Research at IOTA/FAST – Vision and Strategy

Alexander Valishev

IOTA/FAST Collaboration Meeting

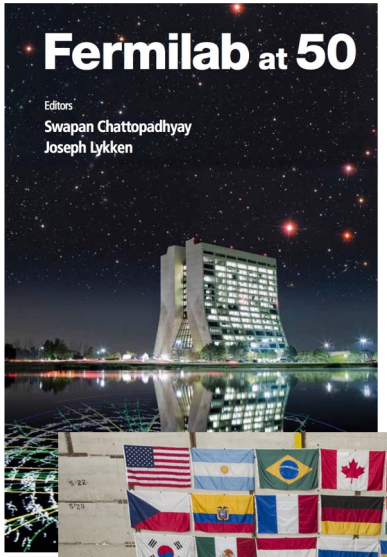
12 March 2024

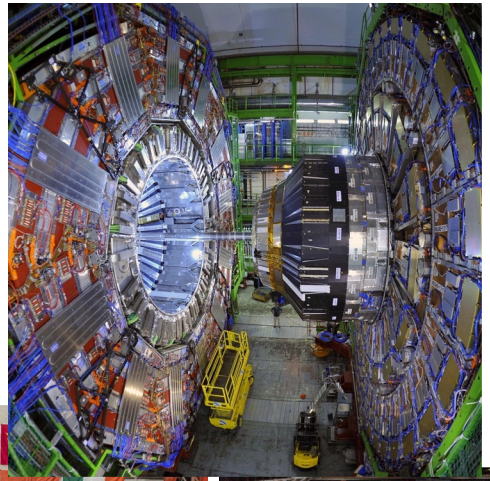
Fermilab is America's particle physics and accelerator laboratory

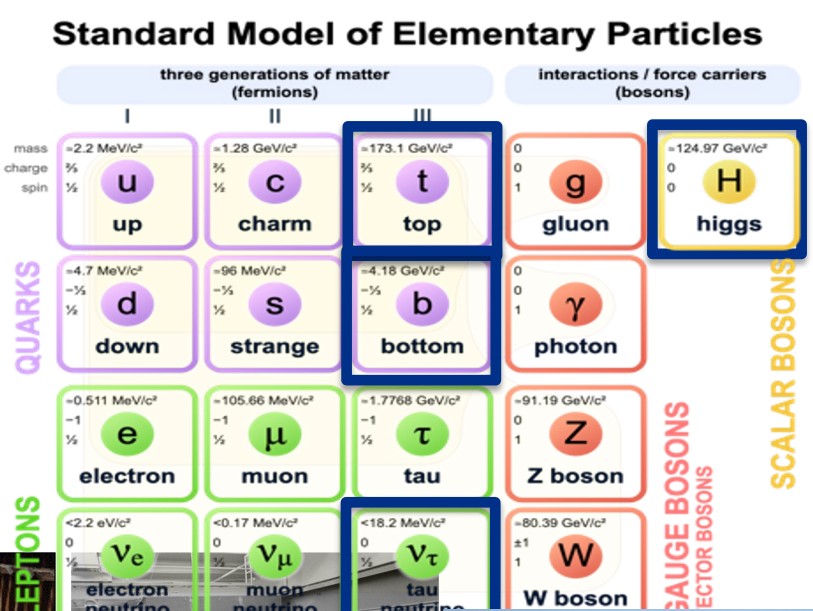
We bring the world together to solve the mysteries of matter, energy, space and time.

- Our vision is to solve the mysteries of matter, energy, space and time for the benefit of all. We strive to:
  - lead the world in neutrino science with particle accelerators
  - lead the nation in the development of particle colliders and their use for scientific discovery
  - advance particle physics through measurements of the cosmos
- Our mission is to drive discovery by:
  - building and operating world-leading accelerator and detector facilities
  - performing pioneering research with national and global partners
  - developing new technologies for science that support U.S. industrial competitiveness

50 Years of Discovery







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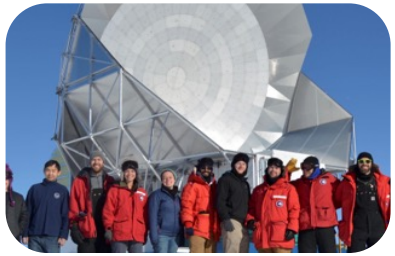
Strategic Thrusts: Pillars of our vision for Fermilab

