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

Giulio Stancari
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Workshop on Megawatt Rings and IOTA-FAST Collaboration Meeting
Fermilab, May 9, 2018 `https://indico.fnal.gov/event/16269`

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Introduction

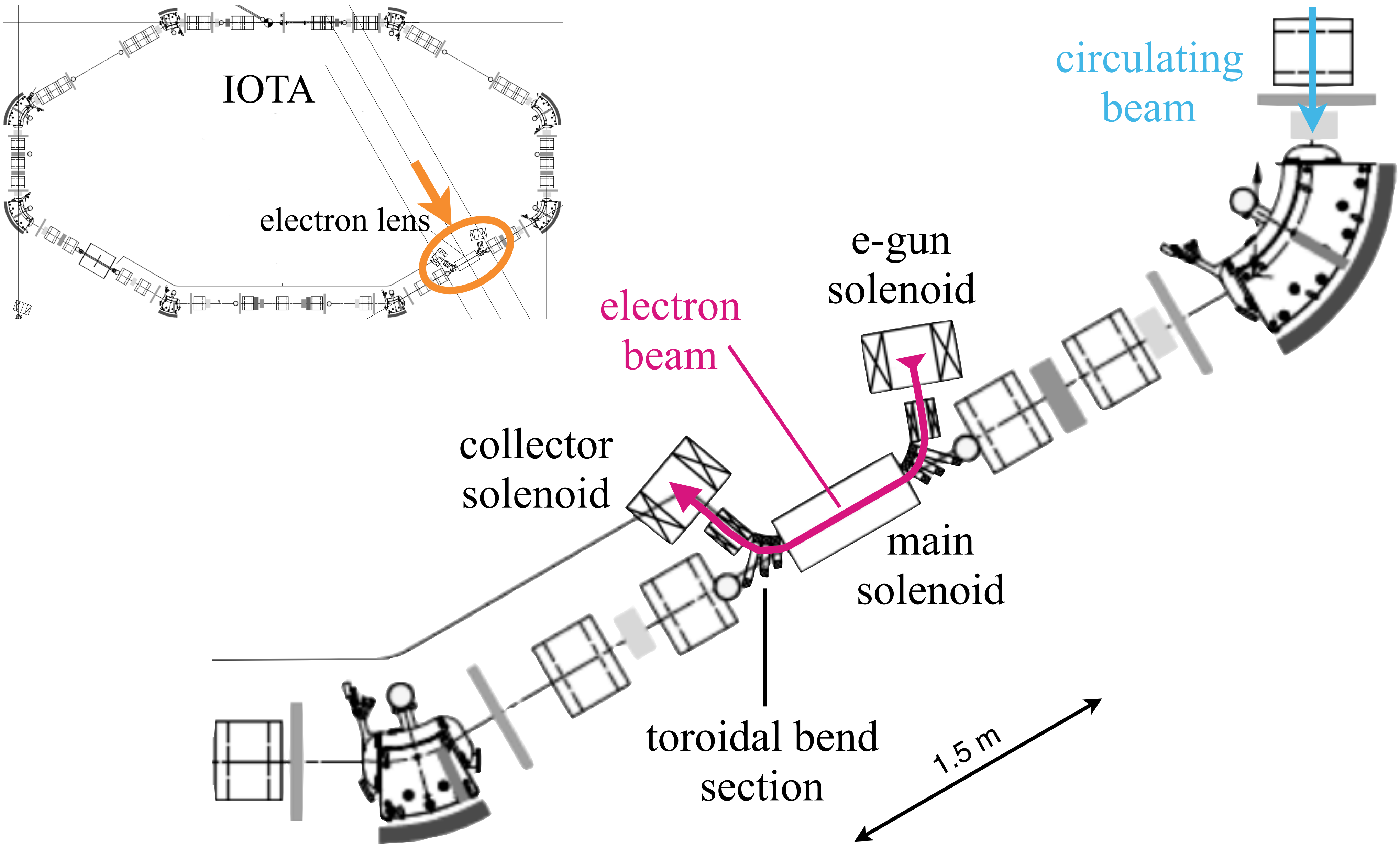
The three main roles of the IOTA electron lens

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

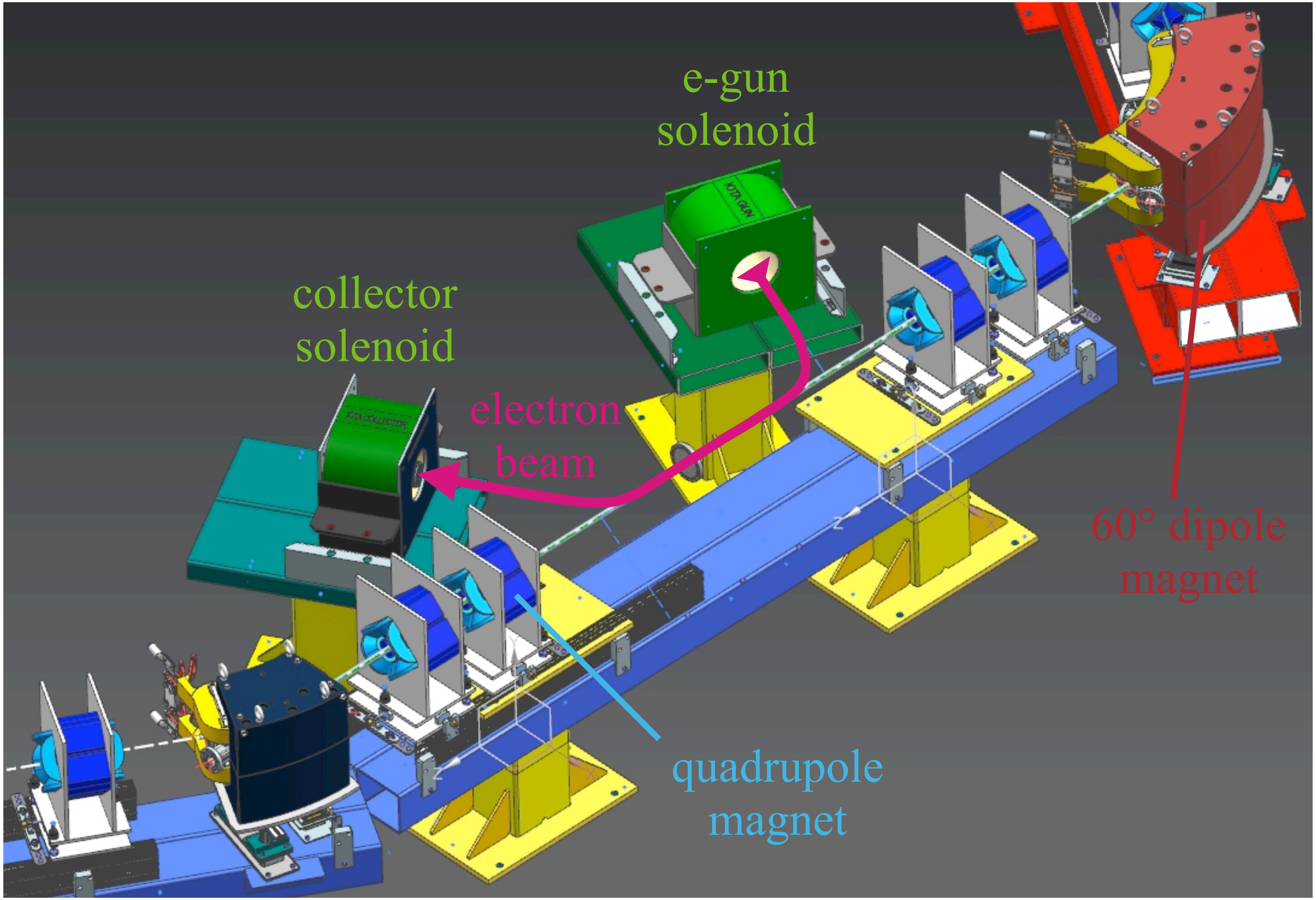
[“Electron lens” = magnetically confined electrons acting on the circulating beam]

Antipov et al., JINST **12**, T03002 (2017)

