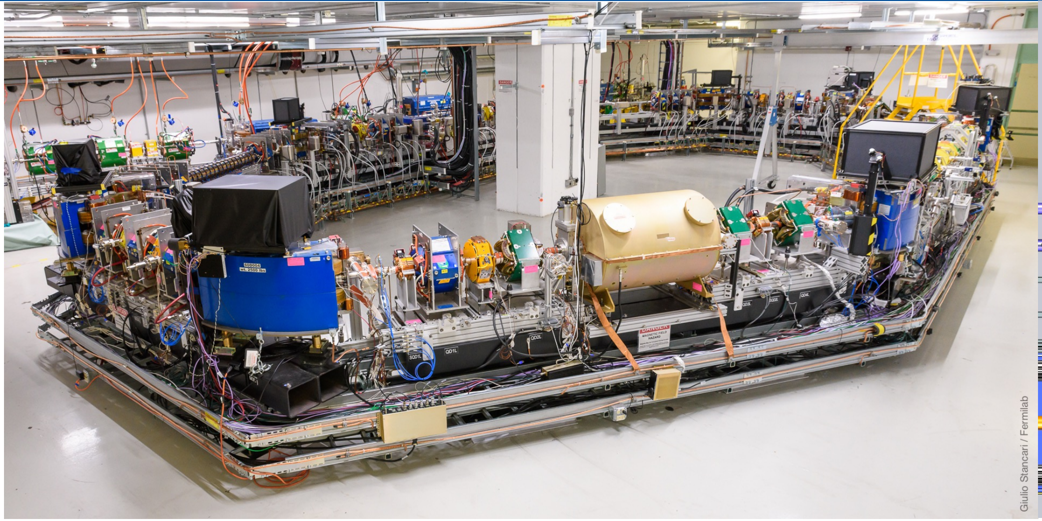
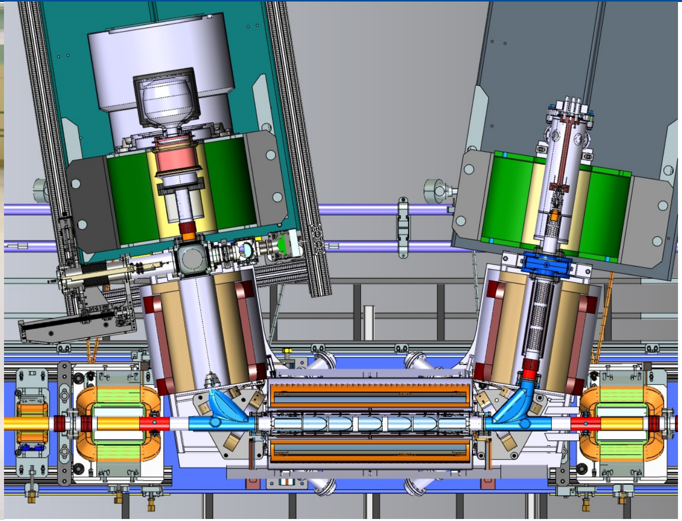




Experiments on Electron Cooling and Intense Space-Charge at IOTA

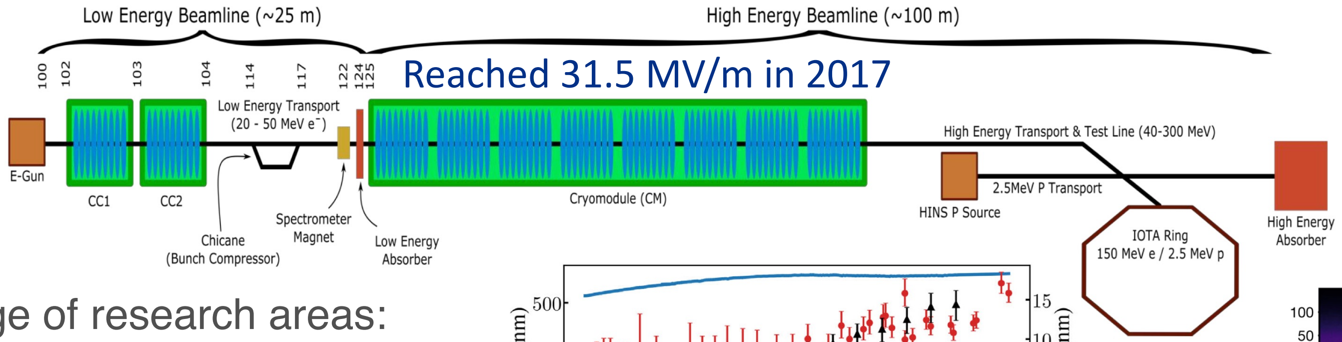
Nilanjan Banerjee, MaryKate Bossard, John Brandt, Young-Kee Kim, Sergei Nagaitsev, Giulio Stancari

In partnership with:

THE UNIVERSITY OF CHICAGO

The FAST/IOTA Facility

The Fermilab Accelerator Science and Technology (FAST) facility and the Integrable Optics Test Accelerator are dedicated to beam physics research.

