Fermilab Accelerator Science and Technology (FAST) Facility

Eric Prebys
Accelerator Physics Center
Fermilab
A Brief History of Fermilab (evolving slide)

- 1968: construction begins
- 1972: first beams
  - 200–400 GeV proton beams
  - Highest energy lab ever since
- ~1985: (until recently)
  - “Tevatron”: first superconducting synchrotron.
  - 900 GeV x 900 GeV p-pBar collisions
- Upgraded in 1997
  - Main Injector-> more intensity
  - 980 GeV x 980 GeV p-pBar collisions
  - Intense neutrino program
- Soon the second most powerful collider

Fermilab is now the only remaining US High Energy Physics Lab

With the LHC now the highest energy collider, the lab must focus on different types of physics.
Fermilab Firsts and Records

• Firsts:
  – First separated function synchrotron:
    • Main Ring, 1972
  – First superconducting synchrotron/collider
    • Tevatron, 1983 (first collisions in 1986)
  – First permanent magnet storage ring
    • Recycler, 2000

• Records:
  – Highest energy proton beam
    • Main Ring, 1972 (breaks AGS record) ➞ 1983 (broken by Tevatron)
    • Tevatron, 1983-2008 (broken by LHC)
  – Highest energy hadron collider
    • Tevatron, 1986 (breaks SppS record) ➞ 2009 (broken by LHC)
  – Highest hadronic luminosity
    • Tevatron, 2005 (broke ISR *p-p* record!) ➞ 2011 (broken by LHC)
  – Highest energy p-pbar collider
    • Tevatron, 1986 (breaks SppS record) ➞ present
  – Highest p-pbar luminosity
    • Tevatron, 1992 (broke SppS record) ➞ present
Context: P5 Report

• The “Particle Physics Project Prioritization Panel” (P5) advises the DOE Office of High Energy Physics on research funding priorities in high energy physics

• After a lengthy process, the panel released a report in May, 2014. Top priorities for Fermilab:
  – Support the LHC and its planned luminosity upgrades
  – Pursue the g-2 and Mu2e muon programs*
  – Focus on a high energy neutrino program to determine the mass hierarchy and measure CP violation.
    • “Flagship” activity
    • Will ultimately require a “multi-megawatt” beam at 60-120 GeV
  – Continue at least R&D toward a future linear $e^+e^-$ collider (ILC)

*E. Prebys, UCD Colloquium, March 28, 2016

FAST supports these
ILC-Related R&D

• This is the easy one…
• Over the last ~15 years, Fermilab has gone from having no SRF program to becoming one of the world leaders.
• Fermilab areas of interest include
  – Increasing gradient and high-gradient-Q of cavities
  – Source/LEBT/RFQ/MEBT development
  – Bunch manipulation
  – Systems and integration issues.
• This work is largely orthogonal to the rest of the Fermilab program
• Understanding the rest of the program requires some understanding of the lab’s long term plans…
Orientation: Accelerator Complex

- Following the LHC turn-on, FNAL has transitioned to an intensity based program

  **Recycler:** Formerly for pBar storage, now to “pre-stack” protons for the Main Injector

  **Accumulator/Debuncher:** Formerly for pBar accumulation, re-tasked for muon program.

- Intensities are limited by the 8 GeV proton source, which is still largely original.

  LBNF (120 GeV)
  
  MiniBoone (8 GeV)
  
  NuMI (120 GeV)

  Neutrinos

  ~45 years old!

  Linac/400 MeV

  Booster/8 GeV

  Tevatron

  CDF detector

  A0

  A1 line

  P1 line

  TeV extraction collider aborts

  Switchyard 120 GeV +secondaries
Current Long Baseline $\nu$ Program

- The “Neutrinos from the Main Injector” (NuMI) line uses 120 GeV neutrinos from the Main Injector to produce neutrinos, which are detected in
  - MINOS: 725 km away
  - NO$\nu$A: 810 km, 14.6 mrad off axis
- Produces narrower energy spread, which is important for physics goals
Future Program: LBNF ➔ DUNE

• Fermilab will construct a new “Long Baseline Neutrino Facility” (LBNF) beam line to produce neutrinos for the “Deep Underground Neutrino Experiment” (DUNE), located at the “Sanford Underground Research Facility” (SURF) in Lead, SD, 1300 km away.

• Truly international effort, including 150 institutions in 27 countries.

• Physics program extends 20-30 years.
Critical Issue: Space Charge Limit

• The maximum useful injected charge into the Booster is limited by the space charge tune-shift, which can drive harmonic instabilities.

\[ \Delta \nu \approx \frac{Nr_0}{2\pi \epsilon N \beta \gamma^2} FB \lesssim 0.2 \]

total protons
normalized emittance
\( \epsilon_N = \epsilon \beta \gamma = \text{constant} \)

“Bunch factor” = \( \frac{I_{\text{peak}}}{I_{\text{ave}}} \)
(Reduce with higher RF harmonics)

= 3 for 95% Gaussian emittance
1 for 100% uniform (painted) emittance

• So the maximum accelerated charge grows rapidly with increasing energy

\[ N_{\text{max}} \propto \beta \gamma^2 \]

• Could gain an additional factor of \( \beta \gamma \) if we were not constrained by the MI admittance

doesn’t include improvement of going to uniform distribution with painting
Staged Plan to Increase Intensity

• Proton Improvement Plan (PIP) (ongoing)
  – Numerous improvements to maximize potential of existing complex.
  – Provide 700 kW to NuMI + 30 kW to 8 GeV program
• PIP-II (CD-0)
  – Keep existing Booster, but increase cycle rate from 15 to 20 Hz
  – Replace existing 400 MeV linac with 800 MeV superconducting linac that has CW capability
  – Deliver 1.2 MW to NuMI or LBNF
  – Support 8 GeV program and 800 MeV program
    • (eg. 100kW 800 MeV beam to Mu2e-II)
• PIP-III (conceptual)
  – Keep PIP-II linac
  – Replace Booster with “something”
  – Deliver 2.5 MW to LBNF + ??

