SIMULATION AND FIRST RESULTS OF THE ELBE SRF GUN II

P. Lu, H. Vennekate, HZDR & TU Dresden, Germany
A. Arnold, U. Lehnert, P. Murcek, J. Teichert, R. Xiang, HZDR, Germany

Abstract

Recently a new SRF gun has been installed at HZDR, which is named of ELBE SRF Gun II. Stable operation at 8 MV/m RF Gradient has been achieved. The energy and energy spread have been measured for different laser phases. And the results are compared with the beam simulations in this publication. The minimum energy spread is 10 keV at a laser phase of 50°, this is true for both simulation and measurement. In addition, the phase space has been measured and compared to simulation. The determined transverse emittance is in the order of 0.4 µm.

At present the bunch charge is less than 1 pC generated by a bare cooper cathode, which has been installed for first tests of the SRF cavity. In future, the installed UV laser is planned to be operated in either the 13 MHz mode or the 500 kHz mode. The bunch charge will be respectively 77 pC or 1 nC. A simulation based study is in progress, aiming to look for the according "high bunch charge" parameters of the gun and an optimization of the beam transport to the ELBE accelerator.

The code packages ASTRA and elegant are combined in a Labview interface to perform the simulation studies. A 1D model, including space charge effect, is applied to the electron emission and the low energy beam transport in ASTRA. From the exit of the gun cavity, elegant takes charge of the beam transport simulation in the ELBE accelerator. The requirement for the SRF gun to realize 1 nC operation mode is discussed.

INTRODUCTION

ELBE SRF Gun II

The ELBE (Electron Linac with high Brilliance and low Emittance) SRF Gun II [1]has been set up at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) in May 2014. This SRF Gun is an improved version of the ELBE SRF Gun I [2] with a fine grain 3½-cell Nb cavity for realizing higher beam energy up to 9 MeV , and a superconducting solenoid for an improvement in emittance compensation [3]. Figure 1 shows the section view of the gun cryostat.

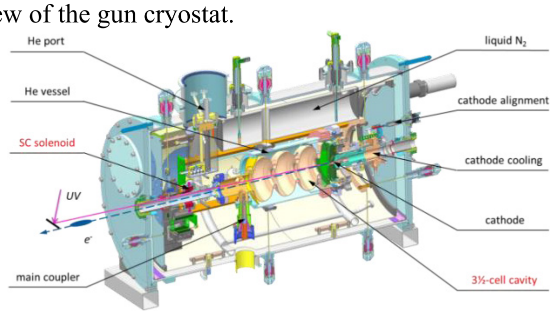

Figure 1: construction of the ELBE SRF Gun II.

The standard material for the gun cathodes is Cs_2Te[4], which has been used in the ELBE SRF Gun I. In this paper all measurement results are from a copper cathode, which has been installed for the current commissioning phase. New Cs_2Te cathodes are under preparation and will replace the copper cathode in the near future.

Compared to the old cavity, the new Niobium SRF cavity generates higher fields at the cathode position in the half-cell. This feature reduces the range of the space charge effect dominated region for low energy bunches near the cathode. Furthermore, the reduced power dissipation on the cavity wall is another improvement, which allows higher gradients in the superconducting cavity at similar helium consumption.

A 258 nm UV laser is used to excite electrons from the cathode cooled by liquid Nitrogen. The laser parameters have serious impacts on the gun's behavior. The synchronization between the laser and the RF generation, characterized by the laser phase, influences both the energy gain of the beam and the emittance. The initial structure of the extracted bunch is directly determined by the laser pulse shape itself. A uniformly distributed, large laser spot is expected to exploit the quantum efficiency of the cathode. Meanwhile for a certain bunch charge, a larger laser spot results in a reduced space charge effect. This direct dependency of the beam quality on the laser spot size could be reproduced by the simulations.

Beam Transport

Electron bunches from the ELBE SRF Gun II are supposed to be transported through a dogleg beam line and into the linac beam line of the ELBE, which is primarily designed for a thermionic gun. Therefore, it is necessary to simulate the entire beam transport to get the optimized parameters for this particular setup.

The longitudinal phase space can be manipulated by two accelerator modules and two chicanes. The beam should be focused longitudinally at the final target position and kept defocused in transport to reduce the space charge effect. Since the longitudinal elements also have a significant influence on the transverse beam parameters, they have to be optimized first. Proceeding on the basis of fixed cavity phases and chicane bending angles, transverse elements like a super conducting solenoid and in total 35 quadrupoles can be used to achieve the desired transverse phase space.