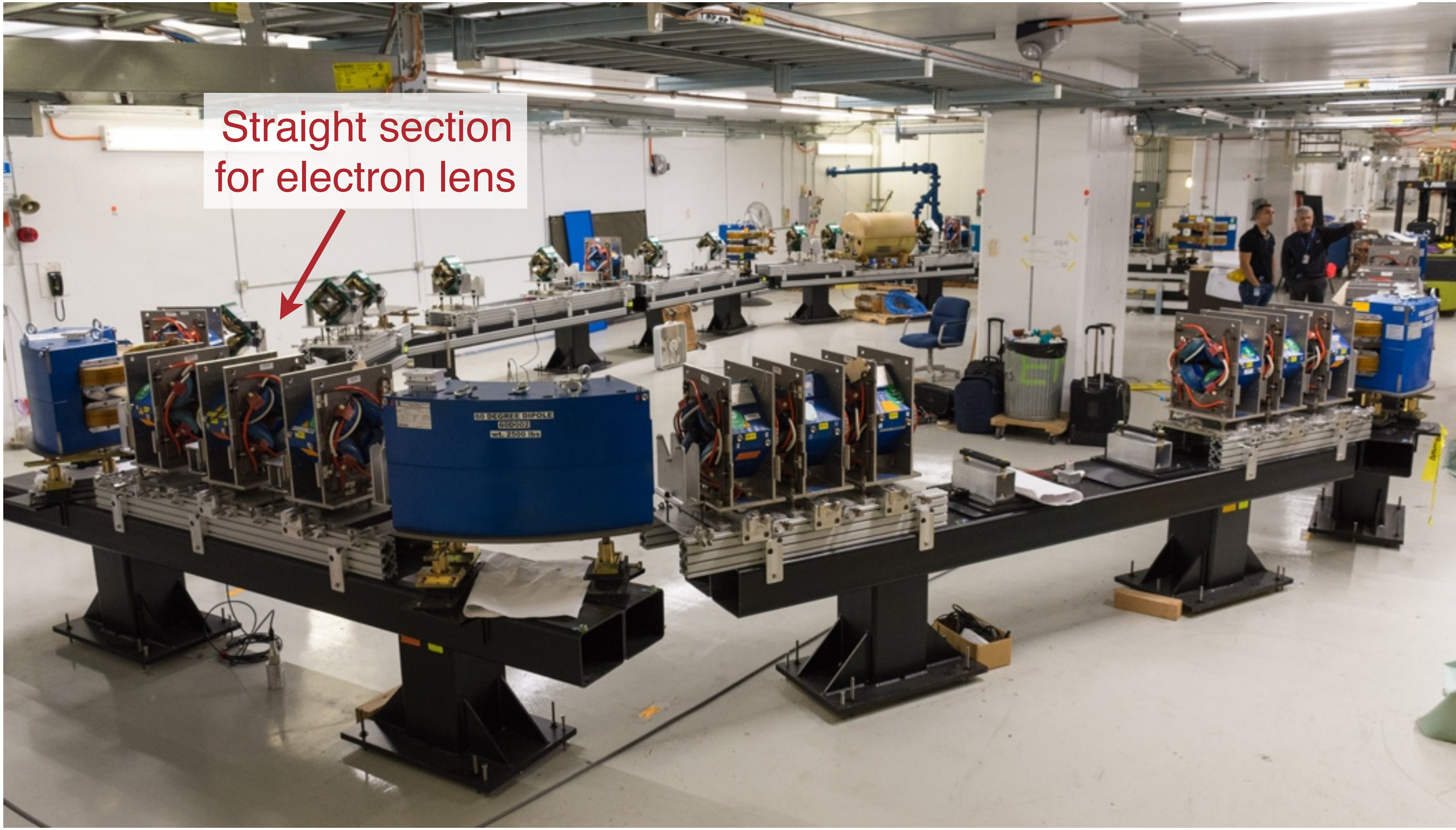
Electron-lens layout in IOTA



Electron-lens layout in IOTA



Electron lens section in IOTA



The broader electron-lens landscape and other projects

In the Fermilab Tevatron collider (2001-2011)

- ***long-range beam-beam compensation (tune shift of individual bunches)***
  - Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)
- ***abort-gap cleaning during regular collider 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)

In RHIC at BNL (2015-present)

- ***head-on beam-beam compensation for luminosity improvement***
  - Gu et al., Nucl. Instrum. Methods A **637**, 190 (2011)
  - Luo et al., Phys. Rev. ST Accel. Beams **15**, 051004 (2012)
  - Gu et al., Nucl. Instrum. Methods A **743**, 56 (2014)
  - Fischer et al., Phys. Rev. Lett. **115**, 264801 (2015)
  - Luo et al., Phys. Rev. Accel. Beams **19**, 021001 (2016)
  - Thieberger et al., Phys. Rev. Accel. Beams **19**, 041002 (2016)
  - Gu et al., Phys. Rev. Accel. Beams **20**, 023501 (2017)
  - Fischer et al., Phys. Rev. Accel. Beams **20**, 091001 (2017)

The broader electron-lens landscape and other projects

Current areas of research

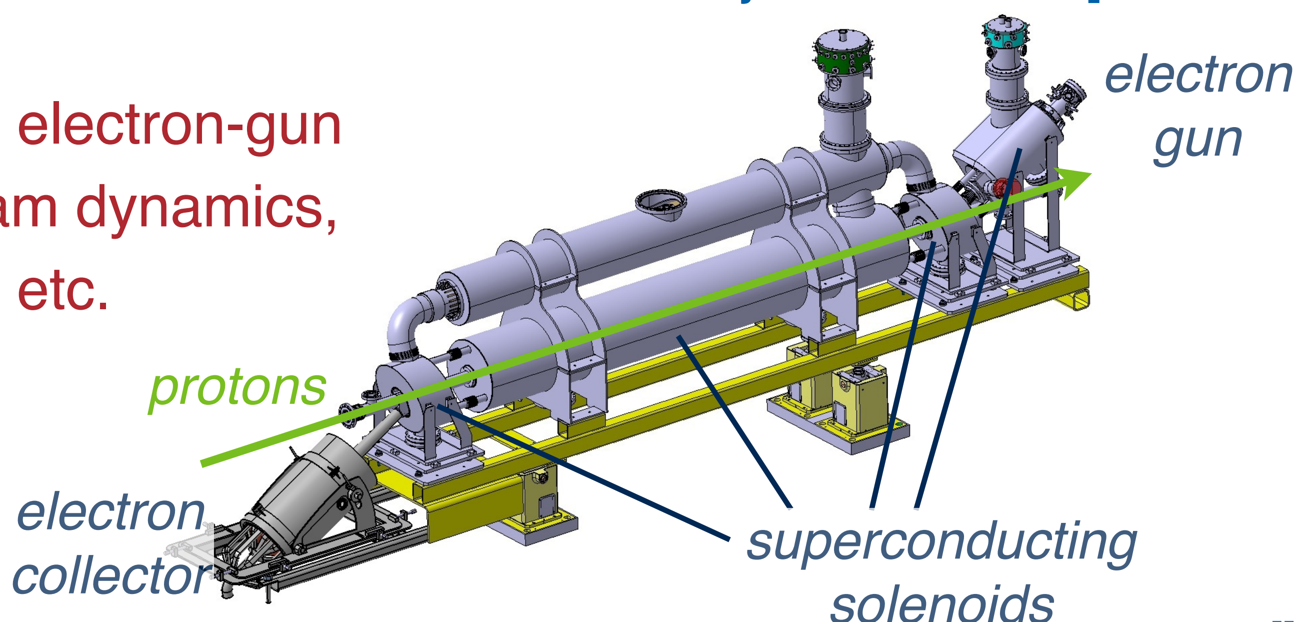
- ***nonlinear integrable lattices*** *in the Fermilab Integrable Optics Test Accelerator (IOTA)*
  - Nagaitsev, Valishev et al., IPAC12
  - Stancari, arXiv:1409.3615
  - Antipov et al., JINST **12**, T03002 (2017)
- ***hollow electron beam scraping*** *of protons in LHC*
  - Stancari et al., CERN-ACC-2014-0248
  - Bruce et al., IPAC15
  - Oct. ’16 review: <https://indico.cern.ch/event/567839>
  - Zanoni et al., J. Phys. Conf. Series **874**, 012102 (2017)
- ***long-range beam-beam compensation*** *as charged, current-carrying “wires” for LHC*
  - Valishev and Stancari, arXiv:1312.5006
  - Fartoukh et al., Phys. Rev. ST Accel. Beams **18**, 121001 (2015)
- ***tune-spread generation for beam stability (Landau damping)*** *in HL-LHC or FCC*
  - Shiltsev et al., Phys. Rev. Lett. **119**, 134802 (2017)
- **space-charge compensation** of high-intensity hadron beams (IOTA, SIS18 at GSI)
  - Antipov et al., JINST **12**, T03002 (2017)
  - Park et al., NAPAC16
  - Ondreka et al., IPAC17; Stem and Boine-Frankenheim, IPAC17

Synergies with hollow lens for HL-LHC

Hollow electron beams for active halo control in LHC

- demonstrated experimentally in Tevatron, more tests in RHIC in 2018
- conceptual design for LHC completed [Stancari et al., CERN-ACC-2014-0248]
- technical design in preparation
- recent reviews for HL-LHC
  - need for halo control [Oct. 2016, <https://indico.cern.ch/event/567839>]
  - project readiness [Oct. 2017, <https://indico.cern.ch/event/648237>]
  - recommended for inclusion in HL-LHC Project baseline [Mar. 2018]

Collaborations on electron-gun development, beam dynamics, magnetic system, etc.



Beam Physics and Design Parameters

Roles of the IOTA electron lens

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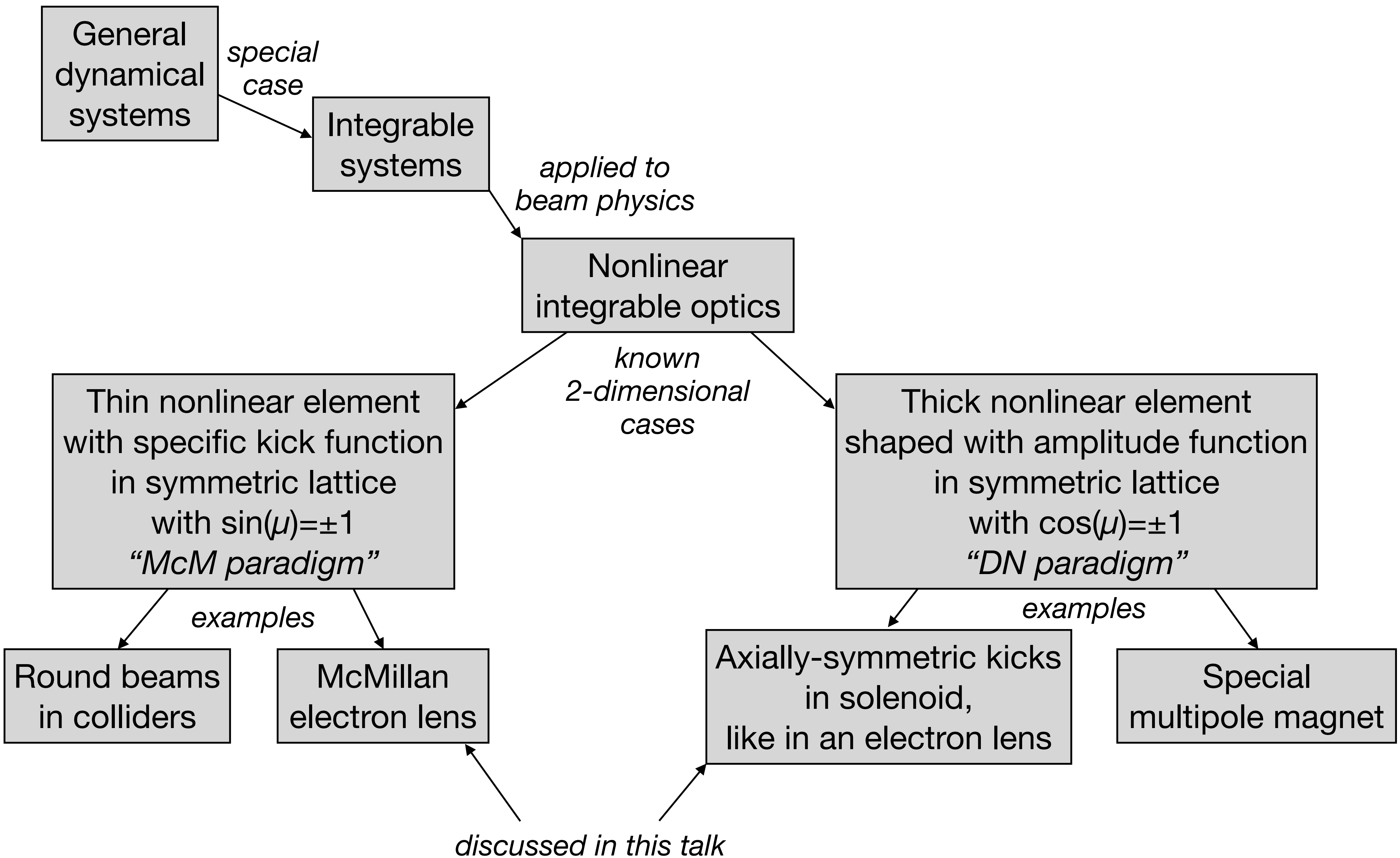
Nonlinear integrable optics and electron lenses