Deliver groundbreaking science and technology innovation

Building for Discovery: Project Execution

Diversify and empower our workforce

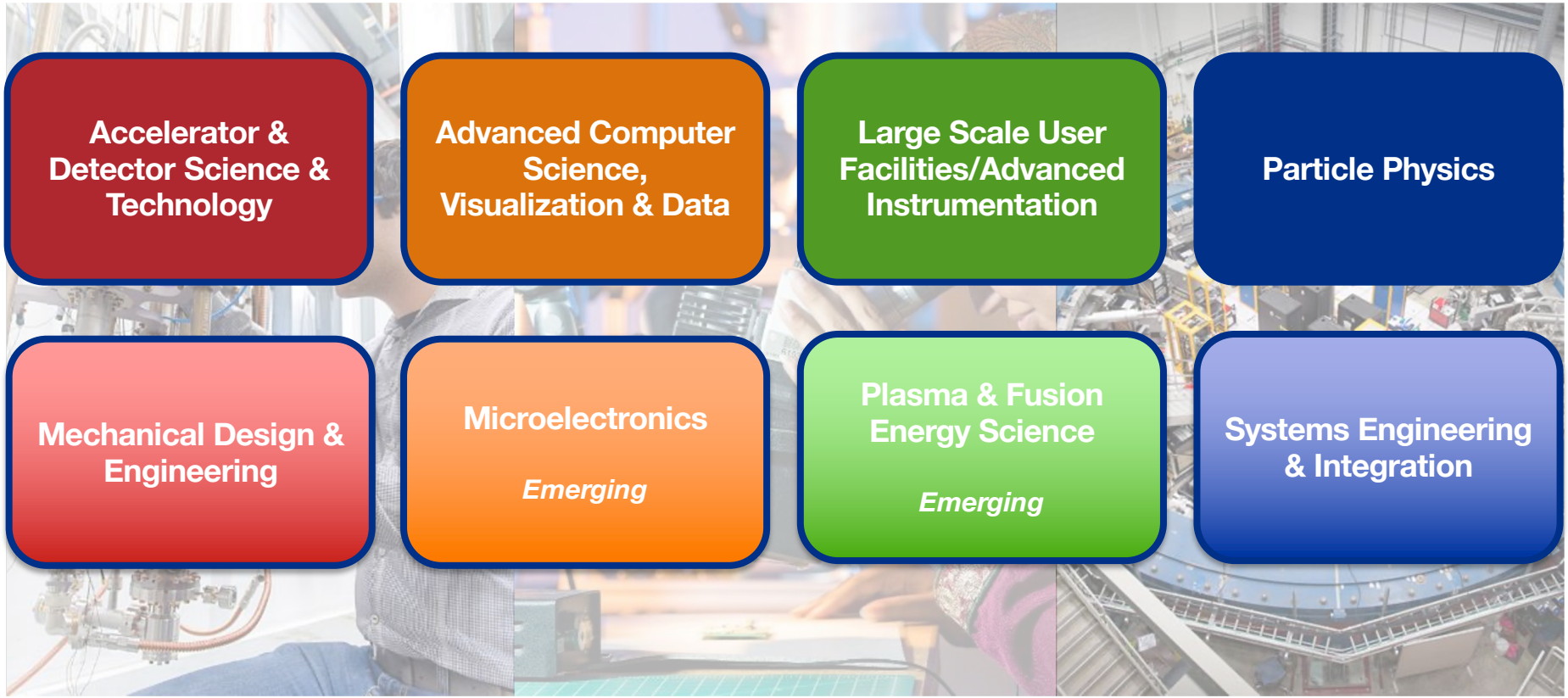
Transform business & operations, execute sustainable campus strategy integrated with science vision



Forge strong alliances with UChicago, ANL, URA and other national/international institutions

Develop Strategic Plan for Fermilab's next 20 Years

Fermilab Core Capabilities



Fermilab and US HEP Strategy

- Our overall strategy: exploit core capabilities to advance the field of particle physics in the U.S.
  - Aggressively pursue US HEP priorities, based on P5 report
  - Expand connections by exploring opportunities to address other priority issues (e.g. DOE initiatives requiring accelerator science and technology, QIS, industrial connections) and to leverage resources across partnering institutions
- Engagement with community is key
  - The success of HEP community and success of the laboratory are tightly connected
  - International engagements are essential for advancing the P5 priorities, keeping U.S. engaged
- Accelerator research is an integral part of lab strategy

Accelerator Science at Fermilab

Accelerator science and technology research at Fermilab is aligned with community goals

- Short-term
  - In support of ongoing accelerator operations and current projects (LBNF, PIP-II, Mu2e)
- Medium- and long-term
  - To enable future capabilities, predominantly through the DOE General Accelerator R&D program
    1. Superconducting RF
    2. High-Field Magnets
    3. Accelerator and Beam Physics (ABP)
    4. High-Power Targets

- Fermilab hosts the US Particle Accelerator School

Addressing the Accelerator S&T goals requires a dedicated facility

- Need for experimental beam-physics research, especially in circular accelerators
- Difficult to conduct R&D in main complex
  - Production machines must operate 24/7 for HEP users
  - Disruptive studies – opportunities limited by time, impact on operations
  - Hardware modifications expensive and time consuming
- Dedicated R&D facility is an efficient way to conduct proof-of-principle experiments, capture other high-impact research opportunities, train researchers
- Such facilities are vital long-term tools for HEP and the broader accelerator Community (highlighted by 2016, 2022 Facilities Operations Reviews)
- 2015 P5 HEPAP subpanel: “Construct the IOTA ring and conduct experimental studies of high-current beam dynamics in integrable non-linear focusing systems.”