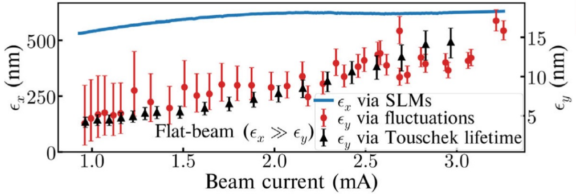


Reached 31.5 MV/m in 2017

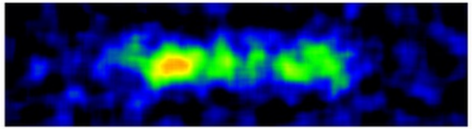
S. Antipov et al, JINST 12 T 03002, 2017.

Operational with 150 MeV electrons since 2018.

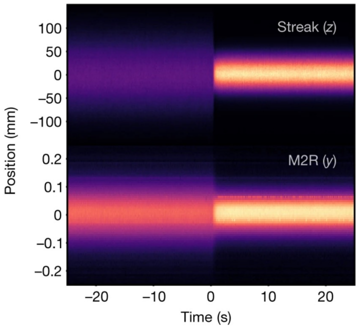
Wide range of research areas: Non-linear integrable optics, optical stochastic cooling, photon generation, single electron dynamics, quantum statistics of undulator radiation, coherent instabilities, electron lens and more!



I. Lobach et al., Phys. Rev. Lett. 126, 134802, 2021.



A. Romanov et al., JINST 16 P12009, 2021.



J. Jarvis, et al., Nature 608, 287–292, 2022.

Overview

1. Motivation and Conceptual Design

2. Beam Experiments using Electron Cooling

3. Hardware Configuration and Status

Motivation and Conceptual Design

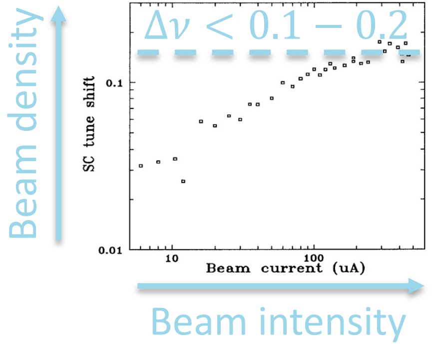
Maximizing Brightness and Intensity

Four grand challenges of accelerator and beam physics facing the community are:

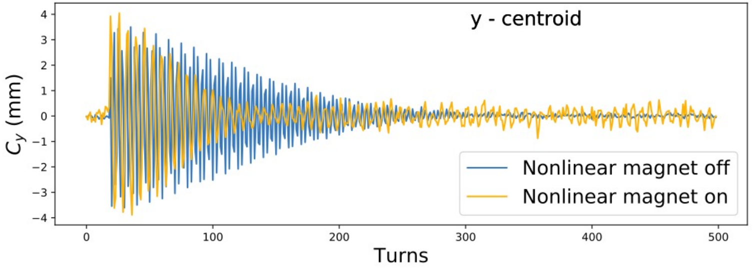
1. Beam Quality: Limited by heating due to Intra-Beam Scattering, resonance crossing, etc.
2. Beam Intensity: Limited by collective effects and particle losses.
3. Beam Control
4. Beam Prediction: Limited by error fields and non-linearity of space-charge.

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

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



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

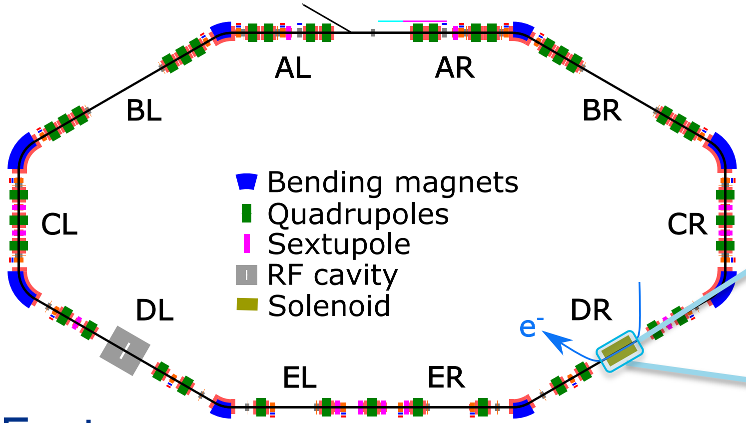


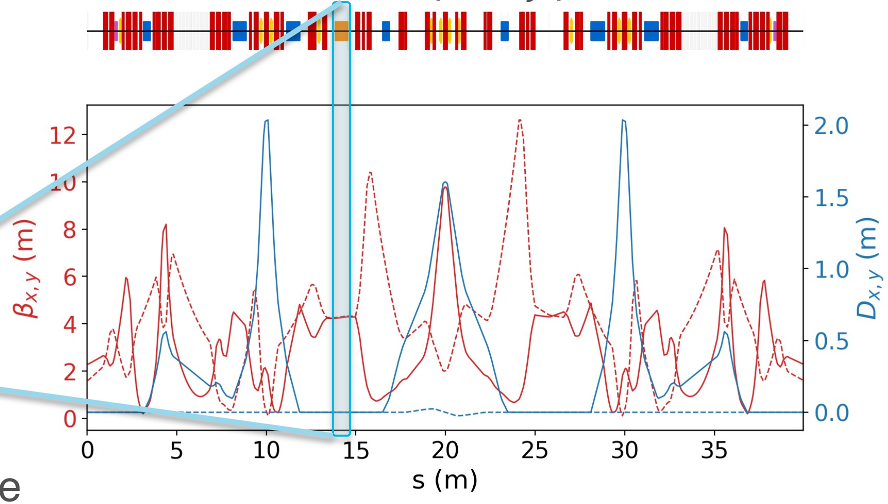
C. C. Hall et al., in Proc. IPAC'19, paper WEPTS070, 2019

How much tune spread is needed to stabilize stored beam?

