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Physics and Technology of Electron Lenses for the Fermilab Integrable Optics Test Accelerator (IOTA) and for the Large Hadron Collider at CERN (HL-LHC)

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Contributors and collaborators

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LARP

HiLumi HL-LHC PROJECT

Support from the US DOE LHC Accelerator Research Program and the CERN HL-LHC Project (HiLumi)

Contents

- Introduction to the projects
- What's an electron lens?
- Hollow electron beams for beam halo control in Tevatron and HL-LHC
- Research with electron lenses in the Fermilab Integrable Optics Test Accelerator (IOTA)
- Conclusions

Current research areas

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>]
- inclusion in HL-LHC Project baseline to be evaluated in March 2018

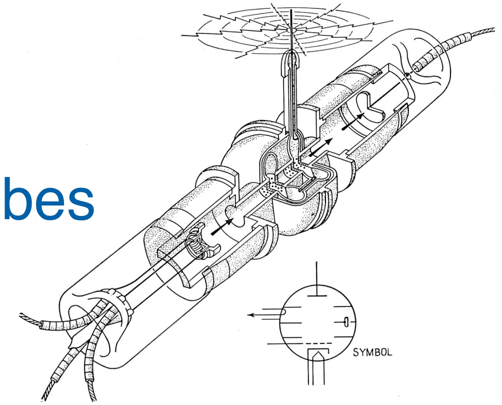
Electron lenses for IOTA at Fermilab

- new storage ring to be commissioned in 2018
- electron lens installation planned for 2019
- beam physics research enabled by electron lens
  - nonlinear integrable optics
  - beam cooling
  - space-charge compensation
  - other topics, e.g. Landau damping of instabilities, hollow beams

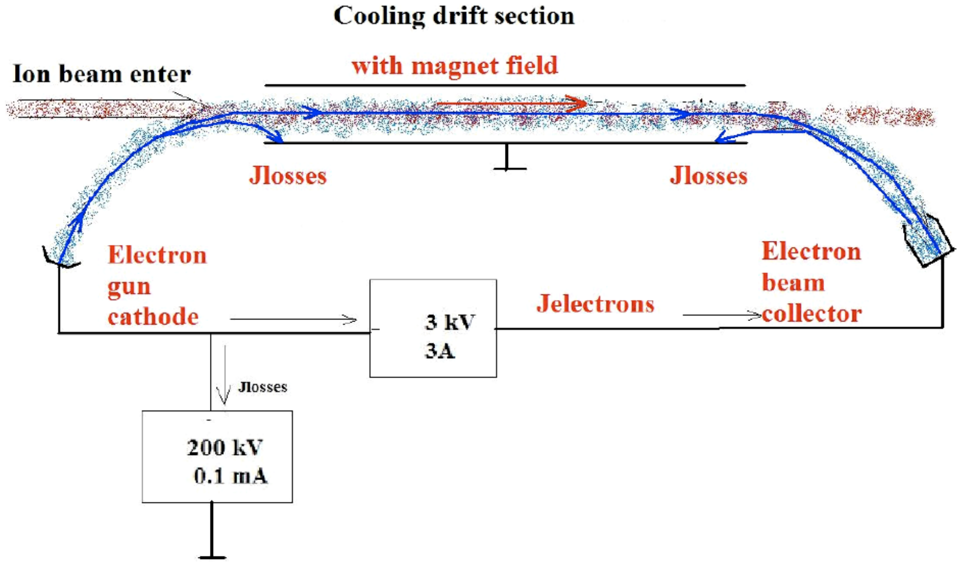
Electron lenses

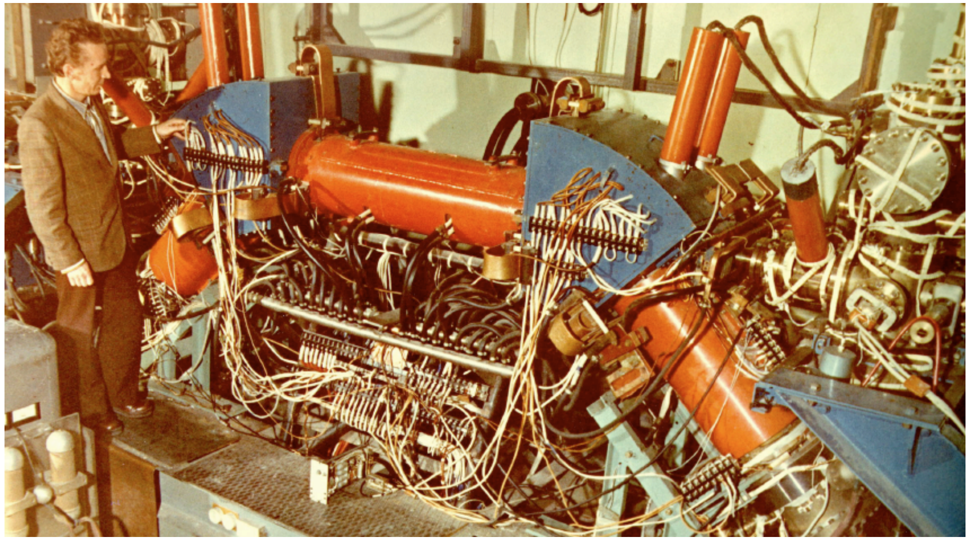
Early applications of low-energy electron beams

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

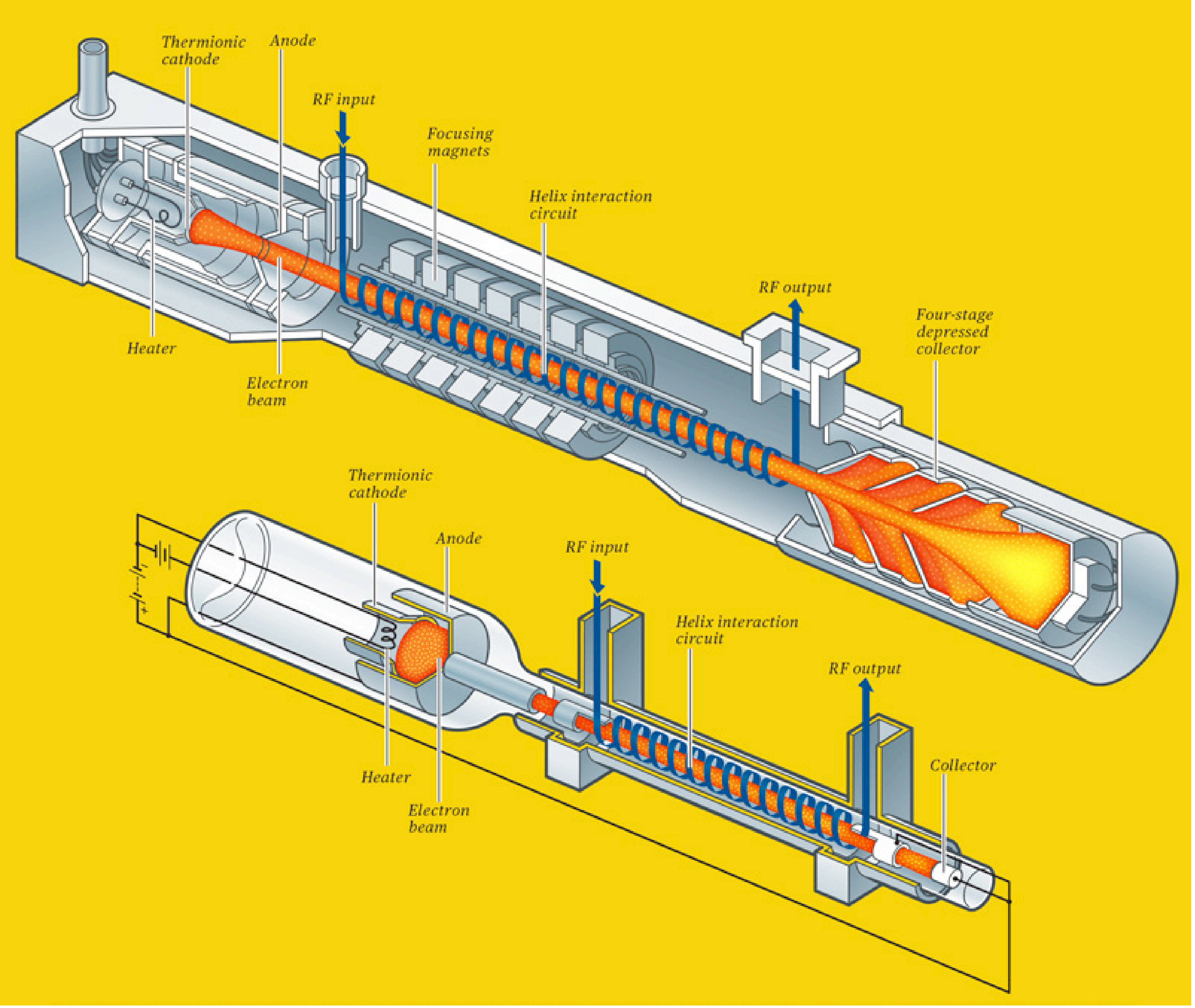


Electron cooling, proposed in 1965 to increase brightness of antiprotons for colliders: heavy charged particles exchange heat with co-propagating electrons through Rutherford scattering in overlap region





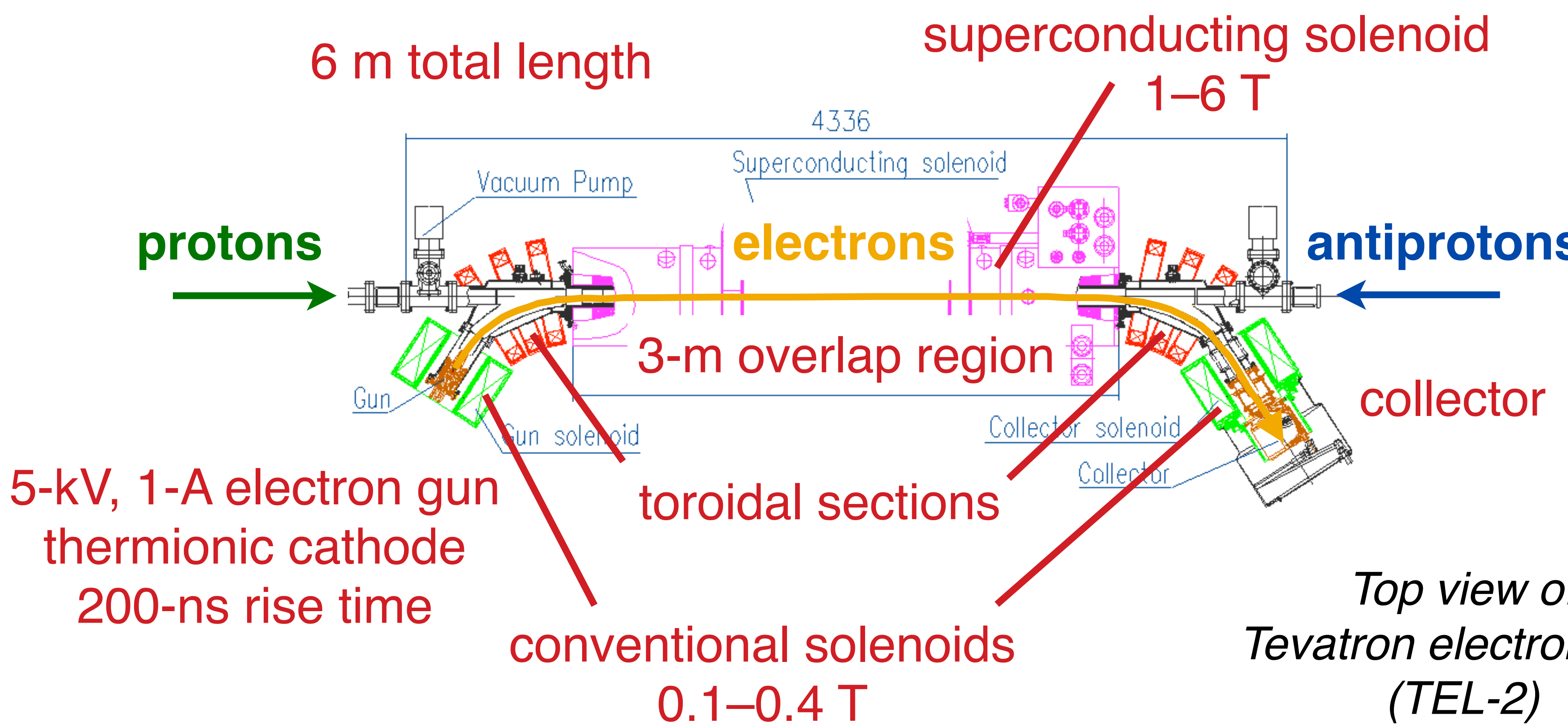
Common elements: electron source, focusing, collector



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

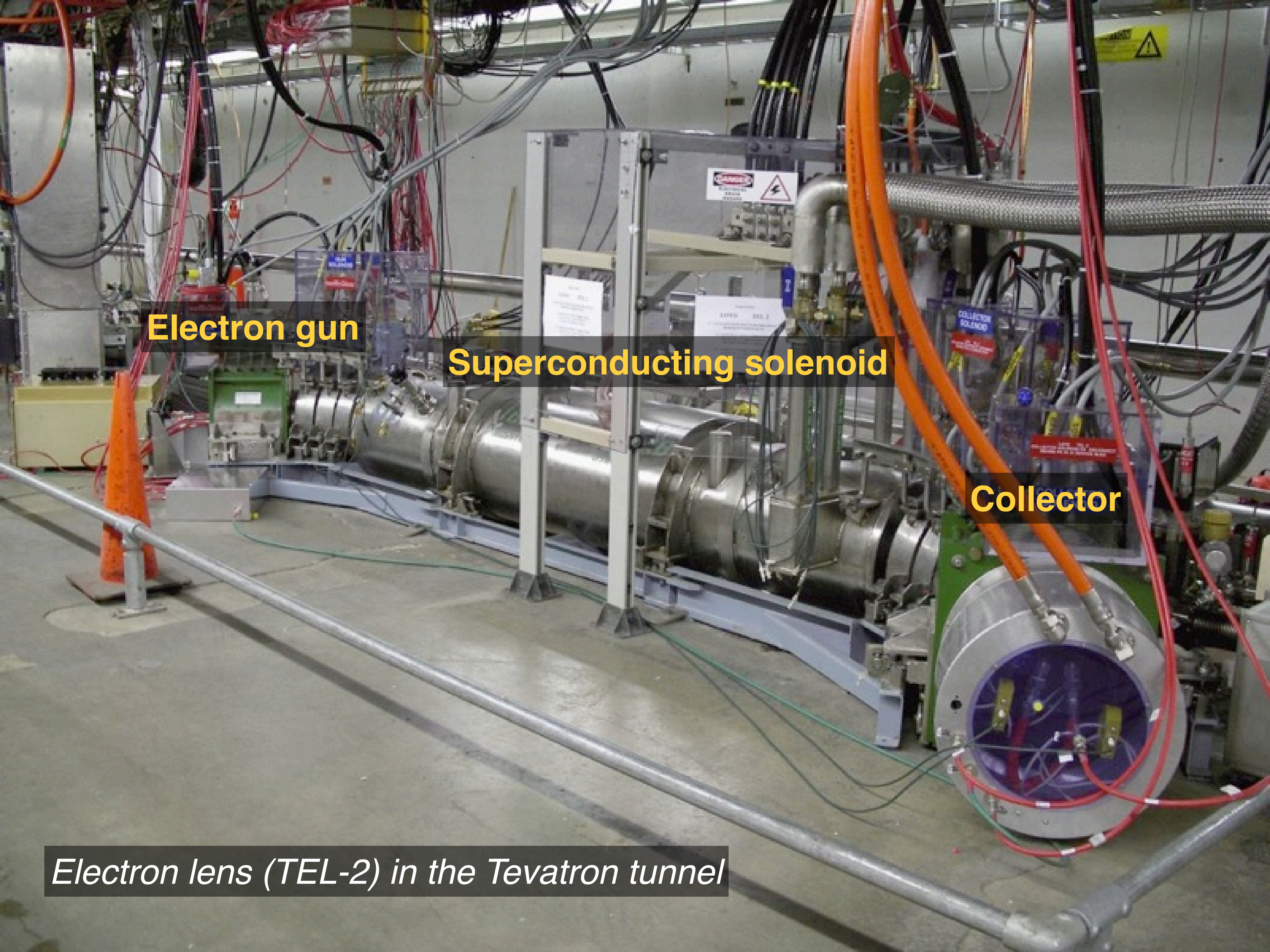
What's an electron lens?

