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The IOTA Ring: Present Status and Plans

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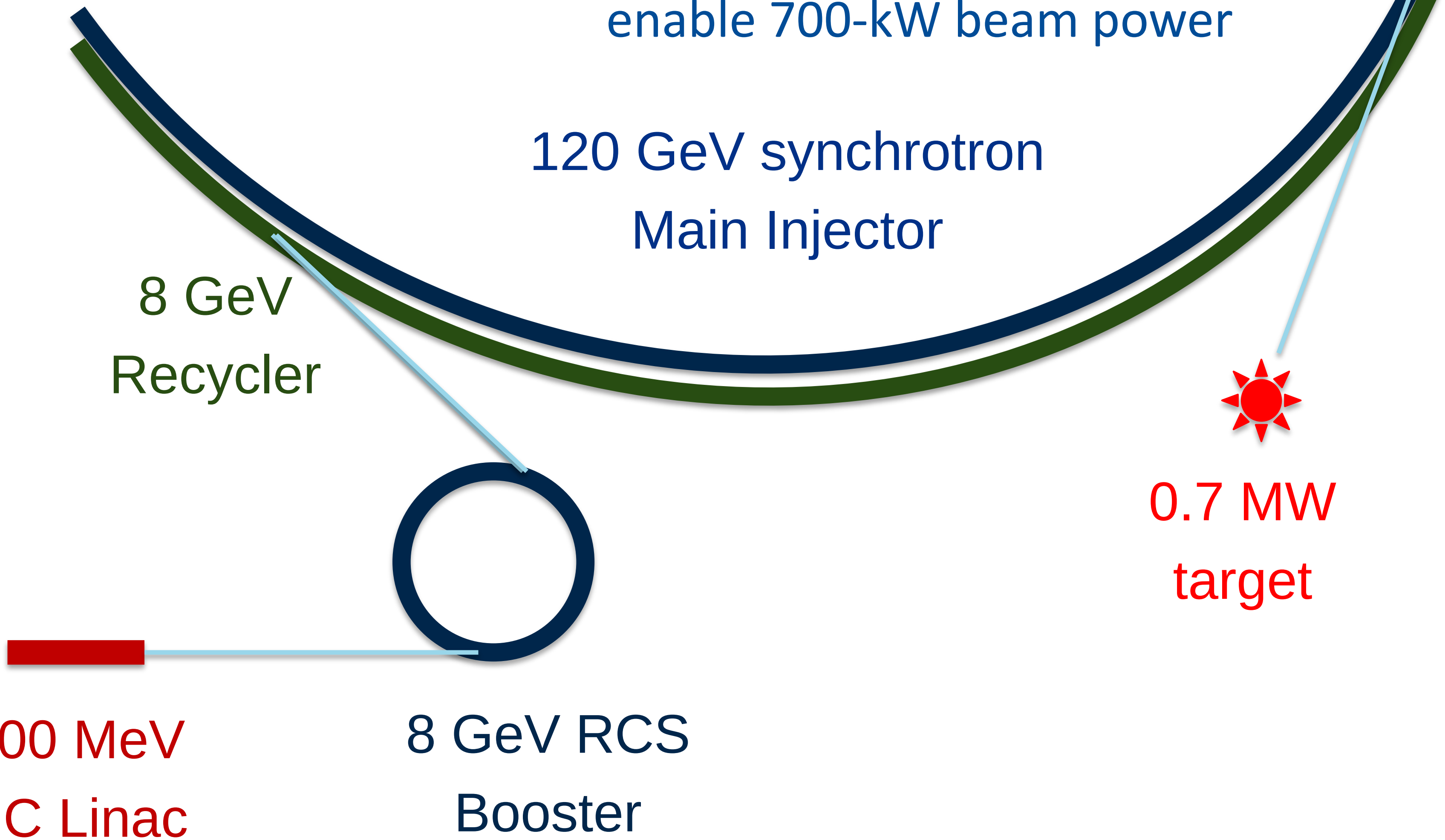
HB2014 East Lansing, MI

11 November 2014

Fermilab 400-kW (now) to 700-kW (2016) complex

Proton Improvement Plan (PIP): increase Booster proton flux, enable 700-kW beam power



Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

The P5 report, May 2014

The enormous physics potential of the LHC, which will be entering a new era with its planned high-luminosity upgrades, will be fully exploited. The U.S. will host a world-leading neutrino program that will have an optimized set of short- and long-baseline neutrino oscillation experiments, and its long-term focus is a reformulated venture referred to here as the Long Baseline Neutrino Facility (LBNF). The Proton Improvement Plan-II (PIP-II) project at Fermilab will provide the needed neutrino physics capability. To meet budget constraints, physics needs, and readiness criteria, large projects are ordered by peak construction time: the Mu2e experiment, the high-luminosity LHC upgrades, and LBNF.

Proton Improvement Plan-II (PIP-II, Fermilab)

- Goal: Provide >1 MW at the time of LBNF startup (~2023)
- 800 MeV superconducting pulsed linac + enhancements to existing complex; extendible to support >2 MW operations and upgradable to continuous wave (CW) operations
  - Builds on significant existing infrastructure
  - Capitalizes on major investment in superconducting rf technologies
  - Eliminates significant operational risks inherent in existing linac
  - Siting consistent with eventual replacement of the Booster as the source of protons for injection into Main Injector
- Whitepaper available at

  projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232

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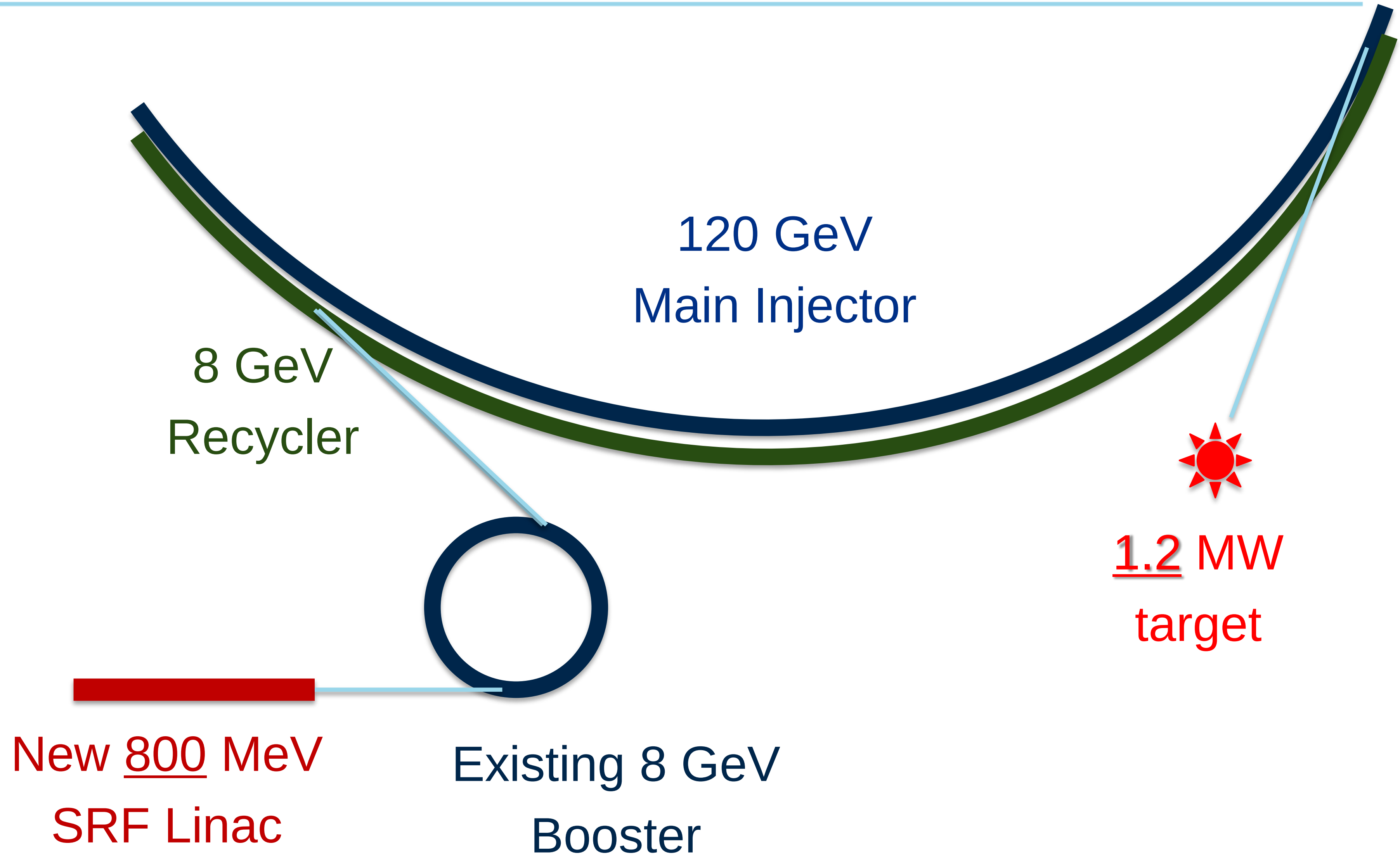
PIP-II schematic



