The IOTA Research Program and Possible Studies Relevant for the FCC

Giulio Stancari
Fermilab and UChicago
on behalf of the IOTA/FAST team

- IOTA/FAST Facility
- Research Highlights
- Synergies with FCC?

FCC Week   San Francisco   June 11, 2024

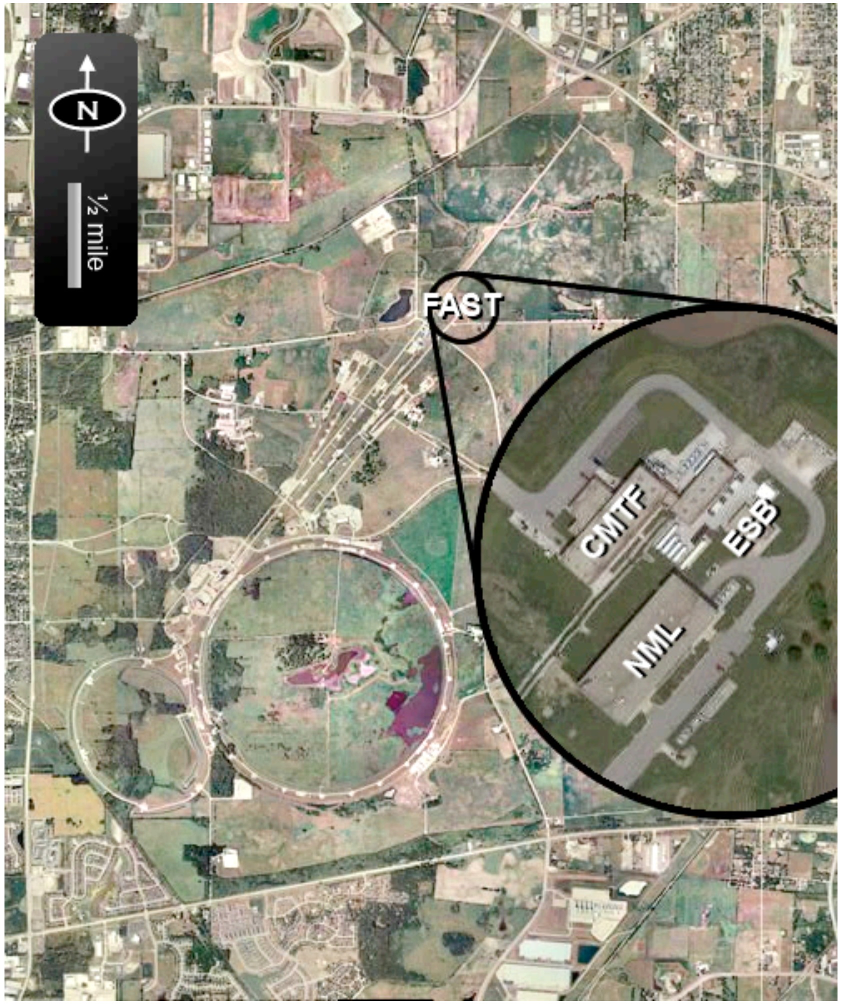
indico.cern.ch/event/1298458

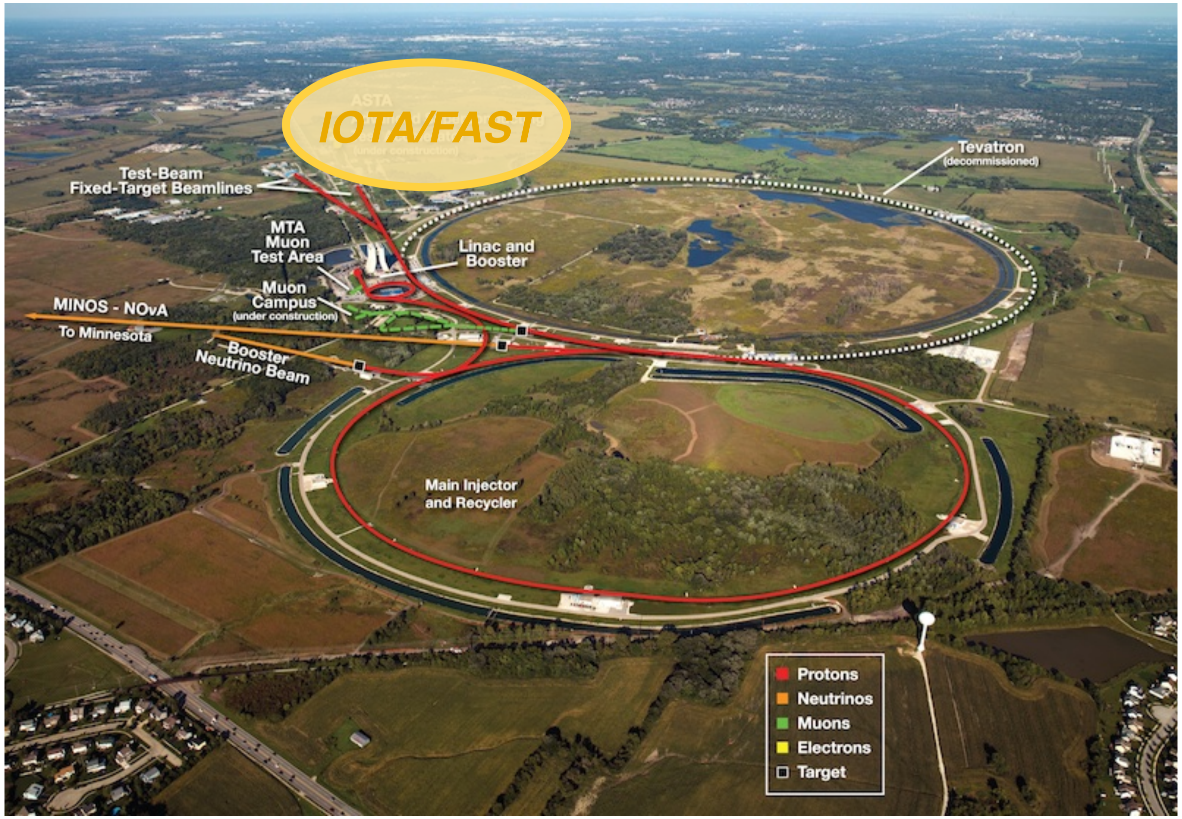
FERMILAB-SLIDES-24-0123-AD

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.

IOTA and the FAST Facility at Fermilab

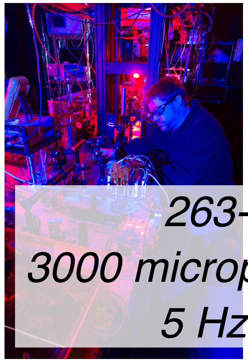
The Integrable Optics Test Accelerator (IOTA) is part of the Fermilab Accelerator Science and Technology (FAST) facility, located on the north side of the Fermilab campus





