Using an Electron Cooler for Space Charge Compensation in the GSI Synchrotron SIS18

William D. Stem
Oliver Boine-Frankenheim
Outline

- Motivation: FAIR high-intensity upgrades
- Space-charge tune shift as an intensity-limiting factor
- Electron lens tune shift compensation
- Resonance stopband analysis
- Short comment on charge exchange
- Some preliminary experimental results
  - (taken last week!)
- Outlook
Outline

- Motivation: FAIR high-intensity upgrades
  - Space-charge tune shift as an intensity-limiting factor
  - Electron lens tune shift compensation
  - Resonance stopband analysis
  - Short comment on charge exchange
  - Some preliminary experimental results
    - (taken last week!)
- Outlook
High-Intensity at FAIR

FAIR experiments require high-intensity secondary beams
- Final intensities to reach above $10^{11}$ uranium ions per cycle
Space-Charge Tune Shift in FAIR Beams

The space-charge-induced incoherent tune shift sets a restrictive intensity limit on beams.

\[ \Delta Q_{SC,y} \approx \frac{NZ^2 r_p}{2 \pi \varepsilon_y \beta_0^2 \gamma_0^3 A B_f} \]

Tune Spread: \( Q_y = Q_{0,y} + \Delta Q_{SC,y} \)

\[ |\Delta Q_{SC}| \leq 0.25 \]


\[ |\Delta Q_{SC}| \approx 0.2 - 0.4 \]

V.D. Shiltsev, Electron Lenses for Super-Colliders, 2016

GSI FAIR reference Particle: U\(^{28+}\)

<table>
<thead>
<tr>
<th>( E, ) injection</th>
<th>11.4 MeV/u</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N )</td>
<td>2.0e11</td>
</tr>
<tr>
<td>( B_f )</td>
<td>0.3</td>
</tr>
<tr>
<td>( \varepsilon_x, \varepsilon_y )</td>
<td>150,50 mm-mrad</td>
</tr>
<tr>
<td>( \Delta Q_x, \Delta Q_y )</td>
<td>0.25,0.45</td>
</tr>
</tbody>
</table>
Electron Lenses

E lens tune shift (co-propagating):

\[ \Delta Q^e = (1 - \beta_e \beta_0) \frac{Z}{A} \frac{L_e r_p}{2 \beta_0^2 \gamma_0} \frac{I_e}{e \pi a^2 \beta_e c} \]

Items we are addressing:

- How many do we need?
- What is the percentage of tune shift each lens compensator should produce?
- Half integer resonances
- Effect on both the incoherent (single particle) and coherent (envelope) stop bands
- Ionization and capture cross sections/ beam lifetimes for heavy ions
- Pulsed electron beam for bunch compensation (future)
Electron Lenses

E lens tune shift (co-propagating):

\[
\Delta Q^e = (1 - \beta_e \beta_0) \frac{Z}{A} \frac{L_e r_p}{2 \beta_0^2 \gamma_0} \frac{I_e}{e \pi a^2 \beta_e c} \]

Items we are addressing:

- How many do we need?
- What is the percentage of tune shift each lens compensator should produce?
- Half integer resonances
- Effect on both the incoherent (single particle) and coherent (envelope) stop bands
- Ionization and capture cross sections/ beam lifetimes for heavy ions
- Pulsed electron beam for bunch compensation (future)
Electron Lenses

SPACE-CHARGE COMPENSATION OPTIONS FOR THE LHC INJECTOR COMPLEX*


$E_{\text{lens tune shift}}$ (co-propagating):

$\Delta \beta = (1 - \beta) \beta_0 \beta_0'^2 \gamma_0^2 \sin \angle \bbox[1pt]{\theta \phi} \approx \frac{1}{2} \beta_0'^2 \gamma_0^2 \sin \angle \bbox[1pt]{\theta \phi}$

