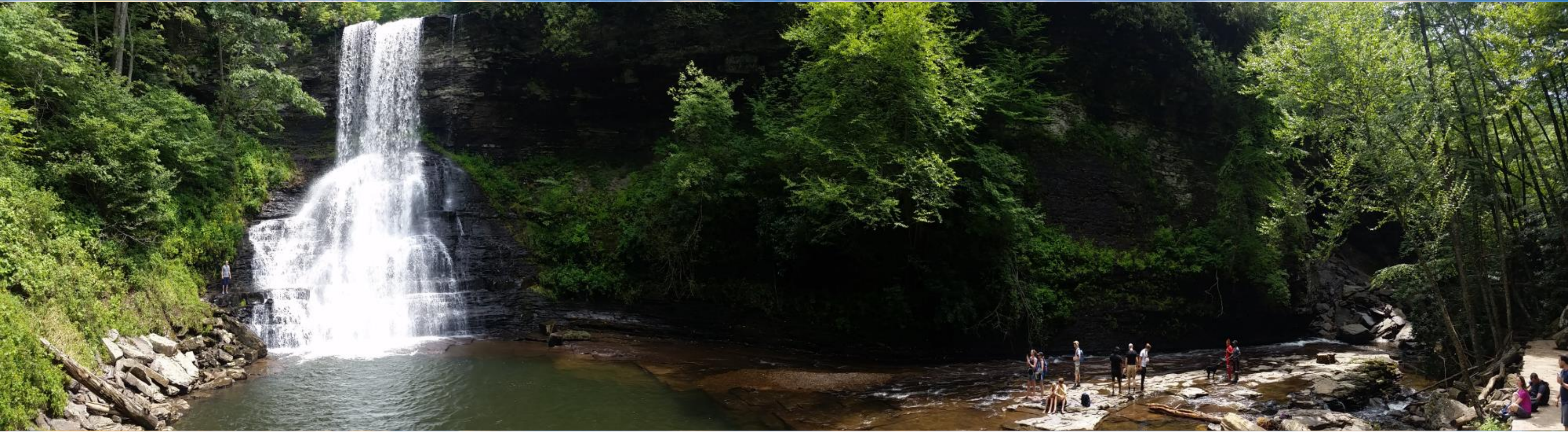


The Integrable Optics Test Accelerator

Ben Freemire (NIU) & Jeff Eldred (FNAL)

NuFact 2018, Virginia Tech

Thursday, 16 August, 2018

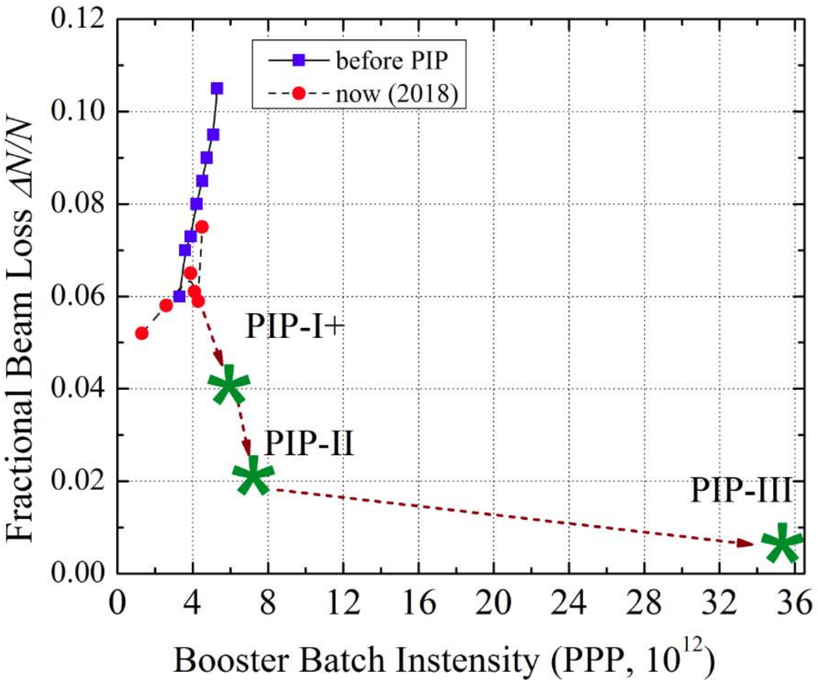
In partnership with:

Northern Illinois University

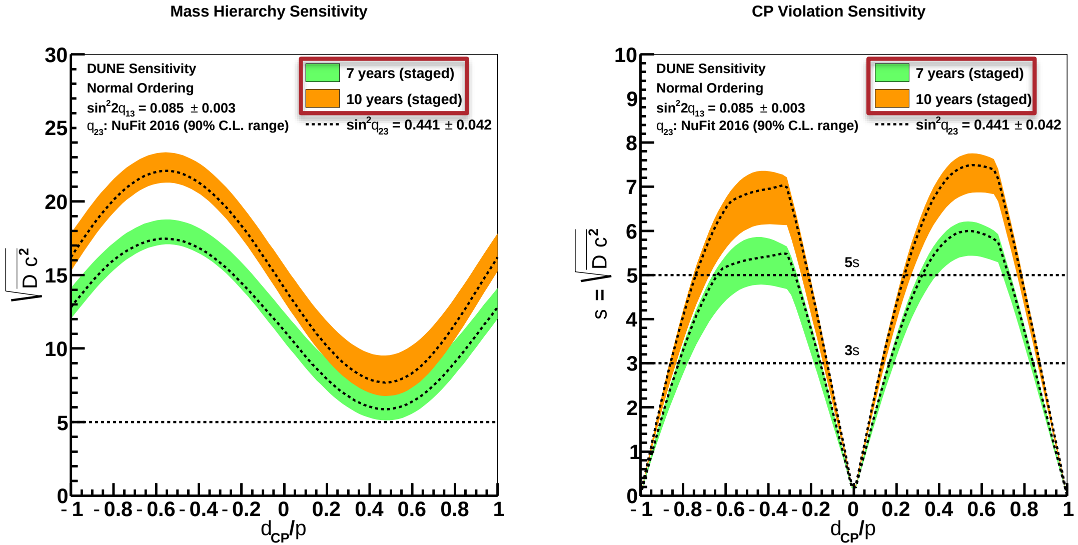
Contents

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



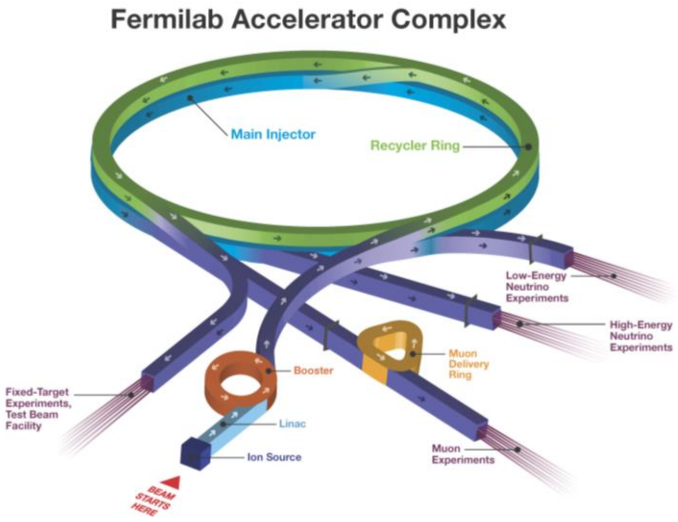
DUNE Physics Sensitivity & Staging

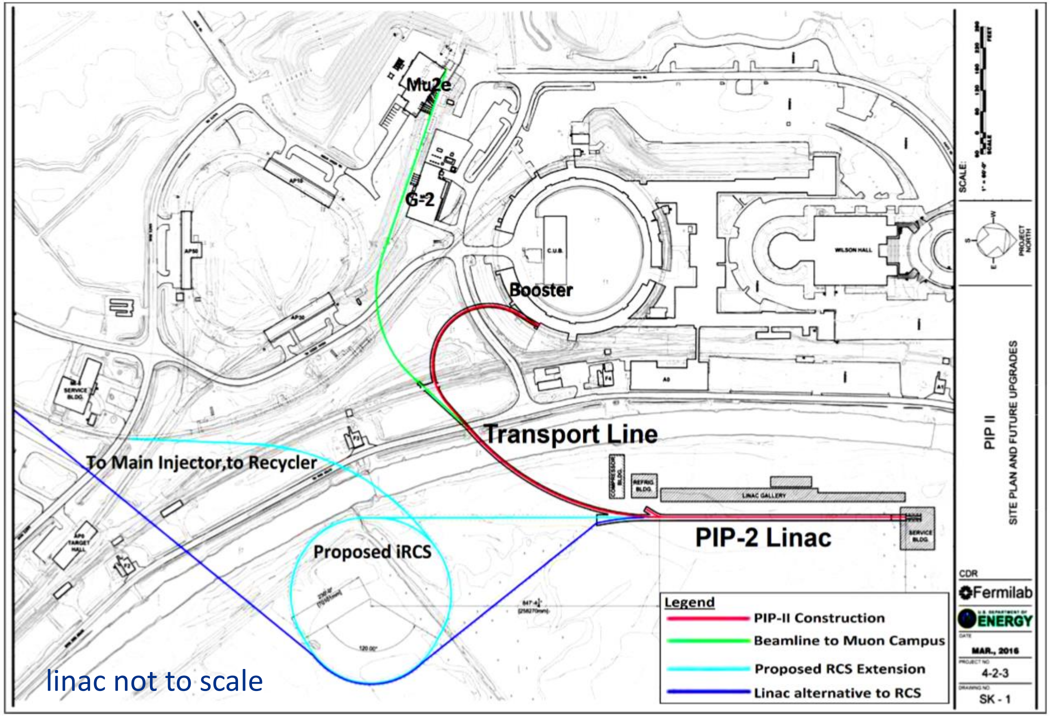


S. Söldner-Rembold,
FNAL Users Meeting 2018

- **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 δ_{CP}
- **Relies on staged implementation of LBNF**
  - Increase detector fiducial mass
  - *Increase beam power 1.2 →2.4 MW*

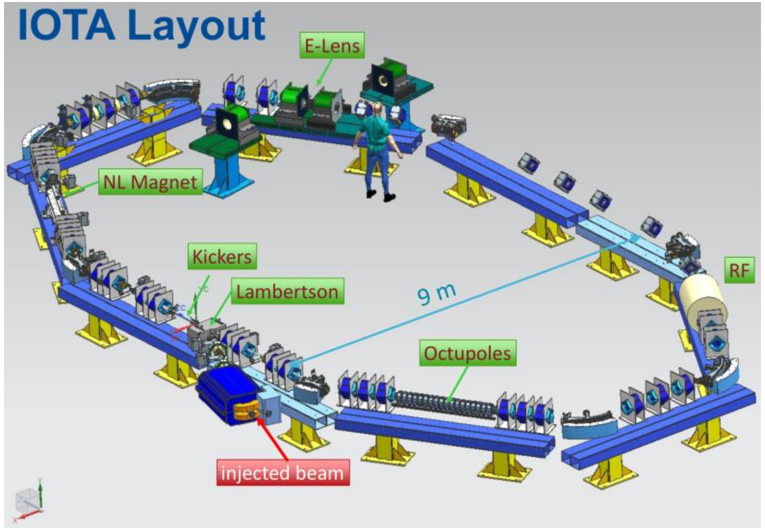
Fermilab Accelerator Complex of the Future

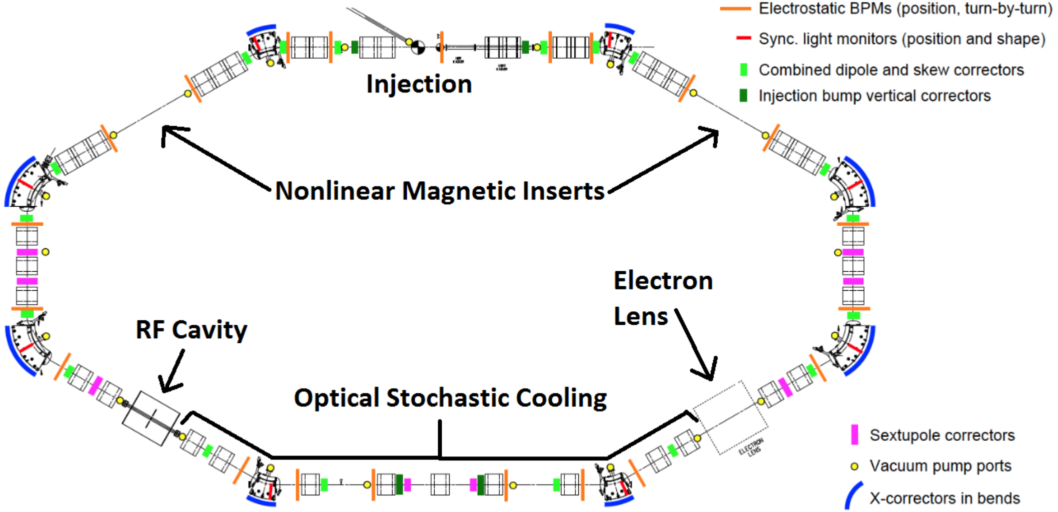




- To achieve 1.2 MW (PIP-II), NC linac must be replaced with SC linac
- To achieve 2+ MW (PIP-III), booster must be replaced
- ‘Integrable’ RCS is robust & cost-effective solution

