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DESIGN AND BEAM DYNAMICS OF THE ELECTRON LENS FOR SPACE CHARGE COMPENSATION IN SIS18*

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Abstract

An electron lens for space charge compensation is being developed at GSI to increase the ion beam intensities in SIS18 for the FAIR project. It uses an electron beam of 10 A maximum current at 30 keV. The maximum magnetic field on axis is 0.6 T, considerably higher than the field of the existing SIS18 electron cooler. The magnetic system of the lens consists of solenoids and toroids. The toroids' vertical field component creates a significant horizontal orbit deflection in the circulating low rigidity ion beams. To correct this deflection, four correction dipoles have been introduced. As is common for electron lenses, the high-power electron beam is not dumped at ground potential, but rather in a collector with a bias potential with respect to the cathode. The present design foresees a bias potential of 3 kV, leading to a power dissipation of 30 kW, distributed over a large surface area by placing the collector in an appropriately shaped magnetic field of a pre-collector solenoid. This contribution reports on the design of the lens and presents the results of beam transport simulations for the electron beam with and without space charge and a representative ion beam, performed using the 3D CST STUDIO.

INTRODUCTION

We present the design and beam dymanics of the electron lens for space charge compensation (SCC) in the SIS18 heavy ion synchrotron as a part of the future FAIR complex at GSI. Beam space charge (SC) poses a main intensity limitation in the charged particle dynamics at low and medium energies. The main motivation of this work is to improve the ion beam intensity limitation in SIS18 and subsequently in SIS100. The existing SIS18 is equipped with an electron cooler. The electron lens is designed in a similar way, yet the axial magnetic field is one order of magnitude higher than that of the electron cooler as it is designed for a high electron current of 10 A. Details of electron gun and test bench is explained in [1]. Initially, a demonstrator lens will be built to validate the concept and benchmark simulations in SIS18 [2].

ELECTRON LENS DESIGN

The electron lens is comprised of the magnetic system, consisting of solenoids and toroids to guide the electron beam onto the ion beam path in order to create the desired interaction, and a collector, which serves as a disposal area for the electrons at the end. The overall length of the device is about 8 m, while the interaction region, where the electron beam will overlap the ion beam, has a length of 3.36 m. Magnetic field simulations along the electron lens were carried out using CST 3D Studio Suite [3]. The magnetic system has been designed for a maximum longitudinal field of 0.6 T, which is not straightforward to achieve owing to the tight space constraints. The field distribution along the electron beam path has been optimized for flatness to avoid creation of magnetic traps for ions. Each toroid consists of 9 coils, with a current density of 12 A/mm^2, including water cooling channels and ground insulation. Figure 1 displays the magnetic components, and their geometrical arrangements. An electron beam transport simulation without space charge, shown in Fig. 2, was carried out to ensure proper flow of the particles throughout the lens.

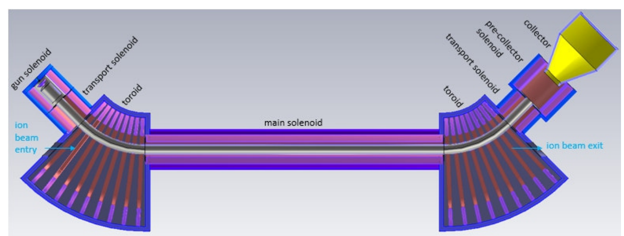

Figure 1: Cross sectional view of the magnet layout of the electron lens. The main solenoid is located between the two toroids. It defines the interaction region where the space charge compensation happens due to the overlap between electron and ion beam.

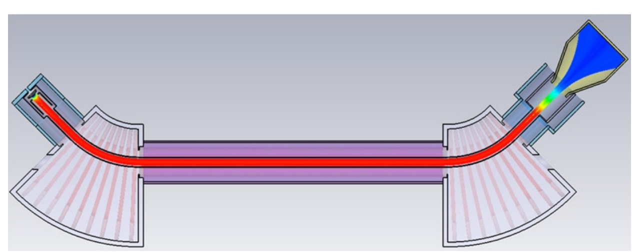

Figure 2: The beam transport simulation result of the electron beam extracted from the cathode, and tracked throughout the lens to the collector.

Electron Beam Space Charge Potential

The electron beam with a diameter of 52 mm and a current of 11 A is accelerated using the extraction voltage of 30 kV. The beam tracking simulations including space charge have been performed using CST 3D particle tracking program. The space charge potential of the electron beam is shown in

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Fig. 3. At the beam center, it corresponds to approximately 9 percent of the electron kinetic energy. In general, the kinetic energy of the electrons depends on the space charge potential at their respective radial position. The kinetic energy distribution during the acceleration process is plotted in Fig. 4 as a function of beam radius. It can be seen that the semi-parabolic radial distribution gets flatter as the beam accelerates, which means that the effect of space charge reduces with increasing energy.

