The Integrable Optics Test Accelerator

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• Fermilab Accelerator & Science Technology facility and Integrable Optics Test Accelerator
• Experimental Program – Integrable Optics
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Present Hadron Machine Limitations

- Beam loss major contributor to machine operating limits
- 1 W/m loss accepted, *independent of beam power*
- Larger beam power means better control of losses
- We will use Fermilab as an example in this talk
- Upgrade plans call for larger bunch intensity & beam power
- 1.2 MW seems achievable using existing technology
- **Innovative accelerator physics techniques** enable 2+ MW operation
DUNE Physics Sensitivity & Staging

- DUNE needs 2.4 MW beam power to achieve physics goals
  - Allows for 5σ measurement of mass hierarchy, and 3-5σ measurement of CP violation for most values of $\delta_{CP}$
- Relies on staged implementation of LBNF
  - Increase detector fiducial mass
  - Increase beam power 1.2 →2.4 MW

S. Söldner-Rembold, FNAL Users Meeting 2018
To achieve 1.2 MW (PIP-II), NC linac must be replaced with SC linac

To achieve 2+ MW (PIP-III), booster must be replaced

‘Integrable’ RCS is robust & cost-effective solution
Integrable Optics Test Accelerator

- Fermilab Accelerator & Science Technology (FAST) facility home to the Integrable Optics Test Accelerator (IOTA)
- Storage ring for advanced beam physics research
- Accepts both electrons and protons
- Experimental program includes:
  - Nonlinear Integrable Optics
  - Space Charge Compensation
  - Optical Stochastic Cooling
Nonlinear Integrable Optics
Nonlinear Integrable Optics

- Strong nonlinear focusing can be beneficial to accelerator beams:
  - *Decoherence* suppresses beam halo formation
  - *Landau damping* mitigates collective instabilities
  - *Steep Hamiltonian* resistant to perturbations

- However, octupoles introduce fourth-order resonances which have to be carefully corrected or avoided

- For nonlinear integrable optics, the lattice optics are carefully tuned so that the nonlinear channel *does not introduce any resonances*

- There will be two integrals of motion for the two transverse degrees of freedom
Danilov-Nagaitsev Integral Design

Time-independent kick:

- Drift with matched beta functions and zero dispersion
- Followed by T insert with pi-integer phase advance
- Appropriate selection of potential in drift provides time-independent kick (avoid resonances)

Nonlinear kick separable in elliptic coordinates:

V. Danilov, S. Nagaitsev “Nonlinear Lattices with One or Two Analytic Invariants” PRST-AB 2010.
IOTA Lattice

Nonlinear insert:
Simulation of Anti-Damper in the IOTA Lattice

- Emulate a collective instability with an anti-damper:
  \[
  \frac{\Delta p}{p} = g \langle x \rangle
  \]

- Nonlinear element reduces max centroid oscillation by factor of 50 and reduces particle loss by factor of 100

Without nonlinear magnet

With nonlinear magnet
1. Design for a standard FODO lattice with arcs and straights
2. Match beta in nonlinear insert with focusing triplet
3. Adjust FODO cell to eliminate dispersion in nonlinear insertion
4. Adjust phase-advance between nonlinear insertions to pi-integer

- Nonlinear Integrable Optics at cost of increased circumference
Integrable RCS Design

- Periodicity: 12
- Circumference: 636 m
- Bend-radius rho: 15.4 m
- Max. beta x,y function: 28 m
- Max. dispersion function: 0.22 m
- RF insertion length: 7.2 m, 4x 1.3 m
- NL insertion length: 12.7 m
- Insert phase-advance: 0.3
- Minimum c-value: 3 cm
- Beta at insert center: 5 m
- Betatron tune: 21.6
- Natural chromaticity: -79
- Synchrotron tune: 0.08
Transverse Beam Halo in iRCS Simulation

Conventional

Integrable

Waterbag

Eldred, Valishev IPAC 2017
High Intensity Simulation of iRCS

- Beam injected with 20% mismatch
- Laslett tune shift of 0.4, corresponding to $3.2 \times 10^{13}$ protons
- Stable for at least 5,000 revolutions, *halo strongly suppressed*
- Caveat: perfect lattice with no errors
Space Charge Compensation
Another way of mitigating beam loss is through space charge compensation.

Undesirable effects of Coulomb repulsion can be mitigated by making beam pass through plasma column of opposite charge with same charge distribution. Required total charge of plasma column decreases with increasing beam energy.

Concept successfully applied to transport high current, low energy proton and H⁻ beams in RFQs of linacs.