IOTA/FAST is a dedicated accelerator research facility

- Research at Fermilab Accelerator Science and Technology (FAST) facility is centered at the Integrable Optics Test Accelerator (IOTA) ring
- IOTA/FAST is the only US dedicated facility for intensity-frontier accelerator R&D
- At present, IOTA/FAST is not a Users Facility – it operates as collaboration
- IOTA/FAST operates in support of P5 mission and objectives, but not directly for projects
- Primary customer is HEP GARD, which funds research and operations
- The facility is managed by Accelerator Research Division in Fermilab's Accelerator Directorate (AD/ARD)


IOTA/FAST Collaboration Meeting '19

FAST Facility - Evolution

- 2006 - Fermilab's New Muon Lab (NML) fixed-target hall was converted to an SRF accelerator test facility for ILC R&D (funded with ILC R&D Infrastructure funds)
- 2010 - 150-meter tunnel extension and service building constructed with ARRA funds
- 2011 - Nearly all accelerator and facility components purchased with ARRA funds
- 2015 - Facility re-purposed for Accelerator Science & Technology R&D based around IOTA research program (Re-named: FAST)
- 2016 – Grid Computing Facility that occupied portion of facility relocated to create a concentrated center for Fermilab accelerator research

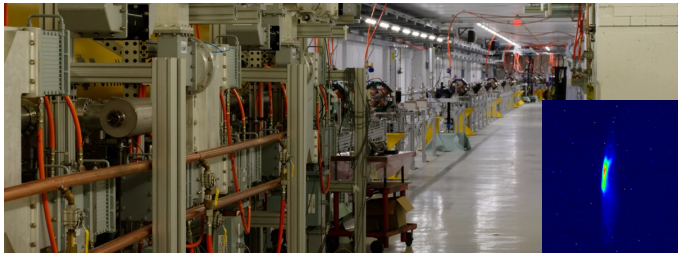
NML During Removal of Chicago Cyclotron Magnet(CCM) (2006)

FAST Facility under construction in repurposed NML building

ILC-Type Cryomodule installed in FAST Injector

FAST SRF linac has successfully met design goals in 2017

- Commissioned to full design energy of **300 MeV**; ~90% up-time
- World-record beam acc. by ILC-type CM: **>31.5MV/m** (~250MeV gain)
- Primary use – beam delivery to IOTA
- Active scientific program:
  - HOM excitation in SRF cavities & effects on beam emittance
  - Advanced beam diagnostics using synchrotron radiation
  - Machine learning algorithms for optimization of accelerator controls
  - 4D phase-space tomographic reconstruction of the beam
  - Flat-beam transformations of high-intensity magnetized beams
  - High-power inverse free-electron laser studies
  - Beam-noise studies to support Coherent Electron Cooling



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IOP Institute of Physics
Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

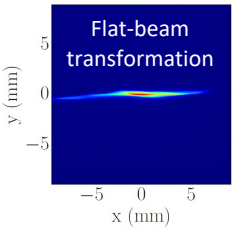
PAPER

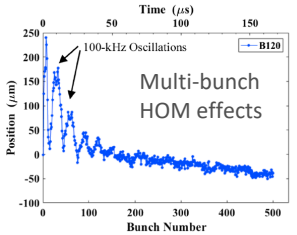
Record high-gradient SRF beam acceleration at Fermilab

D Broemmelsiek, B Chase, D Edstrom, E Harms, J Leibfritz, S Nagaitsev, Y Pischalnikov, A Romanov, J Ruan, W Schappert, V Shiltsev, R Thurman-Keup and A Valishev
Fermi National Accelerator Laboratory, PO Box 500, Batavia, IL 60510, United States of America

Submacropulse electron-beam dynamics correlated with higher-order modes in Tesla-type superconducting rf cavities

A. H. Lumpkin, R. Thurman-Keup, D. Edstrom, J. Ruan, N. Eddy, P. Prieto, O. Napoly, B. E. Carlsten, and K. Bishofberger
Phys. Rev. Accel. Beams **21**, 064401 – Published 4 June 2018





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Integrable Optics Test Accelerator – machine for testing novel concept

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 084002 (2010)

