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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

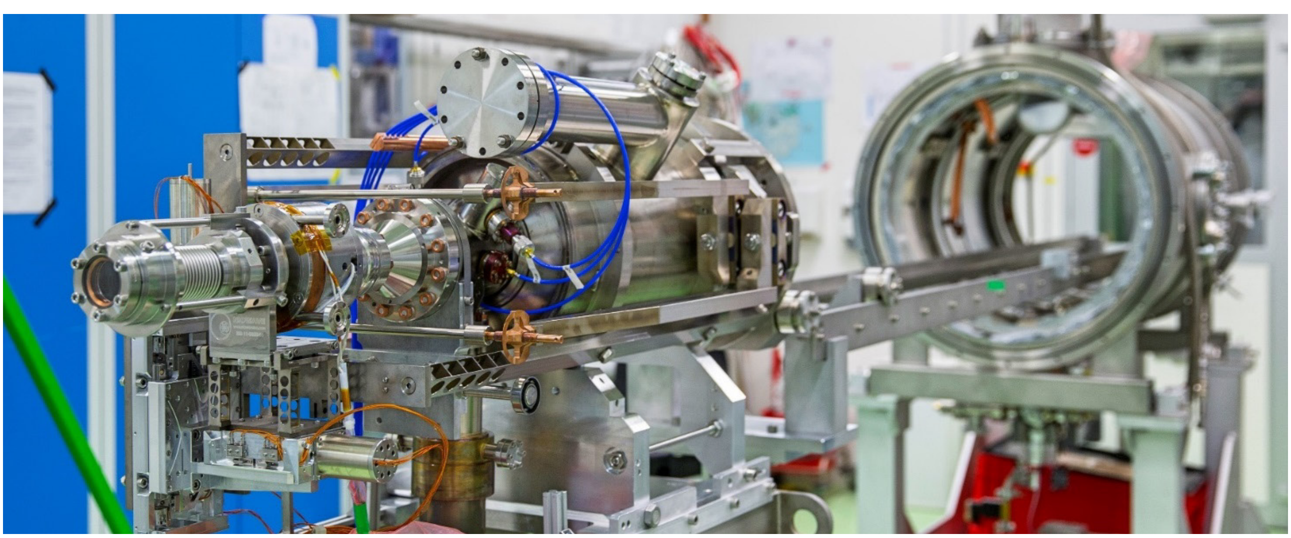

Figure 1: Photograph of SRF gun II during final assembly of the cold mass (front) into the cryomodule (background).

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SRF GUN DESIGN

The design of the SRF gun was last published in detail elsewhere [6], therefore, only a brief overview is given here. The entire electron source is very compact, measuring only 1.3 m in length and 0.9 m in diameter. Despite its small size, beam energies up to 5 MeV and average currents up to 1 mA have been demonstrated. The electron bunch at the exit of the gun is already relativistic and short enough for further acceleration by the LINAC, which significantly simplifies the beam transport and reduces the overall effort.

Main part of the gun is a 3½ cell 1.3 GHz Nb cavity based on the TESLA shape as well as a choke cell, both surrounded by a LHe vessel (see Fig. 1). On one side of the cavity, the cathode ends almost flush with the backwall of the half cell. The cathode is mounted in a multi-purpose cooling and support insert, that provides a temperature of 77 K and allows for cathode transfer into the cold gun. In addition, thermal and electrical isolation from the cavity is realized to provide a DC bias for the multipacting suppression. Last but not least, the cathode can be moved axially by remote stepper motors to find the best RF focus. At the other end of the cavity, the fundamental RF power coupler, two HOMs loads, and a superconducting solenoid on an xy-motion stage are assembled. The latter provides early beam focusing and emittance compensation.

CAVITY / CATHODE INTERPLAY

One of the most important questions arises from the interaction of a normal-conducting cathode with a photoactive layer and the superconducting cavity. The latter is extremely demanding in terms of an absence of particulates and other contaminants. In order to gain knowledge, the cavity performance was constantly tracked over the past 10 years (see Fig. 2).