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



Top view of Tevatron electron lens (TEL-2)

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

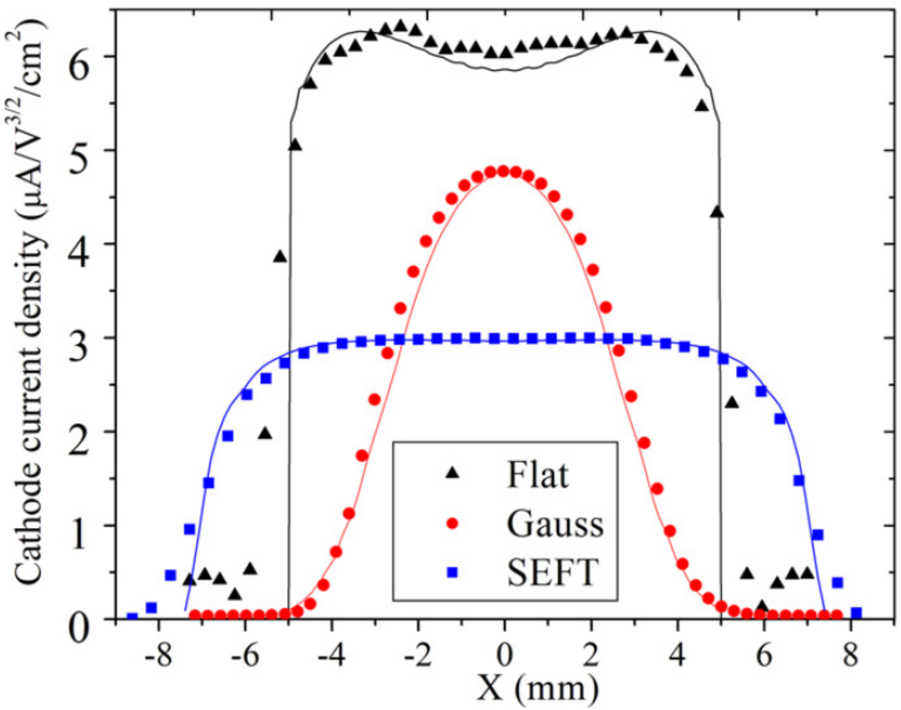


Electron lens (TEL-2) in the Tevatron tunnel

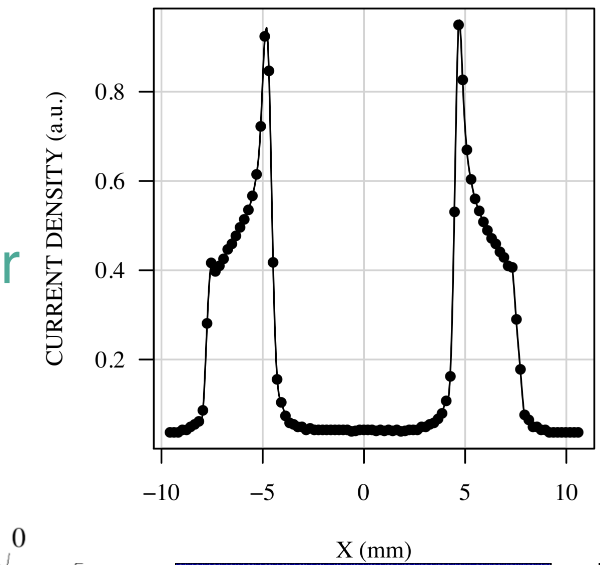
First main e-lens feature: control of electron beam profile

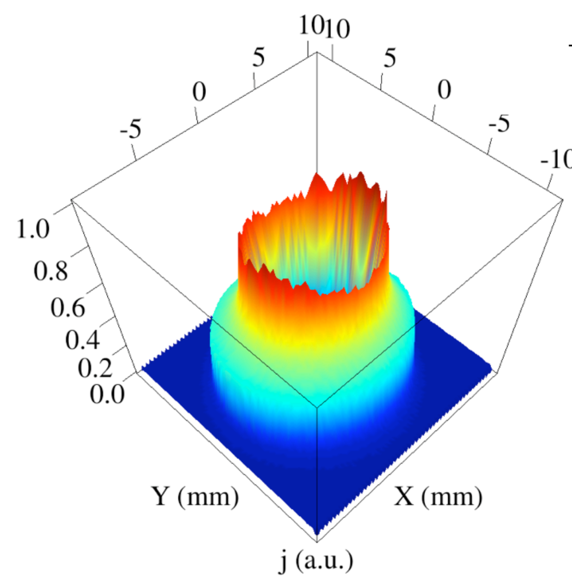
Current density profile of electron beam is shaped by cathode and electrode geometry and maintained by strong solenoidal fields

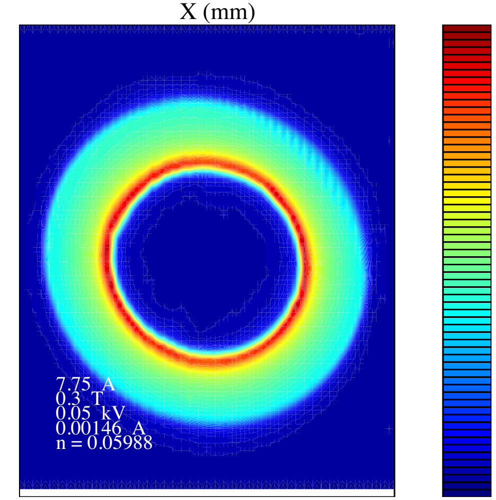
Flat profiles for bunch-by-bunch betatron tune correction



Hollow profile for halo scraping



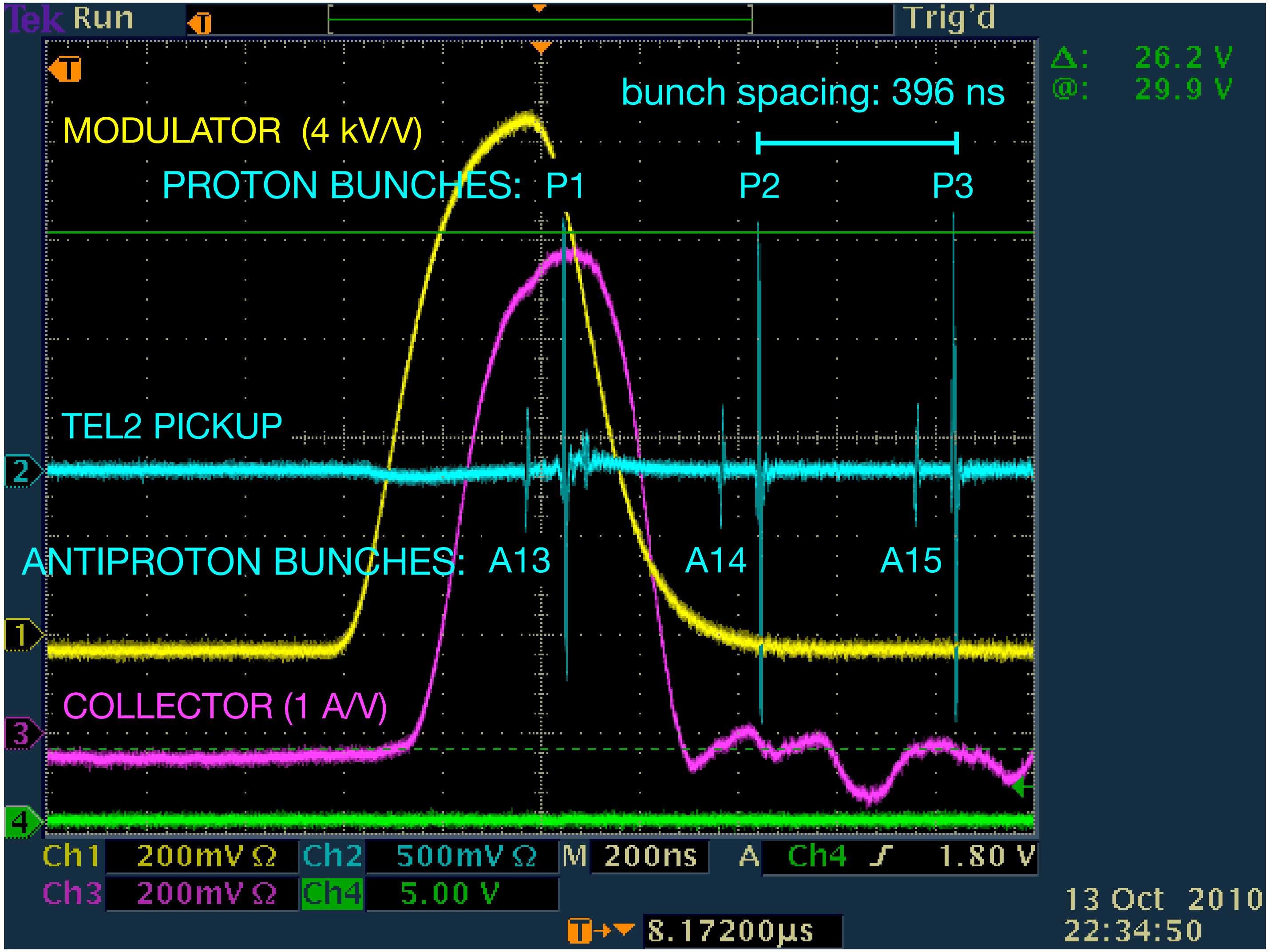




Gaussian profile for compensation of nonlinear beam-beam forces

Second main e-lens 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 (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)

Applications of electron lenses

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
  - Stem and Boine-Frankenheim, IPAC17

Hollow electron beams for active halo control

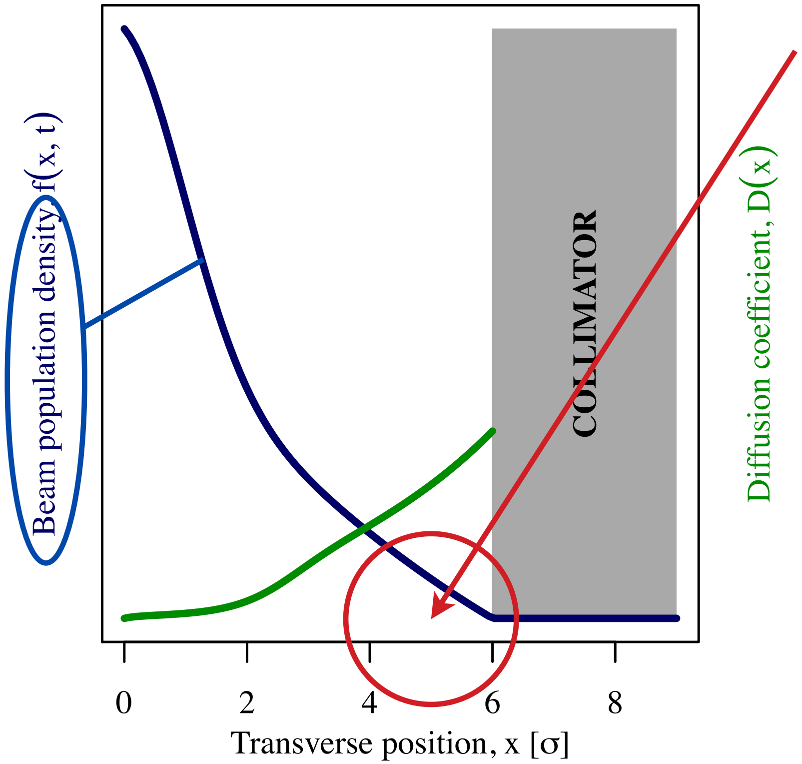
Collimation and beam halo are critical for LHC

- LHC and HL-LHC represent **huge leaps in stored beam energy**

	Tevatron	LHC 2012	LHC 2016	LHC nominal	HL-LHC
Stored energy per beam	2 MJ	140 MJ	250 MJ	**362 MJ**	**692 MJ**

- **No scrapers exist** in LHC for full beam at top energy
- **Minimum design HL-LHC lifetimes** (e.g., slow losses during squeeze/adjust) **are close to plastic deformation** of primary and secondary collimators: (692 MJ) / (0.2 h) = 1 MW
- Significant program of collimation system upgrades under way

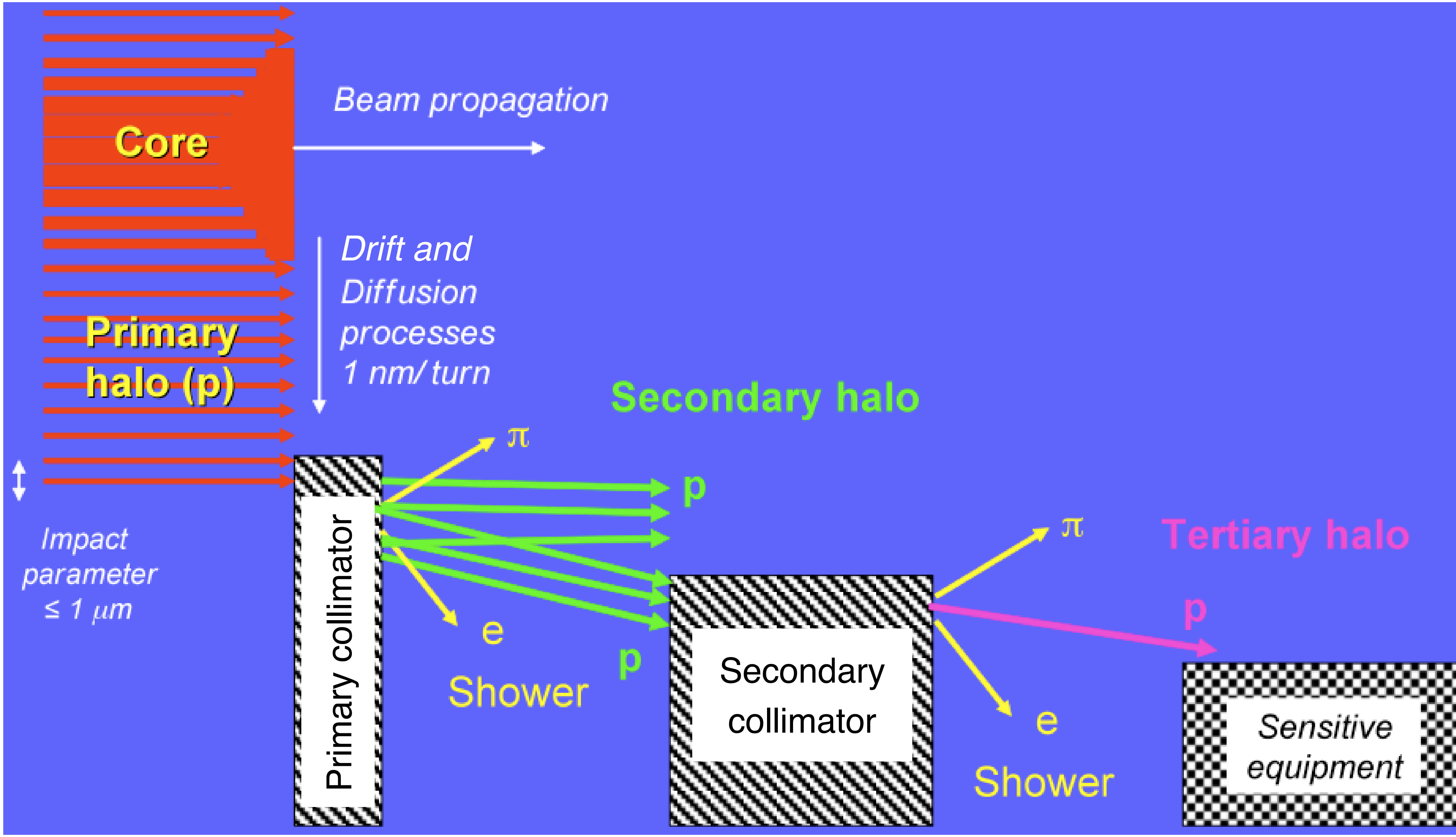
Collimation and beam halo are critical for LHC



- **Halo populations** (e.g., 4σ to 6σ) in LHC are **poorly known**. Collimator scans and van-der-Meer luminosity scans indicate 0.1%-5% of total energy, which translates to 0.7 MJ to 35 MJ at 7 TeV.
- **Quench limits**, **magnet damage**, or even **collimator deformation** will be reached with fast crab-cavity failures (~2σ orbit shift) or other fast losses

- Hence the **need to measure and monitor the halo, and to remove it at controllable rates**. Beam halo monitoring and control are **one of the major risk factors for HL-LHC**
- **Hollow electron lenses are the most established and flexible tool for controlling the halo of high-power beams**

Conventional multi-stage collimation system



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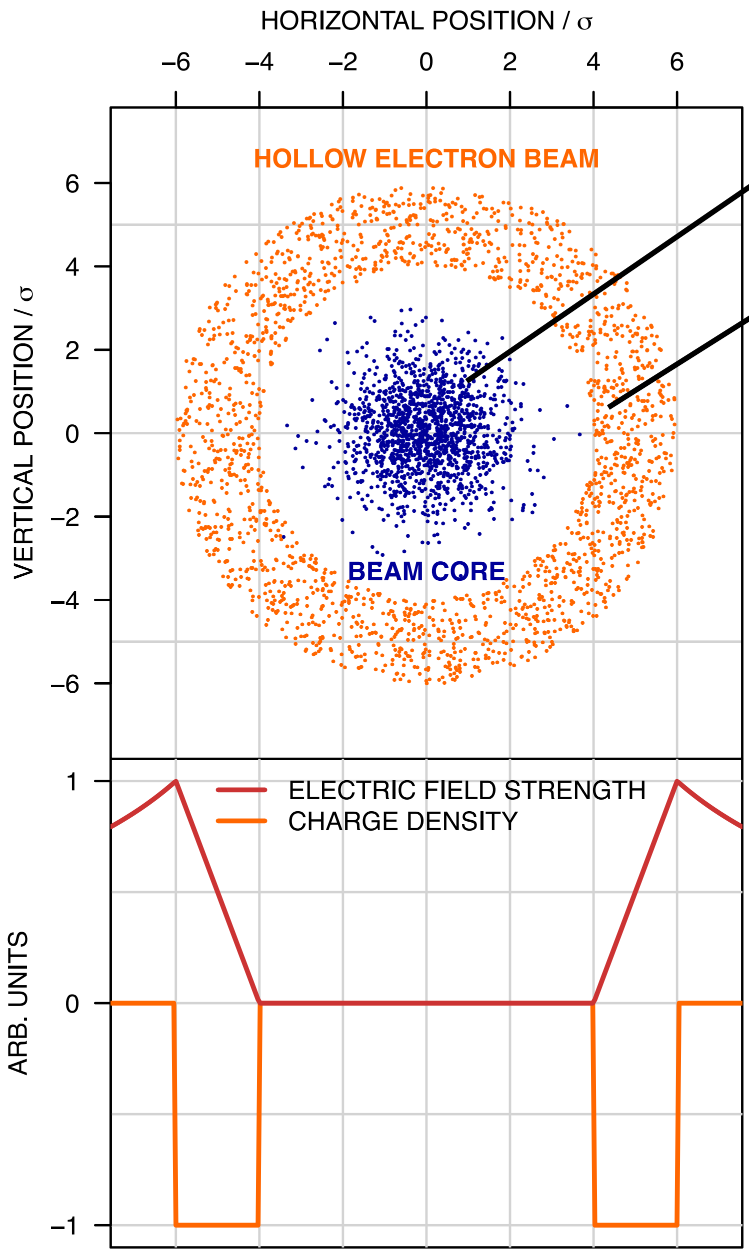
Concept of hollow electron beam scraper



