

Space Charge Measurement and Compensation Studies: A-2 Session Lead Talk

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Overview

- Session Themes
- Research Opportunities at IOTA
- Session Contributions and Discussion Topics



Main Session Themes

Beam Measurements

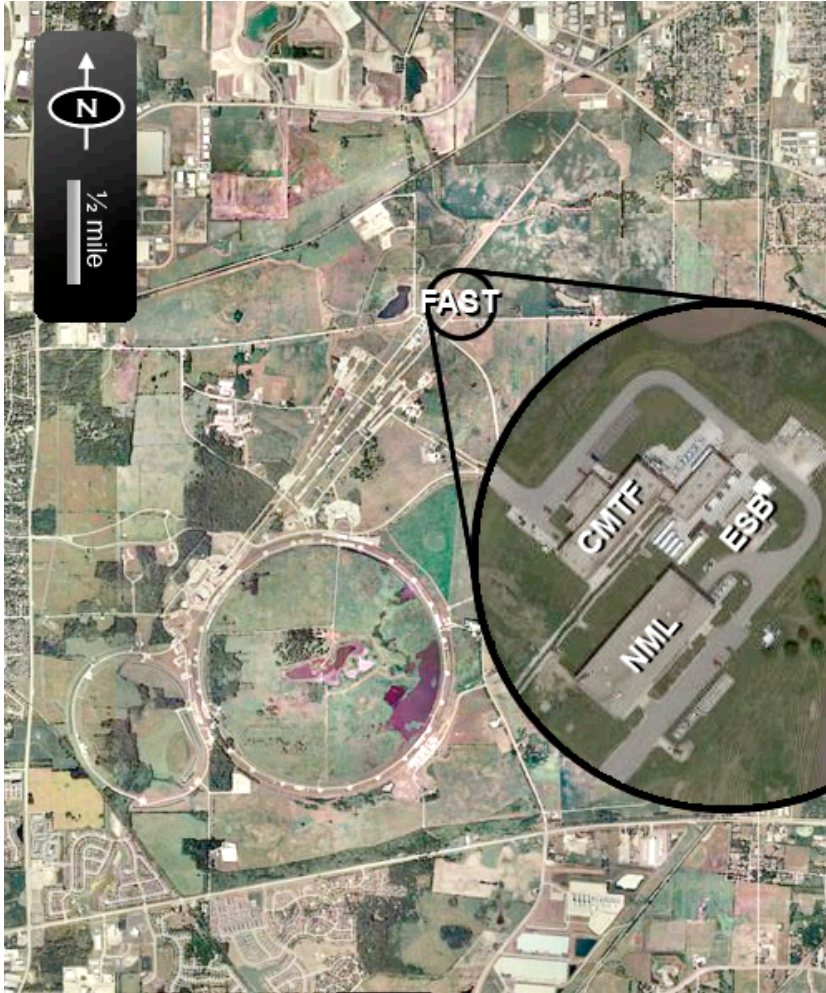
What are the key physical quantities? What experimental methods are used? How do we quantify uncertainties?

Space-Charge Compensation

What methods are viable? How do we model the physics? What are the main achievements?

IOTA and the FAST Facility at Fermilab

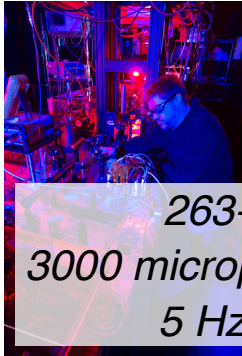
The Integrable Optics Test Accelerator (IOTA) is part of the Fermilab Accelerator Science and Technology (FAST) facility, located on the north side of the Fermilab campus





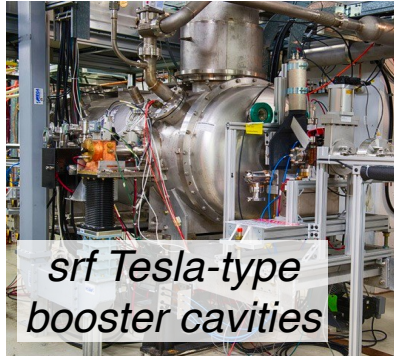
Overview of the IOTA/FAST Facility at Fermilab

Photoinjector



263-nm laser
3000 micropulses @ 3 MHz
5 Hz rep. rate

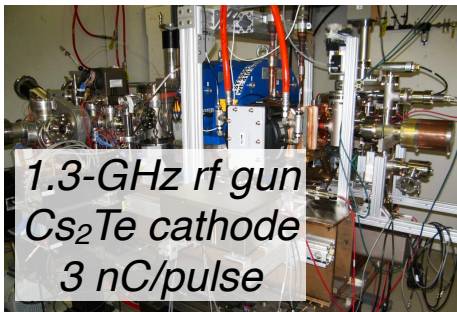
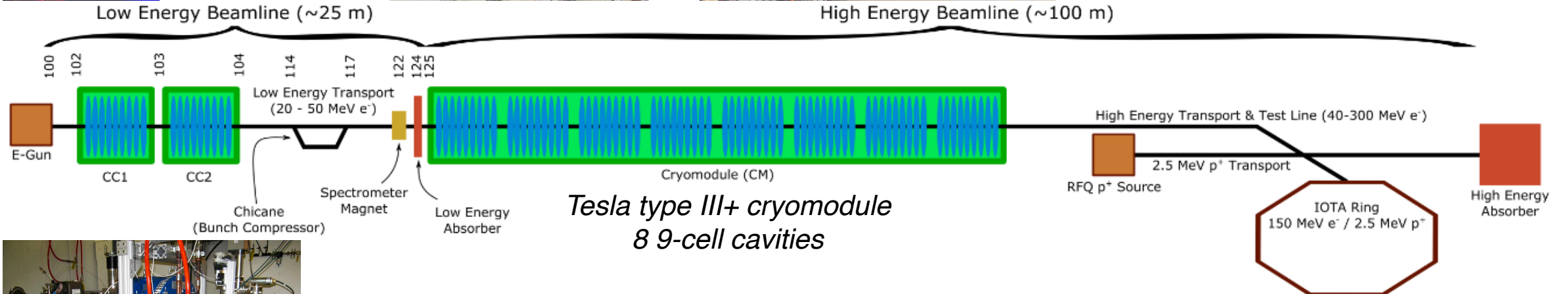
Superconducting Linac



