using expensive metals like niobium, with minimal material waste thanks to powder recyclability. Despite its advantages, LPBF presents challenges such as poor surface finish, residual porosity, and impurities in the raw materials. These issues have been investigated, and ongoing research continues to address them [1]. The process involves layer-by-layer laser melting of metal powder, with layer thickness influenced by the powder's particle size distribution.

Additive Manufactured (AM) cavities play a key role in evaluating the potential of AM for particle accelerator applications that include ultra-high vacuum (UHV) compatibility, cryogenic operation, integration of complex internal cooling channels and seamless multimaterial structures. AM has shown promising results in producing accelerator components and ancillaries [2, 3].

In this study, two seamless AM cavities were fabricated: one out of copper and one of niobium. A major challenge has been avoiding internal support structures, especially in down-facing regions. Previous work investigated the minimum down-facing angle required to eliminate supports [4]. The cavity design was refined to ensure uniform wall thickness, particularly in the iris region, which had previously suffered from leaks due to thinning caused by chemical processing. The improved design successfully addressed this issue.

The copper cavity was then coated with a Nb layer by DC magnetron sputtering technique (DCMS).

## EXPERIMENTAL METHODS

### *Additive Manufacturing of Nb Cavity*

Additive manufacturing was carried out at INFN section of Padua, DIAM laboratory. For the Nb bulk cavity, spherical niobium powder (AMtrinsic®, Taniobis GmbH, Germany) with a particle size distribution of 20 µm to 60 µm was used. Printing was performed with an EOS M100 DMLS system (EOS GmbH, Germany), equipped with a 200 W Yb:YAG laser with a wavelength of 1064 nm. A layer thickness of 30 µm was selected. The process took place in an argon-controlled atmosphere, maintaining oxygen levels below 0.1 % to minimize contamination. A range of densities of the as-printed parts was measured to be from 98.17 % to 99.87 %.

### *Nb AM 6 GHz Surface Treatments*

A Nb AM cavity underwent a protocol similar to the copper one. It started with vibro-tumbling for a total of 30 hours, removing approximately 10 µm. Instead of plasma electrolytic polishing (PEP), a standard electrolytic polishing (EP) treatment was applied, using a closed-circuit system that recirculates the electrolyte for Nb EP (sulphuric acid, 98 %, and hydrofluoric acid, 46 %, mixed in a 9:1 volume ratio) at ambient temperature (25 °C), for a total of 4 hours, removing a total combined of 92 + 142 + 130 = 364 µm. Before RF measurements, the cavity was cleaned in an ethanol bath and then subjected to the HPR protocol.

### *Additive Manufacturing of Cu Cavity*

Additive manufacturing was carried out in Turku, Finland, by EOS Finland Oy. As for the Nb cavity, for the printing process, commercially pure copper powder was used (EOS Copper CuCP). The cavity was printed using a M290 machine equipped with a 1 kW, Yb IR laser operating at 1060 nm. Argon was used inside the printing chamber to reduce oxygen down to 0.1 %. The building platform was not heated.

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# ACTIVITIES ON MEDIUM GRAIN NIOBIUM AT DESY*

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*Abstract*

Within the ITN (ILC Technology Network) activity led by KEK, the so-called "Medium Grain Niobium" is investigated with respect to its possible application for a large-scale SRF cavity production for the International Linear Collider ILC. In the framework of the KEK-DESY collaboration, the niobium material for two 1.3 GHz single-cell cavities was supplied by KEK. After fabrication and initial surface treatment by electropolishing in industry, the cavities have been tested successfully at DESY with gradients above 40 MV/m after an additional Low-T heat treatment. Subsequently, a heat treatment at medium temperatures around 350°C (Mid-T heat treatment) in the DESY furnace was applied. The vertical cryogenic test showed the typical performance after Mid-T heat treatment for both cavities. The Q-value increased up to (20 -25) MV/m and achieved up to $3.5 \cdot 10^{10}$. The maximum gradients were limited at 28 MV/m and 30 MV/m by breakdown, respectively. In addition, the effect of Ultra High Vacuum (UHV) heat treatments on state-of-the-art fine grain niobium at temperatures between 800°C and 1100°C has been studied on samples with respect to grain growth, mechanical and thermal properties.

## INTRODUCTION

The ITN activity led by KEK [1–4] is investigating the potential of "Medium Grain (MG) Niobium" with respect to its possible application for a large-scale SRF cavity production. First studies of the mechanical properties of MG niobium showing promising results as a possible alternative to standard fine grain niobium have been presented in [5]. The related successful fabrication and cold test results of the first two single-cell cavities at KEK were described in [6, 7]

In the framework of the KEK-DESY collaboration, niobium (Nb) discs used for the fabrication, surface treatment and vertical test of two 1.3 GHz DESY single-cell cavities were made available by KEK.

For comparison, the effect of UHV heat treatments on state-of-the-art fine grain niobium at temperatures between 800°C and 1100°C has been studied at DESY on samples with respect to grain growth, mechanical and thermal properties.

## NB PROPERTIES, FABRICATION AND SURFACE TREATMENT

The niobium billet was ordered by KEK within the ITN activity and has been manufactured by ATI Specialty Alloys & Components. Within the KEK-DESY collaboration, DESY received six discs with a sufficient diameter for 1.3 GHz cavity production. Four of these discs have been used to produce two single-cell cavities at Zanon Research & Innovation SRL (ZRI). While the electrochemical surface removal was carried out at ZRI, the heat treatments, cleanroom assembly and vertical tests were performed at DESY.

### *Nb Properties*

The niobium billet showed 100 % recrystallization and a Residual Resistance Ratio RRR-value above 450. The six discs received at DESY show a strongly inhomogenous grain size distribution (Fig. 1). As incoming inspection, the standard DESY Nb quality control based on eddy-current scanning [8] was applied without notable defects found. No further material analysis based on small samples has been performed so far.

Figure 1: Medium grain disc as received at DESY.

### *Fabrication*

The deep drawing process at ZRI required modifications compared to fine grain Nb sheets. The MG discs showed a good formability with a significantly different behaviour; especially the iris area was critical. After the forming, all four discs could be used for further fabrication. No overall grinding of the inner surface was applied resulting in an "orange peel" type surface, but some local areas have been ground. The electron beam welding parameters applied were in the typical range for fine grain Nb sheets. For a future series production additional optimization can be foreseen.

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# CHARACTERIZING AND CONTROLLING RECOVERY AND RECRYSTALLIZATION IN NIOBIUM FOR IMPROVED SRF CAVITY PERFORMANCE*

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*Abstract*

Crystal defects, such as dislocations and low-angle boundaries, provide sources of magnetic flux trapping in the Nb materials used for superconducting radio frequency (SRF) resonating cavities. Improving the performance of SRF cavities, as measured through the quality factor, requires reducing these defects. SRF cavity production involves deformation processing, such as rolling and forming, and strategic annealing heat treatments. The resulting microstructures can be recovered, recrystallized, or both. Because recovery leaves many defects that can trap flux, recrystallization should improve cavity performance. Thus, processing schedules that produce complete recrystallization without excessive grain growth need to be designed. Solutions to this problem require understanding physical metallurgy and differentiating between recovered and recrystallized regions of microstructure. Backscattered electron microscopy techniques are applied to this end. We demonstrate that the conditions required to produce fully recrystallized microstructures depend on Nb impurity content, suggesting that processing schedules may need to be adjusted by material heat or lot. We also demonstrate that processing can be used to control growth of recrystallized grains to maintain mechanical strength in fully recrystallized materials. Forming cavities from *cold-rolled* Nb sheet material may provide strategic new routes to obtain microstructures that improve SRF cavity performance.

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## INTRODUCTION

Very high purity forms of ASTM Type 5 niobium [1] have become the standard materials for superconducting radio frequency (SRF) cavity production. The success of pure niobium is because it has the highest critical superconducting temperature among elemental superconductors, approximately 9.25 K, a high critical magnetic field, and excellent fabricability, including both formability and weldability. Advances in metallurgical production techniques now enable niobium of very high purity, as reflected through the high residual resistivity ratio (RRR) values regularly achieved today. The elimination of interstitial elements has improved SRF performance. An important avenue to further improve SRF performance is to improve material microstructure. Crystal defects, such as dislocations and low-angle boundaries, provide sources of magnetic flux trapping that can degrade performance. Furthermore, the features associated with dislocation substructure in recovered microstructure can provide sites for the preferential precipitation of niobium hydrides, which also trap magnetic flux and degrade performance [2–4]. Improvements to SRF cavity microstructures might be achieved through new, strategic thermomechanical processing routes that reduce undesirable dislocation substructure by full recrystallization.

SRF cavities are produced from rolled sheet that is typically annealed to create a soft condition prior to forming the final cavity shape. Depending on the rolling and annealing processes used to produce a sheet, its microstructure may be recovered, recrystallized, or a combination of these conditions. Flat sheet is formed into the desired cavity shape. For a typical TESLA shape, formed cavity halves are welded together using electron beam welding, and multiple cavities are welded together at the iris to beam tubes to produce a single structure. The whole structure is then annealed, with a typical annealing temperature in the vicinity of 800 °C. A variety of surface treatments can be applied before and/or after the annealing heat treatment, but these are not considered in the present study. Both the processing prior to final

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# RF MEASUREMENTS AND PERFORMANCE TESTS AT 4 K OF CRYOMODULE 1 CAVITIES FOR HELIAC

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*Abstract*

A new superconducting (sc) continuous-wave (cw) linear accelerator (linac) is currently being built at GSI to meet the future requirements in research on superheavy elements (SHE) synthesis and material science with a particular focus on fusion studies. The HElmholtz LInear ACcelerator (HELIAC) will provide ion beams in the energy range from 1.4 AMeV to 7.3 AMeV with a mass-to-charge ratio ($A/q$) of up to 6. For acceleration, superconducting multi-cell crossbar-H-mode (CH) cavities operating at a resonance frequency of 217 MHz are used. Additionally, superconducting single spoke buncher cavities are employed for longitudinal beam matching within the CH sections. In 2023/2024, the first cryomodule, CM1, consisting of three CH cavities, one buncher, and two sc solenoids, was commissioned with beam at the GSI test stand. This paper presents RF measurements and performance tests of the cavities conducted during the initial operation of CM1.

## INTRODUCTION

Figure 1 presents a schematic layout of the future HELIAC accelerator facility [1–3]. An 18 GHz ECR ion source will deliver heavy-ion beams with $A/q$ of up to 6 and a maximum beam current of 1 mA. The normal-conducting (nc) injector section operates at 108 MHz and primarily consists of a 4-rod RFQ followed by two alternating-phase focusing (APF) IH drift tube cavities [4, 5] providing an injection energy of 1.4 AMeV into the superconducting main linac section. This main part operates at 217 MHz and comprises four sc cryomodules (CM1-CM4). Each cryomdoule houses three sc multi-gap CH cavities [6,7], one sc single spoke resonator (SSR) for longitudinal bunching [8] and two sc 9 T solenoids for transverse beam focusing. The CH cavities are based on the EQUUS (EQUidistant mUlti-gap Structure) beam dynamics concept [9] which features equidistant accelerating gaps and enables efficient acceleration with high beam transmission. A key feature of HELIAC is its variable output energy in the range of 1.4 to 7.3 AMeV, which is of particular interest for future user experiments in fields such as fusion materials and the synthesis of superheavy elements [10]. As part of the 'Advanced Demonstrator Project', cryomodule CM1 was successfully commissioned with $^{4}He^{2+}$ and $^{40}Ar^{8+}$ ion beams in 2023/2024 [11,12]. However, the initial commissioning phase was conducted without the sc buncher cavity, as its resonance frequency under operational conditions deviated by +100 kHz from the target value. This discrepancy is attributed to an overcompensation of the expected helium bath pressure during the cavity design process. Consequently, the buncher will be returned to the manufacturer for frequency adjustment in Q1 2026. Therefore, this contribution focuses on the performance characterization of the sc CH cavities CH0, CH1 and CH2 installed in cryomodule CM1.

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## HELIAC TEST SETUP

As part of realizing the HELIAC project, the first cryomodule CM1 was built as a demonstrator and tested with beam at the existing GSI High Charge State Injector (HLI) facility [13]. In 2022, all components of CM1 were delivered to Helmholtz Institute Mainz (HIM), where assembly of the cold string was carried out under ISO-class 4 cleanroom conditions [14, 15]. Following the cleanroom assembly, the cold string was mounted onto the mechanical support frame outside the cleanroom, and subsequently integrated into the cryostat. Final alignment of all components was performed using a laser tracker system. CM1 was then transported from Mainz to GSI Darmstadt. To evaluate the operational suitability of the cryomodule under realistic accelerator conditions — particularly the performance of the superconducting CH cavities — a dedicated test area was established at GSI [16]. This test facility, connected to the HLI beamline, enables extensive investigations of beam parameters using advanced diagnostic equipment, as well as detailed RF testing of the superconducting cavities. The beamline comprised two normal-conducting rebuncher cavities for longitudinal beam matching, two quadrupole doublets for transverse focusing, two phase probes for time-of-flight (TOF)-based beam energy measurements, and a secondary electron emission monitor (SEM) grid for transverse beam profile diagnostics. Additional diagnostics included beam current transformers for transmission measurements, a Feschenko-type bunch shape monitor, and a slit-grid device for transverse emittance measurement. Altogether, this setup enabled a full 6D beam characterization and provided a versatile test platform for components and procedures relevant for the future HELIAC operation. Figure 2 shows the fully equipped CM1 module inside the radiation-shielded test cave at GSI. RF power was delivered to the sc CH cavities via

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# FABRICATION OF THE PROTOTYPE SPOKE CAVITY FOR THE JAEA-ADS LINAC

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*Abstract*

Japan Atomic Energy Agency (JAEA) has been proposing an accelerator-driven nuclear transmutation system (ADS) to efficiently reduce high-level radioactive waste generated in nuclear power plants. As a first step toward the practical design of the JAEA-ADS linac, we are currently prototyping a low-$\beta$ ($\approx$0.2) single-spoke cavity. The fabrication process for the prototype spoke cavity was investigated in fiscal year 2019, and the actual cavity fabrication started in 2020. Most of the cavity parts were shaped in fiscal year 2020 using press-forming and machining. We started joining the shaped cavity parts together by electron-beam welding in 2021, and the major three parts, the body and two lids, were fabricated through fiscal year 2023. In 2024, we adjusted the resonance frequency of the cavity by trimming the ends of the cavity parts. The cavity fabrication was finally completed by circumferentially welding the body and two lids together in fiscal year 2024.

## INTRODUCTION

JAEA has been proposing an ADS as a future nuclear system to efficiently reduce high-level radioactive waste generated in nuclear power plants. In the ADS, long-lived nuclides are transmuted into short-lived or stable ones. One of the key R&D subjects for realizing the ADS is the reliability of the accelerator [1, 2]. In the JAEA-ADS, a high-power proton beam of 30 MW with a final energy of 1.5 GeV is required with high reliability. Since the accelerator needs to be operated in CW mode, a superconducting (SC) linac would be a suitable solution. The latest design of the JAEA-ADS linac is reported in Refs. [3, 4]. As shown in Fig. 1, the proposed linac consists of a normal-conducting radio-frequency quadrupole (RFQ), half-wave resonator (HWR), low-$\beta$ and high-$\beta$ single-spoke resonators (SSR1 and SSR2, respectively), and low-$\beta$ and high-$\beta$ elliptical cavities (ELL1 and ELL2, respectively).

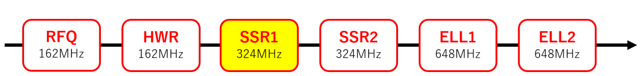


Figure 1: Proposed acceleration structure of the JAEA-ADS linac.

As a first step toward the practical design of the JAEA-ADS linac, we have decided to prototype the low-$\beta$ ($\approx$0.2) single-spoke cavity, and conduct a high-field performance test of the prototype spoke cavity at liquid helium temperature. This prototyping will provide various insights on the development of SC cavities with TEM $\lambda/2$-mode resonance. In addition, the high-field cavity testing will provide valuable information such as how much field gradient can be achieved with reasonable stability. Therefore, both prototyping and performance-testing are essential to ensure the feasibility of the JAEA-ADS linac. In this paper, the fabrication of the prototype spoke cavity for the JAEA-ADS linac is presented.

## CAVITY DESIGN

The prototype spoke cavity with an operating frequency of 324 MHz was designed by electromagnetic simulation [5], and its dimensional parameters were optimized for higher cavity performance [6–8]. Figure 2 shows the cross-sectional views of the designed cavity with surface electric and magnetic field distributions. The cavity's design parameters are listed in Table 1. A multipactor analysis of the designed cavity without coupler ports is presented in Ref. [7].

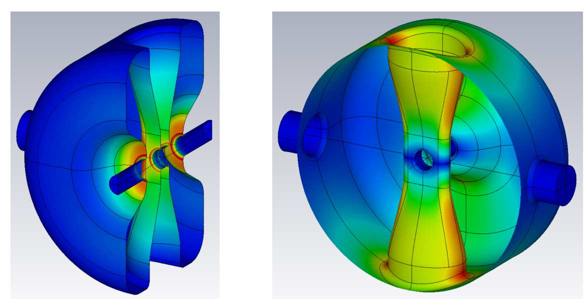

Figure 2: Cross-sectional views of the designed cavity with surface electric (left) and magnetic (right) field distributions.

Table 1: Design Parameters of the Prototype Spoke Cavity

| Parameter | Value |
|---|---|
| $f_0$ | 324 MHz |
| $\beta_g$ | 0.188 |
| $\beta_{opt}$ | 0.24 |
| Beam aperture | 40 mm |
| Cavity diameter | 498 mm |
| Cavity length | 300 mm |
| $L_{eff} = \beta_{opt}\lambda$ | 222 mm |
| $G = Q_0 R_s$ | 90 Ω |
| $T(\beta_{opt}) = V_{acc}/V_0$ | 0.81 |
| $r/Q = V_{acc}^2/\omega U$ | 240 Ω |
| $E_{peak}/E_{acc}$ | 4.1 |
| $B_{peak}/E_{acc}$ | 7.1 mT/(MV/m) |

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# MEASUREMENT OF LOW ACCELERATING GRADIENTS IN 1.3 GHZ CAVITIES AT DESY

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*Abstract*

During last few years, an extensive efforts for obtaining $Q_0$ vs $E_{acc}$ characteristic of SRF cavities at very low accelerating gradients have been conducted in several laboratories around the world. In the Accelerator Module Test Facility (AMTF) at DESY, several attempts of such measurements were performed, mainly focused on the comparison between the widely used decay measurements technique and the standard vertical test. To ensure good quality of the signals at very low gradients, several hardware adaptations of the existing test - stand were introduced. In this paper, compliance between two measurement ideas is presented, as well as some cross-checking ideas, which could give an overview of the measurement quality at very low RF amplitudes.

## INTRODUCTION

In order to obtain the $Q_0$ vs $E_{acc}$ characteristic of superconducting cavitiy several different methods can be used. The most commonly used one is to feed the cavity with RF power, usually with some feedback system, which allows to keep the cavity in perfect resonance for at least several seconds. After reaching steady state, the RF is switched OFF and the measurement point is calculated based on the power, frequency and decay curve. Then the amplitude of the RF power is changed and the next measurement point is obtained. For the scope of this paper this method is called Standard Vertical Test (SVT). This measurement idea, even though very accurate has one big disadvantage: an extensive amount of time, typically few to several hours, is needed to obtain the entire $Q_0$ vs $E_{acc}$ plot. Due to this fact, a faster methods of the measurement were proposed [1]. The so called decay measurement (DEC), is based on only one measurement of the decay curve of the stored energy, which contains all information about the $Q_0$ and $E_{acc}$ in case the coupling factors of the cavity are well-known. This idea seems to be very attractive from several perspectives. The most important one is the amount of time - typically one minute - needed to perform such measurement. However, in order to make sure that this method is valid, it was decided to compare the results from DEC and SVT methods for low fields, i.e. low rf power levels. In this paper we discuss both measurement ideas, their limitations and possible improvements to get a more universal tool to perform measurements in the range of tens of kV/m. Interpretation of the results for some of the DESY single cavities can be found in another paper from this conference [2].

