ELBE SRF GUN II – EMITTANCE COMPENSATION SCHEMES

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Abstract

In May 2014 the first SRF photo injector at HZDR has been replaced by a new gun, featuring a new resonator and cryostat. The intention for this upgrade has been to reach for higher beam energies, bunch charges and therefore an increased average beam current, which is to be injected into the superconducting, CW ELBE accelerator, where it can be used for multiple purposes, such as THz generation or Compton back-scattering. Because of the increased bunch charge of this injector compared to its predecessor, it demands upgrades of the existing and/or novel approaches to alleviate the transverse emittance growth. One of these methods is the integration of a superconducting solenoid into the cryostat. Another method, the so called RF focusing, is realized by displacing the photo cathode's tip and retracting it from the last cell of the resonator. In this case, part of the accelerating field is sacrificed for a better focus of the electron bunch right at the start of its generation. Besides particle tracking simulations, a recent study, investigating on the exact position of the cathode tip with respect to the cell's back plane after tuning and cool down, has been performed.

THE ELBE SRF GUN II

The ELBE SRF Gun, which is located at the ELBE accelerator center, Dresden, is a RF photoinjector with a 3-1/2-cell TESLA-shaped, pure niobium resonator at its heart. It is operated with a Nd-Yb UV light laser at about 260 nm, while the cavity is cooled down with superfluid helium at 2 K, hence, making it a superconducting photoinjector. In early 2014 the ELBE SRF Gun I has been replaced by its second, upgraded version. Besides a newly improved resonator, the cryostat itself has been extended in order to house an additional superconducting solenoid for emittance compensation for the generated electron bunches. [1]

Although, the gun itself is superconducting, the photocathodes are operated at liquid nitrogen temperature, i.e. 77K. During the installation of the SRF Gun II (see Fig. 1) a bulk copper cathode has been installed inside the cryostat. Since spring 2015 a transfer system has been added to the injector, making it possible to exchange the cathodes without warming up any part of the cryostat. (An updated version of this transfer system, limiting the part being exchanged each time to the very tip of the cathode, has been developed in cooperation with HZB, Berlin, and is currently in the construction phase of the first test setup, see [2].) Besides

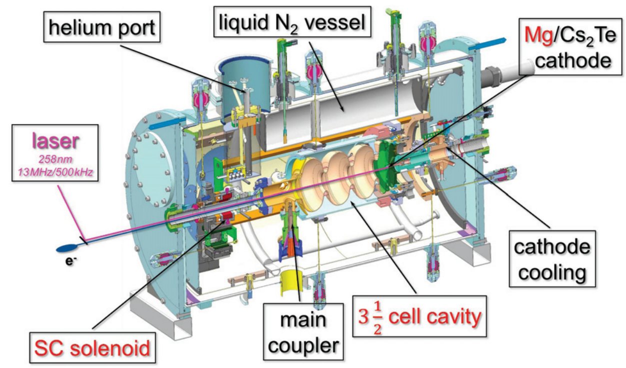

Figure 1: Overview of the design of the ELBE SRF Gun II.

the initial copper cathode, the SRF Gun II is planned to be operated with bulk Mg-tip cathodes — QE $\approx 1-2\cdot10^{-3}$ [3] — and eventually Cs_2Te coated cathodes, aiming for a QE of several percent. [4]