Transverse nonlinear integrable optics in IOTA with e-lens

- 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
    - *any* axially symmetric kick in solenoid (**electron lens option #2**)

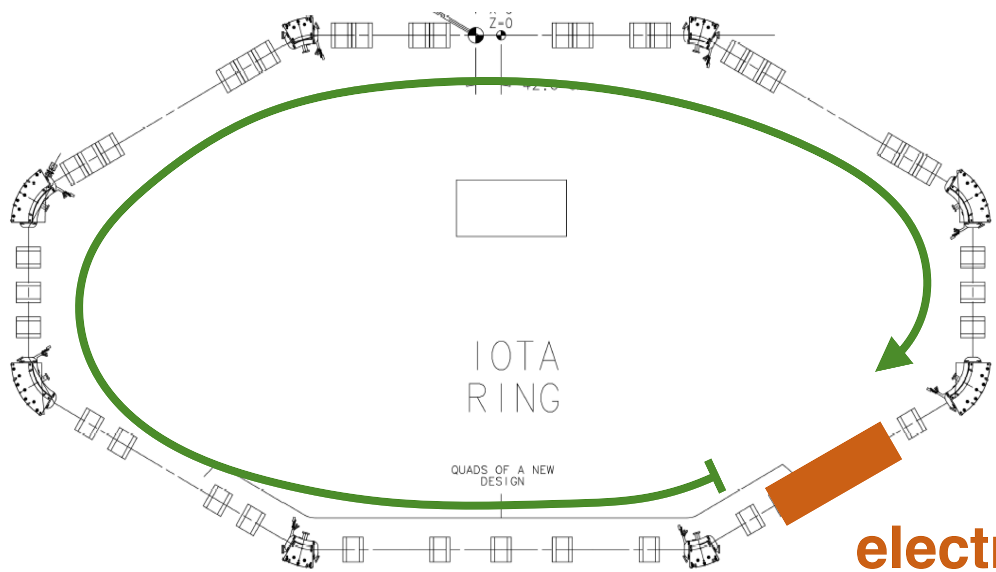
linear arc:

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

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



electron lens

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

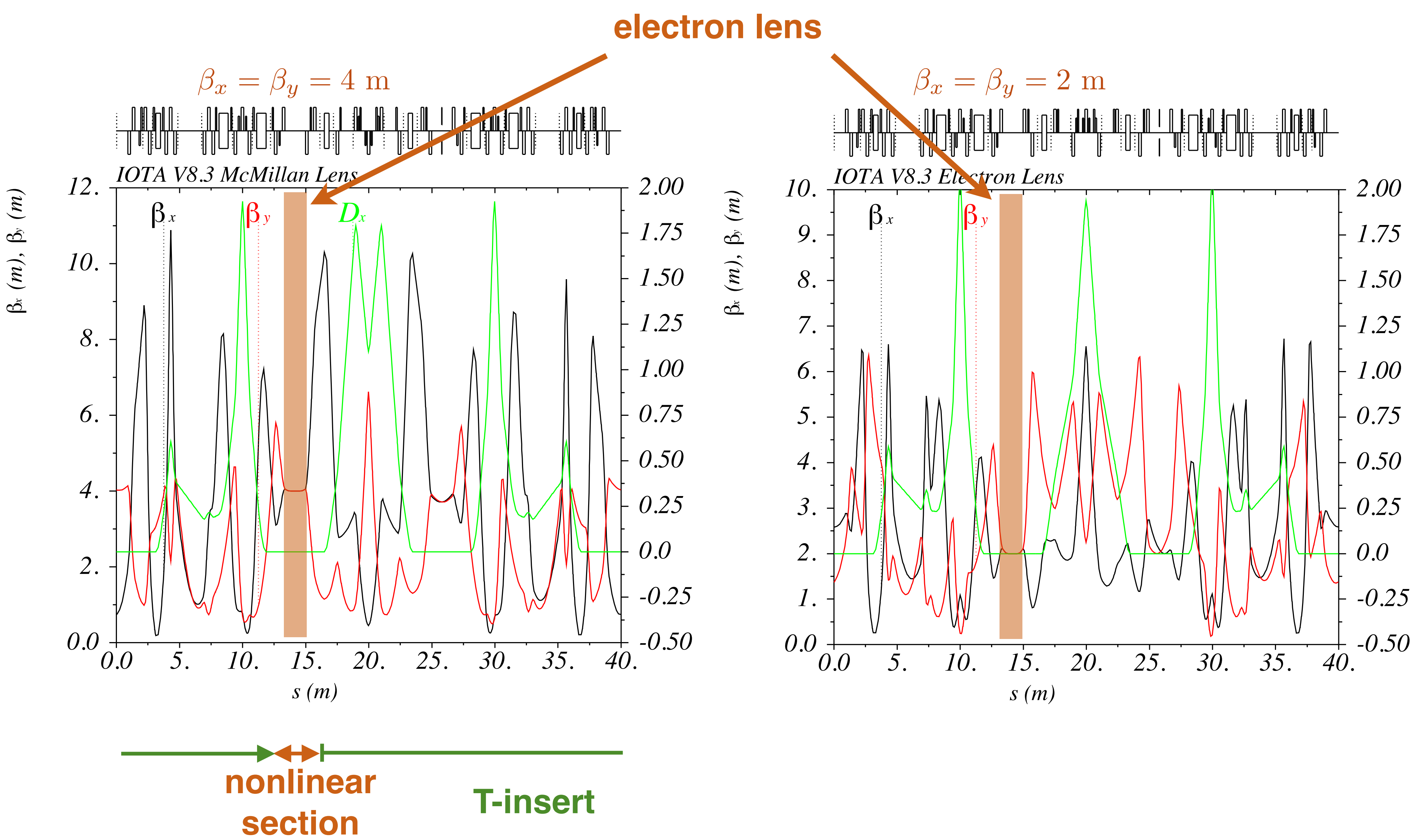
2. Axially symmetric kick in long solenoid

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

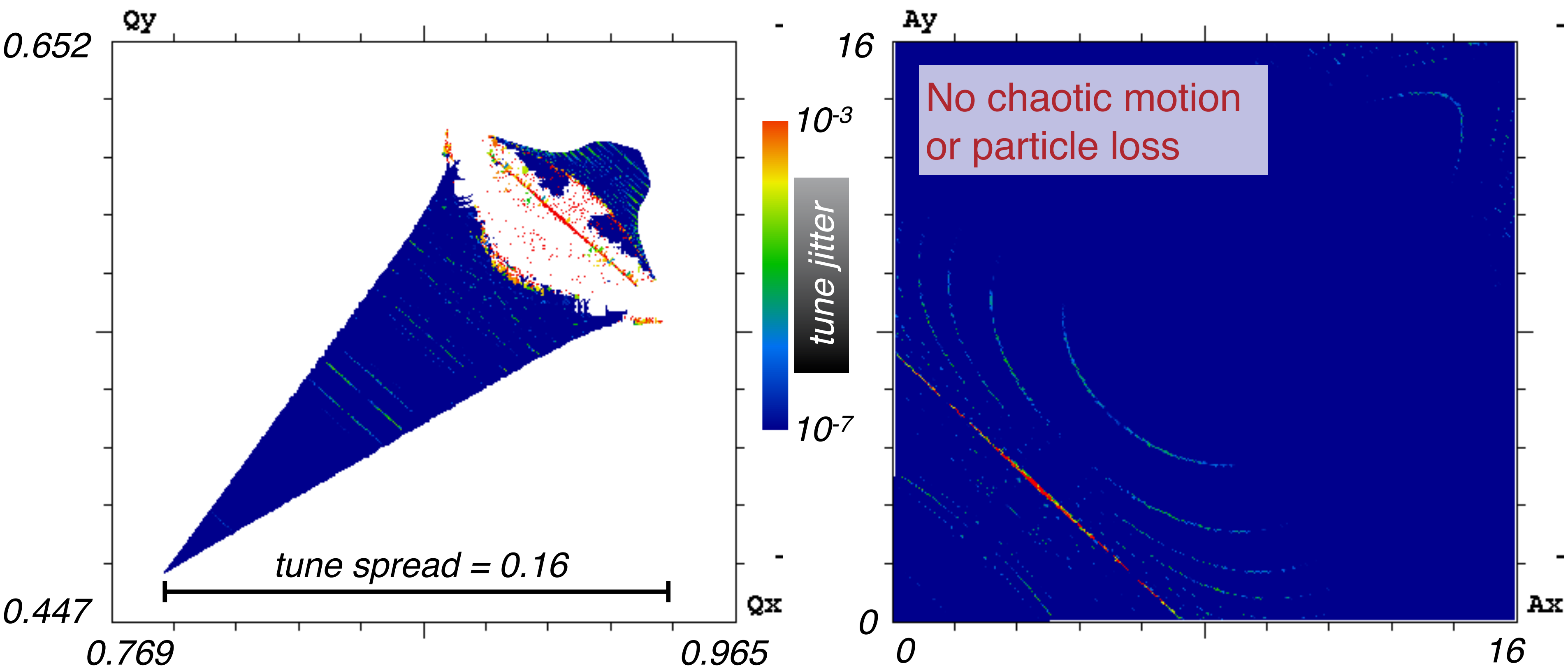
IOTA lattices with electron lens



Tracking simulations and frequency-map analysis

IOTA with McMillan lens in 0.7-m solenoid, k_e = 0.6 /m (1 A)
IOTA lattice v6.6, $\beta_x = \beta_y$ = 3 m