srf Tesla-type
booster cavities

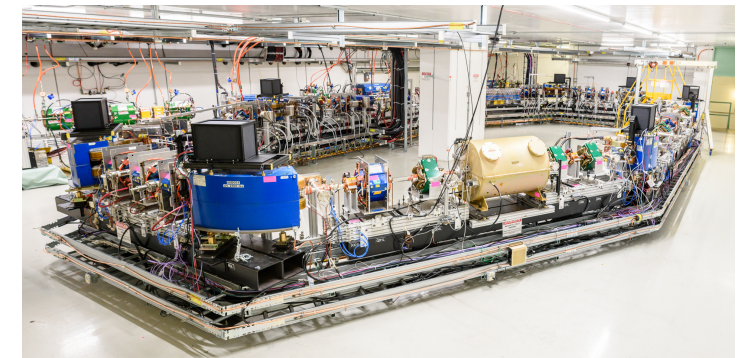


High Energy Beamline (~100 m)



1.3-GHz rf gun
Cs₂Te cathode
3 nC/pulse

IOTA Storage Ring



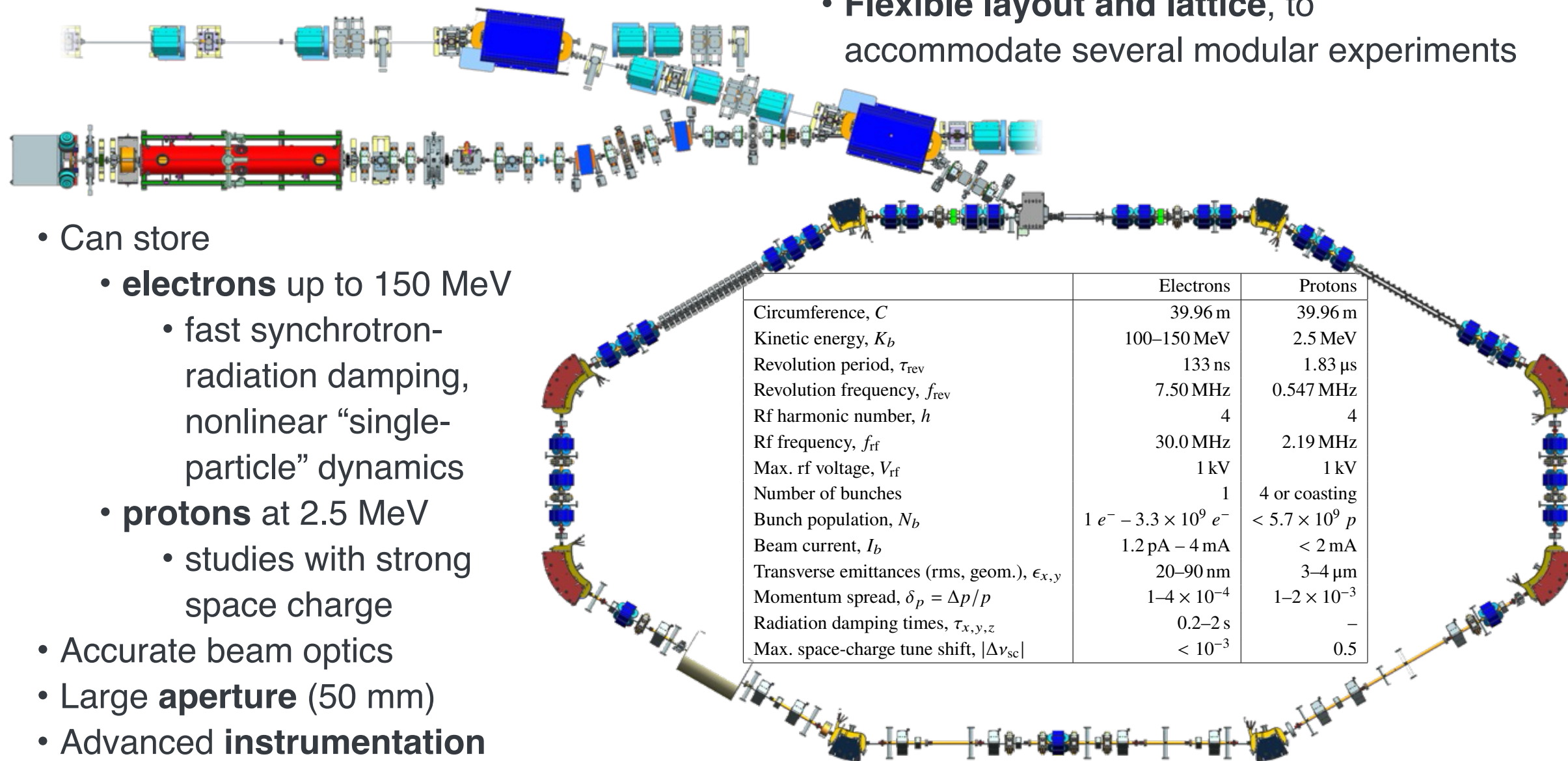
Antipov et al., JINST **12**, T03002 (2017)