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

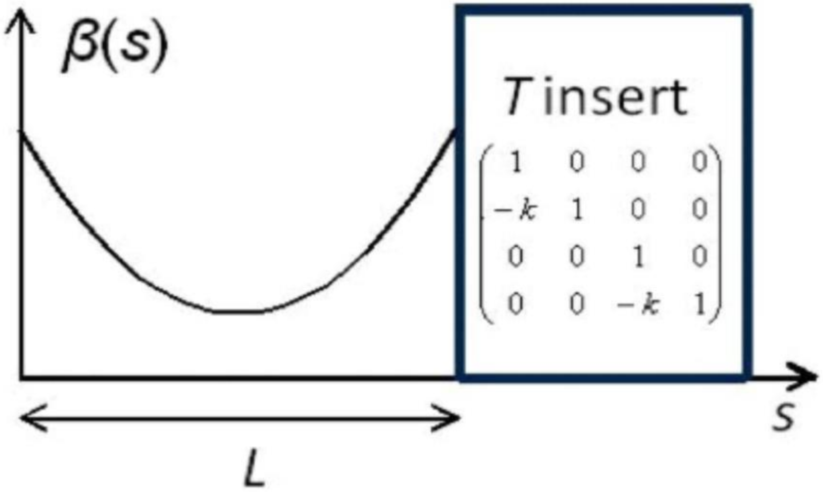
- However, octupoles introduce fourth-order resonances which have to be carefully corrected or avoided

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

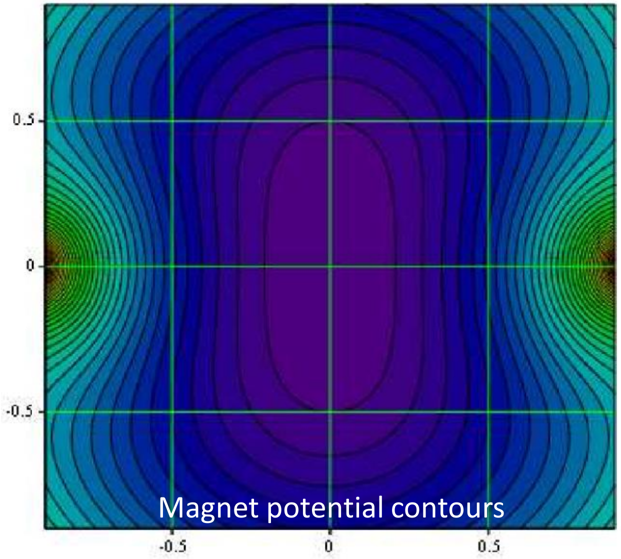
- There will be two integrals of motion for the two transverse degrees of freedom

Danilov-Nagaitsev Integral Design

Time-independent kick:



Nonlinear kick separable in elliptic coordinates:

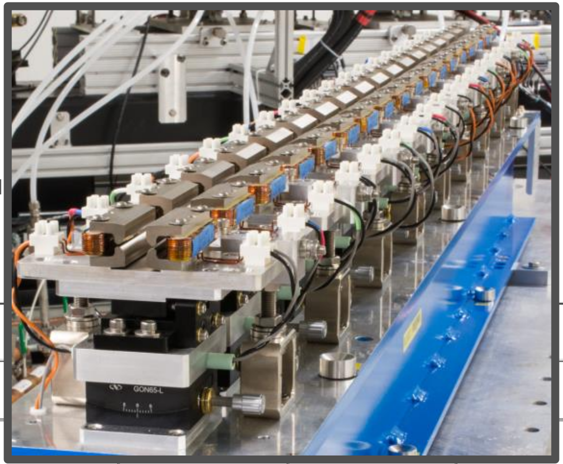


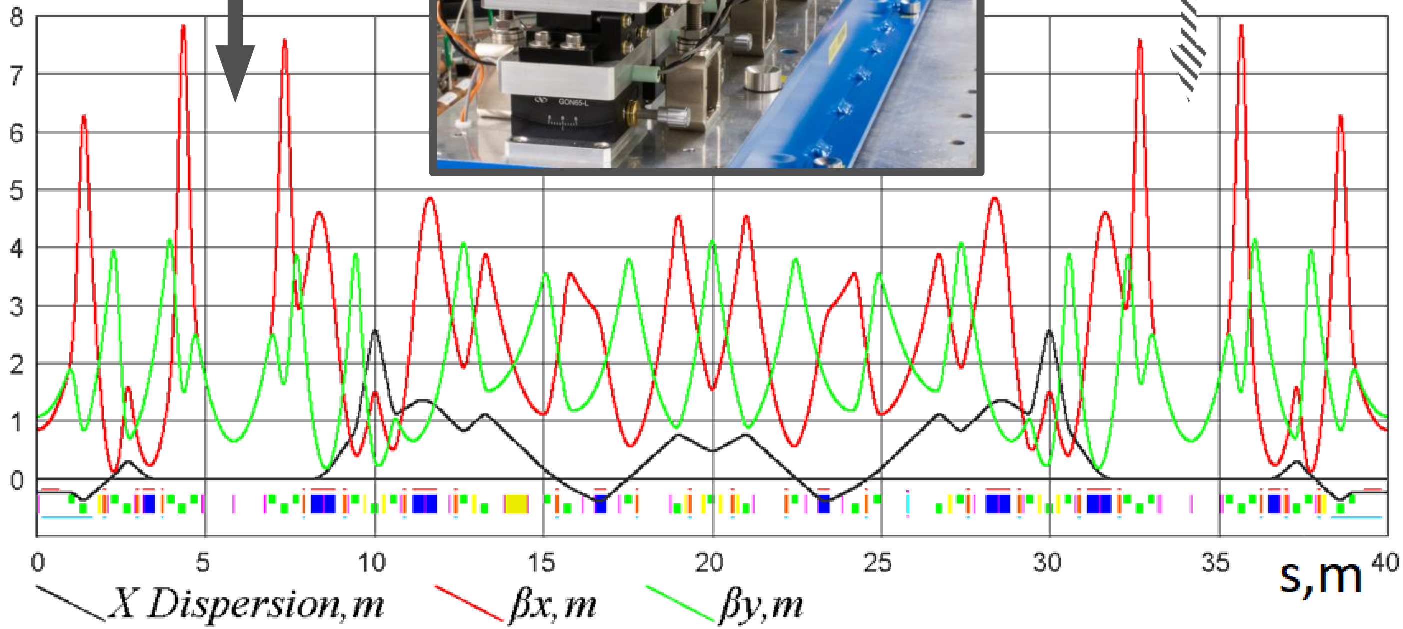
V. Danilov, S. Nagaitsev "Nonlinear Lattices with One or Two Analytic Invariants" PRST-AB 2010.