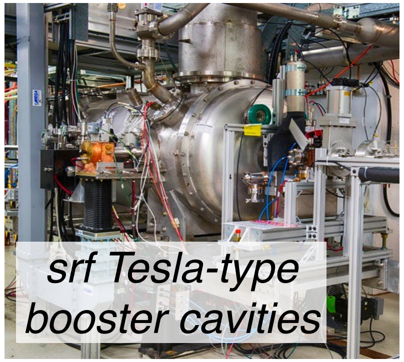
Overview of IOTA/FAST

Photoinjector

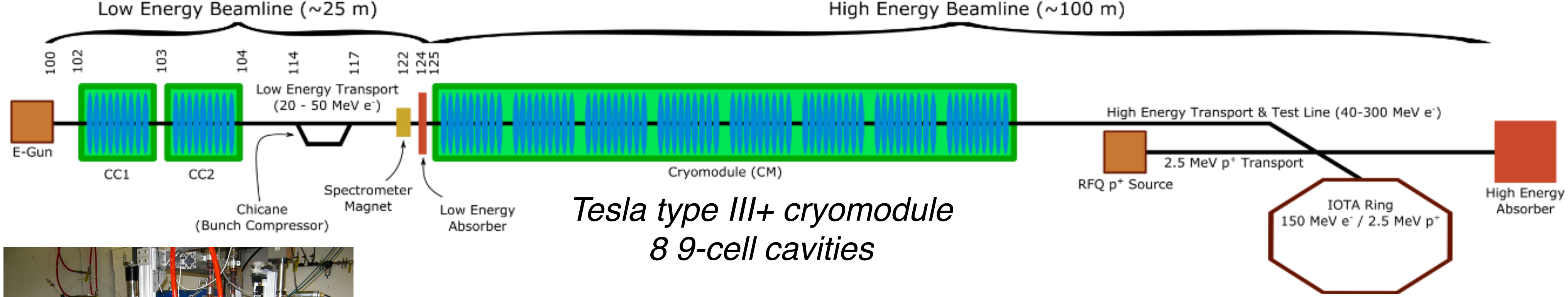


263-nm laser
3000 micropulses @ 3 MHz
5 Hz rep. rate

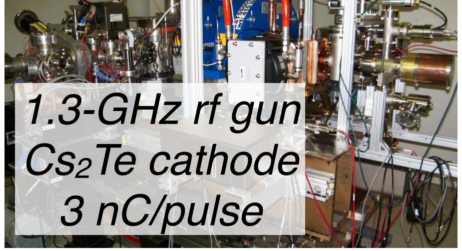
Superconducting Linac



srf Tesla-type
booster cavities

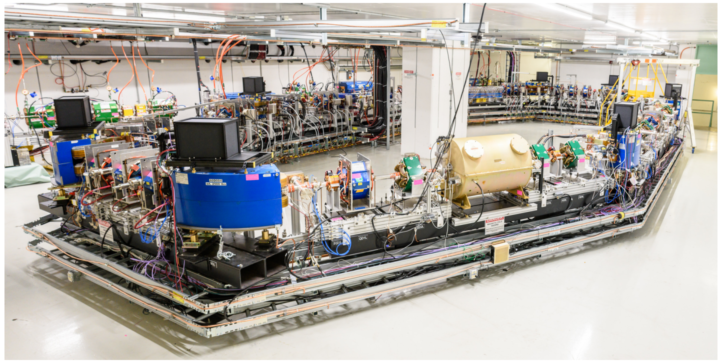


Tesla type III+ cryomodule
8 9-cell cavities



1.3-GHz rf gun
Cs_2Te cathode
3 nC/pulse

IOTA Storage Ring

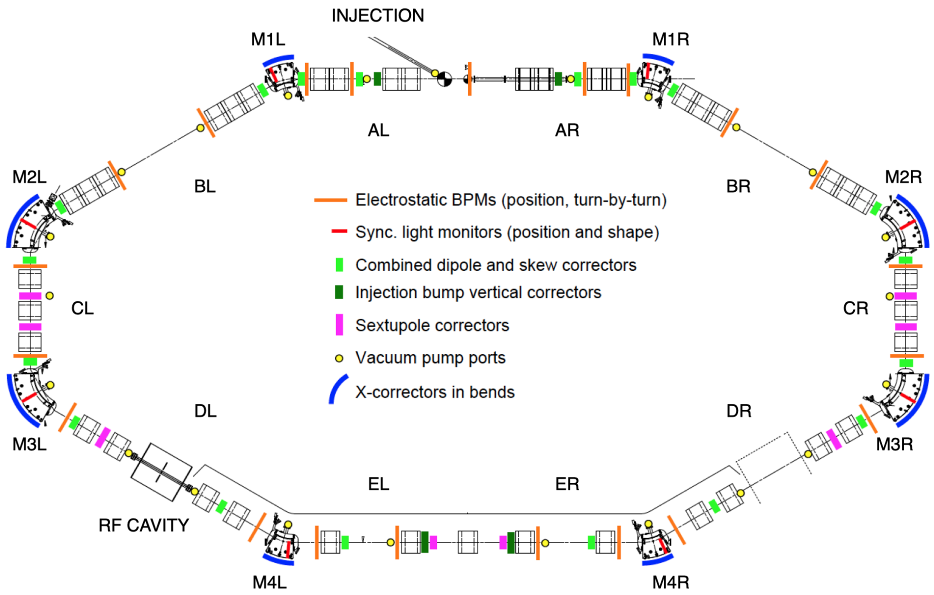


Antipov et al., JINST **12**, T03002 (2017)
Broemmelsiek et al., New J. Phys. **20**, 113018 (2018)

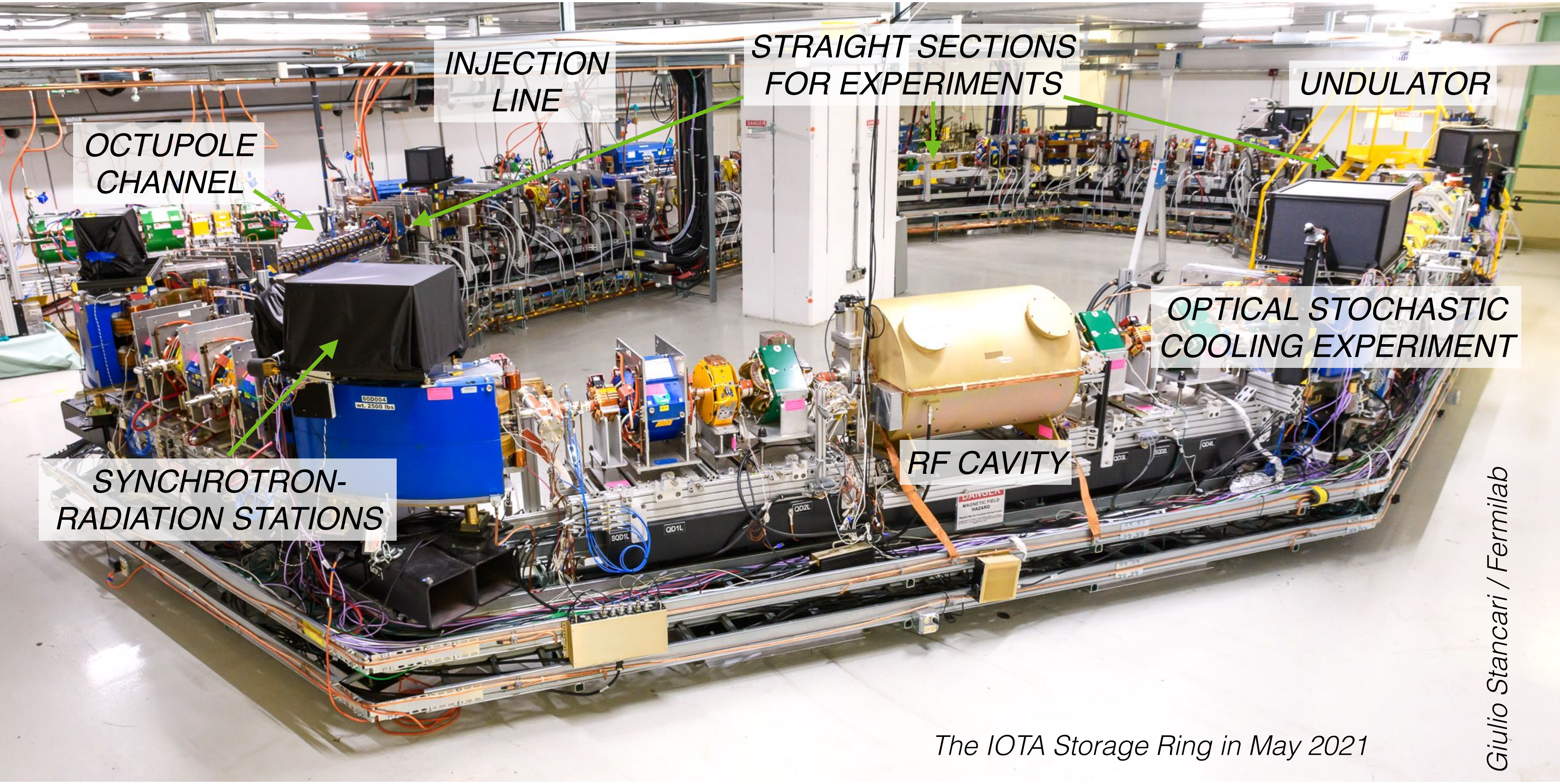
Main features of IOTA

- **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, $\lvert\Delta\nu_{\text{sc}}\rvert$	$< 10^{-3}$	0.5