Broemmelsiek et al., New J. Phys. **20**, 113018 (2018)



The IOTA Storage Ring

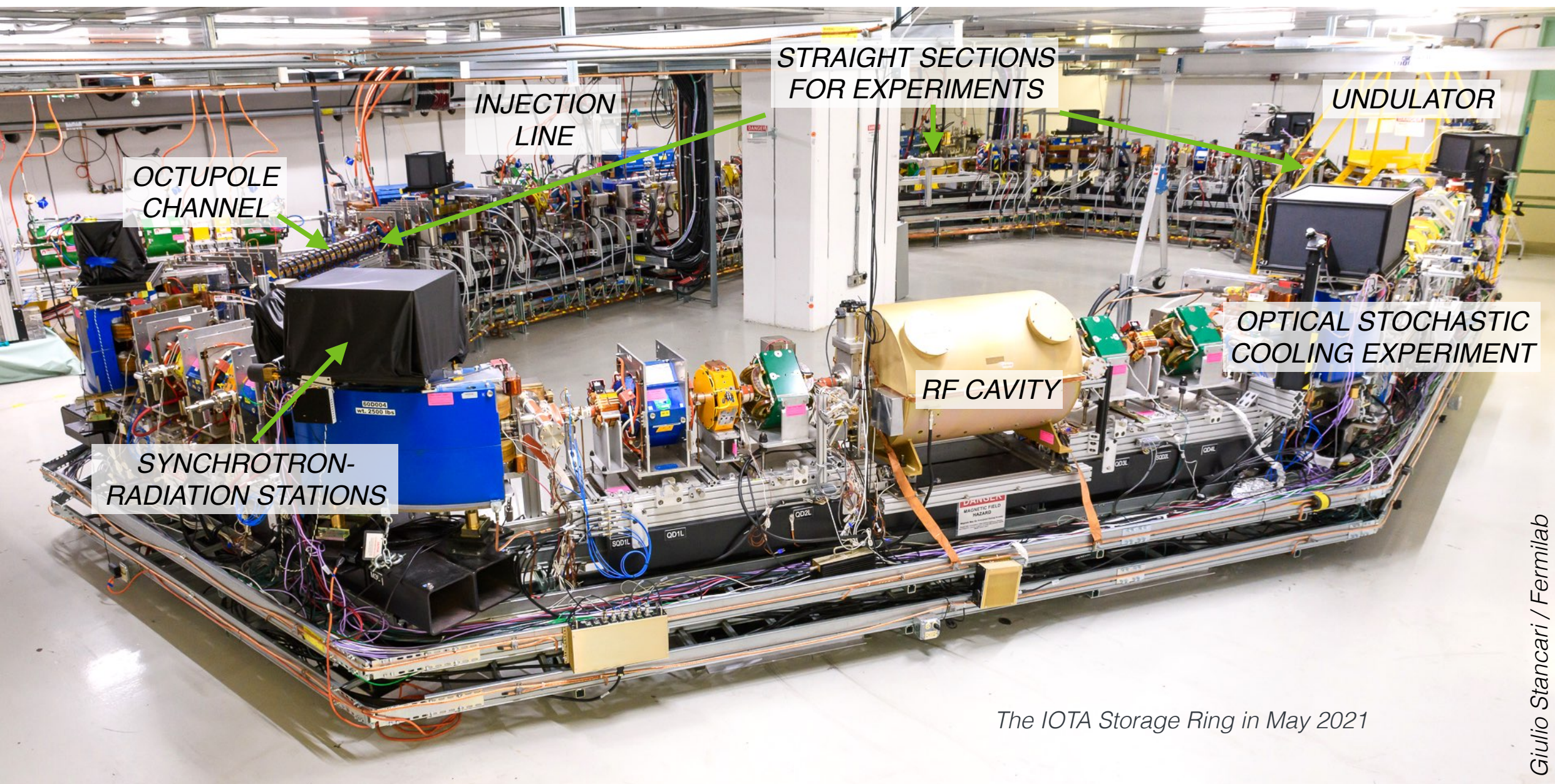
- **Dedicated to beam physics research**
- **Flexible layout and lattice**, to accommodate several modular experiments



- Can store
 - **electrons** up to 150 MeV
 - fast synchrotron-radiation damping, nonlinear “single-particle” dynamics
 - **protons** at 2.5 MeV
 - studies with strong space charge
- Accurate beam optics
- Large **aperture** (50 mm)
- Advanced **instrumentation**