- **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)**

IOTA Lattice

Nonlinear insert:

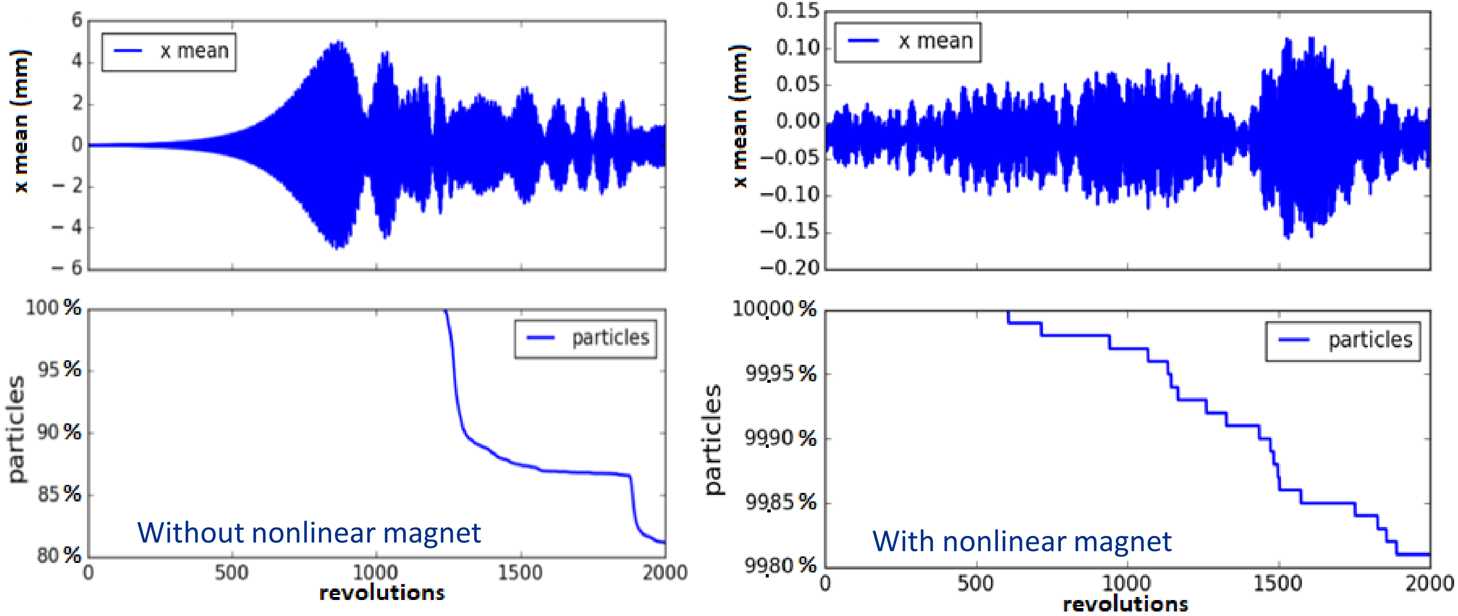




Simulation of Anti-Damper in the IOTA Lattice

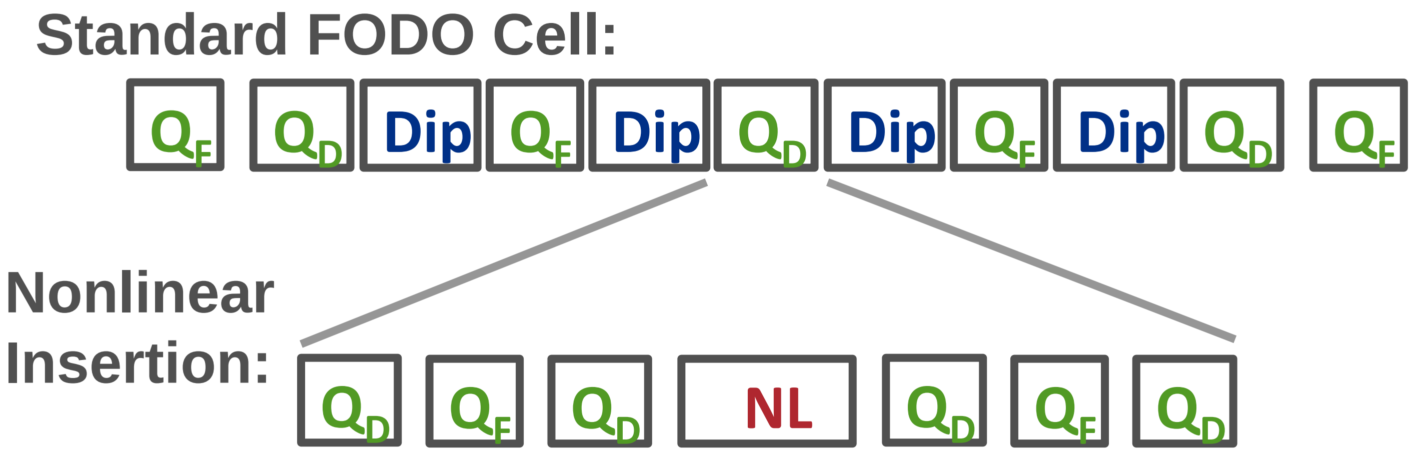
- **Emulate a collective instability with an anti-damper:** $$\frac{\Delta p}{p} = g \langle x \rangle$$

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



Stern, Amundson, Macridin, IPAC 2018

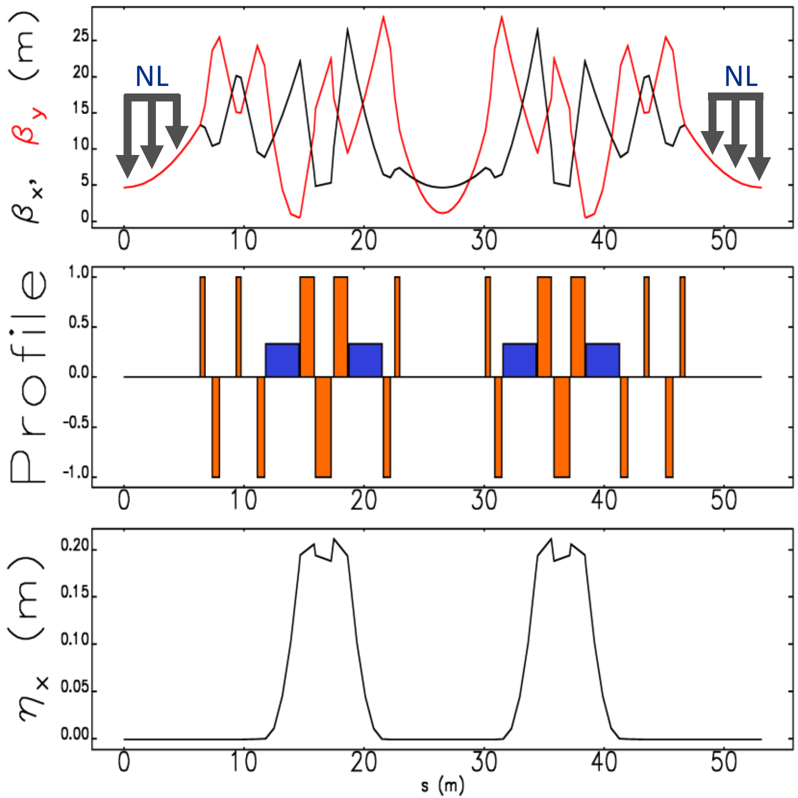
General Lattice Strategy for Integrable Optics



