Accelerator R&D Toward Proton Drivers for Future Particle Accelerators

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Acknowledgement

I have drawn on material from:

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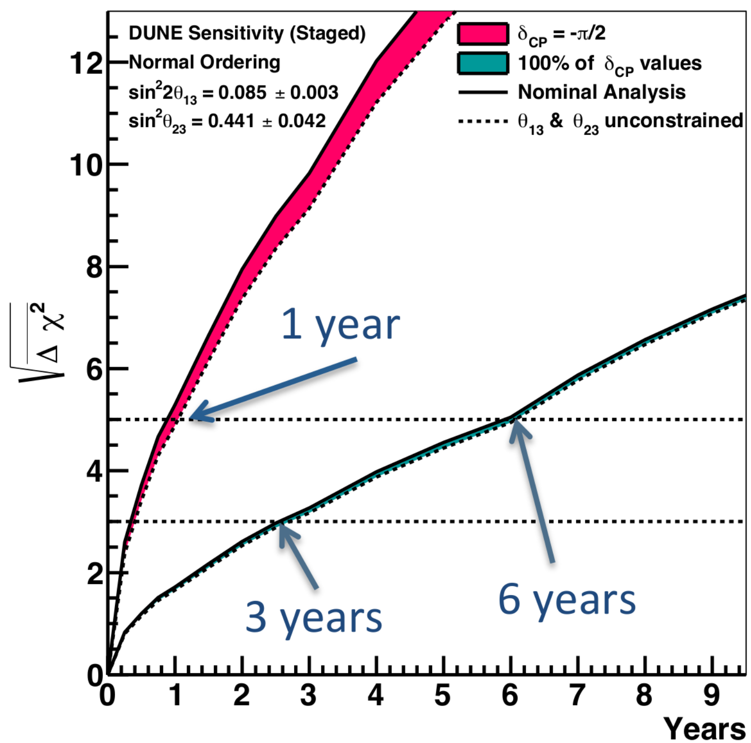
Outline

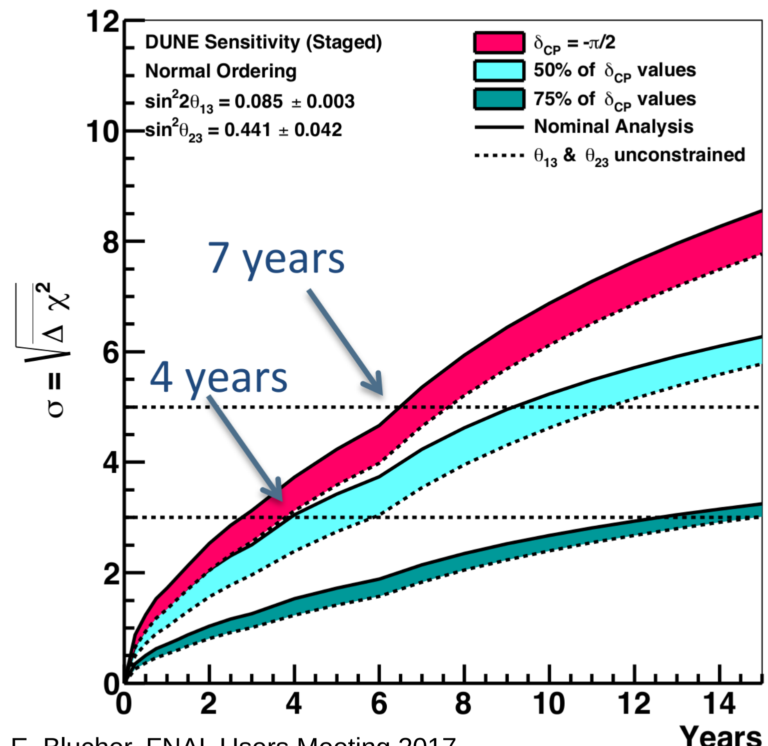
- LBNF/DUNE & Fermilab
- FAST/IOTA
- Experimental Program
- Schedule
- Summary

DUNE Sensitivity

Mass Hierarchy Sensitivity



CP Violation Sensitivity



E. Blucher, FNAL Users Meeting 2017

- Aim for 5σ measurement
  - Possible for mass hierarchy within 6 years for all δ_{CP} values
  - At best possible for CP violation within 9-11 years for only 50% of all δ_{CP} values
- Increased flux will cut down on required running time

LBNF/DUNE Staging

- ~2026: Begin operations – 1.07 MW (80 GeV) beam, 20 kt far detector
- ~2027: 30 kt far detector
- ~2029: 40 kt far detector
- ~2032: 2.14 MW (80 GeV) beam

Time (years)	Exposure (kt-MW-years)
5	171
7	300
10	556
15	984

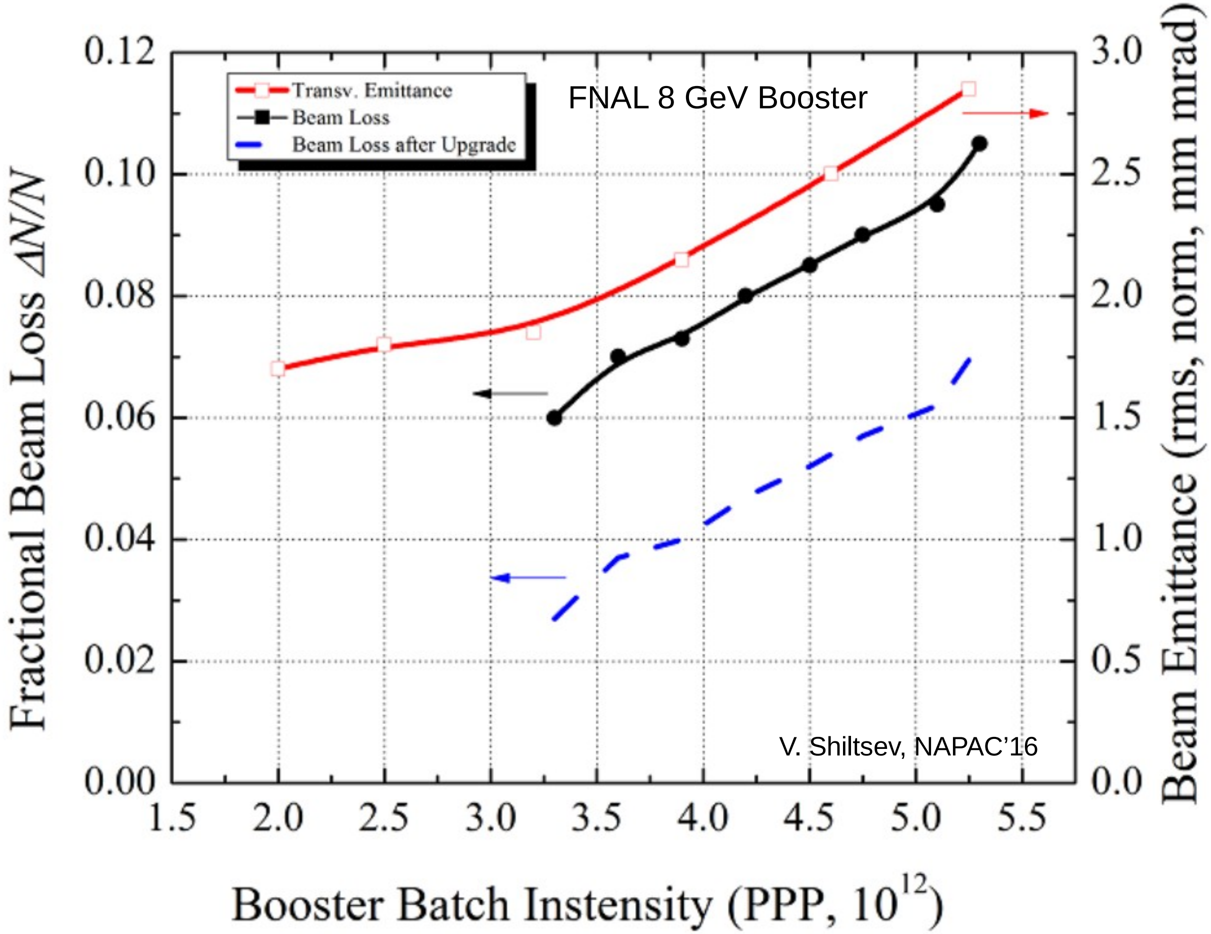
E. Blucher, FNAL Users Meeting 2017

Accelerator Upgrades

- DUNE physics program requires 900 kt-MW-yr
  - For current 40 kt design detector and recent 700 kW beam operation, ~ 32 years operations required!!!
- Can accomplish with >2 MW beam power
- Hard to do
  - Beam loss
    - Damage/destruction of accelerator at large energy
    - Activation of components at high current
    - **Losses must be kept to <0.1% at high intensity**

Space Charge

- Space charge has been a limiting factor on the performance of particle accelerators
  - Leads to particle loss
- Overcoming space charge is crucial for the next generation of high intensity accelerator