Rapid Cycling Synchrotron (RCS) or pulsed linac?
The PIP-II Injector Experiment (PXIE) is designed to test the technology needed for the PIP-II Linac.

Among other things, PXIE will investigate:
- Low Energy Beam Transport (LEBT) pre-chopping.
- Validation of chopper performance.
- Bunch extinction.
- Operation of Half Wave Resonator (HWR) in close proximity to 10 kW absorber.
- Emittance preservation.

What I’ll be talking about:
- We are here (2.1 MeV)
- 40 m, ~25 MeV
- 10 MeV
- 25 MeV

FAST/IOTA
Beyond PIP-II: Linac vs. RCS

- The linac option would provide more beam at 8 GeV or lower energies, which could support a very diverse physics program, however.
- Unless there is a major breakthrough in SRF technology, it would cost significantly more than the RCS option.
- The strong feedback from the DOE is that we should pursue the most cost effective way to deliver high power beam to LBNF/DUNE, with no specific mandate for a lower energy program. Therefore...

- We are pursuing the rapid cycling synchrotron as the primary option, with the linac as backup
  - There might be a breakthrough in SRF technology
  - Priorities have been known to change
## PIP-III Straw Man Parameters*

<table>
<thead>
<tr>
<th></th>
<th>PIP-II</th>
<th>PIP-III (RCS, no Recycler)</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MI/Recycler</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Energy</td>
<td>120</td>
<td>120</td>
<td>60 GeV</td>
</tr>
<tr>
<td>Cycle Time</td>
<td>1.2</td>
<td>1.45</td>
<td>0.95 sec</td>
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<td>Protons per pulse (extracted)</td>
<td>7.50E+13</td>
<td>1.89E+14</td>
<td>1.98E+14 ppp</td>
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<tr>
<td>Slip Stacking Efficiency</td>
<td>97</td>
<td>99</td>
<td>%</td>
</tr>
<tr>
<td>Injection Turns</td>
<td>1</td>
<td>1</td>
<td>%</td>
</tr>
<tr>
<td>Beam Power</td>
<td>1.2</td>
<td>2.5</td>
<td>2 MW</td>
</tr>
<tr>
<td><strong>Proton Source</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection Energy (Kinetic)</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8-2.0 GeV</td>
</tr>
<tr>
<td>Extraction Energy (Kinetic)</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0 GeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>474</td>
<td>474</td>
<td>474 m</td>
</tr>
<tr>
<td>RF Frequency (extraction)</td>
<td>52.8</td>
<td>52.8</td>
<td>52.8 MHz</td>
</tr>
<tr>
<td>Cycles to Recycler</td>
<td>12</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Cycle Rate</td>
<td>20</td>
<td>20</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Beam Cycle Rate to MI</td>
<td>10</td>
<td>15</td>
<td>4.14</td>
</tr>
<tr>
<td>Protons per Pulse (extracted)</td>
<td>6.44E+12</td>
<td>3.18E+13</td>
<td>3.33E+13</td>
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<tr>
<td>Protons per Pulse (injected)</td>
<td>6.63E+12</td>
<td>3.22E+13</td>
<td>3.37E+13</td>
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<tr>
<td>Beam Power to Recycler/MI</td>
<td>82</td>
<td>168</td>
<td>269 kW</td>
</tr>
<tr>
<td>Beam Power to 8 GeV Program</td>
<td>82</td>
<td>645</td>
<td>584 kW</td>
</tr>
</tbody>
</table>

~6x record Booster protons per pulse
~4x record Main Injector protons per pulse

*P. Derwent
Mitigating Space Charge in Synchrotron

- Recall:
  
  \[ N_{\text{max}} \propto \epsilon_N \left( \beta \gamma^2 \right) \]

  Can paint beam to increase emittance, but limited by Main Injector aperture (~20-25 \( \pi \)-mm-mr)

  Can increase injection energy (costly)

