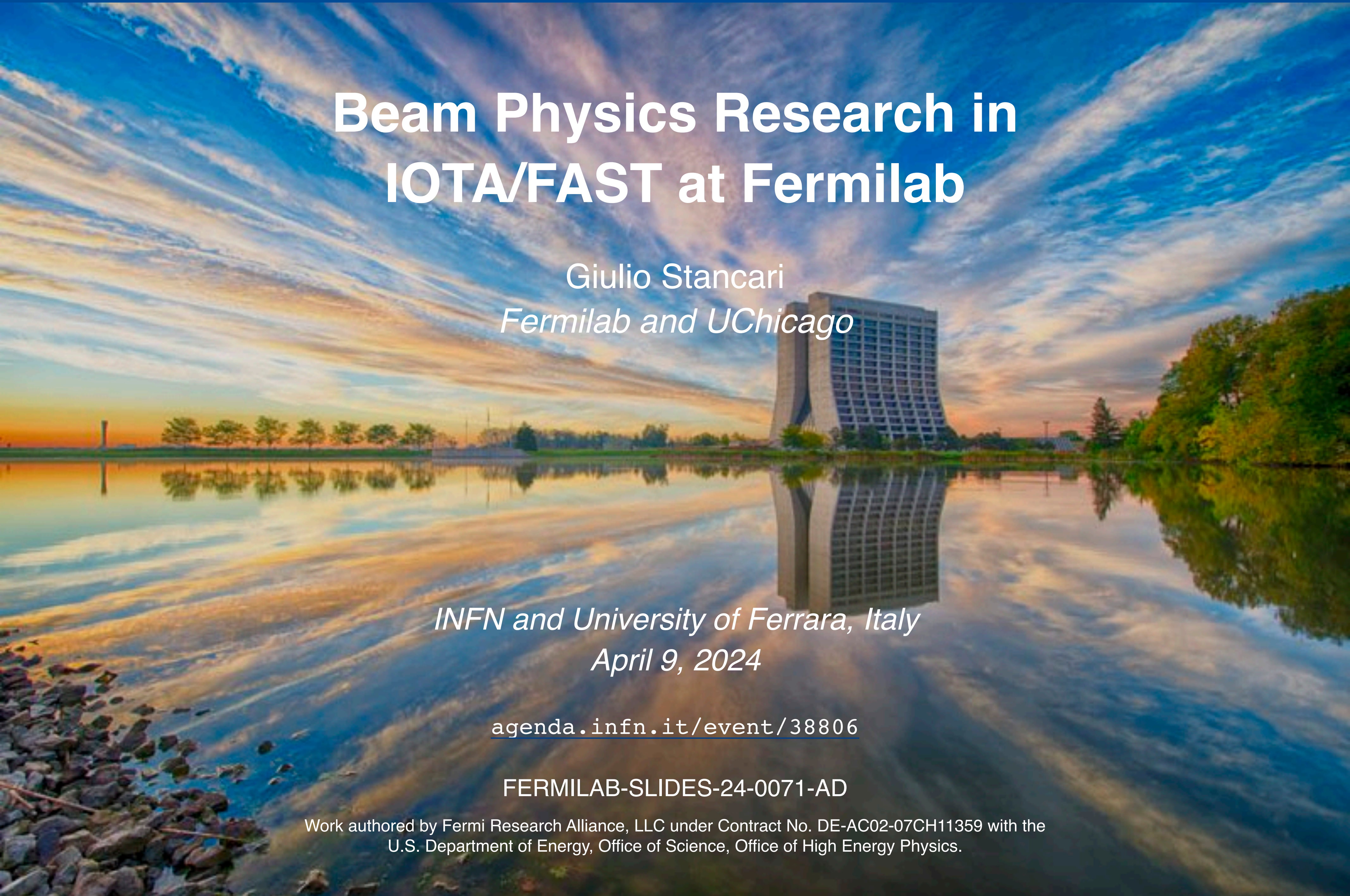


Beam Physics Research in IOTA/FAST at Fermilab

Giulio Stancari

Fermilab and UChicago

INFN and University of Ferrara, Italy

April 9, 2024

agenda.infn.it/event/38806

FERMILAB-SLIDES-24-0071-AD

Work authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

About your speaker

Senior scientist at Fermilab and UChicago

Chair of the IOTA/FAST Scientific Committee

Research

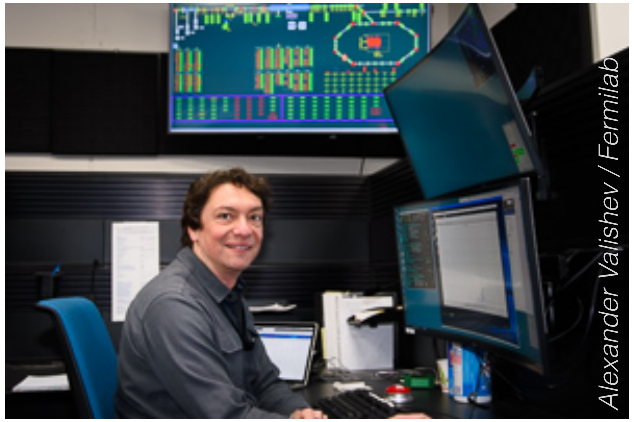
- Master and PhD at U. Ferrara / Fermilab in particle physics: charmonium spectroscopy, hadron form factors, scintillating-fiber detectors
- Post-doc at Fermilab: antiproton source, charmonium experiments
- Researcher at INFN Ferrara/Legnaro: production and trapping of radioactive francium for atomic spectroscopy and parity violation
- Professor at Idaho State U. / Jefferson Lab: positron source for CEBAF
- Scientist at Fermilab: beam dynamics in Tevatron, IOTA and LHC, electron lenses, nonlinear integrable optics, dynamics of single electrons, optical stochastic cooling, synchrotron-light detection

Teaching

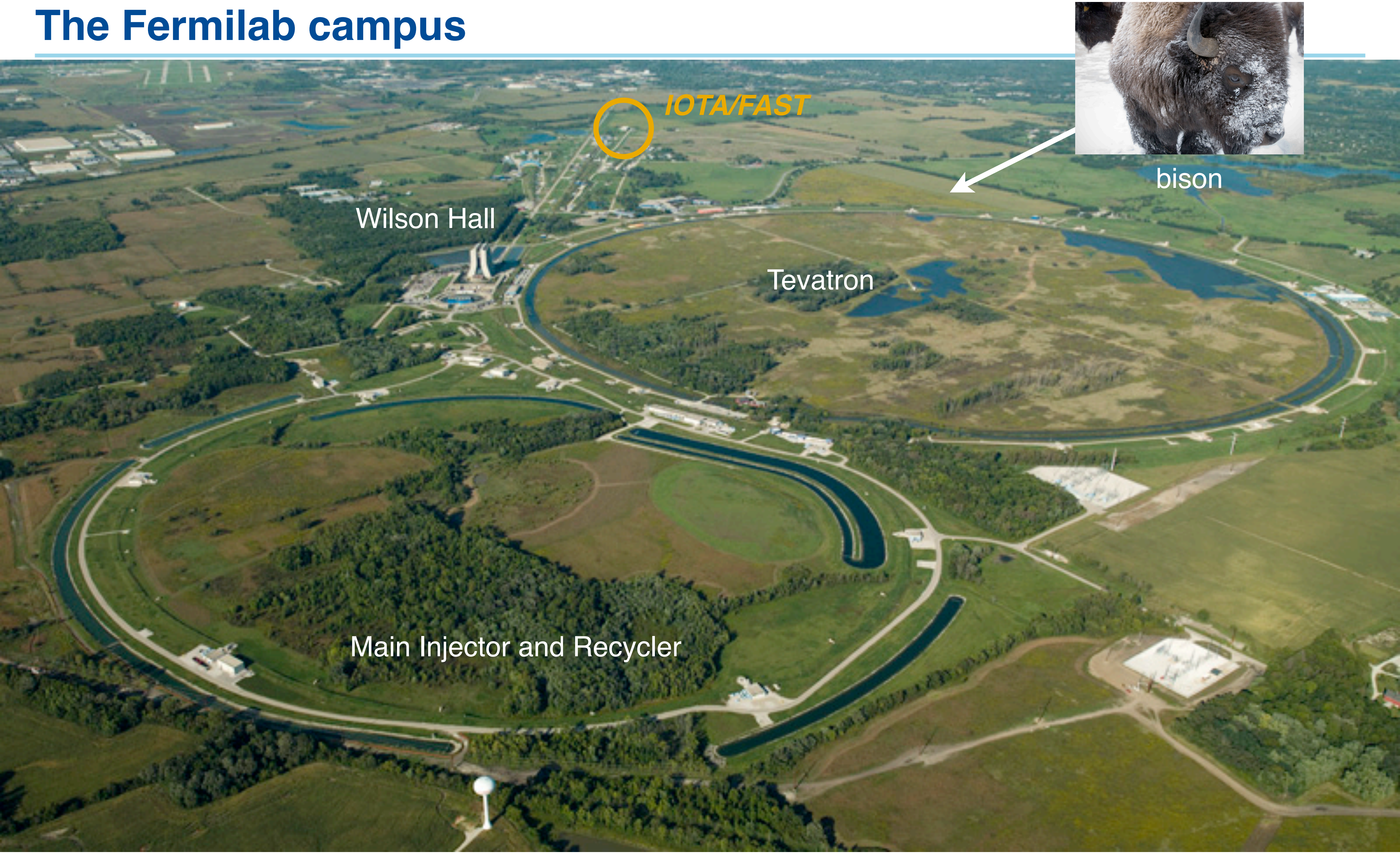
electromagnetism, accelerator physics, seminars for high-school students and teachers