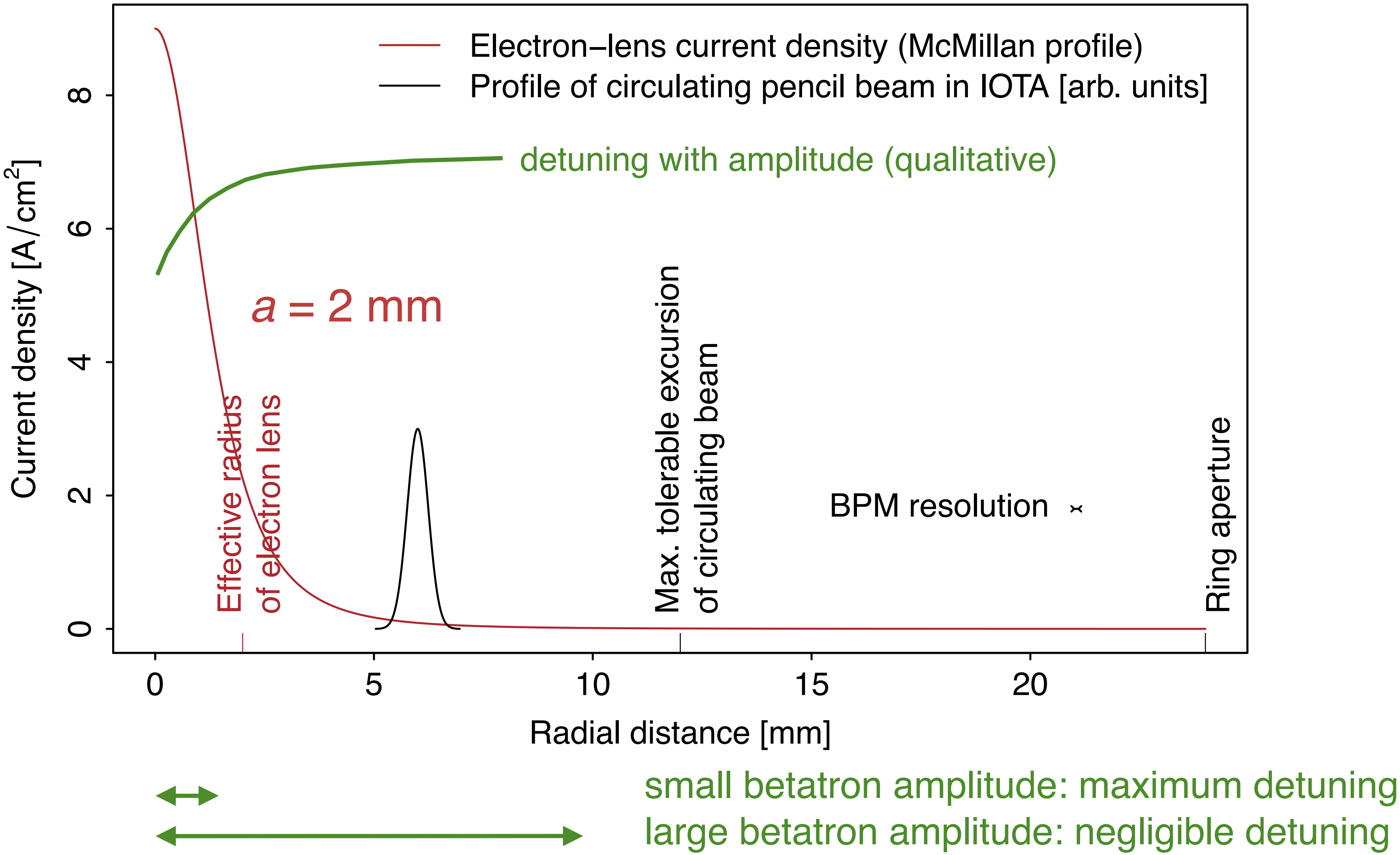
$$\frac{\beta k_e}{4\pi} = 0.14$$



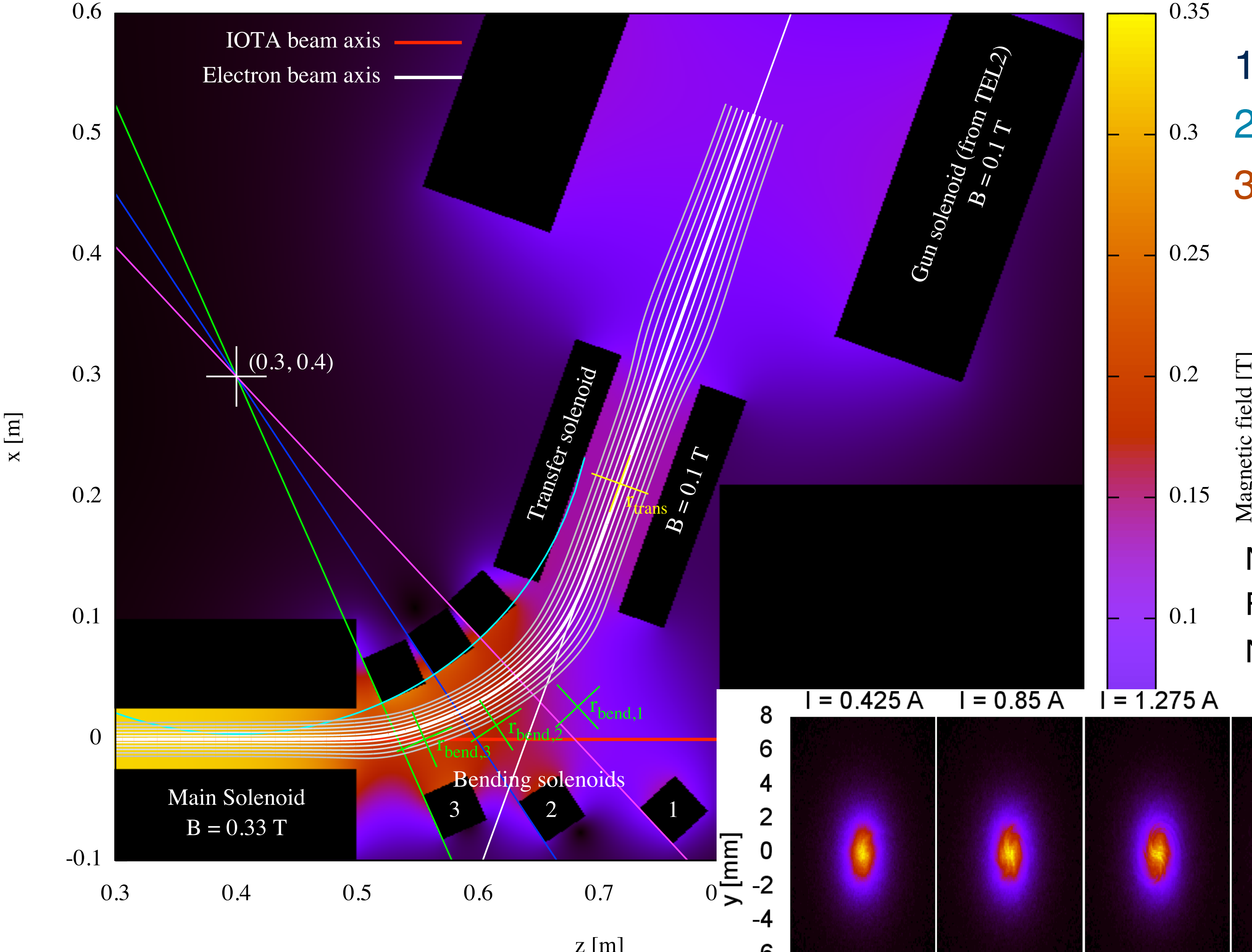
Tune spread of ~ 0.4 is achievable with β = 4 m and electron beam current of 2 A

Choice of electron-lens beam size in 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

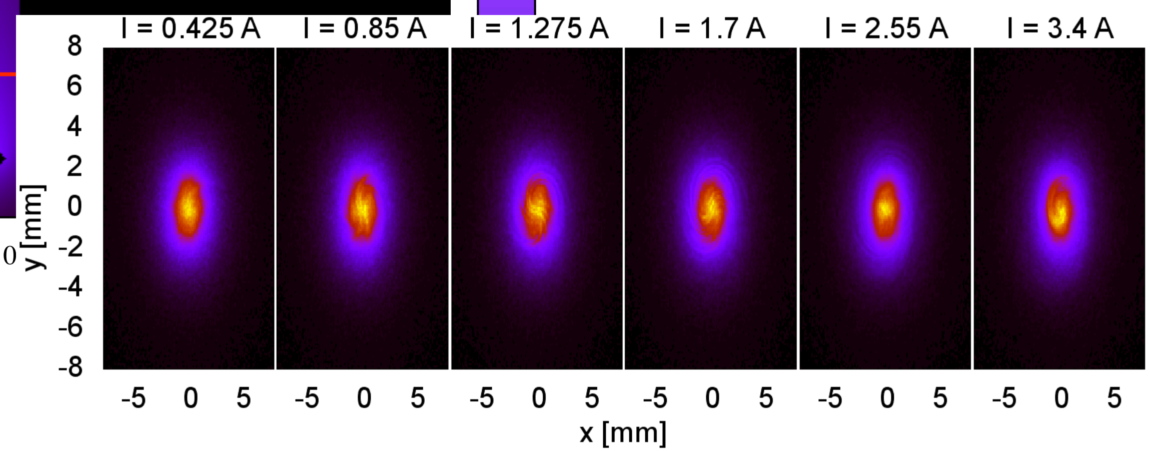


Design of beam transport in electron lens



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

Noll and Stancari, FERMILAB-TM-2598-AD-APC; Noll, PhD Thesis (2016)



Minimize distortions

Provide input for tracking in ring

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Typical IOTA electron-lens parameters

Cathode-anode voltage	0.1 — 10 kV
Electron beam current	5 mA — 3 A
Current density on axis	0.1 — 12 A/cm^2
Main solenoid length	0.7 m
Main solenoid field	0.1 — 0.8 T
Gun/collector solenoid fields	0.1 — 0.4 T
Max. cathode radius	15 mm
Lattice amplitude function	2 — 4 m
Circulating beam size (rms), e^-	0.1 — 0.5 mm
Circulating beam size (rms), p	1 — 5 mm

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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 option determined the co-propagating configuration of the e-lens

Cooling rates of 0.1 s are achievable

Emittances can be reduced by a factor 10

Better models of magnetized cooling are needed for predictions

→ *see also Bruhwiler's talk*

Does nonlinear integrable optics combined with cooling enable higher brightnesses?