To date, more than 30 different photo cathodes (1 Cu, 9 Mg, 21 Cs_2Te) have been used in the gun. After commissioning with a pre-installed pure copper cathode, an on-axis peak electric field of more than 26 MV/m was achieved, corresponding to the first beam with an energy of 5 MeV. However, after the first Cs_2Te cathode was installed end of 2015, the cathode plug overheated within minutes, causing the entire semiconductor layer to be evaporated into the cavity. The reason was a poor thermal contact between the Mo plug and the copper body of the cathode. The resulting Cs contamination led to a massive increase in field emission and a tremendous reduction of the cavity gradient. Fortunately, most of the Cs contamination could be pumped out by means of a thermal cycle to room temperature together with subsequent RF conditioning, and 80% of the original performance could be recovered.

For the next five years, magnesium was used as an interim solution. A total of nine cathodes were activated by means of laser cleaning in the transport chamber shortly before being inserted into the gun. During this period, there was no further deterioration in cavity performance. The Mg cathodes behaved completely inconspicuous and proved to be perfectly compatible with the SRF cavity; even multipacting was not observed.

Since 2020, again Cs_2Te is been used. Now, in order to guarantee a good thermal contact, on Cu plugs instead of Mo. The preparation of the cathodes is done in-house. We managed to maintain high quantum efficiency (QE) from vapor deposition, over storage all the way to the transfer into the gun. But once installed, each cathode exhibits slightly different behaviour in terms of multipacting, lifetime/robustness and QE during operation. The latter is typically between 0.5% and 2%, depending on the quality of the Cs_2Te layer. One exception is the actual cathode that still has 5% even after several weeks of routine beam operation. A cathode is typically used for 500–1000 h of beam hours and lasts between ¼–1 year in the gun. Both are limited only by the warm-up cycle of the LHe refrigerator, which degrades the QE due to poor vacuum conditions in the cavity. There is no other reason not to use a cathode for longer.

Since the lifetime, according to what was observed so far, depends neither on the overall extracted charge nor on the dwell time in the cavity, but rather on its chemical composition, it is planned to optimize the cathode preparation process by improved analysis methods.

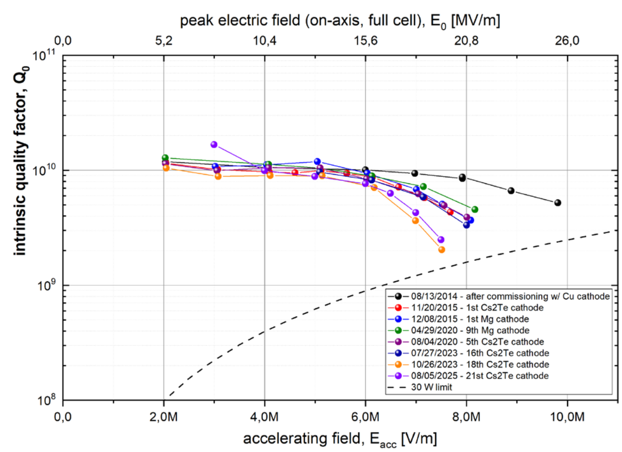

Figure 2: Comparison of Q_0 vs. E_{acc} over the past 10 years. The diagram shows a long period of 8 years w/o performance degradation until mid of 2023 when a field emitter was activated suddenly and w/o prior notice.

Conversely, however, the cavity seems to be affected by the presence of a Cs_2Te cathode. Over days and weeks of RF operation, a slow increase in radiation dose can be measured near the SRF gun, indicating gradual Cs contamination. In addition, a sudden and unannounced drop of cavity performance occurred in the autumn of 2023, presumably as a result of an activated field emitter. Whether this is related to the aforementioned deterioration is not certain, but still likely.

Nevertheless, as there has been no comparable event in the eight years before or since then, it is assumed that both SRF cavities and Cs_2Te cathodes can be used jointly. But it is a fragile coexistence and further investigation on the cavity/cathode interplay is required.

