

Accelerators and Beam Physics Research

Giulio Stancari
Fermilab

Fermilab-Pisa Summer School
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About your speaker

Senior scientist at Fermilab, Head of the Accelerator Research Department

Research

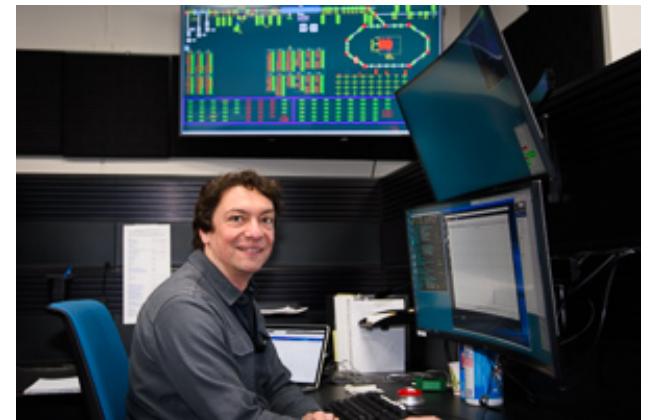
- Master and PhD at U. Ferrara / Fermilab in particle physics: charmonium spectroscopy, hadron form factors, scintillating-fiber detectors
- Post-doc at Fermilab: antiproton source, charmonium experiments
- Researcher at INFN Ferrara/Legnaro: production and trapping of radioactive francium for atomic 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, ...



Why study accelerator physics and technology?



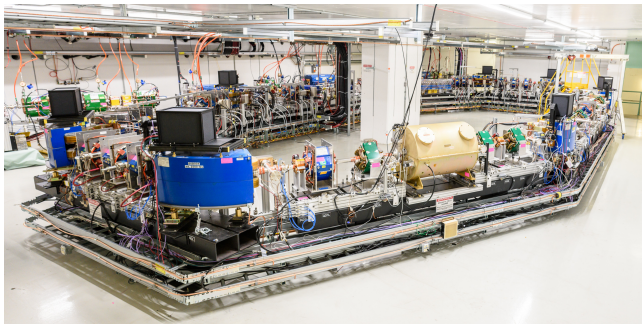
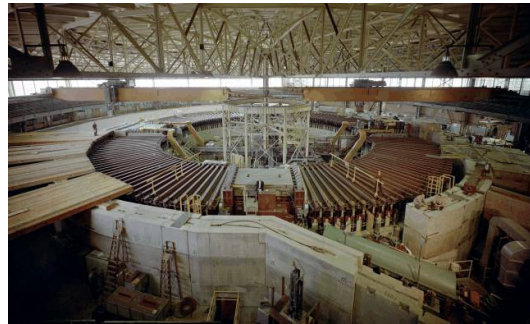
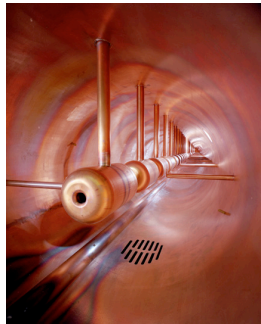
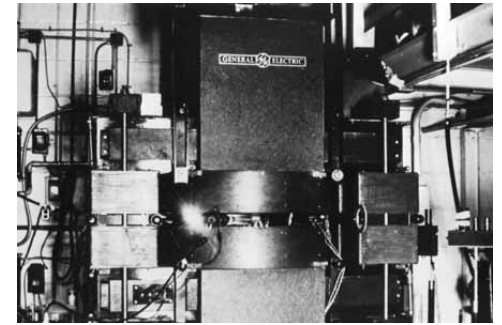
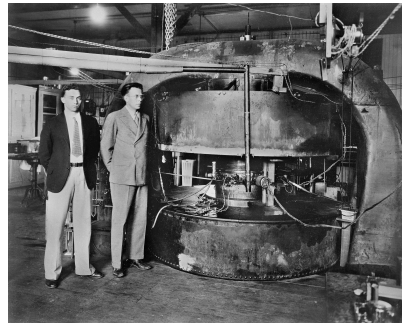
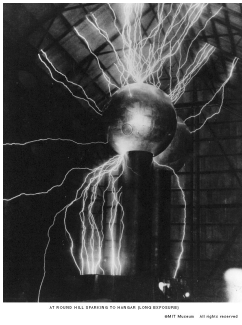
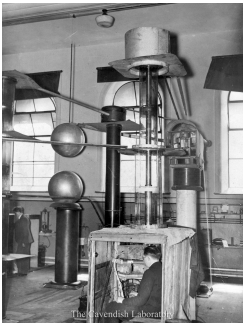
REWARDING: Connected to **fundamental science** (nuclear and particle physics, material science, biology, ...) and **exciting applications** (medical diagnostics and treatment, industrial processes, ...)

CHALLENGING and **DIVERSE:** You can find areas that match your interests in **applied math, physics, engineering, computing, ...**

RELEVANT for many fields of science and technology. Essential to **design experiments, analyze data, explore new applications**

OPPORTUNITIES: If you like the subject, there may be a **career** path for you. Several **theses, internships, fellowships** and **jobs** are available.

Evolution of particle accelerators



Interplay between **physical principles** and **technologies**

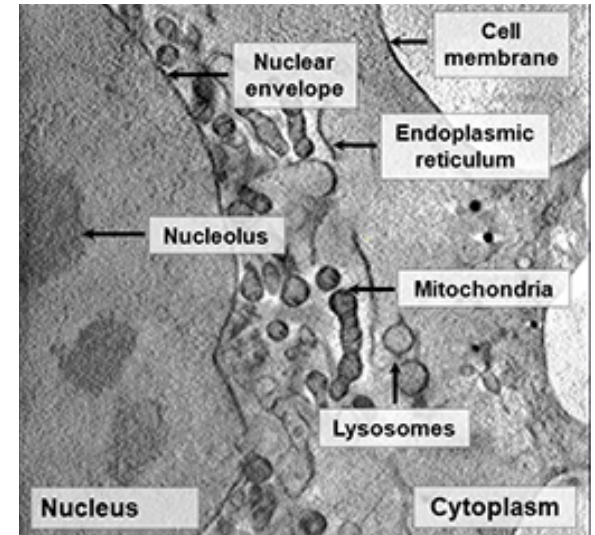
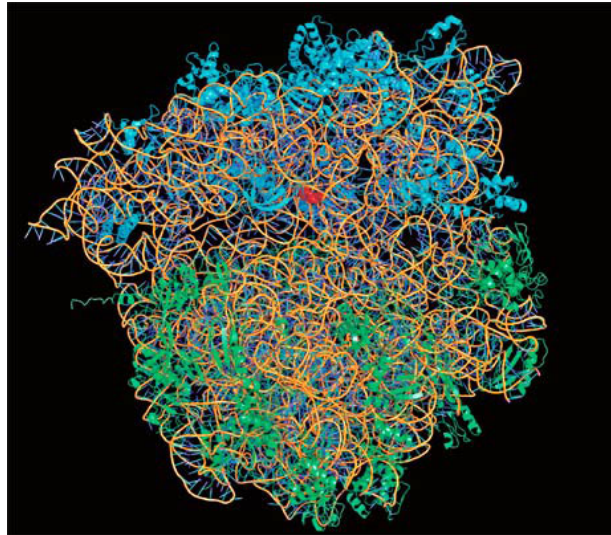
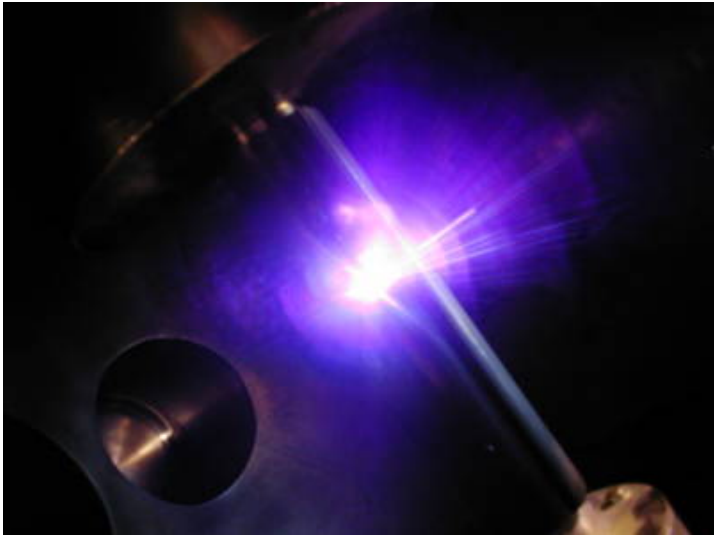
What are accelerators used for?

- **Particle and nuclear physics**

creation of new forms of matter, study of the fundamental interactions, measurement of particle properties and cross sections

- **Biology, chemistry and material science**

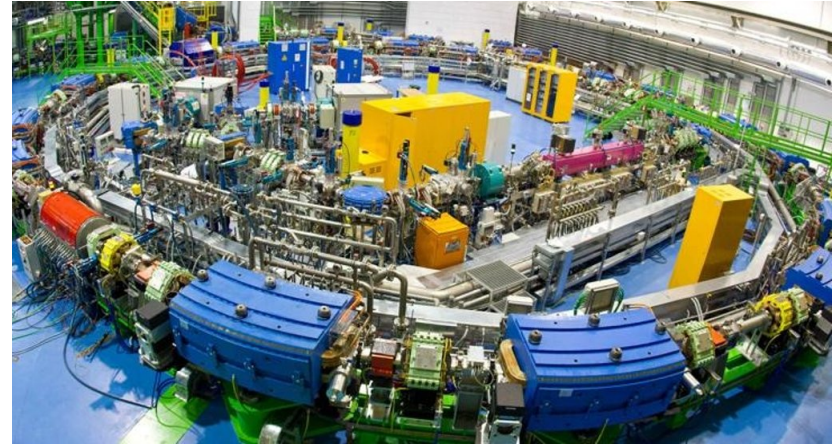
FEL (“free-electron lasers”) to measure the structure and dynamics of microscopic systems with synchrotron light, neutron sources to investigate the structure of solids, ...



What are accelerators used for?

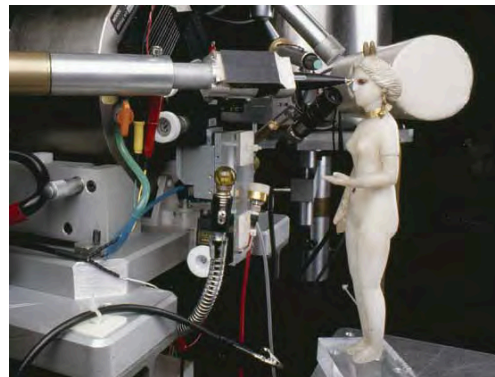
- **Medicine**

radiotherapy, hadron therapy, isotope production for diagnostics, sterilization,...