Interests and hobbies

playing music, photography, running, swimming, …

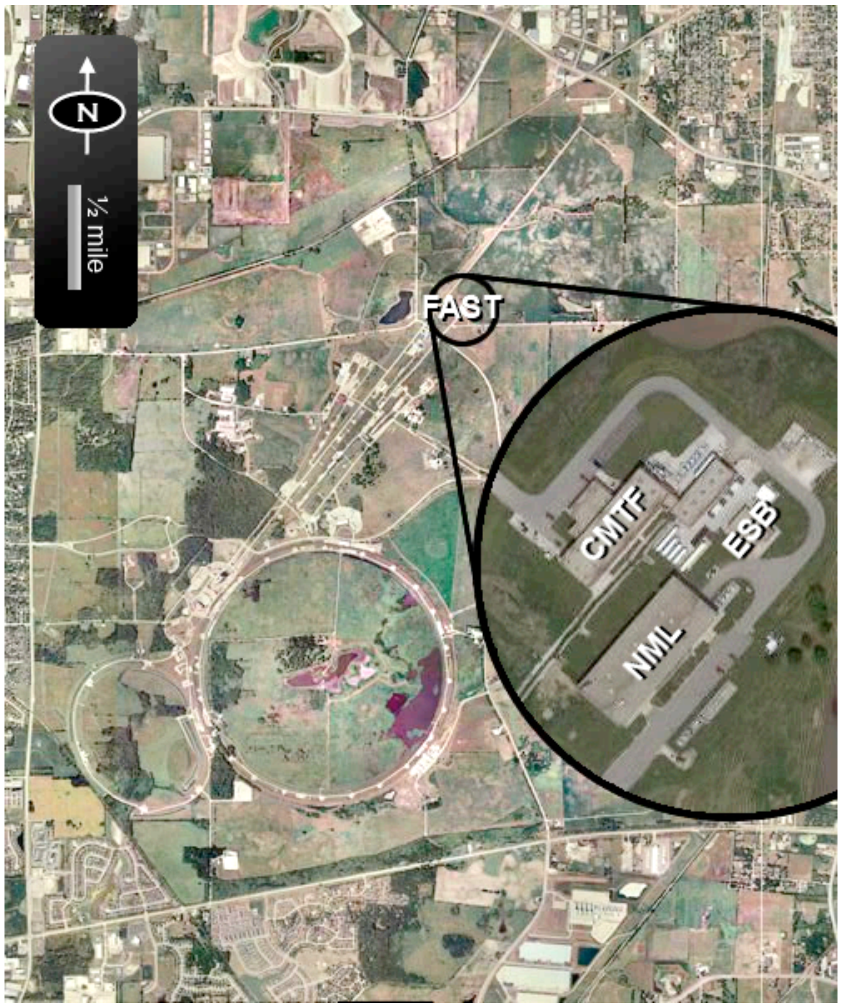


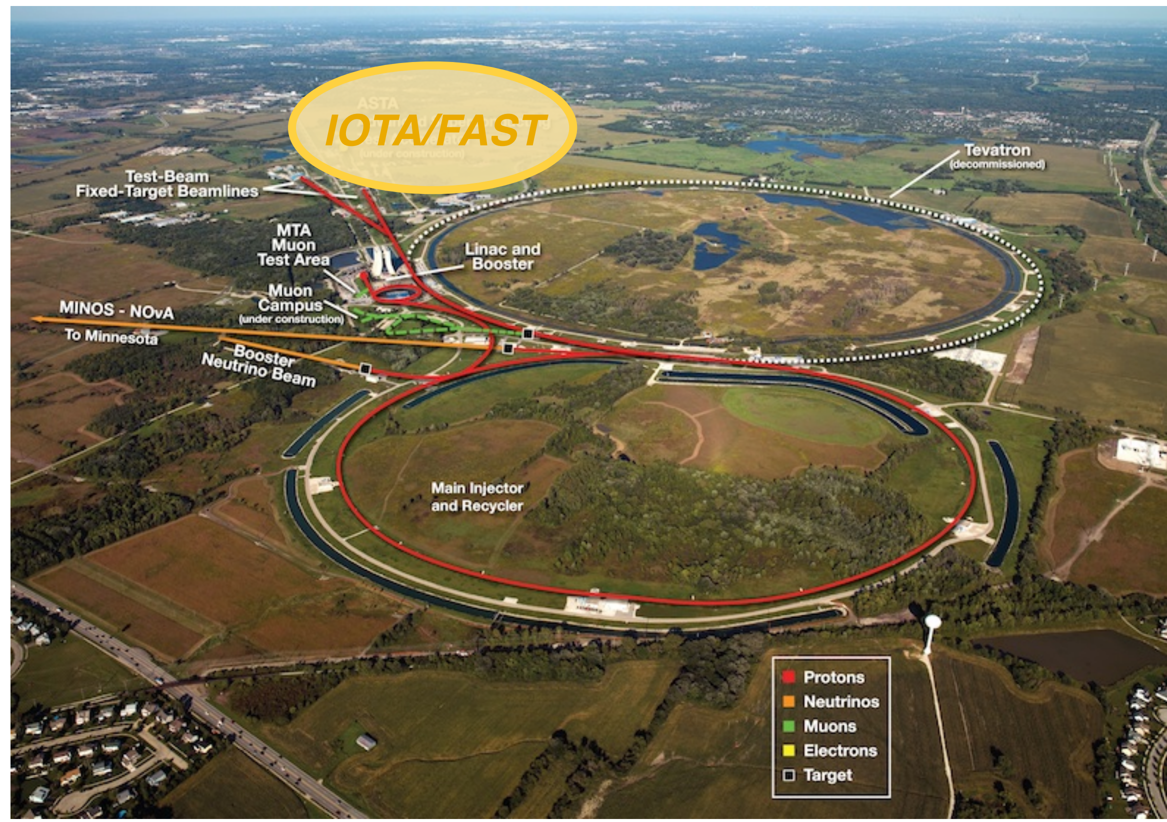
The Fermilab campus



IOTA and the FAST Facility at Fermilab

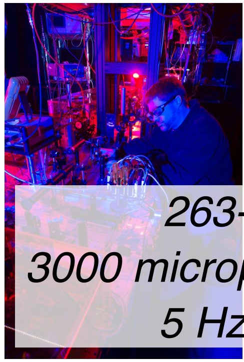
The Integrable Optics Test Accelerator (IOTA) is part of the Fermilab Accelerator Science and Technology (FAST) facility, located on the north side of the Fermilab campus





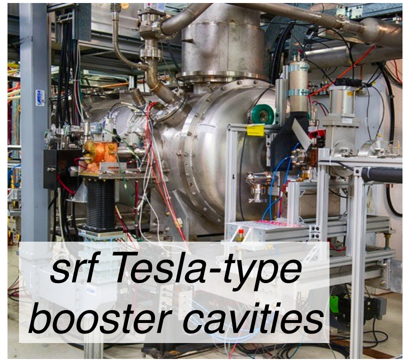
Overview of IOTA/FAST

Photoinjector

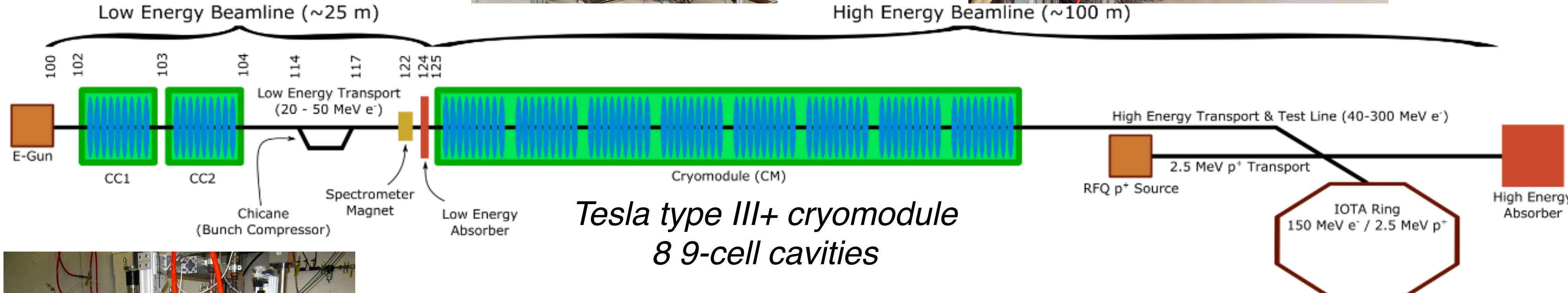


263-nm laser
3000 micropulses @ 3 MHz
5 Hz rep. rate

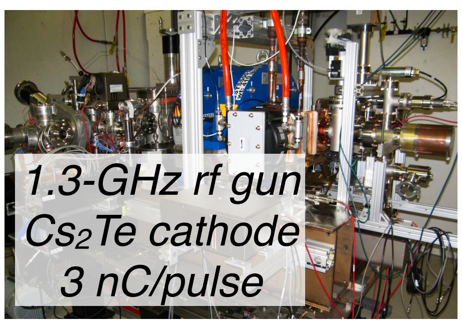
Superconducting Linac



srf Tesla-type booster cavities

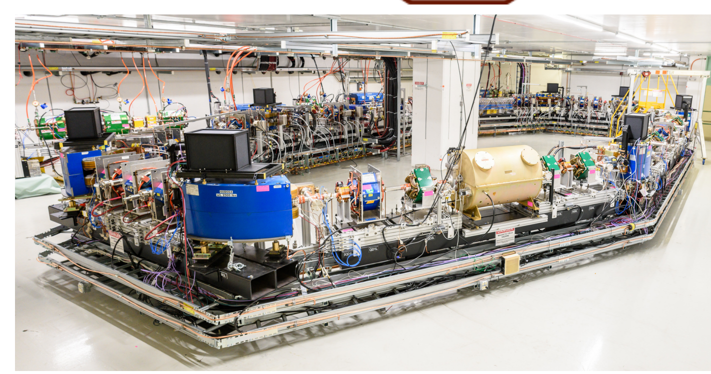


Tesla type III+ cryomodule
8 9-cell cavities



1.3-GHz rf gun
Cs_2Te cathode
3 nC/pulse

IOTA Storage Ring

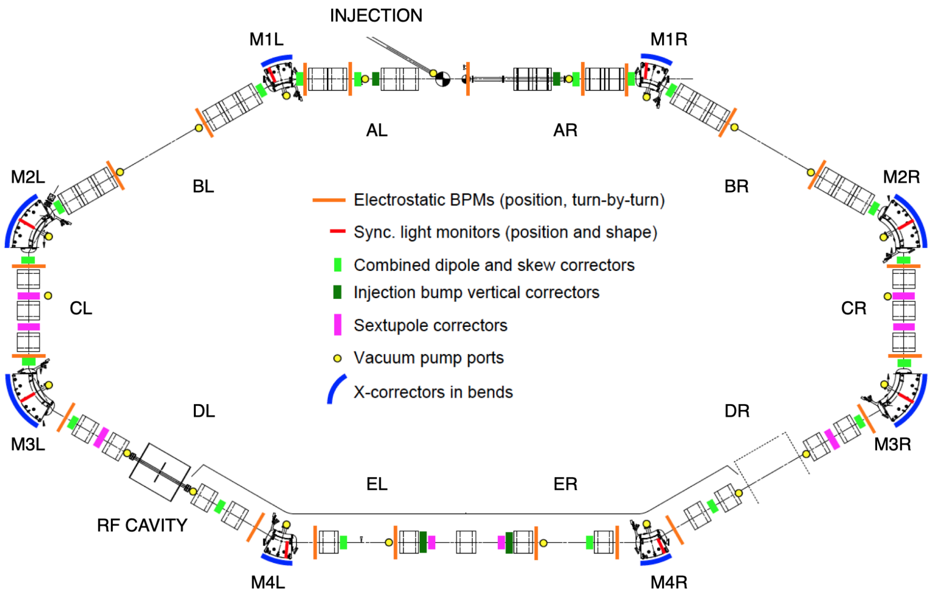


Antipov et al., JINST **12**, T03002 (2017)
Broemmelsiek et al., New J. Phys. **20**, 113018 (2018)

