Accelerator and Beam Physics Research at Fermilab

Giulio Stancari

Fermilab

University of Chicago
Enrico Fermi Institute
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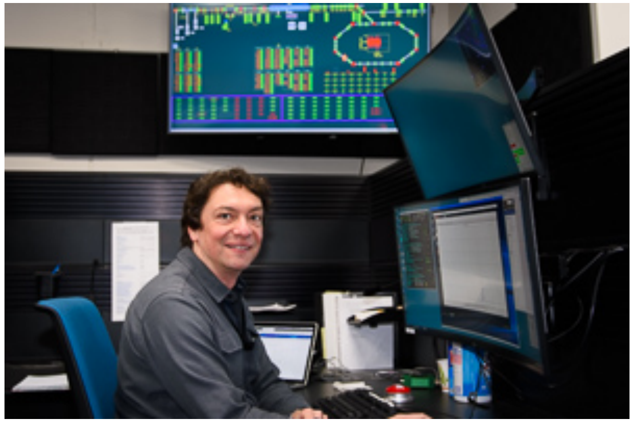
FERMILAB-SLIDES-23-066-AD efi.uchicago.edu/events/event/1657/

About your speaker

Senior scientist at Fermilab, 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, …

Why study accelerator physics and technology?

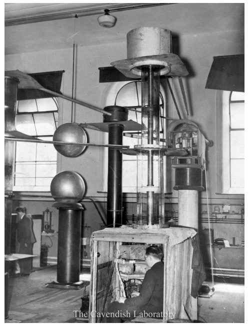
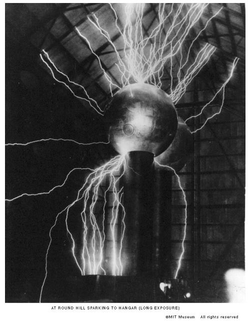
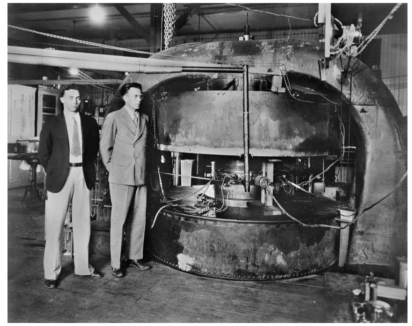
REWARDING: Connected to **fundamental science** (nuclear and particle physics, material science, biology, …) and **exciting applications** (medical diagnostics and treatment, industrial processes, …)

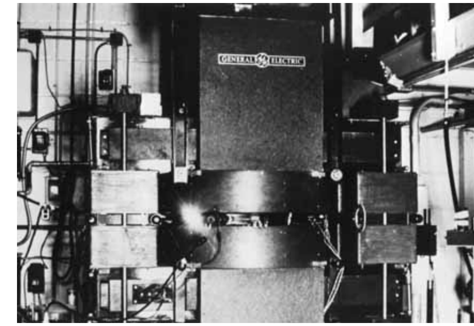
CHALLENGING and **DIVERSE**: You can find areas that match your interests in **applied math**, **physics**, **engineering**, **computing**, …

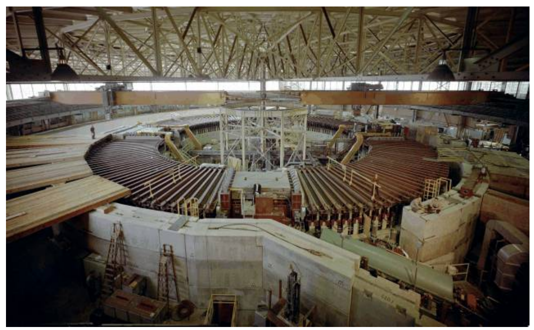
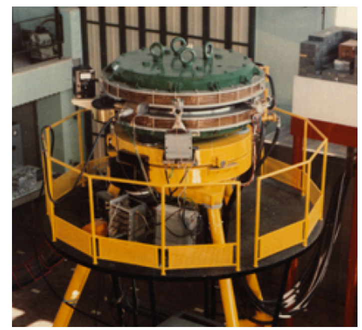
RELEVANT for many fields of science and technology. Essential to **design experiments**, **analyze data**, **explore new applications**

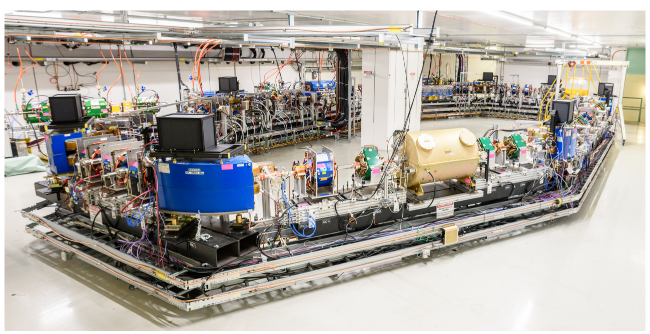
OPPORTUNITIES: If you like the subject, there may be a **career** path for you. Several **theses**, **internships**, **fellowships** and **jobs** are available.

Evolution of particle accelerators



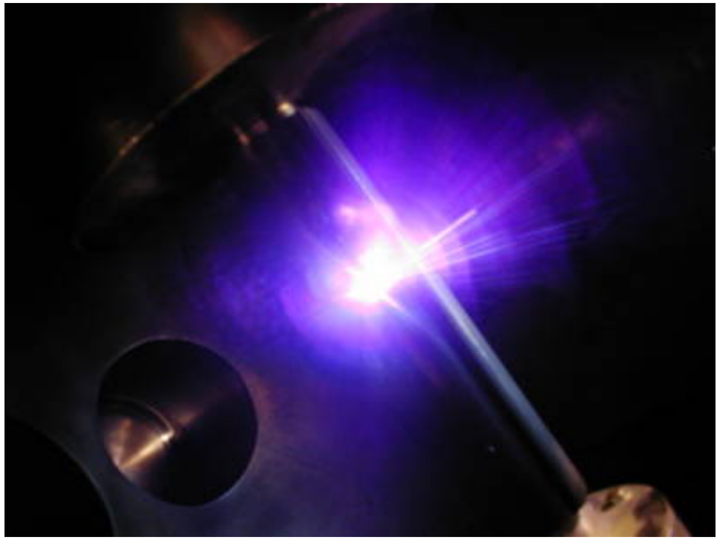



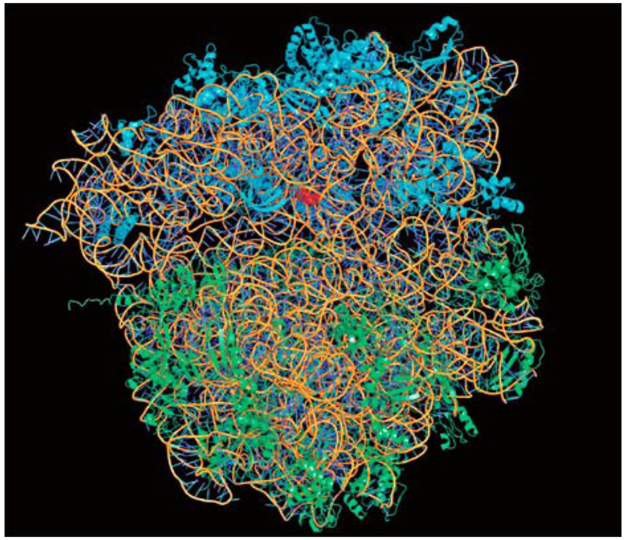



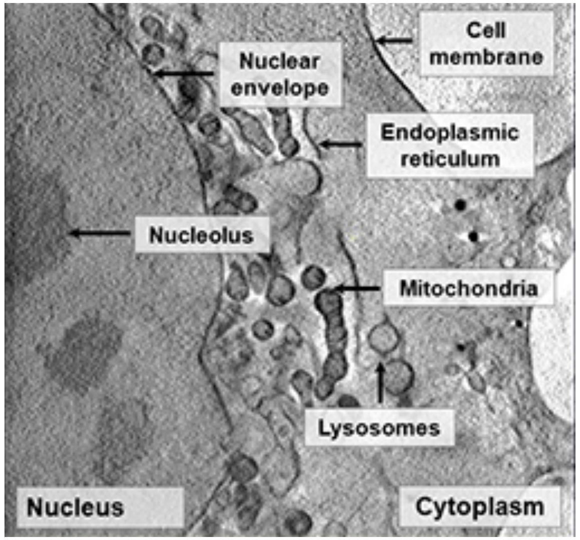
Interplay between **physical principles** and **technologies**

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, …







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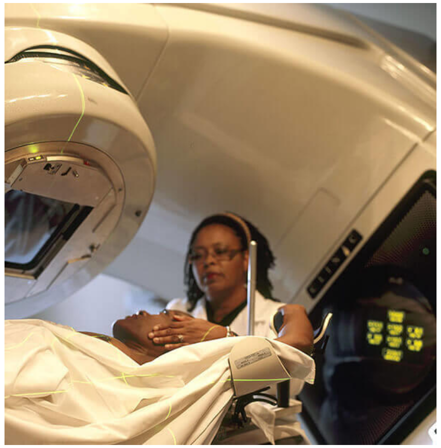
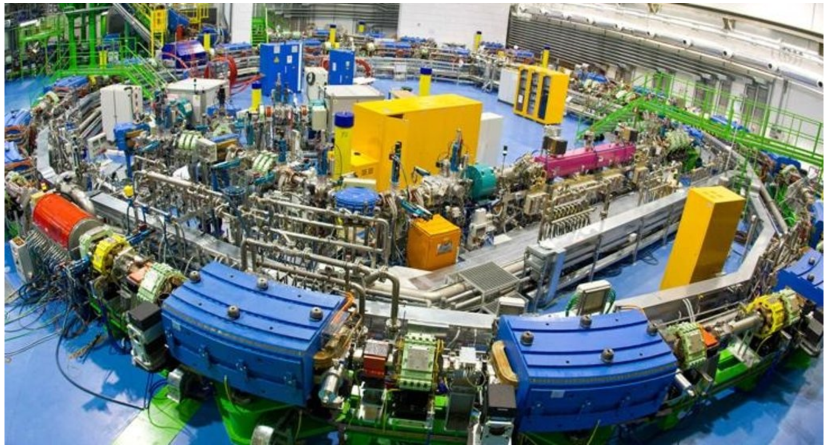
What are accelerators used for?