RF FOCUSING

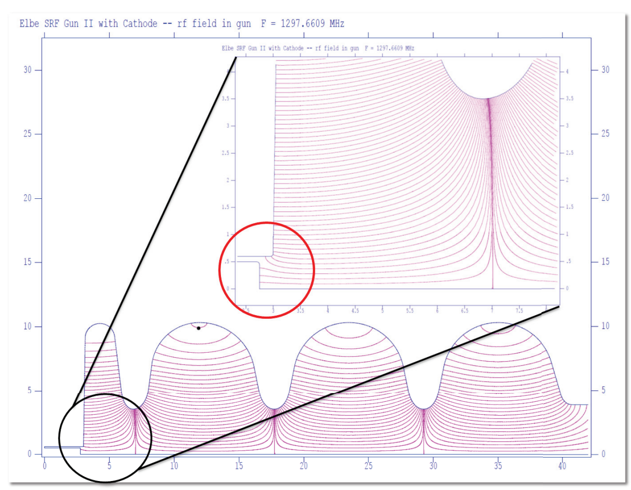

Figure 2: Example of the transverse electrical field lines affecting the cathode tip. In the indicated area the effect of RF focusing becomes visible, as the field representations indicate the additional focus towards the central gun axis for a retracted cathode.

The idea of RF focusing is born out of the geometry of the gun cavity. Since being thermally isolated from the niobium resonator, the cathode has to be inserted into the first half cell through a narrow tube. If synchronized correctly

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ISBN 978-3-95450-178-6

to the laser phase, the standing longitudinal electric wave "grabs" the emitted electrons and accelerates them towards the gun's exit. The electric field lines begin to have a focusing effect when the photocathode is retracted even a few hundred microns. Electrons emitted (further) away from the cathode's center, receive an additional "kick" towards the gun's axis, as illustrated in figure 2 generated with the SUPERFISH code. [5, 6]

Nevertheless, this early electron lens does not come with no cost at all. Caused by the retraction, the electron bunch does not "see" the full field of the half cell, parts of the energy are not added up in direction of the beam line, as they are utilized for the focusing. As the simulation shows — see figure 3 — the "lost" beam energy is small compared to the gain in the rest of the resonator. For the chosen example of a bunch charge of 250 pC[1] and a cathode tip put 2 mm behind the back plate plane, the kinetic Energy reaches about 3.396 MeV, whereas electrons emitted from a non-retracted cathode gain 3.483 MeV, a relative disadvantage of less then 3 %.[2]

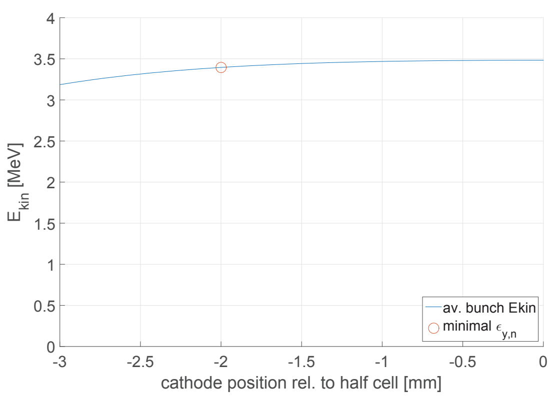

Figure 3: Diagram of kinetic energy at the gun's exit versus the position of the retracted cathode tip, zero being no retraction at all. The highlighted spot corresponds to a minimal emittance at 2.8m from cathode as found by the scan shown in figure 4.

Simulation of High Bunch Charges

In order to visualize the possible gain in terms of emittance compensation, numerical simulations using ASTRA [7] for the particle tracking and SUPERFISH for the generation of the field files have been carried out. These simulations are supposed to cover the operation with higher bunch charges which are aimed for by the use of bulk Mg cathode tips, i.e. several hundred pC. To reduce the relatively large effect of beam halo deteriorating the absolute value of the emittance, ASTRA's output of 90 % of the particle's rms emittance, also referred to as the "core emittance", is used in the following. Furthermore, to gain in commensurability with experiment, the simulated results are compared at exactly 2.796 m, the location of the second screen station in the local diagnostics beam line. This station represents the first opportunity of determining the transverse beam emittance.