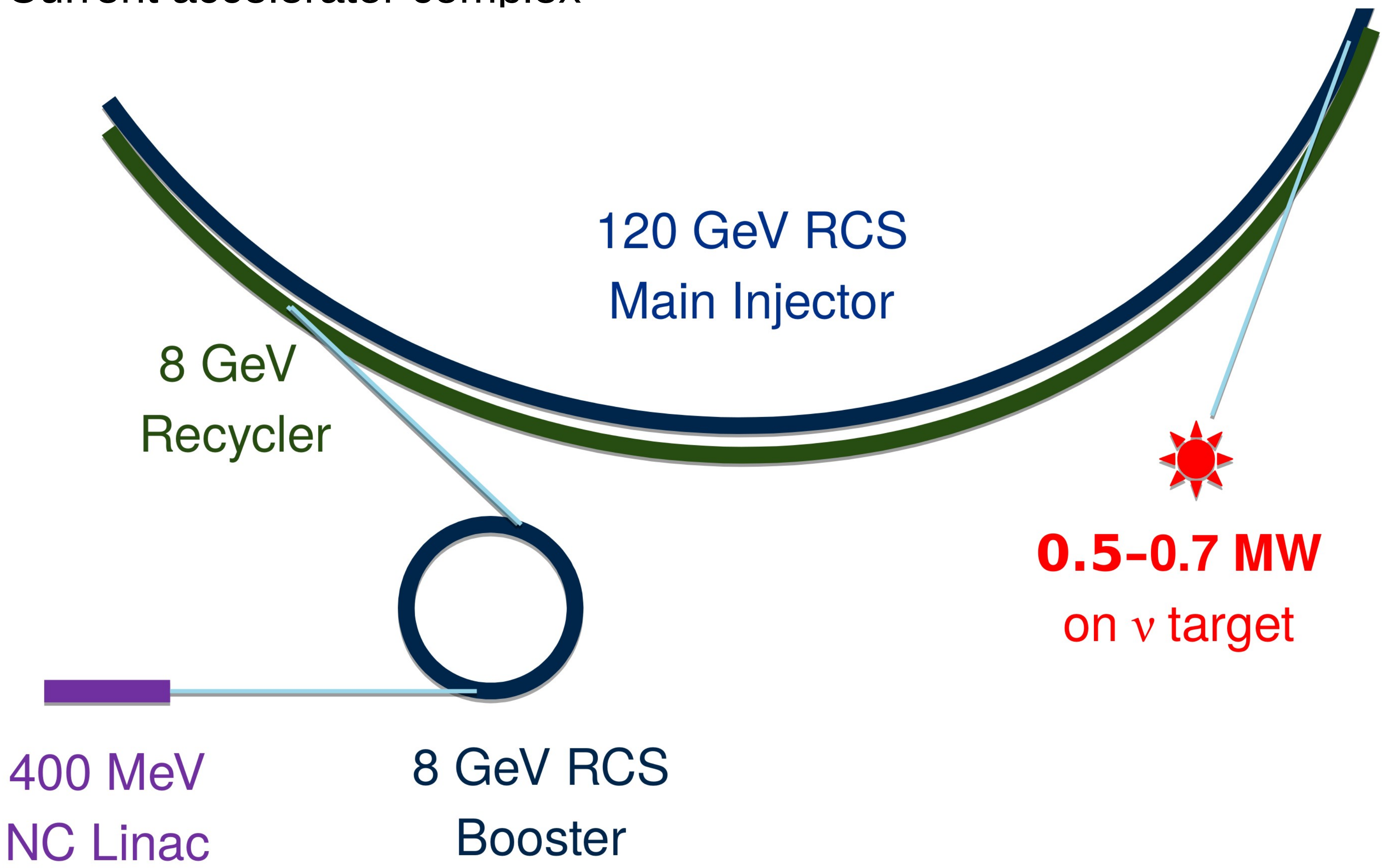


IOTA – Big Picture

- Cost effective path to multi-MW beam power must be discovered
  - *Either* reduce cost of SRF by factor of 3-4
  - *Or* increase performance of synchrotrons by 3-4
  - (*And* develop targets capable of handling power)
- IOTA presents a path toward increasing performance, and it’s cheap!
  - Conventional magnets and RF cavities
  - Standard beam pipe size and material
- IOTA will be the only dedicated ring based accelerator test facility in the US for high intensity research

