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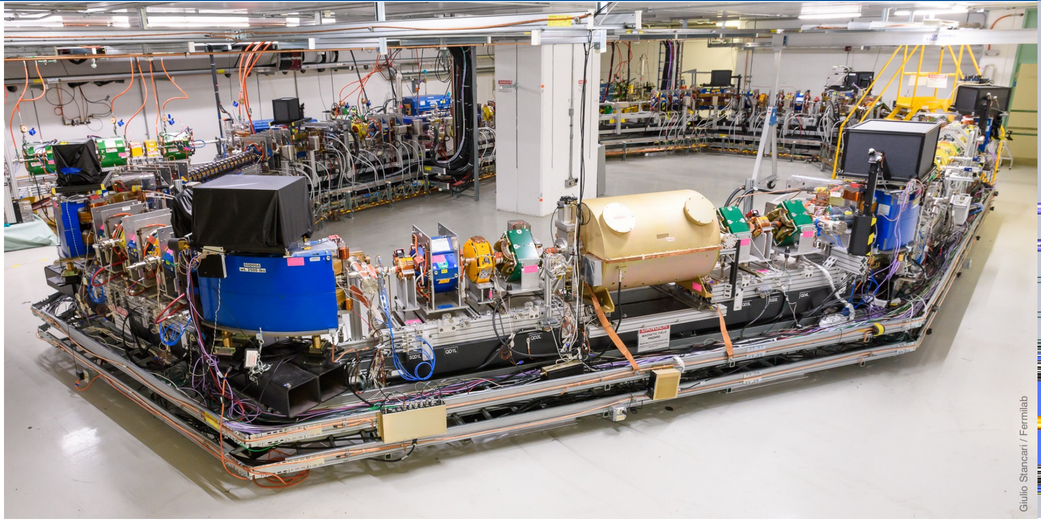

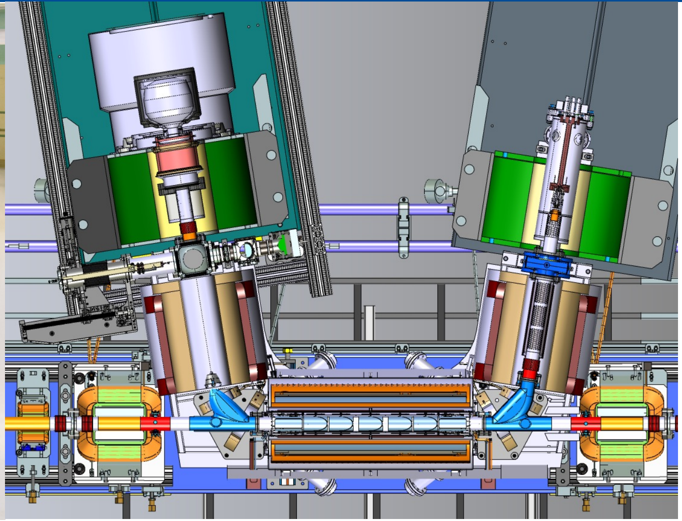

Electron cooling with space-charge dominated proton beams at IOTA

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The 13th International Workshop COOL’21

1 November 2021

In partnership with:

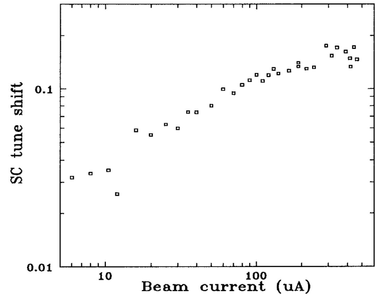
THE UNIVERSITY OF CHICAGO

Overview

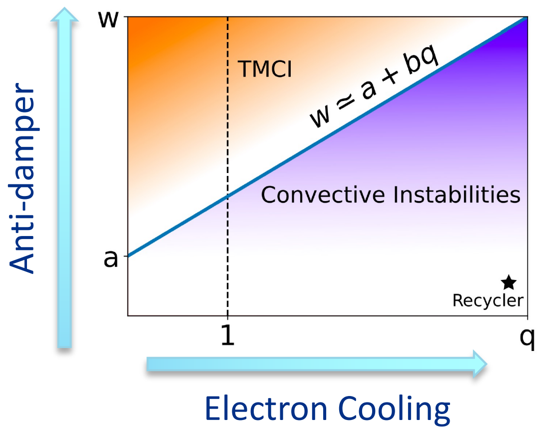
- Goals
- Implementation
- Simulations
- Hardware
- Future Work
- Conclusion

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.