Table 1: Simulation Parameters

accelerating gradient	laser phase	bunch charge	pulse duration	spot diameter
$7\,\frac{\text{MV}}{\text{m}}$	58°	250 pC	6 ps	4 mm

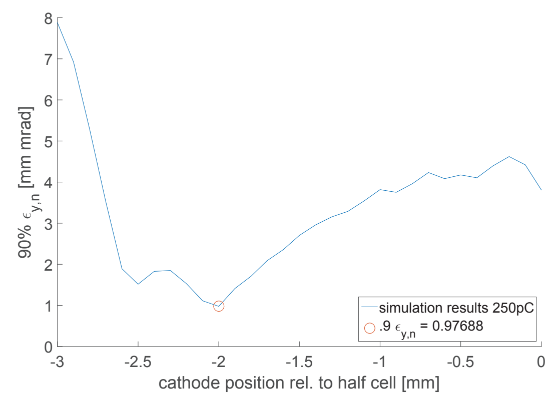

Figure 4: Scan of the transverse core emittance at the second screen ($z = 2.8$ m) station for different cathode positions behind the back plane of the resonator.

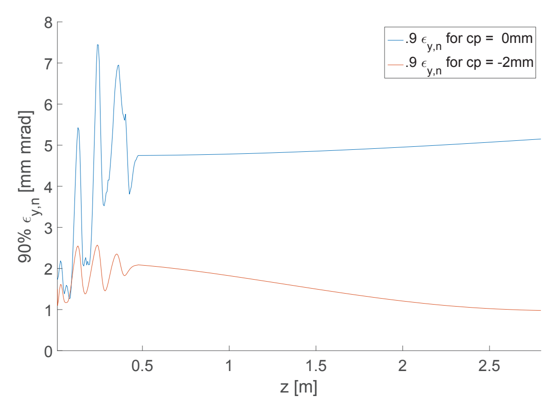

Figure 5: The evolution of the core emittance for a 250 pC bunch along the beam line with and without RF focusing.

Figure 4 shows the result for a scan of the vertical, normalized emittance in dependence of the distance between cathode front surface and the back plate plane of the half cell. The latter one defines the zero along the z-axis. As indicated, the minimum emittance value can be achieved around a value of 2 mm. In figure 5 the development of the transverse emittance of this minimal case and the case of no RF focusing are compared along the beam line. The same is done for the beam radius over the first meter in figure 6. Here, the effect of the focusing at the very beginning of

[1] at 7 MV/m

[2] The chosen 2 mm correspond to a minimal transverse emittance at 2.8 m, the position of the (first) emittance diagnosis setup.

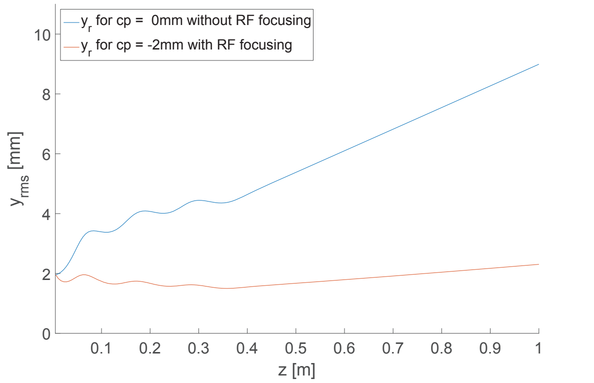

Figure 6: Comparison of the development of the beam radius for the first meter along the beam line for a 250 pC bunch with and without RF focusing.

the electron bunch generation can be observed best. As all the components in the considered part of the beam line are rotationally symmetric, ϵ_y and $y_r ms$ represent the entire transverse phase space.

Cathode Position

Cathode Tuner Since the functional tip of any photocathode in the ELBE SRF Gun is set at the end of a > 10 cm long copper body, the simplest approach to affect its location inside the cavity is to in-/decrease the length of the body's neck. While this option is rather inconvenient during operation, it is still available as an option for larger steps of retraction. A more subtle and precise mechanism, depicted in figure 7, has been realized in the current gun. The total range of this so called "cathode tuner" covers a distance of 1.2 mm with a theoretical resolution of 1 µm.

