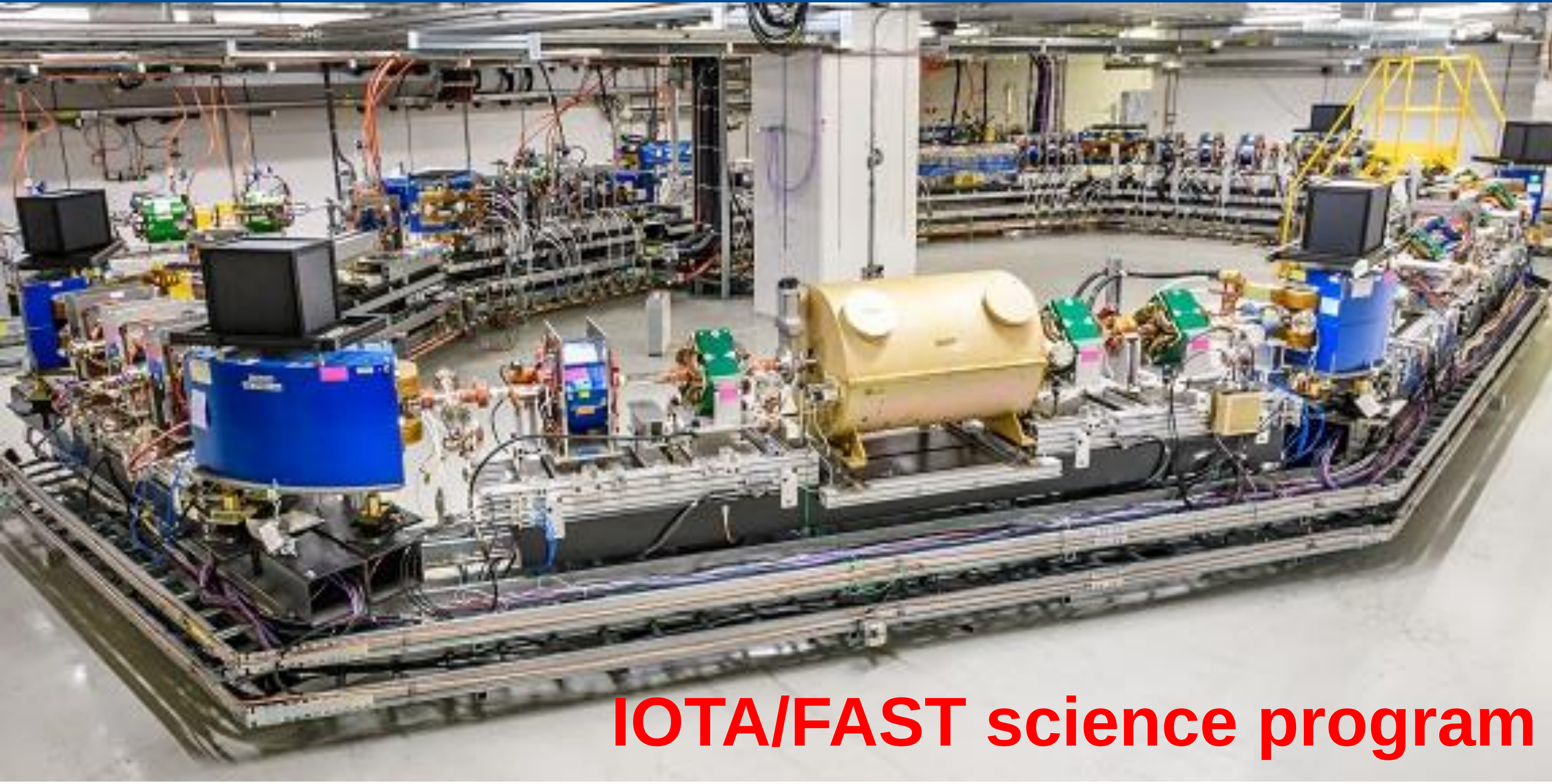
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

