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ESS SUPERCONDUCTING LINAC COLD TECHNICAL COMMISSIONING

N. Elias, A. Bhattacharyya, A. Gevorgyan, P. Goudket, M. Jensen, M. Koopmans, A. Krawczyk, C. Maiano, M. Nabywaniec, D. Nicosia, P. Pierini†, H. Przybilski, M. Skiba, A. Svensson, E. Trachanas, P. van Velze, M. Wang, European Spallation Source, Lund, Sweden

Abstract

The European Spallation Source (ESS) superconducting linear accelerator represents a key component in delivering high-intensity proton beams for cutting-edge neutron science research. This paper details the first cold technical commissioning of the superconducting linac in its present 2MW configuration, focusing on the performance validation of cryomodules, superconducting radio-frequency (SRF) cavities and associated systems. ESS achieved first (probe) beam operation at energies greater than 800 MeV on the tuning beam dump on May 16th, 2025.

INTRODUCTION

The ESS superconducting linac is designed, in its final configuration with 13 spoke (SPK), 9 medium beta (MB) and 21 high beta (HB) elliptical cryomodules (CMs) to provide a 5 MW proton beam at an energy of 2 GeV [1]. As part of the staged development of the facility, up to 5 HB cryomodules were installed in 2024 for a total energy of 870 MeV and a beam capability of 2 MW. SPK cavities are fed by 26 tetrode-based RF power stations rated for 400 kW [2] and elliptical cavities by 56 RF klystrons rated for 1.6 MW [3]. Each cavity is individually powered by a single power station, equipped with a low-level RF system (LLRF) in charge of field stabilization [4]. Beam commissioning on the tuning beam dump (12 kW) started in April 2025, with the achievement of acceleration above 800 MeV on the 16th of May, 2025 [5].

Six additional HB cryomodules will be installed in the tunnel to increase the beam power and energy capability to 3 MW and 1.3 GeV in summer 2025, before the Beam on Target (BOT) phase, which is foreseen in Spring 2026. BOT will start after receiving the licence for Intentional Neutron Production (INP) from the safety authorities.

ESS CRYOMODULE PREPARATION

Site Acceptance Tests

All ESS CM installed in the linac had to pass a Site Acceptance Test (SAT) to verify RF and cryogenic performances after delivery from the in-kind partners. SPK CM have been tested at the FREIA laboratory in Uppsala, Sweden [6] and MB and HB elliptical CM have been tested at the ESS Test Stand 2 in Lund [7]. Before installation reports of mechanical & electrical inspections, vacuum leak checks in the different circuits, cryogenic and RF testing, for system configuration and traceability, are stored along with design information received from in-kind partners.

All data related to measurement provided by in-kind partners during cavity fabrication and CM assembly is joined to the test data acquired in the ESS testing facilities and consolidated in the ESS cavity database [8], for rapid access during the linac technical commissioning activities.

All tested CM exceeded the design gradients foreseen by the ESS linac design. A summary of all measured RF performances for the 27 CM installed for the 2 MW phase is shown in Fig. 1, with reference to the design requirements.

At the moment of writing this contribution 5 out of the remaining 16 HB CM have been tested at Test Stand 2, which continues operation during the 2 MW linac commissioning: 6 will be installed in July 2025 to provide 3 MW capability to the ESS Linac. The installation of the last 10 for 5 MW capability is deferred after the science run following BOT, presumably in 2027.

Figure 2 shows the timeline of the CM testing and facility preparation since the start of testing in 2020. In green boxes the major cryogenics milestones are indicated.