- **Beam core** is unaffected (field-free region)
- **Halo** experiences nonlinear, tunable, possibly pulsed transverse kicks:

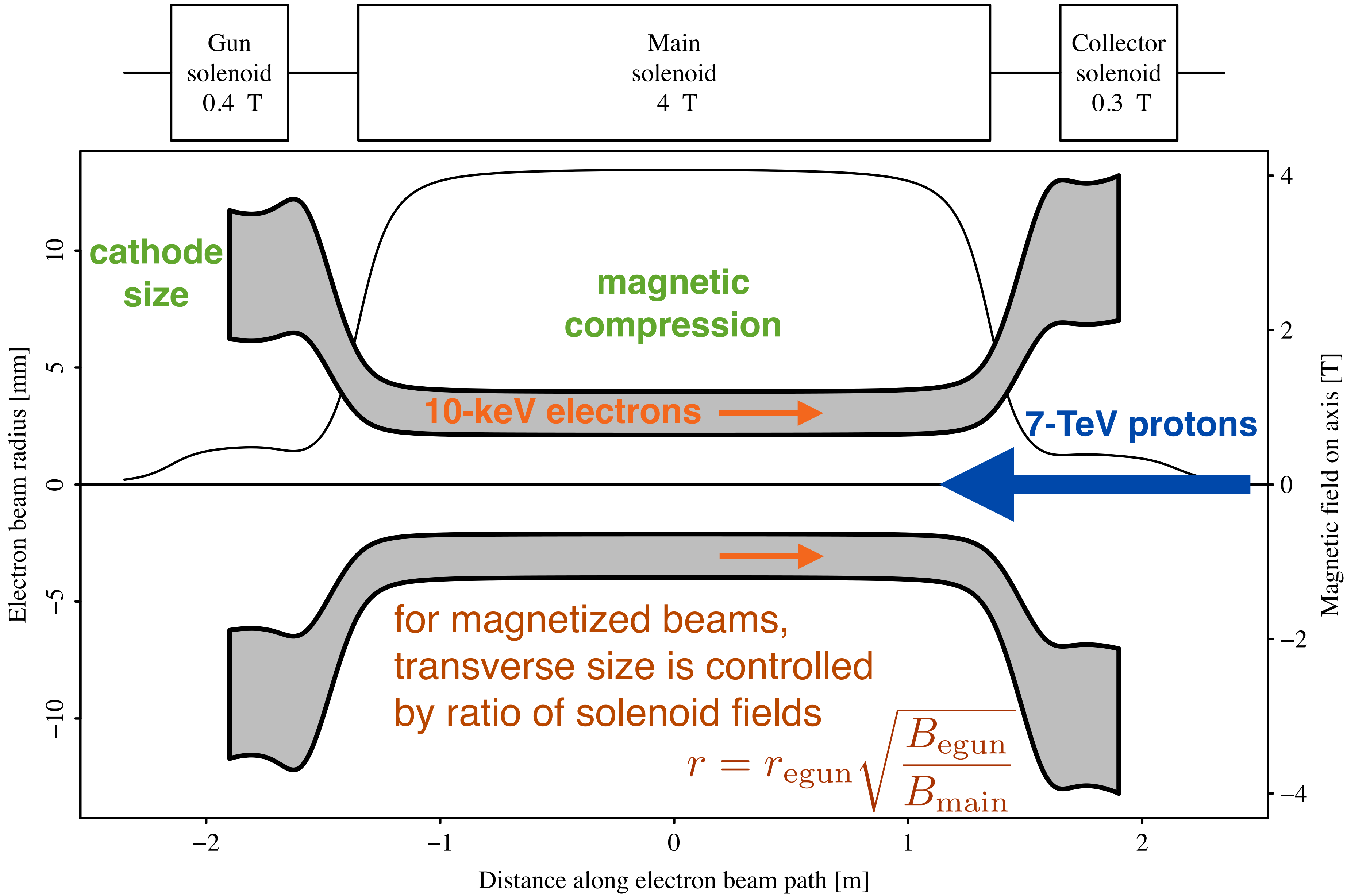
$$\theta_r = \frac{2\, I_r\, L\, (1 \pm \beta_e \beta_p)}{r\, \beta_e\, \beta_p\, c^2\, (B\rho)_p} \left(\frac{1}{4\pi\epsilon_0} \right)$$

No metal close to the high-power beam:
no material damage or impedance

Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08

Fermilab

e^- beam size matched to p beam size by solenoid fields



Features of hollow electron beam halo control

Advantages

- Can be close (or even overlap) with the main beam
- No material damage
- Continuously variable strength ("variable collimator thickness")
- Works as a soft scraper by enhancing diffusion
- Pulsed operation (resonant excitation) is possible to enhance halo removal
- Low impedance
- No breakup for ion collimation
- Position and size control by magnetic fields (no motors, bellows, ...)
- Based upon established electron-cooling / electron-lens technology

Potential issues

- Alignment and symmetry of electron beam must be accurate
- Stability of the beams must be ensured

Experimental studies with hollow electron beams

- Conducted in the Fermilab Tevatron collider with hollow gun installed in electron lens (TEL-2)
- Started Oct. 2010, ended Jun. 2011 (collider run ended Sep. 2011)
- Mostly at top energy (980 GeV) because of availability, stable conditions, and collimator configuration
- Chose to act on antiprotons because of lower emittances and intensities, smaller beam sizes (therefore larger solenoid fields for stability), and collimator positions

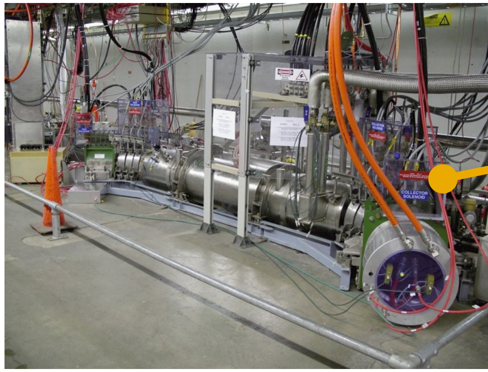
Experimental studies with hollow electron beams

Main goals and observables

- basic compatibility with collider operations
- particle removal
- removal rate vs. transverse oscillation amplitude
- effects on the core: emittance, luminosity
- effects on transverse beam diffusion
- effects on loss-rate fluctuations (beam jitter, tune changes)

Stancari et al., Phys. Rev. Lett. **107**, 084802 (2011)
Stancari et al., IPAC11 (2011)
Stancari, APS/DPF Proceedings, arXiv:1110.0144 [physics.acc-ph]

Collimation and electron lenses in the Tevatron



TEL-2

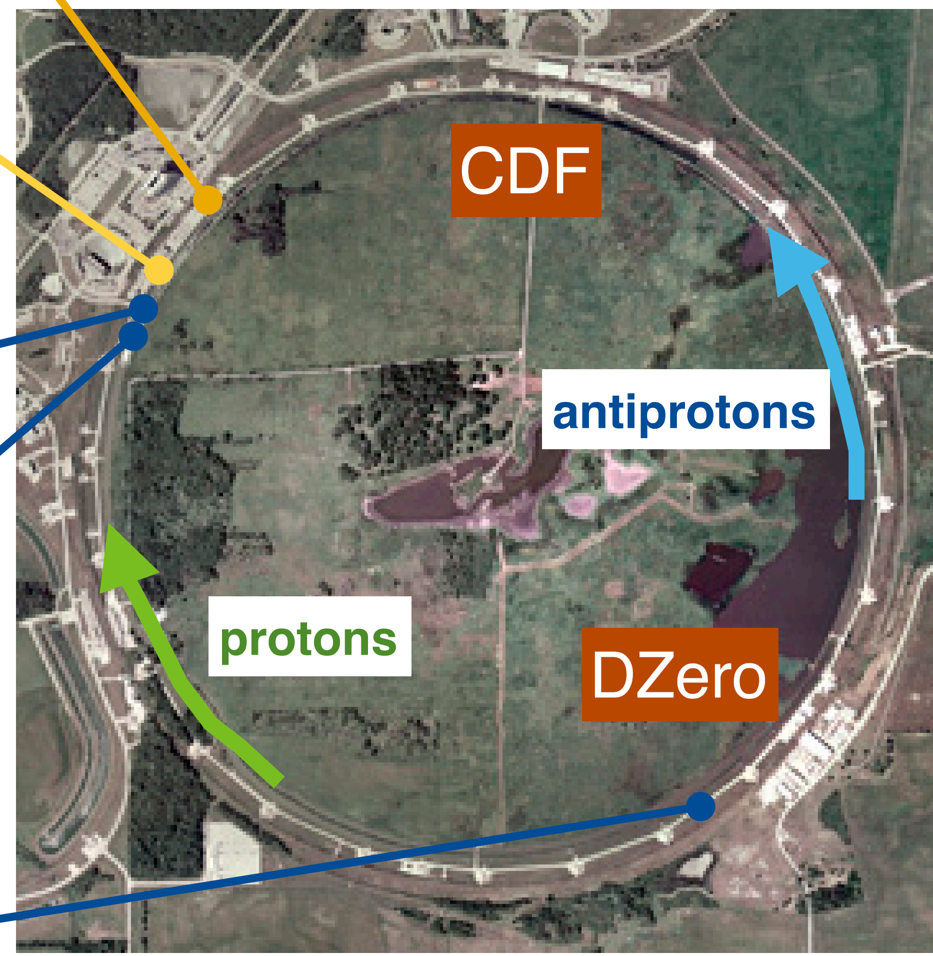
- *backup for operations*
- *beam-beam compensation studies*
- *hollow-beam collimation studies*

TEL-1

- *abort-gap cleaning during operations*
- *beam-beam compensation studies*

Primary (F49)

Secondary (F48)



Antiproton collimators

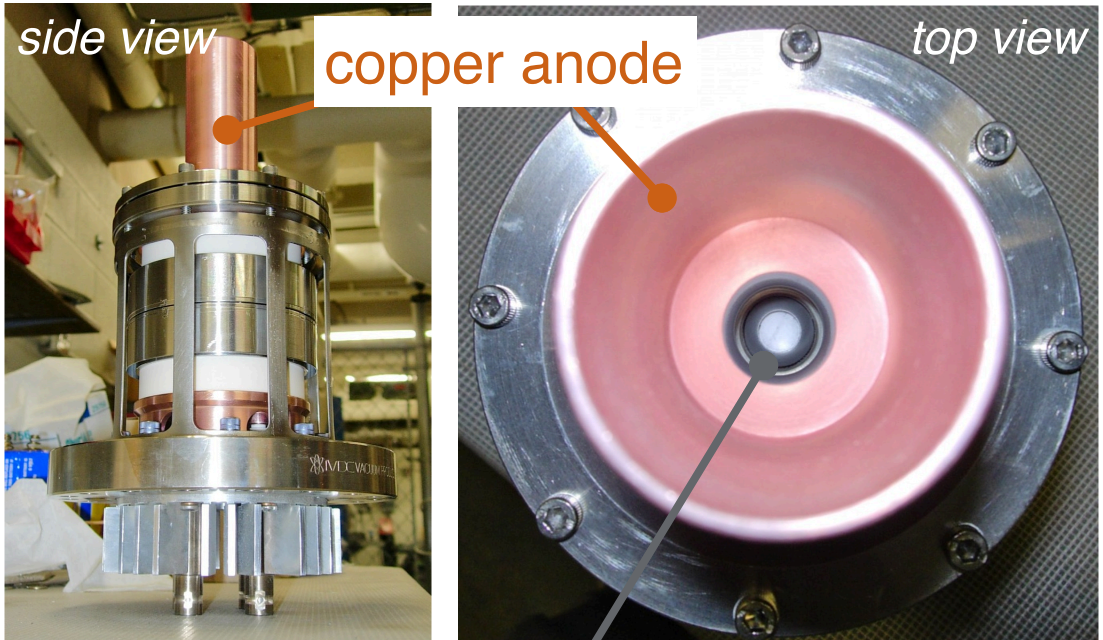
L-shaped

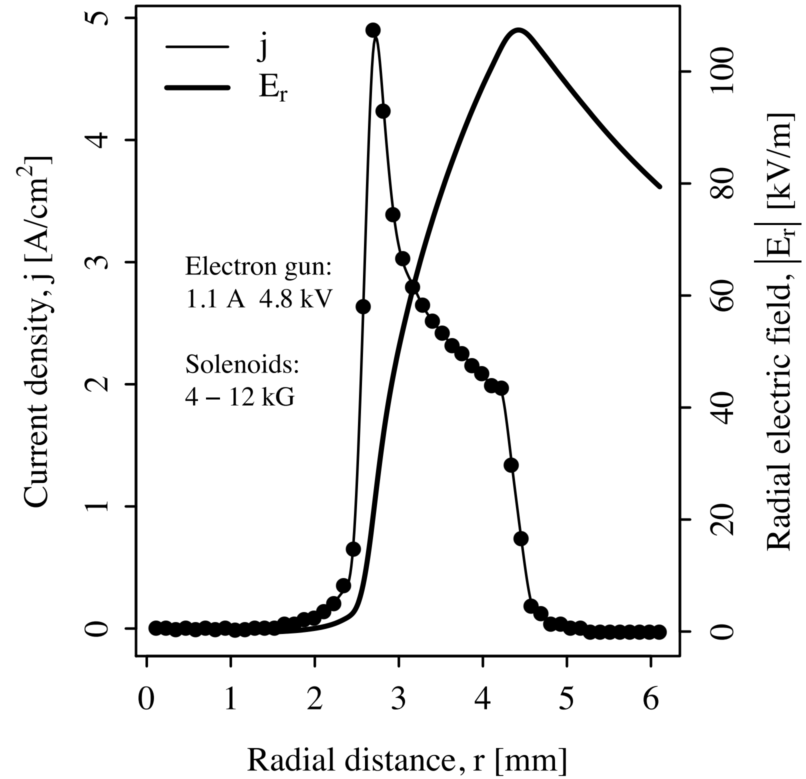
5-mm tungsten primaries at 5 sigma

1.5-m steel secondaries at 6 sigma

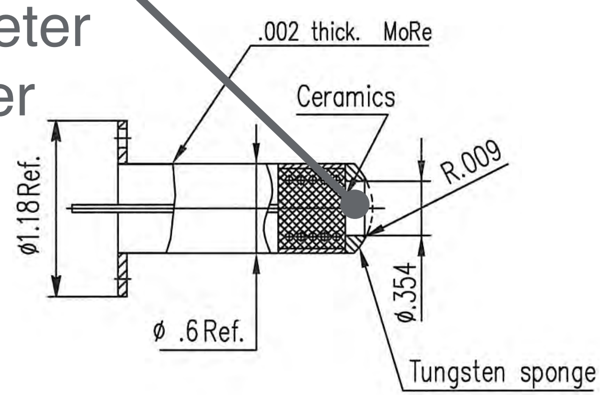
Secondary (D17)

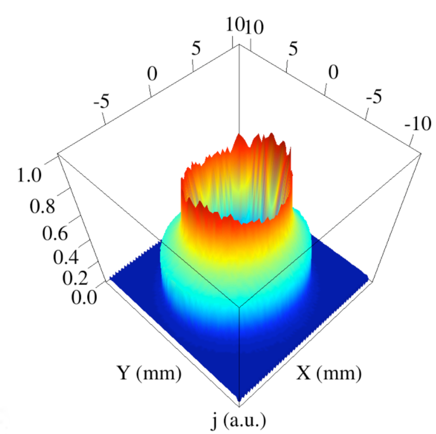
15-mm hollow electron gun: geometry and fields

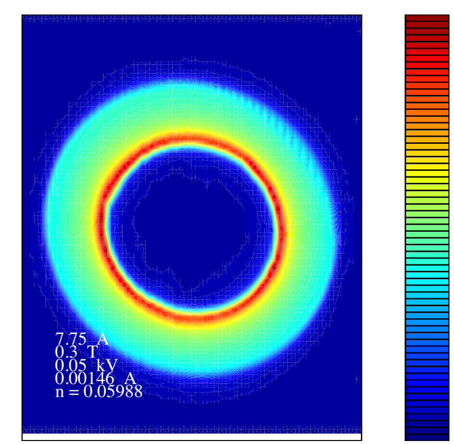




tungsten dispenser cathode
convex surface
15-mm outer diameter
9-mm hole diameter