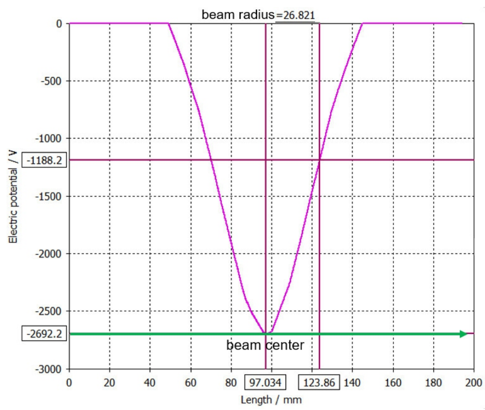

Figure 3: Space charge potential of the electron beam with 52 mm diameter at the location of the anode for 11 A current. Since the charge distribution is not uniform, the space charge potential is the maximum at the beam center and decreases non-linearly towards the edges. The potential is zero where the cylindrical anode is placed.

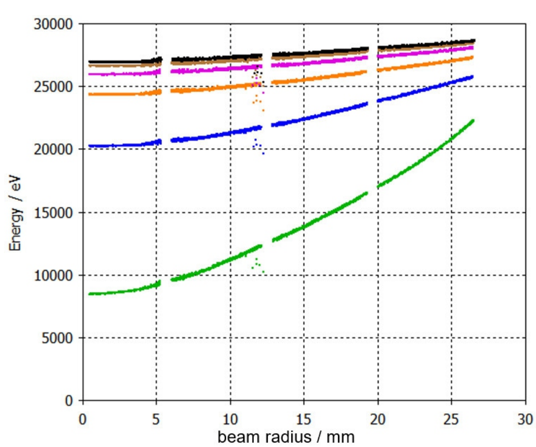

Figure 4: Electron beam acceleration process including space charge. The curves show the increasing kinetic energy of the electrons up to their final kinetic energy.

Collector Design

Due to the high power of the electron beam, losses generally have to be kept below a fraction of 10^{-4} at a current of 10 A. To achieve this goal, the collector has to be designed for a very high efficiency. To this end, the collector potential should be as close as possible to the cathode potential. These two requirements are in conflict with each other, because good screening to obtain low current loss requires high collector potential (high power loss), whereas low collector potential gives poor collection efficiency and eventually leads to a reflection of the beam. In the present design, considering the beam space charge effects, 3 kV potential difference is applied to the collector, leading to a power dissipation in the collector of 30 kW. Consequently, the stopped beam needs to be distributed over a large surface area. This is achieved by placing the collector in the appropriately shaped magnetic field of a separate pre-collector solenoid, where the shape of the field can be influenced by the longitudinal position of the collector and the geometry of the soft iron casing of the solenoid. While a preliminary design of the collector exists, some important details are still under investigation, especially the cooling concept and the proper handling of secondary electron emission (SEE). Detailed studies of the latter effect are ongoing. The results will be used to optimize the position of repeller electrodes in the pre-collector solenoid. Figure 5 shows the potential distribution obtained from a collector simulation, using an electron beam of 11 A with space charge in the axial magnetic field of 0.6 T. Charged particle dynamics studies are carried out using the CST particle tracking program, and SEE calculations are based on the Furman model [4].

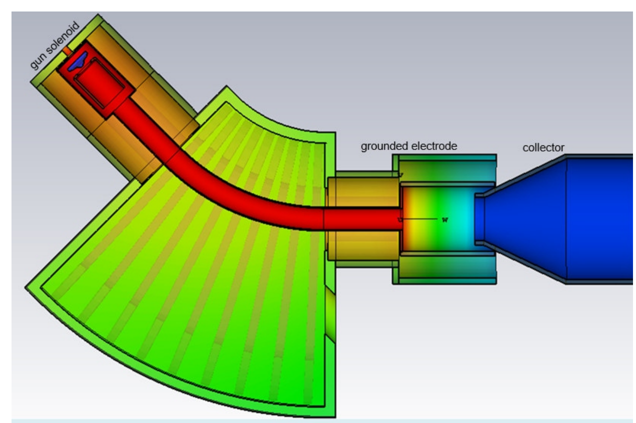

Figure 5: Electrical potential for the collector study. Cathode potential is −30 kV (blue), anode is on ground (red).

Toroids and Correction Dipoles

The geometrical dimensions of the toroidal coils are as follows: height and width are 1 200 mm and 940 mm, respectively; the length occupied by the coils is 1 167 mm. The impact of the 45° bending toroids on the trajectory of the ion beam has been investigated and the necessity for corresponding corrector magnets identified. The toroids unavoidably introduce a vertical field component seen by the ion beam, that has been simulated using CST and compared to an analytical calculation assuming an ideal toroid magnetic field. Results are shown in Fig. 6, from which it can be seen that the magnitude of the vertical field on the ion beam orbit

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reaches up to 0.3 T. The vertical field results first in a horizontal deflection of the ion beam, which then in addition entails a (smaller) vertical deflection as well, owing to the coupling of both planes of transverse motion created by the strong longitudinal field inside the toroid. The magnitude of this deflection depends on the magnetic rigidity of the ion beam and attains its maximum value in SIS18 for the lightest ions. For ion beam orbit tracking simulations, a beam of $^{12}C^{6+}$ at 11.4 MeV/u, corresponding to a magnetic rigidity of 0.98 Tm, has been used, which is representative for the most challenging light ion beams accelerated in SIS18. Other ion beams with a higher ratio of mass to charge are less critical, since they are relatively less affected due to their higher magnetic rigidity at the standard injection energy of 11.4 MeV/u in SIS18. At the exit of the toroidal field, the deflection angle is estimated to be about 12°. At this position, the centre of mass of the ion beam would acquire about 100 mm offset from the axis in the horizontal plane and 11 mm offset in the vertical plane.

