Space Charge Compensation Measurements for ECRIS beams

Daniel Winklehner
D. Leitner, G. Machicano, P. Marti, D. Cole, L. Tobos
NSCL/MSU

Outline:
– Introduction
– Hardware
– Measurements
– Discussion
ECRIS and LEBT

• Current ECR ions sources like Venus and SuSI are able to create up to 20 mA of beam

• Next (4th) generation ECRIS even more!

• These are regimes, where space-charge effects become important factors for:
  – Beam size
  – Beam quality
  – Transmission

• Especially in the Low Energy Beam Transport (LEBT) system before the analyzing magnet

• Have to consider SC in design and simulations

• What is space-charge?

For next generation ECRIS see other talks at this workshop
Space Charge (SC)

\[ E_r = \frac{I}{2\pi \varepsilon_0 \beta c a^2} \frac{r}{a} \]

\[ \Phi(r) = \Delta \phi \left( 1 + 2 \ln \frac{b}{a} - \frac{r^2}{a^2} \right) \]

\[ \Delta \phi = \frac{I \cdot (1 - f_c)}{4\pi \varepsilon_0 \beta c} \]
Space Charge (SC)

- Coulomb repulsion between beam ions
- Collective effect – creates self-field of the beam
- Defocusing term in Hill’s equation – beam growth
- Simple model of the beam: Uniformly charged cylinder

  - Radial electric field: \( E_r = \frac{I}{2\pi \varepsilon_0 \beta c} \frac{r}{a^2} \)

  - Radial Potential: \( \Phi(r) = \Delta \phi \left( 1 + 2 \ln \frac{b}{a} - \frac{r^2}{a^2} \right) \); \( \Phi(r) = 2 \Delta \phi \ln \left( \frac{b}{r} \right) \); with \( \Delta \phi = \frac{I \cdot (1 - f_e)}{4\pi \varepsilon_0 \beta c} \)

  (a = beam radius, b = beam line radius, I = beam current, \( \beta c \) = velocity)

- If the beam were to experience the full self-field at all times bad for beam transport of high current beams! – Luckily: Compensation
Space Charge Compensation (SCC)

- As the beam goes through the residual gas in the beam line – interaction:
  - Collisions
  - Charge exchange

- Electrons are separated from gas atoms/molecules
- Electrons are trapped in beam potential, ions are expelled
- Electrons effectively lower the beam potential
- Process is steady-state, governed by rates of electrons created and captured and electrons leaving the beam.
- From Soloshenko#:

\[
\Delta \phi = \sqrt{3L} \left( \frac{M}{m} \right)^{1/2} \left( \frac{\varphi_i}{V_0} \right)^{1/2} n_+^{1/2} \left( \frac{1}{n_0 \sigma_e} + \frac{v_+ \sigma_i r_0}{2 v_i \sigma_e} \right)^{1/2} \cdot e
\]

Space Charge Compensation (SCC)

- As the beam goes through the residual gas in the beam line – interaction:
  - Collisions
  - Charge exchange

- Electrons are separated from gas atoms/molecules
- Electrons are trapped in beam potential, ions are expelled
- Process is steady-state, governed by rates of electrons created and captured and electrons leaving the beam.
- From Soloshenko#:

\[
\Delta\Phi = \sqrt{3}L \left( \frac{M}{m} \right)^{1/2} \left( \frac{\varphi_i}{V_0} \right)^{1/2} n_+^{1/2} \left( \frac{1}{n_0 \sigma_e} + \frac{\nu_+ \sigma_i r_0}{2\nu_i \sigma_e} \right)^{1/2} \cdot e
\]

Space Charge Compensation (SCC)

- As the beam goes through the residual gas in the beam line – interaction:
  - Collisions
  - Charge exchange
- Electrons are separated from gas atoms/molecules
- Electrons are trapped in beam potential, ions are expelled
- Process is steady-state, governed by rates of electrons created and captured and electrons leaving the beam.

From Soloshenko#:

\[
\Delta \Phi = \sqrt{3L} \left( \frac{M}{m} \right)^{1/2} \left( \frac{\varphi_i}{V_0} \right)^{1/2} n_{+}^{1/2} \left( \frac{1}{n_{0} \sigma_e} + \frac{v_{+} \sigma_i r_0}{2v_i \sigma_e} \right)^{1/2} \cdot e
\]


Dominates for low pressures

\(\Delta \Phi \) increases when \(n_0\) decreases
Space Charge Compensation (SCC)

- As the beam goes through the residual gas in the beam line – interaction:
  - Collisions
  - Charge exchange

- Electrons are separated from gas atoms/molecules

- Electrons are trapped in beam potential, ions are expelled

- Electrons effectively lower the beam potential

- Process is steady-state, governed by rates of electrons created and captured and electrons leaving the beam.

