Space Charge Compensation Using Electron Columns and Electron Lenses at IOTA

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Outline and Acknowledgments

- Space Charge Compensation (SCC)
- Electron Lens
  - Main features and current status
- Electron Column
  - Concept and simulation studies
- Summary

- Acknowledgments
  - Team: V. Shiltsev, G. Stancari, J.C.T. Thangaraj, and D. Milana
  - FAST-IOTA Group at Fermilab
Space Charge Compensation
Space Charge (SC) – Crucial Challenge at High Intensity

Compensate
- Add Opposite Charges
- A Neutral Plasma
- Electron Lens
- Electron Column

Accelerate
- SC Tune Shift \( \sim \gamma^{-3} \)
- Cons: Expensive LINACs

Control
- Integrable Lattice
- Scraping
- Compensation w/ Solenoid in RF Photoinjector

Cons: Expensive LINACs
The IOTA ring is being built at Fermilab to study Space Charge Compensation.

- D. Edstrom (TUPOA19), D. Bruhwiler (WEA2IO02), C. Hall (WEA4CO02), N. Cook (WEPOA31), A. Romanov (THPOA23, THPOA24)

Circumference = 40 m, 70 MeV/c proton beam
Space Charge Compensation at IOTA Ring

• Two ways of compensation are being done at IOTA

  – Co-propagating beam of opposite charge (electron lens)
    • Robust, precise control of transverse profile of the e-beam
    • Experimentally mature “Swiss Knife,” employed in Tevatron, RHIC, and now LHC.

  – Passive compensation of the proton beam (electron column)
    • Self-ignition: Use protons to ionize the vacuum and to generate electrons
    • Electrons are approximately rest longitudinally compared to co-moving electrons in electron lens
    • Trap/Match/Control the electrons and their profile – solenoid and electrodes.
Electron Lens
What’s an Electron Lens?

- Magnetically confined, low-energy electron beam, pulsed if needed.
- Circulating proton beam is affected by electromagnetic fields generated by electrons.
- Transverse stability provided by strong axial magnetic fields.

V. Shiltsev et al., PRL 99, 244801 (2007)
V. Shiltsev et al., PRST-AB 11, 103501 (2008)
E-Lens: Control of Transverse Electron Beam Profile

Transverse density profile of electron beam is shaped by cathode and electrode geometry, and maintained by strong solenoidal fields.

Gaussian profile for compensation of nonlinear beam-beam forces

Flat profiles for bunch-by-bunch betatron tune correction
E-Lens: Control of Longitudinal Electron Beam Profile

Pulsed electron profile could match to proton bunch profile, if needed.


Beam synchronization in the Tevatron
Status of Electron Lens Experiment Setup at IOTA Ring

• Hardware
  – We recycle components from the Tevatron electron lenses
  – Vacuum tests of gun and collector completed
  – Girders and supports are being designed and fabricated
  – Aim to assemble e-lens in straight configuration for checkout by the end of 2018
Status of Electron Lens Experiment Setup at IOTA Ring

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- **Several effects are being studied, for instance:**
  - lattice deviations from ideal case and misalignments
  - impact of chromaticity-correction sextupoles on integrability
  - azimuthal asymmetries in electron lens kicks due to bending sections
  - effect of fringe fields on ring optics
  - perveance of electron gun and accuracy of beam profile
  - chromatic effects of the electron lens
  - These studies involve numerical simulations and experiments at the Fermilab electron-lens test stand
Electron Column
Proposed the Experimental Setup for Electron Column - V. Shiltsev (2007)*

Historical Success and Challenges

• Several experimental attempts have been made
  – Linacs:
    • In linear machines, successfully applied to transport high-current low energy proton and $H^-$ beam (gas focusing), Gabor lens, etc.
  – Circular machines
    • Novosibirsk PSR, G. I. Dimov, V. E. Chupriyanov (1984)
      – Conditions: few mTorr, $H_2$ gas, 1 MeV protons, 100 turns, 6.8 m
      – Cons: No stabilizing B-field, e-p instabilities a major obstacle
    • At Fermilab, M. Chung (2014) used WARP 3D code to test the idea of e-column in IOTA Ring.
      – Conclusion: Over-compensations - too much electron accumulations.
Our Approach to Space Charge Compensation using E-Column at IOTA Ring

• Strong magnetic field stabilizes the e-column, and prevents e-p instabilities

• In IOTA, we will use e-lens central solenoid for e-column operation.