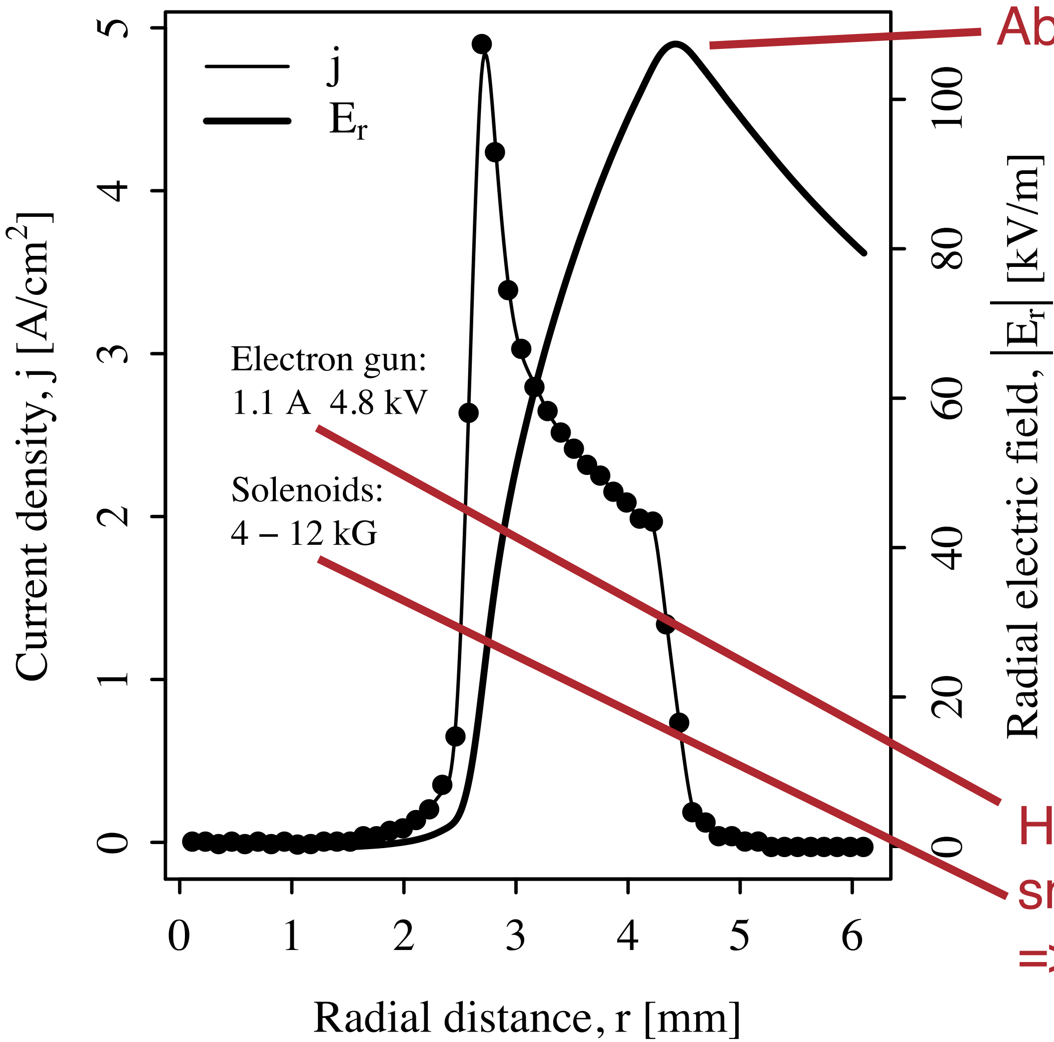






Current densities, fields, and kicks

Nonlinear transverse kick depends on current density at e-gun, magnetic compression in solenoids, and (anti)proton magnetic rigidity

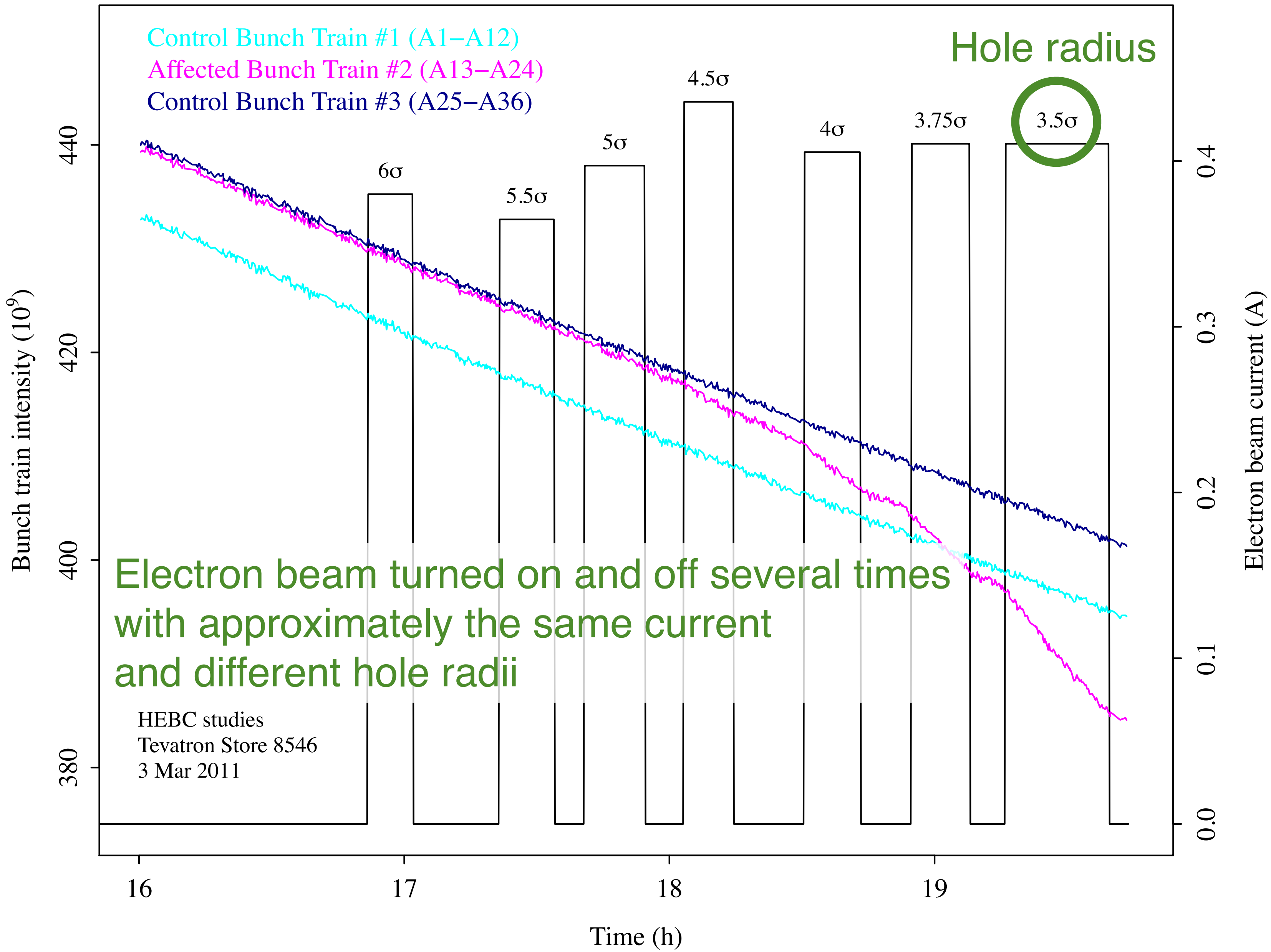


About **0.3 *µ*rad** max in TEL-2 at 980 GeV

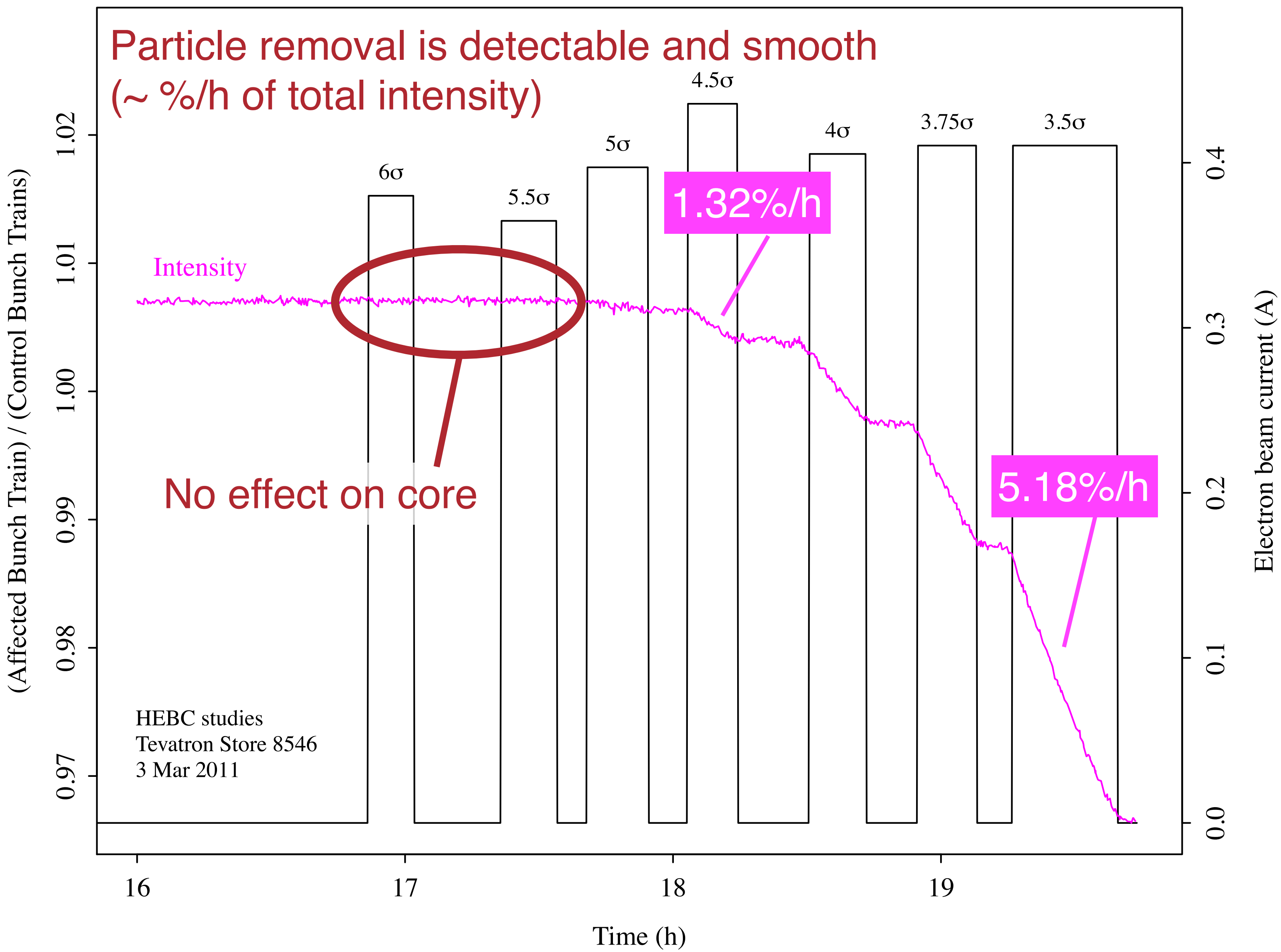
Nonlinear deterministic kicks are complementary (i.e., small and tunable) to random multiple scattering in primary collimators (17 *µ*rad rms in Tevatron)

HL-LHC e-gun prototype reached 6 A + smaller beam sizes in HL-LHC
=> similar transverse kicks

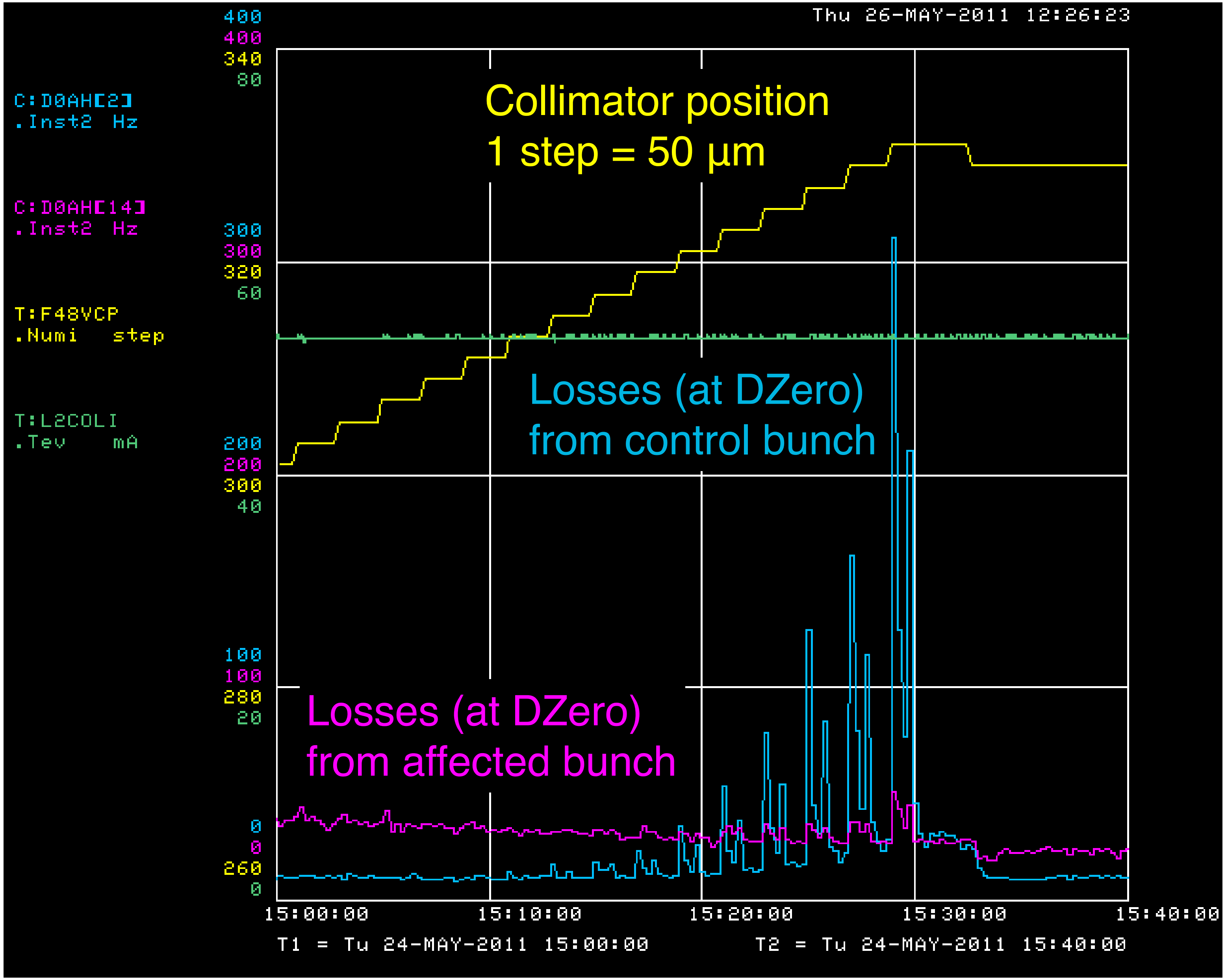
Electron lens on antiproton bunch train #2



Relative removal rate of affected bunch train



Suppression of loss spikes during collimator steps



Conceptual design report of electron lenses for LHC

FERMILAB-TM-2572-APC

Conceptual design of hollow electron lenses for beam halo control in the Large Hadron Collider*

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Fermi National Accelerator Laboratory, PO Box 500, Batavia, Illinois 60510, USA

R. Bruce, S. Redaelli, A. Rossi, and B. Salvachua Ferrando

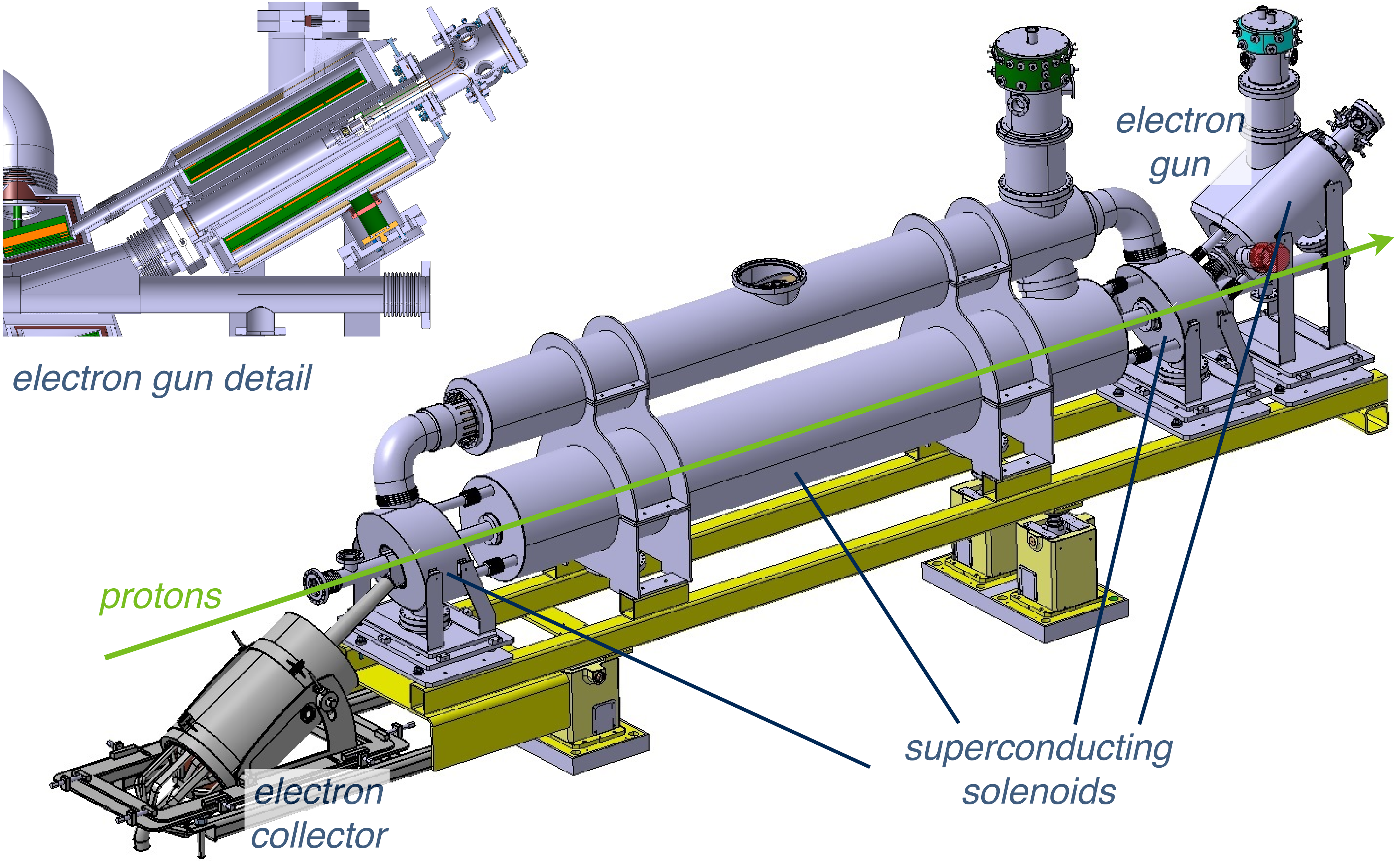
CERN, CH-1211 Geneva 23, Switzerland

(Dated: May 9, 2014)

Collimation with hollow electron beams is a technique for halo control in high-power hadron beams. It is based on an electron beam (possibly pulsed or modulated in intensity) guided by strong axial magnetic fields which overlaps with the circulating beam in a short section of the ring. The concept was tested experimentally at the Fermilab Tevatron collider using a hollow electron gun installed in one of the Tevatron electron lenses. Within the US LHC Accelerator Research Program (LARP) and the European FP7 HiLumi LHC Design Study, we are proposing a conceptual design for applying this technique to the Large Hadron Collider at CERN. A prototype hollow electron gun for the LHC was built and tested. The expected performance of the hollow electron beam collimator was based on Tevatron experiments and on numerical tracking simulations. Halo removal rates and enhancements of halo diffusivity were estimated as a function of beam and lattice parameters. Proton beam core lifetimes and emittance growth rates were checked to ensure that undesired effects were suppressed. Hardware specifications were based on the Tevatron devices and on preliminary engineering integration studies in the LHC machine. Required resources and a possible timeline were also outlined, together with a brief discussion of alternative halo-removal schemes and of other possible uses of electron lenses to improve the performance of the LHC.