- Other ways?
  - This is where FAST comes in!
## RCS Comparisons

<table>
<thead>
<tr>
<th></th>
<th>Booster (now)</th>
<th>Booster (PIP-II)</th>
<th>PIP-III RCS (800 MeV)</th>
<th>PIP-III RCS (2 GeV)</th>
<th>JPARC RCS</th>
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</thead>
<tbody>
<tr>
<td>Circumference [m]</td>
<td>474</td>
<td>474</td>
<td>474</td>
<td>474</td>
<td>348</td>
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<tr>
<td>Injection Energy [MeV]</td>
<td>400</td>
<td>800</td>
<td>800</td>
<td>2000</td>
<td>400</td>
</tr>
<tr>
<td>Extraction Energy [MeV]</td>
<td>8000</td>
<td>8000</td>
<td>8000</td>
<td>8000</td>
<td>3000</td>
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<tr>
<td>Injection Current [mA]</td>
<td>30</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>RF Harmonic</td>
<td>84</td>
<td>84</td>
<td>84</td>
<td>84</td>
<td>2</td>
</tr>
<tr>
<td>Emittance (normalized) [pi-mm-mr]</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>102</td>
</tr>
<tr>
<td>Protons/batch [1e12]</td>
<td>4.2</td>
<td>6.6</td>
<td>34</td>
<td>34</td>
<td>84</td>
</tr>
<tr>
<td>Bunching Factor</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Gaussian factor</td>
<td>3.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
<td>Tune Shift Parameter</td>
<td>-0.43</td>
<td>-0.11</td>
<td>-0.43</td>
<td>-0.13</td>
<td>-0.28</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Output power, max [kW]</td>
<td>80.64</td>
<td>168.96</td>
<td>870.4</td>
<td>870.4</td>
<td>1008</td>
</tr>
</tbody>
</table>

2.5 MW @ 60 GeV

Too big for “ordinary” synchrotron. Can FAST help? We’d rather not build the expensive linac extension if we don’t have to
What are “Nonlinear Integrable Optics”?

- All accelerators today are based on physics worked out in the 1950s

- Stable orbits based on “linear” optics
  - The defining magnetic lattice contains only dipole and quadrupole terms.
  - The result is a system in which particles experience a transverse force which depends linearly on their deviation from a reference orbit. Described in general by a “Hill’s Equation”

\[ x'' + K(s)x = 0; \quad K(s + C) = K(s) \]
Interesting Footnote

- Strong focusing was actually previously invented by a Greek elevator engineer named Nicholas Christofilos, who applied for a patent in 1950.

- After they became aware of it, Courant and Snyder recognized the priority of Christofilos’ work in their 1958 paper, which lays the groundwork for all synchrotrons built to this day.
All the Accelerator Physics U Need 2 Know

• We can describe (strongly focused) particle motion in terms of initial conditions and a “beta function” $\beta(s)$, which is only a function of location along the nominal path, and follows the periodicity of the machine.

$$\beta(s)$$

In other words, particles undergo “pseudo-harmonic” motion about the nominal trajectory, with a variable wavelength.

• In other words, particles undergo “pseudo-harmonic” motion about the nominal trajectory, with a variable wavelength.

• Note: $\beta$ has units of [length], so the amplitude has units of [length]^{1/2}

The “betatron function” $\beta(s)$ is effectively the local wavenumber and also defines the beam envelope.
Formalism: Coordinates and Conventions

- We generally work in a right-handed coordinate system with $x$ horizontal, $y$ vertical, and $s$ along the *nominal* trajectory ($x=y=0$).

Note: $s$ (rather than $t$) is the independent variable.

Particle trajectory defined at any point in $s$ by location in $x,x'$ or $y,y'$ “phase space”

- Unique initial phase space point $\rightarrow$ unique trajectory

\[ \frac{dx}{ds} \equiv x' \approx \theta \]
Transfer Matrices

- Dipoles *define* the trajectory, so the simplest magnetic “lattice” consists of quadrupoles and the spaces in between them (drifts). We can express each of these as a linear operation in phase space.

\[
\Delta \theta = \Delta x' = -\frac{x}{f}
\]

**Quadrupole:**

\[
x = x(0)
\]

\[
x' = x'(0) - \frac{1}{f} x(0)
\]

\[
\Rightarrow \begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} x(0) \\ x'(0) \end{pmatrix}
\]

**Drift:**

\[
x(s) = x(0) + sx'(0)
\]

\[
x'(s) = x'(0)
\]

\[
\Rightarrow \begin{pmatrix} x(s) \\ x'(s) \end{pmatrix} = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x(0) \\ x'(0) \end{pmatrix}
\]

- By combining these elements, we can represent an arbitrarily complex ring or line as the product of matrices.

\[
M = M_N \ldots M_2 M_1
\]
Hamiltonian Treatment of Accelerators

- Like other mechanical systems, accelerators are treated with Hamiltonian formalism. For a simple system, the Hamiltonian is given by:

\[ H = \frac{p_x^2}{2} + \frac{p_y^2}{2} + K(s)\left(\frac{x^2}{2} + \frac{y^2}{2}\right) \]
Motion in a Linear System

- Properties of linear lattices
  - Explicit solution
  - In the paraxial approximation ($\sin\theta \sim \tan\theta \sim \theta$), particles undergo a fixed number of oscillations per orbit (“tune”) which is independent of amplitude.

- Nonlinear terms are dealt with perturbatively, and generally lead to chaotic instability at high amplitudes
Betatron Tune

As particles go around a ring, they will undergo a number of betatrons oscillations $\nu$ (sometimes $Q$) given by

$$\nu = \frac{1}{2\pi} \int \frac{ds}{\beta(s)}$$

This is referred to as the “tune”

We can generally think of the tune in two parts:

Integer: magnet/aperture optimization

6.7

Fraction: Beam Stability
Instabilities In Linear Systems

• A unique tune leads to inherent instabilities
  – Tune spread ➔ ”Landau Damping”
• Lattice imperfections lead to harmonic instabilities

\[ k_x \nu_x \pm k_y \nu_y = \text{integer} \Rightarrow \text{(resonant instability)} \]

“small” integers ➔ Avoid lines in the “tune plane”

• In particular, space charge can shift the tune onto an instability
  – Space charge limit
Do Accelerators Need to be Linear?

