Electron lenses for experiments on nonlinear dynamics with wide stable tune spreads in the Fermilab Integrable Optics Test Accelerator

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Outline

- **Introduction and motivation**
  - high-power machines for particle physics
  - the role of nonlinear integrable optics
  - the Fermilab IOTA ring
  - electron lenses
- **Nonlinear integrable optics with electron lenses in IOTA**
  - Integrable optics scenarios with electron lenses
    - 1. thin kicks of McMillan type
    - 2. axially symmetric kicks in long solenoid
  - Design considerations
- **Conclusions and next steps**

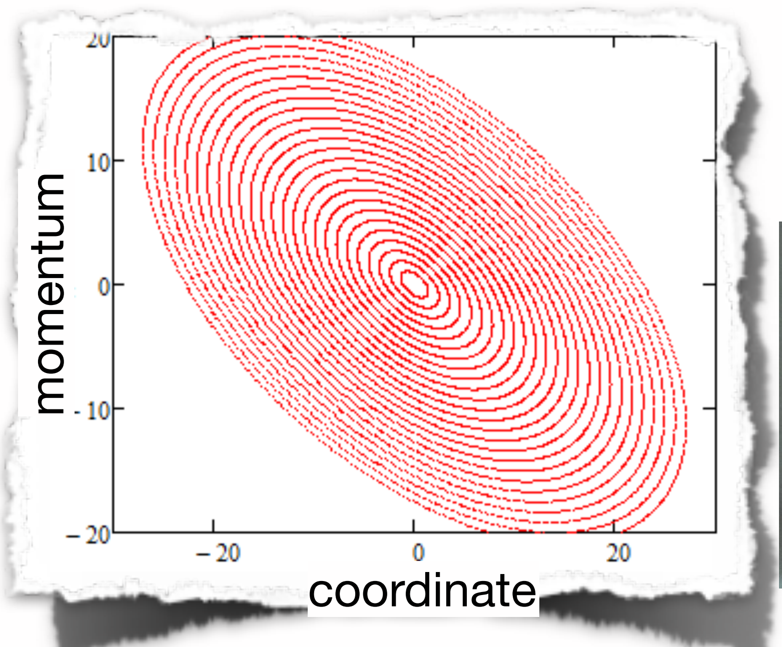
Motivation

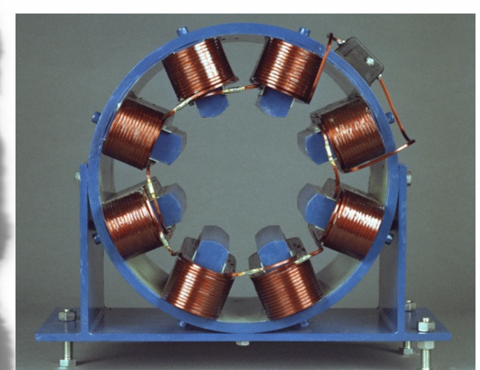
- **High-power machines** are needed to study **neutrinos** and **rare processes** in particle physics
- Limitations:
  - **losses** and **beam halo**
  - **space-charge effects**
  - transverse and longitudinal **instabilities**
- **Innovative accelerator designs** could significantly reduce the cost of machines in the megawatt range, as emphasized by **US particle physics community priorities:** <www.usparticlephysics.org/p5>
- A **possible roadmap** towards high-intensity rings:
  - develop **theories and models** for high-intensity circular machines
  - perform **proof-of-principle experiments** at ASTA/IOTA
  - design a **new kind of rapid-cycling synchrotron**
    - nonlinear optics and wide tune spread to suppress instabilities
    - stable motion up to large amplitudes
    - self-consistent or compensated space charge
- **Education and training** of accelerator scientists and engineers

Mainstream accelerator lattices

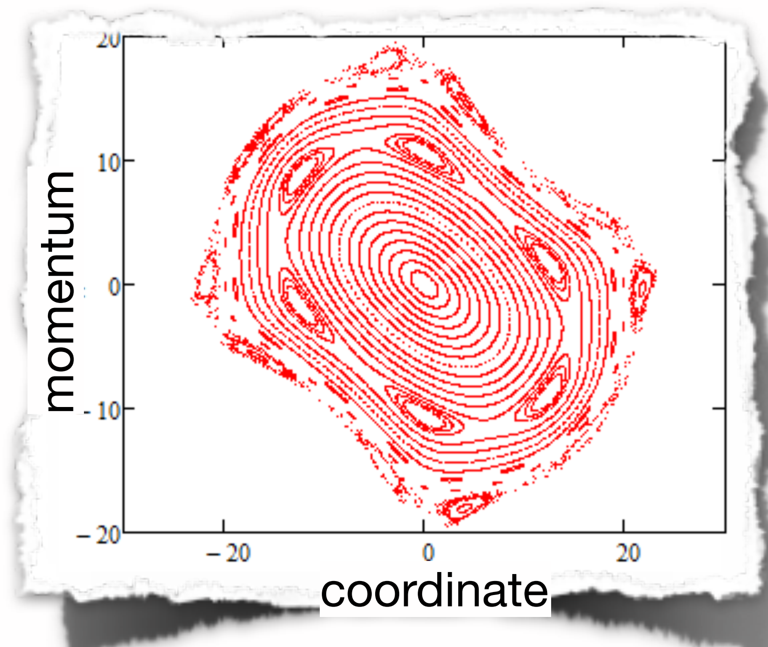
- **Conventional strong-focusing accelerators** are **based upon linear elements** (dipoles and quadrupoles). Same design betatron frequency for all particles. In the ideal case, the Courant-Snyder invariant is conserved
- **Nonlinear elements are necessary** (e.g., sextupoles for chromaticity, octupoles for Landau damping) **or unavoidable** (e.g., space-charge and beam-beam forces)
- Stability depends on initial conditions. Nonlinearities are the sources of resonances and their driving terms. Motion is unstable at large amplitudes.

linear lattice





effect of single octupole



Intrinsically nonlinear stable lattices?

- Advantages of a **nonlinear optics** with a **large natural tune spread**
  - increased Landau damping
  - improved stability to periodic perturbations
  - suppression of halo formation in space-charge dominated beams, driven by resonance between linear optics and space-charge breathing modes
  - mitigation of two-stream instability in space-charge compensation schemes

Can accelerators be nonlinear yet stable?

If motion is **integrable**, i.e. with *n* independent conserved quantities for *n*-dimensional dynamics, then it is **bounded** and therefore **stable**

The search for nonlinear integrable lattices

McMillan (1967) found a 1-dimensional solution: a **specific thin kick** in a linear lattice (rational polynomial function) yields an **integral of motion that is quadratic in coordinate and momentum**

The map [after] [before]

$$\left.\begin{aligned} x' &= y \\ y' &= -x + f(y) \end{aligned}\right\} \quad \text{with} \quad f(x) = -\frac{Bx^2 + Dx}{Ax^2 + Bx + C}.$$

conserves the quantity $Ax^2y^2 + B(x^2y + xy^2) + C(x^2 + y^2) + Dxy$

It can easily be **extended to 2D** in an **uncoupled symmetric lattice**. The **axially symmetrical kick** **can be generated by a charge distribution, such as an electron lens**

McMillan, UCRL-17795 (1967)
Danilov and Nagaitsev, PRSTAB **17**, 124402 (2014)
Mane, arXiv:1502.02604 [physics.acc-ph] (2015)

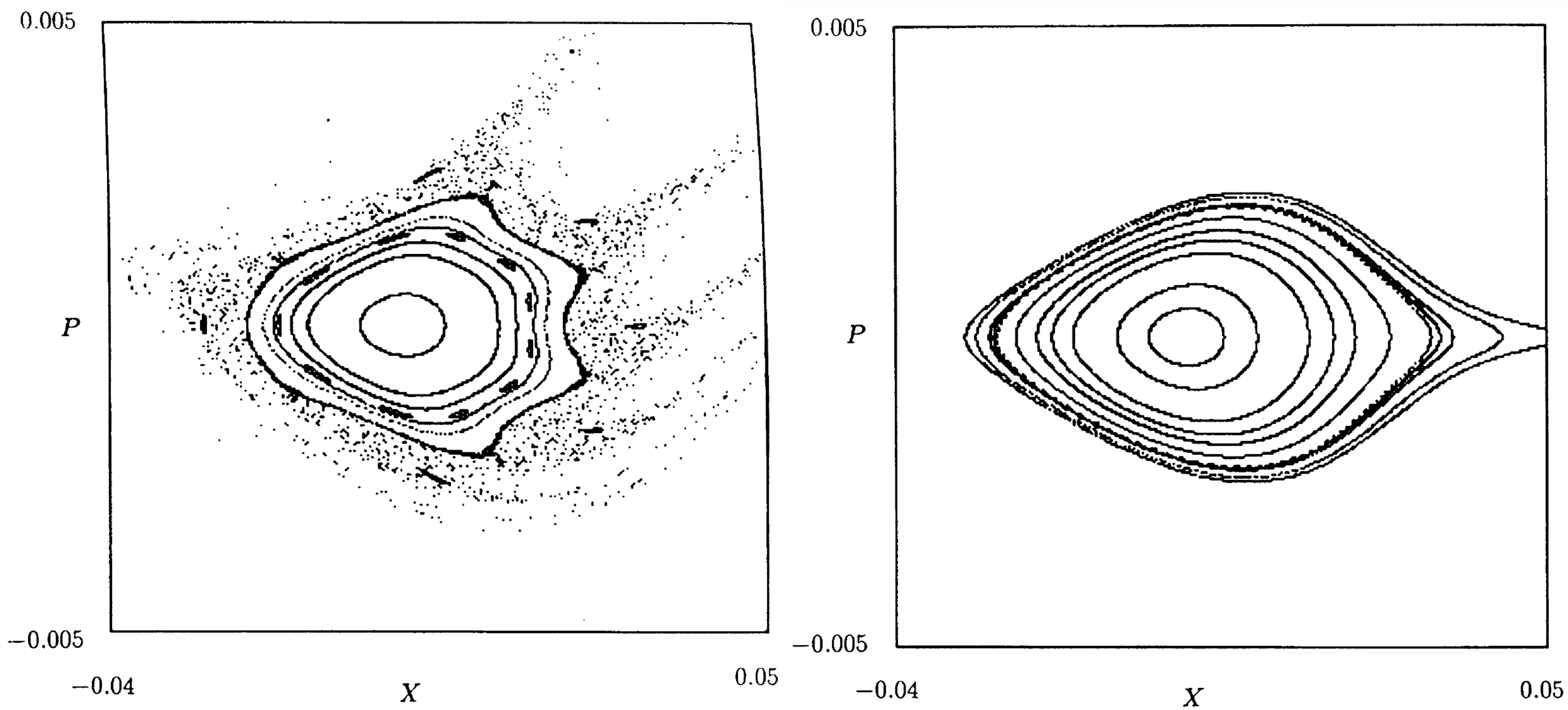
The search for nonlinear integrable lattices

- Danilov and Perevedentsev (1990s) studied extensions to 2D and proposed **"round colliding beams"** (i.e., equal beta functions, tunes, emittances, and no coupling in arcs):
    - **longitudinal component of angular momentum** is conserved, dynamics is "quasi integrable"
    - dynamics would be completely integrable if one could achieve a "McMillan-type" charge distribution in the opposing beam

Benefits of round beams were **demonstrated experimentally** at BINP VEPP-2000 $e^+ e^-$ collider: achieved record tune spread of 0.25 (Romanov, NA-PAC13)

The search for nonlinear integrable lattices

Chow and Cary (1994) and Wan and Cary (1998, 2001) proposed an empirical method to increase dynamic aperture by minimizing the size of islands and chaotic regions with appropriately chosen sextupole, octupole, and decupole elements.



Calculated Poincaré maps for the Berkeley ALS before and after optimization

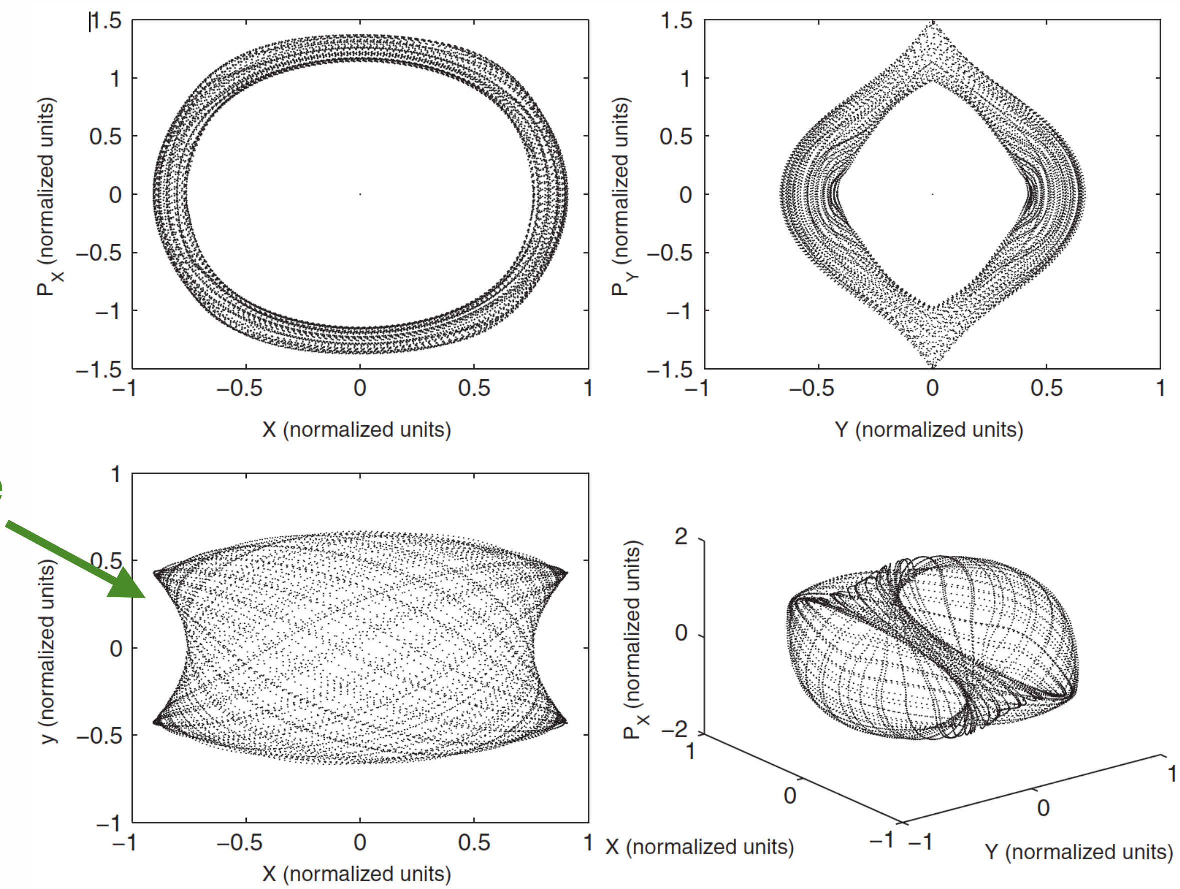
Chow and Cary, PRL **72**, 1196 (1994)

The search for nonlinear integrable lattices

- Danilov and Nagaitsev (2010) found an **analytical solution for transverse motion with 2 invariants that can be implemented with Laplacian potentials (i.e., special multipole magnets)**. Integrals of motion are:
  - longitudinal component of angular momentum
  - “McMillan type” quantity, quadratic in momenta

Examples of projected integrable trajectories

Characteristic hourglass shape in transverse plane



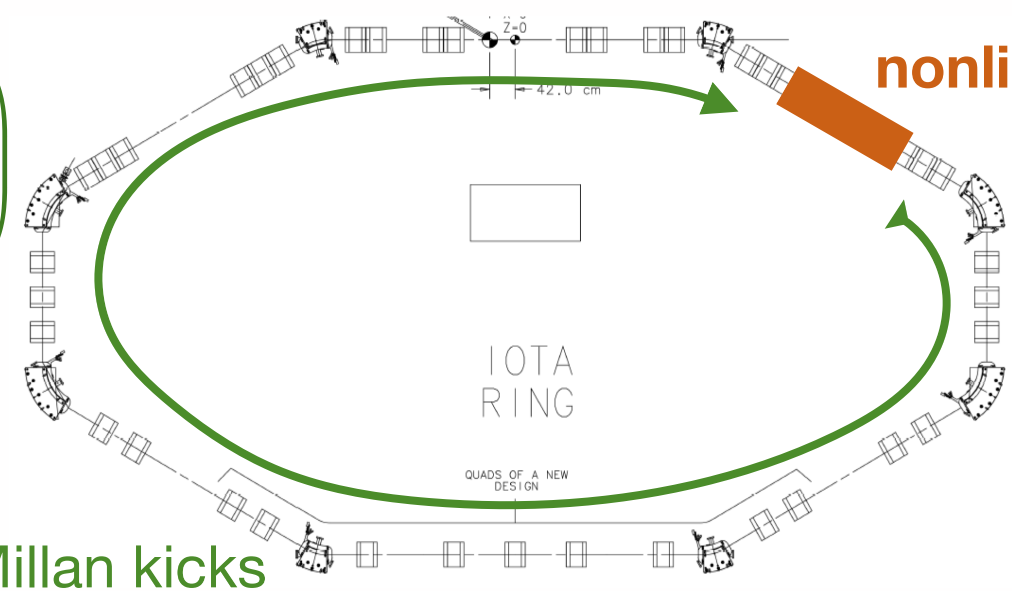
Danilov and Nagaitsev, PRSTAB **13**, 084002 (2010)