The IOTA storage ring



The IOTA Storage Ring in May 2021

Giulio Stancari / Fermilab

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

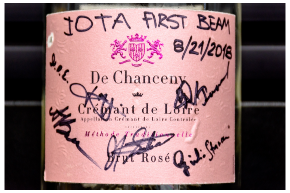
Examples of RESEARCH AREAS

- **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



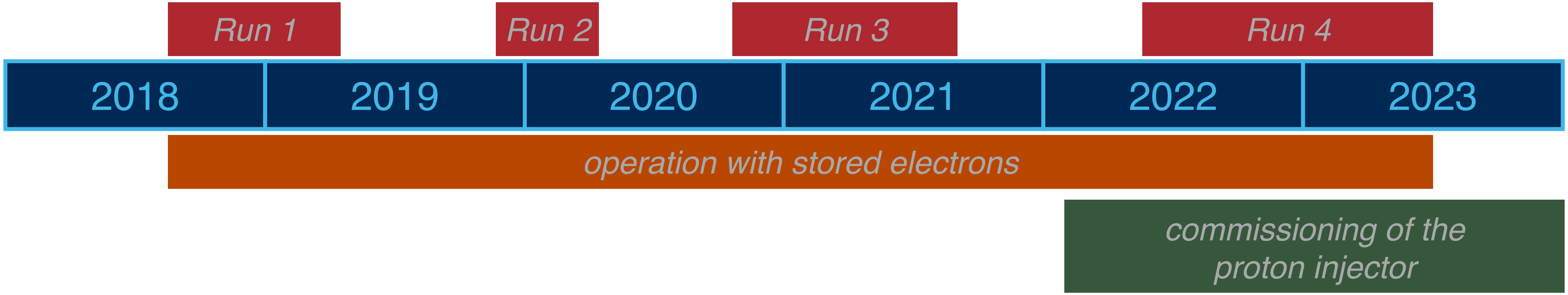
Construction completed (July 2018)

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
- Commissioning of protons in IOTA in 2024; next electron run in early 2025

Nonlinear Integrable Optics (NIO)

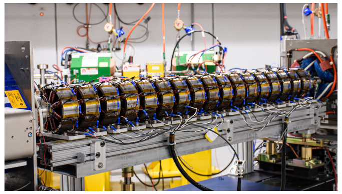
(1) In a real accelerator, is it possible to have a **nonlinear lattice** that stabilizes the beam via **Landau damping**, suppresses resonances and does **not reduce dynamic aperture**?

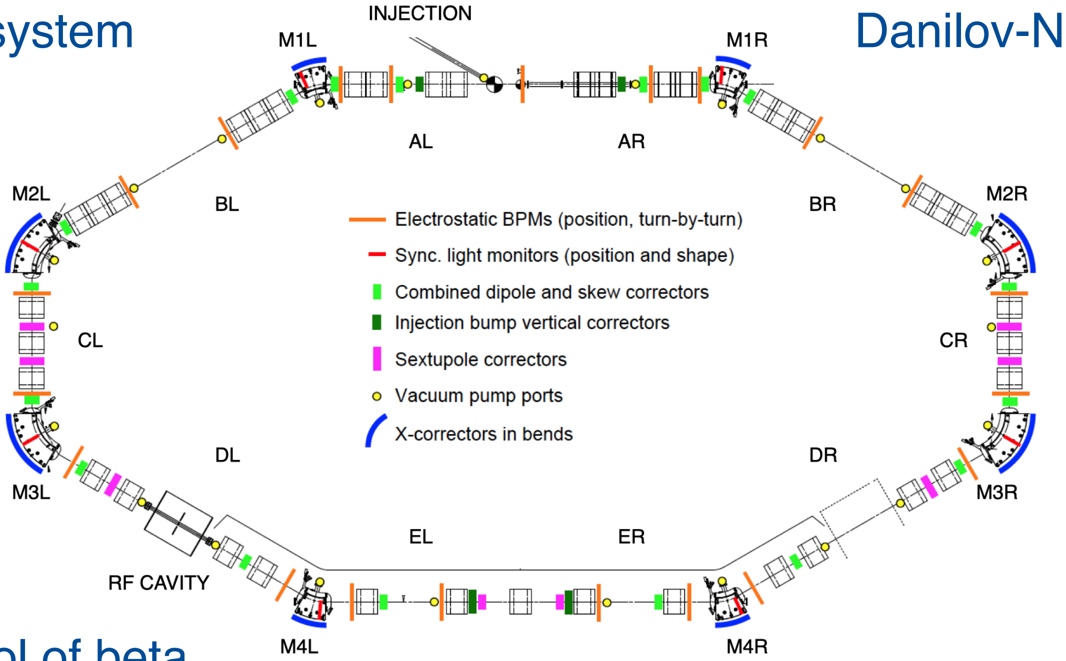
(2) How **robust** are nonlinear integrable lattices agains imperfections?

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

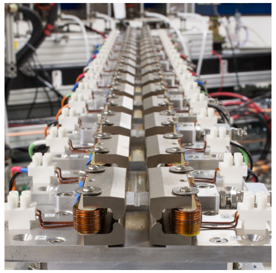
Two implementations:

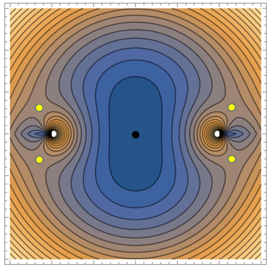
(A) Segmented octupole channel
Quasi-Integrable (QI) system





(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

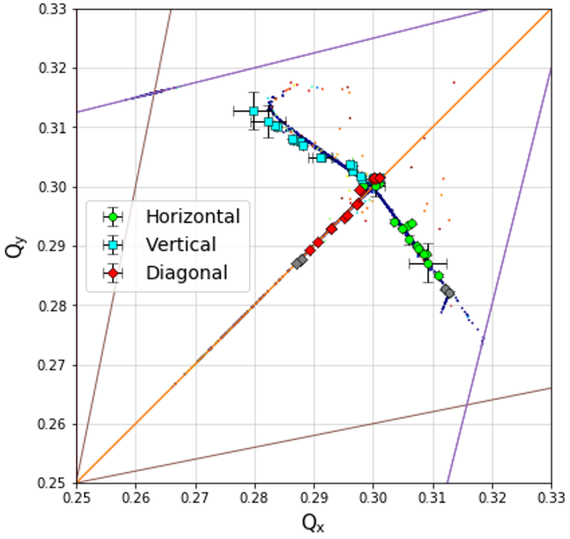
Observed large detuning with amplitude

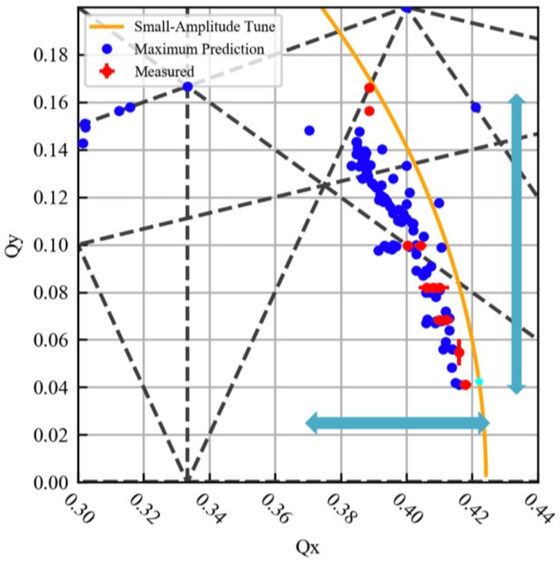
QI system (octupole channel)