Stancari et al., COOL15

Antipov et al., JINST **12**, T03002 (2017)

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Space-charge compensation in rings

Space-charge compensation **routinely used** in **linacs**, **rf photoinjectors**

In **rings**, it would **enable higher intensities**

A challenging subject: is the **local correction** of a **global effect** possible?

Issues: high charge densities, lattice distortions, beam-plasma instabilities

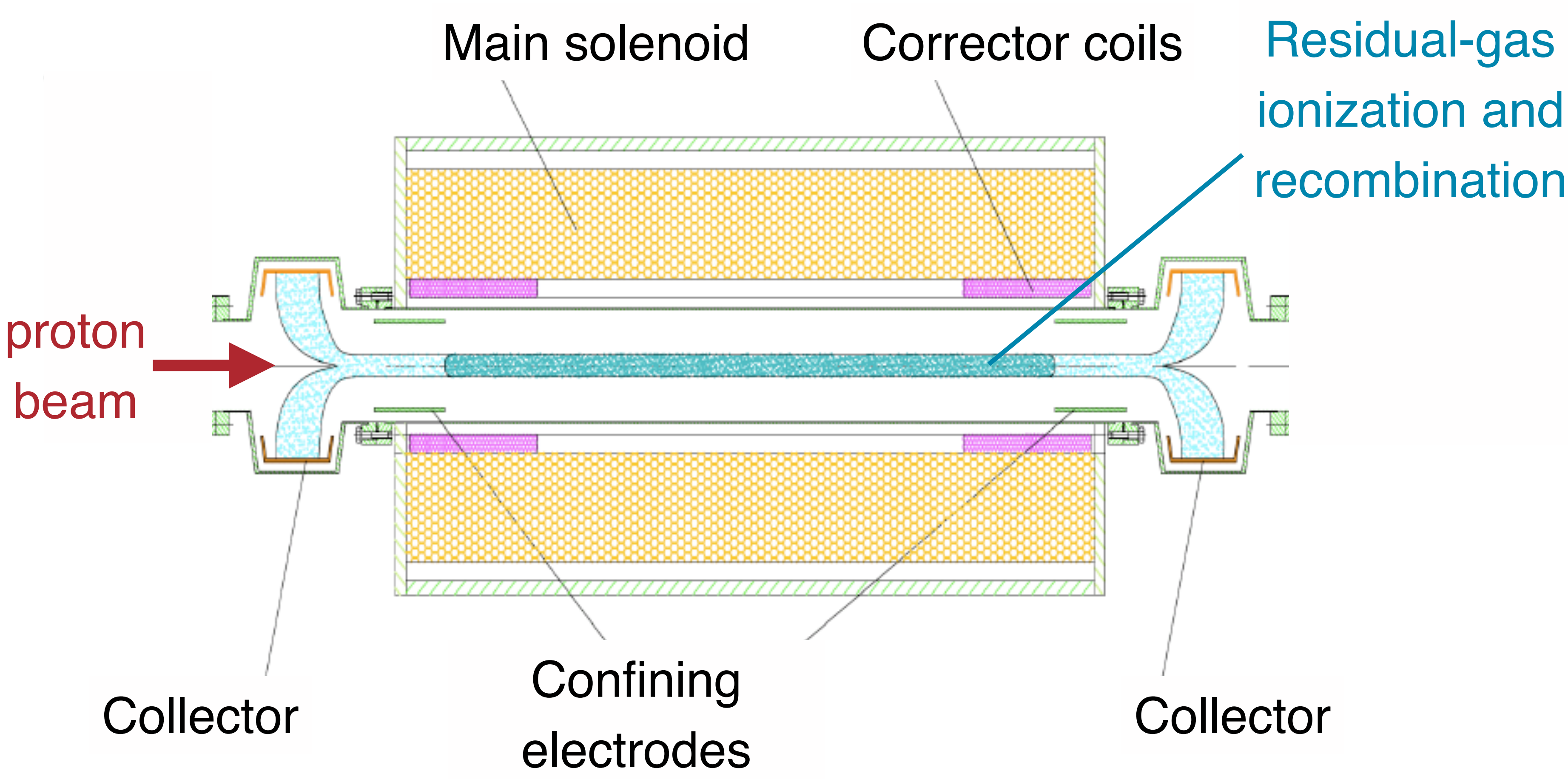
Implementation with **electron lens** has **advantage** of **magnetic confinement** for stability

Two concepts:

- **given profile** (transverse and maybe longitudinal) **from electron gun** or
- **electrons from residual-gas ionization** trapped in Penning-Malmberg configuration (“**electron column**”)

Numerical simulation studies necessary to guide experiments in IOTA

Concept of electron column



In strong field, ionization electrons mirror transverse profile of protons

How does the e-column evolve?

→ *Next talks: Stern, Freemire*

Experimental Apparatus

Electron guns: 10.8-mm Gaussian

Reused from Tevatron beam-beam compensation studies

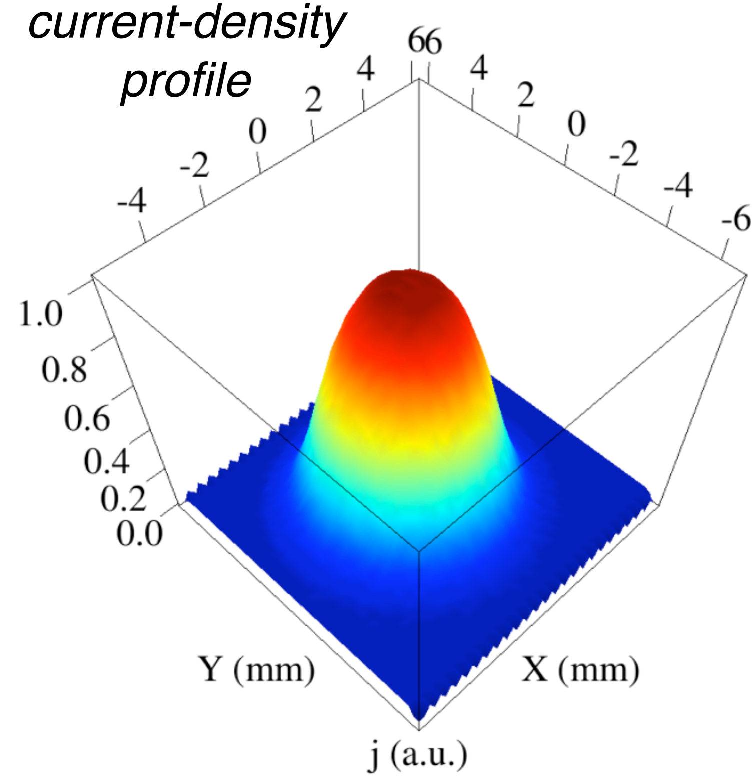
New tungsten dispenser cathodes available

In IOTA, it can be used for tests of nonlinear integrable optics, electron cooling, and space-charge compensation

side view

top view

measured current-density profile



Yields 1.7 A at 5 kV

Design of the McMillan electron gun

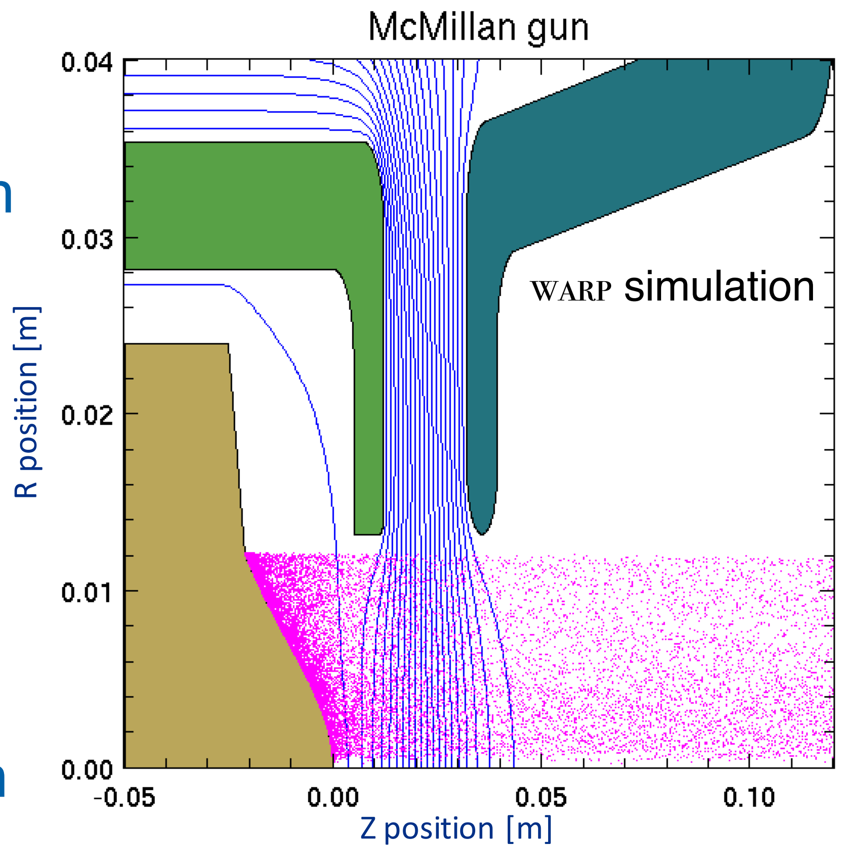
Is it possible to generate the required current-density profile? $j(r) = \frac{j_0 a^4}{(r^2 + a^2)^2}$

