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IOTA electron lens: nonlinear optics, cooling, and space-charge compensation

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Fermilab

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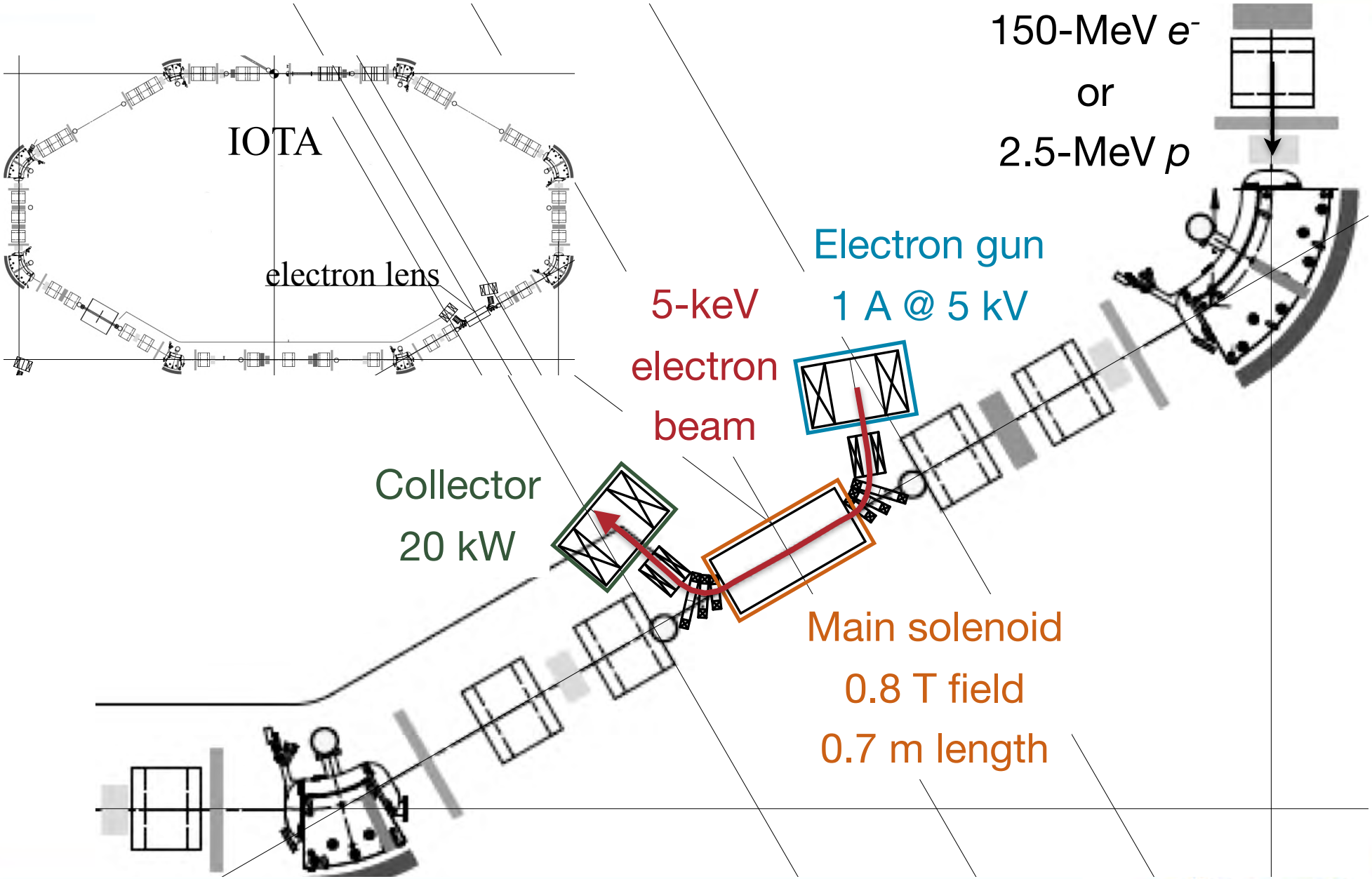
Layout


IOTA
electron lens
150-MeV e^-
or
2.5-MeV p
Electron gun
1 A @ 5 kV
5-keV
electron
beam
Collector
20 kW
Main solenoid
0.8 T field
0.7 m length

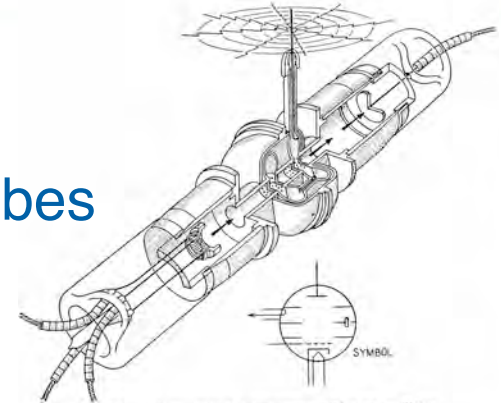
Magnetized electron beam section (“e-lens”) in IOTA

- **Nonlinear element for integrable optics**
  - thin McMillan lens
  - thick axially symmetric lens
- **Electron cooling**
  - extend range of proton emittances and lifetimes
  - new research on electron cooling reach in integrable lattice
- **Space-charge compensation in rings**
  - shaped beam from electron gun
  - trapped electron column

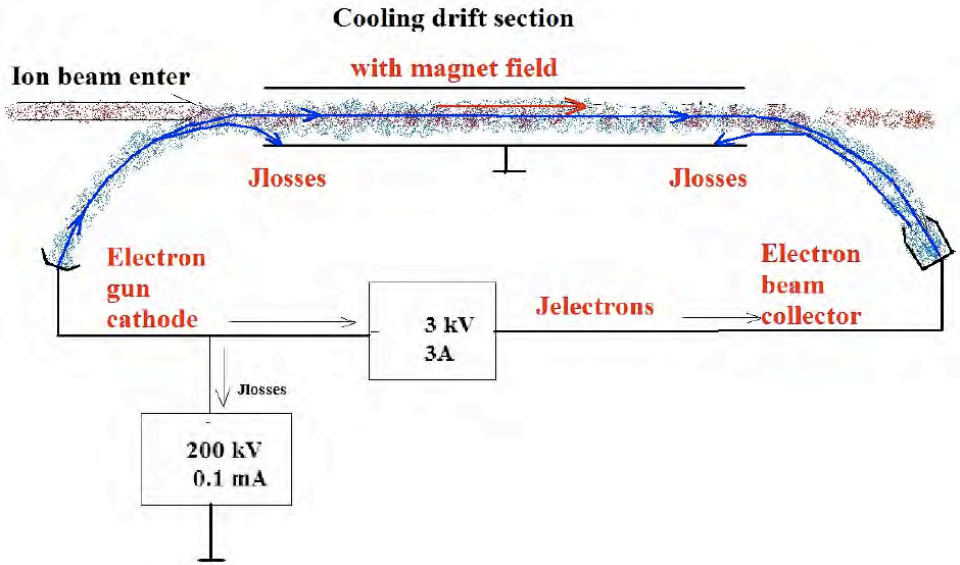
Electron lenses

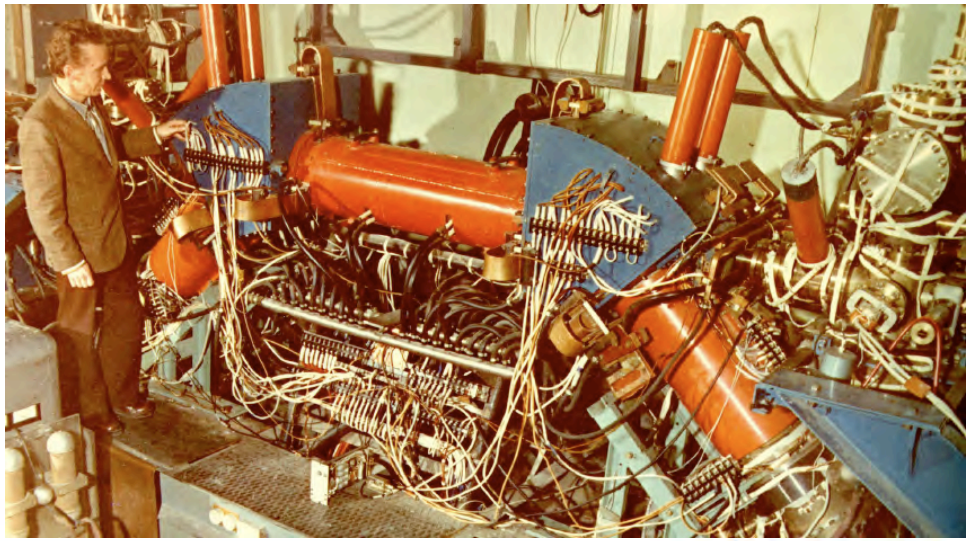
Early applications of electron beams

Electron beams with keV kinetic energies studied in 1930-1950s for development of **vacuum tubes**: diodes, triodes, cathode-ray tubes, microwave amplifiers, phototubes