Nonlinear accelerator lattices with one and two analytic invariants

V. Danilov
Spallation Neutron Source Project, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA

S. Nagaitsev
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
(Received 3 March 2010; published 25 August 2010)

HB 2010 FERMILAB-CONF-10-390-AD

NONLINEAR OPTICS AS A PATH TO HIGH-INTENSITY CIRCULAR MACHINES*

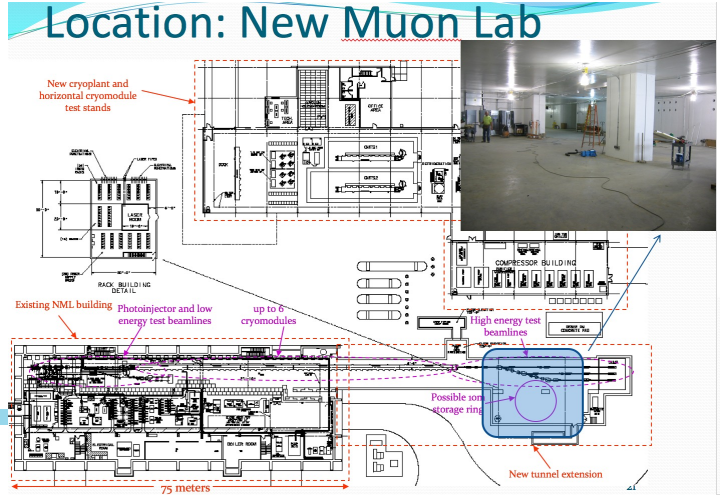
S. Nagaitsev#, A. Valishev FNAL, Batavia, IL 60510, U.S.A
V. Danilov SNS, Oak Ridge, TN 37830, U.S.A.

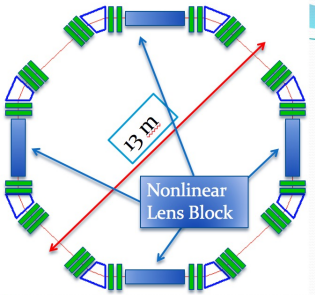
PAC'11 FERMILAB-CONF-11-114-AD-APC

RING FOR TEST OF NONLINEAR INTEGRABLE OPTICS

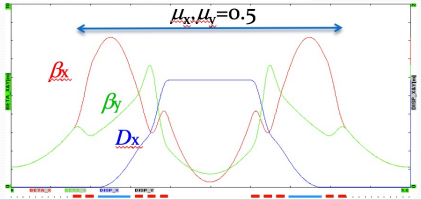
A. Valishev, S. Nagaitsev, V. Kashikhin FNAL, Batavia, IL 60510, U.S.A.
V. Danilov SNS, Oak Ridge, TN 37830, U.S.A.

Location: New Muon Lab





e- Energy	150 MeV
Circumference	38 m
Dipole field	0.5 T
Betatron tunes	Qx=Qy=3.2 (2.4 to 3.6)
Radiation damping time	1-2 s (10^7 turns)
Equilibrium emittance, rms, non-norm	0.06 μm



Nonlinear lens block	
Length	2.5 m
Number of elements	20
Element length	0.1 m
Max. gradient	1 T/m
Pole-to-pole distance (min)	~ 2 cm

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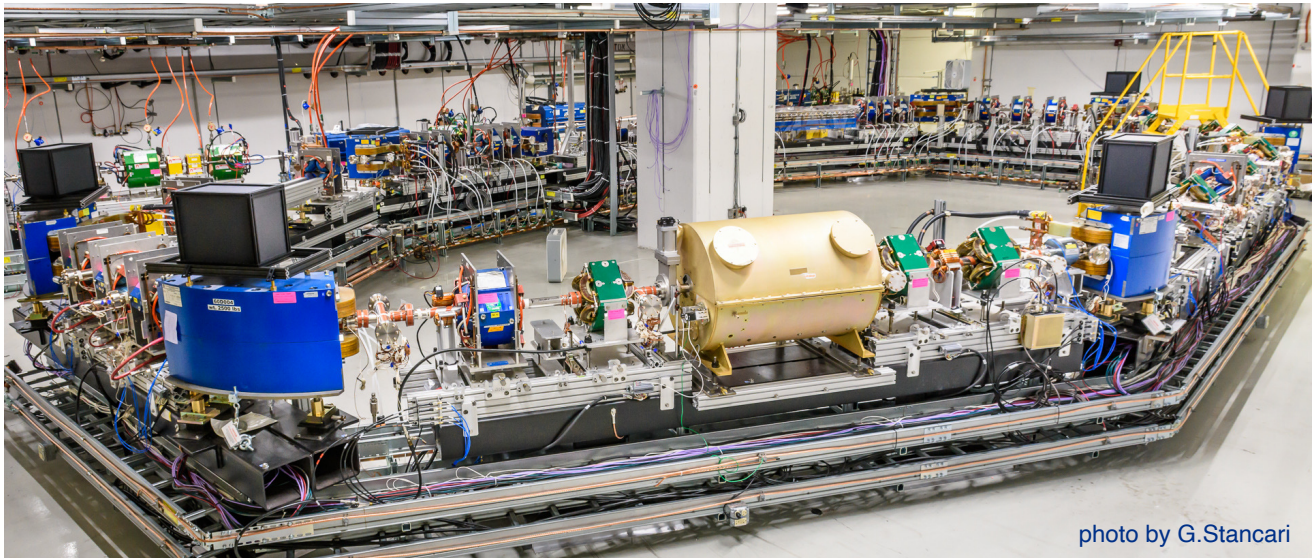
IOTA ring construction completed in 2018



- Commissioned with electrons at 47MeV, 100MeV, and 150MeV; 2.5MeV protons to follow.
- Key features:
  - Flexibility; Accuracy/precision; Small scale