Work in progress

Contrasting requirements of high yield and peaked distribution

Optimization of the e-gun geometry to match the desired profile

Space-charge-limited emission determined mostly by E-field at surface =>
•optimize E-field first (fast)
•then, refine beam profile (slower), iterating calculation of space-charge-limited emission



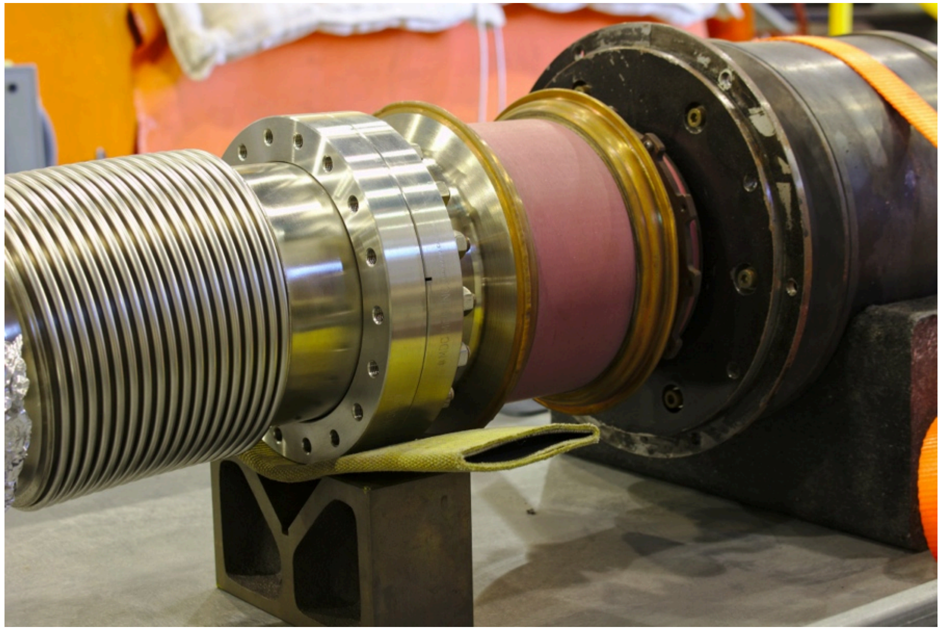
Collector

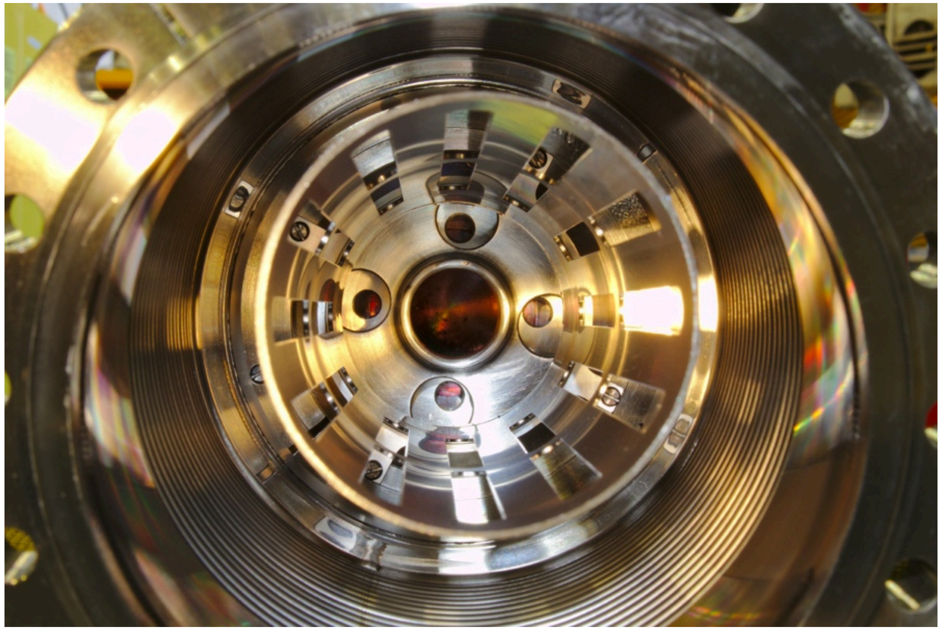
Reused from Tevatron electron lens (TEL-2)

Water-cooled copper assembly

It can dissipate 50 kW

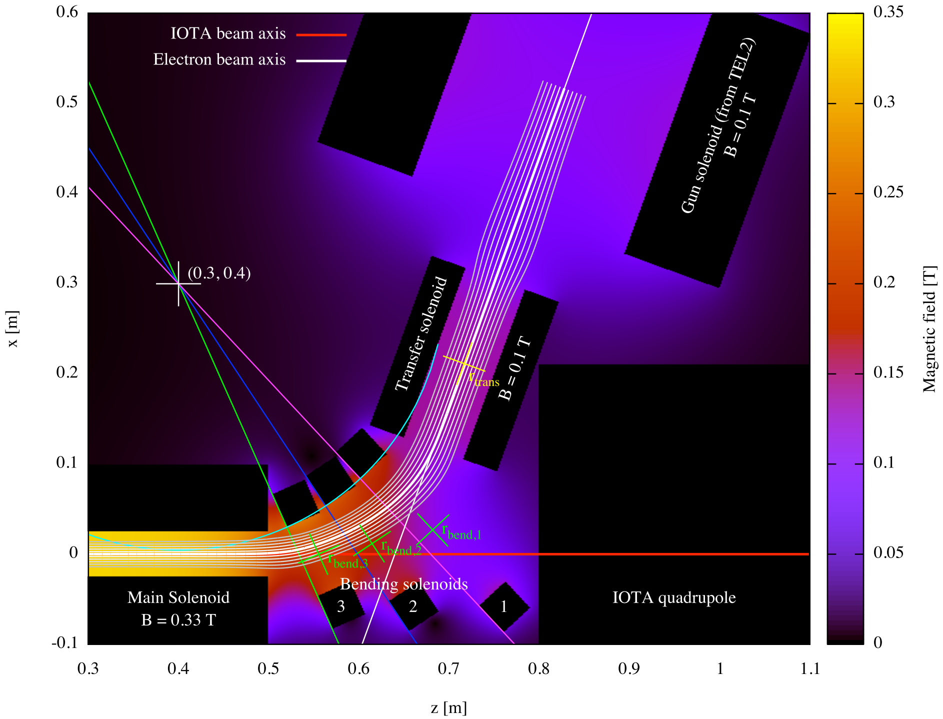
Vacuum tests complete



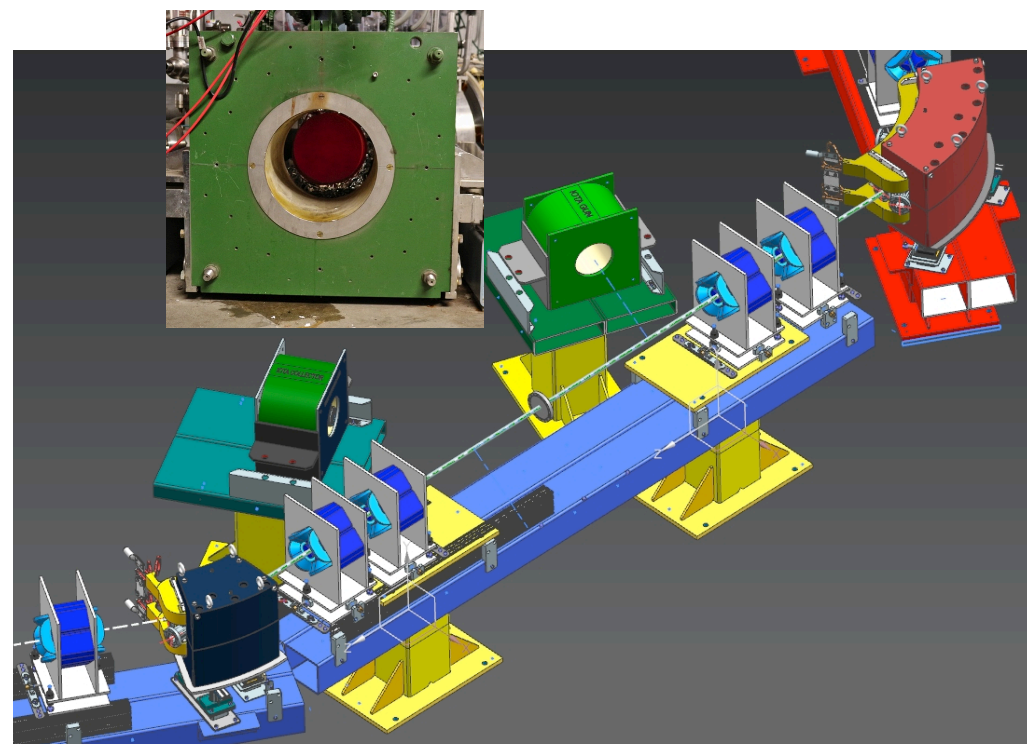


Magnetic system

Baseline design is scaled-down version of Tevatron e-lens (TEL-2), with 3 coils in toroidal section (70° bend) and added transport solenoids



Gun and collector solenoids recovered from TEL-2, awaiting measurements and tests



Main solenoid, transport solenoids, toroidal sections and dipole correctors need to be designed and built (likely by external contractors)