Proposed configurations for transverse nonlinear integrable optics

- The lattice is made of **2 main building blocks**
  - an **axially symmetric, linear arc with specified phase advance**, equivalent to a thin lens ("**T-insert**")
  - a **nonlinear section** with equal beta functions and
    - nonlinear magnet or
    - thin, round McMillan-type kick (**electron lens option #1**) or
    - <u>any</u> axially symmetric kick in solenoid (**electron lens option #2**)

T-insert

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

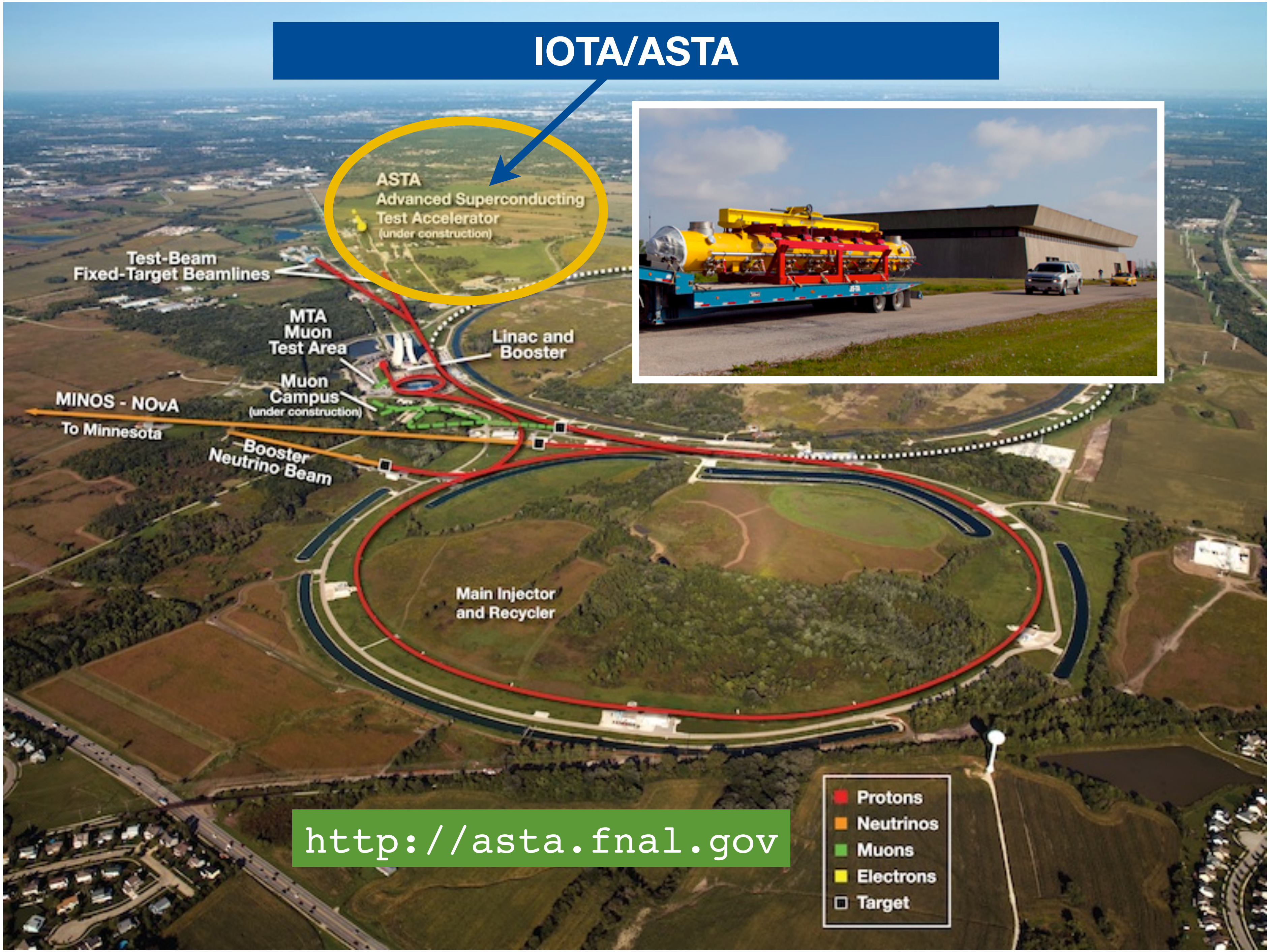


nonlinear element

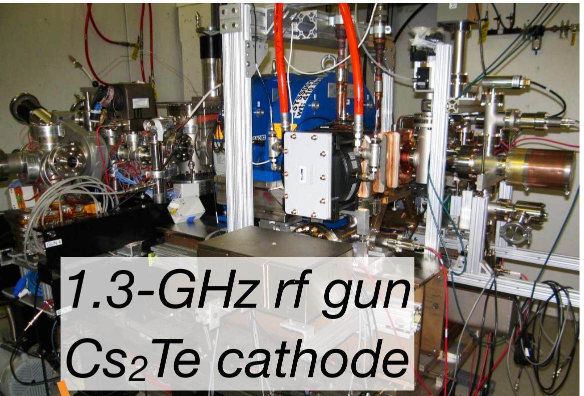
$$\begin{pmatrix} 0 & \beta & 0 & 0 \\ -1/\beta & 0 & 0 & 0 \\ 0 & 0 & 0 & \beta \\ 0 & 0 & -1/\beta & 0 \end{pmatrix}$$ for McMillan kicks

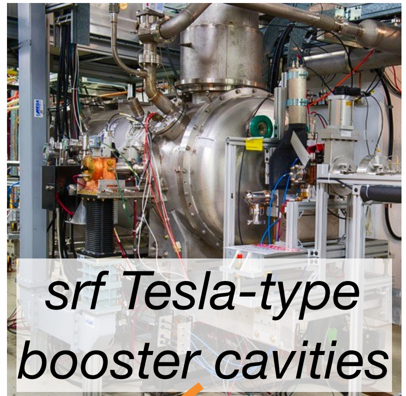
Existing large high-intensity machines may be tuned so that arcs become one or more "T-inserts"

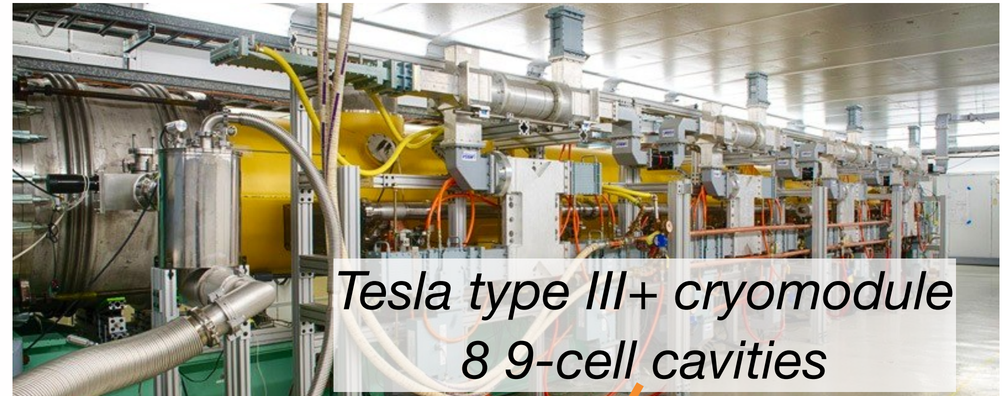
A beam physics research center at Fermilab

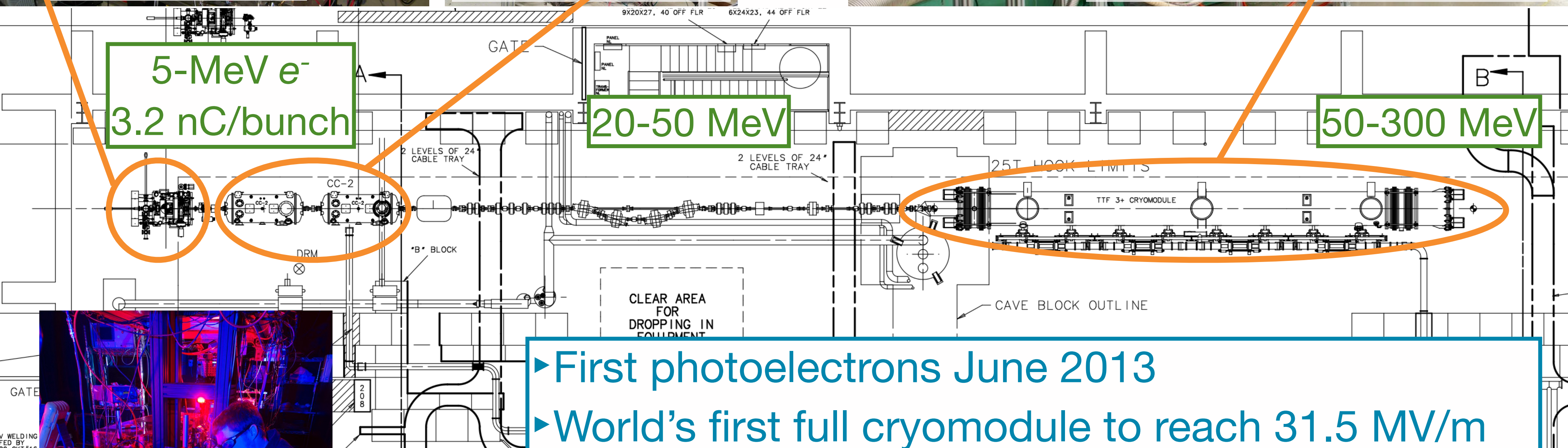


ASTA photoinjector

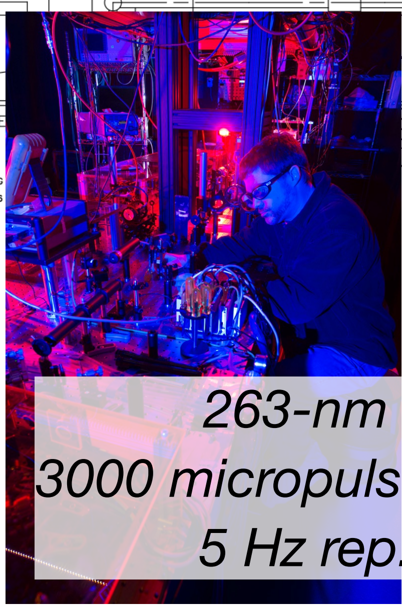






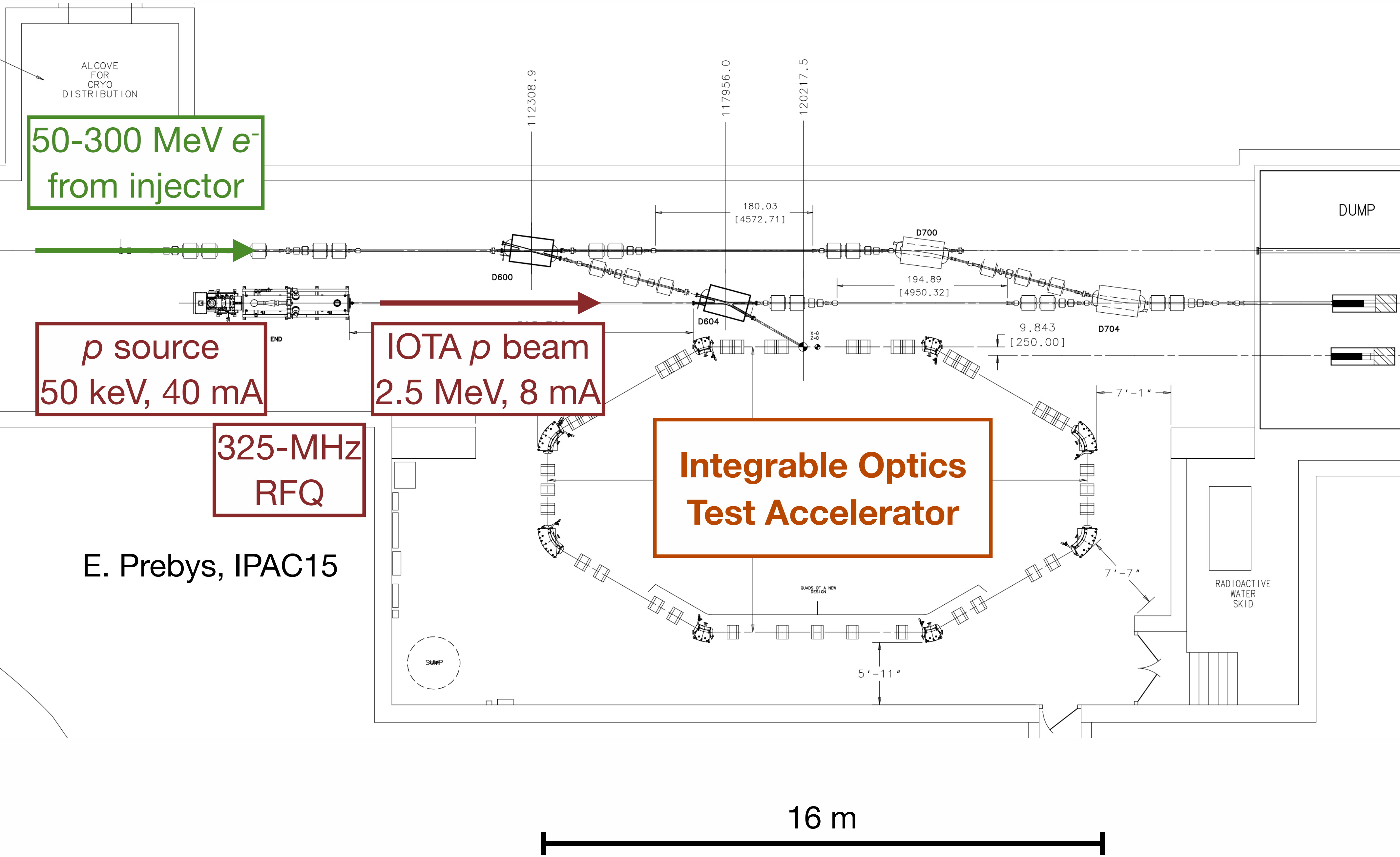


- First photoelectrons June 2013
- World's first full cryomodule to reach 31.5 MV/m average gradient (Oct 2014)
- 20-MeV beam line commissioning Mar-May 2015



D. Crawford et al., IPAC15

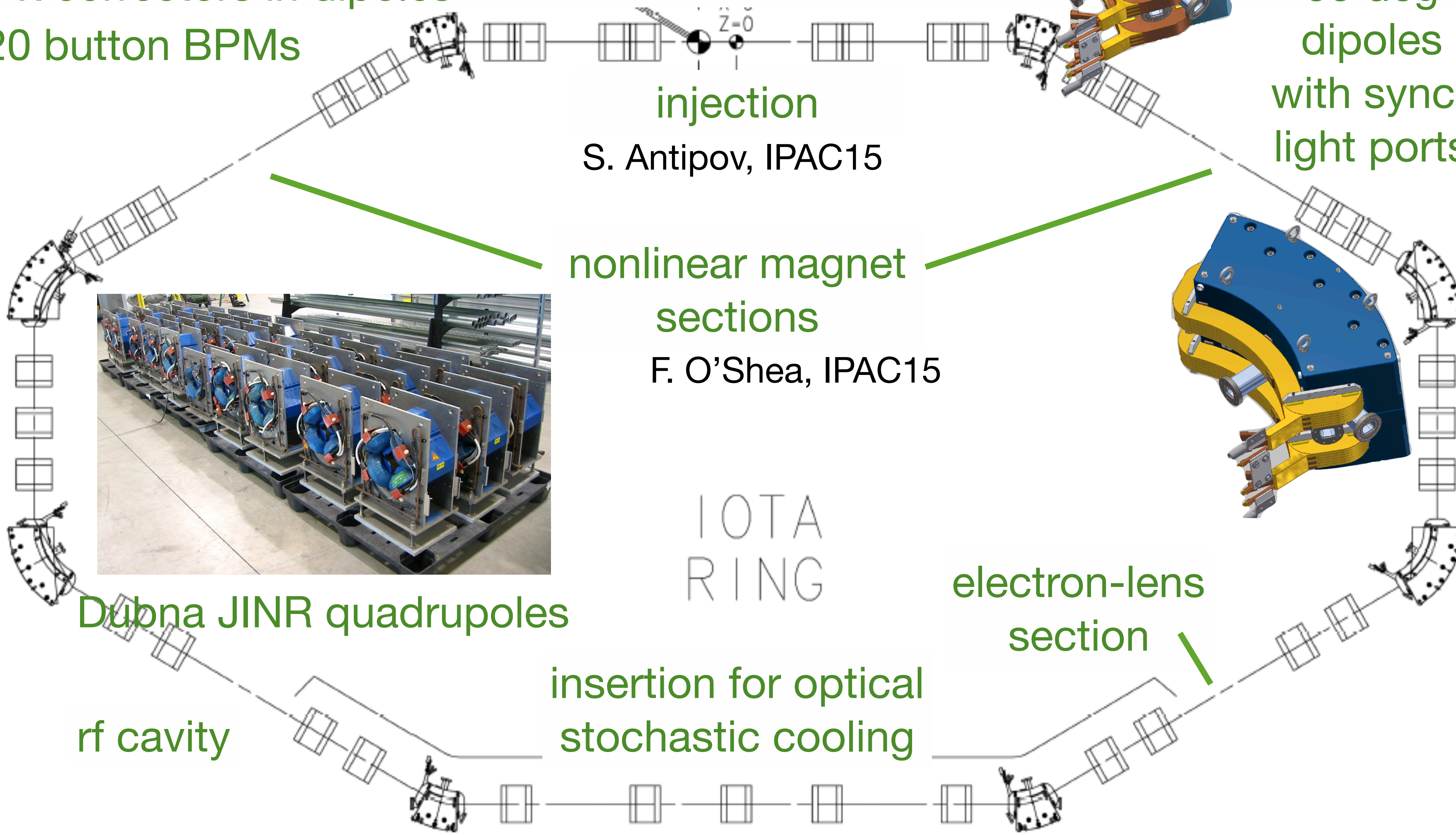
High-energy beam lines and IOTA (under construction)



