

OVERCOMING THE SPACE CHARGE LIMIT: DEVELOPMENT OF AN ELECTRON LENS FOR SIS18*

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Abstract

The ‘Facility for Anti-Proton and Ion Research’ (FAIR) presently under construction will deliver intense ion beams to its experimental users. The requested intensities require filling the existing synchrotron SIS18, which serves as injector to FAIR, up to the space charge (SC) limit. Operation under these conditions is challenging due to the large tune footprint of the beam, demanding delicate control of adverse effects caused by machine imperfections to avoid emittance growth and beam loss. To facilitate the high intensity operation, the installation of an electron lens for SC compensation into SIS18 is foreseen. This requires an electron beam of a current of several amperes with longitudinal and transverse distributions matched to those of the ion beam during the cycle. The electron beam needs to be RF modulated at a bandwidth of a few MHz with time varying amplitude ranging from DC to fully modulated, while the transverse size needs to be continuously adapted to the adiabatically shrinking ion beam. This contribution reports on the requirements on an electron lens for SC compensation in SIS18.

INTRODUCTION

The heavy ion synchrotron SIS18 of the GSI facility will serve as main injector to the FAIR facility presently under construction. For light ions, like Ar¹⁸⁺, the maximal intensity per SIS18 cycle is limited today by the space charge (SC) tune shift at injection. Since the design goals of FAIR ask for significantly higher average intensities, SIS18 will operate with intermediate charge states like Ar¹⁰⁺ for FAIR, created by omitting the stripping stage between injector UNILAC and SIS18 used to date. While this reduces the SC tune shift in SIS18, the corresponding gain in intensity is expected to be exhausted by planned upgrade programs for the ion sources and the injector UNILAC. Thus, the SC tune shift in SIS18 is expected to remain a bottle-neck for reaching ultimate heavy ion intensities at FAIR.

Therefore, GSI has decided to investigate the option of compensating the SC effect by means of an electron lens, a scheme that was considered in the past [1] and has recently seen renewed interest [2]. SC compensation by electron lenses is challenging in low energy hadron accelerators like the SIS18 due to the fact that the ion beam is bunched. An ideal compensation therefore requires an electron beam longitudinally modulated at the bunch frequency, taking into account the variation of the bunch structure during the acceleration cycle, all this while keeping the transverse electron beam profile matched to that of the ion beam.

In order to demonstrate the feasibility of building an electron lens for SC compensation in SIS18, a project for the development of such a lens has been started. This contribution reports on the boundary conditions and requirements on an electron lens for SC compensation in SIS18 following from the evolution of space charge throughout the SIS18 cycle, focusing on recent activities towards the development of an RF modulated electron gun, which forms the core component of an electron lens for SC compensation in bunched beams. A prototype of such a gun will be developed by a European collaboration including GSI, CERN, the Institute of Applied Physics (IAP) of Frankfurt University, and Riga Technical University (RTU) in the scope of an ARIES [3] work package.

SPACE CHARGE IN THE SIS18 CYCLE

For the calculation of the evolution of the SC tune shift during the SIS18 cycle and the corresponding requirements on an electron lens for SC compensation, a reference beam of Ar¹⁰⁺ with an intensity of $2.5 \cdot 10^{11}$ particles per cycle has been used. This beam is representative for beams of lighter ions with intermediate charge states suffering from SC limitation after the injector upgrades. Furthermore, FAIR experiments have expressed their interest in intensities above 10^{12} particles per second of this beam. The relevant parameters of the reference beam are summarized in Table 1.

Table 1: Parameters of the Reference Beam

Ion species	Ar ¹⁰⁺
Injection energy	11.4 MeV/u
Extraction energy	700 MeV/u
Ramping speed	10 T/s
Hor. emittance (inj.)	150 μm
Vert. emittance (inj.)	50 μm
Particles per cycle	$2.5 \cdot 10^{11}$

The peak vertical SC tune shift at the center of an ion bunch in SIS18 can be approximated as follows:

$$\Delta Q_y^{sc} \approx -\frac{Z}{A} \frac{r_p}{2\pi\epsilon_y\beta\gamma} \frac{N_b Z}{B_f\beta\gamma^2}$$

Here, A and Z denote mass and charge number of the ions, N_b the number of particles *per bunch*, β and γ the usual relativistic factors. The vertical plane has been chosen because in SIS18 the vertical tune shift is larger and dominates the losses induced by SC. Since the normalized emittance $\epsilon_y\beta\gamma$ is a conserved quantity, the behaviour of ΔQ_y^{sc} during the SIS18 cycle is determined by a combination of the damping

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with $\beta^{-1}\gamma^{-2}$ due to the energy gain and the time evolution of the peak ion current described by the variation of the inverse bunching factor B_f^{-1} .