$N_C = 4$

- What is the percentage of tune shift each lens compensator can produce?
- Focusing error instabilities and required number of compensators
- Effect on both the incoherent (single particle) and coherent (envelope) stop bands
- Ionization and capture cross sections/beam lifetimes
- Pulsed electrons for bunch compensation (future)
Electron Lens Concept

\[ \beta_e \neq \beta_{\text{ion}} \]

\(e^-, \text{ions}\)
Electron Lens Concept

\[ \sigma_{x,y} \geq \sigma_{x,y} \quad \beta_e \neq \beta_{ion} \]
Electron Lens Concept

\[ \sigma_{x,y} \geq \sigma_{x,y} \quad \beta_e \neq \beta_{ion} \]

\[ \sigma_{x,y} \]

- Match transverse profiles

\[ e^-, \text{ions} \]
Electron Lens Concept

$\sigma_{x,y} \geq \sigma_{x,y}$  \hspace{1cm} $\beta_e \neq \beta_{ion}$

- Match transverse profiles
- Center ion beam in lens or suffer closed orbit distortion
Electron Lens Concept

- Match transverse profiles
- Center ion beam in lens or suffer closed orbit distortion
- Match longitudinal bunch profiles (pulsed electron beam)
Outline

- Motivation: FAIR high-intensity upgrades
- Space-charge tune shift as an intensity-limiting factor
- Electron lens tune shift compensation
- Resonance stopband analysis
- Short comment on charge exchange
- Some preliminary experimental results
  - (taken last week!)
- Outlook
Coherent Stopbands, Envelope Equations

**Start Somewhere:**

**Simple Studies**

\[
X'' + \kappa_x(s)X - \frac{2K}{X+Y} - \frac{\varepsilon_x^2}{X^3} = 0
\]

\[
Y'' + \kappa_y(s)Y - \frac{2K}{X+Y} - \frac{\varepsilon_y^2}{Y^3} = 0
\]

\[
X(s) = \sqrt{\varepsilon_x \beta_x(s)}
\]

\[
Y(s) = \sqrt{\varepsilon_y \beta_y(s)}
\]
Coherent Stopbands, Envelope Equations

Start Somewhere: Simple Studies

\[ X'' + \kappa_x(s)X - \frac{2K}{X + Y} - \frac{\epsilon_x^2}{X^3} = 0 \]
\[ Y'' + \kappa_y(s)Y - \frac{2K}{X + Y} - \frac{\epsilon_y^2}{Y^3} = 0 \]

\[ X(s) = \sqrt{\epsilon_x \beta_x(s)} \]
\[ Y(s) = \sqrt{\epsilon_y \beta_y(s)} \]

What happens when we add an electron lens every cell?
Coherent Stopbands, Envelope Equations

No Compensation

\( Q_x \) vs. \( \varphi_y \)

Mismatch factor

\( 10^{-1} \) to \( 10^{1} \)
Coherent Stopbands, Envelope Equations

**Half Compensation**

![Graph showing Coherent Stopbands and Envelope Equations with Half Compensation](image)
Coherent Stopbands, Envelope Equations

**Full Compensation**

![Graph showing the Full Compensation of mismatch factor vs. Qx and Qy](image)
Number of compensators needed depends on the stability criterion:

\[ |\cos \varphi_0 - 2\pi \Delta Q \sin \varphi_0| < 1 \]

\[ \varphi_0 \equiv 2\pi Q_0 / N_c \]

*SIS18, U^{28+} Full Compensation*
Single Particle Resonance Stopbands
(Orbit Instabilities)

\[ SIS18, \ U^{28+} \]
\[ \Delta Q_e = 0.1 \]

- **coherent tune**
- **incoherent tune**
Outline

- Motivation: FAIR high-intensity upgrades
- Space-charge tune shift as an intensity-limiting factor
- Electron lens tune shift compensation
- Resonance stopband analysis
- Short comment on charge exchange
- Some preliminary experimental results
  - (taken last week!)
- Outlook
Cross Sections and Beam Lifetimes