- **Medicine**

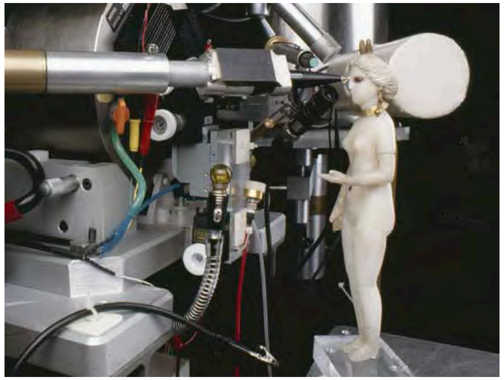
  radiotherapy, hadron therapy, isotope production for diagnostics, sterilization,…





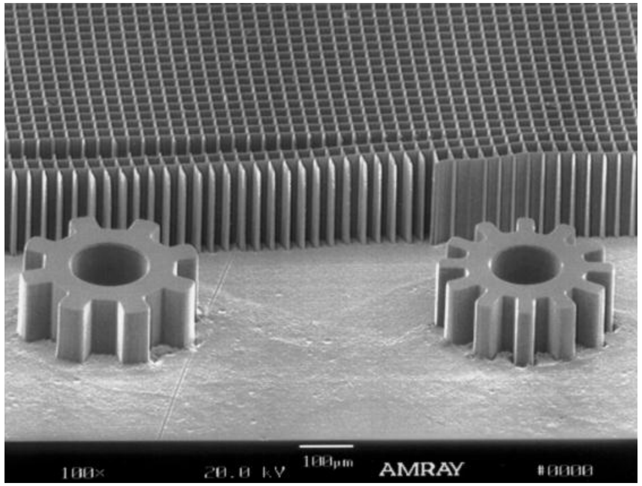
- **Archeology and art**

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



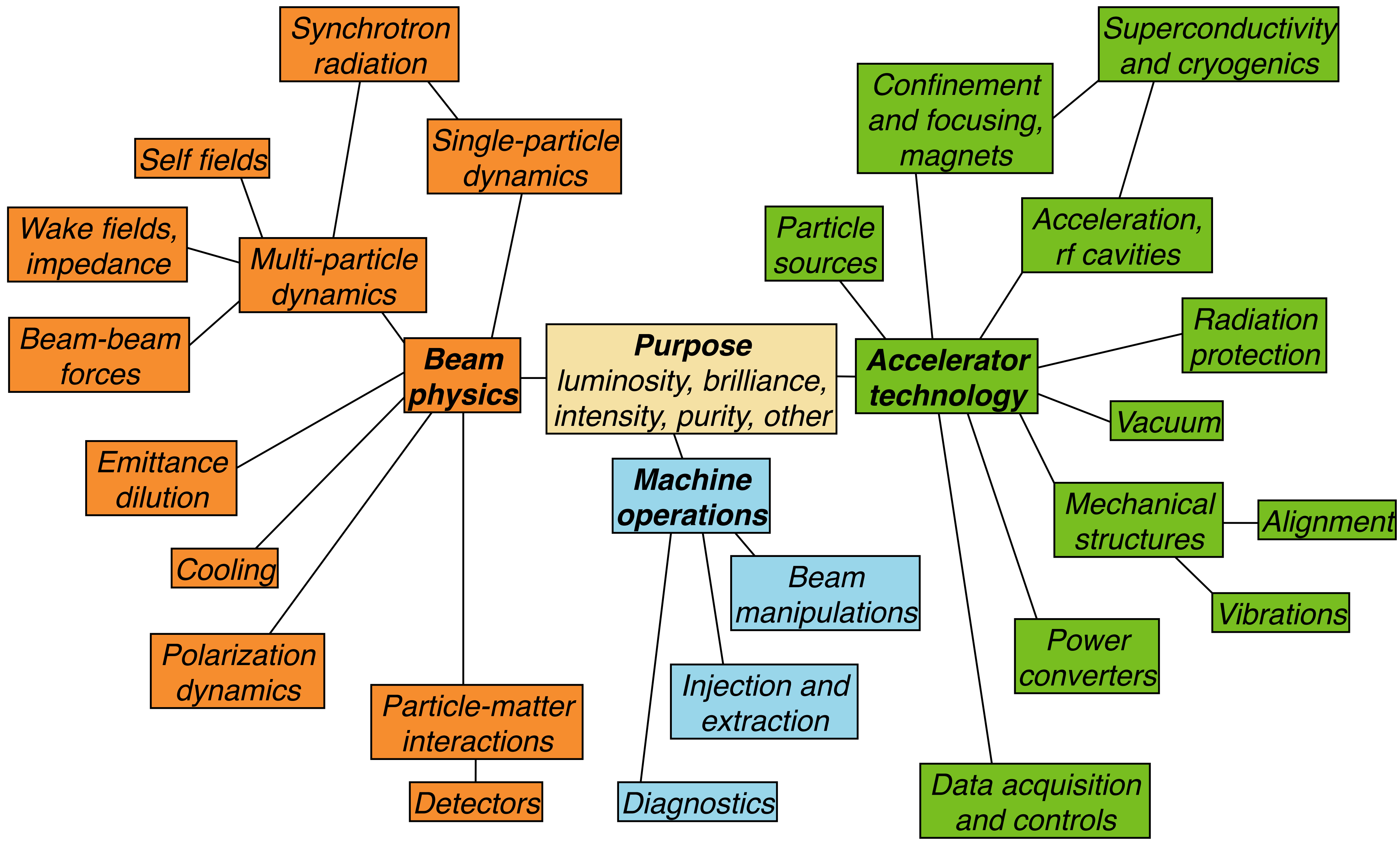
