Acknowledgments

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The Olympic Motto for Accelerators

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MORE ENERGY INTENSITY BRIGHTNESS
Energy Frontier – the Past of Colliders
Intensity Frontier – High Power

graphic courtesy J-PARC
Stored Beam Energy

graphic LHC Design Report

A. Valishev | Beam Dynamics Challenges in HEP Accelerators

12/1/2014
Beam Energy/Intensity – Consequences

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Tevatron Run II</td>
<td>2 MJ</td>
</tr>
<tr>
<td>LHC Run I</td>
<td>140 MJ</td>
</tr>
<tr>
<td>LHC Design</td>
<td>360 MJ</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>675 MJ</td>
</tr>
</tbody>
</table>

Particle losses lead to
– activation of machine components
– quenches of superconducting components
– damage to collimators, etc.

Damage to 1.5m long Tevatron Collimator in 2003 magnet quench
The Challenges

• Modern machines are designed for precise control of the beam in the process of capturing, acceleration, and storage with the goals to:

  – Avoid beam halo formation and related particle losses
  – Preserve beam quality (brightness)
  – Ensure long-term stability

These can be achieved by a variety of ways…
This Talk is About

Selected novel methods of designing focusing lattices of circular accelerators with improved particle stability. The discussed methods are based upon a common physical principle – reduction of chaos in betatron oscillations and on improved “integrability”

Two major topics that will be discussed

1. Beam-Beam effects
2. Novel nonlinear integrable focusing lattices
Particle Confinement in Rings

Charged particles are kept moving around a circular orbit with the use of static transverse magnetic fields.

\[ \vec{F} = e\vec{v} \times \vec{B} \]

\[ \begin{align*}
  x'' + K_x(s)x &= 0 \\
  y'' + K_y(s)y &= 0
\end{align*} \]

\[ K_{x,y}(s + C) = K_{x,y}(s) \]

Linear focusing – dipole and quadrupole magnets

x,y motion – betatron oscillations

Longitudinally the beam is kept bunched with time-varying electrical field. s-motion is usually weekly coupled to x-y.
Linear Focusing

In the case of linear focusing the system possesses two integrals of motion (Courant-Snyder invariants)

\[
I_{x,y} = \frac{1}{2 \beta_{x,y}(s)} \left( (x,y)^2 + \left( \frac{\beta'_{x,y}(s)}{2} (x,y) - \beta_{x,y}(s)(x,y)' \right)^2 \right)
\]

\( \beta(s) \) is a periodic function (referred to as amplitude function).

\[
\left( \sqrt{\beta} \right)^\prime + K(s) \sqrt{\beta} = \frac{1}{\sqrt{\beta^3}}
\]

All particles in the beam have equal oscillation frequencies (tunes). Phase space trajectories (Poincare sections) are ellipses

\[
\psi = 2\pi \nu = \oint \frac{ds}{\beta}
\]
Nonlinear Aberrations

The particle beams are usually non-monochromatic (typical momentum spread $\Delta p/p$ is $10^{-4} \div 10^{-2}$). Focusing with electromagnets depends on particle’s momentum. For quadrupole:

$$K = \frac{e}{pc} L \frac{\partial B_y}{\partial x} \approx \frac{e}{p_0 c} L \frac{\partial B_y}{\partial x} \left( 1 - \frac{\Delta p}{p} \right)$$

Due to chromatic focusing, tunes now have a spread

When tune reaches integer, focusing stability is lost

[Graphic courtesy M.Borland]
Chromaticity Correction

The chromaticity is corrected with sextupole magnets.

\[
\begin{align*}
    x'' + K_x(s)x &= S(s)(x^2 - y^2) \\
    y'' + K_y(s)y &= -S(s)2xy
\end{align*}
\]

The motion is no longer integrable, chaotic at certain amplitudes (loss of stability = Dynamic Aperture)
Beam-Beam Interactions

In colliders in addition to the focusing magnets, particles experience interactions with electromagnetic field of counter-rotating beam.

\[
F \propto \Delta \nu_{BB} \frac{1}{r} \left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)
\]

\[
\Delta \nu_{BB} = \xi = \frac{N r_0 \beta}{4 \pi \gamma \sigma^2}
\]

Even though beam-beam adds relatively little to focusing – typical tune shift for LHC is 0.02 at lattice tune of 60, the beam-beam force is strongly nonlinear and localized in time.
In proton operation:

3 head-on collisions (CMS, ATLAS, LHC-B)

about 100 long-range at $\sim 9\sigma$ separation
LHC operation in 2012

Luminosity evolution for fill 2728 compared to model including:
- Particle losses due to luminosity and unknown source $\tau=200$ h
- Emittance growth due to IBS, SR damping and unknown growth with $\tau=40$ h