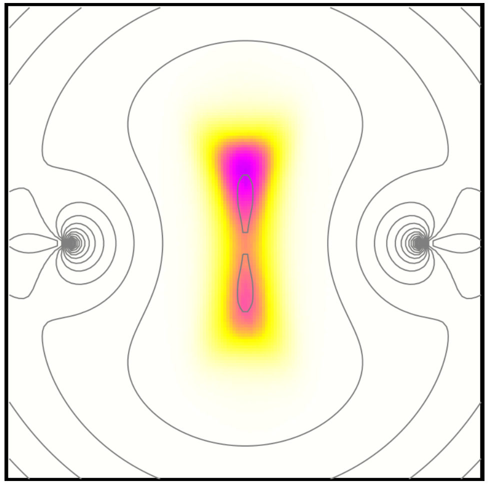
Achieved detuning of 0.04

DN system (elliptic potential)

Achieved detuning of 0.08







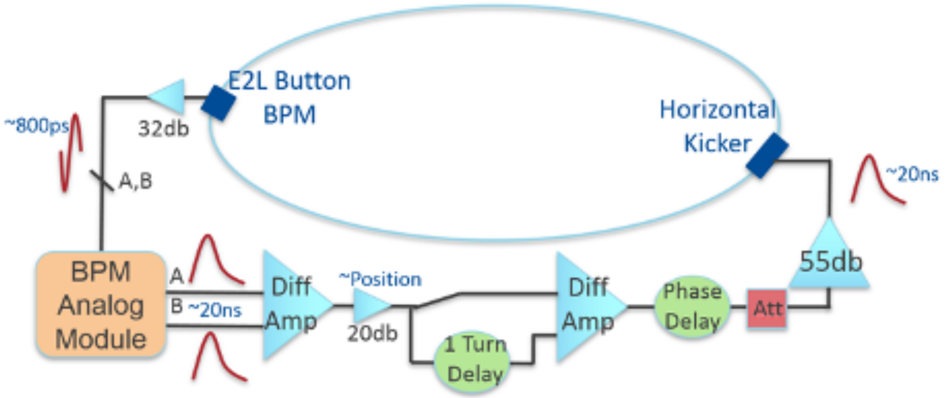
Crossed integer resonance without beam loss

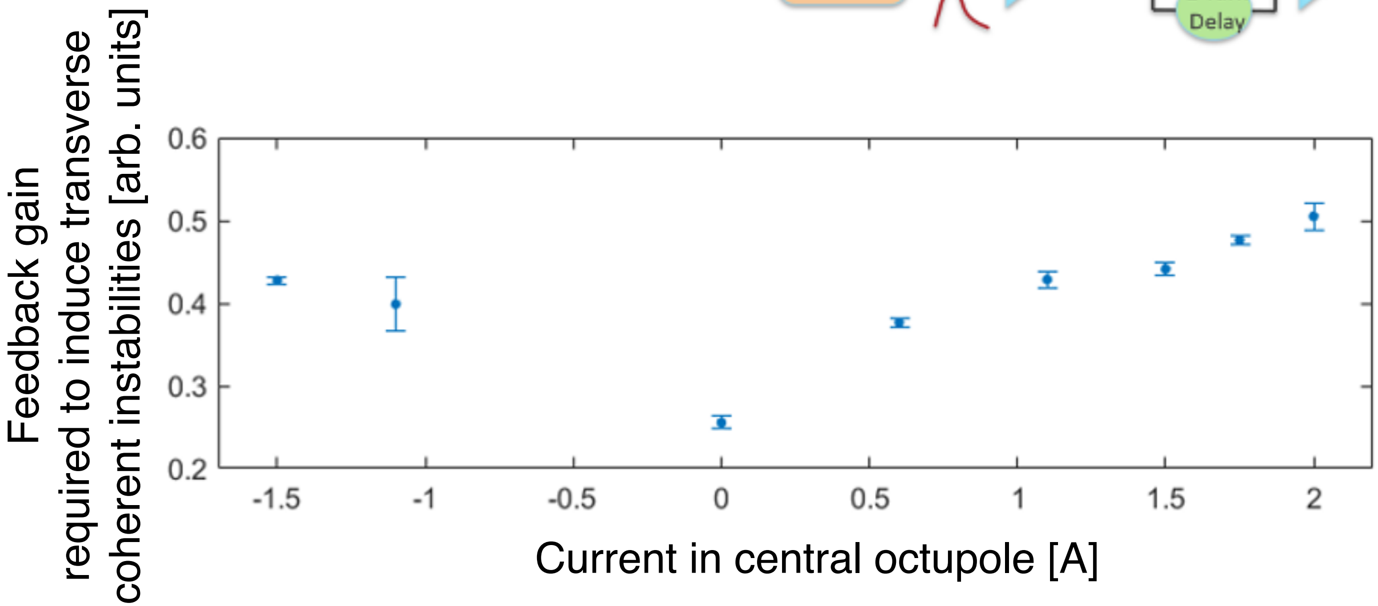
Valishev et al., IPAC 2021
Kuklev, PhD Thesis, U. Chicago (2021)
Szustkowski, PhD Thesis, NIU (2020)
Wieland et al., IPAC 2024

Observed predicted transverse splitting into stable beamlets

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

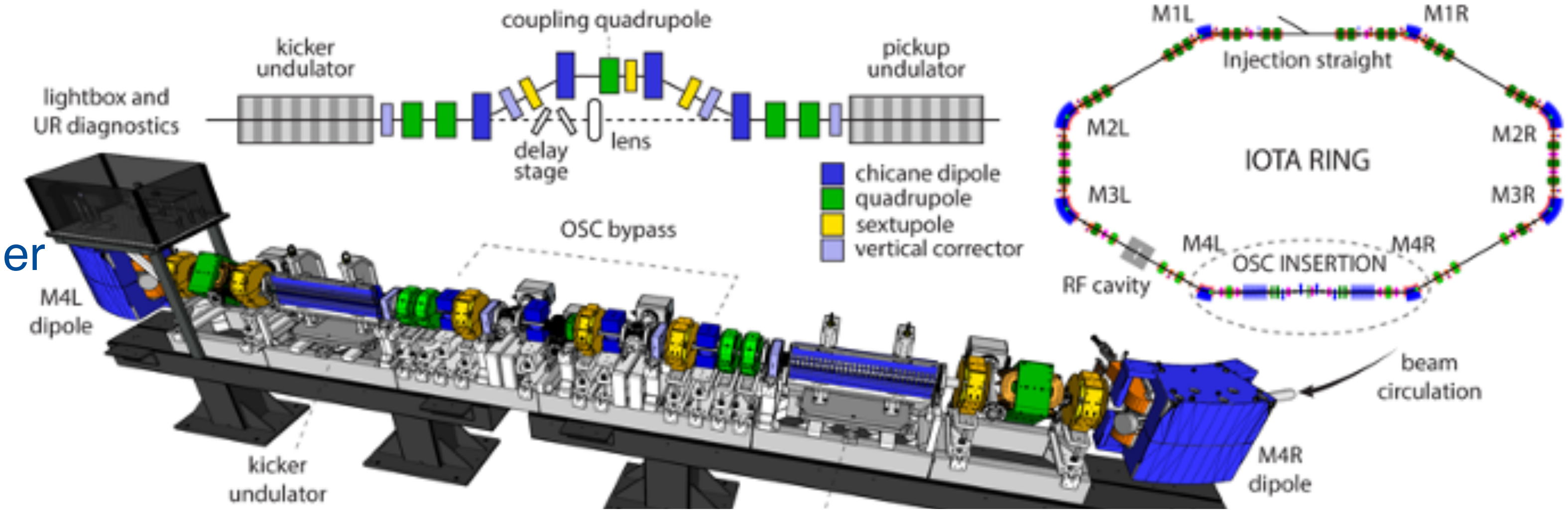
Valishev et al., IPAC 2021
Eddy et al., Beams-doc-9171 (2021)
Duncan et al., IPAC 2024