- From Soloshenko#:

\[ \Delta \phi = \sqrt{3} L \left( \frac{M}{m} \right)^{1/2} \left( \frac{\varphi_i}{V_0} \right)^{1/2} n_+^{1/2} \left( \frac{1}{n_0 \sigma_e} + \frac{v_+ \sigma_i r_0}{2 v_i \sigma_e} \right)^{1/2} \cdot e \]


Dominates for low pressures
\( \Delta \phi \) increases when \( n_0 \) decreases
Measuring Space Charge Compensation

\[ \overline{E}_{\text{kin}} = \frac{5}{2} k_B T \rightarrow \sim 65 \text{ meV} \]
Measuring Space Charge Compensation

- Secondary ions have energy depending on distance from beam center at time of ionization

- Assumptions:
  - Very low initial kinetic energy (dimolecular gas, T = 293 K)
  - Secondary ions do not gain significant energy through collisions

- Measure ion-energy distribution with Retarding Field Analyzer (RFA)

- Design considerations:
  - Flat vs. Curved
  - Single vs. Double Aperture Collimation

- $\Delta \Phi$ can then be obtained from the resulting spectrum

- Comparison with theoretical $\Delta \Phi$ for uncompensated beam yields $V_e$
Measuring Space Charge Compensation

- Secondary ions have energy depending on distance from beam center at time of ionization.

- Assumptions:
  - Very low initial kinetic energy (dimolecular gas, T = 293 K)
  - Secondary ions do not gain significant energy through collisions.
  - \( E_{kin} = \frac{5}{2} k_B T \rightarrow \sim 65 \text{ meV} \)

- Measure ion-energy distribution with Retarding Field Analyzer (RFA).

- Design considerations:
  - Flat vs. Curved.
  - Single vs. Double Aperture Collimation.

\[ \Delta \Phi \text{ can then be obtained from the resulting spectrum.} \]

\[ \Delta \Phi = \frac{I \cdot (1-f_e)}{4\pi\epsilon_0\beta c} \]

Compared to theoretical \( \Delta \Phi \) for uncompensated beam yields \( f_e \).
Retarding Field Analyzer (RFA)

- Mesh 1 voltage = 0 V
- Mesh 2 voltage = 0 V
- Mesh 3 voltage = -450 V
Retarding Field Analyzer (RFA)

- Mesh 1 voltage = 0 V
- Mesh 2 voltage = 15 V
- Mesh 3 voltage = -450 V

Voltage (V)/Energy (eV)

- 30 eV ion
- 20 eV ion
- 10 eV ion
- Electron
Retarding Field Analyzer (RFA)

- Mesh 1 voltage = 0 V
- Mesh 2 voltage = 25 V
- Mesh 3 voltage = -450 V
Retarding Field Analyzer (RFA)

- Mesh 1 voltage = 0 V
- Mesh 2 voltage = 35 V
- Mesh 3 voltage = -450 V
Analysis (LEDA source example)
Analysis (LEDATA source example)

• Typical RFA spectrum

• 2 Methods of analysis:
  – Take $\frac{dI}{dV}$ and use base width (subtract 1.2 V for detector resolution)
  – Fit the graph with 3 straight lines to obtain $\Phi_{\text{center}}$ and $\Phi_{\text{edge}}$

• Result:
  – Meth. 1: $\Delta \Phi \sim 4.6$ V  
    Neutralization $\sim 78.4\%$
  – Meth. 2: $\Delta \Phi \sim 3.8$ V  
    Neutralization $\sim 83.0\%$

(Closer for lower beam currents in the same measurement set)
Analysis (LEDA source example)

- Typical RFA spectrum

- 2 Methods of analysis:
  - Take $\text{d}I/\text{d}V$ and use base width (subtract 1.2 V for detector resolution)
  - Fit the graph with 3 straight lines to obtain $\Phi_{\text{center}}$ and $\Phi_{\text{edge}}$

- Result:
  - Meth. 1: $\Delta \Phi \sim 4.6$ V
    Neutralization $\sim 78.4\%$
  - Meth. 2: $\Delta \Phi \sim 3.8$ V
    Neutralization $\sim 83.0\%$

(Closer for lower beam currents in the same measurement set)
Analysis (LED source example)

- Typical RFA spectrum
- 2 Methods of analysis:
  - Take $dI/dV$ and use base width (subtract 1.2 V for detector resolution)
  - Fit the graph with 3 straight lines to obtain $\Phi_{\text{center}}$ and $\Phi_{\text{edge}}$
- Result:
  - Meth. 1: $\Delta\Phi \sim 4.6$ V
    Neutralization $\sim 78.4\%$
  - Meth. 2: $\Delta\Phi \sim 3.8$ V
    Neutralization $\sim 83.0\%$