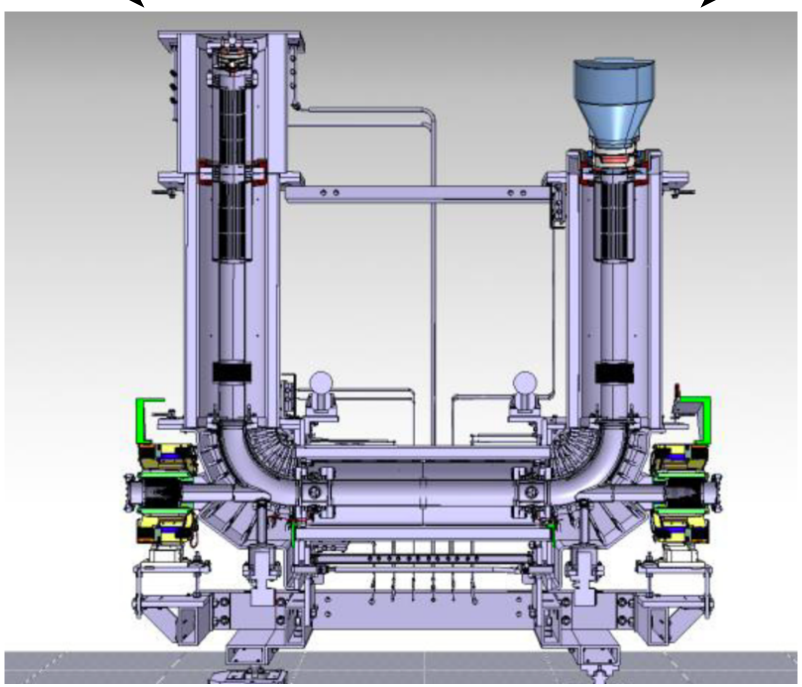
Magnetic system

Also considering alternative designs, such as compact ELENA electron cooler at CERN

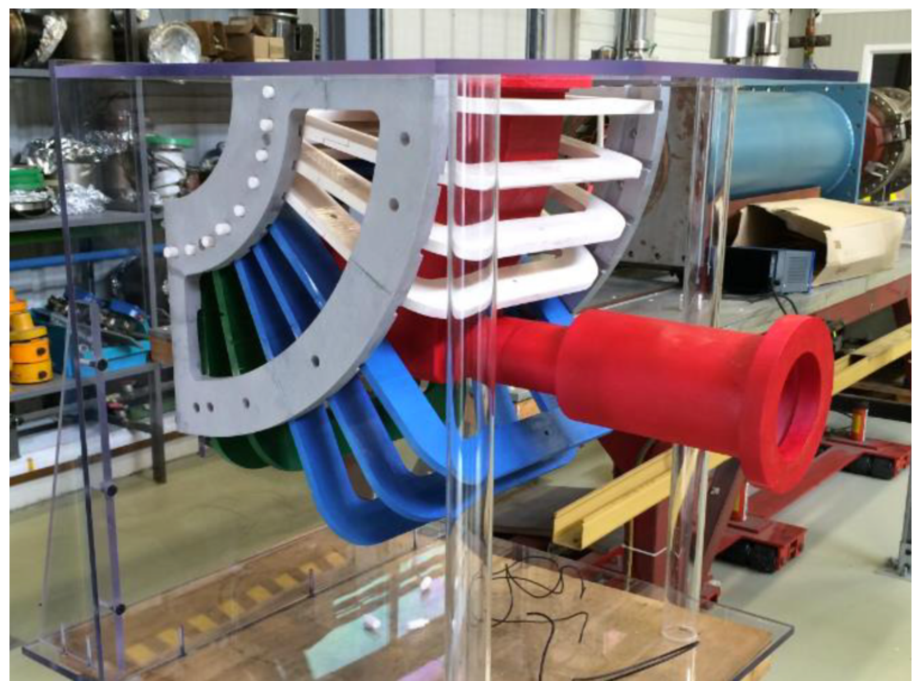
NEG coating of surfaces would allow solenoid continuity and fewer pumping ports

2.3 m

Tranquille et al., IPAC16



ELENA electron cooler



Compact toroidal section (3D print)

Power converters

Several power supplies can be reused:
- high-voltage system
- magnet powering (partial)
- filament heater

Modulator specs in progress: single flexible device vs. separate modules

Main diagnostic devices

E-lens beam **current**

- cathode toroid
- collector toroid

E-lens beam **profile**

- YAG screen (low intensity, fast)
- pinhole scan (high intensity, slow)

Circulating beam **profile** (*p* only)

- recombination monitor

Beam **position** (both e-lens and circulating)

- strip-line beam-position monitors

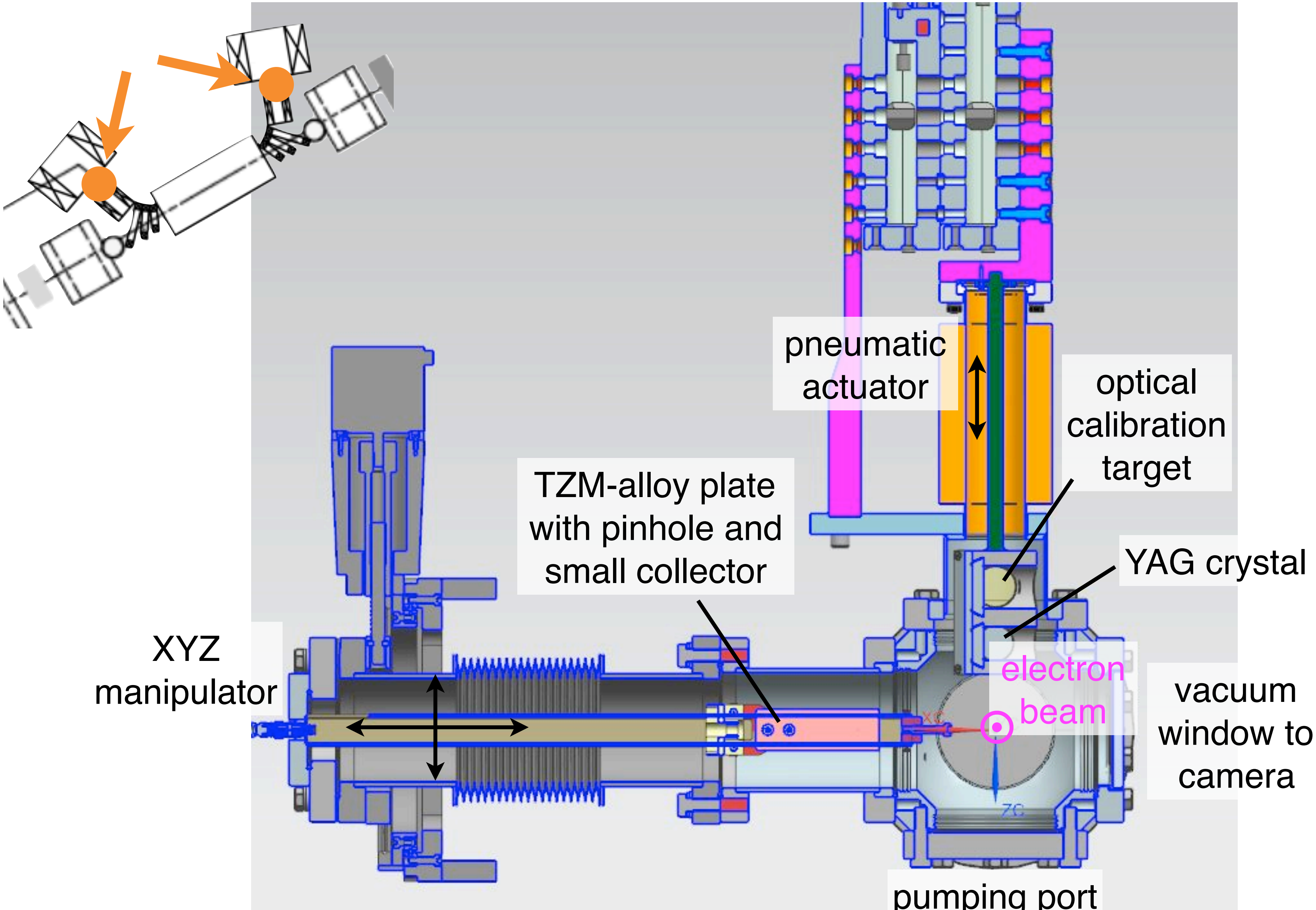
Pulse **timing**, e-column charge **oscillations**

- strip-line beam-position monitors
- split electrodes

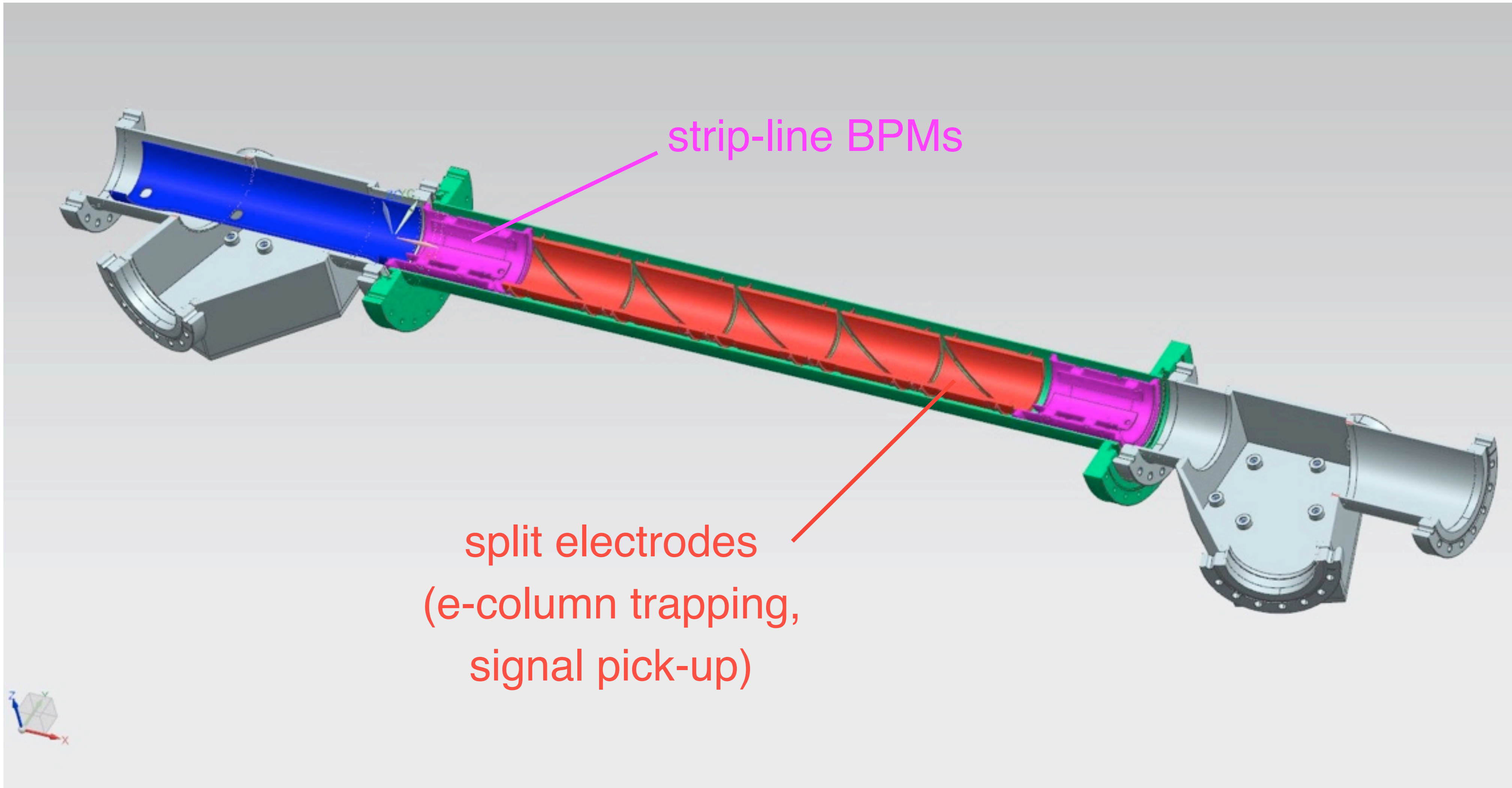
Solenoid **field**, e^- **density** and **temperature**