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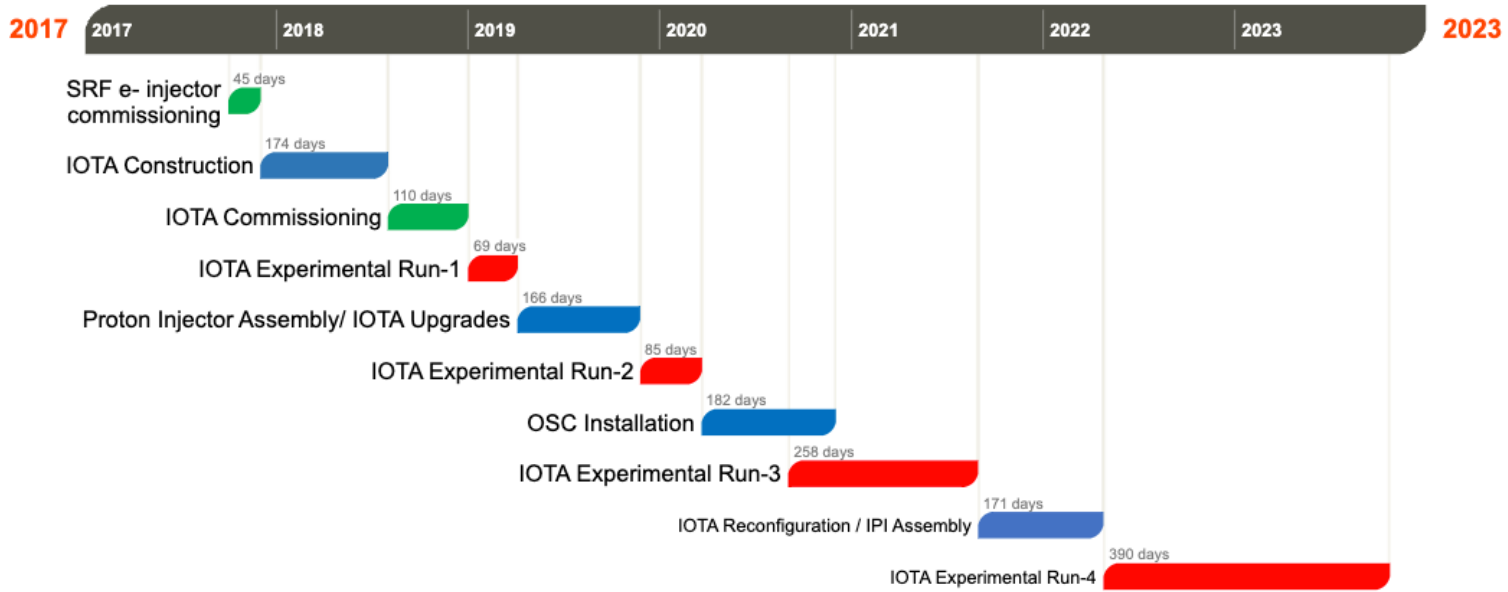
Research program simultaneously with continued facility development

- Balance priorities and resources
- Interleave facility development with beam runs
- Staged approach to research



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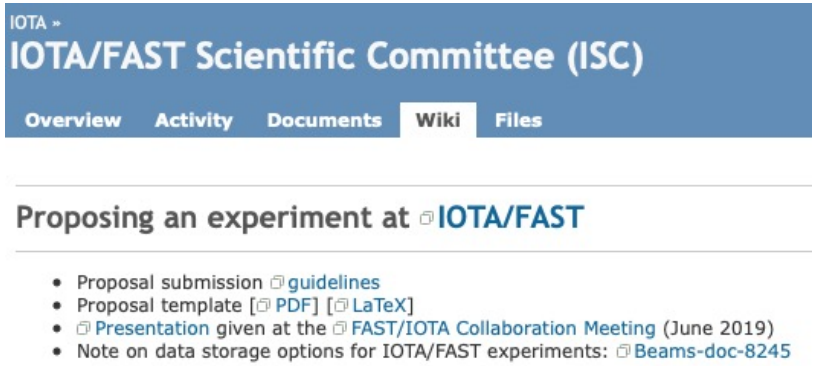
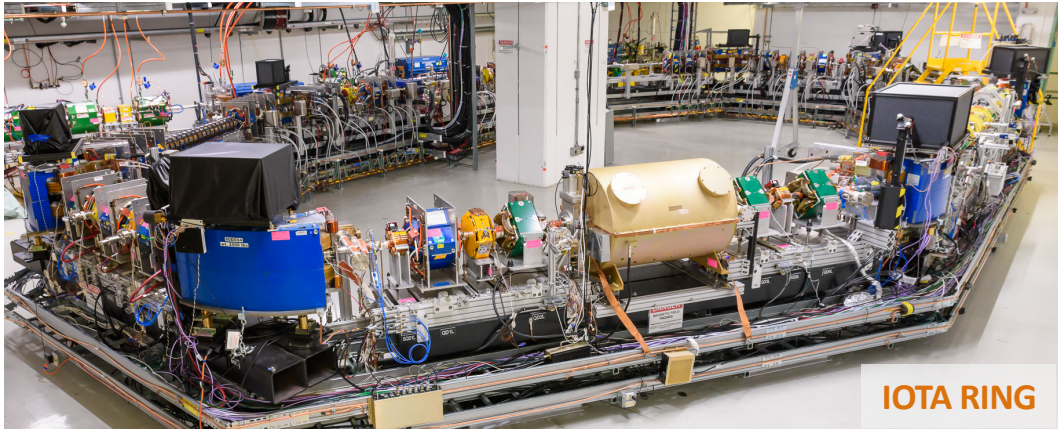
Research priorities are established by IOTA Scientific Committee

