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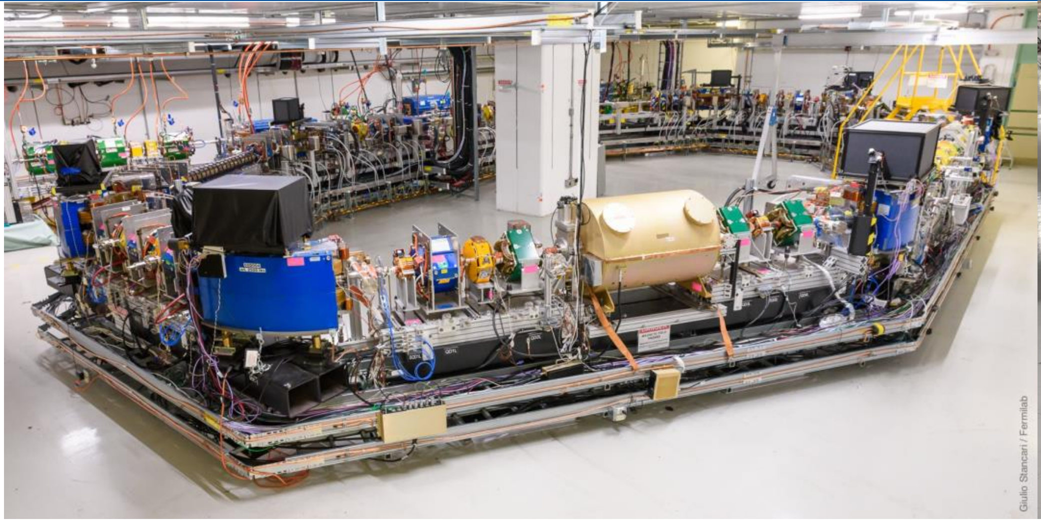
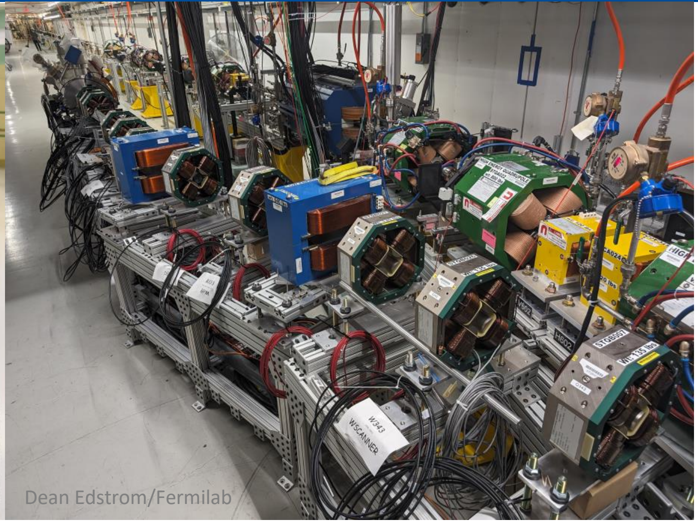




High-intensity operations with 2.5 MeV protons in IOTA

Nilanjan Banerjee

In partnership with:

THE UNIVERSITY OF CHICAGO

Overview

1. Motivation and Planned Experiments

2. Beam Parameters and Lattice Considerations

3. Hardware Configuration and Status

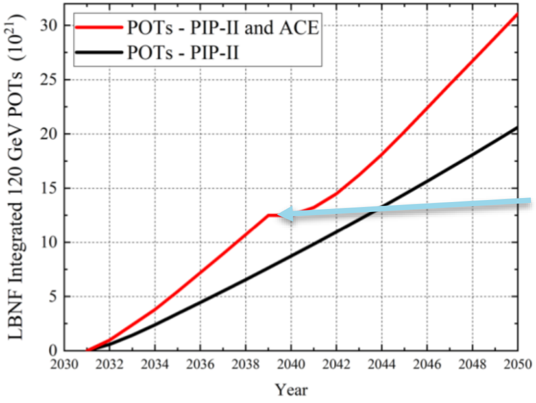
Motivation and Planned Experiments

Maximizing Brightness and Intensity in ACE and Beyond

The proton program in IOTA was proposed for research into multi-megawatt hadron rings. Our research program addresses the four grand challenges of accelerator and beam physics facing the community:

1. Beam Quality: Space-charge, cooling
2. Beam Intensity: NIO, Landau damping
3. Beam Control
4. Beam Prediction

J. Blazey et al, Accelerator and Beam Physics Roadmap, DOE Accelerator Beam Physics Roadmap Workshop, 2022



Possible booster upgrade with RCS: $|\Delta\nu_{SC}| = 0.2$ @ 2 GeV injection.

R. Ainsworth et al., An Upgrade Path for the Fermilab Accelerator Complex, 2022.

R. Ainsworth et al., Report from the Fermilab Proton Intensity Upgrade Central Design Group, 2023.

De-risk new booster design by finding methods to maximize beam intensity and quality for a range of beam storage times.

Enhancing Beam Quality

Realize a super-periodic lattice

Allocate more space for the tune footprint.

Compensate for space charge forces

Minimize tune footprint due to space charge.

Tune-shift compensation per lens is limited.