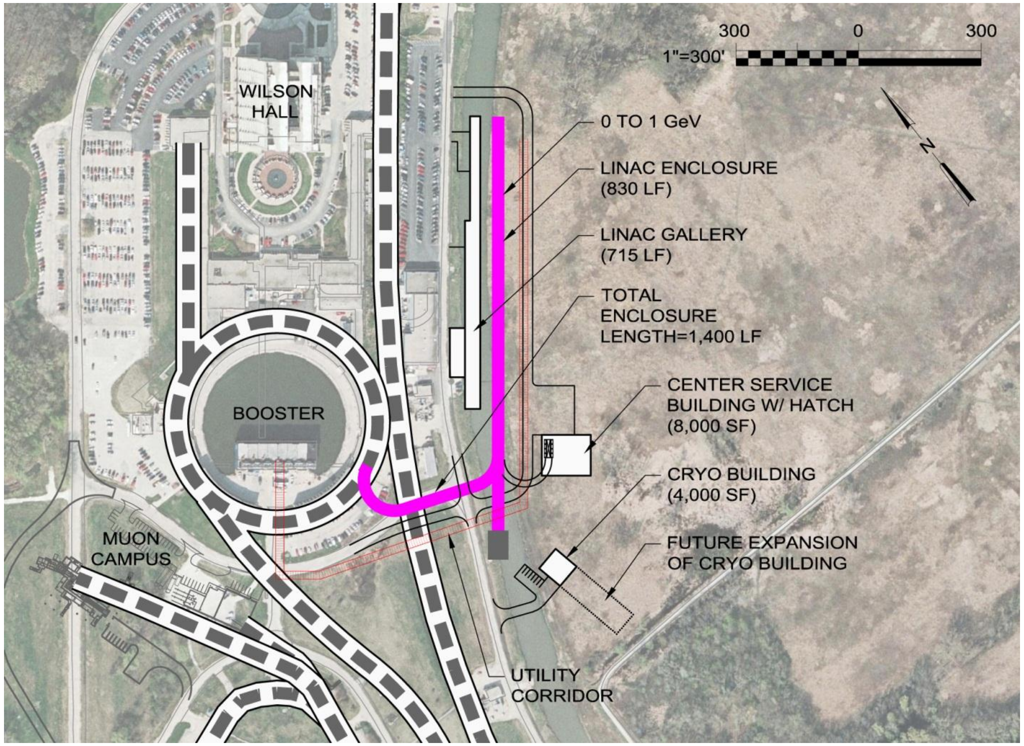
PIP-II Performance Goals

Performance Parameter	PIP-II	
Linac Beam Energy	800	MeV
Linac Beam Current	2	mA
Linac Beam Pulse Length	0.5	msec
Linac Pulse Repetition Rate	20	Hz
Linac Beam Power to Booster	13	kW
Linac Beam Power Capability (@>10% Duty Factor)	~200	kW
Mu2e Upgrade Potential (800 MeV)	>100	kW
Booster Protons per Pulse	6.4×10^{12}	
Booster Pulse Repetition Rate	20	Hz
Booster Beam Power @ 8 GeV	120	kW
Beam Power to 8 GeV Program (max)	80	kW
Main Injector Protons per Pulse	7.5×10^{13}	
Main Injector Cycle Time @ 120 GeV	1.2	sec
LBNF Beam Power @ 120 GeV*	1.2	MW
LBNF Upgrade Potential @ 60-120 GeV	>2	MW

*LBNF beam power can be maintained to ~60 GeV, then scales with energy

PIP-II Status

- Development phase
  - R&D program supports 2018-2019 construction start
  - Collaboration with India
- Strong support from P5, U.S. DoE, and the Fermilab Director
- Five year construction period would support operations startup in 2023

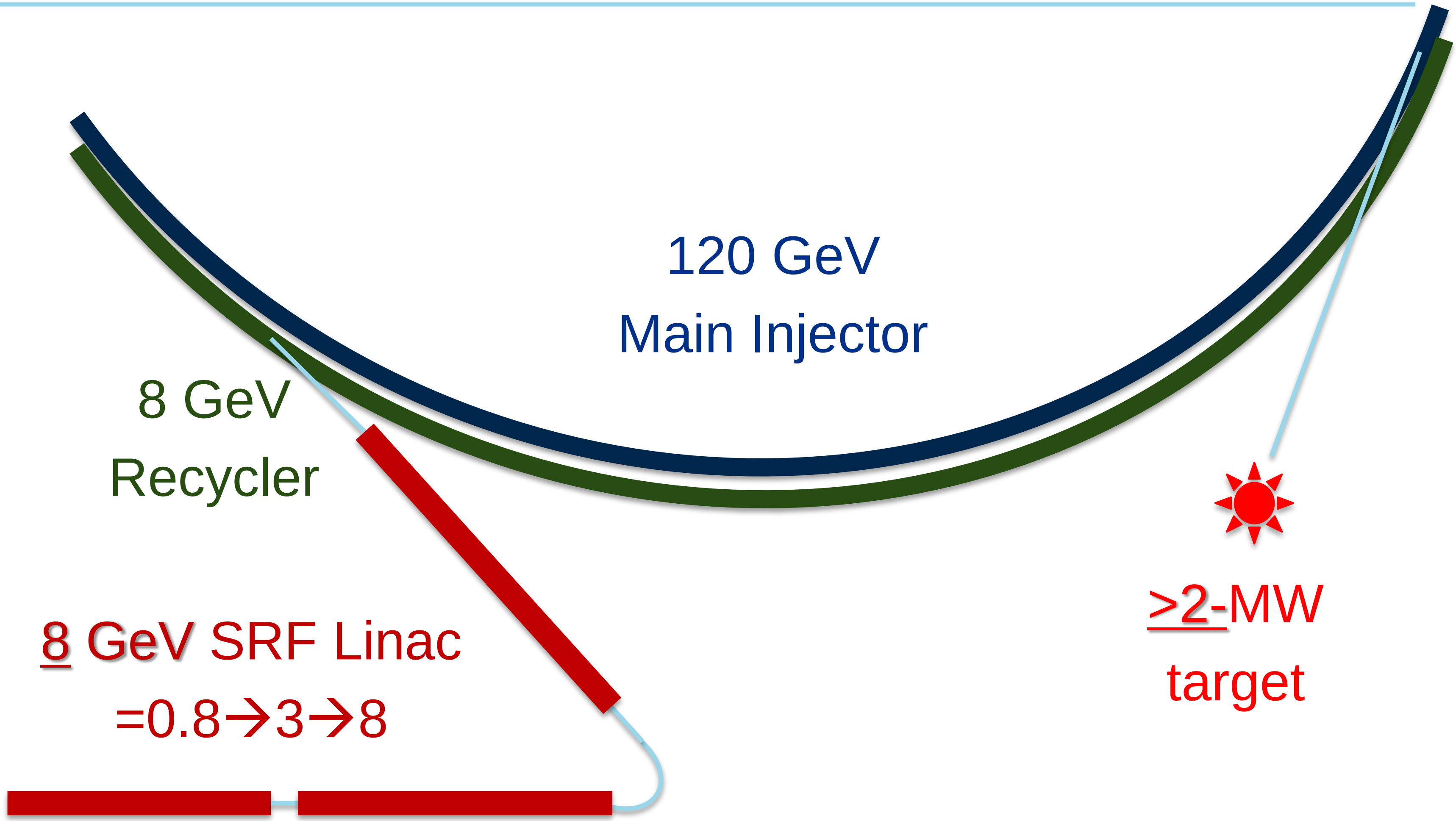


R&D toward multi-MW beams and targets at Fermilab

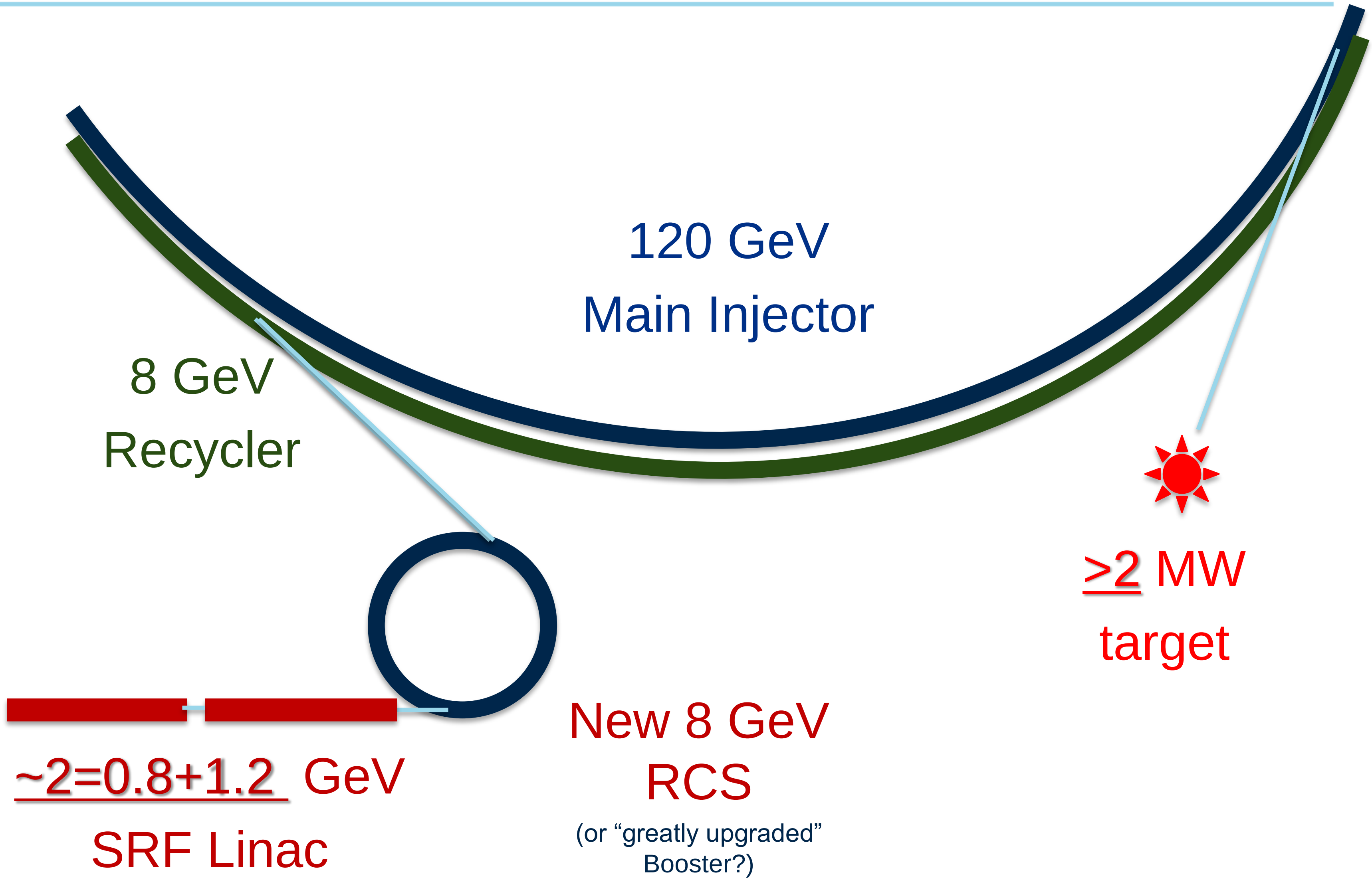
	PIP-II	Beyond PIP-II (mid-term)		
	1st 10 years	2nd 10 years		
To Achieve :	100 kT-MW-year	500 kT-MW-year		
We combine :		Option 1	Option 2	Option 3
Mass	10 kT	50 kT	20 kT	10 kT
Power	1 MW	1 MW	2.5 MW	5 MW

