Research with the IOTA Electron Lens:

Nonlinear Integrable Optics, Landau Damping, Space-Charge Compensation and Electron Cooling

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Fermilab

FAST/IOTA Collaboration Meeting

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indico.fnal.gov/event/43231

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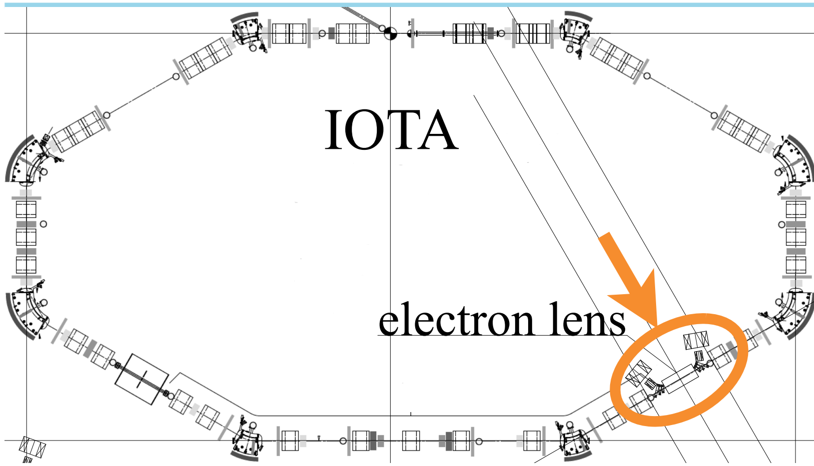
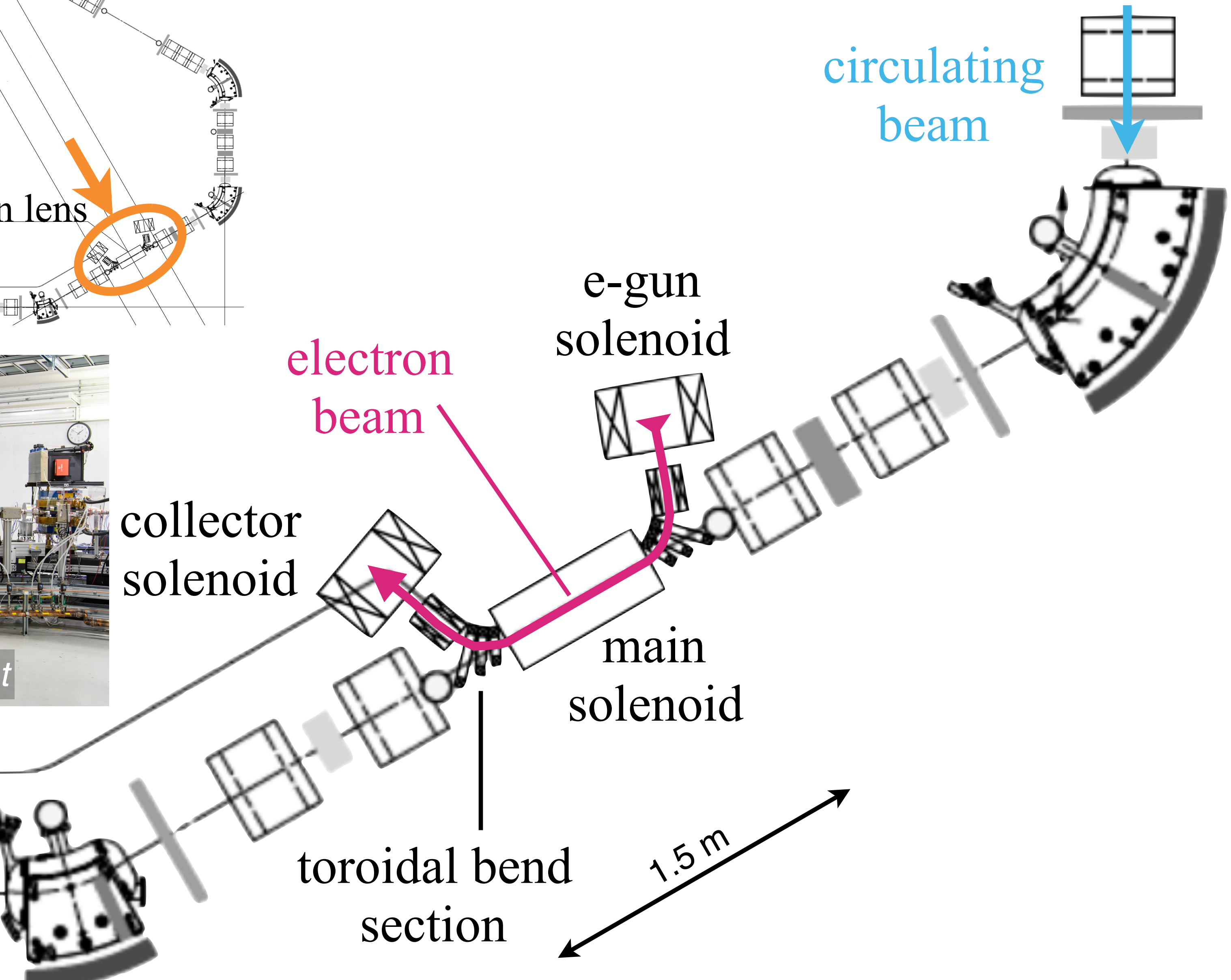
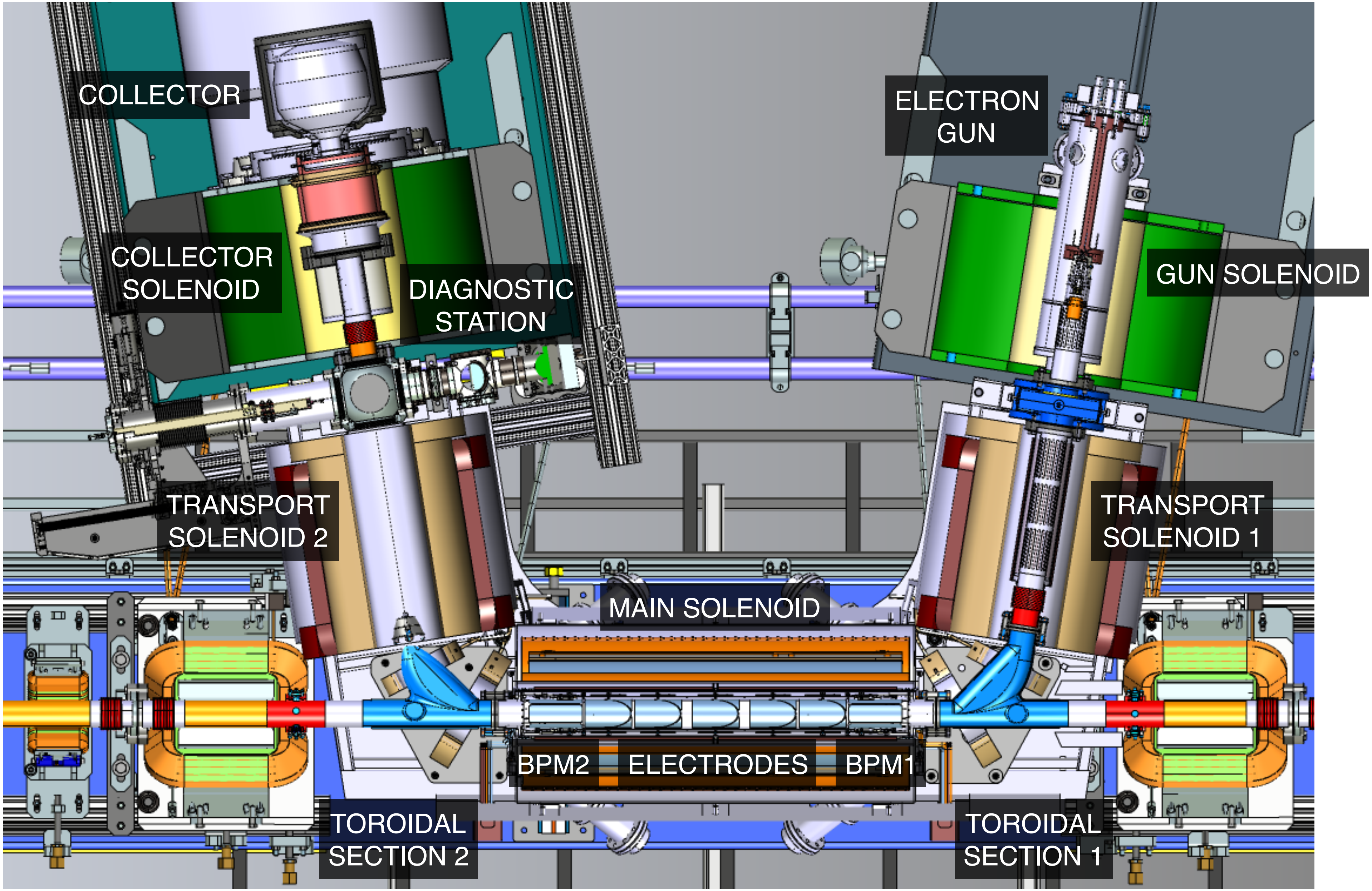
Electron Lens Layout in IOTA