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## DECAY MEASUREMENT

The decay mesaurement is used by some laboratories [3, 4], in order to get $Q_0$ vs $E_{acc}$ characteristics in the low accelerating field region where performing standard measurement becomes difficult and requires major modifications of the test-stand environment due to the low rf power levels and signal to noise ratio (SNR). Usually, the energy decay plot is gathered using a Spectrum anlyzer, connected to cavity probe antenna. Apart from such decay plot, several values and parameters taken during standard vertical test operation are needed in order to perform the required calculations:

- $P_{trans}$ - power transmitted at calibration point
- $Q_{ext}$ - external quality factor of the input antanna
- $Q_{transmitted}$ - Quality factor representing the the pick - up antenna
- $K_t$ - probe calibration coefficient, used later for calculating the accelerating field

In Fig. 1 the standard decay curve calibrated to power transmitted is shown. The red dot represents a marker of the RF level 20 dB above the noise level. Having all of the required data, recalculation is done in such steps [5].

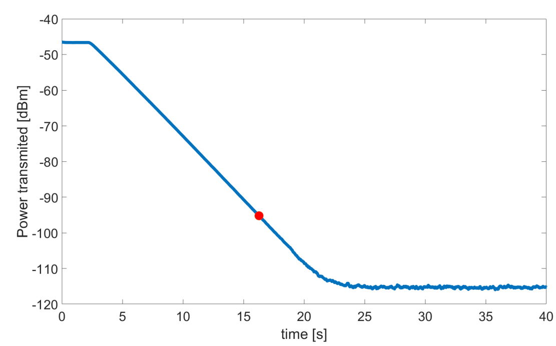


Figure 1: Standard $P_{transmitted}$ decay curve taken with spectrum analyzer.

For each point on the decay curve we calculate the accelerating gradient.

$$E_{acc} = k_t * \sqrt{P_{transmitted}}. \quad (1)$$

Then, for each point tau (decay coefficient) is calculated from the following equation:

$$\tau = -P(t) / \frac{d}{dt} P(t) \quad (2)$$

and $Q_l$ - Loaded Quality factor of the entire measurement system

$$Q_l = 2 * \pi * f_0 * \tau. \quad (3)$$

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# MAGNETIC ENVIRONMENT OPTIMIZATION IN SRF TESTING AT INFN-LASA

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*Abstract*

Minimizing residual magnetic fields during SRF cavity cooldown is essential for reducing surface resistance and improving the quality factor. At LASA-INFN, we implemented an active compensation system using Helmholtz-like coils in vertical test cryostats. The setup is optimized to reduce the average magnetic flux through the cavity surface by accounting for the spatial inhomogeneity of the residual field. Experimental studies on PIP-II prototype cavities confirm the critical role of magnetic field conditions during cooldown. Observations suggest that, if a quench occurs in the presence of such external fields, trapped flux can cause a lasting degradation of the quality factor.

## INTRODUCTION

Magnetic flux trapping has long been recognized as a key mechanism limiting cavity performance, contributing a dissipation term to the surface resistance. In the recent context of SRF R&D aimed at achieving high $Q$, this topic has gained increasing importance and has prompted significant experimental effort. This is particularly true in the wake of advanced cavity treatments, such as nitrogen doping and mid-temperature bake [1, 2], where the impact of flux trapping has been shown to be even more pronounced compared to standard cavity preparations.

For both these high-$Q$ treatments it has been observed that, in parallel with the reduction of the temperature-dependent surface resistance $R_{BCS}(T)$, the contribution from trapped flux, $R_{tf}(B)$, increases, with a magnitude that depends on the annealing temperature of the cavity. The balance between these two contributions is determined by their different frequency dependences: $R_{BCS}(T)$ increases as $f^2$, while $R_r(B)$ follows $f^2$ for $f \ll f_0$ and becomes frequency independent for $f \gg f_0$, where $f_0$ is the depinning frequency [3].

The depinning frequency itself depends on the electron mean free path and is typically expected to lie between 100 MHz and 10 GHz. In this interval, which overlaps with the operating range of RF cavities, the transition between the two asymptotic regimes naturally results in an almost linear frequency dependence of the residual resistance. This implies that cavities operating at lower frequencies, $f \lesssim 1$ GHz, are more sensitive to trapped flux in terms of performance, since the trapped-flux term dominates the overall surface resistance. Conversely, at higher frequencies, $f \gtrsim 1$ GHz, the $f^2$ growth of $R_{BCS}(T)$ becomes the leading contribution.

In this framework, the case of the PIP-II LB650 cavities currently under production at LASA-INFN [4] represents an emblematic challenge. Their relatively low frequency of 650 MHz places them in the regime where trapped flux is expected to play a dominant role, while the adoption of the mid-temperature bake—known among high-$Q$ treatments to be particularly prone to increased flux sensitivity—further enhances the risk of a dramatic rise in residual resistance.

Several strategies have been adopted to mitigate this effect, such as the choice of 900 °C as the annealing temperature in the cavity production recipe. In the next section, we describe the approach implemented at the LASA-INFN vertical test facility to experimentally minimize the contribution of trapped flux to the residual resistance, thus enabling a more accurate assessment of cavity performance.

## THEORY OF FIELD MINIMIZATION

The trapped-flux contribution to the residual resistance can be expressed as $R_{tf} = SB_{\mathrm{ext,sc}}$. Here, $S$ is the sensitivity to trapped flux, and $B_{\mathrm{ext,sc}}$ is the field trapped in the cavity once it becomes superconducting. The trapped field can in turn be written as $B_{\mathrm{ext,sc}} = \eta B_{\mathrm{ext}}$, where $B_{\mathrm{ext}}$ is the external field present before the cavity transitions to the superconducting state, and $\eta$ is the trapped flux efficiency, which depends on the cooldown rate and represents the fraction of the external field actually trapped in the cavity surface after the transition from the normal to the superconducting state.

Overall, the trapped-flux contribution to the residual resistance can thus be expressed as the three-fold product:

$$R_{tf} = \eta\, S\, B_{\mathrm{ext}}, \tag{1}$$

where $\eta$ depends on the cooldown conditions, becoming smaller for faster cooldowns and higher temperature gradients; $S$ depends on the cavity frequency, material properties, and treatment history; and $B_{\mathrm{ext}}$ is simply the external magnetic field present across the cavity volume in the cryostat.

In the vertical test facility of LASA [5], the cavities are typically cooled at a rate of less than 1 K min$^{-1}$ near the transition temperature of 9.2 K. Fig. 1 shows the typical trend of temperatures and magnetic field measured along the length of a PIP-II LB650 multicell cavity. As can be seen, the slow cooldown rate and the correspondingly small temperature gradient of approximately 0.2 K m$^{-1}$ result in a trapping efficiency of about 92%.

The facility is mainly dedicated to testing sub-GHz cavities for proton acceleration, such as those for the ESS and PIP-II projects. Based on past measurements at LASA, the flux trapping efficiency has been observed to vary depending

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# DEVELOPMENT OF A COBOT-ASSISTED HIGH PRESSURE RINSING SOLUTION FOR SRF CAVITIES

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*Abstract*

IJCLab has been contributing to several SRF accelerators in the world (SPIRAL2, ESS, PIP-II) and in particular was in charge of the design, surface preparation and qualification in vertical cryostat of low beta (i.e. complex 3D shape) resonators as Quarter Wave Resonators (QWR) and Spoke Resonators. One of the main challenges of these complex geometries is the final surface cleaning by High Pressure Rinsing (HPR) to limit or in the best case suppress the Field Emission (FE) at nominal gradient. While standard HPR methods have effectively reduced FE, they could not eliminate it in these geometries. Since 2024, triggered and motivated by PIP-II prototyping phase, IJCLab is investing in COBOT technology (COllaborative roBOT) in an effort to improve HPR capabilities, leveraging the flexibility and precision of cobots to perform complex trajectories for optimal surface coverage. This paper will summarize the on-going R&D activities at IJCLab.

## INTRODUCTION

High Pressure Rinsing (HPR) is one of the key processes in order to obtain superconducting cavities with accelerator gradients in the order of MV/m and above. The principle is to expose all the RF surface to an ultra-pure water jet with enough kinetic energy to remove any dust particles or chemical residues that could become electron emission sites under high fields, thus limiting the usable gradient and increasing cryogenic load. The water jet typically comes from a multi-hole nozzle mounted on a wand, which is supplied by a high-pressure pumping system. This wand is usually designed in order to penetrate inside the cavity through different holes: beam ports, coupler ports, and eventually dedicated ports [1]. This process has to be realized in a cleanroom environment in order to not contaminate the cavity again.

The SUPRATech [2] facility at IJCLab is equipped with such a system, and extensive experience was gained through the SPIRAL2 and ESS construction projects, where standard rinsing techniques proved sufficient. However, with the PIP-II project [3], the limitations of the legacy system became evident. Specifically, for SSR2 cavities, tilted trajectories are required to ensure water jet coverage of critical regions [4, 5]. These constraints motivated the development of a new, more flexible solution based on cobot technology.

The PIP-II SSR2 cavity campaign made these drawbacks particularly clear, motivating the search for a flexible robotic approach.

## LEGACY HPR SYSTEM

The first and only one HPR station (see Fig. 1) built at SUPRATech served for multiple international projects. The mechanical system consists of a wand mounted on a vertical guide, capable of linear motion along the cavity axis and continuous rotation. Ultrapure water, generated outside the cleanroom, is pressurized by a pump to 100 bar with a nominal flow of 10 l/min. In addition to this system, a dedicated forklift allows cavity transport and control vertical position and rotation of the cavity along a horizontal axis inside the cleanroom.

Figure 1: Picture of the ISO-4 dedicated cleanroom for cavity cleaning and assembling of the SUPRATech facility that shows the HPR mechanical system on the left, and the cavity manipulation system on the right.

This system has demonstrated reliability and contributed to the successful qualification of Spiral2 QWRs and ESS double spoke cavities. Nevertheless, several limitations were identified:

- Restricted trajectories: Only a vertical rinsing path is possible.
- Design constraints: To make cavities compatible with this HPR system, designers had to include dedicated rinsing ports, sometimes conflicting with optimal RF geometry or mechanical requirements.
- Manual handling: Each orientation change requires operator intervention, increasing contamination risks and extending processing time.

## MAIN DESIGN CONSIDERATIONS

Firstly, from the very early stage of the cobot study, it was decided to keep the legacy HPR system completely operational, with the slight exception that the water feeding system will be derivate to make significant infrastructure costs saving. The cobot should access the four ports of an SSR2 cavity that connect with the inner volume: two beam ports and two coupler ports. The access of the beam port should be horizontal, and the access from the coupler ports should be vertical and tilted with inclination capability up

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# STRAIN GAUGE-BASED POSITION MONITORING OF SRF CAVITY

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*Abstract*

The variable pulse-length storage ring (VSR) cavities, featuring protruding waveguides and higher order modes (HOM) absorbers, are designed to be installed as part of the cold string in a spaceframe within a cryogenic vessel. Precise alignment of the cavities during installation and continuous position monitoring during operation are required to prevent damage of other cold string components such as bellows. To achieve this, strain gauges are installed on the rods suspending the cavity within the spaceframe, measuring the superimposed strains.

To validate this approach, assembly tests were conducted, comparing strain gauge measurements with laser tracker data. The results demonstrate that strain gauge-based monitoring enables continuous position tracking of the cavity. Operation within a vacuum vessel at low temperature still needs to be tested.

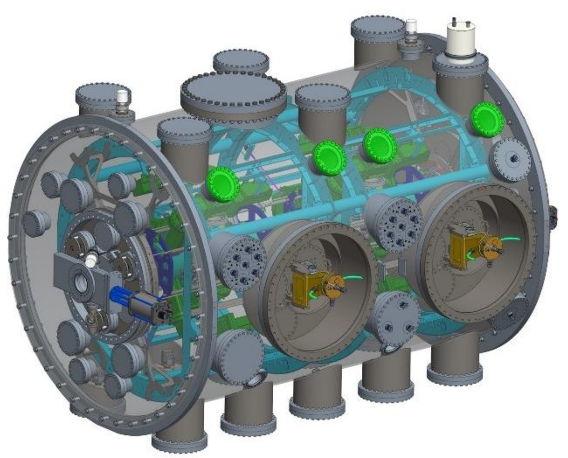

Figure 1: Simplified view of VSR DEMO setup: Cryogenic vessel (transparent grey), ports for laser tracker (light green), spaceframe (light blue), HOM absorber (dark green) and support disc (dark blue) for SRF Cavity.

## INTRUDUCTION

The VSR DEMO cold string setup consists of two fundamental power couplers (FPCs), each connected to a 1.5 GHz SRF cavity [1]. These two cavities are linked via a collimating shielded bellows (CSB) and require exceptional position stability. This is primarily because the CSB offers limited length compensation, owing to its compact bellows design. Additionally, the FPC extends from outside into the module, connecting both the vessel and the cold string; thus, any positional change of the cavity directly induces misalignment in the FPC. Although bellows are integrated into the coupler assembly, their ability to compensate for displacement — especially in directions perpendicular to the central axis — is strongly constrained. To prevent damage to these bellows, particularly those on the FPC, it is essential to continuously monitor the cavity's position, especially during thermal transitions such as cool-down and warm-up (see Fig. 1)

## MOTIVATION

High-accuracy absolute position measurements can be achieved using laser trackers; however, this technique requires direct visual access to optical targets mounted on the cavity. In the planned configuration, two targets are mounted on each support disc, allowing one laser tracker to trace the corresponding cavity (see Fig. 2).

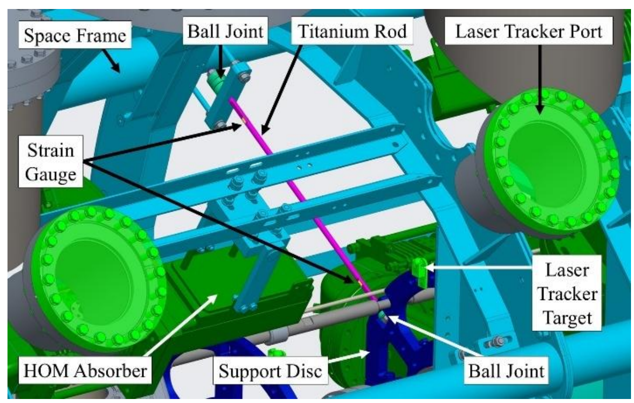


Figure 2: simplified view of VSR DEMO: rods with strain gauges near spaceframe and near support disc, and laser tracker view paths. Cryogenic vessel, magnetic and thermal shields are invisible.

Two trackers are required for both cavities, which are positioned at elevated locations to ensure a clear line of sight in the cryomodule. Refractive-index changes along the optical path, caused by different media (air, glass, vacuum), will be compensated using the Measurement In Different Media Adaptation System (MIDAS) [2]. Ensuring unobstructed sightlines is challenging due to the multiple cold-mass layers — such as thermal shields, multilayer insulation, and piping — and the limited available mounting positions for the targets. Moreover, tracking only two points per support disc prevents full spatial reconstruction of cavity motion, as at least a third point would be required.

The support discs are connected radially to the spaceframe by titanium rods, so that any deformation of the cavities is transferred to these rods as a load change (see Fig. 3).

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# HYBRID WIRE LASER ADDITIVE MANUFACTURING AND CNC MACHINING FOR ADVANCED SRF CAVITY FABRICATION*

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*Abstract*

The fabrication of Superconducting Radio Frequency (SRF) cavities traditionally relies on forming and welding high-purity metal sheets, resulting in a local surface discontinuity that degrades the final SRF performance. In this work, we propose and explore a novel hybrid approach combining Wire Laser Additive Manufacturing (WLAM), with in situ CNC machining for the fabrication of mono-cell 1.3 GHz SRF cavity. This technique enables the layer-by-layer deposition of high-purity metals with precise dimensional control, while alternating subtractive steps to maintain tolerances and surface quality crucial for RF performance. The hybrid WLAM and CNC machining stands as a candidate for next-generation SRF cavity production minimizing material waste, eliminating the need for electron beam welding, through the direct creation of complex geometries, and enhancing the surface finishing in the as-built condition. Results on stainless steel 1.3 GHz prototype are presented.

## INTRODUCTION

In recent years, the field of particle accelerator research and applications has advanced rapidly, driven by the design of next-generation infrastructures such as the FCC-ee and the Muon Collider. These cutting-edge projects impose stringent demands on critical components, such as accelerating cavities, superconducting magnets, and cryogenic systems requiring high RF, thermal, and mechanical performance, long-term reliability, and scalable production methods.

Conventional manufacturing technologies based on plastic forming, electron-beam welding, and surface treatments, although well-established, are reaching their limits. For instance, superconducting RF cavities made from niobium through standard workflows involve multiple steps forming, welding, mechanical polishing, annealing, and chemical electropolishing. While these processes can deliver excellent performance in laboratory settings, they present major challenges in terms of repeatability, functional integration, and cost-effective scaling to industrial production.

In this context, seamless cavity manufacturing has emerged as a promising approach to overcome limitations associated with welds and assembly tolerances. Two main techniques have been investigated:

- Spinning [1,2], in which a metal disc or tube is plastically deformed over a mandrel to form a cavity single o multi-cell. This technique is under active development at various laboratories, including INFN-LNL, due to its potential for reduced material waste and smoother internal surfaces. However, challenges remain in terms of dimensional control and the uniformity of mechanical properties across the formed part, particularly for high-purity niobium and copper.
- Hydroforming [3], which uses internal fluid pressure to deform a seamless tube into the desired cavity shape. This method eliminates welds and has shown good results in producing elliptical cell cavities, with successful implementations at institutes like KEK. Nevertheless, hydroforming requires precise control of material thickness and long and intense post processing treatments.

On the other hand, Additive Manufacturing (AM) has emerged as a complementary and disruptive technology to address the limitations of both traditional and seamless cavity production [4]. In particular, here it is reported the Wire Laser Additive Manufacturing (WLAM), also known as Wire-based Laser Metal Deposition (W-LMD), which differs from LPBF in the form of the raw material: a wire that is melted by the laser and deposited through a nozzle layer by layer [5,6]. WLAM is well-suited for producing larger components, offering high deposition rates and compatibility with hybrid workflows, including CNC machining for surface finishing. Concluding, the WLAM proof-of-concept efforts, led by INFN-LNL, would demonstrate the feasibility of combining AM technology and CNC machining for surface finishing, opening up a new way of producing seamless SRF cavities.

## EXPERIMENTAL PROCEDURE

The INFN research on WLAM aims to drive innovation in components engineering and design by pushing the boundaries of seamless RF cavity fabrication. The development of the Wire Laser Additive Manufacturing (WLAM) combined with CNC machining to produce accelerator cavities, is a proprietary INFN patent [7].

The WLAM + CNC hybrid approach is carried out by LNL in close collaboration with a private company MELTIO based on the development of a first attempt of prototype of 1.3 GHz in stainless steel (see Fig. 1) and for future projects funded by INFN as MAAT* (Metal Additive manufacturing for Accelerator Technologies). Additionally, Meltio is currently working on pre commercial solutions, fundamental for the project. This innovation includes the development of a novel inert manufacturing cell,

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# HOM ANTENNA UPGRADES AND CAVITY REFURBISHMENT FOR MESA ER-MODE

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*Abstract*

The Mainz Energy-Recovering Superconducting Accelerator is currently under construction at the Institute for Nuclear Physics on the campus of the Johannes Gutenberg University Mainz. A future upgrade is planned for the multi-turn Energy Recovery (ER) mode, increasing the beam current from 1 mA to 10 mA in continuous wave at 1.3 GHz. Simulations have shown an increased power deposition of 3 W in the Higher Order Modes (HOMs) of the TESLA cavities. The power, which is deposited by the passing electron beams through the cavity, is reduced in the cavity through the HOM dampers, but the power at the HOM antenna will increase up to 1 W. This will exceed the current limits and lead to a quench of the antenna. The quench limit could be increased by using an alternative superconducting material with a higher critical temperature than Niobium. Two candidates like $Nb_3Sn$ on Cu and NbTiN on Nb will be coated as a thin film on the antenna. Simulations have shown that the limit can be increased up to 1.1 W for NbTiN on Nb and 4.7 W for $Nb_3Sn$ on Cu. Two TESLA cavities, from a cryomodule (CM) of the decommissioned ALICE project, are refurbished in the clean room infrastructure of the Helmholtz Institute Mainz (HIM). The performance of the cavities will be tested in several configurations: after refurbishment, with the original antenna design, with coated antennas, and in the fully assembled cryomodule with an electron beam.