- **Archeology and art**

^{14}C dating, sensitive chemical analyses of small samples, creating art



What are accelerators used for?

- **Industrial processes**

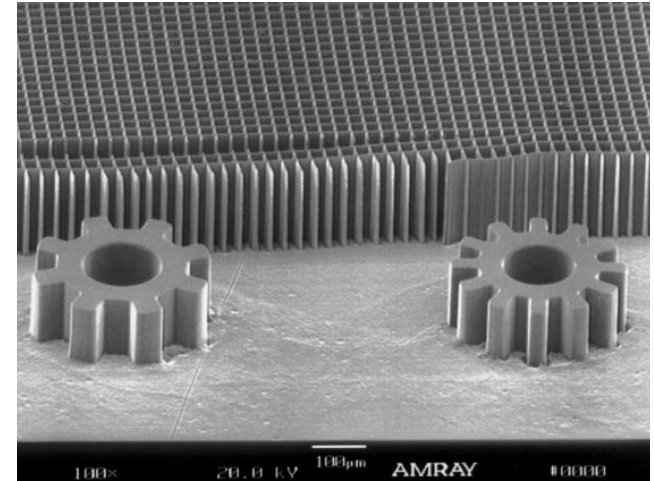
ion implants in semiconductors, micro-lithography, food sterilization, polymerization, treatment of materials

- **Defense**

detection of illicit cargo, neutralization of suspicious packages, ...

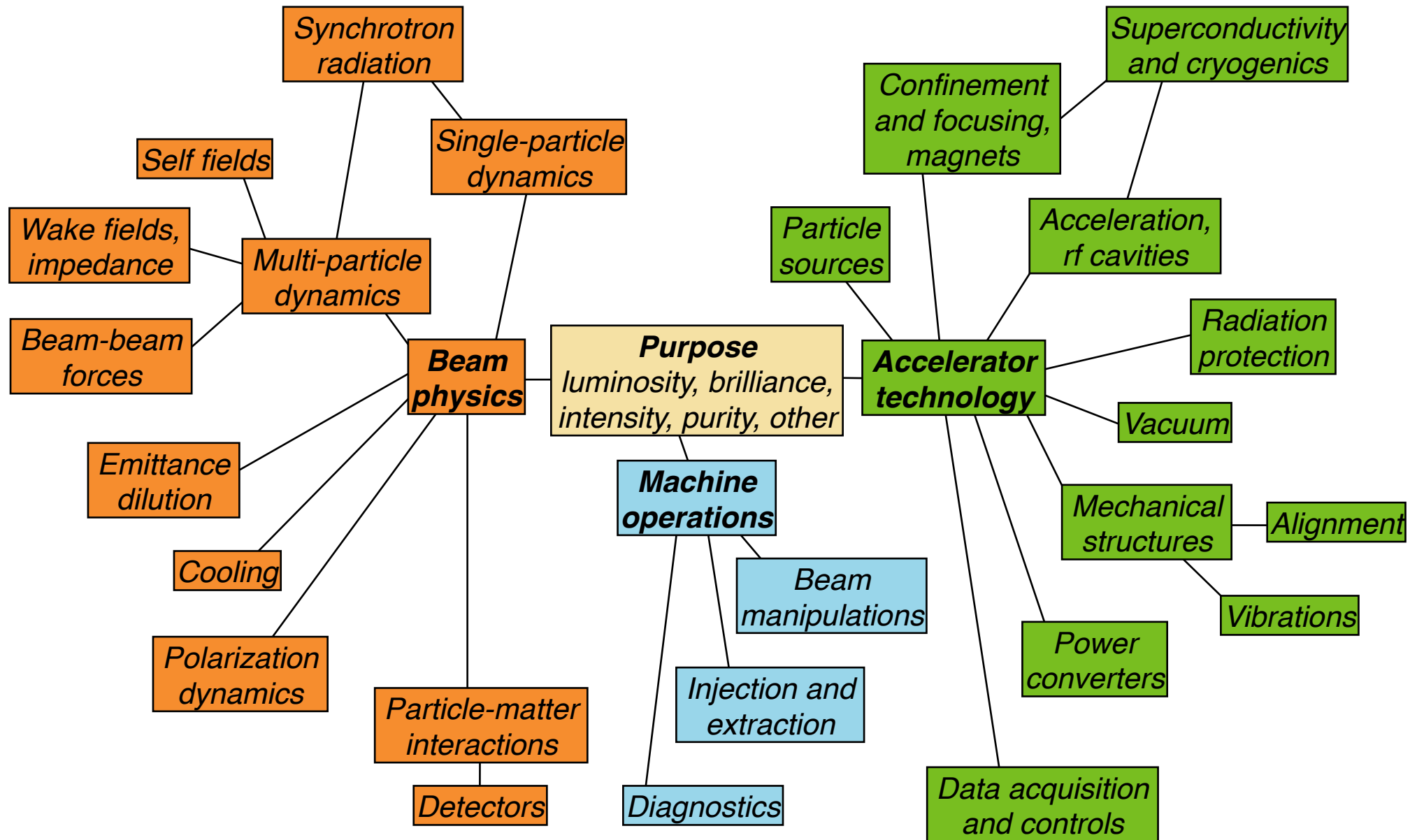
- **Energy and environment**

activation of nuclear fission reactors (Accelerator-Driven Systems), nuclear fusion, treatment of radioactive waste, ...



There are **tens of thousands of accelerators in the world**. Most of them are used in **industry** and **medicine**.