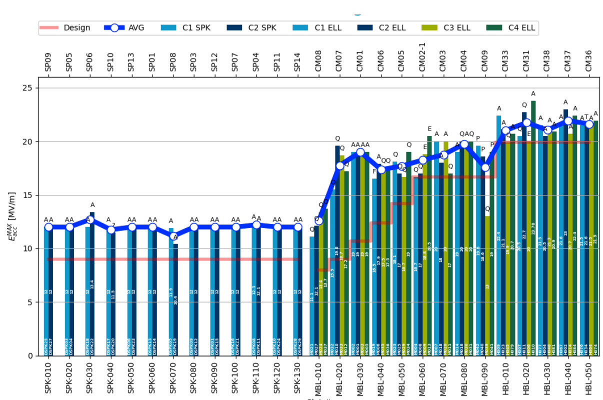

Figure 1: Plot of the CM RF performances of the ESS CM. Bottom axis is the location in the linac and the top axis is the individual CM serial number. Bars indicate individual cavity performances achieved in the CM test. The red line indicates the ESS design gradient along the machine and the blue line the average gradient per CM.

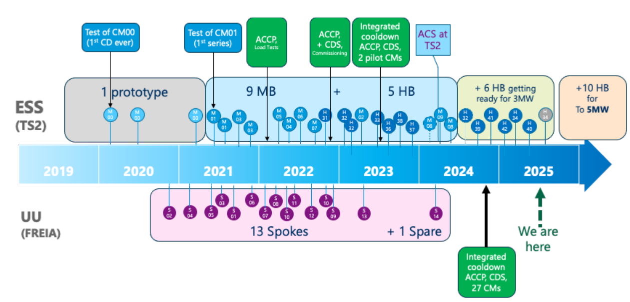

Figure 2: Timeline of the preparation of the ESS linac.

† paolo.pierini@ess.eu

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CM Installation for 2 MW Phase

The CM installation started in April 2023 with the pilot installation of one SPK and one MB unit, which was completed in June [9]. The series installation was then organized, and the remaining 25 CM for the 2 MW configuration were installed from August 2023 to July 2024, at the rate of approximately 2 CM per month.

Coupler Conditioning

Warm coupler conditioning of the couplers started in July 2024 at the end of the CM installation and was completed in mid-October. Conditioning is performed running through an EPICS controller (IOC) a standard sequence of power sweeps at increasing duty cycles, ending with the nominal value of 4%. Vacuum levels are used as process variables for increasing or decreasing RF power during the conditioning. After cooldown and before tuning the cavities to operation a second stage of cold (non-resonant) coupler conditioning has been performed.

Both SPK and MB/HB couplers have bias capabilities to suppress possible multipacting levels during operation. However, no bias has been applied during the conditioning process, preferring to perform a thorough cleaning of the surfaces and leaving the bias as a future mitigation in case of onset of degradation in operation. Arc detectors and electron pickups are monitored by the interlock system.

CRYOGENIC OPERATION

Cooldown

The cooldown of the entire linac started on the 26 of November 2024, liquid level accumulation at 4.5K started after approximately 2 days and 2K operation with the cold compressors at 26 mbar was achieved on December 11.

Cold Operation and Availability

Stability of the first months of operation has been affected by several "teething" challenges of the ESS conventional and control system infrastructure, which led to several trips of the cryoplant. Cold compressor operation has been limited until recently by impurities clogging its inlet filter, due to air ingress from the safety relief line, which is connected at each CM with pressure relief valves. 2K operation has been extended considerably from 10-15 days to several weeks by maintaining a clean He flow in the line. A summary of the cold operation and of the first cryogenic operational experience is presented elsewhere in details in these Proceedings [10].

CAVITY TUNING AND CALIBRATION

After the short non-resonant coupler conditioning stage, performed in January 2025, cavities have been tuned to the operation frequency (352.2105 MHz for the SPK and 704.421 MHz for the MB/HB elliptical).

All tuning operations are performed through the EPICS interfaces using the ESS LLRF system driving the RF power sources, limiting the use of RF instrumentation (e.g. VNA) only for possible debugging and problem-solving.

The Far Tuning Tool

The natural frequencies of the cavities at cold are many bandwidths away from the RF source excitation frequency and need active tuning before operation.