The bunch emission from the cathode and the acceleration in the gun are simulated with ASTRA, and further beam transport is computed using elegant[5]. The Coherent Synchrotron Radiation (CSR) effect[6] in the bending magnets, as well as the following short drifts, and the Longitudinal Space Charge (LSC) effect[7] in other

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drifts are considered. Besides, a simplex optimization procedure is applied for the transverse elements.

MEASUREMENTS FOR LOW BUNCH CHARGES

Although at the moment only a bare copper cathode is applied with low bunch charge of < 1 pC, it is still sufficient to perform the beam based alignment and the energy measurements.

The laser position on the cathode is scanned to determine the center of the electric field of the cavity. When the beam position on the downstream YAG screen does not change with the laser phase, the laser spot is considered to be centered. After that, the position of the superconducting solenoid is adjusted by two perpendicular steppers with the goal, that the beam position remains stable for different solenoid currents. Alignments of further elements still need to be done. As Figure 2 shows, the energy and energy spread are measured in the diagnostics beamline by using the 180° dipole.

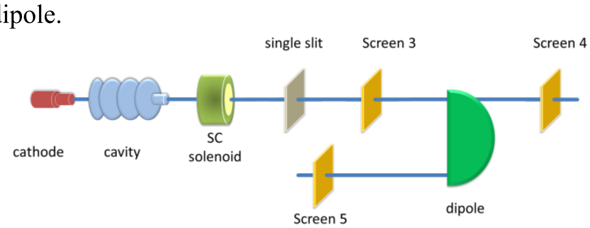

Figure 2: Diagnostics beamline for ELBE SRF gun II.

After the beam has been centered on screen 4 using the solenoid, the bending dipole is used to focus it on screen 5. The current of the dipole corresponds to the beam's kinetic energy while the beam spot size on screen 5 is related to the energy spread. The transverse size and divergence of the beam also contributes to the beam spot size on screen 5. However, to estimate this error requires the detailed phase space analysis at the entrance of the dipole, which is not measurable with the present beam line. Instead, the beam spot size on screen 5 has been determined by simulation and was compared with the measurement results.

As shown in Figure 3, the measured and simulated curves of the energy versus laser phase have the same trend, but a systematic error exists. The calibration of the dipole current to the energy might be the reason.

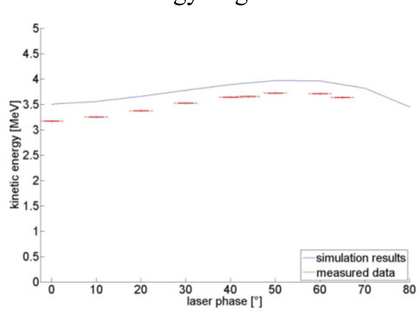

Figure 3: Measured and simulated kinetic energy of the beam versus laser phase.

Figure 4 plots the simulated standard deviation of the electron energy statistics, as well as both measured and simulated energy spread calculated from the beam spread on Screen 5, which includes the influence from beam divergence. According to the simulation, the contribution of the beam divergence will enlarge the beam size spread on Screen 5 by about 35%.

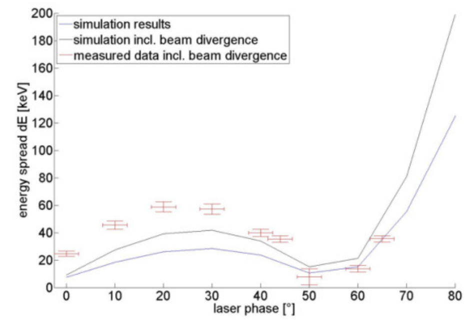

Figure 4: Measured and simulated energy spread with different laser phase.

As shown in Figure 2, a single slit is used to sample the beam while the beam lets are recorded on Screen 3 in order to calculate the transverse emittance. Figure 5 gives the emittance versus laser phase at a gradient of 6 MV/m. The simulation here has been performed with an estimated value for the initial laser spot size of 0.3 mm.

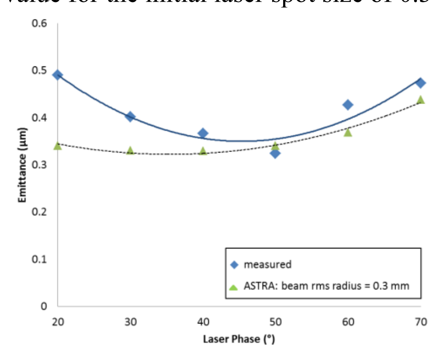

Figure 5: Transverse emittance versus laser phase.

SIMULATION FOR HIGH BUNCH CHARGES

As mentioned above, new Cs_2Te cathodes will be installed to achieve an increased bunch charge of 77 pC in 13 MHz mode and 1 nC in 500 kHz mode. The 77 pC beam optimization of the gun and the beam transport system has already been discussed in reference [8]. In this contribution the focus is on the task of the 1 nC operation mode.