What are accelerators used for?

- **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



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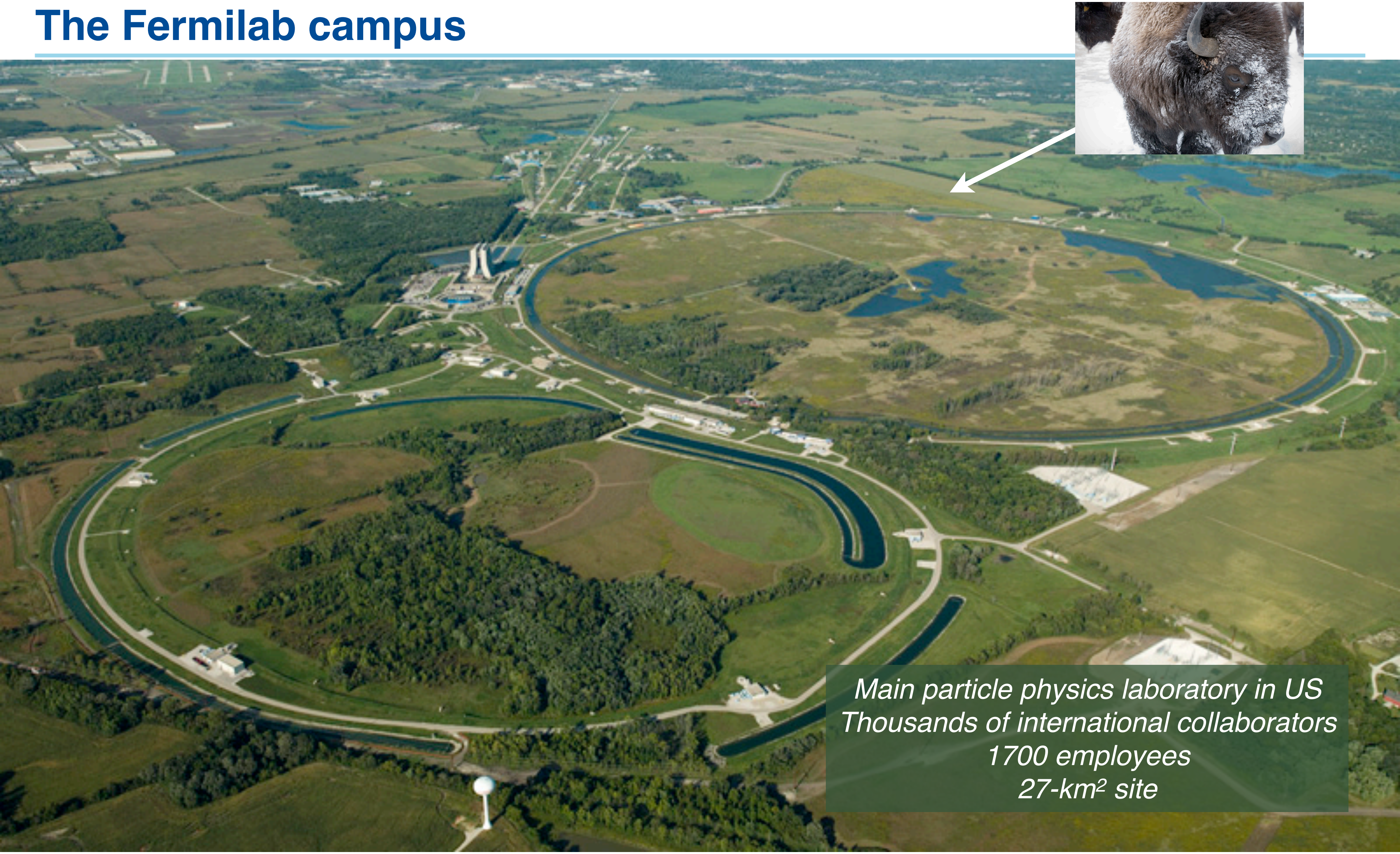
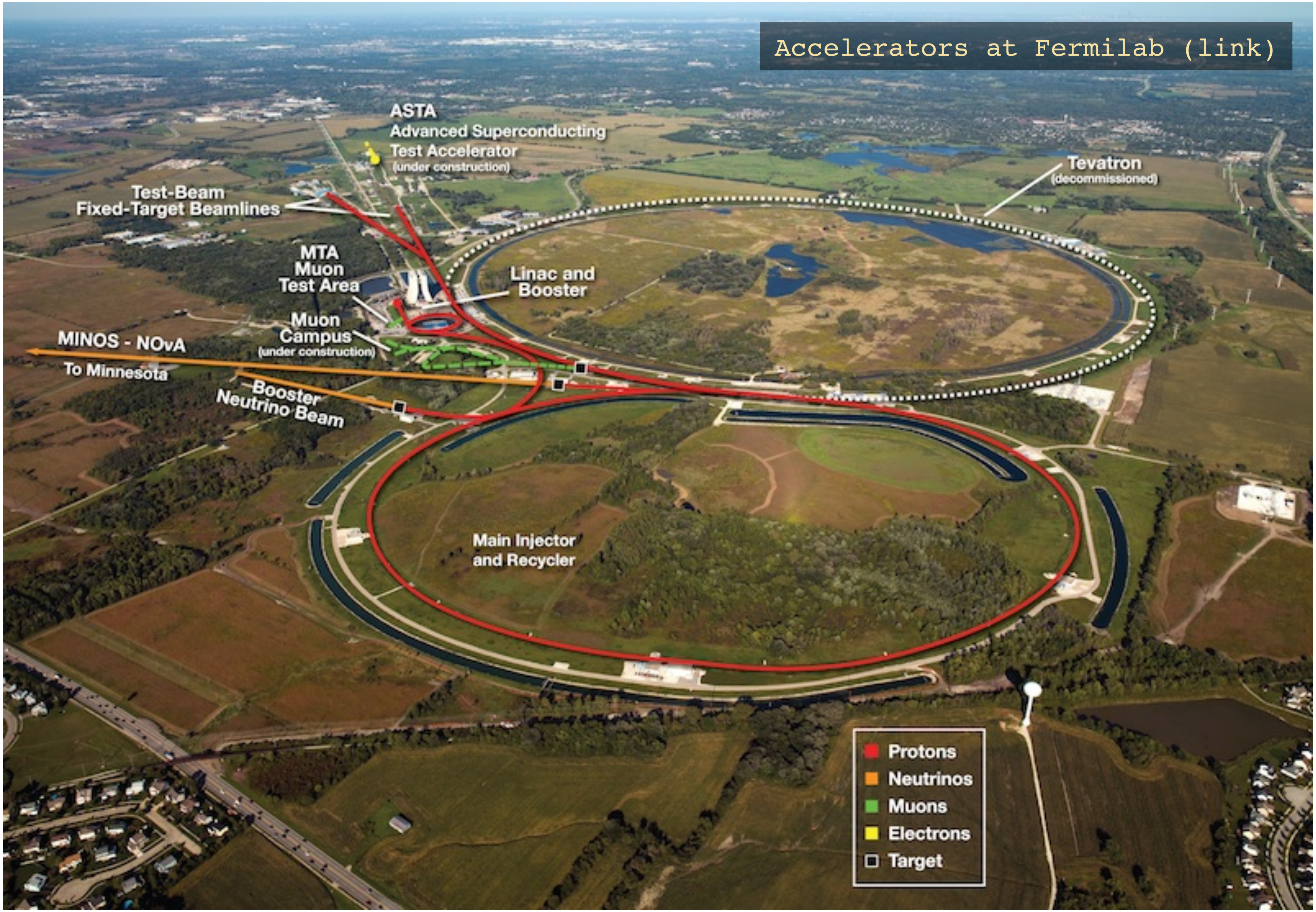
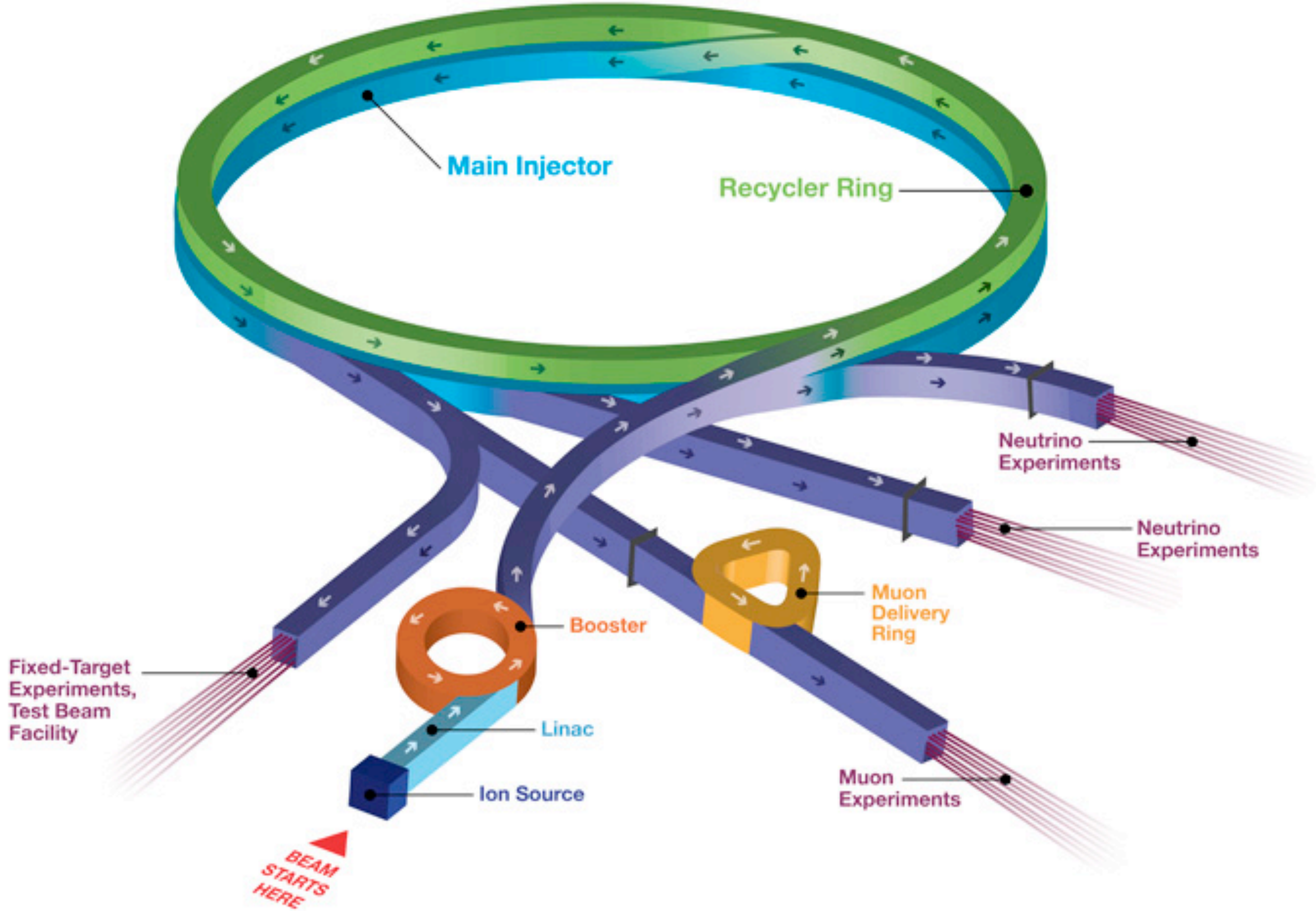
The Fermilab campus