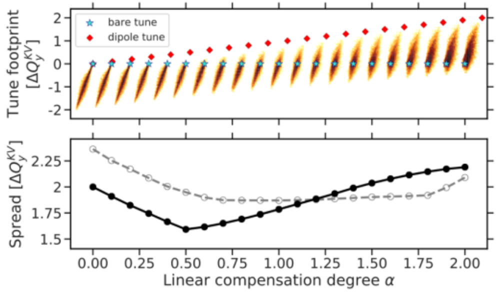
Gaussian or McMillan?

Electron cooling

Cool hadrons via thermal energy exchange with co-propagating electron beam. Constrained by space-charge.

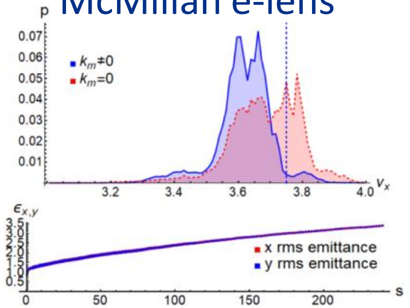
How to maximize phase-space density of stored beam and minimize beam loss in a ring for given number of turns?

Pulsed e-lens with flat transverse profile.



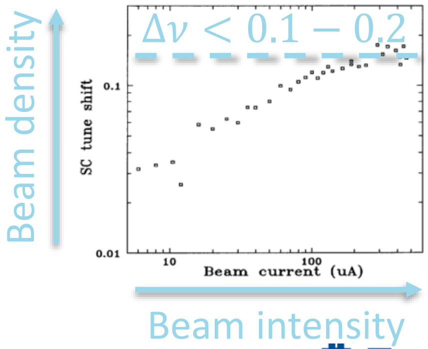
A. Oeftiger and O. Boine-Frankenheim, arXiv:2310.02365, 2023.

McMillan e-lens



S. Nagaitsev et al., JINST 16 P03047, 2021.

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

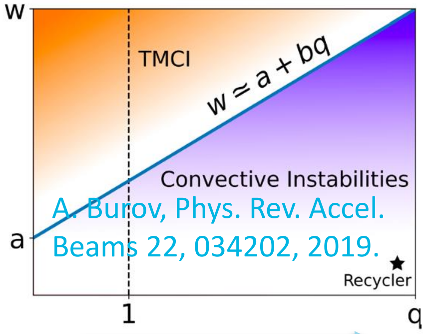


Enhancing Beam Intensity

Interplay of space-charge and coherent instabilities

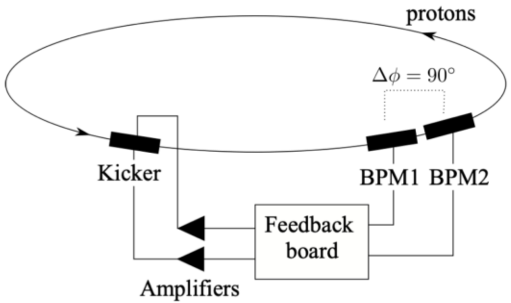
Measure instability growth rate and head tail amplification as a function of tune shift and impedance.

Wakefield Amplitude (Waker)



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

SC Tune Shift (Electron Cooling)



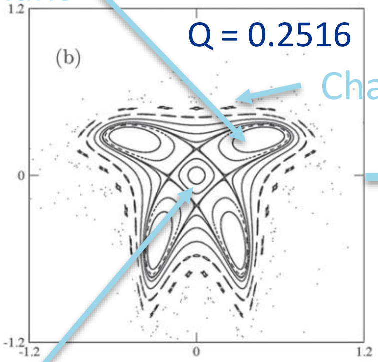
Wake Building Feedback System

O. Mohsen et al., in Proc. NAPAC'22, pp. 124-127, 2022.

Demonstration of Non-linear Integrable Optics

Measure conservation of invariant quantities with protons.

Resonant

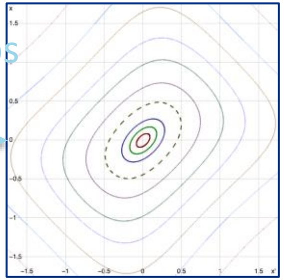


Q = 0.2516

Chaos

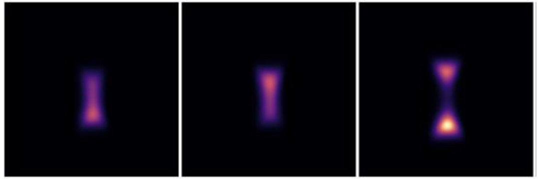
Regular non-resonant

Sextupole map



McMillan map

Conserves 2 functions



J. Wieland et al., IOTA/FAST collaboration meeting, 2024.

Danilov-Nagaitsev system stable at integer resonance

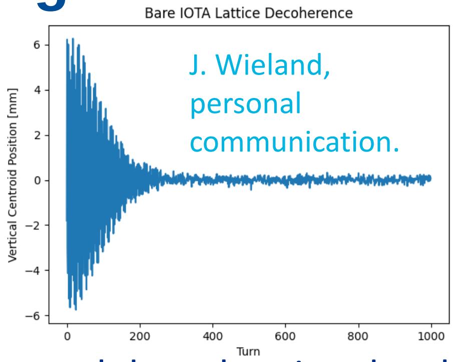
Flagship experiment of Integrable Optics Test Accelerator!

Tunable Landau Damping with Space Charge

Demonstrate integrable optics and Landau damping.