It is of great importance to determine the minimal cavity energy/gradient to realize the desired bunch charge, since the field emission from the cavity wall increases exponentially with the field; and the dissipated RF power on cavity requires more helium cryogenic power. Also, when operating at high gradient, to compensate the strong Lorenz force detuning is a big challenge for the tuning system.

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Sufficient quantum efficiency of the cathode and laser power is assumed for the 1 nC task. A large initial bunch size with a uniform distribution is recommended in order to minimize the space charge effect, which will strongly expand the 3D bunch size, as shown in Figure 6. What is also shown is that higher laser phase corresponds to smaller beam size after the cavity, but enlarges the bunch's longitudinal expansion.

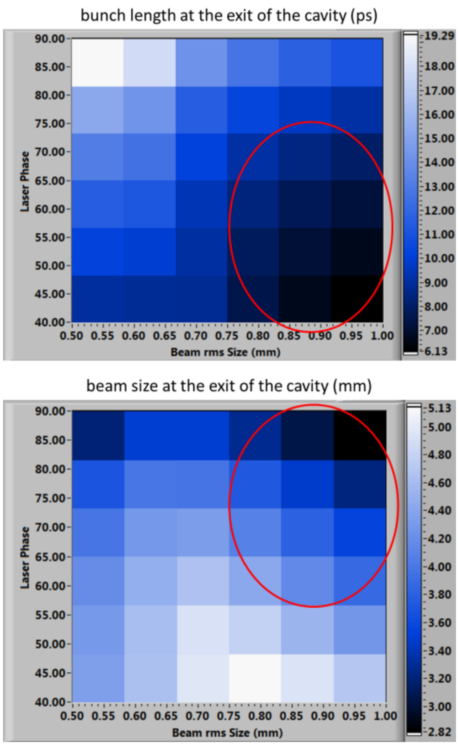

Figure 6: Simulation results: Expansion of the 3D bunch size at the exit of the SRF gun versus initial beam size. Different laser phases are scanned. Red areas are proper parameters.

For the reason mentioned above, a uniform laser spot is applied with the radius of 2.0 mm (in ASTRA, σ_x/σ_y=1.0 mm). A 2D scan of the RF gradient and the laser phase has been performed, and some results at the gun exit are plotted in Figure 7.

As of experience of the further beam transport in the dogleg from simulation, a bunch exiting the SRF cavity should be less than 5 mm of rms radius to be able to pass though the dogleg. Otherwise, the large beam halo in the dipoles and quadrupoles will result in a significant emittance increase. In Figure 7, from the beam size distribution at the exit of the gun, a triangular shaped area of the parameter space of cavity gradient and laser phase is selected. However, the energy spread distribution shows a valley-like area that has a comparable small energy spread. The overlap of these two areas has a minimum gradient of roughly10 MV/m, while the emittance in this area is over 5 µm.

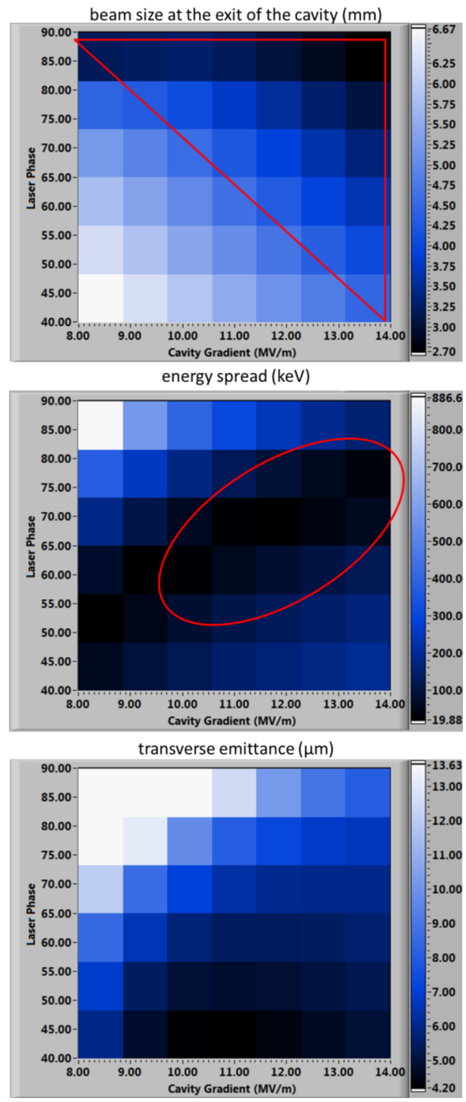

Figure 7: Simulation results: RF gradient and laser phase scanning for the beam with bunch charge of 1 nC. Results are given for the exit of the SRF cavity.