SPK cavities need 60-120 kHz of tuning (full bandwidth ~ 1.7 kHz) and MB/HB cavities 160-260 kHz (full bandwidth ~ 1 kHz). A far tuning tool, based on the cavity frequency identification from the Fourier transform of the field pickup signal in the LLRF digitizers assists the operation of the tuner motor of the cold tuning system in this heavily detuned condition.

The Fine Tuning

When the cavity approaches the RF station excitation frequency the fine tuning is performed by increasing the field level in the cavity and flattening the phase along the pulse. A detuning server is also built into the LLRF IOC to provide detuning information from the cavity decay and along the RF pulse, to achieve optimal tuning conditions.

Gradient Calibration and Loop Closure

Once the cavities have been tuned to the operation frequency, a low power (5-10 kW) RF pulse is applied to calibrate the cavity field in the desired engineering units for operation. The calibration factor relating the cavity field pickup power reading to the accelerating gradient (in MV/m) is computed from the cavity severely over coupled formula at the calibration pulse and then applied during regular operation. At this point the LLRF control loop parameters are set and closed loop operation can be switched on, controlling the cavity with the desired gradient setpoint.

CAVITY CONDITIONING

The last preparation step, before handing over the cavities to the beam commissioning team for the cavity phasing, is to bring the cavities close to their limiting performances. While ramping up the field the activity on the protection mechanisms at the coupler (arc detectors, electron pick-ups) and the cryogenic conditions (valve opening, level measurements) are monitored to detect the approaching conditions of a cavity limitation (quench, multipacting, strong field emission, …).

Once the cavity limit is reached or approached closely, all interlock protections are set to limit the cavity operation within a safe margin, to avoid the operation team running into quenches or breakdowns. Thresholds for cavity field and reflected power are used to enforce the safe operation environment, by using the limiting performances assessed during the SAT at the test stands (or amending them during the cavity ramp up, if needed).

RF Pulse Settings

The nominal ESS RF pulse is a 3.2 ms pulse, with 2.86 ms flat top for beam acceleration and a maximum repetition rate of 14 Hz. This imposes a maximum time of 350 us to fill the superconducting cavities and reach the field stabilization requirements for the beam. Such a long

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RF pulse at relevant gradients requires active piezo compensation to limit the LLRF power required for addressing the Lorentz Force Detuning (LFD). Both SPK and MB/HB elliptical cavities are equipped with a fast action provided by two piezo stacks in the cold tuning system. While feed forward LFD compensation algorithms have been successfully tested during Test Stand 2 operation, these are not yet fully implemented in the LLRF system software layer.

For the BOD commissioning case an RF pulse of 1 ms, with a fill time of 300 us is currently used for all cavities. As the dynamic LFD is moderate in this case, the LLRF can compensate its effect within the power budget available from the source. Figure 3 shows the RF traces and detuning along the pulse for one HB cavity operating at the design value of 20 MV/m. Closed loop operation at the nominal ESS pulse structure will be established after the finalization of the LFD algorithms into the LLRF IOC.