- Motion will be stable if we can identify conserved integrals of motion ➔ "Integrable"
- There has been a long search for integrable nonlinear systems.
- Early work
  - Orlov (1963)
  - McMillan (1967) – 1D solution
  ✓ Perevedentsev, Danilov (1990) – generalization of McMillan case to 2D, round colliding beams. **Require non-Laplacian potentials to realize**
2D Generalization of McMillan Mapping

SOME THOUGHTS ON STABILITY
IN NONLINEAR PERIODIC FOCUSING SYSTEMS

Edwin M. McMillan
September 5, 1967

• 1D – thin lens kick
  \[ x_i = p_{i-1} \]
  \[ f(x) = -\frac{Bx^2 + Dx}{Ax^2 + Bx + C} \]
  \[ p_i = -x_{i-1} + f(x_i) \]
  \[ Ax^2 p^2 + B(x^2 p + xp^2) + C(x^2 + p^2) + Dxp = \text{const} \]

• 2D – a thin lens solution can be carried over to 2D case in axially
  symmetric system (non-Laplacian!)

1. The ring with transfer matrix

\[
\begin{pmatrix}
  0 & \beta & 0 & 0 \\
  -\frac{1}{\beta} & 0 & 0 & 0 \\
  0 & 0 & 0 & \beta \\
  0 & 0 & -\frac{1}{\beta} & 0 \\
\end{pmatrix}
\]

\[ c = \cos(\phi) \]
\[ s = \sin(\phi) \]

2. Axially-symmetric thin kick

\[ \theta(r) = \frac{kr}{ar^2 + 1} \]
2D Generalization of McMillan Mapping

- The system is integrable. Two integrals of motion (transverse):
  - Angular momentum: \( xp_y - yp_x = \text{const} \)
  - McMillan-type integral, quadratic in momentum

\[
\begin{align*}
px_i &= \text{const} \\
y_i &= \text{const}
\end{align*}
\]

- For large amplitudes, the fractional tune is 0.25
- For small amplitude, the electron (defocusing) lens can give a tune shift of \( \sim -0.3 \text{ per cell !} \)
- Potentially, can cross an integer resonance
Verification: VEPP-2000

- Danilov and Perevedentsev’s “round colliding beams”
  - equal beta functions, tunes, and emittances
  - no coupling
- Under these conditions
  - longitudinal component of angular momentum is conserved
  - dynamics is “quasi integrable”
- This was demonstrated experimentally at the BINP VEPP-2000 e+ e- collider, which achieved record tune spread of 0.25 (Romanov, NA-PAC13)
- Solution would be fully integrable if beams had “McMillan distribution”
  - Can also be achieved with electron lenses!
We can test this: IOTA Electron Lens

- Capitalize on the Tevatron experience and recent LARP work
- Re-use Tevatron EL components
Laplacian Solution*

- Start with a Hamiltonian
  \[ H = \frac{p_x^2}{2} + \frac{p_y^2}{2} + K(s)\left(\frac{x^2}{2} + \frac{y^2}{2}\right) + V(x, y, s) \]

- Choose s-dependence of the nonlinear potential such that \( H \) is time-independent in normalized variables
  \[ z_N = \frac{z}{\sqrt{\beta(s)}}, \]
  \[ H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_N^2 + y_N^2}{2} + \beta(\psi)V\left(x_N\sqrt{\beta(\psi)}, y_N\sqrt{\beta(\psi)}, s(\psi)\right) \]
  \[ p_N = p\sqrt{\beta(s)} - \frac{\beta'(s)z}{2\sqrt{\beta(s)}}, \]

- This results in \( H \) being the integral of motion

- Note: there is no requirement on \( V \) – can be made with any conventional magnets, i.e. octupoles

1. Start with a round axially-symmetric linear lattice (FOFO) with the element of periodicity consisting of
   a. Drift L
   b. Axially-symmetric focusing block “T-insert” with phase advance $n\times\pi$

2. Add special nonlinear potential $V(x,y,s)$ in the drift such that

$$\Delta V(x, y, s) \approx \Delta V(x, y) = 0$$
Nonlinear systems can be more stable!

• 1D systems: non-linear (unharmonic) oscillations can remain stable under the influence of periodic external force perturbation. Example: \( \ddot{z} + \omega_0^2 \sin(z) = a \sin(\omega_0 t) \)

• 2D: The resonant conditions \( k\omega_1(J_1, J_2) + l\omega_2(J_1, J_2) = m \) are valid only for certain amplitudes; i.e. the tune depends on the initial conditions!