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

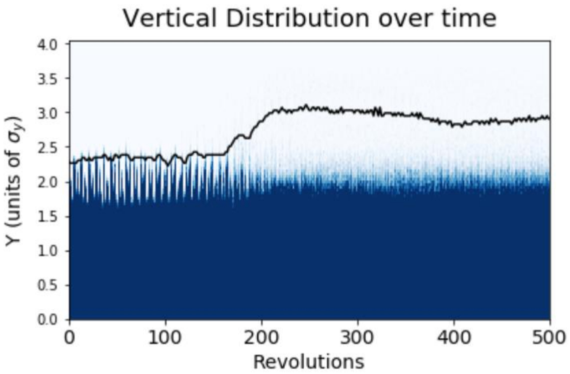
Betatron tune: 21.6

Natural chromaticity: -79

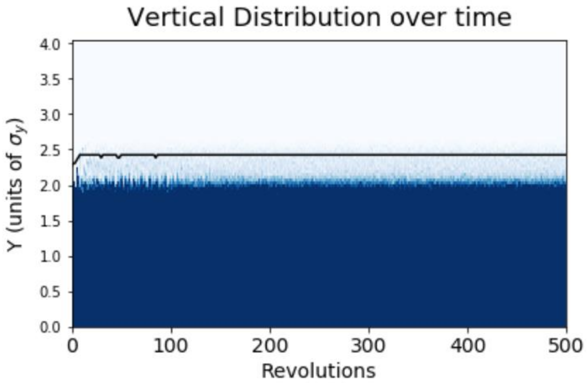
Synchrotron tune: 0.08

Eldred, Valishev IPAC 2018

Transverse Beam Halo in iRCS Simulation

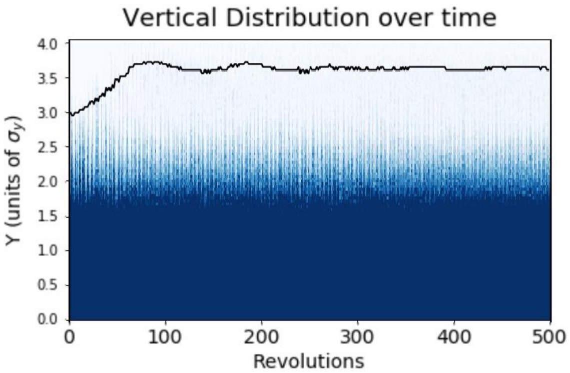


KV

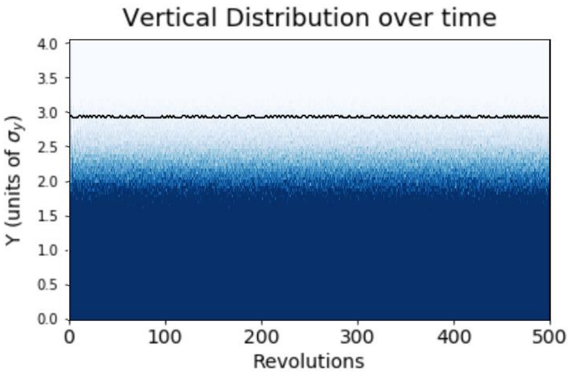


Conventional

Integrable



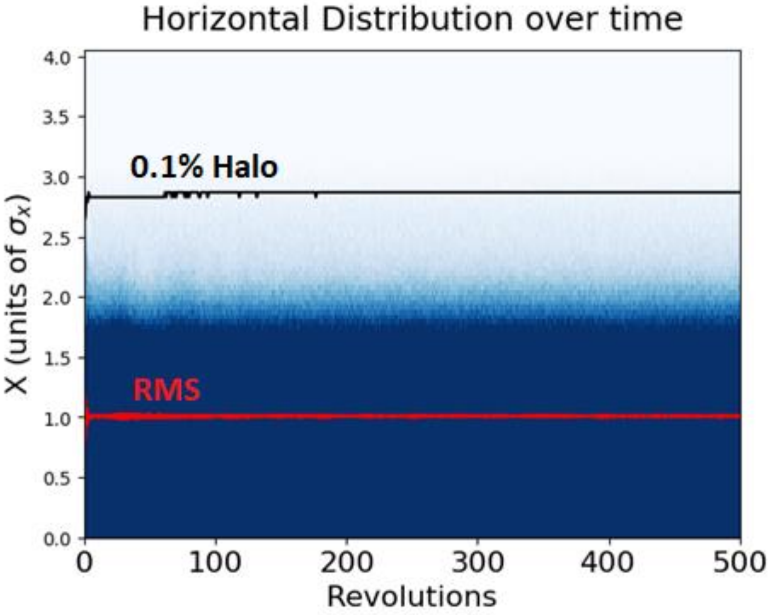
Waterbag



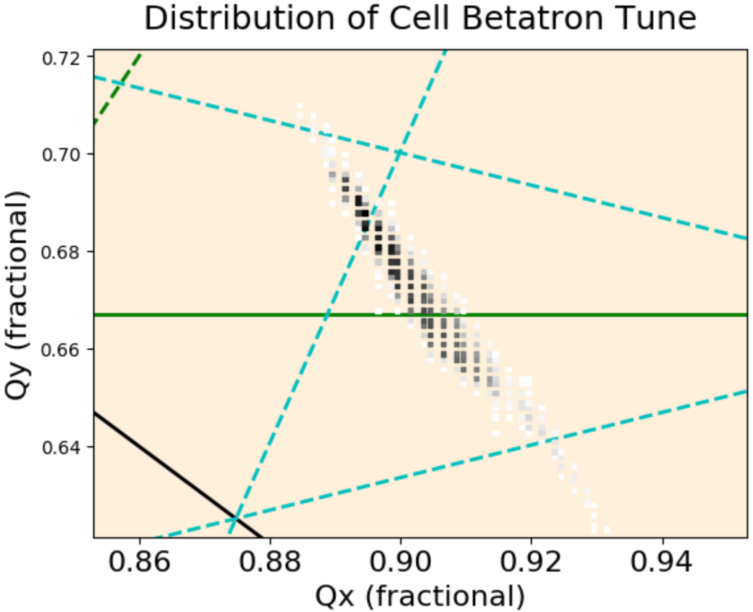
Eldred, Valishev IPAC 2017

High Intensity Simulation of iRCS

- **Beam injected with 20% mismatch**
- **Laslett tune shift of 0.4, corresponding to 3.2e13 protons**
- **Stable for at least 5,000 revolutions, *halo strongly suppressed***
- **Caveat: perfect lattice with no errors**