- Strategy after PIP-II depends on the technical feasibility of each option and the analysis of costs/kiloton versus costs/MW
- R&D on cost-effective SRF, control of beam losses in proton machines with significantly higher currents (Q_{SC}) and on multi-MW targets

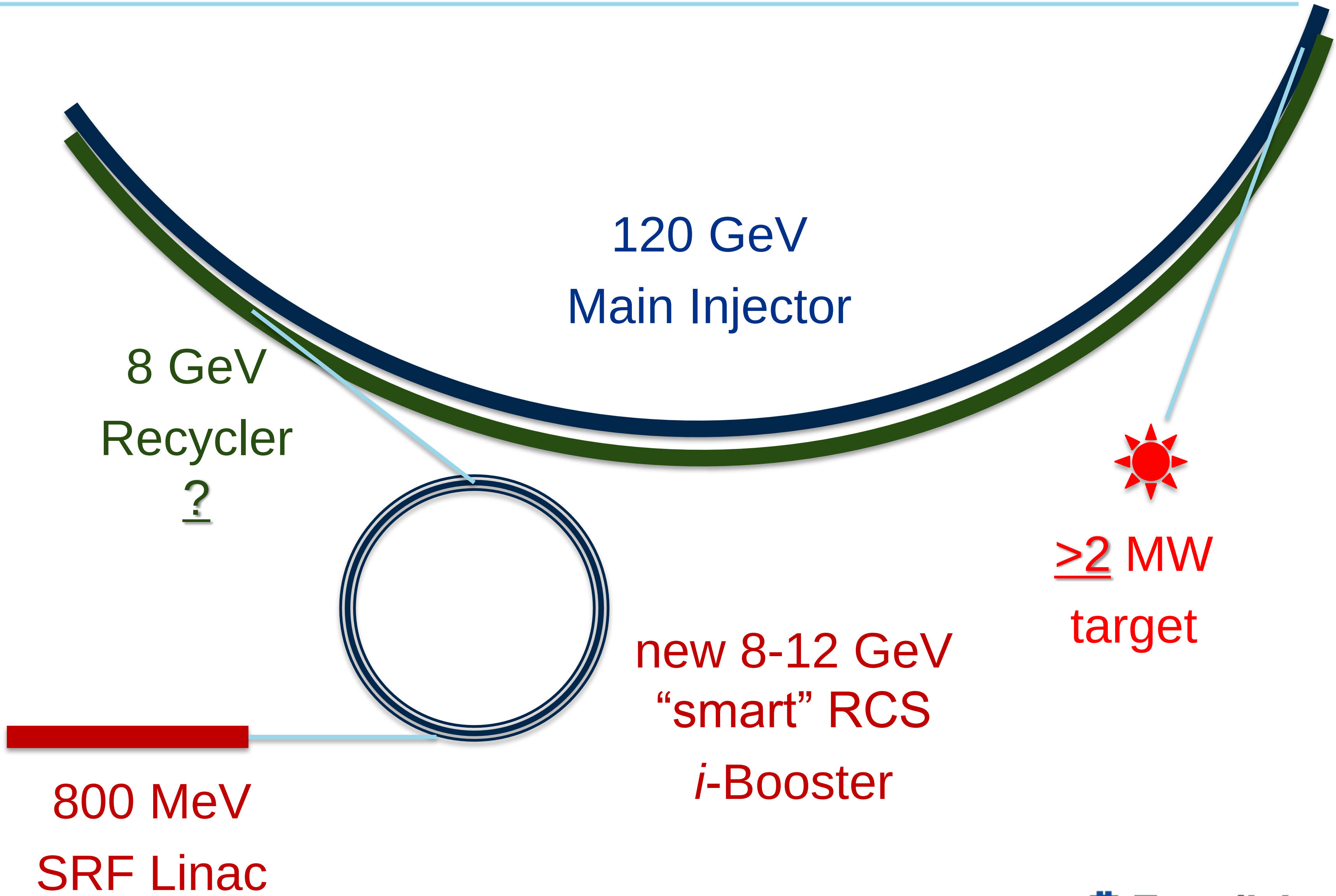
PIP-III “multi-MW” - Option A



PIP-III “multi-MW” - Option B



PIP-III "multi-MW" - Option C



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PIP-III: Intelligent choice requires analysis and R&D

- Either increase the performance of synchrotrons by a factor of 3-4:
  - E.g. space-charge tune shift >1
  - Space-charge compensation
  - Increased Landau damping
  - Suppress beam losses
- Or reduce the cost of SRF / GeV by a factor of 3-4:
  - Several opportunities

A roadmap for high-intensity rings

1. Increase dynamic aperture of rings with strong sextupoles and octupoles
   - Single particle dynamics
   - Also, addressed by the light-source community
2. Develop the theoretical basis of beam instabilities with strong space charge
3. Develop highly-nonlinear focusing lattices with reduced chaos
4. Reduce chaos in beam-beam effects
5. Ultimately, develop accelerators for super-high beam intensity
   - Self-consistent or compensated space-charge
   - Strong non-linearity (for Landau damping) to suppress instabilities
   - Stable particle motion at large amplitudes

Addressed by IOTA

Landau damping rate estimate

- A. Burov, "Head-Tail Modes for Strong Space Charge", PRST-AB, 2009

Landau damping rate is computed as

$$\Lambda_x \cong -\frac{Q_s}{\pi}\int \Delta x^2 J_x \frac{\partial f}{\partial J_x} d^3 J$$

$$f(\mathbf{J}) = \exp(-J_x - J_y - J_z)$$

This yields

$$\Lambda_x \cong \frac{\delta Q_{xx}^2}{\Delta Q_{sc}} \underbrace{F(\mathrm{sgn}(a_{xx}), |a_{xy}/a_{xx}|)}_{\text{Damping factor}}; \quad \delta Q_{xx} \propto a_{xx}$$

For octupoles:

$$dQ_x = a_{xx} J_x + a_{xy} J_y =$$
$$= dQ_{xx} + dQ_{xy}$$

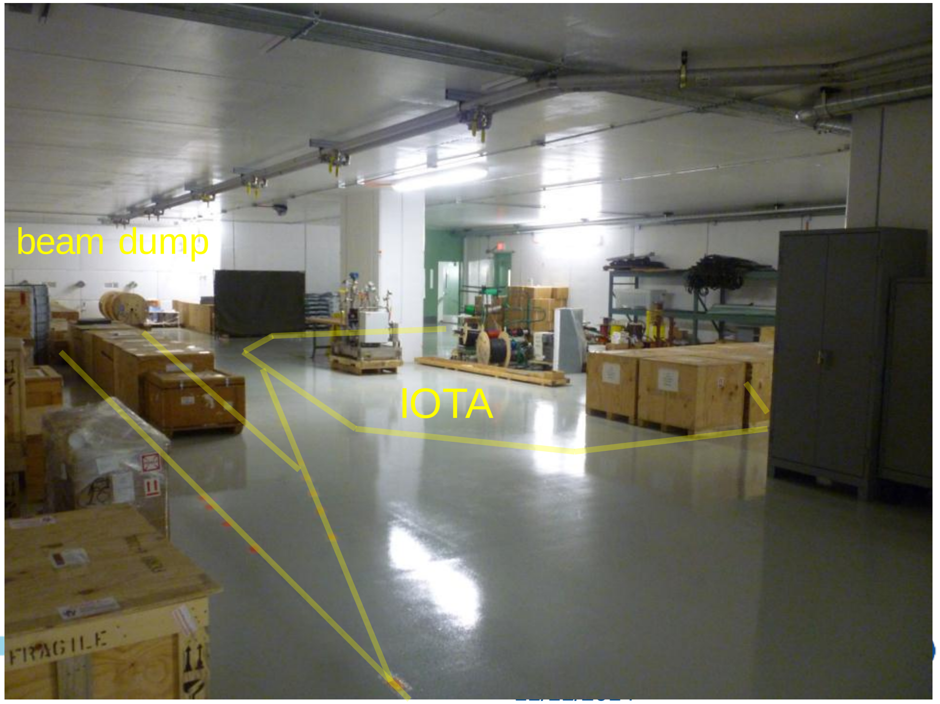
Does Focusing Need to be Linear?