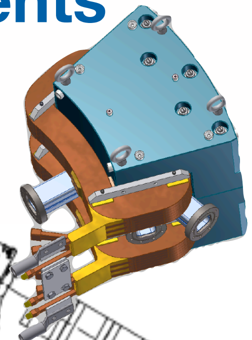
E. Prebys, IPAC15

IOTA layout and main components

20 x/y/skew correctors
8 x correctors in dipoles
20 button BPMs



injection
S. Antipov, IPAC15



30 deg and
60 deg
dipoles
with sync-
light ports

nonlinear magnet
sections
F. O'Shea, IPAC15

Dubna JINR quadrupoles

electron-lens
section

insertion for optical
stochastic cooling

rf cavity

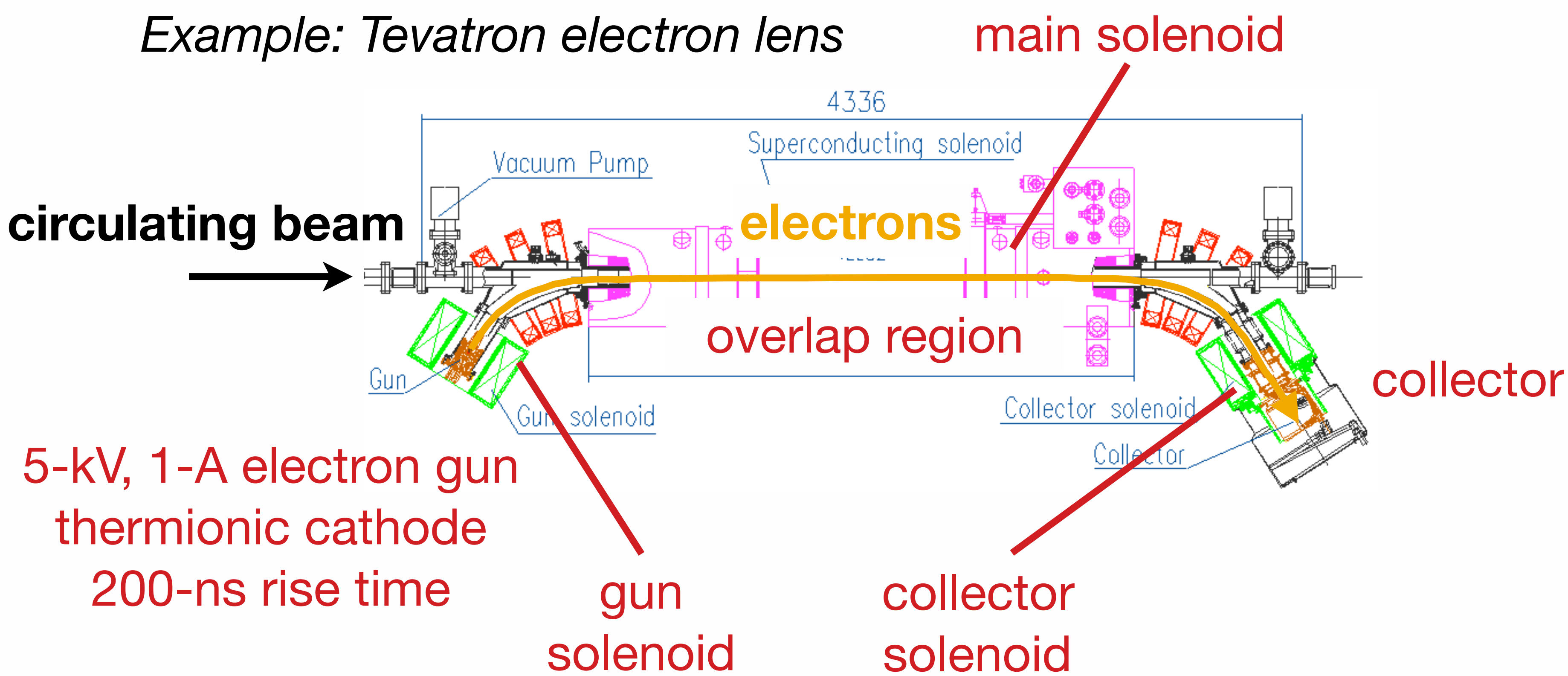
IOTA parameters for circulating electrons

e^- beam energy	150 MeV
gamma rel.	294.54
e^- beam intensity	10^9 particles, 1 bunch
circumference	40 m
revolution freq. / period	7.49 MHz / 0.133 μs
bend field	0.7 T
pipe diameter	50 mm
max. beta function h / v	12 m / 5 m
momentum compaction	0.02 — 0.1
betatron tune	3 — 5
natural chromaticity	-5 — -10
transverse rms emittance	10—40 nm
synch. rad. damping time	0.6 s (5×10^6 turns)
rf frequency	30 MHz (h = 4)
rf voltage	1 kV
synchrotron tune	$(2 - 5)\times10^{-4}$
rms bunch length	12 cm
rms momentum spread	1.4×10^{-4}

What's an electron lens?

- Pulsed, magnetically confined, low-energy electron beam
- Circulating beam affected by electromagnetic fields generated by electrons
- Current-density profile shaped by cathode and electrode geometry
- Stability provided by strong axial magnetic fields

Example: Tevatron electron lens



For IOTA, we will use a 0.5-T resistive solenoid in the overlap region

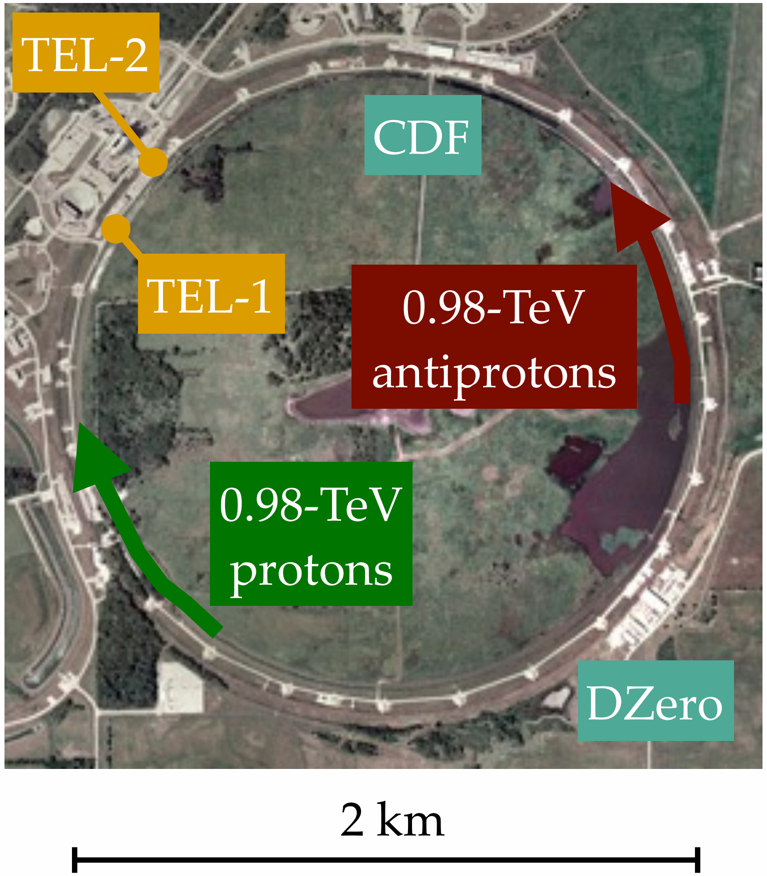
Shiltsev et al., Phys. Rev. ST Accel. Beams **11**, 103501 (2008)

Applications of electron lenses

In the Fermilab Tevatron collider

- ***long-range beam-beam compensation (tune shift of individual bunches)***
  - Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)
- ***abort-gap cleaning (for years of regular operations)***
  - Zhang et al., Phys. Rev. ST Accel. Beams **11**, 051002 (2008)
- ***studies of head-on beam-beam compensation***
  - Stancari and Valishev, FERMILAB-CONF-13-046-APC
- ***demonstration of halo scraping with hollow electron beams***
  - Stancari et al., Phys. Rev. Lett. **107**, 084802 (2011)

Tevatron electron lenses



Presently, used in RHIC at BNL for head-on beam-beam compensation, luminosity improvements

- G. Robert-Demolaize, X. Gu, IPAC15

Current areas of research

- ***generation of nonlinear integrable lattices*** in the Fermilab Integrable Optics Test Accelerator
- ***hollow electron beam scraping*** of protons in LHC
  - R. Bruce, IPAC15
- ***long-range beam-beam compensation*** as charged, current-carrying "wires" for LHC
  - A. Valishev, IPAC15
- to ***generate tune spread for Landau damping*** of instabilities before collisions in LHC

Nonlinear integrable optics with electron lenses

Use the electromagnetic field generated by the electron distribution to provide the desired nonlinear field.
Linear focusing strength on axis ~ 1/m: $k_e = 2\pi \frac{j_0 L (1 \pm \beta_e \beta_z)}{(B\rho)\beta_e \beta_z c^2} \left(\frac{1}{4\pi\epsilon_0} \right).$

1. Axially symmetric thin kick of McMillan type

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

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

achievable tune spread $\sim \frac{\beta k_e}{4\pi}$

Larger tune spreads in IOTA
More sensitive to kick shape

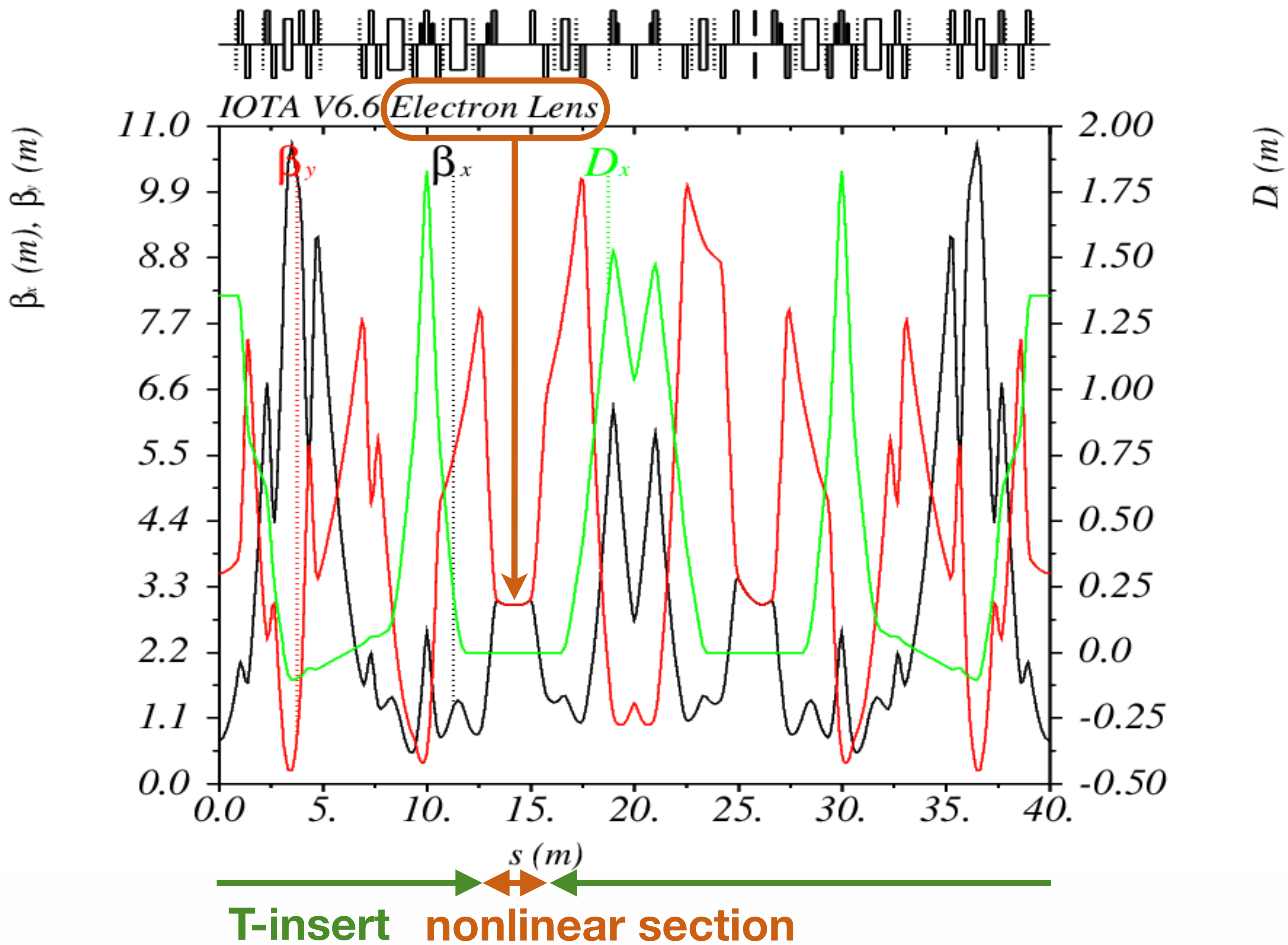
2. Axially symmetric kick in long solenoid

Any axially-symmetric current distribution

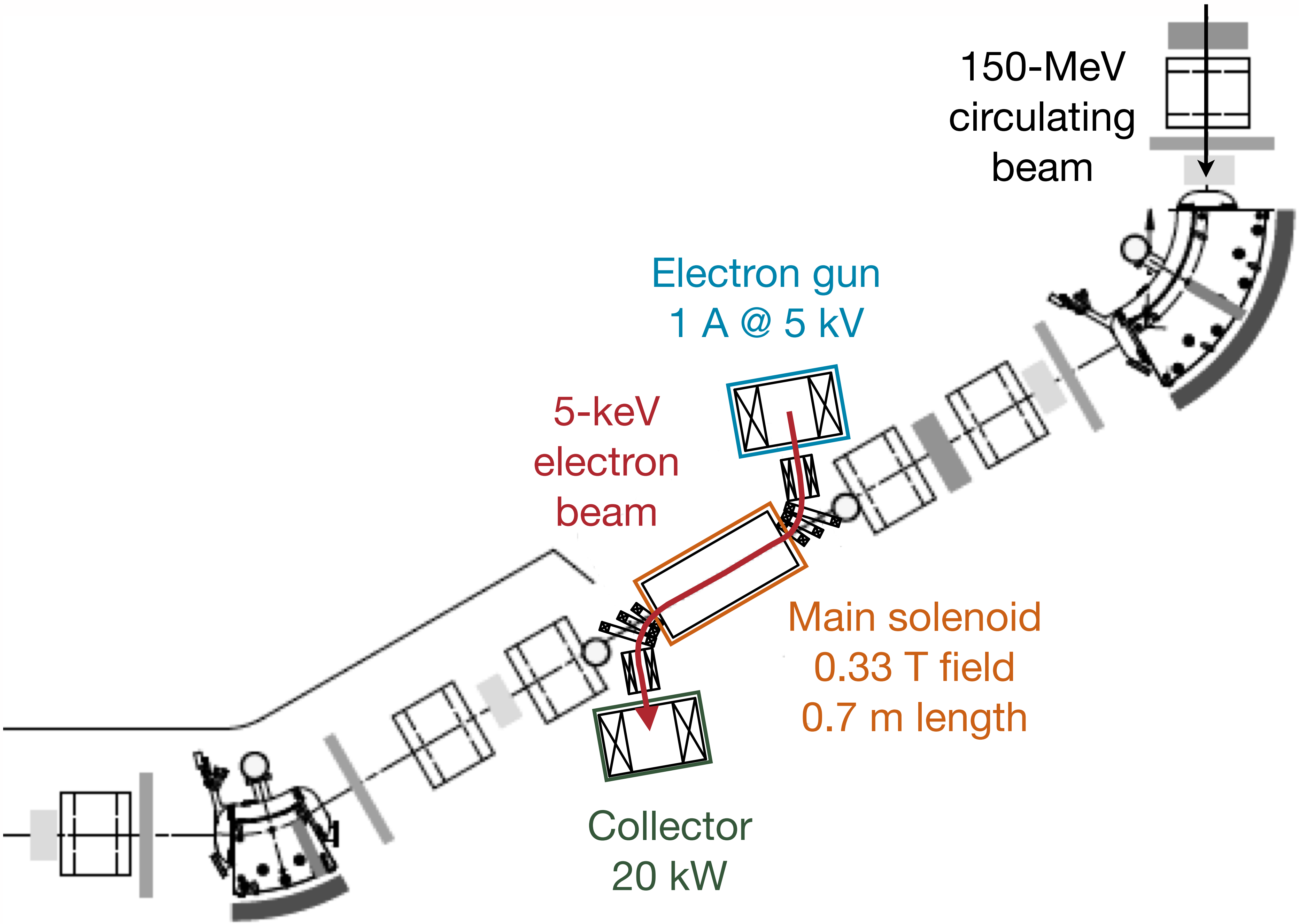
$$\sim \frac{L}{2\pi\beta} = \frac{L B_z}{4\pi (B\rho)}$$