- Danilov-Nagaitsev magnets
- Octupole string

A. Valishev et al., in Proc. IPAC’21, pp. 19-24, 2021.
N. Kuklev et al., in Proc. IPAC'21, pp. 1964-1967, 2021.
V. Danilov and S. Nagaitsev, Phys. Rev. ST Accel. Beams 13, 084002, 2010.



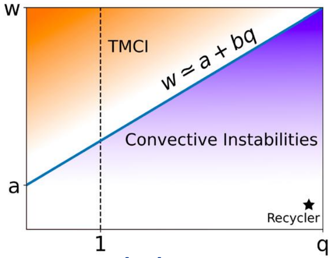
Experimental data showing decoherence due to chromatic tune spread in electron bunches.

Electron cooling enables:

1. Single particle dynamics experiments with pencil beam and low energy spread.
2. Measurement of minimum tune spread required to mitigate coherent instabilities with space-charge.

V. Danilov and S. Nagaitsev, Phys. Rev. ST Accel. Beams 13, 084002, 2010.

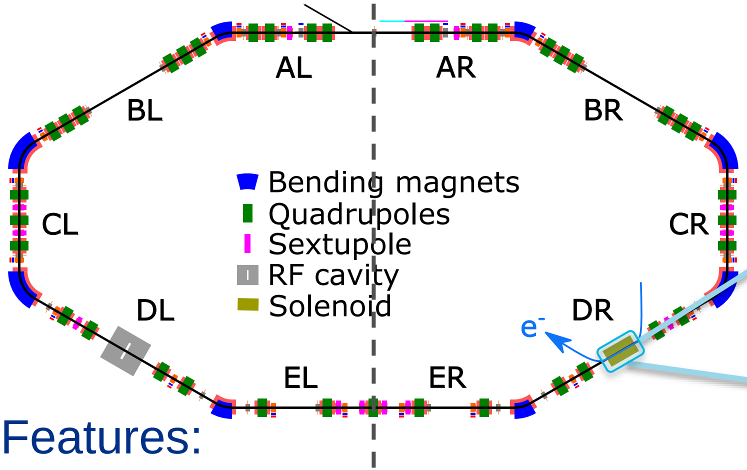
?

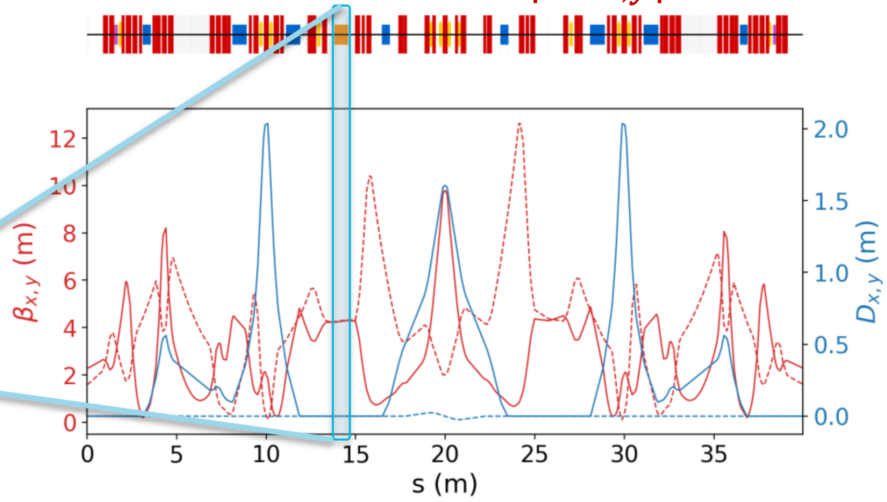


Instability Parameter Space

The Proton Program at IOTA

IOTA is a storage ring which will circulate 2.5 MeV protons up to $|\Delta\nu_{x,y}| \sim 0.5$.





Features:

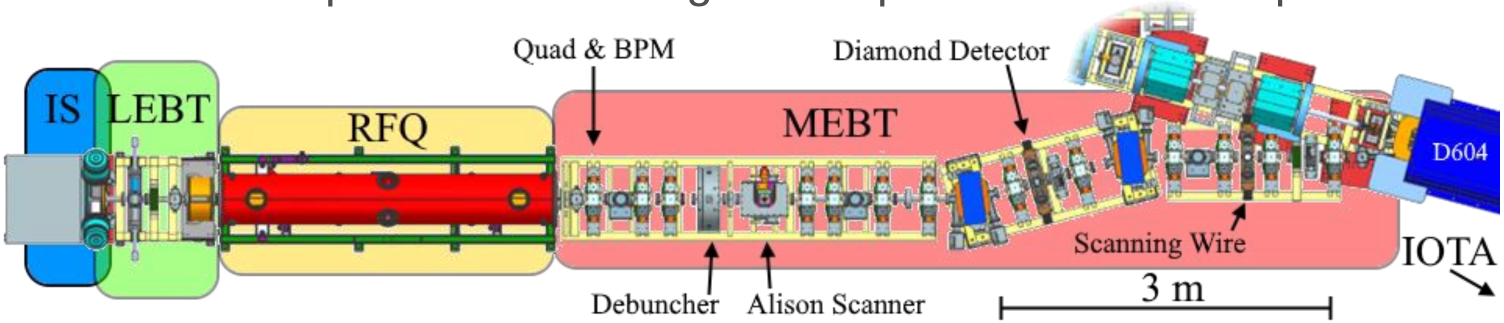
- All (skew) quadrupoles, correctors and sextupoles are independently controlled.
- Rf cavity for adiabatic capture.
- Single-turn injection.
- Electron lens/cooler of length 0.7 m.