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

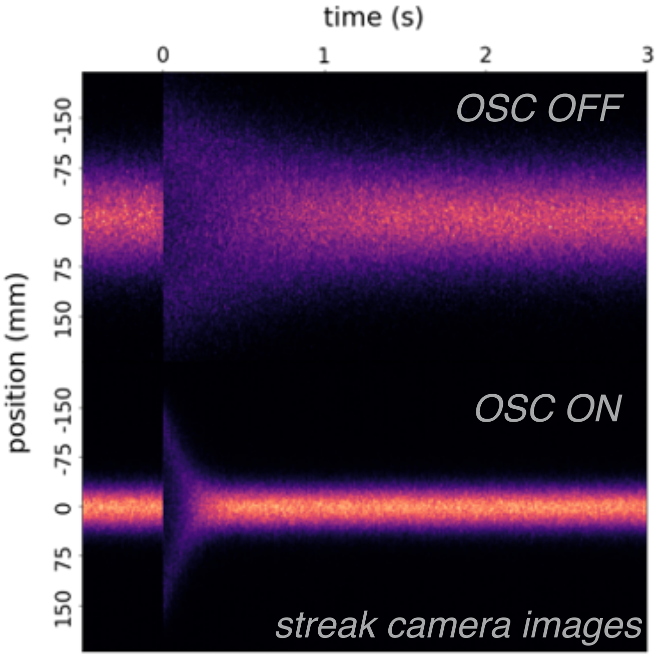


Technological challenges:

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

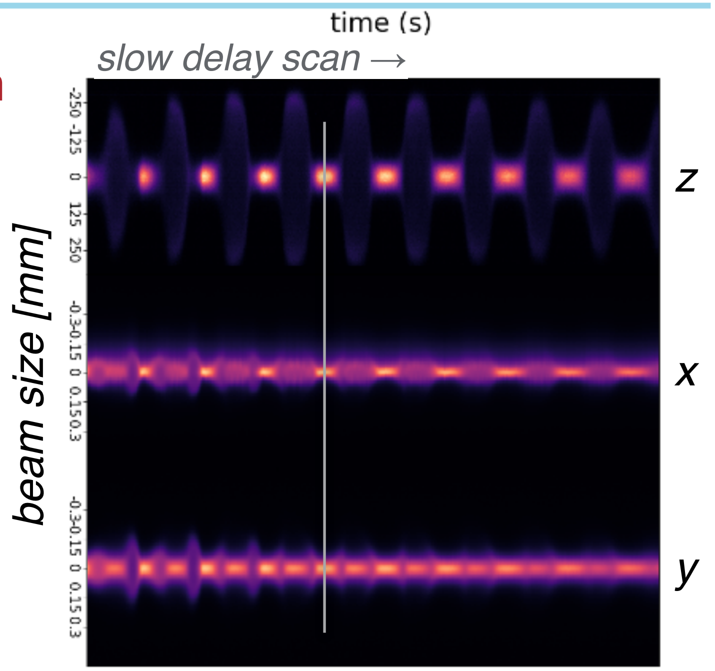
van der Meer, RMP **57**, 689 (1985)
Mikhailichenko and Zolotorev, PRL **71**, 4146 (1993)
Zolotorev and Zholents, PRE **50**, 3087 (1994)
Lebedev, Jarvis et al., JINST **16**, T05002 (2021)

Optical stochastic cooling: first results



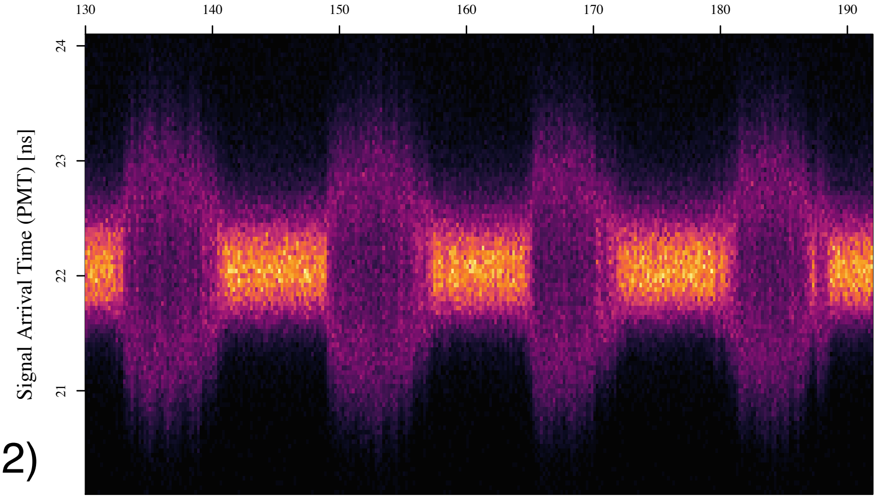
↑ *rf ping*

Simultaneous cooling in all degrees of freedom



Observed heating and cooling of a single electron!

Measured cooling rates 8x faster than natural radiation damping

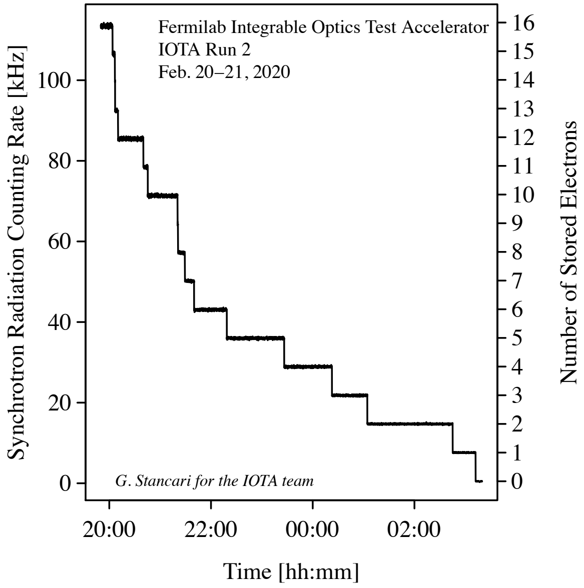


Jarvis, Lebedev, Romanov et al., Nature **608**, 287 (2022)

Dynamics of single electrons

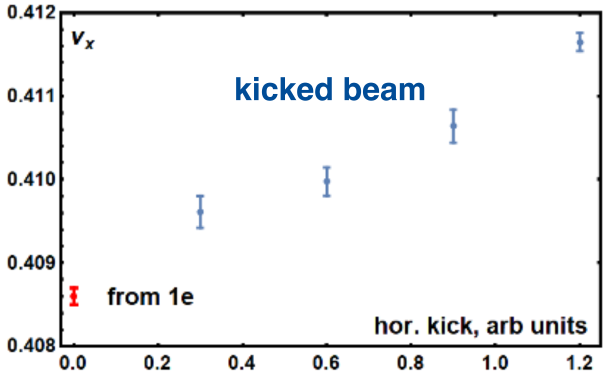
Single electrons (or a known given number of electrons) can be stored for minutes to hours (in a single bucket or multiple buckets)