Smaller tune spreads in IOTA
More robust

IOTA lattice with electron lens



Electron-lens layout in IOTA

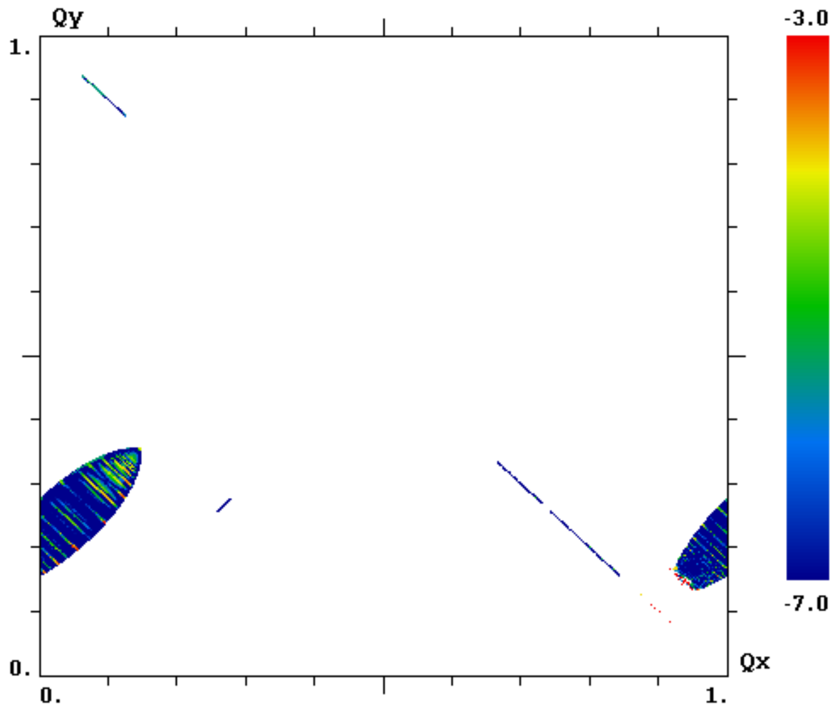


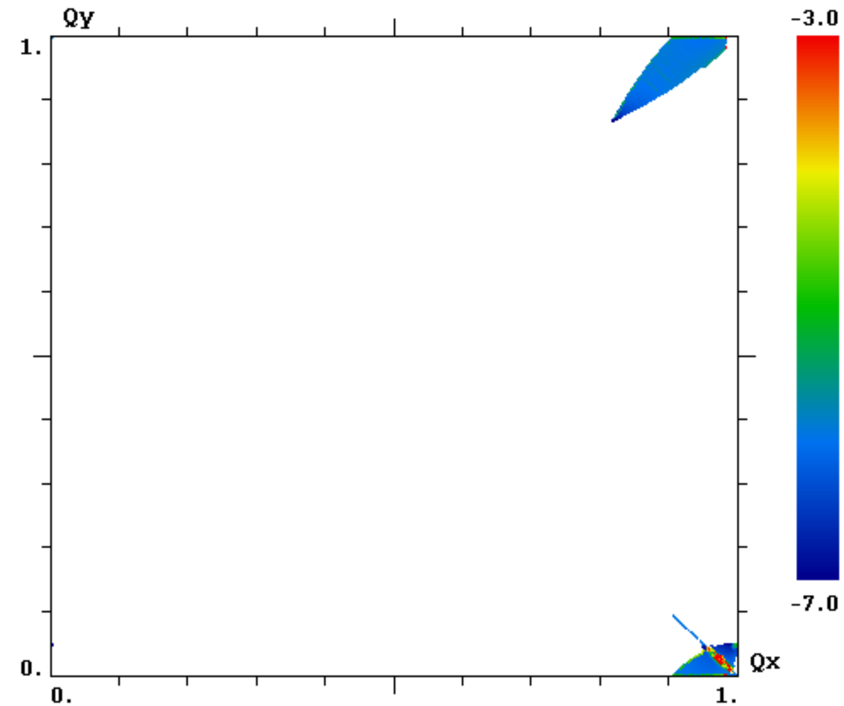
First feasibility studies: tracking and stability

1. Axially symmetric thin-lens kick (extended McMillan case)

2. Axially symmetric time-independent Hamiltonian with thick lens

Frequency-map analysis: tune jitter in tune space



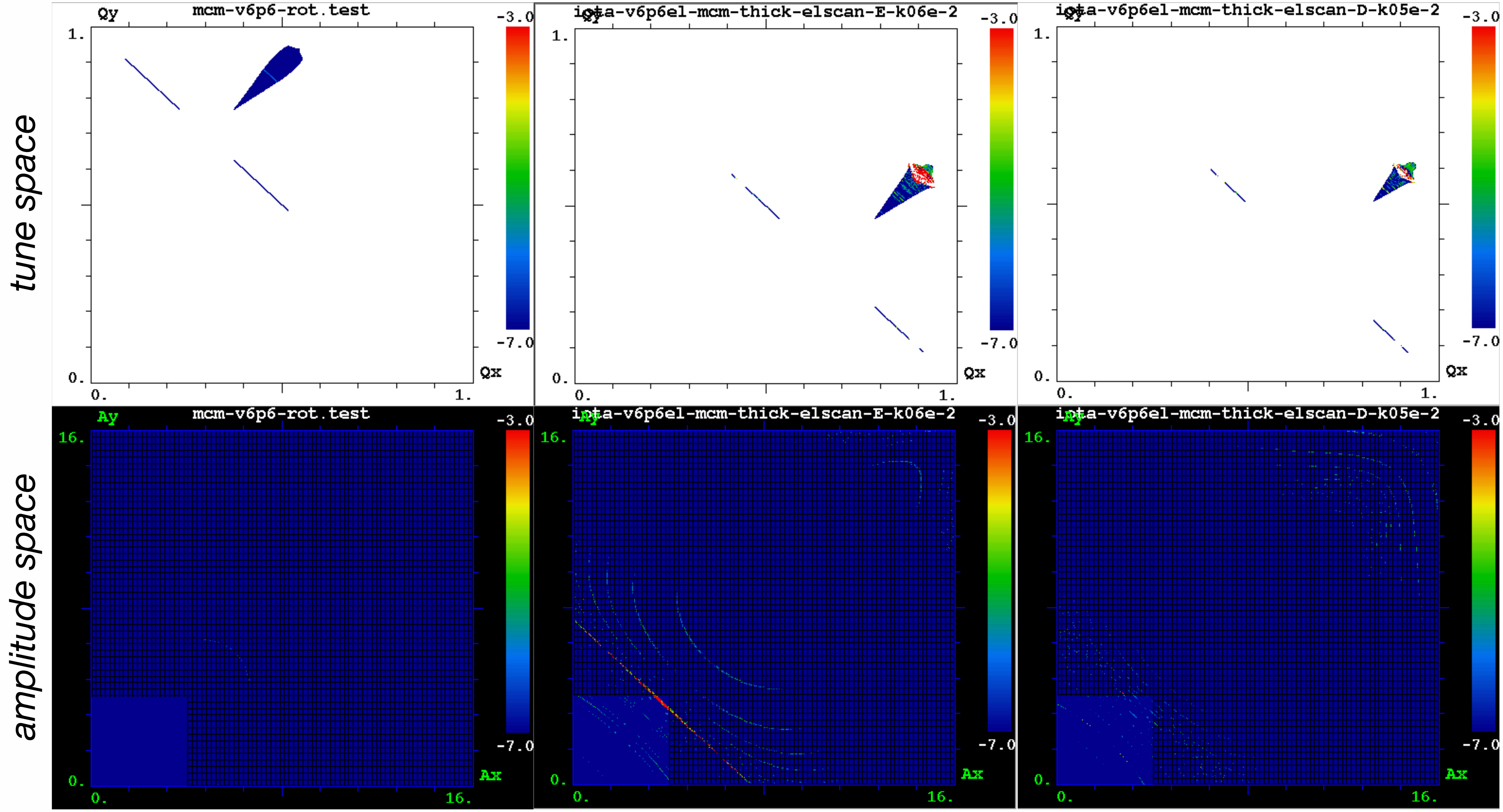


In both cases

- there are 2 transverse invariants
- the beam can cross integer resonances without particle loss

Frequency map analysis of McMillan electron-lens kicks in IOTA

ideal case: thin kick, no solenoid   *electron lens with 0.7-m solenoid*

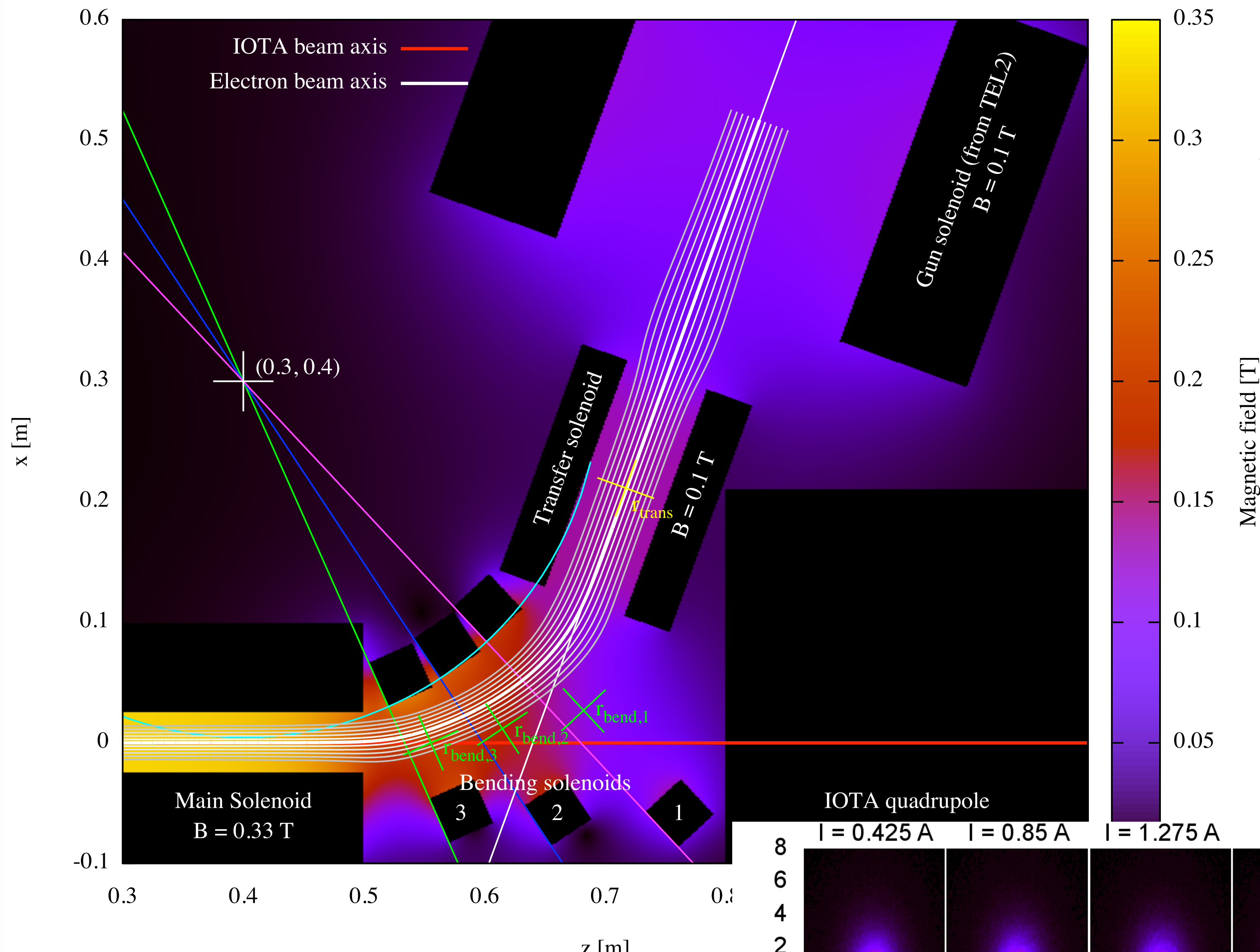


focusing strength k_e [1/m]: 0.6 (1 A)   *0.6*   *0.5*

Typical tune spread of ~0.2

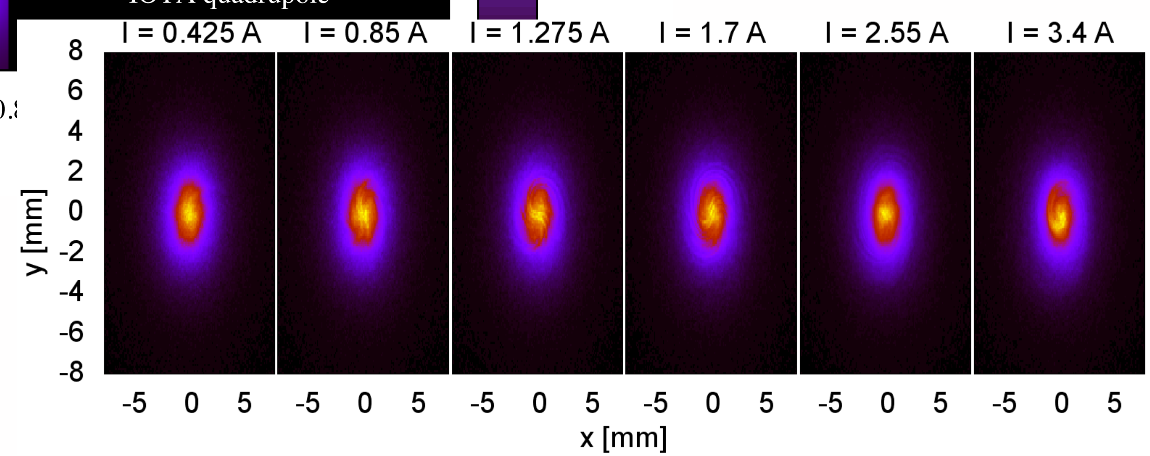
No particle loss

Design of beam transport in electron lens



1. Field-line mapping
2. Single-particle tracking
3. Tracking with space charge

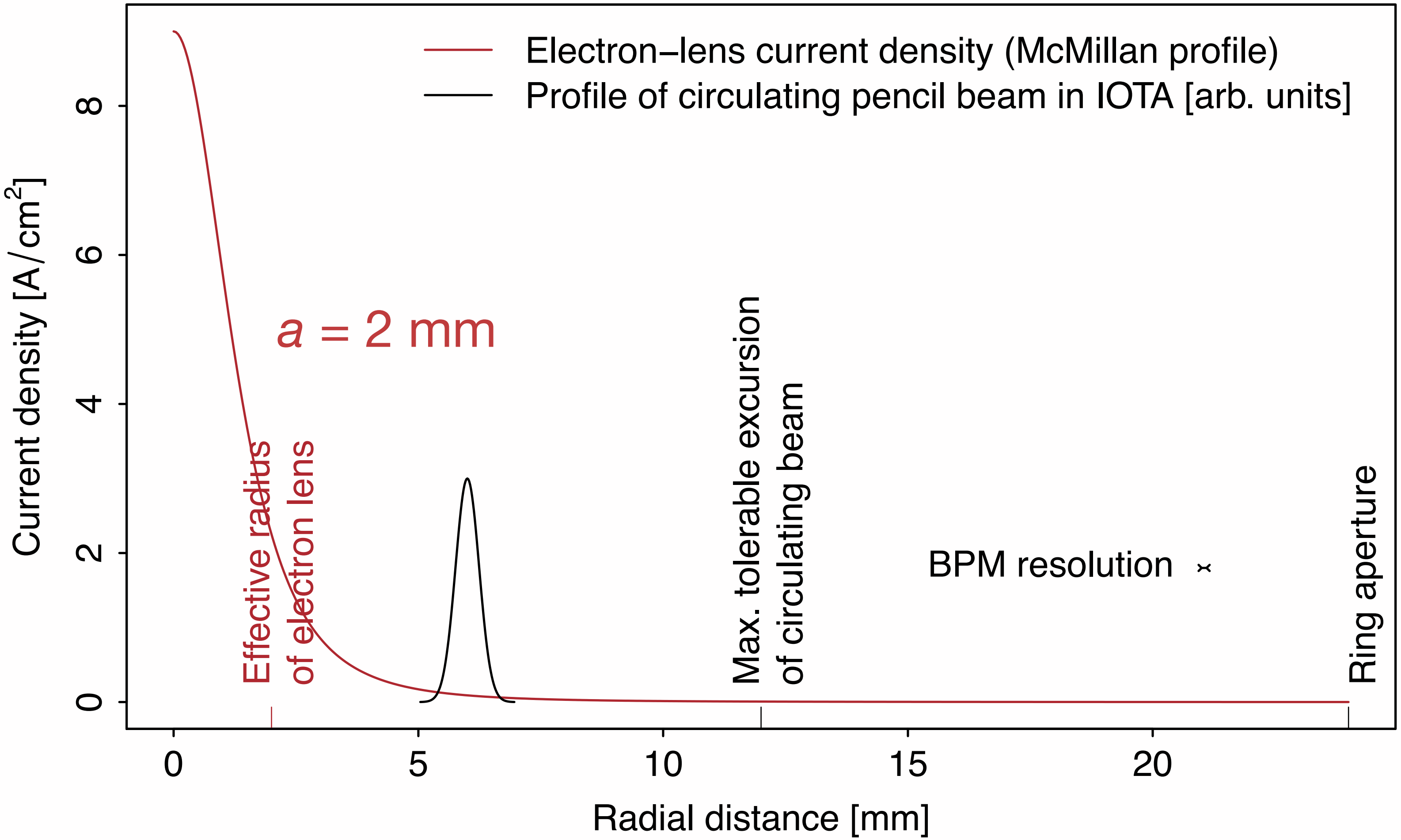
D. Noll



Minimize distortions
Provide input for tracking in ring

Choice of electron-lens beam size for IOTA

Beam size in electron lens should allow the circulating pencil beam to sample a wide range of tunes, taking aperture and BPM resolution into account



small betatron amplitude: maximum detuning

large betatron amplitude: negligible detuning

Typical IOTA electron-lens parameters

Amplitude function	3 m
Circulating beam size (rms)	0.24 mm
Main solenoid length	0.7 m
Main solenoid field	0.33 T
Gun/collector solenoids	0.1 T
Cathode-anode voltage	5 kV
Beam current	1.1 A
Max. current density in overlap region	9 A/cm^2
Effective radius in overlap region	2 mm
Max. radius in overlap region	12 mm
Effective radius at cathode	3.6 mm
Max. radius at cathode	22 mm