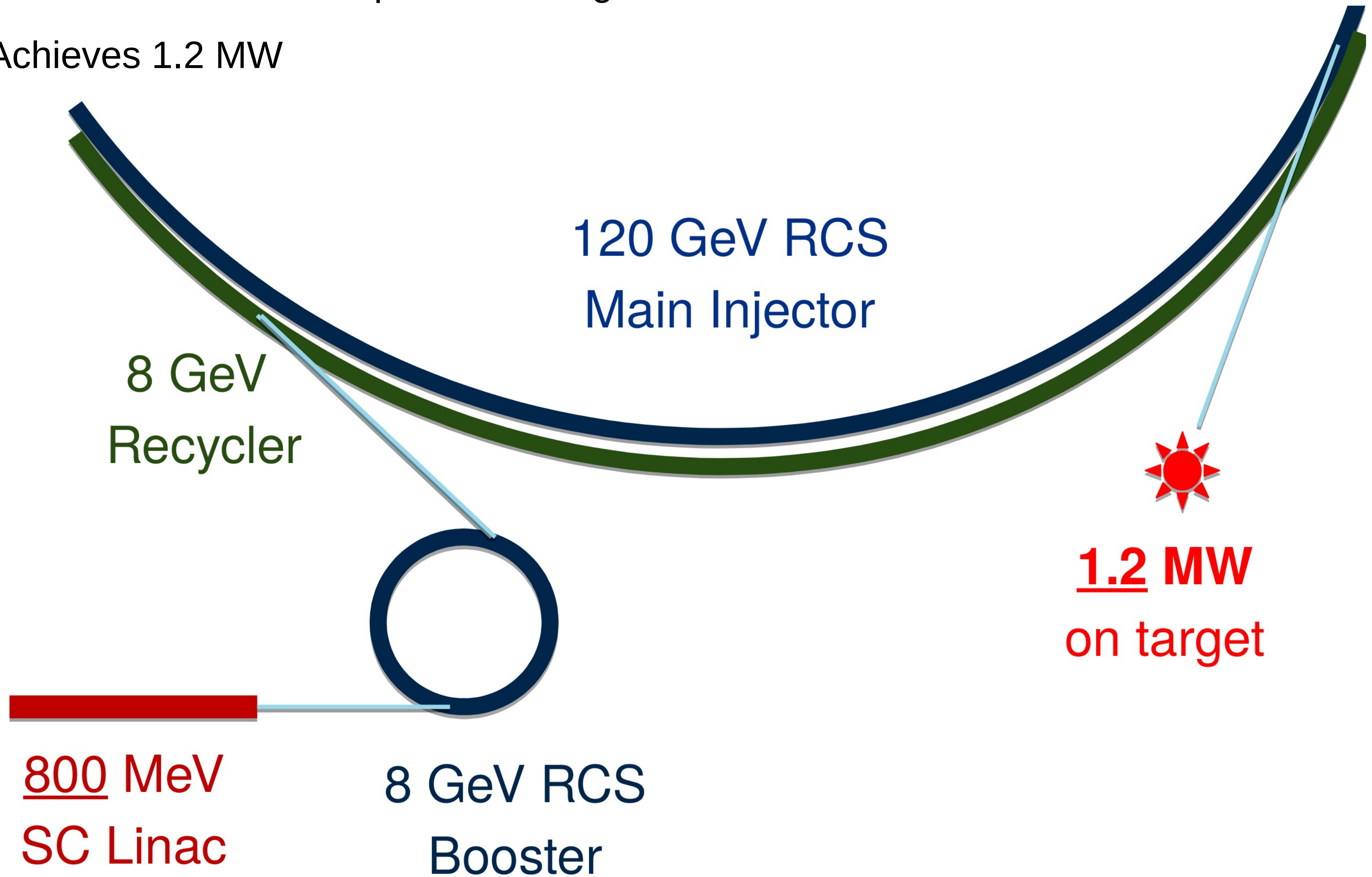
Path to MW Beam Power at Fermilab

- Current accelerator complex



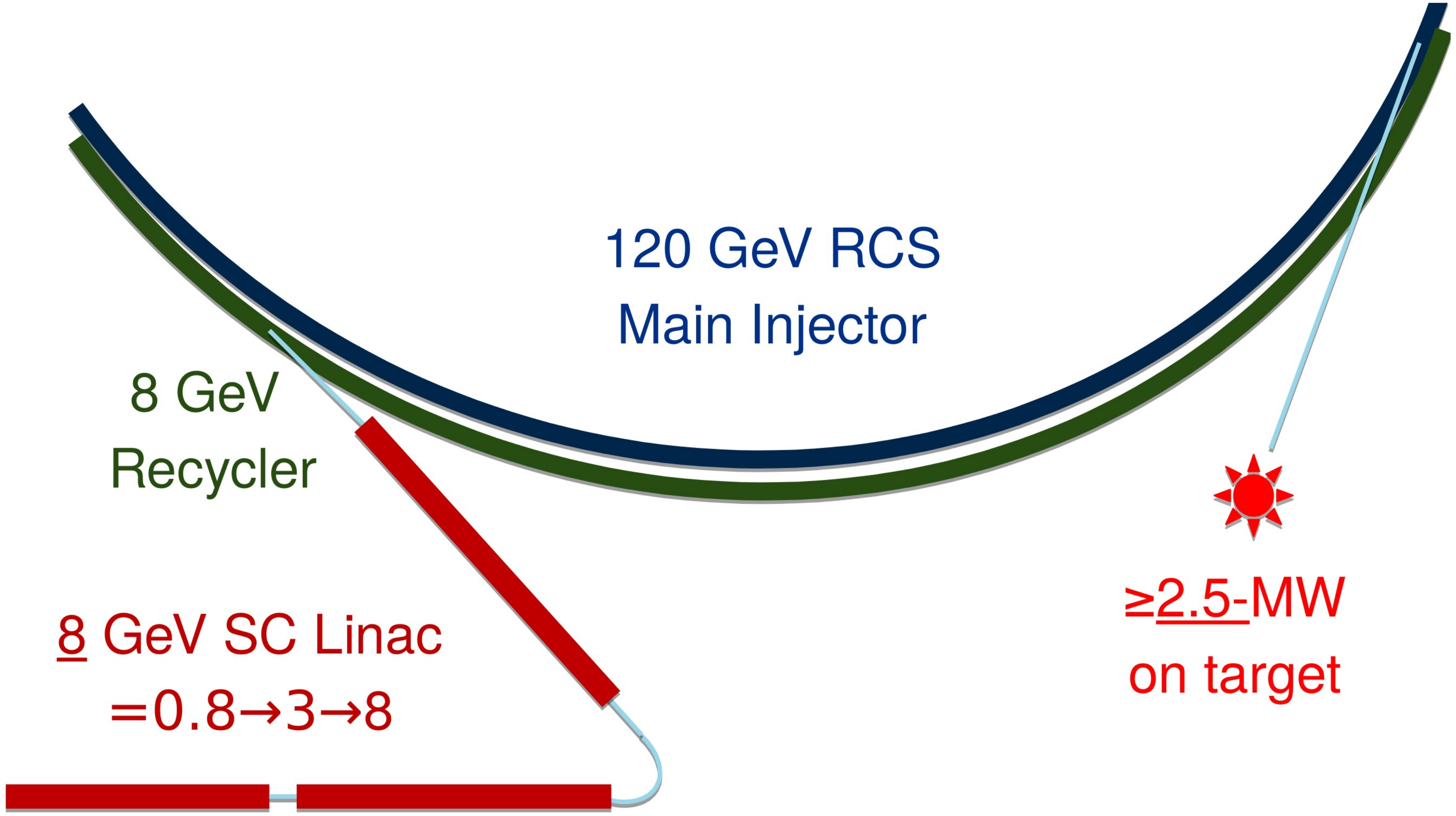
Proton Improvement Plan-II

- PIP-II with 800 MeV superconducting linac
- Achieves 1.2 MW



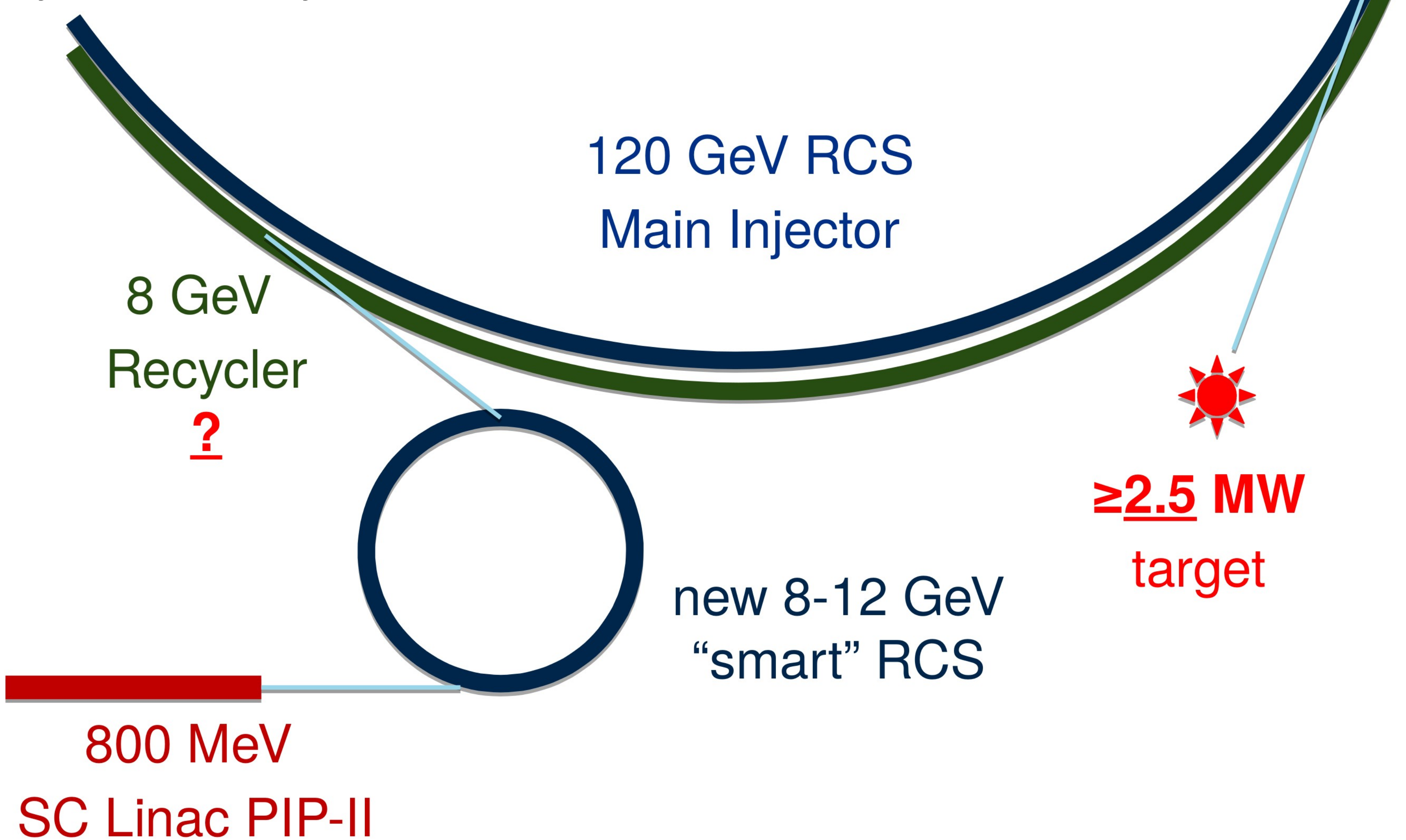
PIP-III Option 1

- PIP-II plus 8 GeV superconducting linac
- Still injected into Recycler



PIP-III Option 2

- PIP-II plus 8-12 GeV Rapid Cycling Synchrotron
- May not need Recycler



FAST

- Fermilab’s Accelerator Science and Technology (FAST) facility home to Integrable Optics Test Accelerator
- Purpose of FAST is to
  - Study physics of high brightness beams
  - Develop high intensity accelerators for particle physics (one of three major experimental activities toward producing multi-MW beams at Fermilab)
- FAST/IOTA will be home to 300 MeV electron beam, 2.5 MeV proton beam, and storage ring to host experiments

Integrable Optics Test Accelerator

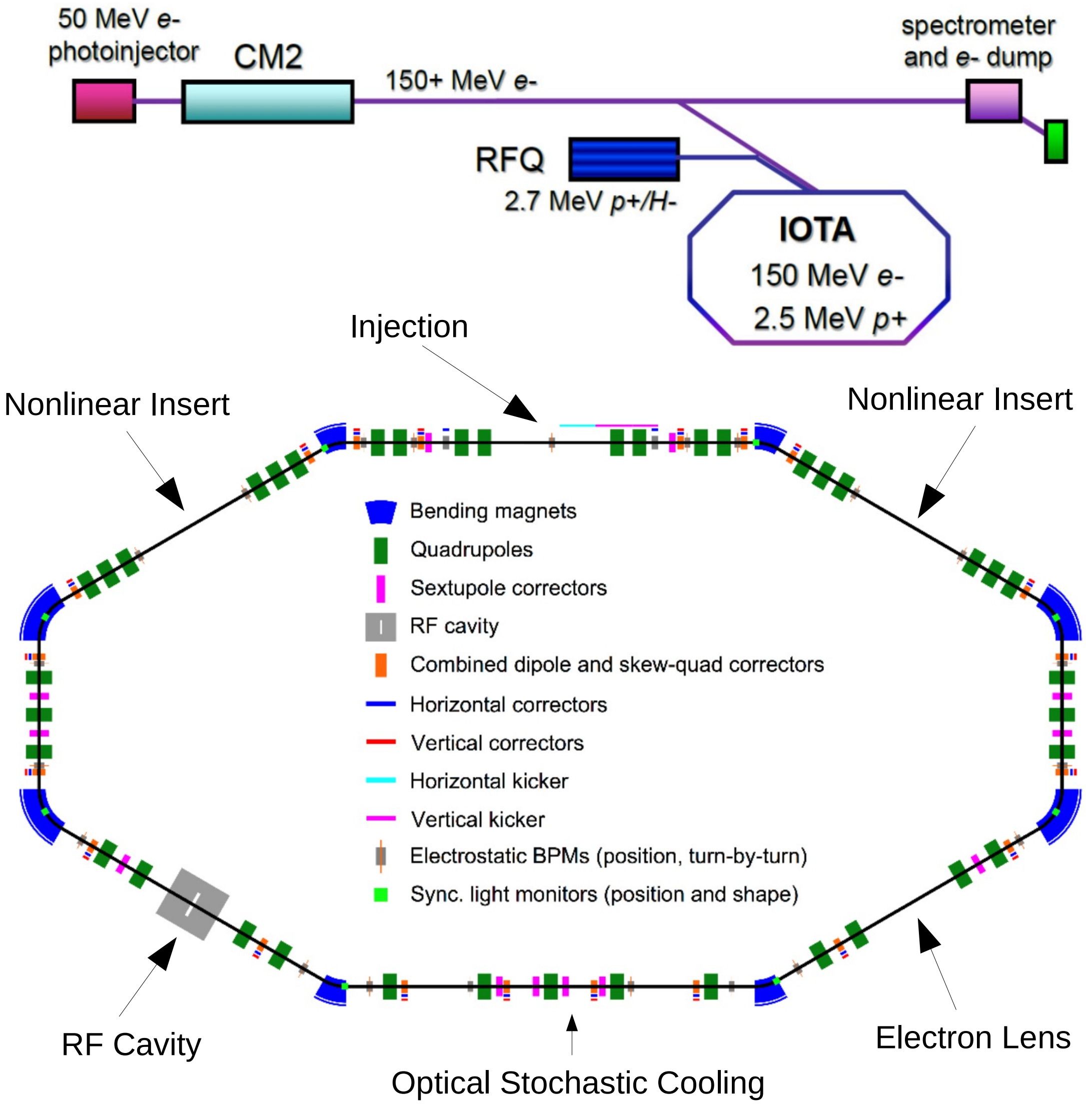
- IOTA Experimental program highlights include:

1) Demonstrating techniques to build accelerators that are strongly nonlinear yet stable
   - Achieve large tune spreads (~0.25) without loss of dynamic aperture
2) Exploration of features of space charge dynamics in rings and effect of nonlinear integrable optics
   - Beam halo formation, space charge compensation
3) Observation of optical stochastic cooling
4) Electron cooling

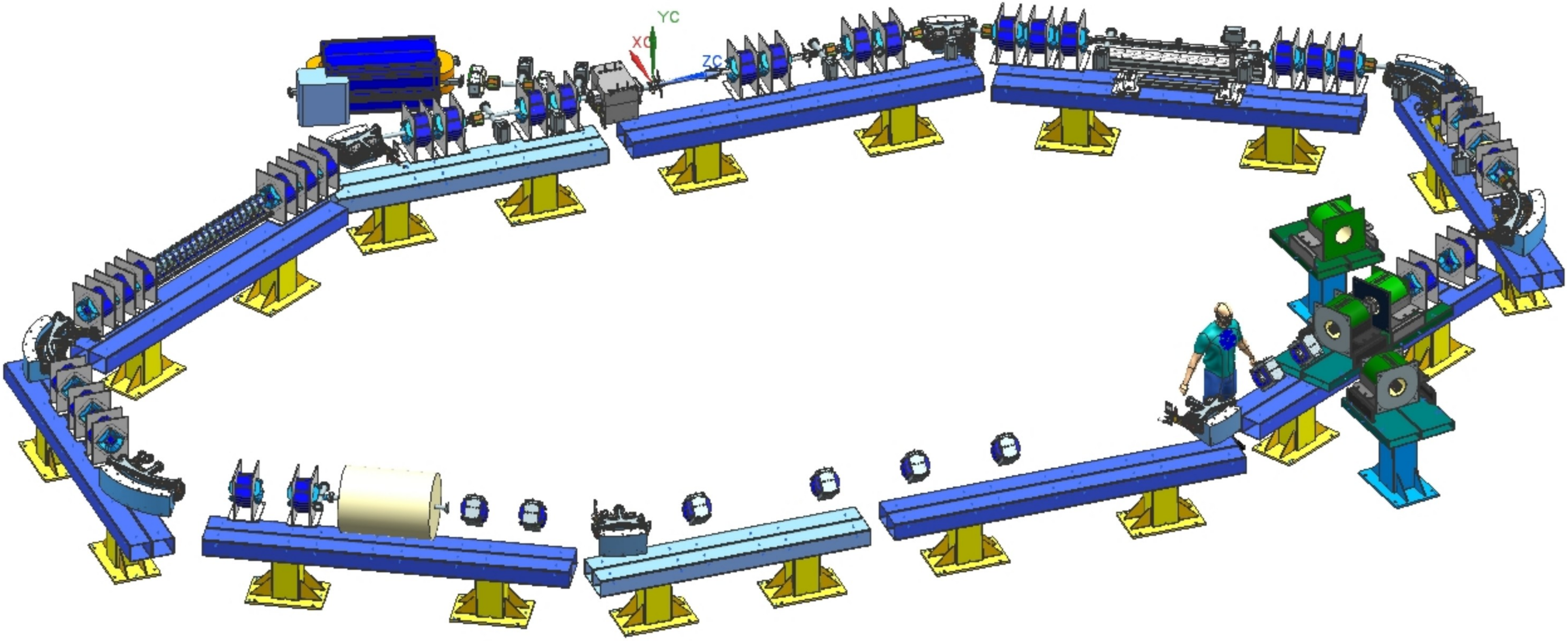
- Initial experiments with low charge electron bunches emulate single particle dynamics with negligible space charge
- Later experiments with high charge, low energy protons emulate collective effects with space charge