According to this simulation, it is assumed that higher than 10 MV/m is the limit for the gradient, Therefore, we made a simulation of the beam transport in this case. The kinetic energy of the beam after the ELBE SRF Gun II is 4.9 MeV, the transverse emittance has a value of 5.6 µm, the bunch length is 11.2 ps (5 ps from cathode) and the energy spread is 46 keV.

The maximum of the beam size is located in the first solenoid of the dogleg, where the dimension halo almost equals the beam pipe's inner diameter and the nonlinear effect of the quadrupole increases the horizontal emittance by 6 µm. The chicanes also increase the transverse emittance, if the CSR effect is considered for their dipoles. The dispersion out of the bending beam line is minimized to be zero. At the end of the simulation, after the second chicane, the beam energy is at 29 MeV, the transverse emittance is 30 µm in the horizontal plane and 13 µm vertical, the bunch length is compressed to 2.8 ps and the energy spread is 317 keV.

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Figure 8 illustrates the beam size profile and the different phase spaces. Results show, that at this gradient a 1 nC bunch is possible to be generated by the SRF Gun II and can transported through the ELBE beam line. However, the transverse emittance needs to be optimized and the maximum beam size might cause beam loss and serious radiation in reality.

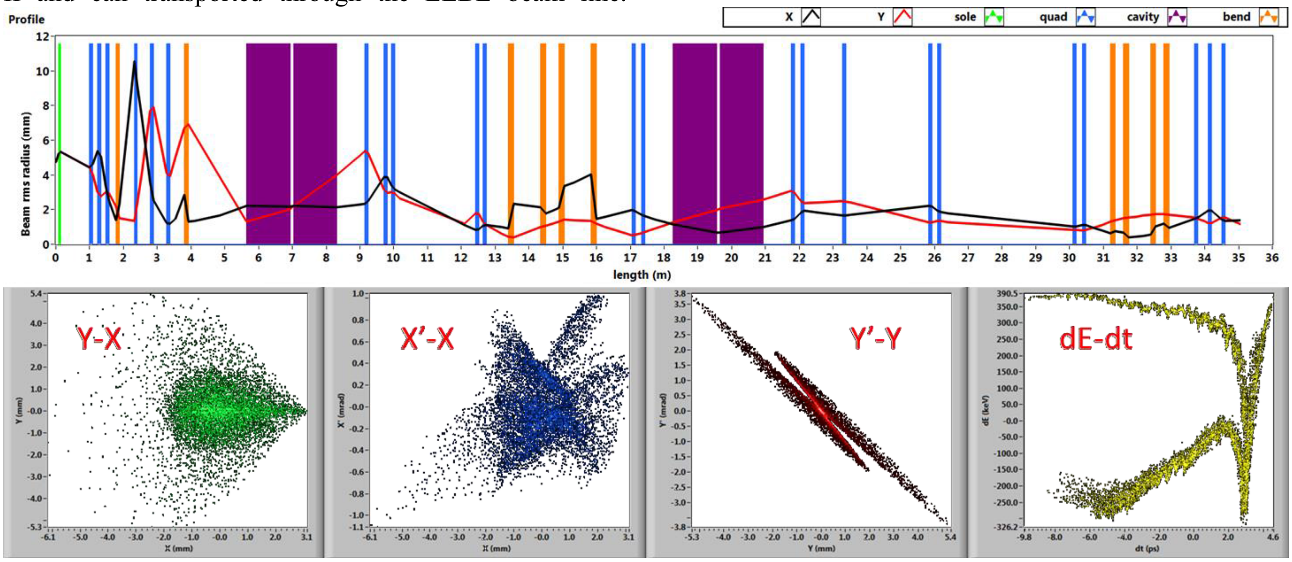

Figure 8: Beam transport and phase spaces of 1 nC, 10 MV/m. The massive X phase space is due to the CSR effect and the nonlinear longitudinal phase space is the result of LSC effect and the bunching of the chicanes.

CONCLUSION

The ELBE SRF Gun II has been installed at HZDR and its commissioning is in progress. The work of pushing the cavity's gradient is continued. Up to now, low bunch charge measurements have been performed and compared with beam dynamics simulations. The simulation work is focused on the 1 nC bunch charge operation. As a first result of these studies, with the present beam line arrangement, 10 MV/m turns out to define the minimum gun gradient for this high bunch charge mode for the ELBE accelerator facility.

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