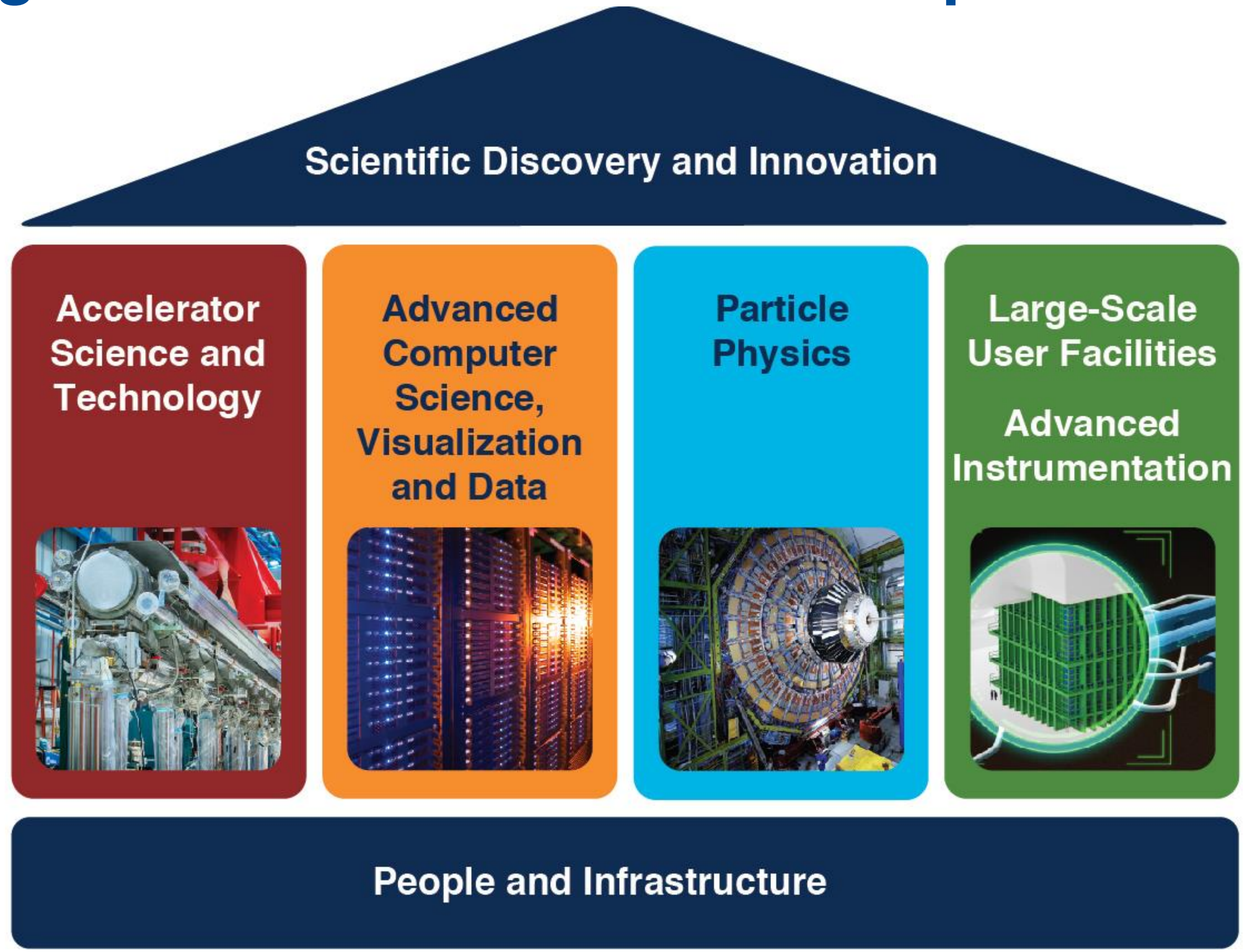


IOTA/FAST science program

Sergei Nagaitsev
Fermilab/UChicago

October 27, 2021

Strategic context: Fermilab core capabilities



Fermilab has four core capabilities that depend on people and infrastructure. These are the elements that define the scope of what we do.

Fermilab's strategic priorities

- Lead the world in neutrino science with particle accelerators.
- Lead the nation in the development of particle accelerators and their use for scientific discovery.
- Build and operate world-leading accelerator and detector facilities.
- Perform pioneering research with national and global partners.
- Advance particle physics through measurements of the cosmos.
- Develop new technologies for science that support US industrial competitiveness.
- Leverage Fermilab's business systems to support growth and operational excellence.
- Attract, develop, and retain a diverse group of talented people.

Fermilab strategy in a nutshell

- Our overall strategy: exploit core capabilities to strengthen 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 smooth out resource/funding profiles.
- Fermilab GARD is an integral part of this strategy

2013 P5 provided physics drivers for accelerator research and development

	Intensity Frontier Accelerators	Hadron Colliders	e^+e^- Colliders
Current Efforts	PIP	LHC	
	PIP-II	HL-LHC	ILC
Next Steps	Multi-MW proton beam	Very high-energy proton-proton collider	1 TeV class energy upgrade of ILC *
Further Future Goals	Neutrino factory *	Higher-energy upgrade	Multi-TeV collider *

Table 1: Particle accelerators foreseen by the P5 strategic plan to carry out future accelerator-based particle physics research. ***(* The priority and urgency of some accelerators depends upon how physics unfolds at current or Next Step ac-***

P5 accelerator R&D sub-panel (2014)

Recommendation 2. Construct the IOTA ring, and conduct experimental studies of high-current beam dynamics in integrable non-linear focusing systems. (p. 9, 18)

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Snowmass 2021

- Getting ready to update our research drivers and priorities though the DPF/DPB community planning process
  - https://snowmass21.org/
- Accelerator Frontier
  - The Accelerator Frontier activities include discussions on high-energy hadron and lepton colliders, high-intensity beams for neutrino research and for the “Physics Beyond Colliders”, accelerator technologies, science, education and outreach as well as the progress of core accelerator technology, including RF, magnets, targets and sources. Participants will submit LoI, contributed papers, take part in corresponding workshops and events, contribute to writing summaries and take part in the general Snowmass'21 events.