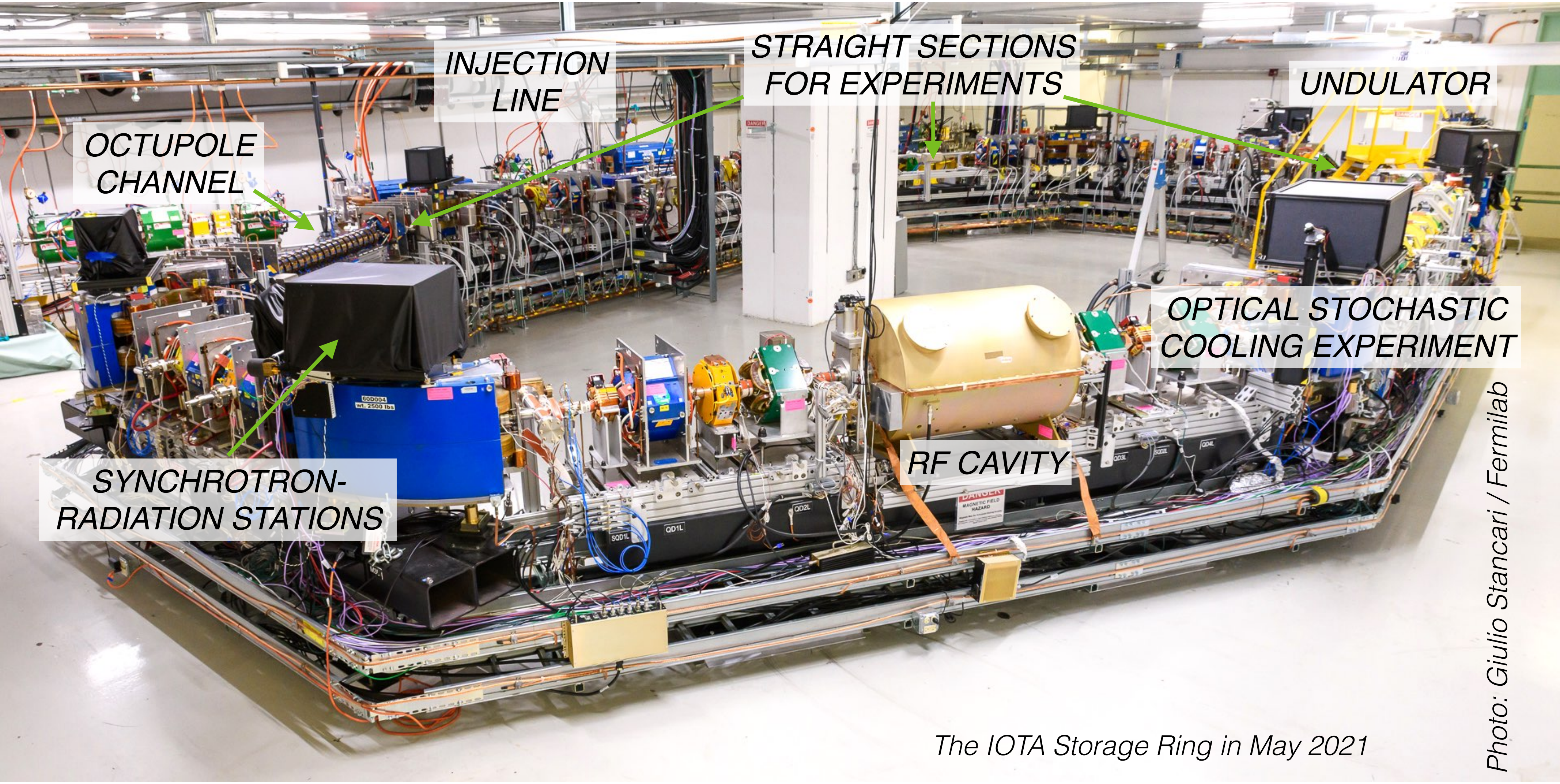
Main features of IOTA

- **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**

	Electrons	Protons
Circumference, C	39.96 m	39.96 m
Kinetic energy, K_b	100–150 MeV	2.5 MeV
Revolution period, τ_{rev}	133 ns	1.83 μs
Revolution frequency, f_{rev}	7.50 MHz	0.547 MHz
Rf harmonic number, h	4	4
Rf frequency, f_{rf}	30.0 MHz	2.19 MHz
Max. rf voltage, V_{rf}	1 kV	1 kV
Number of bunches	1	4 or coasting
Bunch population, N_b	$1\ e^- - 3.3 \times 10^9\ e^-$	$< 5.7 \times 10^9\ p$
Beam current, I_b	1.2 pA – 4 mA	< 2 mA
Transverse emittances (rms, geom.), $\epsilon_{x,y}$	20–90 nm	3–4 μm
Momentum spread, $\delta_p = \Delta p/p$	$1\text{–}4 \times 10^{-4}$	$1\text{–}2 \times 10^{-3}$
Radiation damping times, $\tau_{x,y,z}$	0.2–2 s	–
Max. space-charge tune shift, $\lvert\Delta\nu_{\mathrm{sc}}\rvert$	$< 10^{-3}$	0.5



The IOTA storage ring



The IOTA research program

GOALS

- **Address** the **challenges** posed by **high-intensity** and **high-brightness machines**, such as instabilities and losses
- Carry out **basic research** in beam physics
- Provide **education** and **training** for scientists, engineers and technicians

Examples of RESEARCH AREAS

- **mitigation** of **beam losses** and **coherent instabilities** via Landau damping, with nonlinear magnets or electron lenses
- **optical stochastic cooling** and **electron cooling**
- **classical** and **quantum properties** of **undulator radiation**
- novel **beam instrumentation**
- **statistical analysis of large data sets** for accelerator optimization

SUPPORTED mainly by

- the **high-energy-physics community** at large (P5, Snowmass community planning), through the US DOE HEP General Accelerator R&D (GARD) sub-program
- **external collaborators** and research groups

IOTA timeline

Construction completed (July 2018)

First circulating beam (Aug 21, 2018)

Nonlinear integrable optics demonstration (Run 2)

COVID-19 lockdown (March 2020)

First observations of optical stochastic cooling (April 20, 2021)

Run 1 — *Run 2* — *Run 3* — *Run 4*

2018 | 2019 | 2020 | 2021 | 2022 | 2023

operation with stored electrons

commissioning of the proton injector

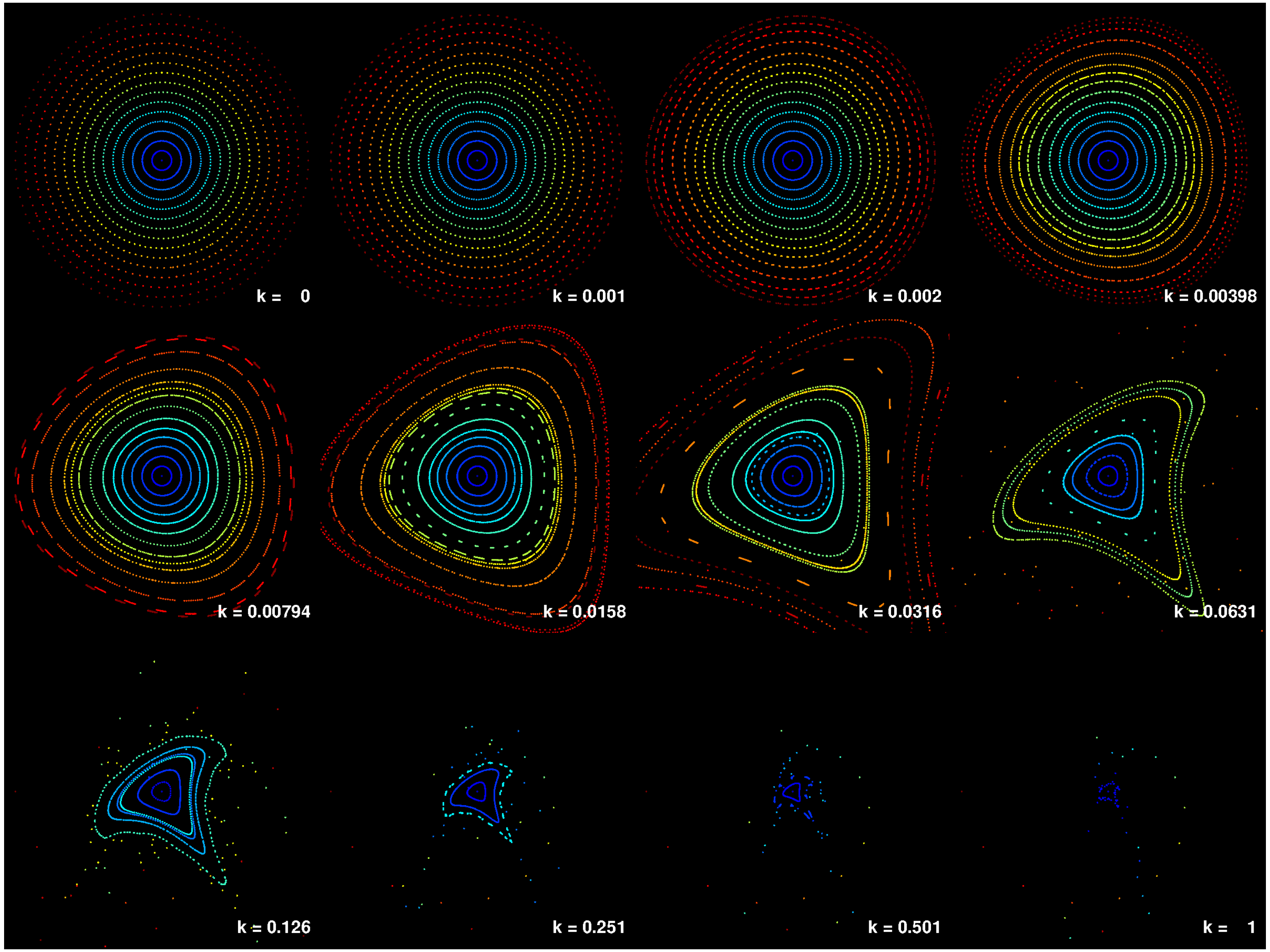
- The machine runs beam a few months per year
- Experimental runs are interleaved with shutdowns for maintenance and installations

Nonlinear Integrable Optics (NIO)

Accelerators are designed with linear forces to approximate harmonic particle motion. Nonlinearities are necessary and unavoidable. **Can an accelerator be designed with intrinsic nonlinearities to improve beam stability and avoid particle loss?**

Linear phase space
constant oscillation frequencies vs. amplitude, bound trajectories

Nonlinear forces are introduced
dependence of frequency with amplitude, chaos, restricted dynamic aperture, losses



Nonlinear Integrable Optics (NIO)

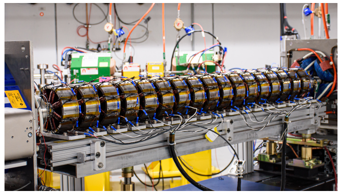
(1) In a real accelerator, is it possible to have a **nonlinear lattice** that stabilizes the beam via **Landau damping**, suppresses resonances and does **not reduce dynamic aperture**?