(Closer for lower beam currents in the same measurement set)
Analysis (LEDA source example)

• Typical RFA spectrum

• 2 Methods of analysis:
  – Take $dI/dV$ and use base width (subtract 1.2 V for detector resolution)
  – Fit the graph with 3 straight lines to obtain $\Phi_{\text{center}}$ and $\Phi_{\text{edge}}$

• Result:
  – Meth. 1: $\Delta \Phi \sim 4.6$ V
    Neutralization $\sim 78.4\%$
  – Meth. 2: $\Delta \Phi \sim 3.8$ V
    Neutralization $\sim 83.0\%$

(Closer for lower beam currents in the same measurement set)
Analysis (LEDA source example)

• Typical RFA spectrum

• 2 Methods of analysis:
  – Take $dI/dV$ and use base width (subtract 1.2 V for detector resolution)
  – Fit the graph with 3 straight lines to obtain $\Phi_{\text{center}}$ and $\Phi_{\text{edge}}$

• Result:
  – Meth. 1: $\Delta \Phi \sim 4.6$ V
    Neutralization $\sim 78.4\%$
  – Meth. 2: $\Delta \Phi \sim 3.8$ V
    Neutralization $\sim 83.0\%$

(Closer for lower beam currents in the same measurement set)

\[ \Delta \phi = \frac{I \cdot (1 - f)}{4\pi \cdot \varepsilon_0 \cdot \beta c} \]
Artemis A: The RFA is located between source and the analyzing magnet after an electrostatic quadrupole doublet.

SuSI: RFA is located in diagnostic box 1 ~46 cm after the plasma aperture.

LEDA injector source: RFA is located in a diagnostic box ~50 cm after the plasma aperture.
Artemis Measurements

- First measurements
- Only one aperture in Retarding Field Analyzer
- Electrostatic Quadrupole settings to maximize current in Retarding Field Analyzer
- Beam current measured with Faraday Cup = 550 $\mu$A
- Saturation Current in agreement with theoretical prediction from continuity equation with 40% transmission

\[
(I_{RFA})_S = \frac{r_a^2 \cdot T \cdot I \cdot (\sum n_g \sigma_i)}{2d} \; ; \; T = 0.4
\]

- More or less 0% neutralization, maybe slightly increasing tendency
LEDA Measurements
2 Aperture Collimation

RFA Saturation Current

Calculated, $T = 0.1$?!?

Measured

Neutralization

$P = 2.1 \times 10^{-6}$ Torr

LEDA - Pressure Comparison

6.4 mA, 70 keV Proton Beam

National Science Foundation
Michigan State University

D. Winklehner, 9/12/2013, Slide 24
SuSI Measurements

- $\Delta \Phi_{\text{measured}} > \Delta \Phi_{\text{uncompensated}}$
  - "negative" neutralization
- Moving Retarding Field Analyzer perpendicular to beam: Asymmetry
Complexity of Measuring ECR neutralization

• Triangular Beams
• Multiple Species
  – ionization cross-sections depend on charge state
• Beam lines not infinite pipes concentric with beam!
  – -> Longitudinal v-component
• Simulations show large difference in obtained neutralization value for triangular or round beams…
Summary and Conclusions

• A new Retarding Field Analyzer was built at the NSCL

• Extensive Simulations have been conducted to determine the feasibility of the design and the theoretical resolution.

• Preliminary measurements have been carried out at three different sources (SuSI, Artemis and LEDA injector source), all three currently at the NSCL.

• The measurements showed trends that neutralization increases with pressure and/or beam current, which is in accord with previous results by other groups.

• These measurements also suggest, that in the current low energy beam line configurations of SuSI and Artemis only low neutralization can be observed.

• But: Some behaviors unexplained → future work
Outlook

• Measure Beam Cross-Sections with Quartz or KBr beam viewer

• As the neutralization can change throughout the LEBT, alternative positions for the retarding field analyzer will be explored in order to obtain a more complete picture of neutralization in ECR LEBTs.

• Investigate asymmetric beams further through simulation (and possibly running ECR sources with and without sextupole).

• Further investigate current reduction with 2nd aperture.

• Build/borrow? a small electron gun to do calibration measurements in order to confirm the theoretical accuracy and resolution.
Acknowledgements

• Thanks to the NSCL electrical engineering department and the machine shop for continuous support!
• Thanks to the Michigan Institute for Plasma Science and Engineering (MIPSE) for their support!
• Thanks to Guillaume Machicoane, Felix Marti, Dallas Cole, and Larry Tobos for letting me “play” with their ECR sources :o)

And thank you for your attention…Questions?