EMITTTANCE COMPENSATION FOR AN SRF PHOTO INJECTOR

H. Vennekate*[1,2], A. Arnold[1], P. Kneisel[3], P. Lu[1,2], P. Murcek[1], J. Teichert[1], I. Will[4], and R. Xiang[1]

[1]Helmholtz-Zentrum Dresden-Rossendorf – [2]Technical University Dresden – [3]Thomas Jefferson National Accelerator Facility – [4]Max-Born-Institut

Abstract

Many future electron accelerator projects such as energy recovery linacs (ERLs), high power free electron lasers (FELs) and also some of the new collider designs rely on the development of particle sources which provide them with high average beam currents at high repetition rates, while maintaining a low emittance. Superconducting radio frequency (SRF) photo injectors represent a promising concept to give just that, offering the option of a continuous wave (CW) operation with high bunch charges. Nevertheless, emittance compensation for these electron guns, with the goal of reaching the same level as normal conducting sources, is an ongoing challenge. This paper is going to discuss several approaches for the 3-1/2-cell SRF gun installed at the accelerator facility ELBE at the Helmholtz Center Dresden-Rossendorf including the installation of a superconducting solenoid within the injector's cryostat and present the currently used method to determine the beam's phase space.

MOTIVATION

The motivation of the design and development of an SRF photo injector is to combine the advantages of well known normal conducting injectors, such as thermionic or photo DC guns, and normal conducting (NC) RF injectors. While the latter ones usually generate the best, so smallest, beam emittance values and are able to provide hight bunch charges, DC guns give the option to operate at much higher repetition rates—eventually CW mode—and therefore offer high beam currents. Instead of normal conducting RF accelerator structures, including injectors, which are limited in their repetition rate due to the large power loss by electrical heating, a superconducting RF resonator is able to accelerate charged particles in CW operation making it possible, to build a whole CW particle accelerator. Turning the injector itself superconducting too, gets the advantages of both sides—DC and RF—together. Nevertheless, while it is a common approach to focus an RF gun's beam using a solenoid around or at least close to the resonator's exit, this is very complicated for the concept of a superconducting structure. Hence, alternatives have to be developed.

The HZDR at Rossendorf, Germany, has started to develop a 3-1/2-cell niobium electron gun in 2004 [1] and is currently operating it at the ELBE accelerator facility. This gun can supply the local linac with electrons at a repetition rate of up to $13\,\mathrm{MHz}$.

* h.vennekate@hzdr.de

EMITTANCE COMPENSATION

Since the presence of any additional magnetic field at the location of the RF cavity of the injector is unfavorable, the first approach to reduce the emittance growth has been the installation of a large solenoid just outside the gun's cryostat and its magnetic shielding. Such a magnet can focus the electron beam similar to an optical lens with its refractivity being represented by the integral of its quadratic magnetic field on the beam axis along its spatial extent in this dimension.[2]. The used solenoid has a diameter of about $70\,\mathrm{cm}$ and is $12\,\mathrm{cm}$ long. It reaches a maximum magnetic field on the beam axis of about $440\,\mathrm{mT}$, which corresponds to a quadratic field integral of $\int_{z'} B_z^2\,\mathrm{d}z = 0.012\,\mathrm{T}^2\mathrm{m}$. The distance to the cathode of the gun is roughly $1.1\,\mathrm{m}$.

In addition to the solenoid outside the gun cryostat, another effect inside the resonator itself aids to focus the electron bunches released by the cathode. The Rossendorf design of the SRF gun combines a 3-1/2-cell superconducting resonator with normal conducting photo cathodes contained in an elaborate cooling system, making it possible to exchange the individual cathodes without warming up the whole SRF part of the injector. The NC cathodes are inserted into the first half-cell of the niobium cavity through a small feed through. Their front surface is coated with Cs_2Te, which emits electrons when excited by photons of a certain wavelength from an external laser. When retracted for a few millimeters into the connection tube, the front side of the cathode "sees" a certain electric field due to the RF fields inside this rod. These fields contribute to directing the electrons along the beam axis. This RF focusing is described in more detail in [3]. Its improvement is also part of the present research at HZDR.