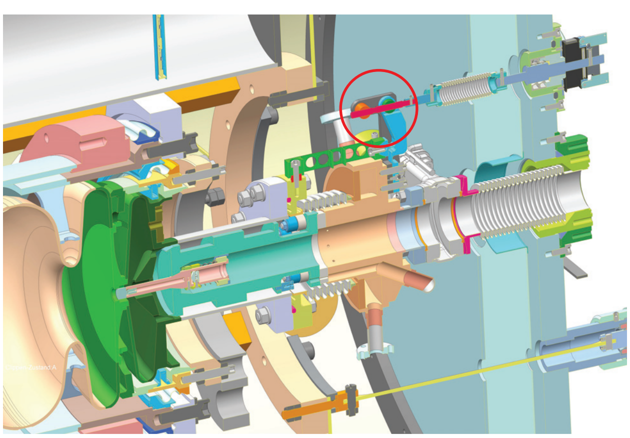

Figure 7: CAD image for the cathode cooler, half cell of the resonator and the cathode tuner inside the gun cryostat. The indicated mechanism connects the cathode holder to a gear outside the cryostat, making it possible to move the cathode tip in and out of the resonator during operation.

Cathode Localization As mentioned earlier, the resonator and the photocathode are cooled down to different temperatures. Hence, in combination with all other uncertainties during installation, it is hard to predict the cathode's exact position within the gun when taken into operation. While measurements of the change in the resonator frequency only offer an indirect approach, recently, a setup for the direct metering has been developed by F. Roscher [8]. This system is built around a laser driven distance measuring device using the same vacuum mirror as the regular gun laser to compare the total distance values for the half cell's back plate surrounding the cathode hole and the cathode tip itself. The result of such a measurement of the default starting position of the copper cathode, is summarized in figure 8. The combined results of all measurements locate the cathode tip at -1.56 ± 0.02 mm with respect to the half cell's rear plane.

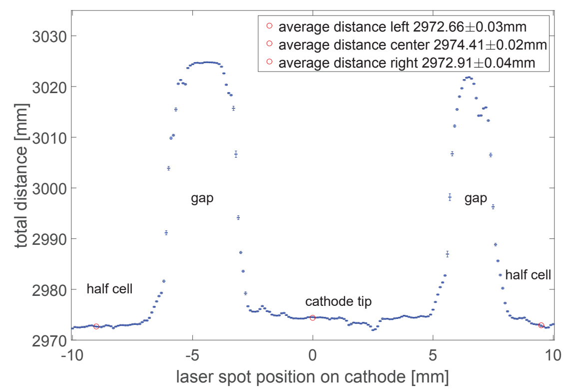

Figure 8: Result of a cathode localization measurement. The distance values left and right of the center represent the distance of the measuring device to the half cell around the cathode, while the inner part represents the distance to the cathode's front tip. The gaps in between are less wide in reality (> 1 mm), but cause a much larger signal here due to the size of the scanning laser's spot at this distance .

Low Bunch Charge Measurements

The results of the localization measurement mentioned above, have been used to perform a first scan of the transverse emittance versus different cathode positions in the tube connecting it to the cavity. For this scan, a horizontally aligned slit mask, located in the second screen station, so roughly 2.8 m from the electron generation, has been used. The cut out beamlets are measured on YAG screen in another screen station 75 cm down the beam line. The setup is described in more detail in [9]. Because of the low QE of the bulk copper cathode still being used up to today, these measurements were performed wit a comparatively low bunch charge of about 1.6 pC.