The Proton Program at IOTA

IOTA will be configured to recirculate 2.5 MeV protons up to $|\Delta\nu_{x,y}|\sim0.5$.





Features:

- All (skew) quadrupoles and correctors are independently controlled.
- Both bunched beam and coasting.
- Single turn injection.
- Electron lens/cooler with length 0.7 m.

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

At the Laslett tune shift of 0.5, Intra-Beam Scattering driven transverse emittance growth time-scale is a few seconds. Electron cooler must compensate for heating.

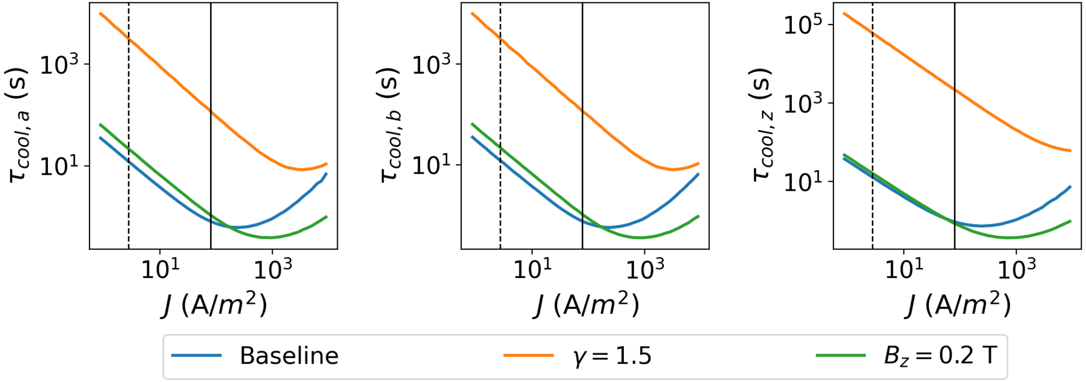
Electron Cooler Design Parameters

Electron beam parameters aim to provide a cooling time of ~ 1 - 10 seconds to control equilibrium emittance at different bunch charges.

We estimated the cooling time using the Parkhomchuk model assuming:

- Flat transverse distribution of the electron beam.
- Ideal solenoid field.
- Matched proton beam.

For the baseline design we chose two electron coolers with an order of magnitude difference in cooling time.

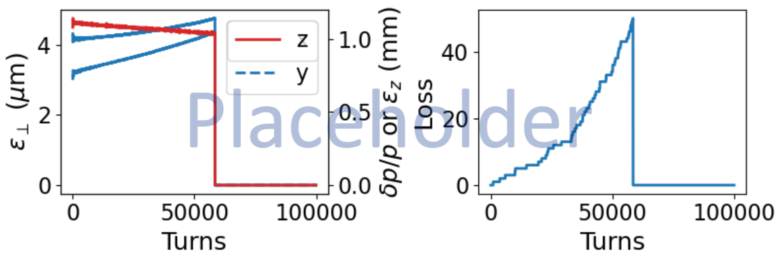


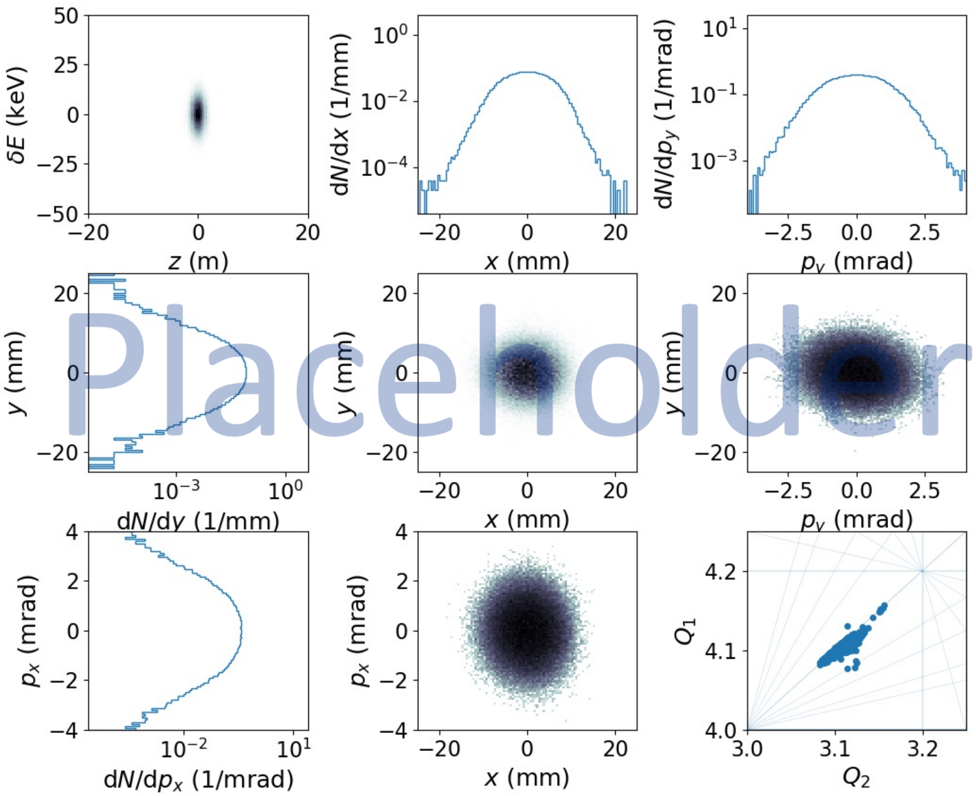
r (mm)	I (mA)	J (A/m²)	$\tau_{cool,a,b,z}$ (s)
18	80	78.6	0.79, 0.74, 0.94
14	1.7	2.76	12, 12, 13