The IOTA Storage Ring

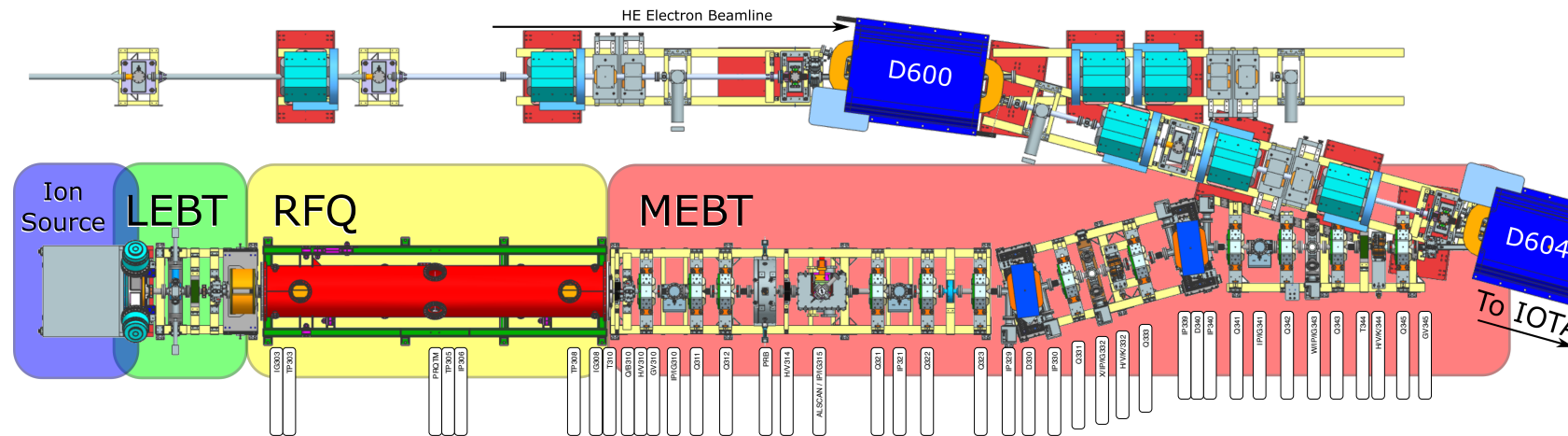


The IOTA Storage Ring in May 2021



The IOTA Proton Injector

Key facility upgrade for the research program on space-charge-dominated beams

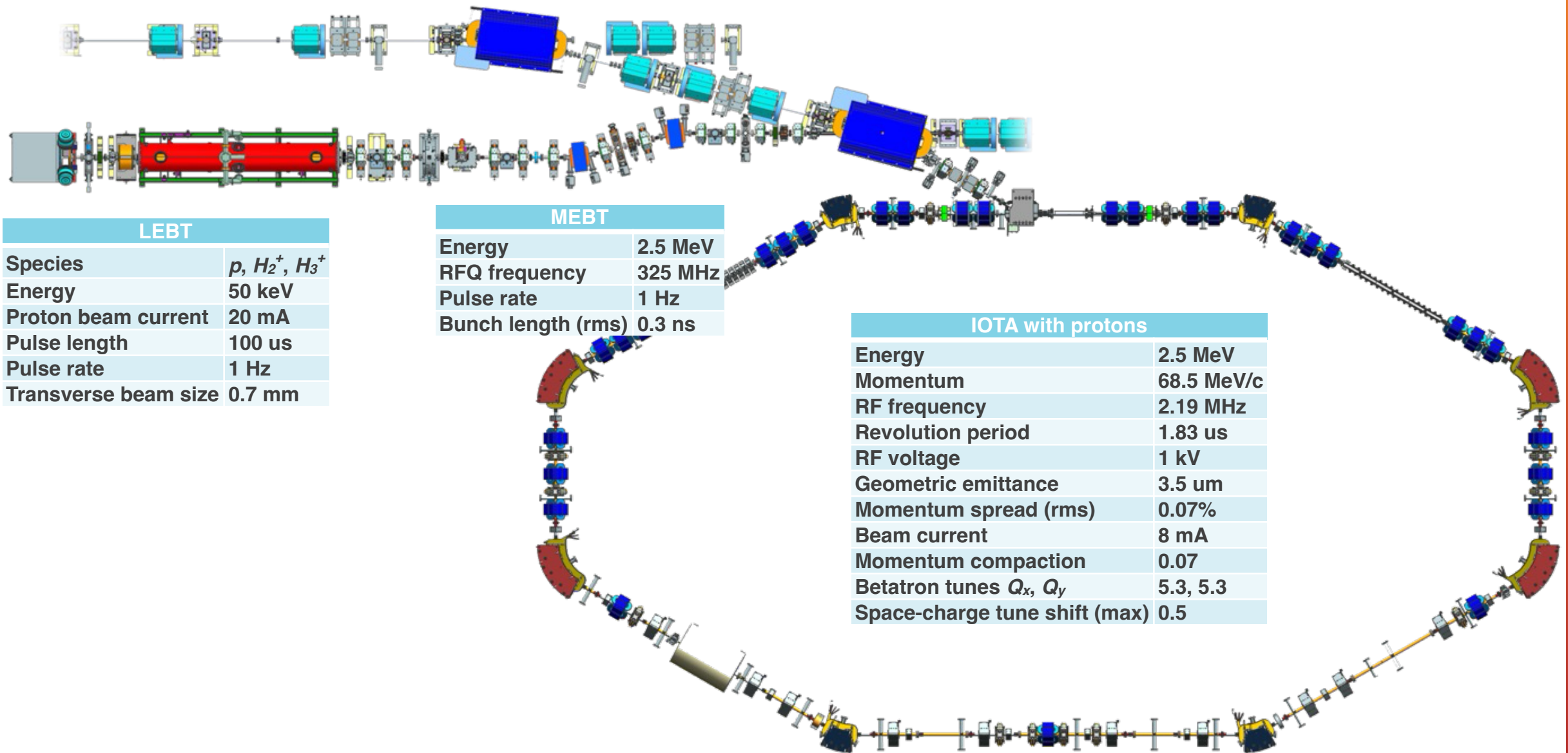


Construction completed: Sep 2025
First circulating protons in IOTA: Jan 2026
Commissioning under way



A. Romanov et al., IPAC 2026

IOTA Proton Injector Parameters



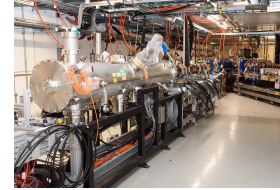
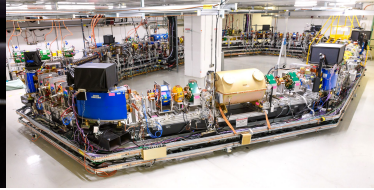
LEBT	
Species	p, H_2^+, H_3^+
Energy	50 keV
Proton beam current	20 mA
Pulse length	100 μ s
Pulse rate	1 Hz
Transverse beam size	0.7 mm