- Are there "magic" nonlinearities with zero resonance strength?
- The answer is – yes (we call them "integrable")
- Search for a lattice design that is strongly nonlinear yet stable
  - Orlov (1963) -- attempt failed (non-integrable)
  - McMillan (1967) – first successfull 1-D example
  - Perevedentsev, Danilov (1990 - 1995) – several 1D, 2D examples
  - Cary and colleagues (1994) – approximate integrability
- Our goal (with IOTA) is to create practical nonlinear accelerator focusing systems with a large frequency spread and stable particle motion in the presence of large space charge.
  - Danilov, Nagaitsev, Phys. Rev. ST Accel. Beams 13, 084002 (2010)

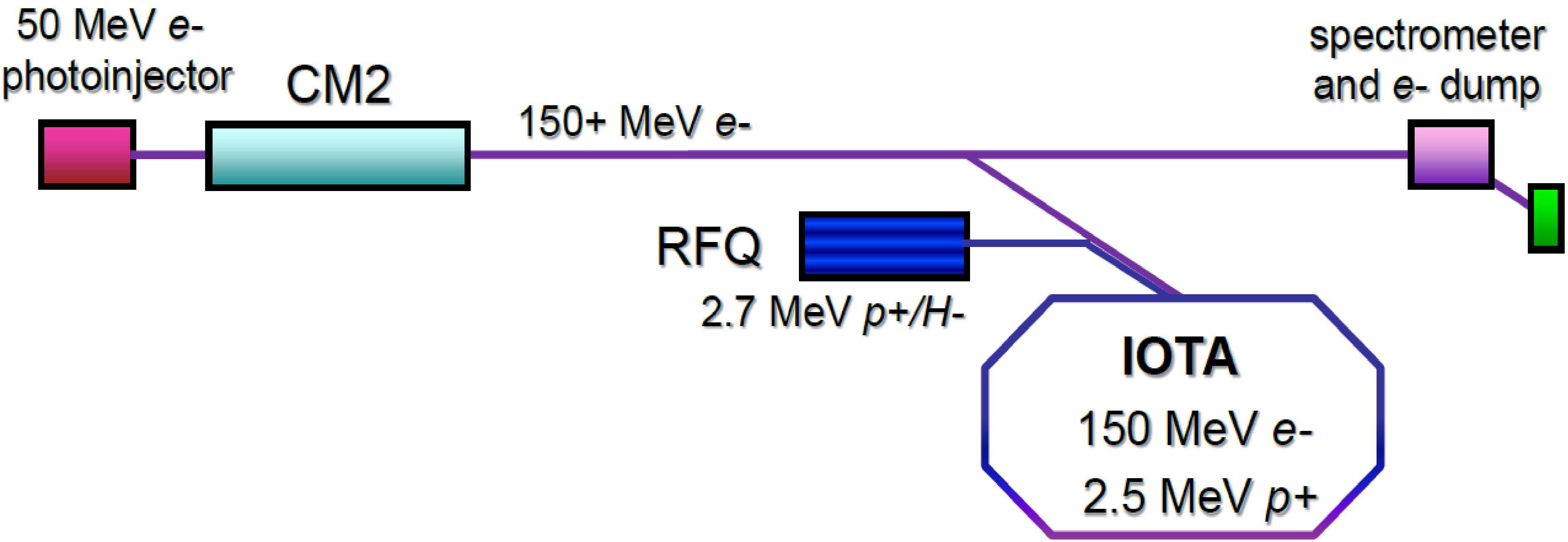
Motivation and Strategy

- We propose an **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 – ΔQ_{SC}>1, lower losses, stable beams
  - become the focal point for collaboration and training
- **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

ASTA Facility



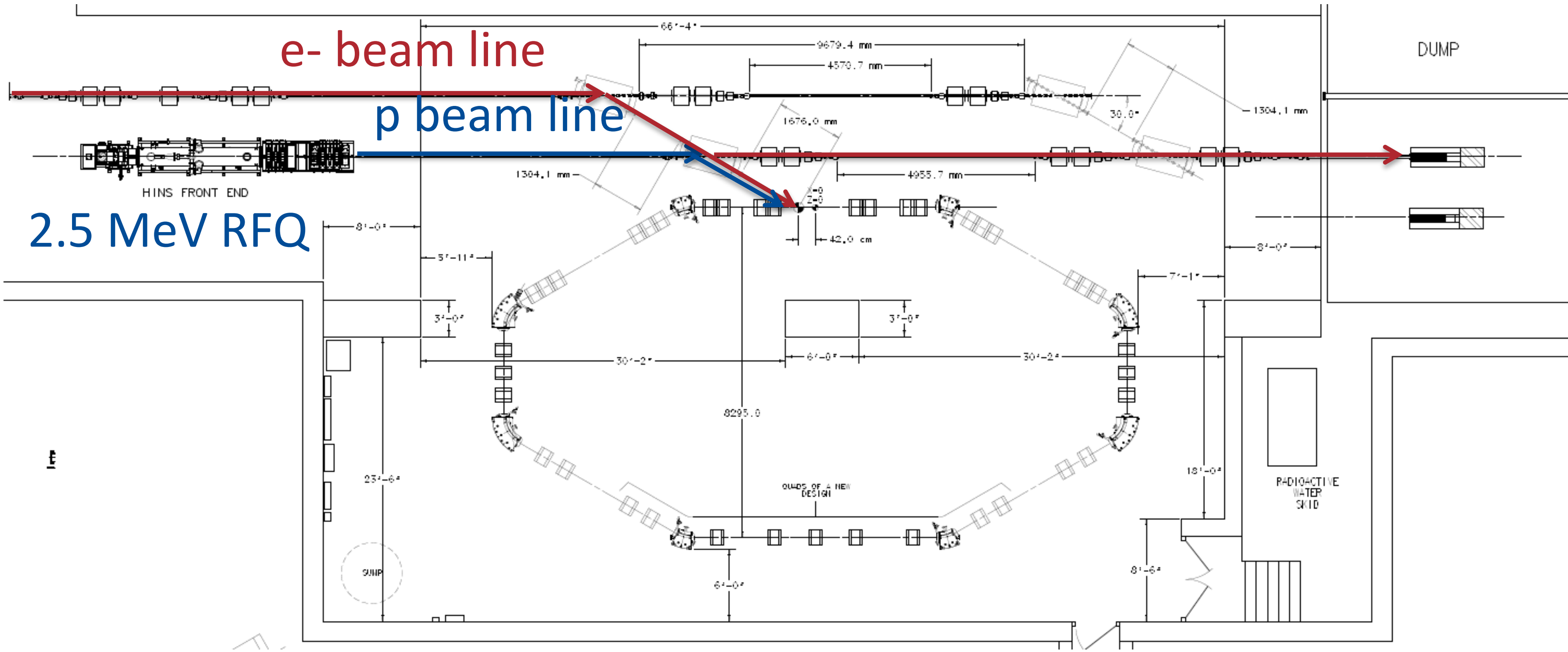
ASTA Schematic



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**

IOTA Ring



e- beam line
p beam line
2.5 MeV RFQ
HINS FRONT END
DUMP
66'-4"
9679.4 mm
4570.7 mm
1676.0 mm
1304.1 mm
4955.7 mm
30.0°
42.0 cm
8'-0"
5'-11"
3'-0"
30'-2"
6'-0"
30'-2"
7'-1"
8295.0
23'-6"
18'-0"
QUADS OF A NEW DESIGN
RADIOACTIVE WATER SKID
SUMP
6'-0"
8'-6"

IOTA Physics Drivers

1. Experimental demonstration of **Nonlinear Integrable Optics lattice**

2. **Space Charge Compensation** in high intensity circular accelerators

Integrable Optics Test Accelerator Goals 1

We are constructing the Integrable Optics Test Accelerator ring with the ***goal to demonstrate the possibility to implement nonlinear integrable optics in a realistic accelerator design***

Staged approach

•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 Goals 2

- In Phase II, using the proton beam, work will be directed towards
  - Achievement of large tune spread within a circulating beam
  - Achievement of space charge suppression in a nonlinear accelerator lattice
    - Studies of applications in future high intensity machines
- IOTA is a multi-purpose machine. In addition to the primary goal, the ring can accommodate other Advanced Accelerator R&D experiments and/or users
  - Optical Stochastic Cooling
- Excellent potential for collaboration. Present collaboration: BINP, ORNL, RadiaBeam, RadiaSoft, U.Chicago, UMD, IIT, TechX, JINR
- Educating the next generation of accelerator physicists

Plan of Activities

Phase 1: FY15-17

1. Construction of main elements of the ASTA/IOTA facility: a) IOTA ring; b) electron injector based on existing ASTA electron linac; c) proton injector based on the existing proton source and 2.5-MeV RFQ; d) special equipment for AARD experiments.
2. Commissioning of the IOTA ring with electron beam.
3. Study of single-particle dynamics in integrable optics with electron beams.

Plan of Activities

Phase 2: FY18-20

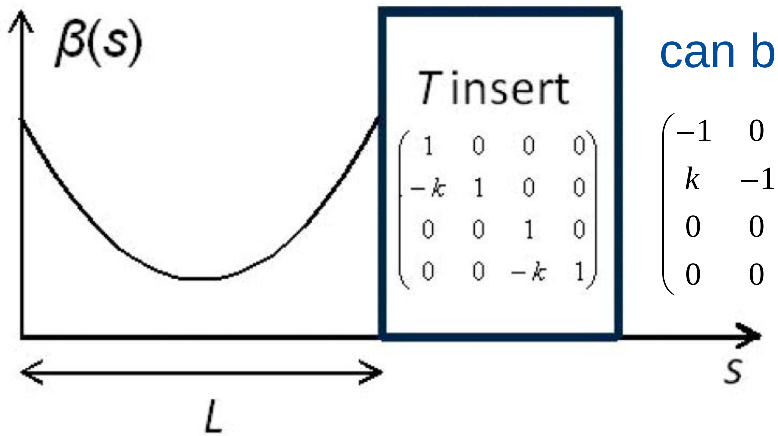
1. Commission IOTA operation with proton beams.
2. Carry out space-charge compensation experiments with nonlinear optics and electron lenses.