The Fermilab accelerator complex

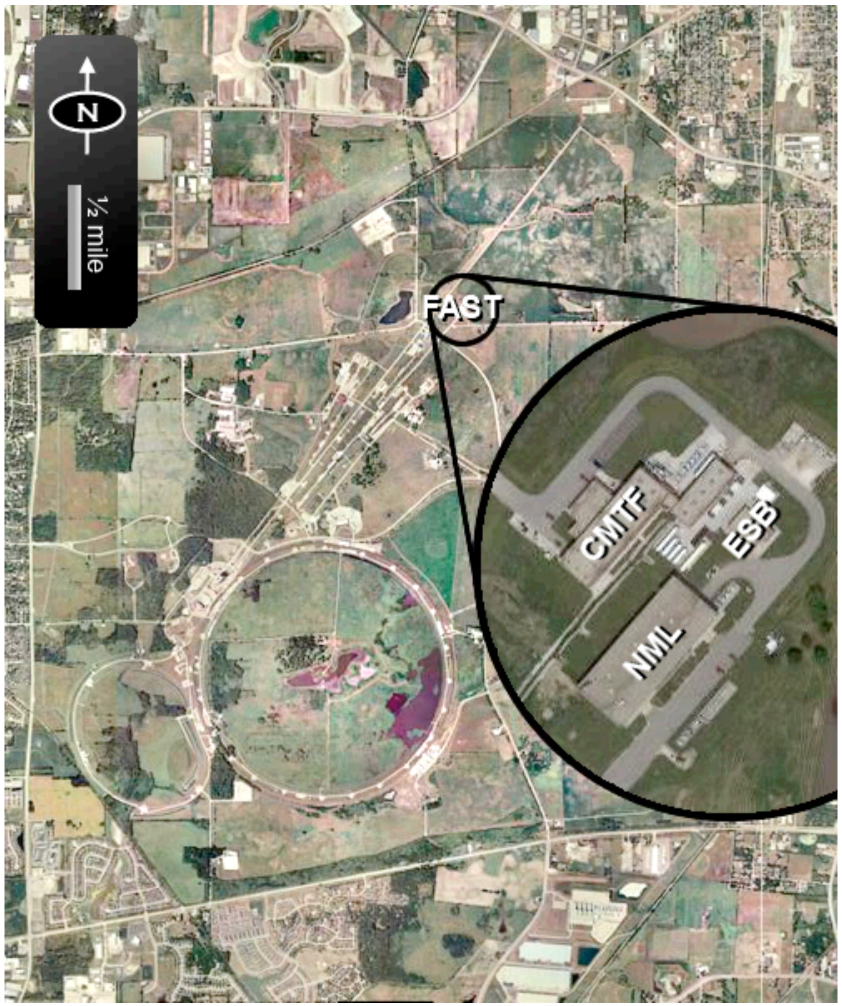


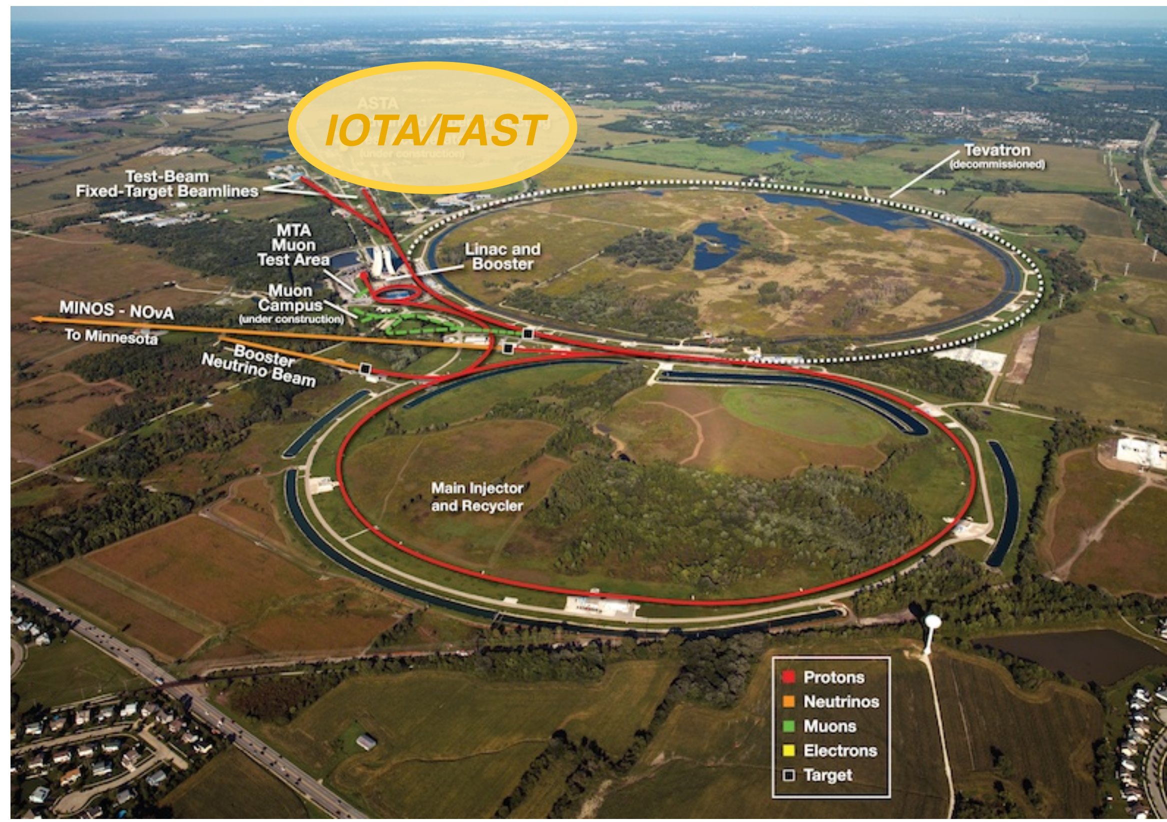
The Fermilab accelerator complex



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

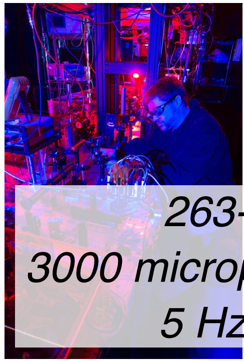




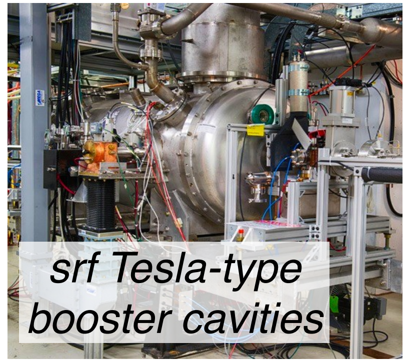
Overview of IOTA/FAST

Photoinjector

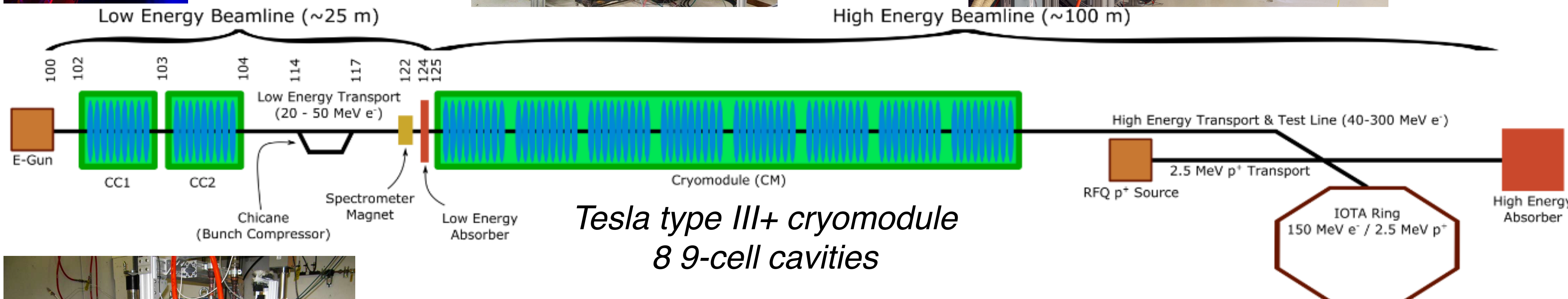
Superconducting Linac



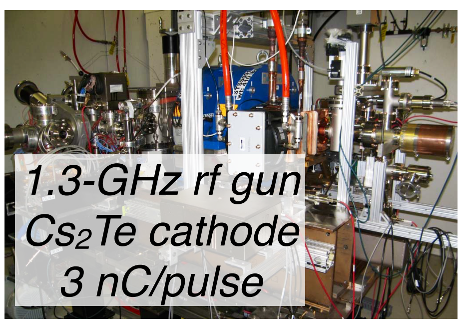
263-nm laser
3000 micropulses @ 3 MHz
5 Hz rep. rate



srf Tesla-type booster cavities

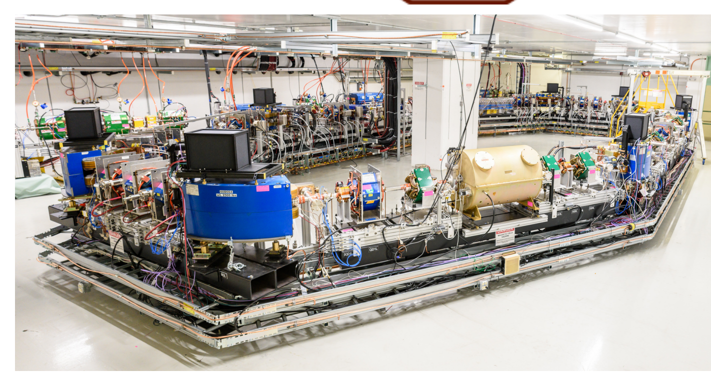


Tesla type III+ cryomodule
8 9-cell cavities



1.3-GHz rf gun
Cs_2Te cathode
3 nC/pulse

IOTA Storage Ring

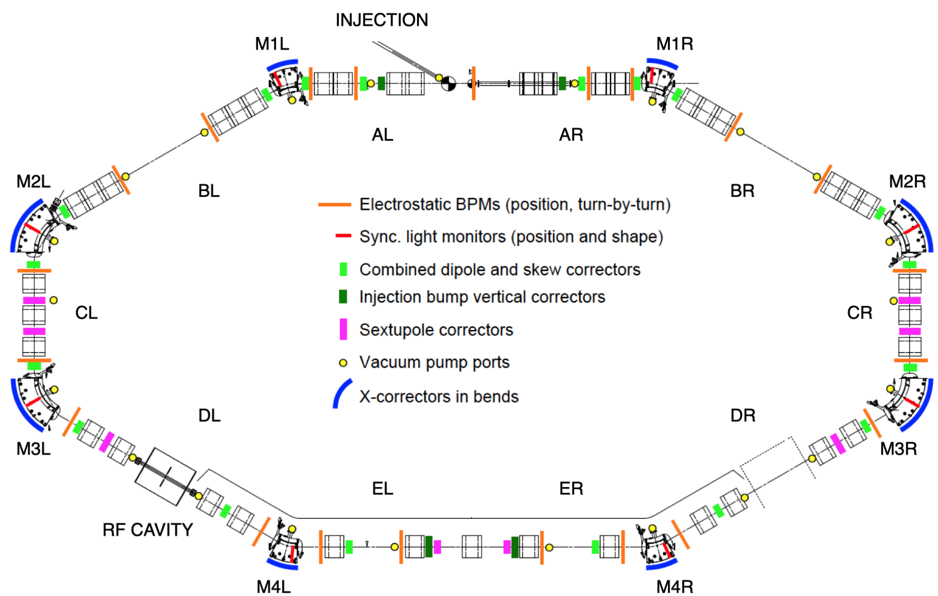


Antipov et al., JINST **12**, T03002 (2017)
Broemmelsiek et al., New J. Phys. **20**, 113018 (2018)

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, $\delta_p = \Delta p / p$	$1–4 \times 10^{-4}$	$1–2 \times 10^{-3}$
Radiation damping times, $\tau_{x,y,z}$	0.2–2 s	–
Max. space-charge tune shift, $\lvert\Delta\nu_{\text{sc}}\rvert$	$< 10^{-3}$	0.5



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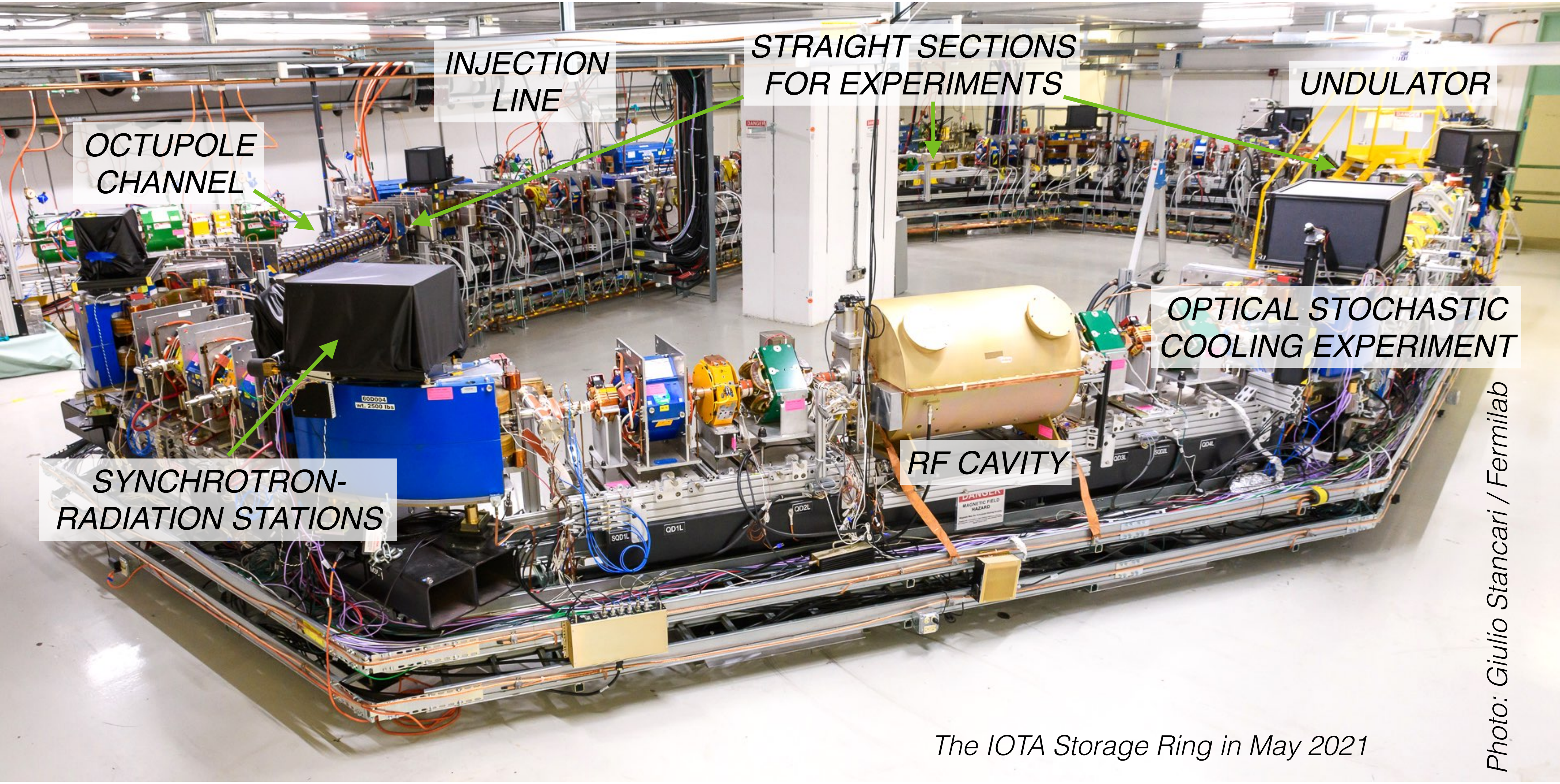
The IOTA storage ring



The IOTA Storage Ring in May 2021

Photo: 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**
- **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 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)

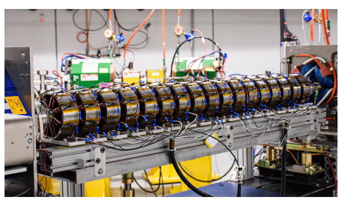
(1) In a real accelerator, is it possible to have a **nonlinear lattice** that stabilizes the beam via **Landau damping**, suppresses resonances and does **not reduce dynamic aperture**?