• Nekhoroshev’s condition guaranties detuning from resonance and, thus, stability.
Space Charge in Linear Optics

- System: linear FOFO 100 A linear KV w/mismatch
- Result: quickly drives test-particles into the halo

$$\Delta Q_{sc} \sim -0.7$$
Space Charge in NL Integrable Optics

- System: linear FOFO 100 A linear KV w/mismatch
- Result: nonlinear decoherence suppresses halo

$\Delta Q_{sc} \sim -0.7$

Tech-X, RadiaSoft simulation
Studies at Fermilab: FAST/IOTA

- The former New Muon Lab (NML) was originally being developed as an R&D facility for the ILC.
  - Original plan was for three ILC cryomodules.
- This evolved into a plan for an electron-based study program.
- DOE reviews concluded that there are numerous electron-based facilities in the country, but that the IOTA portion was unique.
- On their recommendation, the priorities of the facility were modified to focus on the IOTA ring.
  - Primary purpose for the electron beam is as an injector
  - Will also support an ancillary R&D program.
Current Plan for FAST/IOTA

• Because the emphasis of the facility has changed, so has had the name: ASTA/IOTA ➞ Fermilab Accelerator Science and Technology (FAST) Facility
  – Reduce cryomodules from three to one
  – Primary mission is as an injector for IOTA
**Parameter** | **ILC nominal** | **Range**
---|---|---
Bunch charge | 3.2 nC | 10pC to > 20 nC
Bunch spacing | 333 ns | <10 ns to 10 s
Bunch train | 1 ms | 1 bunch to 1 ms
Train rep. rate | 5 Hz | 0.1 Hz to 5 Hz
Transverse emit. | 25 mm-mrad | 1 to 100 mm-mrad
r.m.s. bunch length | 1 ps | 10fs to 10ps
Beam energy | 300 MeV | 50-300 MeV
• Progress
  – Electron source and cryomodule are in place
  – First 50 MeV electron beam
First Electrons Through Photoinjector!

- Sign-offs Wednesday, 25 March, 2015
- Electrons beyond the gun - Wednesday, 25 March
- Beam after CC2, towards end of line – Thursday, 26 March
- Electrons seen at low energy beam absorber (≈20 MeV) – Friday morning, 27 March
Validating Nonlinear Optics

• Both electron lenses and nonlinear magnetic elements involve discrete insertions in an otherwise conventional lattice.
  – Albeit a lattice with strict control over lattice functions!
• This allows for the design of a fairly simple “test bed” to evaluate the efficacy of these solutions.
Integrable Optics Test Accelerator (IOTA)

2.5 MeV RFQ

e-beam line
p beam line
IOTA layout and main components

20 x/y/skew correctors
8 x correctors in dipoles
20 button BPMs

Dubna JINR quadrupoles

rf cavity

insertion for optical stochastic cooling

IOTA RING

nonlinear magnet sections

injection

30 deg and 60 deg dipoles with sync-light ports

electron-lens section
## IOTA Parameters (Electrons)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal kinetic energy</td>
<td>$e^-: 150$ MeV</td>
</tr>
<tr>
<td>Nominal intensity</td>
<td>$e^-: 1 \times 10^9$</td>
</tr>
<tr>
<td>Circumference</td>
<td>40 m</td>
</tr>
<tr>
<td>Bending dipole field</td>
<td>0.7 T</td>
</tr>
<tr>
<td>Beam pipe aperture</td>
<td>50 mm dia.</td>
</tr>
<tr>
<td>Maximum b-function (x,y)</td>
<td>12, 5 m</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>0.02 - 0.1</td>
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<tr>
<td>Betatron tune (integer)</td>
<td>3 - 5</td>
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<tr>
<td>Natural chromaticity</td>
<td>-5 - -10</td>
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<tr>
<td>Transverse emittance r.m.s.</td>
<td>0.04 $\mu$m</td>
</tr>
<tr>
<td>SR damping time</td>
<td>0.6s ($5 \times 10^6$ turns)</td>
</tr>
<tr>
<td>RF V,f,h</td>
<td>1 kV, 30 MHz, 4</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>0.002 - 0.005</td>
</tr>
<tr>
<td>Bunch length, momentum spread</td>
<td>12 cm, $1.4 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Nonlinear Magnet

- Joint effort with RadiaBeam Technologies (Phase I and II SBIR)

FNAL Concept: 2-m long nonlinear magnet

RadiaBeam short prototype. The full 2-m magnet will be designed, fabricated and delivered to IOTA in Phase II
IOTA Goals for Integrable Optics

The IOTA experiment has the goal to demonstrate the possibility to implement nonlinear integrable optics with a large betatron frequency spread $\Delta Q > 1$ and stable particle motion in a realistic accelerator design.

Benefits of nonlinear integrable optics include

- Increased Landau damping
- Improved stability to perturbations
- Resonance detuning
Integrable Optics Test Accelerator (IOTA)

- **Unique features:**
  - Can operate with either electrons or protons (up to 150 MeV/c momentum)
  - Large aperture
  - Significant flexibility of the lattice
  - Precise control of the optics quality and stability
  - Set up for very high intensity operation (with protons)

- **Based on conventional technology** (magnets, RF)

- **Cost-effective solution**
  - Balance between low energy (low cost) and discovery potential
IOTA Staging – Phase I

Phase I will concentrate on the academic aspect of single-particle motion stability using e-beams

- **Achieve large nonlinear tune shift/spread** without degradation of dynamic aperture by “painting” the accelerator aperture with a “pencil” beam
- Suppress strong lattice resonances = cross the integer resonance by part of the beam without intensity loss
- Investigate stability of nonlinear systems to perturbations, develop practical designs of nonlinear magnets
- The measure of success will be the achievement of high nonlinear tune shift = 0.25
IOTA Staging – Phase I

