Status of the development of the electron lens for space charge compensation at GSI

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Abstract. At GSI a prototype electron lens for space charge (SC) compensation is currently being designed and main components as the RF-modulated electron gun are already under commissioning. The goal of this project is the (partial) compensation of SC forces within the ion beam by an overlapping electron beam. This may help to increase the intensity of primary beams, especially in the FAIR facility and potentially all large synchrotrons operated at the SC limit. For an effective SC compensation, the generated electron beam needs to follow the transverse and longitudinal beam profile of the ion bunch structure. The requirements are maximum currents of 10 A and grid modulation to cover a broad frequency range from 400 kHz to 1 MHz. The RF-modulated electron gun was designed and manufactured in the scope of the ARIES collaboration and is currently being tested at the E-Lens Lab of Goethe-University Frankfurt. A dedicated test bench was built for commissioning of the major e-lens components and diagnostics. In this contribution the overall set-up will be presented putting special emphasis on the beam dynamics and collector design as well as simulation results of the electron gun.

1. Introduction

The prototype electron lens for space charge compensation is being designed for the integration into the SIS18 and potentially the SIS100 synchrotron at GSI/FAIR. However, the SIS18 will serve as testbed to demonstrate the space charge compensation scheme and the electron lens with an interaction length of 3.36 m will be installed in one of the available drift sections [1]. The SIS18 ion beam has an elliptical cross section over the length of the interaction region and has to be transversally embedded into a homogeneous electron beam while the pulse needs to be exactly matched to the bunch form in order to avoid over-compensation of the bunch head and tail as presented in [2]. During acceleration of the ion beam the SC tune spread reaches its maximum. Therefore, the prototype electron lens shall support operation within the ramp leading to high requirements on frequency and bandwidth of the e-gun modulator.

A modulated electron gun was designed based on the parameters of the SIS18 and constructed in the scope of the ARIES collaboration WP16 [3]. In the course of this project, a test stand at Goethe-University Frankfurt was build to commission the gun. But it will also serve as test bench for further e-lens components as well as the diagnostics. In the following the status of test stand and the electron lens development with its underlying components will be presented.

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2. Electron lens design and beam dynamic studies

The space charge compensation (SCC) electron lens for SIS18 is currently designed at GSI and a 3D model of the actual, integrated layout is presented in figure 1. The layout of the magnetic

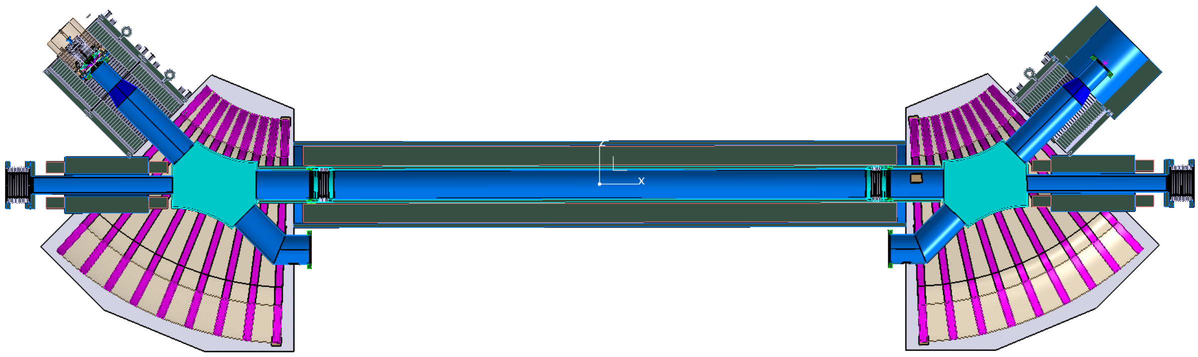

Figure 1. Preliminary 3D model of the SCC electron lens.

system comprises two identical solenoids in the gun branch, two solenoids in the collector branch, two toroids, a main solenoid as well as two correction dipoles, all covered in an iron housing. It has been designed for a maximum longitudinal field of 0.6 T. As a result of the vertical field of the toroids two corrector dipoles are required to compensate the deflection of the ion beam. Due to lack of space in the synchrotron, the dipoles are integrated into the toroids but are positioned not to affect the electron trajectories.