Phase 3: FY21 and beyond

1. Study the application of space-charge compensation techiques 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 ASTA/IOTA facility

Design Goals and Features

- The concept of IO rests on the idea of interleaving nonlinear potential (*Magnets* or *Electron Lenses* placed in drifts with equal β-functions) with axially symmetric focusing blocks (T-inserts)

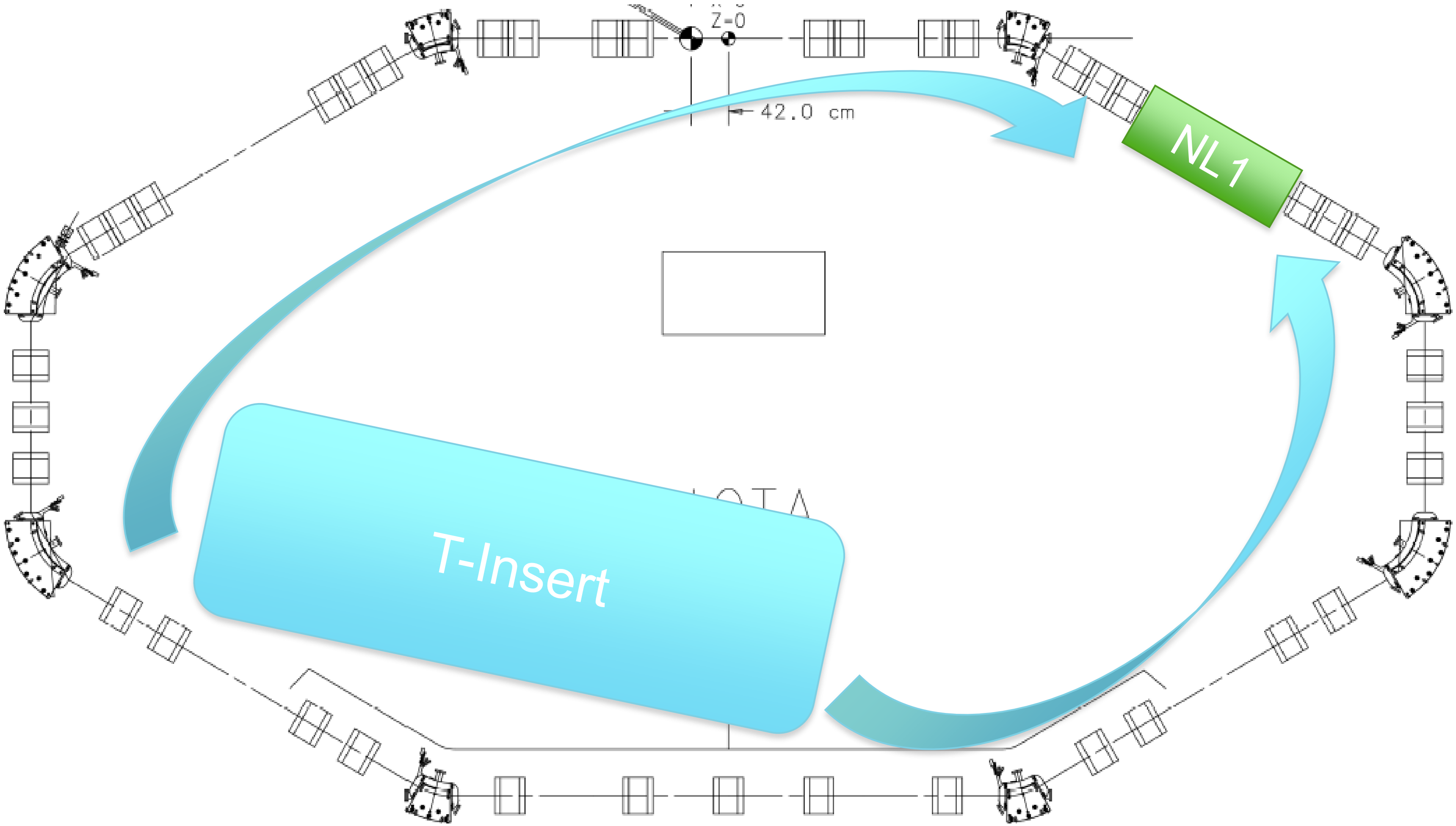


can be also

$$\begin{pmatrix} -1 & 0 & 0 & 0 \\ k & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & k & -1 \end{pmatrix}$$

- T-insert
  - Betatron phase advance is 0.5 or 1.0, achromatic.
  - May be built using conventional dipole and quadrupole magnets
  - N.B.: an existing machine may be re-tuned such that its arcs become one or more T-inserts

IOTA Layout (1-Magnet Option)



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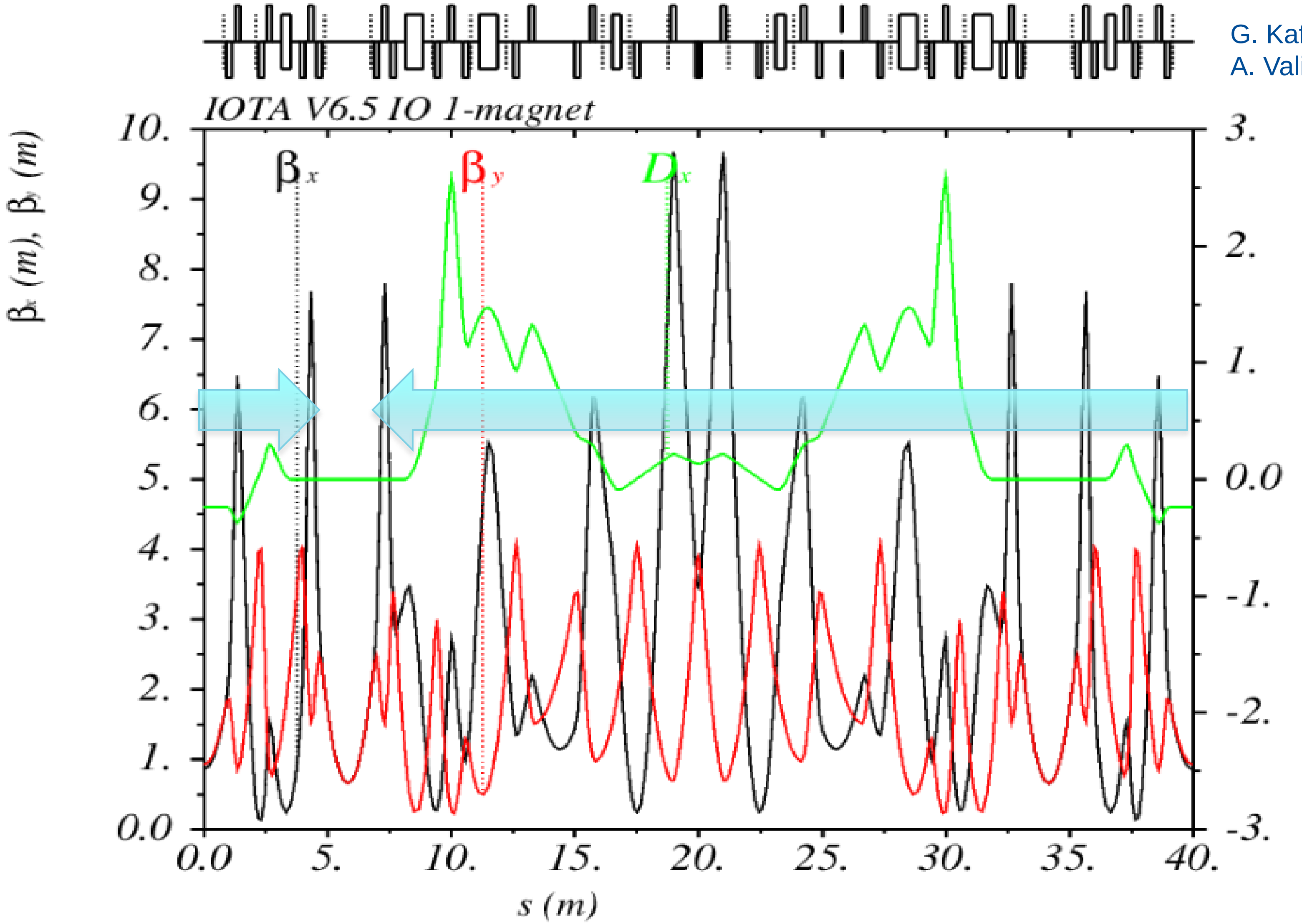
Design Goals and Features 2

- Machine lattice must provide enough flexibility to accommodate
  - 1 or 2 for nonlinear magnets (~2 m each), and corresponding number of elements of periodicity (T-Inserts)
  - An Electron Lens (2 m)
  - Optical Stochastic Cooling (5 m for undulators and chicane)
- 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 β-function, and 0.001 or better control of betatron phase
  - This is why Phase I will make use of e- beams as such parameters are not reachable in such a small ring operating with protons

IOTA Optics (1-Magnet Option)