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

Simulations in PyORBIT with Space-Charge and Cooling

We simulate our experiments using a transverse PIC space-charge model and the Parkhomchuk model of cooling.





Agreement with MAD-X?

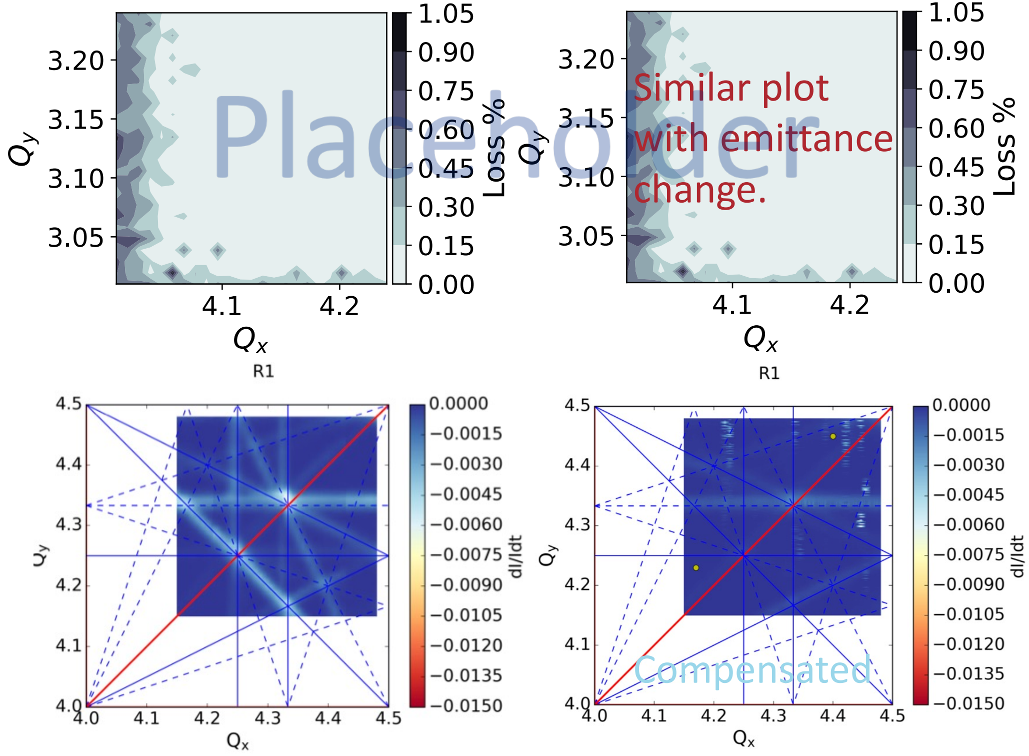
Beam Experiments using Electron Cooling

Optimization of the Bare Lattice to Maximize Tune Shift

What is the maximum space-charge tune shift of stored beam we can achieve?

1. Optimizing the linear lattice configuration, including tunes and transverse coupling.

2. Compensating for specific resonance driving terms using sextupoles.

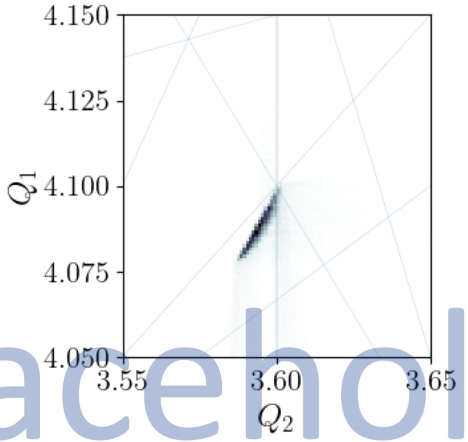


F. Asvesta *et al.*, in *Proc. IPAC'22*, pp. 2056-2059, 2022.

Working Point Evolution to Offset Tune Shift due to Cooling

As the beam cools, the entire tune footprint moves downwards in the tune plane and crosses resonances.

Move the bare lattice tune in sync with the space-charge tune shift.