IOTA Lattice

- Injection for electrons or protons
- Experiments fit in long straight sections
  - One or two nonlinear inserts
  - Nonlinear electron lens
  - Space charge compensation
  - Optical stochastic cooling
- RF cavity provides proton bunches and replaces electron energy lost to synchrotron radiation



IOTA 3D



Beam Parameters

Parameter	Electrons	Protons	Units
Circumference	40		m
Revolution period	0.133	1.83	μs
Experimental straight sections	4 (3)		
Kinetic energy	150	2.5	MeV
Vacuum	300	6	10^{-10} torr
Beam lifetime (time)	30	5	min
Beam lifetime (turns)	13.5	0.169	10^9 rev
Beam current	2.4	8	mA
Number of particles	2	90	10^9
Beam size, x, y	0.6, 0.4	6, 4	mm
Bunch length	0.0108	1.7	m
Bunching frequency	Single bunch	2.18	MHz
Space charge tune shift (unbunched, bunched)	0	-0.5, -1.2	

IOTA Experimental Program

Integrable Optics History

- Search for stable solutions that are strongly nonlinear
  - Orlov (1963)
  - McMillan (1967) – 1D solution
  - Perevedentsev & Danilov (1990) – generalization of McMillan case to 2D, required non-Laplacian potentials
    - VEPP-2000 at BINP demonstrated record beam-beam tune shift of ~0.25 in 2013 using round colliding beams with 1 invariant
  - Chow & Cary (1994)
  - Danilov & Nagaitsev (2010) – Solution for nonlinear lattice with two invariants of motion possible with Laplacian potential (special magnets), PRSTAB 13, 084002
    - To be experimentally verified in IOTA

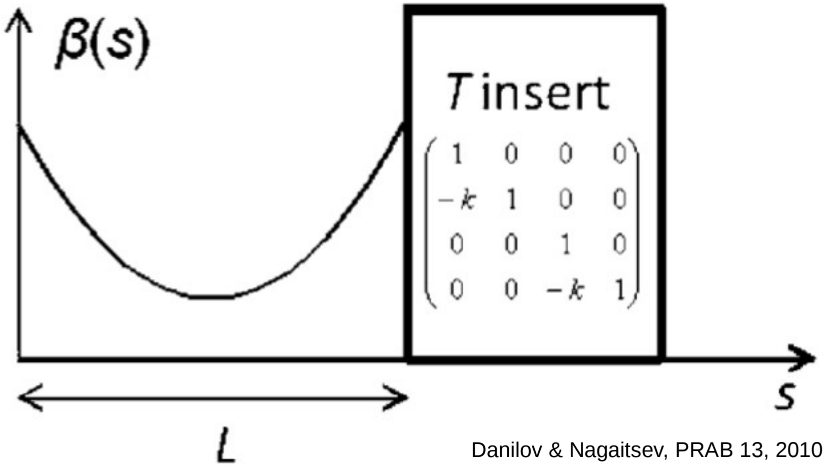
Perturbed Hamiltonian

- For a perturbed Hamiltonian system

$$H = h(J_1, J_2) + \epsilon q(J_1, J_2, \theta_1, \theta_2)$$

h, q are analytic functions and ε is a small perturbation

- Under special conditions on h, the system remains stable for exponentially long time
  - Functions h satisfying this condition "steep" functions
- One steep function (Hamiltonian) being implemented in IOTA
  1) Drift of length L with $\beta_x = \beta_y$
  2) Optics insert, T, with transfer matrix that of thin axially symmetric lens



Danilov & Nagaitsev, PRAB 13, 2010

Nonlinear Integrable Optics (IO)

- Nonlinearities with zero resonance strength are called “integrable” = having a sufficient number of conserved quantities (i.e. integrals of motion)
- 2-D system, such as transverse focusing, requires two integrals of motion
- Possible to construct nonlinear dynamic system with two integrals of motion by introducing additional transverse magnetic field along drift
  - Potential satisfies Laplace equation → can be implemented with conventional electromagnet

$\psi' = 1/\beta(s)$

- First integral of motion: time independent Hamiltonian (for time independent choice of potential)
- Second integral of motion is quadratic function of momenta

$$H = \frac{p_x^2 + p_y^2}{2} + \frac{x^2 + y^2}{2} + \beta(\psi) V\left(x\sqrt{\beta(\psi)}, y\sqrt{\beta(\psi)}, s(\psi)\right)$$

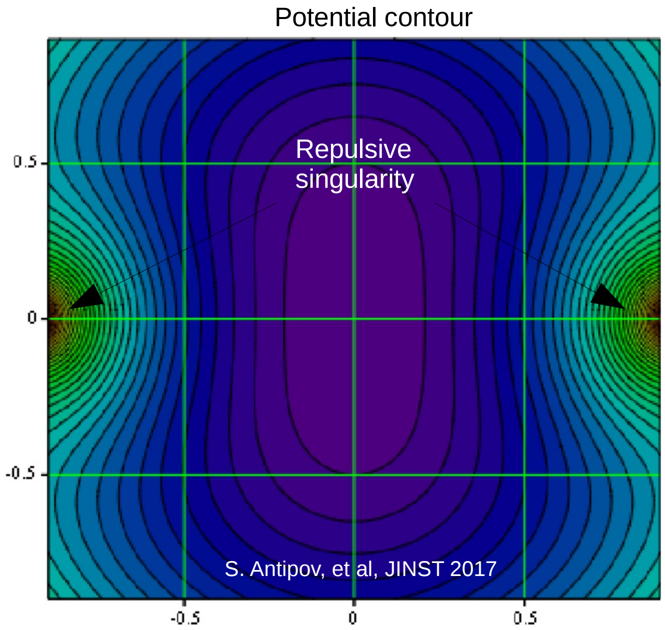
$$I = (x p_x - y p_y)^2 + c^2 p_x^2 + \frac{2c^2 t \xi \eta}{\xi^2 - \eta^2}\left(\eta\sqrt{\xi^2-1}\cosh(\xi)^{-1} + \xi\sqrt{\eta^2-1}\left(\frac{\pi}{2} + \cosh(\eta)^{-1}\right)\right)$$

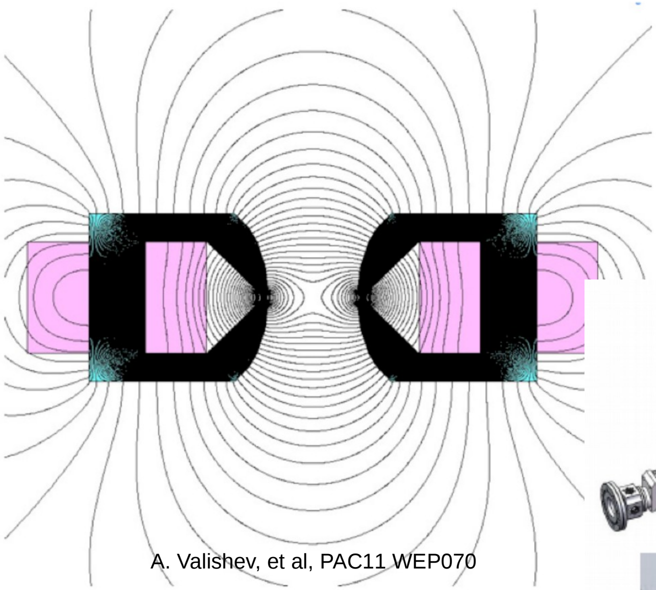
$$\xi = \frac{\sqrt{(x+c)^2+y^2} + \sqrt{(x-c)^2+y^2}}{2c} \qquad \eta = \frac{\sqrt{(x+c)^2+y^2} - \sqrt{(x-c)^2+y^2}}{2c}$$

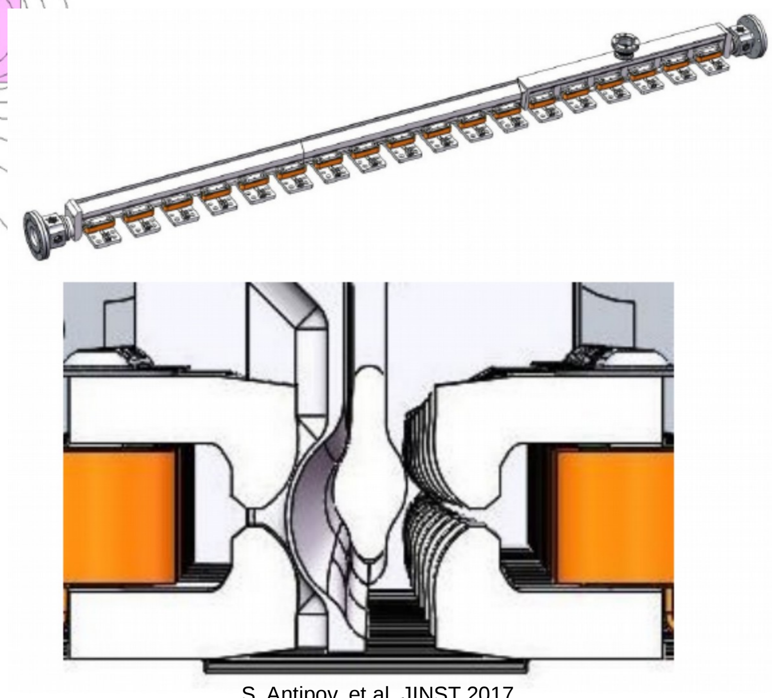
t, c arb. const.