## MAINZ ENERGY-RECOVERING SUPERCONDUCTING ACCELERATOR

The Mainz Energy-recovery Superconducting Accelerator (MESA) [1] is currently under construction at the Institute for Nuclear Physics in Mainz and will provide two operational modes. In the External Beam (EB) mode, a continuous wave (cw) and spin-polarised electron beam with 150 µA and 155 MeV will be delivered to the P2 Experiment. In the Energy-Recovery (ER) mode of MESA, the cw electron bunches are accelerated up to 105 MeV at 1 mA and guided to the MAGIX Experiment. After interacting with the gas jet target of MAGIX, the electron bunches are guided back into the cavities with a phase shift of 180° returning their energy to the cavity, which is used to accelerate new electron bunches. In the ER mode, four electron beams travel through the cryomodules in each RF phase: two electron bunches are accelerated, while the other two are decelerated. Figure 1 shows a scheme of the ER mode of MESA.

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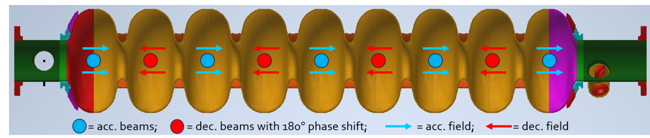

Figure 1: Scheme of the ER mode for MESA

## POWER LIMITS IN ER MODE

In a future upgrade for MESA, a new electron source is planned for the ER mode to increase the beam current up to 10 mA. A potential limitation of the accelerator operation is the beam-excited Higher Order Modes (HOMs) in the superconducting cavities, which are in the MESA Enhanced ELBE-type Cryomodules (MEEC). The power of the excited HOMs can be described by the following formula, with approximately 30% estimated at the HOM antennas [2]:

$$P_{\mathrm{HOM}} = N \times q \times k \times I, \tag{1}$$

where $N$ is the number of beams in the cavity, $q$ the bunch charge, $k$ the loss factor, and $I$ the average beam current. In the ER mode, two beams are accelerated and decelerated at the same time, yielding a total of four electron bunches in each RF phase. The upgrade to 10 mA would lead to an increased power limit from 30 mW to 1000 mW, as shown in Table 1.

In a worst-case scenario where the whole power at the HOM antenna would be converted into thermal loss at the antenna tip, the antenna would heat up. Thermal simulations show that an HOM antenna made from niobium would quench at a thermal loss of 330 mW [3]. The expected power would therefore lead to a quench in the HOM antenna in the 10 mA ER mode.

This power limit could be increased by using alternative superconducting materials with a higher critical temperature than niobium. Two candidates are NbTiN and $Nb_3Sn$, since both can be applied as thin films on substrates. One can change to a substrate with high thermal conductivity, such as Oxygen Free High Thermal Conductivity (OFHC) copper. Studies of NbTiN on niobium and $Nb_3Sn$ on copper have shown that the power limits can be increased up to 1100 mW and 4700 mW, respectively. Both coatings would exceed the expected limit for MESA.

Table 1: Beam induced power in HOMs and HOM antenna

| I (mA) | q (pC) | $P_{HOM}$ (mW) | $P_{Antenna}$ (mW) |
|---|---|---|---|
| 1 | 0.7 | 30 | 10 |
| 10 | 7.7 | 3000 | 1000 |

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# LOCAL MAGNETIC FIELD EVOLUTION IN SHIELDED SRF CAVITIES DURING THERMAL CYCLING IN A CRYOMODULE-LIKE CONFIGURATION

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*Abstract*

The performance of superconducting RF (SRF) cavities is crucial to build advanced and efficient particle accelerators. A comprehensive understanding of the remanent magnetic field evolution at cavity surfaces during thermal cycling is essential for efficient and high-performance acceleration systems since trapped magnetic flux formation can significantly increase the dissipated power in the SRF surfaces and is especially important for the development of new high-Q cavities.

At FREIA laboratory, Uppsala University, an investigation of the remanent magnetic field evolution was performed during cool-down/warm-up cycles of a superconducting RF (SRF) single spoke cavity (352 MHz) produced for the MINERVA/MYRRHA project. Hereby, the cavities were each equipped with a dedicated magnetic shield in a horizontal test cryostat. Upon cool-down, the change in the cavity-surrounding magnetic field was observed as a consequence of the Seebeck and Meissner effects. These effects differentiate between generated thermoelectric currents due to temperature gradients across dissimilar metals and the change of magnetic fields in vicinity of the cavity walls when an SRF cavity expels or redistributes trapped magnetic fluxes upon transitioning from the normal conducting to the superconducting state. The estimated influence of the remanent magnetic field dynamics on SRF cavity performance is discussed.

## INTRODUCTION

In the frame of Phase I of the MYRRHA project [1], referred to as MINERVA, FREIA [2] oversees the cryogenic RF testing of all SRF cavities meant for the main MINERVA linac. During an accelerator's lifetime a cavity cryomodule will go through several thermal cycles, thus emphasizing the importance of studying remanent MF dynamics for future reference. In the presented study we complement previous investigations of the MFs generated during cool-down and warm-up of SRF cavities [3, 4] by experiments and numerical simulations of this effect for manufactured MINERVA cavities.

## EXPERIMENTAL SETUP

In the frame of cryogenic high-field SRF cavity acceptance tests of the MINERVA cavities [5], FREIA relies on a horizontal cryostat HNOSS [6]. It can host up to three MINERVA cavities plus magnetic shields (MGSs), as shown in Fig. 1.

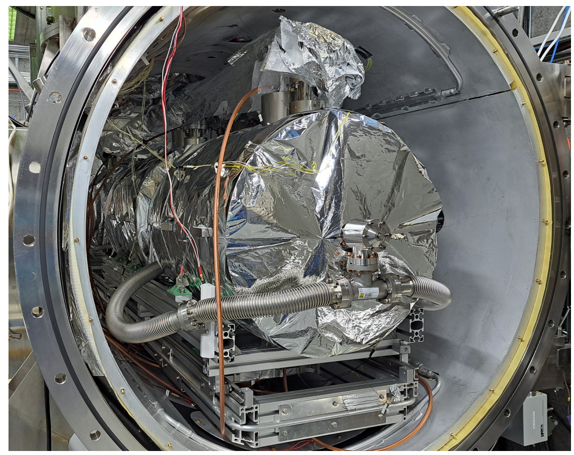

Figure 1: Picture of HNOSS with three cavities with their respective MGSs installed.

For a MINERVA cryomodule, the Earth's magnetic field shall be reduced inside an MGS to less than 2 μT (20 mG). This value may be exceeded locally due to openings required for cavity auxiliary components (e.g. ports for fundamental RF power coupler, 2 K pumping, He fill lines and RF field probe) and the beam tubes. Note that HNOSS is equipped by design with a global MuMETAL® magnetic shield. It covers the inner walls of the cryostat vessel (at room temperature). This provides an already reduced MF (<2 μT) for two cavities located close to the end lids of HNOSS (otherwise higher)[1]. For a cavity placed in the middle the use of an MGS is therefore mandatory for RF cavity acceptance tests. This setup allows to perform precise measurements of the remanent MFs.

At the time of writing, a total of 15 MINERVA cavities have been RF tested in HNOSS, initially housing two cavities per cool-down, but lately up to three cavities for maximum cavity acceptance test throughput. Note that HNOSS was designed to accommodate only two cavities using two individual He cooling and vacuum pumping lines. Therefore, the addition of a third cavity (placed in the middle) required utilizing the lines of a neighboring cavity. This means that a pair of cavities must share a combined He flow during

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[1] Verified by flux gate measurement within HNOSS before tests.

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# THE DEVELOPMENT OF 648 MHz ELLIPTICAL PROTO CAVITY FOR CSNS-II *

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*Abstract*

Since the second half of 2022, the design of the CSNS-II elliptical cavities was completed and their manufacturing was initiated. After nearly three years of research, we have successfully developed three prototype elliptical cavities. Vertical tests demonstrated a maximum gradient of 25.7 MV/m, significantly surpassing the operational requirement of 14 MV/m. This achievement has laid a solid foundation for the construction of CSNS-II. This paper details the design, fabrication, post-processing, and vertical testing of $\beta = 0.62$ elliptical cavities, covering challenges and solutions.

## INTRODUCTION

In the planned upgrade of the China Spallation Neutron Source Phase II (CSNS-II), a superconducting linear accelerator composed of double-spoke cavities and elliptical cavities will be installed after the existing room temperature Drift Tube Linac (DTL) [1]. The beam energy of the linear accelerator will be increased from 80 MeV to 300 MeV, and the peak beam current will be raised from 15 mA to 50 mA. Subsequently, the beam will be injected into the rapid cycling synchrotron (RCS) [2], which has added magnetic alloy cavities, where the proton beam power will rise from 100 kW to 500 kW and the average beam current will increase from 62.5 µA to 315 µA. Finally, the proton beam will be directed to the target station, which will have 11 additional beam lines for different experiments. The entire plan is shown in Fig. 1 [3]. The whole superconducting cavity accelerator comprises 18 cryomodules installed in a 92-meter tunnel(Fig. 2). [4, 5]

## DESIGN

The design of the elliptical cavity involves using the Superfish simulation software for 2D calculation and the CST simulation software for 3D modeling. Due to the relatively good symmetry and simple structure of the elliptical cavity, efficient parameter iterations can be conducted using Superfish during the electromagnetic design process. Once the geometric parameters are determined, CST is used for modeling and further Multipacting (MP) optimization of the cavity design. The key parameters of the elliptical cavity are shown in Fig. 3.

The obtained geometric parameters of the entire cavity are showed in Table 1.

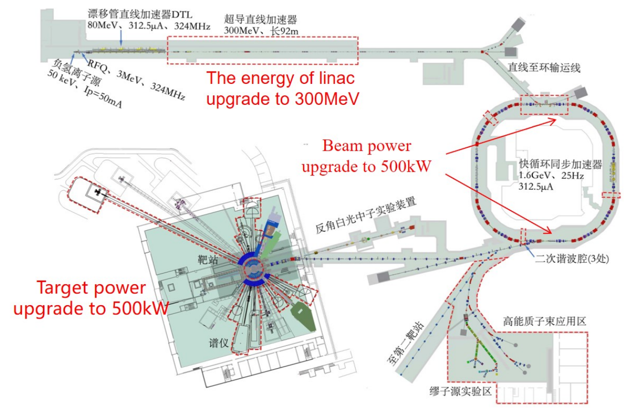


Figure 1: Overall upgrade layout of CSNS-II.

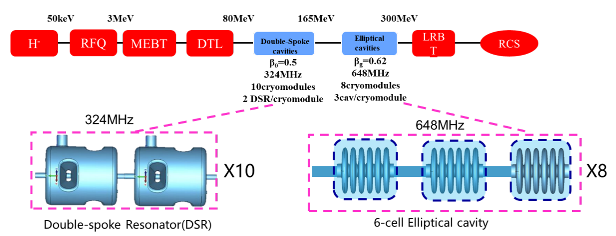


Figure 2: The layout of the upgraded linear accelerator for CSNS-II.

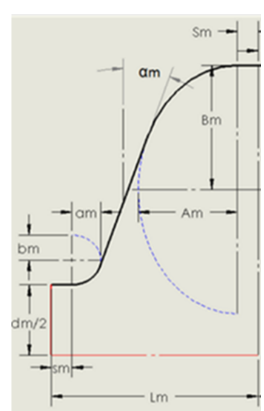


Figure 3: The main parameters of an elliptical cavity.

MP optimization is a critical focus in superconducting cavity design. For elliptical cavities, MP predominantly occurs near the equatorial region (Fig. 4). Therefore, the probability of MP can be reduced by improving both the geometric design and material properties of this area. Replacing the arc-shaped equatorial section with a flat-top structure effectively suppresses MP generation (Fig. 5). Simulations

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# DEVELOPMENT OF 1.3 GHz 3-CELL SUPERCONDUCTING CAVITIES FOR HIGH-CURRENT APPLICATION

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*Abstract*

1.3 GHz 3-cell superconducting cavities were proposed and developed for the injector of the high-brightness free electron laser based on energy recovery linac scheme. The average beam current is 10 mA and injector energy is 10 MeV. The beam tube of the cavity is enlarged to damp higher-order modes (HOMs) and to keep beam stability. Three cavities have been fabricated. An intrinsic quality factor of $2.0 \times 10^{10}$ at 12.0 MV/m and a maximum accelerating gradient of 25.6 MV/m were achieved in the vertical test of the first bare cavity. Design, fabrication, surface treatment, and RF test results will be presented in this paper.

## INTRODUCTION

Energy Recovery Linacs (ERLs) represent a promising technology for next-generation high-power free electron lasers (FELs) and light sources [1–3]. A high-brightness ERL-FEL based on superconducting radio-frequency (SRF) techology was recently studied. The injector section of the ERL-FEL was designed to accelerate a 10 mA electron beam to 10 MeV [4]. This demands cavities capable of operating at high accelerating gradients with high quality factors while maintaining effective higher-order mode (HOM) damping for beam stability. A 1.3 GHz 3-cell cavity was proposed as the SRF cavity for the injector cryomodule. This paper reports on the cavity design, fabrication, surface treatment, and vertical test results of the 1.3 GHz 3-cell superconducting prototype cavities.

## CAVITY DESIGN OPTIMIZATION

### *RF Design*

The cavity design maximizes the use of existing TESLA cavity technology while implementing specific optimizations for high-current operation. The beam pipe on one side is enlarged to damp HOMs, namely large beam pipe (LBP). The other side is kept as same as TESLA cavity's design, namely small beam pipe (SBP). The transition part between end-cell and LBP is optimized to suppress HOMs while keeping good accelerating efficiency. The cavity incorporates twin fundamental power couplers (FPCs) to handle large CW RF power. Details of the RF design can be found in Ref [5]. The main RF parameters are summarized in Table 1.

Table 1: Main RF Parameters of 1.3 GHz 3-Cell Cavity

| Quantity | Value |
|---|---|
| Frequency [MHz] | 1300 |
| Length [mm] | 643 |
| Small beam pipe diameter [mm] | 78 |
| Large beam pipe diameter [mm] | 100 |
| R/Q [Ω] | 329 |
| G [Ω] | 272 |
| $E_{pk}/E_{acc}$ | 2.0 |
| $B_{pk}/E_{acc}$[mT/(MV/m)] | 4.26 |

### *HOM Analysis*

Higher-order mode damping is critical for high-current operation. The enlarged 100 mm beam pipe diameter was optimized to provide effective HOM suppression while maintaining reasonable geometric constraints. HOM impedances were calculated using CST Eigenmode solver. The highest $Q_{ext} \times R_{\|}/Q$ for monopole modes is $1.9 \times 10^4$ Ω at 2450.7 MHz, which is much less than the power absorption capacity of 100 W in the absorber [6]. For dipole modes, the highest $Q_{ext} \times R_{\perp}/Q$ values are $3.0 \times 10^4$ Ω/cm for X polarization and $2.0 \times 10^4$ Ω/cm for Y polarization, both well below the instability threshold of $5 \times 10^7$ Ω/cm [5].

## MECHANICAL DESIGN STUDY

### *Helium Pressure Sensitivity and Detuning Effect*

The mechanically evaluated and optimized cavity model is illustrated in Fig. 1. The frequency stability of the 3-cell injector cavity is dominated by helium bath pressure, which deforms the cavity wall and elongates the helium vessel. The helium pressure sensitivity ($df/dp$) can be expressed as

$$df/dp = df_{cell}/dp + df_{length}/dp, \quad (1)$$

where cell-wall deformation contributes only marginally, while axial elongation of the helium vessel end walls governs the overall detuning, as shown in Fig. 2.

Parametric simulations varying the stiffening ring radius show that $df/dp$ first increases and then decreases with radius. Very small radii or the absence of a stiffening ring

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# THE INFLUENCE OF ROLLING DIRECTION AND SURFACE PINNING OF DEFORMED GRAIN BOUNDARIES DURING RECRYSTALLIZATION IN HIGH-RRR NIOBIUM SHEET*

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*Abstract*

The ability to accurately and consistently quantify the recrystallized (Rx) microstructure of heat-treated high-purity Nb used in superconducting radiofrequency (SRF) applications is critical to improve material processing and cavity production. Deep drawing of SRF cavity half-cells results in different strain paths in different locations (which includes prior rolling history). Cavity production typically chemically removes the damaged surface layer followed by a 3-hour 800 °C vacuum anneal. Dislocation substructures that develop during the anneal are known to be sources of magnetic flux trapping, and higher temperature anneals between 900 and 1000 °C can reduce these defects and improve cavity performance. As the microstructure differs in each lot, rolling coupons in different directions could identify variations in Rx response and provide guidance for an optimal anneal for a given lot. Comparing the microstructure in the same place before and after annealing was done on polished surfaces. However, surface pinning of grain boundaries preserved the as-rolled microstructure, in contrast to the bulk, where there was no boundary pinning. The effect of the strain path on Rx is exaggerated on the polished and pinned surface. Removal of surface grains reveals similar Rx microstructures with larger grain sizes. Hence, it is critical for the SRF community to understand where measurements are taken (surface vs. interior) to accurately quantify the extent of Rx present in the material.

## INTRODUCTION

Cavity production for superconducting particle accelerators has improved to the point that the theoretical limiting field can be occasionally achieved [1]. The lack of consistent performance arises from various factors such as trapped magnetic flux, resulting from metallurgical defects including impurities and dislocation substructures such as low angle grain boundaries [1, 2]. Dislocation recovery occurs due to lower temperature and slow heating rates that enable many dislocations to disappear, but the geometrically necessary dislocations (GNDs) that are required to maintain orientation gradients resulting from plastic deformation reorganize to form low angle grain boundaries. For the LCLS-II, some cavities showed improved performance following heat treatments at 900-1000 °C, but there was also grain growth that lowers the yield strength [3]. To investigate optimal heat treatments, it is hypothesized that a recrystallization (Rx) anneal will cause high angle grain boundary mobility to sweep out dislocation substructure such as low angle grain boundaries that can trap flux. Also, because pure Nb sheet often has variable microstructure, the optimal heat treatment temperature may depend on the actual microstructure state. Thus, coupons from a given lot could be deformed in a way that is representative of cavity forming and heat treated to identify an optimal heat treatment schedule. To explore this possibility, the effects of prior rolling history, heating rate, and annealing temperature were examined using coupon samples as reported in Ref. [3]. In this study, assessments of the GND density at each pixel were used to estimate the fraction of Rx grains; low GND material is recrystallized, while high GND density material is recovered, retaining orientation gradients from deformation. There is a well-defined threshold that separates these two populations as shown in Fig. 1. As this study showed minimal Rx after a standard 3-hour 800 °C vacuum anneal in contrast to many other studies, and an anomalous result discussed further below, the cause of this difference was investigated.

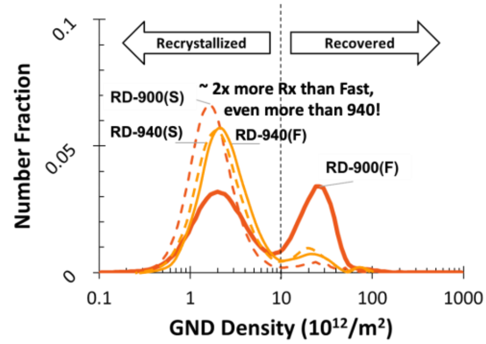


Figure 1: Data from [4] that illustrates a bimodal population of recrystallized and recovered grains from EBSD maps based upon GND density. The RD-900(S) was electropolished twice, accounting for the high Rx fraction.