The results given in figure 10 show a large deviation from the simulation of a similar set of parameters — see table 2 — given in the same plot. At this low bunch charge, the actual space charge forces affected by the RF focusing play a less role than for e.g. the thermal emittance. In addition, the shape of the laser intensity distribution on the cathode during

ISBN 978-3-95450-178-6

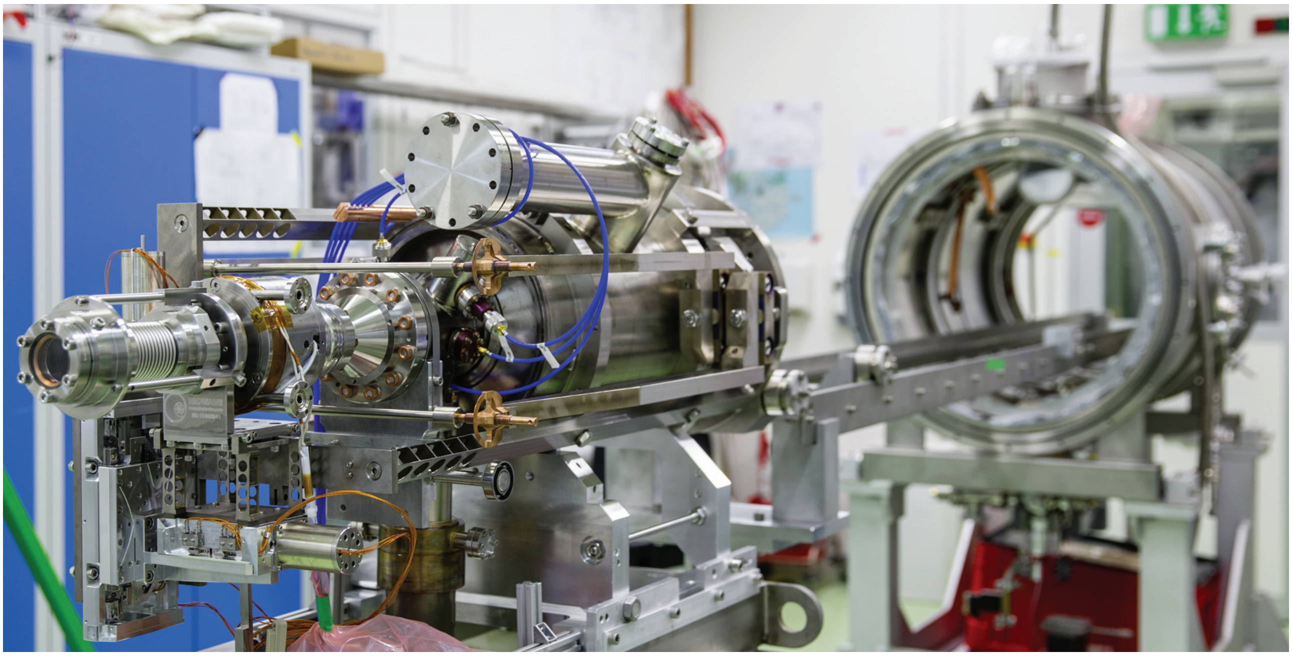

Figure 9: Photograph taken of the cavity string including the SC solenoid and its horizontal and vertical stepper before insertion into the cryostat in the right part of the picture.

the measurement has been rather Gaussian than the desired uniform distribution. Nevertheless, the trend predicted by the simulation can already be recognized in the experimental data.

Table 2: Experimental Parameters

accelerating gradient	laser phase	bunch charge	pulse duration	spot diameter
$7.164\,\frac{\mathrm{MV}}{\mathrm{m}}$	60°	1.66 pC	6 ps	2 mm

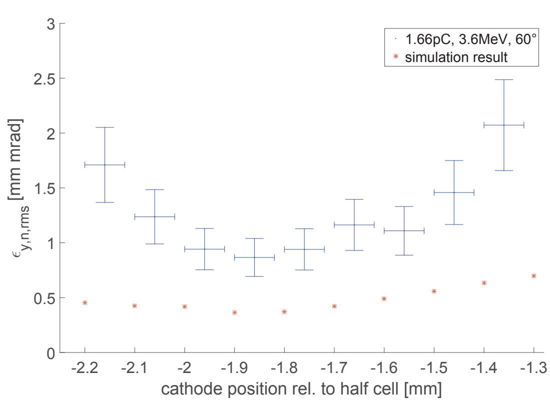

Figure 10: Result of a first test scan of the transverse emittance versus the cathode position performed with a low charge bunch.