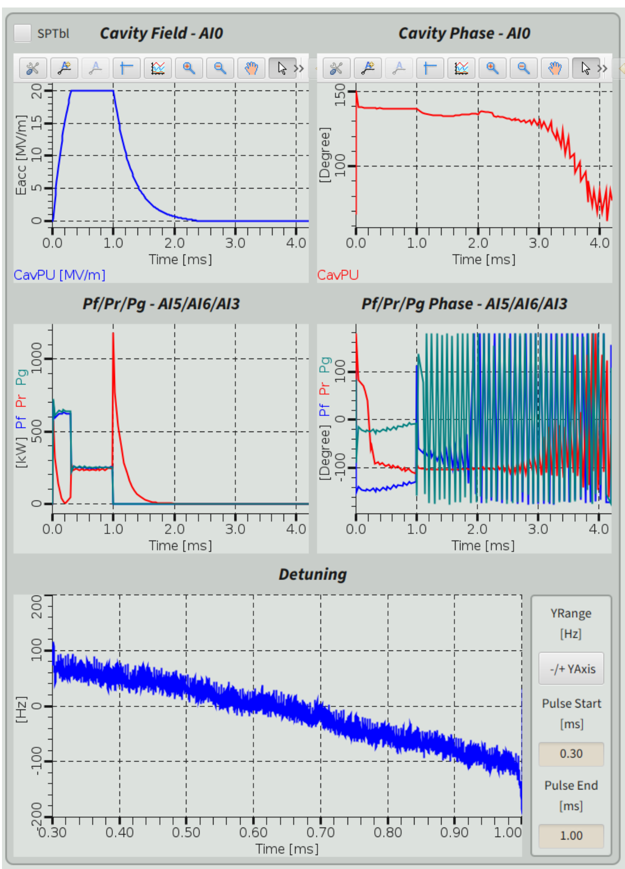

Figure 3: RF traces and detuning along the pulse for an HBL cavity operating (with no beam) at its design gradient of 20 MV/m. The cavity is filled in 300 μs, followed by 700 μs of flat top for beam operation. Head to tail LFD is limited to ~ 200 Hz along the entire pulse. Cavity full bandwidth is ~ 1 kHz.

LINAC STATUS

With the completion of the cavity conditioning of all cavities at the highest achievable fields, the cavities have been handed over to the beam commissioning team for the linac setup, setting the cavity gradients and phasing them according to the beam physics design and performing beam energy measurements with BPM in the transfer line after the superconducting linac [5]. The nominal beam energy of ~870 MeV has been measured with the full transmission of the probe beam of 5 μs length and 6 mA current.

Cavity Settings

Figure 4 shows the machine cavity field settings during the commissioning run.

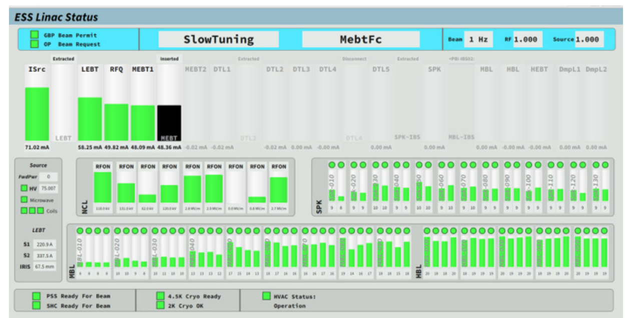

Figure 4: ESS Linac status during commissioning. The upper bar plot represents the beam intensity and destination (currently at the source faraday cup). Middle bar plot is the field in the normal conducting front end (left) and spoke section (right) and lower bar plot is the field profile along the elliptical linac.

RF Operation Experience

RF operation of the entire linac within the operational limits enforced for all cavities is proceeding smoothly, with a very minimal occurrence of breakdowns or arc interlocks in the early days of operation. As all instrumentation in the linac tunnel is radiation hard, operation in the field emission region, as characterized in the test stand, is permitted. Spurious concurrent interlocks on several arc detector fibres may occur during cavity phasing or beam steering, induced by beam losses or strong field emission bursts. A veto system is being considered to mitigate this issue.

CONCLUSION

The first technical commissioning step for the BOD phase of the ESS superconducting linac has come to an end with the measurement of the proton beam energy above 800 MeV in front of the temporary beam dump. The nominal energy of 870 MeV has been achieved a few days later by refining the cavity phasing. Probe proton beams of 5 μs, 6 mA current are regularly accelerated by the cavities excited by a 1 ms RF pulse. The technical commissioning now is giving way to the beam commissioning phase, where beam length, intensity and repetition rate will be gradually increased according to the accelerator commissioning plan [5].

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The successful BOD commissioning of the ESS linac is a large team effort from all the in-kind partners contributors of the Project and the teams in the Operation, Integrated Control System and Accelerator Divisions at ESS.

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