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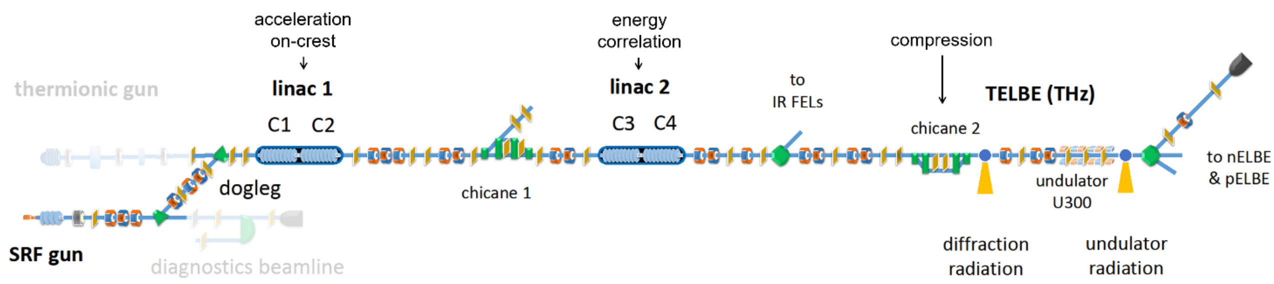

Figure 3: Beamline layout for THz radiation production at ELBE.

ROUTINE USER OPERATION

User operation of the SRF gun started in 2018, at first for terahertz (THz) and later also for neutron generation. In particular the first is very demanding for the injector and the entire accelerator because electron bunches must be compressed to a very short duration while users require excellent short- and long-term stability, both in terms of arrival time and THz pulse amplitude.

The overall beam transport is shown in Fig. 3 and can be described as follows. As the THz output scales inversely with bunch length and squared with number of electrons, beam energy and bunch charge out of the gun are intended to be as high as possible. Incidentally, this is why the thermionic DC injector of ELBE is not suitable for this job. Limited by the available accelerating gradient of about 8 MV/m, the SRF gun delivers a 4 MeV beam with 200–250 pC bunch charge and a repetition rate between 50–250 kHz, continuously. After guiding this beam through an achromatic dogleg transition, it is further accelerated up to 26–28 MeV and imprinted with a correlated energy spread, both by the ELBE-type SRF LINAC modules. The last step is the compression by means of a magnetic chicane down to approximately 100fs into the electromagnetic undulator where bunches then starts to radiate. As a result, super-radiant and coherent terahertz radiation with frequencies ranging from 0.05 to 2.5 THz and pulse energies of up to 10µJ (for ≤1 THz) as well as a few µJ (for ≤2.5 THz) is made routinely available to the users.

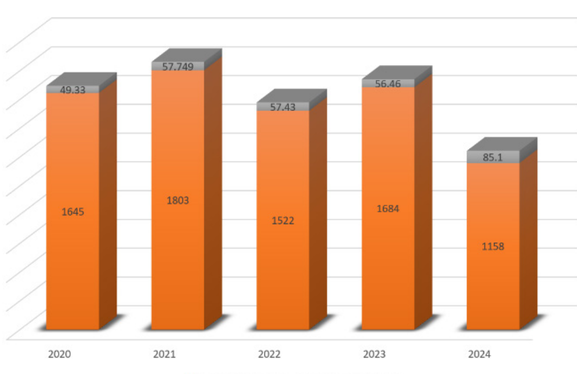

Figure 4: Accumulated user beam time hours and total extracted charge per year.

The SRF injector delivers typically 1600–1800 beam hours per year, which is 35 to 40 % of the total ELBE user beamtime, and the total extracted charge is approximately 50 C (see Fig. 4). The last year's numbers differ as the beam was exclusive provided to THz users while a lot of charge was accumulated during high current runs (see below).