*intensity beam1*

$\sim 4 \ %/h$

*horizontal emittance*

*intensity beam2*

*vertical emittance*
Tevatron store 6200, $L_0=2.95 \times 10^{32}$

- Luminosity
- $N_{\text{Antiprotons}}$
- $N_{\text{Protons}}$
- L Integral
- Bunch Length
- Horiz. Emittance
- Vert. Emittance

$\sim 6 \% / \text{h}$
Tune Footprint

Betatron ampl. $A = 6 \sigma$
Nonlinear detuning
Small betatron amplitude

Linear lattice tune
Defocusing beam-beam proton-proton collisions
Frequency Map Analysis


- Based on precise tune determination from FFT of turn-by-turn particle coordinate (2D tracking)
- Evaluate tune jitter in sliding time window \(\rightarrow\) resonances
- When the dynamic system is (or very close to) integrable, nonlinear resonances disappear – this must be clearly seen in FMA plot
- Imperfections violate integrability. Then FMA easily allows to determine the regular and stochastic areas in phase space
Frequency Map Analysis

\[ \xi = 0.03 \]

7th order
10th order
13th order

A. Valishev | Beam Dynamics Challenges in HEP Accelerators
Space Charge Effect

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

Net force

\[ E - \beta B = E / \gamma^2 \]

Self space-charge is modulated in time due to the bunch size variation along the accelerator.

Leads to effects similar to beam-beam.

Limits maximum current in high-intensity low energy machines.
Space Charge in Linear Optics

ΔQ_{sc} \sim -0.7

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

Tech-X, RadiaSoft simulation
Intermediate Conclusions

• Linear accelerator lattices are stable by design. There are two non-commuting invariants of motion. All particles have equal oscillation frequencies (independent of amplitude).

• Nonlinear aberrations of the focusing are unavoidable (due to chromaticity), and some are introduced intentionally (e.g. sextupoles for chromaticity correction).

• Additional significant sources of nonlinearities are beam-beam interaction in colliders or self space charge in high intensity machines.

• Nonlinearities lead to unstable and chaotic motion
  – Nonlinearities shift tunes with amplitude
  – Time-dependence results in resonant conditions
Do Accelerators Need to be Linear?

Search for solutions that are strongly nonlinear yet stable

Additional invariants of motion improve stability

• Orlov (1963)
• McMillan (1967) – 1D solution
✓ Perevedentsev, Danilov (1990) – generalization of McMillan case to 2D, round colliding beams.
  – Round colliding beams possess 1 invariant – VEPP-2000 at BINP (Novosibirsk, Russia) commissioned in 2006. Record-high beam-beam tune shift ~0.25 attained in 2013
• Chow, Cary (1994)
✓ Nonlinear Integrable Optics: Danilov and Nagaitsev solution for nonlinear lattice with 2 invariants of motion that can be implemented with Laplacian potential, i.e. with special magnets – Phys. Rev. ST Accel. Beams 13, 084002 (2010)
2D Generalization of McMillan Mapping

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

• 2D – a thin lens solution can be carried over to 2D case in axially symmetric system

1. The ring with transfer matrix

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

\[ c = \cos(\phi) \]
\[ s = \sin(\phi) \]
\[ I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \]

2. Axially-symmetric thin kick

\[ \theta(r) = \frac{kr}{ar^2 + 1} \]

Can be created with electron lens
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

- For large amplitudes, the fractional tune is 0.25
- For small amplitude, the electron (defocusing) lens can give a tune shift of \( \sim -0.3 \)
- Potentially, can cross an integer resonance
Round Colliding Beams

- McMillan mapping requires special shape of the nonlinear lens. Colliding beams are usually 3D Gaussian. Will one integral of motion improve stability?
  - Yes! Reducing 2D system to 1D eliminates coupling resonances
  - VEPP-2000 collider at BINP (Novosibirsk, Russia)
    - $e^+e^-$ collider at $\phi$-meson energy
    - Axially symmetric linear focusing in arcs
    - Round beams at IPs

- World record beam-beam tune shift $\xi=0.25$ in 2013

A. Romanov et al., NA-PAC'13

graphic courtesy BINP
Further, the system can be made close to 2D integrable through proper longitudinal shaping of the colliding bunches.