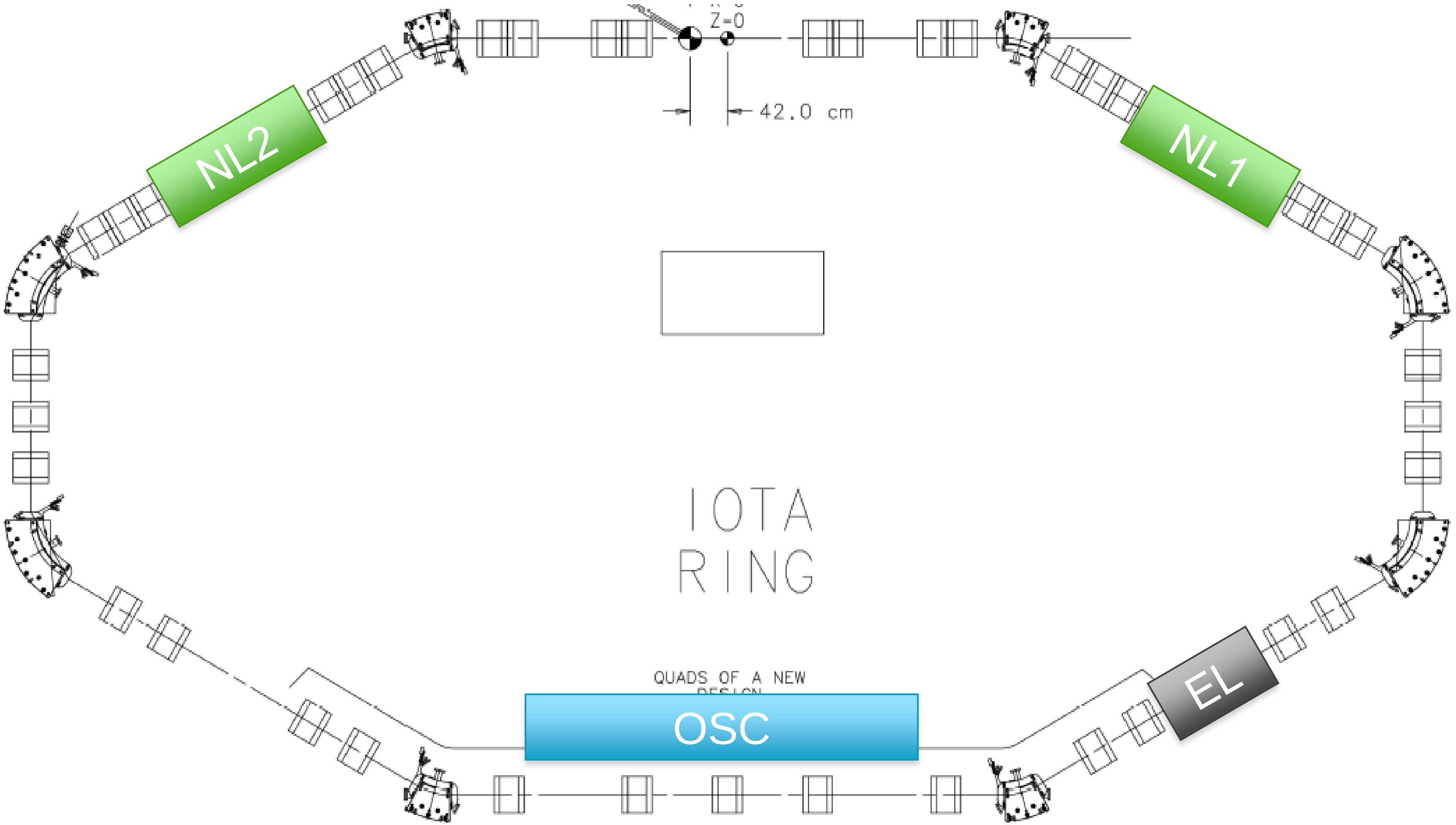


G. Kafka
A. Valishev

Design Goals and Features

- Since we intend to sample the nonlinearities with a pencil beam
  - machine aperture must be large enough - beam pipe Φ=2”
  - must have a h-v kicker
- The machine must be capable of operating with electrons as well as protons
- The machine must fit in the existing hall area
- Be inexpensive and reuse available components whenever possible

IOTA Layout



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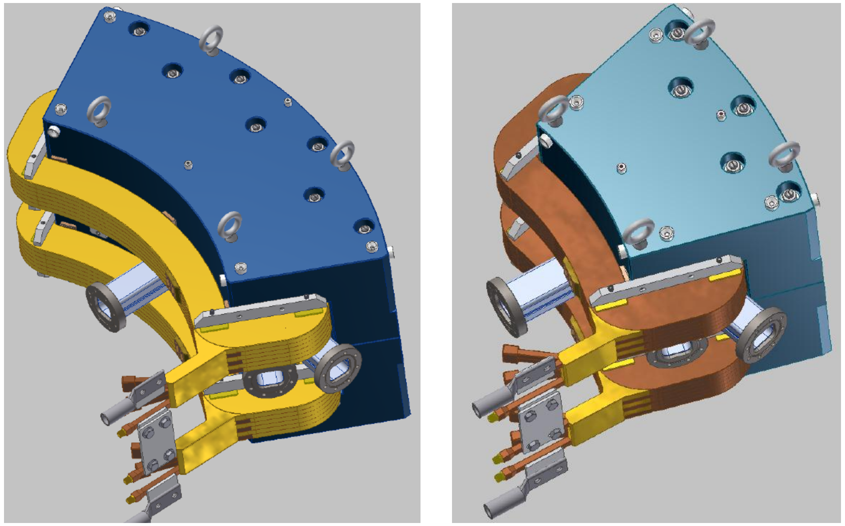
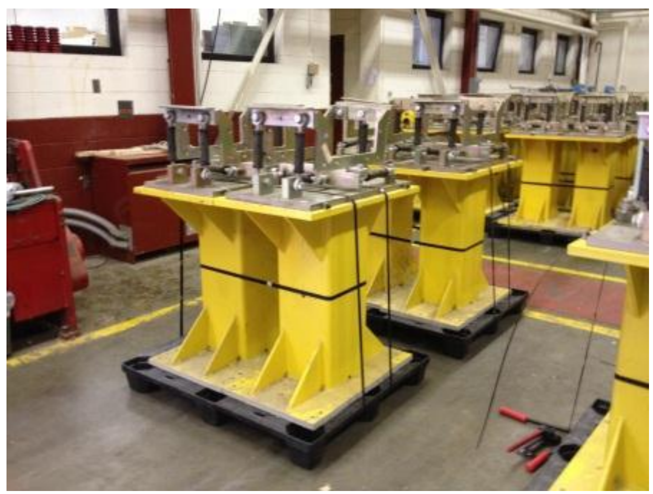
Ring Elements in Hand



Dipole magnets (ordered)

32 quads from **JINR (Dubna)** received

Vacuum chambers
for dipoles (received)



Magnet support stands
from **MIT** (received)

Also:

BPMs and electronics
Vacuum system
Dipole power supply
Corrector power supplies

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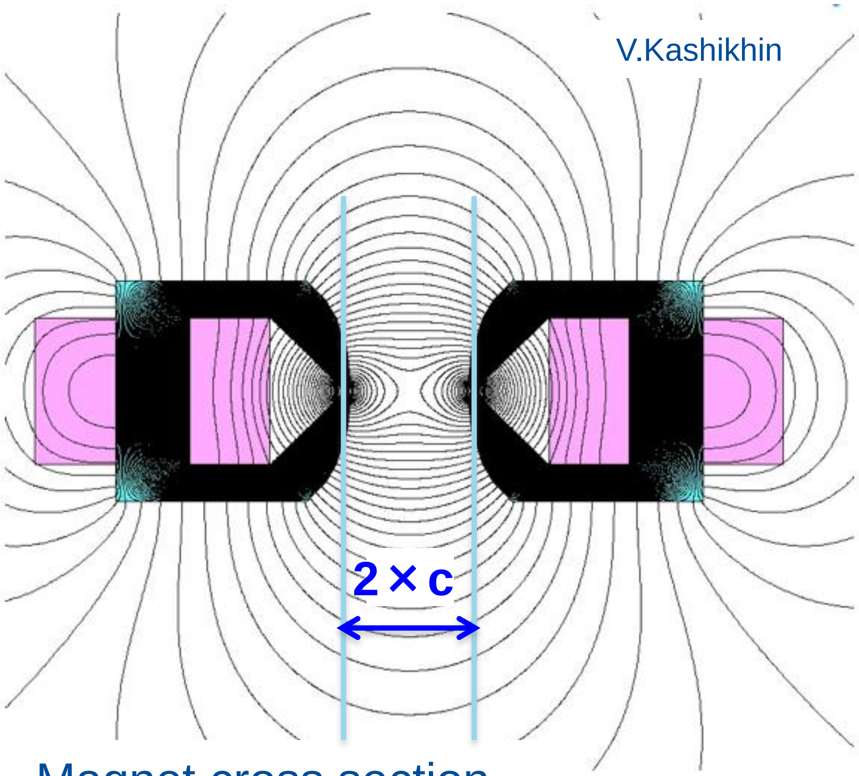
IOTA Parameters

Nominal e^- beam energy	150 MeV(g=295) or lower
Nominal e^- beam intensity	1×10^9
Circumference	40 m
Bending field	0.7 T
Beam pipe aperture	50 mm dia.
Maximum b-function (x,y)	12, 5 m
Momentum compaction	0.02 $\div$ 0.1
Betatron tune	3 $\div$ 5
Natural chromaticity	-5 $\div$ -10
Transverse emittance r.m.s.	0.1 μm
SR damping time	0.6s (5×10^6 turns)
RF V,f,q	10 kV, 30 MHz, 4
Synchrotron tune	0.002 $\div$ 0.005
Bunch length, momentum spread	2 cm, 1.4×10^{-4}

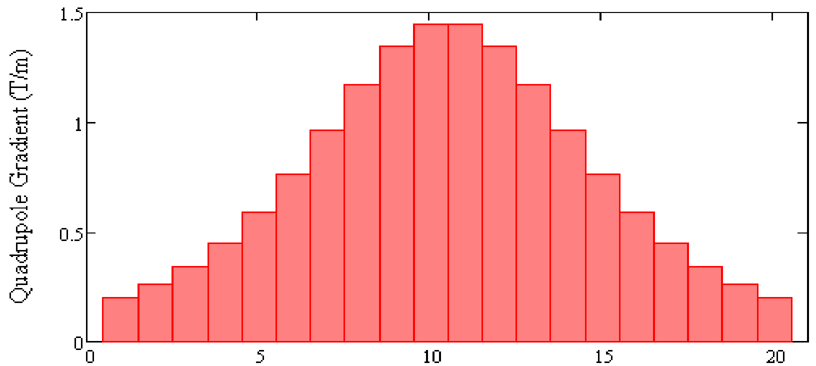
Nonlinear Magnet

Practical design – approximate continuously-varying potential with constant cross-section short magnets