Next steps

Several effects need to be accurately studied, for instance:

- lattice deviations from ideal case
- impact of chromaticity-correction sextupoles on integrability
- azimuthal asymmetries in electron-lens kicks
- accuracy of beam profile at electron gun
- chromatic effects of the electron lens
- misalignments

These studies will be based on numerical simulations and on experiments at the Fermilab electron-lens test stand

see also
S. Webb, IPAC15
K. Ruisard, IPAC15

Summary and conclusions

- Among the goals of beam-physics research at Fermilab are:
  - to address the **high-intensity** requirements of particle physics for advancing the knowledge of **neutrinos** and **rare processes**
  - to investigate the feasibility, benefits, and robustness of **transverse nonlinear integrable optics in a real machine**
  - to study **space-charge dynamics** and mitigation in circular machines
  - to provide **education** in beam physics and accelerator technology
- The **Integrable Optics Test Accelerator (IOTA)** was designed
  - to store both **150-MeV** e^- or **2.5-MeV** p
  - to provide flexible lattices and diagnostics for **nonlinear integrable optics with magnets** and **electron lenses**, and for other fundamental experiments
- **Electron lenses** may provide a flexible way to implement nonlinear integrable lattices in accelerators
  - basic concepts and expected performance were studied
  - parameters are within the present state of the art
  - more theory, modeling, and experiments are needed and planned
- New **collaborators** and **ideas** are always welcome. Also, Fermilab currently has a few **job openings** in accelerator physics for researchers who may be interested.

Thank you for your attention!

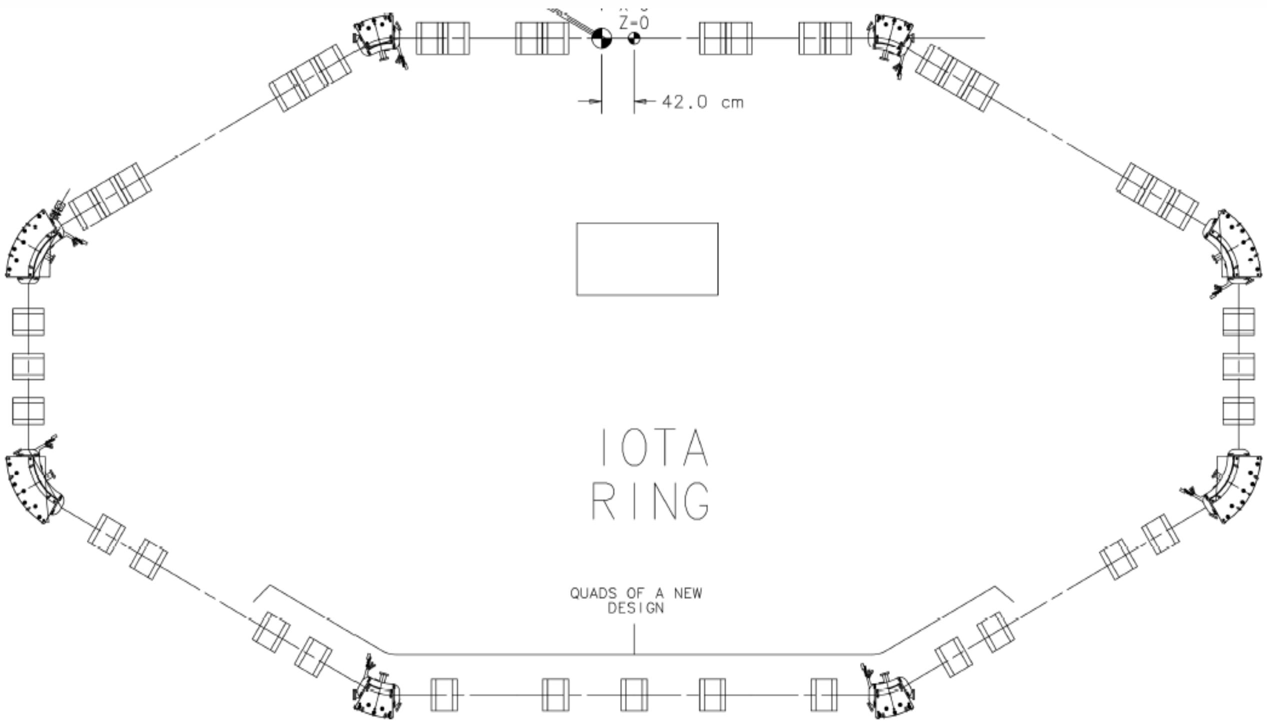
Backup slides

Integrable Optics Test Accelerator (IOTA)

Is it possible to design a highly nonlinear lattice with large dynamic aperture and a correspondingly wide tune spread to avoid instabilities?

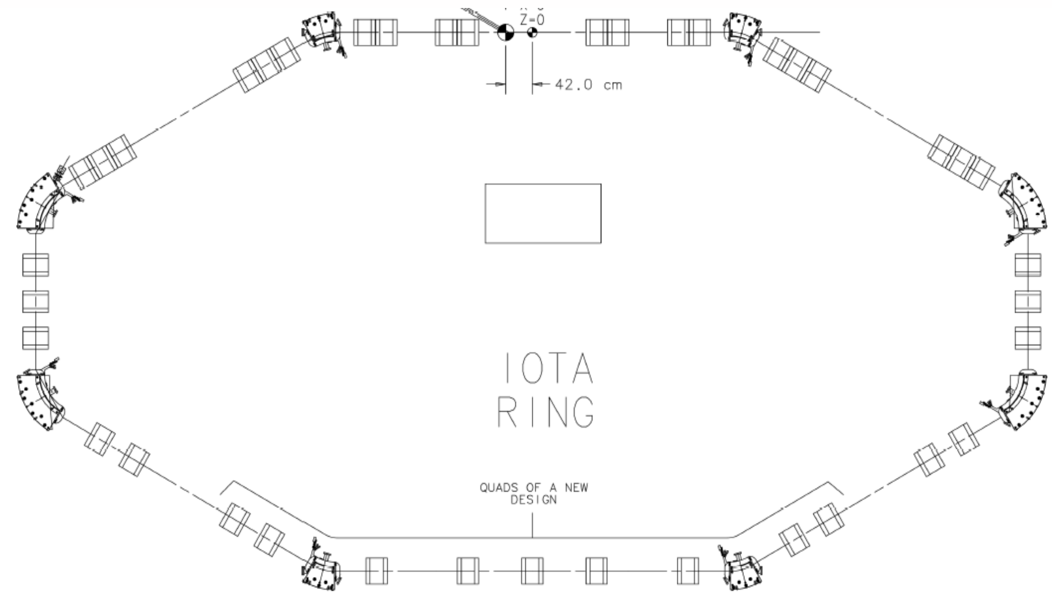
IOTA project goal: demonstrate ~0.25 nonlinear tune spread without loss of dynamic aperture <u>in a real machine</u>

50 – 150 MeV e^- beams; 10^9 e^-/bunch
40 m circumference
flexible lattice and diagnostics



IOTA design criteria

- Lattice flexibility
  - 1 or 2 nonlinear magnets (2 m each)
  - 1 electron lens (2 m long)
  - round "thin quadrupole" sections with $n\pi$ phase advance ("T-inserts")
  - optical stochastic cooling experiment (5 m undulators and chicane)
- Constraints
  - large aperture (50 mm diam.) to sample nonlinearities with pencil beam
  - horizontal and vertical kicker for phase-space painting
  - accept both 150-MeV electrons or 2.5-MeV protons
  - space and cost



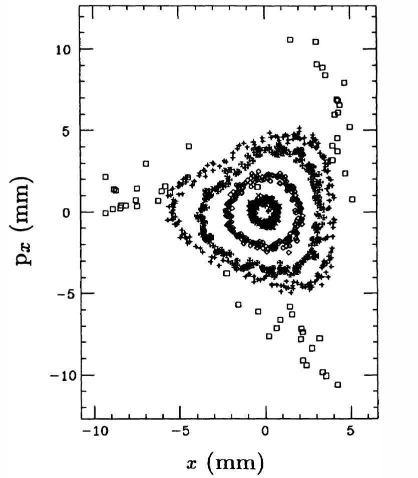
IOTA experimental program

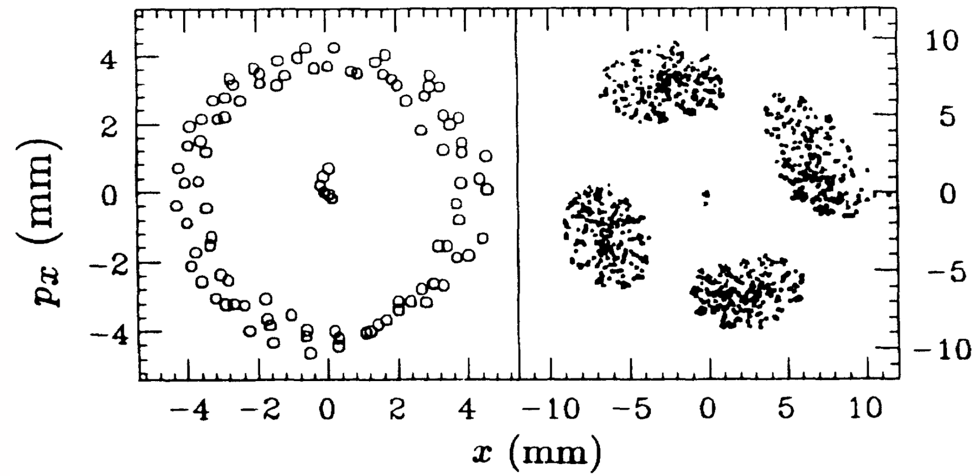
- **Single-particle motion with electron beams (Phase I)**
  - measure and control **closed orbit and lattice** with required precision
  - implement
    - quasi-integrable optics with **octupoles** and
    - integrable optics with **nonlinear magnets** and **electron lens**
  - **kick electron bunch transversely** and **record turn-by-turn intensities, beam positions, and sync-light profiles**
  - paint aperture to measure **detuning vs. amplitude** and **dynamic aperture** (synchrotron damping helps to cover available phase space)
  - **cross resonances** without loss of intensity
  - **test robustness** of nonlinear system against perturbations and imperfections
- Main goal: achieve 0.25 tune shift without loss of dynamic aperture

From linear lattice to nonlinear dynamics

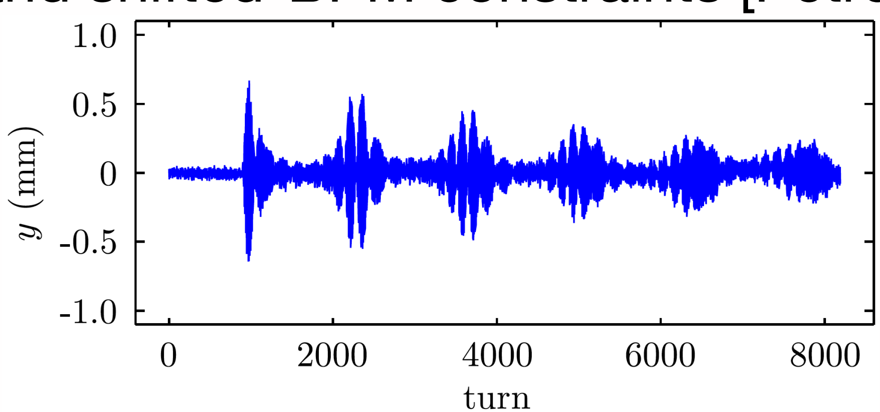
After establishing precise linear lattice, main goal is to observe detuning and lifetime vs. amplitude. Some measurements will be based on experimental techniques used at IUCF Cooler Ring and Fermilab Tevatron

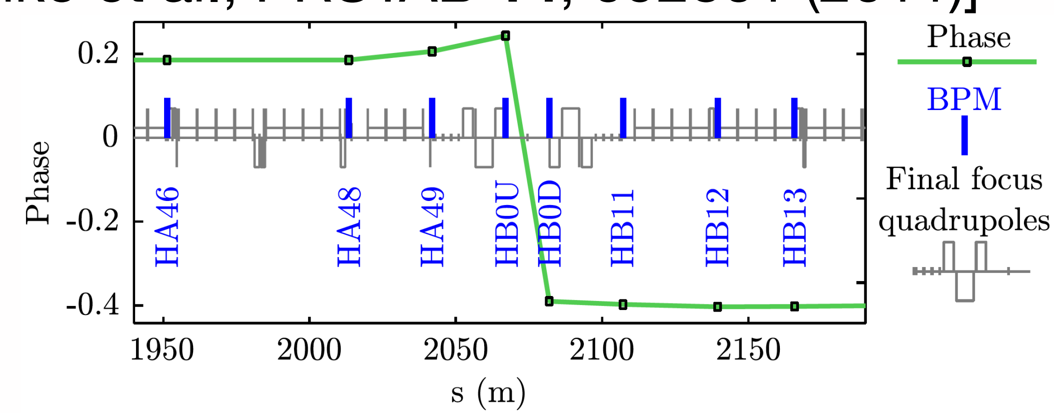
Experimental Poincaré maps at IUCF [e.g., Caussyn et al., PRA **46**, 7942, (1992)]





Model-independent analysis of Tevatron turn-by-turn data, including coupling and shifted-BPM constraints [Petrenko et al., PRSTAB **14**, 092801 (2011)]





IOTA experimental program

- <u>**Proton injection (Phase II)**</u>
  - inject **2.5-MeV protons** from RFQ
  - achieve **0.6 space charge tune shift**
  - investigate **integrable optics with protons and space charge**
  - study **space-charge dynamics**
  - **space-charge compensation** experiments with **electron columns**

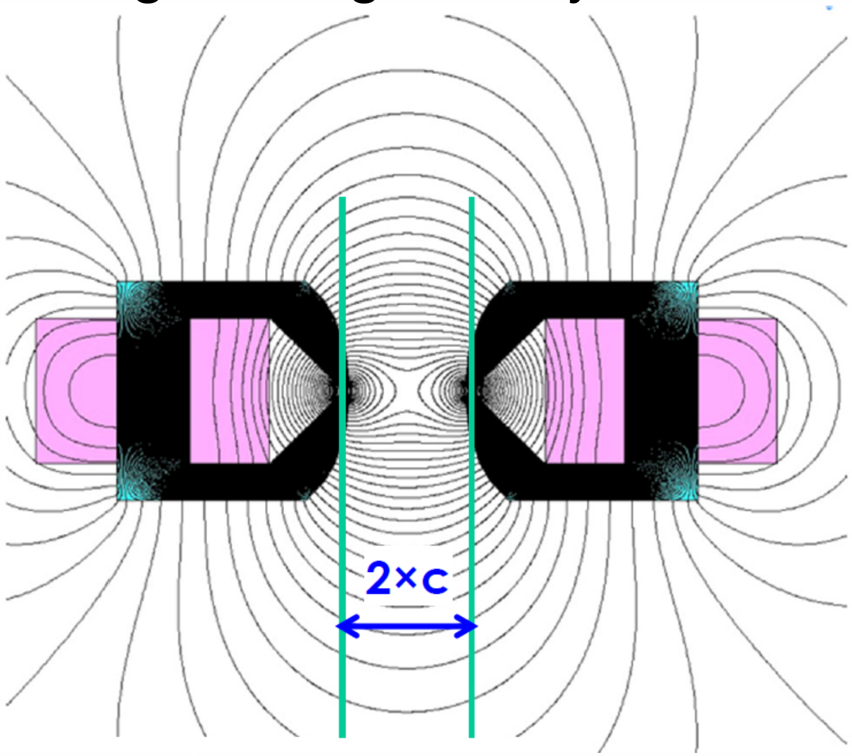
- Other experiments under consideration
  - optical stochastic cooling demonstration
  - electron wave function and radiation emission

