USING AN ELECTRON COOLER FOR SPACE CHARGE COMPENSATION IN THE GSI SYNCHROTRON SIS18*

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Abstract

For the future operation of the SIS18 as a booster synchrotron for the FAIR SIS100, space charge and beam lifetime are expected to be the main intensity limitations. Intensity is limited in part by the space-charge-induced incoherent tune shift in bunched beams. A co-propagating, low energy electron lens can compensate for this tune shift by applying opposing space-charge fields in the ion beam. In this paper, we study the effect of using the existing electron cooler at the SIS18 as a space charge compensation device. We anticipate beta beating may arise due to the singular localized focusing error, and explore the possibility of adding additional lenses to reduce this error. We also study the effect of electron lenses on the coherent (collective) and incoherent (single-particle) stopbands. Furthermore, we estimate the lifetime of partially stripped heavy-ions due to charge exchange process in the lens.

INTRODUCTION

The future Facility for Antiproton and Ion Research (FAIR) project will include several scientific experiments that require high-intensity (more than 10^{11} ions) primary beams to produce sufficiently high-intensity secondary beams. The incoherent tune shift due to space charge is one of the main intensity-limiting factors standing in the way of this goal. This tune shift, in terms of ion beam parameters, is given by

$$\Delta Q_y^{SC} \approx \frac{NZ^2 r_p}{2\pi A \epsilon_y \beta_0^2 \gamma_0^3 B_f}, \tag{1}$$

where N is the number of particles, Z and A are the charge and mass number of the ion beam, respectively, r_p is the classical proton radius, ϵ_y is the four-times rms beam emittance, γ_0 and β_0 are the relativistic factors of the ion beam, and B_f is the bunching factor.

Many authors estimate a maximum attainable space charge tune shift of 0.2-0.4 [1, 2]. The FAIR reference ion, U^{28+}, will reach a space charge tune shift of 0.25 horizontally and 0.45 vertically at its injection energy. It is clear that a tune shift mitigation process is necessary to obtain the target intensities.

Electron lenses have been studied as a way to compensate for this tune shift [2–5]. Electron lenses are low energy co- or counter-propagating electron beams that provide a localized, amplitude-dependent space charge kick to the ion beam. The tune shift due to co-propagating electron lens with density n_e over interaction length L_e is given by

$$\Delta Q_y^e = -\frac{Z}{A}\frac{\beta_y r_p n_e L_e}{2\gamma_0 \beta_0^2}(1-\beta_0\beta_e), \tag{2}$$

where β_y is the beta function in the electron lens and β_e is the relativistic factor for the electron beam. The electron density in the cooler n_e is given by

$$n_e = \frac{I_e}{e\pi a^2 \beta_e c}, \tag{3}$$

for electron current I_e, electron charge e, speed of light c, and rms electron beam radius a. For an electron lens to work as designed, the ion beam must be centered inside the electron beam, $\beta_0 \neq \beta_e$ to prevent cooling, the transverse density profiles of the two beams should match, and the electron beam must be pulsed to match the longitudinal density profile of the bunched ion beam.

CHALLENGES

There are numerous challenges one must face when designing an electron lens. Among these are resonances, instabilities, and charge exchange. This paper discusses how we are addressing each of these problems in the SIS18, and how each help to answer the ultimate question: how many electron lenses are necessary for space-charge compensation.

Resonances and Instabilities

The localized focusing structure of the electron lens has an impact on both the coherent (betatron) and incoherent (single particle) stopbands. Equation (2) acts not only on the incoherent tune but also the collective tune of the ion beam. Furthermore, half-integer resonance stopbands due to single particle closed orbit instabilities are determined by the stability criterion [6, 7]. Fig. 1 plots a stability diagram that represents the combined effect of a single electron lens on both the incoherent and coherent tunes of the ion beam. In this simplified case, the electron lens fully compensates for an ion beam that has a space charge tune shift of 0.1 in both planes. The incoherent tune shifts to the standard working point of the SIS18 ($Q_x = 4.2$, $Q_y = 3.3$), while the coherent tune, unaffected by the incoherent space charge tune shift, also shifts by 0.1 in both planes. The result is a compensated beam with a coherent tune offset. Since the instabilities only act only on single particle orbits, Fig. 1 represents an example of stable compensation.