Fermilab GARD includes

- SRF
- High-field magnets
- High-power targets
- Advanced Accelerator Concepts
- Accelerator and Beam Physics
- GARD AI/ML
- USPAS

- All thrusts are a combination of science and technology
- Accel and Beam Physics is cross-cutting

https://arxiv.org/abs/2101.04107

Accelerator and Beam Physics Research Goals and Opportunities

Working group: S. Nagaitsev (Fermilab/U.Chicago) *Chair*, Z. Huang (SLAC/Stanford), J. Power (ANL), J.-L. Vay (LBNL), P. Piot (NIU/ANL), L. Spentzouris (IIT), and J. Rosenzweig (UCLA)

Workshops conveners: Y. Cai (SLAC), S. Cousineau (ORNL/UT), M. Conde (ANL), M. Hogan (SLAC), A. Valishev (Fermilab), M. Minty (BNL), T. Zolkin (Fermilab), X. Huang (ANL), V. Shiltsev (Fermilab), J. Seeman (SLAC), J. Byrd (ANL), and Y. Hao (MSU/FRIB)

Advisors: B. Dunham (SLAC), B. Carlsten (LANL), A. Seryi (JLab), and R. Patterson (Cornell)

January 2021

ABP Grand Challenges

- **Grand challenge #1 (beam intensity):** How do we increase beam intensities by orders of magnitude?
- **Grand challenge #2 (beam quality):** How do we increase beam phase-space density by orders of magnitude, towards quantum degeneracy limit?
- **Grand challenge #3 (beam control):** How do we control the beam distribution down to the level of individual particles?
- **Grand Challenge #4 (beam prediction):** How do we develop predictive "virtual particle accelerators"?

ABP research areas

- Single particle dynamics and non-linear effects. Polarized beams
- Space charge effects and mitigation
- Beam instabilities, control and mitigation; conventional wakefields
- High brightness / low emittance beam generation.
- Beam quality preservation and advanced beam manipulations. Beam-beam effects.
- Beam cooling and radiation effects in beam dynamics;
- Advanced accelerator instrumentation and controls
- Modeling and simulation tools (including energy deposition); fundamental theory and applied math
- Machine Learning/AI
- Early conceptual integration and optimization, maturity evaluation

  -- focus on combining science and technology

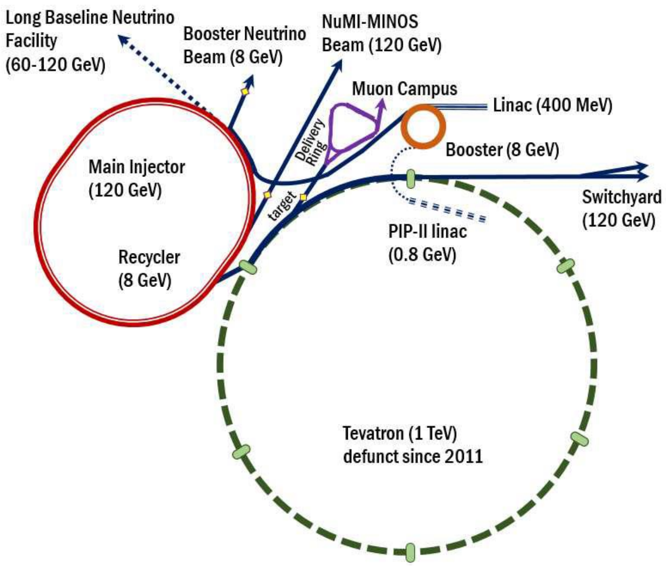
Our GARD ABP focus

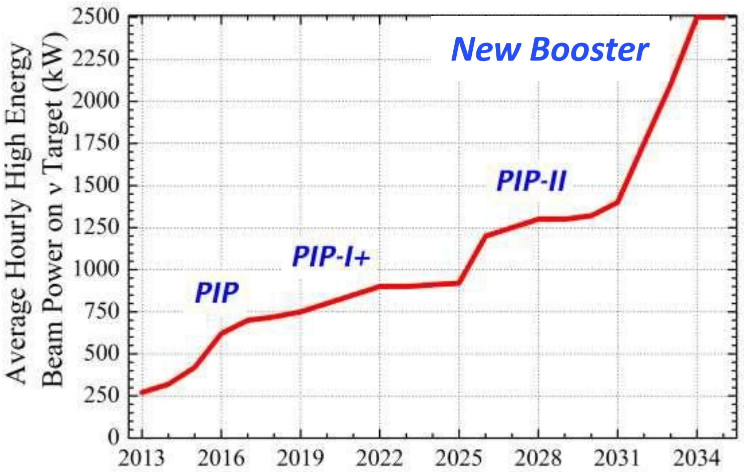
- Main focus:
  - IOTA-based research program
  - Theory and modeling in support of Fermilab Accelerators and future upgrades
- Our research effort at Fermilab closely focuses on solving GARD ABP Grand Challenges

Accelerator and beam physics

Of particular interest for FNAL and HEP:

- Mitigation of beam losses at high-intensity:
  - Booster, Recycler and MI are intensity-limited by losses (~1 W/m).
- Mitigation of instabilities in high-brightness beams:
  - Fast instabilities which can not be suppressed by external dampers
  - ECA project (R. Ainsworth)
- Beam cooling
  - Future colliders
  - Quantum limits/properties of beams