## EXPERIMENTAL PROCEDURE

### *Coupon Sample Extraction and Free Surface Sample Preparation and Heat Treatment*

Coupons were extracted from remnant pieces of RRR ~350 sheet used to make a low-β cavity for the MSU FRIB. The impurity content of the Nb sheet is as follows:

- ~ 0.008 wt.% Ta
- < 0.0005 wt.% H
- < 0.001 wt.% W, Ti, Fe, Si, Mo, Ni, Zr, Hf, O, N, C

The original rolling direction was identified by visible striations allowing for samples to be rolled in the original rolling direction (RD) and the original transverse direction (TD) to approximately 30% reduction as shown in Fig. 2.

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# HIGH INTENSITY PROTON CRYOMODULE PARASITIC RADIATION ANALYSIS

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*Abstract*

Experimental evidence of parasitic radiation originating from cavity field emission or beam losses and interacting with cryomodule diagnostics has been collected.

We focus on the case of spurious triggering of power coupler interlock system which is based on the light detection of arcs and its transmission in optical fibers. Scenarii of radiation interaction are modelled using Geant4, aiming at reproducing several experimental observations, in the case of ESS high beta cryomodules and investigate possible mitigation techniques.

## INTRODUCTION

The ESS elliptical Medium and High Beta cryomodules (MBL and HBL CMs respectively) provide proton acceleration in the ESS linac starting at 216 MeV. As of September 2025, protons have been accelerated in 13 MBL and 6 HBL, above 800 MeV [1]. Prior to the start of beam commissioning, CMs are tested in Test Stand 2 (TS2), where they experience individual power coupler (FPC) conditioning at room temperature, cooldown, FPC conditioning and cavity field ramp-up at nominal 2K temperature. Those steps are repeated for CMs after tunnel installation and cooldown.

Already during the field ramp-up of cavities in TS2 occurrence of spurious triggering of non-energized FPCs window arc interlocks have been observed while another cavity was ramped up to its nominal gradient. The severity ranges from triggering one unrelated FPC arc detector up to all eight FPC arc detectors (2 for each coupler). This situation had further developments during cavity field ramp-up in the linac tunnel where arc detectors belonging to 3 CMs could be triggered by a single radiation event originating from a cavity.

The FPC RF windows are equipped with two viewports one on the vacuum side, one on the air side. If an arc occurs, an arc detection system triggers the shutdown of RF power for the particular cavity within 10 µs. Photomultiplier tubes (PMT) H10721-110 from Hamamatsu and custom signal amplification has proved to provide an efficient combination for ensuring coupler protection since the early stages of ESS FPC development [2]. In contrast to the setup used during CM validation tests carried out at CEA-Saclay on 10 CMs before their delivery to Lund, the PMT are not receiving the direct light at the FPC viewports neither in TS2 nor in the linac. Instead, optical fibers ensure the transport of a fraction of the arc light from the viewport to the arc detectors units (ADU) installed in the klystron gallery. The roughly 30 m long fibers are 2 mm PMMA core, cladded with a fluorinated polymer and polyethylene-jacketed stepped-index multimode optical fiber from Mitsubishi (ESKA-SH8001).

The false triggering of FPC interlocks has to be understood and mitigated to prevent an expected reduction in linac availability. In a general way, it is beneficial to reduce the signal background due to radiation.

## INTERACTION OF CM RADIATION WITH OPTICAL FIBERS

The core material of the fibers PMMA does not provide a scintillation mechanism so we do not expect X-rays or γs emitted to produce light directly. The bremsstrahlung spectrum for a single ESS HB cavity at nominal gradient extends up to 16 MeV. This range spans all three interaction mechanisms of photons with matter, namely ionization, Compton scattering and pair creation. With a refraction index of PMMA $n$ at around 1.49 in the visible range, Cherenkov light can be generated along electron or positron trajectories in the core, if the threshold energy of 180 keV is exceeded. The number of photons generated per electron track length in PMMA increases to its maximum value around 5 MeV (Fig. 1.) for e+ or e-.

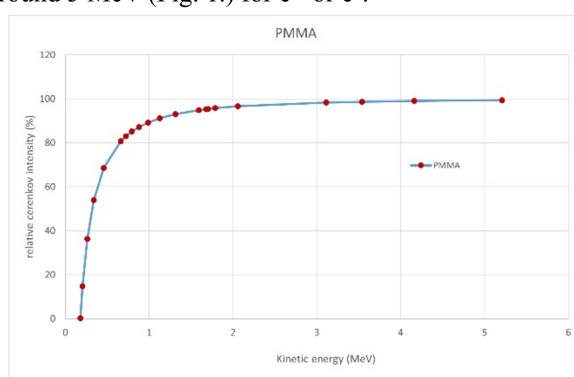


Figure 1: Relative intensity of Cherenkov radiation in PMMA for electrons or positrons.

Whether the photons propagate in the fiber through total internal reflection depends on the angle of $e^+$ or $e^-$ track with respect to the fiber axis, and of their velocity factor $\beta$ which determines the Cherenkov angle $\cos \theta_C = 1 / n\beta$. Since the optical fibers layout in the TS2 or the linac tunnel reflects the rather convoluted arrangement of cable trays, and considering the multiplicity of scenarii for radiation generation (FE, FPC emission, relative cavity RF phases,) resorting to Monte-Carlo simulation for the evaluation of the Cherenkov photon yield is required (see modelling section further in the paper.)

A simple experimental test was carried out to confirm the light generation in the ESKA fiber, independently of

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# PROGRESS OF SUPERCONDUCTING QUARTER-WAVE RESONATORS FOR HIAF AT IMP*

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*Abstract*

Three superconducting linear accelerators are under construction at the Institute of Modern Physics (IMP) of the Chinese Academy of Sciences (CAS). One of them is the High Intensity Heavy-ion Accelerator Facility (HIAF), 96 superconducting radio frequency (SRF) cavities housed in 17 cryomodules were fabricated, prepared, and installed in the accelerator tunnel in 12 months for the HIAF project. The vertical test of the SRF cavity and the cryomodule is skipped due to our stringent quality management and control. The mass production of the SRF cavity shows good performance, and a higher accelerating gradient than the operation specification is achieved. In this paper, an overview of the cavity design, production fabrication, string and cryomodule assembly, and operation status is introduced.

## INTRODUCTION

Presently, three accelerator projects based on superconducting radio-frequency technology are under construction at the Institute of Modern Physics (IMP), Chinese Academy of Sciences. One of them is the High Intensity Heavy-ion Accelerator Facility (HIAF), which will mainly focus on nuclear physics, atomic physics, heavy-ion applications and interdisciplinary research. It consists of two ion sources, a high-intensity heavy ion superconducting linear accelerator, a 45 mT accumulation and Booster Ring and a multi-function storage ring system [1].

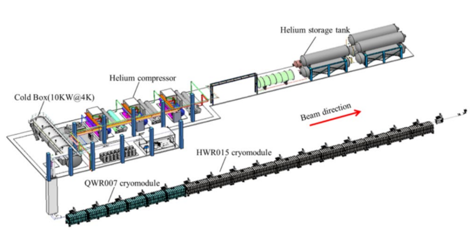


Figure 1: Layout of the high-intensity heavy ion superconducting linear accelerator [2].

The layout of the high intensity heavy ion superconducting linear accelerator of HIAF is shown in Fig.1 [2]. which is composed of two types of cavities, i.e., the 30 superconducting quarter-wave resonators with a frequency of 81.25 MHz and an optimal beta (v/c, v is the charged particle velocity, c is light velocity) of 0.07 labelled as QWR007, the 66 superconducting half-wave resonators with a frequency of 162.5 MHz and an optimal beta(v/c) of 0.15 labelled as HWR015. Six QWR007 cryomodules (five QWR007 cavities in each cryomodule) and eleven HWR0015 cryomodules (6 HWR015 cavities in each cryomodule).

In the past several years, IMP has developed tens of low-beta superconducting radio-frequency cavities with different types. The cavities have been successfully operating in the CiADS 25 MeV demo facility [3]. The production and integration process of low-beta cavities based on the characteristics of low-frequency and low-β superconducting cavities has been optimized. A complete quality management system for the manufacturing and surface processing of the SRF cavities was established. The vertical and horizontal testing steps were omitted for mass production. We emphasize and implement the full-life-cycle surface quality control and add online surface treatment methods as a guarantee for pollution control. Since the main performance limit of low-beta cavities is field emission, therefore, we eliminated the traditional tests (i.e., vertical test), strengthened process control and online repair capabilities.

Now, all the cryomodules have been assembled and installed in the accelerator tunnel of HIAF. In July 2025, we conducted the cryogenic test for the six QWR007 cryomodules; the performance of all the QWR cavities meets the specifications of the project. The cooling of the HWR015 cryomodules is undergoing. In this contribution, the overview of QWR007 development will be presented, including the design, fabrication, vertical test, horizontal test of the QWR007 cavities, etc.

## DESIGN OF QWR007 CAVITY

The EM and mechanical design were conducted using CST Microwave Studio and the software ANSYS, respectively. The goal of EM design is to minimize $E_{pk}/E_{acc}$ and $B_{pk}/E_{acc}$ ratios, maximizing geometric factor G and R/Q for the QWR007 cavity. Therefore, reducing the possibility of field emission and thermal quench, minimizing the cryogenic loss of the cavity. The main focus of mechanical design is to minimize the frequency sensitivities of the cavity to helium fluctuation (df/dp) and Lorentz force (LFD). Meanwhile, the design also takes into account ease of post-surface processing, low fabrication difficulty, and cost. Finally, a cylinder-shaped outer conductor was chosen, and two rinsing ports were set on the bottom and top of the cavity, respectively, for efficient high-pressure rinsing. Table 1 gives the RF parameters of QWR007 at 2 K. The EM dis-

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# PIP-II LB650 CRYOMODULES TEST BENCH AT CEA

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*Abstract*

The Proton Improvement Plan - II (PIP-II) project at Fermi National Accelerator Laboratory (Fermilab) is the first U.S. accelerator initiative to include major in-kind contributions (IKC) from international partners. As part of the French contribution, the French Alternative Energies and Atomic Energy Commission (CEA) will deliver ten 650 MHz low-beta (LB650) cryomodules. These cryomodules incorporate superconducting cavities provided by INFN-LASA (Italy), Fermilab (USA), and DAE-VECC (India), as well as RF power couplers and tuning systems from Fermilab. The scope of work carried out by CEA includes the design, manufacturing, integration, and performance testing of the cryomodules. This paper focuses on recent progress related to the Site Acceptance Tests (SAT) for the main equipment of cryogenic and RF systems and the preparation of the test stand for the LB650 cryomodules. It highlights the ongoing efforts and progress made in preparing the infrastructure, as well as the steps being taken to ensure readiness for the upcoming cryogenic and high-power RF testing phases of the LB650 cryomodules.

## INTRODUCTION

The central element of PIP-II is an 800 MeV linear accelerator designed to deliver 1.2 MW of proton beam power from the Main Injector [1]. CEA's major contribution to this project is the design [2], fabrication, assembly [3], and testing of ten LB650 cryomodules. An overview of CEA's contribution to PIP-II can be found in [4].

One of the most significant activities within CEA's scope [4] is the construction of a new test bench dedicated to the qualification of LB650 cryomodules at the Supratech Cryo/HF facility in Saclay [5]. Each LB650 cryomodule will undergo comprehensive cryogenic and RF testing at CEA to demonstrate compliance with the Acceptance Criteria List [6]. Several key procurements and the initial description of the test bench were reported in [7]. The procurement process, technical validation of major equipment, and construction of the test bench are now well advanced, with the technical requirements being met.

This paper presents an updated overview of CEA's activities on the realization of the cryomodule test bench and the performance validation of key procurements, namely the associated cryogenic and RF power systems.

## CRYOMODULE TEST BENCH

For a more detailed understanding of the expected equipment performance, the reader is referred to [6] for details on the test plan and acceptance criteria for the LB650 cryomodules, and to [7] for information on the definition of the main procurements.

The cryomodule test cave, shown in Fig. 1 is currently being upgraded, taking into account radiation calculations based on the expected operation conditions of LB650 cryomodule in conformance with the test plan [6] and acceptance criteria.

Four 19 kW CW solid-state amplifiers (SSAs), operating at 650 MHz and required to feed the four superconducting cavities of the cryomodule in parallel and independently, have been procured and thoroughly tested at CEA.

The associated RF circulators and loads, delivered more than one year ago, have also been validated under RF power operating conditions and in several operational configurations. Details on the RF power test results are provided in a subsequent section of this paper.

The waveguide RF network has been designed to allow flexible operation: in case of an SSA failure, the RF power feeding a cavity can be quickly switched to the nearest SSA using the rapid connections provided by the waveguides. Most of the waveguide components have been procured, and the remaining ones are expected to be delivered before the end of 2025.

The design of the control and instrumentation racks has been finalized, and most of the hardware has been procured. The integration of the equipment into the racks is currently being prepared.

Regarding cryogenic equipment, the commissioning of the new cold box was done at CEA and the equipment has achieved the expected performance. A summary of results will be presented later in this document.

The design of the cryodistribution system, which mainly includes the Valve Box and the transfer lines, has been successfully finalized. A significant portion of the Main Cryogenic Transfer Line (MCTL) has been procured, and installation is currently being carried out.

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# ASSEMBLY OF THE LIPAc SRF LINAC CRYOMODULE

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*Abstract*

In complement to the development activities for fusion reactors (JT-60SA & ITER), Fusion for Energy contributes to the R&D for material characterisation facilities. The LIPAc, technical demonstrator for the production and acceleration of a D+ beam, will be used for neutron production by nuclear stripping reaction on a liquid Li target.

Since its first beam in 2014, the LIPAc construction and commissioning continues and will be concluded with the cryomodule installation aiming for beam validation at nominal power.

The cryomodule assembly, started in March 2019, was paused for two and half years, devoted to improve the pumping, repair, cold tests and high pressure rinse the solenoids. In August 2022, the cleanroom activities resumed with the cavity/coupler assembly but had to be paused again to fix a leaking bellows on a solenoid. In September 2024, the beam line left the cleanroom to start the cold mass assembly phase which was concluded in January 2025 with the cold mass insertion. In March 2025, the cryomodule was transported to the accelerator vault for the last assembly steps before its integration. The team is working on the connection of the super-conducting solenoids. The final leak tests of the cryomodule, conclusion of its assembly, are expected in the second half of 2025.

This paper presents the technical challenges encountered and their solutions, highlighting continuous progress in overcoming complex integration issues across a synergic international collaboration.

## INTRODUCTION

Since the completion of the cleanroom assembly in September 2024 [1, 2], the IFMIF LIPAc [3-5] team entered into the second phase of the cryomodule assembly. The eight half-wave resonators (HWR), β 0.094, Ea 4.5 MV/m operating at 4.45 K and 175 MHz [6, 7], and the eight focusing and steering superconducting solenoid packages, designed to operate up to 6 T [8], could be dressed in the different elements leading to the constitution of the cold mass.

The cryomodule assembly is the result of an international collaboration between CEA, which procured the various components of the cryomodule—HWRs, Fundamental Power Couplers (FPC), support frame, shields, cryogenic and vacuum vessels [9, 10] —and CIEMAT, which provided the superconducting solenoids and current lead packages. The FPCs, developed and procured by CEA [11, 12], where conditioned in Madrid by CIEMAT [13].

Regarding the assembly, the contract was awarded to Research Instruments GmbH (RI), which regularly deployed teams to Japan and also participated in cold leak tests in Europe for the superconducting solenoids. Fusion for Energy and QST support RI teams onsite with technical issues and heavy handling operations, in collaboration with local companies.

## COLD-MASS ASSEMBLY

### *HWR Frequency Control*

The first task following the cleanroom assembly was a control of the resonance frequency of each of the superconducting cavities after such a long period. The network analyser was connected to the FPC through a 6 1/8” coax line to type-N adaptor and to the RF pick-up installed on the cavities. Signal amplification was performed on the coupler side. Measurements taken at room temperature in Japan were correlated with those taken at 4 K during vertical tests at CEA.

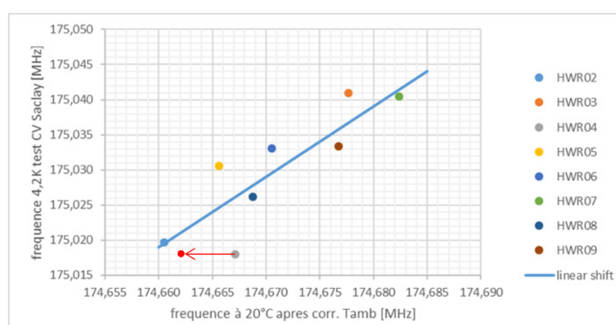


Figure 1: $f_0$ correlation at 4 K and 300 K.

It was observed that the HWR09 frequency deviated from the cluster of data points. A mechanical constraint was suspected and later identified as a bellows support used during the cleanroom assembly. Once the support was removed, the frequency aligned with the rest of the data points, Fig. 1.

### *First Alignment*

Before the initial alignment of the beamline, the final support and adjustment system was installed. This system

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# IMPROVED CALORIMETRIC CAVITY MEASUREMENT TECHNIQUES FOR THE HB650 PROTOTYPE CRYOMODULE FOR PIP-II*

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*Abstract*

Measuring cavity quality factors in a cryomodule requires calorimetric techniques because of the heavy input over-coupling. This involves using physical parameters of the cryogenic system such as mass flow, bath pressure, helium liquid level to estimate dynamic heat load of SRF cavities, often calibrated with heaters. The main challenges of these techniques are reducing sources of variation and error in the system to below the precision level required for the low dynamic heat levels added by the cavities and identifying and incorporating all of the important parameters into the analysis. For testing of the prototype HB650 cryomodule for PIP-II, we've developed a completely data-driven fitting technique that significantly reduces the error of the resulting qualify factor measurements which reducing the overall length of the measurement. This technique with example analyses and error analysis will be presented.

## INTRODUCTION

A challenge for the testing of SRF cryomodule is the measurement of critical cavity parameters with a heavily over-coupled input RF coupler. The mismatch between these couplers and the cavities themselves precludes direct electrical measurement of the losses in the cavity, and so calorimetric techniques are used.

Fundamentally, these techniques use heaters in the 2 K helium bath to calibrate some cryogenic parameter (e.g., flow, pressure). This parameter is then used to calculate the heat dissipated by the cavity, which can be combined with gradient extracted from the calibrated LLRF system to give a cavity Quality Factor.

There are a few limitations or assumptions required for this technique:

- The heater used is measured accurately (generally true if done via 4-wire measurement) and gradient is well calibrated in the LLRF system.
- The heater power is dissipated entirely in the 2 K bath. This is certainly not a priori true, but a well-designed system (heater in the bath, or in well-sunk thermal well) can greatly reduce heater power lost to non-2 K bath.
- That the region of your variation of the chosen parameter does not introduce other non-linear effects (e.g., large pressure changes change saturation temperature).
- That the chosen parameter (e.g., flow, bath pressure) does not have other confounding influences, i.e., that you can actually control this parameter.

The first two assumptions are system design features; design a good system and these are well-handled. The third limitation pushes the choice of parameters to outlet helium mass flow from the 2 K bath. Bath pressure rise is a traditional other parameter, but this strongly couples in other non-linear effects, especially the change in liquid helium saturation temperature and other thermal parameters, which is confounding to the ultimate measurement of Q0.

## PIP2IT Q0 MEASUREMENT PROCEDURE

The PIP2IT test stand at FNAL thus uses the following procedure for measurement of Q0:

1. Fix JT inlet valve with the cryogenic system in stability, fixing the input enthalpy flow.
2. Turn on heater to fixed value, and wait for 2 K Helium Bath pumping flow to stabilize at a new, higher value. Note: This causes drop of liquid inventory.
3. Return to stability with heater off, then energize cavity with RF system to fixed gradient of interest.
4. The change in pumping flow from 'static' condition to heater calibrates Watts to grams/second, and this calibration is used to give cavity dissipated power at the gradient used, and thus Q0.