• Match/control the transverse profile with B-field, voltages on electrodes, and vacuum pressure.
  - Investigate dynamics of electrons and ions in E and B fields
  - Primary proton beam considered as stable.
  - WARP-3D simulations have been performed on the Fermilab Wilson Cluster
### WARP 3D Simulation Parameters

<table>
<thead>
<tr>
<th>IOTA Beam parameters:</th>
<th>Apparatus parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam species</td>
<td>Length</td>
</tr>
<tr>
<td>Proton</td>
<td>1 m</td>
</tr>
<tr>
<td>Beam energy</td>
<td>Electrode size</td>
</tr>
<tr>
<td>$2.5 \text{ MeV (p }= 70 \text{ MeV/c)}$</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Average beam current</td>
<td>Wall radius</td>
</tr>
<tr>
<td>8 mA</td>
<td>25 mm</td>
</tr>
<tr>
<td>RMS beam size</td>
<td>Solenoid field</td>
</tr>
<tr>
<td>5.5 mm</td>
<td>0 ~ 0.2 T</td>
</tr>
<tr>
<td>Beam distribution</td>
<td>Voltages on Electrodes</td>
</tr>
<tr>
<td>-Uniform in longitudinal direction</td>
<td>-200 ~ 0 V</td>
</tr>
<tr>
<td>-Gaussian in transverse direction</td>
<td>(for initial test)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gas parameters:</th>
<th>Numerical parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main gas species</td>
<td>Particle injection/step</td>
</tr>
<tr>
<td>$\text{H}_2$</td>
<td>100 (~7500)</td>
</tr>
<tr>
<td>Pressure</td>
<td>Time step</td>
</tr>
<tr>
<td>$10^{-3} - 10^{-5} \text{ Torr}$</td>
<td>$&lt; 2\pi/\omega_{ce}$</td>
</tr>
<tr>
<td>Neutralization time</td>
<td>15 psec</td>
</tr>
<tr>
<td>0.86 $\mu$s (for $10^{-3}$ Torr)</td>
<td>Boundary conditions</td>
</tr>
<tr>
<td>Processes considered</td>
<td>Absorbing boundaries for</td>
</tr>
<tr>
<td>$p + \text{H}_2 \rightarrow p + \text{H}_2^+ + e$</td>
<td>particles</td>
</tr>
<tr>
<td>$e + \text{H}_2 \rightarrow \text{H}_2^+ + 2e$</td>
<td></td>
</tr>
</tbody>
</table>

Space Charge Compensation Using Electron Columns and Electron Lenses at IOTA

10/13/2016
Some Practical Numbers and Limits

- Proton beam potential at the center is given by \( \phi = \frac{30I}{\beta} = \frac{30 \times 8 \text{ mA}}{0.07} \approx 3.5 \text{ V} \)
- If e-column length is 1 \( m \) and the circumference is \( \sim 40 \text{ m} \), we need about \( 3.5 \text{ V} \times 40 = 140 \text{ V} \) for full space charge compensation. At this stage, our study is limited to 1-m channel only. No ring is considered (no circulation).
- Larmor radius (for 100 eV, 0.1 \( T \)) < 0.5 \( mm \), \( r_L = 3.37 \ [\mu m] \ \frac{\sqrt{T_L \text{ [eV]}}}{B \ [T]} \) \(<\ approx \) proton beam radius

- Our goal is three-fold
  - Match transversely [‘resistive’ solenoid field and electrodes]
  - Compensate longitudinally [electrodes]
  - Neutralize quickly i.e. neutralization time should not be too long may few turns at max. Revolution time is \( \sim 1.8 \ \mu s \)
Neutralization Time for Various Parameters

![Graph showing average electron density vs. time for different magnetic field and voltage conditions.]

- B = 0.0 T and V = 0 V
- B = 0.1 T and V = -5 V
- B = 0.1 T and V = -10 V
- B = 0.1 T and V = -50 V
- B = 0.1 T and V = -200 V
- Proton Density
Under Compensation

Transverse Density Profile

Longitudinal Density Profile

B = 0.0 T

V_l = 0.0 V

V_r = 0.0 V

P = 1e-3 Torr
Over Compensation

Transverse Density Profile

Longitudinal Density Profile

$B = 0.1 \ T$

$V_l = -200.0 \ V$

$V_r = -200.0 \ V$

$P = 1\ e^{-3} \ Torr$
Asymmetric Voltages on Electrodes

\[ V_l = -50 \, V \quad \text{and} \quad V_r = -5 \, V \]

\[ V_l = -5 \, V \quad \text{and} \quad V_r = -50 \, V \]

\[ B = 0.1 \, T \]

\[ P = 1e-3 \, \text{Torr} \]
Vacuum: Knob to Control the Degree of SC Compensation

Transverse Density Profile

Longitudinal Density Profile

\[ B = 0.1 \, T \]

\[ V_l = -5.0 \, V \]

\[ V_r = -5.0 \, V \]

\[ P = 5e-4 \, \text{Torr} \]
Evolution of Particles inside the Electron Column

\[ B = 0.1 \, T, \, V = -5.0 \, V, \, \text{and} \, P = 5 \times 10^{-4} \, \text{Torr} \]

D. Milana (2016)
Summary

- Space Charge Compensation (SCC) experiments with both e-lens and e-column are being pursued in IOTA ring at Fermilab.

  - **E-Lens:**
    - External e-beam will be used to match and SCC circulating proton beam in IOTA ring. Experimental setup is being assembled.

  - **E-Column:**
    - Simulations show that the density profile of e-column can be tuned with axial B-field, electrode voltages, and vacuum pressure for (partial/full/over) SCC. Experiment will use the E-Lens setup.

  - **NEXT STEPS:**
    - Simulate circulating proton beam with external focusing and multiple passes through the e-column in IOTA.
    - Continue construction, tests, and installation of both IOTA e-lens and e-column.