MEBT	
Energy	2.5 MeV
RFQ frequency	325 MHz
Pulse rate	1 Hz
Bunch length (rms)	0.3 ns

IOTA with protons	
Energy	2.5 MeV
Momentum	68.5 MeV/c
RF frequency	2.19 MHz
Revolution period	1.83 μ s
RF voltage	1 kV
Geometric emittance	3.5 μ m
Momentum spread (rms)	0.07%
Beam current	8 mA
Momentum compaction	0.07
Betatron tunes Q_x, Q_y	5.3, 5.3
Space-charge tune shift (max)	0.5



Timeline



Run 1 Aug 15 - Apr 3

Run 4 Apr 1 - Oct 23

Run 2 Nov 27 - Mar 21

Nov 4 - Jun 14
Run 5p

Run 3 Oct 8 - Aug 29

Run 6e

Jul 31 ♦ **IOTA construction completed**

Sep 30 ♦ **Proton injector completed**

Mar 20 ♦ **COVID-19 lockdown**

Jan 28 ♦ **Circulating protons in IOTA**

Apr 20 ♦ **OSC observed**

The machine runs beam a few months per year

Experimental runs are interleaved with shutdowns for maintenance and installations

Commissioning of protons in IOTA in 2026



Mission of the Facility and of the Research Program

- **Address** the **challenges** posed by **high-intensity** and **high-brightness machines**, such as instabilities and losses
- Carry out **research in beam physics**: space charge, cooling, phase-space control, radiation generation, ...
- **Test new technologies**: equipment, diagnostics, controls, software, operations
- Provide **education** and **training** for scientists, engineers and technicians

Small accelerators with flexible apparatus for short- to medium-term research are a precious asset for the Fermilab program and for the community in general

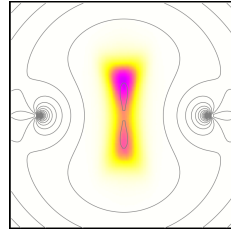
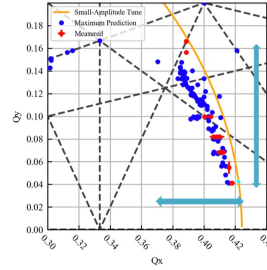
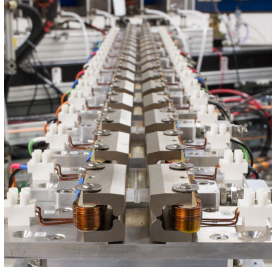
Supported mainly by

- the **high-energy-physics community** at large, through the US DOE HEP General Accelerator R&D (GARD) sub-program
- **external collaborators** and research groups at labs and universities



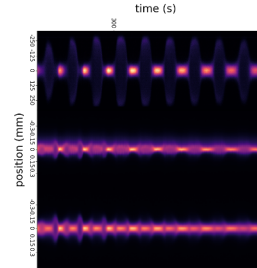
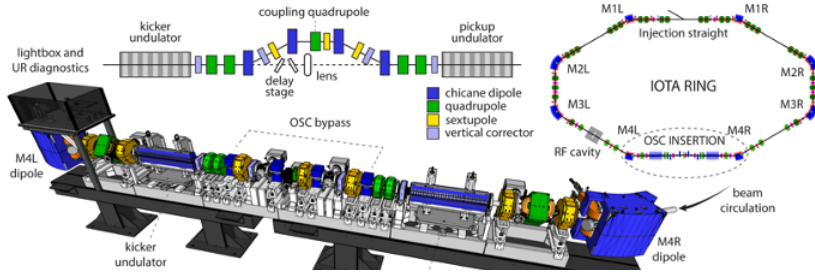
Selected IOTA Research Highlights

Nonlinear Integrable Optics



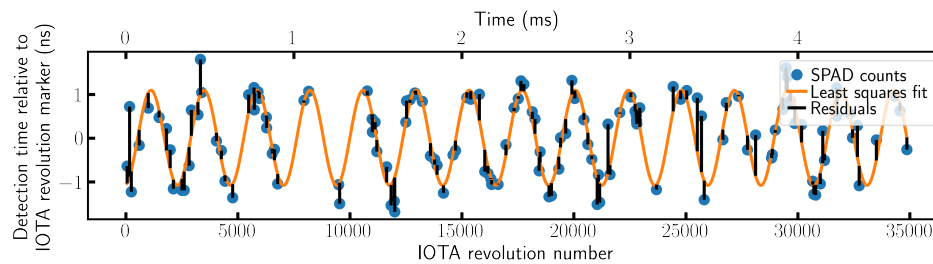
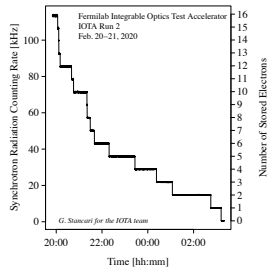
Valishev et al., IPAC 2021
Kuklev, PhD Thesis, U. Chicago (2021)
Szustkowski, PhD Thesis, NIU (2020)
Wieland et al., IPAC 2024
Wieland, PhD Thesis, MSU (2026)
Wieland et al., arXiv:2607.21863 (2026)

Optical Stochastic Cooling



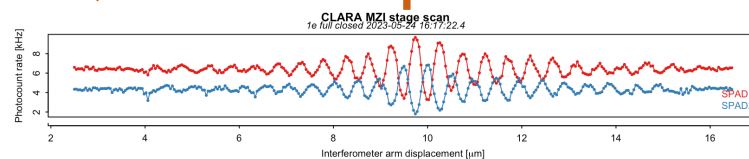
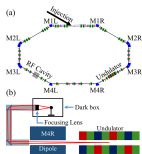
Jarvis, Lebedev, Romanov et al.,
Nature **608**, 287 (2022)