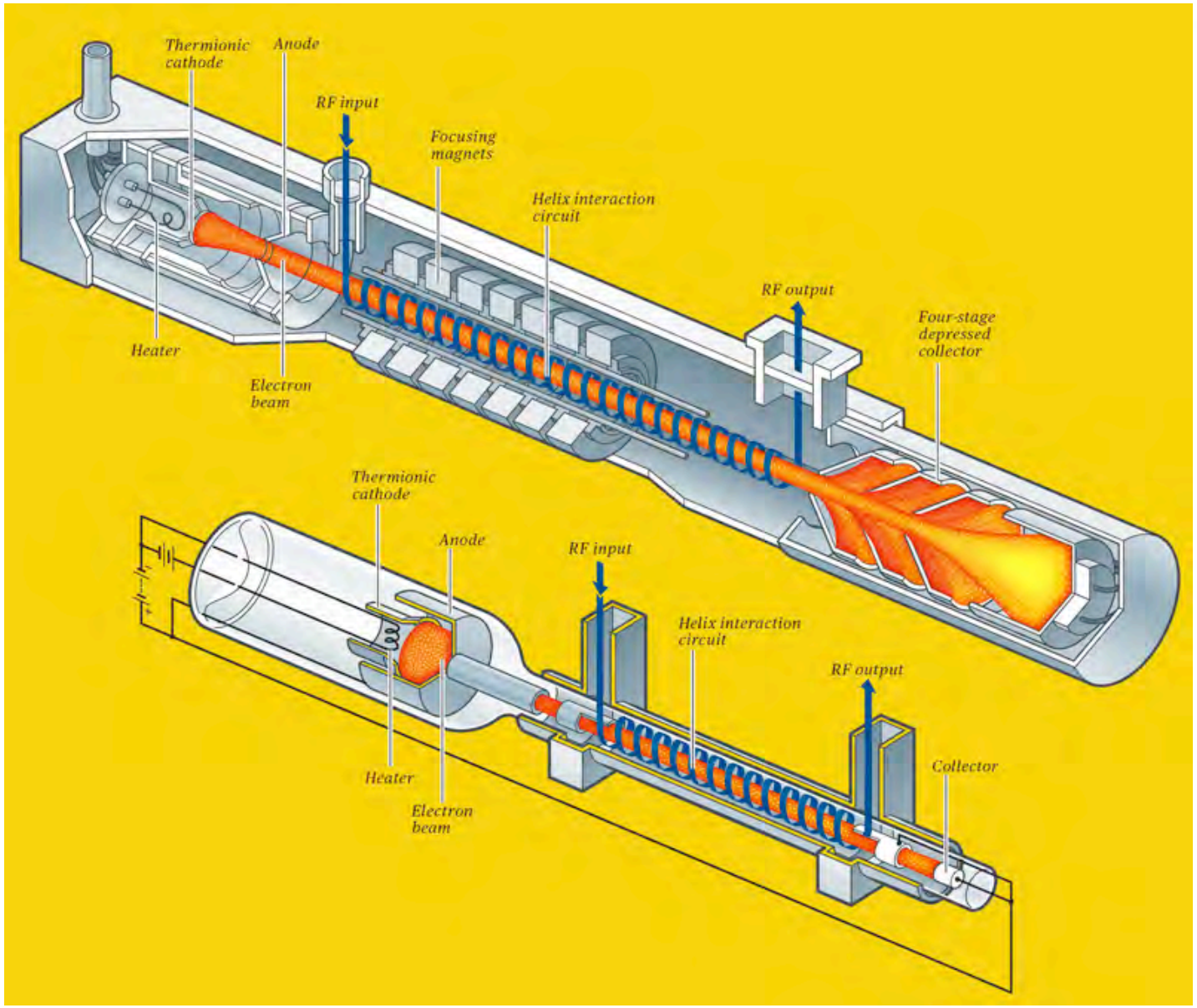


Electron cooling (proposed in 1965 to increase brightness of antiprotons for colliders): heavy charged particles exchange heat with electrons through Rutherford scattering in overlap region





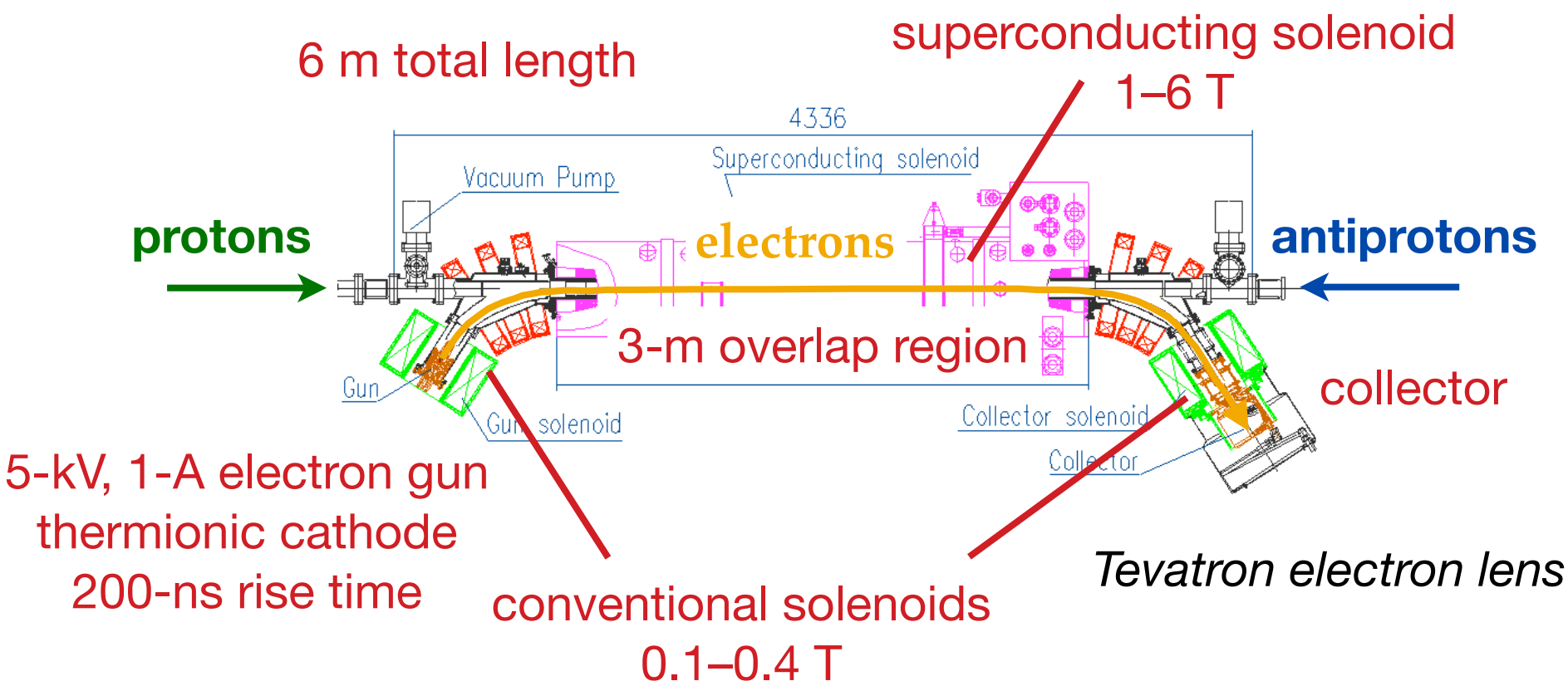
Common elements: electron source, focusing, collector



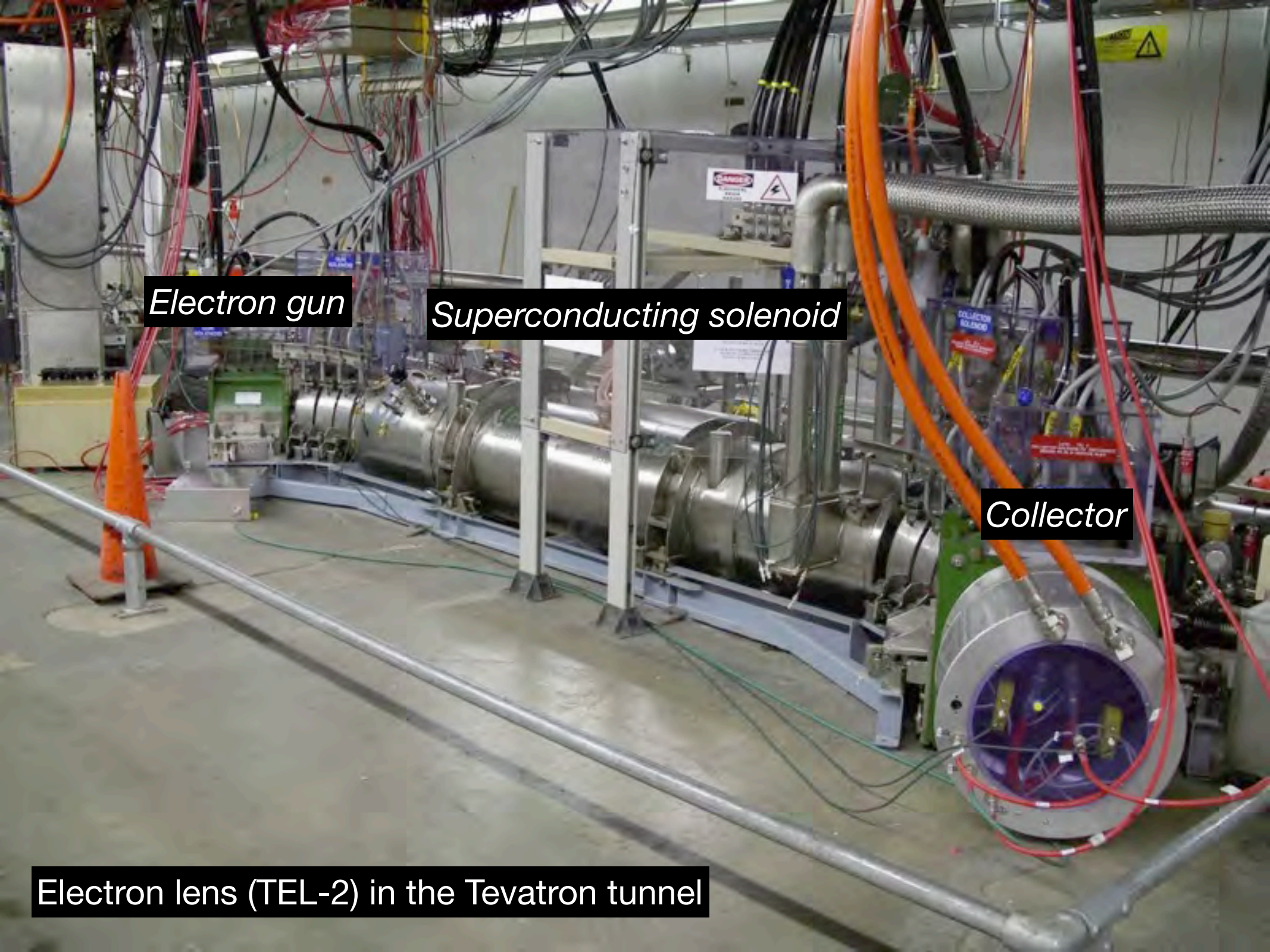
Traveling-wave tube. J. Provost, IEEE Spectrum, Dec. 2015

What's an electron lens?