### *Challenges with Basic Technique*

As can be seen in Fig. 1, the background flow rate in 'stable' conditions with only static load is not perfectly stable. Critically, the variation is on the order of tenths of grams/second, which is the level of expected signals for both heater and cavity.

This causes a major challenge for the analysis of calorimetric Q0 measurements: how is the region of 'stability' chosen for each state? Without making more assumptions about the system, flow with heater or cavity on must be done by hand, and is optimally left to stabilize for a long time so that drifts and oscillations can be averaged. However, as noted above, because of the fixed JT, the liquid inventory is changing during measurement, so the time available for stabilization is limited before non-linear effects are introduced.

## PROCEDURE OPTIMIZATION

The goal of this study was to find a technique that could, making as few assumptions as possible, do the following:

- Use all of the data available instead of a smaller subset during 'stability' periods

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# RF IN-SITU HEATING OF A SINGLE AND NINE-CELL 1.3 GHz CAVITY*

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*Abstract*

RF *in-situ* heating of cavities can contribute to achieving high accelerating gradients ($E_{acc}$) and high quality factors ($Q_0$). In this work we present RF *in-situ* heating experiments on a 1.3 GHz TESLA-shaped single- and a nine-cell cavity. By sequentially driving all accessible eigenmodes for the nine-cell cavity, we observed mode-specific heating patterns as expected. Inhomogeneous heating, which was observed for the $\pi$-mode, could most likely be attributed to an overlength antenna. A maximum temperature of 140 °C (600 W) was reached for the nine-cell cavity and 240 °C for the single-cell cavity, although this is certainly not the limit. With an improved setup, higher temperatures would certainly be possible. These results show that RF *in-situ* heating is a practical complement to conventional baking in a furnace (at moderate temperature), with the remaining challenges lying primarily in temperature uniformity.

## INTRODUCTION

High acceleration gradients $E_{acc}$ and high quality factors $Q_0$ can be achieved by heat treatments of a cavity [1]. However, the heating processes are carried out in furnaces where the cavity is exposed to air and water afterwards (due to high pressure rinsing), which leads to oxidation of the niobium and can also cause contamination. For moderate temperatures ($T < 350$ °C), this issue could be overcome by *in-situ* heating. A few studies on *in-situ* heating have already been published, showing promising results [2, 3]. However, the heating was achieved using heating strips, which is difficult to implement in an accelerator cryomodule. By applying a radio frequency electromagnetic field at room temperature to the cavity (here called RF-heating), the cavity can be heated under UHV conditions without being exposed to air. Furthermore, this configuration could be in principle implemented in the cryogenic module, although some design changes would have to be made and the feasibility would have to be demonstrated. The possibility of proper heating in a cryogenic module would be advantageous for accelerators without gas processing capabilities where plasma processing cannot be performed e.g. due to too long uninterrupted module strings. An initial, still preliminary investigation into RF heating was recently reported [4]; this study was conducted entirely independently of the work presented herein. In the work presented here, we will further investigate RF heating and explain the experimental setup. In addition, first heating results for a TESLA-shape 1.3 GHz nine-cell and a single-cell cavity will be presented, whereby temperatures in the mid-T range (approx. 240 °C) have already been achieved for a single-cell with the current setup.

## EXPERIMENTAL OVERVIEW

**Experimental Setup** For the RF *in-situ* heating studies, a 1.3 GHz TESLA-shape single-cell 1AC2 and nine-cell Z84 niobium cavity was used, each of which was fixed in a frame so that the cavity could be evacuated. A photo of the experimental setup is shown in Fig. 1 a) for the nine-cell cavity. The single-cell cavity is shown in Fig. 1 b).

The cavities were equipped with a input and a pickup antenna, allowing RF driving as well as monitoring of the resonant response. The antenna length for the nine-cell was set to 108 mm and for the single-cell to 219 mm with an antenna radius of 2.5 mm. In the case of the nine-cell cavity, a vacuum pump station was connected however, for technical reasons, this was not the case for the single-cell. Temperature monitoring was carried out using sensors attached to several points on the nine-cell cavity. Sensor TR1 was located on the RF plug, while TR2, TR3 and TR4 were located on the equator of the cavity of cells 1, 3 and 9 (see Fig. 1). In addition, an infrared measuring device was used to monitor the temperatures as well. For the single-cell cavity, three temperature sensors were positioned at the lower beam tube (TR1), on the equator (TR2) and on the upper beam tube (TR3).

**Experiment Implementation** The RF signal was generated by a signal generator, with the RF power $P_{forward}$ provided by an amplifier (up to 1000W) and fed into the cavity via a fixed copper antenna (inset in Fig. 1, bottom left). A directional coupler was used to measure $P_{forward}$ and the reflected power $P_{reflected}$, enabling monitoring of the cavity parameters. The excitation was performed as a first test in case of the nine-cell cavity in all eigenmodes and for the single-cell in its eigenmode. For this, the eigenmodes were measured at room temperature using a spectrum analyser, whose values were then used as start frequencies $f$ for the heating. Since, the frequency is temperature dependent, it was adjusted during the power ramping accordingly to minimise the reflection power $P_{reflected}$. The nine-cell cavity was first driven with an input power of 300 W in order to compare the modes (see Table 1). In addition, 600 W was tested for the $\pi$ mode (see Fig. 3 a)) and a maximum power of 500 W was tested in case of the single-cell cavity (see Fig. 4).

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# UTILIZATION OF REMOTE MONITORING TOOLS IN THE LONG-TERM OPERATION OF THE SUPERCONDUCTING LINAC AT RIKEN

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*Abstract*

The RIKEN superconducting heavy-ion linear accelerator (SRILAC) began operation in 2019 as a booster of the existing RILAC (RIKEN Heavy-Ion Linac) for superheavy element search experiments and has now entered its sixth year of operation. SRILAC is routinely operated continuously for several months, during which the superconducting cavities exhibit state changes, such as reductions in RF output, temporary RF (Radio Frequency) regulation unlocks, fluctuations in liquid helium tank pressure, and variations in cavity vacuum levels. These events, if not properly managed, can lead to cavity quenches or interruptions of beam delivery, highlighting the importance of continuous monitoring and rapid operator responses. Compared with normal-conducting accelerators, the number of critical parameters that need to be monitored in a superconducting linac is significantly larger, making long-term operation particularly demanding. To support stable operation and effective information sharing, we developed complementary web-based monitoring tools that provide online visualization of the accelerator status, including trend graphs, machine protection system alarms, and control screen streaming through standard web browsers. These tools have contributed to sustaining the high availability of SRILAC by helping operators track system conditions both in the control room and remotely. This paper reports on the operational experience gained at SRILAC, emphasizing the role of such monitoring practices in sustaining stable long-term performance.

## INTRODUCTION

The RIKEN superconducting heavy-ion linear accelerator (SRILAC) has been operating successfully for almost five years as a booster to the existing RILAC (RIKEN Heavy-Ion Linac), continuously delivering heavy-ion beams for superheavy element synthesis experiments [1]. Despite initial hardware problems such as a broken coupler in the early days and increased X-ray emission in several superconducting cavities, corrective measures, including high-power processing, have stabilized the system. By fine-tuning the low-level RF (Radio Frequency) control [2] and cryogenic system [3], an availability exceeding 99% has been achieved, ensuring reliable long-term beam delivery [4].

Compared with normal-conducting accelerators, superconducting linear accelerators (linacs) such as SRILAC require the monitoring of a significantly larger number of parameters, including RF, vacuum, and cryogenic conditions. During extended operation over several consecutive months, fluctuations in cryogenic or vacuum conditions must be carefully monitored to avoid cavity quenches or interruptions in beam delivery. Therefore, continuous monitoring and rapid responses are critical for sustaining stable operation. In fact, the consistently high availability of SRILAC has been supported not only by improvements in hardware and control systems [5], but also by the deployment of remote monitoring tools that enhance the ability of operators to follow system conditions in detail and respond promptly to anomalies.

At the RIBF (Radioactive Isotope Beam Factory), the experimental physics and industrial control system (EPICS) serves as the basis of the control infrastructure with standard GUI tools such as operator panels and archive viewers [6,7]. However, during the extended operation of SRILAC, its limitations became apparent, particularly in relation to quick-trend visualization and the efficient handling of large parameter spaces. To address these issues, we developed new web-based monitoring tools that complement the existing EPICS interfaces. These applications provide online visualization of the accelerator status, including parameter trends, machine protection system (MPS) alarms, and operator screens, thereby supporting the long-term operation of SRILAC in a more flexible and accessible manner. At the RIBF, web-based applications such as electronic logbooks and archive viewers have already been deployed and accessed through reverse proxy connections [8,9], and these earlier experiences provided the foundation for developing new tools tailored to SRILAC operations.

## DEVELOPMENT AND OPERATION OF WEB APPLICATIONS

### *Trend Monitoring with Web-based Data Viewer*

We developed and are operating a dedicated web-based archive viewer called the Archiver Appliance Chart (AA Chart) to retrieve and visualize the time-series data stored in the EPICS Archiver Appliance (Fig. 1). This tool retrieves archived data through the AA retrieval API and provides interactive visualization functions. Time-series data from the accelerators, including the SRILAC, are archived in the EPICS Archiver Appliance [10,11]. The number of records currently stored in the Archiver Appliance exceeds 200,000, a significant increase from the approximately 20,000 stored before the introduction of the SRILAC. Following its successful deployment in the SRILAC, the Archiver Appliance was extended to cover the entire RIBF control system, leading to substantial growth. Although the Archiver Appliance includes a standard data viewer, it is

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# MOCK-UP WAVEGUIDE LOOP DEVELOPMENT TOWARDS A HALF-METER SCALE TRAVELING-WAVE (TW) SRF CAVITY

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*Abstract*

Traveling-Wave (TW) technology can push the accelerator field gradient of niobium SRF cavity to 70 MV/m or higher beyond the fundamental limit of 50-60 MV/m in Standing-Wave regime. The success of TW resonance excitation in a proof-of-principle 3-cell SRF cavity in 2K liquid helium encouraged to advance TW technologies necessary more for future accelerator-scale one. Fermilab has proposed a preliminary RF design of a half-meter scale TW cavity by considering the physical dimensions of existing SRF facilities and the lessons learned from the 3-cell. It consists of a 7-cell structure and a power feedback waveguide (WG) loop with new TW excitation and control schemes such as, double directional coupler and two WG tuners. Mock-up waveguide loop development was launched under Fermilab LDRD program to demonstrate those new RF schemes at a room temperature. Fabrication drawings of a mock-up loop were completed. Here details and plans of the development are reported.

## INTRODUCTION

The 1st demonstration of TW resonance excitation at a cryogenic temperature was successfully achieved with a niobium 1.3 GHz 3-cell proof-of-principle SRF cavity in a collaboration between Fermilab and Euclid Techlabs [1]. In parallel with that 3-cell developments, Fermilab begun the RF design process of 0.5-1 meter scale TW cavity for advancing TW technologies necessary more for future accelerator scale one. Considering the physical dimensions of available SRF facilities (for fabrication, processing, and cryogenic testing with low/high-power RF) and high-power RF and beam applications, a preliminary RF design of a half-meter scale TW SRF cavity was proposed (Fig. 1) [2]. It consists of a 7-cell structure, the inner cell shape is identical to that of the 3-cell TW cavity, and a power feedback waveguide (WG) loop with novel techniques to establish and control TW resonance in a structure such as a double directional coupler and a two-tuner system. Multiple critical developments are needed to realize a half-meter scale (7-cell) TW cavity [3]. One of them is a demonstration of those new RF techniques on a WG loop. To focus and proceed that, a seed project of a low-cost mock-up WG loop development was awarded and launched under the LDRD program at Fermilab. In a mock-up loop, 7-cell structure will be replaced with an equivalent simple straight waveguide structure (Fig. 2). Fabrication of a mock-up loop using alternatives to niobium materials such as copper or aluminum can effectively model the most important RF properties of these novel techniques and motivate later investment in a full-scale niobium version once the operative principles have been demonstrated.

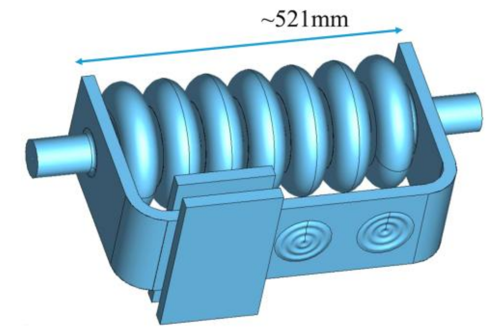


Figure 1: A preliminary RF design of a half-meter scale (7-cell) TW cavity [2].

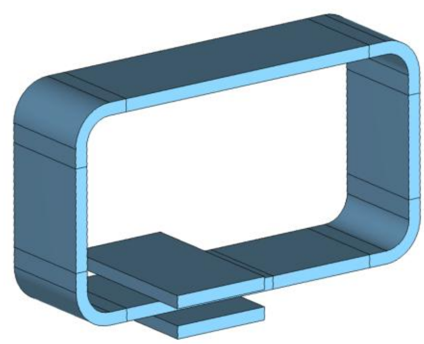

Figure 2: A preliminary RF design of a mock-up WG loop.

## NEW TECHNIQUES ON A WG LOOP OF A 7-CELL TW CAVITY

### *Double Directional Coupler*

Figure 3 shows the models of the 3-cell TW cavity and RF ports on WG highlighted with the circles. Two unity couplers on the 3-cell WG for RF feeds (red circle in Fig. 3) are replaced with a powerful directional coupler for a TW 7-cell shown in Fig. 4 as an input directional coupler. Advantages are:

1. only one high power RF coupler is needed to feed a cavity,
2. TW resonance excitation and control are simplified compared to the 3-cell procedures which require to adjust phases and amplitudes of two RF input sources [4].

Three RF monitoring couplers on the 3-cell WG (purple circle in Fig. 3) are also replaced with a directional coupler shown in Fig. 4 as a monitoring directional coupler. It reduces the efforts on calibrations and monitoring signal processing to evaluate a TW mode in a structure. Figure 4

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# FEATURE OF NC25 MATERIAL AND IMPACT ON FLUX TRAPPING WHEN USED THEM FOR SRF CAVITY ASSEMBLY*

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*Abstract*

FRIB has developed high Q and high gradient 0.53HWRs within a DOE grant program. In this study, flux trapping produces 80% of the residual surface resistance (Rres) was discovered. Thermoelectric current due to Seebeck effect (Dynamical magnetic contamination) at the dissimilar metal joints nearby cavity is a main contribution of it. Other contributions are DC magnetic contaminations: insufficient earth magnetic fields and the magnetized components nearby cavity. Uniform cool-down and active field cancellation could reduce the ambient fields to ~ 3 mG, and the resultant Rres ~ 1.5 nΩ. We experience that SUS bolts/nuts are magnetized, up to 1 Gausses after work. We replaced all SUS bolts/nuts on the cavity flanges with NC25 ones which are perfectly non-magnetized material. The ambient field was reduced to 1.5 mG and the resultant Rres was ~ 1 nΩ. Qo at low field reached ~ 9 x E+10 at 2 K. NC25 looks to be a very suitable material for cryogenic engineering. This paper will report the features of NC25 material and the impact of NC25 bolts/nuts on Rres, when used them to cavity assembly.

## FIRST MOTIVATION OF NC BOLTS/NUTS

NC is copper-nickel alloys. The number behind NC means rate of electric conductivity compared to pure copper at room temperature, i.e., NC25 has electric conductivity of 25% of pure copper. First motivation to consider NC material for bolts/nuts was to resolve gnawing issue when SUS bolts are screwed on NbTi beam pipe flange taps of the FRIB 0.085QWRs. Figure 1 at the top shows the issue.

## FEATURS OF NC25 MATERIALS

NC25 has excellent mechanical properties and suitable features to use SRF engineering. Here, we introduce the features.

### *Excellent Machinability and Smooth Machined Surface*

Photos on Fig. 1 left (SUS316L) and bottom (NC25) compare the microscope image of the screw surfaces, which show the much smoother machined surface with NC25 than that of SUS316L. Screw smoother surface of NC25 bolt mitigates the gnawing issue. FRIB finally used electropolished or silver-plated SUS316L bolts/nuts for cavity assembly with all production cavities and resolved this problem. There was no chance to use NC25 bolts during FRIB production, but more study about the NC25 bolts and nuts took place in the DOE grant project after FRIB completion.

### *Harder and Stronger Mechanical Property than SUS*

As illustrated in Fig. 2 kindly provided by Yamato Gokin Co. Ltd. [1], NC materials are harder and stronger than SUS materials. NC materials have 3-4 times harder and

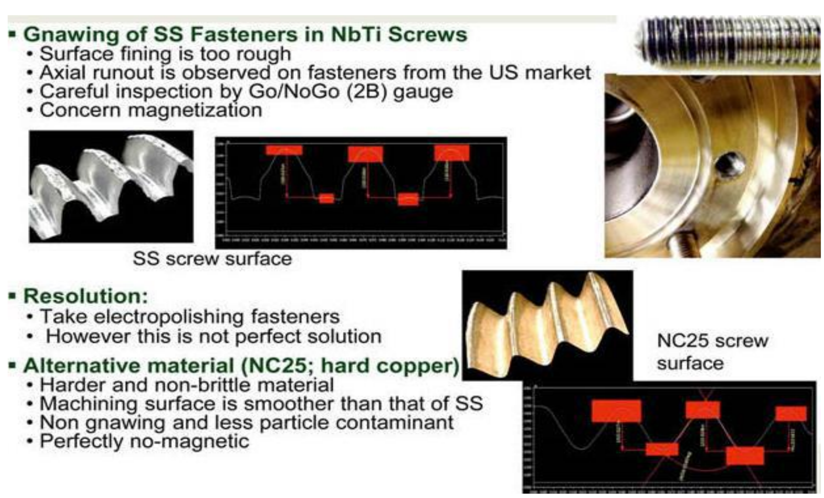


Figure 1: Motivation, gnawing issue SUS316L bolts and tap on the beam pipe flange. Top left shows the micro image of SUS316Lscrews, right bottom is for NC25 screws.

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# PRELIMINARY THERMAL LOAD CALCULATIONS OF SUPERCONDUCTING DEFLECTING CAVITIES FOR ELETTRA 2.0

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*Abstract*

Picosecond-long X-ray pulses of moderate intensity and high repetition rate are highly sought after by the light source community, especially for time-resolved fine spectroscopic analysis of matter in the linear response regime. We investigate the upgrade of the Elettra 2.0 diffraction-limited storage ring light source with superconducting radiofrequency transverse deflecting cavities generating a steady-state vertical deflection of selected electron bunches. In this paper, a preliminary design of the cryomodule of the deflecting cavities is reported; both static and dynamic thermal loads are calculated using an analytical approach. The dynamic loads are calculated assuming both bulk Nb and Nb3Sn thin film cavities. The two different solutions involve different cryogenic plants, which will be discussed.

## WORKING PRINIPLE

Two superconducting (SC) RF (Radio Frequency)cavities, resonant respectively at a 6-fold (3 GHz) and 6.5-fold frequency (3.25 GHz) of the main RF of the Elettra 2.0 ring, determine a steady-state configuration of vertically tilted bunches, with varying inclination along the ring circumference [1]. The charge distribution reaches the equilibrium in the 6-dimensional phase space [2]. The photon beam emitted by tilted bunches exhibits a longitudinal-vertical correlation (t,y). A vertical slit at some distance from insertion device (ID) samples the central portion of the stretched photon pulse, thus selecting a short portion in time, though at some reduced flux.

The RF design of crab cavities is based on the Quasi-waveguide Multicell Resonator (QMiR) [3], which uses trapped dipole-like e.m. mode for the deflection of the electron bunch.

## DESIGN OF CRAB CAVITIES

The prototype of QMiR cavity was built and successfully tested at a 2 K vertical cryostat and demonstrated a record transverse kick of 2.6 MV by Fermilab [4]. The crabbing scheme for Elettra 2.0 is shown in Fig. 1. The geometry and the dimension of a single crab cavity is shown in Fig 2 [5].