In circular machines, suppression of e-p instabilities can be achieved using a solenoidal magnetic field of sufficient strength.
Electron Lenses

- Electron Lenses successfully deployed at Fermilab (and Brookhaven and …) to compensate space charge tuneshift
- External electron beam injected co-propagating with beam for short region

- Transverse profiles must be carefully matched
- Electron gun provides electron beam
- Strong solenoid magnet confines electrons and suppresses instabilities
- Additional magnets needed for injection and extraction
Electron Columns

- **Similar to Electron Lens**
  - Electrons provide negative charge to compensate Coulomb repulsion
- **Electrons produced by ionization of gas by beam in region of Column**
- **Electron transverse distribution matches beam intrinsically**
- **Electrodes at both ends provide longitudinal confinement**

- **Solenoid magnet confines electrons transversely**
  - Strong enough to suppress e-p instability
  - Weak enough to allow plasma ions to escape
- **Does not require electron gun, collector, or transport magnets**
- **Does require additional pumping to maintain vacuum in rest of ring**
Electron Column Status

• Space charge compensation using an Electron Column planned for proton beam operation in IOTA

• Simulation studies underway to
  – Predict evolution of beam and Column
  – Optimize Column parameters
    • Gas density
    • Electric & magnetic field strength

• Two passes of the IOTA proton beam through Electron Column show space charge compensation
  – Some key plasma processes missing
    • Recombination
    • Particle collisions

• Inclusion of rest of IOTA lattice in simulation underway
Particle Distributions After First Pass

- Transverse profile of plasma electrons at Column center and beam well matched after first pass
- Density of electrons approaching that of beam

Freemire, et al, IPAC 2018
To quantify effect of space charge compensation, simulations with ionization (SCC) and without ionization (no SCC) performed

Significant reduction in radial electric field within beam radius observed
Particle Distributions After Second Pass

- Transverse distribution of electrons still closely matched to that of beam
- Density of electrons now greater than beam
- Ion density also surpasses beam density
  - Leads to reduction in space charge compensation
Space Charge Compensation After Second Pass

- Degree of space charge compensation similar to first pass
- Transverse slice shown at center of Column
- Plasma oscillations result in non-homogeneity of local density
- Compensation determined by average plasma distribution over length of Column
Status & Schedule

• Vacuum system for IOTA ring completed July 30th
• Cooldown of cryomodules underway
• Commissioning of electrons in IOTA imminent
• Experiments with electrons through 2019
• Shutdown to install RFQ for proton beam late 2019
• Experiments with protons ~2020
Outlook

• Accelerator R&D at IOTA could lead the way to more intense beams, both at Fermilab and abroad

• FAST/IOTA excellent opportunity for accelerator physics & engineering students

• Strong experimental program at IOTA including
  – Nonlinear integrable optics
  – Space charge compensation
  – Optical stochastic cooling
  – ...

• We welcome collaborators interested in developing technology to enable the production of bright beams
Acknowledgements

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• The rest of the Electron Column group:  Giulio Stancari, Chong Shik Park, Moses Chung, Chad Mitchell, and Gregg Penn

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Backup Slides
### Electron Column Simulation / IOTA Parameters

#### Beam Parameters

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Beam Species</td>
<td>Proton</td>
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<tr>
<td>Beam Energy</td>
<td>2.5 MeV (p = 68.5 MeV/c)</td>
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<tr>
<td>Beam Current</td>
<td>8 mA</td>
</tr>
<tr>
<td>Beam Pulse Length</td>
<td>1.77 µs</td>
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<tr>
<td>Beam Distribution</td>
<td>KV (transverse), Step function (longitudinal)</td>
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</tbody>
</table>

#### Hardware Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Column Length</td>
<td>1 m</td>
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<tr>
<td>Pipe Radius</td>
<td>2.54 cm</td>
</tr>
<tr>
<td>Electrode Positions</td>
<td>0, 100 cm</td>
</tr>
<tr>
<td>Electrode Strength</td>
<td>-5 V</td>
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<tr>
<td>Solenoid Field</td>
<td>0.1 T</td>
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#### Gas Parameters

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<tbody>
<tr>
<td>Gas Species</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>Gas Density</td>
<td>1.65x10^{13} cm^{-3} (5x10^{-4} torr)</td>
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<tr>
<td>Ionization Process</td>
<td>p + 2H\textsubscript{2} → p + e + H\textsuperscript{3+} + H</td>
</tr>
<tr>
<td>Ionization Cross Section</td>
<td>1.82x10^{-17} cm\textsuperscript{2}</td>
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<tr>
<td>Plasma Electron Energy, Spread</td>
<td>45 eV, 19 eV</td>
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#### Numerical Parameters

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<tr>
<td>Particles Injected/Step</td>
<td>500</td>
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<tr>
<td>Grid Spacing, x,y,z</td>
<td>0.5, 0.5, 1.0 cm</td>
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<tr>
<td>Time Step</td>
<td>70 ps</td>
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<tr>
<td>Simulation Length</td>
<td>1.83 µs</td>
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<td>Number of Passes</td>
<td>2</td>
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