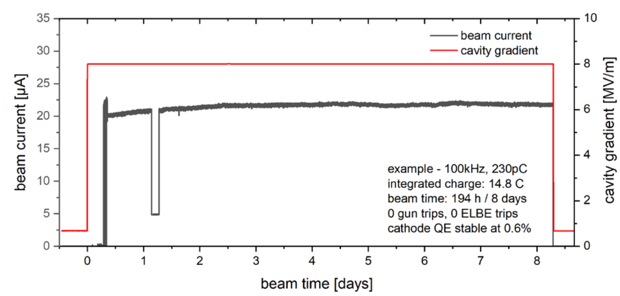

Figure 5: Typical reliability plot of the SRF gun w/o any trips during operation for an 8-day user experiment.

The gun operates very reliably for typically a week (or 200 hours) with minimal number of trips and negligible downtime (Fig. 5). It maintains a very stable performance with an arrival-time jitter as low as 40 fs (RMS) at the user experiment, primarily influenced by the 2nd ELBE LINAC module. Compared to ELBE's thermionic electron source, the THz output power is typically 10 times higher and significantly more stable, both in terms of jitter and power. For the latter a pulse to pulse amplitude fluctuation is in the order of 3% (RMS).

Notably, after two decades of worldwide development efforts on SRF guns at numerous institutes, the ELBE SRF gun at HZDR stands out as the only system that routinely provides user beam.

MILLIAMPERE-LEVEL FEL OPERATION

In addition to routine user operation, another important long-term goal was achieved recently. More than 20 years ago, the HZDR conducted a proof-of-concept experiment that demonstrated the compatibility of a half-cell SRF cavity with a normal conducting Cs_2Te cathode. At the same time, the development of a multi-cell gun cavity was already well underway. In a corresponding publication from 2004, a detailed SRF gun concept was presented that was intended to serve as an electron source delivering an average beam current of 1mA for a free electron laser (FEL) such as the ones at the ELBE [7]. The authors were "convinced that the superconducting RF gun is the first candidate for a high current and high brightness injector" for FELs. However, it took another 20 years before practical proof was conclusively provided, again at the HZDR.

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During dedicated machine-development (MD) shifts, the SRF gun was pushed to an average current of up to 1 mA, which is 100x more than in the standard user runs. As the corresponding average beam power in the machine exceeds 10 kW, all safety measures were checked first to ensure that the operation is stopped immediately in case of an interlock. Main protection is provided by two analog systems, referred to as beam loss monitor (BLM) and differential current monitor (DCM). The first detects secondary radiation utilizing a long coaxial cable as ionization chamber in parallel to the beamline, while the second compares the beam current between two points, either two stripline BPMs or a BPM and the beam dump. Interlock is fired when a threshold of ~typ. 10µA CW or 400 µA/ms is exceeded. A fast logic system is combining all events from BLM, DCM, vacuum system, person safety and all other components (e.g. RF, magnets, screens, dumps etc.) and blocking the laser by two consecutive shutters. The first one is a very fast (<µs) acousto-optic modulator (AOM) while the second is a very reliable mechanical shutter with a closing time of less than 2 ms.

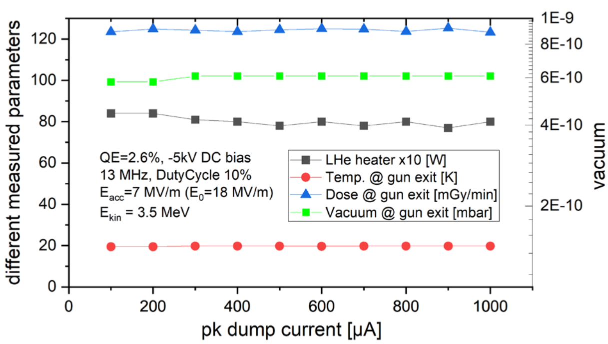

Figure 6: Vacuum, temperature and radiation dose at the gun exit as well as RF loss as a function of the peak current.

The average current was increased in two phases. In Phase 1, the drive laser built by Max-Born-Institut (MBI) in Berlin was set to a repetition rate of 13 MHz and the duty cycle was reduced to 10%. The produced electron beam was guided 5 m downstream along a diagnostics beamline into a small dump, which limits the average current. The laser power was then stepwise increased up to a peak current of 1mA (corresp. to 77 pC), while critical parameters such as radiation dose, temperature and vacuum at the gun exit as well as the dissipated heat load into helium bath were carefully observed (see Fig. 6). As there was no correlation between the beam current and theses values, it was concluded that beam loss in the vicinity of the gun is negligible and consequently Phase 2 was started.