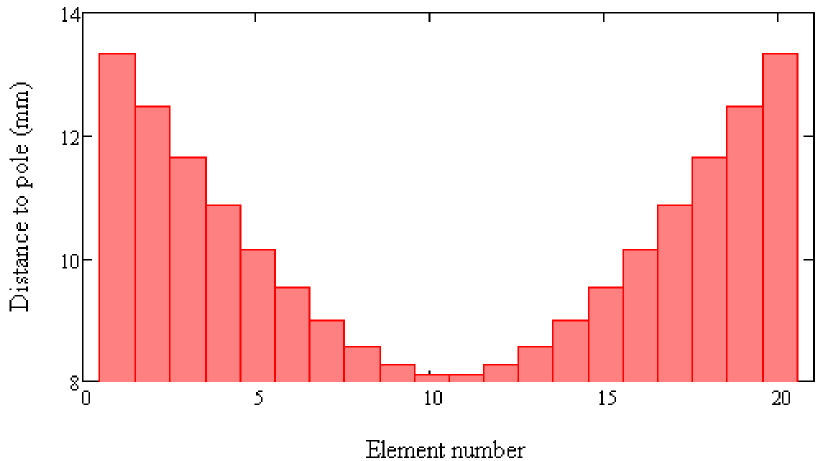


Magnet cross section

Quadrupole component of nonlinear field

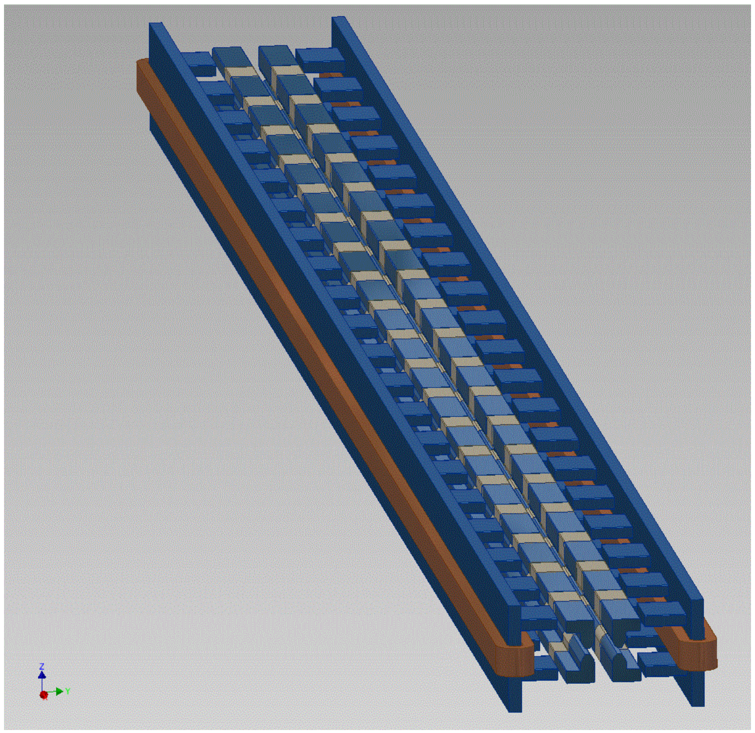


Distance to pole **c**

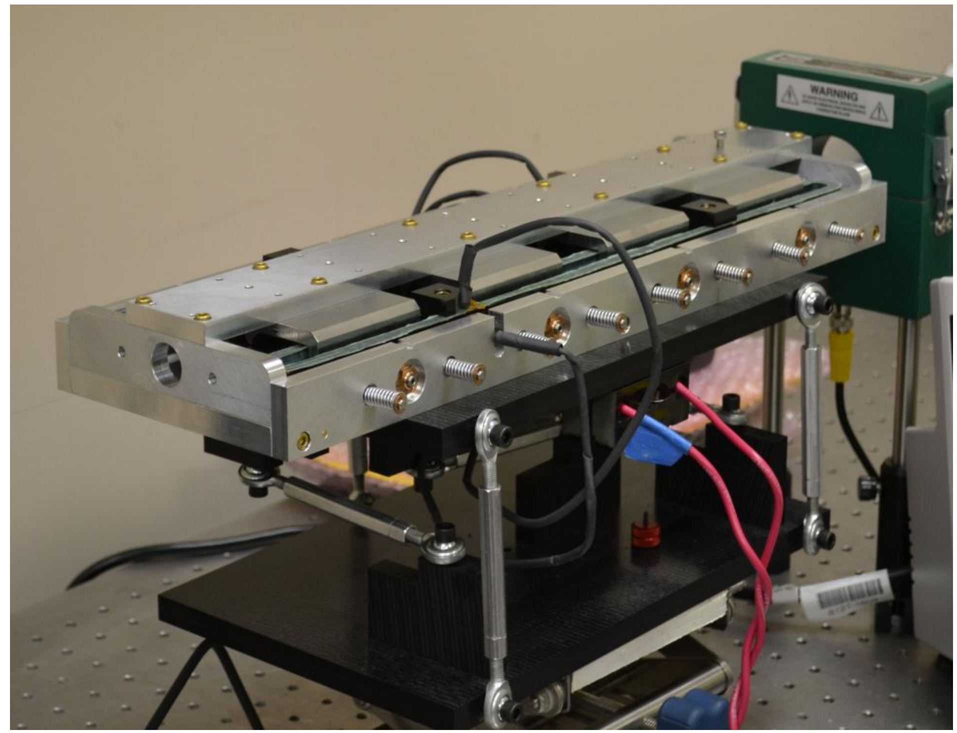


Nonlinear Magnet

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



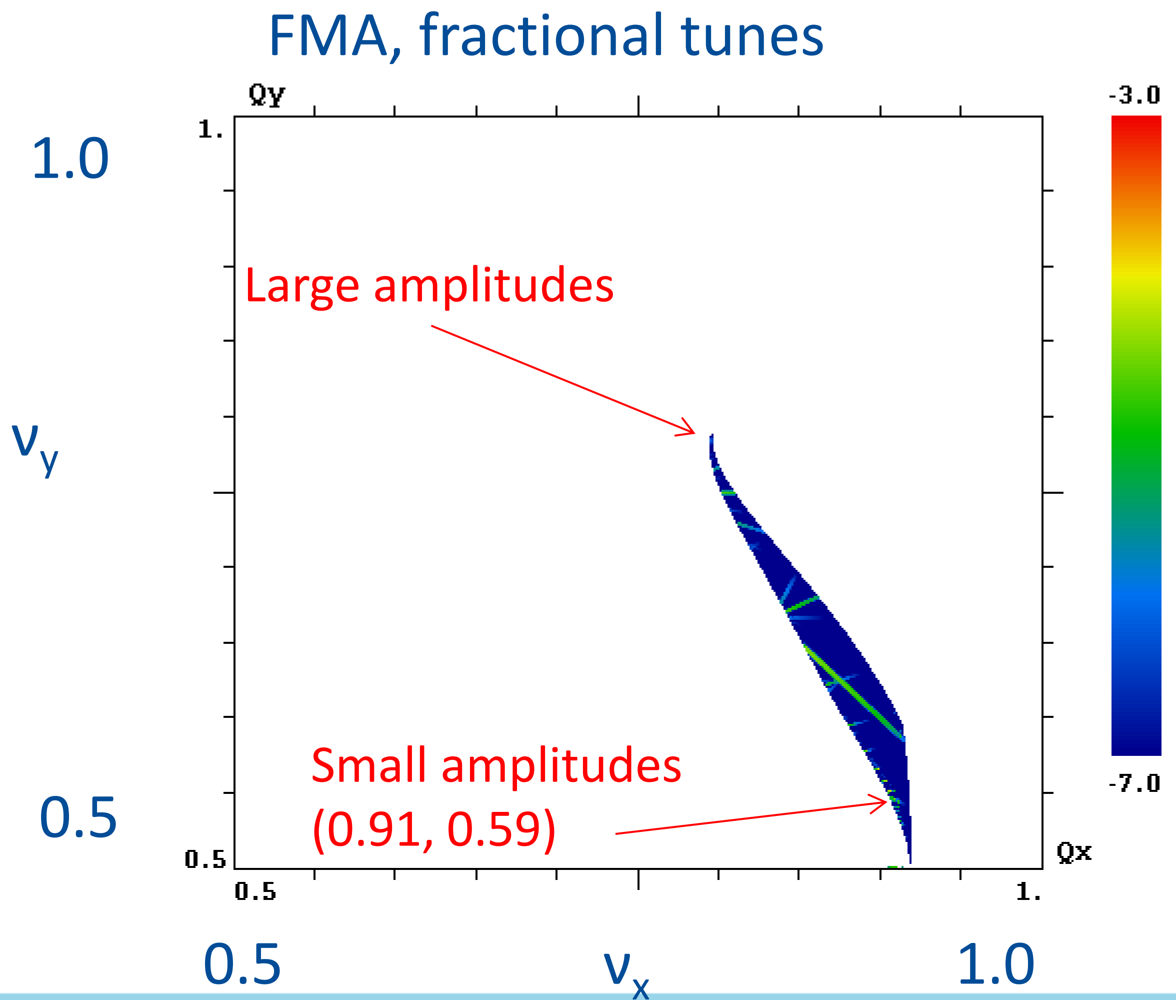
FNAL Concept: 2-m long nonlinear magnet



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

Tune foot-print for an ideal nonlinear lens

- A single 2-m long nonlinear lens creates a tune spread of ~0.25.