Nonlinear Magnet

- Hamiltonian time independence requires nonlinear potential must continuously change along length of nonlinear section
- Potential dependent on strength parameter, t, and geometric parameter, c



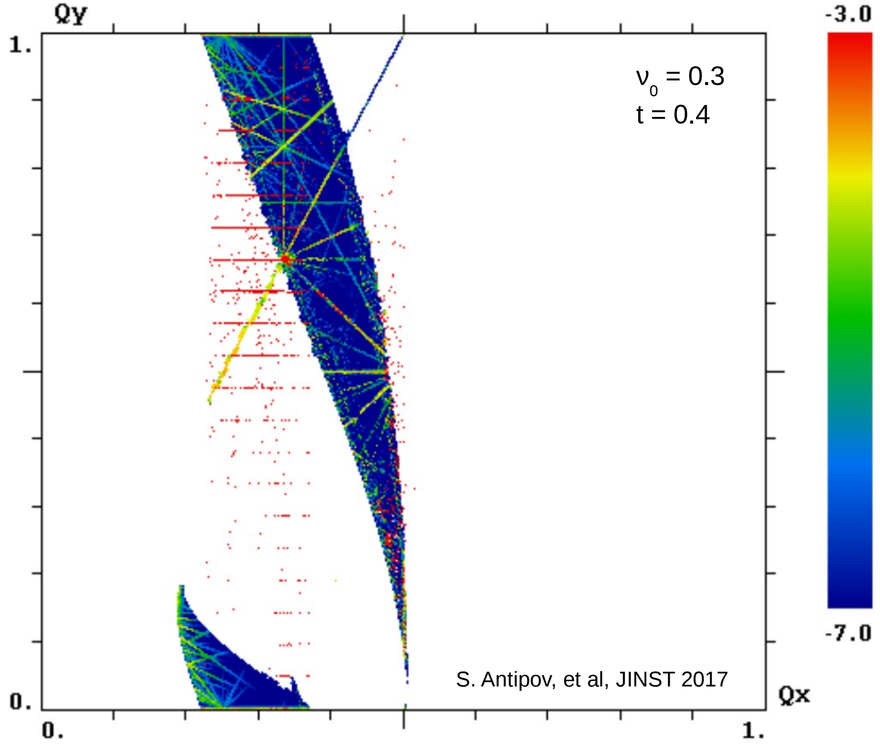




- Continuously varying potential approximated by 18 thin magnets
- IOTA nonlinear insert 1.8 m long, c varies from 8-14 mm, horizontal beam pipe aperture 12-21 mm

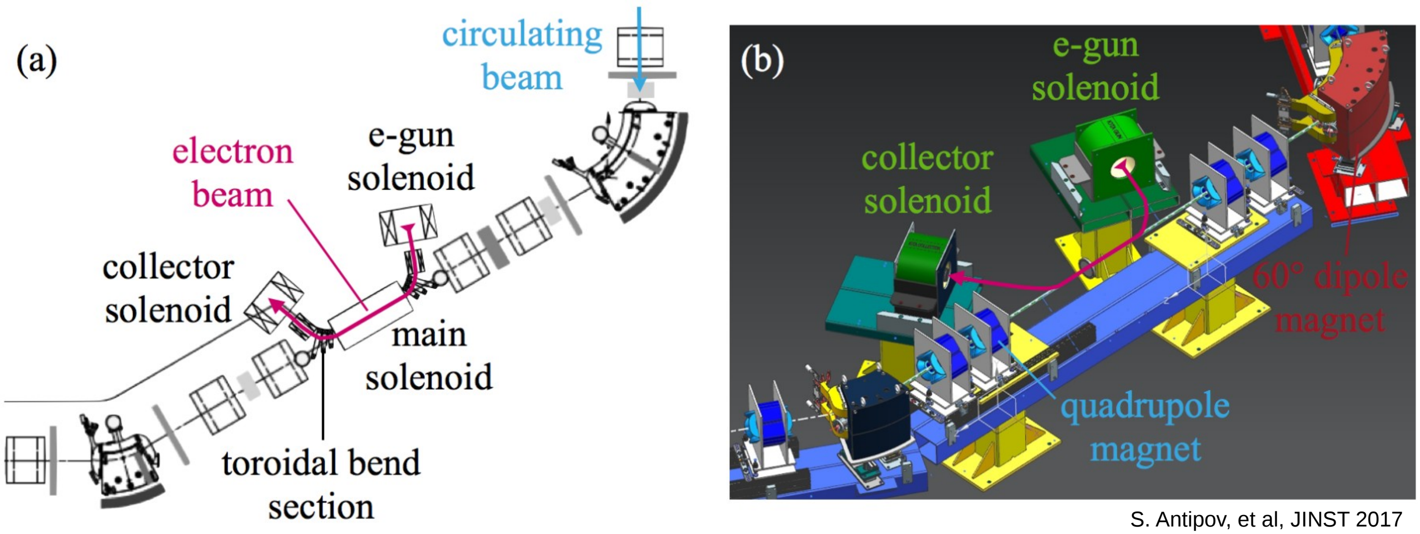
Tune Spread

- Simulations with single and multi particle tracking codes done to determine achievable tune spread in machine built using such magnets
  - Imperfections taken into consideration (no space charge)
- Tune footprint shows achievable vertical tune spread exceeding 1 using four nonlinear elements (cells)
- In IOTA, only 1 cell tested (0.25 max.)



IO with Nonlinear Electron Lens

- In IOTA, electron beam generated by thermionic cathode, confined and transported by axial magnetic fields, finally steered into collector
- As nonlinear element, provide tunable transverse kick dependent on betatron amplitude



S. Antipov, et al, JINST 2017

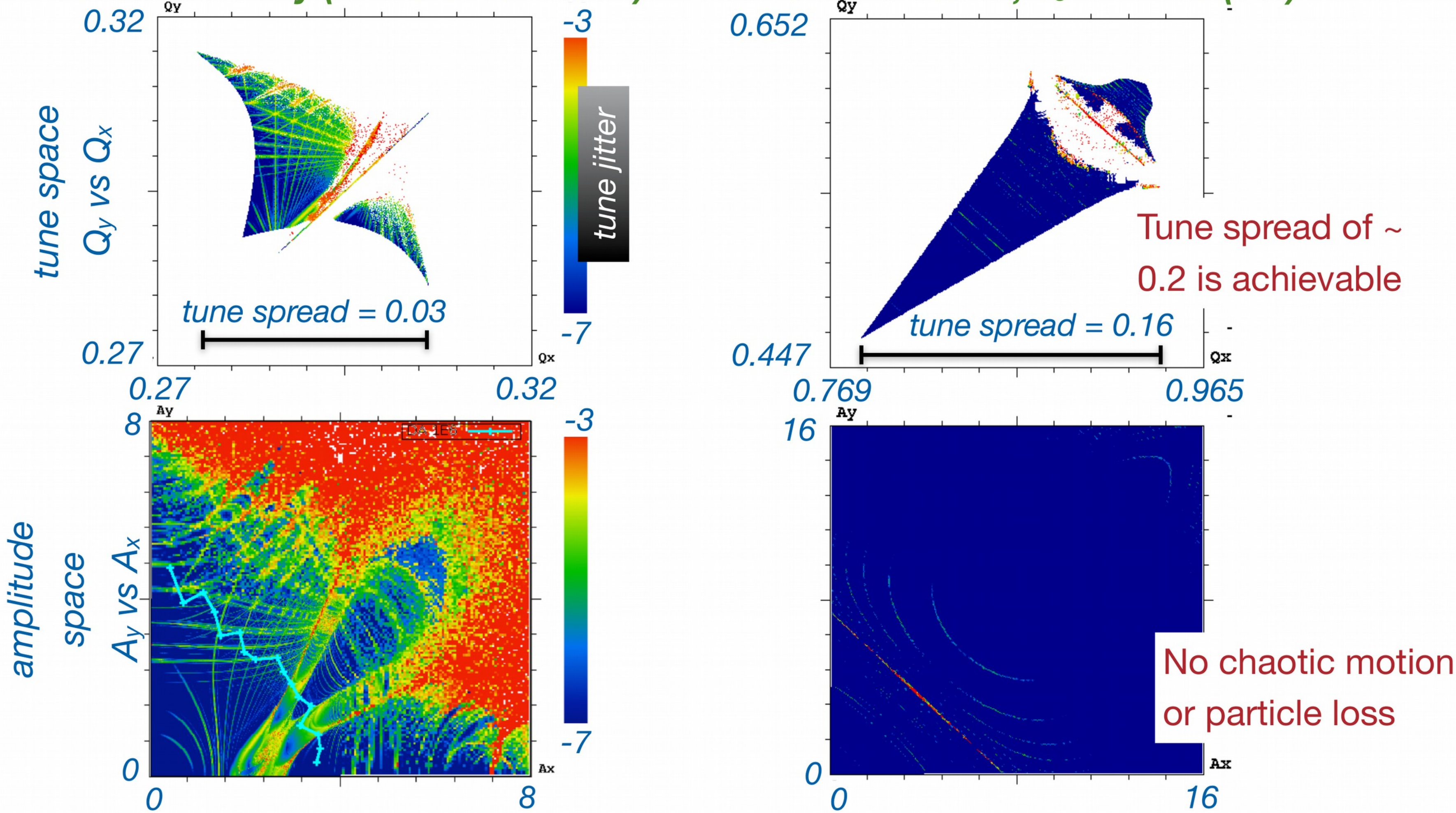
- Two applications of electron lenses for nonlinear integrable optics
  - McMillan type thin radial kick, $\Delta\nu \sim \beta_{x,y} k_e / 4\pi$

    k_e = focusing strength
  - Thick axially symmetric kick, $\Delta\nu \sim L/(2\pi\beta_{x,y})$

Frequency maps: conventional vs. nonlinear integrable

example of conventional machine with nonlinearity (beam-beam force)