FERMILAB-TM-2572-APC
arXiv:1405.2033
CERN-ACC-2014-0248

LHC electron-lens design



Main hollow electron lens functions in HL-LHC

Halo depletion to protect against fast orbit drifts (e.g., crab-cavity failures)

Smoothing of loss spikes during operation of the machine: squeeze, adjust, beta* leveling, orbit jitter (ground motion, cultural noise)

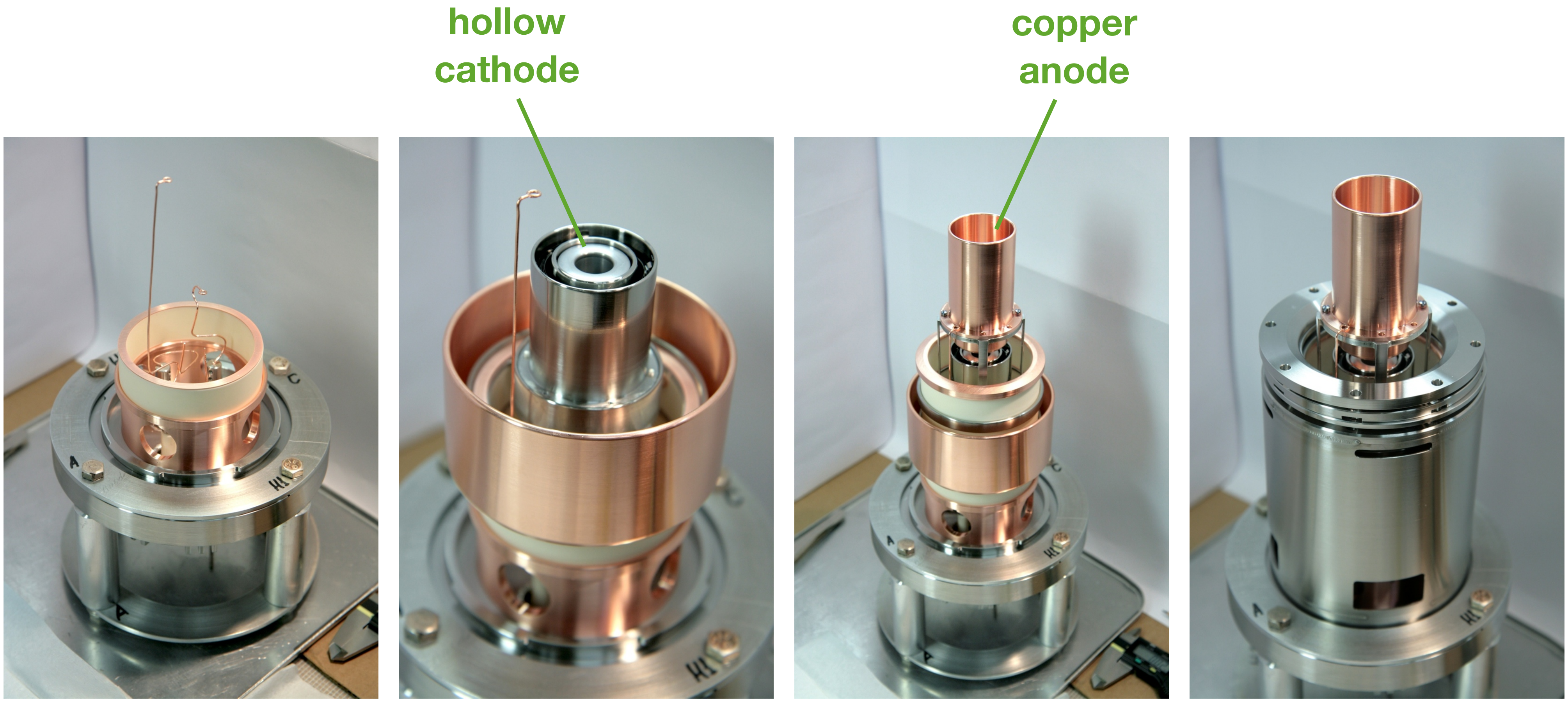
Impact parameter control and better collimation efficiency for ions

Slow/continuous beam scraping functionality

Potential performance improvements (in combination with collimator hierarchy): beta* reach, crossing angle flexibility, pile-up distribution

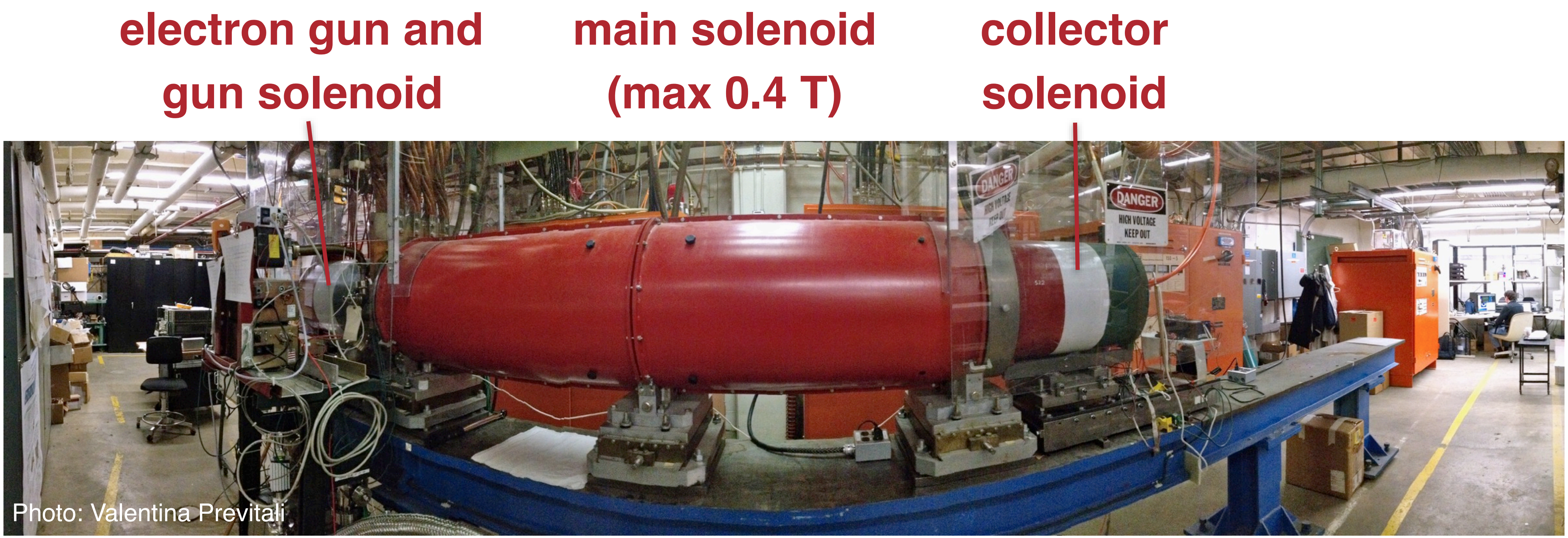
New diagnostics and beam dynamics research tool

Hollow electron gun prototypes for the LHC



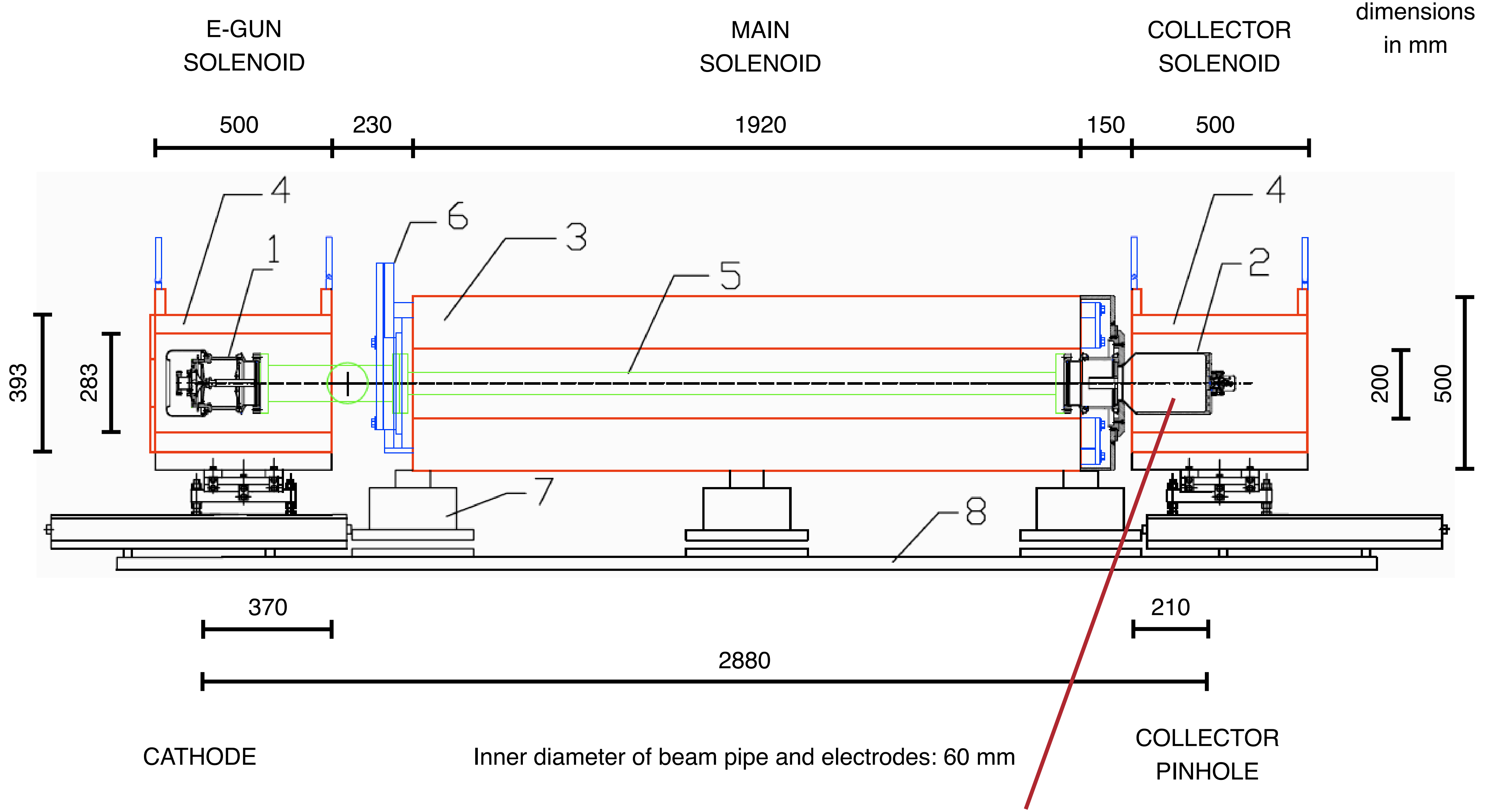
- 25.4 mm outer diameter, 13.5 mm inner diameter
- Built and characterized at Fermilab electron-lens test stand
- A CERN-built twin was also tested at Fermilab
- Delivers 6 A at 10 keV

Fermilab electron-lens test stand



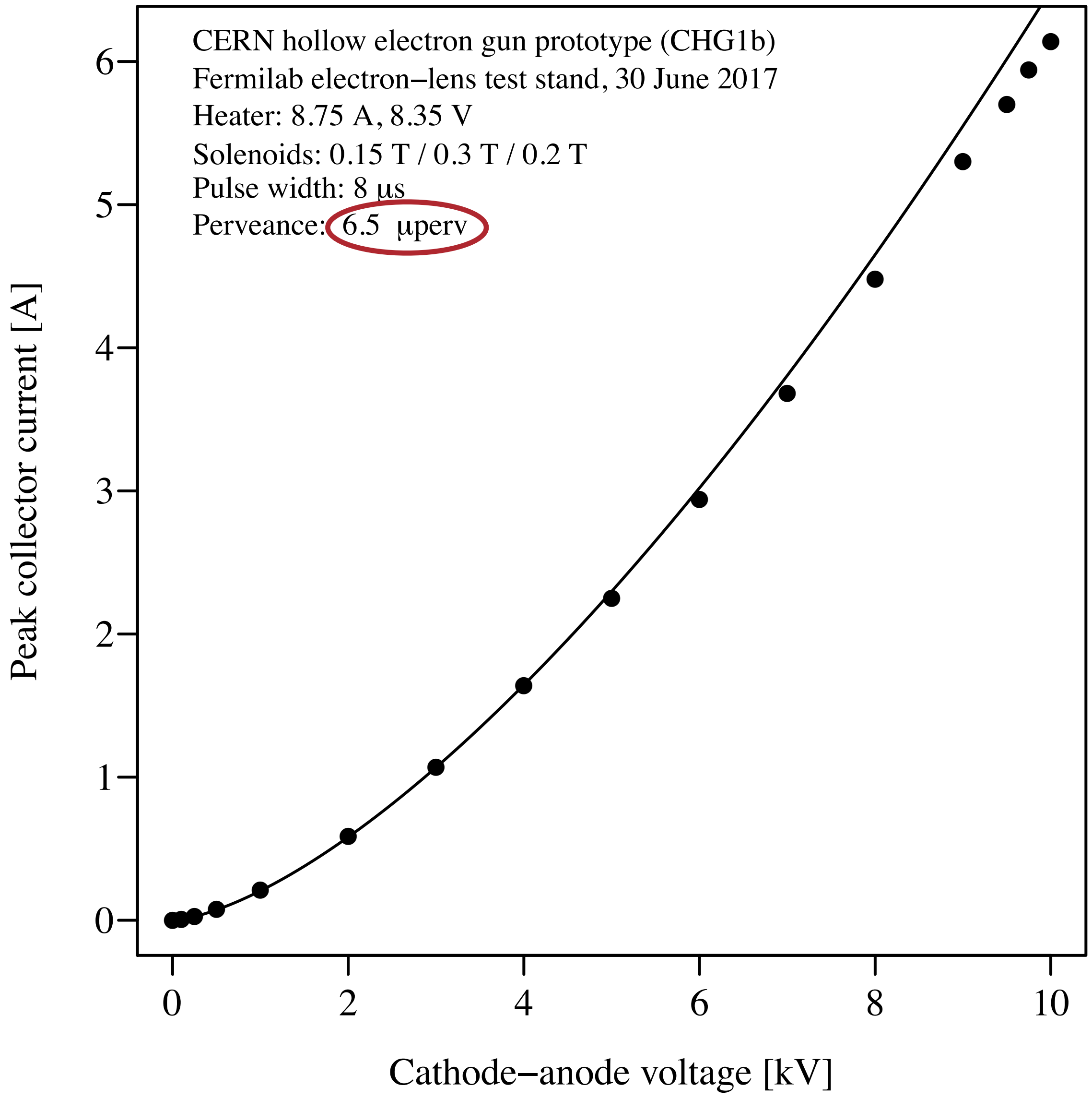
- Only operational e-lens test stand in the world
- Used for development of electron lenses and to study magnetized electron beam dynamics