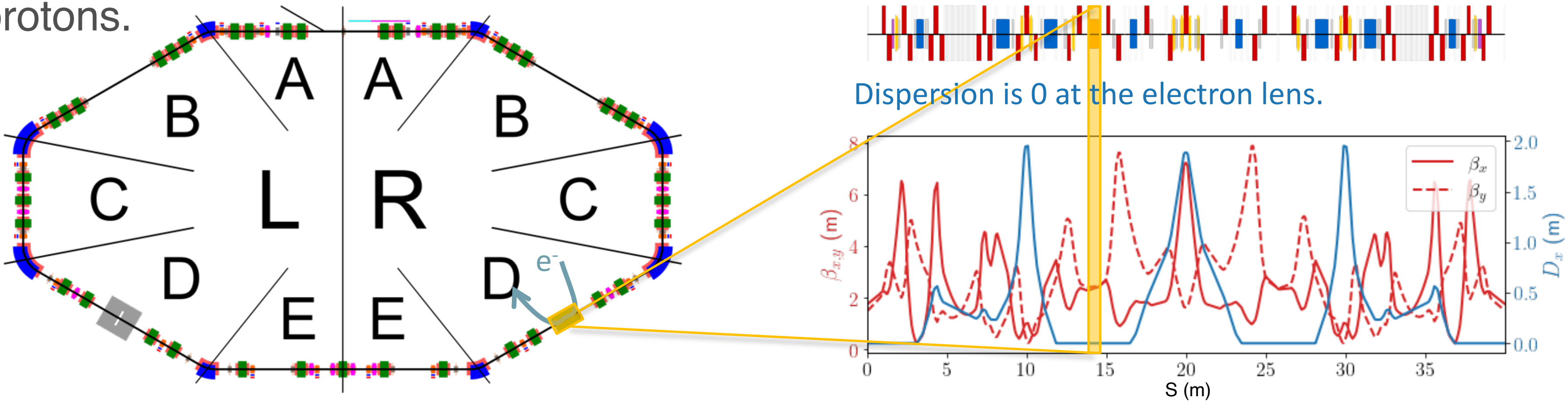
S. Nagaitsev et al., Proceedings Particle Accelerator Conference, 1995, pp. 2937-2939



A. Burov, Phys. Rev. Accel. Beams 22, 034202, 2019

Implementation

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



C	KE	τ_{rev}	h	N_{bunch}	$A_{x,y}$	$\nu_{x,y}$
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

Operating Parameters

$\epsilon_{x,y}$ (μm)	σ_p/p	σ_s (m)
4.3, 3.0	1.32×10^{-3}	0.79

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

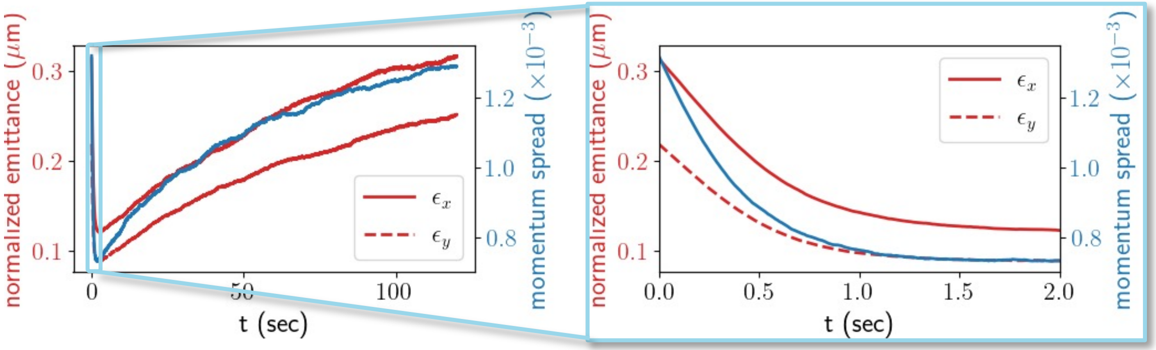
	Coasting		Bunched	
Current (mA)	2.25	6.25	0.248	1.24
Bunch Charge (nC)	2.28	11.4	0.113	0.565
Tune Shifts ($\Delta\nu_{x,y}$)	-0.076, -0.10	-0.38, -0.50	-0.076, -0.10	-0.38, -0.50
RGS (s)	$\tau_{RGS,single}$= 1060*, τ_{RGS,ϵ_x}= 25.8*, τ_{RGS,ϵ_y}= 15.8*			
IBS $\tau_{IBS,x,y,s}$ (s)	32.0, 20.9, 40.4	6.40, 4.19, 8.08	43.4, 29.9, 115	8.69, 5.97, 23.01
Cooling times (s)	1.00, 0.87, 0.496		1.00, 0.87, 0.992	