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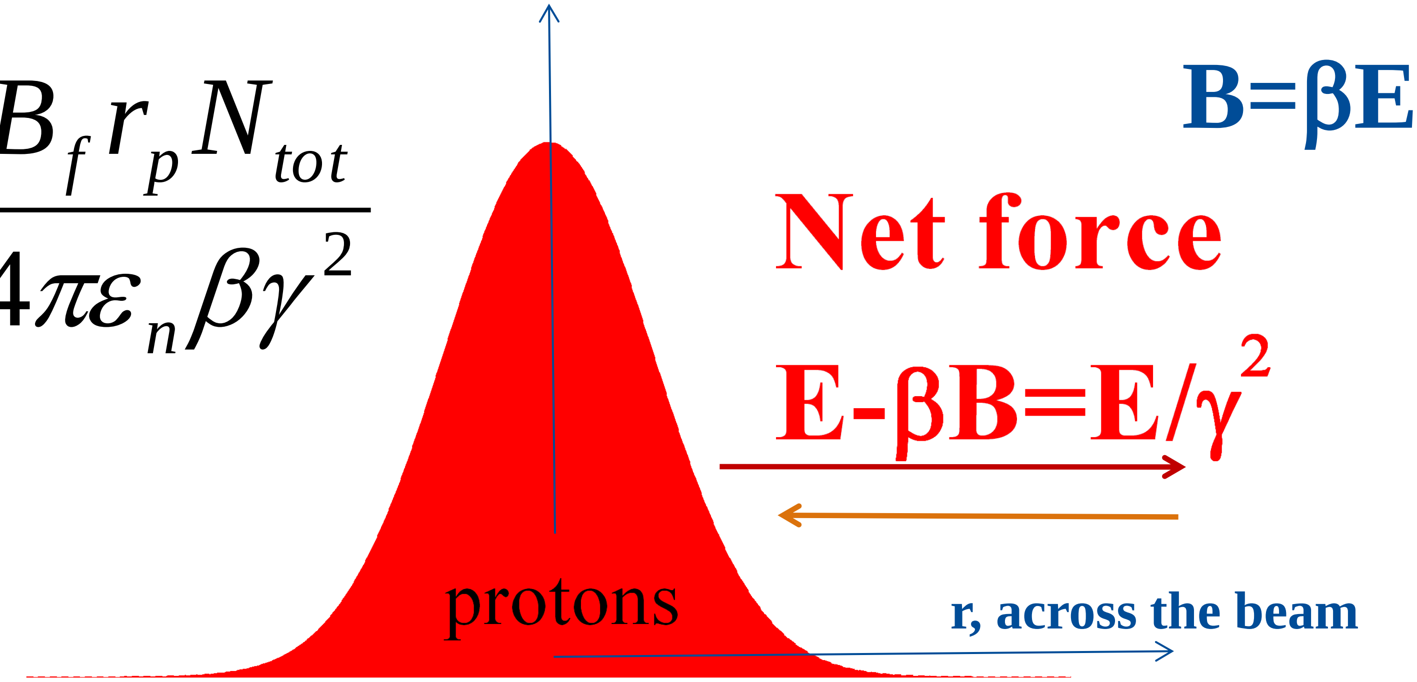
Space Charge Compensation

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

B=βE

Net force

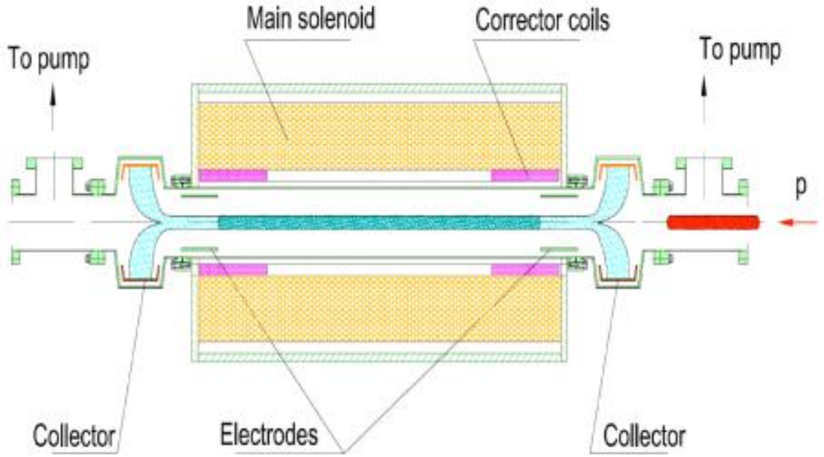
$E-\beta B = E/\gamma^2$



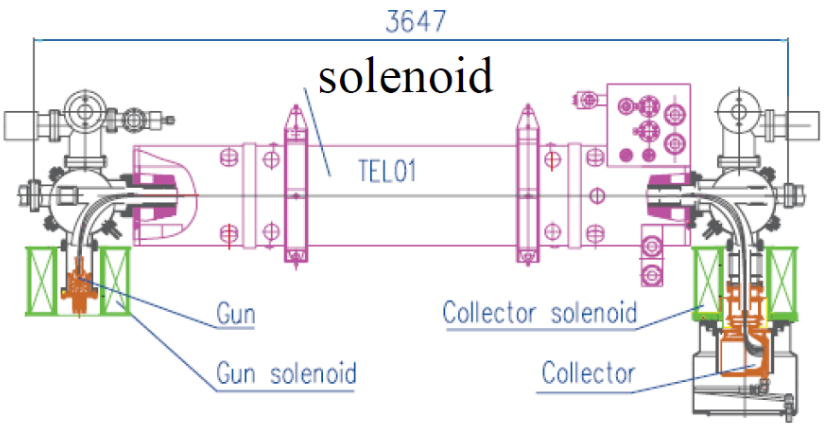
A. Burov, G. Foster, V. Shiltsev, FNAL-TM-2125 (2000)

Possible Implementations

E-column concept



E-lens concept



1. The impact of electrons is equal to the total impact of space-charge over the ring

$$\left|\Delta \nu_{sc}\right| = \frac{N_{b,tot} r_{cb}}{2\pi \beta_b^2 \gamma_b^3 \varepsilon} \frac{\hat{I}}{\bar{I}} = \Delta \nu_e = \frac{N_e r_{cb}}{2\pi \beta_b^2 \gamma \varepsilon} \qquad \frac{N_e}{N_{b,tot}(\hat{I}/\bar{I})} = \frac{1}{\gamma_b^2} = \eta_0 \frac{N_{ec} L_{ec}}{C}$$

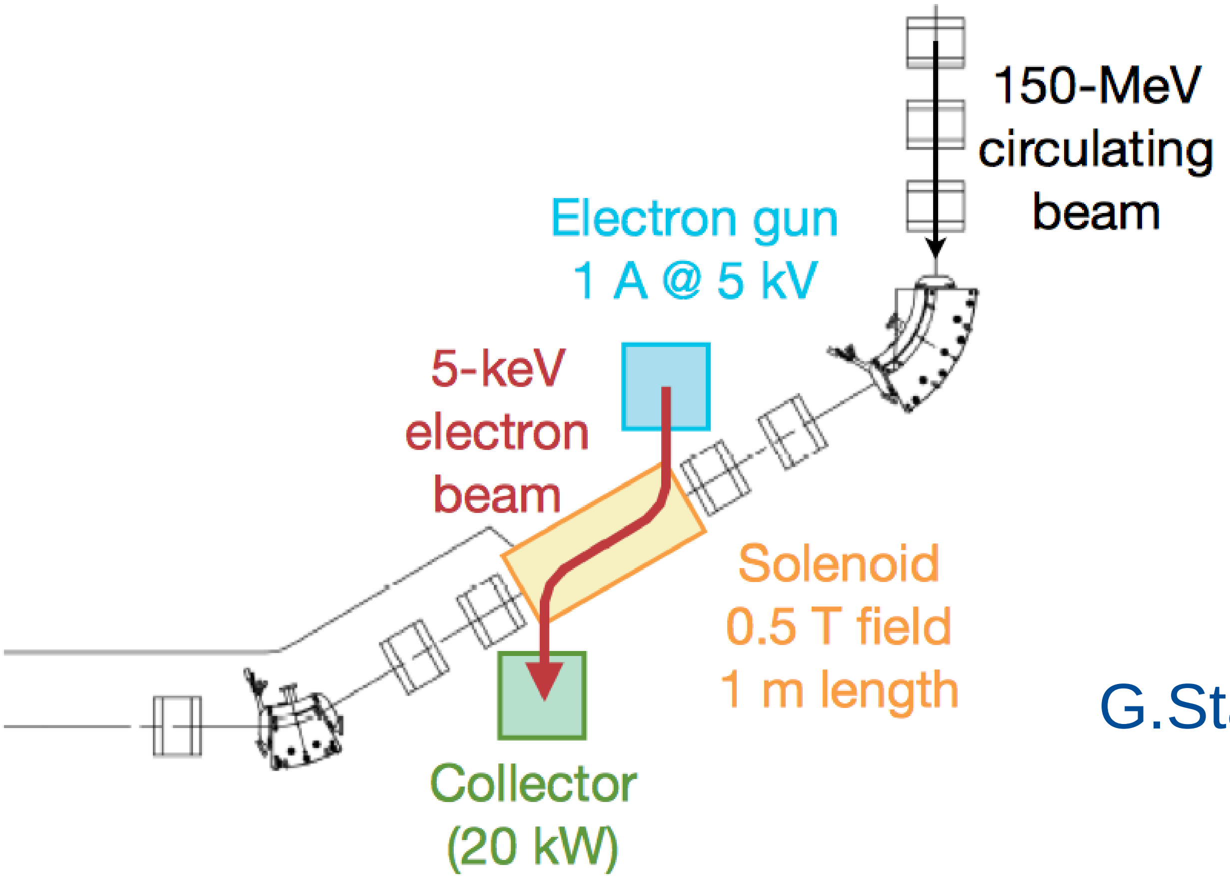
2. The transverse profile of the electron is made the same as that of the proton beam

→ use of solenoid

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

IOTA Electron Lens

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



G.Stancari

Summary

- Theory and modeling to develop the basis for the next generatio high intensity circular machines – in progress
- Proof-of-principle experiments at ASTA/IOTA – First experiments planned for 2016
- 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