IOTA D-Right straight



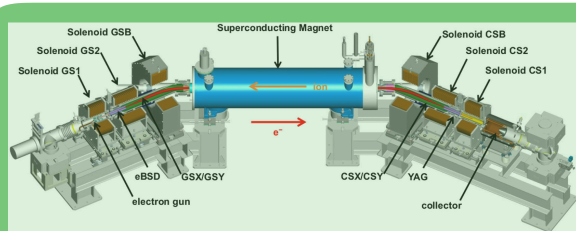
IOTA Electron Lens Layout - Top View



Electron Lenses: Flexible Instruments for Beam Physics

Fermilab Tevatron collider (2001-2011)

- head-on and long-range beam-beam compensation
- abort-gap clearing
- first studies of halo scraping with hollow beams

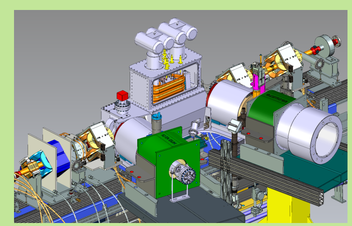


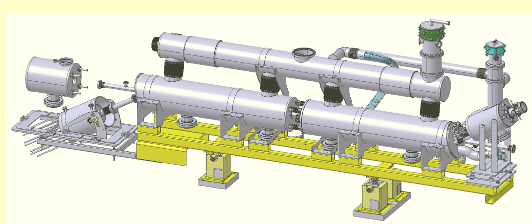
RHIC at BNL (2015-present)

- head-on beam-beam compensation
- further studies of halo scraping

IOTA (starting in 2021?)

- nonlinear integrable optics
- tune-spread generation
- space-charge compensation
- electron cooling of protons





LHC (2025 installation, 2027 run; part of HL-LHC)

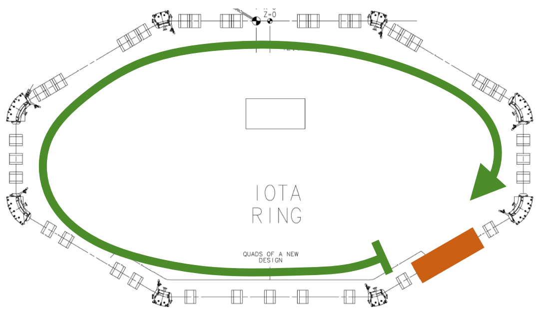
- active halo control with hollow beams
- option for tune-spread generation

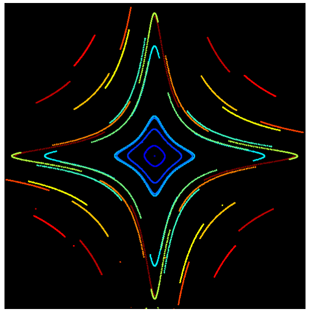
Beam Physics Research with the IOTA Electron Lens

"Electron lens" = magnetically confined electrons acting on the circulating beam

First with *circulating electrons*, then with *circulating protons*:

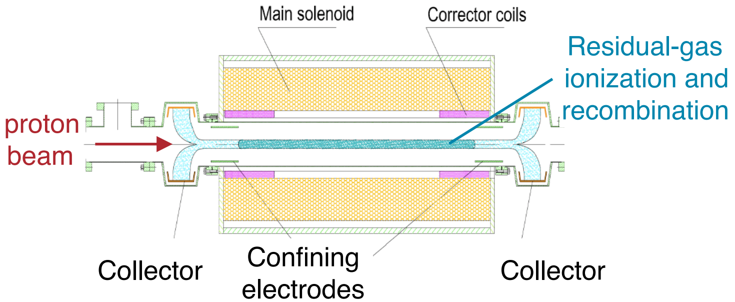
- **Nonlinear element for integrable optics**
  - thin McMillan lens
  - thick axially symmetric lens
- **Tune-spread generator for stability**





With *circulating protons*:

- **Space-charge compensator**
  - shaped beam from electron gun
  - trapped electron column from residual gas
- **Electron cooler**
  - extend range of proton emittances, lifetimes and tune spreads for space-charge experiments
  - new research on electron cooling reach in nonlinear lattice



Main **challenges**:

- compact device
- multiple functions

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

Nonlinear Integrable Systems based on Electron Lenses

Use the **electromagnetic field** generated by the **electron distribution** to provide the **desired nonlinear field**

Linear focusing strength on axis
Tunable intensity (~ 1 m^{-1})
and time structure

$$k_e = 2\pi \frac{j_0 L (1 \pm \beta_e \beta_z)}{(B\rho)\beta_e \beta_z c^2} \left(\frac{1}{4\pi\epsilon_0} \right).$$

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 (0.2)
More sensitive to kick shape

2. Axially symmetric kick in long solenoid

Any axially-symmetric current distribution

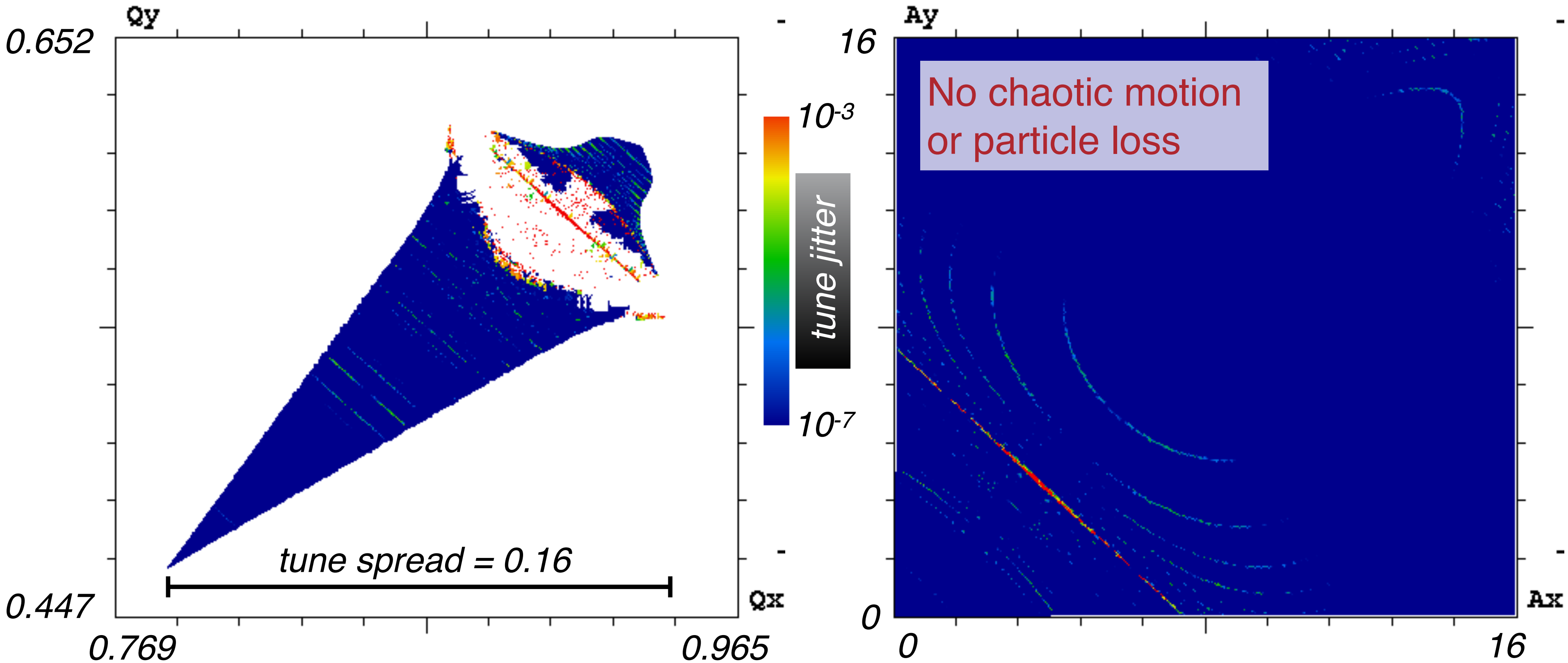
Achievable tune spread $\sim \frac{L}{2\pi\beta} = \frac{LB_z}{4\pi(B\rho)}$

Smaller tune spreads in IOTA (0.06)
More robust

Example of Tracking Simulations and Frequency-Map Analysis

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

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

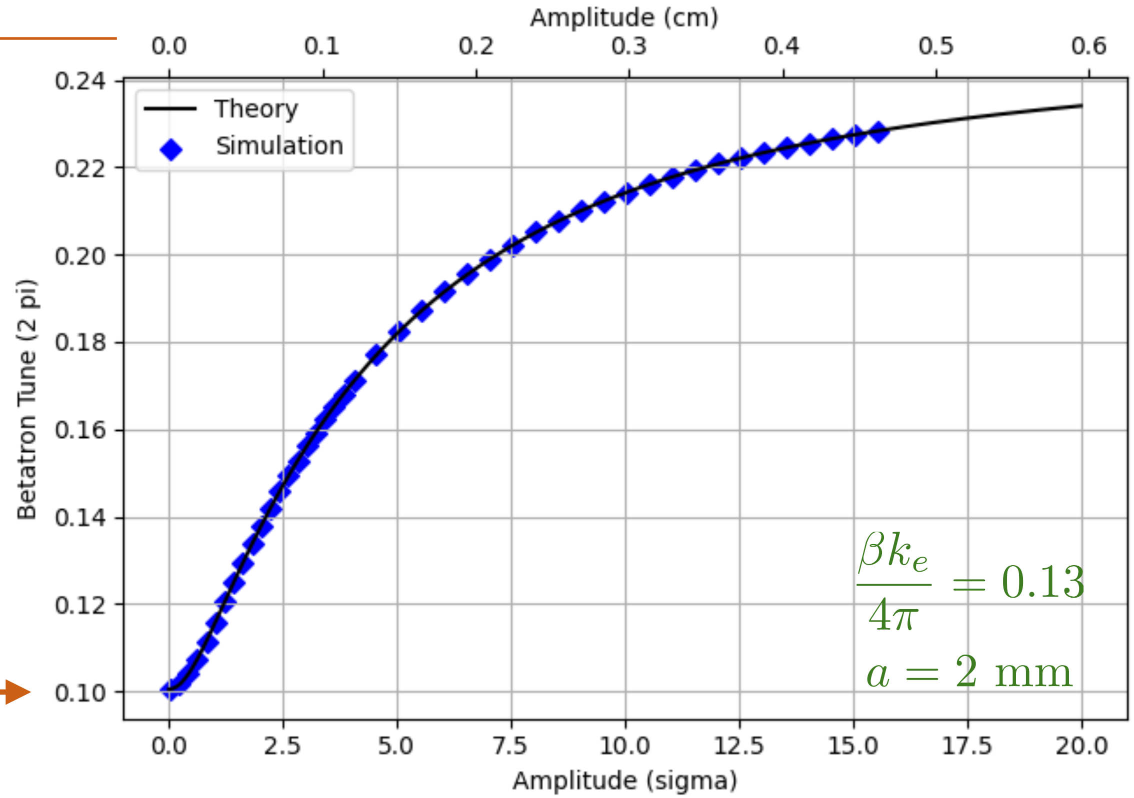


Tune spread of ~ 0.4 is achievable with β = 4 m and electron beam current of 2 A

Tune vs. Amplitude with McMillan Electron Lens

Analytical calculation and numerical tracking (Lifetrac) of detuning vs. amplitude