For that purpose, beam current was reduced to 0.5 mA, a level that is sufficient to operate the ELBE IR-FEL (U37). Starting from a standard setting (for the thermionic injector), the beam transport was first optimized at a low duty cycle all the way down through the FEL undulator into the dump. Once lasing was achieved, the average current was increased stepwise up to full beam power of 13 kW, always accompanied by careful machine tuning. Finally, after a few hours, 100% transmission into the dump and negligible beam loss along the entire accelerator were achieved. The optical FEL power was on the same level as for the thermionic injector, while setting up the beam transport was significantly easier due to better transverse emittance.

Similar to the Phase 1 findings, the critical parameters at the gun exit again appeared to be unaffected, despite a five-fold increase in average current and regardless of whether the beam is on or off (see Fig. 7).

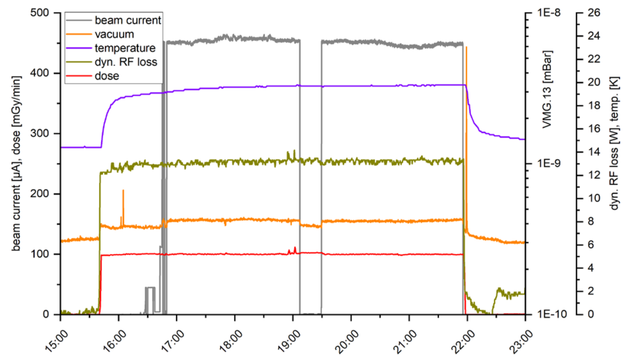

Figure 7: Vacuum, temperature and radiation dose at the gun exit as well as RF loss over the course of 5h while extracting an average current of 450 µA.

In order to estimate the stability of the generated electron bunches, several measurements have been done under the influence of full CW beam loading. Amplitude and phase noise of the cavity field have been measured to be 0.01% and 30 fs (both 10 Hz - 1 MHz) using an FSWP signal source analyser from R&S. On the other hand, readout of a beam position monitor in the dispersive dogleg section over the course of 45 min revealed a current stability of 3 µA (0.7%) RMS, whereas pointing was about 50 µm RMS, corresponding to a beam jitter of 100 fs, mainly dominated by the photocathode laser stability.

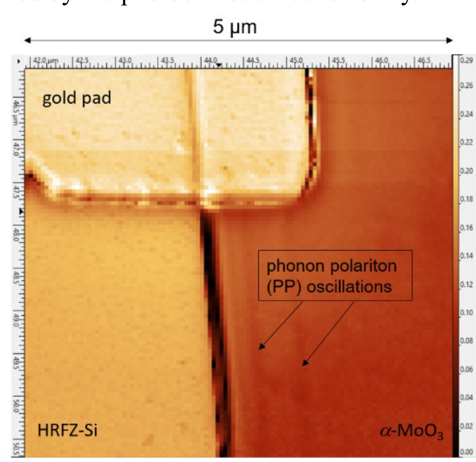

Figure 8: Processed s-SNOM image (5 µm x 5 µm) of 2D flake of a-MoO3 (right side) on HRFZ-Si with a gold pad (top left). The observed multiple weak phonon polariton oscillations and the high contrast between the substrate and sample are indicative of very low noise in the FEL beam.

To further test the performance of the FEL, the IR beam was directed to one of the user labs, hosting a setup for scattering-Scanning Nearfield Optical Microscopy (s-SNOM). This technique serves as highly effective metric of FEL performance, because it is extremely sensitive to

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most types of noise in the FEL beam even more than any diagnostics that characterizes FEL beam directly. The low noise and high contrast of the processed s-SNOM image in Fig. 8 indicates the exceptional high stability of the FEL driven by the ELBE SRF gun. Furthermore, this stability was maintained over the multiple hours needed to acquire an s-SNOM image.