Fermilab electron-lens test stand

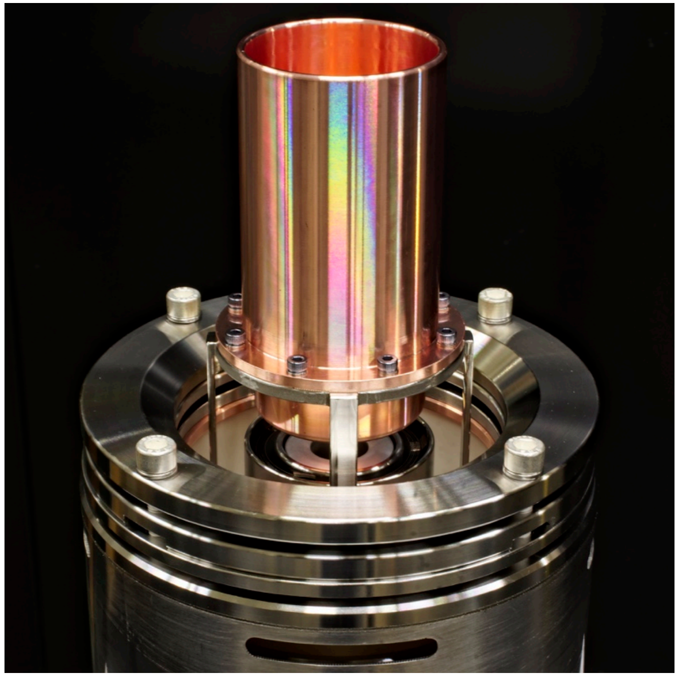


Total current and current-density profile are measured at the collector

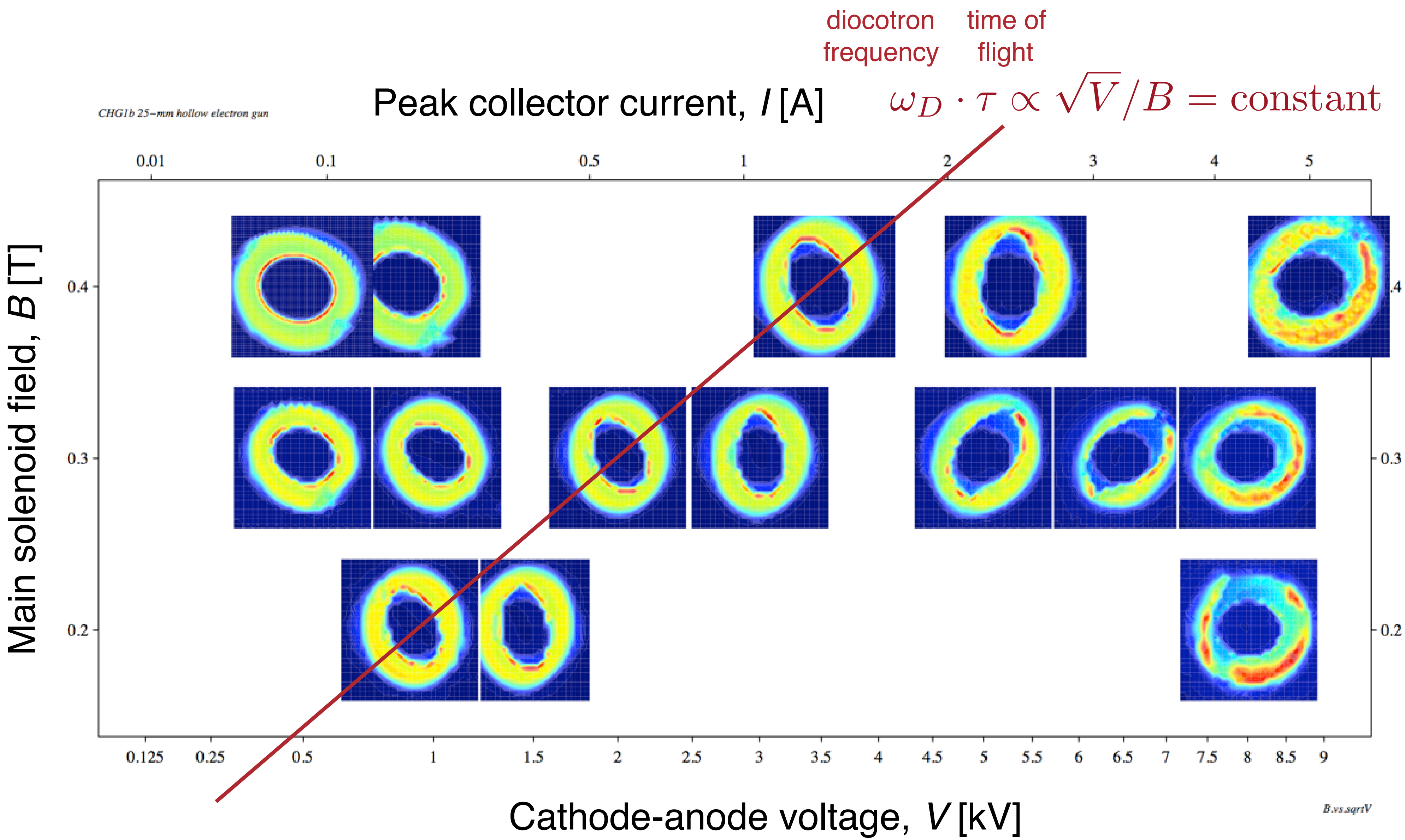
Measured performance of 25-mm e-gun (CHG1b)



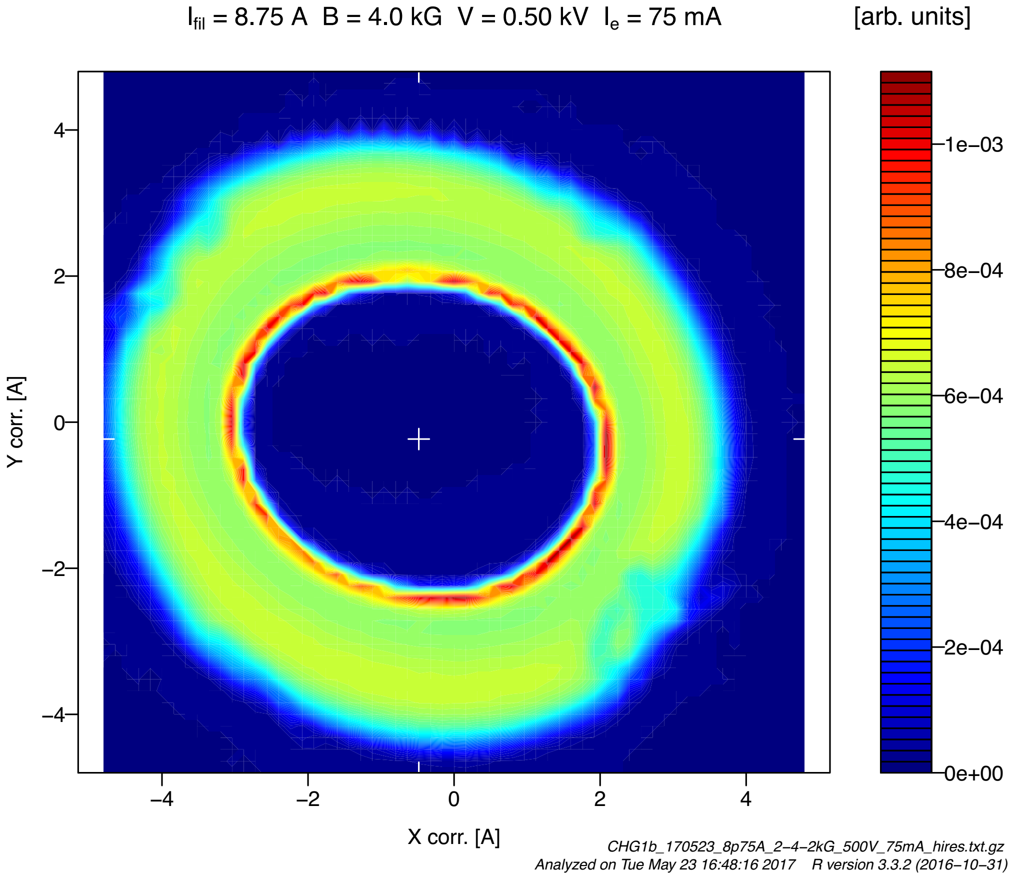
Reached 6 A at 10 kV

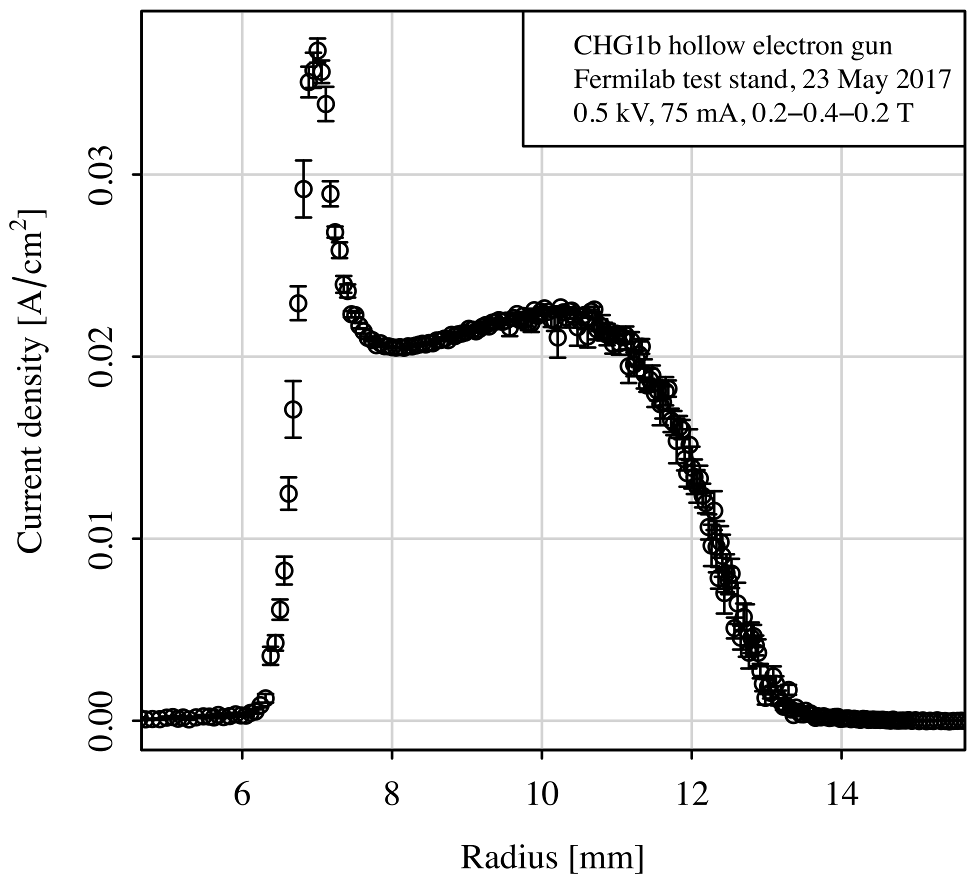


Measured profile evolution and scaling (CHG1b e-gun)



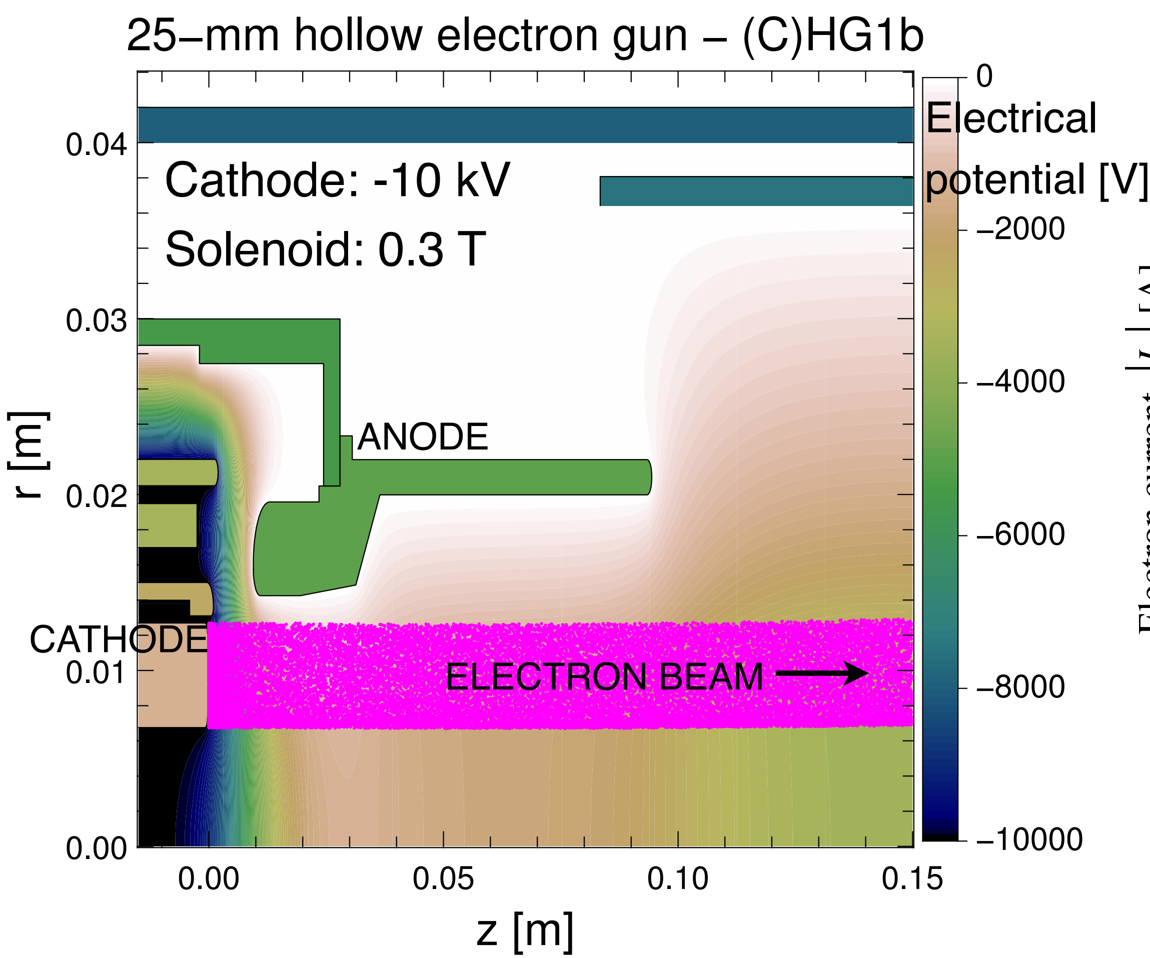
Measured current-density profile (CHG1b e-gun)

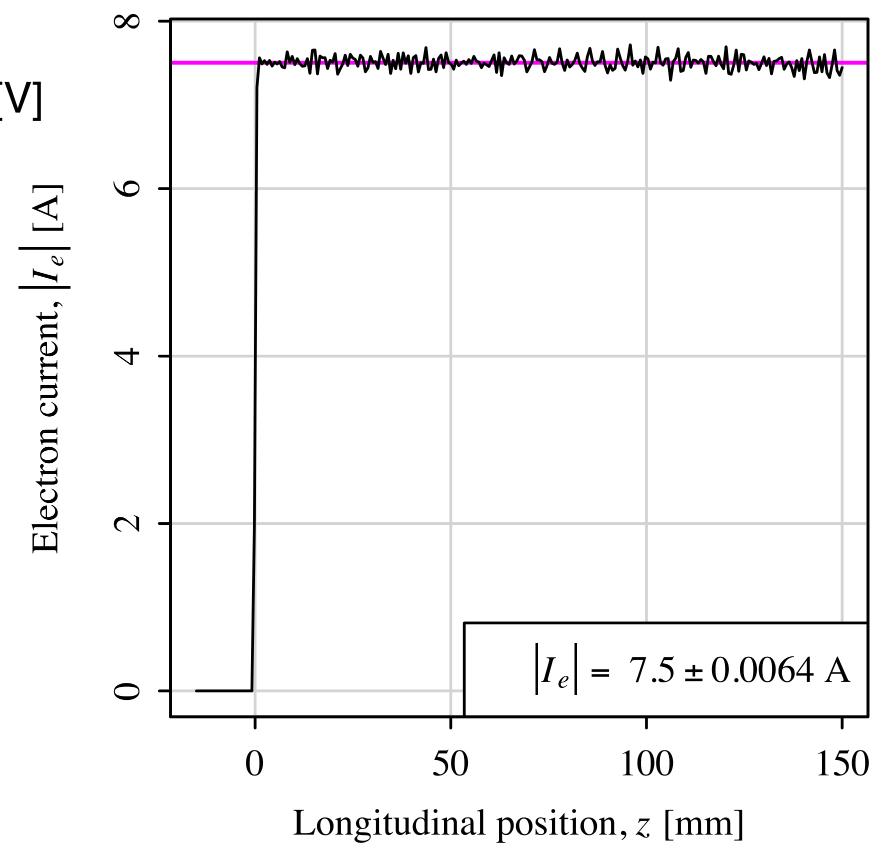




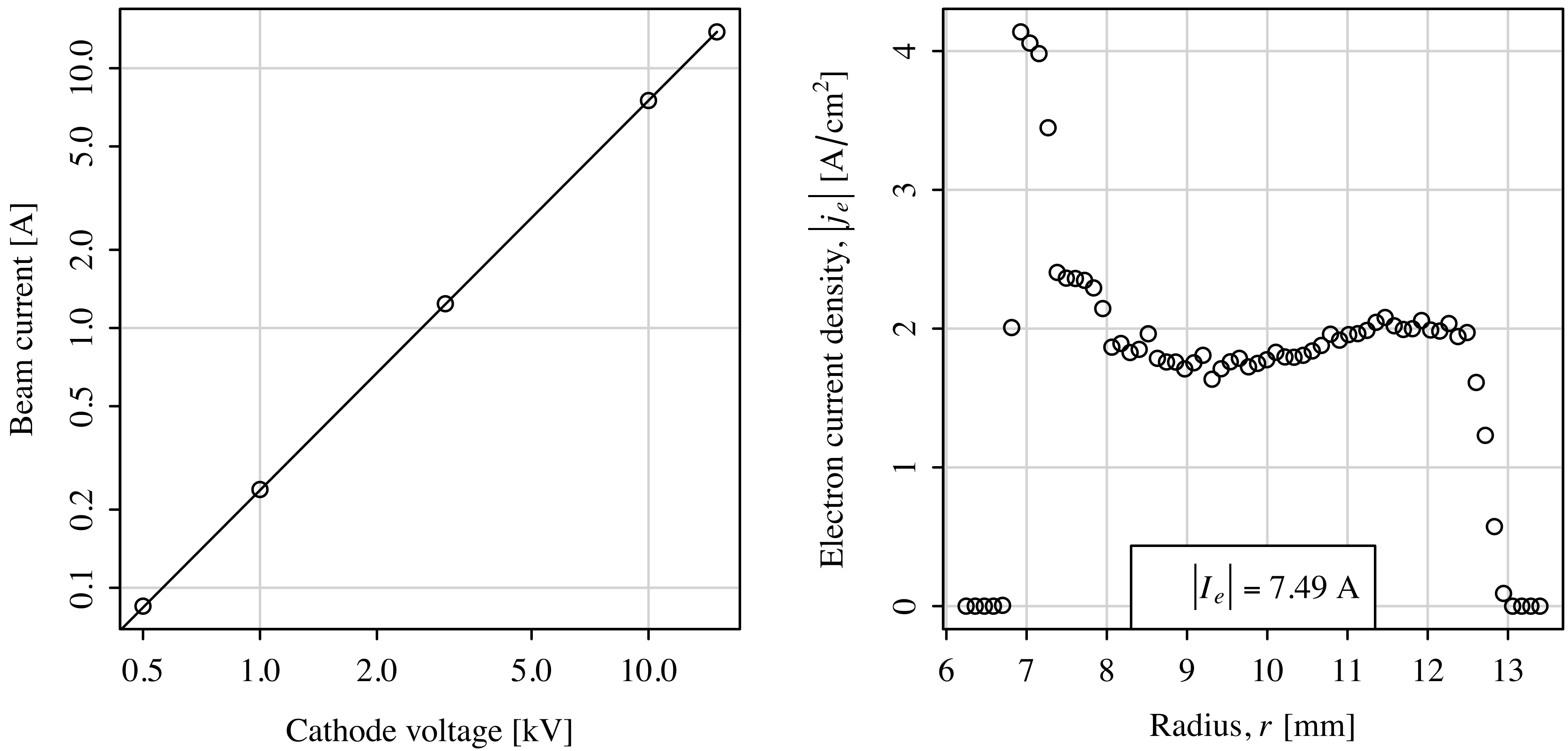
Data file: CHG1b_170523_8p75A_2-4-2kG_500V_75mA_hires.txt.gz