Accelerator physics and technology concept map

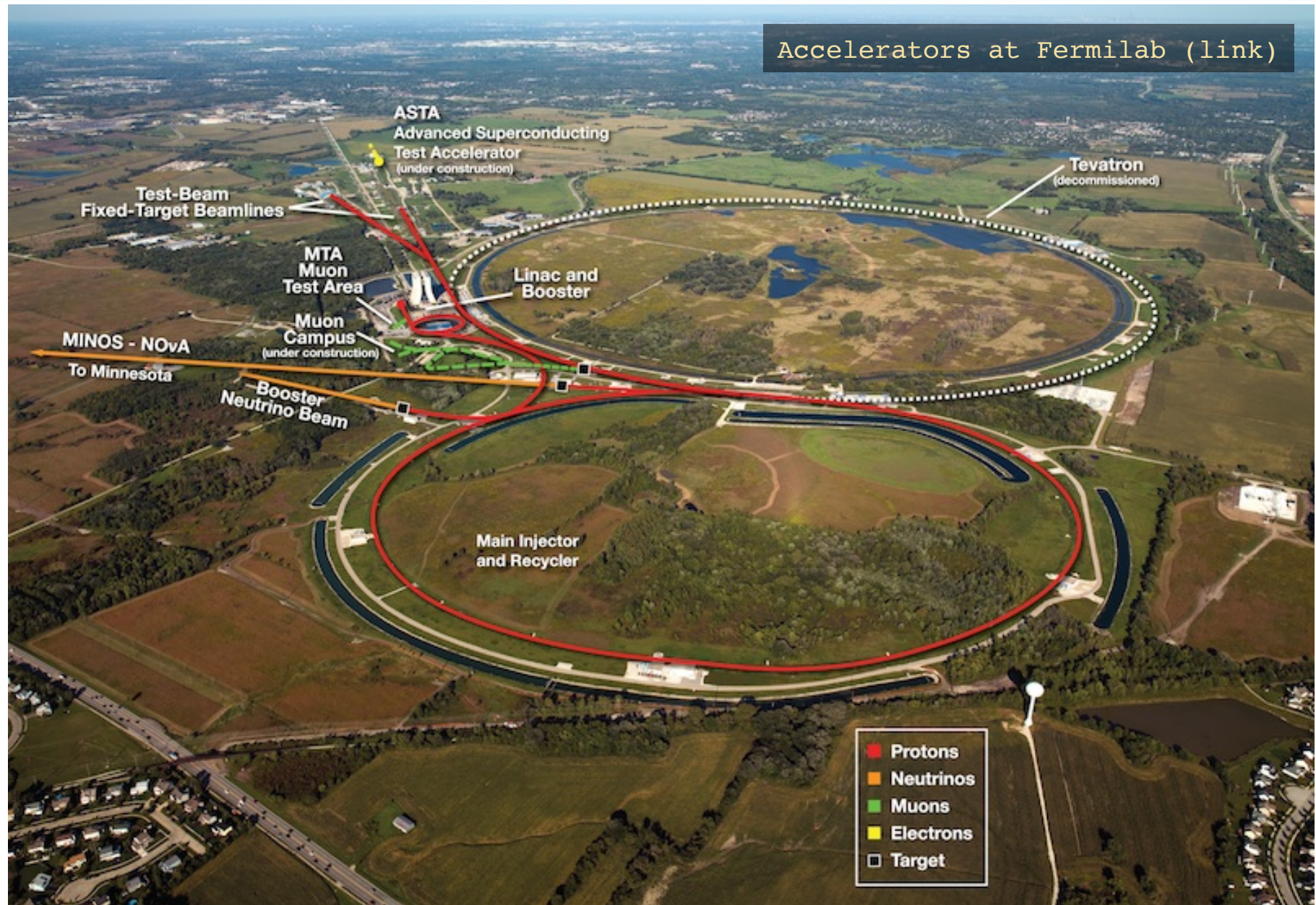


The Fermilab campus

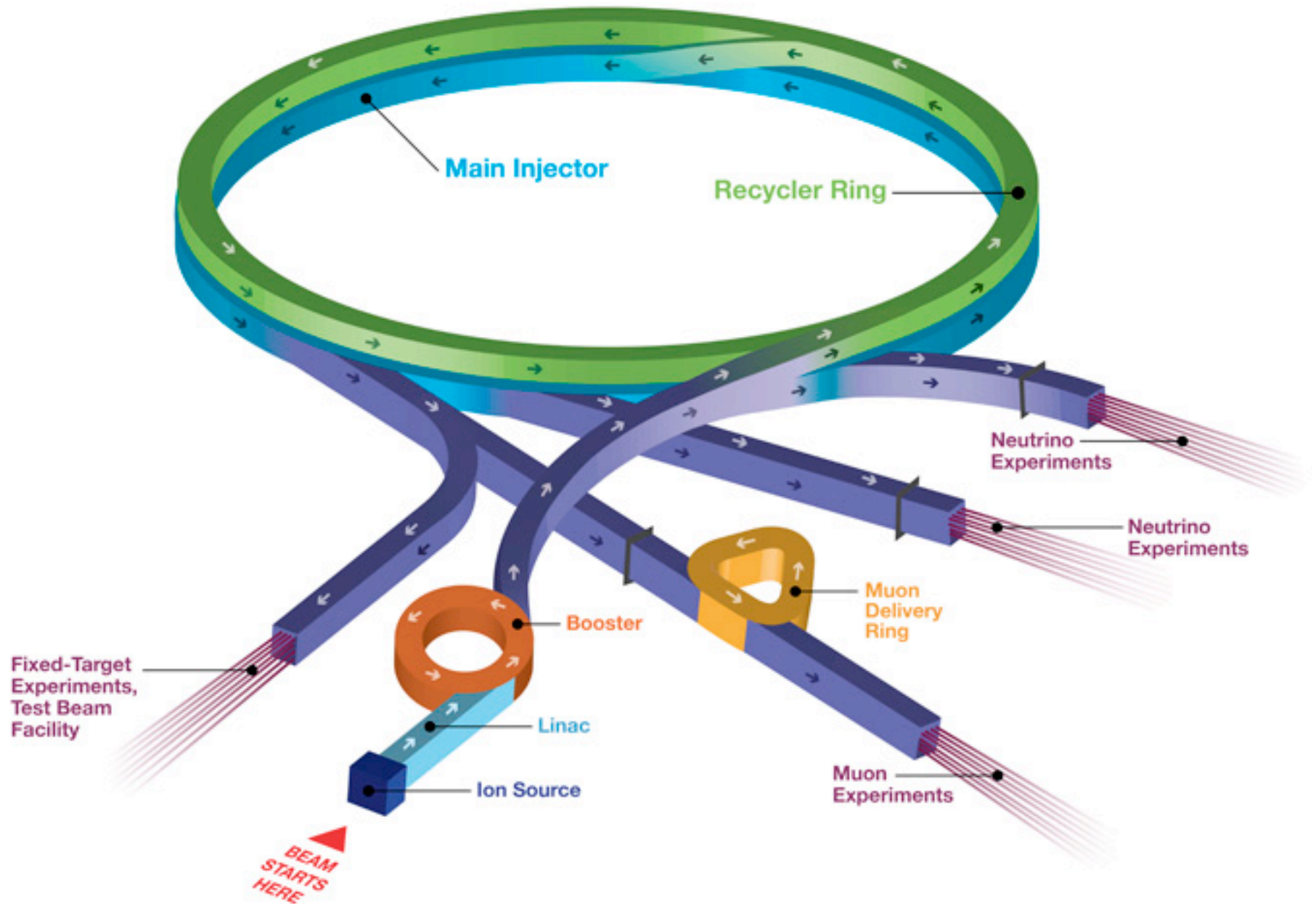


*Main particle physics laboratory in US
Thousands of international collaborators
1700 employees
27-km² site*

The Fermilab accelerator complex

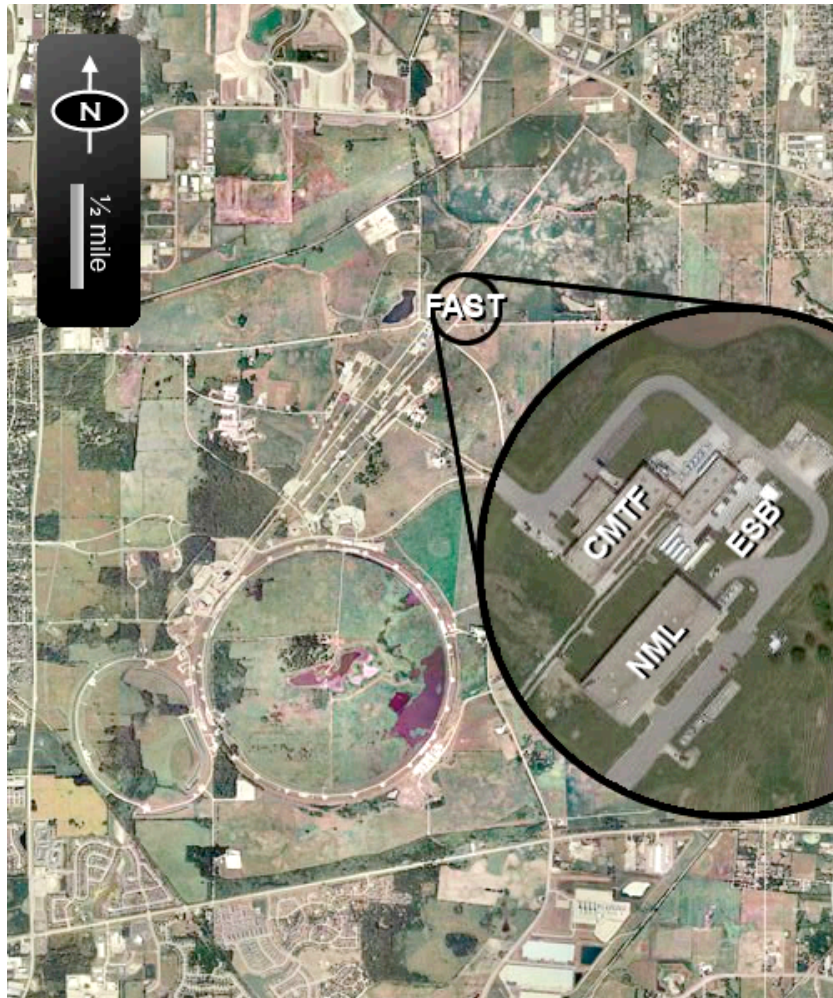


The Fermilab accelerator complex



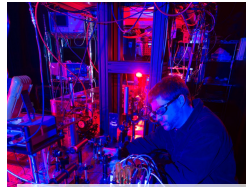
IOTA and the FAST Facility at Fermilab

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



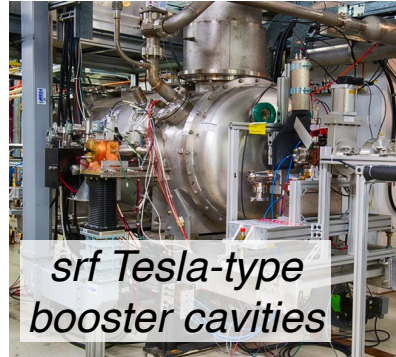
Overview of IOTA/FAST

Photoinjector



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

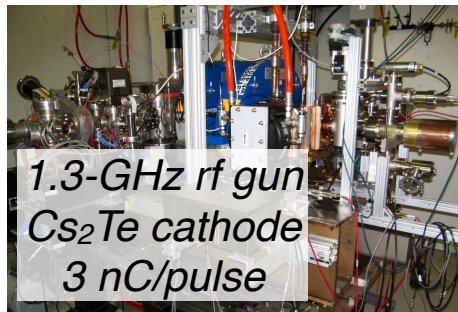
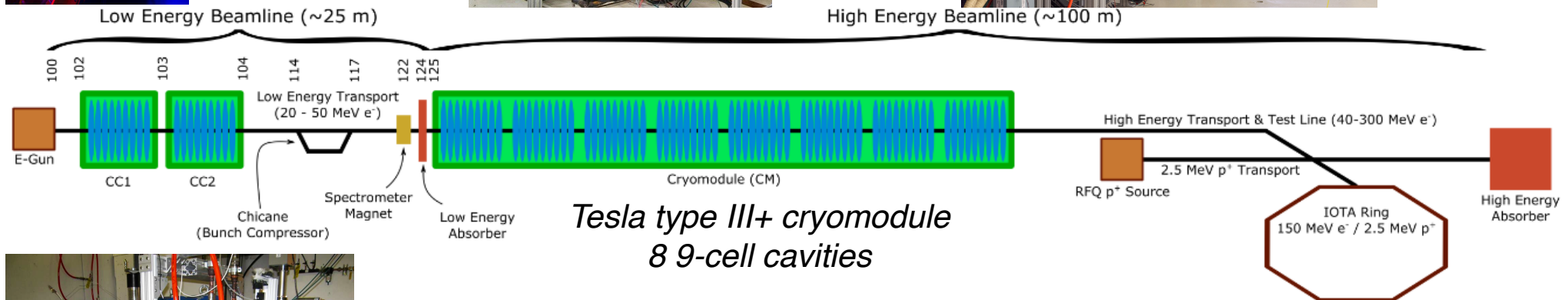
Superconducting Linac



srf Tesla-type
booster cavities

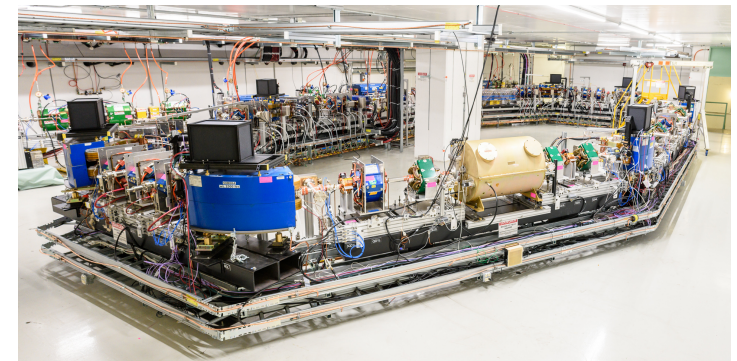


High Energy Beamline (~100 m)



1.3-GHz rf gun
Cs₂Te cathode
3 nC/pulse

IOTA Storage Ring



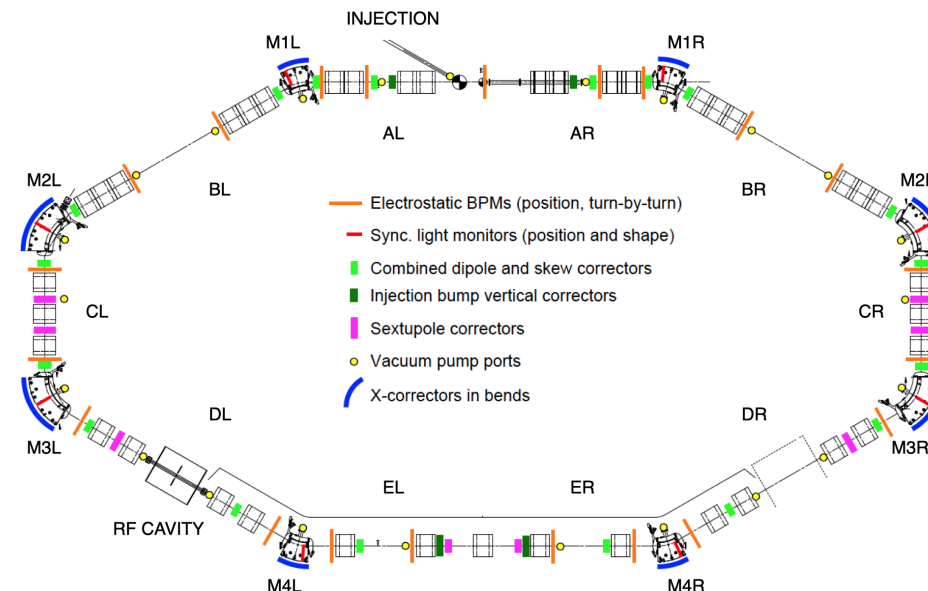
Antipov et al., JINST **12**, T03002 (2017)