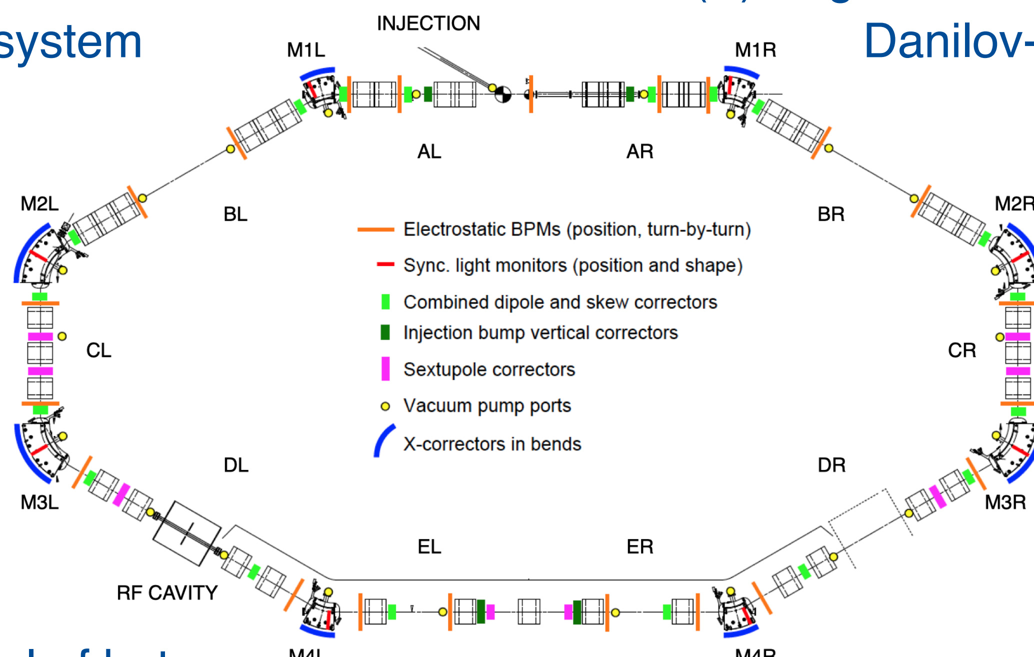
(2) How **robust** are nonlinear integrable lattices agains imperfections?

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

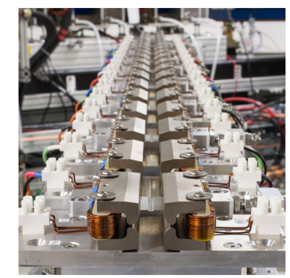
Two implementations:

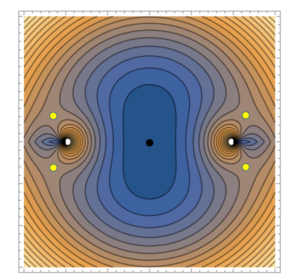
(A) Segmented octupole channel
Quasi-Integrable (QI) system





(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)

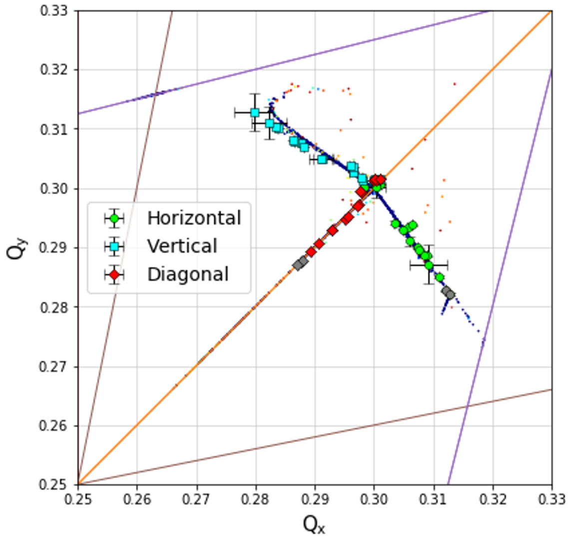
NIO experiments

Demonstrated integrable focusing systems experimentally

Observed large detuning with amplitude

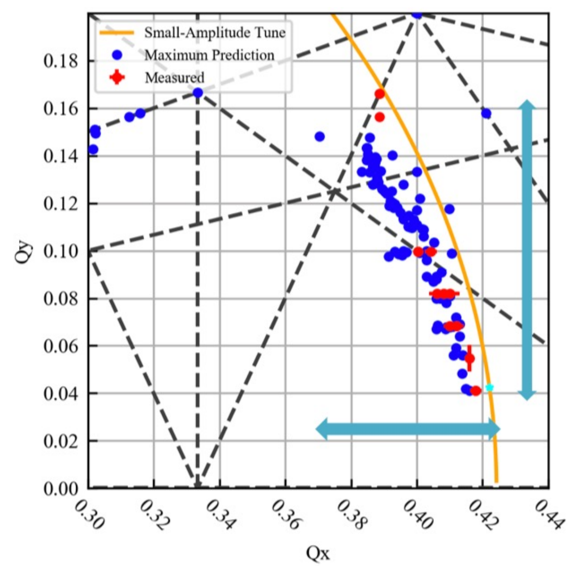
QI system (octupole channel)

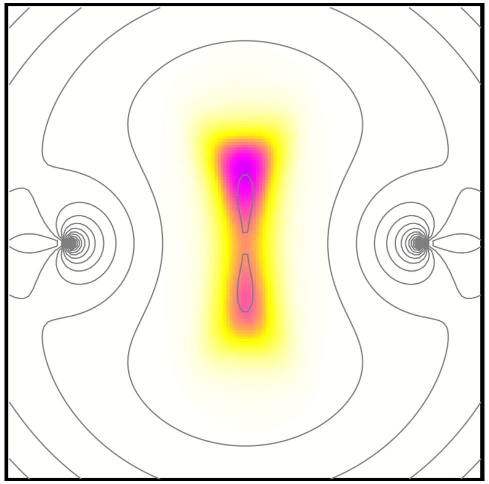
Achieved detuning of 0.04



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)

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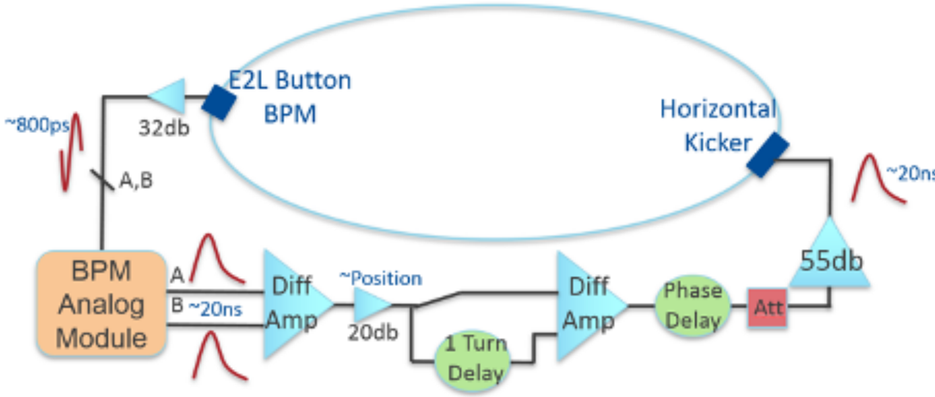
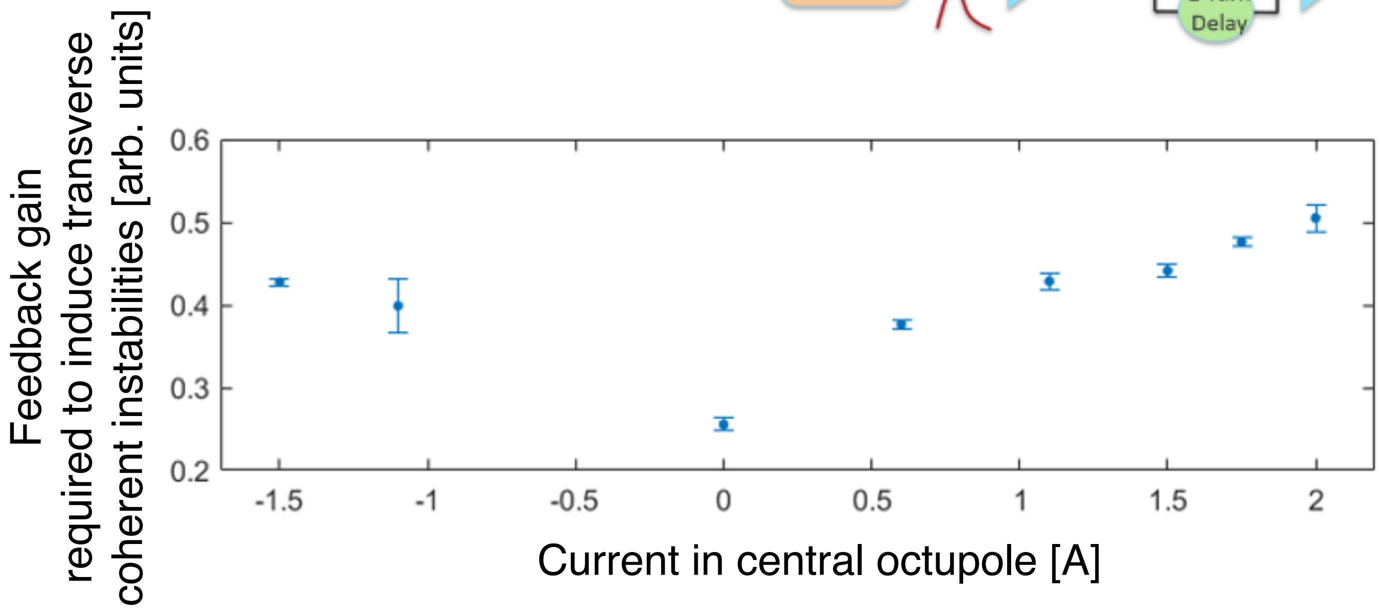
Nonlinear integrable optics and instability thresholds