Single-Electron Tracking



Stancari, FERMILAB-FN-1116-AD (2020)
Romanov et al., JINST **16**, P12009 (2021)
Lobach et al., JINST **17**, P02014 (2021)
Romanov et al., IPAC 2024; NAPAC 2025

Classical and Quantum Properties of Radiation

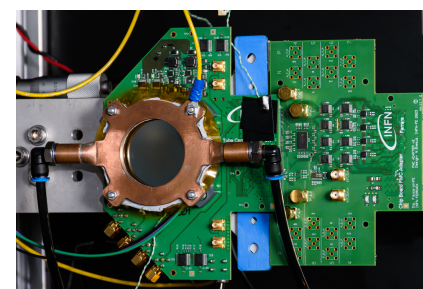
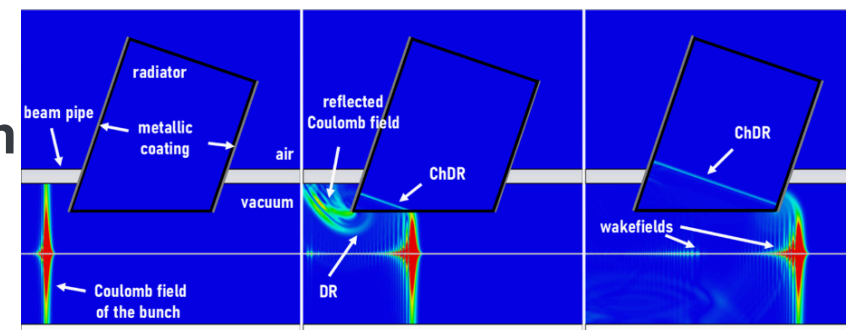
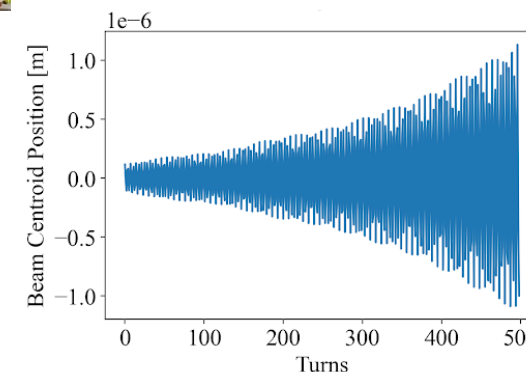


Lobach et al., PRAB **23**, 090703 (2020)
Lobach et al., PRAB **24**, 040701 (2021)
Lobach et al., PRL **126**, 134802 (2021)
Lobach, PhD Thesis (2021)
Stancari et al., IPAC 2024 and 2026



Near-Term Plans: Experiments with Electrons

- characterize **new nonlinear magnet** in preparation for experiments with protons (NIO)
[Fermilab, UChicago]
- measure **stability diagrams** through **controlled instability thresholds** to evaluate nonlinear lattices (NIOLD)
[Fermilab, UChicago]
- measure **Cherenkov diffraction radiation** with a known number of electrons as **non-destructive longitudinal beam diagnostics** for light sources and colliders (CheDiRa)
[CERN, Fermilab]
- commission **new single-photon imaging detector** with **high spatial and temporal resolution** (Pixyte)
[INFN, Fermilab, CERN]



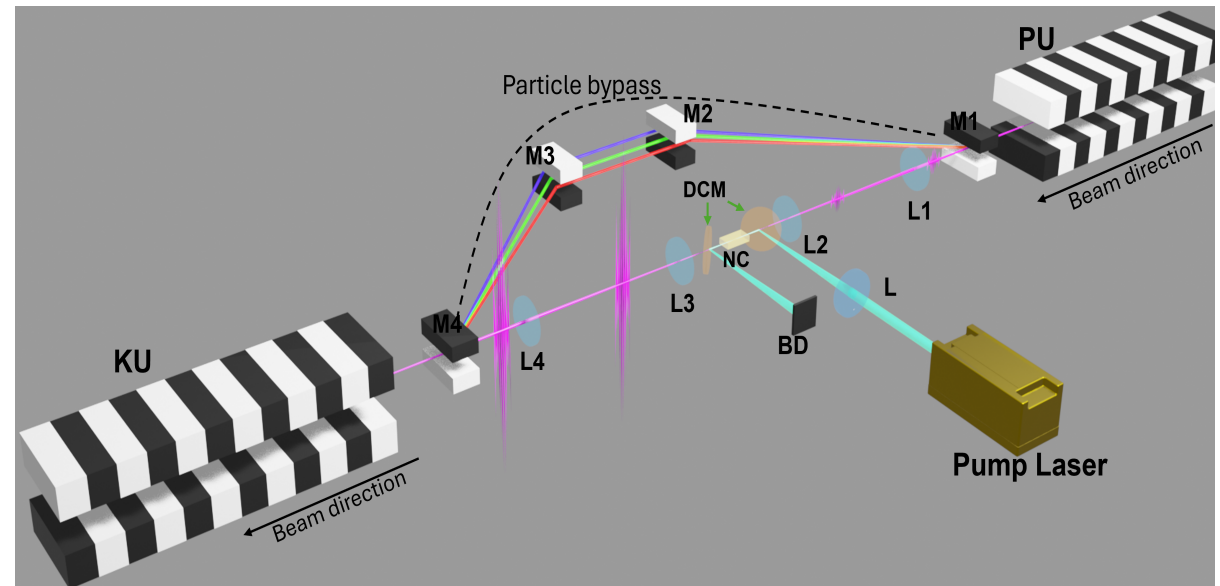


Near-Term Plans: Experiments with Electrons

Preparations for **optical stochastic cooling with amplification**:
parametric amplifier, specialized optics, magnetic lattices

- Dramatically reduce cooling times
- Test new types of beam manipulation, such as optical stochastic crystallization (OSX) for steady-state micro-bunching, as a unique next-generation light source

Jarvis et al., ECA Grant
Wallbank and Jarvis, FEL 2024; arXiv:2409.06619
Mondal et al., NAPAC 2025





Upcoming Research on Space Charge with Protons in IOTA

Prerequisite: What **experimental conditions** are achievable? **Proton dynamics scenarios** in IOTA

Banerjee, Romanov, Stancari and Wallbank, JINST **21**, T04001 (2026)

Does **nonlinear integrable optics** enable higher intensities?