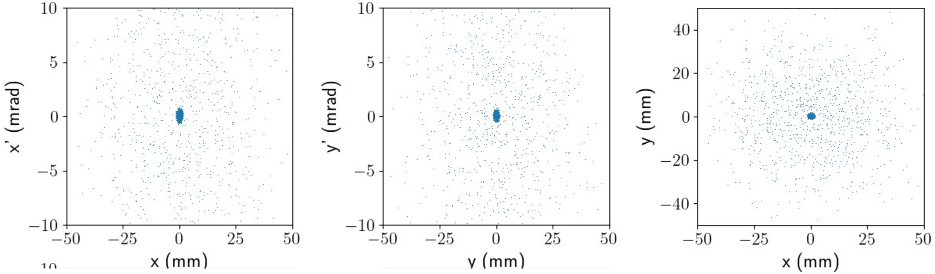
Emittance growth and beam loss due to space charge under active investigation.

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

Simulations in JSPEC

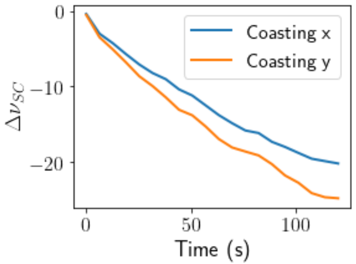
- Cooler parameters
  - Electron source: DC 1.36 kV, 10 mA, ϕ12 mm, 1 V jitter, 1400 K
  - Solenoid: 0.1 T, 0.7 m, flatness: 2 x 10^{-4}
- JSPEC simulations
  - Only electron cooling and Intra-Beam Scattering.
  - Halo formation due to IBS.
  - **No space charge!**





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!



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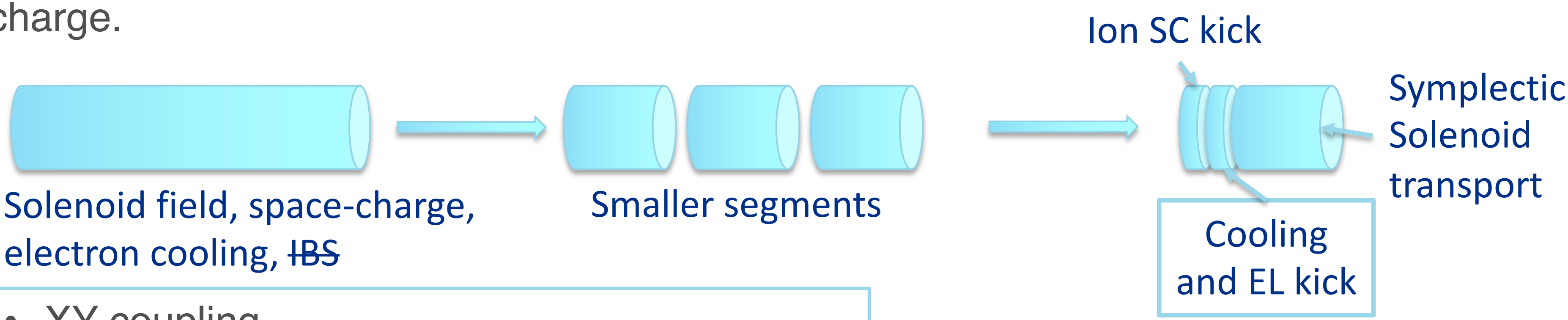
Inclusion of Electron Cooling in PyORBIT

Space charge forces will limit the equilibrium core density.

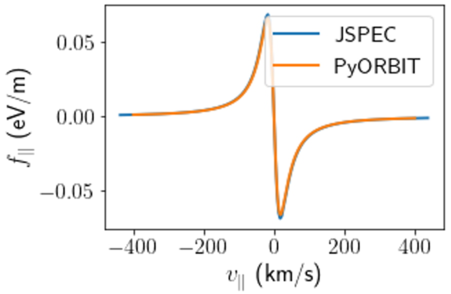
PyORBIT is an extendible particle tracking code with a PIC space-charge model. Implemented an electron cooler extension to enable cooling simulations with space-charge.

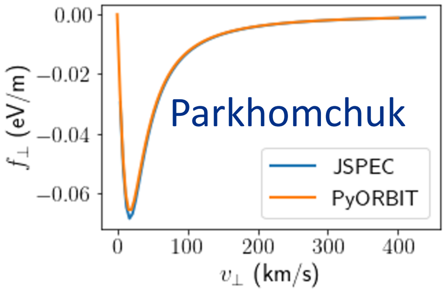


- XY coupling
- Static space charge of the electron beam.
- Dynamic space charge of ion beam.