• The magnet quality, optics stability, instrumentation system and optics measurement techniques must be of highest standards in order to meet the requirements for integrable optics
  – 1% or better measurement and control of $\beta$-function, and 0.001 or better control of betatron phase

• This is why **Phase I needs pencil e⁻ beams** as such optics parameters are not immediately reachable in a small ring operating with protons
Experimental Procedure

• Two kickers, horizontal and vertical, place particles at arbitrary points in phase space
• Measure beam position on every turn to create a Poincare map

• As electrons lose energy due to synchrotron radiation, they will cover all available phase space
• Can control the strength on the nonlinearity

• Final goal – measure dependence of betatron frequency on amplitude
Phase II: Proton Injection

- Luckily, we have an extra RFQ just lying around…
- The HINS (“High Intensity Neutrino Source”) was developed as the front end of a pulsed “Project X” 8 GeV proton linac

- Because of cooling problems, it never reached its design pulse rate
- ProjectX (now PIP-II) specification was changed to a CW front end
  - HINS->PXIE
- HINS RFQ available for our use
The Integrable Optics Test Accelerator (IOTA) is an experimental synchrotron being built at Fermilab to test the concept of non-linear "integrable optics". These optics are based on a lattice including non-linear elements that satisfy particular conditions on the Hamiltonian. The resulting particle motion is predicted to be stable but without a unique tune. The system is therefore insensitive to resonant instabilities and can in principle store very intense beams, with space charge tune shifts larger than those which are possible in conventional linear synchrotrons. The ring will initially be tested with pencil electron beams, but this poster describes the ultimate plan to install a 2.5 MeV RFQ to inject protons, which will produce tune shifts on the order of unity. Technical details will be presented, as well as simulations of protons in the ring.

## INTRODUCTION

Table 1: HINS Parameters for IOTA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle type</td>
<td>proton</td>
<td>-</td>
</tr>
<tr>
<td>Kinetic Energy</td>
<td>2.5</td>
<td>MeV</td>
</tr>
<tr>
<td>Momentum</td>
<td>68.5</td>
<td>MeV/c</td>
</tr>
<tr>
<td>$\beta$</td>
<td>.073</td>
<td>-</td>
</tr>
<tr>
<td>Rigidity</td>
<td>.23</td>
<td>T-m</td>
</tr>
<tr>
<td>RF structure</td>
<td>325</td>
<td>MHz</td>
</tr>
<tr>
<td>Current</td>
<td>8</td>
<td>mA</td>
</tr>
<tr>
<td>Circumference</td>
<td>39.97</td>
<td>m</td>
</tr>
<tr>
<td>Total Protons</td>
<td>$9.1 \times 10^{10}$</td>
<td>-</td>
</tr>
<tr>
<td>RMS Emittance (un-normalized)</td>
<td>4</td>
<td>$\pi$-mm-mrad</td>
</tr>
<tr>
<td>Tune shift</td>
<td>-.51$\times B$</td>
<td>-</td>
</tr>
<tr>
<td>Pulse rate</td>
<td>&lt;1</td>
<td>Hz</td>
</tr>
<tr>
<td>Pulse length</td>
<td>1.77</td>
<td>$\mu$sec</td>
</tr>
</tbody>
</table>

All particle optics to date has been based on linear magnetic systems of quadrupoles and dipoles. Higher order multipoles are treated perturbatively, and generally lead to instabilities if they are large enough. It has long been known that very specific conditions can produce stable orbits in non-linear magnetic systems [1] [2]; however, it was not until fairly recently that specific magnetic lattices were proposed that satisfy these conditions [3]. Such systems have stable orbits, but not unique tunes. They are therefore extremely insensitive to harmonic instabilities, thereby allowing the storage of beams with intensities beyond those which would otherwise be limited by space charge tune shift.

The Integrable Optics Test Accelerator (IOTA) at Fermilab is being built to test this concept, and is described in detail elsewhere [4]. Initial tests will use a 150 MeV electron beam from the Advanced Superconducting Test Accelerator (ASTA) facility at Fermilab [6]. By varying initial conditions, this electron beam can be used to probe the optical space of the ring; however, since the space charge effects on the electron beam will be negligible, it will not serve as a direct test of the inherent stability.

As a next step, we therefore plan to reuse the 2.5 MeV RFQ, which was built for Fermilab's High Intensity Neutrino Source (HINS) program [5]. This RFQ became available when the lab chose to focus instead on a CW ion source for its high intensity program.
Phase II (cont’d)

After the IOTA commissioning, we will move the existing 2.5 MeV proton/H- RFQ into the FAST hall to inject protons into the IOTA ring.

- Allows tests of Integrable Optics with protons and realistic space charge beam dynamics studies
- Allows space charge compensation experiments
- Unique capability

$\Delta Q_{sc} = 0.5$ for one-turn injection

*multi-turn injection possible

2.5 MeV RFQ
Space Charge Compensation

\[ \xi_{SC} = \frac{B_f r_p N_{tot}}{4\pi\varepsilon_n \beta \gamma^2} \]

\[ B = \beta E \]

Net force \[ E - \beta B = \frac{E}{\gamma^2} \]

protons

r, across the beam

Plan of Activities and Status

Phase 1: FY15-17

1. Construction of main elements of the FAST/IOTA facility:
   a) electron injector based on existing FAST electron linac
      • Low energy injector operational. HE beamline construction in FY15. Connect CM2 and send beam down HE beamline in FY16
   b) IOTA ring
      • Most components procured. Begin assembly in FY16
   c) proton injector based on existing HINS proton source in situ
      • Resurrecting the ion source in FY15, RFQ in FY16
   d) special equipment for AARD experiments.