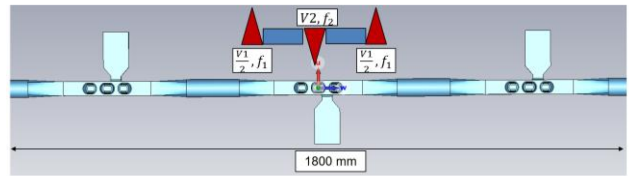


Figure 1: Proposed crabbing scheme for Elettra2.0.

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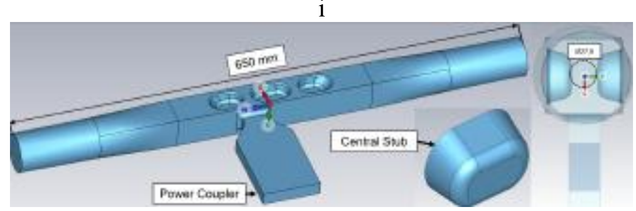


Figure 2. The stub shape for the crab cavities.

## Q0, RSF AND DYNAMIC THERMAL LOAD FOR Nb CAVITY @ 4K

The effective deflecting voltage determines the dynamic thermal load of the superconducting devices. Below the critical temperature or $T < T_c/2$, with $T_c$ the critical temperature, the BCS contribution to the surface resistance $R_{sf}$ dominates. The product $G = Q_0 R_{sf}$ results a characteristic of the geometry of the cavity, and only dependent from the operational temperature of the device:

$$G = Q_0 R_{sf} = Q_0 \omega^2 \lambda_L^3 \mu_0^2 \sigma(T) \exp\left(-\frac{\Delta}{K_B T}\right),$$

where $\lambda_L$ is the characteristic penetration depth of a static or microwave magnetic field in a superconductor such as niobium, and $\Delta$ is the superconducting gap, or binding energy of Cooper pairs.

For the equilibrium temperature $T < T_c/2$, $R_{sf}$ of pure niobium can be expressed in practical units:

$$R_{sf}[\Omega] \approx \alpha \times 10^{-4} \frac{(f[GHz])^2}{T} \exp\left(-\frac{17.67}{T}\right),$$

where usually $\alpha \approx 1.25$ for $T \approx 2-5$ K.

We can now estimate the power associated to the current losses per RF period on the internal wall of a tuned SC RF deflecting cavity in pure niobium, or “dynamic thermal load”:

$$P_{th} = \frac{\omega_0 U_0 R_{sf}}{G} d_f \equiv \frac{\Delta V_\perp^2}{2R_{sh}} d_f \ .$$

For a pure Nb deflecting cavities system as needed in the Elettra 2.0 light source, is reported in Table 1.

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# NEW CLEANROOM NITROGEN PURGE SYSTEM TO BE USED FOR SUPERCONDUCTING RADIO FREQUENCY CAVITY STRING BUILD AT STFC*

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*Abstract*

STFC has built new infrastructure to enable particulate control whilst building superconducting radio frequency (SRF) cavity string and beam line assemblies. The facility includes an ISO4 cleanroom, low particulate high pressure rinse, and most recently, a nitrogen purge system that can allow varying and controlled purge of filtered nitrogen through vacuum vessels as they are built. The nitrogen purge ensures that particulate ingress onto sensitive surfaces, such as within high beta RF cavities, is minimised. This paper describes the new slow pump slow vent vacuum systems, nitrogen purge system, their capabilities, and early results from validation testing to ensure that it operates within the required specification.

## INTRODUCTION

The new cleanroom facility was built as part of STFC's in-kind contribution to build PIP II HB650 cryomodules [1, 2]. An ISO 4 cleanroom is essential for SRF cavity string assembly to ensure optimal performance and reliability. These cavities operate under ultra-high vacuum and cryogenic conditions, where even microscopic particles can cause field emission, quenching, or increased RF losses. ISO 4 environments maintain strict particle control, preserving surface cleanliness critical for superconductivity. Clean assembly conditions also protect sensitive components like RF couplers and tuners, ensure vacuum integrity, and support predictable cryogenic behaviour. Adhering to ISO 4 standards aligns with international protocols followed by leading accelerator facilities [3, 4].

## SLOW PUMP SLOW VENT VACUUM SYSTEM

Slow pump and slow vent (SPSV) procedures are essential for minimizing particulate contamination during SRF cavity string assembly. Rapid pressure changes can dislodge settled particles or introduce contaminants into sensitive regions, jeopardizing the ultra-clean surfaces required for optimal superconducting performance. Controlled, gradual pressure transitions help preserve cleanroom integrity, prevent particle mobilization, and safeguard critical components from damage or contamination. This methodical approach is fundamental to meeting the stringent cleanliness standards necessary for reliable accelerator operation [5].

Figure 1 illustrates the new SPSV system design implemented in the STFC cleanroom. The system features an Edwards nXDS10i scroll pump, which backs a Leybold MAG400 turbomolecular pump. MKS 150 series bellows

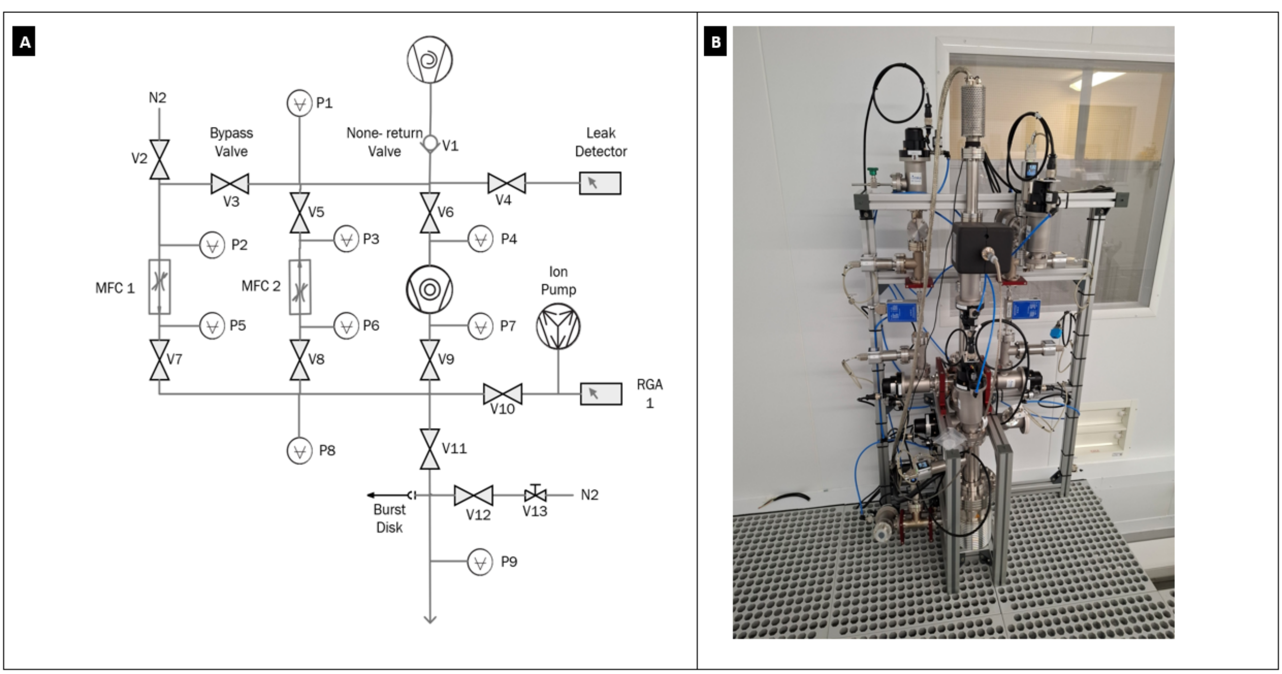


Figure 1. a) Schematic view of the SPSV systems and b) image of an as built SPSV system.

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# STRING ASSEMBLY FOR THE FIRST HELIAC CRYOMODULE

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*Abstract*

The first cryomodule of the superconducting (sc) Helmholtz Linear Accelerator HELIAC was assembled at the Helmholtz Institute Mainz (HIM). It contains three sc multigap crossbar H-mode cavities, as well as two sc solenoids and one sc buncher cavity. Individual components weigh up to 120 kg, while the complete 5 m long cold string has a mass of about 600 kg. The cleanroom at HIM was prepared and allowed a complete cleaning in an ISO-class 6 area with a dedicated ultrasonic cleaning and rinsing installation. Assembly with minimized particle contamination was carried out in the 43 m² ISO Class 4 area, where the heavy components were positioned using specialized rail wagons and lifting devices. Outside the cleanroom, the finished cold string was insulated and mounted within its thermal shielding and support frame, which then was integrated into the cryogenic vessel.

## INTRODUCTION

The Helmholtz Linear Accelerator HELIAC [1-3] is a superconducting (sc) continuous wave (cw) linear accelerator for heavy ions, currently under development at GSI (Helmholtzzentrum für Schwerionenforschung) in Darmstadt and the Helmholtz Institute in Mainz (HIM). Its primary purpose is to provide higher beam intensities for superheavy element (SHE) research [4], but also for other experiments in the low energy regime. Figure 1 presents a schematic layout of the HELIAC, and its key parameters summarized in Table 1. After the ion source and a normal-conducting (nc) injector linac [5, 6], the main acceleration will be performed in four cryogenic modules using superconducting crossbar H-mode (CH) cavities [7, 8]. These cavities are operated at 216.8 MHz cooled to 4 K using liquid helium. The output energy of the linac can be continuously varied between 1.4 MeV/u and 7.6 MeV/u for ions with a mass-to-charge ration of up to 6.

Following the successful operation of a superconducting CH cavity with ion beam in 2017 [9], the HELIAC project entered the next stage. In addition to the development of the normal conducting (nc) pre-accelerator, the goal was to construct the first of up to four cryomodules for the superconducting section [10, 11]. In Fig. 1 the first of the four cryomodules (CM1) is shown in magnification. CM1 houses three sc CH accelerating cavities [12, 13], one sc single spoke buncher cavity for longitudinal beam focusing [14] and two sc 9 T solenoids [11] for transverse beam focusing.

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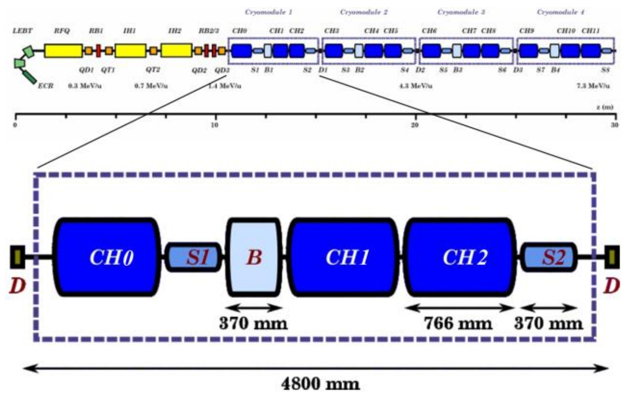


Figure 1: Schematic layout of the HELIAC and its first cryomodule CM1. The ion source to the left, followed up by a normal conducting section (yellow) and the superconducting part (blue). The positions of its CH cavities, the buncher (B) and its two solenoids (S) are shown.

Table 1: General Characteristics of the HELIAC

| Characteristic | Value |
|---|---|
| Frequency (nc-section) | 108.4 MHz |
| Frequency (sc-section) | 216.8 MHz |
| Mass-to-charge ratio (A/q) | ≤ 6 |
| Repetition rate | Continuous wave |
| Beam current | ≤ 1 mA |
| Injector energy | 1.4 MeV/u |
| Output energy | 1.4 MeV/u to 7.6 MeV/u |
| LHe operation | 4.2 K |
| Total length | Approx. 30 m |

The assembly of such a cold string, approximately 5 m in length and weighing about 600 kg, as well as treatment and preparation of its components, had to be carried out in specialized cleanroom facilities The relatively new HIM building, which went into operation in 2017, comprises such a cleanroom and other infrastructure for SRF projects at GSI and Johannes-Gutenberg University in Mainz [15, 16].

## CLEANROOM PREPARATIONS

A detailed overview of the HIM cleanroom (CR) has already been given in Ref. [15, 16]. The facility is equipped with a heavy-duty aluminum double floor with rail tracks that allow heavy cold strings to be moved through its

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# EXPANSION OF THE LINE-UP OF HIGH CAPACITY 4 K GM-JT CRYOCOOLER SYSTEM

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*Abstract*

Recent advancements in $Nb_3Sn$ cavity development have enabled the design of SRF accelerators utilizing compact mechanical cryocoolers instead of helium liquefiers, simplifying system architecture and reducing costs. In this background our company has released a high-effciency, high-capacity 4 K GM-JT (Gifford-McMahon-Joule-Thomson) cryocooler system with 10W-class cooling capacity at 4.2 K. This system provides higher efficiency and superior cooling performance in comparison to GM or PT (Pulse-Tube) cryocooler systems. So, it contributes to reducing power consumption, installation footprint, and maintenance costs for customer systems. To further promote the adoption of GM-JT cryocooler systems, ongoing development efforts focus on expanding low-vibration line-up, shortening cooldown times, and broadening operational temperature ranges.


## INTRODUCTION

Currently, SRF accelerators employ liquid helium cryoplants subcooled to 2 K to cool the cavities. Niobium (Nb) has traditionally been the material of choice for SRF cavities; however, $Nb_3Sn$ has recently been identified as a promising alternative [1]. Owing to its higher critical temperature of 4.3 K, compared to 2 K for Nb, direct conduction cooling with compact cryocoolers becomes feasible, thereby enabling simplification of system design and reduction of overall cost. Nevertheless, existing cryocooler systems (such as GM and PT types) provide only limited cooling capacity, which necessitates the use of multiple units and consequently introduces challenges in efficiency, footprint, and maintenance. To overcome these limitations, SHI (Sumitomo Heavy Industries) has been developing a large-capacity, high-efficiency 4 KGM-JT cryocooler with a cooling capacity of 10 W at 4.2 K. In this contribution, we present the line-up of GM-JT cryocooler system and additional available options.

## OUTLINE OF 4 K GM-JT CRYOCOOLER SYSTEM

### *System Configuration*

Figure 1 shows the 4 K GM-JT cryocooler system configuration. GM-JT cryocooler (RJT-100) requires two separately compressors for the JT (J117V) and the GM (E-77A) lines. And this cryocooler system requires a separately shield cooling system against radiation heat. However, the required cooling capacity of the shield cooler depends on the customer system, so the shield cooling system is prepared by customer [2].

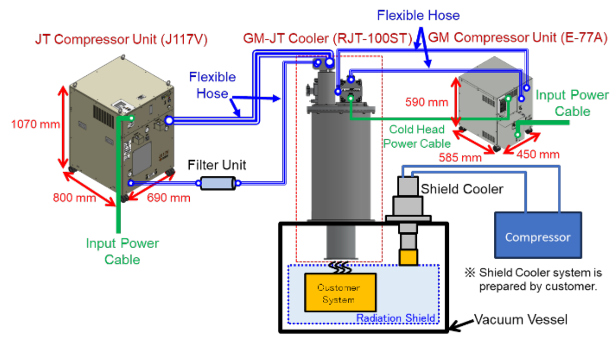


Figure 1: 4 K GM-JT cryocooler system configuration.

### *Specification*

Table 1 shows the specification of 4 K GM-JT cryocooler system. The 4 K cooling interface are available in stage type (RJT-100ST).

Table1: Specification of 4 K GM-JT Cryocooler System

| | Specification |
|---|---|
| 4 K cooling capacity | RJT-100ST (Stage type): 9.0 W @ 4.2 K |
| Compressor units power Consumption | • J117V: 6.6 kW or less<br>• E-77A: 7.5 kW or less |
| Compressor input power LV or HV | • LV: AC200 V class at 50/60 Hz, 3phase<br>• HV: AC400 V class at 50/60 Hz, 3phase |
| Compressors cooling system | Water cooling (Both J117V and E-77A) |
| Environment conditions | • Indoors (without dew)<br>• Ambient temperature: 5~28 deg.C.<br>• Humidity: 25~85 %RH |
| Outside dimensions, Mass | RJT-100ST: Φ350 mm H: 1040 mm (60 kg) |
| Regulatory Compliance | UL/cUL, CE, RoHS, UKCA |
| Maintenance interval | 10,000 hours (This interval is the shortest object) |

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# PRELIMINARY DESIGN OF CONTINUOUS WAVE LOW-LEVEL RF SYSTEMS FOR $S^3$FEL*

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*Abstract*

In the Shenzhen Superconducting Soft X-ray Free Electron Laser ($S^3$FEL), Continuous Wave (CW) Low-Level Radio Frequency (LLRF) systems perform critical functions including adjusting the power coupling of accelerator cavities, regulating the amplitude and phase of the RF field, and maintaining the resonance frequency and phase of the cavities. These functions are essential to ensure the electron beam operates at the accelerating phase. Within $S^3$FEL, each superconducting cavity is driven by a solid-state amplifier (SSA), with each SSA paired with a dedicated LLRF system. Based on the distinct acceleration cavities employed, the CW LLRF systems for $S^3$FEL are categorized into four types: 1. Primary accelerator LLRF systems (superconducting, 1.3 GHz; quantity: 168), 2. Harmonic cavity LLRF systems (superconducting, 3.9 GHz; quantity: 16), 3. VHF electron gun LLRF systems (room temperature, 216 MHz; quantity: 4), 4. Buncher LLRF systems (room temperature, 1.3 GHz; quantity: 2). These four LLRF system categories exhibit differing requirements for RF field and acceleration cavity control. This report presents the preliminary design schemes for these four types of CW LLRF systems.

## INTRODUCTION

Free-electron lasers (FEL) [1, 2] developed in the 1970s. With the wide applications in photochemistry, materials science, biology and other fields. Developed countries such as the United States, Japan, and Germany have actively started deploying FEL facilities. To obtain high-quality electron beams, it is essential to ensure strict stability in cavity voltage and phase, which low-level radio frequency (LLRF) control of the cavities is necessary. The buncher, VHF electron gun [3] and superconducting cavity (1.3 GHz, 3.9 GHz) has different structures and physical characteristics, so the distinct functions of LLRF need be designed accordingly. This paper primarily introduces the physical performance targets that these types of cavities need to achieve, the LLRF functions designed based on these physical performance targets. After completing the LLRF design, the LLRF functional verification was conducted at the Dalian Advanced Light Source (DALS) and then electron beam transmission experiment at 1 MHz was completed. According to the LLRF verification outcomes, the shortcomings need to improve to get better performance for preparing for the Shenzhen $S^3$FEL project.

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## LLRF FOR BUNCHER

The buncher use velocity modulation technology to enable electrons operating at the zero-phase point. When electrons that are ahead of the synchronous phase arrive at the bunching cavity, they enter a decelerating phase, whereas electrons that lag behind the synchronous phase and arrive at the cavity experience an accelerating phase. Consequently, electrons near the zero phase are drawn closer to the synchronous electrons, achieving a bunching effect. The physical targets required for the buncher are outlined in Table 1.

Table 1: Physical Targets of Buncher

| Parameter | Value | Unit |
|---|---|---|
| Operating Frequency | 1300 | MHz |
| Detuning | 0~500 | Hz |
| Cavity Voltage | 340 | kV |
| Amplitude Stability | 0.02 | % |
| Phase Stability | 0.02 | ° |

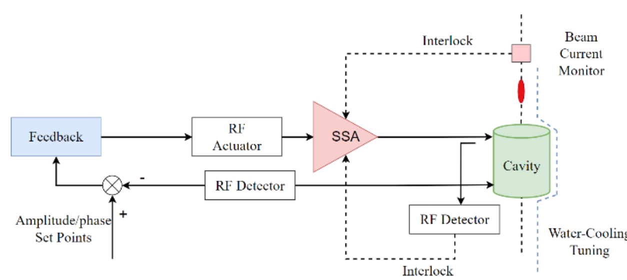


Figure 1: The LLRF control logic for buncher.