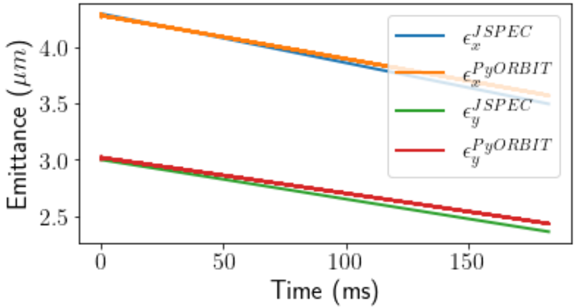
Benchmarking

Use the Parkhomchuk cooling force model for a magnetized cooler.





Verified results between JSPEC without IBS and PyORBIT without space charge.



Relevant Scales

Various scales determine cooling regime and numerical simulation parameters.

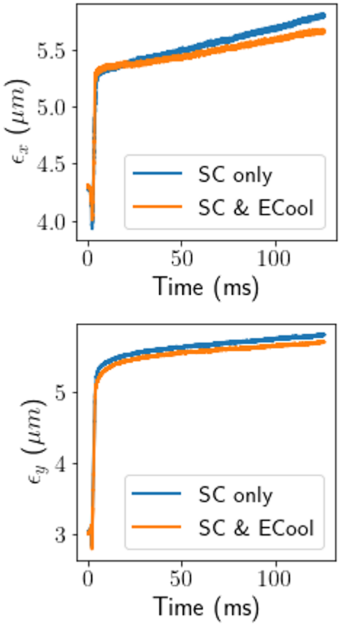
Scales	Values for coasting beam at 6.25 mA
e- Temperatures	$T_{e,\perp} = 1407.35\ \mathrm{K}, T_{e,\parallel} = 22.27\ \mathrm{K}, T_{e,eff} = 34.69\ \mathrm{K}$
p Temperatures	$T_{p,\perp} = 8.66\times10^{4}\ \mathrm{K}, T_{p,\parallel} = 1.01\times10^{5}\ \mathrm{K}$
p plasma period	$\tau_p = 127\ \mathrm{ns}$
p length scales	$d_p = 29.1\ \mu\mathrm{m}, \lambda_{D,p} = 4.98\ \mathrm{mm}$

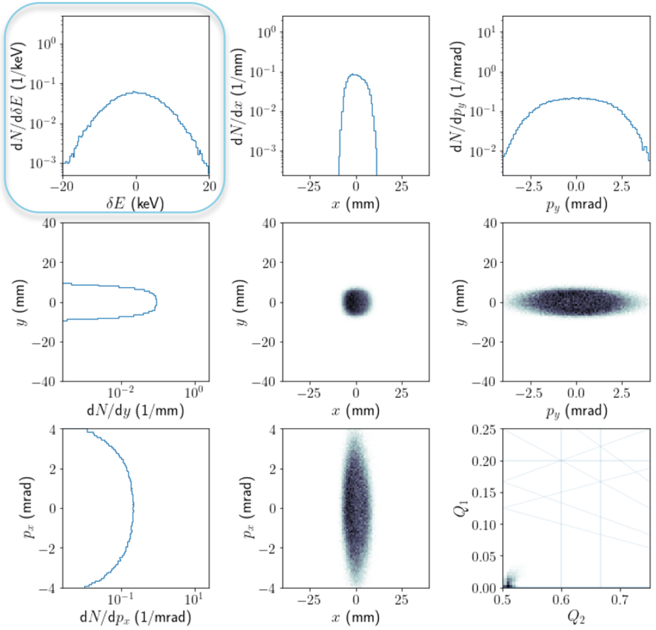
τ_{rev}	$\Delta s_{\mathrm{PIC}} = c\beta[\Delta t_{\mathrm{PIC}}]$	Δx_{PIC}	N_{macro}
1.83 µs	< 20 cm [0.91 ns]	50/64 ~ 0.78 mm	10^5

As the beam cools, $\tau_p, d_p, \lambda_{D,p}$ go down! Using fixed simulation parameters for now.