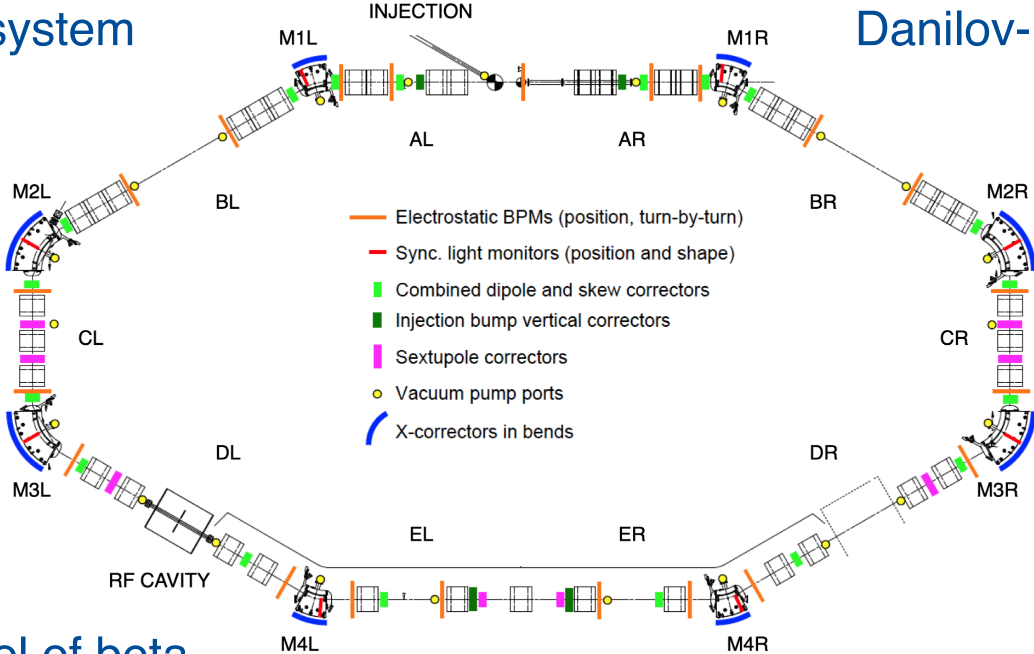
(2) How **robust** are nonlinear integrable lattices agains imperfections?

(3) Can the benefits of NIO be **demonstrated in a high-intensity synchrotron**?

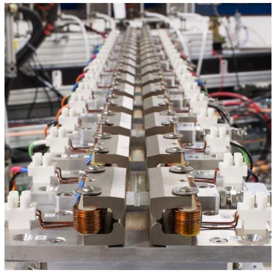
Two implementations:

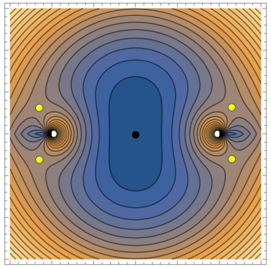
(A) Segmented octupole channel
Quasi-Integrable (QI) system





(B) Segmented elliptic-potential magnet
Danilov-Nagaitsev (DN) system





Both require fine control of beta functions (~1%) and phase advances (~10^{-3}) through the nonlinear section

Danilov and Nagaitsev, PRAB 13, 084002 (2010)
Valishev et al., PAC (2011)
Mitchell et al., PRAB **23**, 064002 (2020)

NIO experiments

Demonstrated integrable focusing systems experimentally

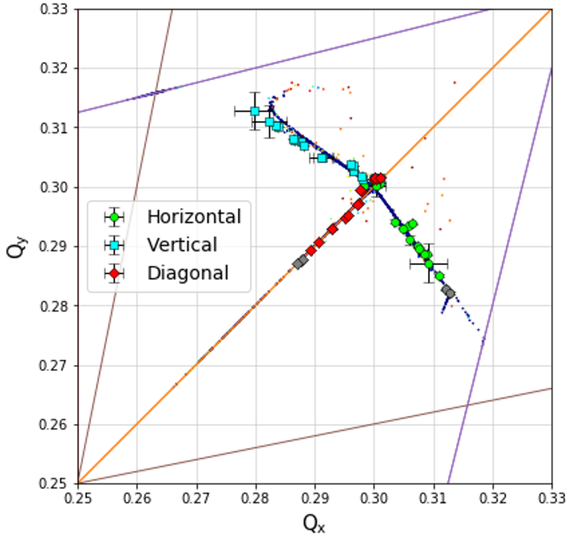
Observed large detuning with amplitude

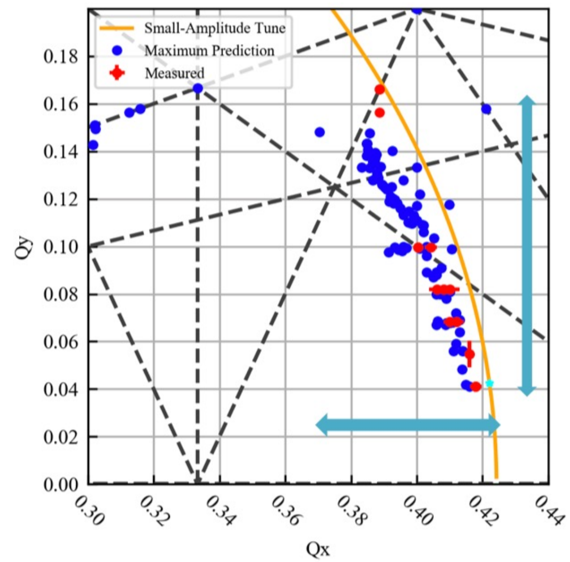
QI system (octupole channel)

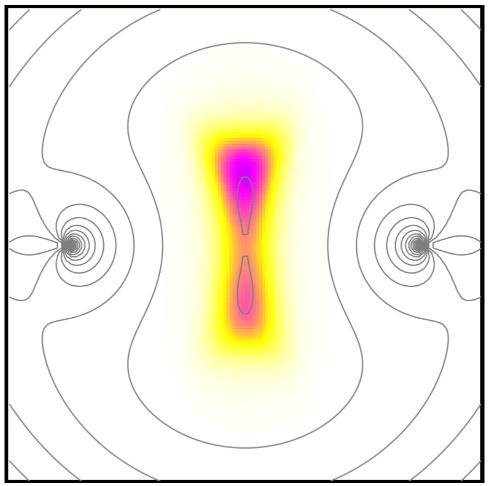
Achieved detuning of 0.04

DN system (elliptic potential)

Achieved detuning of 0.08







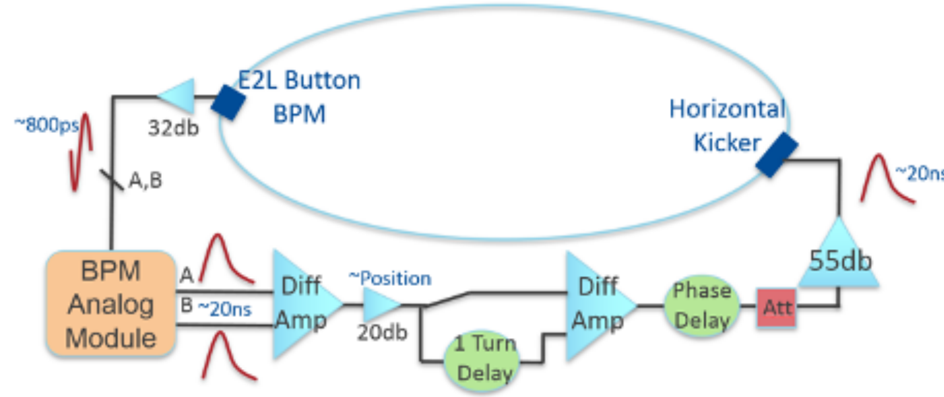
Crossed integer resonance without beam loss

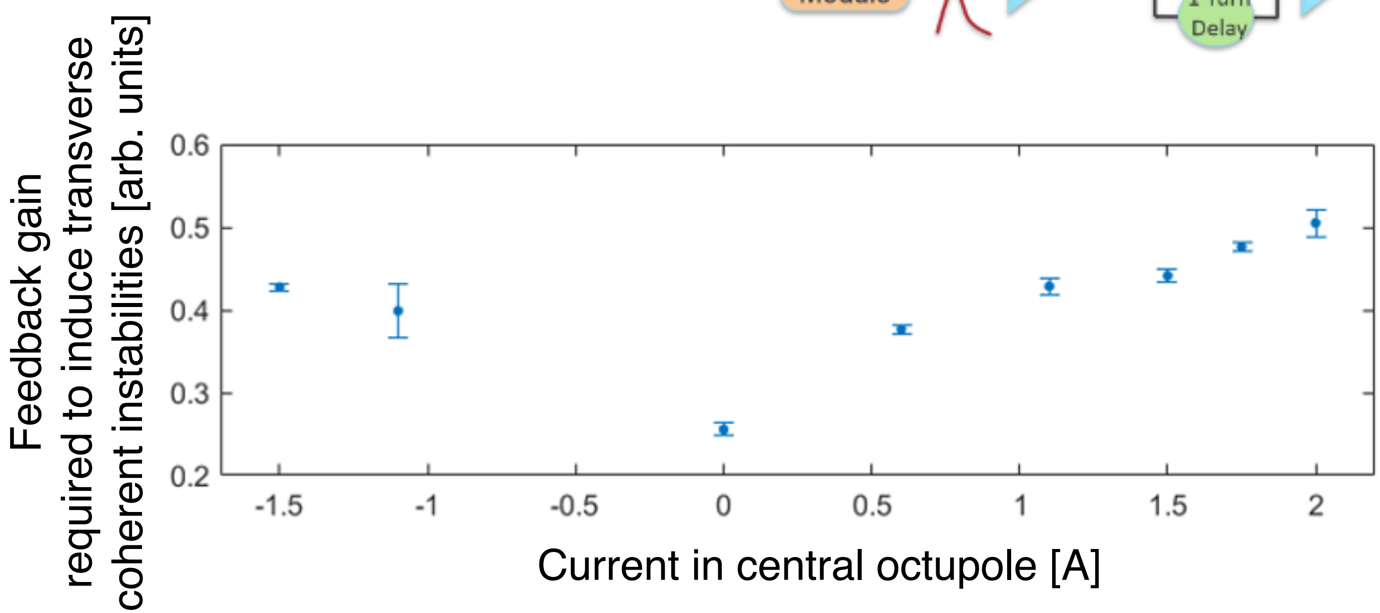
Observed predicted transverse splitting into stable beamlets