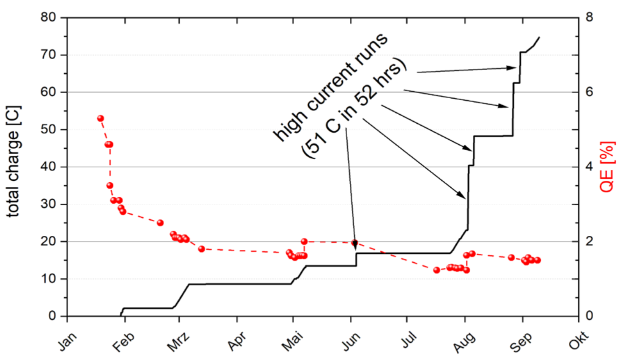

Figure 9: Evolution of QE and accumulated charge extracted from a single cathode over nine months in 2024, all five high-current runs are highlighted.

This experiment marks a major milestone in the global development of SRF guns, as all CW hard X-ray FELs (e.g. LCLS II, SHINE, EuXFEL-cw) are also pursuing superconducting electron sources, alongside their normal-conducting counterparts, which are still favored due to their higher level of maturity. To the authors' knowledge, it is the first time ever that an IR-FEL was driven in CW by an SRF gun and, at the same time, also a highly sensitive user experiment was conducted utilizing the generated radiation. Equally important is the demonstration of a reliable operation over five MD shifts (12h each) with high average current and minimal beam loss both near the gun and throughout the entire accelerator. And it is be noted that over a period of 52 hours, a total charge of 51 C was extracted from a single Cs_2Te cathode, which was maintaining a high QE of 1.6% without any signs of deterioration (Fig. 9).

SUMMARY

In the past 10 years, an improved version of the ELBE SRF gun, designated as gun II, was commissioned and successfully transitioned into user operation. Although the achievable acceleration gradient in daily operation remained behind expectations [6], the electron source has successfully made the transition from a prototype to a mature device in terms of stability, availability, and reliability. To date, approximately 1800 hours of beam time are delivered each year, with a bunch charge of 200–250 pC and a repetition rate of 50–250 kHz.

In addition, the beam current could also be pushed by two orders of magnitude to 1 mA to drive one of the ELBE IR-FELs in continuous-wave mode. The generated optical beam was transferred to an extremely sensitive user experiment, known as s-SNOM. The observed low noise level and high contrast of the processed image provide clear evidence of the exceptional stability of the electron beam.

Other important questions, especially concerning the cathode / cavity interplay, have been addressed as well. Although, a fast, medium and slow QE degradation is observed for most of the cathodes during the first month of operation, it later settles to an almost constant value. The mechanism behind is not yet fully understood, but it is assumed that it is related to a non-uniform chemical composition of the photoactive layer, either due to contamination by foreign atoms (during preparation process) or due to variations in the stoichiometric ratio between caesium and tellurium. From QE mapping it is known that all coatings have less robust regions, which degrade more rapidly under the influence of the vacuum or the CW RF field. Nevertheless, the QE is not affected by charge extraction itself.

Conversely, also the cavity seems to be slightly influenced by the presence of Cs_2Te cathodes. Over days and weeks of RF operation, a slow increase in radiation dose can be measured near the SRF gun, indicating gradual contamination. It cannot be excluded that this effect is associated with an activated field emitter, which caused the first performance degradation after a stable period of 8 years.

OUTLOOK

As part of our further development, the first 3.5 cell cavity out of gun I was recently refurbished at HZB. The achieved field during vertical test exceeded E_0=30 MV/m, which is 50 % higher than in the operational gun. As this will allow significant higher bunch charge (e.g. >500 pC), a significant increase in THz output is expected as well. The next gun will also be equipped with a modified superconducting solenoid that has 50 % lower spherical aberration to improve transverse emittance at high bunch charge. Last but not least, the new injector will also feature an automatized cathode transfer system.

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