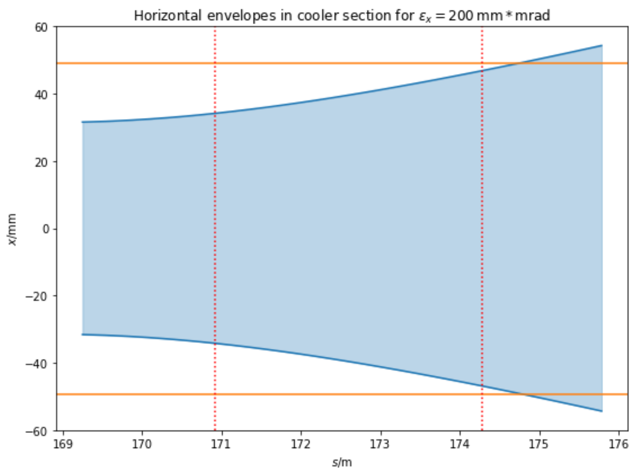

Figure 2. Calculated ion beam envelopes in the interaction section of the SCC electron lens. The red lines mark the interaction region, while the yellow lines represent the required horizontal size of the electron beam.

The requirements on the transverse expansion of the electron beam in the interaction region are defined by an acceptance of ϵ_x=200 mm·mrad. Within the length of the interaction section l=3.36 m the envelope of the ion beam (depicted in figure 2) opens up from 35 mm to 46 mm in x and 22 mm in y.

The ion bunch has to be transversally embedded into the electron beam to avoid resonances as a result of non-linearities by the beams' transverse field. However, the cathode size is limited with respect to homogeneous heating, for this reason it seems favorable not to expand the cathode to the required ion beam radius but rather expand the electron beam in the main solenoid in the interaction section. According to the magnetic expansion factor [4]

$$k = \frac{r_{gun}}{r_{main}} = \sqrt{\frac{B_{main}}{B_{gun}}} \tag{1}$$

a beam expansion of 49.5 mm is reached by lowering the magnetic field in the main solenoid to 0.3 T. For the correct set-up of the compensation scheme, it has to be taken into account that electrons experience a drift motion inside the toroidal fields and an ExB-rotation under the influence of the beams' space-charge especially in the main solenoid.

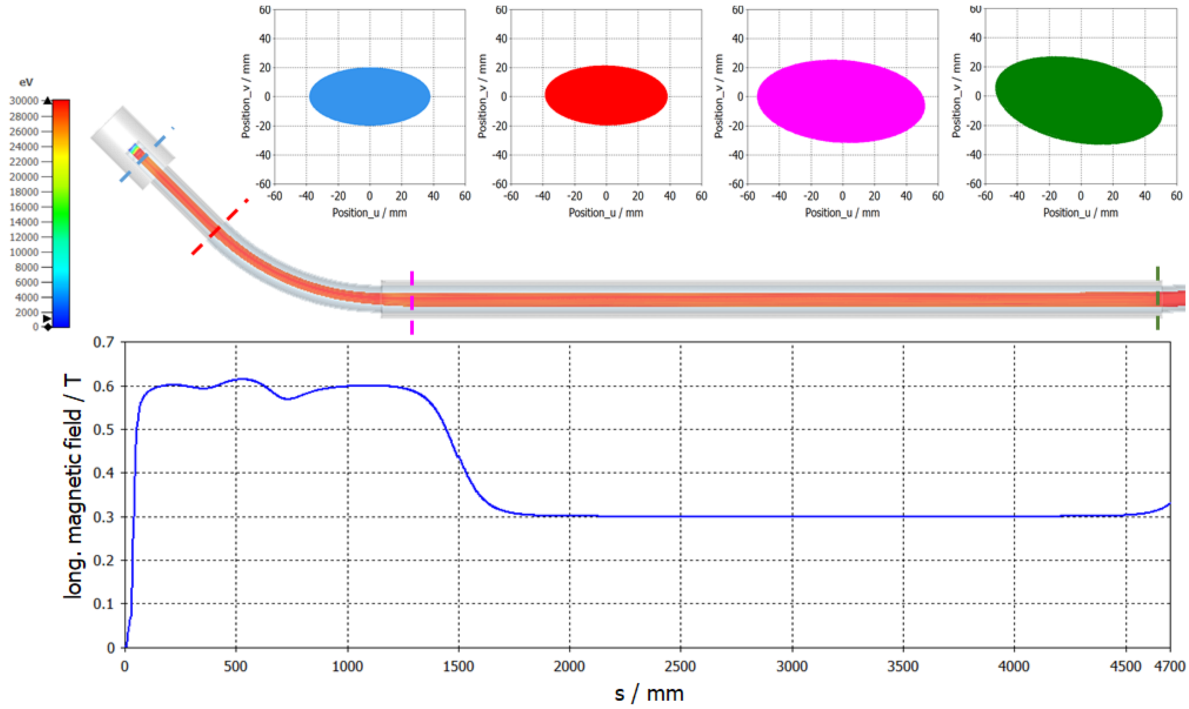

Figure 3. Electron beam dynamics along the electron lens. The color code indicates the beam distribution along the beam path (top). Calculated longitudinal magnetic field along beam path (bottom).