Placeholder

Interplay of Space-Charge and Coherent Instabilities

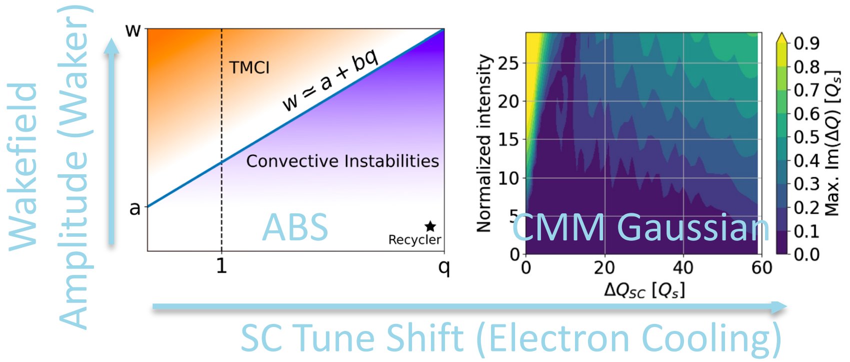
How are coherent instabilities affected by space-charge? The 2.5 MeV protons at IOTA provide strong space-charge but weak impedance.

Measure instability growth rate and head-tail amplification in the parameter space using:

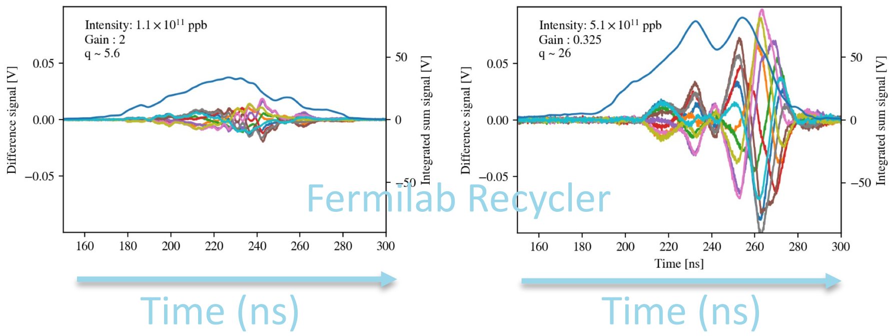
- Controlled wakefields generated using the wake-building feedback system.

  R. Ainsworth et al., in Proc. HB'21, pp. 135-139, 2021.
  O. Mohsen et al., in Proc. NAPAC'22, pp. 124-127, 2022.

- Electron cooling to enforce an equilibrium phase-space distribution, independent of bunch charge.



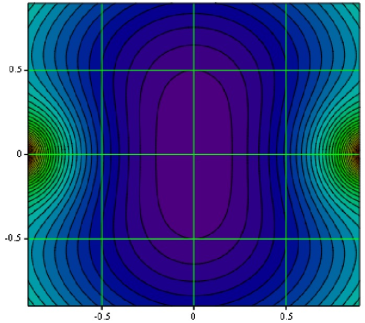
ABS: A. Burov, Phys. Rev. Accel. Beams 22, 034202, 2019.
CMM: X. Buffat et al., Phys. Rev. Accel. Beams 24, 060101, 2021.



Tunable Landau Damping with Space-Charge

Non-linear Integrable Optics enable large amplitude-dependent tune spreads while keeping single-particle dynamics stable.

Flagship project for the Integrable Optics Test Accelerator!



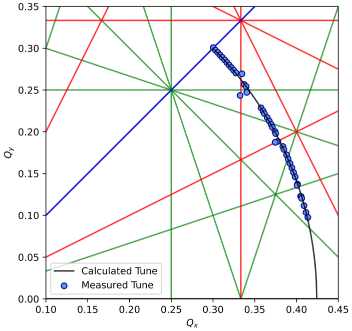
V. Danilov and S. Nagaitsev, Phys. Rev. ST Accel. Beams 13, 084002, 2010.
S. Antipov et al, JINST 12 T03002, 2017.

Electron cooling enables:

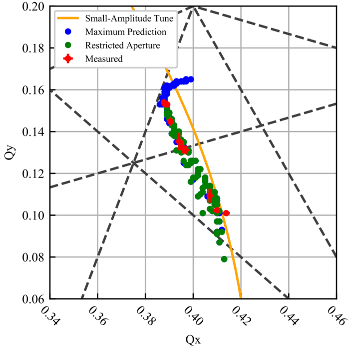
1. Single particle dynamics experiments with pencil beam and low energy spread.