- Pulsed, magnetically confined, low-energy electron beam
- Circulating beam affected by electromagnetic fields generated by electrons
- Stability provided by strong axial magnetic fields



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

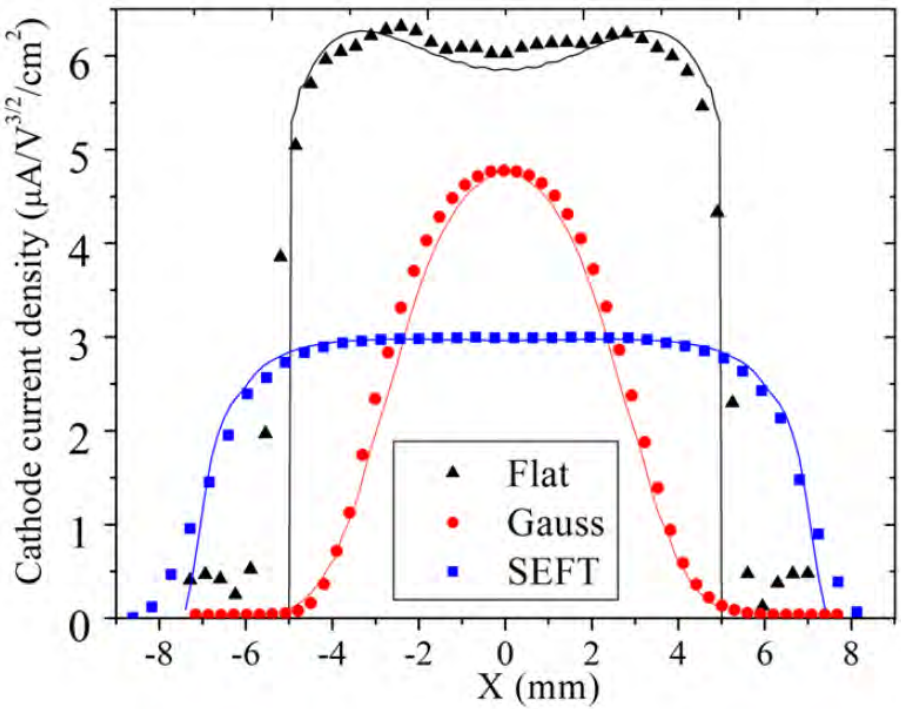


Electron lens (TEL-2) in the Tevatron tunnel

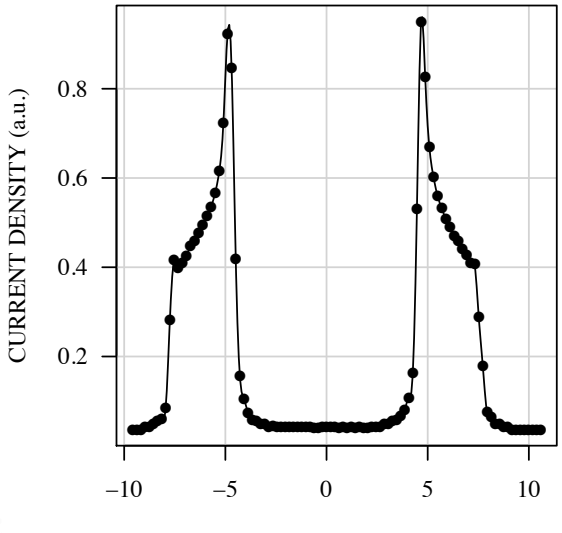
First main feature: control of electron beam profile

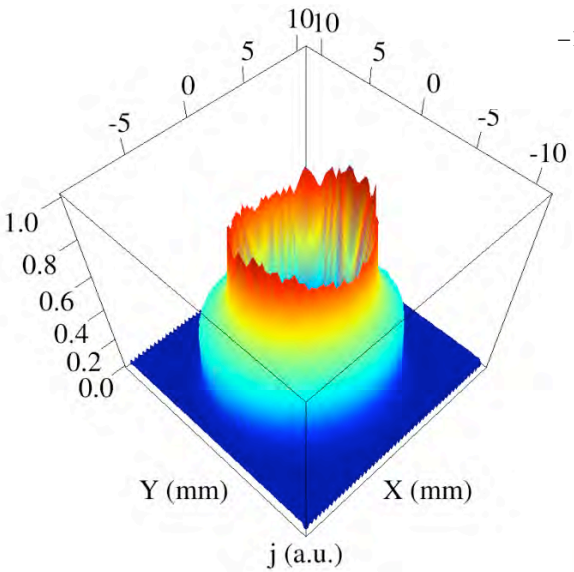
Current density profile of electron beam is shaped by cathode and electrode geometry and maintained by strong solenoidal fields

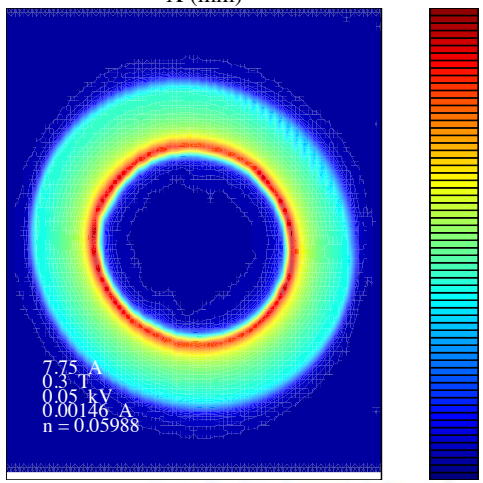
Flat profiles for bunch-by-bunch betatron tune correction



Hollow profile for halo scraping



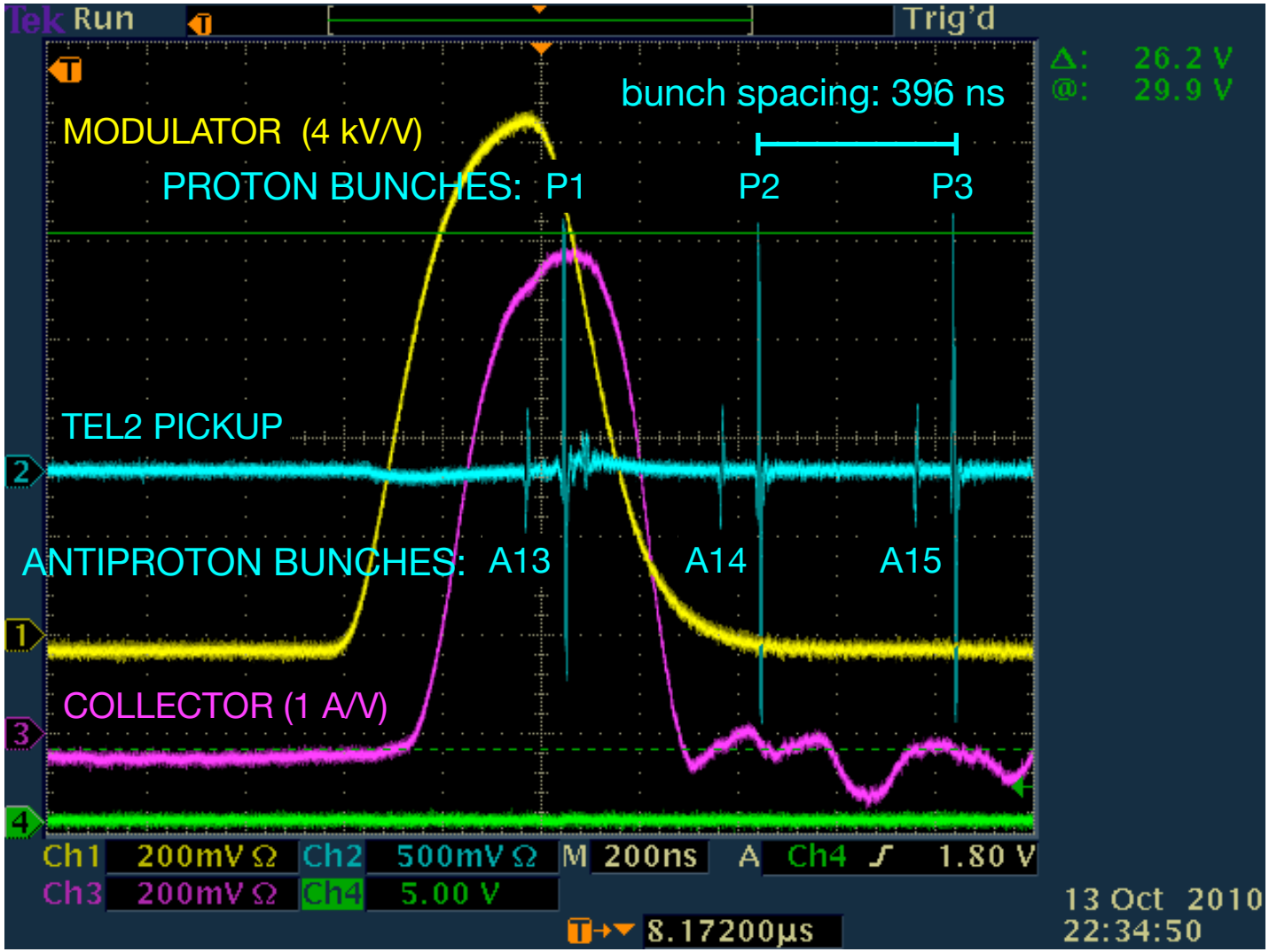




Gaussian profile for compensation of nonlinear beam-beam forces

Second main feature: pulsed electron beam operation

Beam synchronization in the Tevatron



Pulsed electron beam could be **synchronized with any group of bunches**, with a different intensity for each bunch