Figure 3 presents the beam transport simulation calculated using CST-PS [5] of an elliptic beam distribution with a=35 mm, b=20 mm, I=23.8 A and U_a=30 kV tracked through the electron lens device considering space-charge. This beam distribution was calculated for a gun perveance of 4.8 μP but without modulation grid. The colour code indicates the location of the beam distributions along the beam path: in blue is the generated electron beam distribution behind the gun, in red is the beam distribution after passing the first straight section, in magenta is the beam distribution at the entrance, and in green is the beam distribution at the exit of the main solenoid. The magnetic field was calculated using CST EM Studio and was imported into the beam transport simulation in order to save calculation time.

3. Test stand

At Goethe-University Frankfurt a dedicated laboratory (E-Lens Lab) was provided to construct a test stand for investigation of electron beam dynamics, diagnostics and commissioning of major electron lens components. It was equipped with a high voltage platform to power the electron gun and recycle the beam in an energy recovery system that is planned to be installed.

Figure 4 shows a picture of the test stand. It will be successively used in different stages according to the commissioning requirements. In the first stage, pyrometric measurements to characterize the heating process of the cathode are performed. For this reason, instead of a beam dump a pyrometer is installed after the second solenoid. In the second stage, a Faraday cup (FDC) will be installed in the diagnostic box and first low current beam extraction experiments as well as beam modulation will be performed. In the third stage the electron gun will be powered to 18 kV (5 A beam current) and the beam will be dumped in a high-performance FDC designed for 27 kW beam power deposition. For these three design stages accompanying beam transport simulations have been done (see [6] for more details). In the final stage the gun can be powered to its design parameters and the collector is installed in the second solenoid.

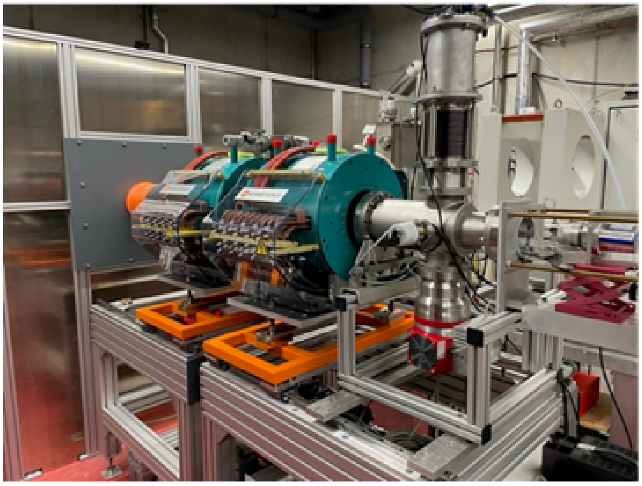

Figure 4. Test stand for the main electron lens components and diagnostics at Goethe-University Frankfurt.

The testing of the electron gun designed within the scope of ARIES (IRME-gun) is currently performed at the test stand (see figure 4) at Goethe-University Frankfurt and first results of the heat-up experiments look very promising. More details on the gun design can be found in [7].

4. Electron gun and collector

4.1. Electron gun

The IRME-gun makes use of a novel method for cathode heating. The cathode as well as the modulation grid are made of tungsten due to its robustness, maintenance and easy handling. But it requires temperatures about 2500°C in order to generate sufficient emission currents. The necessary heating is provided by the generation of an arc discharge in a plasma chamber located right behind of the cathode.

The cathode of the gun under commissioning has a round Gaussian profile and was developed to study the influence of non-linear transverse current density distribution on the space charge compensation scheme. Nonetheless, an electrode design for generation of an elliptic homogeneous electron beam profile is required for the SCC lens and different concepts for creation of an elliptic beam as well as different grid designs are currently being investigated.