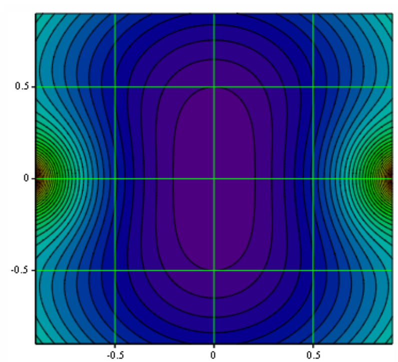
Schedule and plans

- 2015–2017
    - complete ASTA injector
    - start research program with injector
    - build IOTA
    - commission proton injector
    - commission IOTA with electrons
    - single-particle dynamics experiments with electrons
- 2018–2020
    - commission IOTA with protons
    - first space-charge experiments
- 2021 —
    - apply results to next generation of high-intensity machines
    - expand program to serve accelerator and particle physics communities

The nonlinear magnet

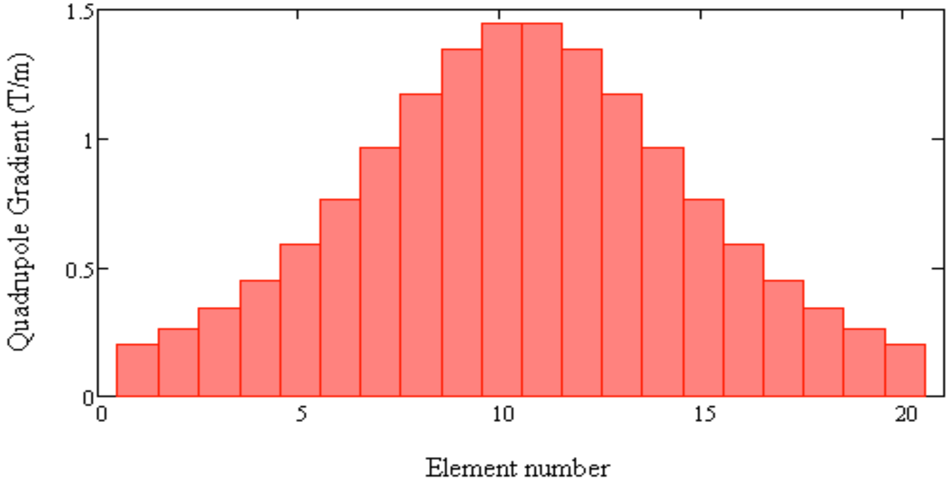
The nonlinear element is a special multipole with longitudinally dependent strength and geometry



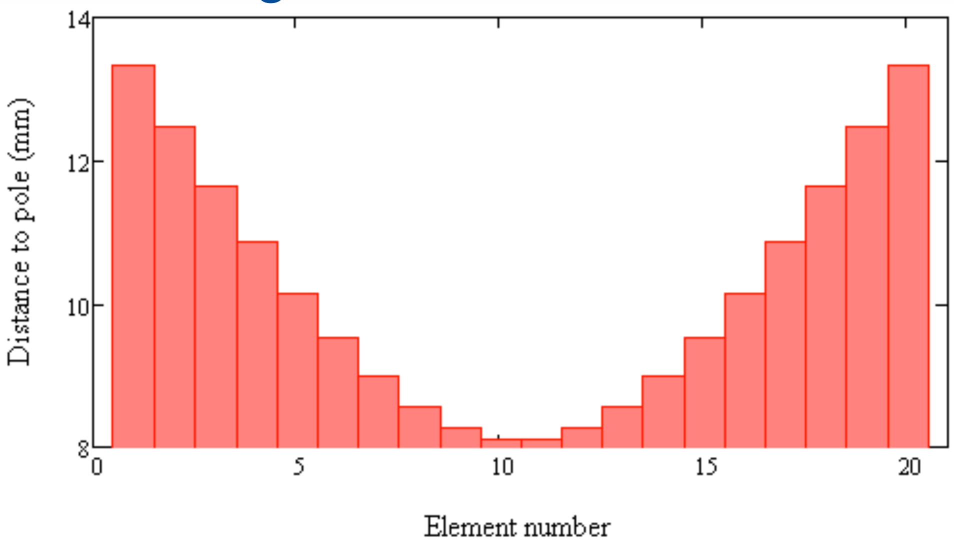


Magnetic field and potential

Quadrupole component vs. longitudinal coordinate

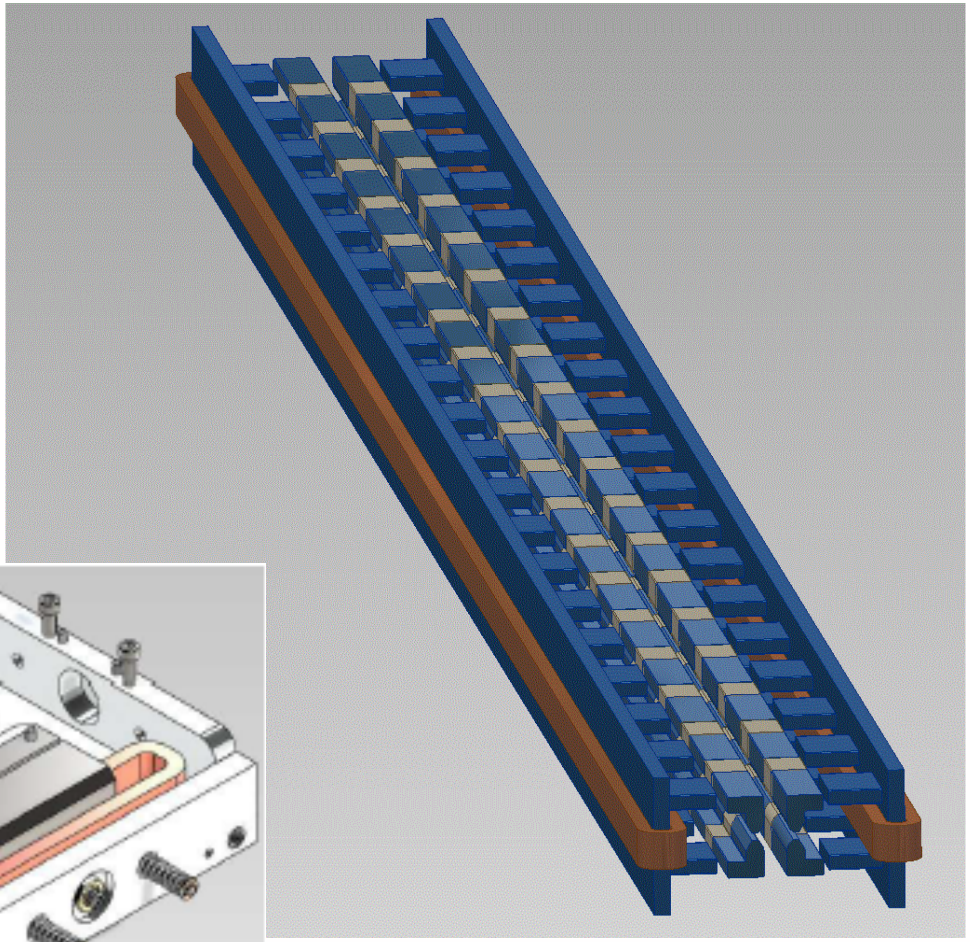


Pole distance vs. longitudinal coordinate



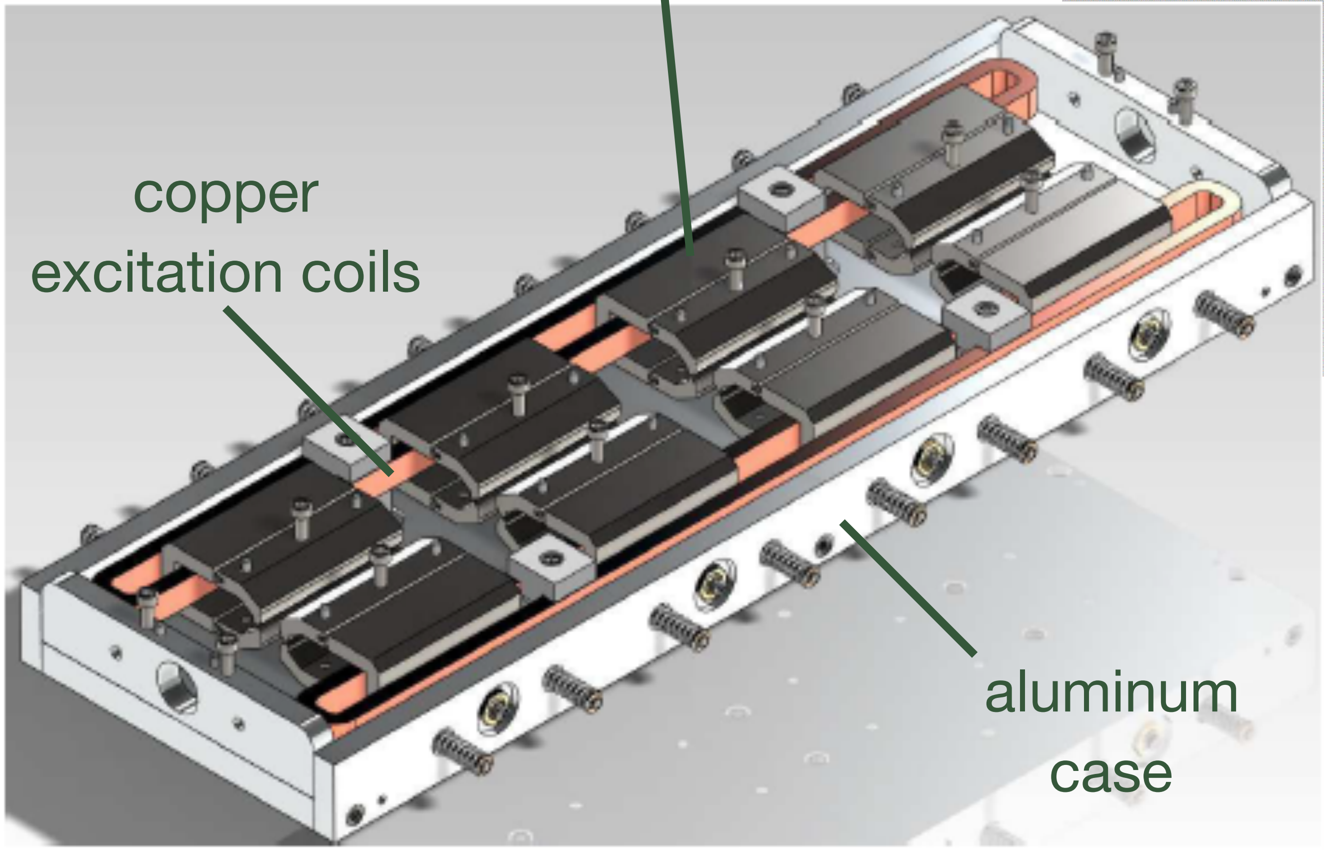
The nonlinear magnet

Fermilab design with 20 segments



stainless-steel poles and return yokes

copper excitation coils



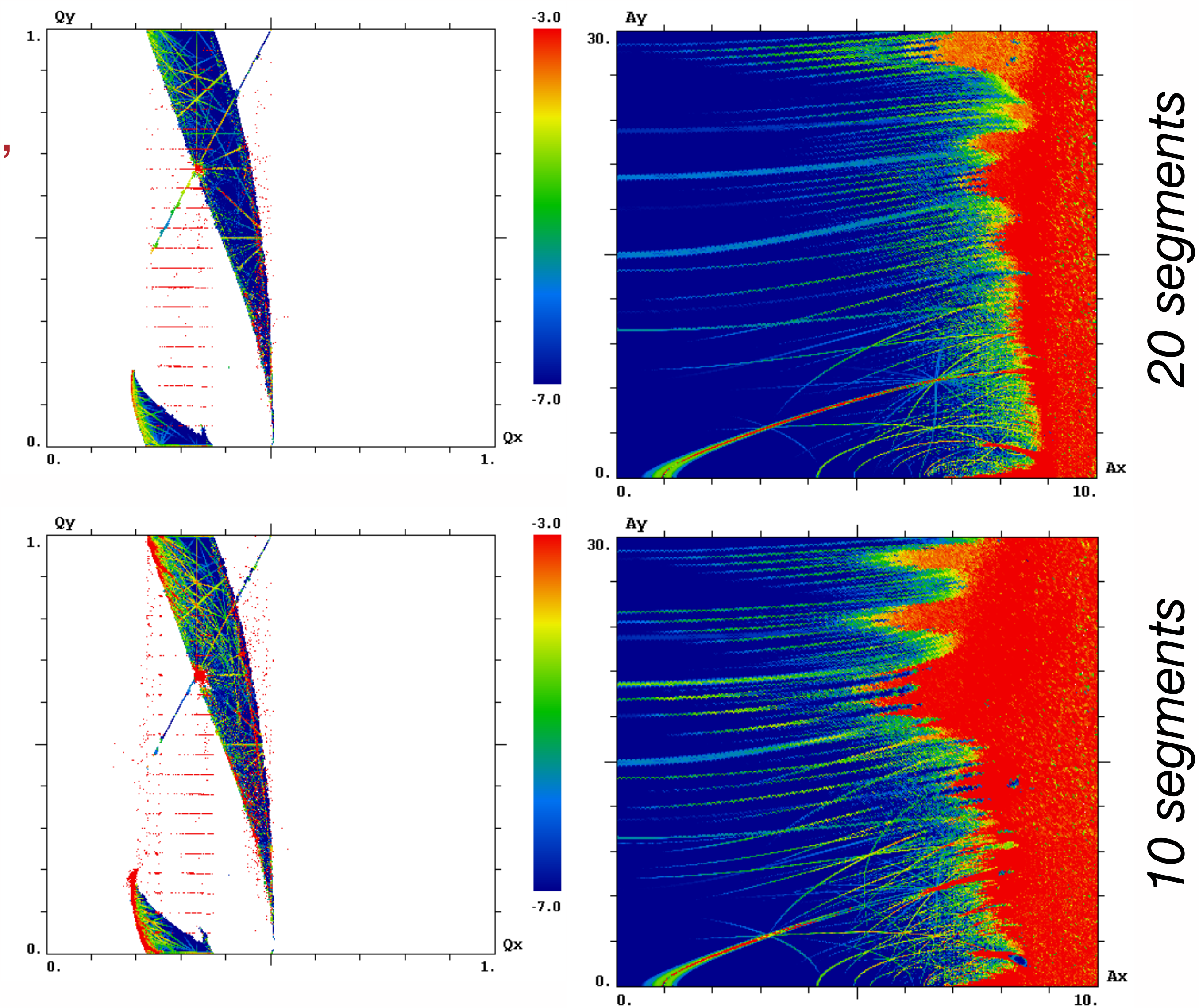
aluminum case

Radiabeam prototype with 4 segments

Tracking simulations with nonlinear magnets

Frequency-map analysis in tune and amplitude spaces (`Lifetrac` code)

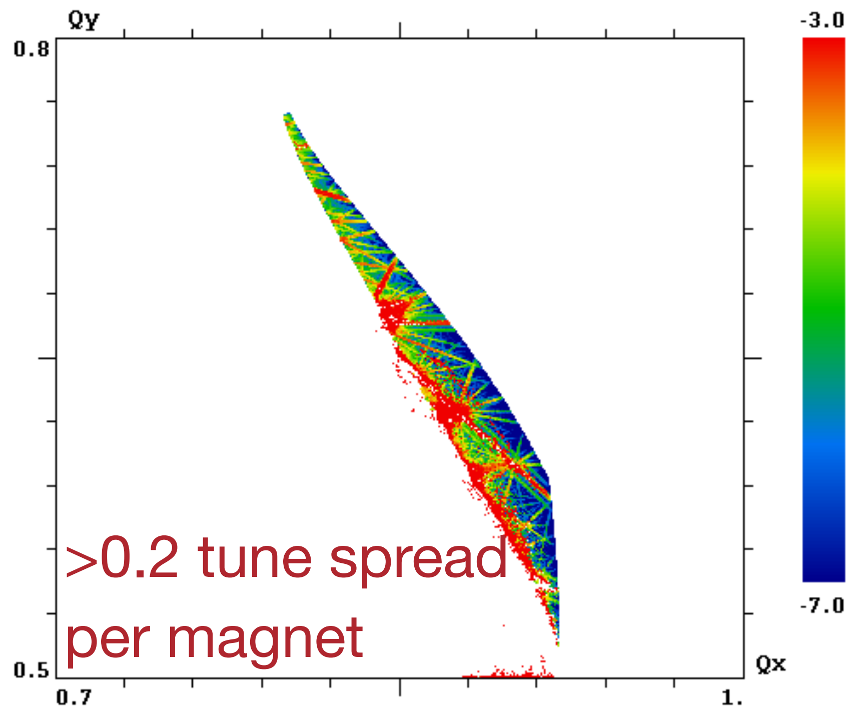
Very large tune spread, crossing integer resonance, with no lifetime degradation