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
- ***halo scraping with hollow electron beams***
  - Stancari et al., Phys. Rev. Lett. **107**, 084802 (2011)

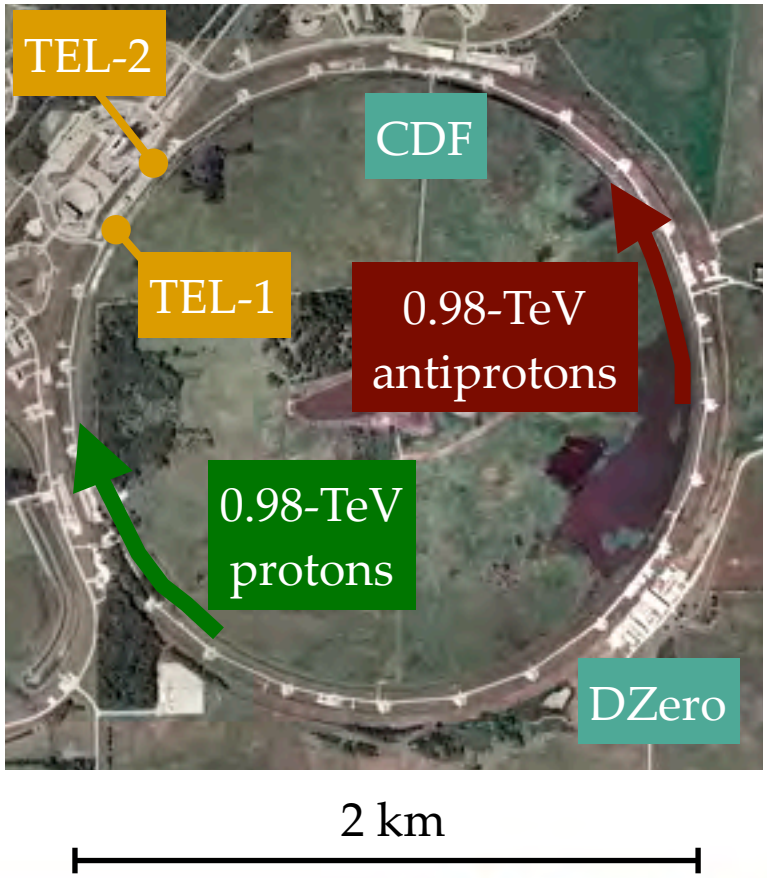
Presently, in RHIC at BNL

- ***head-on beam-beam compensation***
  - Fischer et al., Phys. Rev. Lett. **115**, 264801 (2015)

Current areas of research

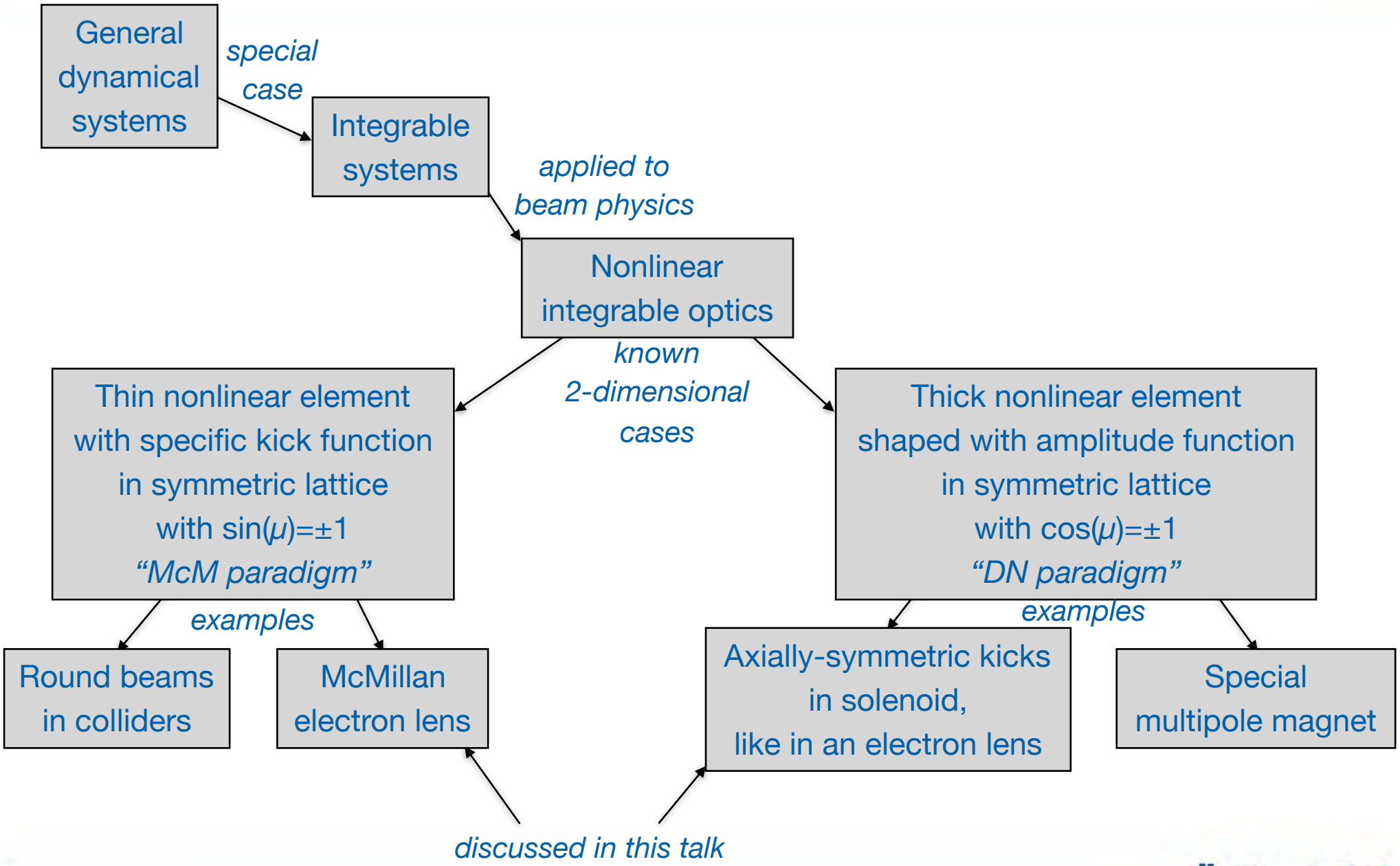
- ***generation of nonlinear integrable lattices***
  in the Fermilab Integrable Optics Test Accelerator
- ***hollow electron beam scraping*** of protons in LHC
- ***long-range beam-beam compensation***
  as charged, current-carrying "wires" for LHC
- to ***generate tune spread for Landau damping***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

Tevatron electron lenses



Electron lenses for nonlinear integrable optics

Dynamical systems and beam physics



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

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

Proposed configurations for transverse integrable optics

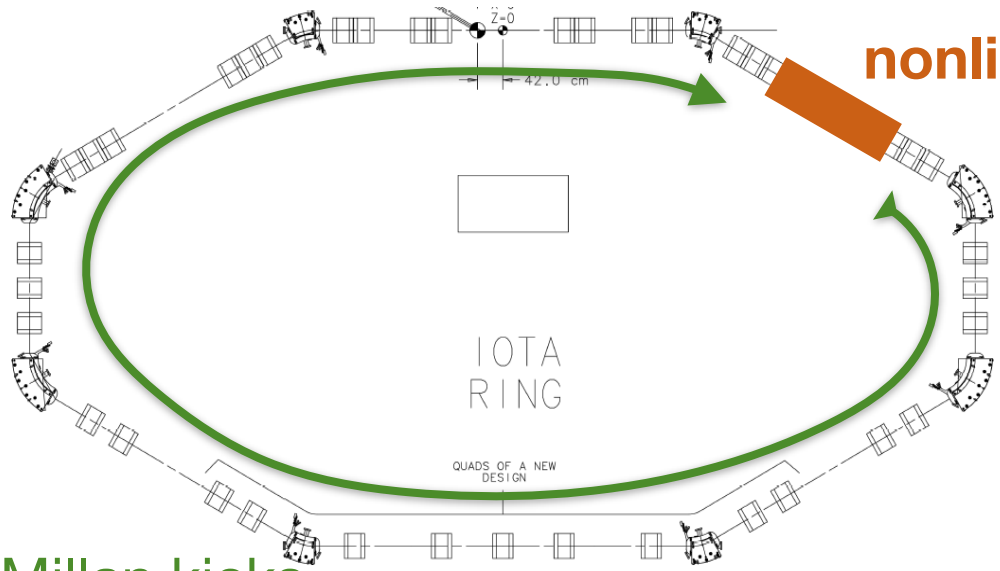
- The lattice is made of **2 main building blocks**
  - an **axially symmetric, linear arc with specified phase advance**, equivalent to a thin lens (“**T-insert**”)
  - a **nonlinear section** with equal beta functions and
    - nonlinear magnet or
    - thin, round McMillan-type kick (**electron lens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

linear arc:

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

or

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



nonlinear element

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

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

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

Smaller tune spreads in IOTA

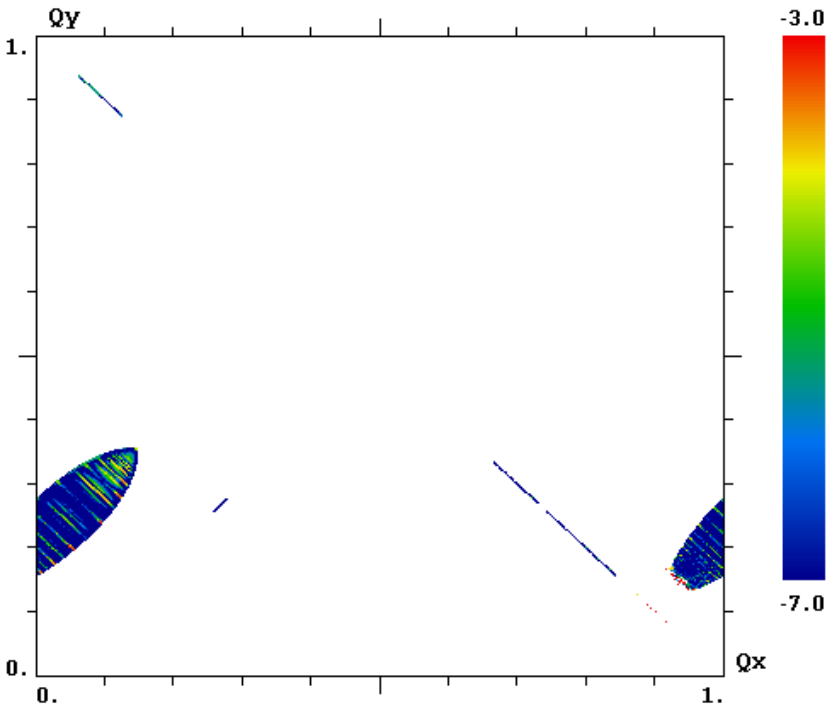
More robust

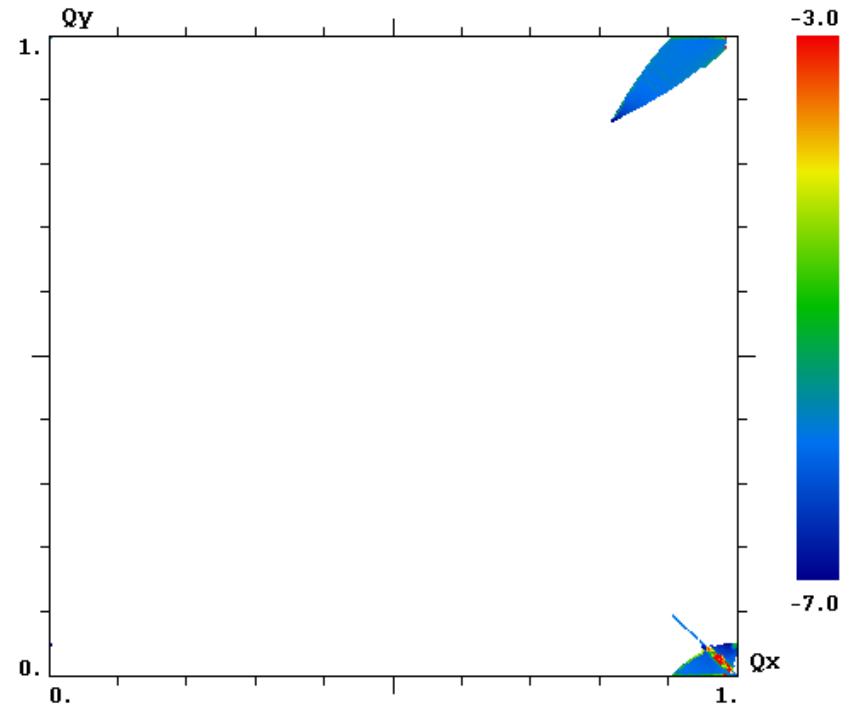
First feasibility studies: tracking and stability

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

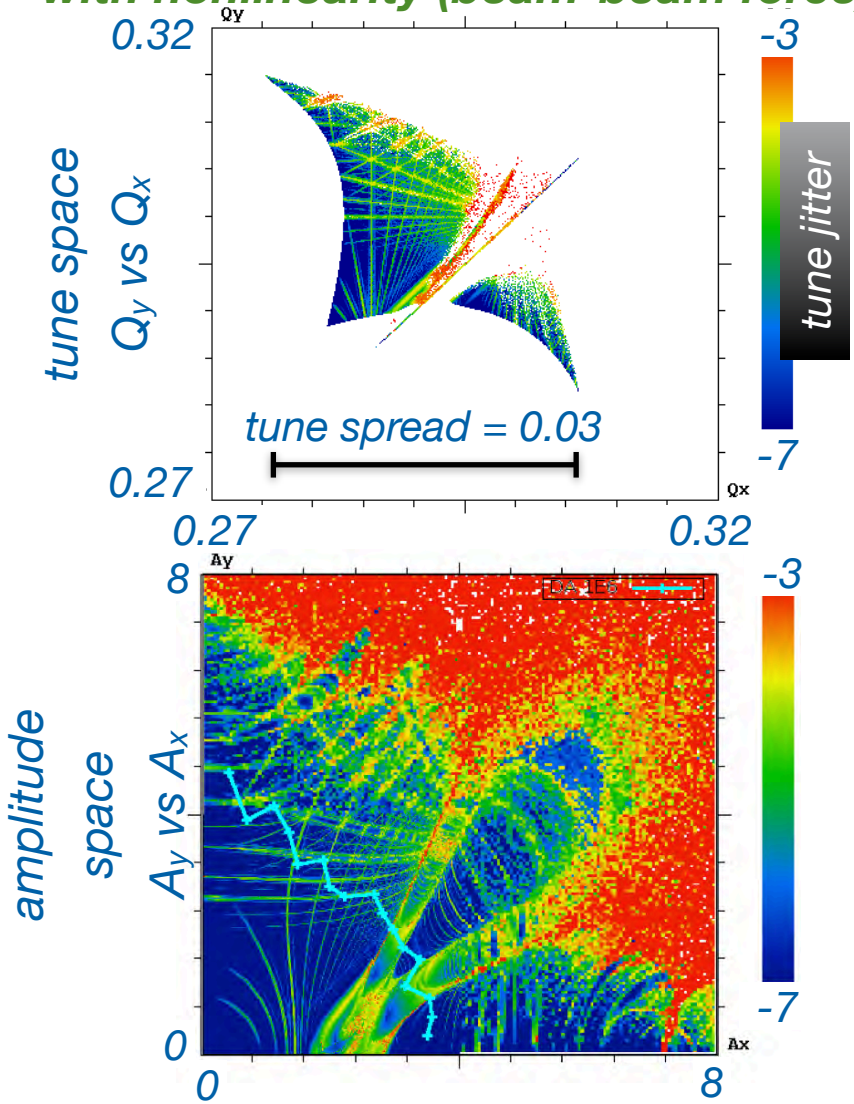
there are 2 transverse invariants

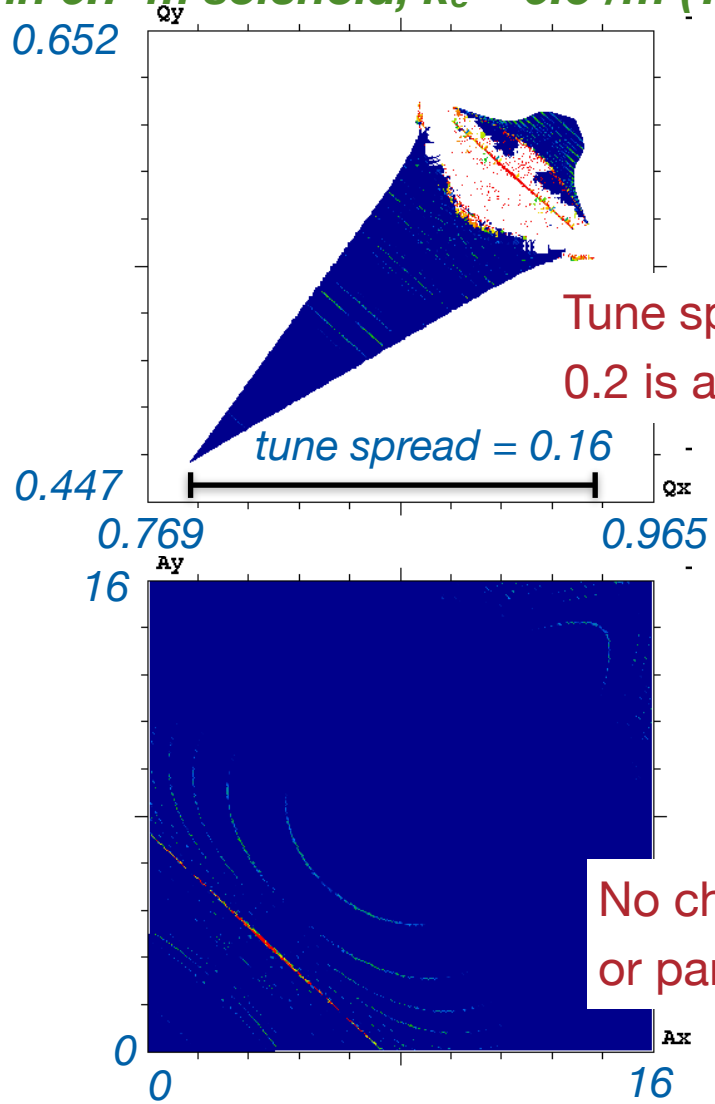
the beam can cross integer resonances without particle loss