A straightforward option is, of course, the usage of an elliptic cathode. Another option is beam shaping by using quadrupole coils integrated into the gun solenoid. By choosing the latter option, a variation of the beams' aspect ratio is possible during operation. For both options an electrode system was designed and optimized to have a perveance of 4.8 μP. Besides this, different grid designs with beamlet and target structure are being studied with respect to beam control and modulation (see figure 5). In the current electrode design the grid has a positive voltage of 800 V compared to cathode in order to extract the required beam current. This leads to a power deposition of almost 4 kW and secondary electron generation between cathode and grid. The influence of the secondary electrons will be further investigated numerically as well as experimentally at the test stand. The extracted current for the beamlet grid is I_{ex}=11.7 A and I_{ex}=12 A for the target-style grid.

Figure 5 shows as an example a symmetric gun design with cathode radius r_c=26.5 mm and an integrated quadrupole to vary the aspect ratio of the electron beam.

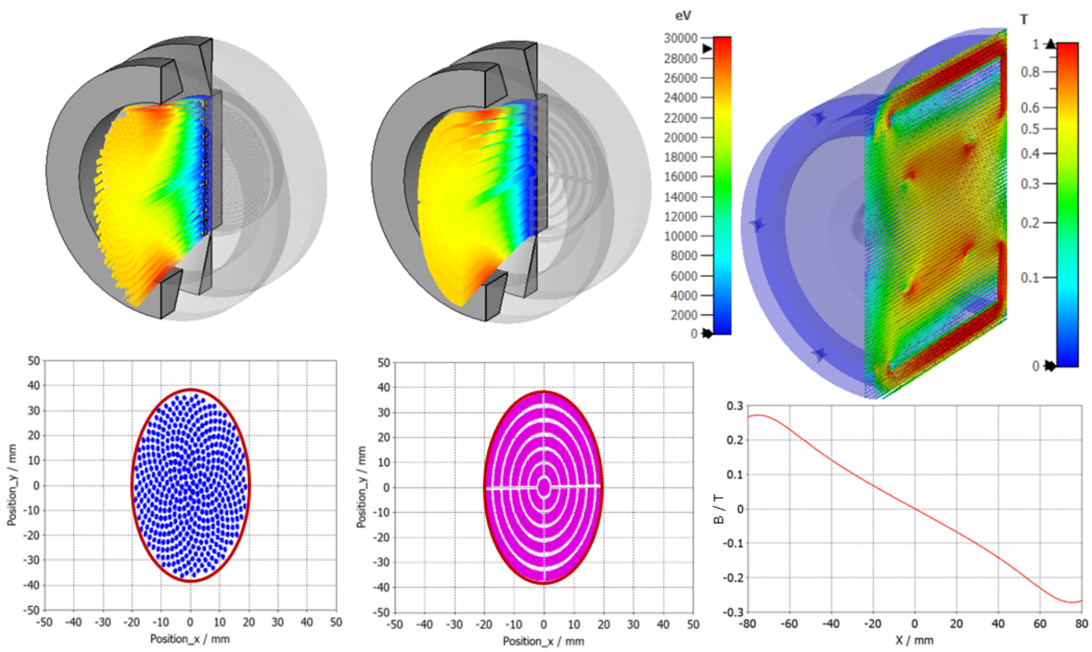

Figure 5. Simulated beam extraction for a beamlet-style grid (left), a target-style grid (middle) and magnetic system including a quadrupole for beam shaping with corresponding B_x (right).

Another aspect of the studies is also the evaluation of the beam dynamics of the extracted beam in the interaction region, which has either a target or a beamlet structure depending to the grid. The beam dynamic studies of the different beamlet structures will be performed in the next step.

4.2. Collector design

The maximum power of the extracted electron beam is almost 300 kW for modulation frequencies between 400 kHz and 1 MHz. For this reason, the beam needs to be decelerated before being dumped in the collector. The challenge in the collector design is to reduce the deposited beam power to a minimum but still fully dump the beam while depressing secondary electrons that are generated at the collector wall. In the actual collector set-up the beam is decelerated, while being expanded by the fringe field of the collector solenoid and finally dumped on the collector walls. While the electron beam is decelerated the beam potential can grow in the order of a few kV and has to be considered in the choice of the collector potential. Regarding the secondary electron emission (SEE), simulations using CST particle studio based on the Furman model [8] indicate that especially reflected electrons have to be mitigated. Different collector designs were studied in order to reduce the SEE. But a final mitigation strategy and for this reason a final collector set-up is still under investigation.

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