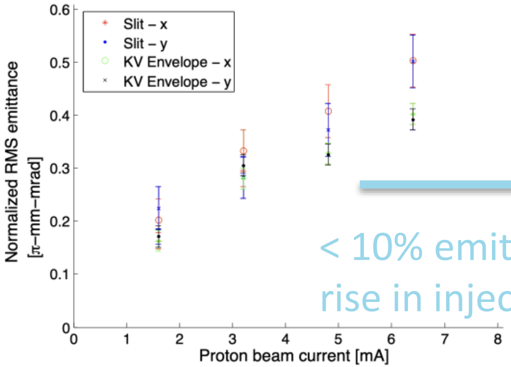
K (MeV)	$\epsilon_{x,y}$ (μm)	$\sigma_\delta \times 10^3$	$I_{\max}$ (mA)
2.4 - 2.6	3 - 7	1 - 3	7

Beam Parameters and Lattice Considerations

2.5 MeV Proton Injector

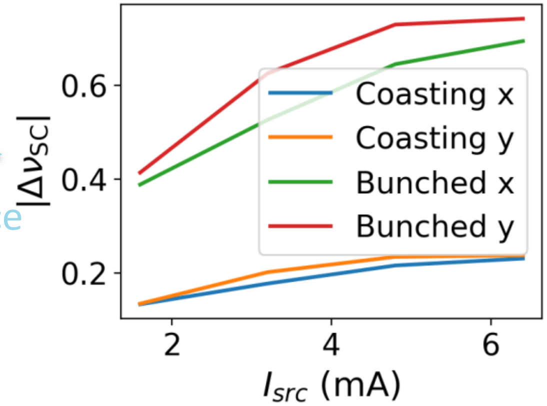
Injector beamline capable of delivering macro-pulses of 2.5 MeV protons at 1 Hz.





< 10% emittance rise in injector

W. M. Tam, PhD Thesis, Indiana University, Bloomington, 2010.

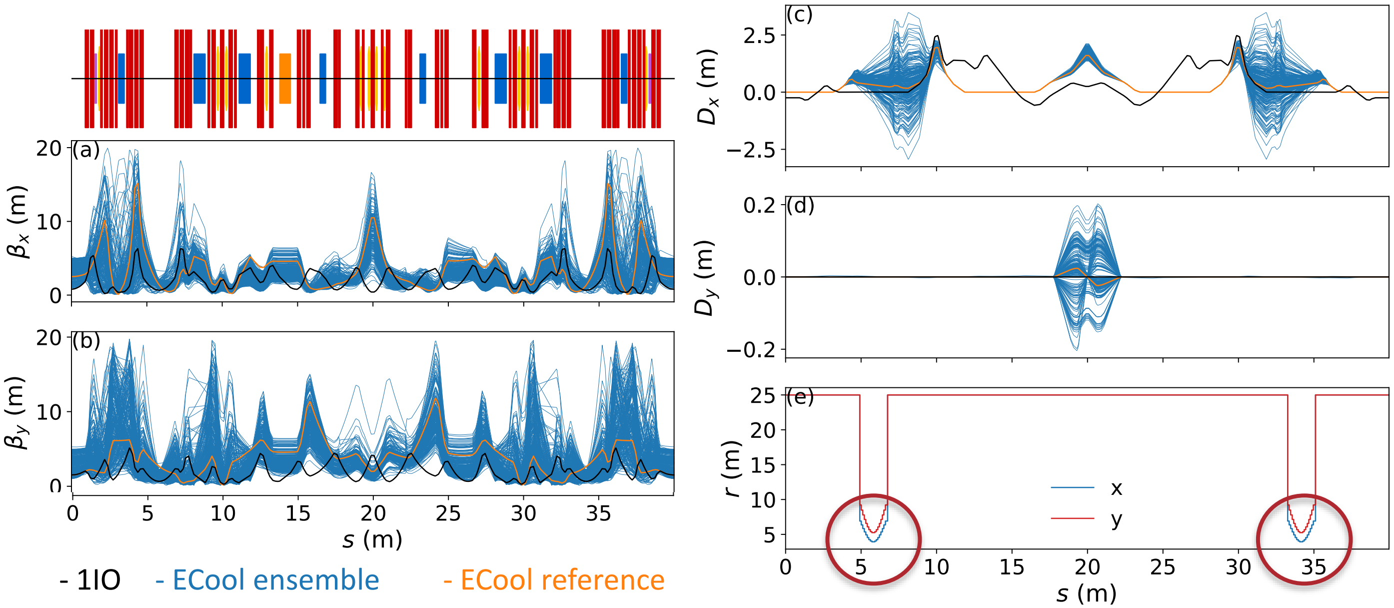


- The maximum incoherent tune shift for coasting beam saturate around 0.25.
- We can reach tune shifts above 0.5 for bunched beam.

Can change orifice diameter to increase current.

Lattices for Proton Operations

The lattice with the Danilov-Nagaitsev non-linear magnet will be used to commission protons in IOTA.