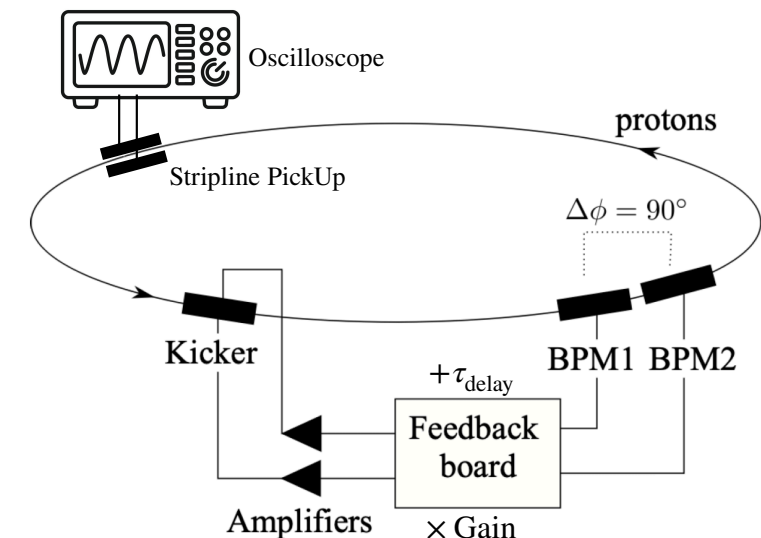
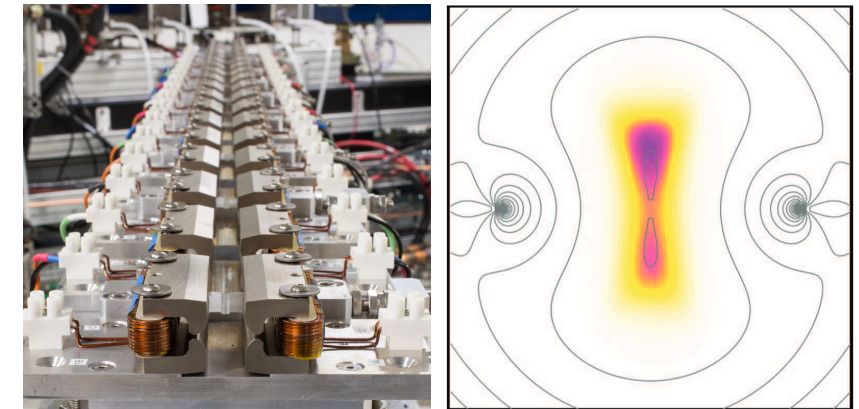
[Wieland, Romanov, Valishev et al.]

Measurement of **collective instability thresholds** and the role of convective instabilities, using feedback to mimic impedance

[Ainsworth, Gonzalez-Ortiz et al.]

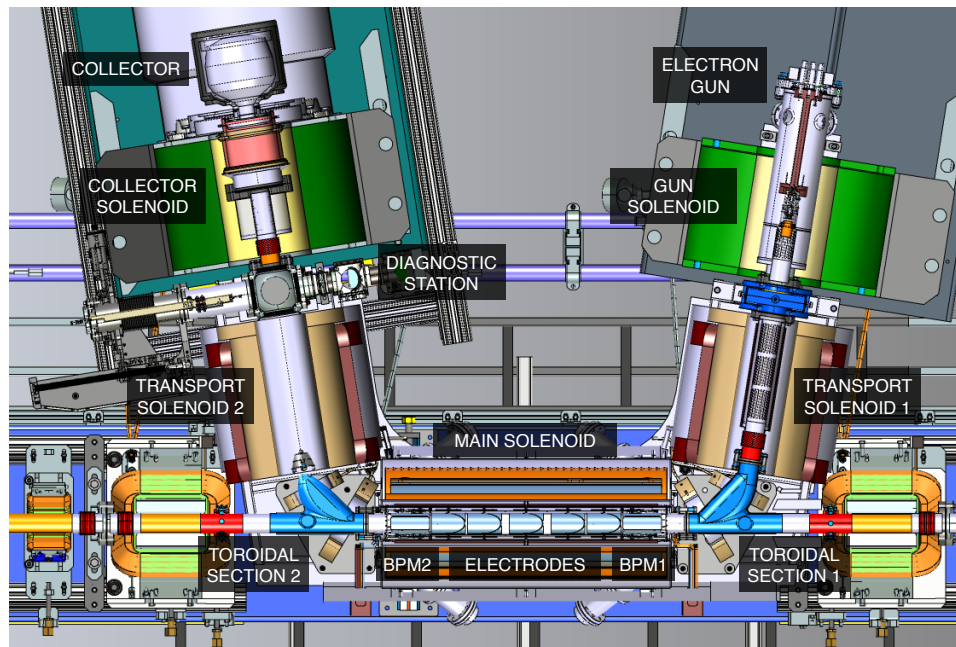
Can **space-charge-induced Landau damping** mitigate transverse coherent instabilities?

[Oeftiger, Straniero et al.]