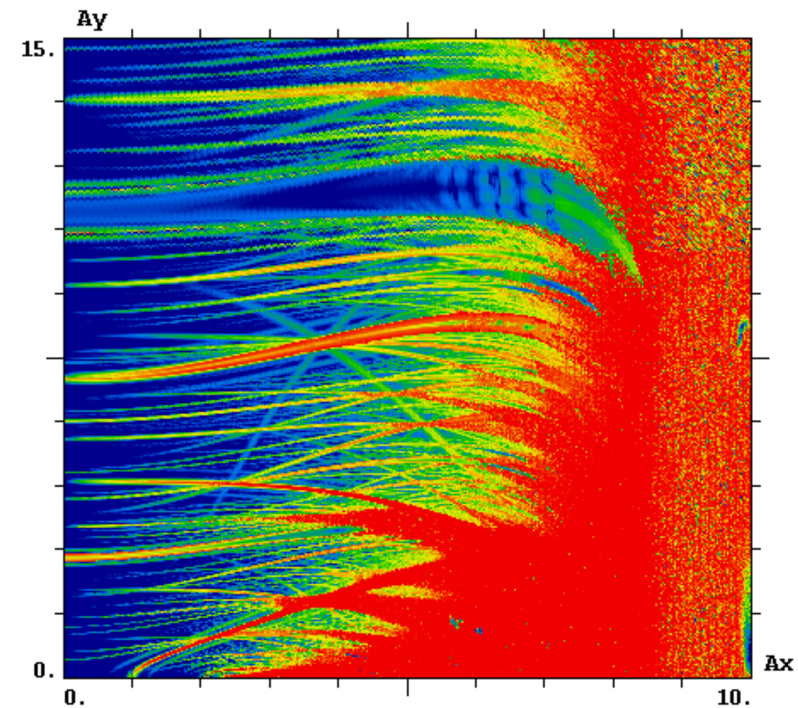


No resonance overlap, stochastic layers, or diffusion

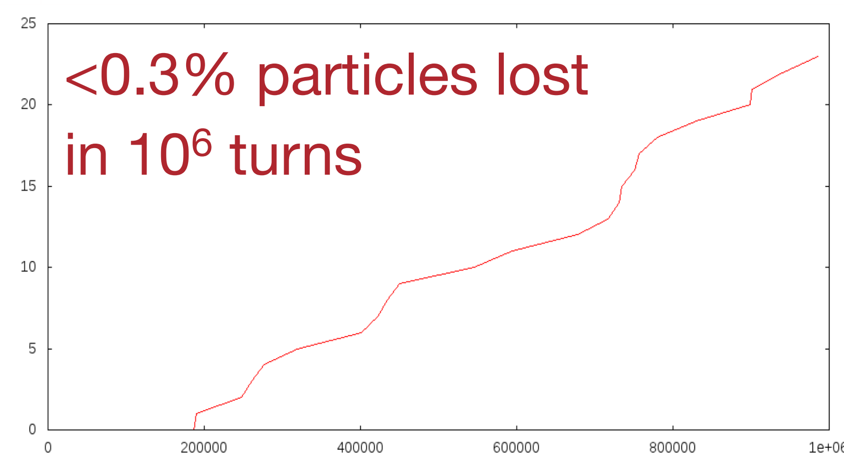
Tracking with imperfections

Including misalignments, tilts, gradient errors, lattice imperfections

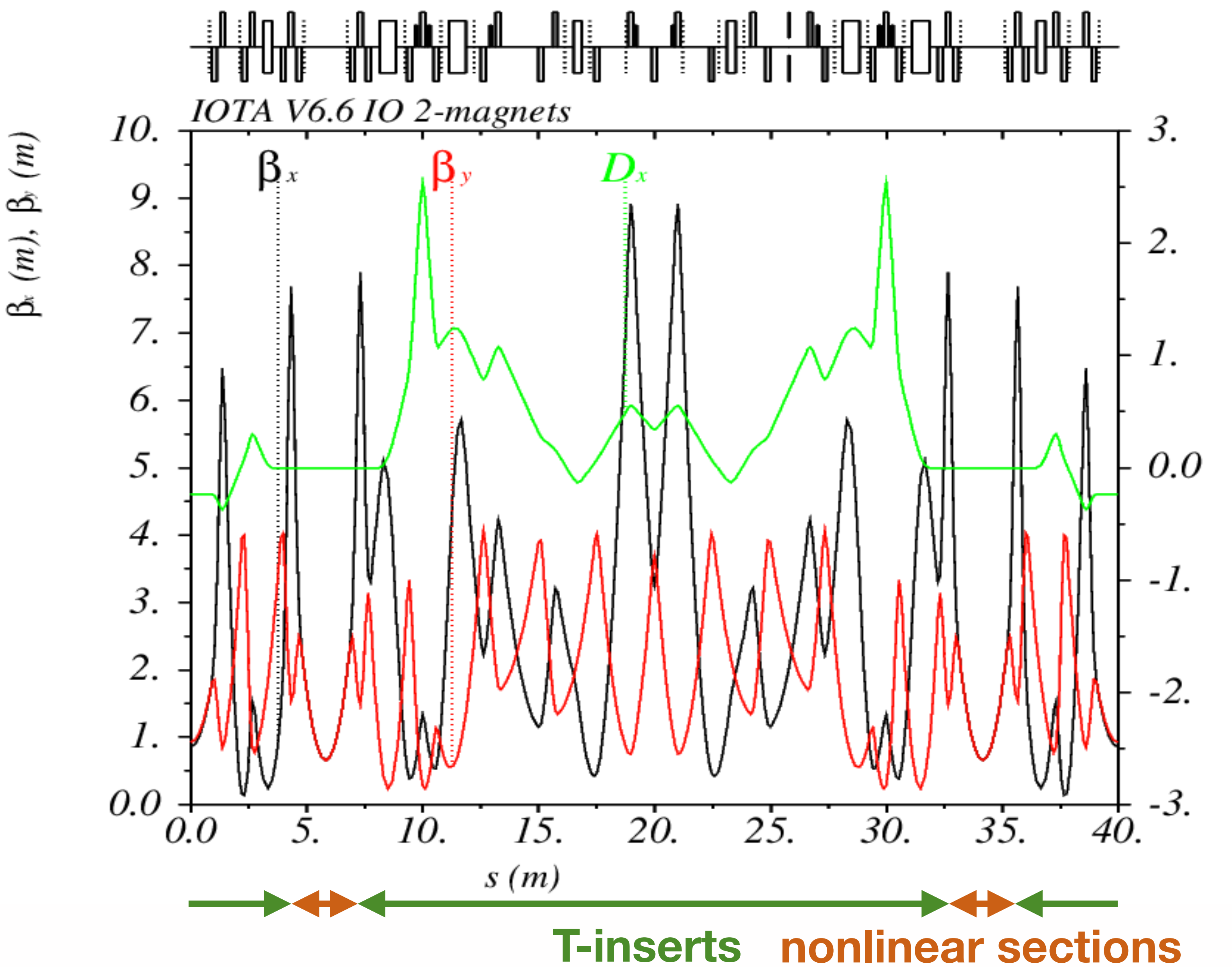




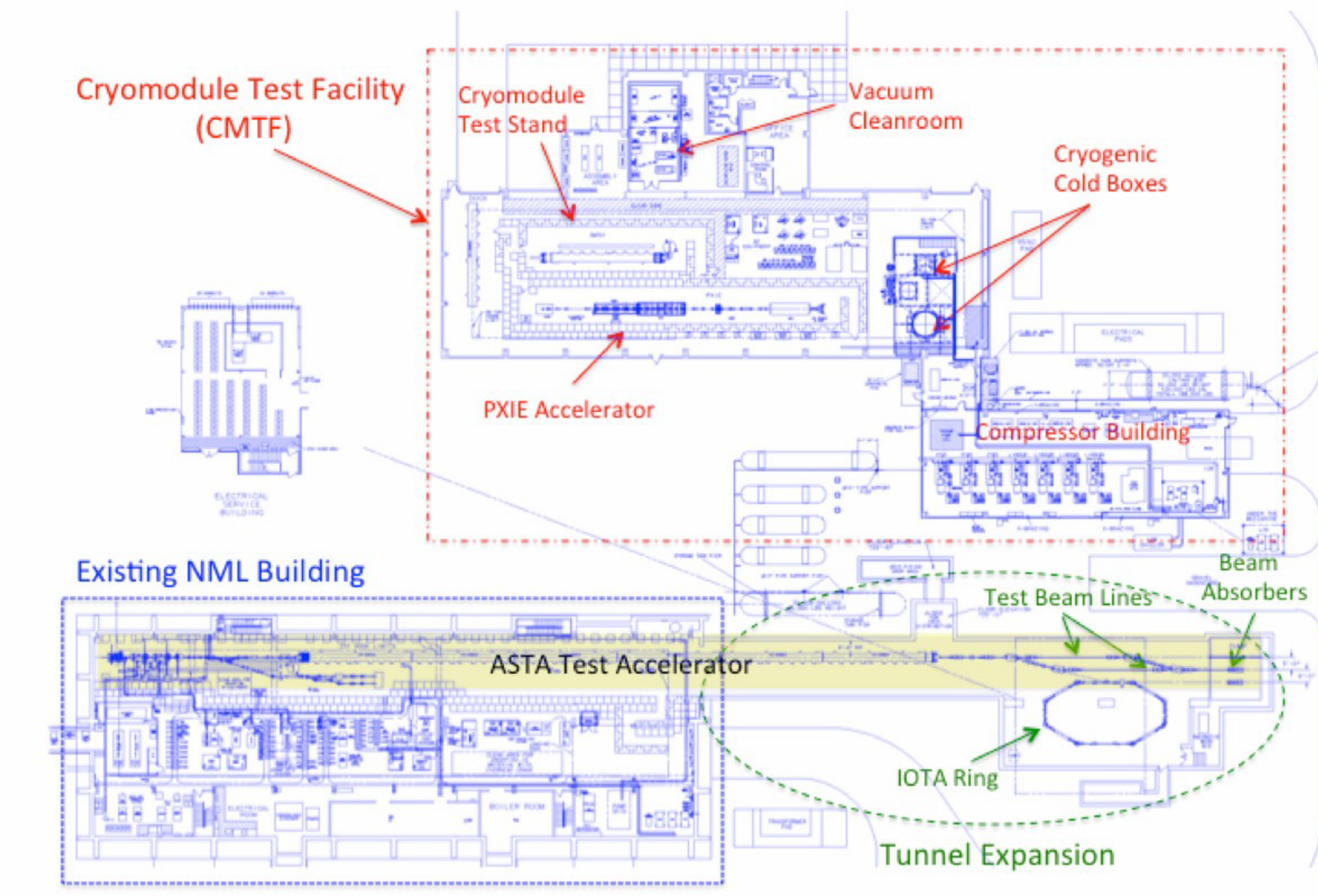
Simulations suggest that a proof-of-principle experiment to demonstrate large tune spreads with acceptable lifetimes is feasible