$\nu(r \gg a) = 1/4$



$$\nu(0) = \frac{1}{2\pi} \arccos\left[\left(\frac{\beta k_e}{4\pi}\right) 2\pi\right]$$

Experimentally, the electron beam size *a* is adjusted to fit the accessible tune spreads to the aperture of the machine

Nagaitsev and Zolkin, Phys. Rev. Accel. Beams **23**, 054001 (2020)
Cathey et al., Beams-doc-8422 (in preparation)

McMillan Electron-Gun Design

Is it possible to generate the required current-density profile?

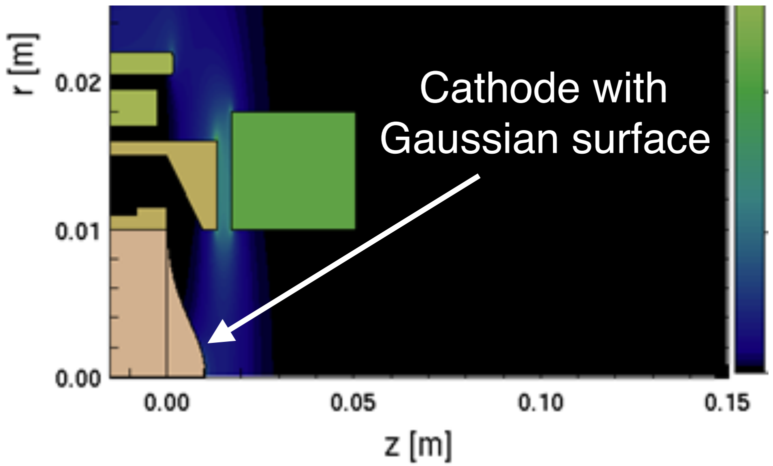
$$j(r) = \frac{j_0 a^4}{(r^2 + a^2)^2}$$

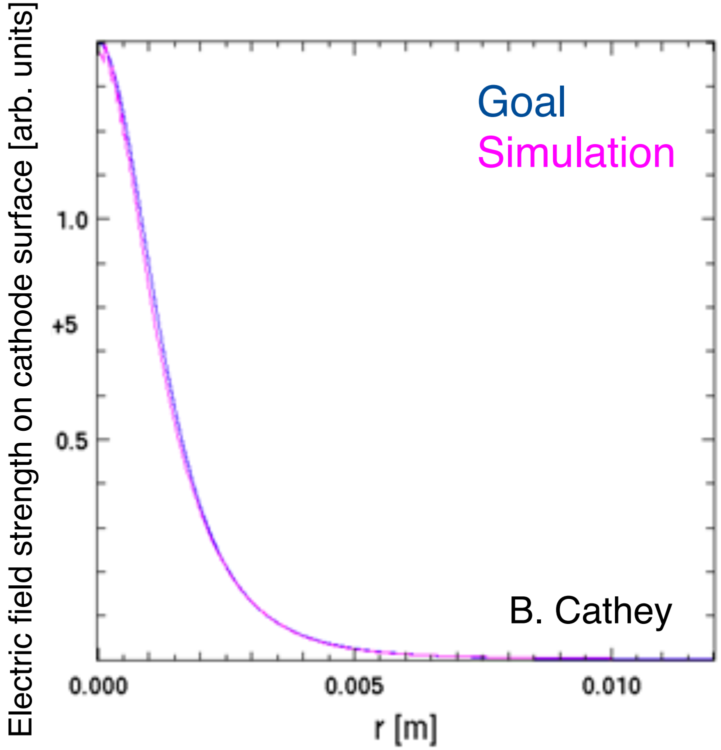
Contrasting requirements of high yield and peaked distribution

Space-charge-limited emission determined mostly by **electric field at surface**:

- optimize E-field first (fast)
- then, refine beam profile (slower), iterating calculation of space-charge-limited emission

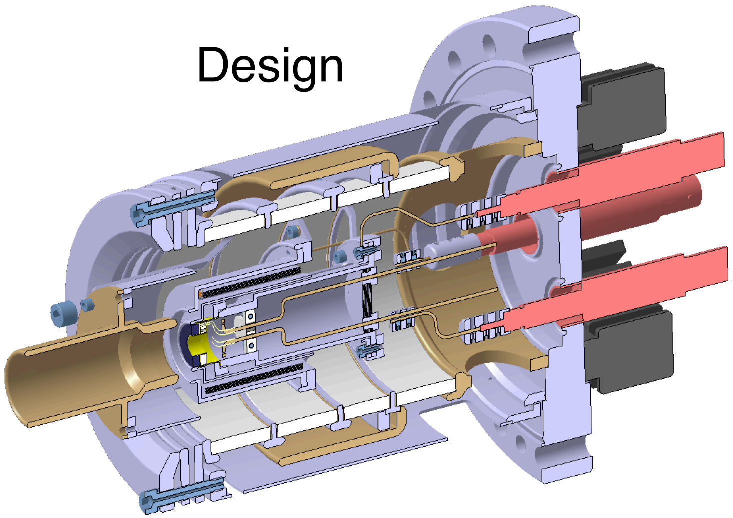
Optimization of the e-gun geometry to match the desired profile with Warp and other codes for comparison (work in progress)