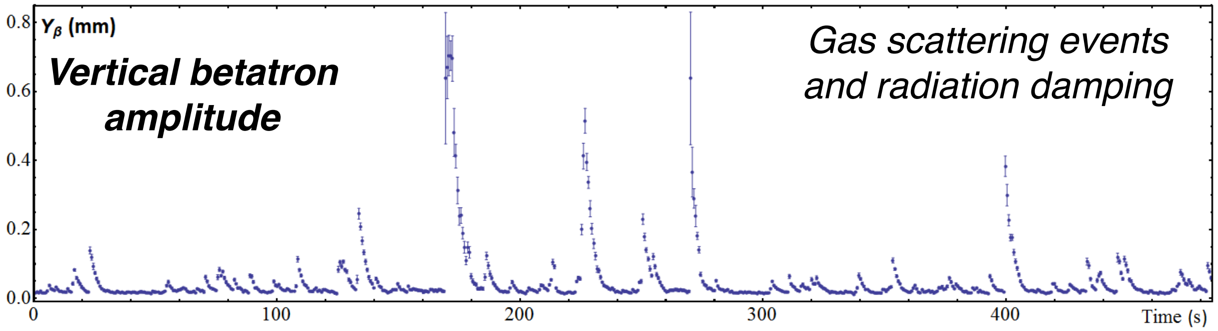
Discrete steps in intensity decay



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

Tune vs. amplitude

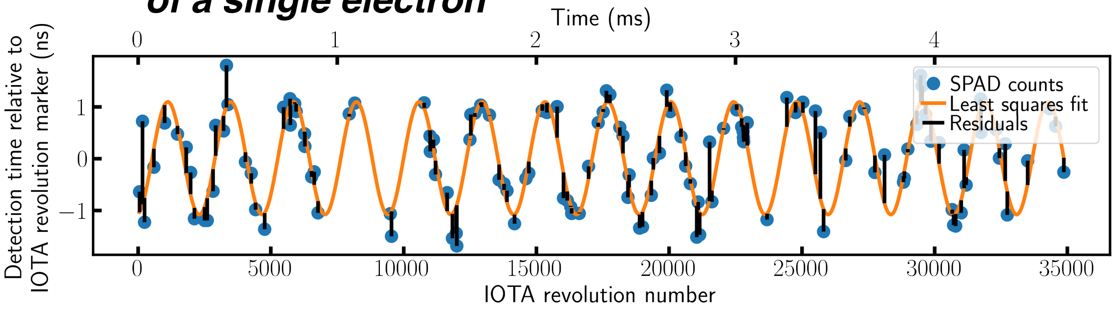




Vertical betatron amplitude

Gas scattering events and radiation damping

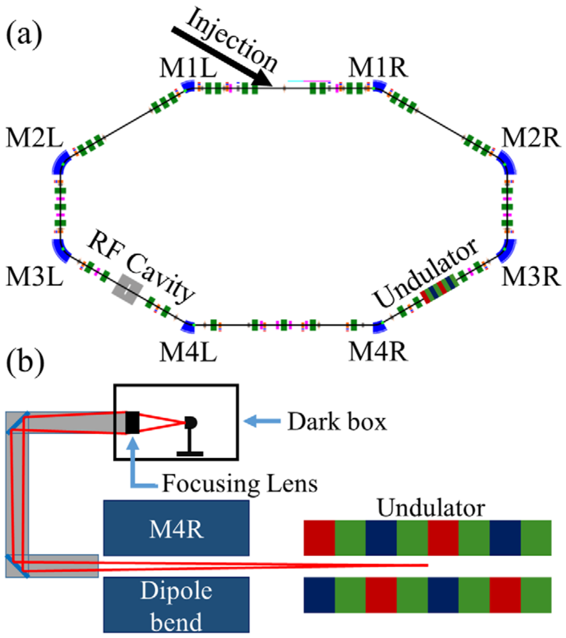
Synchrotron oscillations of a single electron



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)
Romanov et al., IPAC 2024

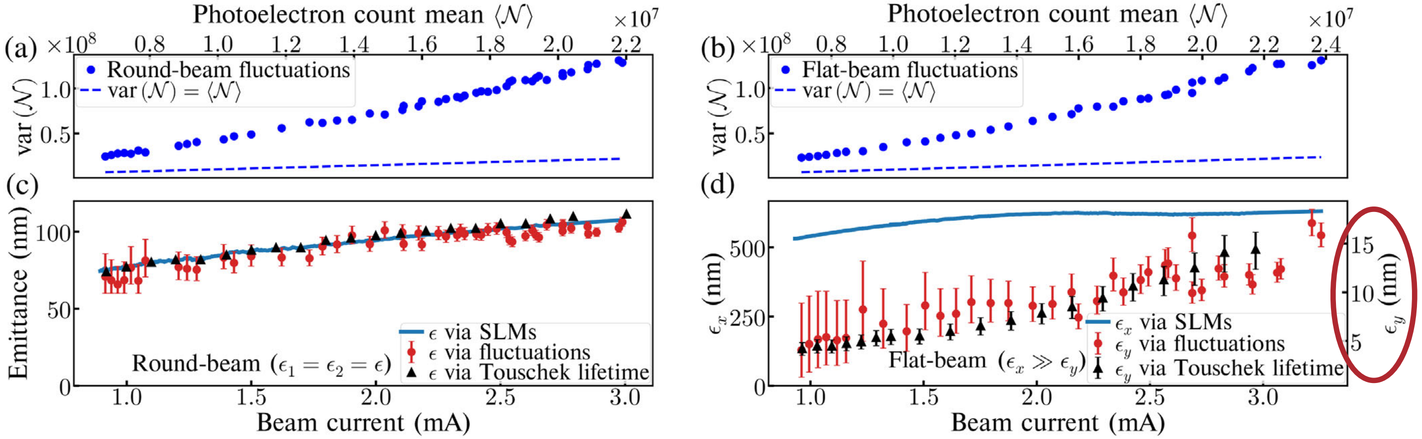
Classical and quantum properties of undulator radiation

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

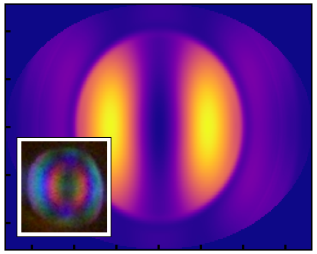


Verified that intensity fluctuations contain a calculable term that depends on beam sizes (interference)

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



Intensity fluctuations can be used to infer small beam emittances

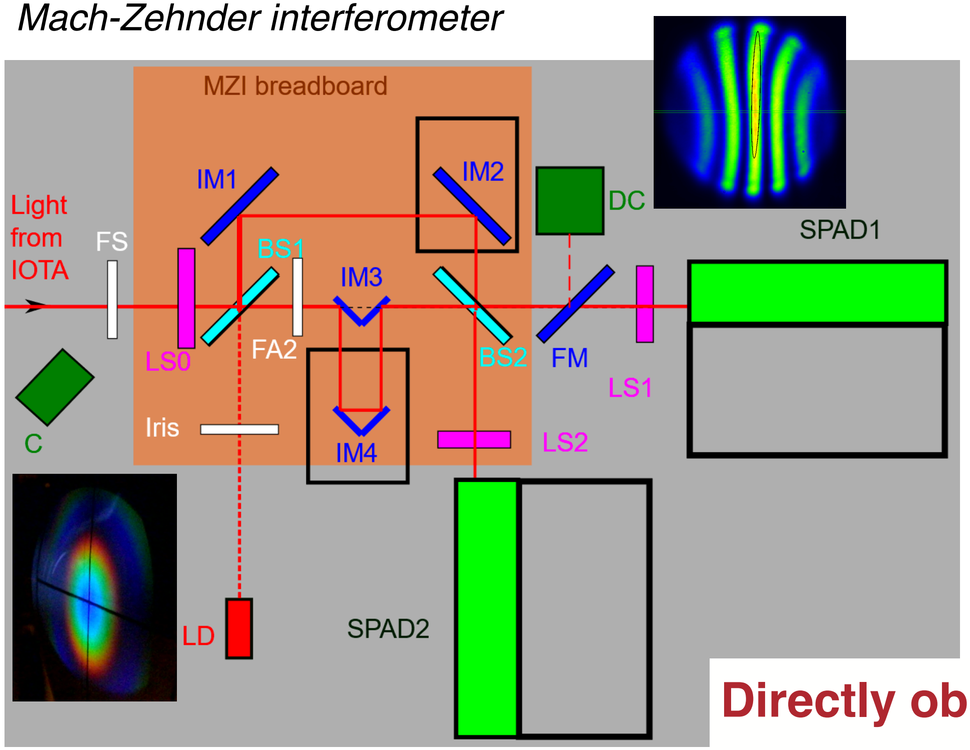


Lobach et al., PRAB **23**, 090703 (2020)
Lobach et al., PRAB **24**, 040701 (2021)
Editors' Suggestion, Featured in Physics → Lobach et al., PRL **126**, 134802 (2021)
Winner of the 2022 APS DPB Award → Lobach, PhD Thesis (2021)

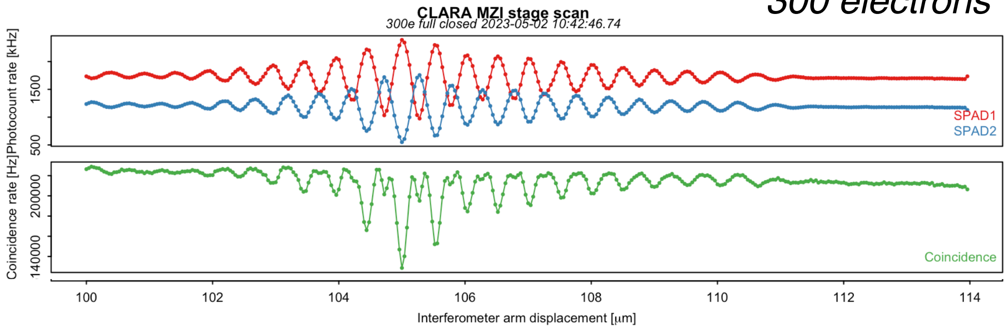
Interferometry of radiation from single electrons

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?