Predicted performance of (C)HG1 25-mm e-gun (Warp calculation)





Warp simulation of space-charge-limited emission (CHG1 e-gun)



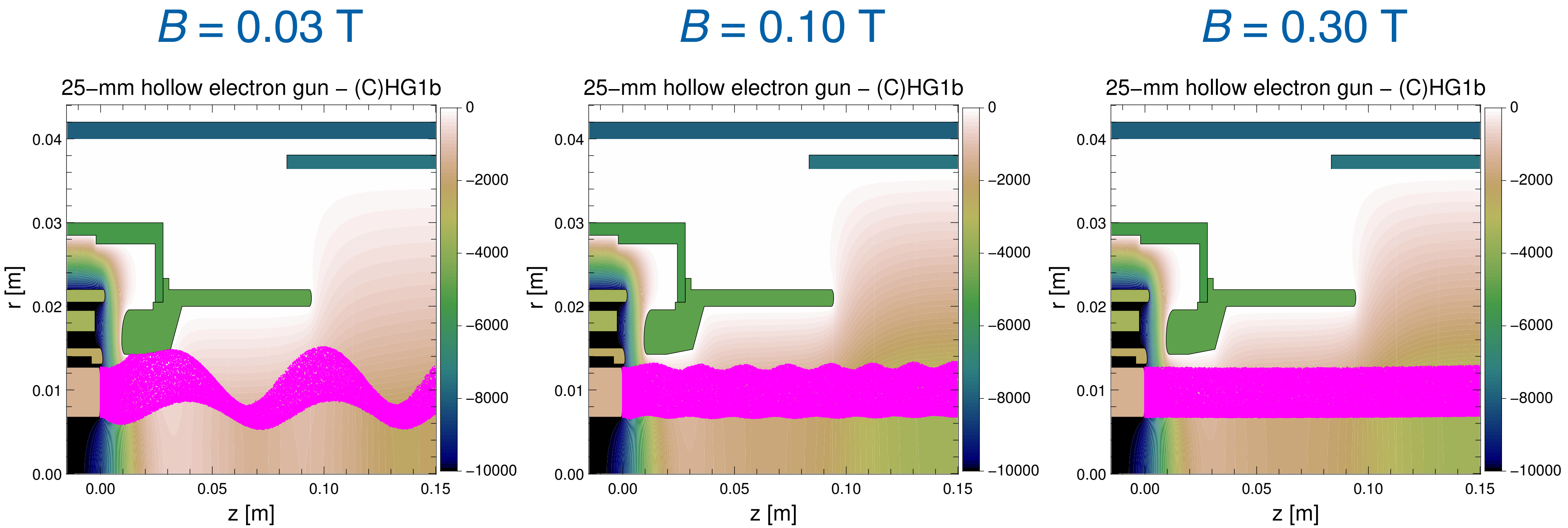
Predicted perveance is 7.5 uperv (vs. 6.5 measured)

Current-density distribution shows inner peak and sharp outer edge at 0.15 m downstream of cathode (measurements were taken at 2.8 m)

Simulated emission vs. solenoid field at the e-gun

$V = 10$ kV

$I = 7.5$ A

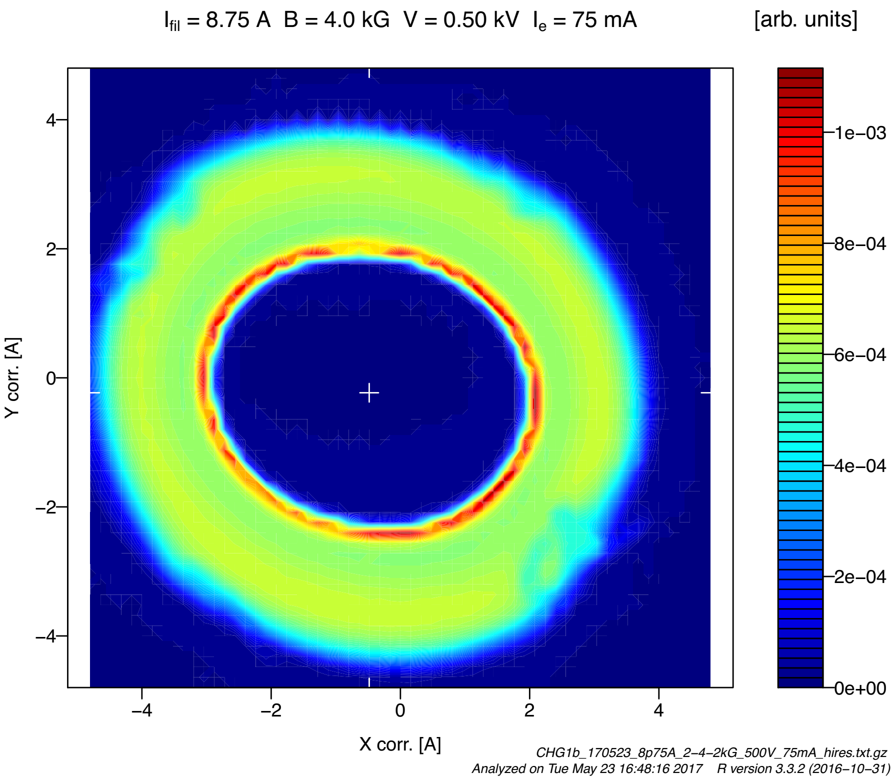


Used to verify minimum required magnetic field for a given current

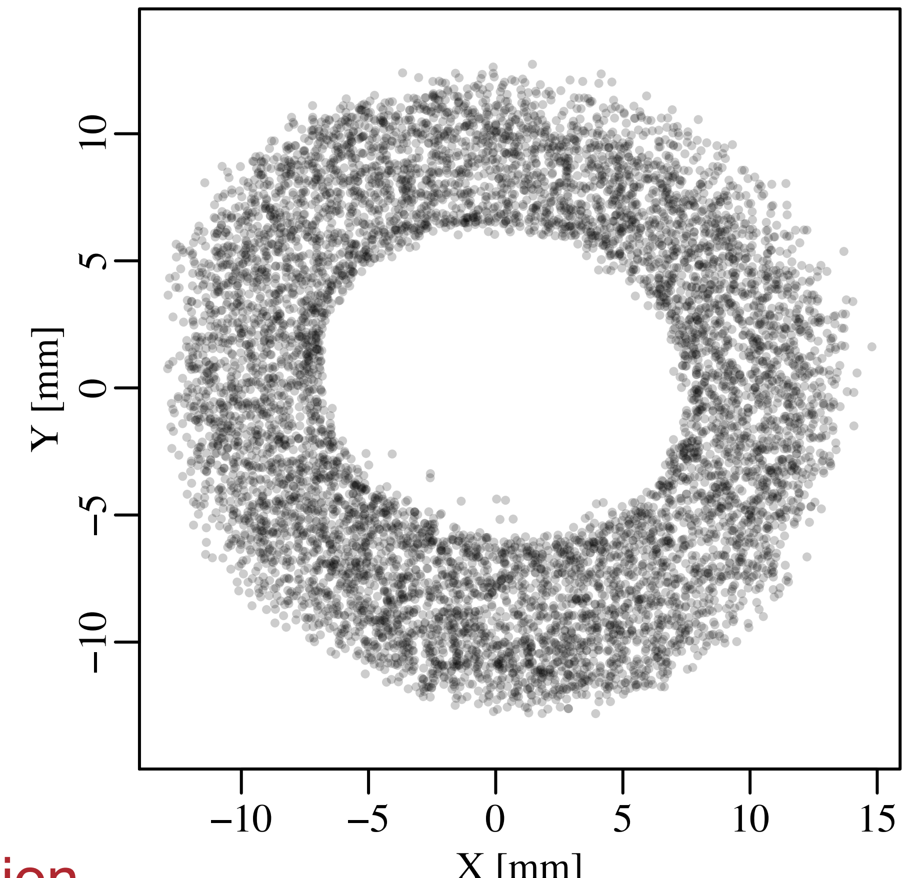
Estimates of the residual field on axis

- If the hollow electron beam is not axially symmetric, the residual electromagnetic fields will perturb the core of the circulating beam
- From the measured profiles, the residual fields are calculated with Warp
- The fields are parameterized in symplectic form [Stancari, FERMILAB-FN-0972-APC, arXiv:1403.6370 (2014)] for use in tracking simulations of the circulating beam to evaluate emittance growth and losses

Generation of particle distributions



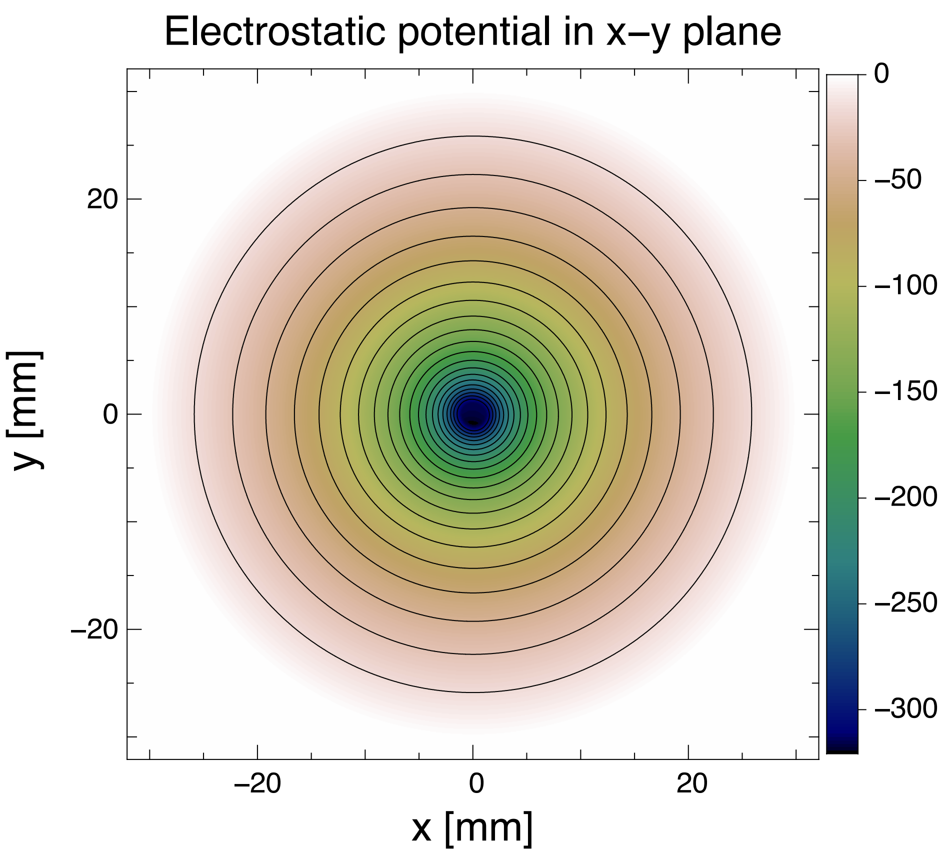
From measured profile...

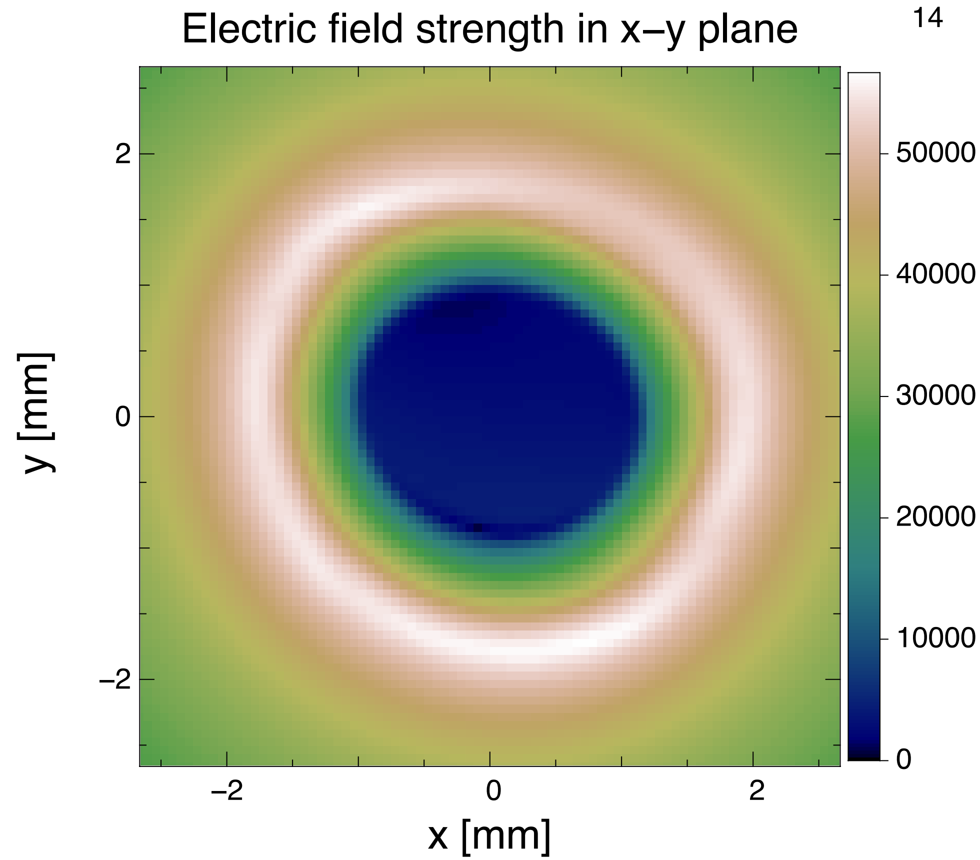


...to particle distribution

Calculation of potentials and fields with boundaries

Particle distributions are entered in Warp to calculate potentials and fields

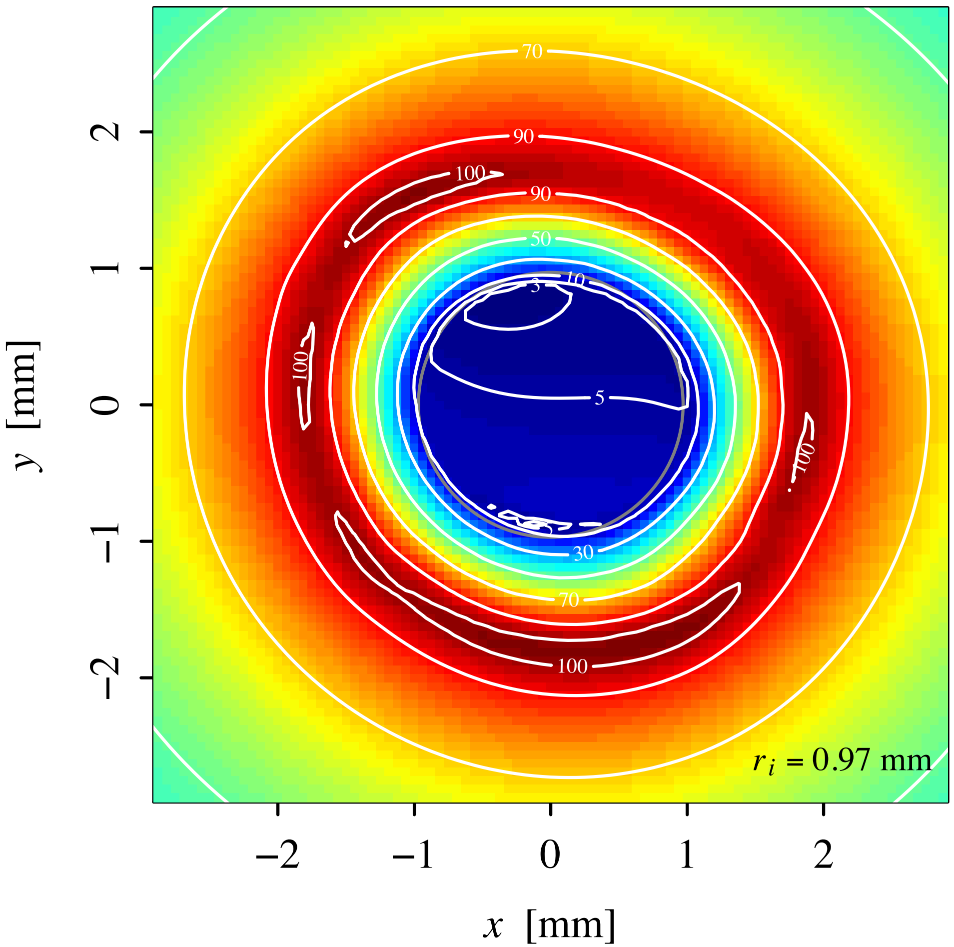


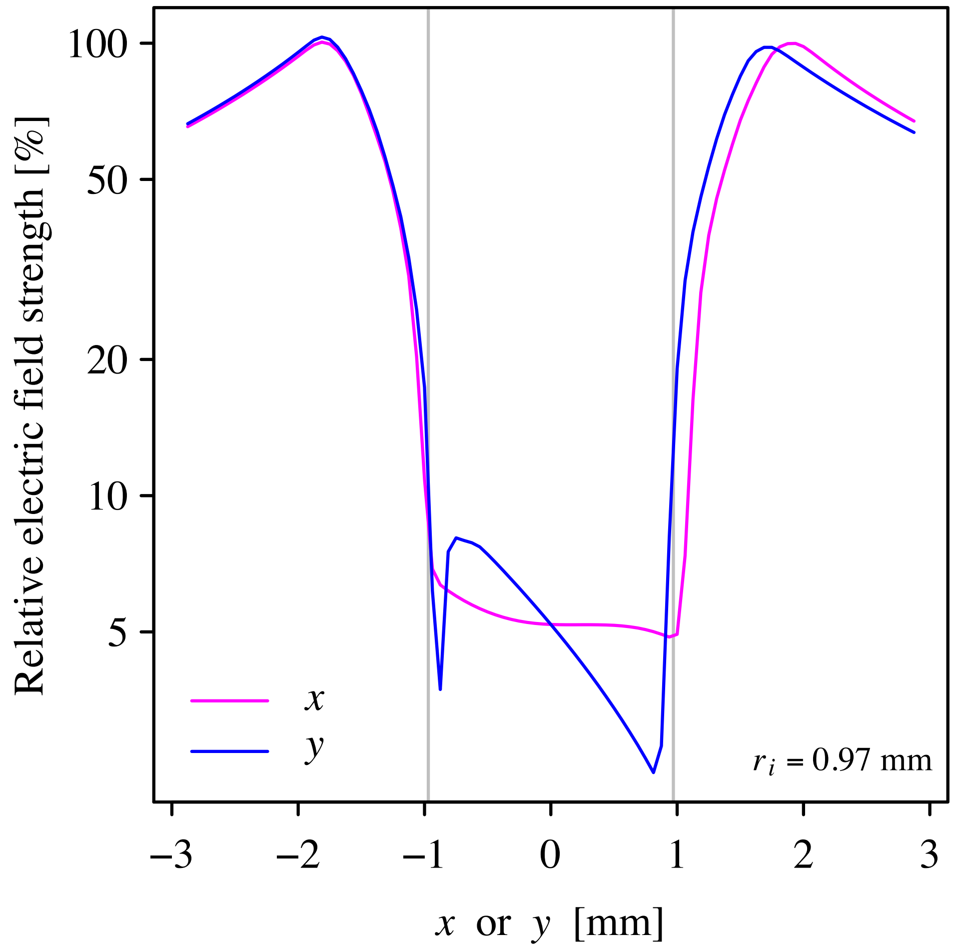


Examples with inner e-beam radius = 0.97 mm and 30-mm inner radius of vacuum chamber (HL-LHC configuration)