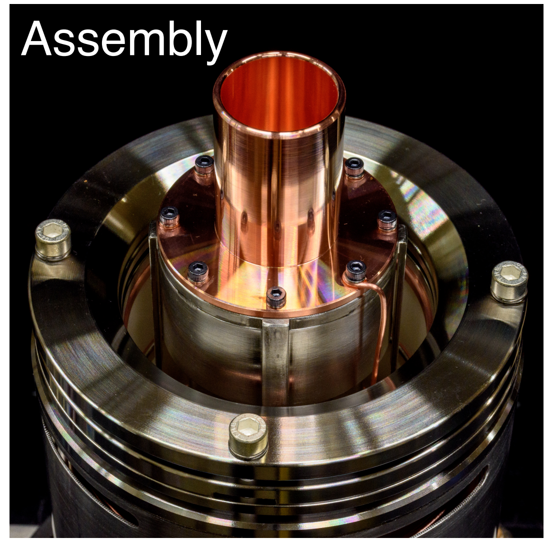


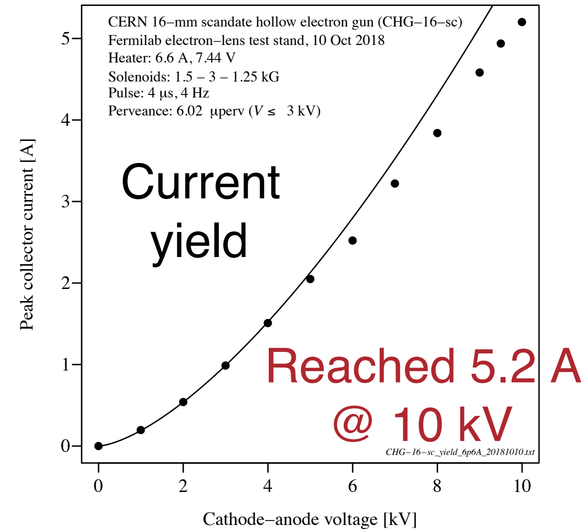


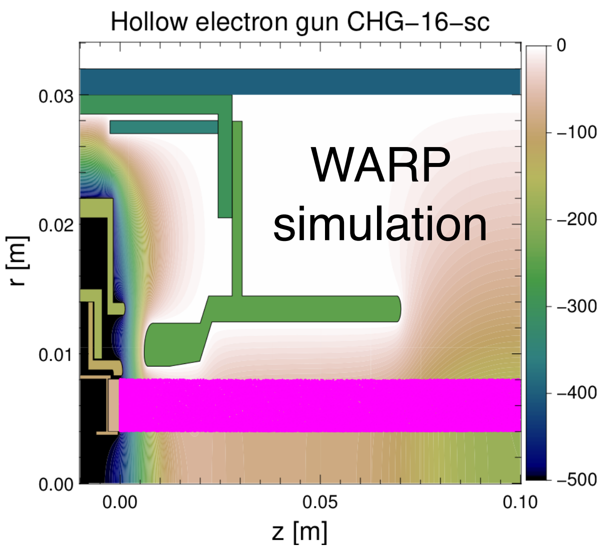
Electron Gun Development at Fermilab and CERN

Example: CHG-16-sc hollow gun

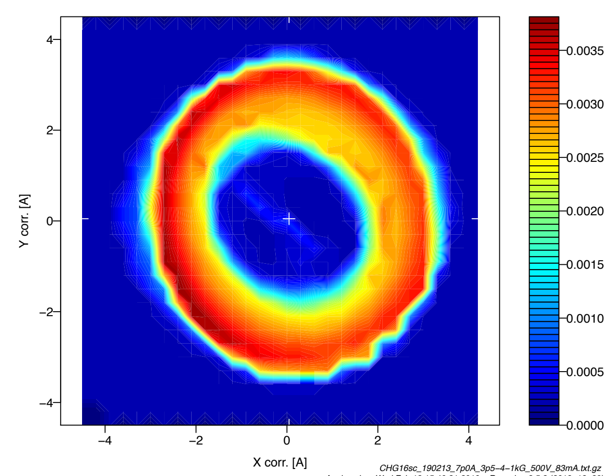








Measured current-density profile



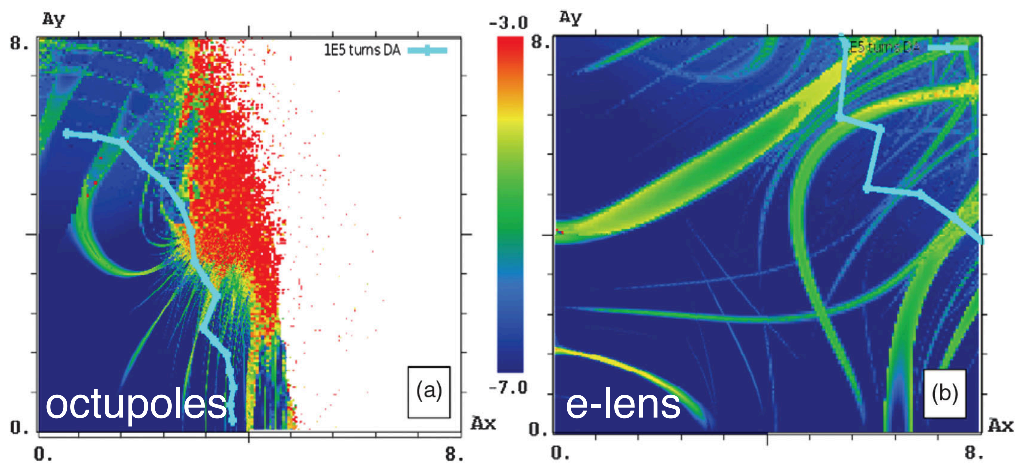
Electron Lens as Tune-Spread Generator for Landau Damping

From Tevatron and RHIC experience, we know that **electron lenses can generate tune spread** with negligible effects on lifetime

This is useful when other mechanisms (e.g., beam-beam) are absent or not adjustable

Octupoles are often used in storage rings, but they act on tails, reduce dynamic aperture, and may require many elements and high currents. **Electron lenses** act directly on the core. One electron lens could replace hundreds of superconducting octupoles in LHC or FCC.

LHC protons FMA and DA
Comparable Landau damping



Could tune-spread generation with electron lenses also improve the **stability of low-energy, space-charge-dominated beams**?

Studies of these effects can be carried out at IOTA

Shiltsev et al., PRL **119**, 134802 (2017)
Alexahin et al., arXiv:1709.10020, FERMILAB-TM-2655-APC (2017)