2. Commissioning of the IOTA ring with electron beam – FY17

Plan of Activities – Outlook

Phase 2: FY18-20

1. Commission IOTA operation with proton beams.
2. Carry out space-charge compensation experiments with nonlinear optics and electron lenses.

Phase 3: FY21 and beyond

1. Study the application of space-charge compensation techniques to next generation high intensity machines.
2. Expand the program beyond these high priority goals to allow Fermilab scientists and a broader accelerator HEP community to utilize unique proton and electron beam capabilities of the FAST/IOTA facility.
Open Questions

• Instrumentation:
  – Loss monitors:
    • Protons don’t get out of beam pipe!
    • Tentatively chosen diamond-based loss monitors in vacuum
  – Transverse proton development
    • Ionization Profile Monitor?
    • Gas jet?
    • Electron Deflection?
    • One of these plus retractable loss monitors for tails

• Experimental program:
  – Fermilab has R&D has always been very “mission-oriented”
  – No real experience with a general purpose accelerator physics facility
Collaboration

• A lot of interest to participate in IOTA from the accelerator community
  – 2 annual Collaboration Meetings, ~60 participants
  – ‘IOTA Focused Workshop’

• Significant intellectual and in-kind contributions, expressions of interest
  – NIU, UMD, RadiaSoft, CERN, ORNL, BINP, Colorado State, Univ. Mexico – integrable optics, space charge effects, phase space manipulation
  – LBNL, ANL – optical stochastic cooling demonstration
  – UMD – multi-pickup beam profile monitor for IOTA
  – JINR – integrable optics and space charge, contributed quadrupole magnets for IOTA
  – Univ. Frankfurt – electron lens
International *Space Charge Collaboration* at IOTA

- Collaborating institutions (at present): Fermilab, ORNL, CERN, RadiaSoft, UMD

- Work on the scientific case, hardware development, simulations, planning and execution of space charge compensation experiments with protons in IOTA

- Major topics
  - Operation of IOTA with protons, injection, and space charge measurements
  - Space charge compensation in nonlinear integrable lattice
  - Special magnets
  - Electron lens
  - Space charge compensation with electron columns
  - Space charge suppression with circular modes – for FCC
Training and University Collaboration

• Excellent connection to the university community through the Joint Fermilab/University PhD program
  – Already 9 graduate students doing thesis research at FAST/IOTA
    • 7 NIU, 1 U.Chicago, 1 IIT, 2 more to join soon

• Partnership with university groups
  – NIU – DOE GARD grant on OSC
  – Univ. of Maryland – NSF grant for IOTA-related work
  – Univ. Frankfurt – IOTA electron lens
  – Univ. Mexico – ASTA linac commissioning
  – Colorado State – ASTA gun stability
  – Interest from: UC Berkeley, MIT, Oxford
Summary

• Experimental accelerator R&D at IOTA is one of the cornerstones of the proposed national R&D thrust “Multi-MW Beams and Targets”, and is well aligned with P5 priorities

• IOTA offers a unique scientific program aiming at breakthrough research to allow for x3-5 increase of beam intensity in future proton rings
  – IOTA augments the US program lacking ring facilities for accelerator research and training

• IOTA experiments are a great opportunity to explore something truly novel with circular accelerators

• IOTA will be a strong driver of national and international collaboration and training
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• F.O’Shea, A.Murokh (RadiaBeam)
• R.Kishek, K.Ruisard (UMD)
• JINR, Dubna
• Backups
Optical Stochastic Cooling Demonstration

- **Goal:**
  - Experimental demonstration of the optical stochastic cooling technique (1st – no optical amplifier, then with OPA)

- **Why IOTA:**
  - Need IOTA – low energy (~100 MeV – minimal synchrotron radiation damping) flexible lattice e- storage ring

- **Motivation:**
  - Beam cooling for high energy accelerators
Backstory: Weston Illinois

- The footprint of what is now Fermilab started out as a planned community called “Weston”. Developer William Riley promised homes, apartments, shopping centers, parks, etc.
- After a very small part was built, the project went bankrupt.
- Riley disappeared (possibly into witness protection).
- The local mayors convinced the state to offer up the land to the government to site the proposed N.A.L.
- The remains of Weston became “The Village”, which now houses visitors to the lab.
Need accelerator R&D beam facilities!

FAST

October 18, 2016

University of California, Davis
Space Charge in Linear Optics

- System: linear FOFO 100 A, linear KV w/mismatch
- Result: quickly drives test-particles into the halo

\[ \Delta Q_{sc} \sim -0.7 \]

Tech-X, RadiaSoft simulation

Fermilab
ASTA/IOTA: Original Proposal

- This facility began life as the “Advanced Superconducting Test Accelerator (ASTA)”, designed as a test bed for ILC technology
  - Front end + 3 cryomodules = ~800 MeV electron
  - Designed an electron-based experimental program around this facility
- Tacked on the “Integrable Optics Test Accelerator (IOTA)” to test non-linear integrable optics.
Existing Infrastructure

- **IOTA capitalizes on the investments** made by OHEP for highly successful ILC/SRF R&D Program.