The designed half-bandwidth of the buncher is 65 kHz. Detuning caused by external disturbances and noise has a relatively minor impact on the amplitude and phase of the cavity voltage in the buncher. Therefore, tuning control of the buncher can be achieved using relatively slow water-cooling tuning methods, while the LLRF primarily implements RF control to stabilize the amplitude and phase of the cavity voltage. The room-temperature cavity is a traveling-wave cavity, and excessive reflected power can lead to worse vacuum and waveguide window arcing. Hence, it is essential to monitor the reflected power and design an interlock system to shut down the power supply of SSA when necessary. The LLRF control logic diagram applied to the buncher is shown in Fig. 1.

When the designed LLRF is applied to the buncher of the DALS, the buncher can achieve a cavity voltage of 340 kV at a reference frequency of 1.3 GHz, with closed

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# SEARCHING FOR AXIONS: A NEW SRF CAVITY-BASED PROGRAMME AT CERN

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*Abstract*

As part of the Quantum Technology Initiative (QTI) at CERN, a programme to develop a novel SRF cavity for axion searches has been launched. This Axion Detector Demonstrator (QTI_ADD) is based on the heterodyne approach to axion detection, and a dedicated superconducting radio frequency (SRF) cavity design with overlapping, quasi-degenerate modes will be used to search for axion-induced photon conversion from a driven, resonant cavity mode (pump mode) to a second, distinct mode (signal mode), with the frequency spacing between them being proportional to the prospective axion mass. While the programme is in its initial stages, several suitable cavity concepts are presented and the cryogenic and signal acquisition systems are outlined. Of particular interest are the forecasted constraints which arise from the anticipated measurement setup, with a sub-kelvin cryogenic detector volume now foreseen, and axion mass scans to be performed using a non-mechanical tuning system. Key design choices and implications for the expected axion search sensitivity are discussed, and the envisioned timeline for this QTI_ADD facility and its first measurement programme are addressed.

## INTRODUCTION

The axion, originally proposed to resolve the strong CP problem in quantum chromodynamics [1–3], is also a well-motivated candidate for dark matter [4–6]. Generically, the predicted axion–photon coupling is described [7, 8],

$$\mathscr{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma}\, a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}, \qquad (1)$$

where $g_{a\gamma\gamma}$ is the axion-photon coupling constant, $a$ is the axion field, $F_{\mu\nu}$ is the electromagnetic field strength tensor, $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$ is its dual, and $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields respectively. This interaction is the basis for haloscopes and helioscopes, experiments that monitor for axion–photon conversion in strong static magnetic fields. However, such techniques are not well-suited for probing axions in the low mass range. The former approach relies on a resonant radio frequency (RF) cavity being tuned to the axion mass, and therefore the cavities required become prohibitively large at axion masses below ~ 1 µeV. In the latter approach, below ~1 × $10^{-3}$ eV the momentum mismatch between the axion field and any photons which are produced results in the loss of coherence over the magnet length, thereby limiting the signal strength.

To probe low axion mass ranges, the heterodyne approach was proposed [9–13]. In this technique an RF cavity is designed to support two distinct electromagnetic modes, referred to as the 'pump' mode ($\omega_0$) and 'signal' mode ($\omega_1$) respectively, whose fields satisfy the condition

$$\int_V \tilde{\mathbf{E}}_1 \cdot \tilde{\mathbf{B}}_0 \, dV \neq 0, \qquad (2)$$

where $\tilde{\mathbf{E}}_1$ is the electric vector field of the signal mode and $\tilde{\mathbf{B}}_0$ is the magnetic vector field of the pump mode.

In accordance with Eq. (1), if the pump mode is driven and the second mode is tuned such that $\omega_1 = \omega_0 + m_a$ (where $m_a$ corresponds to the axion mass), the axion field can resonantly deliver power to the signal mode via the inverse Primakoff effect. If near-degenerate electromagnetic modes are employed, the detection of low-mass axions is then facilitated without requiring the use of excessively large cavities or a strong static magnetic field.

At CERN, a five-year programme dedicated to the development of a demonstrator facility which employs this technique has been launched, with support from CERN's Physics Beyond Colliders (PBC) study [14, 15]. The project, which started in January 2025, has been established within the framework of CERN's Quantum Technology Initiative (QTI) programme [16, 17], a broader effort to develop and exploit quantum sensing, simulation, computing, and communication technologies for high-energy physics (HEP) facilities and other applications. The 2025-2027 period is dedicated to the design, construction and integration of a bespoke axion detection demonstrator which exploits the heterodyne principle. In parallel, existing cryogenic facilities at CERN are being repurposed to provide the experimental infrastructure, and dedicated DAQ systems are being investigated. Integration and system testing is foreseen for 2027, while data-taking runs are expected to commence in 2028.

## QTI_ADD OVERVIEW

The axion detector demonstrator (QTI_ADD) facility will build on a combination of existing CERN infrastructure and

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# DESIGN OF A FAST REACTIVE TUNER FOR 1.3 GHZ TESLA CAVITIES AT MESA*

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*Abstract*

We present a state-of-the-art design of a Ferroelectric Fast Reactive Tuner (FE-FRT), capable of modulating high reactive power in TESLA-type cavities on a microsecond time scale. The Mainz Energy-Recovering Superconducting Accelerator employs 1.3 GHz superconducting radio-frequency (SRF) cavities, achieving quality factors of the order of $10^{10}$. However, detuning of ±25 Hz induced by microphonics has led to the use of strong coupling for the fundamental power coupler, requiring high-power amplifiers, orders of magnitude above the intrinsic dissipation. Current solutions to mitigate microphonics rely on piezoelectric tuners, which are not fast enough for the spectral range of the microphonics. A novel alternative is the FE-FRT, a technology made possible by low-loss ferroelectric materials, which offer sub-microsecond response times. Analytical results are provided along with their validation through finite-element simulations. The FE-FRT can handle substantial reactive power while offering a tuning range of 50 Hz in SRF cavities, resulting in a reduction in peak forward RF power by about an order of magnitude.

## INTRODUCTION

Particle accelerators play a key role in fundamental research. In order to reach high energies, electrons are often accelerated by superconducing radio-frequency (SRF) cavities, providing accelerating fields of tens of MV/m at quality factors of the order of a few times $10^{10}$. However, a common issue is microphonics, which causes a detuning of the resonant frequency, depending on the environment, of up to a few tens of Hz.

The Mainz Energy-Recovering Superconducting Accelerator (MESA) is designed for medium-energy electron beams, focusing on high beam intensity and precision. The peak detuning of SRF cavities at MESA has been measured to be $\Delta f_\mu$=±25 Hz, requiring to set the external quality factor of the fundamental power coupler to about $10^7$ to correct for microphonics [1]. This common technique is applied in several facilities and has the setback of requiring high-power RF sources as most of the forward power gets reflected. In an effort to mitigate this detuning, stepping motor and piezoelectric actuator tuners are employed. However, the response time of such tuners is not sufficiently fast to correct for higher frequency microphonics, which prevents increasing the external quality factor of the fundamental power coupler and thus limits the reduction of reflected power.

The development of low-loss ferroelectric (FE) materials enables a new class of tuners, called Ferroelectric Fast Reactive Tuners (FE-FRT) which exhibit a sufficiently large tuning range as well as extremely fast response time, far beyond any microphonic perturbation.

These FE materials are based on $BaTiO_3/SrTiO_3$-Mg ceramics, having a loss tangent, taken here conservatively as $\tan(\delta) \approx \delta=2.39\cdot10^{-3}$ at 1.3 GHz, thermal conductivity $K$=7.02 W/m and breakdown electric field of 20 MV/m. When applying an electric field of up to 8 MV/m through the FE at 50 °C, its relative permittivity changes from approximately $\epsilon_2$ =129.60 to $\epsilon_1$ =96.41, which are two ends states called state 2 or unbiased and state 1 or biased, respectively. This voltage-controlled permittivity is used to modulate the reactance of the tuner connected to the cavity, and thus change the cavity's frequency. The FEs have been developed and thoroughly investigated by Euclid Techlabs Inc. [2, 3] and used for the development of FE-FRTs along with CERN [4, 5] and others [6, 7]. The response time capability of the FE in bulk form has been measured at <30 ns. The first demonstration of the FE-FRT coupled to a 400 MHz cavity was carried out at CERN in 2019 [8], showing a frequency shift speed on the order of 600 ns.

In this work, we present the design of an FE-FRT to counteract the detuning effect originating from microphonics in 1.3 GHz SRF 9-cell cavities of TESLA/XFEL type.

## ANALYTICAL MODEL

The tuner's layout and choice of parameters follows the procedure described in [9]. The equivalent circuit of the tuner is as shown in Fig. 1. The complete tuner comprises a resonant circuit, which includes an inductance and two capacitors in series: The FE capacitor $C_f$ for tuning the frequency of the resonant circuit and a series capacitor used for coupling the resonator to a transmission line leading to the cavity's port. The length of the transmission line is chosen to be a quarter-wavelength (or odd multiple of quarter wavelengths). The analytic expressions were evaluated using a code written in Maple [10], then simulated in CST Studio Suite [11], including the tuner, a 1.3 GHz 9-cell cavity and all associated coupling ports. The analytical tuner parameters were optimized for the cavity parameters of frequency $f_0$, stored cavity energy $U$, and tuning range $\Delta f$ as given in Table 1. Due to the simplicity of the tuner assembly, a two-wafer annulus-shaped [12] FE capacitor was selected.

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# LCLS-II-HE CRYOMODULE TEST RESULTS AFTER AN UNCONTROLLED VACUUM EVENT*

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*Abstract*

During the installation preparation of the LCLS-II-HE cryomodules, one previously qualified cryomodule experienced an uncontrolled vacuum event. The cavity string vacuum unexpectedly increased to $2.3 \cdot 10^{-3}\ torr$. Simulation showed the vacuum incident may have introduced 0.1 µm sized particulates into the cavity RF volume. Careful analysis of the particulates' path and migration indicated that the particle migration was negligible except for finer particles smaller than 0.1 µm. A repeat test of the cryomodule verified the initial analysis. The cryomodule's performance was intact. All cavities showed no detectable x-ray, consistent with the previous test. Particles of the smaller size may not cause harm to the cryomodule at the administrative limit of the HE cavity gradients. This article describes the vacuum event, analysis, and cryomodule test results before and after.

## VACUUM EVENT

LCSL-II HE cryomodules could spend over a year in storage. To maintain appropriate vacuum levels, a NexTorr, a device with both an ion pump and a NEG pump, is installed to provide active pumping as shown in Figure 1.

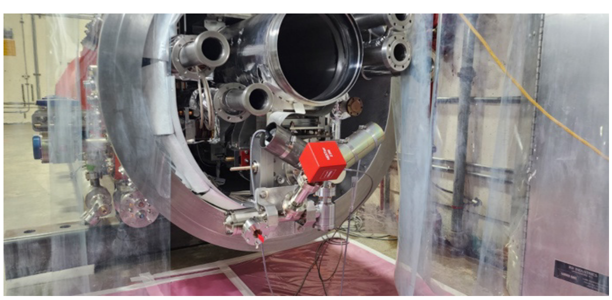

Figure 1: NexTorr pump installed on a cryomodule.

During one such installation, a bolt was removed from the wrong flange connection, as shown in Fig. 2, briefly exposing the cryomodule beamline to clean room air. The mistake was quickly realized, and the connection was retightened. The beamline monitoring system recorded the incident. The leak lasted for under 90 seconds, during which pressure rose from $8 \cdot 10^{-10}\ torr$ to $2.3 \cdot 10^{-3}\ torr$. Once the leak was closed, the pressure later equalized to $8 \cdot 10^{-6}\ torr$. At the time of exposure, the NexTorr was installed with an active NEG between the leak and the beamline vacuum, which absorbed air from the clean room.

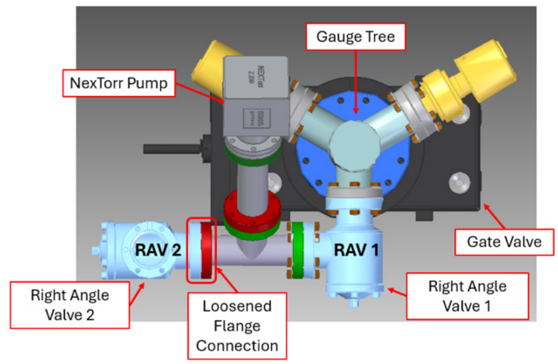


Figure 2: A model of the NexTorr pump identifying the location of the leak.

## ANALYSIS

The vacuum incident was considered an uncontrolled venting. The risk to SRF cavities arises from particles entering high electric field areas, which could lead to field emission, or high magnetic field areas, resulting in a lower quality factor or even early quenching. There are two sources of risk of particle movement. One is the particles entering through the opening. The particles could come from the ambient environment or from the vicinity of the vacuum seal. The particles from the ambient environment are minimized as the flange is in the portable clean room. The particles near the seal come from the sealing actions during the flange assembly. The other is the particles in the vacuum that could get lifted by the molecular flow and migrate to the critical cavity cells. Those particles tend to stay near the sealing flanges under normal conditions, where the venting and evacuation tend to be finely controlled.

The pressure surge indicated that the opening of the flange was around 0.1 µm. There were few performance statistics of SRF cavities impacted by the 0.1 µm particles. Most of the SRF particle counters detect only the 0.3 µm particles.

From the pressure information, the flow rate through the opening was between 0.0002 L/m and 0.02 L/m. The flow rate was considered negligible to cause any disturbance of the particles in the vacuum space, except for the sonic flow at the opening. It was unlikely for the local particles to travel through two 90-degree vacuum paths and a long beam pipe to reach the first cavity at the downstream.

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# IMPROVING THE PERFORMANCE OF MID-T BAKED NIOBIUM CAVITIES THROUGH POST-BAKE SURFACE TREATMENT*

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*Abstract*

The Medium temperature (mid-T) baking of niobium superconducting radio-frequency cavities at 300–350 °C in a vacuum furnace is known to enhance the quality factor ($Q_0$). However, despite this improvement, cavities treated with this process often exhibit premature quench at relatively low accelerating fields. This limitation is suspected to arise from the formation of surface contaminants, such as niobium carbides, during the furnace bake at 350 °C for 3 h. To investigate the influence of potential surface contamination, this study applied an ultralight chemical removal to 1.3 GHz and 650 MHz single-cell cavities that had undergone medium-temperature baking. The removal of the top RF surface layer led to a notable improvement in the quench field and $Q_0$, indicating a beneficial effect of eliminating possible surface residues introduced during the bake.

## INTRODUCTION

Niobium (Nb) made superconducting radio frequency (SRF) cavities are key components in a high energy particle accelerator machine. For efficient accelerator operation, these cavities must show excellent superconducting performance, characterized by a high accelerating gradient ($E_{acc}$) and a high quality factor ($Q_0$). A high $Q_0$ is particularly desirable because it minimizes cryogenic heat load, thereby reducing operational costs.

The $Q_0$ around the medium field can be enhanced by surface modification techniques such as nitrogen doping and mid-T baking, both invented at Fermilab [1, 2]. Mid-T baking is typically performed at 300–350 °C for 3 h, either in-situ or in a vacuum furnace. In-situ baking involves actively pumping the cavity's internal volume to maintain high vacuum conditions during the bake [2], whereas the furnace baking of the cavity is performed by placing the cavity in a vacuum furnace [3, 4]. The vacuum furnace baking is preferred for large-scale production.

However, mid-T baking can result in the formation of non-superconducting niobium carbides (NbC) on the surface, which may limit cavity performance. The extent to which these surface contaminants affect RF performance remains poorly understood. To address this, the present study is focused on the removal of the top RF penetration layer from mid-T baked cavities by ultralight electropolishing (EP) and compares cavity performance before and after this removal to elucidate the role of surface contaminants.

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## SAMPLE PREPARATION AND ANALYSIS

To evaluate the chemical state of the mid-T baked Nb surface and the effect of post-bake ultralight EP, two high-RRR Nb samples (Sample-1 and Sample-2) were prepared following a systematic procedure. Both samples first underwent bulk EP and ultrasonic cleaning, after which they were subjected to mid-T baking at 350 °C for 3 h in the same high-vacuum furnace used for cavity degassing and mid-T baking. Typical furnace temperature and pressure profiles during mid-T baking at 350 °C for 3 h are shown in Fig. 1.

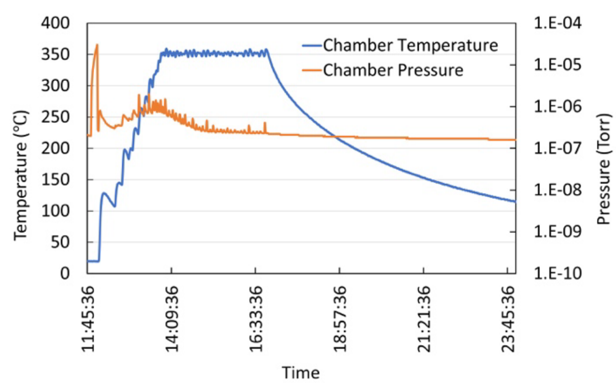


Figure 1: Typical furnace temperature and pressure profiles during mid-T baking at 350 °C for 3 h.

Following baking, Sample-2 received ultralight EP corresponding to approximately 120 nm of material removal. This step was intended to eliminate potential surface and near-surface contamination introduced during the mid-T bake. This ultralight EP was carried out using standard EP electrolyte, which is a mixture of sulfuric acid (96wt%) and hydrofluoric acid (70wt%) in a volumetric ratio of 10:1. The details on the sample EP setup have been reported in reference [5]

Both sample surfaces were analyzed using Secondary Ion Mass Spectrometry (SIMS) to obtain elemental depth profiles. SIMS results for Oxygen (O), carbon (C), and niobium carbide (NbC), each normalized to Nb intensity, are presented as a function of surface depth in Fig. 2. The Intensity of O was found to be similar for both samples. However, Sample-1 exhibited a significantly higher NbC signal than Sample-2. This comparison suggests that the

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# CRYOGENICS FOR SRF ACCELERATOR FACILITIES: RECENT DEVELOPMENTS AND CHALLENGES*

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*Abstract*

Large-scale 4.5 K and 2.0 K helium cryogenic systems are essential for superconducting radiofrequency (SRF) accelerator facilities. Cooling below 4.5 K but above 0.8 K typically relies on sub-atmospheric helium processes, combining vacuum pumping with commercial liquefiers. While effective, these systems are energy-intensive: large-scale (>1 kW) systems consume ~1100 W/W at 2.0 K, while smaller sub-kW systems can reach ~6000 W/W. Because of their critical role, they require extremely high reliability, operating continuously (24/7/365). Over the past few decades, there have been significant advancements in the efficiency and reliability of large-scale cryogenic systems, including the development of warm compressor skids with wide-range operation and the implementation of the Ganni floating pressure process for high turn-down and energy efficiency (e.g., NASA-JSC, 12 GeV-JLab, FRIB). These innovations have led to substantial energy savings and improved system performance for large-scale helium cryogenic systems at numerous U. S. laboratories. However, small-scale cryogenic systems face significant challenges. Most such systems rely on direct vacuum pumping of the cryostat without recovering refrigeration from helium boil-off, severely limiting achievable 2.0 K cooling capacity. Although high efficiency multi-stage cryogenic centrifugal compressor trains (CC's) have been successfully used in large-scale systems (>1.0 kW) to achieve high turn-down ratios, the lack of reliable, high-efficiency sub-kW class 2.0 K refrigeration systems and associated sub-systems (helium recovery and purification) remains a critical gap for laboratories and test facilities. This paper reviews operational experience and advances in SRF cryogenic systems, highlighting recent efforts at FRIB to improve wide-range steady-state and transient operation. It concludes by outlining a path forward: the development of efficient, reliable, and scalable sub-kW 2.0 K refrigeration systems, which are vital for next-generation accelerator research and other advanced scientific applications.