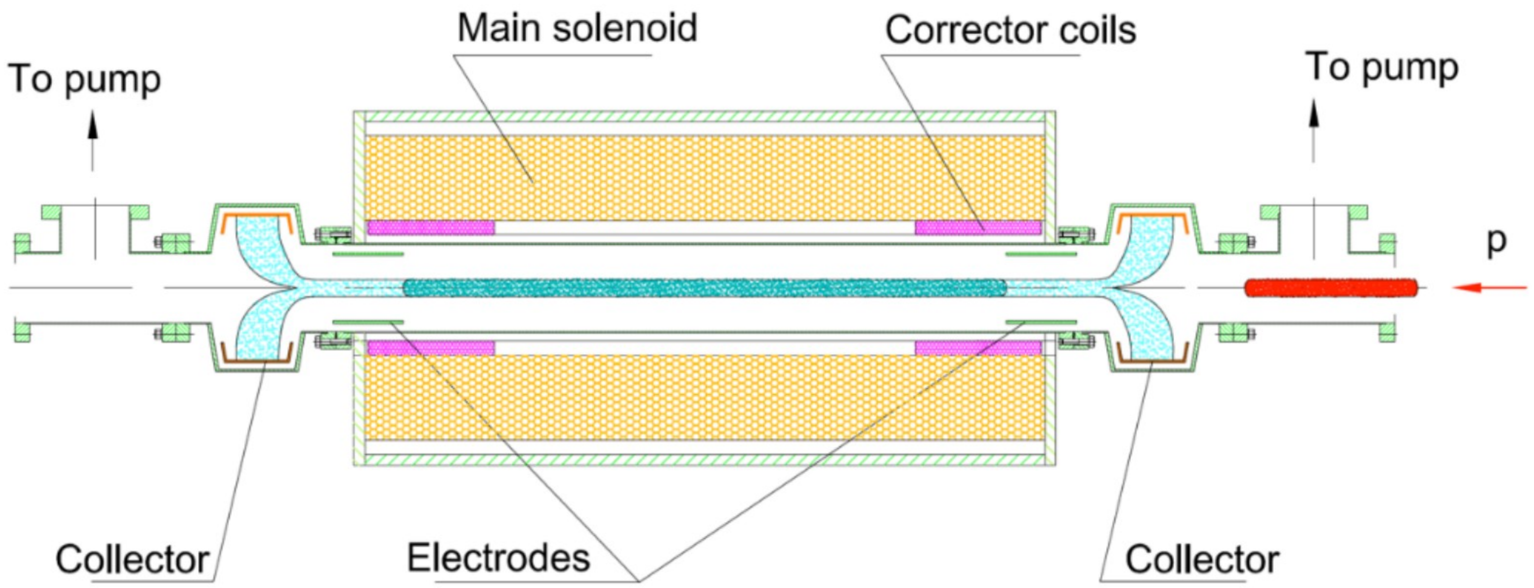
IOTA with nonlinear electron lens in 0.7-m solenoid, k_e = 0.6 /m (1 A)



Resonance overlap, restricted dynamic aperture

SCC with Electron Column

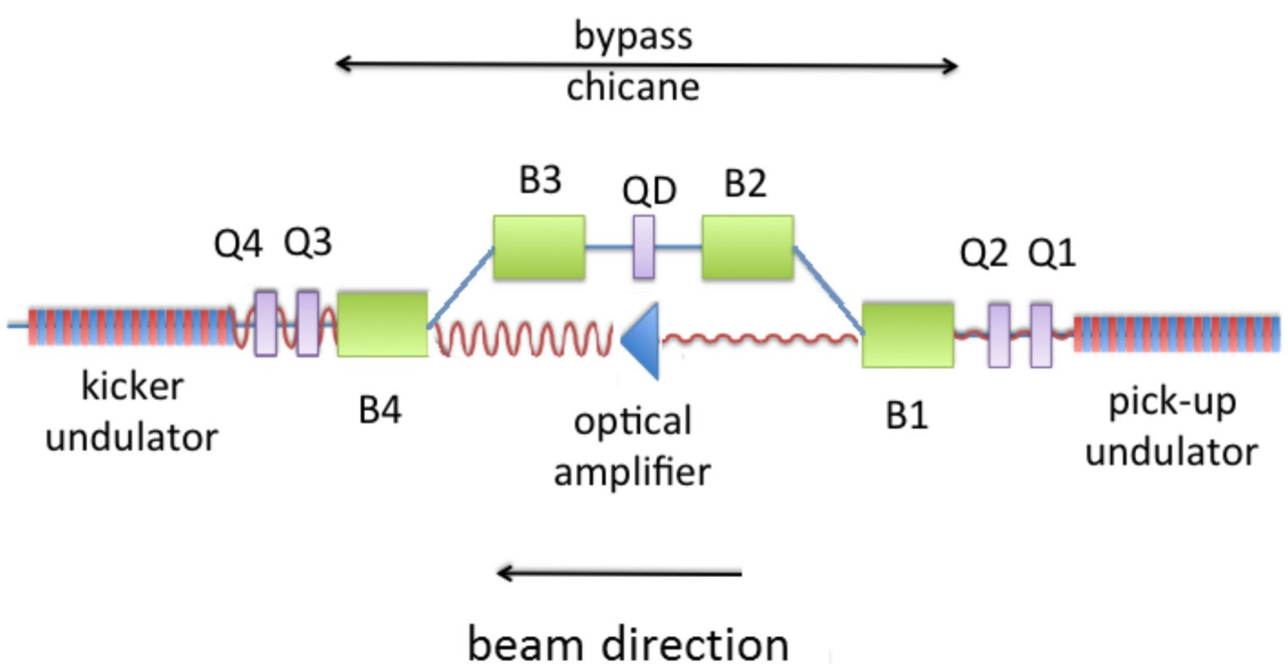
- Proton beam ionizes gas within the interaction region
- Plasma electrons are confined with solenoidal magnetic field and electrodes
- Gas density, magnetic field and electric field strength tuned to create appropriate electron distribution
  - Match transverse profile to that of beam
- As opposed to SCC with electron lens, electron column does not require external source of electrons or transport system



C.S. Park, NAPAC'16

Optical Stochastic Cooling

- Stochastic cooling rate determined by signal acquisition
  - Traditionally 1 – 10 GHz
  - Operating in the optical range (~100 THz) allows increase of cooling bandwidth by orders of magnitude
- Beam send through undulator and emits radiation (pickup)
  - OSC only works for relativistic particles due to frequency of emitted light
- Radiation amplified in optical amplifier and used to kick same bunch in second undulator (kicker)
- Chicane allows for simultaneous arrival of beam and amplified radiation



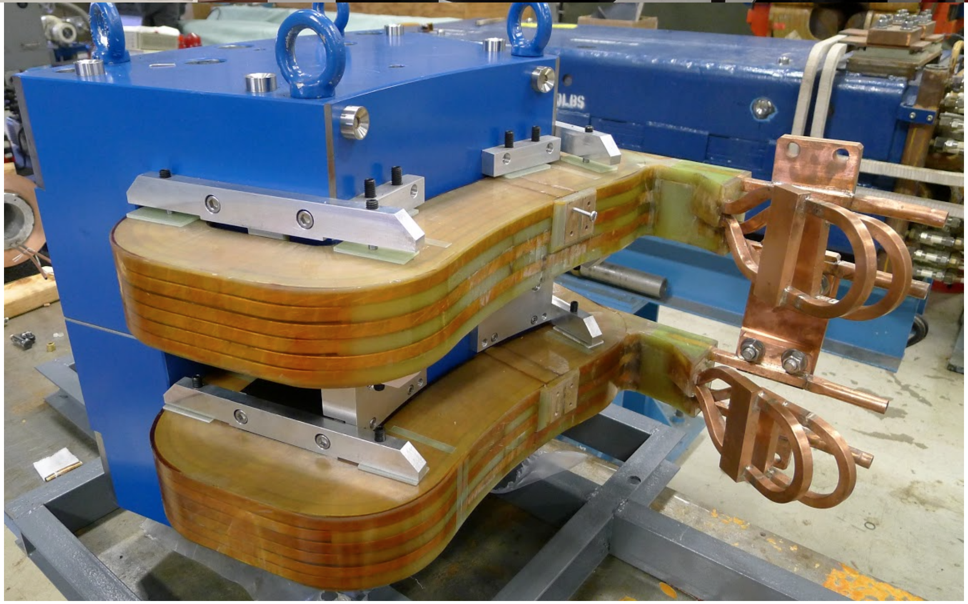
Electron Cooling of Protons in IOTA

- Extends range of beam emittances (brightness) for SCC experiments
- Provides beam diagnostics downstream of electron lens through spontaneous recombination
- *Allows the question of whether limitations on electron cooling from space charge tune spreads and instabilities are alleviated by nonlinear integrable optics to be investigated*
- Cooling rates of about 20 ms are expected, leading to reduction of transverse emittance and increase in space charge tune shift by about a factor of 10

Parameter	Value	Units
Kinetic energy	2.5	MeV
β (relativistic)	0.073	
Number of particles	5×10^{9}	
Beam current	0.44	mA
Normalized RMS emittance	0.3 → 0.03	μm
RMS beam size at cooler	4 → 1.3	mm
Relative momentum spread	5×10^{-4}	
Space charge tune shift	-0.028 → -0.28	
Transverse temperature (avg.)	5 → 0.5	eV
Longitudinal temperature	0.6	eV

Schedule

- Commissioning of 300 MeV electron beamline imminent
  - ~2 month experimental program planned
- IOTA installation begun, expected completion of ring summer 2018
- Electron experiments 2018-2019
- Proton experiments 2019-2020



Outlook

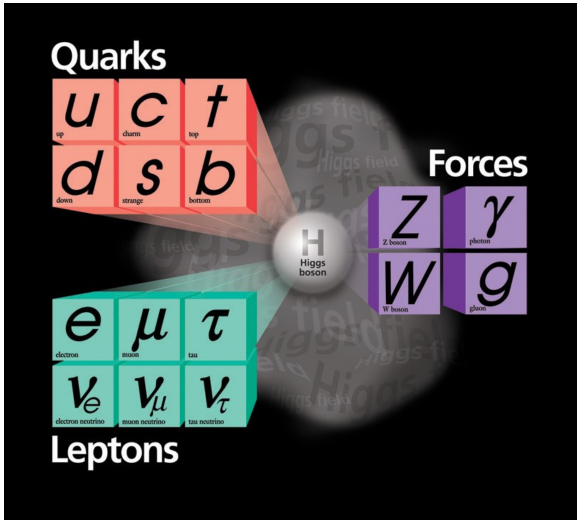
- IOTA offers a diverse physics program aimed at increasing beam intensity for future proton rings 3-5x
  - Demonstration of nonlinear, stable systems with tune shifts ~0.25
  - Investigate space charge dynamics in rings
- Techniques investigated in IOTA should prove invaluable for meeting the physics requirements of DUNE in a reasonable amount of time
- IOTA presents an excellent opportunity for training young accelerator scientists

Thank you for your attention!