Frequency 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)



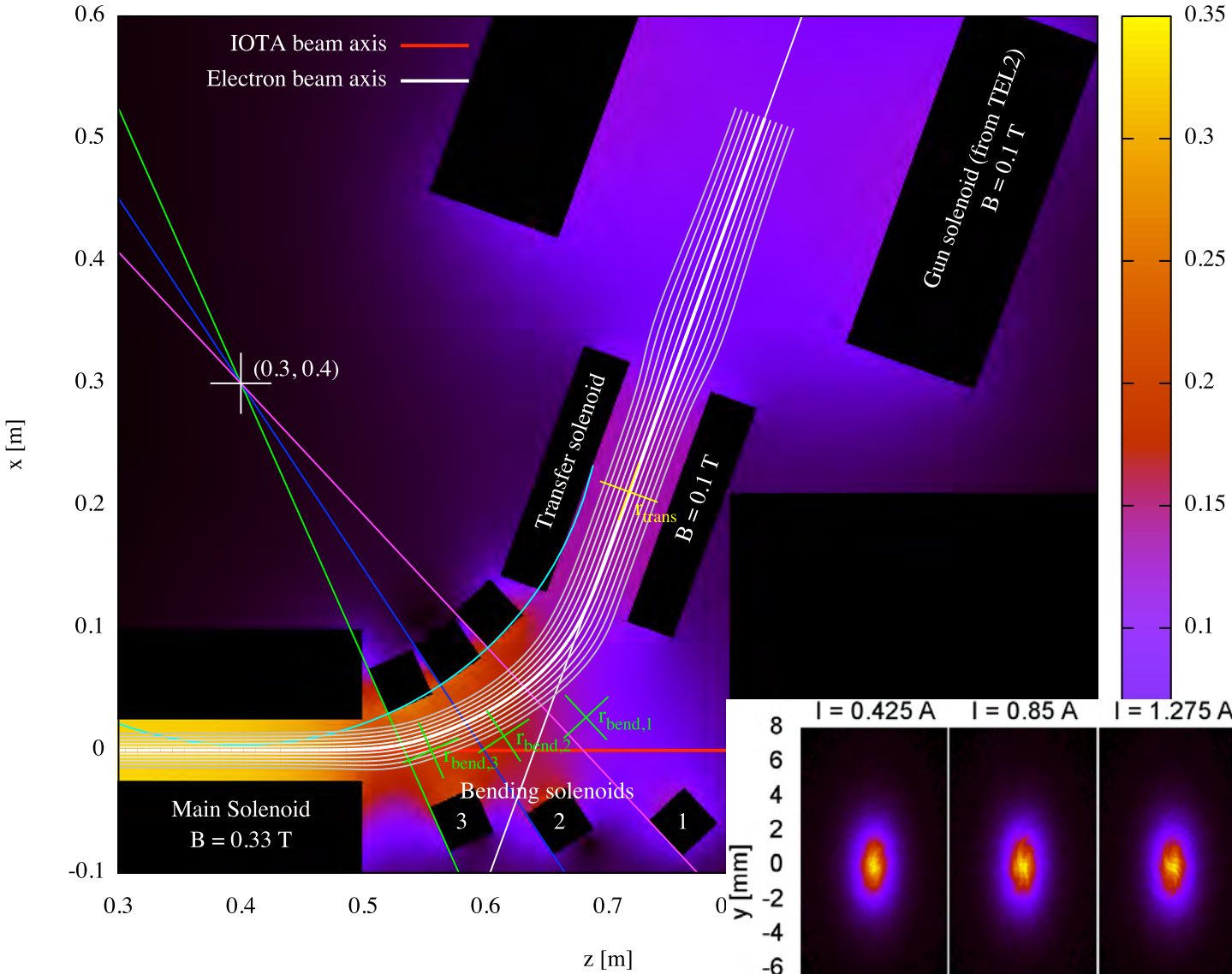


Tune spread of ~ 0.2 is achievable

No chaotic motion or particle loss

Resonance overlap, restricted dynamic aperture

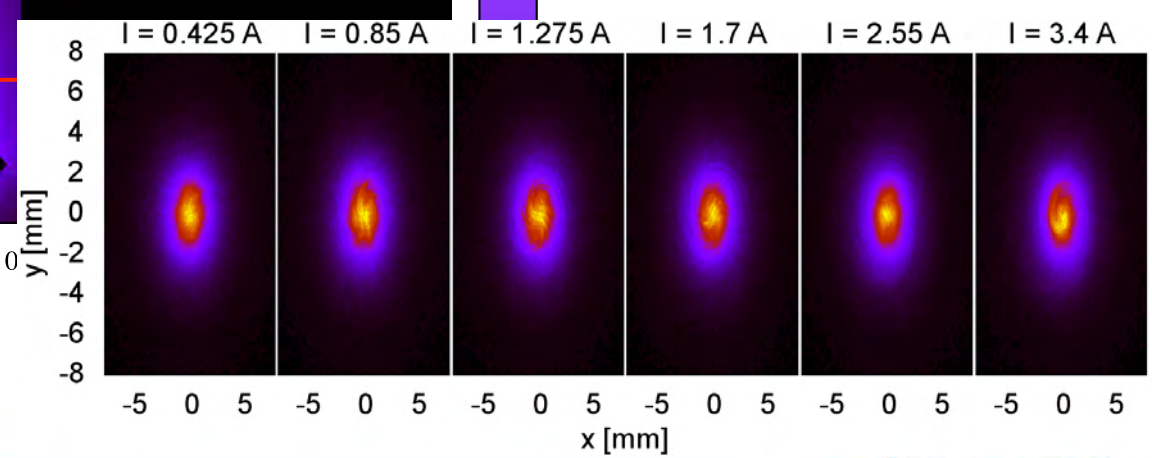
Design of beam transport in electron lens



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

Noll and Stancari, FERMILAB-TM-2598-AD-APC

Noll, PhD Thesis (in preparation)



Minimize distortions

Provide input for tracking in ring

Under study

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
- effect of fringe fields on ring optics
- perveance of electron gun and accuracy of beam profile
- chromatic effects of the electron lens
- misalignments

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

Electron cooling

Electron cooling

1.36-keV electrons match the velocity of 2.5-MeV protons

A wider range of proton lifetimes and brightnesses will be available for experiments

Cooling rates of 0.1 s are achievable

Emittances can be reduced by a factor 10

New research topic: Does nonlinear integrable optics combined with cooling enable higher brightnesses?

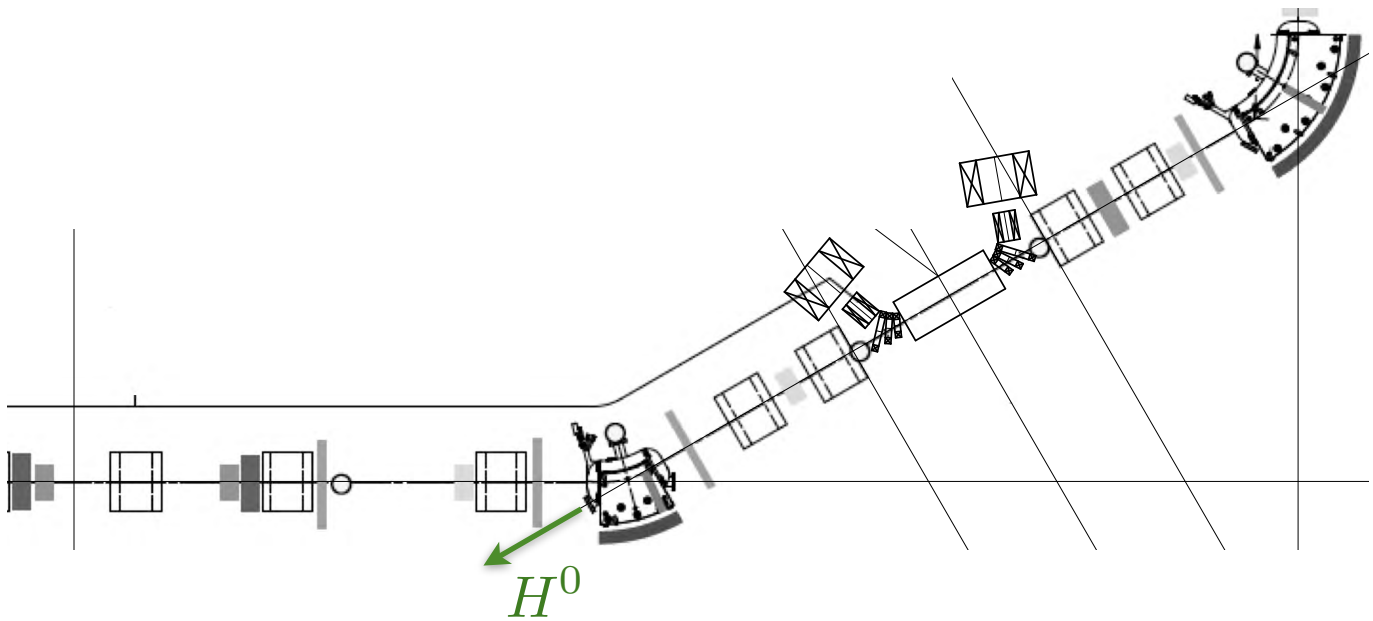
Stancari et al., COOL15

Proton beam diagnostics through recombination

Spontaneous recombination generates neutral hydrogen with distribution of Rydberg states, some of which are Lorentz-stripped in e-lens toroid and IOTA dipole