- Construction of ASTA (formerly NML) began in 2006 as part of the ILC/SRF R&D Program and later American Recovery and Reinvestment Act (ARRA). The facility was motivated by the goal of building, testing and operating a complete ILC RF unit.

- **Multi-million ($>90M) investment** resulted in the successful commissioning of 1.3 GHz SRF cryomodule (CM2).
  - Beam through low-energy photo injector
  - Facility nears completion

- The **addition of IOTA expands scope** to host high-intensity accelerator research.
Possible Implementations

E-column concept

1. The impact of electrons is equal to the total impact of space-charge over the ring
\[ |\Delta v_{sc}| = \frac{N_{b,tot}r_{cb}}{2\pi\beta_b^2\gamma_b^3\epsilon} \tilde{I} = \Delta v_e = \frac{N_e r_{cb}}{2\pi\beta_b^2\gamma_e} \]

2. The transverse profile of the electron is made the same as that of the proton beam
\[ \frac{N_e}{N_{b,tot}(\tilde{I} / \bar{I})} = \frac{1}{\gamma_b^2} = \eta_0 \frac{N_{ec}L_{ec}}{C} \]

3. The system of magnetized electrons and protons is now dynamically stable

E-lens concept

\[ \text{solenoide} \]

Gun

Gun solenoid

Collector solenoid

Collector

\[ \text{E-column concept} \]
IOTA Electron Lens

- Capitalize on the Tevatron experience and recent LARP work
- Re-use Tevatron EL components
Quasi-Integrable System

- Build $V$ with Octupoles

$$V(x, y, s) = \frac{\kappa}{\beta(s)^3} \left( \frac{x^4}{4} + \frac{y^4}{4} - \frac{3x^2y^2}{2} \right)$$

$$U = \kappa \left( \frac{x_N^4}{4} + \frac{y_N^4}{4} - \frac{3y_N^2x_N^2}{2} \right)$$

$$H = \frac{1}{2} (p_x^2 + p_y^2) + \frac{1}{2} (x^2 + y^2) + \frac{k}{4} \left( x^4 + y^4 - 6x^2y^2 \right)$$

- Only one integral of motion – $H$
- Tune spread limited to $\sim$12% of $Q_0$
While dynamic aperture is limited, the attainable tune spread is large.
Special Potential – Second Integral of Motion

• Find potentials that result in the Hamiltonian having a second integral of motion quadratic in momentum
  – All such potentials are separable in some variables (cartesian, polar, elliptic, parabolic)
  – First comprehensive study by Gaston Darboux (1901)

\[ I = Ap_x^2 + Bp_xp_y + Cp_y^2 + D(x, y) \quad A = ay^2 + c^2, B = -2axy, C = ax^2 \]

• Darboux equation

\[ xy(U_{xx} - U_{yy}) + \left(y^2 - x^2 + c^2\right)U_{xy} + 3yU_x - 3xU_y = 0 \]

  – General solution in elliptic variables \( \xi, \eta \), with \( f \) and \( g \) arbitrary

\[ U(x, y) = \frac{x^2}{2} + \frac{y^2}{2} + \frac{f_2(\xi) + g_2(\eta)}{\xi^2 - \eta^2} \]

  – Solution that satisfies the Laplace equation

\[ f_2(\xi) = \xi\sqrt{\xi^2 - 1}\left(d + t\cosh(\xi)\right) \quad g_2(\eta) = \eta\sqrt{1 - \eta^2}\left(q + t\cos(\eta)\right) \]
Maximum Tune Shift

- Multipole expansion of $U$:
  
  \[ U(x, y) \approx \frac{x^2}{2} + \frac{y^2}{2} + t \text{Re}\left( (x + iy)^2 + \frac{2}{3} (x + iy)^4 + \frac{8}{15} (x + iy)^6 + \frac{16}{35} (x + iy)^8 + \ldots \right) \]

- For small-amplitude motion to be stable*, $t < 0.5$

  \[ \nu_1 = \nu_0 \sqrt{1 + 2t}, \quad \nu_2 = \nu_0 \sqrt{1 - 2t} \]

- Theoretical maximum nonlinear tune shift per cell is
  
  - 0.5 for mode 1, or 50% per cell
  - 0.25 for mode 2, or 25% per cell
Single Particle Dynamics in Integrable Optics

Integer resonance $Q_y = m$
Novel Ways to Mitigate Space Charge

• Non-linear integrable optics
  – All synchrotrons ever built are based on linear optics (magnetic quadrupoles). Non-linearities are handled perturbatively, and eventually lead to instabilities.
  – It has been shown* that non-linear magnetic fields that satisfy a very particular set of conditions can result in stable orbits, but without a unique tune
    • Extremely insensitive to harmonic instabilities
    • Stable up to space charge tune shifts of order unity!

• Electron lens
  – A beam of electrons can be used to cancel the space charge effects of the protons
  – Demonstrated in the Tevatron
  – Used operationally at RHIC

*Danilov, Nagaitsev, PRSTAB 2010