Emittance Measurement

The transverse emittance of the beam can be determined in a special diagnosis beam line separate from the actual linear accelerator at Rossendorf. This setup allows a parallel operation of the main machine and the SRF gun. Within the diagnosis beam line several options to measure the emittance, like a quadrupole scan, are available. Most recently, a new single slit scanning method has been established. It uses a movable slit mask to sample a small beamlet out of the entire beam on a YAG screen downstream the beam line. This beamlet is being recorded and analyzed by a LabVIEW program. Moving the slit along the beam gives a complete information of its transverse phase space. A complete description of the method and the used analysis algorithms has been presented at the recent FEL 2013 [4].

ISBN 978-3-95450-143-4

Figure 1 gives a representation of the setup.

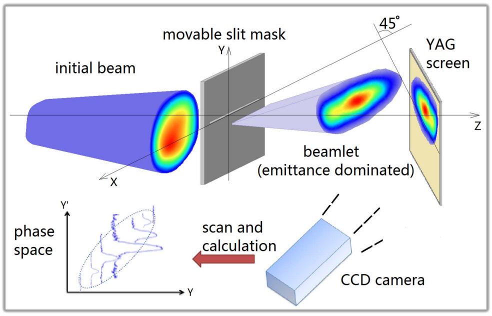

Figure 1: Scheme of the setup for the Single-Slit-Scan Method: The slit mask samples a beamlet of the beam which gets detected on YAG screen at a certain distance. Afterwards the angle distribution of the beamlet on that screen is integrated. Scanning the whole beam with this mask results a representation of the complete phase space [4].

Superconductiong Solenoid

In order to get the focusing forces closer to the cathode and so the initial start of the electron bunch, a new gun cryostat has been designed including a superconducting solenoid next to the SRF cavity, surrounded by an additional magnetic shield. This solenoid is manufactured using NbTi-wires and supposed to be cooled by the same liquid helium supply system as the niobium gun resonator.

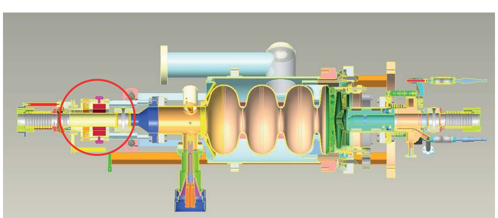

Figure 2: Drawing of the cavity string of the 3-1/2-cell resonator with highlighted position of the superconducting solenoid which is located about 70 cm from the cathode in the first half-cell.

The cooling itself is done via an U shaped tube filled with liquid helium inside a solid copper ring, which is thermally connected to the solenoid yoke via an indium disc as shown in figure 3. The whole structure rests upon two stepping motors, that are able to move the magnet around the beam pipe in the plane perpendicular to the beam axis to compensate for possible errors in its field distribution. The superconducting solenoid has a diameter of 14 cm and reaches a peak magnetic on-axis field of about $B_{z,max} \approx 450\,\mathrm{mT}$. With its length of approximately 6 cm it generates a refractivity of $\int_{z'} B_z^2\,\mathrm{d}z \approx 0.009\,\mathrm{T}^2\mathrm{m}$ at a distance of about 70 cm from the cathode.

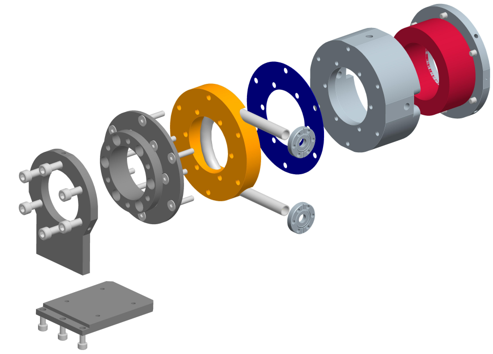

Figure 3: Exploded view of the superconducting solenoid, from left to right: Front plate with base plate, connector, copper cooler with helium pipe, indium disc, solenoid yoke, coil, yoke back plate.