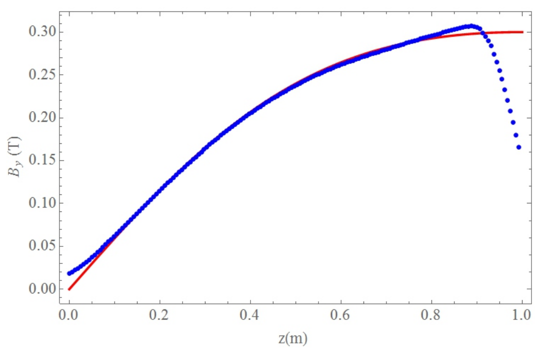

Figure 6: Vertical component of the toroid magnetic field along the ion beam path. Blue dots are simulation results, the red line corresponds to the analytical solution for an ideal toroid.

The horizontal deflection of the ion beam in the toroid magnetic field can be corrected by implementing a pair of dipoles. Due to space restrictions and to maximize their effect, the first dipole is positioned as close as possible to source of the deflection at the exit of and partially integrated into the toroid. The geometrical configuration is shown in Fig. 7, whereas Fig. 8 displays the effect of the orbit correction simulated by tracking $^{12}C^{6+}$ ions.

CONCLUSION

The magnetic system of an electron lens for space charge compensation has been designed for a maximum field of 0.6 T. The field distribution along the electron beam path has been optimized for flatness to avoid creation of magnetic traps for residual gas ions. Current density in the magnet coils has been kept within a feasible range. A preliminary design of the collector has been developed and included in the layout of the lens. The transport of electrons from the high current gun has been investigated with and without space charge, confirming the layout of the lens. The impact

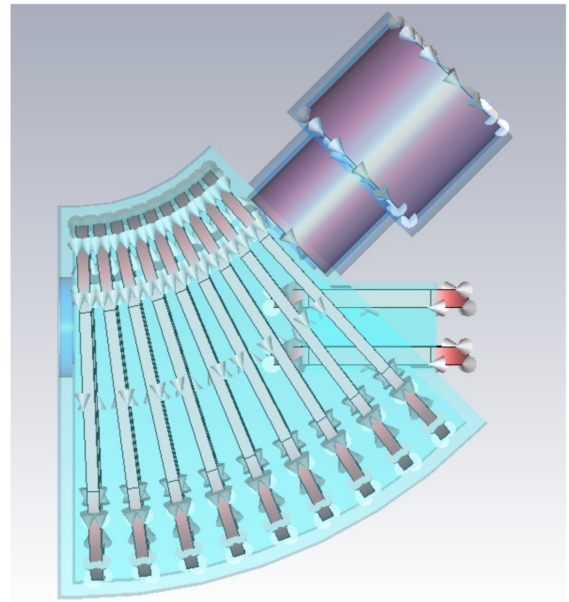

Figure 7: Geometrical configuration of the first dipole corrector for the ion beam path, which is located partially inside the toroid.

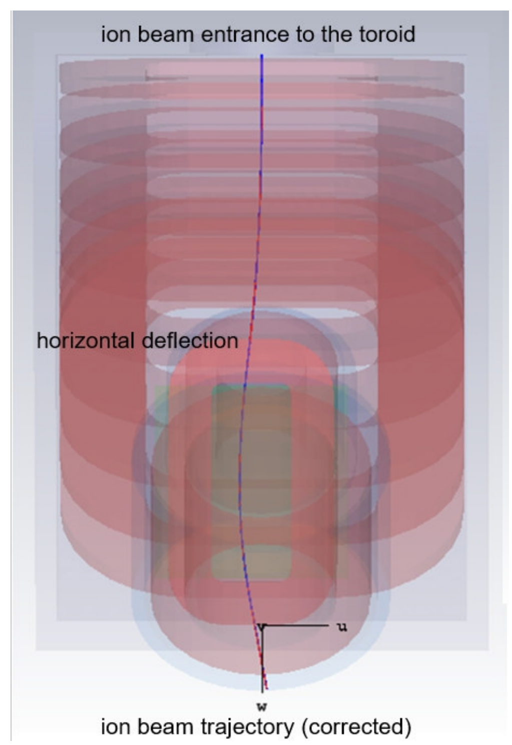

Figure 8: The horizontal deflection of the ion beam is corrected back to the reference orbit by the first dipole.

of the toroids on the ion beam path has been identified and corresponding dipole corrector magnets designed. The electron beam dynamics in the SCC lens under conditions of strong space charge, including direct space charge as well as indirect space charge from the interaction with the vacuum chambers, will now be investigated in detail.

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