Valishev et al., IPAC 2021
Kuklev, PhD Thesis, U. Chicago (2021)
Szustkowski, PhD Thesis, NIU (2020)

Nonlinear integrable optics and instability thresholds

Tested the effect of the NIO QI system on instability thresholds, using a positive feedback (anti-damper) to excite the beam





Observed a factor 2 increase in the instability thresholds with the strength of the octupole channel

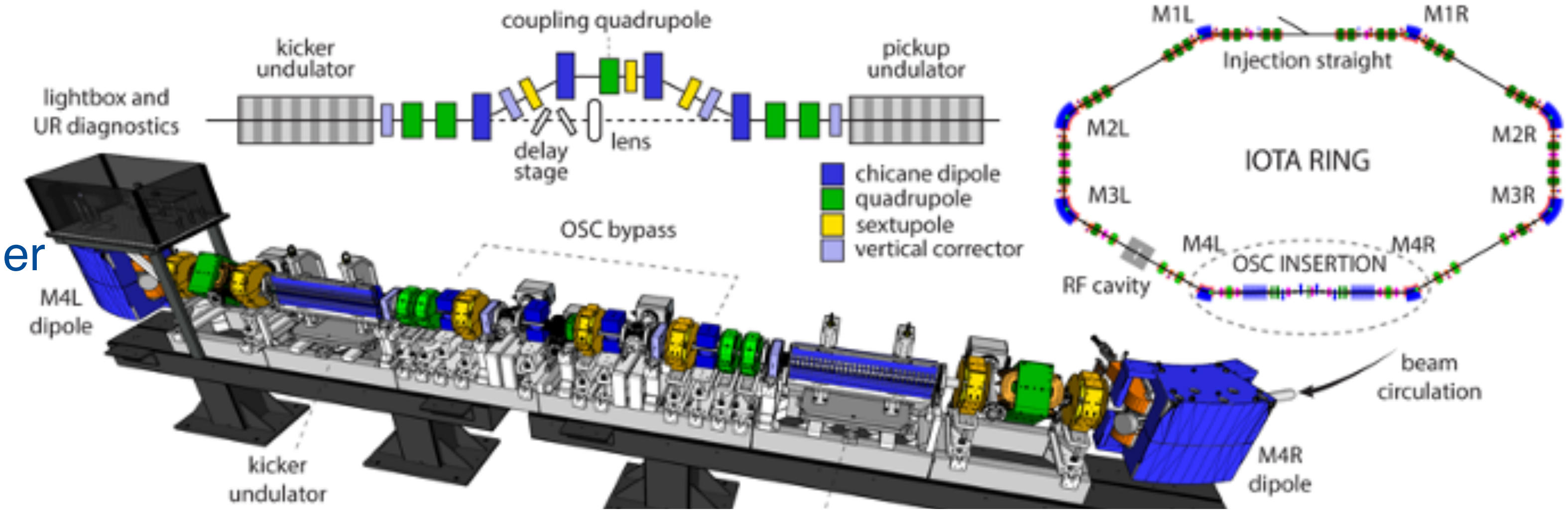
Valishev et al., IPAC 2021
Eddy et al., Beams-doc-9171 (2021)

Optical Stochastic Cooling (OSC): design and apparatus

Can a particle's radiation be used to manipulate its phase space and yield cooling?

Stochastic cooling uses microwave electromagnetic pickups and kickers (bandwidth ~GHz, sample length ~cm). An optical analogue (~10 THz, ~μm) could increase cooling rates by 3 orders of magnitude.

Phase I: no optical amplifier

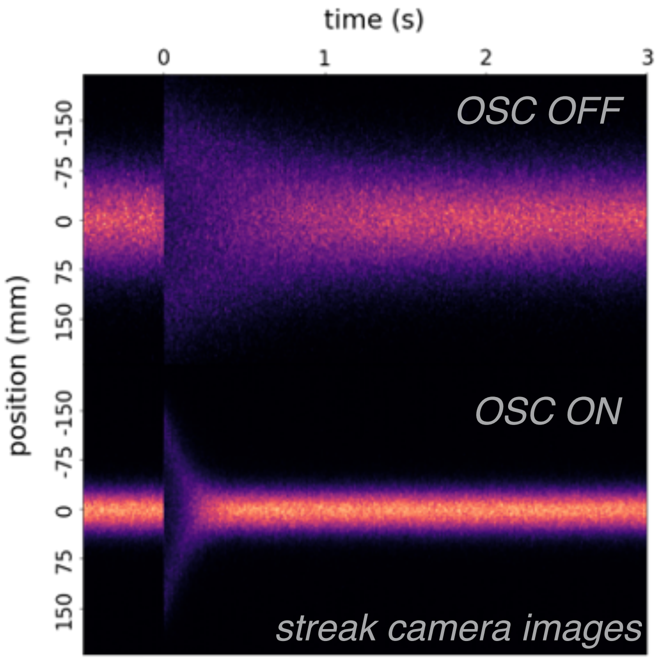


Technological challenges:

- overlap of beam and radiation in the kicker undulator within 0.2 mm, 0.1 mrad, <u>0.3 fs</u>
- relative stability of radiation path and magnetic bypass much smaller than wavelength (μm)

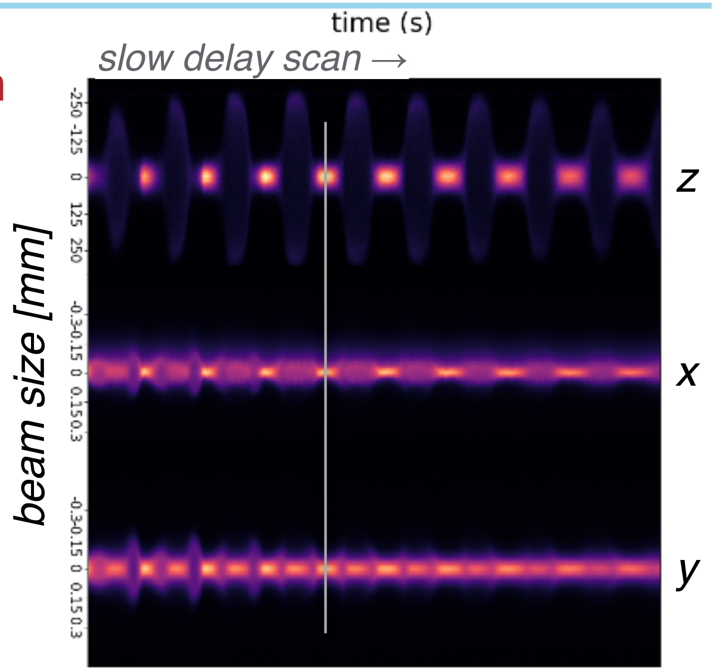
van der Meer, RMP **57**, 689 (1985)
Mikhailichenko and Zolotorev, PRL **71**, 4146 (1993)
Zolotorev and Zholents, PRE **50**, 3087 (1994)
Lebedev, Jarvis et al., JINST **16**, T05002 (2021)

Optical stochastic cooling: first results



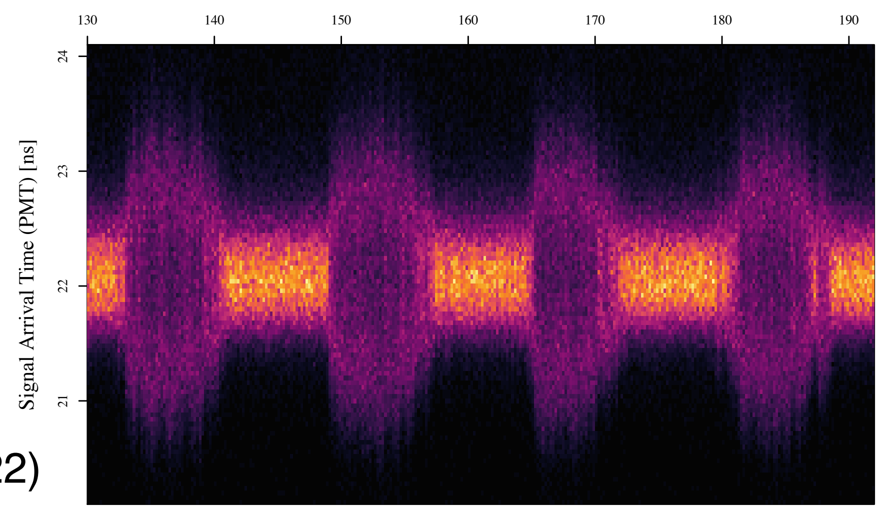
↑ *rf ping*

Simultaneous cooling in all degrees of freedom



Measured cooling rates 8x faster than natural radiation damping

Observed heating and cooling of a single electron!