Eldred, Valishev IPAC 2018



Space Charge Compensation

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

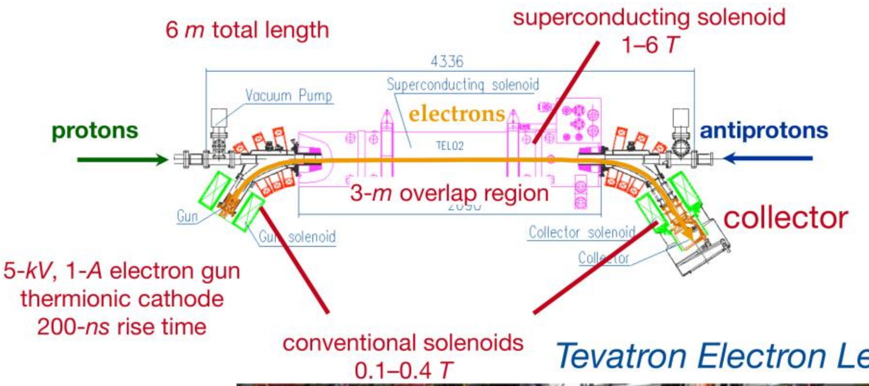
- Concept successfully applied to transport high current, low energy proton and H^- beams in RFQs of linacs

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

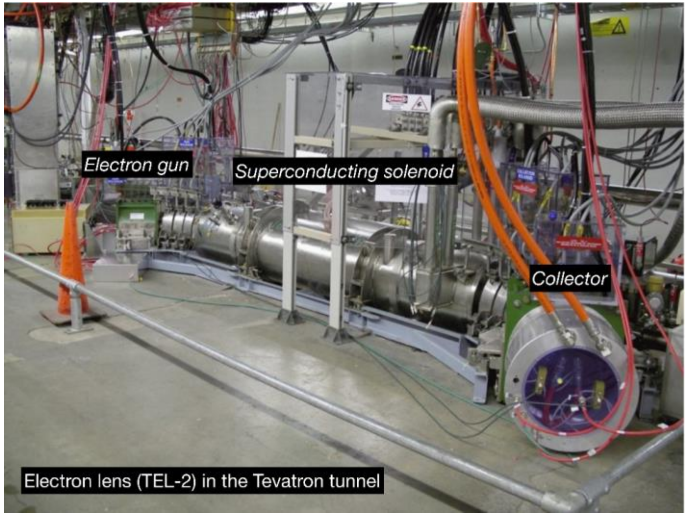
Electron Lenses

- 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



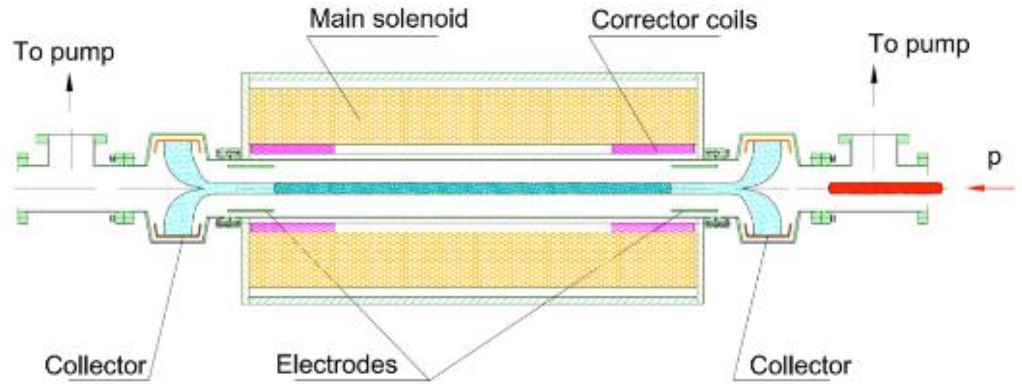
Tevatron Electron Lens



Electron lens (TEL-2) in the Tevatron tunnel

Electron Columns

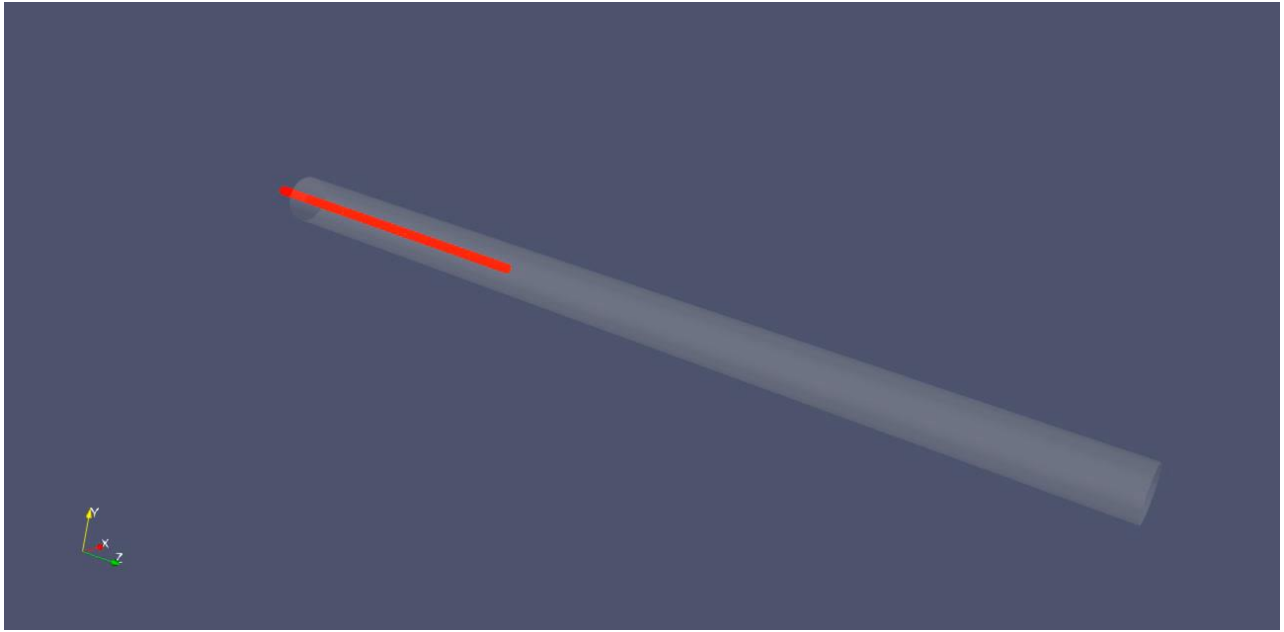
- **Similar to Electron Lens**
  - Electrons provide negative charge to compensate Coulomb repulsion
- **Electrons produced by ionization of gas by beam in region of Column**
- **Electron transverse distribution matches beam intrinsically**
- **Electrodes at both ends provide longitudinal confinement**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