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

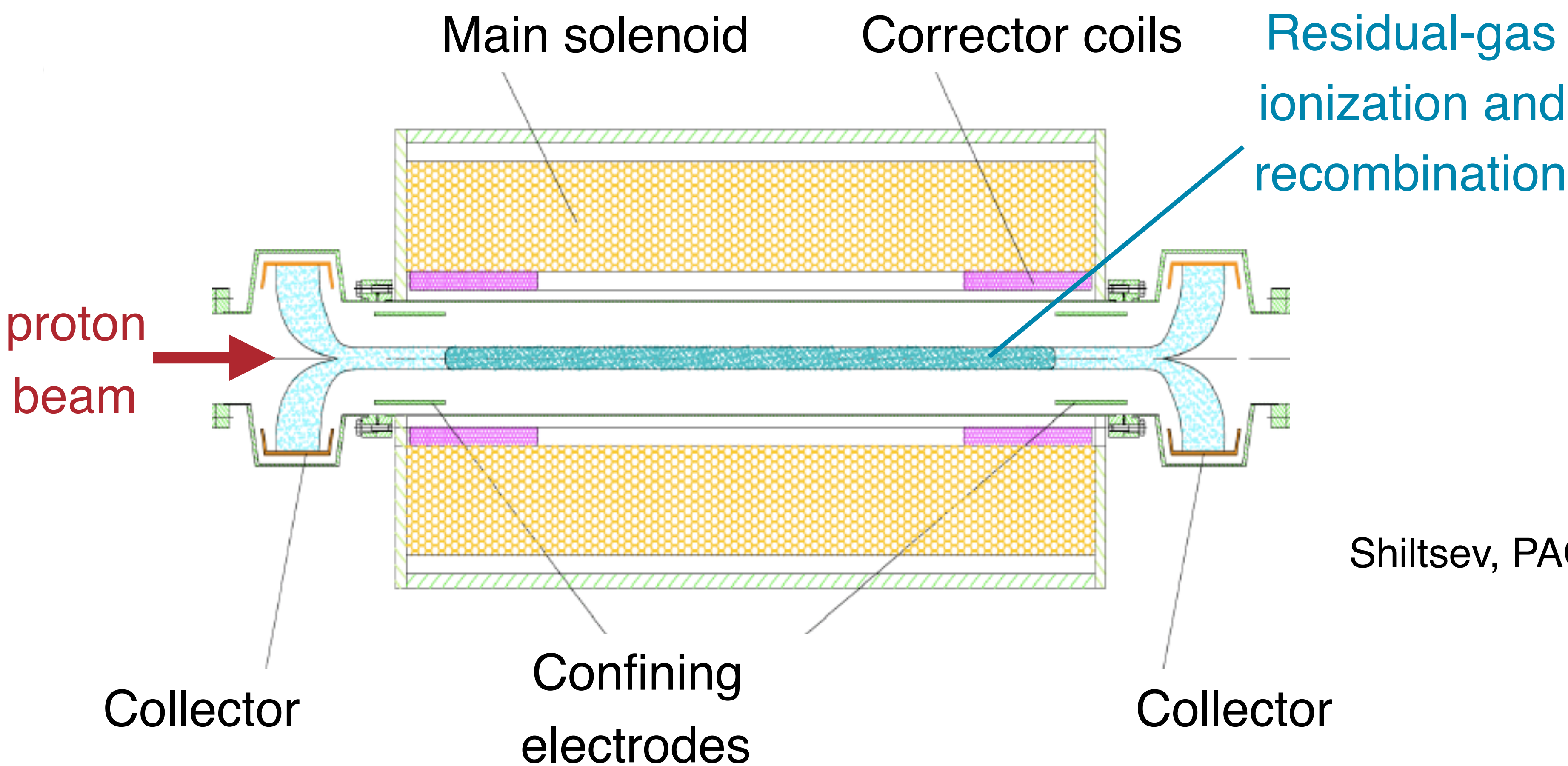
Implementation with **electron lens** has **advantage** of **magnetic confinement** for stability

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



Shiltsev, PAC07

In strong field, ionization electrons mirror transverse profile of protons
How does the electron column evolve?

Physics of Space-Charge Compensation in Rings

- Early experimental studies demonstrated higher intensities or desired tune shift, but also instabilities

  Dimov and Chupriyanov, Part. Accel. 14, **155** (1984) (BINP PSR, no confinement)
  Shiltsev et al., PAC09 (Tevatron, limited parameters and diagnostics)

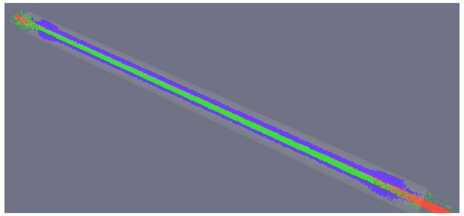
- Simulations with *rigid* e-columns show benefits on emittances and lifetimes, but also lattice distortions and resonances, depending on the number of devices

  Burov et al., FERMILAB-TM-2125 (2000) [Fermilab Booster]
  Alexahin and Kapin, Fermilab Beam-docs 3108 (2008) [Fermilab Booster]
  Aiba et al., PAC07 [LHC injectors]
  Boine-Frankenheim and Stem, NIM A **896**, 122 (2018) [GSI SIS]
  Stern et al., Beams-doc-6790 (2018) [Fermilab RCS model]

- Campaign of *self-consistent* simulations was started for IOTA

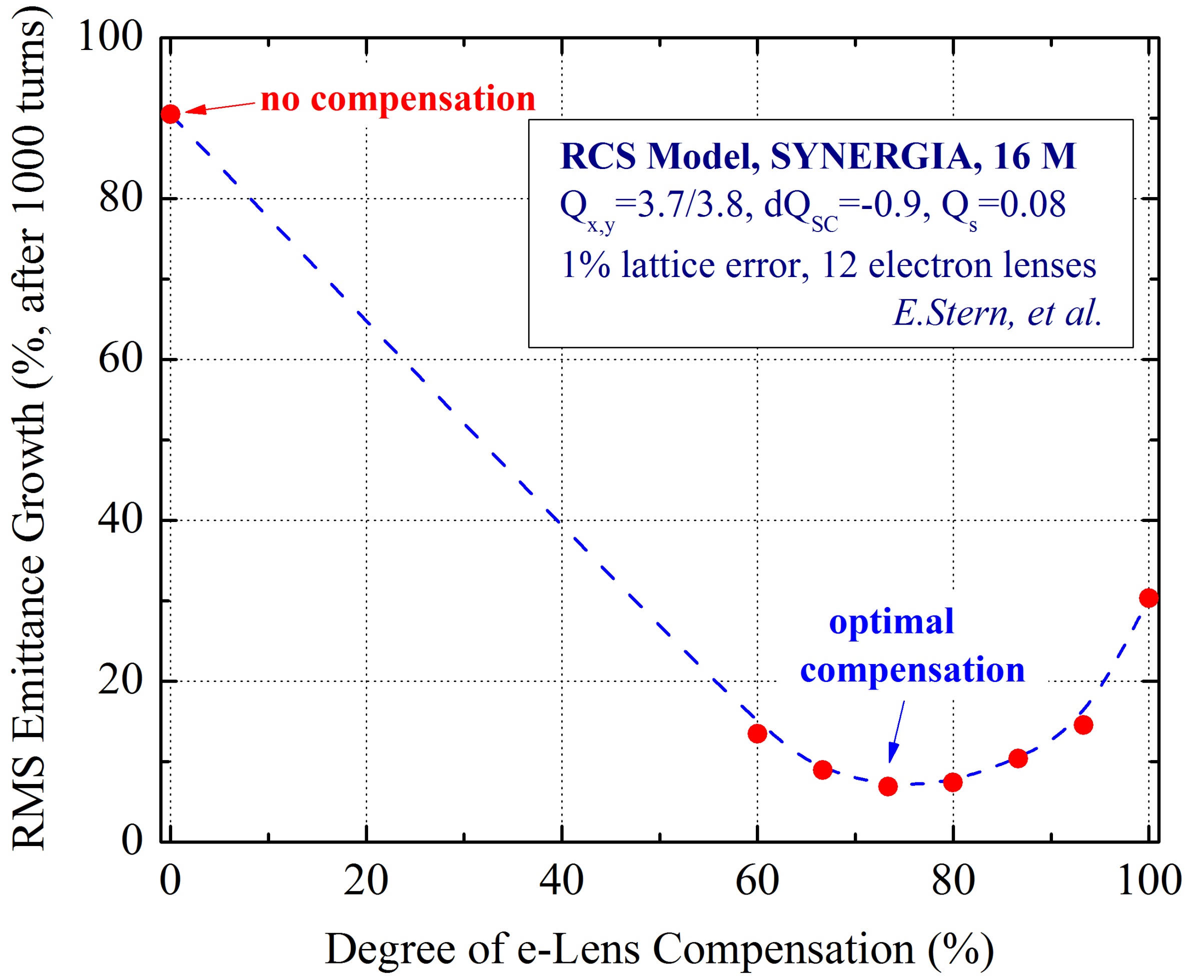
  Single pass, with gas ionization: Park et al., NAPAC16
  Two passes, no lattice: Freemire et al., HB18
  Multi-pass integration Synergia+Warp: Freemire et al., IPAC19