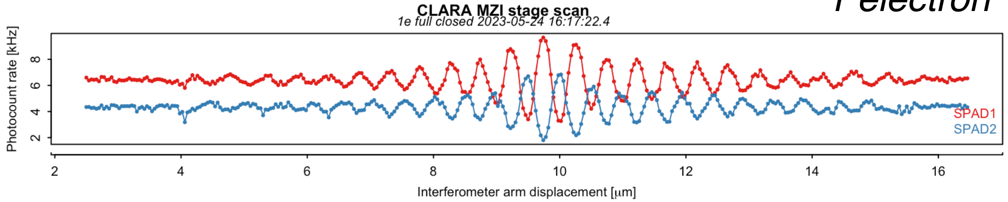
Mach-Zehnder interferometer



300 electrons



1 electron



Directly observed the temporal coherence of undulator radiation from single electrons at the femtosecond scale

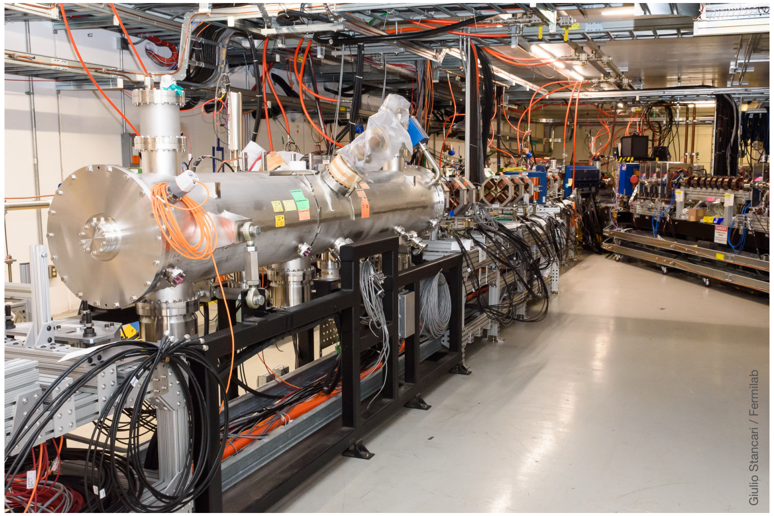
Observables: count rates vs. delay, distributions of arrival times, correlations

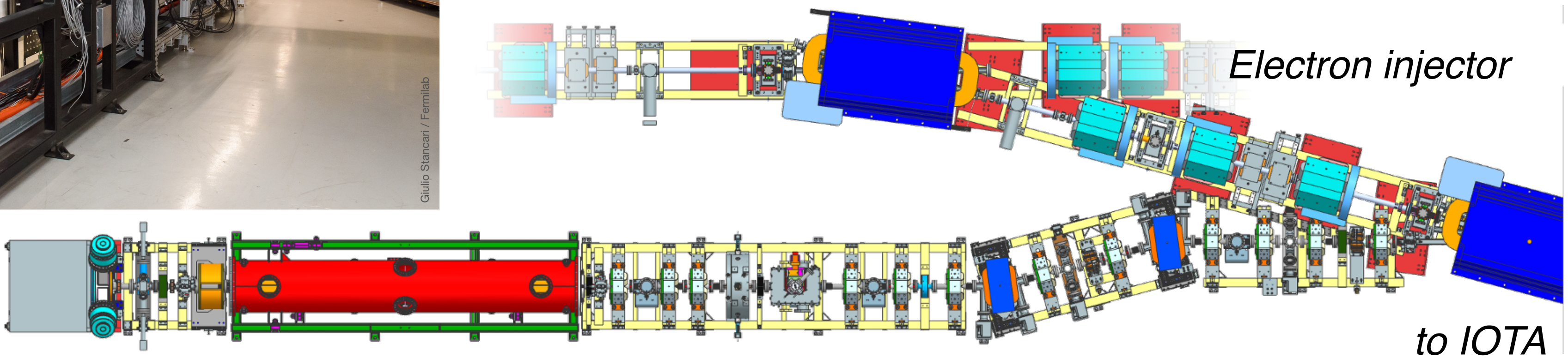
Stancari et al., IPAC 2024

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.)
$\Delta\nu_{\mathrm{sc}} \sim 0.5$





Electron injector

to IOTA

50-kV duoplasmatron source

RFQ

	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*

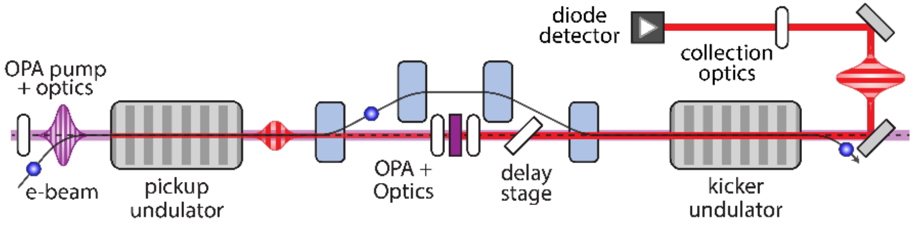
IOTA (Proton)	Proton Beam Energy	2.5	*MeV*
	Relativistic β	$2.66 \cdot 10^{-3}$	
	Circumference	40	*m*
	Proton RF Frequency	2.19	*MHz*
	Revolution Period	1.83	*µs*
	RF Voltage	50	*kV*
	Geometric Emittance	0.3	*µm*
	Δp/p (RMS)	0.3	*%*
	Beam Current	8	*mA*
	RMS Beam size β = 10 m	4.5	*mm*
	Momentum compaction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

Examples of Upcoming Research

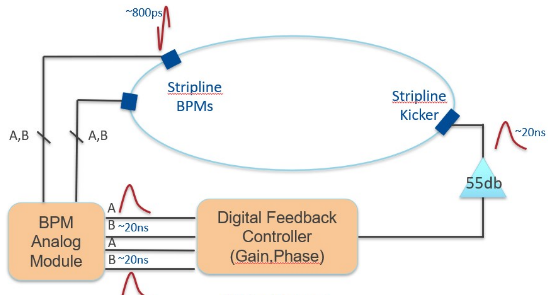
Optical Stochastic Cooling with Amplification

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

Jarvis et al., ECA Grant



Ainsworth et al., ECA Grant

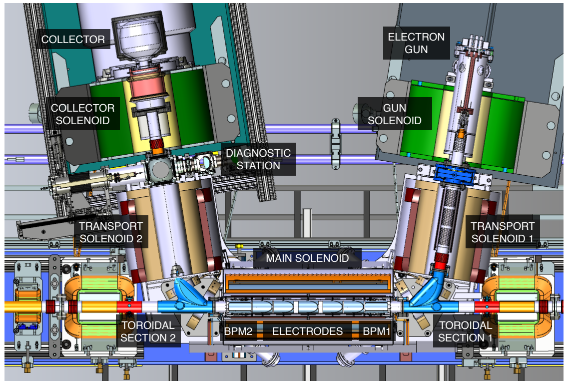


Instabilities, Space Charge and Controlled Feedback

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

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)

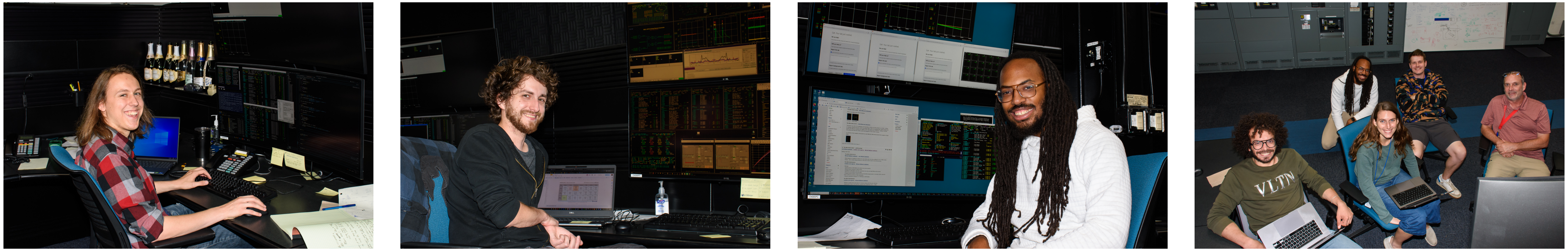
Possible Research Topics Relevant for FCC

What can we learn about a 90-km machine in a 40-m ring?