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

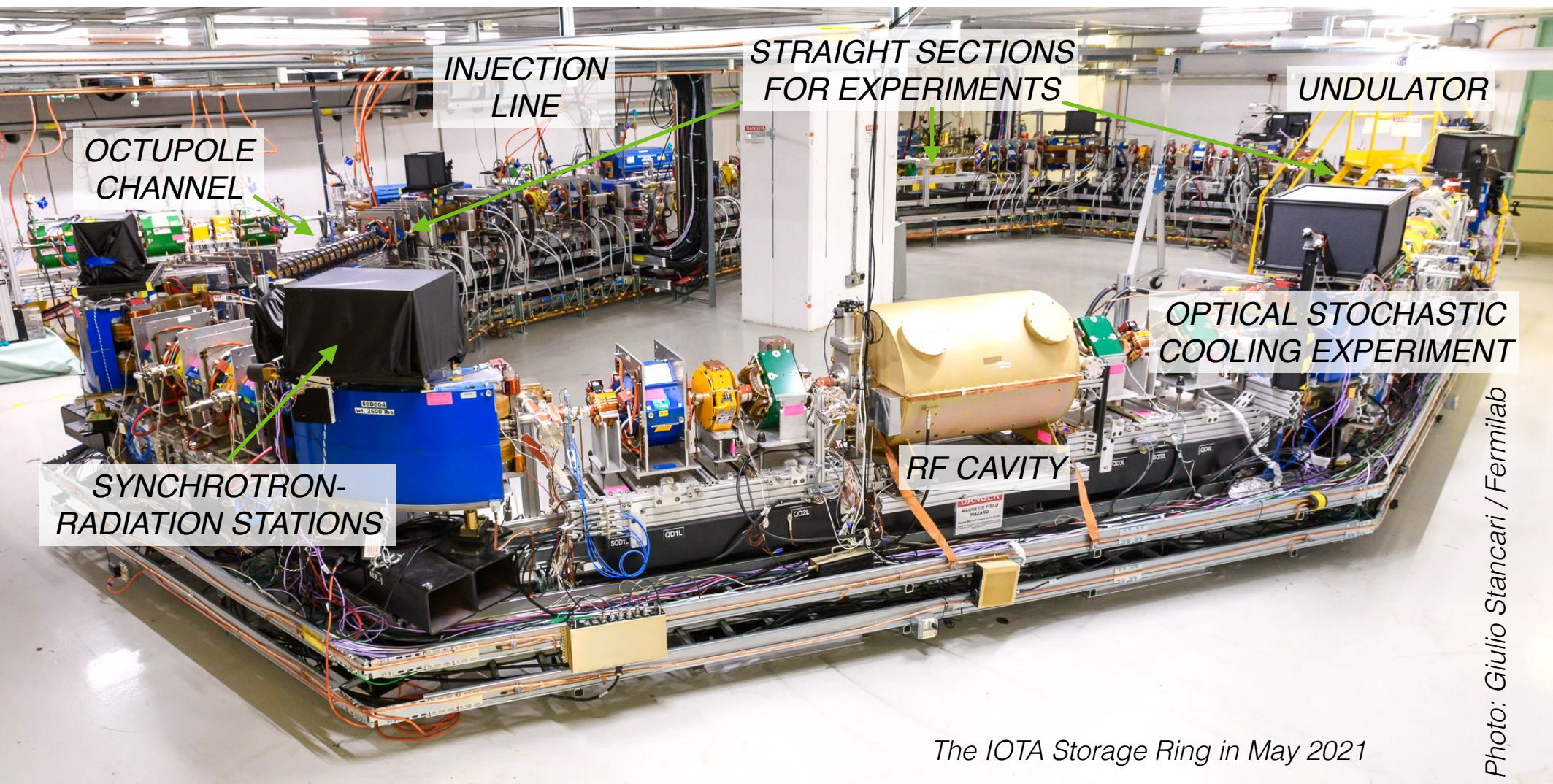
Main features of IOTA

- **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, $\delta_p = \Delta p/p$	$1-4 \times 10^{-4}$	$1-2 \times 10^{-3}$
Radiation damping times, $\tau_{x,y,z}$	0.2–2 s	–
Max. space-charge tune shift, $ \Delta\nu_{\text{sc}} $	$< 10^{-3}$	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**
- **machine learning** 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
experiments*

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

*COVID-19 lockdown
(March 2020)*

Run 1

Run 2

Run 3

Run 4

2018

2019

2020

2021

2022

operation with stored electrons

*commissioning of
the proton injector*

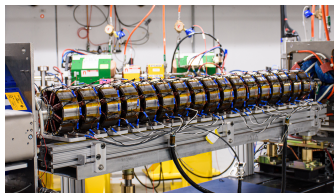
- The machine runs beam a few months per year
- Experimental runs are interleaved with shutdowns for maintenance and installations

Nonlinear Integrable Optics (NIO)

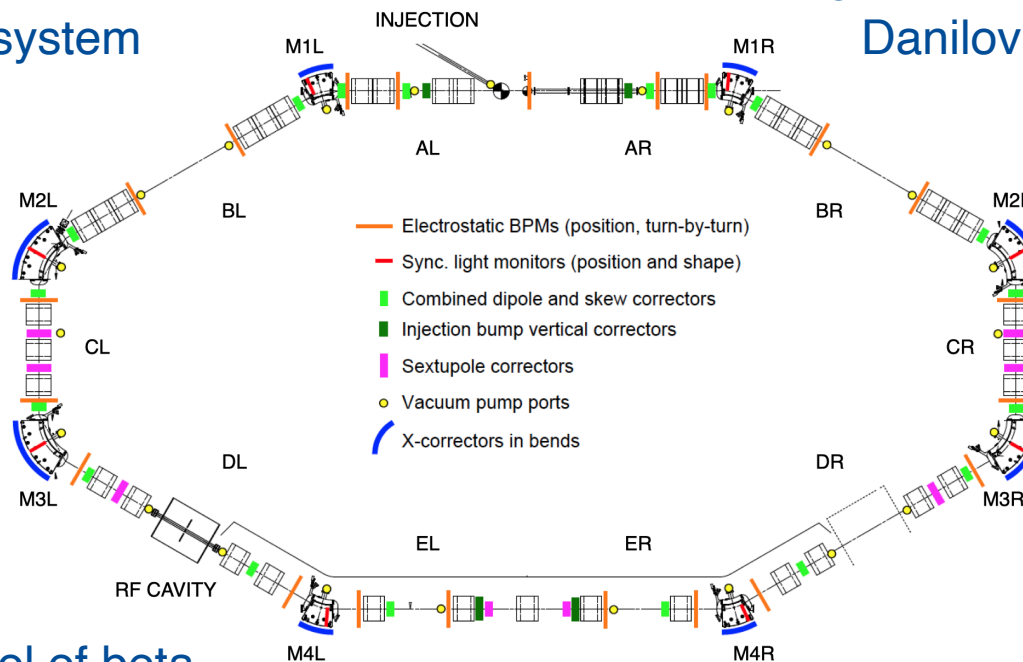
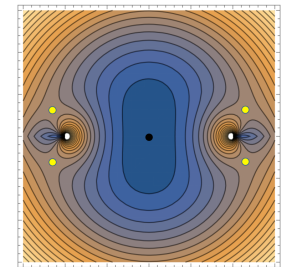
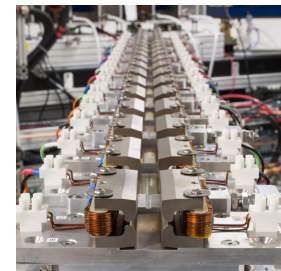
- (1) In a real accelerator, is it possible to have a **nonlinear lattice** that stabilizes the beam via **Landau damping**, suppresses resonances and does **not reduce dynamic aperture**?
- (2) How **robust** are nonlinear integrable lattices against imperfections?
- (3) Can the benefits of NIO be **demonstrated 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 ($\sim 1\%$) and phase advances ($\sim 10^{-3}$) through the nonlinear section

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

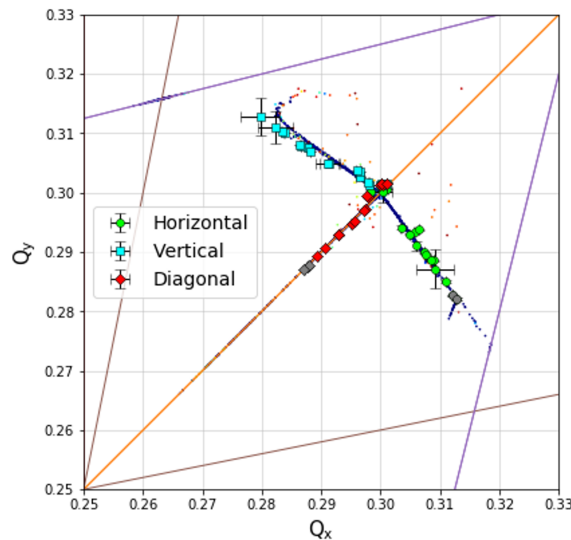
NIO experiments

Demonstrated integrable focusing systems experimentally

Observed large detuning with amplitude

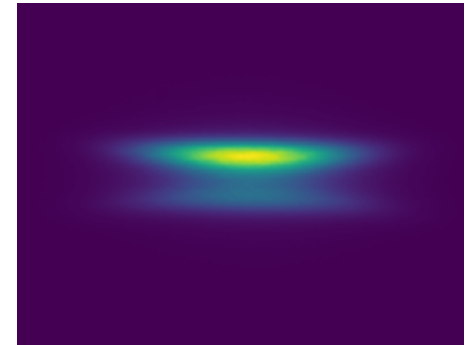
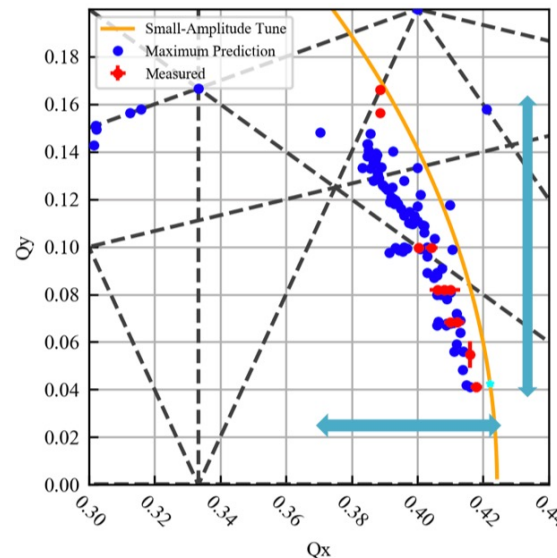
QI system (octupole channel)