## BACKGROUND

Cryogenics is essential for particle physics facilities using superconducting radio frequency (SRF) technology, which require cooling at 4.5 K or below. Cooling at these temperatures is an energy-intensive process, requiring 250 Watts or more per Watt of cooling at 4.5 K, and up to 6000 Watts per Watt of cooling at 2.0 K [1]. In the late 1960s, industrial helium refrigerators designed by Samuel Collins at BNL (~200 W at 4.5 K) and Stanford (30 W at 1.8 K) were considered large-scale cryogenic systems [2], where reliability and capacity mattered more than the operating efficiency. By the late 1980s, cryogenic system sizes had expanded to over 25 kW at 4.5 K (BNL) and 4.6 kW at 2.0 K (JLab) [2]. Despite this dramatic increase in scale, the overall design philosophy remained largely unchanged from earlier decades. Due to the niche field of application, many cryogenic system components were adapted from other industries rather than purpose-built. As a result, these systems were typically designed for fixed operating points but often operated under '*off-design*' conditions and at part load with reduced efficiencies. This mismatch between the design intent and operational reality highlighted the need for more flexible and efficient cryogenic process cycles, ultimately motivating innovations such as the Ganni floating pressure cycle [3] and other advanced component developments.

This paper details the progressive and synergistic advancements in helium cryogenic process components, such as warm compressors, turbo-expanders, liquid-nitrogen pre-cooling systems, heat exchangers, and cryogenic centrifugal compressors – that have enabled the successful deployment and operation of refrigeration systems based on the Ganni floating pressure cycle. It examines current challenges in designing sub-atmospheric (2.0 K) refrigeration systems and related sub-systems that are critical for accelerators using SRF technology and explores potential technological pathways for their future improvement.

## CRYOGENICS FOR SRF CAVITIES

SRF cavities require ultra-low temperatures to sustain superconductivity and achieve the high quality factors essential for efficient particle acceleration. These cavities typically operate at 4.5 K or below, with many modern large-scale accelerators employing sub-atmospheric helium cooling at 2.0 K to further reduce surface resistance and improve performance.

Traditionally for large-scale accelerators, this cooling is supplied by evaporation-based cryogenic helium refrigeration / liquefaction systems. In these systems, SRF cavities are immersed in saturated liquid helium within a cryostat, where helium's saturation properties impose a pressure constraint on the cryostat temperature. Lower load temperatures require proportionally reduced pressures to maintain the corresponding saturation conditions. The vapor boiled off from the sub-atmospheric load must be re-pressurized before returning to the helium liquefier. This requires a compression system capable of achieving large pressure ratios (typically 30 to 70) depending on the load temperature

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# SRF CAVITY DEVELOPMENT FOR THE FCC-ee AT 400/800 MHz

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*Abstract*

FCC-ee is the baseline for future lepton collider projects at CERN. To meet specific physics objectives, CERN is developing two types of accelerating cavities in collaboration with international partners. For low-energy applications, namely the Z-pole, W, and H physics cases, CERN is working on 400 MHz seamless cavities with Nb-coating technology, in partnership with KEK. Prototype cavity development is ongoing at CERN using HiPIMS technology. In parallel, a novel bulky Nb-coated cavity design, known as SWELL, is undergoing testing at CERN. For higher-gradient applications required for $t\bar{t}$ operation and the booster, 800 MHz bulk niobium cavities are being developed in collaboration with Fermilab, Cornell university, and IJCLab. This paper will cover the SRF cavities development for FCC-ee. It also highlights the ongoing international collaborations with leading institutes worldwide aimed at addressing the key technical challenges of the FCC-ee RF program.

## INTRODUCTION

The Future Circular Collider (FCC) is a proposed next-generation accelerator complex to succeed the Large Hadron Collider (LHC) at CERN. The project is envisioned in two main stages: an initial electron–positron collider (FCC-ee), followed by a proton–proton collider (FCC-hh). Both machines would share the same 91 km circumference tunnel and much of the supporting infrastructure.

FCC-ee is planned to operate at four beam energy levels: 45.6 GeV (Z-pole), 80 GeV (W pair production), 120 GeV (Higgs boson studies), and 182.5 GeV ($t\bar{t}$ operation). In the current design, each beam is allocated a fixed synchrotron radiation (SR) power budget of 50 MW per beam [1]. Since SR losses grow with the fourth power of the beam energy, this power limitation implies that the circulating beam current must decrease accordingly, yielding high beam currents at the Z-pole and progressively lower currents toward the $t\bar{t}$ energy. The tunnel layout accommodates three rings: two for the electron and positron beams of the main collider, and a third for the booster, which ramps particle energies from 20 GeV to the desired collision energy.

To meet the different requirements across energy stages, the FCC-ee RF system will use superconducting elliptical cavities at two frequencies: 400 MHz for the Z/W/H modes (aimed for high-current operation) and 800 MHz for the $t\bar{t}$ and booster cavities (optimized mainly for high-gradient, low-current operation). This paper provides an overview of the proposed SRF cavity systems for FCC-ee, outlining performance targets, the technical solutions under investigation, and R&D efforts exploring advanced designs such as the Slotted Waveguide Elliptical (SWELL) cavity concept.

## FCC-ee RF BASELINE

To accommodate the different RF requirements of FCC-ee, a hybrid RF system using both 400 MHz and 800 MHz superconducting cavities was adopted since the initial design phase [2]. The 400 MHz frequency was mainly driven by Z working point requirement to balance cavity dimensions, beam dynamics constraints, higher-order mode (HOM) management, and the technical feasibility of power couplers and RF sources.

In the FCC conceptual design report [2], single-cell 400 MHz cavities were considered for Z, four-cell 400 MHz for W and H, and five-cell 800 MHz for $t\bar{t}$ and the booster. However, further optimization and the adoption of reverse phase operation (RPO), inspired by the Super-KEKB experience [3], led to the selection of two-cell 400 MHz cavities for Z, W, and H, enabling a uniform cavity type across all these modes. This configuration requires 132 cavities per beam and reduces the input power per cavity at the Z working point from approximately 1 MW to 0.38 MW in CW mode, simplifying the fundamental power coupler (FPC) design. It also allows flexible switching between low-energy operation modes which comes at the cost of installing all 400 MHz cavities from the start and creating stricter limits on HOMs at the Z-pole, since the beam passes through more cavities.

The two-cell 400 MHz cavities provide up to 2.1 GV of accelerating voltage. For the H and $t\bar{t}$ operation modes, long gaps in the bunch-filling patterns allows us to prevent encounters between counter-rotating bunches, and to use a common RF system for both beams. For the $t\bar{t}$ collider, 800 MHz six-cell cavities are considered to deliver the remaining 9.2 GV. The choice of higher frequency and more cells for the $t\bar{t}$ mode reduces cavity size, saves cost and space, and is feasible due to the lower beam currents. The same 800 MHz cavities are also planned for the booster machine.

In total, 408 six-cell 800 MHz cavities are required for the collider and 448 for the booster. At 400 MHz, a total of 264 cavities are needed. At both frequencies, the cavities are grouped into cryomodules, each containing four cavities. A list of the key RF parameters of the cavities is given in Table 1. All physics objectives should be achieved within 15 years of operation which includes one year shutdown to install additional RF system for five years operation in $t\bar{t}$ mode. After installation of the cavities for $t\bar{t}$ operation it

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# RF DIPOLE CRYOMODULE TESTS *

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*Abstract*

The first RF Dipole crab cavity cryomodule, jointly developed by CERN and UK-STFC under the HL-LHC project [1], was built for proton beam tests in the SPS machine. In 2024, the cryomodule was tested in the CERN horizontal test facility prior to its installation in the SPS. During acceptance tests, two critical non-conformities related to the fundamental power couplers were identified. This paper presents the mitigation of these non-conformities and the subsequent validation tests that led to successful continuous wave (CW) operation. Key aspects of RF performance, cryogenics, alignment, and frequency tuning are also discussed.

## INTRODUCTION

Superconducting compact RF crab cavities are foreseen for installation in the HL-LHC configuration to partially compensate for the geometric crossing angle, thereby enhancing the luminosity by increasing the effective overlap of the colliding bunches. Two types of crab cavities are being deployed. Radio Frequency Dipole (RFD) [2] cavities will be installed on either side of Interaction Point (IP) 1 (ATLAS) to provide horizontal crabbing, whereas Double Quarter Wave (DQW) cavities [3–6] will be positioned around IP 5 (CMS) for vertical crabbing.

A prototype RFD cryomodule (see Fig. 1) for testing at the SPS was jointly built by the HL-LHC UK collaboration and CERN, with the assembly work carried out at the STFC Daresbury Laboratory (UK). The cryomodule hosts two RFD cavities [7], both manufactured at CERN. Hereafter, we refer to these cavities as RFD1 and RFD2. Additional complex RF and vacuum components—such as the Fundamental Power Couplers (FPCs), RF transmission lines, and Plug-in Modules (PIMs)—were also fabricated at CERN and delivered to the UK collaboration, where the string assembly and cryostat assembly were performed.

## RF DIPOLE CAVITY AND CRYOMODULE

### Cavity Testing

Each RFD cavity was tested at three stages of assembly: bare, jacketed, and dressed configurations. All tests were performed in a vertical cryostat with the cavity fully immersed in 2 K liquid helium. The jacketed configuration consists of the niobium bare cavity equipped with a cold

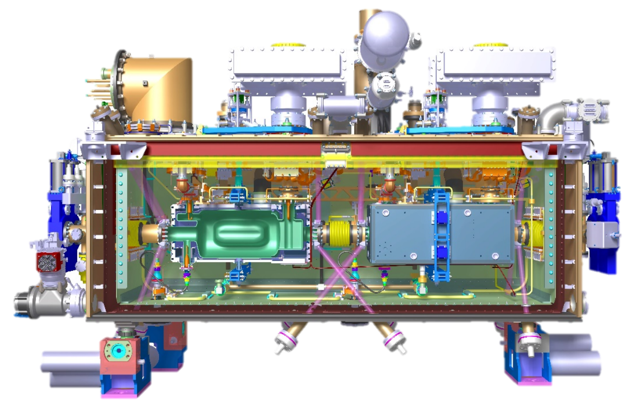

Figure 1: Cross section of the RFD cryomodule hosting two cavities (courtesy CERN EN-MME).

magnetic shield and a bolted-welded titanium helium tank. In the dressed configuration, the jacketed cavity is assembled with the Higher Order Mode (HOM) couplers and field antenna (FA) [8]. The RFD1 bare cavity reached a maximum transverse voltage of 4.4 MV with a quality factor of $Q_0 = 3.5{\times}10^9$ and peak surface fields of $E_{peak}$ = 44.9 MV/m and $B_{peak}$ = 70.7 mT. Prior to helium tank assembly, the cavity underwent a light buffered chemical polishing (BCP) [9] due to early field emission onset near the nominal operating voltage (3.4 MV). In the jacketed configuration, the performance improved, reaching 5 MV with $Q_0 = 3.8{\times}10^9$ and no quench was observed (see Fig. 2). In the dressed configuration, the cavity again reached 5 MV with $Q_0 = 4{\times}10^9$. During this test, a vacuum leak was observed, and the RF measurements were carried out at 2.5 K. The leak was later traced to the FA at 300 K and was successfully closed by re-tightening the flange. For both, the jacketed and dressed configurations, the tests were intentionally stopped by the operator after reaching 5 MV.

The RFD2 cavity achieved outstanding performance in both bare and jacketed configurations, with a maximum transverse voltage of 7 MV, with $Q_0 = 6{\times}10^9$ and peak fields of $E_{peak}$ = 71 MV/m and $B_{peak}$ = 112 mT. After installation of the HOM couplers in the dressed configuration, the performance degraded slightly, with a maximum voltage of 5 MV. The RF test results of the RFD2 cavity are shown in Fig. 3. In both cavities, the performance is limited by field emission.

Following the qualification of each cavity in its dressed configuration, a beam screen with an amorphous carbon

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# EXPERIMENTAL DEMONSTRATION OF THE SLOTTED WAVEGUIDE ELLIPTICAL SWELL CAVITY FOR HIGH INTENSITY SRF ACCELERATORS

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*Abstract*

In the context of the FCC study where strongly damped RF structures are required to accelerate high beam currents, a new slotted waveguide cavity called SWELL has been proposed. We have designed a 400 MHz two-cell SWELL cavity based on an elliptical cavity shape split into four quadrants making it compatible with niobium-on-copper coatings. A first prototype at 1.3 GHz has been designed, fabricated and tested in the SM18 facility at CERN to demonstrate the feasibility of this new cavity concept. This paper reports on the design and manufacturing steps of the cavity including thin film coating and the assembly process in clean environment. RF test results of this prototype at cryogenic temperature are presented and compared with standard TESLA-shaped cavity performances. The measurement of the trapped flux surface resistance is reported and discussed. We also highlight advances in the design and development plan of such a cavity concept for future high intensity SRF accelerators.

## INTRODUCTION

The Slotted Waveguide Elliptical (SWELL) cavity is a novel superconducting radiofrequency (SRF) topology based on niobium-on-copper (Nb/Cu) technology, developed for high-current accelerator applications. Introduced in 2020 as part of the Future Circular Collider (FCC) study [1], it was designed to support the acceleration of electron and positron beams at currents up to 1.3 A to the Z-pole energy of 45.6 GeV [2,3]. Transverse Higher Order Modes (HOMs) are particularly problematic due to the risk of coupled-bunch instabilities (CBIs). The SWELL design addresses this by introducing radial waveguide slots in the elliptical cavity wall, oriented perpendicularly to the RF surface. These slots couple strongly to the transverse HOM current lines, allowing efficient extraction via coaxial RF couplers and matched loads. This ensures a low external quality factor ($Q_{\text{ext}}$) for dangerous HOMs, significantly increasing the CBIs threshold. Meanwhile, the fundamental mode, whose current lines run parallel to the slots, remains unaffected.

The SWELL concept is directly inspired by normal-conducting RF structures developed for linear colliders, and the Compact Linear Collider (CLIC) study in particular [4–8]. The concept of applying slotted damping to SRF cavities has also been explored before [9, 10]. In 2010, a 1.3 GHz multi-cell bulk niobium cavity with three damping waveguides was developed for Energy Recovery Linacs and a three-cell prototype was tested with limited performances ($E_{\text{acc}}$ = 2.4 MV/m at 4.2 K with a $Q_0$ of $1.4 \times 10^8$).

The SWELL concept is based on these earlier designs, with the main challenge being how to adapt slotted waveguide structures in an SRF cavity structure made with a niobium thin film coating on a copper cavity substrate. If such concept can be achieved, it would offer both excellent HOMs damping and the cost and cooling advantages of thin-film technology. It would open the door to a new type of SRF cavity well suited for high-current accelerators.

## RF DESIGN OF 400 MHz SWELL CAVITY FOR FCC-ee

The first SWELL cavity design for FCC-ee was a two-cell 600 MHz cavity aimed at operation in the Z, WW, and ZH modes [11, 12] of FCC-ee. This frequency offered a compromise between beam-induced HOM power, surface resistance (favoring low frequencies), and cavity compactness and gradient performance (better at higher frequencies).

Once it was confirmed that only the frequency of 400 MHz was adapted to Z pole operation, due to beam-beam interaction considerations, a new 400 MHz two-cell SWELL design was developed (Fig. 1).

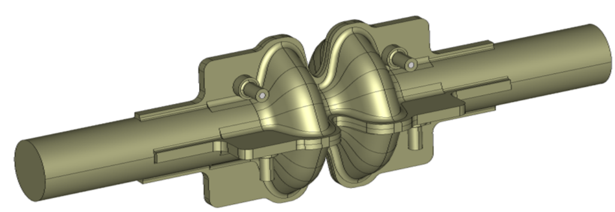

Figure 1: 400 MHz two-cell SWELL cavity RF design with slots and coaxial HOMs extractors.

The chosen two dimensional geometry was the one optimized and proposed for the baseline two-cell elliptical cavity which suppresses longitudinal HOMs and minimize surface fields. As expected, the adding of waveguide slots increased the peak surface fields but this was mitigated by breaking azimuthal symmetry as performed in [11], limiting the increase of $E_{pk}/E_{acc}$ and $B_{pk}/E_{acc}$ by only 25% and 12.5%, respectively. At $E_{\text{acc}}$ = 13 MV/m (FCC specification in vertical cryostat), $E_{pk}$ is 32.5 MV/m and $B_{pk}$ is 78 mT, which is considered to be compatible with Nb/Cu technology at 4.5 K.

Wakefield and eigenmode simulations confirmed excellent transverse HOMs damping, comparable to single-cell

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# DETECTION OF HIGH-F GRAVITATIONAL WAVES USING SRF CAVITIES

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*Abstract*

Today, apart from some isolated R&D efforts, there are no gravitational wave (GW) experiments, yet which explore a large part of the vast frequency range above the LIGO/Virgo band. It is planned to establish an experiment at Deutsches Elektronen-Synchrotron (DESY) and at the Superconducting Quantum Materials and Systems (SQMS) Center at Fermi National Accelerator Laboratory (Fermilab) to search for high-frequency GWs in the frequency range of 10 kHz to 100 MHz. The basic idea is to use superconducting radiofrequency (SRF) cavities to detect tiny harmonic deformations induced by GWs which change the boundary conditions of the oscillating electromagnetic field.

This paper summarizes the challenging environmental boundary requirements, and the R&D to operate a cavity using a low level RF (LLRF) system which pushes beyond state-of-the-art accuracy and resolutions and a seismic noise mitigated cryostat at 1.8 K.

The focus of this paper is the warm and cold commissioning of a prototype cavity, built 20 years ago during the MAGO collaboration, and its first measurement in our collaborative research project.

## INTRODUCTION

In the search for gravitational waves (GWs) the central focus has been on the Hz to kHz frequency range, which is where the strongest signals from known astrophysical objects were expected. This is the frequency band where the LIGO/Virgo interferometers discovered GWs in 2015 which were produced in the merging of two massive black holes [1]. Yet, interferometers are not the only technology developed in the search for GWs. Electromagnetic (EM) cavities can also be employed in the search for GWs, where the mechanical structure of the cavity itself plays the role of the resonant bar. In this setup, the electromagnetic eigenmodes of the cavity serve as mechanical-to-EM transducers, analogous to Weber bars, where the transducer is an LC circuit. In this detection concept, an electromagnetic resonator is configured with two nearly degenerate modes, where RF power is injected into only one mode. An incoming GW can transfer power from the loaded mode (0) to the quiet mode ($\pi$) which is maximized when the resonant condition $|\omega_\pi - \omega_0| = \omega_g$ is met. This process, in which signals of two frequencies are combined, is commonly referred to as heterodyne detection. The power transfer is indirectly induced by the deformation of the cavity walls, which leads to the described mode mixing.

The idea to detect GWs with superconducting radiofrequency (SRF) cavities dates back to the 1970's. Towards the end of the 70's Pegoraro et al. [2, 3] and Caves [4] published papers which proposed the heterodyne detection and the mechanical interaction of GWs with the cavity wall. In the 80's Reece et al. [5, 6] started an experimental R&D programme which was based on the configuration proposed by Pegoraro. This work was based on pillbox cavities and the excited mode was measured through the reflection of the input ports. It was shown that small (order of $10^{-17}$ cm) harmonic displacements were detectable with such a superconducting parametric converter.

This detection concept was further developed starting at the end of the 90's within the MAGO proposal with the goal for a scaled-up experiment with 500 MHz cavities as a CERN-INFN collaboration [7–9]. Since this proposal stems from the time before the discovery of GWs, the aim was to reach frequencies in the lower kHz range which have sensitivity to astrophysical sources. Although the final project was not funded, three SRF niobium cavities were built during the R&D activities. The first cavity (a pill-box cavity) was used as a proof-of-principle experiment, which demonstrated the working principle and the development of an RF system to drive and read out the cavity with the necessary precision [7–9]. The second prototype cavity had two spherical cells with fixed coupling. The third cavity, shown in Fig. 1, is a spherical 2-cell cavity (denoted `PACO-2GHz-variable`) with an optimized geometry and a tunable coupling cell to change the coupling between the cells and so the frequency difference between the two modes. This cavity was never treated nor tested until now within this project [10], prompted by renewed theoretical interest in this type of setup [11].

## WARM COMMISSIONING

**Geometry** Since the cavity was fabricated over 20 years ago, limited information was available, and it exhibited significant deviations from the nominal geometry. Therefore, the first crucial step was to conduct a comprehensive survey of both the cavity's geometry and its wall thickness. The

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