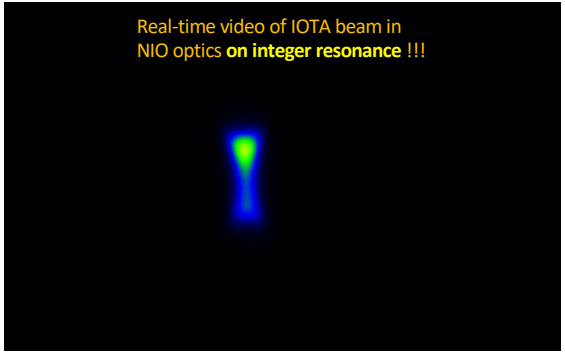
- ISC evaluates experimental proposals and, together with the Fermilab Directorate, establishes research priorities for the facility
- ISC is chaired by G.Stancari who presents a detailed talk in this session

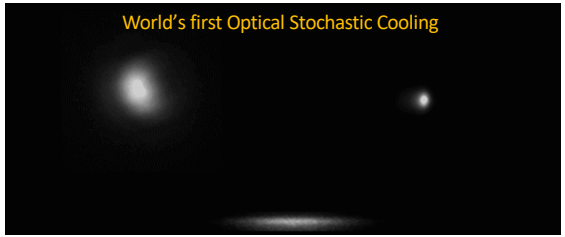


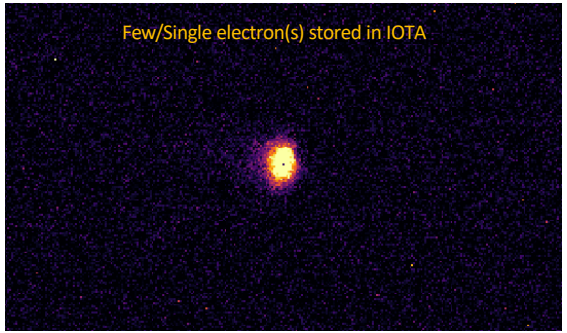
A growing portfolio of R&D at IOTA:

- Suppression of coherent instabilities via Landau damping (nonlinear integrable optics, electron lenses)
- Mitigation of space-charge effects (NIO, e-lenses)
- Advanced beam cooling: Optical Stochastic Cooling
- Photon and Quantum Science with a single electron
- Development of novel instrumentation and methods
- ...









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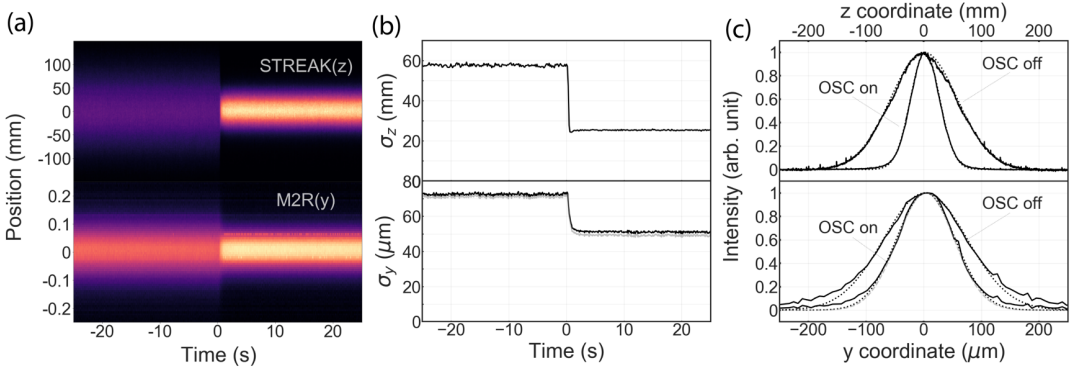
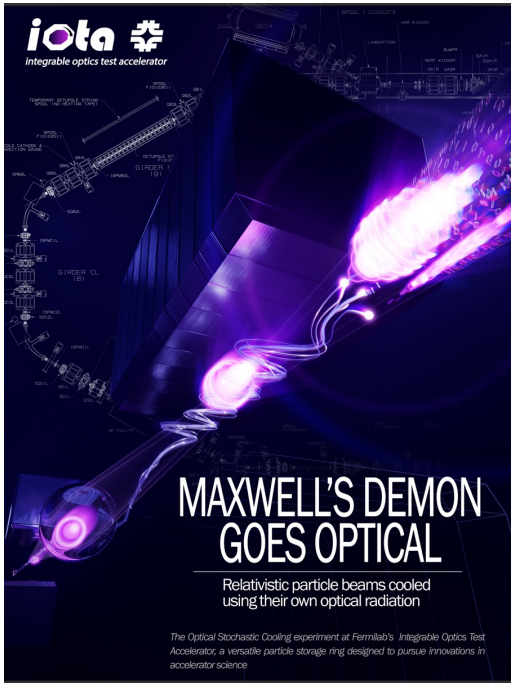
Optical Stochastic Cooling