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

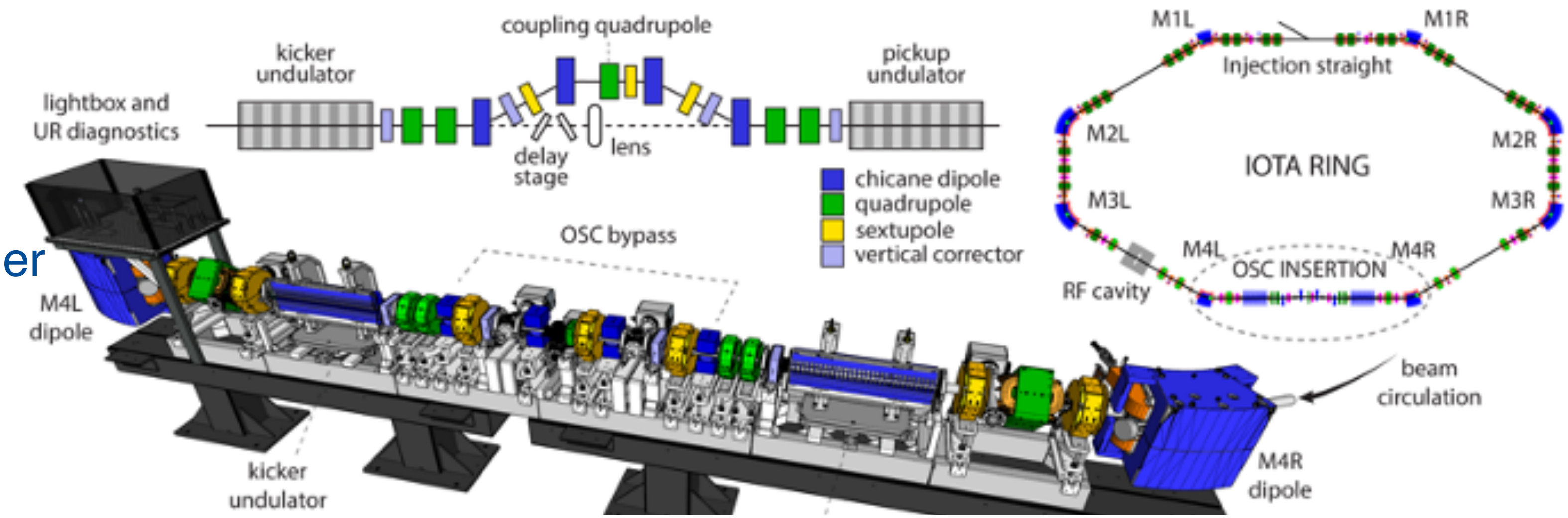
Valishev et al., IPAC 2021
Eddy et al., Beams-doc-9171 (2021)

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

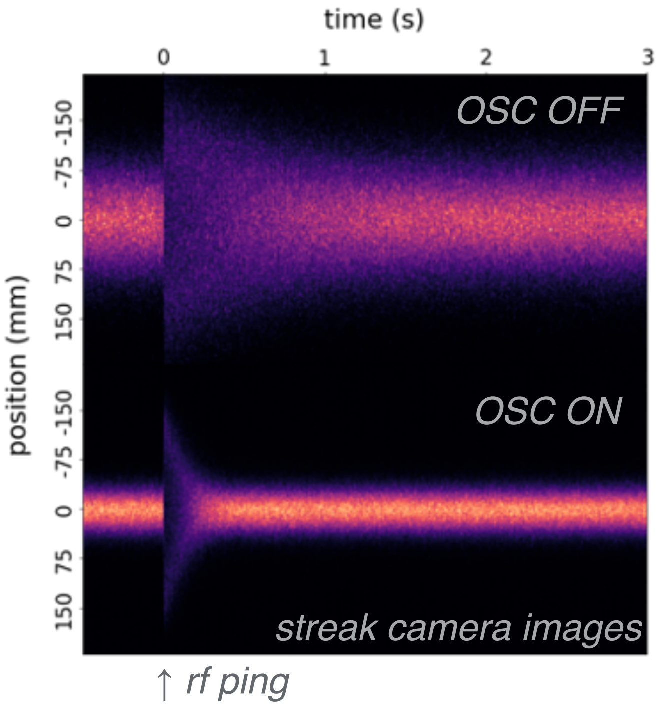


Technological challenges:

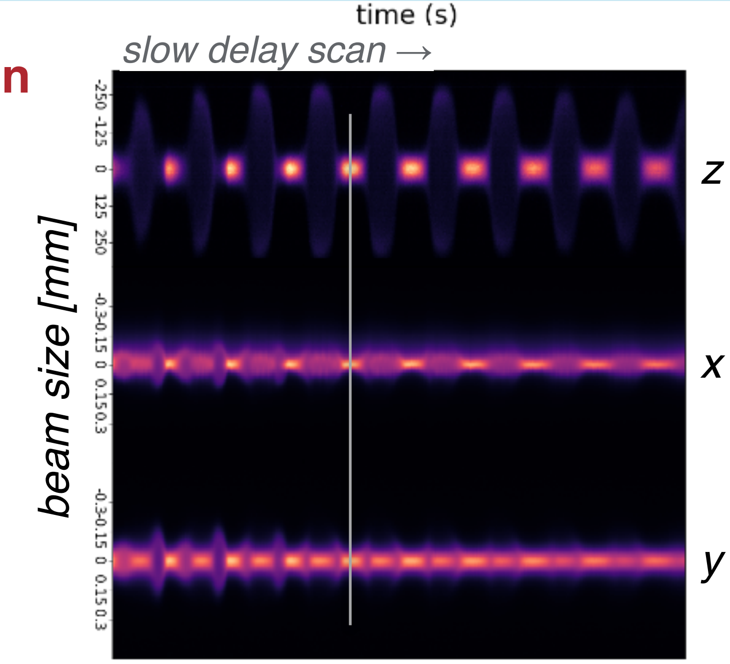
- overlap of beam and radiation in the kicker undulator within 0.2 mm, 0.1 mrad, <u>0.3 fs</u>
- relative stability of radiation path and magnetic bypass much smaller than wavelength (μm)

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)

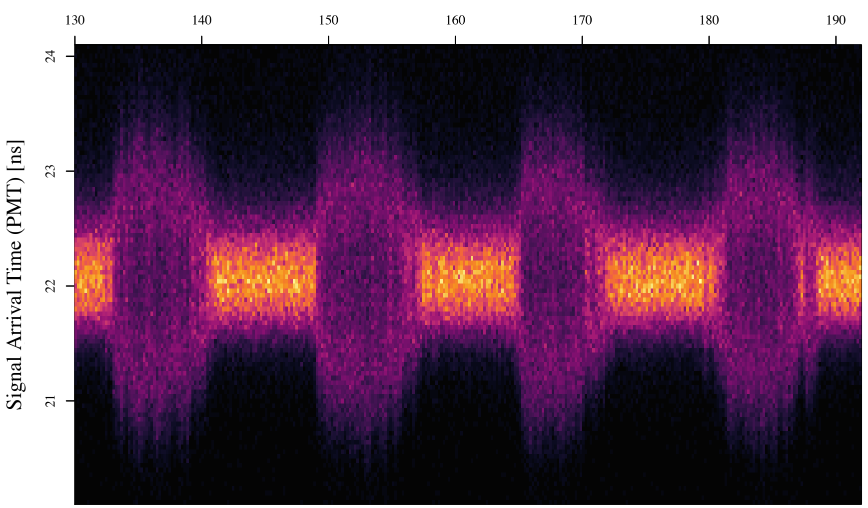
Optical stochastic cooling: first results



Simultaneous cooling in all degrees of freedom



Observed heating and cooling of a single electron!



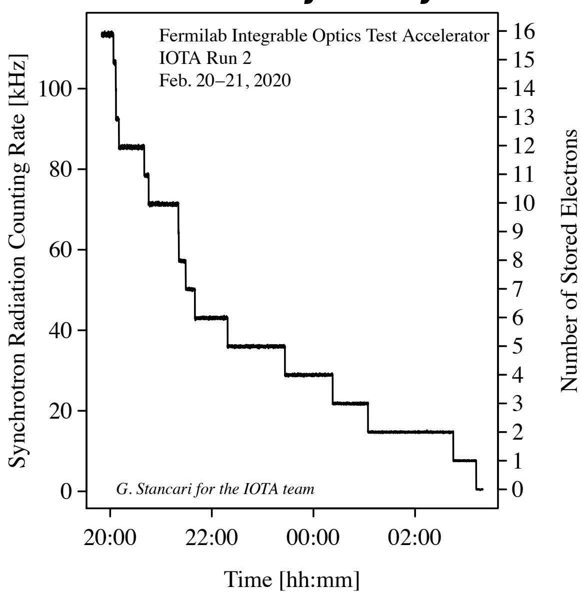
Measured cooling rates 8x faster than natural radiation damping

Lebedev, IOTA/FAST Collab. Meeting (2021)
Jarvis, IOTA/FAST Collab. Meeting (2021)
Jarvis, Lebedev, Romanov et al., arXiv:2203.08899,
Nature **608**, 287 (11 August 2022)

Dynamics of single electrons

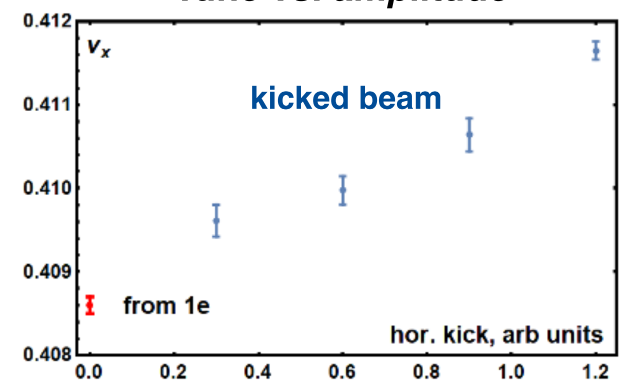
Single electrons (or a known given number of electrons) can be stored for minutes to hours (in a single bucket or multiple buckets)

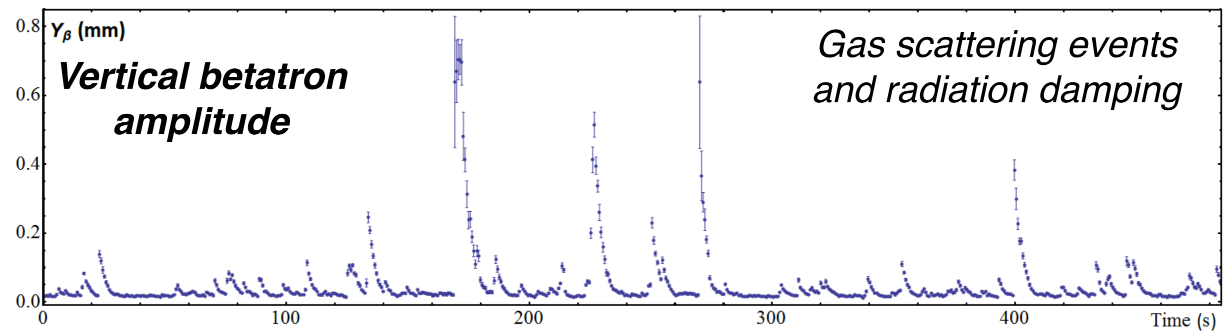
Discrete steps in intensity decay



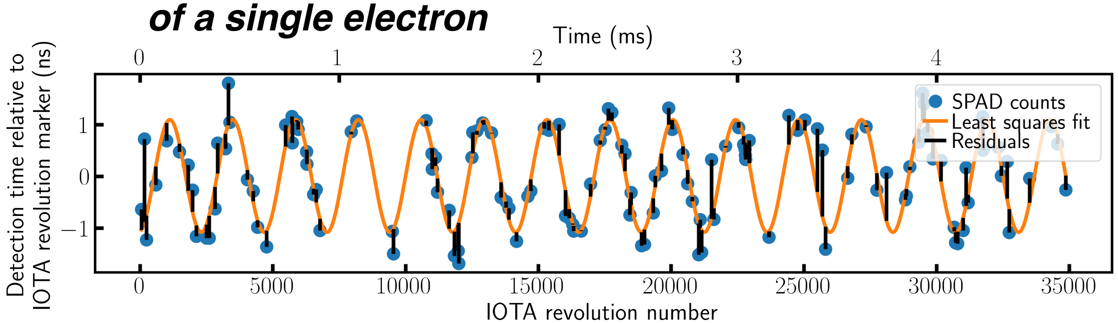
Tracking 1 e^- in all 3 dimensions yields "single particle" lifetimes, emittances, tunes, damping times, beam energies and gas scattering rates