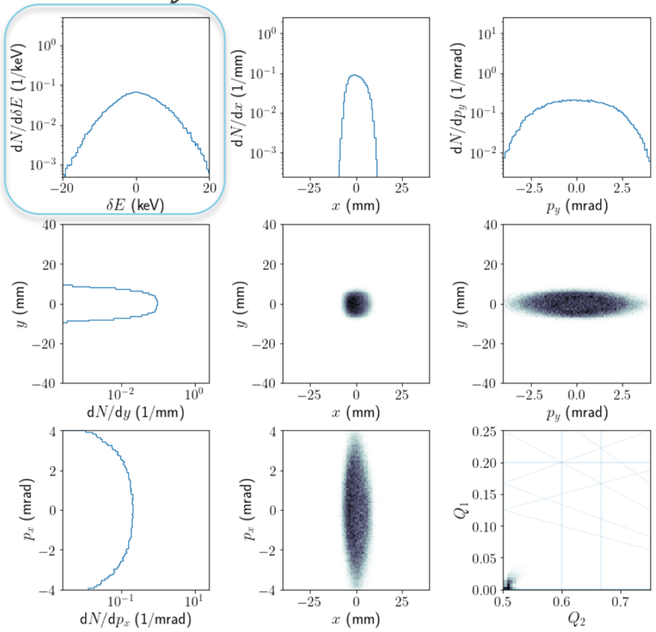
Preliminary Results at Design Current

Simulated cooling with space charge for the IOTA lattice at $\Delta\nu_y = -0.5$





SC Only

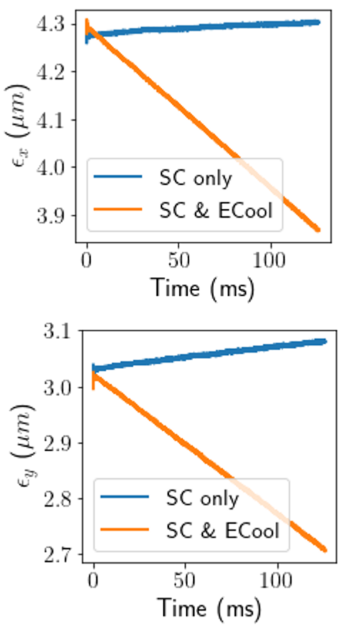


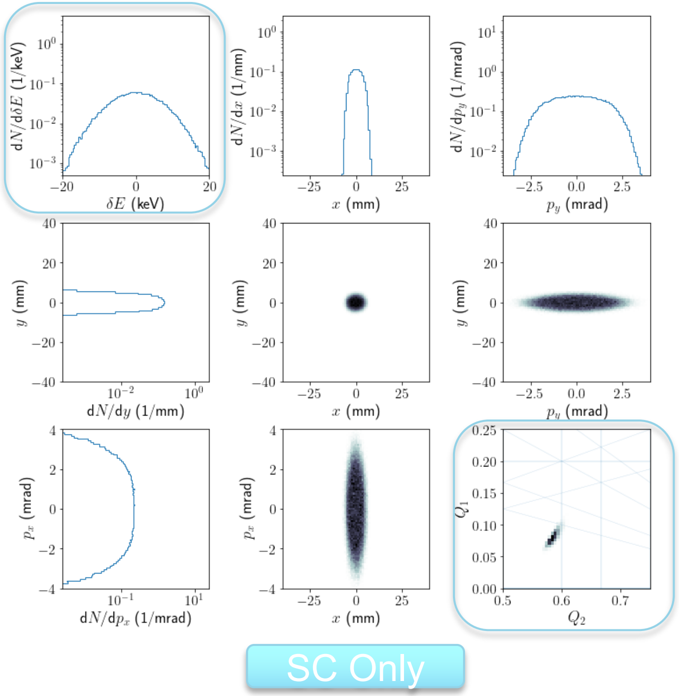
SC and ECool

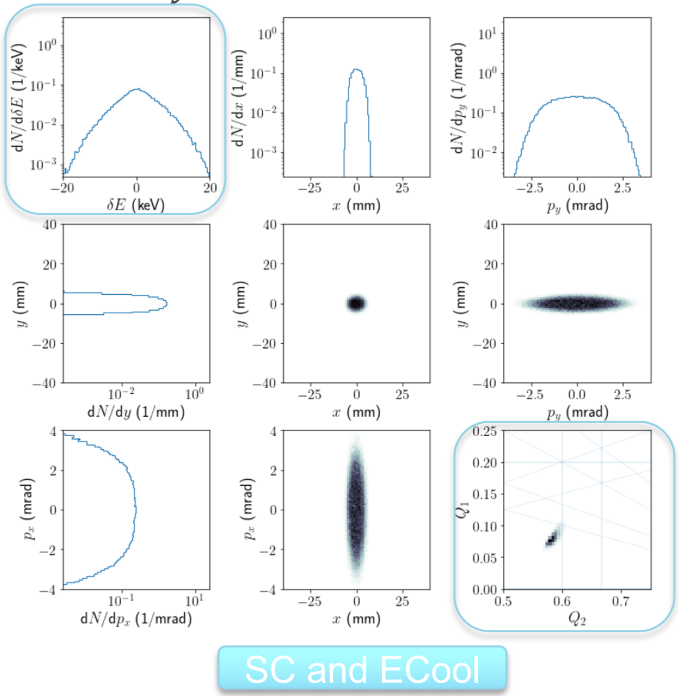
Electron cooling can counter space-charge to some extent.