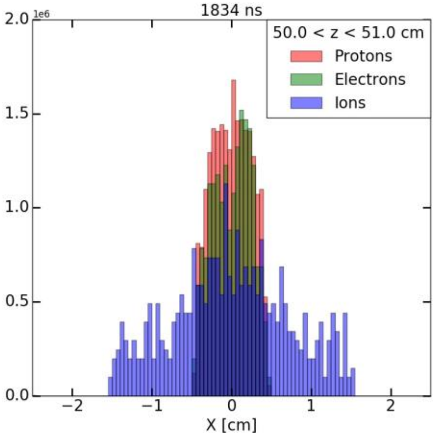


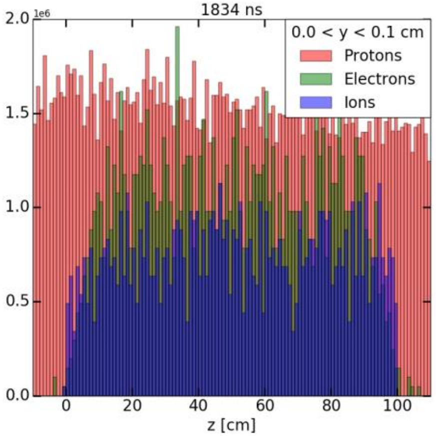
Electron Column Status

- 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



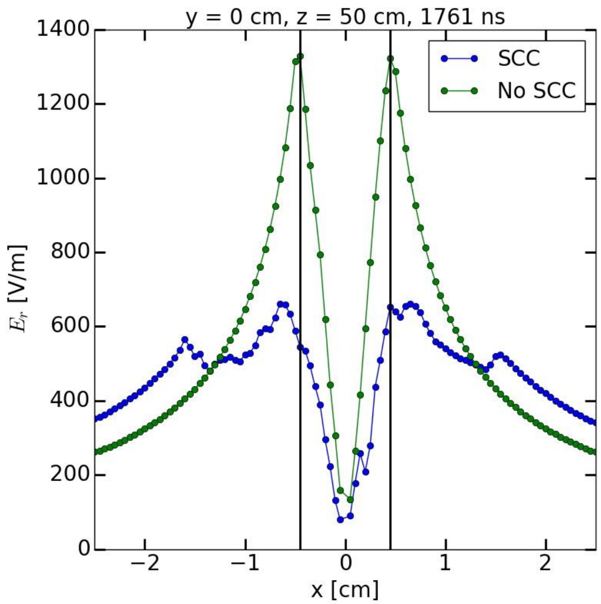


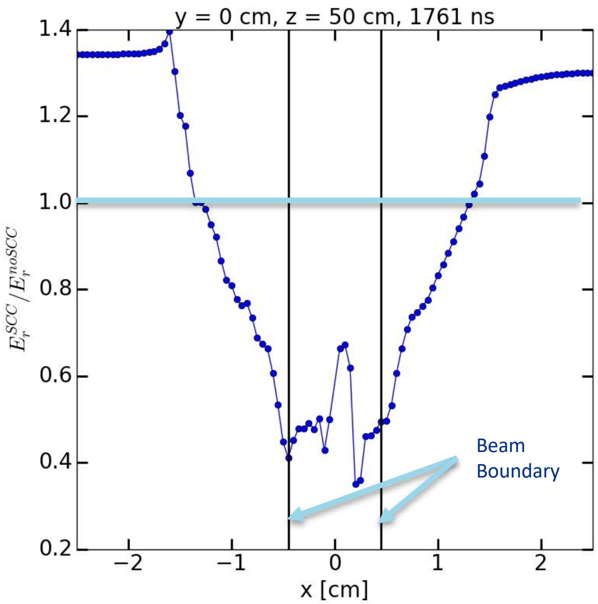


- Transverse profile of plasma electrons at Column center and beam well matched after first pass
- Density of electrons approaching that of beam