C (m)	39.96
f_{rev}(MHz)	0.547
h	4
Q_x, Q_y, Q_s	5.3, 5.3, **0.01**
$\epsilon_{mx}, \epsilon_{my}$ (μm)	23, 40

The special non-linear magnets pose strict aperture restrictions.

Emittance Growth and Beam Loss

The primary sources of emittance growth and beam loss are:

1. Residual Gas Scattering

   Single scattering events lead to a finite lifetime. 10 mins @ 4.2 x 10^{-8} Torr measured in atomic hydrogen equivalents.

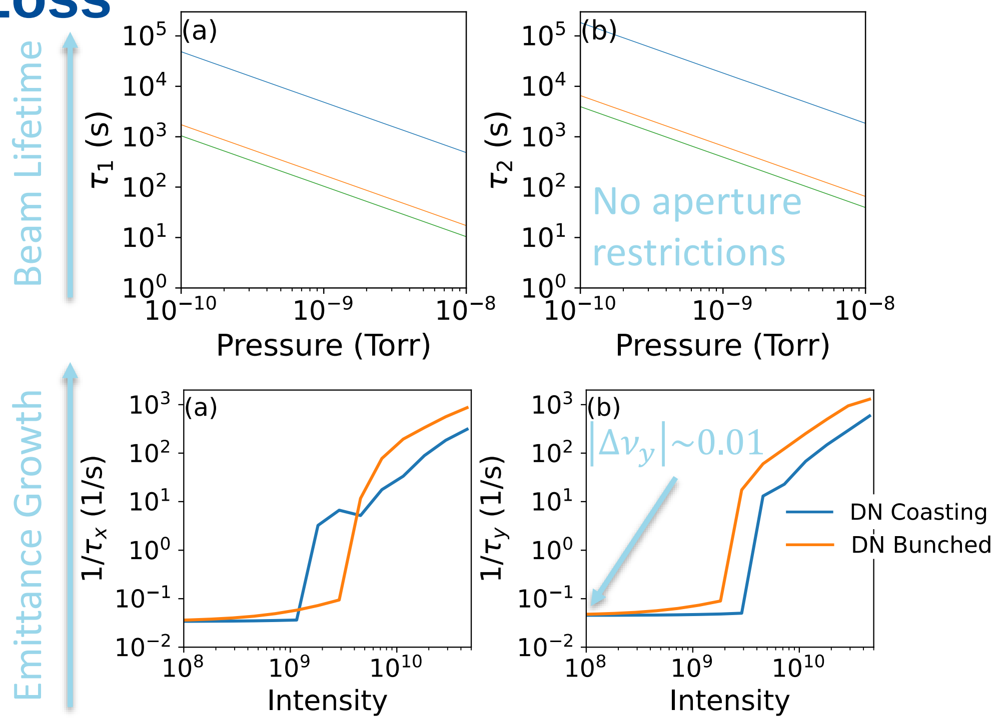
   Multiple scattering events lead to emittance growth independent of intensity.

   Baking can reduce residual pressure and increase lifetime.

2. Intra-Beam Scattering

3. Space-charge driven diffusion

   Functions of bare lattice and phase-space distribution.



Electron cooling can allow us to compensate for emittance growth and enforce equilibrium.

Comparison of Space-Charge Codes

We need estimates of emittance growth and beam loss as a function of intensity due to space-charge in the presence of field and misalignment errors.

Xsuite

Transverse frozen

Supports GPU acceleration!

G. Iadarola, in Proc. HB'23, Geneva, Switzerland, Oct. 2023, pp. 73-80.

PyORBIT

Transverse 2.5D Electrostatic PIC

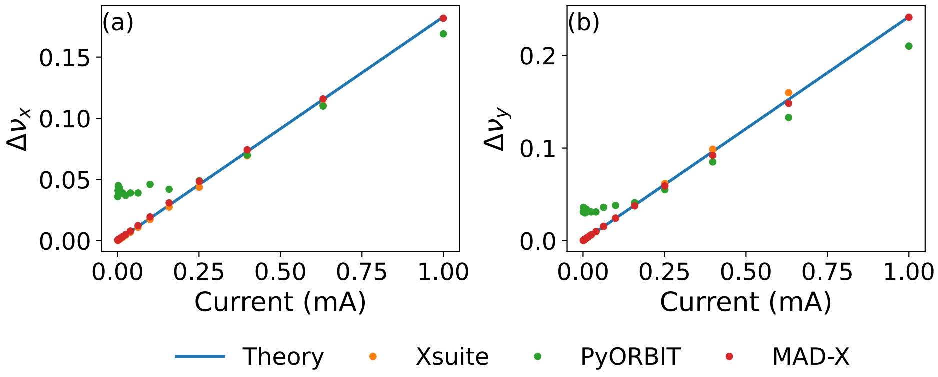
A. Shishlo et al., Procedia Computer Science 51, pp. 1272-1281, 2015.