Upcoming Research on Space Charge with Protons at IOTA

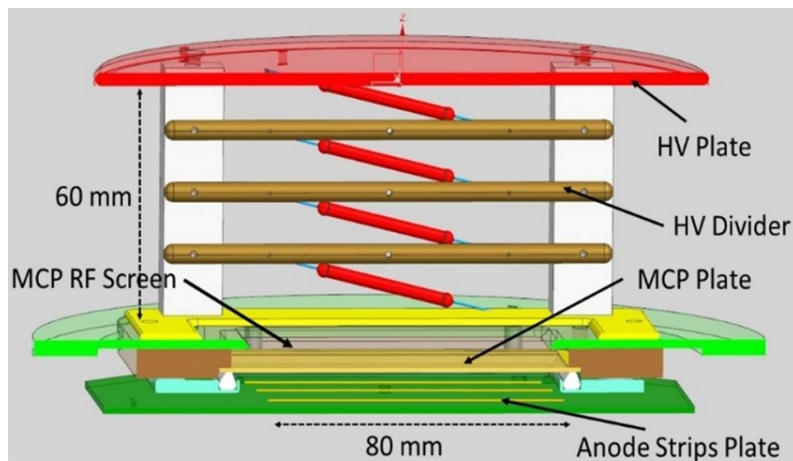


Can **electron lenses** be used for **nonlinear integrable optics** and **space-charge compensation**?

[Stancari et al., JINST **16**, P05002 (2021); Park et al., JINST **16**, P03048 (2021)]

Development of new fast and accurate **beam diagnostics**: ionization profile monitors, diamond beam loss monitors, gas-sheet profile monitors, etc.

[Piekarz et al., JINST **20**, T10007 (2025); Warner et al.; Szustkowski et al.]



Improve **numerical modeling** of beam dynamics with space charge [Banerjee, Mitchell, Shatilov, Wieland et al.]

New ideas welcome!

IOTA/FAST web site
fast.fnal.gov

IOTA/FAST Scientific Committee
cdcv.s.fnal.gov/redmine/projects/ifsc/wiki/

BeamNetUS
beamNetUS.org



Collaboration Meeting 2024
indico.fnal.gov/e/62181

Special Issue of the Journal of Instrumentation
iopscience.iop.org/journal/1748-0221/page/extraproc90



IOTA/FAST Scientific Committee (ISC)

Overview

Activity

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Proposing an experiment at IOTA/FAST

Proposal submission guidelines: Beams-doc-7363

Proposal template PDF LaTeX

Note on data storage options for IOTA/FAST experiments: Beams-doc-8245

Presentation given at the IOTA/FAST Collaboration Meeting (March 2024)

Presentation given at the IOTA/FAST Collaboration Meeting (October 2021)

Presentation given at the IOTA/FAST Collaboration Meeting (June 2020)

Presentation given at the IOTA/FAST Collaboration Meeting (June 2019)

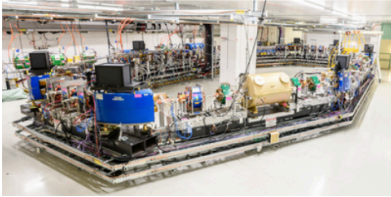


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Proposing an experiment at IOTA/FAST

Contacts

Experiments

Future Runs

IOTA with protons

IOTA with electrons

FAST Linac

Run 6e (August - December 2026)

IOTA

FAST Linac

Run 5p (4 November 2025 - May 2026)

IOTA

Run 4 (1 April 2022 - 23 October 2023)

IOTA

FAST Linac

Run 3 (8 Oct 2020 - 29 Aug 2021)

IOTA

FAST Linac

Run 2a (Nov 27, 2019 - Dec 20, 2019) and Run 2b (Feb 17, 2020 - Mar 21, 2020)

IOTA

FAST Linac

Run 1 (Aug 15, 2018 - Apr 3, 2019)

IOTA

FAST Linac

Attachments

Contacts

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Journal of Instrumentation

Accelerator Science and Technology Research at the Fermilab
Integrable Optics Test Accelerator

Editors

Giulio Stancari and Alexander Valishev from Fermi National Accelerator Laboratory

Space Charge 2026 Oxford 30 Sep 2026

FERMI NATIONAL ACCELERATOR LABORATORY

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Session Contributions

Cristhian Gonzalez-Ortiz (Fermilab, USA)

Experimental Studies of Space Charge and Collective Beam Instabilities with the Fermilab Recycler Waker System

Markus Kirk (GSI/FAIR, Germany)

Plans for Space-Charge Compensation with Electron Lenses at GSI

Yu Du (IMP, China)

Circumventing Space Charge: Toward Transport-Free Tomography of High-Dimensional Phase Space in High-Intensity Linacs

Ippei Yamada (J-PARC, Japan)

Emittance Growth Under Space Charge Neutralization Condition in Low-Energy Beam Transport



Additional Discussion Topics

What interesting **scientific or technological questions could be studied at IOTA**?

How do we better **quantify prediction uncertainties** of existing space-charge models? For instance, systematics due to approximations and assumptions. How do we improve our practices to include uncertainty quantification in calculations?

IOTA can store a **known small number of electrons**. Could one learn something interesting or useful about **scattering** and **space charge** from experiments with 1, 2, 3, ..., 100 electrons?

Are there good examples of **dimensional analysis** and **dynamical similarity** used in space-charge physics to deduce scaling laws or predictions? [E.g., constant perveance of space-charge-limited e-gun vs. scaling of linear dimensions]

Can **analogue systems** and **computing** assist in studying complex systems where analytical or numerical solutions are hard to obtain?

...**[your ideas]**...

*Thank you for your attention and
for your contributions to the Discussion!*



Fermi*FORWARD*



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