The SIS18 is filled at injection using phase space painting in the horizontal plane. Up to twenty turns are injected from the UNILAC during about 100 μs . Immediately following injection, the amplitude of the SIS18 RF system is raised during 16 ms to adiabatically capture the beam in two pure dual-harmonic bunches at the main harmonic $H = 2$. During bunching, the bunching factor B_f decreases from one to about 0.5. Next, acceleration is started by simultaneously raising the magnetic guide fields as well as frequency and amplitude of the RF cavities. The transition from zero ramp rate to the maximum rate of 10 T/s is established within 20 ms, during which time the synchronous phase of the beam changes from zero to its acceleration value of about 50 degree. As a consequence, the length of the bunches in the accelerating buckets shrinks and B_f decreases, resulting in a maximum of ΔQ_y^{sc} just before the full ramp rate has been reached. Afterwards, ΔQ_y^{sc} then gets quickly damped by the increasing $\beta\gamma^2$. The evolution of the SC tune shift during the SIS18 cycle is displayed in Fig. 1, together with the inverse bunching factor, for the reference beam defined above. The cycle terminates by a fast extraction of the ion beam to the FAIR facility.

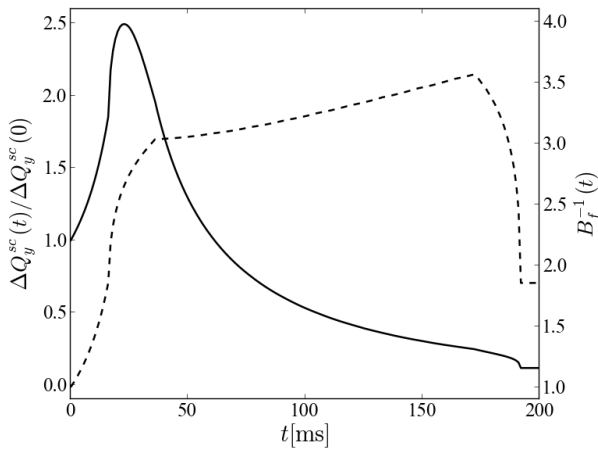


Figure 1: Evolution of SC tune shift ΔQ_y^{sc} (solid line) and inverse bunching factor B_f^{-1} (dashed line) during the SIS18 cycle. For further details refer to the text.

ELECTRON LENS REQUIREMENTS

The evolution of the SC tune shift during the SIS18 cycle must be taken into account in the design of an electron lens for SC compensation. Assuming the transverse profile of the electron beam to match the ion beam's profile, the tune shift created by N_e electron lenses, each carrying a current I_e of electrons with velocity $\beta_e c$ and interacting over a length L_e with the ion beam, can be approximated by:

$$\Delta Q_y^e \approx \frac{Z}{A} \frac{r_p}{2\pi\epsilon_y\beta\gamma} \frac{N_e L_e I_e}{ec\beta\beta_e}$$

In this approximation, the usual term proportional to $\beta\beta_e$ has been dropped due to the smallness of β and β_e for the relevant parts of the SIS18 cycle ($\beta \approx \beta_e \approx 0.2$). Comparing ΔQ_y^e with ΔQ_y^{sc} , it can be seen that the amplitude of the electron current must vary as $B_f^{-1}\gamma^{-2}$ for the compensation to follow the evolution of space charge. Assuming an interaction length $N_e L_e = 10$ m to be available in SIS18, a peak electron current of about $I_e = 31 \text{ A} \cdot \beta_e$ is required for full space charge compensation of the reference beam introduced above, where a minimum bunching factor of 0.2 was assumed to provide some margin, corresponding to a space charge tune shift of $\Delta Q_y^{sc} = -0.3$. The actual value of the peak electron current depends on the choice of electron energy, which in turn is influenced by the gun design.

Besides the peak electron current, another important requirement on the electron lens for SC compensation in SIS18 is the modulation of the electron current at the bunch frequency. This is due to the fact that the SC tune shift of the ion beam varies with the longitudinal position along the bunch. Without modulation, the SC tune shift in head and tail of the bunch would be strongly overcompensated. The

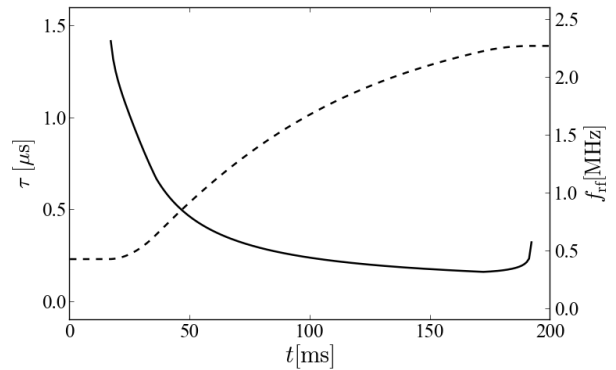


Figure 2: Evolution of bunch length (solid line) and RF frequency (dashed line) during the SIS18 cycle.

required bandwidth of the electron current modulation can be deduced from the evolution of the full bunch length τ during the SIS18 cycle, displayed together with the RF frequency f_{rf} in Fig. 2 for the reference beam defined above. Demanding SC compensation to be active at least until the SC tune shift of the ion beam has dropped below its value at injection, the electron beam needs to be modulated to match a 300 ns long dual harmonic bunch at an RF frequency of 1 MHz. Taking into account the fact that the electron peak current will have been reduced to almost zero at this point, a modulation bandwidth of 5 MHz appears to be sufficient.