MAD-X

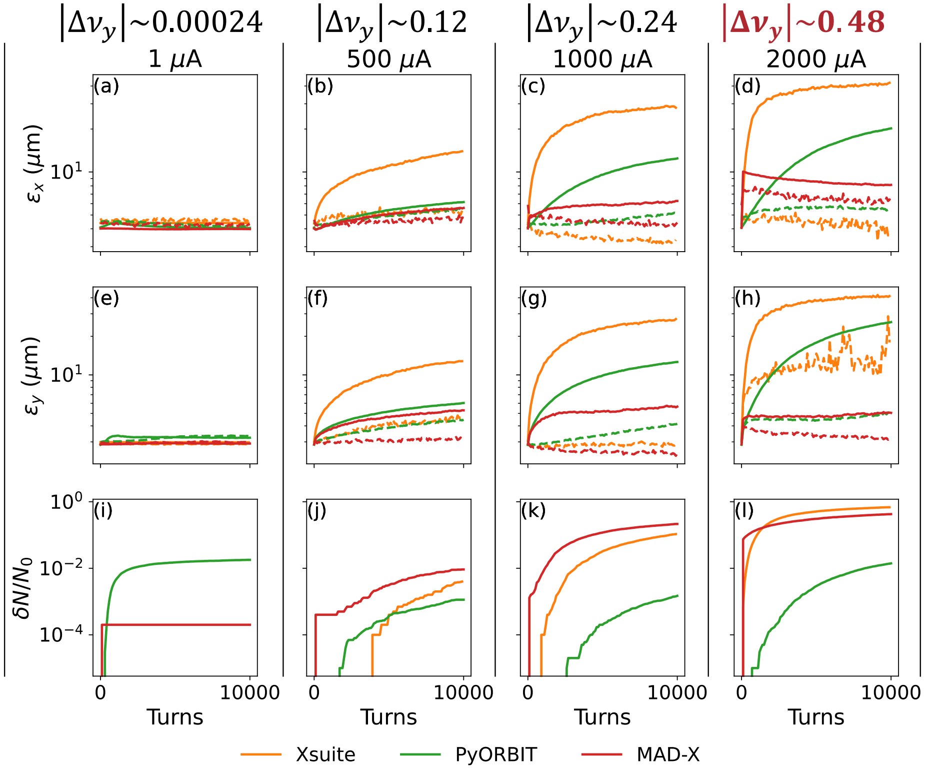
Transverse quasi-frozen

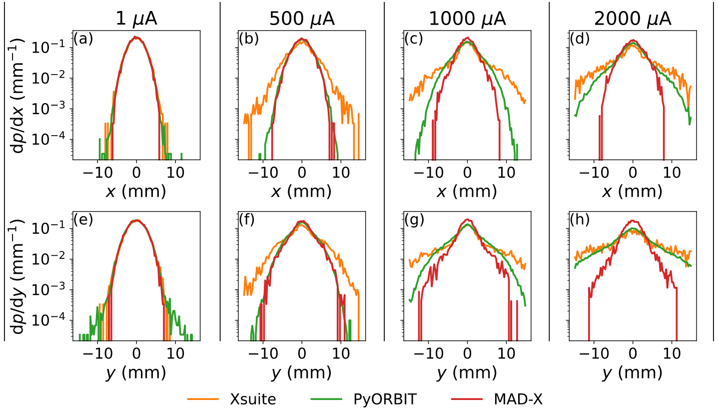
F. Schmidt et al., in Proc. HB’16, Malmö, Sweden, Jul. 2016, pp. 357-361.

Incoherent tune shifts estimated from the models match with expected values.