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**

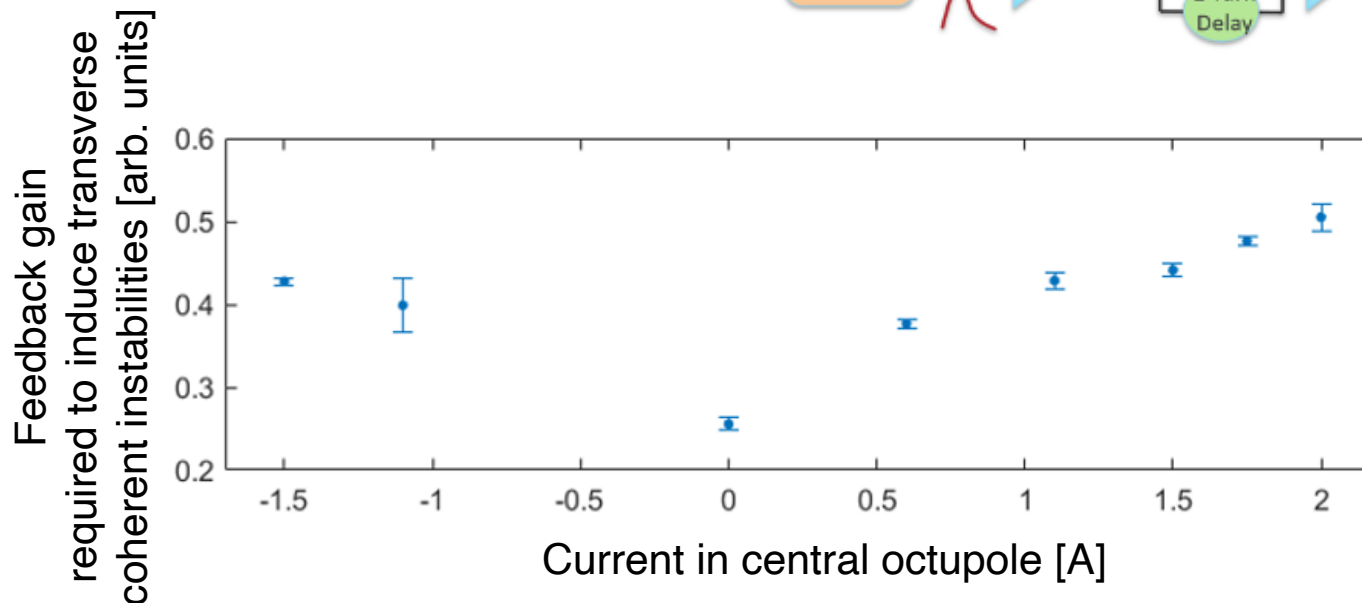
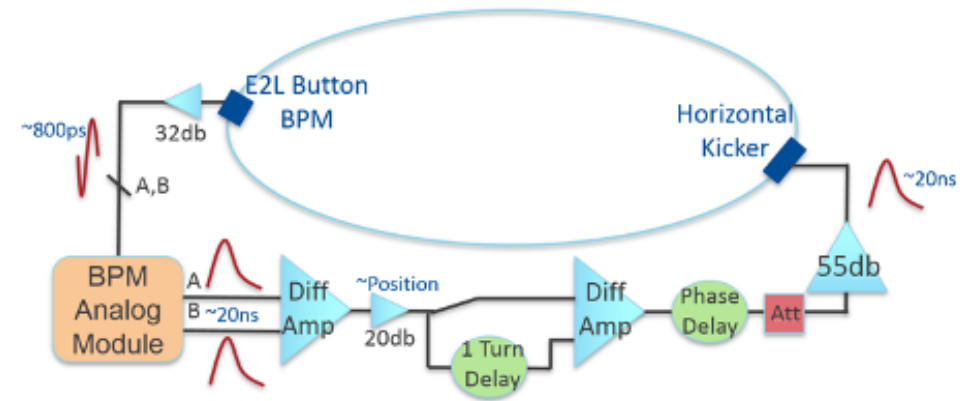
Valishev et al., IPAC 2021

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

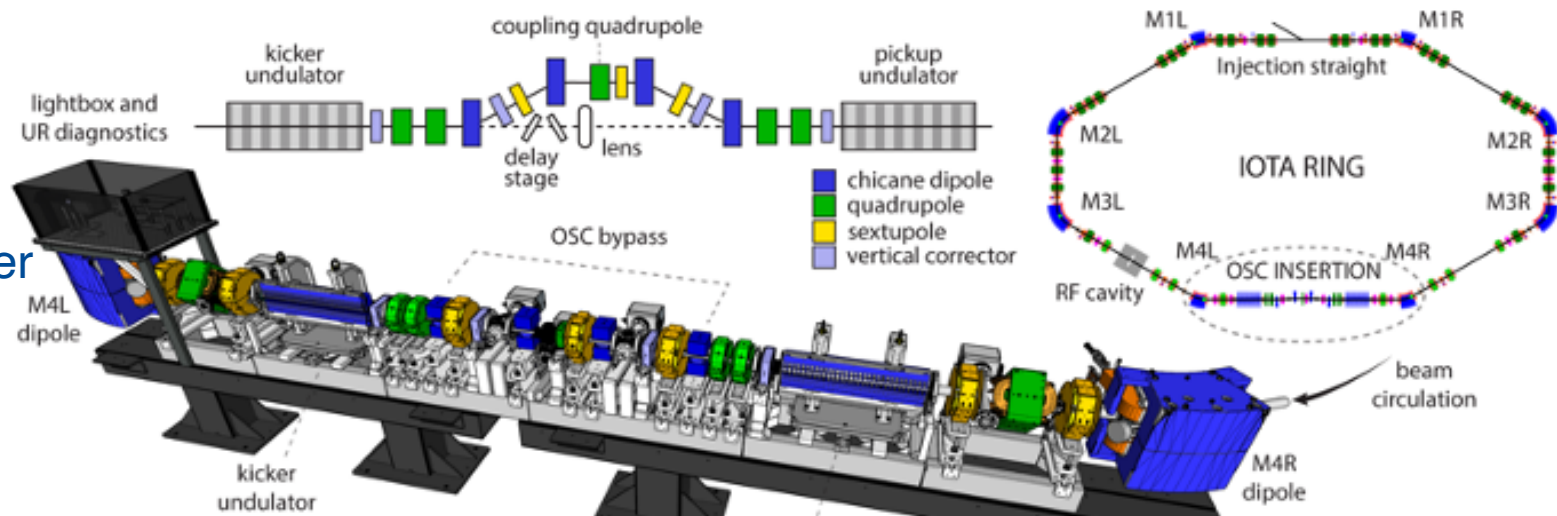
Eddy et al., Beams-doc-9171 (2021)

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 \sim GHz, sample length \sim cm). An optical analogue (~ 10 THz, $\sim \mu\text{m}$) 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)

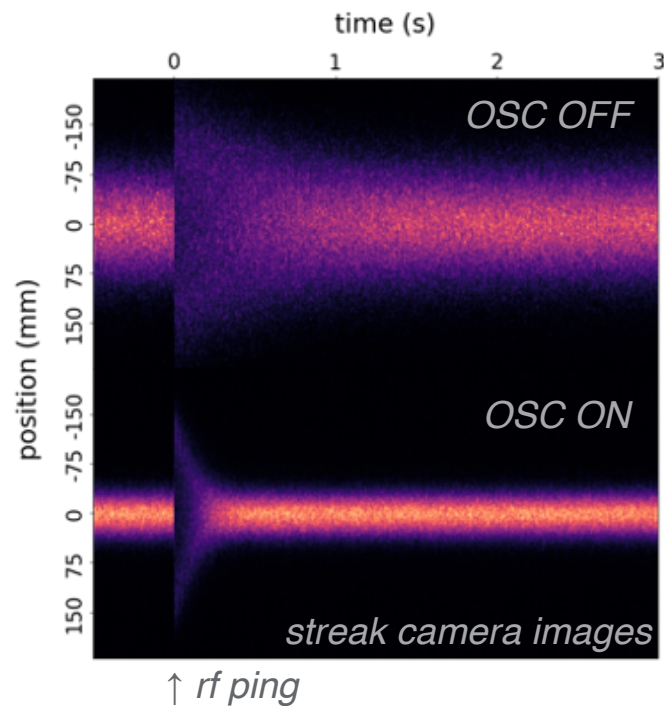
van der Meer, RMP **57**, 689 (1985)

Mikhailichenko and Zolotarev, PRL **71**, 4146 (1993)

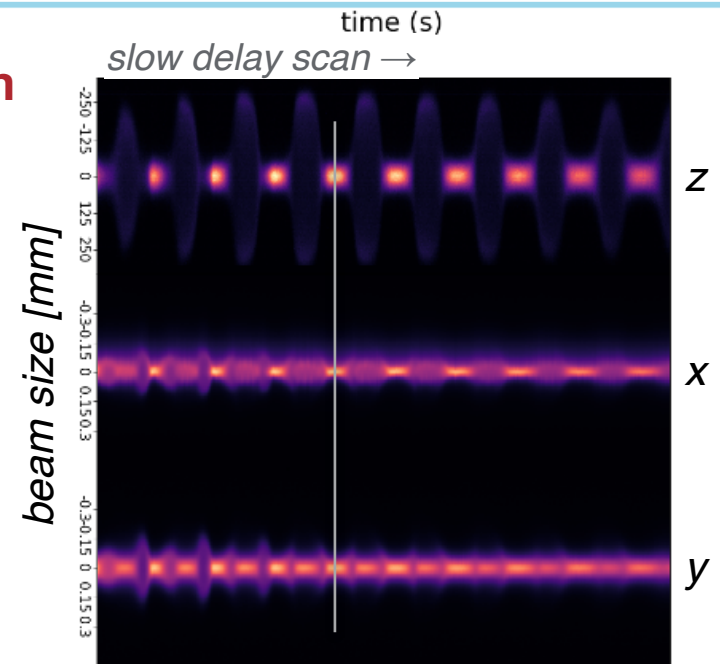
Zolotarev and Zholents, PRE **50**, 3087 (1994)

