Electron cooling with space-charge dominated proton beams at IOTA

Nilanjan Banerjee
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Overview

• Goals
• Implementation
• Simulations
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Goals

• Driven by necessity!
  – Counter emittance growth in 2.5 MeV proton beam.
  – Achieve low energy spread.

• Study large incoherent tune shift
  – Space charge forces limits the minimum emittance reached by coolers.
  – Electron coolers typically operate at tune shifts < 0.01 – 0.1.

• Study instabilities
  – Interplay of wakefields, space-charge and electron cooling.
  – Electron cooling as a knob for space charge parameter.

• Non-linear Integrable Optics with SC and cooling
  – Realize NIO in the multi-particle regime.

S. Nagaitsev et al., Proceedings Particle Accelerator Conference, 1995, pp. 2937-2939
A. Burov, Phys. Rev. Accel. Beams 22, 034202, 2019
Implementation

The Integrable Optics Test Accelerator will be configured to recirculate 2.5 MeV protons.

Dispersion is 0 at the electron lens.

| C       | KE      | $\tau_{\text{rev}}$ | h | $N_{\text{bunch}}$ | $A_{x,y}$ | $v_{x,y}$ |
|---------|---------|---------------------|---|---------------------|-----------|-----------|
| 39.96 m | 2.5 MeV | 1.83 μs             | 4 | Coasting or 4       | 87, 78 μm | 4.117, 3.632 |

G. Stancari et al. JINST 16 P05002, 2021, [https://doi.org/10.1088/1748-0221/16/05/P05002](https://doi.org/10.1088/1748-0221/16/05/P05002)
Operating Parameters

Major sources of emittance growth: **Space charge**, Intra Beam Scattering, Residual Gas Scattering.

| Current (mA) | Coasting | Bunched |
|--------------|----------|---------|
| 2.25         | 6.25     | 0.248   |
| 2.28         | 11.4     | 0.113   |
| -0.076, -0.10 | -0.38, -0.50 | -0.076, -0.10 | -0.38, -0.50 |
| 32.0, 20.9, 40.4 | 6.40, 4.19, 8.08 | 43.4, 29.9, 115 | 8.69, 5.97, 23.01 |
| 1.00, 0.87, 0.496 |          | 1.00, 0.87, 0.992 |

*Based on $P_{\text{eff}} = 4.2 \times 10^{-8}$ Torr measured in Run 2. Aim to achieve $P_{\text{eff}} = 1 \times 10^{-10}$ Torr by baking. [Link](https://indico.fnal.gov/event/43231/contributions/187359/attachments/129996/167589/IBSatIOTAcolaborMeeting.pdf)*

Emittance growth and beam loss due to space charge under active investigation.
Simulations in JSPEC

- **Cooler parameters**
  - Electron source: DC 1.36 kV, 10 mA, φ12 mm, 1 V jitter, 1400 K
  - Solenoid: 0.1 T, 0.7 m, flatness: $2 \times 10^{-4}$

- **JSPEC simulations**
  - Only electron cooling and Intra-Beam Scattering.
  - Halo formation due to IBS.
  - **No space charge!**

Phase space scatter plots at $t = 2$ min.
- Very dense core.
- Diffuse halo at an intensity of $10^{-3}$.
- Tune shift at core reaches -20!
Inclusion of Electron Cooling in PyORBIT

Space charge forces will limit the equilibrium core density.

PyORBIT is an extendible particle tracking code with a PIC space-charge model. Implemented an electron cooler extension to enable cooling simulations with space-charge.

- XY coupling
- Static space charge of the electron beam.
- Dynamic space charge of ion beam.
Benchmarks

Use the Parkhomchuk cooling force model for a magnetized cooler.

Verified results between JSPEC without IBS and PyORBIT without space charge.
Various scales determine cooling regime and numerical simulation parameters.