  Next steps: linear and nonlinear lattices between passes, electron-ion recombination, plasma collisions and thermalization



Potential Impact of Space-Charge Compensation in Rings

Calculated effect of electron lenses in rapid-cycling synchrotron on emittance preservation with strong space charge



Stern et al., Beams-doc-6790 (2018)

Electron Cooling

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

Electron cooling of protons enables a wider range of lifetimes, brightnesses and tune spreads for space-charge 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

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

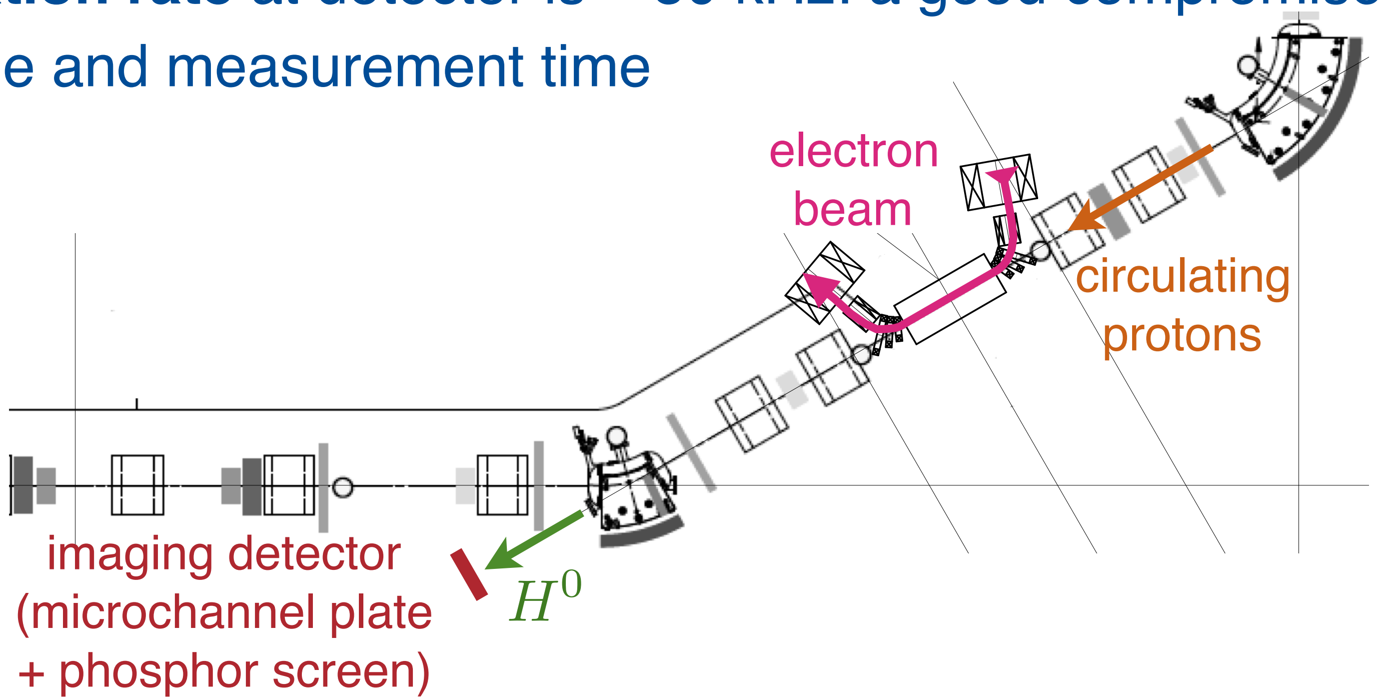
Stancari et al., COOL15

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

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

Recombination rate at detector is ~ 50 kHz: a good compromise between beam lifetime and measurement time



A **critical diagnostic tool** for **cooling**, but also for **proton beam evolution**. Proton beam diagnostics in IOTA is scarce.