Low Current Starting Point

Simulated cooling with space charge for the IOTA lattice at $\Delta\nu_y = -0.1$



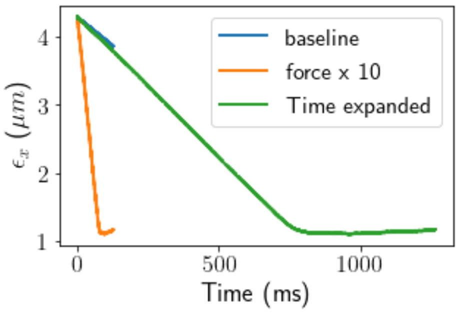


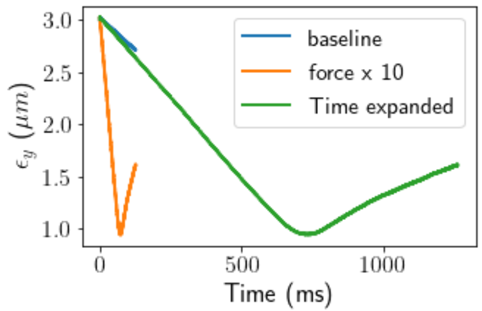


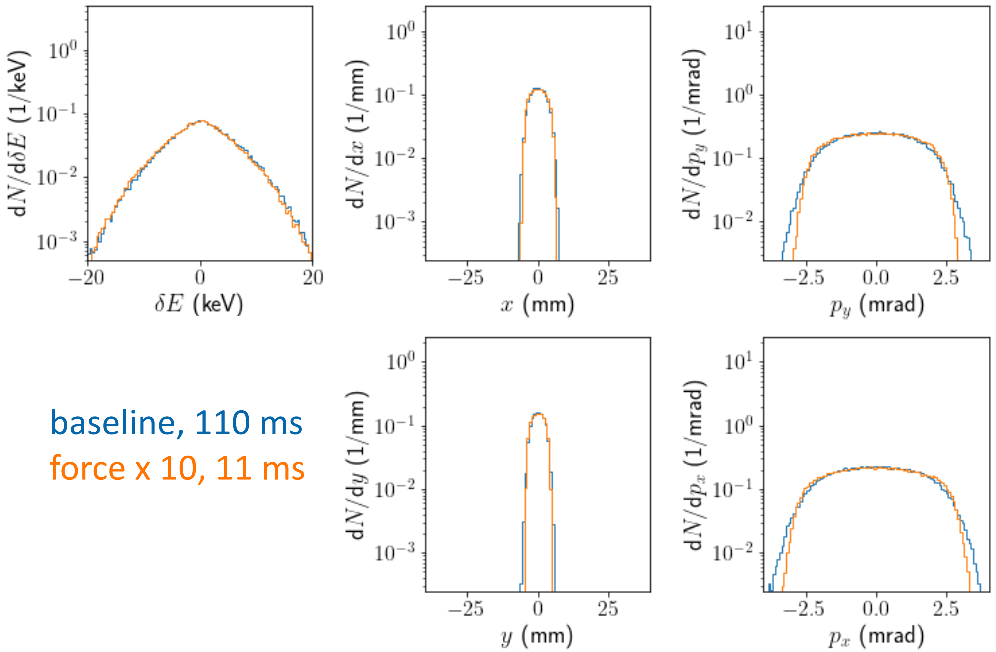
70000 turns not enough. Very long term simulations required!

Artificially Strong Cooling

Scale cooling force by a factor of 10.