Education and Training

– *dedicated research machines*: FAST linac and IOTA storage ring

– *design* of experiments, *construction*, *data taking* and *analysis* on a time scale of months

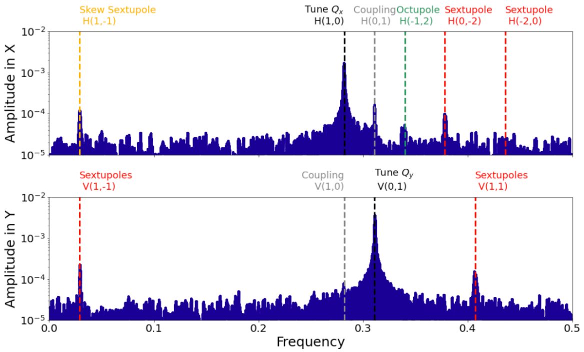


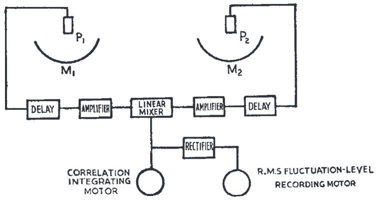
Example of collaboration with CERN:
M. Hofer, N. Kuklev, A. Romanov, G. Stancari, S. Szustkowski, R. Tomás Garcia and A. Valishev,
“Nonlinear Optics Measurements in IOTA,”
CERN-ACC-NOTE-2021-0010 / FERMILAB-FN-1119-AD (2021)

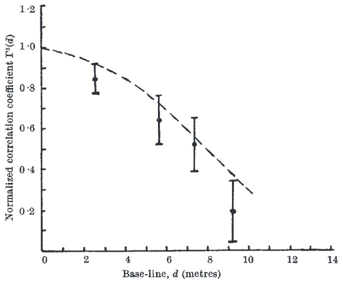
Possible Research Topics Relevant for FCC

Beam Dynamics

- beam-based alignment techniques
- measurements of nonlinear beam optics
- nonlinear beam manipulations including radiation damping
- implementation of advanced lattices
- …

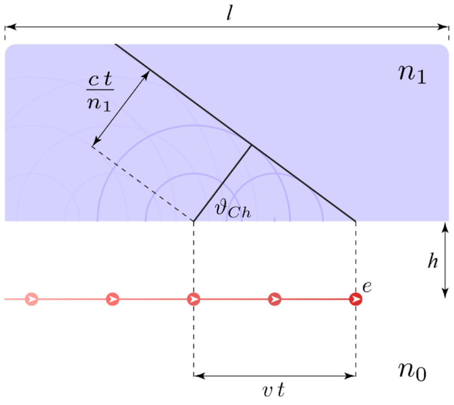


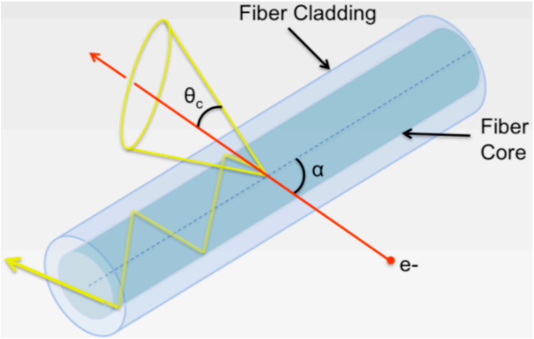




Beam Diagnostics

- quantum-optical techniques for small beam size measurements (i.e., Hanbury Brown and Twiss interferometry)
- studies on Cherenkov diffraction radiation with single electrons for non-invasive bunch monitoring
- fiber-based loss monitors
- …





Particle Detector Development

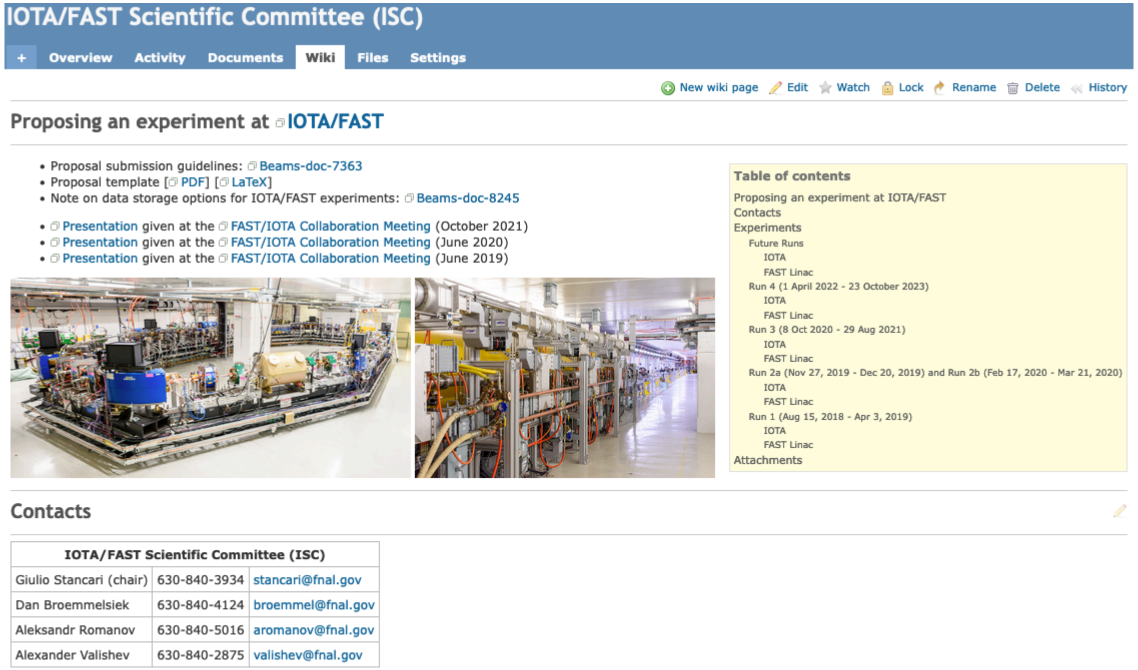
Resources

IOTA/FAST web site

fast.fnal.gov

IOTA/FAST Scientific Committee

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



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 FAST/IOTA Collaboration Meeting (October 2021)
- Presentation given at the FAST/IOTA Collaboration Meeting (June 2020)
- Presentation given at the FAST/IOTA Collaboration Meeting (June 2019)

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Collaboration Meeting 2024

indico.fnal.gov/e/62181

Special Issue of the Journal of Instrumentation

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

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

Acknowledgements

Thanks in particular to

M. Boscolo, M. Giovannozzi, M. Hofer, J. Jarvis, A. Romanov,
B. Salvachua Ferrando, R. Tomás Garcia and A. Valishev

for comments and suggestions

Conclusions

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

Dedicated facility with unique features **may enable studies for FCC**

New **ideas** and **collaborations** are welcome

Dan Svoboda / Fermilab

IOTA/FAST Collaboration Meeting, March 2024