$$p + e^- \rightarrow H^0 + h\nu$$

Recombination rate at detector is ~ 50 kHz



Stancari et al., COOL15

Space-charge compensation

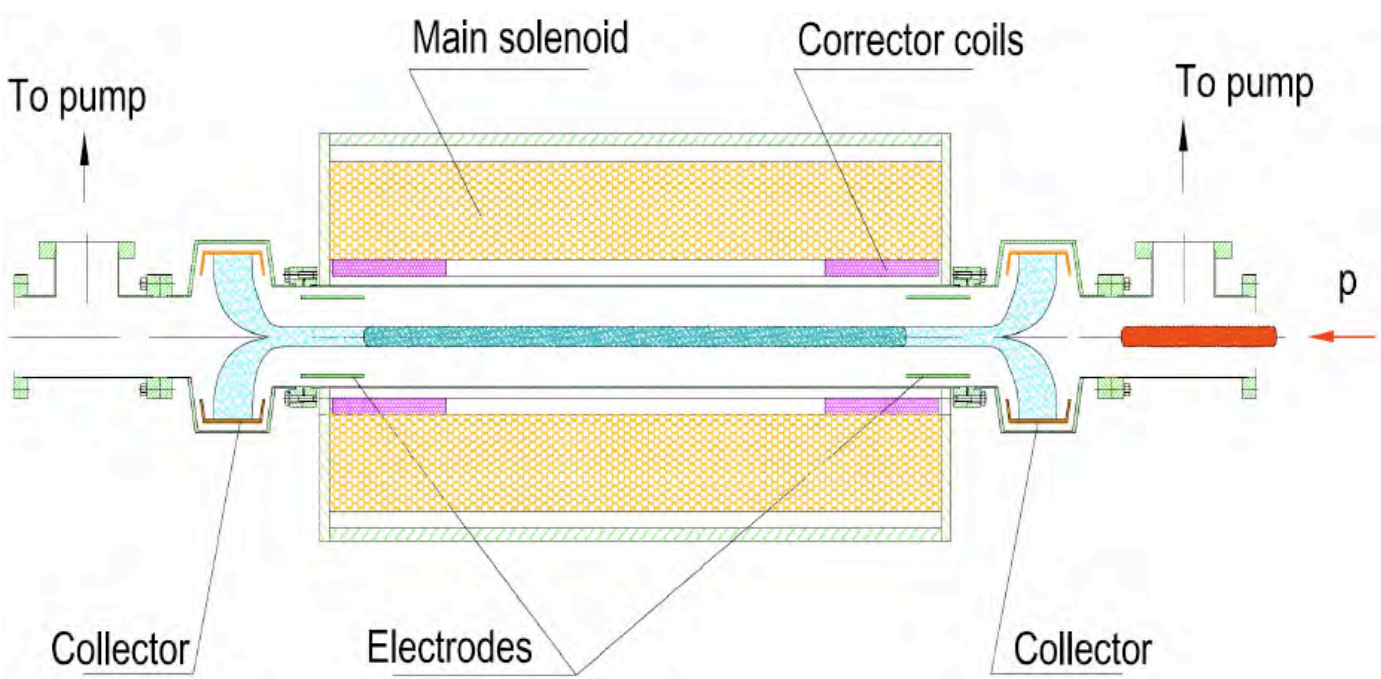
Space-charge compensation in rings

A challenging subject: local correction of global effect?

Preliminary studies suggest benefits

Implementation with electron lens:

- given current-density profile from electron gun OR
- electrons from residual-gas ionization trapped in Penning-Malmberg configuration



see Chong Shik Park's presentation

Hardware status

Electron-lens hardware

When possible, recycle components from Tevatron

TEL-1 and TEL-2 gun and collector assemblies removed from tunnel

Vacuum tests of gun and collector complete

Received “Gaussian” cathodes from HeatWave Labs

Girders and supports are being designed and fabricated

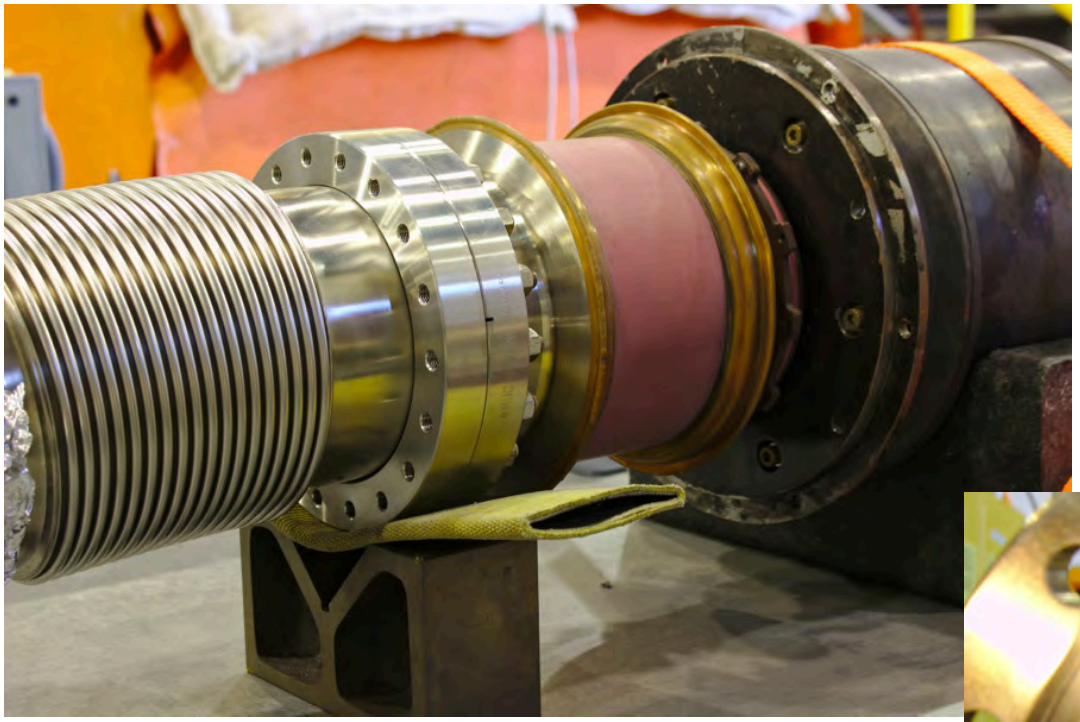
Aim to assemble e-lens in straight configuration for checkout by end of 2016