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. Shape bunch density $\lambda(s)$
   1. **Ideal** distribution
   2. Gaussian with $\sigma_z \sim \sqrt{2} \, \beta^*$

\[
\lambda(s) \propto \frac{1}{\beta(s)} = \frac{1}{1 + (s / 2 \beta^*)^2}
\]

\[
\lambda(s) \propto e^{-s^2 / 2 \sigma_z^2} \approx 1 - s^2 / 2 \sigma_z^2
\]
Time-Independent Hamiltonian

- The Hamiltonian is
  \[ H = \frac{p_x^2}{2} + \frac{p_y^2}{2} + K(s) \left( \frac{x^2}{2} + \frac{y^2}{2} \right) + V_{BB}(x, y, s) \]

- For ideal \( \lambda(s) \) \( H \) is time-independent in normalized variables
  \[ H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_{N}^2 + y_{N}^2}{2} + \beta(\psi)V_{BB} \left( x_{N}\sqrt{\beta(\psi)}, y_{N}\sqrt{\beta(\psi)}, s(\psi) \right) \]
  \[ z_N = \frac{z}{\sqrt{\beta(s)}}, \]
  \[ p_N = p\sqrt{\beta(s)} - \frac{\beta'(s)z}{2\sqrt{\beta(s)}}, \]

- This results in \( H \) being the integral of motion
- The Gaussian beam may be close to integrable
Model Lattice

• Machine tune does not need to be close to integer or half-integer, $Q=n/2+Q_0$!
Ideal distribution $Q = 0.3, \xi = 1$
Gaussian distribution $\sigma = \sqrt{2}\beta$, $\xi = 1$
Intermediate Conclusions

- Constructing nonlinear systems with 1 or 2 integrals of motion is possible with the use of non-Laplacian potential (e.g. beam-beam force)
- Compared to non-integrable systems, dynamics in nonlinear accelerator lattices with some degree of integrability is more stable
  - Nekhoroshev’s condition guaranties detuning from resonance and, thus, stability.
    - Demonstrated with round colliding beams at VEPP-2000
- Can integrable systems be constructed with Laplacian potentials (conventional magnets)?
Nonlinear Integrable Optics with Laplacian Potential

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

\[
\Delta V(x, y, s) \approx \Delta V(x, y) = 0
\]
Time-Independent Hamiltonian

- 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
  \[ z_N = \frac{z}{\sqrt{\beta(s)}}, \]
  \[ p_N = p\sqrt{\beta(s)} - \frac{\beta'(s)z}{2\sqrt{\beta(s)}}, \]

\[
H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_{N}^2 + y_{N}^2}{2} + \beta(\psi)V(x_N\sqrt{\beta(\psi)}, y_N\sqrt{\beta(\psi)}, s(\psi))
\]

\[
H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_{N}^2 + y_{N}^2}{2} + U(x_N, y_N, \psi)
\]

- This results in \( H \) being the integral of motion
- Note there was no requirement on \( V \) – can be made with any conventional magnets, i.e. octupoles
### 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 ~12% of $Q_0$
While dynamic aperture is limited, the attainable tune spread is large.

Joint work with S. Antipov of Univ. Chicago
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)

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

- Darboux equation

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

  - 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

\[
f_2(\xi) = \xi \sqrt{\xi^2 - 1} \left( d + t \tfrac{\cosh(\xi)}{2} \right) \quad g_2(\eta) = \eta \sqrt{1 - \eta^2} \left( q + t \tfrac{\cos(\eta)}{2} \right)
\]
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
What is Unique About These Solutions?

• One can **add the special potential to a drift of a conventional accelerator** (albeit specially designed and carefully controlled) and make the lattice integrable.
  – Does not require new technology for the significant portion of accelerator circumference – same cost!
Single Particle Dynamics in Integrable Optics

Example trajectories
Single Particle Dynamics in Integrable Optics

Integer resonance $Q_y = m$
Effects of Imperfect Implementation

Approximation of continuously varying potential with finite (~20) number of elements

N = 20

N = 10
Effects of Imperfect Implementation – all errors combined

Simulations predict the tune shift / spread of 0.2 to be achievable with one nonlinear lens.
Space Charge in **NL Integrable Optics**

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

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

Tech-X, RadiaSoft simulation
Fermilab’s Accelerator R&D Program

• There is a lack of dedicated ring-based accelerator test facilities in the US for high intensity research
  – This hampers the training of next generation of accelerator scientists for HEP
  – At present, the only machine to study SC effects is UMER at University of Maryland with very low (10keV) electrons

• We started a transformational Accelerator R&D program centered at Fermilab’s ASTA/IOTA – Advanced Superconducting Test Accelerator / Integrable Optics Test Accelerator

• ASTA/IOTA will become a unique machine for revolutionary proof-of-principle R&D towards future high intensity machines
  – push performance limits of rings by 3-5 times to enable multi-MW beam power – $\Delta Q_{SC}>1$, lower losses, stable beams
  – become the focal point for collaboration and training
I. Construct and commission the Integrable Optics Test Accelerator (IOTA) storage ring and its proton and electron injectors, and establish reliable and time-effective operation of the facility for accelerator research program.