Ion: $^{28+}U$  Mechanism: Ionization from free electrons

$\tau = \frac{1}{n_e \sigma_e v_r f}$

*T. Peter and J. Meyer-ter-Vehn, PRA, 1991*
Outline

- Motivation: FAIR high-intensity upgrades
- Space-charge tune shift as an intensity-limiting factor
- Electron lens tune shift compensation
- Resonance stopband analysis
- Short comment on charge exchange
- Some preliminary experimental results
  - (taken last week!)
- Outlook
Benchmarking Experiments in the SIS-18

- **Goals:**
  - Measure coherent tune shift as a function of electron density and compare with experiment
  - Measure the effect of the beam offset on the closed orbit
  - Measure beta beat onset as a function of electron density in the cooler
Benchmarking Experiments in the SIS-18

Goals:

- Measure coherent tune shift as a function of electron density and compare with experiment
- Measure the effect of the beam offset on the closed orbit
- Measure beta beat onset as a function of electron density in the cooler
Benchmarking Experiments

Electron Cooler Parameters

<table>
<thead>
<tr>
<th></th>
<th>June 27, 2016</th>
<th>July 2, 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Xe$^{43+}$</td>
<td>C$^{3+}$</td>
</tr>
<tr>
<td>$U_{\text{kin}}$</td>
<td>6.75 MeV/u</td>
<td>6.78 MeV/u</td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>$\epsilon_x$</td>
<td>36.1 mm-mrad</td>
<td>15.5 mm-mrad</td>
</tr>
<tr>
<td>$\epsilon_y$</td>
<td>40.2 mm-mrad</td>
<td>20.1 mm-mrad</td>
</tr>
<tr>
<td>$Q_{x,y}$</td>
<td>4.32, 3.25</td>
<td>4.32, 3.25</td>
</tr>
</tbody>
</table>
Experimental Procedure

- Low intensity beam at injection energy (<5 turn stacking)

- Measure ion current to approximate SC tune shift (should be negligible!)

- Measure beam profiles with Residual Gas Monitor (RGM) to get emittances

- Measure tune as a function of electron density
  - Used Schottky and Base Band Tune (BBQ) measurement

\[ \beta_{x,y} = 6.7,9.2 \ m \]

\[ \sigma_z = 7.78 \]

\[ \sigma_x = 9.61 \]
Tune Space

Franchetti, HB Proceedings 2008
Tune Space
(Preliminary) Experimental Results!
(Preliminary) Experimental Results!

![Graph showing the relationship between tune shift and electron cooler density.](image)
Conclusions and Outlook

**Conclusions:**
- We are using the SIS-18 in concert with simulation tools to determine the number of electron lenses for high-intensity space charge compensation
- Instabilities/resonances uncovered in the incoherent and coherent stopbands need to be prevented for electron lens commissioning
- One compensator could only (very) partially compensate for space charge. The study will indicate the number needed for full compensation
- Ionization in the SIS18 electron cooler doesn’t seem to play a major role in beam lifetime for the ionization-dominated reference particle U^{28+}

**Future Goals:**
- Beta beat and closed orbit analysis of data taken Saturday, July 2nd (5 days ago!), Collaboration with V. Chetvertkova and G. Franchetti
- Study of the incoherent beam physics with pyORBIT PIC simulations. Compare results to experiment to determine how many electron lenses are needed for compensation
- Pulsed electron lens beam to match longitudinal beam profile
- CRYRING experiments for future space-charge compensation experiments and benchmarking
CRYRING
Acknowledgements and References

▪ Experiment Team
  Oliver Boine-Frankenheim, Rahul Singh, Christina Dimopoulou, Markus Steck, Sabrina Appel, Ivan Karpov

▪ References
  ▪ V. Litvinenko, G. Wang, Phys. Rev. ST-AB