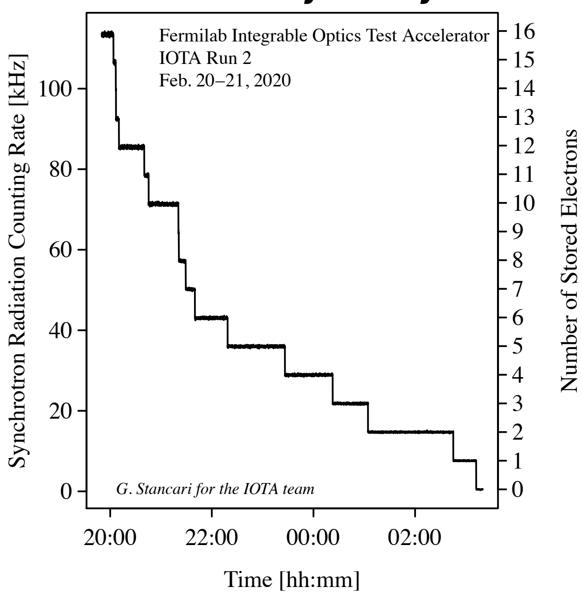


Jarvis, Lebedev, Romanov et al., Nature **608**, 287 (2022)

Dynamics of single electrons

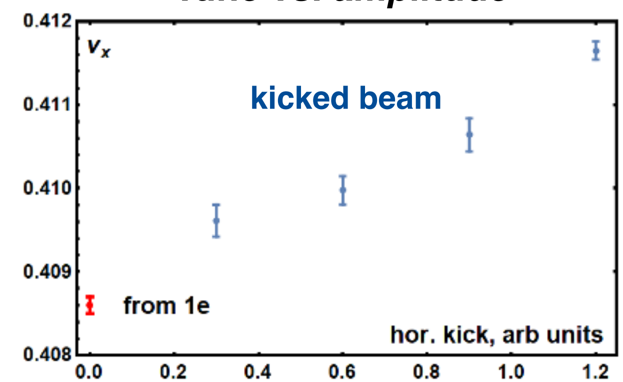
Single electrons (or a known given number of electrons) can be stored for minutes to hours (in a single bucket or multiple buckets)

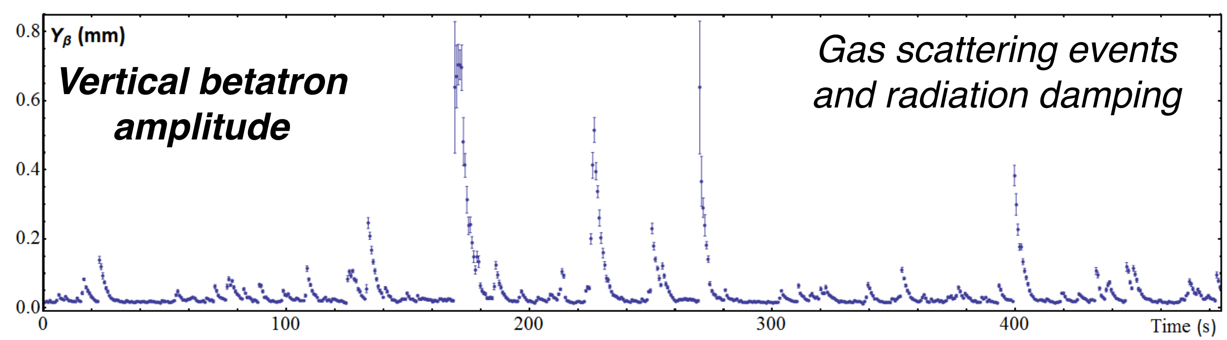
Discrete steps in intensity decay



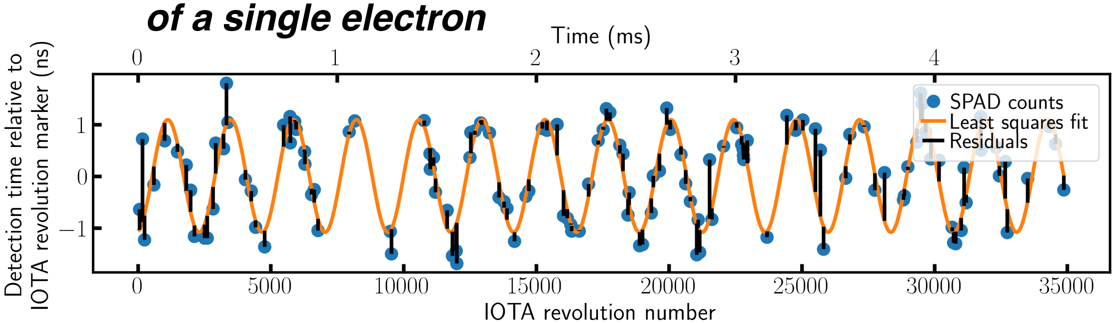
Tracking 1 e^- in all 3 dimensions yields "single particle" lifetimes, emittances, tunes, damping times, beam energies and gas scattering rates

Tune vs. amplitude



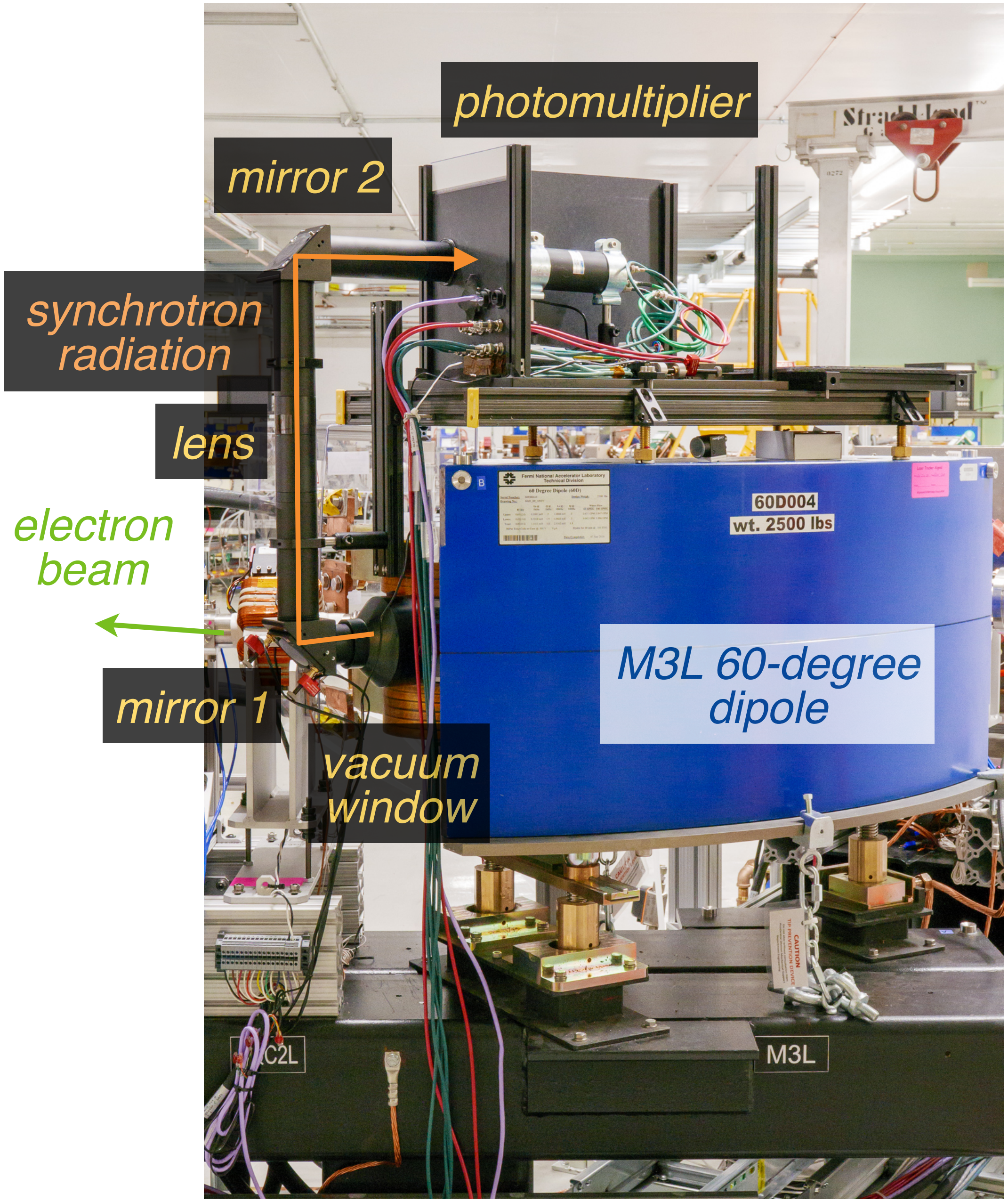


Synchrotron oscillations of a single electron



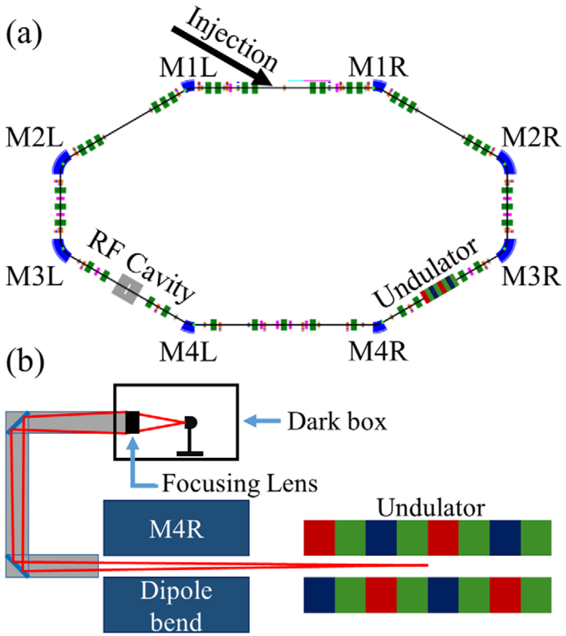
Stancari, FERMILAB-FN-1116-AD (2020)
Romanov et al., JINST **16**, P12009 (2021)
Romanov, IOTA/FAST Collab. Meeting (2021)
Lobach et al., JINST **17**, P02014 (2021)

Detection of synchrotron radiation in IOTA



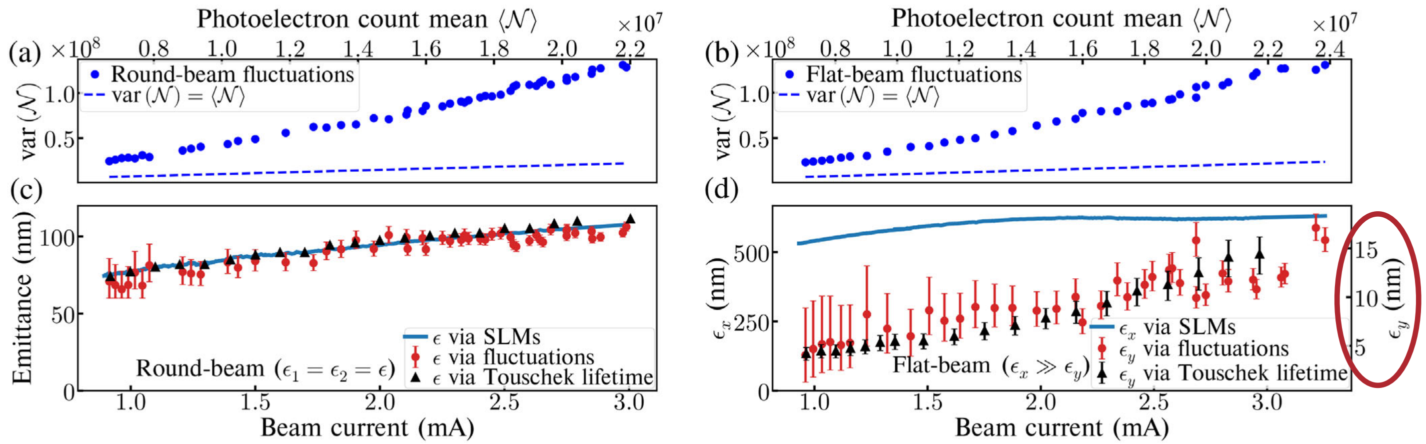
Classical and quantum properties of undulator radiation

What are the statistical properties of undulator radiation from single or multiple electrons? Can they be used for beam diagnostics?