Lebedev, Jarvis et al., JINST **16**, T05002 (2021)

Optical stochastic cooling: first results



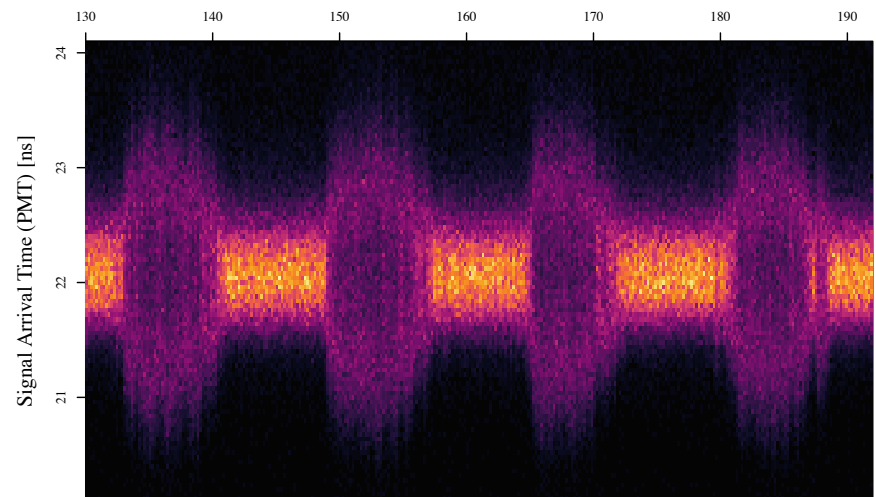
**Simultaneous cooling in
all degrees of freedom**



Observed heating and cooling of a single electron!

**Measured cooling rates 8x faster
than natural radiation damping**

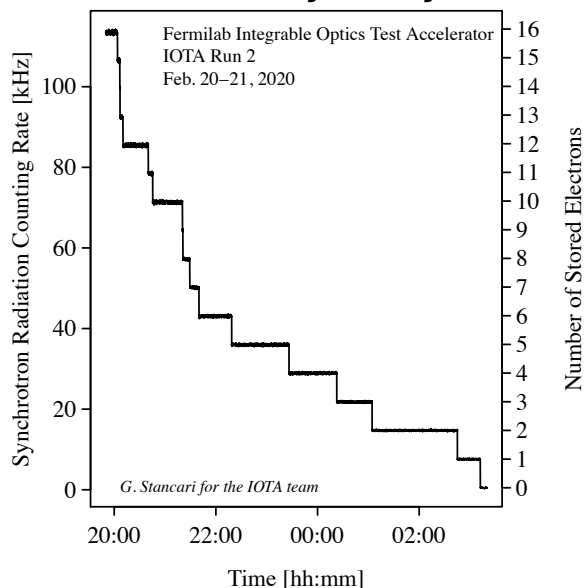
Lebedev, IOTA/FAST Collab. Meeting (2021)
Jarvis, IOTA/FAST Collab. Meeting (2021)
Jarvis, Lebedev, Romanov et al., arXiv:2203.08899,
accepted in Nature (2022)



Dynamics of single electrons

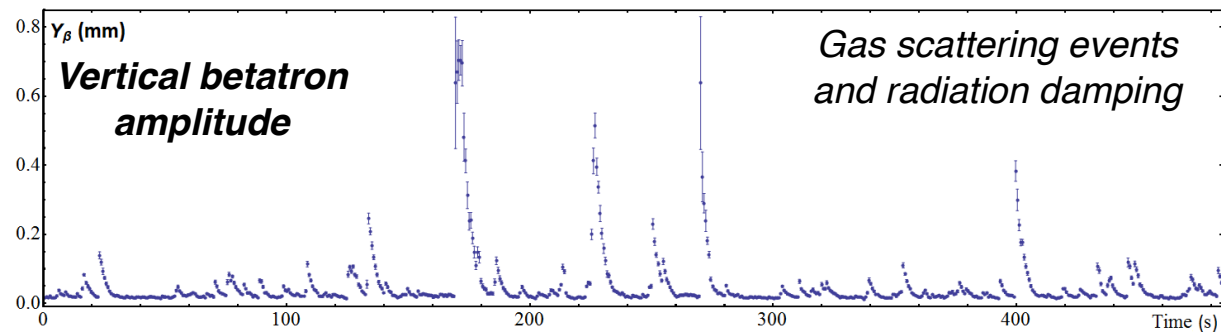
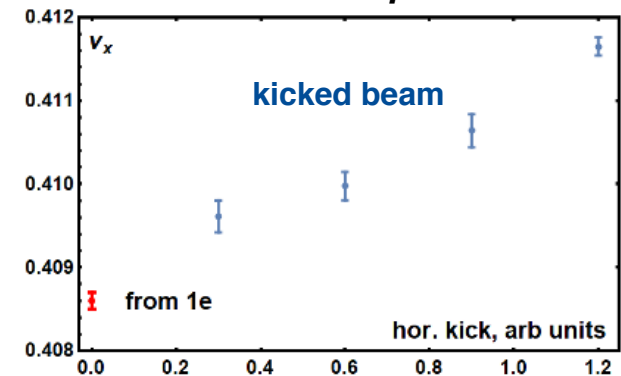
Single electrons (or a known given number of electrons) can be stored for minutes to hours (in a single bucket or multiple buckets)

Discrete steps in intensity decay

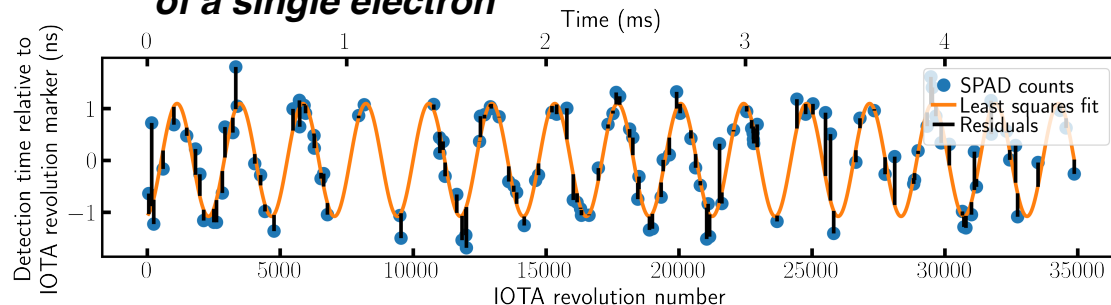


Tracking 1 e^- in all 3 dimensions yields “single particle” lifetimes, emittances, tunes, damping times, beam energies and gas scattering rates