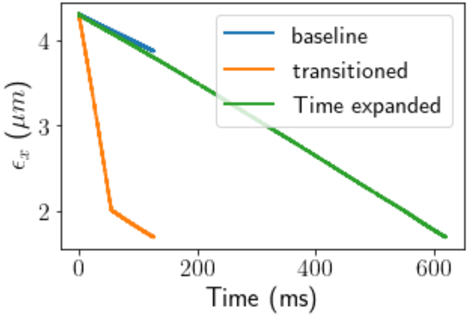
baseline, 110 ms

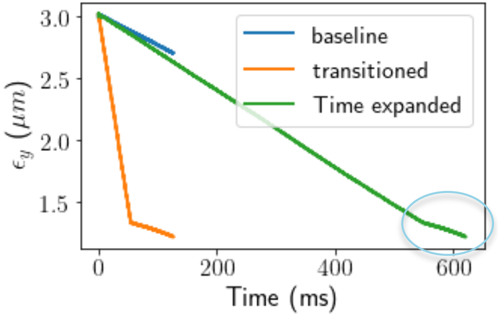
force x 10, 11 ms

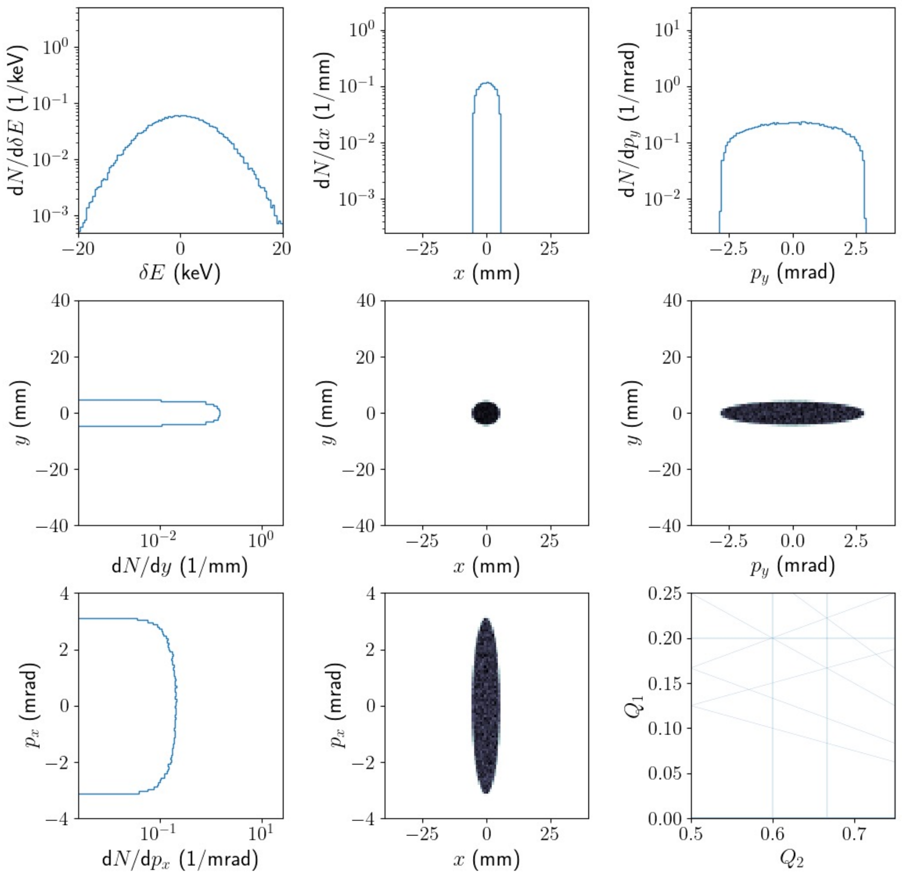
Good agreement within the core in the linear regime. Approximate method of speeding up simulations?