- microwave antenna for cyclotron motion *(under study)*

Diagnostic stations



Electrode and pickup structure inside main solenoid

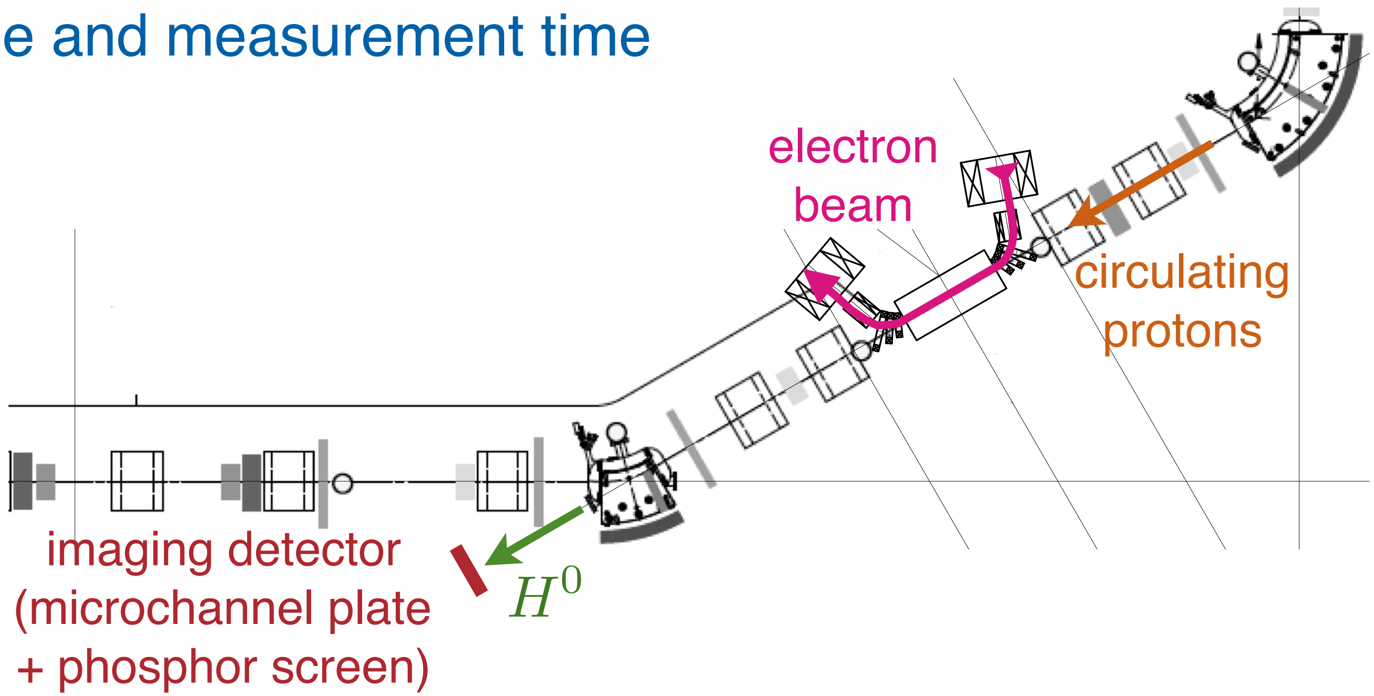


Proton beam diagnostics through recombination

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: a good compromise between beam lifetime and measurement time



A **critical diagnostic tool** for **cooling** and **proton beam evolution**

Image from CERN’s ELENA ring recombination monitor
Tests with H^- stripping on residual gas

Video from CERN’s ELENA ring recombination monitor
Tests with H^- stripping on residual gas

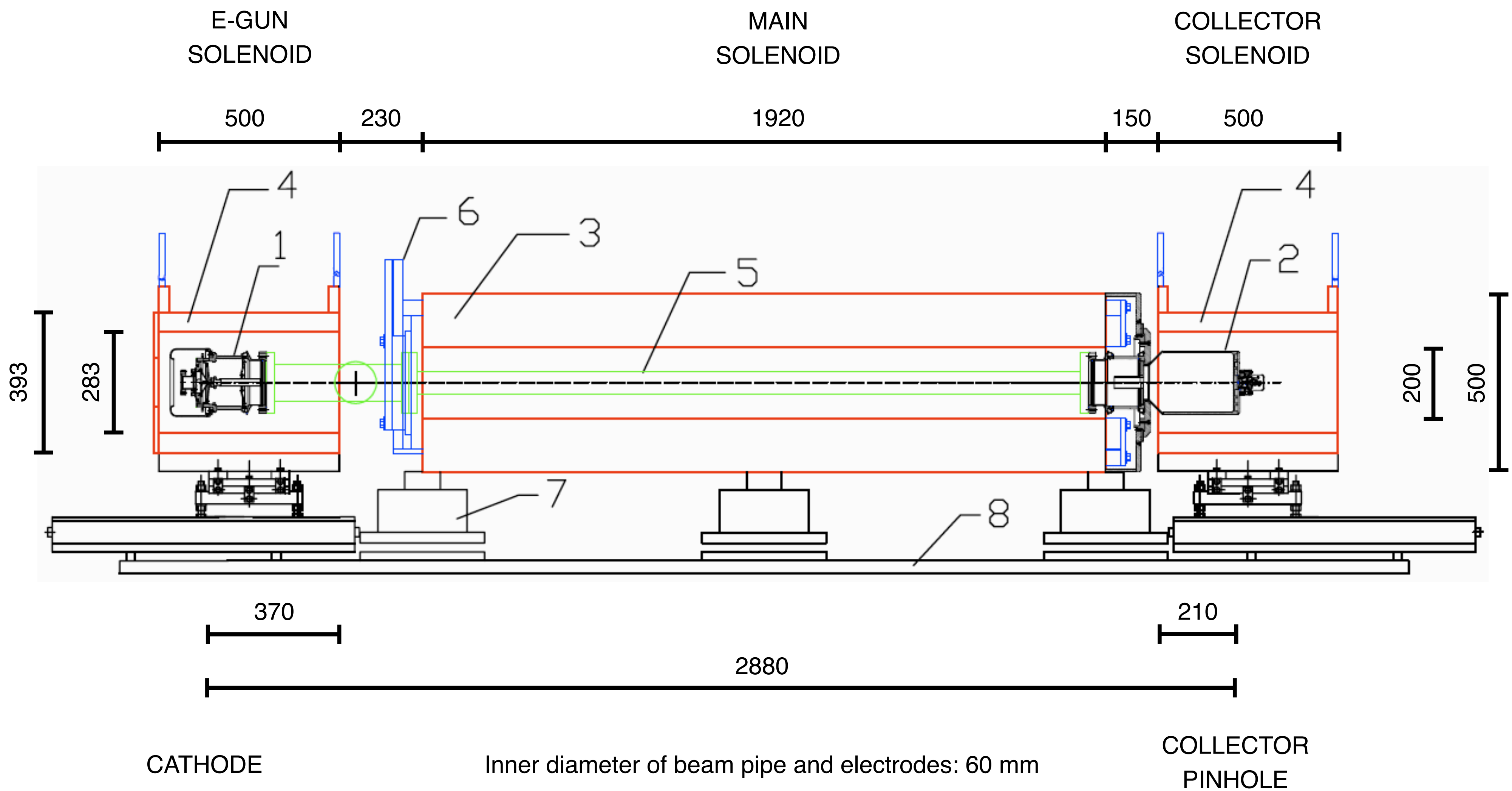
Fermilab electron-lens test stand

electron gun and gun solenoid | **main solenoid (max 0.4 T)** | **collector solenoid**

- The only running electron-lens test stand in the world
- Operational for more than 20 years! We need to keep it healthy
- Main functions:
  - characterize electron guns
  - study magnetized electron beam dynamics with space charge

Fermilab electron-lens test stand

dimensions in mm



Conclusions

Conclusions

The IOTA electron lens will enable new experiments on nonlinear dynamical systems, electron cooling, and space-charge compensation

Design challenges are related to its multiple functions and to the limited physical space

The project is closely related to electron-lens applications in other machines, such as hollow electron beam collimation in LHC

Progress was delayed so far due to limited resources and focus on IOTA ring construction

There are several opportunities for collaborators to make an impact: theory, numerical calculations, diagnostics, apparatus, experiments

A new post-doc position will be opened soon

Thank you for your attention!

For more info: `https://cdcvs.fnal.gov/redmine/projects/iota-e-lens/wiki`