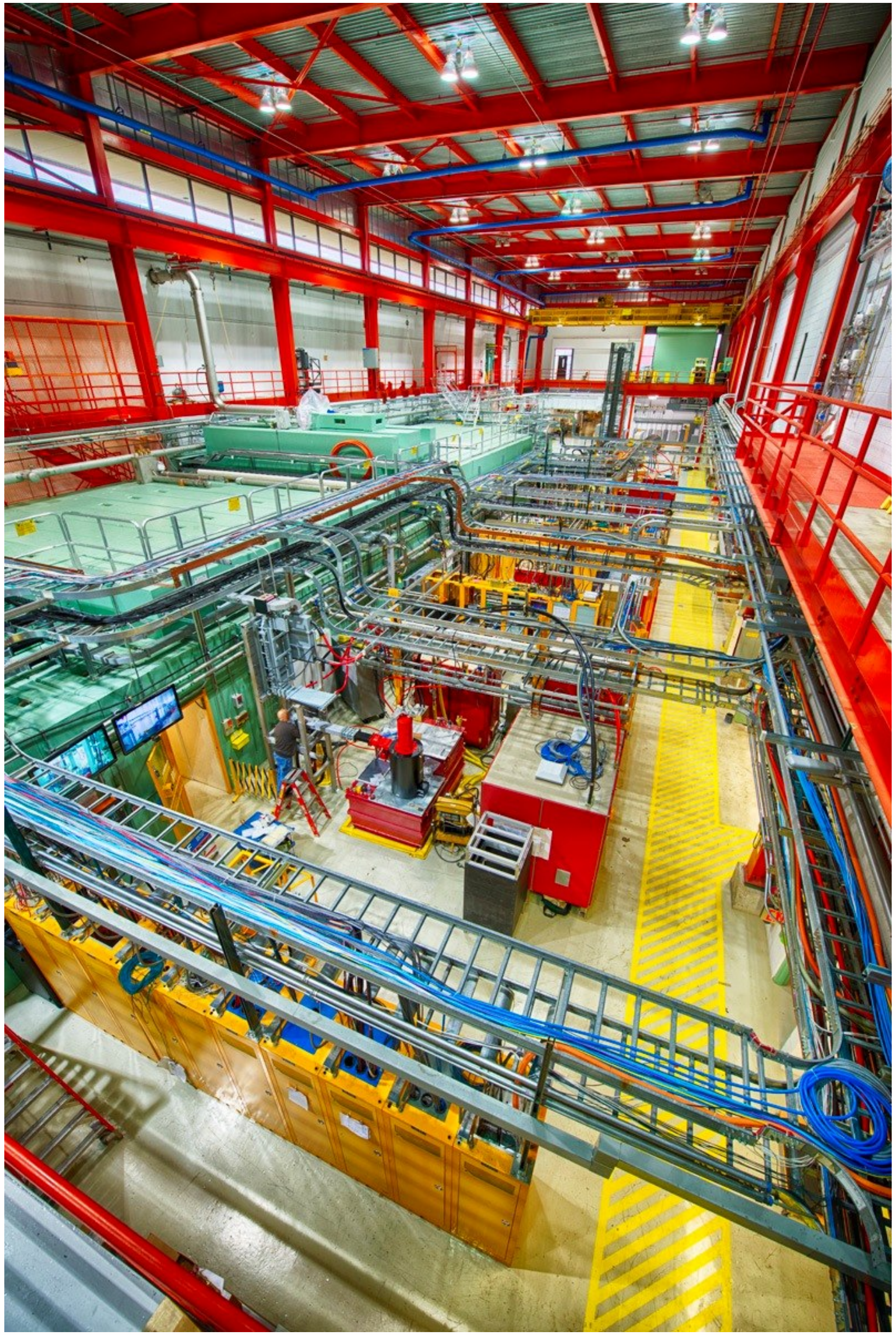
IOTA lattice with 2 nonlinear magnets

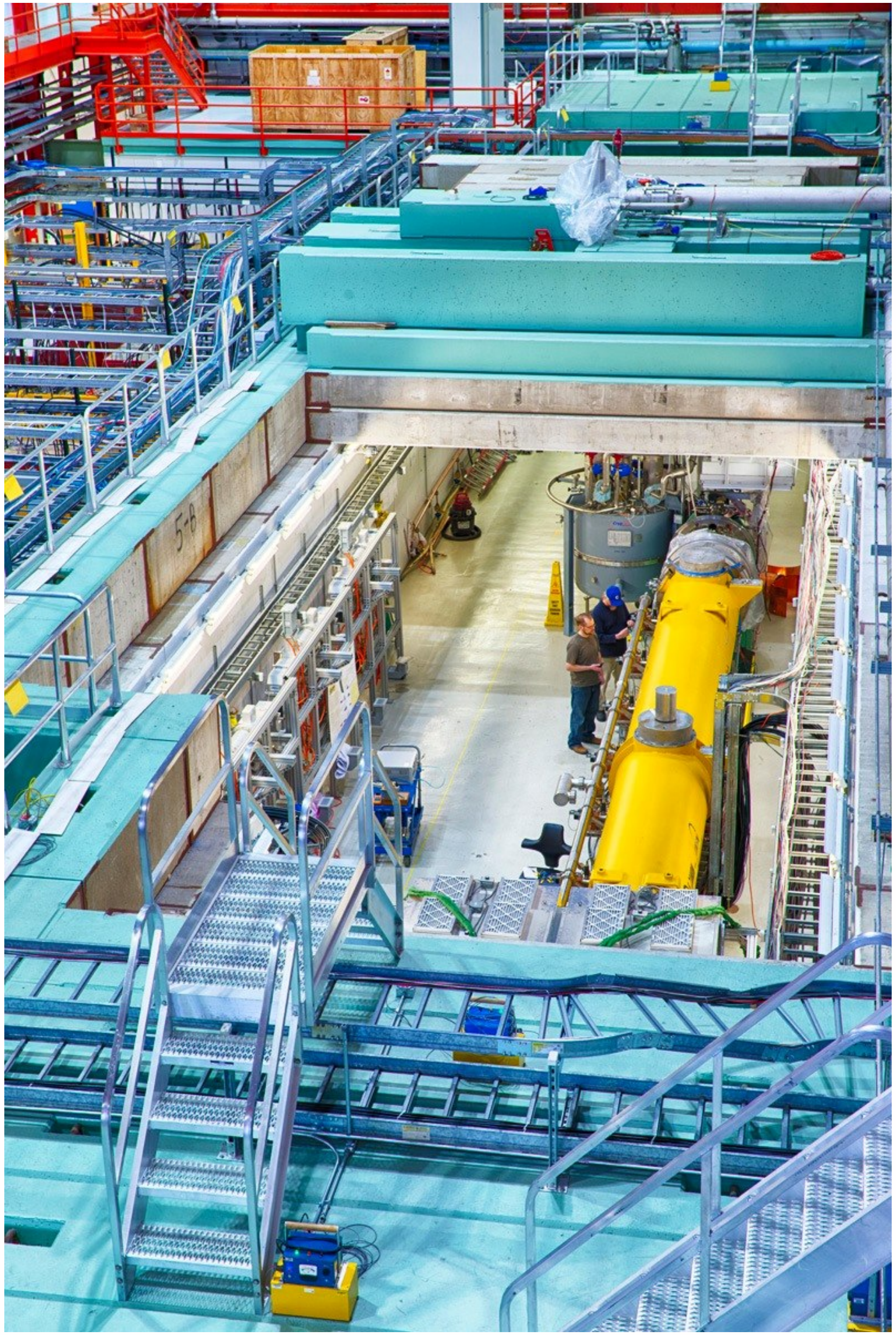


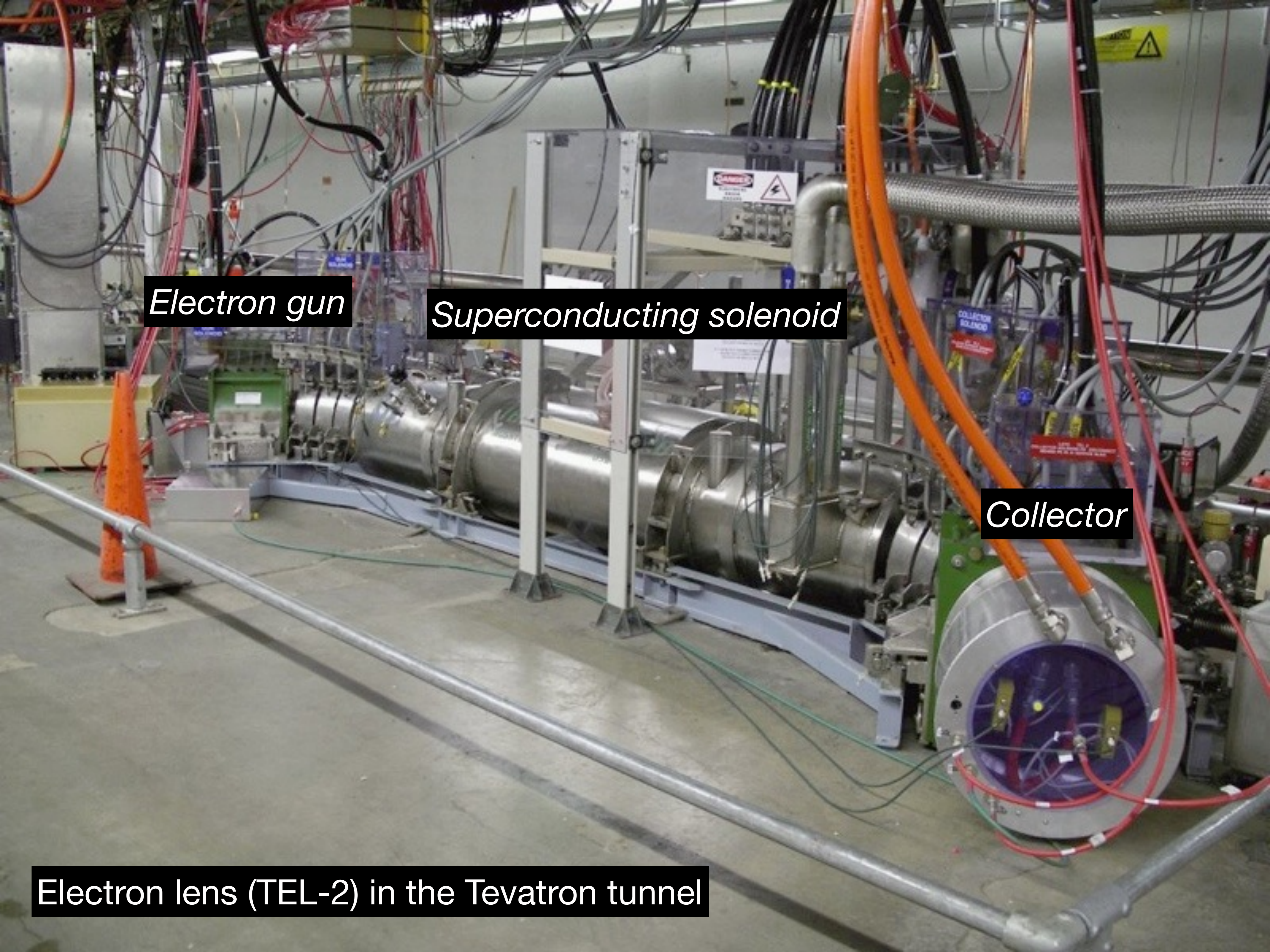
Floor plan of the facility



Interior of the facility

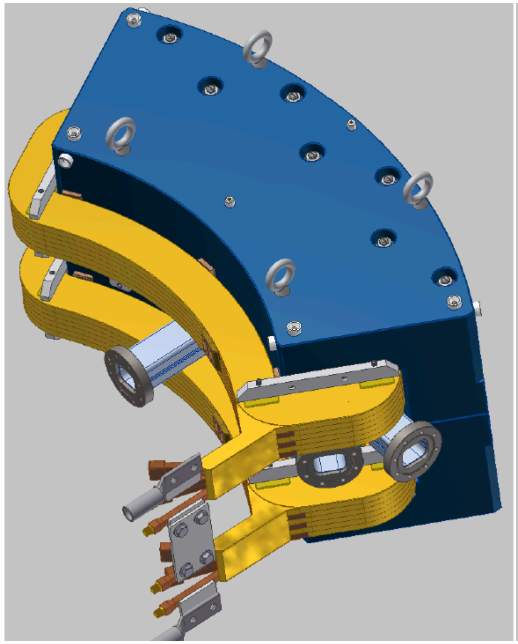


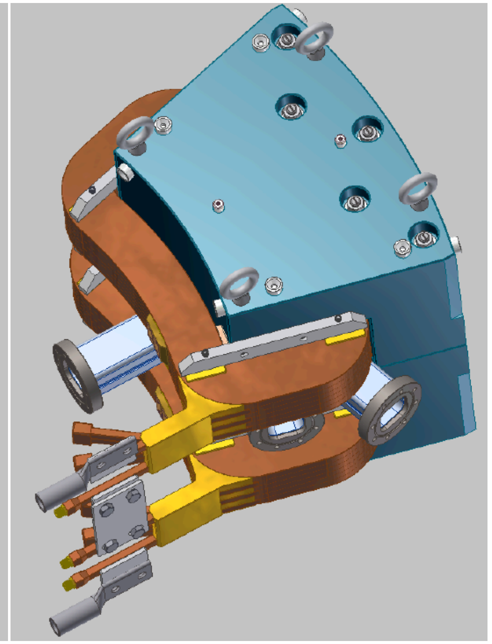




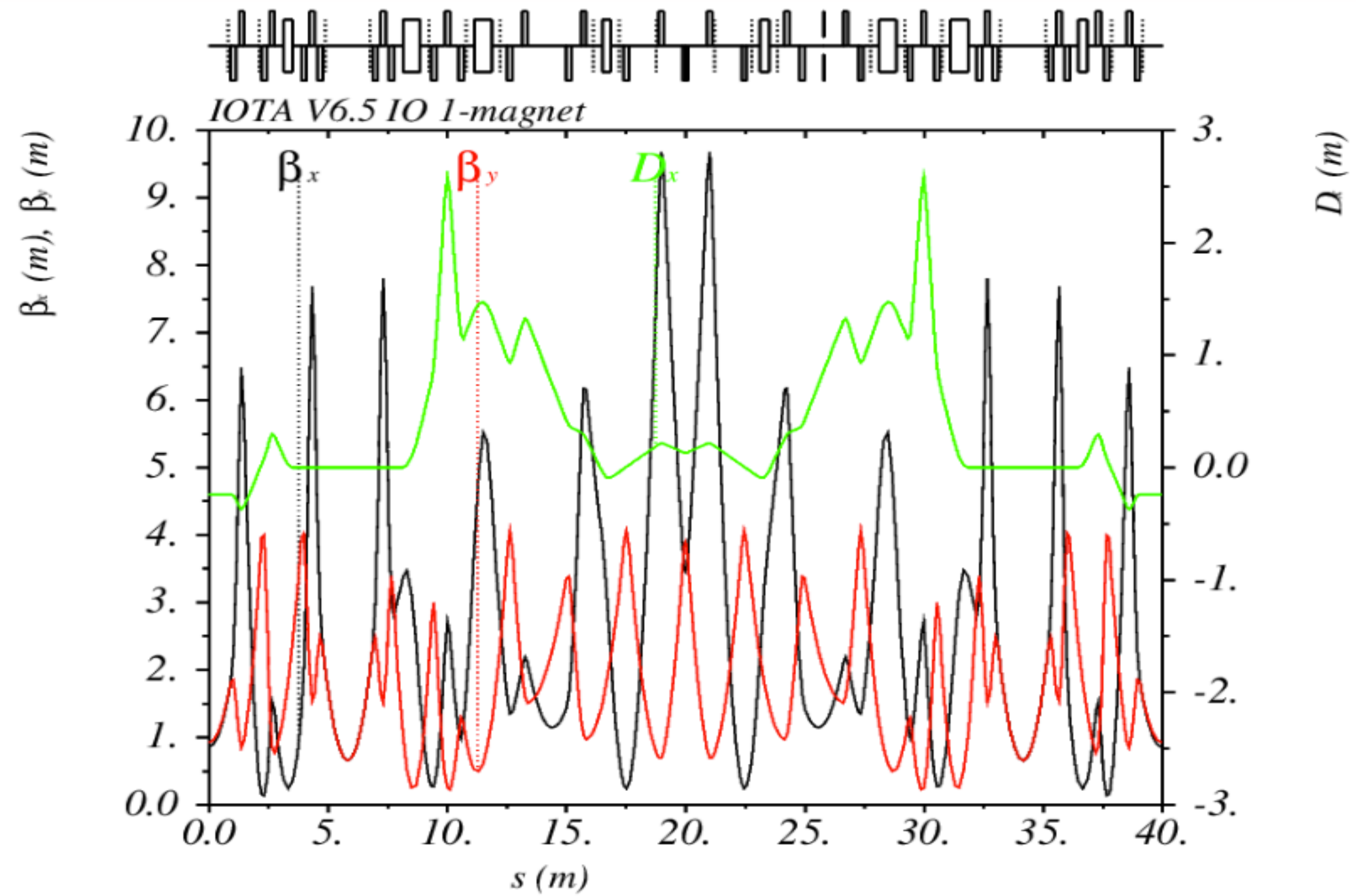
Electron lens (TEL-2) in the Tevatron tunnel

IOTA components

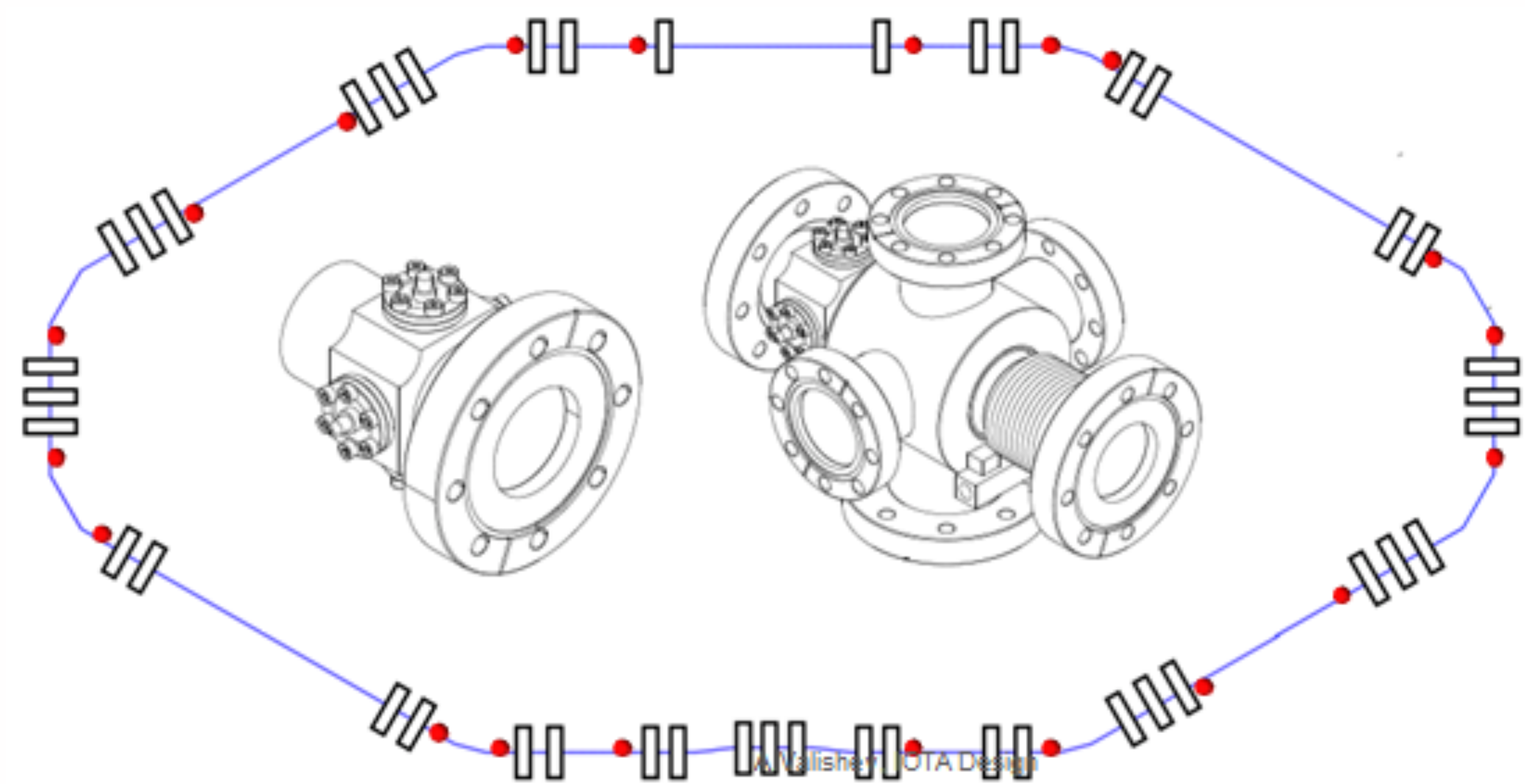




IOTA lattices



IOTA beam position monitors



Optics control challenges

- Integrable optics requires
  - 1% control of beta functions
  - 0.001 control of betatron phase
- Requirements to be met by
  - operation with 150-MeV electrons: pencil beams, 0.6-s synchrotron radiation cooling time, 20 min lifetime
  - magnet quality, individual field measurements, maximum number of independent circuits
  - button BPMs with 1 μm (closed orbit) / 100 μm (turn-by-turn) resolution

Lattice measurements and closed-orbit correction

Simulations of orbit and lattice correction in IOTA suggest that required precision is achievable with BPMs in optimized locations (LOCO + sync light, MAD-X and VEPP-2000 `sixdsimulation` code)

Alignment, calibration, and field errors for closed-orbit correction (Gaussian rms)	
quad shifts (x, y)	0.1 mm
corrector shifts (x, y, s)	0.1 mm
corrector tilts	1 mrad

Corrected closed-orbit variations		
Parameter	**achieved**	**desired**
overall x position (rms)	0.07 mm	
overall y position (rms)	0.11 mm	
x position at insertion (abs)	0.04 mm	< 0.05 mm
y position at insertion (abs)	0.17 mm	< 0.05 mm

Alignment, calibration, and field errors for linear lattice measurement (Gaussian rms)	
quad gradient	1.00%
quad rotation	2 mrad
BPM calibration	4.00%
BPM rotation	35 mrad
corrector cal. (h in dipoles)	1.00%
corrector cal. (h/v/s)	2.00%

Corrected lattice imperfections		
Parameter	**achieved**	**desired**
tunes (abs)	5×10^{-5}	$< 10^{-3}$
beta function (rms)	0.300%	< 3%
beta function at insertion (abs)	0.100%	< 1%
dispersion (rms)	0.2 mm	< 10 mm

Romanov et al., IPAC14

To do: dipole field errors, longitudinal displacements, …