By doing an experimental tune scan, it will be possible to empirically see these instabilities. The results should provide information on how much tune shift each lens should

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produce, and thus how many lenses are required for full compensation.

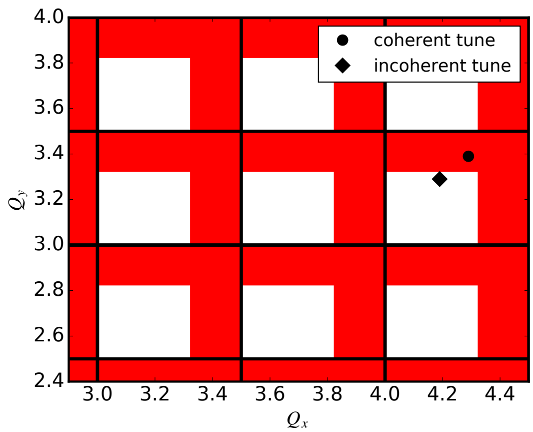

Figure 1: Tune space diagram for an electron lens compensation of 0.1 in the SIS18. The red space represents the single particle closed orbit instability stop bands, and the diamond represents the standard working point of the SIS18.

Charge Exchange

Beam lifetime limitation due to charge exchange inside the electron lens was a concern we explored. Two possible charge exchange mechanisms are ionization and recombination. The FAIR reference ion, U^{28+}, is ionization dominated. The cross section due to ionization of heavy ions by free electrons can be found in Ref. [8]. From there, the lifetime can be calculated using the simple formula, $\tau = 1/(n_e \sigma_e v_r f)$, where σ_e is the ionization cross section, v_r is the relative velocity of the beams, and $f = L_e/C$ is the fractional interaction length of the electron lens.

The calculated cross sections and lifetimes as a function of electron velocity due to ionization in a single electron lens for U^{28+} in the SIS18 are plotted in Fig. 2. The lifetimes due to the ionization mechanism are large compared to the beam lifetime, so we suspect charge exchange will not play a significant role in electron lens space charge compensation.

PRELIMINARY EXPERIMENTS

For the purpose of benchmarking our simulations and calculations, measurements were taken at the GSI synchroton SIS18. The SIS18 electron cooler was re-purposed as an electron lens by modifying the energy and current settings. Goals of the experiments were to measure the coherent tune shift as a function of cooler electron density, to measure the effect of the beam offset on the closed orbit, and to measure beta beat onset, since beta beat can arise from a large axisymmetric focusing error [9]. However, this paper only discusses the coherent tune shift measurement, as the other results are still under analysis.

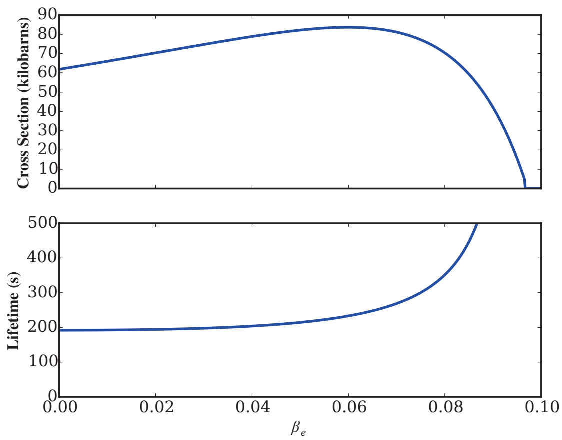

Figure 2: Cross sections and lifetimes as a function of electron velocity due to ionization in a single electron lens for U^{28+} in the SIS18.

Setup and Procedure

Experiments were performed on both coasting and bunched ion beams on a long (5 sec) injection flattop. Noting that Eq. (2) does not depend on ion intensity, a low intensity ($\sim 10^8$ ions) beam was used to eliminate complexity due to space charge. Experiments were performed on two ion species, Xe^{43+} and C^{3+}, but this report only includes results from C^{3+}. The ion beam parameters are shown in Table 1 and the electron beam parameters are shown in Table 2.