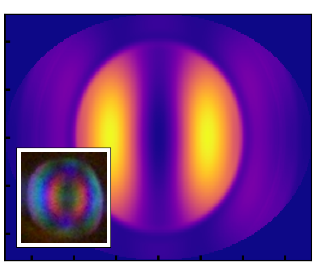


Verified that intensity fluctuations contain a calculable term that depends on beam sizes (interference)

$$\mathrm{var}(\mathcal{N}) = \langle \mathcal{N} \rangle + \frac{\langle \mathcal{N} \rangle^2}{M}$$



Intensity fluctuations can be used to infer small beam emittances



Editors' Suggestion, Featured in Physics → Lobach et al., PRL **126**, 134802 (2021)

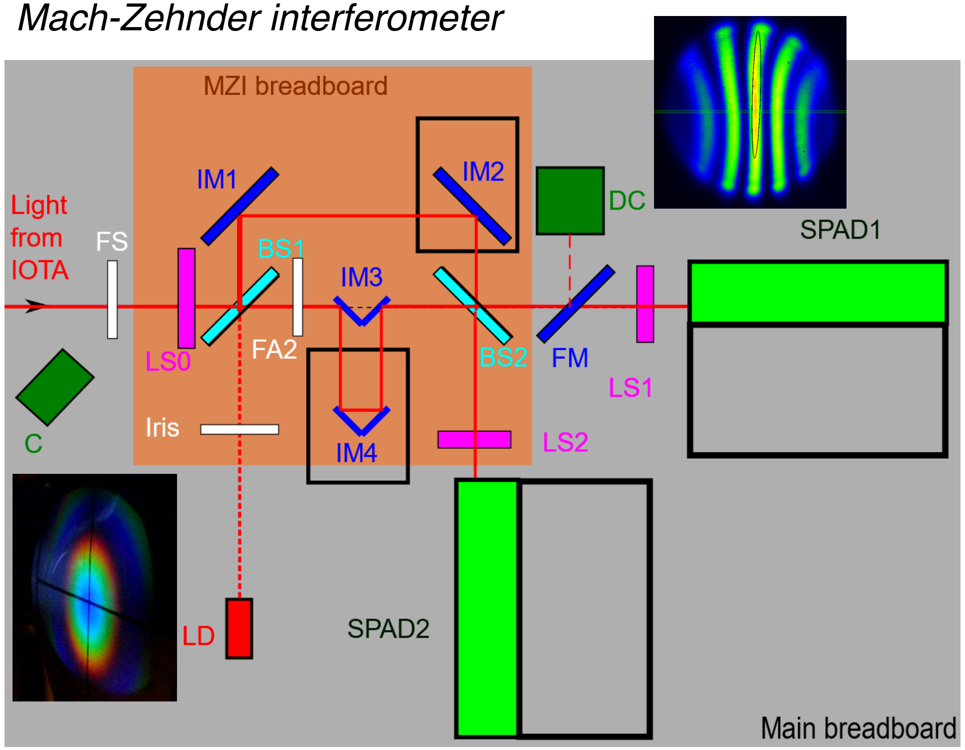
Winner of the 2022 APS DPB Award → Lobach, PhD Thesis (2021)

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)

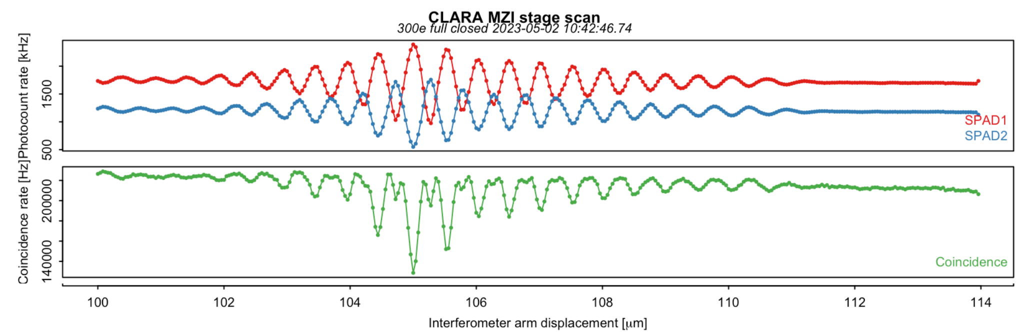
Interferometry of radiation from single electrons

What is the coherence length of undulator radiation from a single electron? Is radiation in a coherent Glauber state or in a Fock number state? Can quantum optical techniques be used for beam diagnostics?

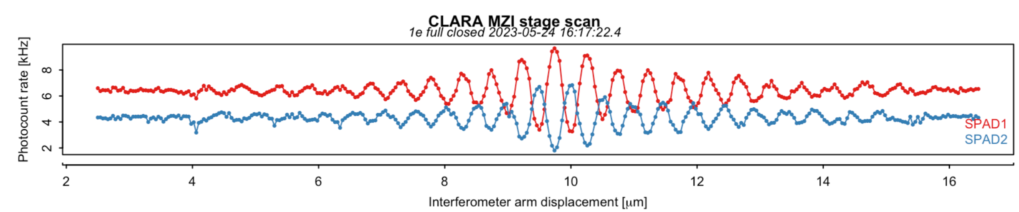
Mach-Zehnder interferometer



~300 electrons



1 electron



Observables: count rates vs. delay, distributions of arrival times, correlations

IOTA Run 4 program (2022-2023)

Run 4 (1 April 2022 - 23 October 2023)

IOTA

ID	Acronym	Title	Spokesperson / Fermilab Liaison	LOI (optional)	Proposal	Presentation	Status	Beam Time	Reports
I-401	NIOLD	IOTA Experiment Nonlinear Optics: Landau Damping	N. Eddy (FNAL)		original revised final	Mar 25, 2022	approved	12 8-h shifts	
I-403	CLARA	Coherence Length of Undulator Radiation	S. Nagaitsev (JLAB) / A. Romanov (FNAL)	PDF	PDF	Sep 9, 2022	approved	(18 x 8 h) + (3 x 4 h) shifts	
I-405	NIO	Nonlinear Integrable Optics	A. Valishev (FNAL)		Beams-doc-9715	Feb 24, 2023	approved	(20 x 8 h) + (4 x 4 h) shifts	
I-406	SETI	Single-Electron Tracking in IOTA	A. Romanov (FNAL)		Beams-doc-9762	June 16, 2023	approved	(3 x 2 h) + (7 x 8 h) shifts	
I-407	LADR	Low-Alpha Demonstration Research	J. Jarvis and M. Wallbank (FNAL)		PDF	Sep 9, 2023	conditional approval	10 4-h shifts	

FAST Linac

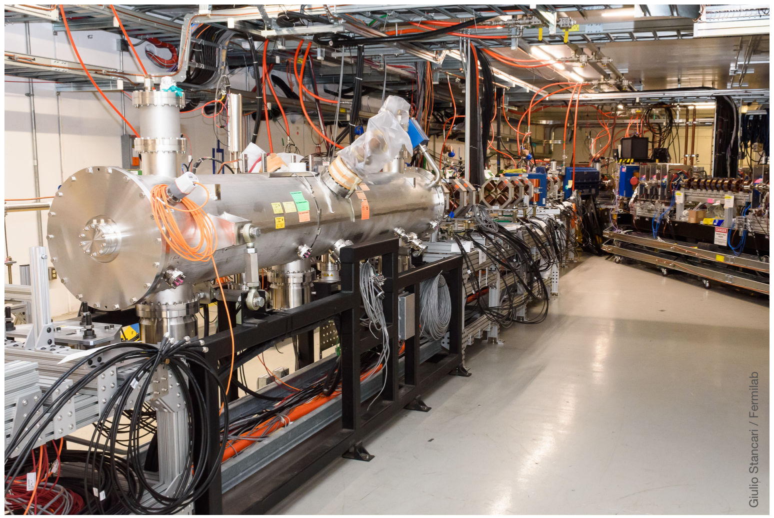
ID	Acronym	Title	Spokesperson / Fermilab Liaison	LOI (optional)	Proposal	Presentation	Status	Beam Time	Reports
I-402	FAST-GREENS	Tapering Enhanced Stimulated Super-Radiant Amplification: Gamma-Ray High Efficiency Enhanced Source	P. Musumeci (UCLA) / D. Broemmelsiek (FNAL)		original final	Apr 4, 2022	approved	3 shift blocks, 10 x 8 h each	Cropp's PhD Thesis Instruments 7, 42 (2023)
I-404	NEB	Noise in Intense Electron Bunches	S. Nagaitsev (JLAB) / J. Ruan (FNAL)	PDF	original final	July 14, 2023	approved	(2 x 4 h) + (3 x 8 h) shifts	

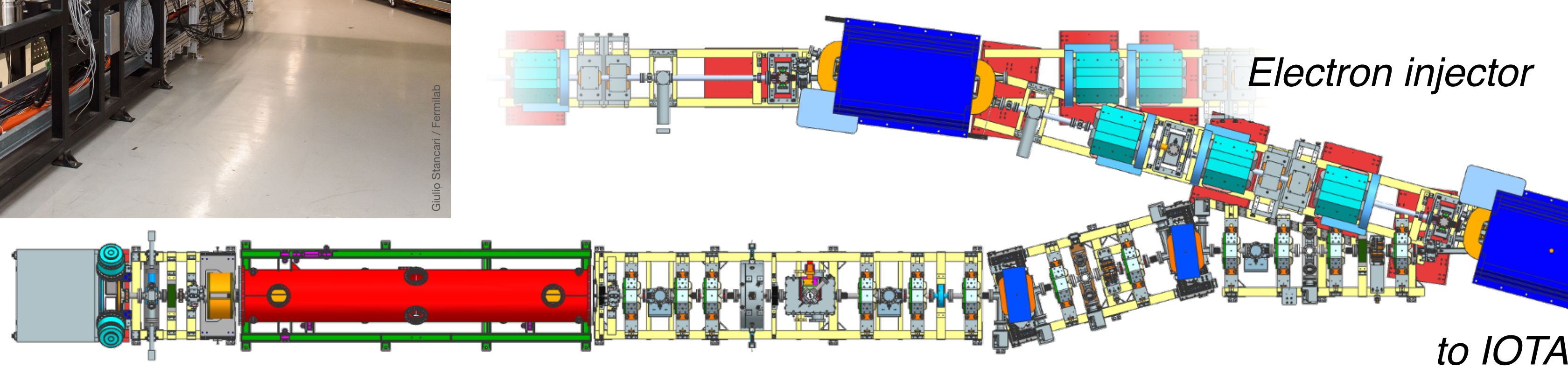
Fermilab

Construction of the IOTA proton injector (2022-2024)