Tune vs. amplitude

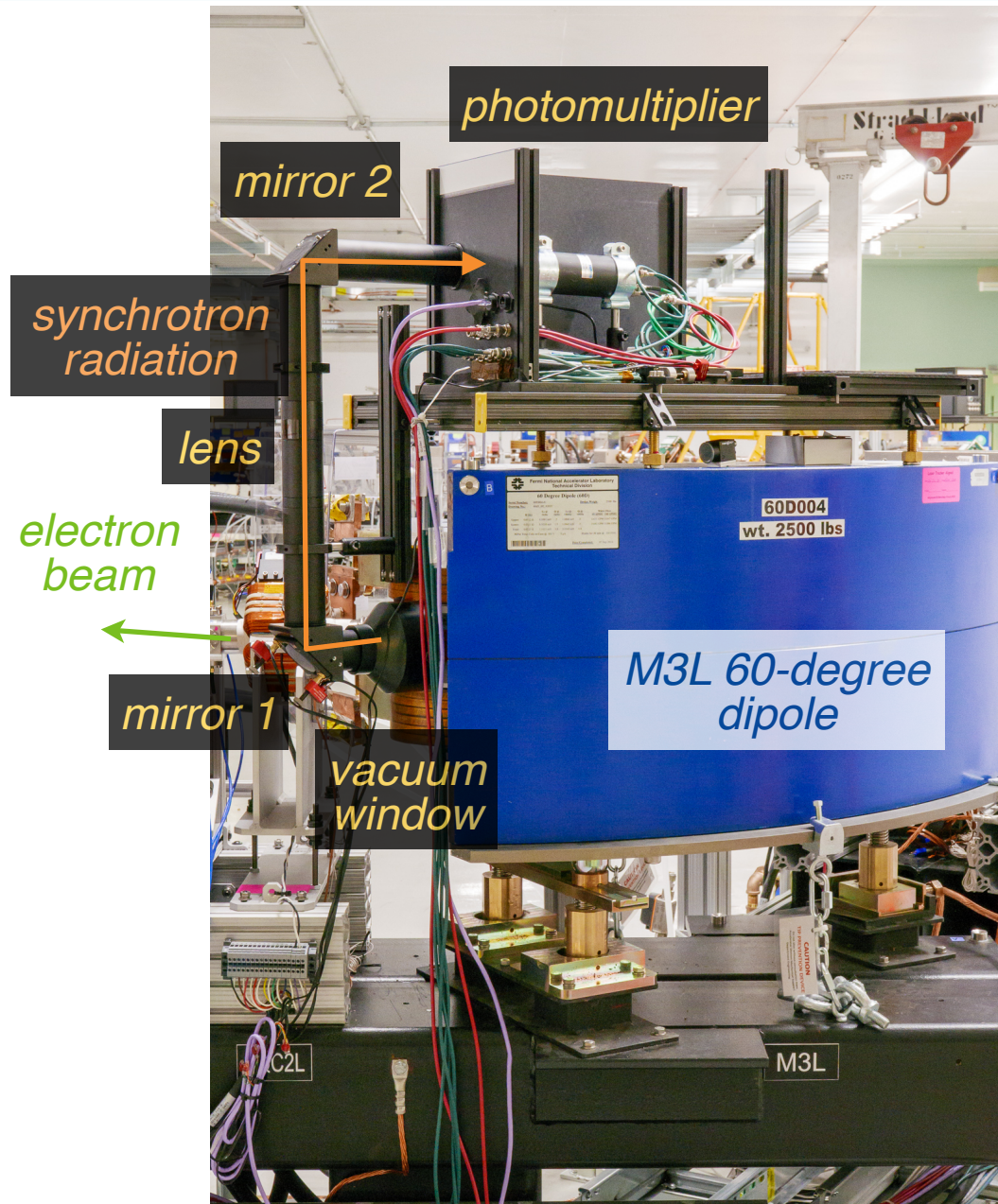


Synchrotron oscillations of a single electron



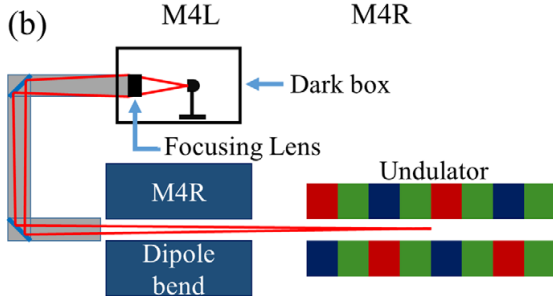
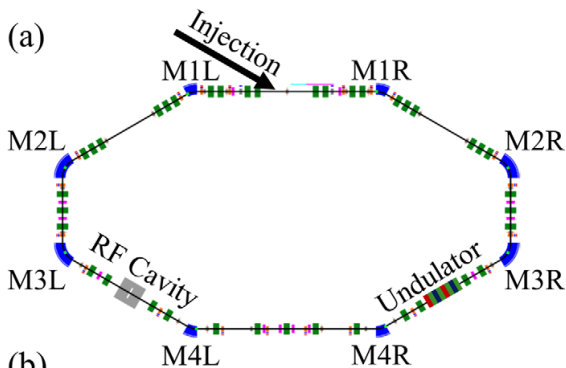
Stancari, FERMILAB-FN-1116-AD (2020)
Romanov et al., JINST **16**, P12009 (2021)
Romanov, IOTA/FAST Collab. Meeting (2021)
Lobach et al., JINST **17**, P02014 (2021)

Detection of synchrotron radiation at IOTA



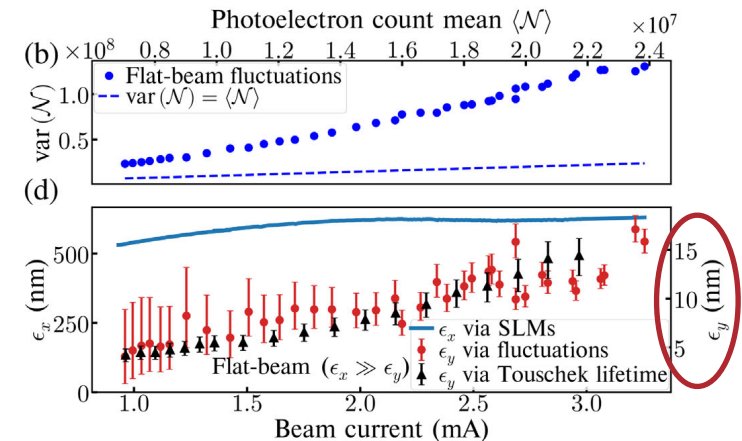
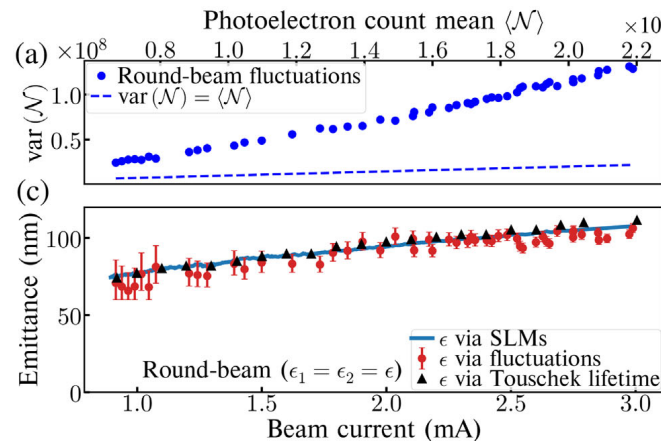
Classical and quantum properties of undulator radiation

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

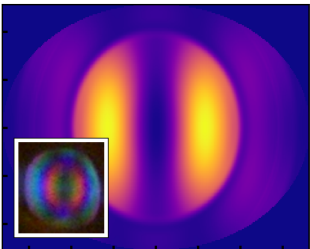


Verified that intensity fluctuations contain a calculable term that depends on beam sizes (interference)

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



Intensity fluctuations can be used to infer small beam emittances



Editors' Suggestion, Featured in Physics

Winner of the 2022 APS DPB Award

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)

IOTA Run 4 program (2022)

Nonlinear Integrable Optics

- Complete systematic studies started in Run 2
- Study conservation of invariants with improved decoherence
- Test new implementations of NIO
- Study the effect on instability thresholds with a flexible feedback system (new strip-lines and digital control of gain and phase)

Single-Electron Phase-Space Tracking

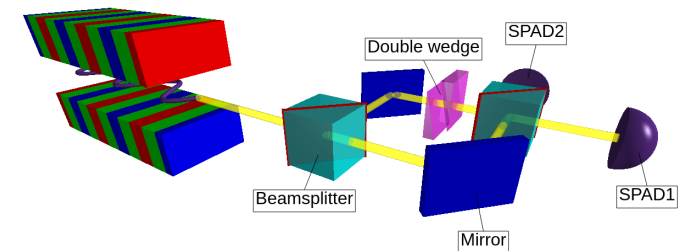
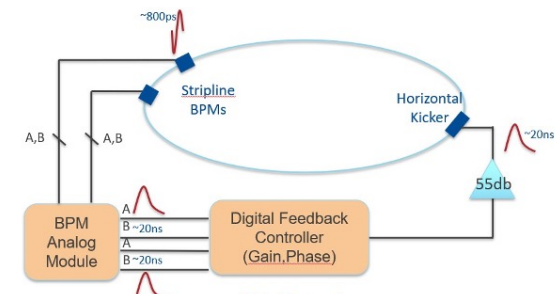
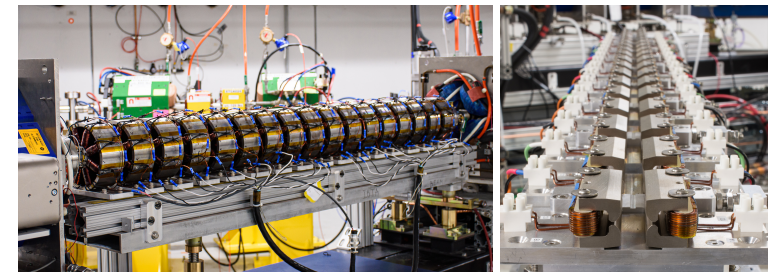
- Improved detectors and methods for general proof of principle and to support the NIO program

Undulator Radiation Interferometry

- Measure the quantum properties of radiation emitted by single electrons

Machine-learning

- Study techniques to improve accelerator operations

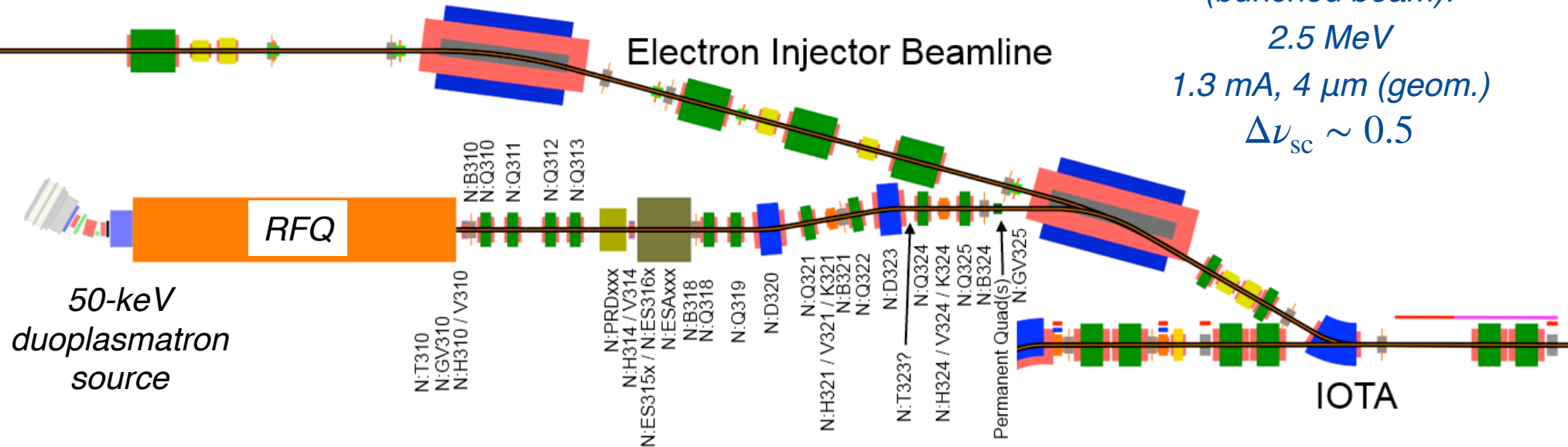


Construction of the IOTA proton source (2022)

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	Nominal (Range)	Unit
Energy	50 (to 60)	kV
Proton Beam Current	20 (to 85)	mA
Proton Beam Charge	20	nC
Pulse length (99%)	1 (1 to 1000)	μs
Source Pulse Rate	1	Hz
Beam Height (from Enclosure Floor)	48.625	in
Transverse Beam Size	700	μm
Normalized Emittance	< 0.2 μm	μm
Divergence	???	
Transverse Dispersion	< 0.15	m

Parameter	Nominal (Range)	Unit
Energy	2.5	MeV
γ_i (Energy) - 1	2.664E-03	
β_i (Energy)	7.285E-02	
Beam Current	20 (1 - 20)	mA
Beam Charge (Total)	36.6	nC
Beam Charge (per Bunch)	61.6	pC
Bunch Train Length	1 (1 - 100)	μs
RF Pulse Rate	1	Hz
Beam Height (from Enclosure Floor)	48.625	in
Beam Pipe Aperture	2.15	in
RFQ & Buncher Frequency	325.0 (± 0.5)	MHz
Phase/Amplitude Stability	1° / 1%	
Beam Pulse	1.77 (1e-2 - 20)	μs
RF Pulse Length	60 (15-150)	μs
Bunch length (1σ) @ RFQ Exit	0.3	ns
BPM response time	< 20	ns