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GARD AI/ML Thrust

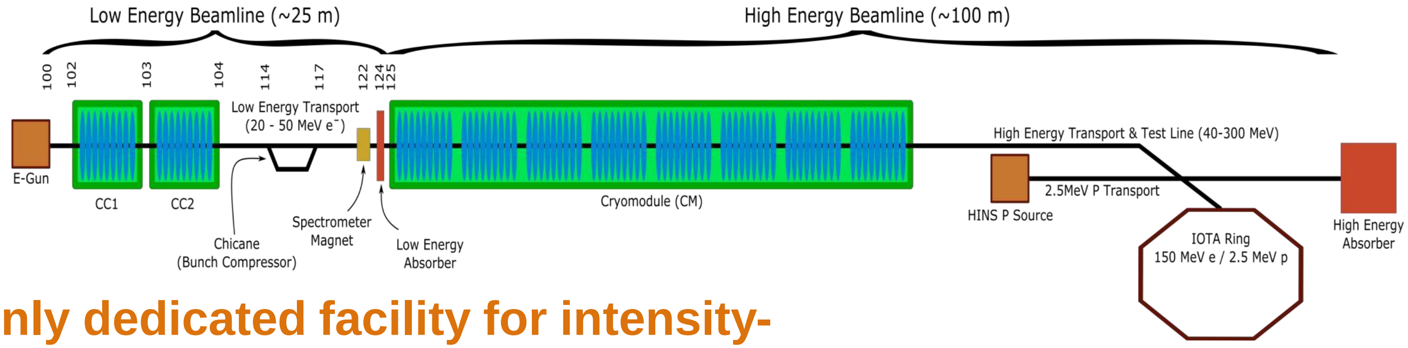
- This is a new thrust introduced to the Fermilab GARD program in 2021
- Includes experimental and theoretical accelerator and beam physics research aimed at applying modern AI/ML techniques to future high-intensity and high-brightness accelerators;
- Development of advanced algorithms for diagnostics and optimization of machine tuning for optimal experimental beam conditions.
  - Goal: improve FAST/IOTA facility operations by providing added reliability and reducing the tuning time between different beam configurations;
- ECA project (J. Jarvis)
- Experimental work in developing AI/ML algorithms in synchrotron radiation camera image analysis;

FAST

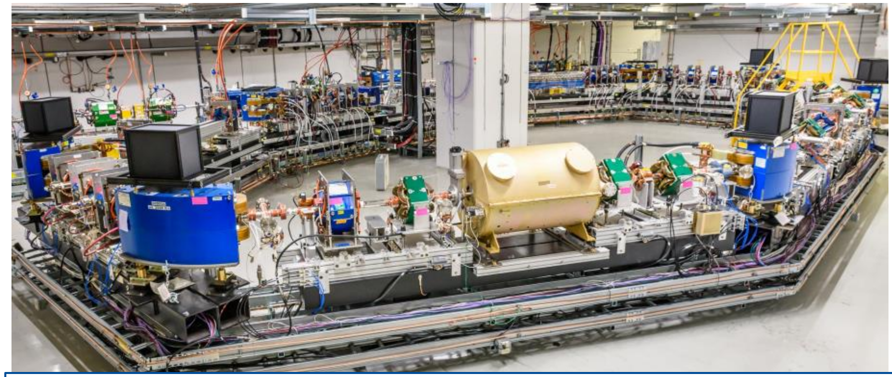
- FAST – Fermilab Accelerator Science and Technology facility
  - Electron linac and experimental area
  - Proton injector
  - IOTA ring
  - Future plans: heavy-ion injector for ion crystals and quantum experiments
- Research at FAST and IOTA is the biggest fraction of the ABP thrust of GARD. It is also a big portion of the Test Facility Ops budget
- The facility is managed and operated by the Accelerator Division
- FAST is not a DOE User Facility, but it welcomes many collaborators to conduct experiments at the electron linac and IOTA.

IOTA/FAST Facility: a center for Accelerator and Beam Physics

- **IOTA/FAST establishes a unique capability at FNAL to address frontier topics in Accelerator and Beam Physics**

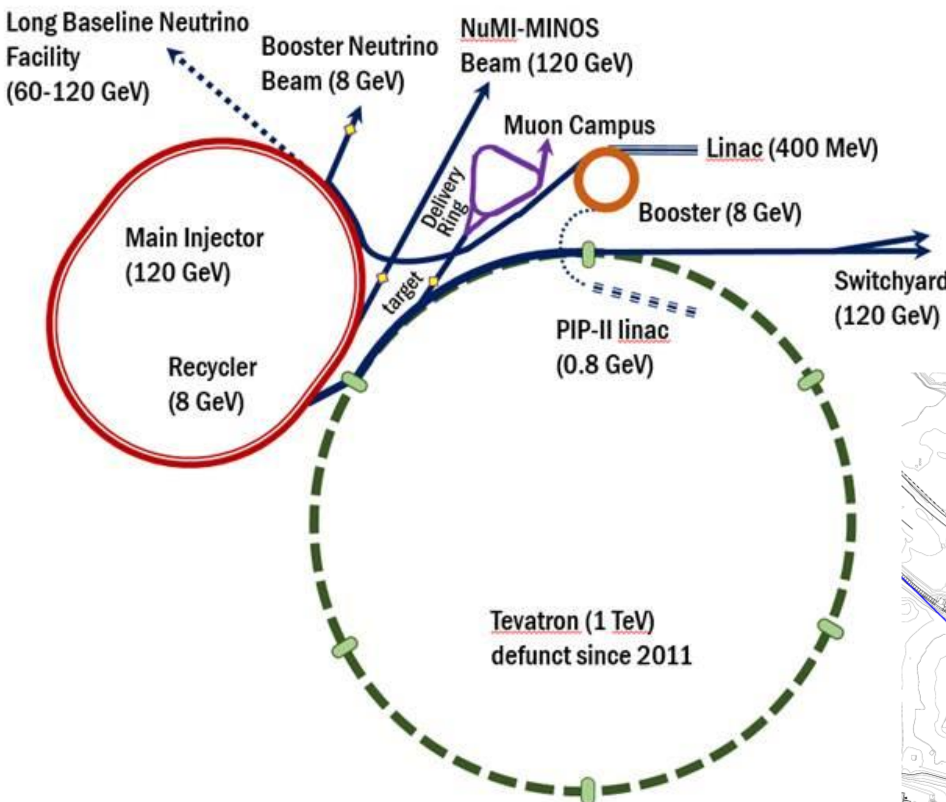


- **The only dedicated facility for intensity-frontier accelerator R&D**
- ~30 Collaborating institutions
  - Student training
- National Lab Partnerships: ANL, BNL, LANL, LBNL, ORNL, SLAC, TJNAF
- Opportunities for R&D with cross-office benefit in DOE/SC
  - Nonlinear Integrable Optics
  - Optical Stochastic Cooling
  - Space-charge compensation
  - Suppression of coherent instabilities