Typical IOTA Electron-Lens Parameters

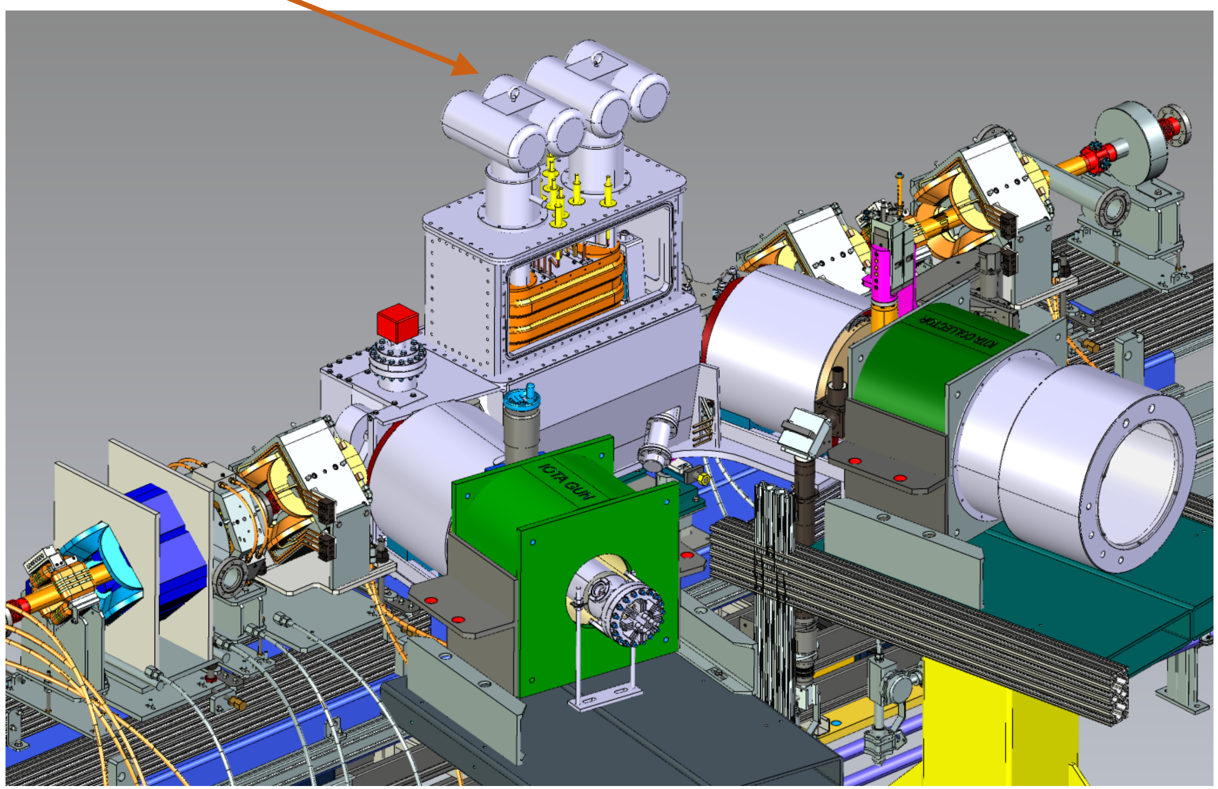
Cathode-anode voltage	0.1 — 10 kV
Electron beam current	5 mA — 3 A
Current density on axis	0.1 — 12 A/cm^2
Main solenoid length	0.7 m
Main solenoid field	0.1 — 0.8 T
Gun/collector solenoid fields	0.1 — 0.4 T
Max. cathode radius	15 mm
Lattice amplitude function	2 — 4 m
Circulating beam size (rms), e^-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

Superconducting Option for the Main Solenoid

Superconducting coils are **compact**, improve **field quality** and lower **power consumption**

Advances in **cryocoolers** enable reliable **stand-alone dry cryogenic systems**

Dhuley et al., Supercond. Sci. Technol. **33** 06LT01 (2020)



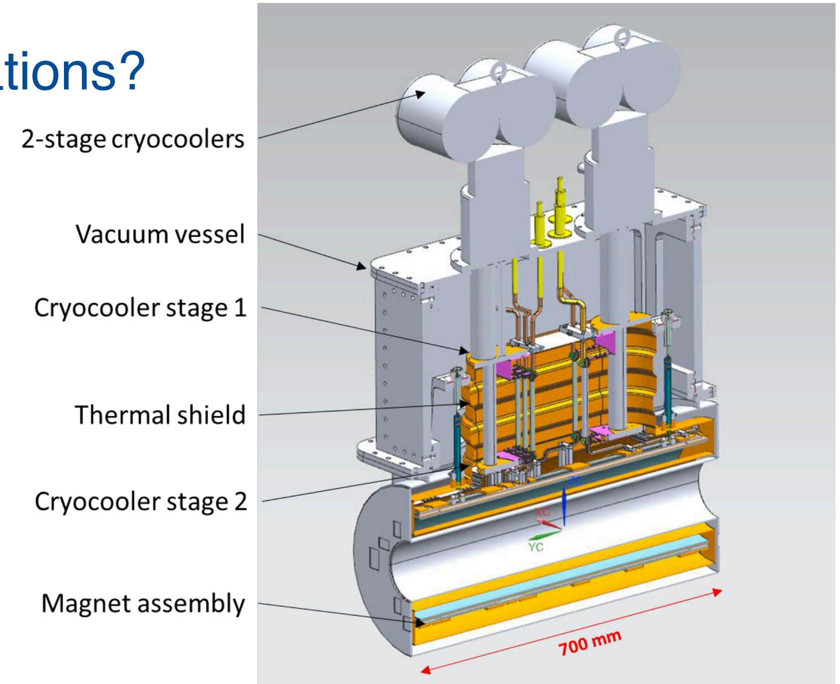
Design developed in collaboration with **CERN Mechanical Engineering** (Perini, Kolehmainen) and **Fermilab experts** (Dhuley, Thangaraj)

Superconducting Option for the Main Solenoid

Are **cool-down times** compatible with IOTA operations?

Estimates with 2 Cryomech PT415 (1.5W@4.2K, 40W@45K):
–18 h with current design
–10 h with improved thermal links and contacts

Dhuley, FERMILAB-TM-2738 (2020)



Cryocoolers introduce mechanical **vibrations** at 1-2 Hz. Can be damped with bellows, copper braids. Need to define tolerable levels from beam dynamics.

Systems are **reliable** and **supported**: cryopumping for semiconductors / material science, MRI magnets; AGS helical magnets @ BNL, SuperCDMS @ FNAL/ SNOLAB, …

Cost is reasonable. Ongoing work on **quench protection**.

Collaborations

CERN (synergistic with HL-LHC electron lenses)
- design, engineering and integration
- development of cathodes and electron guns

LBNL and **RadiaSoft**: Particle-in-cell simulations of space-charge-limited electron guns and electron beam dynamics (Warp)

NIU: detection of radiation from cyclotron motion for advanced diagnostics of electron column density and temperature

Submitted 2 **proposals** to **2020 DOE SBIR** program:
- magnetic system with A. Smirnov (**RadiaBeam**)
- computational modeling of electron beam dynamics with C. Hall (**RadiaSoft**)

Expressions of interest from B. Freemire (**Euclid Techlabs**) on
- design and construction of BPMs and electrodes
- recombination monitor
- diagnostic stations

Conclusions

The **electron lens** is an integral part of the **IOTA research program**: it enables new experiments on **nonlinear dynamics**, **tune-spread generation** for stability, **space-charge compensation**, and **electron cooling**.

The project is **closely related to electron-lens applications in other machines** (RHIC@BNL, HL-LHC, ...). Fermilab has been a leader in this field for 20 years.

Received **very valuable contributions** from **external collaborators**.

Lots of work to do to prepare for construction and experiments: beam dynamics, experiment design, functional requirements, engineering, instrumentation, etc.

Research with electron lenses advances the understanding and control of high-intensity particle beams. We look forward to experiments in IOTA.

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