Tune vs. amplitude



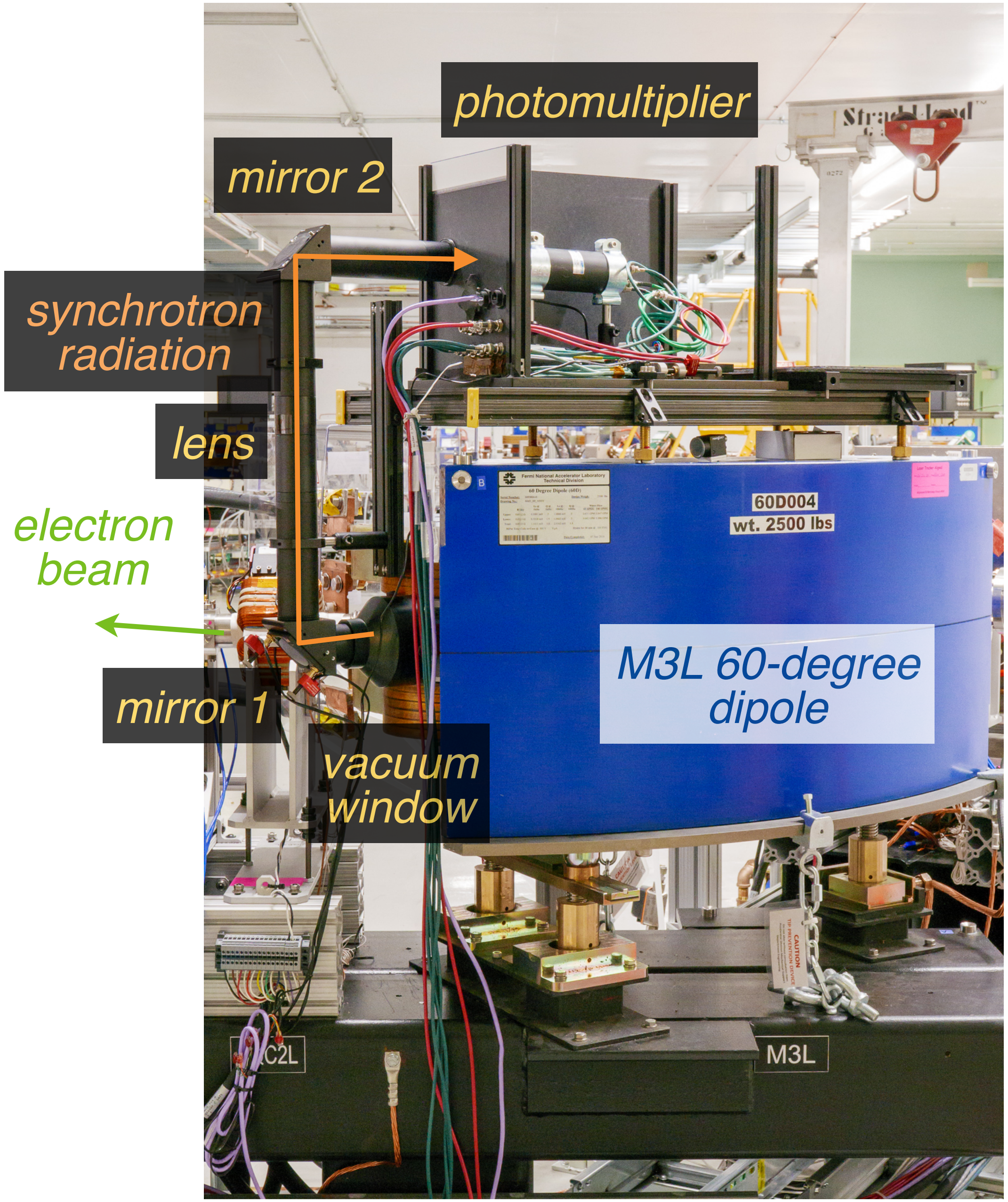


Synchrotron oscillations of a single electron



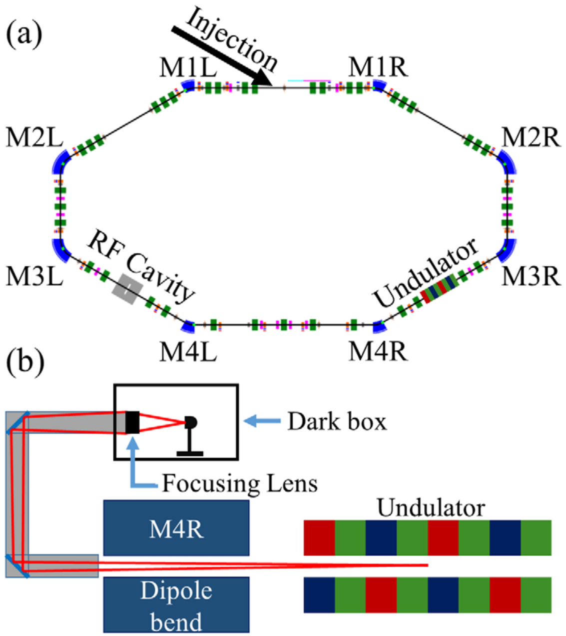
Stancari, FERMILAB-FN-1116-AD (2020)
Romanov et al., JINST **16**, P12009 (2021)
Romanov, IOTA/FAST Collab. Meeting (2021)
Lobach et al., JINST **17**, P02014 (2021)

Detection of synchrotron radiation at IOTA



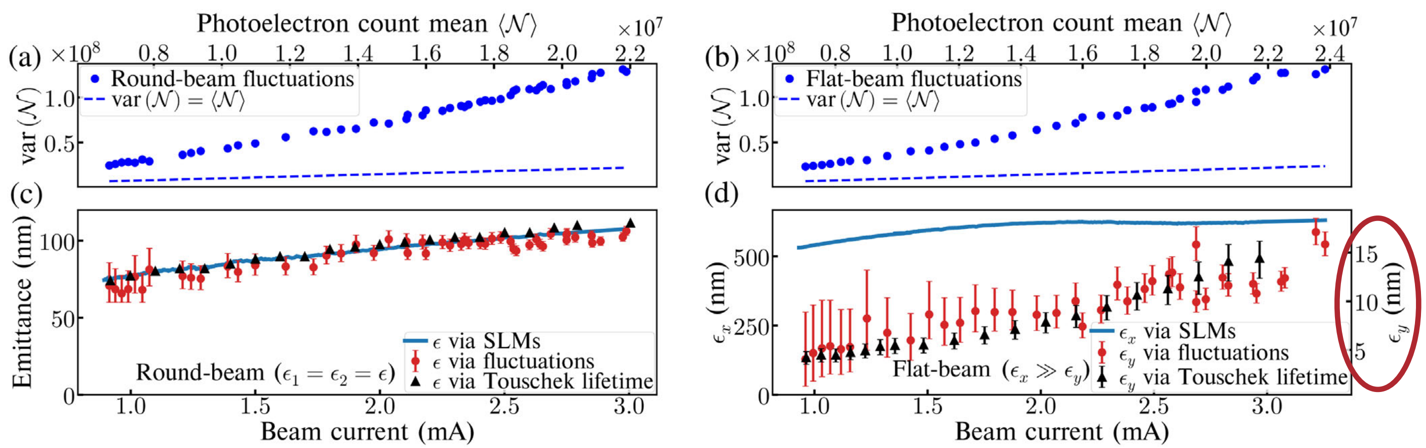
Classical and quantum properties of undulator radiation

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

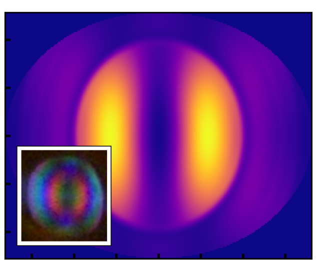


Verified that intensity fluctuations contain a calculable term that depends on beam sizes (interference)

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



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)

IOTA Run 4 program (2022-2023)

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

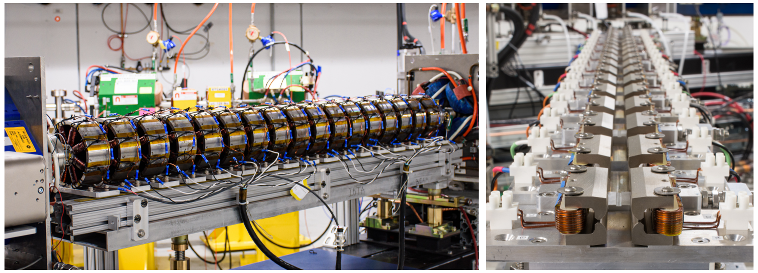
- Improved detectors and methods for general proof of principle and to support the NIO program

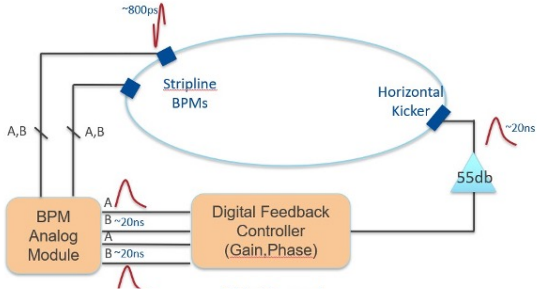
Undulator Radiation Interferometry

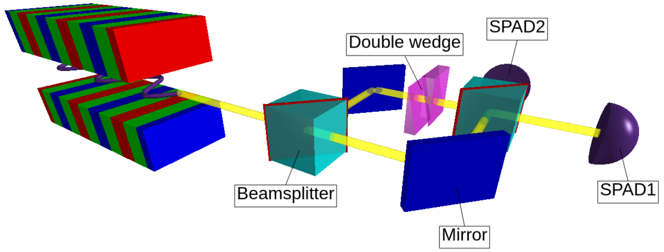
- Measure the quantum properties of radiation emitted by single electrons