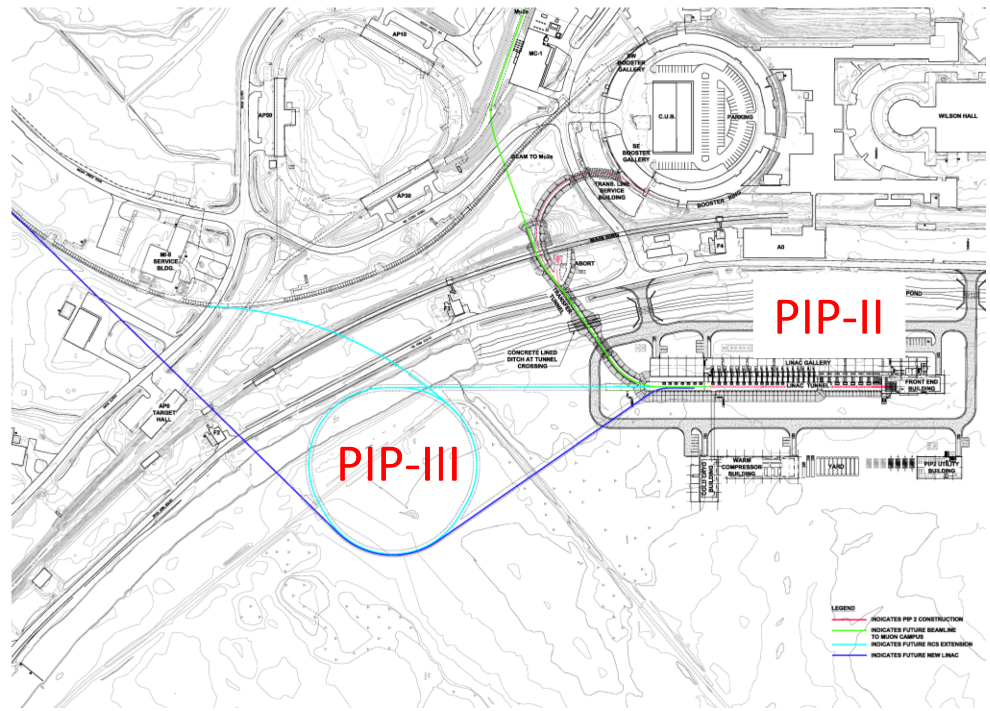


10/16/18 beam circulation at 100 MeV
Jan – Mar, 2019 – First Research Run

IOTA science program highlights



Delivering 8 GeV and 120 GeV protons for neutrino experiments; Muon beams to the g-2 experiment

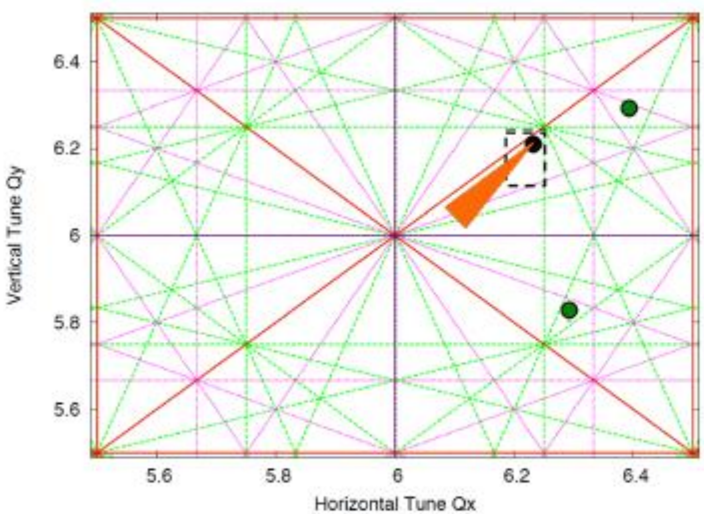


Beam power evolution beyond PIP-II (an example),
as recommended by P5

	Present	PIP-II	New RCS
MI			
Beam Energy[GeV]	120	120	120
Cycle Time[s]	1.33	1.2	1.45
Protons per pulse[1e12]	49	75	190
Power[MW]	0.8	1.2	2.5
Proton Source			
Injection Energy[GeV]	0.4	0.8	0.8-2.0
Extraction Energy[GeV]	8	8	8
Protons per Pulse[1e12]	4.5	6.4	**32**
Beam Power to MI [kW]	38	82	168

Increase the number of particles by a factor of ~8 compared to Booster now!