- World's first Optical Stochastic Cooling (***Nature, 2022***)
- Beam cooling in 1,2 and 3D configurations
- "OSC" of a single electron
- Detailed characterization of OSC experiments and physics
- Invaluable experience for more complex amplified program
- Und. radiation statistics and adv. diagnostics with single electron (led to new LDRD: A. Romanov)
- Excellent validation of IOTA's flexible operations model





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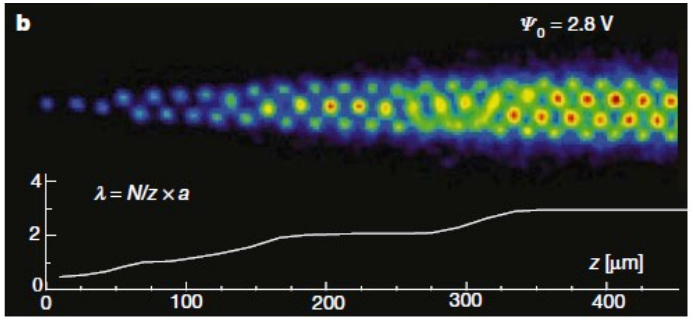
IOTA/FAST Long-Term Strategy

- **Continue Executing R&D mission as directed by P5/HEPAP**
- **Expand IOTA/FAST R&D Into new areas: new capabilities - broad collaborations; especially in response to Snowmass/P5 update**
  1. Exploit unique capability – multi-bunch linac
  2. Quantum science with ultra-cold (crystalline) ion and electron beams
  3. Technology of Nonlinear Magnets and Electron Lenses for future intensity-frontier accelerators
  4. SRF technology development
  5. Laser-plasma based beam injection into rings
  6. Beam cooling technologies



T. Schätz, U. Schramm and D. Habs, "Crystalline Ion Beams", 2001 Nature 412 717.

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Priorities

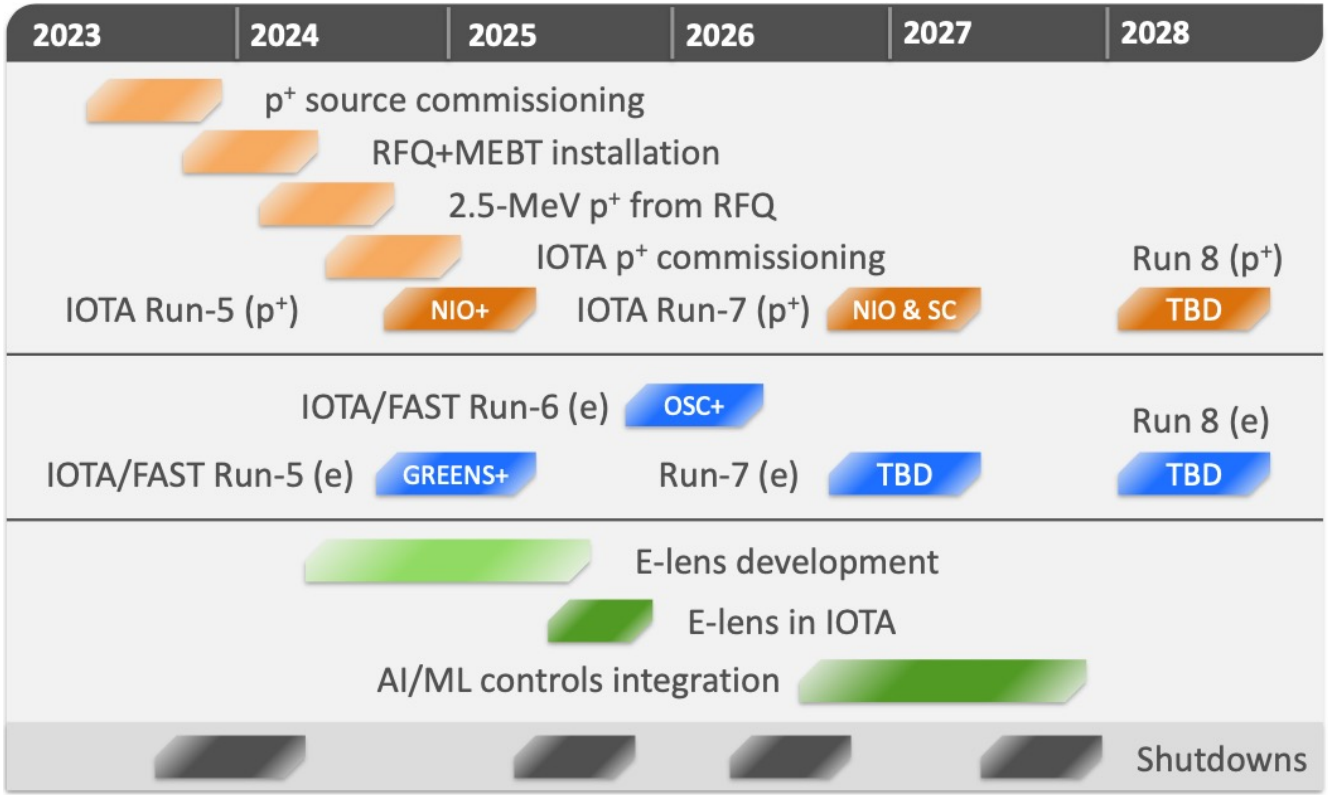
In developing the priorities and schedules we balance present research capabilities, potential impact and available resources