Backup Slides

Neutrinos

- Weakly interacting
- Have mass (< 1 eV)



- Flavor eigenstates related to mass eigenstates through Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
  - Neutrinos oscillate

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta}\\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}\\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$c_{ij}\equiv\cos\theta_{ij}\,,\ s_{ij}\equiv\sin\theta_{ij}$

- Probability of observing conversion between two flavor eigenstates

$$P_{\nu_e\rightarrow\nu_\mu}=\left\{\sin(2\theta)\sin\left[\frac{((m_2^2-m_1^2)c^3)}{(4\hbar E)}z\right]\right\}^2$$

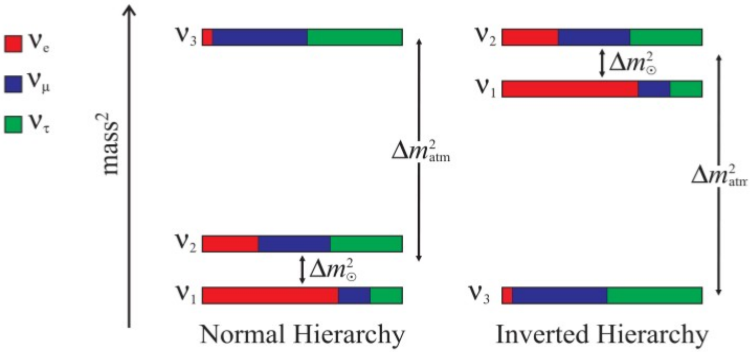
(two neutrino species)

Parameter	Best Fit	Units	Acc. (%)
$\sin^2\theta_{12}$	0.297		5.8
$\sin^2\theta_{13}$	0.0214		4.7
$\sin^2\theta_{23}$	0.437		9.0
δm^2	7.37×10^{-5}	eV^2	2.4
$\lvert\Delta m^2\rvert$	2.5×10^{-3}	eV^2	1.8
δ	1.35	π	

$\delta m^2 = m_2^2 - m_1^2$

$|\Delta m^2| = m_3^2 - (m_1^2 + m_2^2)/2$

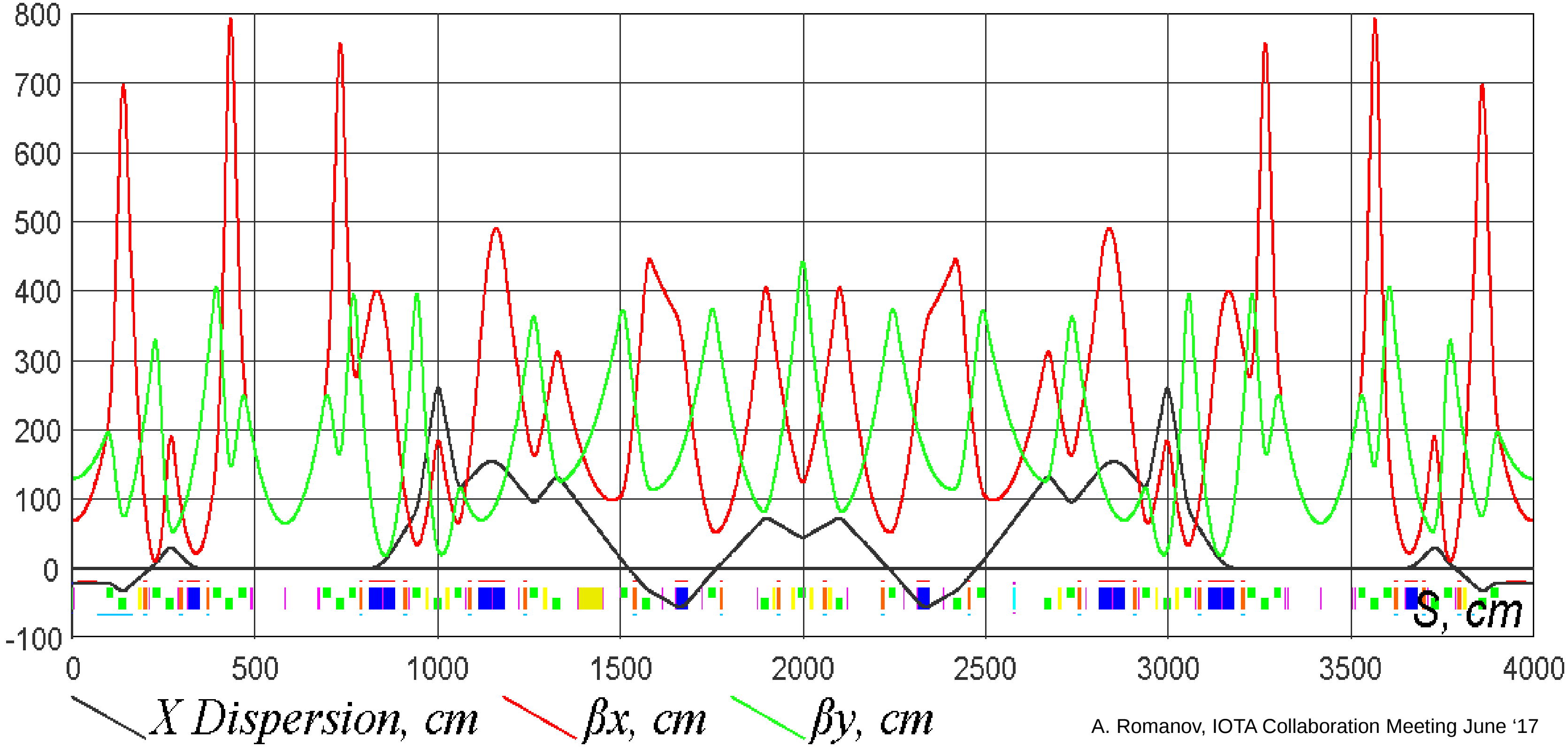
- m_3 either larger or smaller than m_1 & m_2



F. Capozzi, Nucl. Phys. B, 908 (2016)

IOTA Beta Functions

- 1 Nonlinear insert
- Same for electrons and protons



Other Machines

- What about machines such as the Spallation Neutron Source (SNS) or Japan Proton Accelerator Research Complex (J-PARC)?
  - Achieve MW beam power and 0.25 tune spread
  - Costly:
    - Large aperture ceramic beam pipe at J-PARC
    - Phase space “painting” possible at SNS due to large acceptance
- Integrable optics provides a method for achieving large tune spread with small acceptance/aperture (e.g. FNAL Booster, which is 1/10 that of SNS and J-PARC)
  - Significant cost reduction

Beam – Lens Interaction

- Beam experiences linear focusing strength

$$k_e = 2\pi \frac{j_0 L\left(1 \pm \beta_e \beta_z\right)}{\left(B\rho\right)\beta_e \beta_z c^2}$$

j_0 = electron current density
L = lens length
β_e = electron v/c
β_z = beam v/c
Bρ = magnetic rigidity

- Tune shift for small strengths (away from half integer resonances)

$$\Delta\nu = \frac{\beta_{x,y} k_e}{4\pi} = \frac{\beta_{x,y} j_0 L\left(1 \pm \beta_e \beta_z\right)}{2\left(B\rho\right)\beta_e \beta_z c^2}$$

$\beta_{x,y}$ = transverse beta functions

McMillan Type Thin Radial Kick

- Electron lens must have specific current density distribution

$$j(r) = j_0 \frac{a^4}{\left(r^2+a^2\right)^2}$$

a = effective lens radius

- Circulating beam experiences nonlinear transverse kick

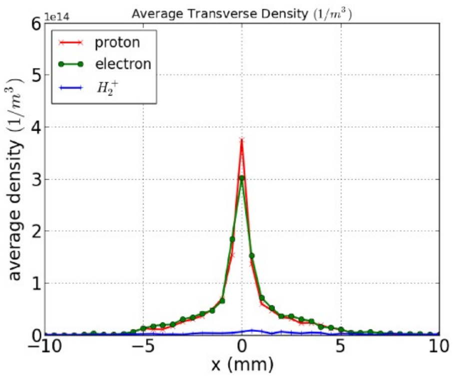
$$\theta(r) = k_e r \frac{a^2}{r^2+a^2}$$

- Two independent invariants of motion if element is thin (L « $\beta_{x,y}$) and betatron phase advance near an odd multiple of π/2
  - Particle trajectories are regular and bounded (neglecting longitudinal effects)
- Achieving and preserving desired current density profile very important
- Achievable tune spread ~ $\beta_{x,y} k_e / 4\pi$

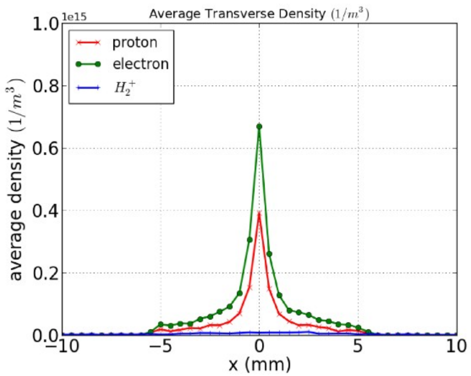
Axially Symmetric Thick Lens Kick

- Relies on section of ring with constant and equal beta functions
  - Achievable with solenoid axial field $B_z = 2(B\rho)/\beta_{x,y}$
  - Same field also confines electrons in lens
- Axially symmetric current distribution conserves Hamiltonian and longitudinal component of angular momentum as long as betatron phase advance is an integer multiple of π
- Achievable tune spread ~ $L/(2\pi\beta_{x,y})$
  - Long solenoids and small beta functions beneficial
  - Insensitive to current density distribution (as opposed to McMillan lens)
  - Smaller achievable tune spread, but more robust than McMillan lens