Table 1: C^{3+} Parameters

U_{kin}	6.78 MeV/u
β_0	0.12
N_{inj}	(2.0-3.0)x10^8
$\beta_{x,lens}$	8.0 m
$\beta_{y,lens}$	15.0 m
ϵ_x	15.5 mm-mrad
ϵ_y	20.1 mm-mrad
$Q_{x,0}$	4.32
$Q_{y,0}$	3.25

Table 2: SIS18 Cooler Parameters

U_{kin}	6.55 keV
β_e	0.16
f_{exp}	2
L_e	3.4 m
I_e	0.0-0.6 A

Measurements of the ion current were recorded from the current monitor. The beam profile was monitored with the SIS18 residual gas monitor (RGM). The emittances (see Table 1) were calculated from the horizontal and vertical profiles by $\epsilon_{x,y} = (2\sigma_{x,y})^2/\beta_{x,y}$. For these emittances, there is an rms ion beam radius of 5.6 mm horizontal and

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8.7 mm vertical in the electron cooler. With an expansion factor f_{exp} of 2, the electron beam has a rms radius of 9.0 mm. Therefore, so long as the ion beam passes through the center of the cooler, the electron beam will completely encapsulate the ion beam in both planes. This is important, because outside the electron beam, electric fields fall off by $1/r$.

Tune measurements were taken using both Schottky and Base Band Tune (BBQ) [10] methods. Due to the tune spread of the ion beam, the tune signal was difficult to resolve using Schottky. Thus, due to improved sensitivity, the BBQ method was the primary tune diagnostic employed in this experiment.

Results

The results for both coasting and bunched ion beams is shown in Fig. 3. Each fractional tune value is normalized to the 0-current tune shift. The tune shift calculated by equation 1 is plotted as the blue line. The shaded region in each part represents the error in the tune measurement with no electron beam present in the cooler. Electron cooler density was limited due to a 3rd order resonant stopband (1,2,11) for which an experimental tune scan reports high beam loss in the SIS18. Results show favorable agreement with the theory, and it can be seen that as expected there is no difference in the tune shift for coasting and bunched beams.

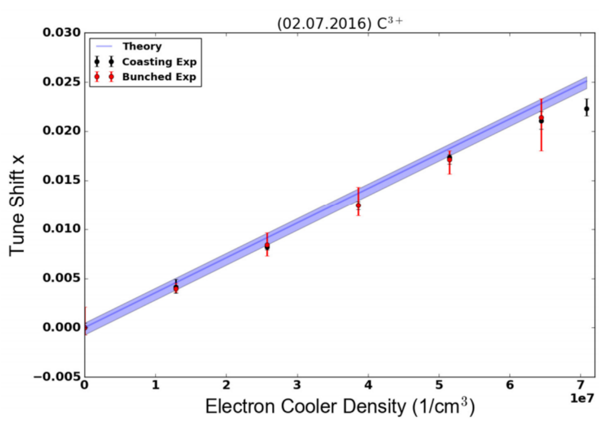

Figure 3: Linear tune shift as a function of electron lens density for both coasting and bunched C^{3+} beams. The theory is a direct calculation from Eq. (2).

CONCLUSIONS AND DISCUSSION

To counteract the intensity-limiting space charge tune shift in the SIS18 when it will be used as an injector for the FAIR SIS100, electron lens techniques will be used. Challenges to overcome include avoiding coherent and incoherent resonance stopbands, limiting beta beat due to localized focusing errors, centering the ion beam in the electron lens, pulsing the electron beam to fit the longitudinal ion beam profile, and more. We do not anticipate charge exchange will be a factor limiting the beam lifetime. Preliminary experiments were performed in the SIS18 electron cooler to benchmark our simulations and calculations, and results for the coherent tune shift show good agreement with theory. In the near future, pyORBIT PIC codes will be used to simulate the incoherent behavior of the beam, and experiments will be performed in the CRYRING [11].

At the HB2016 workshop, S. Nagaitsev proposed new ideas that will provide helpful direction for the future of this work. He introduced a method to measure trapped ions in the electron lens that can compromise the integrity of the fields. He also suggested the use of a McMillan-type electron density profile to eliminate single particle instabilities [12, 13]. These ideas will be explored in future work.

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