GUN DEVELOPMENT

As outlined in the preceding section, an electron lens for SC compensation in SIS18 must in particular provide a modulated electron current following the longitudinal structure of the ion bunches during the cycle, slowly adapting the electron current to match the damped peak SC tune shift. These requirements mainly concern the design of the gun

for the electron lens. By contrast, the necessary magnetic guide fields, which from the Brillouin flow limit can be estimated to be well below 0.1 T for a gun supplying the required I_e/β_e , are easily provided using normal conducting solenoids and toroids. The main challenge of building an SC compensation lens thus lies in the development of the RF modulated electron gun.

The extraction of peak electron currents on the order of 10 A, though seemingly large compared to existing electron lenses, is facilitated by the large size of the ion beam in SIS18. From the values of the beta functions at the possible lens locations in the injection optics, $\beta_x = 7.3$ m and $\beta_y = 8.8$ m, as well as the emittances of the reference beam defined above, the beam radii in the interaction region are given by $r_x = 33$ mm and $r_y = 21$ mm. The cathode can hence be as large as the beam cross section and no compression of the electron beam is required.

Based on standard technology, a thermionic emission cathode with these dimensions can be expected to provide a perveance of $3 \mu\text{A}/\text{V}^{3/2}$. To reach the required electron current I_e/β_e , an extraction voltage of $U_e = 22.3$ kV is necessary, leading to $I_e = 10$ A. A summary of the preliminary design parameters for the electron gun is presented in Table 2.

Table 2: Design Parameters of the RF Modulated Gun

Peak current	10 A
Cathode radius	35 mm
Perveance	$3 \mu\text{A}/\text{V}^{3/2}$
Extraction voltage	22.3 kV
Gun magn. field	> 0.03 T
Peak power	223 kW
Modulation bandwidth	5 MHz

A particular challenge for the design of the modulated gun is posed by the power requirements when using direct anode modulation. Even if the estimated peak power of 223 kW is not supplied over the whole cycle, experience with pulsed electron lenses at other laboratories suggests that direct anode modulation may be hard to realize.

Therefore, two alternative approaches for reducing the power requirements shall be investigated: The first approach aims at increasing the perveance of the gun, thus reducing the extraction voltage. This would at the same time decrease the required electron current, since the SC compensation is proportional to I_e/β_e . Provided the peak power can be reduced sufficiently, direct anode modulation might become feasible. The second approach aims at decreasing the peak power by introducing a separate electrode, like a grid or a diaphragm, close to the cathode to achieve the modulation. This approach has the potential of reducing the peak power by orders of magnitude. It appears, however, much more involved to create a working design that would preserve the transverse profile of the electron beam.

Another design challenge for the electron gun concerns the creation and transport of an electron beam with an ellip-

tical cross section. As mentioned before, the ion beam cross section has an aspect ratio of $r_x/r_y = 1.6$ in the interaction region. For successful SC compensation, the electron beam cross section needs to match this shape. This is a non-trivial task, since the intense electron beam experiences an $E \times B$ drift in the x - y plane, caused by the combination of the axial magnetic field in the electron lens and the electric field created by its own space charge. Preserving the transverse shape of the electron beam under these conditions requires a careful consideration of all effects including the boundary conditions provided by the vacuum chamber and the curved magnetic field lines in the bending sections of the electron lens. There are, however, indications that an elliptical electron beam can be transported without distortion in an elliptical vacuum chamber thanks to the image charges induced by the electron beam in the chamber wall. These considerations show that the design of the electron gun requires an integrated approach studying the beam dynamics of the electron beam from the extraction in the gun through the whole electron lens.

The electron gun satisfying all stated requirements being the most important component of an electron lens for SC compensation in SIS18, GSI aims at constructing a prototype gun to demonstrate the feasibility. Since CERN has interests in a modulated electron gun as a long-term perspective for long range beam-beam compensation, GSI and CERN have initiated the development of an RF modulated electron gun within a European collaboration, including among its partners also the IAP and RTU. This ARIES project comprises the design, manufacturing and testing of an RF modulated electron gun for the application in electron lenses and shall be realized within the next four years.

CONCLUSIONS

GSI is taking efforts to push the heavy ion intensities of its existing accelerators, which will serve as injectors to the FAIR facility, to reach the challenging FAIR design goals. For lighter ions, intensities will ultimately be limited by the SC tune shift at injection in the synchrotron SIS18. To overcome this limitation, GSI has started the development of an electron lens for SC compensation in SIS18. The most challenging component of this lens is constituted by the electron gun required to supply peak currents of 10 A modulated at a bandwidth of 5 MHz. A prototype of such a gun will be built and tested by a European collaboration among GSI, CERN, IAP, and RTU.

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