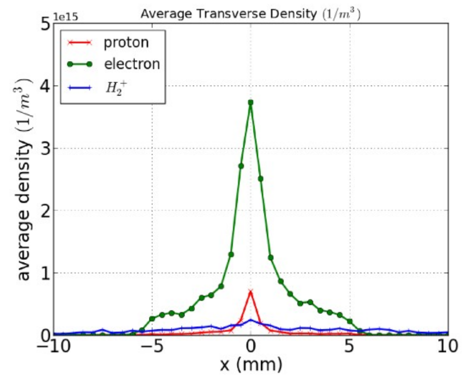
Parameter Optimization



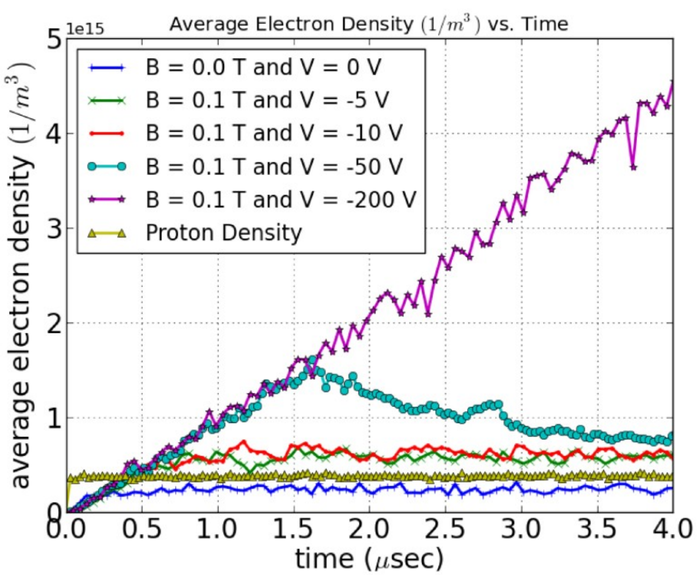
(a) $B = 0.0\ T$ and $V = 0.0\ V$



(b) $B = 0.1\ T$ and $V = -5.0\ V$

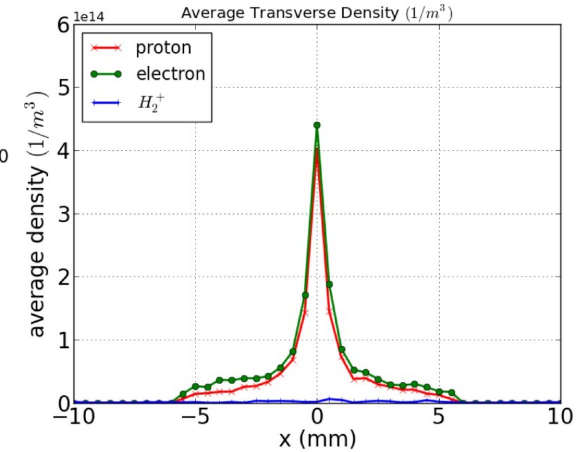


(c) $B = 0.1\ T$ and $V = -200.0\ V$

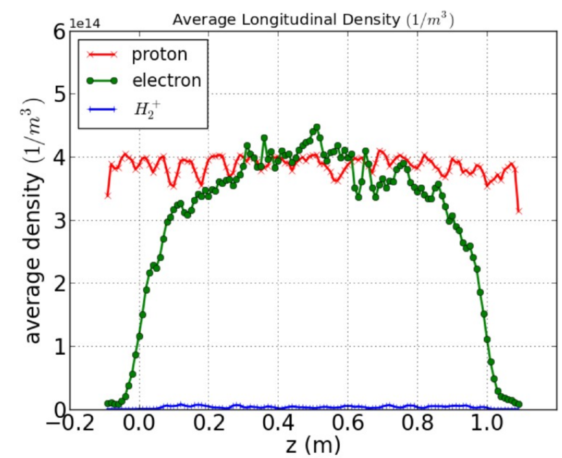


C.S. Park, NAPAC'16

- Simulations done to determine optimal values for gas density, magnetic field, and electrode voltage
- Electron and proton transverse profiles match well for
  - B = 0.1 T
  - V = -5.0 V
  - P = 5×10^{-4} torr (rest of ring 6×10^{-10} torr)



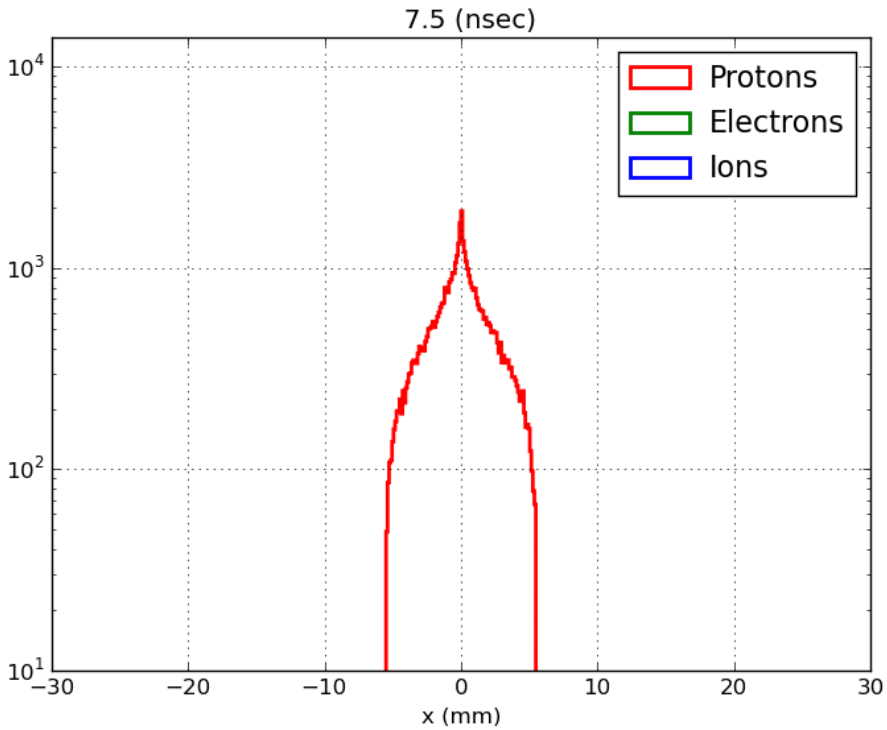
(a) Transverse density profile

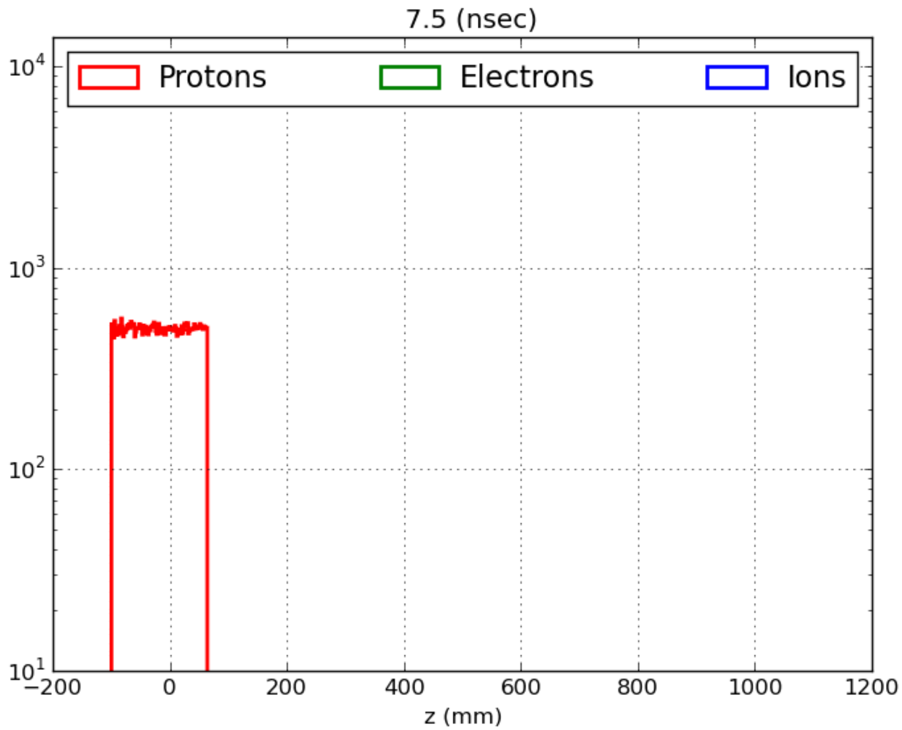


(b) Longitudinal density profile

Recirculating Bunched Beam

- Simulations underway to determine effect of recirculating, bunched beam
- Below animation represents single bunch passage (100 ns) for ~ 1 μs total
- Effect of column on beam to be investigated





OSC Cooling Rates

- Particle passing through chicane receives a s position dependent correction in relative momentum

$$\delta p/p = -\xi_0 \sin(k \Delta s)$$

$k = 2\pi/\lambda$

- Particle displacement on way from pickup to kicker, relative to reference particle (0 displacement and 0 kick)

$$\Delta s = M_{51} x + M_{52} \theta_x + M_{56} (\Delta p/p)$$

M_{5n} = elements of 6x6 transfer matrix
x = particle coordinate
θ_x = particle angle
Δp/p = relative momentum deviation in pickup

- Partial slip factor introduced so longitudinal displacement for particle without betatron oscillations and with momentum deviation Δp/p, relative to reference particle is $\widetilde{M}_{56}\, \Delta p/p$

$$\widetilde{M}_{56} = M_{51} D_p + M_{52} D_p' + M_{56}$$

D = dispersion
D' = derivative in pickup

- Horizontal and vertical cooling rates per turn (for small amplitude oscillations)

$$\begin{bmatrix} \lambda_x \\ \lambda_s \end{bmatrix} = \frac{k \xi_0}{2} \begin{bmatrix} M_{56} - \widetilde{M}_{56} \\ \widetilde{M}_{56} \end{bmatrix}$$

OSC Parameters

- Length of OSC experiment approximately 4 m, beam delay of 2 mm
- 2.2 μm optical amplifier, operated at liquid nitrogen temperature to increase thermal conductivity and reduce thermal stress, decrease optical distortion
- Optical system has two identical lenses
  - Focuses beam radiation onto crystal
  - Focuses amplified radiation into wiggler
- OSC damping times 1/10 that of synchrotron radiation times

Parameter	Value	Units
Beam Energy	100	MeV
Tunes, Q_x, Q_y	6.36, 2.36	
Trans. RMS emittance	2.6	nm
RMS momentum spread	1.06×10^{-4}	
Radiation wavelength at 0 angle	2.2	μm
Dipole magnetic field	0.25	T
Dipole length	8	cm
Horizontal beam offset	35.1	mm
Undulator length	77	cm
Distance from undulator center to OA	1.65	m
Amplifier gain (power)	5	
Lens focal length	80	mm
SR damping times, τ_s, τ_x, τ_y	1.7, 2, 1.1	s
OSC damping times, τ_s, τ_x, τ_y	0.1, 0.17, 0.17	s