Accelerator and Beam Physics Research at Fermilab

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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, …
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

**Beam physics**
- Luminosity, brilliance, intensity, purity, other
- Beam physics
  - Self fields
  - Wake fields, impedance
  - Beam-beam forces
  - Multi-particle dynamics
  - Single-particle dynamics
  - Emittance dilution
  - Cooling
  - Polarization dynamics
  - Particle-matter interactions
  - Detectors

**Purpose**
- Confinement and focusing, magnets
- Particle sources
- Acceleration, rf cavities
- Superconductivity and cryogenics
- Radiation protection
- Vacuum
- Mechanical structures
- Alignment
- Power converters
- Vibrations
- Beam manipulations
- Machine operations
- Injection and extraction
- Diagnostics
- Data acquisition and controls
- Polarization dynamics
- Cooling
- Emittance dilution
- Wake fields, impedance
- Beam-beam forces
- Multi-particle dynamics
- Self fields
- Single-particle dynamics
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
- Tesla type III+ cryomodule
  - 8 9-cell cavities

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**IOTA Storage Ring**

- 1.3-GHz rf gun
- Cs$_2$Te cathode
- 3 nC/pulse

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**Table 1.** Key design parameters of the IOTA ring and its injectors.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>40 m</td>
</tr>
<tr>
<td>Experimental straight sections</td>
<td>4</td>
</tr>
<tr>
<td>Particle species</td>
<td>protons/ $H^-$-ions/electrons</td>
</tr>
<tr>
<td>Particle momentum (max)</td>
<td>70 MeV/c/150 MeV/c</td>
</tr>
<tr>
<td>Maximum space-charge parameter</td>
<td>$Q_{sc}$ $&gt;$ 0.5 $\ll$ 0.8</td>
</tr>
</tbody>
</table>

The IOTA ring parameters are listed in tables 2 and 3 and its layout is depicted in figure 3, where the major magnetic and diagnostic elements are shown.

The ring geometry is defined by 8 main bending dipole magnets (4 30-degree and 4 60-degree bends) and 6 long and 2 short straight sections. The 2 short sections between 60-degree magnets, shown vertically in the figure, are used for dispersion suppression and chromaticity correction. The top horizontal section is used for the beam injection. The lower-left diagonal section is occupied by the accelerating RF cavity. The remaining 4 long sections are designated for the installation of experimental apparatus, such as the nonlinear inserts for integrable optics, the electron lens, and optical stochastic cooling. The ring circumference is 40 m. The nominal bending magnetic field of 0.7 T allows for the maximum electron beam energy of 150 MeV. The 2.5 MeV kinetic energy of

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Antipov et al., JINST 12, T03002 (2017)
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**
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)
- COVID-19 lockdown (March 2020)
- First observations of optical stochastic cooling (April 20, 2021)
- Nonlinear integrable optics demonstration (Run 2)

• 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 (~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
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.

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

Simultaneous cooling in all degrees of freedom

Measured cooling rates 8x faster than natural radiation damping

Lebedev, IOTA/FAST Collab. Meeting (2021)
Jarvis, IOTA/FAST Collab. Meeting (2021)
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)

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

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 (2022-2023)

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

Edstrom, Romanov et al.

Parameter | Nominal (Range) | Unit
---|---|---
Energy | 50 to 60 | kV
Proton Beam Energy | 20 to 85 | mA
Proton Beam Charge | 20 | nC
Pulse length (95% of peak) | 1 (1 to 000) | 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 | 77 | m

Parameter | Nominal (Range) | Unit
---|---|---
Energy | 2.5 | MeV
$\gamma$ (Energy) - 1 | 2.66E-03 | 7.28E-02
$\beta$ (Energy) - 1 | 2.66E-03 | 1.45E-02
Beam Charge (Total) | 20 (1 - 20) | mA
Beam Charge (per bunch) | 6.1 | nC
Bunch Train Length | 1 (1 - 100) | μs
RF Pulse Rate | 1 | Hz
RF & Buncher Frequency | 322.0 ($\pm$ 0.5) | MHz
Phase/Amplitude Stability | 1° / 1° | μs
Beam Pulse | 1.77 (1$\pm$2 - 20) | μs
RF Pulse Length | 60 (15-150) | μs
Bunch length (10%) | 0.3 | ps
BPM response time | < 20 | ns

Parameter | Nominal (Range) | Unit
---|---|---
Proton Beam Energy | 2.5 | MeV
Proton Beam Momentum | 6.85 | MeV/c
Proton Beam Charge | 7.28E-02 | mC
Beam Current | 1.45E-02 | mA
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 | s
X/Y (Unnormalized) Geometric Emittance | 0.3 | μm
δp/δθ (RMS) | 0.3 | μm
Beam Charge | 14.64 | nC
RMS beam size for $\beta = 10$ m | 4.5 | mm
Momentum compaction | 0.07 | 
Betatron tune ($Q_x$, $Q_y$) | 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

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

Jarvis et al., ECA Grant

Birkl et al., Nature 357, 310 (1992)
Habs and Grimm, ARNPS 45, 391 (1995)
Schätz et al., Nature 412, 717 (2001)
Brown and Roser, PRAB 23, 054701 (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!*