SNS ring experience



$$\Delta\nu := -\frac{3 \cdot N \cdot r_p}{2 \cdot \pi \cdot \beta \cdot \gamma^2 \cdot \varepsilon_n \cdot BF}$$

Feature	Cost	Payoff So Far
Large Aperture	$$$$	High ←
Injection Painting	$$$	High ←
Collimation	$$$	High ←
TiN coating	$$$	Unknown
2^{nd} harmonic RF	$$	Medium+
Main sextupoles	$$	Low - None
Main octupoles	$$	None
Sextupole correctors	$	None
Octupole correctors	$	None
Clearing solenoids	$	None
Beam in gap kicker	$	None
Clearing electrodes	$	None

SNS ring: 1 GeV, 1.4e14 fixed energy, storage for ~1000 turns, 1.4 MW

Beam losses are all controlled by collimators

Vacuum chamber: stainless steel, 20 cm diam
Large aperture → high cost of magnets and other devices.

Courtesy of S. Cousineau (SNS)

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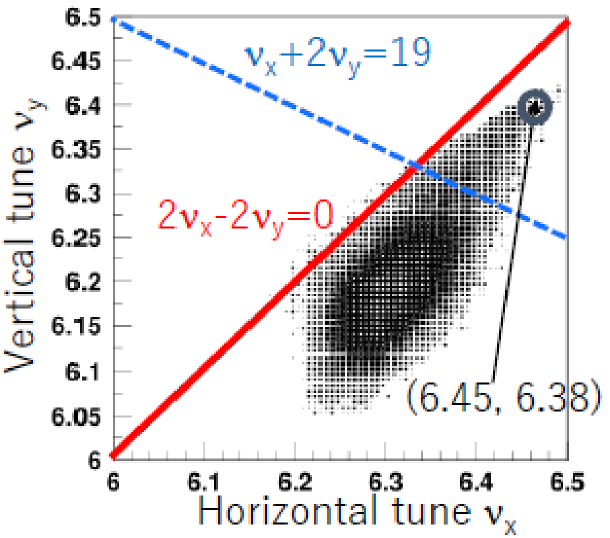
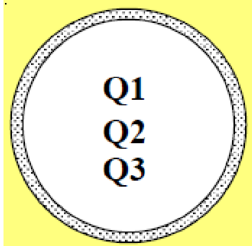
J-PARC RCS experience

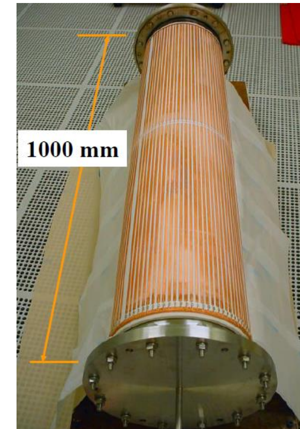
Tune footprint @ injection



Quadrupole Magnets



	Q1	Q2	Q3
Inner dia. (mm)	377	297	257
Length (mm)	1500	1600	1300



RCS ring: 0.4 → 3 GeV, 8.3e13

25 Hz, ~14000 turns, 1 MW

Beam losses are ~300 W (< 1W/m)

Vacuum chamber: ceramic + TiN coating + rf shield

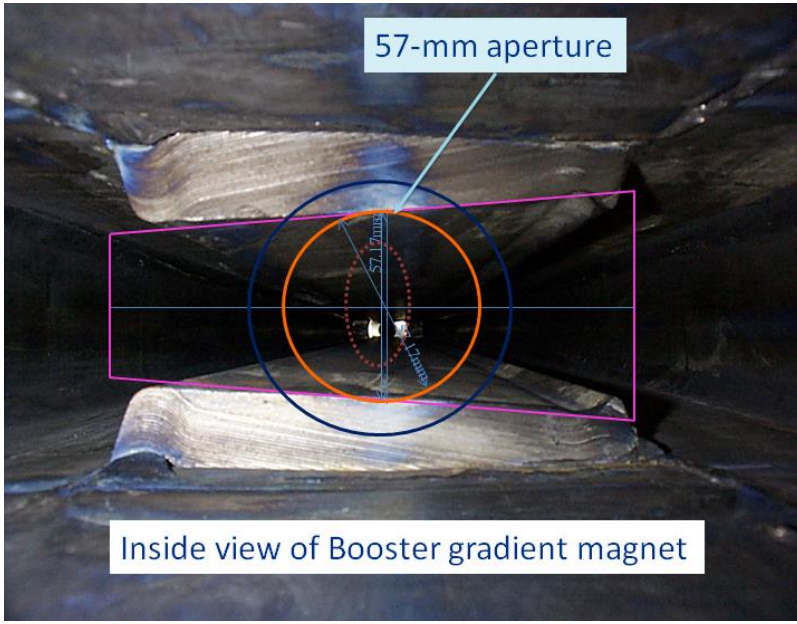
High cost of both vacuum chambers and magnets

Courtesy of J-PARC colleagues

Fermilab Booster experience

Space-charge tune shift: ~0.5

Booster: 0.4 → 8 GeV, 4.5e12
~15000 turns
Beam losses are ~400 W (< 1W/m)



Small aperture, low-cost magnets, no vacuum chamber → instabilities

The Main Injector vacuum chamber is also small: 120 mm x 50 mm

- A new RCS would require to accelerate 32e12 protons
- The physics of space charge and instabilities is fundamental to all future multi-MW rings!