Field mapping As a first step in characterizing the superconducting solenoid, a special installation has been set up. It consists of three stepping motors and a hall probe to determine the magnet's field distribution in beam direction. This setup has been used to map the magnetic field of the solenoid at room temperature using low currents around 60 mA as depicted in the photograph in figure 4. During the measurements, the hall probe scanned a square shaped area of 37 mm^2 inside the imaginary beam pipe—which was not installed at that point—and did record the z-component of the magnetic field for each 1 mm-step of the motors in x- and y-direction. After recording such a field slice, the hall probe advanced again by 1 mm in negative z-direction and scanned the next square of the field as indicated in figure 5. The resulting collections of field slices were used to reconstruct their individual "barycenters" as represented for a single one in 6 and in conclusion to extrapolate the axis of the total solenoidal field.

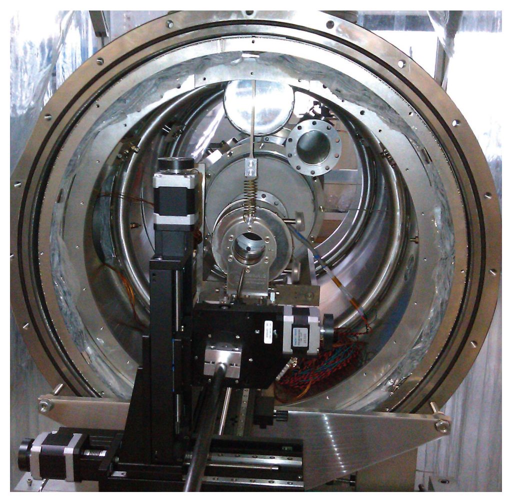

Figure 4: Photograph of the hall probe setup for the room temperature field mapping of the solenoid, the gun cryostat is open and no beam pipe is installed yet.

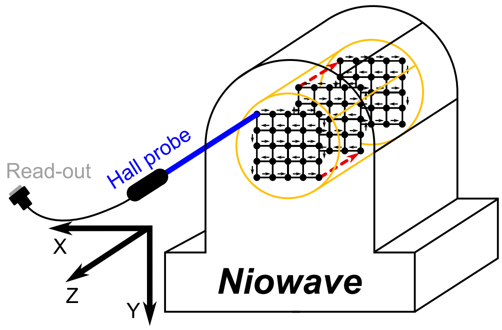

Figure 5: Scheme of the measuring procedure of the field mapping: The hall probe is scanning a square in the plane perpendicular to the beam axis and does take data every 1 mm sized step. After finishing one square it advances to the next by 1 mm.

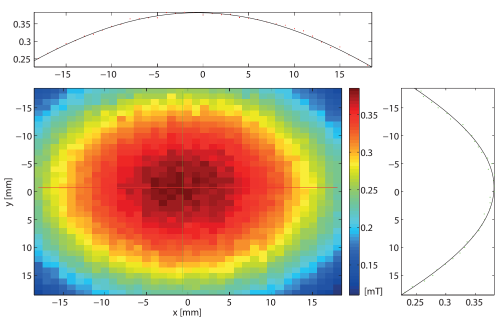

Figure 6: Example of the evaluation of the field slices, the recorded field map is fitted with two Gaussian functions in x- and y-dimension giving a field focus center.

These measurements confirmed that the magnetic axis of the solenoid is mostly in good agreement with its geometric one, as the measured deviations are in the order of magnitude of the uncertainties of the measurement itself.

Table 1: Field Map Results

$\alpha[°]$	$\beta[°]$	Δ_x[mm]	Δ_y[mm]
0.7 ± 1.0	1.5 ± 0.3	-1.0 ± 1.3	0.4 ± 1.0

With the help of four small screws holding the base plate of the solenoid, which rests on a small metal ball, in place, some fine adjustments improving on the measured deviations of the axes could be performed.