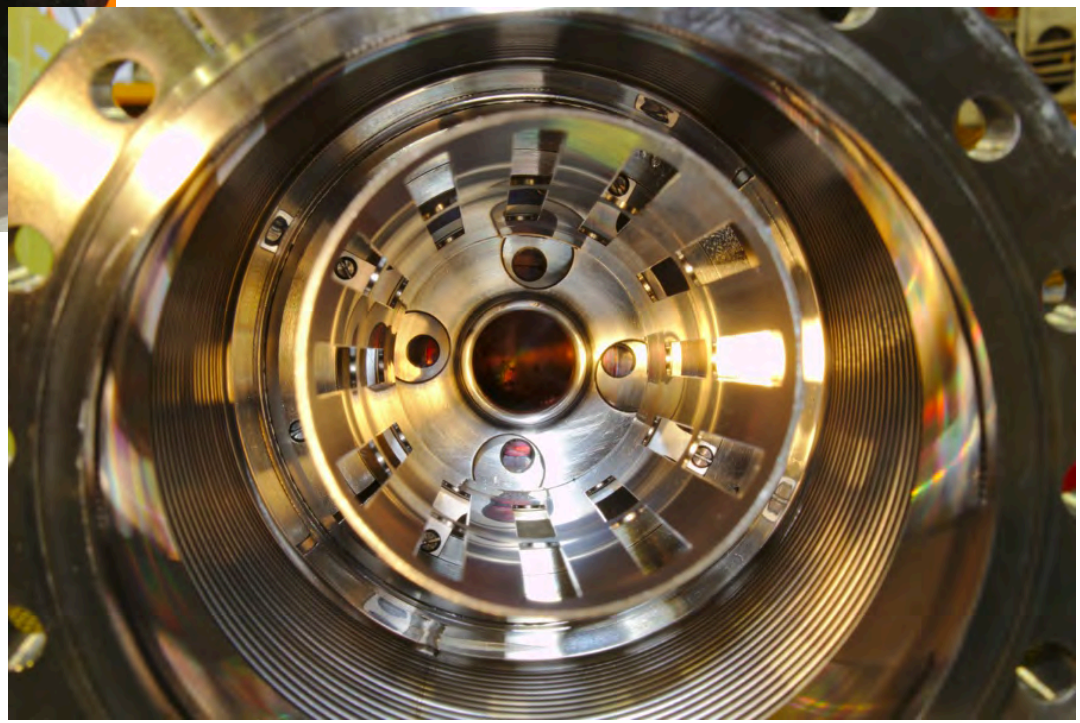
McGee et al., IPAC16

TEL-2 gun and collector

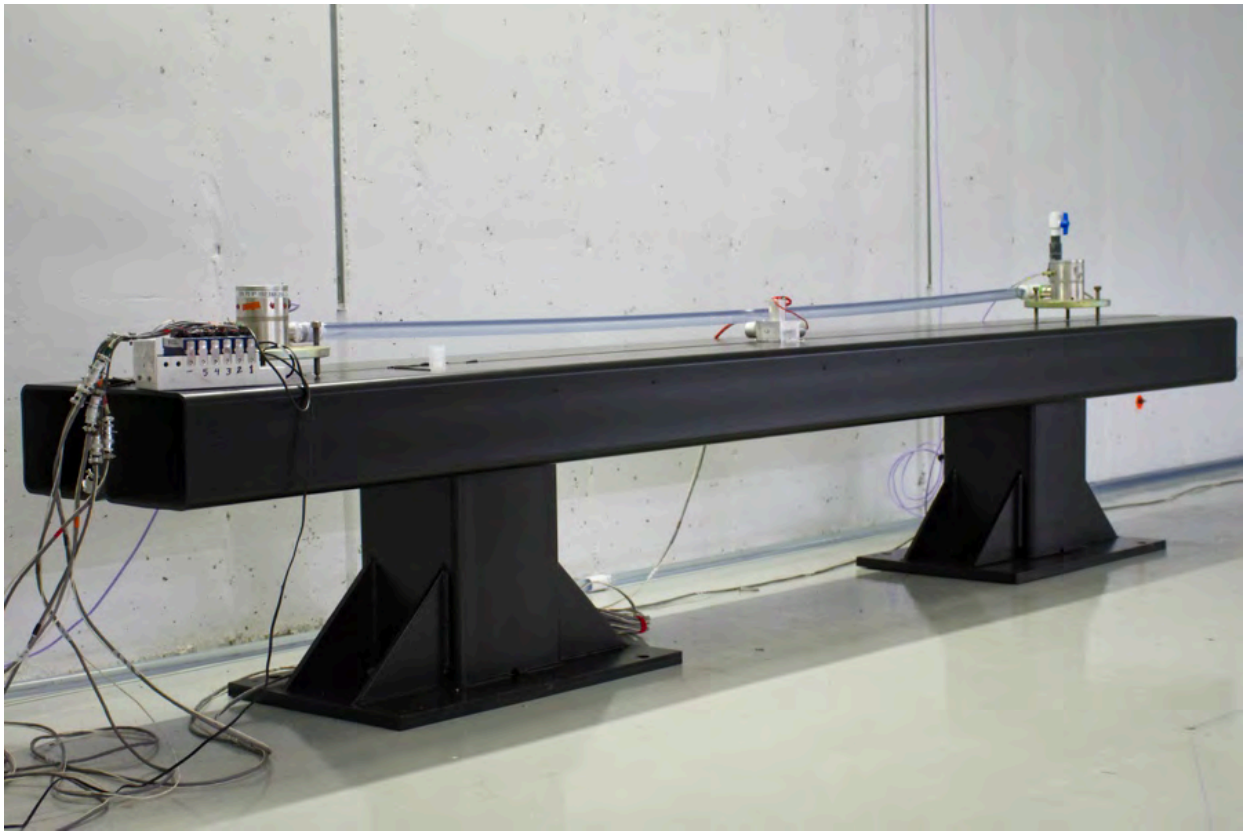
Removal from Tevatron tunnel

TEL-2 collector vacuum tested at NWA



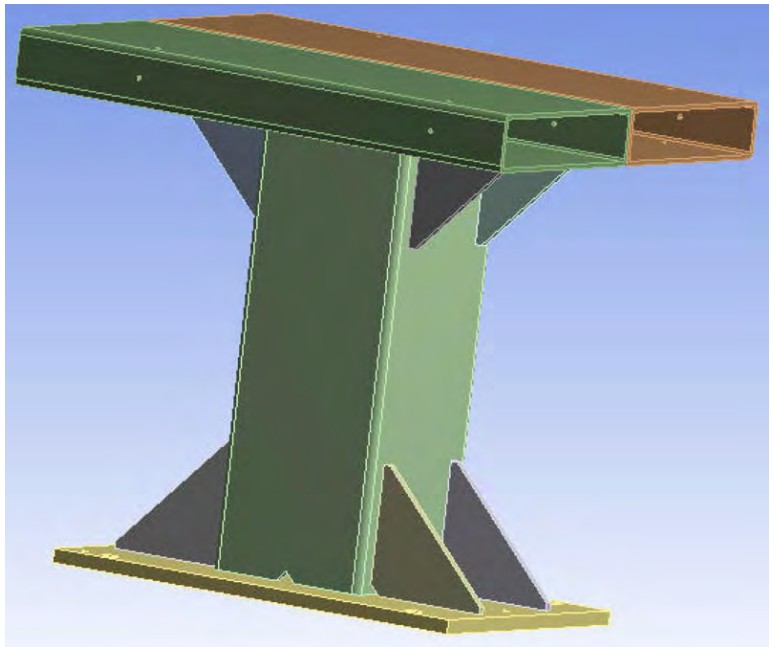


Girders and supports

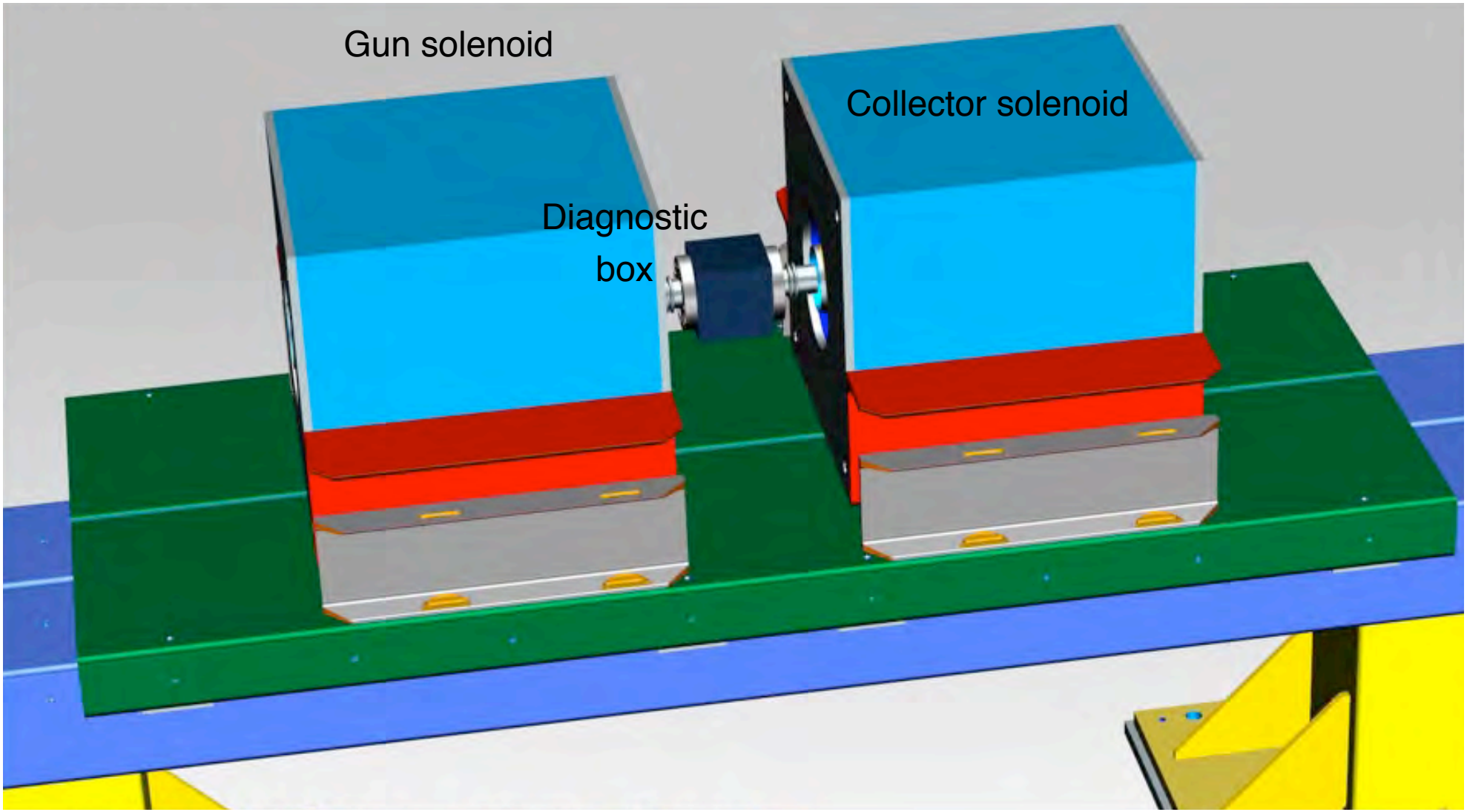


IOTA floor girder

Gun/collector girder



Straight configuration on girder, to test subsystems



Conclusions

Magnetized electron beam section ("e-lens") in IOTA

IOTA e-lens designed to fulfill several purposes:

- **Nonlinear element for integrable optics**
  - thin McMillan lens
  - thick axially symmetric lens
- **Electron cooling**
  - extend range of proton emittances and lifetimes
  - new research on electron cooling reach in integrable lattice
- **Space-charge compensation in rings**
  - shaped beam from electron gun
  - trapped electron column

After an initial conceptual design, many aspects need to be studied in detail

Conclusions

- An **exciting program of general physics and accelerator science** is planned for the Fermilab Accelerator Science and Technology (FAST) facility
  - nonlinear integrable lattices
  - space-charge dynamics
  - optical stochastic cooling
  - single-electron quantum optics
  - high-brightness beams and radiation
- Experiments and theory of **nonlinear integrable dynamics**
  - advance the knowledge of dynamical systems in many fields of science
  - in accelerator physics, they provide a path towards the next generation of high-power machines
- Research on **electron lenses**
  - provides a flexible way to implement nonlinear integrable lattices in accelerators
  - is connected to other applications in beam physics: collimation, beam-beam compensation, ...
- New **collaborators** and **ideas** are always welcome. Also, Fermilab has undergraduate **internships** and **joint PhD** programs for young researchers.