   A. Valishev et al., in Proc. IPAC'21, pp. 19-24, 2021.
   N. Kuklev et al., in Proc. IPAC'21, pp. 1964-1967, 2021.

2. Measurement of minimum tune spread required to mitigate coherent instabilities with space-charge.



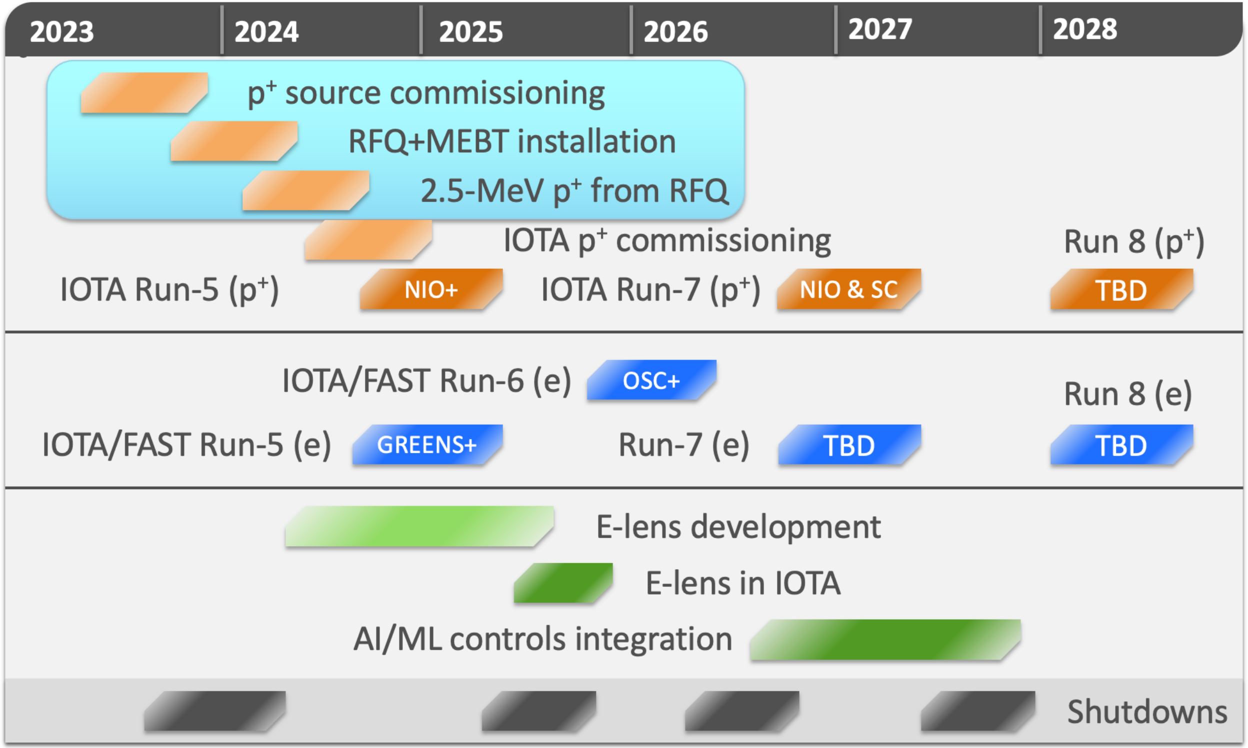
J. Wieland et al., in Proc. IPAC'23, pp. 3230-3232, 2023.



S. Szustkowski, PhD Thesis, Northern Illinois University, 2020.

Hardware Configuration and Status

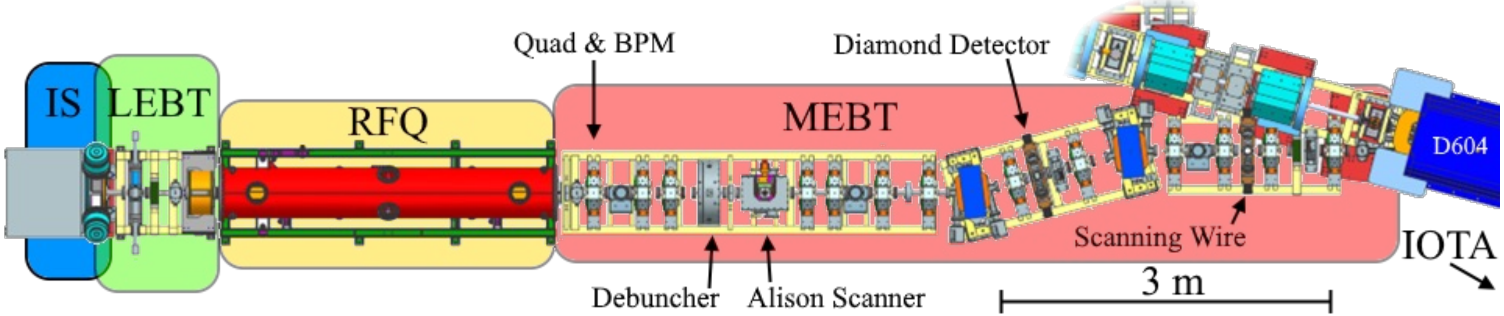
Electron Cooling in 2025



D. Edstrom, IOTA/FAST department meeting, 2023.

2.5 MeV Proton Injector and IOTA RF Configuration

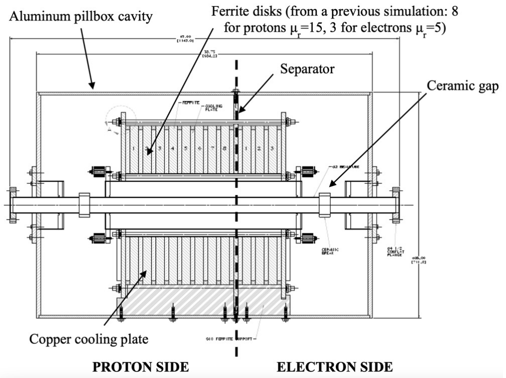
Injector beamline capable of delivering short pulses of 2.5 MeV protons at 1 Hz.