Field Profiles at Low Temperatures In order to check on its superconductivity and the corresponding magnetic field levels at high currents, the solenoid has been cooled down to about 4 K. For this more complex procedure, it had to be installed inside the new gun cryostat, which does include a large heat shield using liquid nitrogen to cool down most of the inside parts. Secondly, the solenoid had to be connected to the internal helium supply system, cooling it down below its transition temperature. This whole process is described in [5]. As shown in figure 7 the same hall probe setup could be used to record the field profiles along the beam axis, this time from outside the gun cryostat through the actual beam pipe.

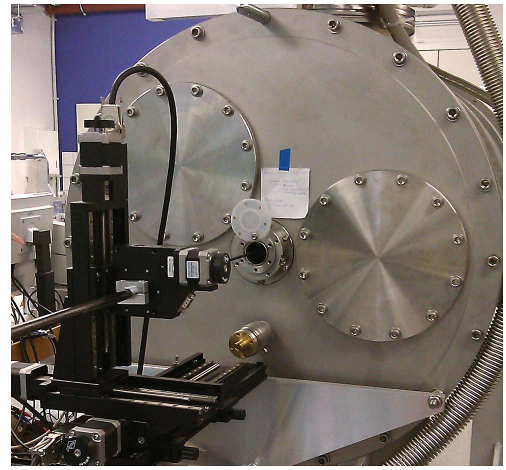

Figure 7: Photograph of the hall probe setup for low temperature experiments, the gun cryostat is closed and the hall probe enters the solenoid field through the installed part of the beam pipe.

Since the time of the solenoid being superconducting was limited by the available helium supply, only the field profiles not the entire distributions were recorded. The coil of the solenoid was connected to a laboratory current source and supplied with 7, 8, 9, and 10 A for this measurement. the results of the measurements are presented in figure 8. The lower part of the illustration shows a 2D representation of the cross section of the beam pipe, the solenoid, and the hall probe and their arrangement. Prior to the experiment, the same geometry has been simulated using the POISSON SUPERFISH solver from LANL. The resulting field profiles are shown in the same plot. Table 2 summarizes the peak field values of the z-components and further parameters of the experiment. The given uncertainties are only of systematical not statistical nature [6].

Table 2: Peak Fields

Vol. $[V]$	Curr. $[A]$	$B_{z,meas}[mT]$	$B_{z,sim}[mT]$
0.8	8	367 ± 1	381
1.3	10	449 ± 1	476

SUMMARY

Conclusion

The 3-1/2-cell SRF gun at HZDR is a successful example of a superconducting injector for CW operation. Yet, compensating the emittance is still a complicated problem that requires sophisticated solutions. The current approach is, to get a solenoidal magnetic field as close to the cathode as possible. This concept has advanced from a normal conducting magnet outside to a superconducting one inside the gun cryostat at Rossendorf. The SC solenoid itself has

ISBN 978-3-95450-143-4

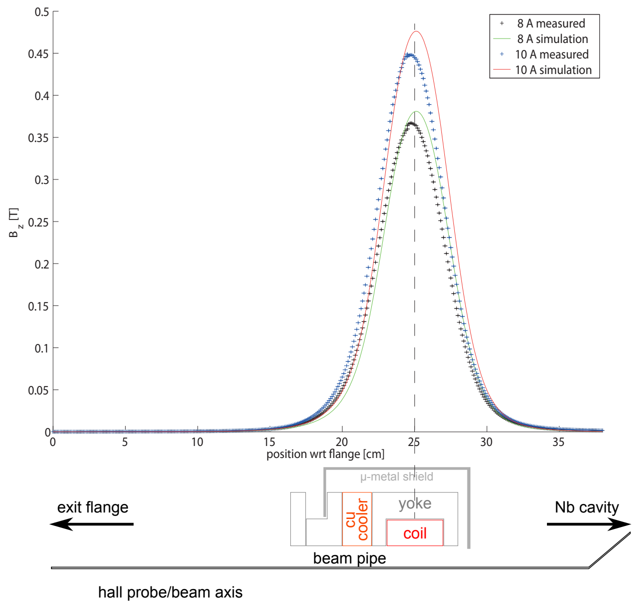

Figure 8: Upper part: Plot of the simulated field profiles for 8 and 10 A combined with the measured data points from the low temperature hall measurement. Lower part: Two dimensional representation of the setup's geometry with the exit flange of the beam pipe as the left and the (imaginary) SC resonator as the right border.