Freemire, et al, IPAC 2018

Space Charge Compensation After First Pass

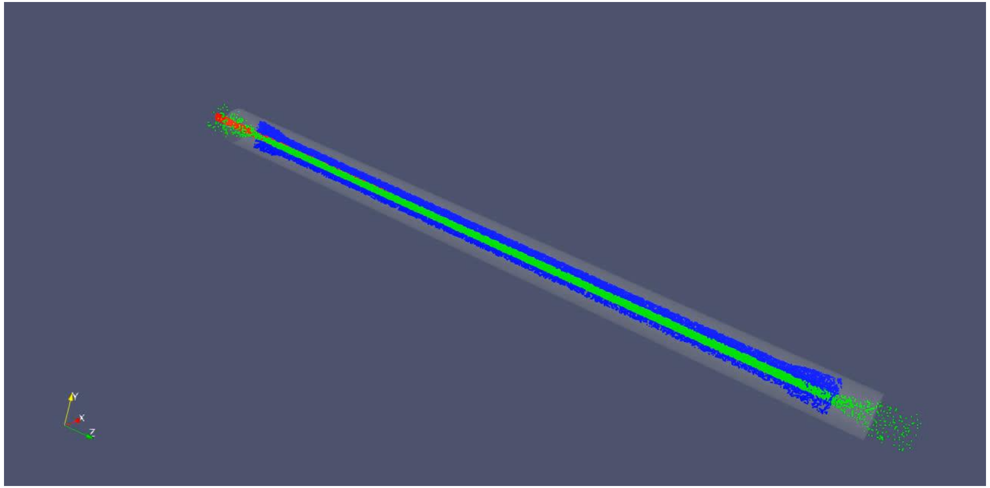


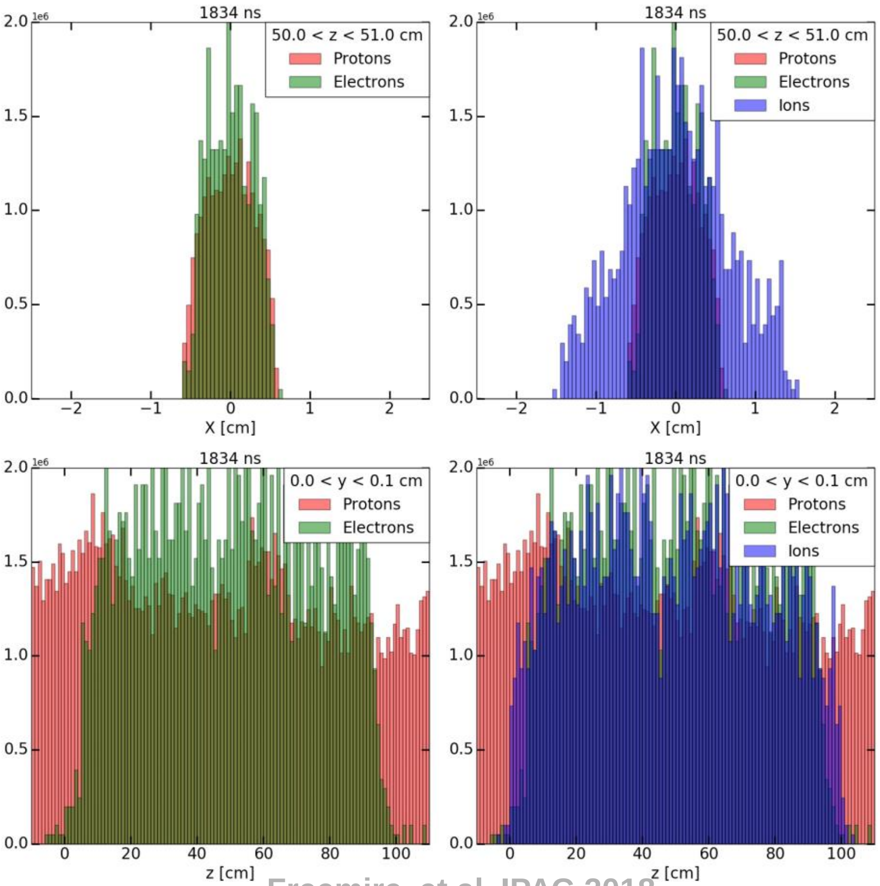


Freemire, et al, IPAC 2018

- 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

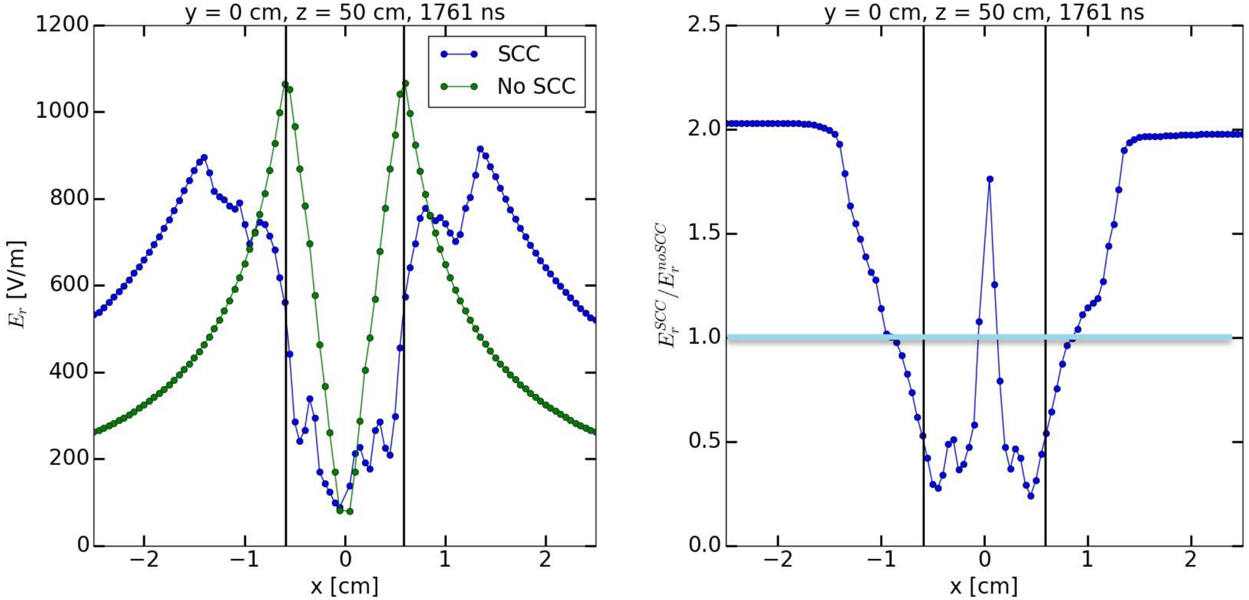




- **Transverse distribution of electrons still closely matched to that of beam**
- **Density of electrons now greater than beam**
- **Ion density also surpasses beam density**
  - Leads to reduction in space charge compensation

Freemire, et al, IPAC 2018

Space Charge Compensation After Second Pass

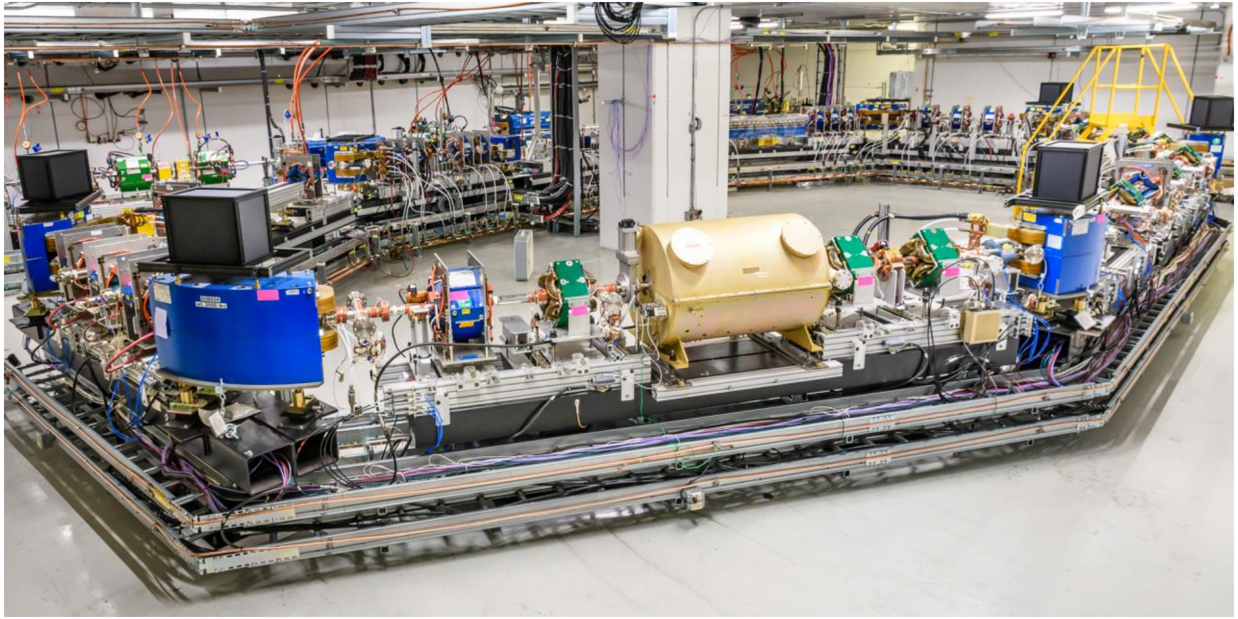


Freemire, et al, IPAC 2018

- **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

- Thank you to all of the FAST/IOTA team, in particular Vladimir Shiltsev, Sasha Valishev, and Swapan Chattopadhyay
- The rest of the Electron Column group: Giulio Stancari, Chong Shik Park, Moses Chung, Chad Mitchell, and Gregg Penn

- This work is supported by the US DOE Office of HEP, and the General Accelerator Research and Development Program

Northern Illinois University

Backup Slides

Electron Column Simulation / IOTA Parameters

Beam Parameters	
Beam Species	Proton
Beam Energy	2.5 MeV (p = 68.5 MeV/c)
Beam Current	8 mA
Beam Pulse Length	1.77 µs
Beam Distribution	KV (transverse), Step function (longitudinal)

Hardware Parameters	
Column Length	1 m
Pipe Radius	2.54 cm
Electrode Positions	0, 100 cm
Electrode Strength	-5 V
Solenoid Field	0.1 T

Gas Parameters	
Gas Species	Hydrogen
Gas Density	1.65×10^{13} cm^{-3} (5×10^{-4} torr)
Ionization Process	$p + 2H_2 \rightarrow p + e + H_3^+ + H$
Ionization Cross Section	1.82×10^{-17} cm^2
Plasma Electron Energy, Spread	45 eV, 19 eV

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