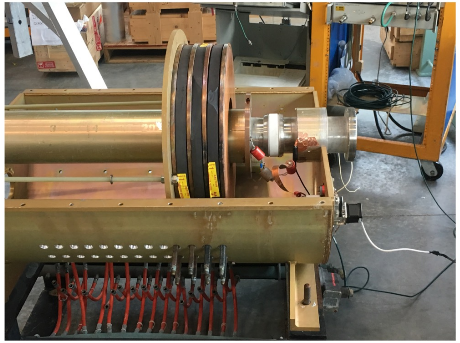


Broadband normal conducting RF system with two gaps, but only 30 MHz gap installed.

h	f(MHz)	V_{min}(V)	$Q_s(V = 1\ \mathrm{kV})$
4	2.187	72	0.01
56	30.62	1000	0.04

E. Prebys, Beams Document 4837-v1, Fermilab, 2015.





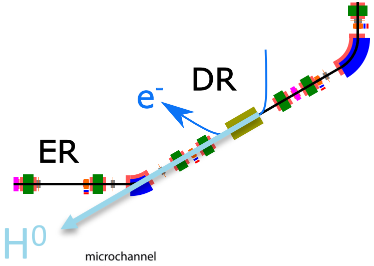
G. M. Bruhaug and K. Carlson, in Proc. NAPAC'16, pp. 432-434, 2016.

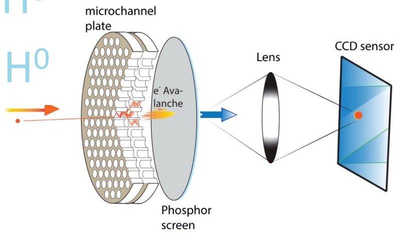
Proton Beam Diagnostics

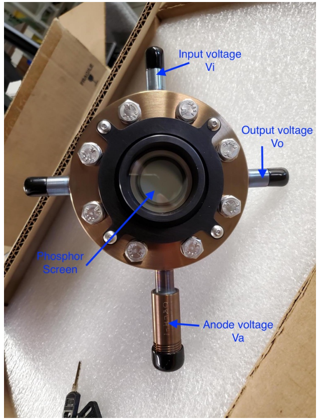
Injector: Toroid, Scanning wire, Allison scanner

Storage Ring:

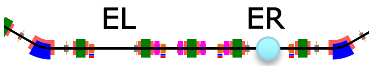
- DCCT: Measure injection efficiency and beam lifetime.
- Beam Position Monitors
  - Use LOCO to configure lattice.
  - Use turn-by-turn centroid positions of pencil beams to measure single-particle dynamics.
- Neutralization monitor
  - Measure equilibrium transverse profile with cooling.
- Ionization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



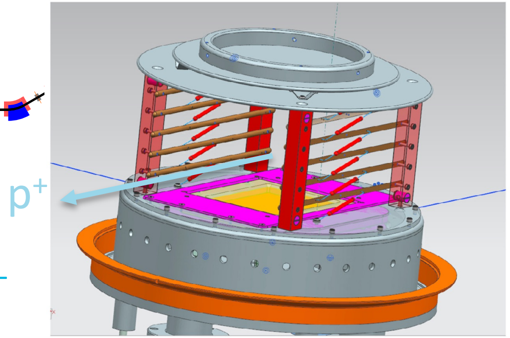




Bongho Kim et al., NIM A, 899, 22-27, 2018.



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



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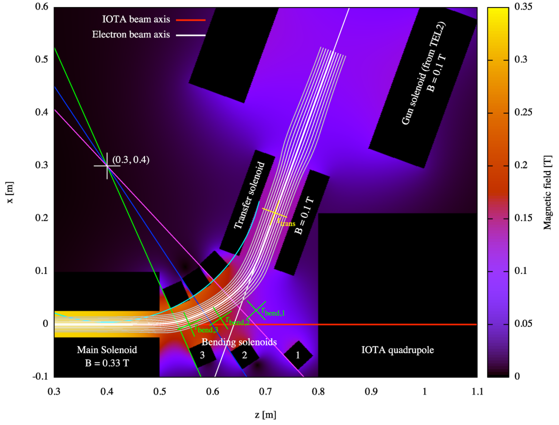
Fermilab

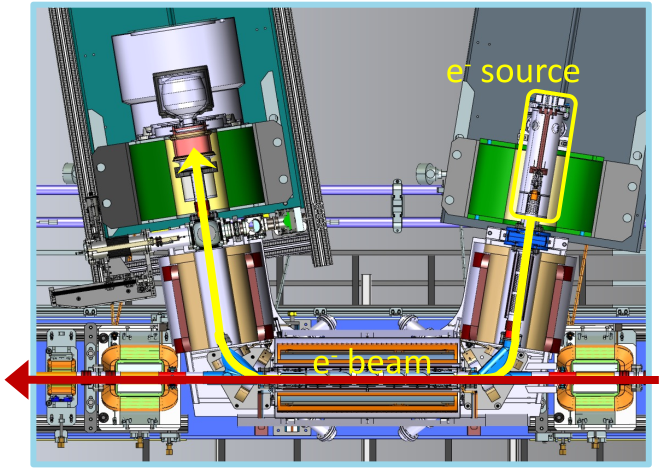
Electron Lens Setup

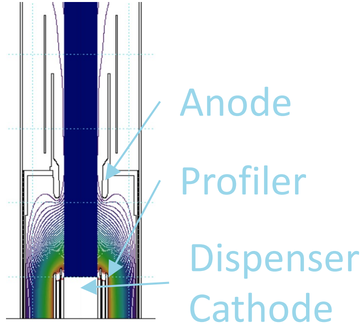
Conceptual design of all parts exist but engineering design needs to be finalized.