SUPERCONDUCTING SOLENOID

SRF Gun I at the HZDR used to be followed by a large, normal conducting solenoid in z direction to alleviate the emittance growth down the beam line. The second version of the SRF injector has moved this magnetic lens inside the cryostat itself and therefore closer to the photocathode. This new superconducting solenoid has been installed in front of the cavity, as shown in figure 9. After a corresponding set of tests during the commissioning phase [10], it is now in operation for almost one year.

Combined with RF Focusing

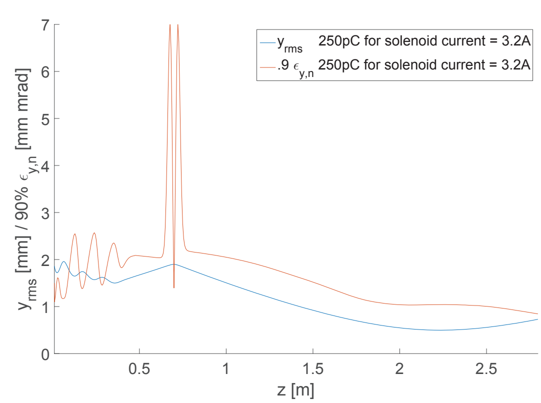

Figure 11: Combination of the impact of RF focusing and the SC solenoid (at about $z = 70\,\mathrm{cm}$) on the core emittance and the transverse extension of the beam.

Although the currently reached bunch charges do not demand its use, the superconducting solenoid's focusing forces on the bunch have already been examined. The predicted effect for higher bunch charges is given by an example shown in figure 11. Here, the emittance-wise optimal cathode position for 250 pC (see figure 4, has been combined with a solenoid current of 3.2 A, corresponding to a $B_{z,max} \approx 152.4\,\mathrm{mT}$. Where the latter one has also been found by simulation, to reduce the transverse emittance at the second screen station the most. The impact on both the emittance as well as on the spatial extend of the bunch along the beam line is displayed in the same plot.

OUTLOOK

Mg-Cathodes

Considering a conclusion for the described schemes of emittance compensation integrated in the ELBE SRF Gun II, one can summarize, that they serve their purpose well as shown in the framework of simulation. Whereas the RF focusing comes at a low price of less energy gain, the SC solenoid has required more sophisticated efforts during installation as reported elsewhere [10]. However, both technologies are up and running, ready to deliver the experimental proof of their concept. After some unfortunate first attempts of the preparation and installation of Cs_2Te cathodes, the currently declared gateway to higher bunch charges at HZDR leads to Mg cathodes. These are known to deliver quantum efficiencies of up to $2 \cdot 10^{-3}$ — a major step compared to the currently used copper cathodes with a QE of about $2 \cdot 10^{-5}$. One of the main issues is the removal of the inactive oxidation layer created on any pure magnesium exposed to air. First attempts to perform a laser cleaning in vacuum recently conducted at Dresden have yielded QE values of up to $0.6 - 0.8 \cdot 10^{-3}$, making the chosen path more and more promising for the near future.

TE-Mode(s)

Another scheme to tackle the problem of emittance compensation within an RF injector is the introduction of a dedicated transverse electric mode. This mode, operating at a frequency close to a higher order mode of the one of the accelerating TM mode, is designed to serve similar to a solenoidal field inside one of the resonator's cells. Although, due to its RF character, it does not represent a fixed field, it will give an averaged focusing to each individual bunch. Further numerical calculations as well as a first practical test of this approach are planned for the near future at HZDR and JLab.

ACKNOWLEDGMENT

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP7 program (EuCARD-2, contract number 312453), as well as the support of the German Federal Ministry of Education and Research grant 05K12CR1 and the help of all the people at the ELBE accelerator at HZDR especially the people of the shift crews. In Addition, special thanks go to F. Roscher for his work at HZDR in '14/'15.

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ISBN 978-3-95450-178-6