Machine-learning

- Study techniques to improve accelerator operations



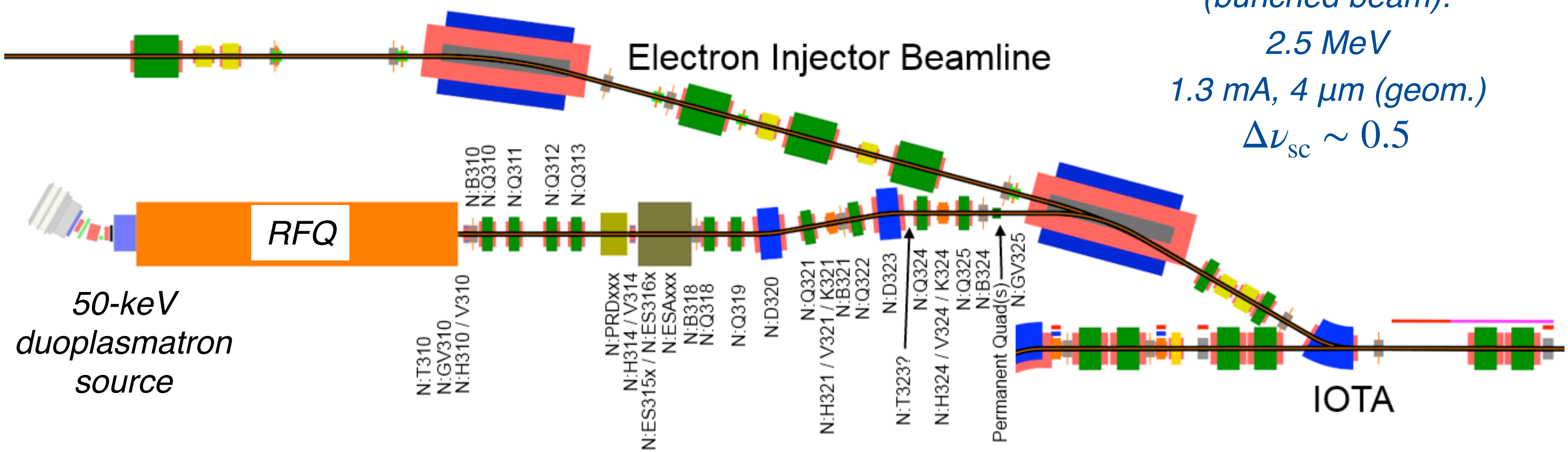




Construction of the IOTA proton source (2022-2023)

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
Source / LEBT	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 um	µm
	Divergence	???	
	Transverse Dispersion	< 0.15	m

	Parameter	Nominal (Range)	Unit
MEBT	Energy	2.5	MeV
	γ_s (Energy) - 1	2.664E-03	
	β_s (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
IOTA Proton	Proton Beam Energy	2.5	MeV
	Proton Beam Momentum	68.5	MeV/c
	β_s (Energy)	7.285E-02	-
	γ_s (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
	Δp/p (RMS)	0.3	%
	Beam Current	8	mA
	Beam Charge	14.64	nC
	RMS beam size for β = 10 m	4.5	mm
	Momentum compaction	0.07	-
	Betatron tune (Qx, Qy)	5.3	-

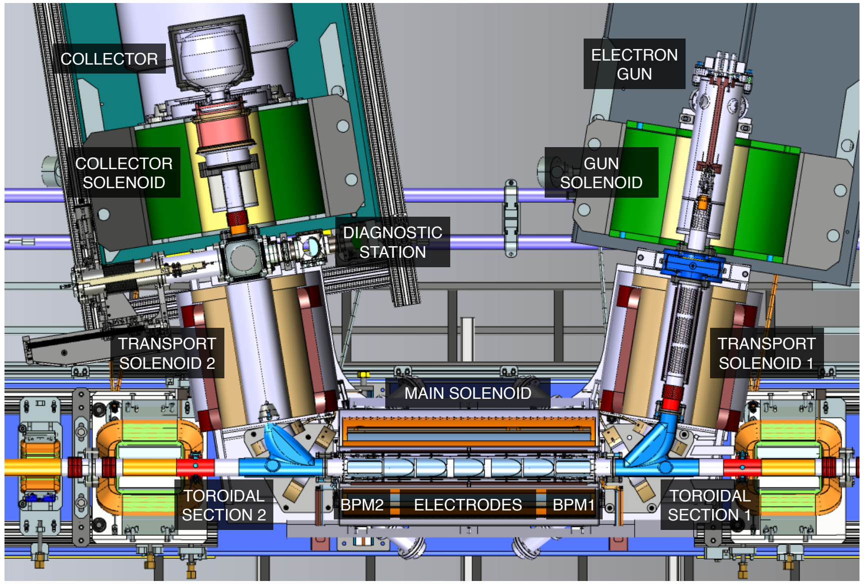
Edstrom, Romanov et al.

Examples of research areas planned after Run 4

Research with the IOTA electron lens

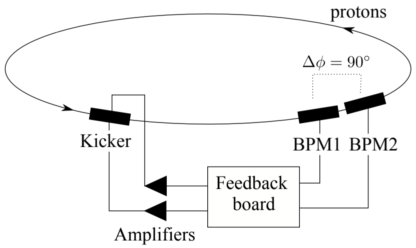
- Novel implementations of NIO schemes
- Electron cooling
- Tune-spread generation for Landau damping
- Space-charge compensation
- Beam diagnostics

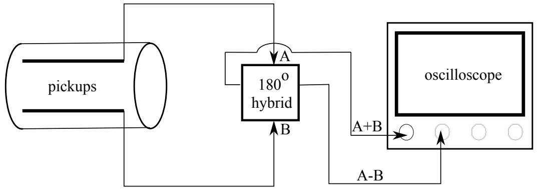
Stancari et al., JINST **16**, P05002 (2021)



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





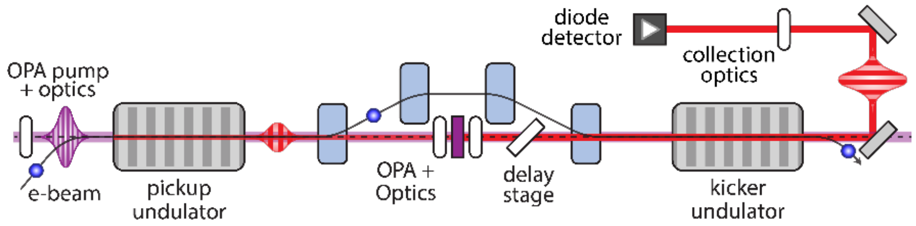
Ainsworth et al., ECA Grant

Examples of research areas planned after Run 4

Optical Stochastic Cooling with Amplification

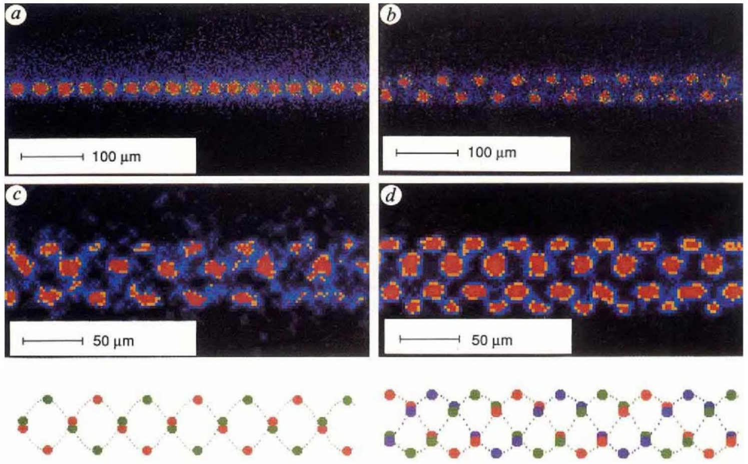
- Development of optical parametric amplifier, transverse sampling, specialized optics
- Demonstration of achievable cooling rates

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



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 current collaborations with UChicago

Led by prof. Y.-K. Kim

Thanks also to S. Nagaitsev (formerly at Fermilab/UChicago, now at JLab/ODU)

- **Beam physics in IOTA with intense self fields and electron cooling**
  - N. Banerjee (UChicago post-doc, now Fermilab Peoples Fellow)
- **Design, construction and test of electron sources for the IOTA electron lens**
  - N. Banerjee, M. Bossard, J. Brandt, S. Kladov
- **Experiments on instability thresholds in IOTA**
  - M. Bossard

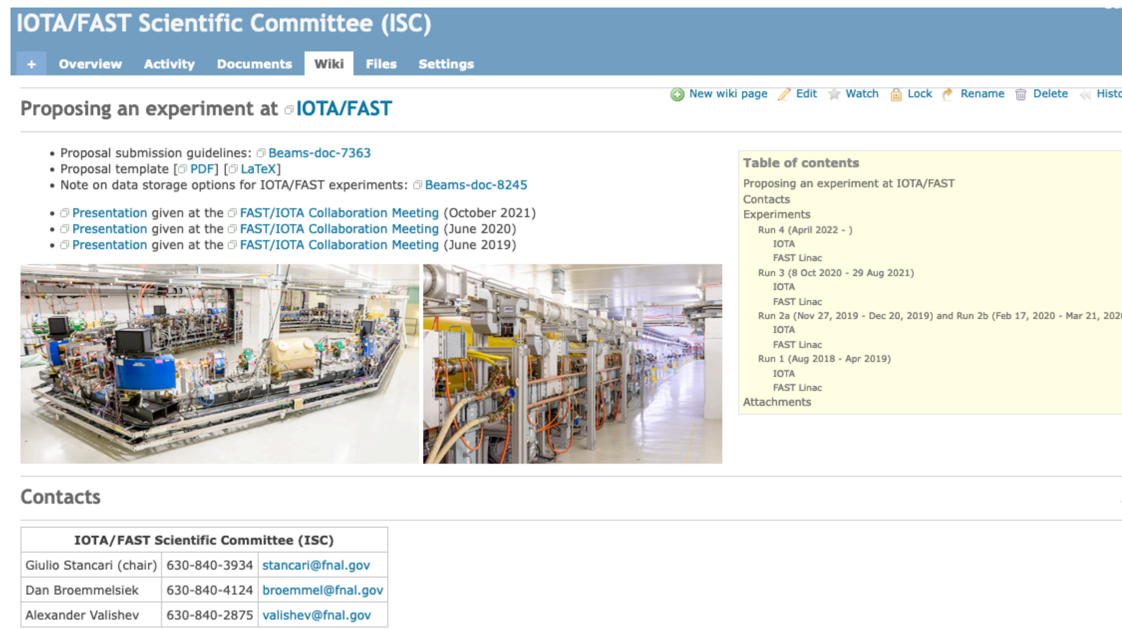
Resources

IOTA/FAST web site

fast.fnal.gov

IOTA/FAST Scientific Committee

cdcvs.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

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