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Challenges of high-power beams

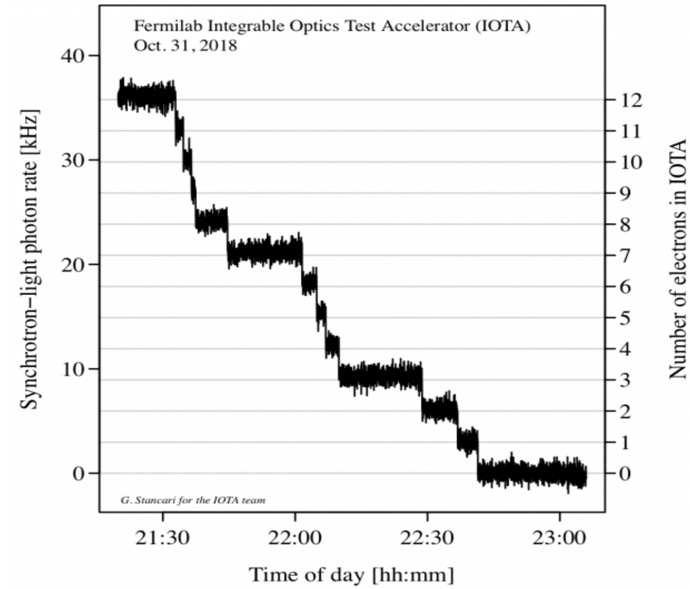
- Uncontrolled beam losses
  - Keep losses at < 1 W/m
    - Fermilab Booster is presently running at the limit of losses (~400 W)
  - Space-charge causes beam halo!
- Beam instabilities (loss of entire beam, emittance degradation)
  - Common resistive-wall instabilities can be mitigated by external dampers
  - As beam space-charge increases, there are more severe types of instabilities appear, e.g. an "electron cloud" instability (observed in the Recycler) can be very fast and can not be damped by dampers

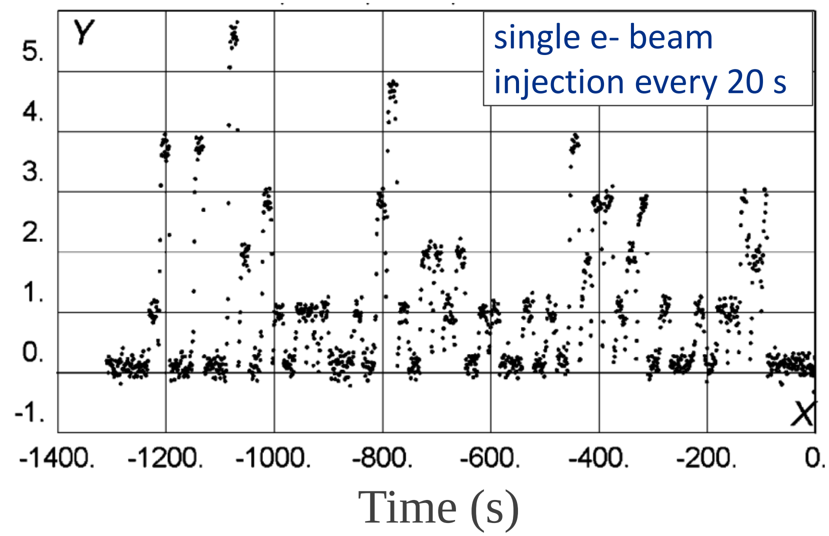
Fermilab Accelerator and Beam Physics components (the core IOTA program)

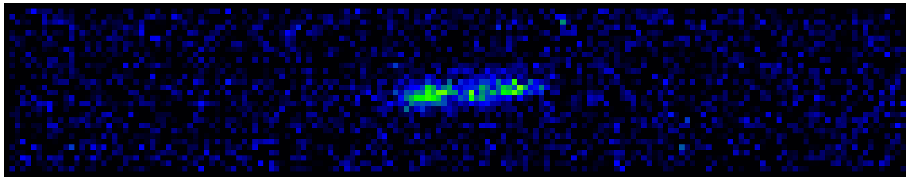
- Beam Instabilities and mitigation
  - Focus: Multi-MW facilities, future colliders
  - IOTA program: nonlinear optics, Landau damping, electron lenses
- Space-charge and mitigation
  - Focus: Multi-MW facilities
  - IOTA program: Electron lenses, space-charge compensation
- Beam cooling
  - Future colliders
  - OSC, EIC cooling R&D
- Modeling tools and theory development in support of the above

IOTA presents unique opportunities in QS

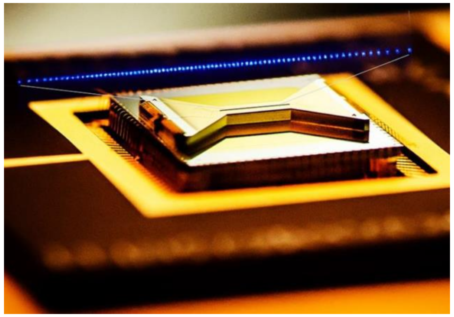
- IOTA demonstrated storage of a **single relativistic electron** for long periods of time (~30 minutes).
- High particle energy (100 MeV) enables observation of SR emission
- This opens the way to a wide variety of quantum experiments
- **2018 Workshop on Single-Electron experiments in IOTA** – 30 participants from U.Chicago, LANL, SLAC, ANL, Princeton, RadiaBeam, BNL, UC Berkeley, Fermilab