Electron Tracking

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



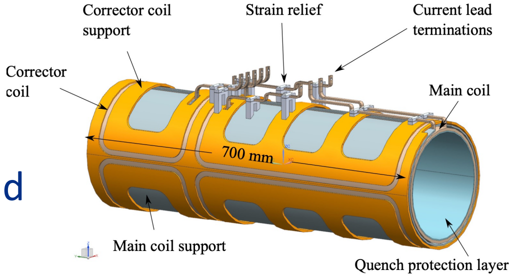


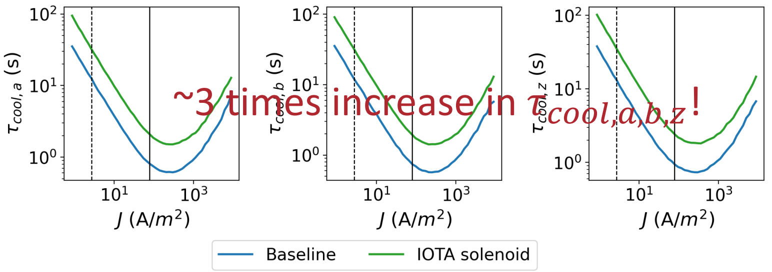
Flat beam gun

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

Conduction cooled SC solenoid

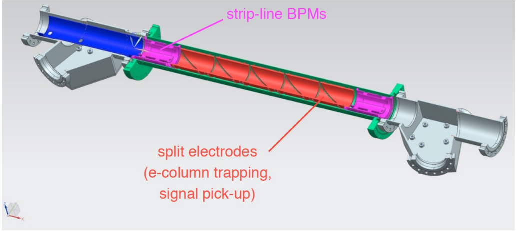
R.C. Dhuley *et al* 2021 *JINST* **16** T03009



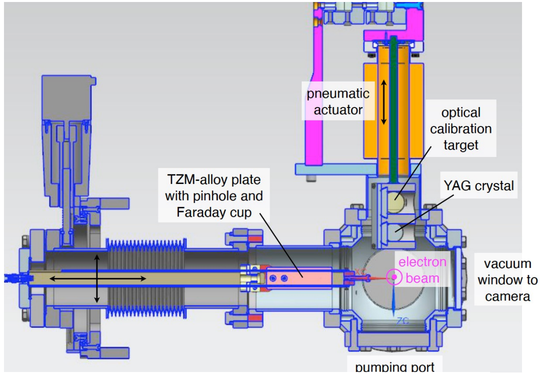


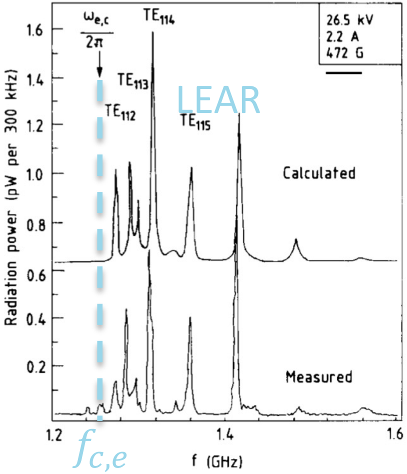
Electron Beam Diagnostics

- Toroids: Measure beam current and losses.
- Stripline BPMs: Align with the proton beam.
- Profile measurement: Measure transverse profile.
- Recombination Monitor: Optimize cooling performance.
- Cyclotron Emission Monitor: Estimate electron density and temperature.

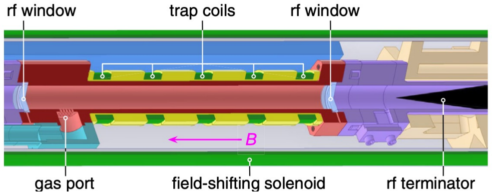


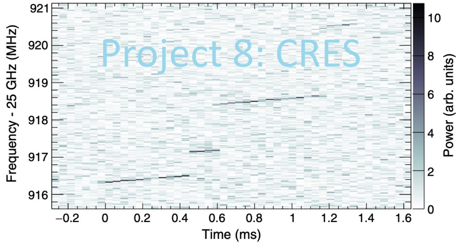
G. Stancari et al, *JINST* **16** P05002, 2021





C. Habfast, PhD thesis, Karlsruhe U., KFK-4188, 1987.





A. Ashtari Esfahani et al., Phys. Rev. Lett. 131, 102502, 2023.
D. M. Asner et al., Phys. Rev. Lett. 114, 162501, 2015.

Conclusion

Acknowledgements

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

Thank You!