Parameter	Nominal (Range)	Unit
Proton Beam Energy	2.5	MeV
Proton Beam Momentum	68.5	MeV/c
β_i (Energy)	7.285E-02	-
γ_i (Energy) - 1	2.664E-03	-
Circumference	40	m
Proton RF Frequency	2.19	MHz
Proton RF Harmonic Number	4	-
RF Voltage	50	kV
Revolution time in IOTA ring	1.83	μs
X/Y (Unnormalized) Geometric Emittance	0.3	μm
$\Delta p/p$ (RMS)	0.3	%
Beam Current	8	mA
Beam Charge	14.64	nC
RMS beam size for $\beta = 10$ m	4.5	mm
Momentum compaction	0.07	-
Betatron tune (Qx, Qy)	5.3	-

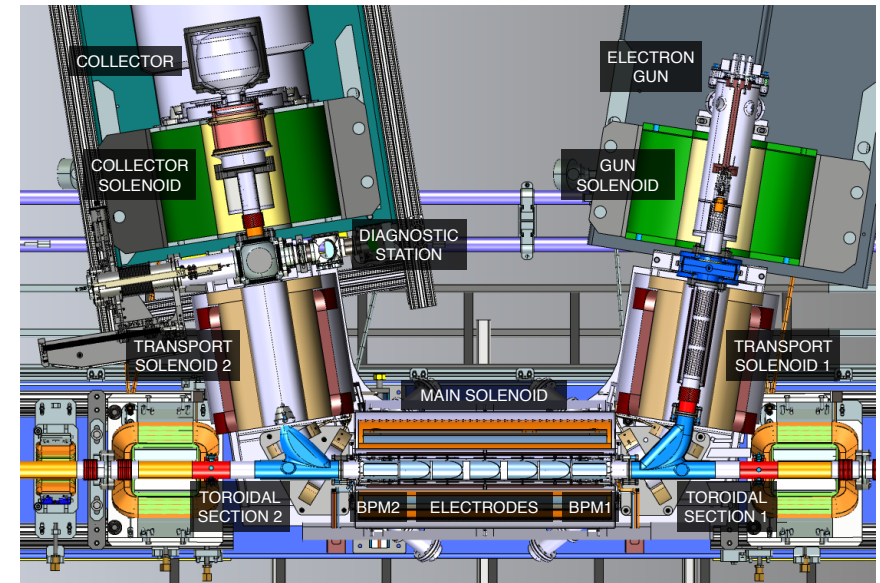
Edstrom, Romanov et al.

Examples of research areas planned after Run 4

Research with the IOTA electron lens

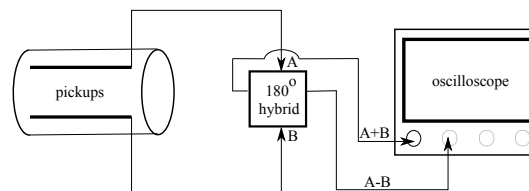
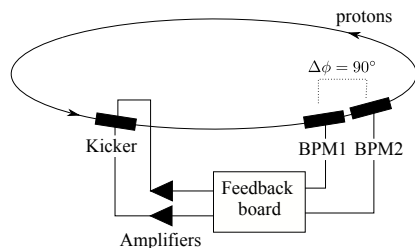
- Novel implementations of NIO schemes
- Electron cooling
- Tune-spread generation for Landau damping
- Space-charge compensation
- Beam diagnostics

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



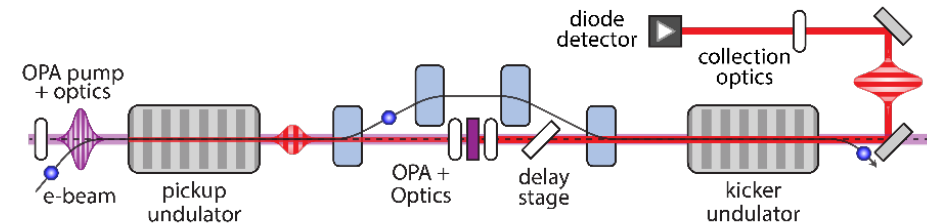
Ainsworth et al., ECA Grant

Examples of research areas planned after Run 4

Optical Stochastic Cooling with Amplification

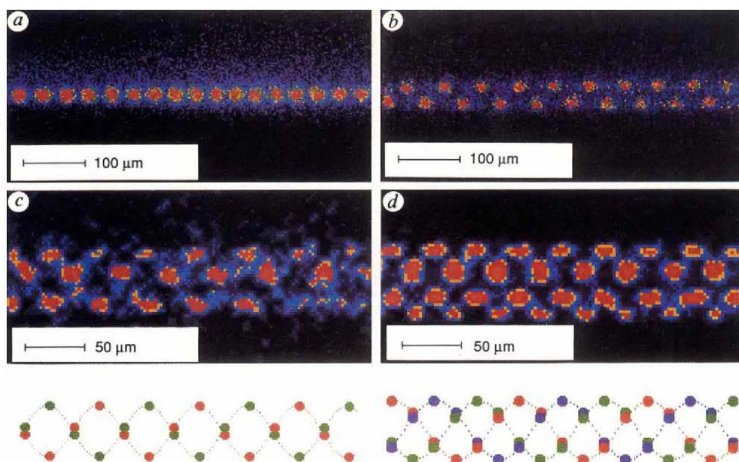
- Development of optical parametric amplifier, transverse sampling, specialized optics
- Demonstration of achievable cooling rates

Jarvis et al., ECA Grant



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



Birkel 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)

Resources

IOTA/FAST web site

fast.fnal.gov

IOTA/FAST Scientific Committee

cdcv.s.fnal.gov/redmine/projects/ifsc/wiki/

Collaboration Meeting 2021

indico.fnal.gov/e/50565

Special Issue of the Journal of Instrumentation

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



IOTA/FAST Scientific Committee (ISC)

+ Overview Activity Documents Wiki Files Settings

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)

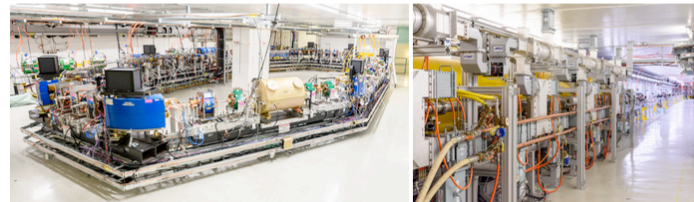


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Proposing an experiment at IOTA/FAST

Contacts

Experiments

Run 4 (April 2022 -)

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 2018 - Apr 2019)

IOTA

FAST Linac

Attachments

Contacts

IOTA/FAST Scientific Committee (ISC)		
Giulio Stancari (chair)	630-840-3934	stancari@fnal.gov
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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



Conclusions

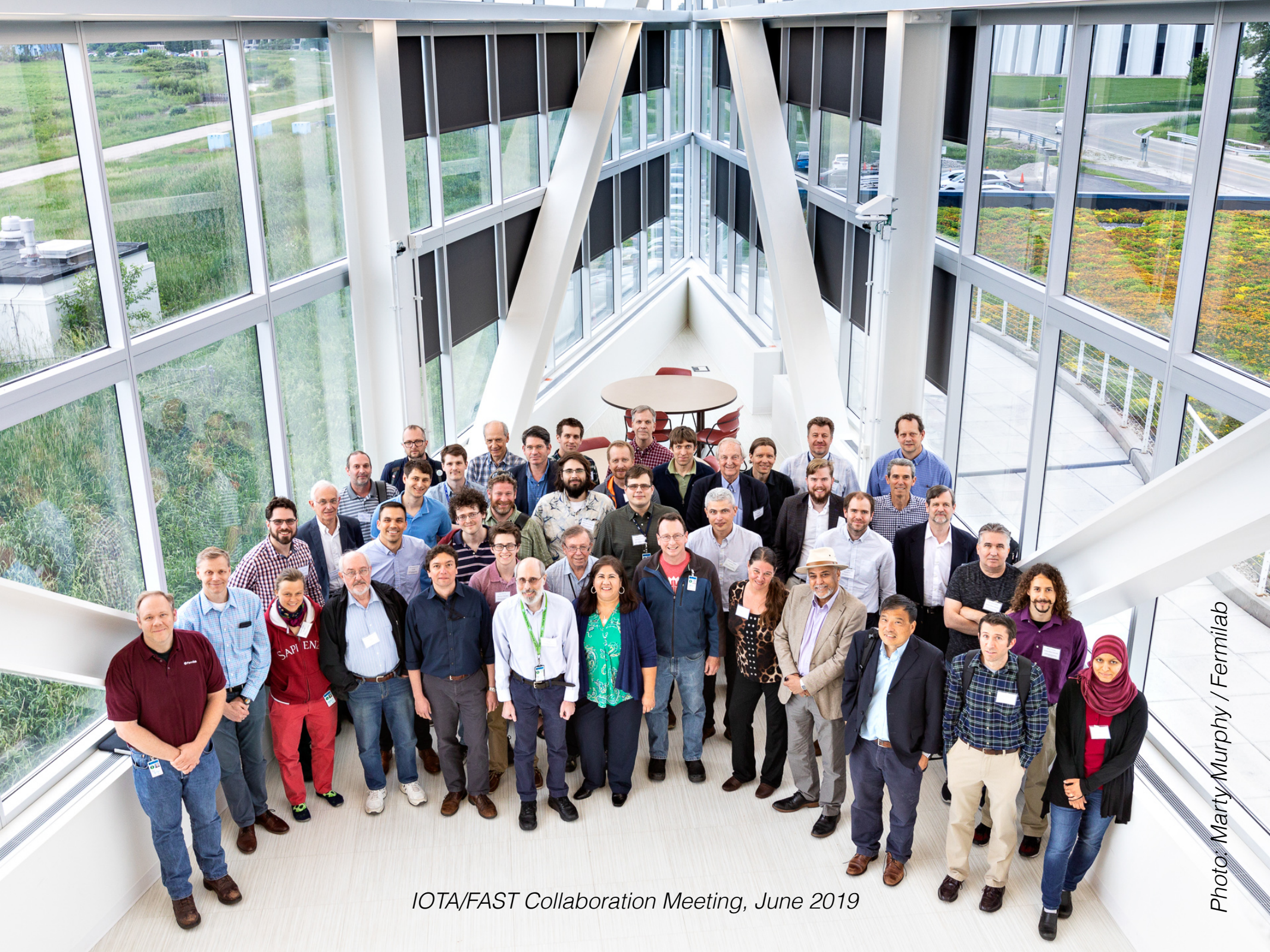
Many **exciting opportunities** for experimental, theoretical and computational research in accelerator physics and technology at Fermilab

Only a few examples mentioned here

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

Thank you for your attention!





IOTA/FAST Collaboration Meeting, June 2019

Photo: Marty Murphy / Fermilab