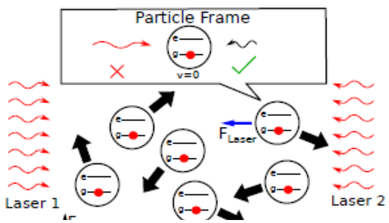


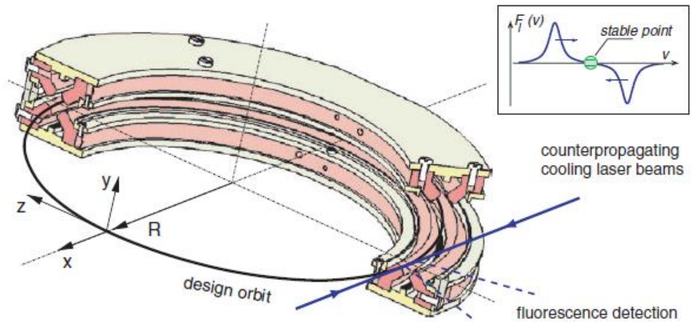


Exploring the scalability of ion QC architectures

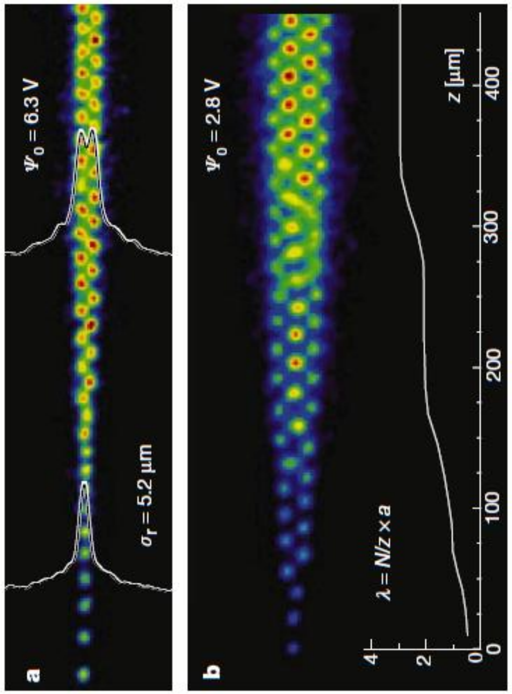


State of the art: ~Tens of ^{171}Yb+ ions (qubits) in a stationary linear ion trap (https://ionq.com/)





PALLAS ring (LMU, Germany) in 2001 achieved a 1-D and 2-D Coulomb crystals in ring with Mg^+ ions by using Doppler laser cooling. Ion temperature was 1 mK, which is still too "hot" for QC applications.
T. Schätz, U. Schramm and D. Habs, "Crystalline Ion Beams", 2001 Nature 412 717.

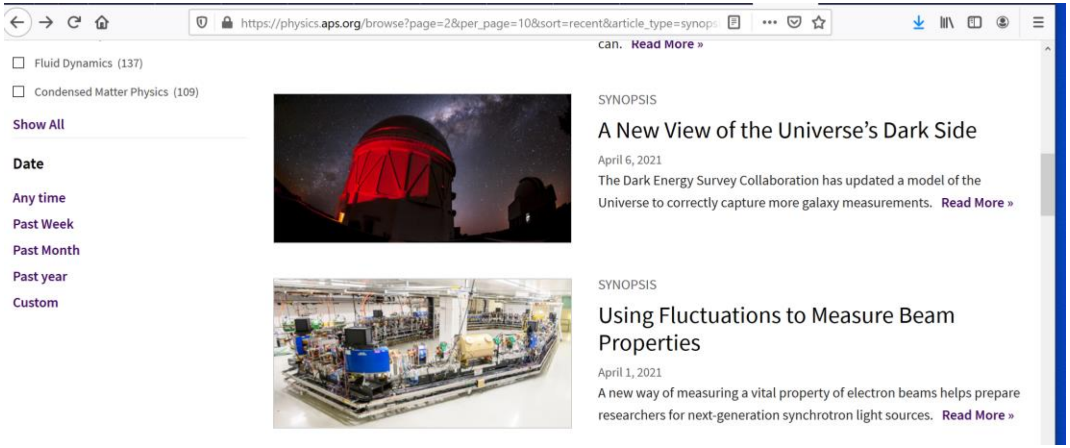


We propose to use unique IOTA infrastructure and our expertise in beams and storage rings to create a 1-D crystal of ~one-million ions (~10 m with 10-µm separation) as a pathfinder for scalability in ion QC

Aim to develop the full suite of capabilities and techniques to create these crystals, achieve ion temperatures of <50 µK and prepare and readout quantum states using external lasers

IOTA Physics program summary

- Run I (2018-2019): IOTA commissioning
- Run II (2020): FAST and IOTA (100 MeV) programs
  - 1 PRL, 2 PRAB, several JINST so far; 2 more in preparation;
  - 2 students graduated
  - Featured at physics.aps.org (PRL editors' suggestion)



- Run III (2021): FAST and IOTA (100 and 150 MeV) programs
  - See presentations at this meeting
  - 2 students graduated

Summary: Accelerator science at FAST

- Fermilab is mostly interested in the IOTA-based science
  - IOTA is capable of circulating both protons and electrons
    - Heavy ions in the future
  - Research focused on high-intensity proton rings: space-charge effects, instability mitigation, beam loss control, beam cooling, QS
- However, there are excellent science opportunities with the FAST electron linac (concurrent with IOTA research):
  - ML/AI
  - Radiation generation
  - High average current experiments with many bunches
  - Complementary to FACET-II and AWA
  - Suitable for LCLS-II commissioning studies and EIC R&D