Reconstructed Movie

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

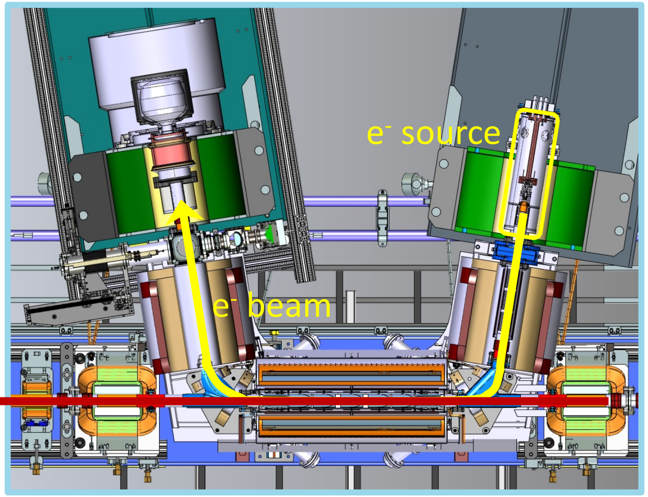


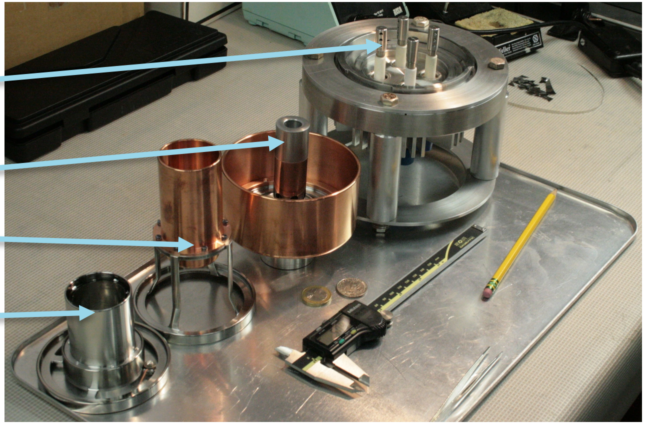




Hardware

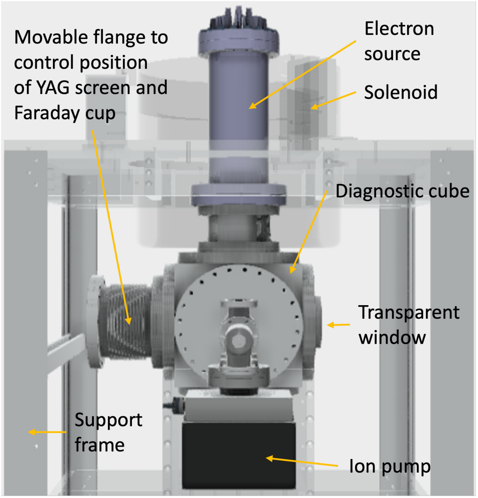
- Electron cooler is part of the e-lens program at IOTA and shares all hardware except for the electron source.
- Thermionic Gun
  - Based on CERN Hollow Gun 1-in design.
  - Cross check design using WARP and TRAK.
  - Will be manufactured at U Chicago.
- Diagnostics:
  - Protons: Beam Position Monitors, DCCT, Recombination Monitor
  - Electrons: Faraday Cup, Profile monitor

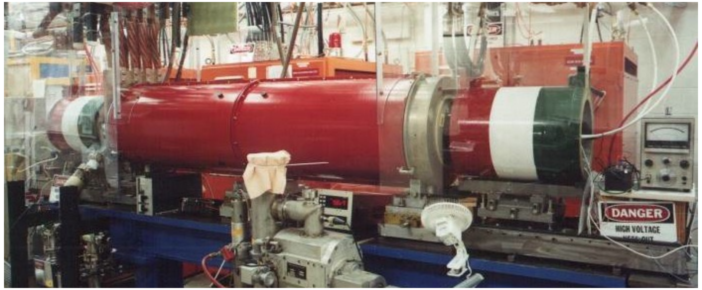




Future Work

- 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.

Acknowledgements

MaryKate Bossard, John Brandt and Young-Kee Kim at The University of Chicago.

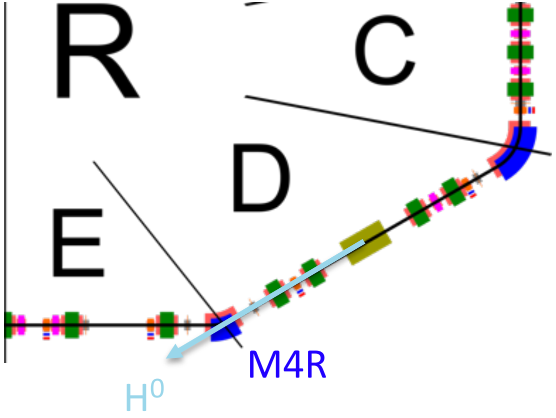
Alexey Burov, Brandon Cathey, Valeri Lebedev, Sergei Nagaitsev, Giulio Stancari and the IOTA/FAST collaboration at Fermilab.

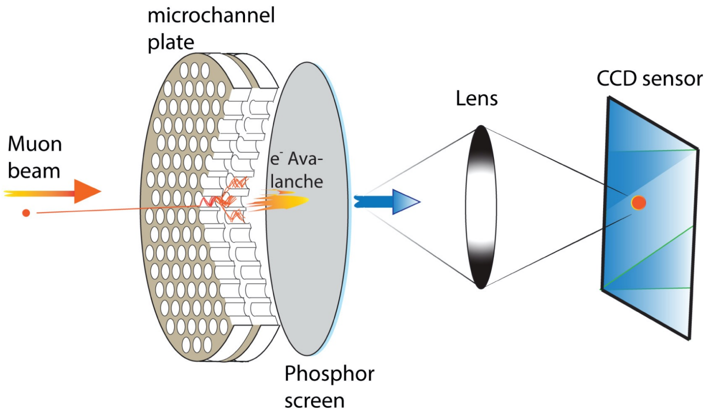
Chad Mitchell, Runze Li and IOTA Physics collaboration members.

Thank You!

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.