been tested at room temperature as well as at low temperature and performs within the range of expectations from earlier simulations. The next step before the final installation is, to analyze its thermal behavior when being operated at high currents for a long time. The solenoid yoke and the links to the liquid helium system have been monitored by temperature sensors during all the tests. The data analysis of these recordings does still demand further investigations and recalibrations of some of the sensors, which is scheduled for the coming weeks. Further tests of the installation may follow.

Outlook

The next mayor step in order to improve the current situation of emittance compensation of the SRF gun at HZDR is the installation of a new gun including the well tested superconducting solenoid. The niobium resonator for this purpose has already been produced at JLab in the US and is currently being processed and tested there. Together with this cavity another large grain cavity has been manufactured and is planed to be tested and eventually also installed in a new cryostat at Rossendorf. Both cavities are supposed to reach much higher gradients than the currently used one, thereby improving the beam's emittance.

Besides these efforts, further concepts to focus the injector's beam at an early stage have been developed. For example, additional studies concerning the RF focusing on the cathode depending on its exact position are projected in the near future. Another ambitious concept is to generate a TE-mode coexisting with the accelerating TM-mode inside the cavity. By choosing certain frequencies, these two modes can be synchronized to get a solenoidal field right into one of the resonator's cells, focusing the released electrons even closer to the cathode than with the superconducting solenoid as shown in figure 9. [7].

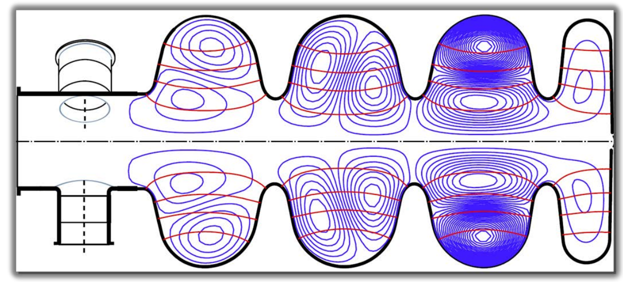

Figure 9: Example of a field distribution of the combination of a TM-mode (red) and a TE-mode (blue) to demonstrate the effect inside the 3-1/2-cell cavity from [7]

ACKNOWLEDGMENT

We acknowledge the help of all the people at the ELBE accelerator at HZDR especially the people of the shift crews, who made it possible to maintain the long cooling cycles of the gun cryostat over several weeks together with Sebastian Hartstock, who always offered a helping hand in the vacuum lab.

Besides that, 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.

REFERENCES

[1] J. Teichert et al., "A Superconducting Photo-Injector with 3-1/2-Cell Cavity for the ELBE Linac", Proceedings EPAC 2004.

[2] M.Reiser, "Theory and Design of Charged Particle Beams", Wiley, New York, 1994.

[3] V. Volkov, D. Jansen, "RF Focussing - An Instrument for Beam Quality Improvements in Superconducting RF Guns", Proceedings EPAC 2000.

[4] P. Lu, "Transverse Emittance Measurement by Slit-Scan Method for an SRF Photo Injector", Proceedings FEL 2013.

[5] P.Murcek, "The SRF Photo Injector at ELBE – Design and Status 2013", Proceedings SRF 2013.

[6] Magnet-Physik Dr. Steingroever GmbH, "Hall-Sonden für FH 54, FH 55", Köln 2008.

[7] D. Jansen, V. Volkov, "Emittance Compensation in a Superconducting RF Photoelectron Gun by a Magnetic RF Field", Proceedings EPAC 2004.