II. Carry out transformative beam dynamics experiments
   a. Integrable optics with non-linear magnets and with electron lenses.
   b. Space charge compensation with electron lenses and electron columns.
   c. Optical stochastic cooling demonstration

III. Open new opportunities for training young researchers

All in collaboration with national and international partners on corresponding modeling, design, and analysis efforts
Existing Infrastructure

- **ASTA/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.
ASTA Facility
ASTA Schematic

50 MeV e- photoinjector → CM2 → 150+ MeV e- → RFQ → IOTA

RFQ: 2.7 MeV p+/H-
IOTA: 150 MeV e- 2.5 MeV p+

spectrometer and e- dump
Integrable Optics Test Accelerator

• **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 Ring

2.5 MeV RFQ

e-beam line
p-beam line
IOTA Layout

NL2

NL1

42.0 cm

OSC

IOTA RING

QUADS OF A NEW DESIGN

EL
## IOTA Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal kinetic energy</td>
<td>$e^{-}$: 150 MeV, $p+$: 2.5 MeV</td>
</tr>
<tr>
<td>Nominal intensity</td>
<td>$e^{-}$: $1 \times 10^9$, $p+$: $1 \times 10^{11}$</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>$0.02 \div 0.1$</td>
</tr>
<tr>
<td>Betatron tune (integer)</td>
<td>$3 \div 5$</td>
</tr>
<tr>
<td>Natural chromaticity</td>
<td>$-5 \div -10$</td>
</tr>
<tr>
<td>Transverse emittance r.m.s.</td>
<td>$e^{-}$: 0.1 µm, $p+$: 2µm</td>
</tr>
<tr>
<td>SR damping time</td>
<td>0.6s ($5 \times 10^6$ turns)</td>
</tr>
<tr>
<td>RF $V,f,q$</td>
<td>$e^{-}$: 1 kV, 30 MHz, 4</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>$e^{-}$: $0.002 \div 0.005$</td>
</tr>
<tr>
<td>Bunch length, momentum spread</td>
<td>$e^{-}$: 2 cm, $1.4 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Ring Elements in Hand

- Dipole magnets (ordered)
- Vacuum chambers for dipoles (received)
- 32 quads from JINR (Dubna) received
- Magnet support stands from MIT (received)

Also:
- BPM bodies and electronics
- Vacuum system
- Dipole power supply
- Corrector power supplies
IOTA Electron Lens

- Capitalize on the Tevatron experience and recent LARP work
- Re-use Tevatron EL components
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
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
IOTA Staging – Phase II

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

\[ \Delta Q_{SC} = 0.6 \text{ for one-turn injection} \]

*multi-turn injection possible

• Allows tests of Integrable Optics with protons and realistic space charge beam dynamics studies

• **Allows space charge compensation experiments**

• Unique capability
Roadmap to High-Intensity Rings

• Theory and modeling to develop basis for high intensity circular machines
• Proof-of-principle experiments at ASTA/IOTA
• Ultimately, develop a recipe for a new generation rapid cycling synchrotron for super-high beam intensity (× 3-5 present)
  – Self-consistent or compensated space-charge
  – Strong non-linearity (for Landau damping) to suppress instabilities
  – Stable particle motion at large amplitudes
participants of the 2nd ASTA Collaboration Meeting, June 2014
Collaboration

• A lot of interest to participate in ASTA/IOTA from the accelerator community
  – 2 annual Collaboration Meetings, ~60 participants

• Significant intellectual and in-kind contributions, expressions of interest
  – NIU, UMD, RadiaSoft, CERN, ORNL, BINP, U.Chicago – 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
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
Training

• Excellent connection to the university community through the Joint Fermilab/University PhD program
  – Already 9 graduate students doing thesis research at ASTA/IOTA
    • 7 NIU
    • 1 U.Chicago
    • 1 IIT
  – 2 more to join soon
  – (see S. Cousineau’s talk)

• Partnership with university groups
  – Univ. of Maryland – NSF grant for IOTA-related work
Summary

• Despite 50 years long history, beam dynamics in accelerators is still a lively field with many open questions requiring innovative solutions.
• The physics of beams has synergies with other branches – mechanics, plasma, etc.
• Fermilab’s ASTA/IOTA offers a unique scientific program aiming at breakthrough research to allow for x3-5 increase of beam intensity in future proton rings.
• ASTA/IOTA experiments are a great opportunity to explore something truly novel with circular accelerators.
• ASTA/IOTA will be a strong driver of national and international collaboration and training.
**LHC / HL-LHC Plan**

- **Run I**
  - 0.75 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)
  - 50 ns bunch
  - High pile up \(\sim 40\)

- **Run II**
  - 1.7 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)
  - 25 ns bunch
  - Pile up \(\sim 45\)

- **Plan approved by CERN management upon preparation in HL-LHC Coord Group and RLIUP**
  - See deliverable D1.7 Common LHC time plan

**Technical bottlenecks:**
- 50 \(\Rightarrow\) 25 ns