Comparison of Space-Charge Codes: Preliminary Results



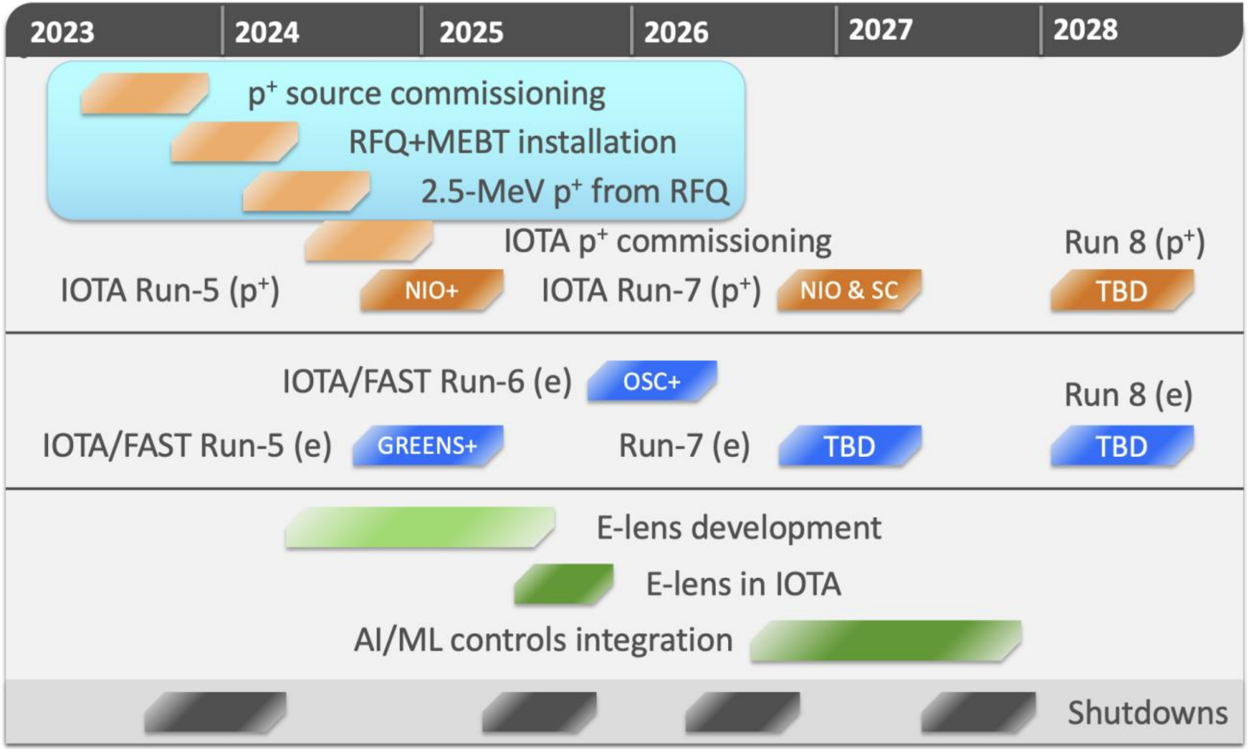


Transverse beam distributions after 10^4 turns.

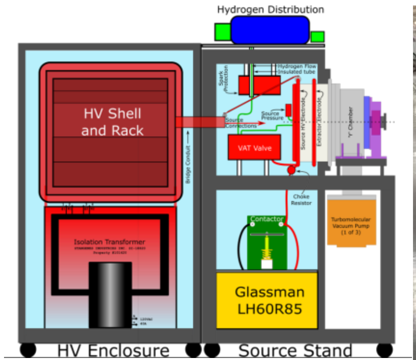
- At moderate and high intensities, no agreement in RMS emittance and beam loss estimates.
- Phase-space density at the beam core agrees within a factor of 2 at moderate current.

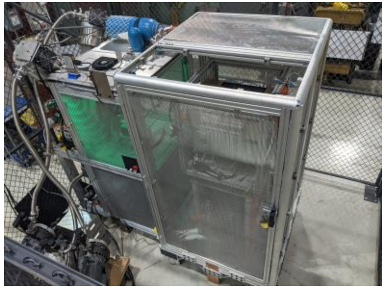
Hardware Configuration and Status

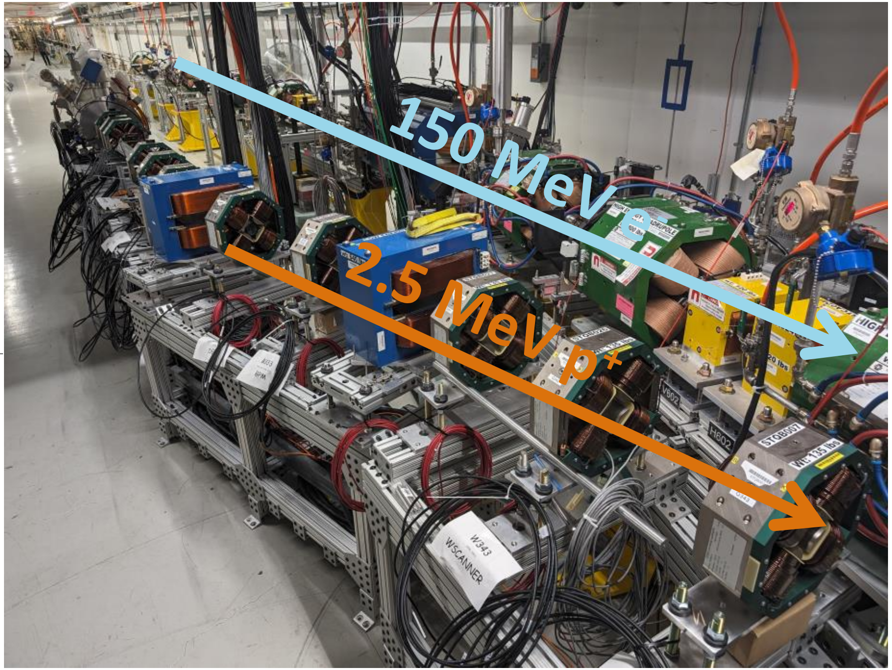
Electron Cooling in 2025



Proton Injector Commissioning







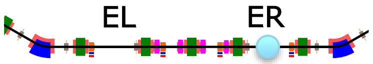
- Commissioning duoplasmatron source outside accelerator enclosure. Protons soon!
- All components of injector beamline in place.
- 350 MHz high-level RF installation in progress.
- Protons in IOTA in fall 2024.

Proton Beam Diagnostics

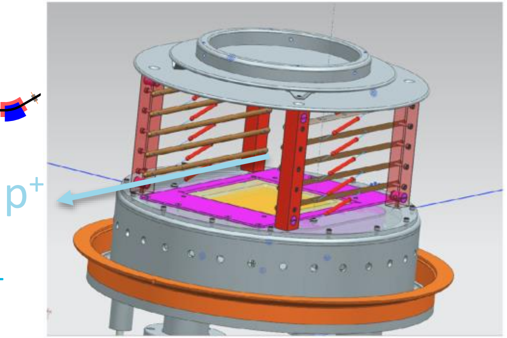
Injector: Toroid, Scanning wire, Allison scanner

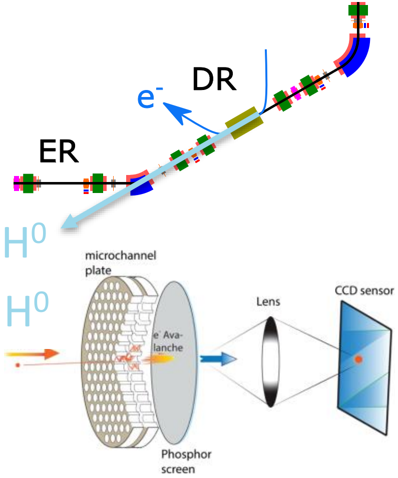
Storage Ring:

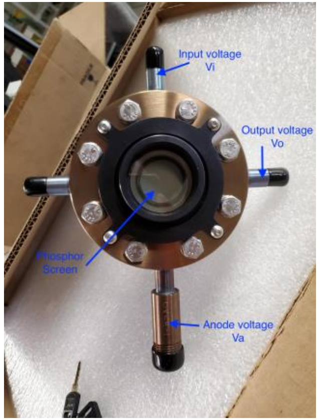
- DCCT: Measure injection efficiency and beam lifetime.
- RWCM: Waveform information of beam, longitudinal Schottky?
- Beam Position Monitors
  - Use LOCO to configure lattice.
  - Use turn-by-turn centroid positions of pencil beams to measure single-particle dynamics.
- Ionization Profile Monitor
  - Measure turn-by-turn evolution of transverse profile.
- Neutralization monitor
  - Measure equilibrium transverse profile with cooling.



V. Shiltsev, NIM A, 986, 164744, 2021.
H. Piekarz et al, Beams Document 9903-v1, Fermilab, 2023.





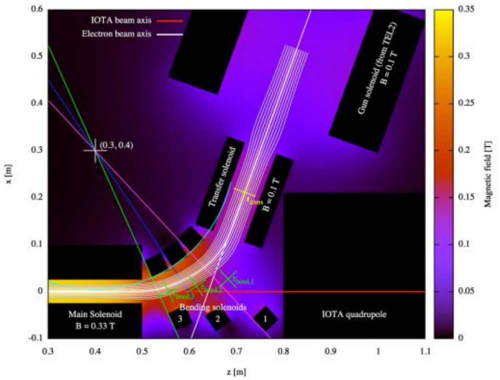


Bongho Kim et al., NIM A, 899, 22-27, 2018.

Electron Lens Setup

G. Stancari et al, *JINST* **16** P05002, 2021

Conceptual design of most parts exist but engineering design needs to be finalized.

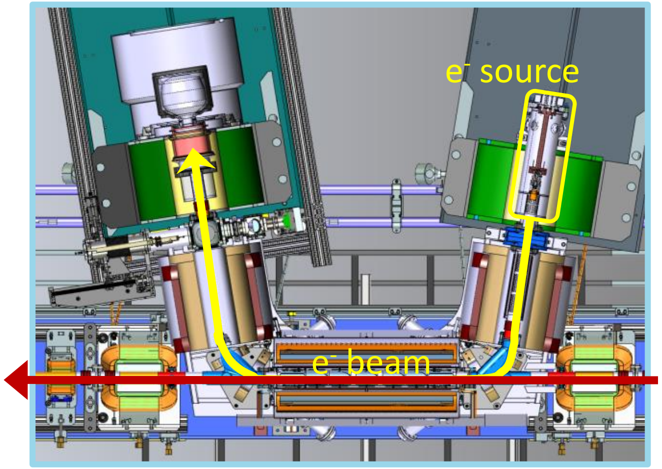


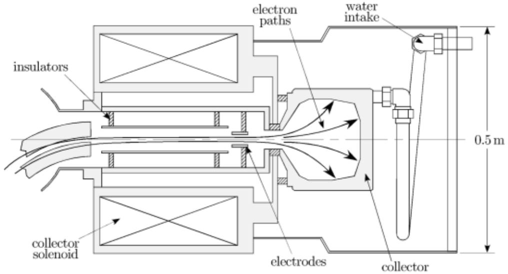
Electron Tracking

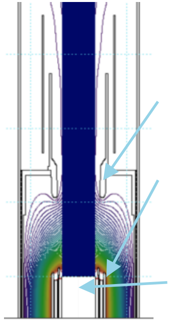
D. Noll and G. Stancari, Technical Memo, Fermilab, 2015. FERMILAB-TM-2598-AD-APC.

TEL-2 Collector

V. Shiltsev et al., Phys. Rev. ST Accel. Beams 11, 103501 , 2008.







Flat beam gun

M. Bossard et al., in Proc. IPAC'23, pp. 646-649, 2023.

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Conclusion

The IOTA 2.5 MeV proton program will study extreme beam conditions in future hadron synchrotrons and storage rings, relevant for a Fermilab Booster replacement.

- Space-charge tune shift approaching -0.5. – Electron cooling and space-charge compensation.
- Adjustable wakefields of arbitrary shapes and magnitudes. – Wake-building feedback system.

We have proposed a few experiments:

- Optimize bare lattice, demonstrate space-charge compensation using electron lens.
- Measure the interplay of coherent instabilities, space-charge and Non-linear Integrable Optics.

Main sources of emittance growth and beam loss include residual gas scattering, intra-beam scattering and space-charge.

- Compare results from different space-charge models and validate with experiments.

Protons in fall 2024, electron lens in late 2025.

Acknowledgements

Rob Ainsworth, Alexey Burov, Brandon Cathey, Sergei Kladov, Valeri Lebedev, Aleksandr Romanov, Alexander Valishev, Mike Wallbank and the IOTA/FAST team at Fermilab.

Thank You!