### Relevant Scales

| Scales                  | Values for coasting beam at 6.25 mA                                                                 |
|-------------------------|-----------------------------------------------------------------------------------------------------|
| e- Temperatures         | \( T_{e,\perp} = 1407.35 \text{ K}, T_{e,\parallel} = 22.27 \text{ K}, T_{e,\text{eff}} = 34.69 \text{ K} \) |
| p Temperatures          | \( T_{p,\perp} = 8.66 \times 10^4 \text{ K}, T_{p,\parallel} = 1.01 \times 10^5 \text{ K} \)      |
| p plasma period         | \( \tau_p = 127 \text{ ns} \)                                                                    |
| p length scales         | \( d_p = 29.1 \text{ µm}, \lambda_{D,p} = 4.98 \text{ mm} \)                                    |

| \( \tau_{rev} \)       | \( \Delta s_{\text{PIC}} = c \beta [\Delta t_{\text{PIC}}] \)                                  | \( \Delta x_{\text{PIC}} \) | \( N_{\text{macro}} \)            |
|------------------------|--------------------------------------------------------------------------------------------------|-----------------|----------------------------------|
| 1.83 \( \mu \text{s} \) | \(< 20 \text{ cm [0.91 ns]} \)                                                                 | 50/64 \( \sim 0.78 \text{ mm} \) | \( 10^5 \)                        |

As the beam cools, \( \tau_p, d_p, \lambda_{D,p} \) go down! Using fixed simulation parameters for now.
Simulated cooling with space charge for the IOTA lattice at $\Delta \nu_Y = -0.5$

Electron cooling can counter space-charge to some extent.
Simulated cooling with space charge for the IOTA lattice at $\Delta \nu_y = -0.1$

70000 turns not enough. Very long term simulations required!
Artificially Strong Cooling

Scale cooling force by a factor of 10.

Good agreement within the core in the linear regime. Approximate method of speeding up simulations?
Reconstructed Movie

Start with a scaled cooling force and switch to the baseline while still in the linear regime.
**Hardware**

- Electron cooler is part of the e-lens program at IOTA and shares all hardware except for the electron source.

- Thermionic Gun
  - Based on CERN Hollow Gun 1-in design.
  - Cross check design using WARP and TRAK.
  - Will be manufactured at U Chicago.

- Diagnostics:
  - **Protons:** Beam Position Monitors, DCCT, Recombination Monitor
  - **Electrons:** Faraday Cup, Profile monitor
Future Work

• Design work
  – Improve simulation fidelity, add non-uniform electron beam.
  – Analyze long term validity of space charge model.
  – Design electron source for cooling.

• Fabrication

• Experiments in IOTA
  – Commission electron lens.
  – Demonstrate cooling at low intensity.
  – Remove NL magnet. Explore high intensity.
  – Install anti-damper and study instabilities.
Conclusion

• **Electron cooling at IOTA** will increase proton lifetime and create low energy spread. Goal to explore large incoherent tune shift, study instabilities and NIO in the multi-particle regime.

• **Implement** using the e-lens setup with dedicated thermionic source for cooling. Operate with zero dispersion at the e-cooler. Space charge and Intra Beam Scattering (IBS) are main emittance growth drivers for 2.5 MeV proton operations.

• **Simulations** with electron cooling and IBS indicates the formation of a very dense core and a diffuse halo, not seen in practice. Developing simulations using PyORBIT which incorporates space charge, electron cooling and x-y coupling. **Ongoing studies.**

• **Plan** to establish electron cooling at low proton currents. Take turn-by-turn measurements of non-linear dynamics. Remove aperture restrictions and commission to high current, study instabilities and NIO in the multi-particle regime.
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Appendix: Recombination Monitor

• Baseline H0 production rate is about 6 kHz.

Bongho Kim et al., NIM A, Volume 899, Pages 22-27, 2018, ISSN 0168-9002
Appendix: Strong Cooling Movie

Develops an instability. Probably not physical.