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

Typical IOTA proton parameters (bunched beam):
2.5 MeV
1.3 mA, 4 μm (geom.)
$\Delta\nu_{sc} \sim 0.5$





	Parameter	Nom.	Unit
LEBT	Energy	50	*keV*
	Proton Beam Current	20	*mA*
	Pulse length (99%)	350	*μs*
	Source Pulse Rate	1	*Hz*
	Transverse Beam Size	700	*μm*
MEBT	Energy	2.5	*MeV*
	RF Pulse Rate	1	*Hz*
	RFQ Frequency	325.0 ± 0.5	*MHz*
	RFQ Duty Factor	< 0.002	*%*
	Phase/Amp. Stability	1° / 1%	
	Beam Pulse	2	*μs*
	Bunch length (1σ)	0.3	*ns*

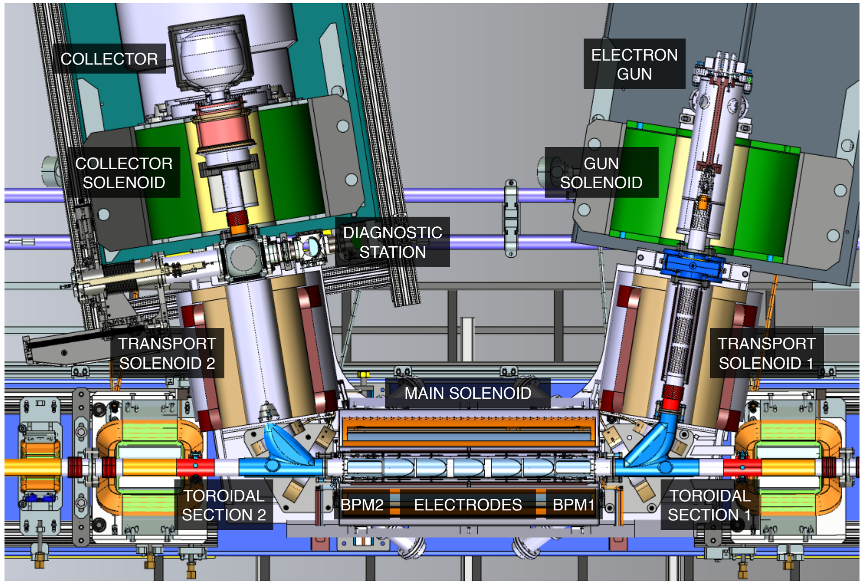
IOTA (Proton)	Proton Beam Energy	2.5	*MeV*
	Relativistic β	$2.66 \cdot 10^{-3}$	
	Circumference	40	*m*
	Proton RF Frequency	2.19	*MHz*
	Revolution Period	1.83	*μs*
	RF Voltage	50	*kV*
	Geometric Emittance	0.3	*μm*
	Δp/p (RMS)	0.3	*%*
	Beam Current	8	*mA*
	RMS Beam size β = 10 m	4.5	*mm*
	Momentum compaction	0.07	
	Betatron tune (Qx, Qy)	5.3	

Examples of research areas planned after Run 4

Research with the IOTA electron lens

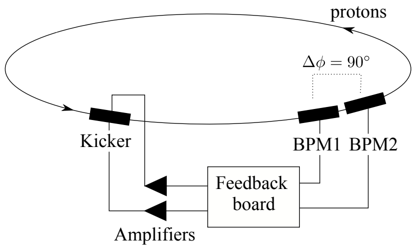
- Novel implementations of NIO schemes
- Electron cooling
- Tune-spread generation for Landau damping
- Space-charge compensation
- Beam diagnostics

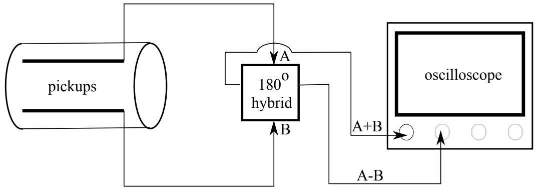
Stancari et al., JINST **16**, P05002 (2021)



Instabilities, Space Charge and Controlled Feedback

- Excite and detect instabilities with a wake-building feedback and intra-bunch monitor over varying wake amplitudes and space-charge intensities





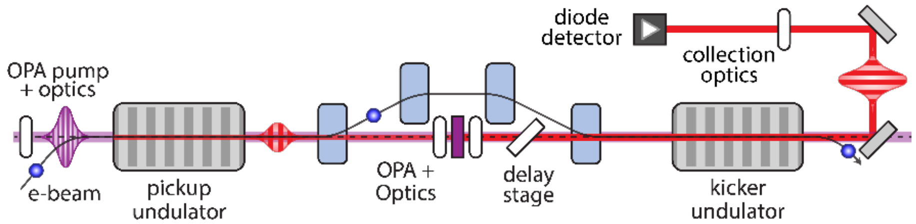
Ainsworth et al., ECA Grant

Examples of research areas planned after Run 4

Optical Stochastic Cooling with Amplification

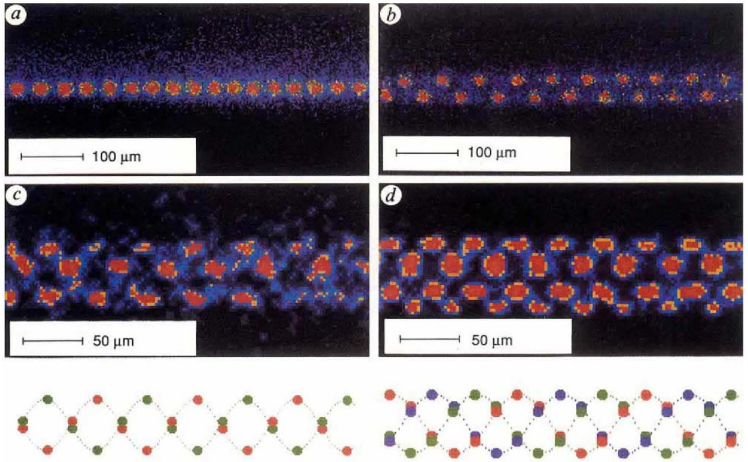
Jarvis et al., ECA Grant

- Development of optical parametric amplifier, transverse sampling, specialized optics
- Demonstration of achievable cooling rates
- New types of beam manipulations



Quantum Computing with Stored Crystalline Ion Beams?

- Preliminary feasibility and scalability studies. Study and mitigation of heating mechanisms in a storage ring.
- Major upgrades: ion source, laser cooling



Birkl et al., Nature **357**, 310 (1992)
Habs and Grimm, ARNPS **45**, 391 (1995)
Schätz et al., Nature **412**, 717 (2001)
Shaftan, NSLSII-ASD-TN-299 and 309 (2019)
Brown and Roser, PRAB **23**, 054701 (2020)
Brown et al., Snowmass White Paper (2020)
Shaftan and Blinov, PRAB **24**, 094701 (2021)

Examples of collaborations with INFN and Unife

A. Scarpelli (Master Thesis), *Development of a Synchrotron Radiation Beam Monitor for the Integrable Optics Test Accelerator* (advisors: E. Luppi, G. Stancari)

Development of a single-photon detector with high spatial and temporal resolution for single-electron tracking, optical stochastic cooling and general beam diagnostics in IOTA, N. V. Biesuz, R. Bolzonella, V. Cavallini, A. Cotta Ramusino, M. Fiorini, E. Franzoso, A. Saputi (INFN/Unife), J. Jarvis, A. Romanov, J. Santucci, G. Stancari (Fermilab)

New ideas and projects are welcome!

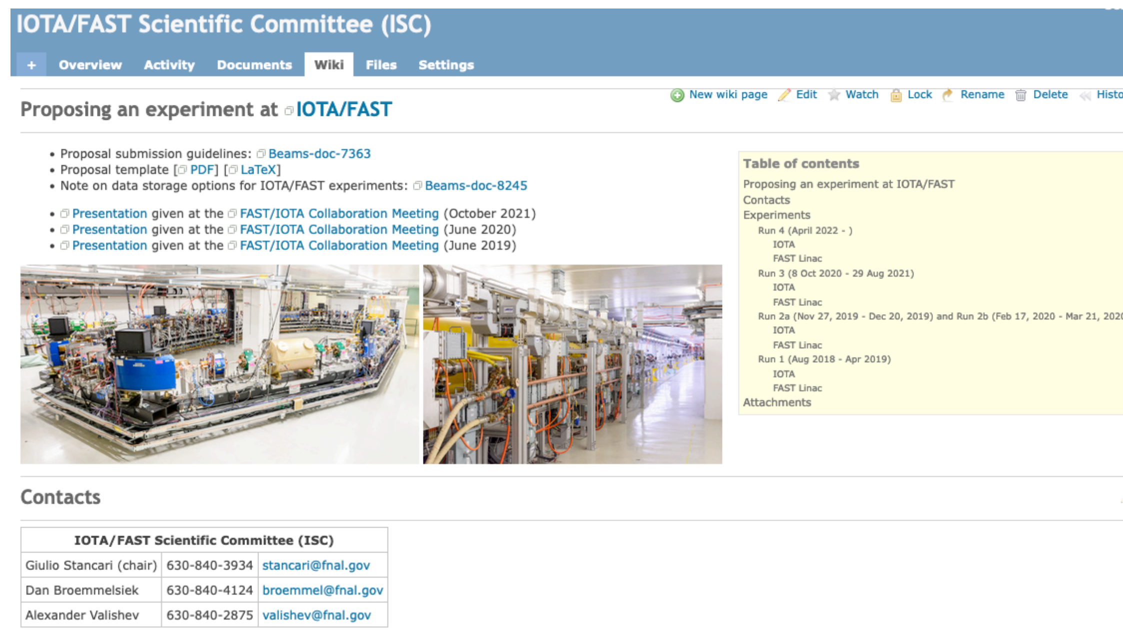
Resources

IOTA/FAST web site

fast.fnal.gov

IOTA/FAST Scientific Committee

cdcvs.fnal.gov/redmine/projects/ifsc/wiki/



Collaboration Meeting 2024

indico.fnal.gov/e/62181

Special Issue of the Journal of Instrumentation

iopscience.iop.org/journal/1748-0221/page/extraproc90

Conclusions

Many **exciting opportunities** for experimental, theoretical and computational research in accelerator physics and technology at IOTA/FAST

Several **resources for students**: summer schools, internships, master theses, joint PhD program, …

New **ideas** and **proposals** are always welcome

Thank you for your attention!

IOTA/FAST Collaboration Meeting, March 2024