I. **IOTA research focused on beam intensity and brightness in proton rings mostly driven by the development of Fermilab's high-energy neutrino program**
   - Prerequisite is the completion of the proton injector and IOTA commissioning with protons
   - Research that can be done with present capabilities

II. **High-impact science aligned with GARD mission**

III. **Collaboration-driven research seeding potentially high-impact directions**

Expected IOTA/FAST Schedule CY23-28



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Future upgrades to enable new capabilities and expand operations

Infrastructure

I. Cryogenics system upgrade
   - Overhaul of NML cryo plant
   - Upgrade of the unsupported control system

II. Low-level RF controls for all SRF
   - Legacy systems

III. HVAC upgrades for ESB & NML
   - Insufficient capacity for normal ops

IV. Expand team: dedicated operations personnel & support staff

Research

I. Beam loss mitigation for high-intensity rings
   - Requires H- charge stripping injection and injection painting in IOTA

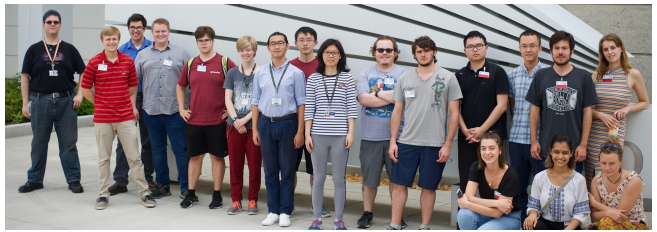
II. Advanced acceleration concepts with high repetition rate and laser-plasma injector
   - Requires high-power laser system

III. Quantum science
   - High-fidelity laser system for read-out and cooling of ions
   - Ion injection/storage

A growing customer base depends on IOTA/FAST for R&D

- Unique facility enabling unique R&D for collaborators and various DOE programs
- **Currently supporting two HEP ECA's and multiple training programs in Accelerator Science and Technology**
  - R. Ainsworth, J. Jarvis – DOE HEP Early Career Awards 2020-2025
  - AST PhD program; Lee Teng and Helen Edwards Internships; DOE SCGSR program; NSF CBB
- New collaborations in Academia, Industry and Nat. Labs every run, including growth in new areas that support DOE SC/HEP/P5 mission but weren't originally planned
- Reliable facility operations and schedule is essential for meeting our obligations to this expanding community



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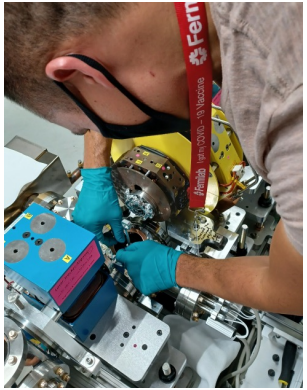



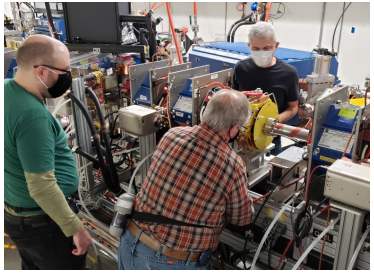

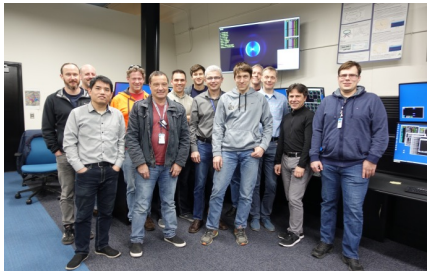

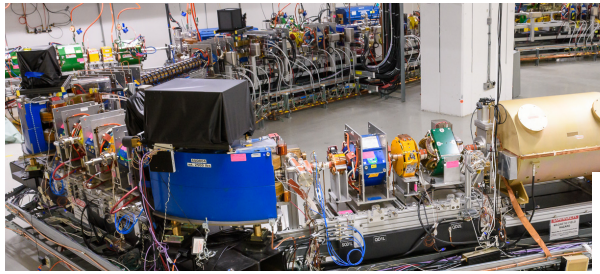
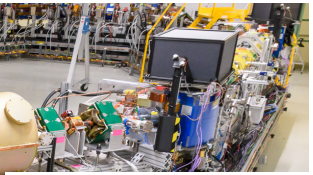

integrable optics test accelerator

iota

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