Analysis of field distributions

Calculations are analyzed to estimate field quality in the center

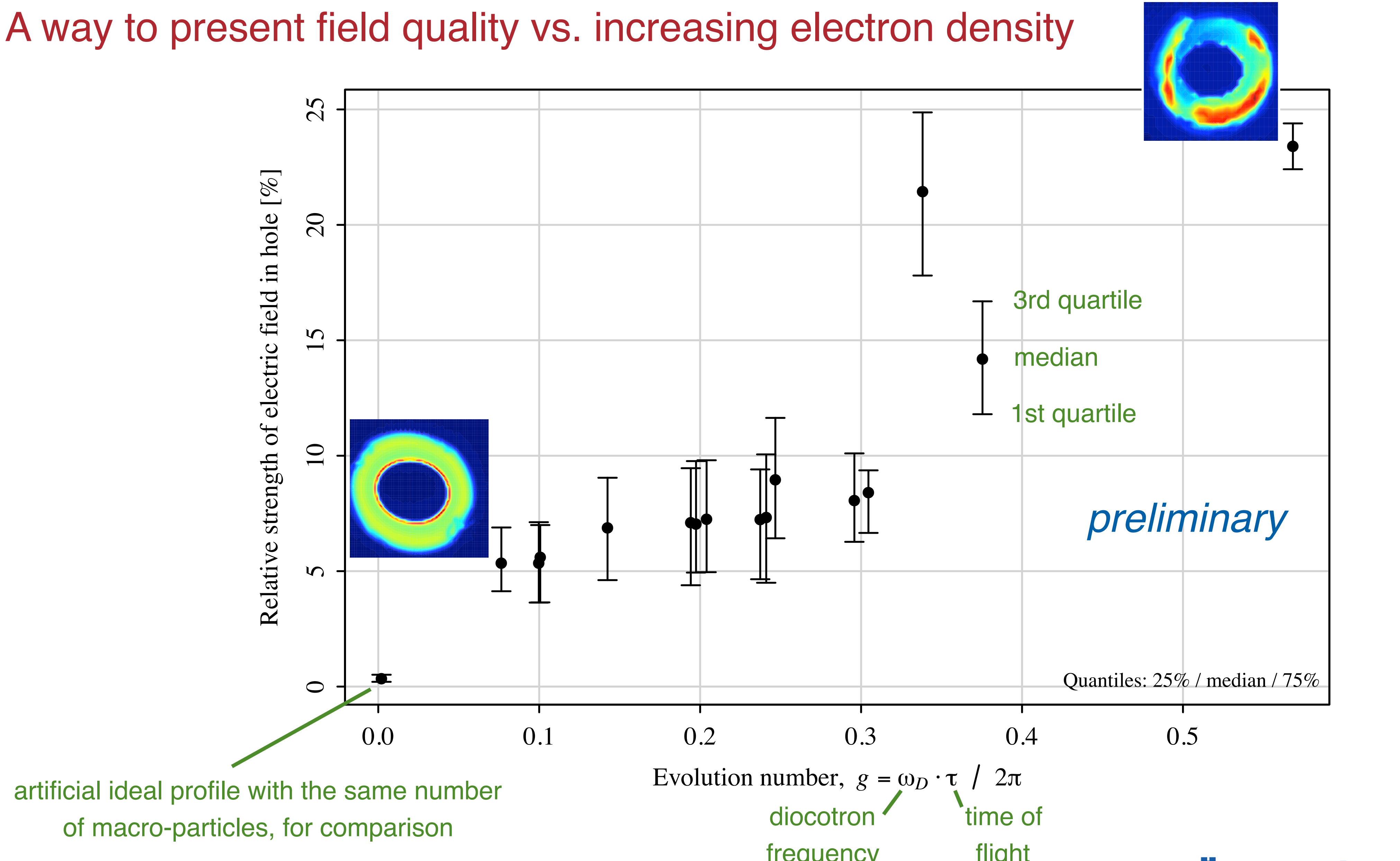




Outputs: mean field, field fluctuations, kick maps for tracking

Electric-field quality vs. evolution parameter

A way to present field quality vs. increasing electron density



The electron lens for the Fermilab Integrable Optics Test Accelerator (IOTA)

FAST: Fermilab Accelerator Science and Technology facility

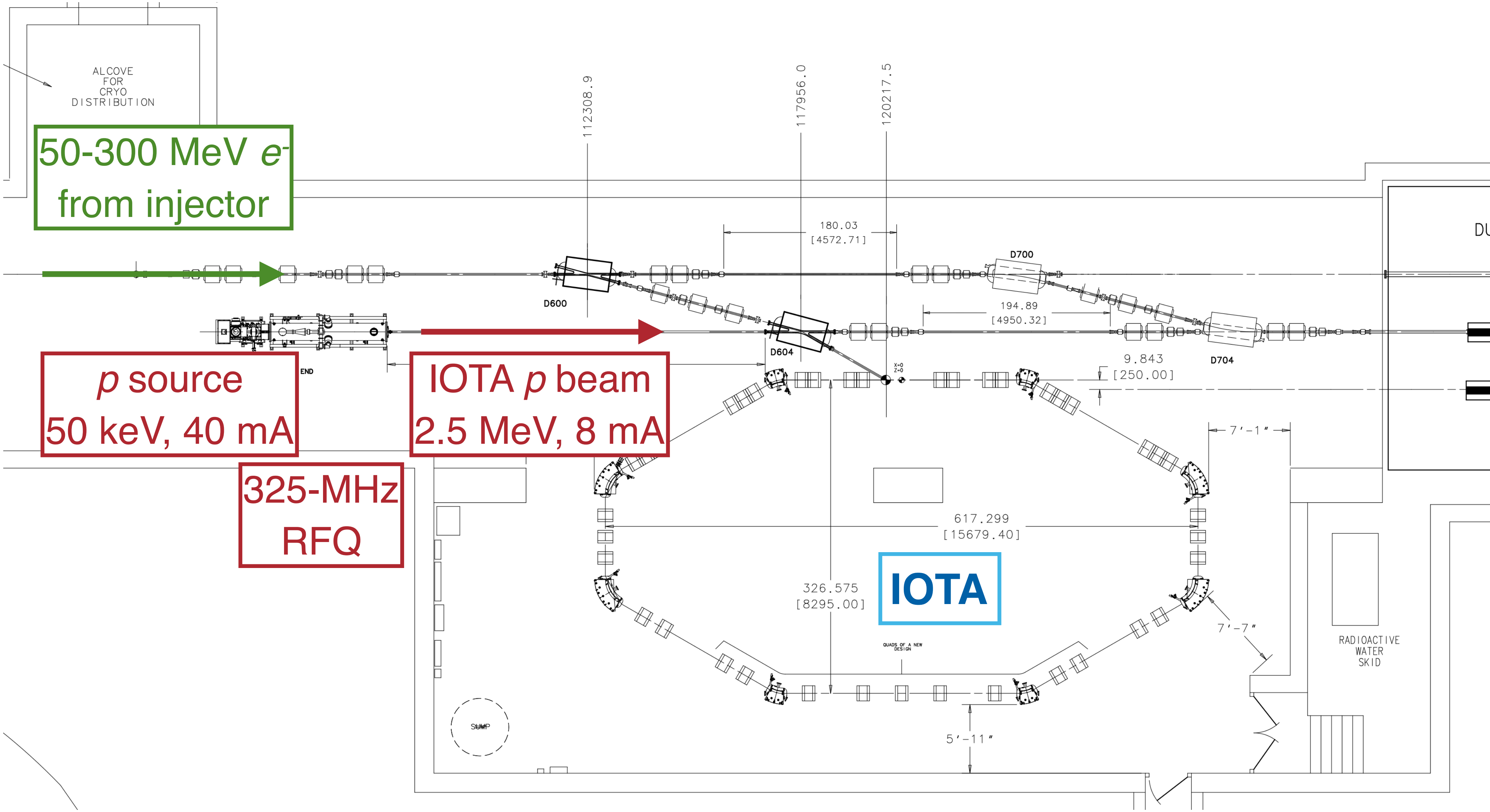
The Fermilab Integrable Optics Test Accelerator (IOTA)

- Small (40 m) storage ring for research with charged-particle beams
- Can operate with both electrons or protons, up to momentum of 150 MeV/c
- Large aperture
- Flexible lattice and precise control of beam optics
- Based on conventional magnets and rf cavity

e^- beam energy	150 MeV
gamma rel.	294.54
e^- beam intensity	10^9 particles
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	0.1 μm
synch. rad. damping time	0.6 s ($5{\times}10^6$ turns)
rf frequency	30 MHz (h = 4)
rf voltage	1 kV
synchrotron tune	0.002 — 0.005
rms bunch length	20 mm
rms momentum spread	$1.4{\times}10^{-4}$

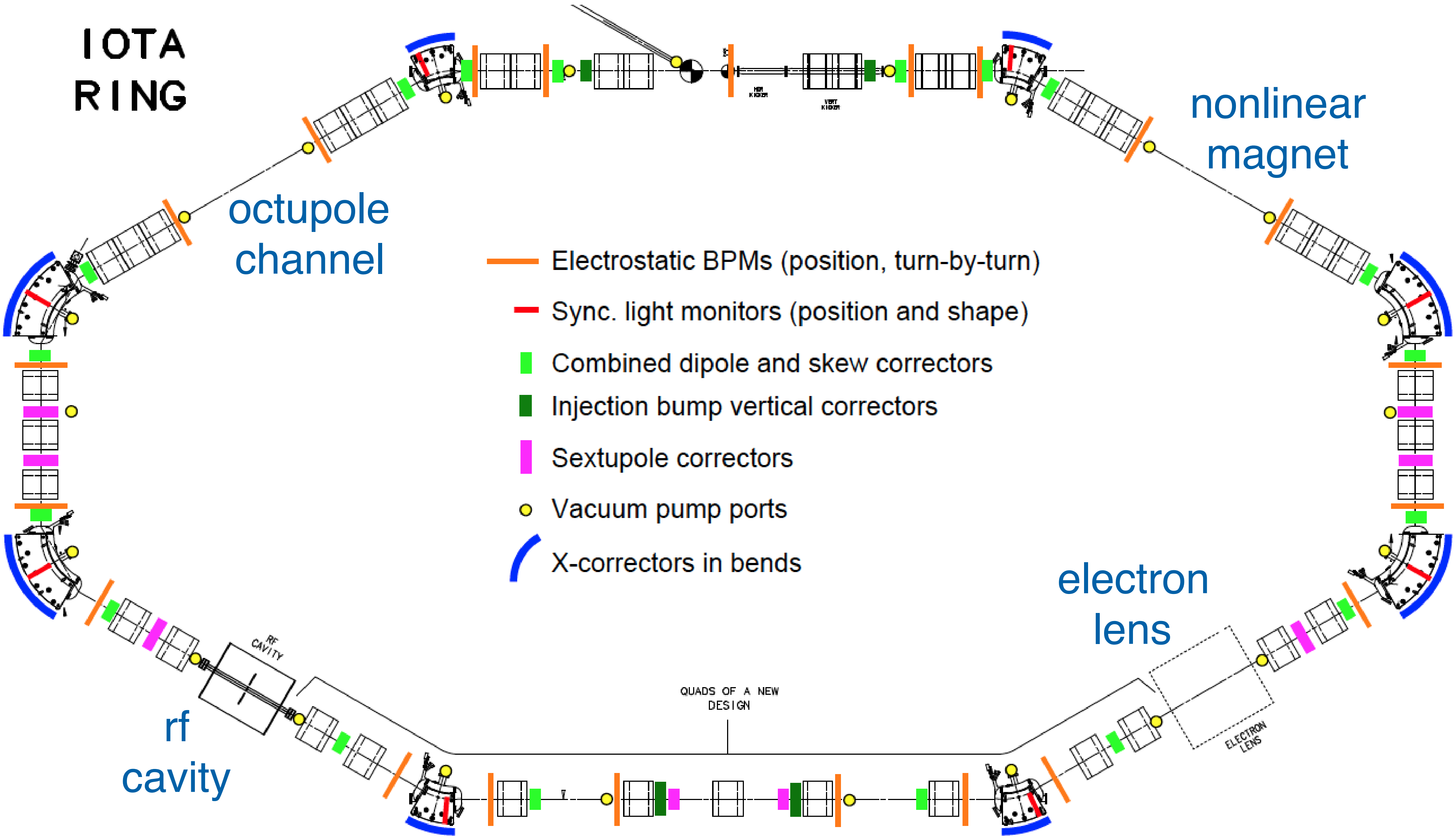
Antipov et al., JINST **12**, T03002 (2017)

Layout of the injectors and of the IOTA ring



Fermilab

Layout of the ring



Fermilab

The IOTA ring

IOTA research program and plans

- **Demonstration of nonlinear integrable optics**
- **Space-charge compensation: nonlinear lattice, electron columns, electron lenses, circular betatron modes**
- **Optical stochastic cooling**
- **Dynamics of annular beams for collimation or halo diagnostics**
- **Electron cooling in nonlinear lattice**
- **Demonstration of injection with laser-plasma accelerator**
- **Quantum physics with single or few circulating electrons**

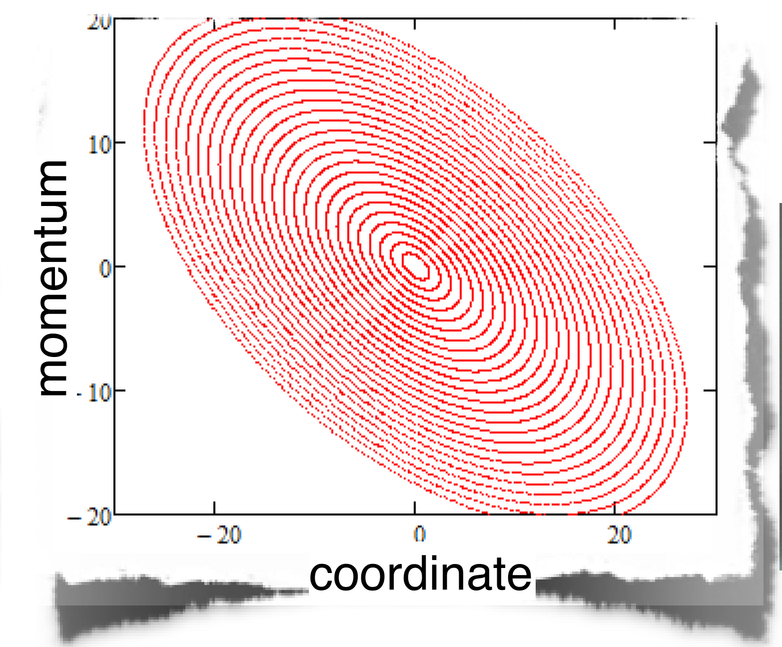
Proposals welcome

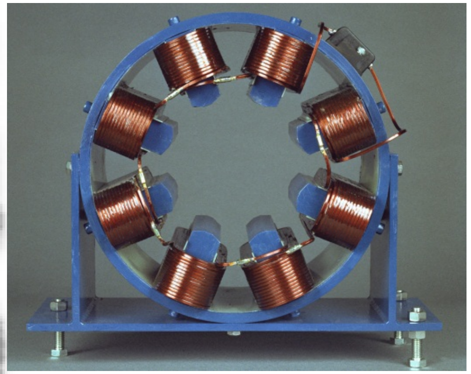
- Complete ring by summer 2018 and start commissioning with electrons
- First experiments with electrons in 2018: integrable particle dynamics with nonlinear magnet and octupole channel
- Commissioning and installation of the proton source: 2019

"Mainstream" accelerator lattices

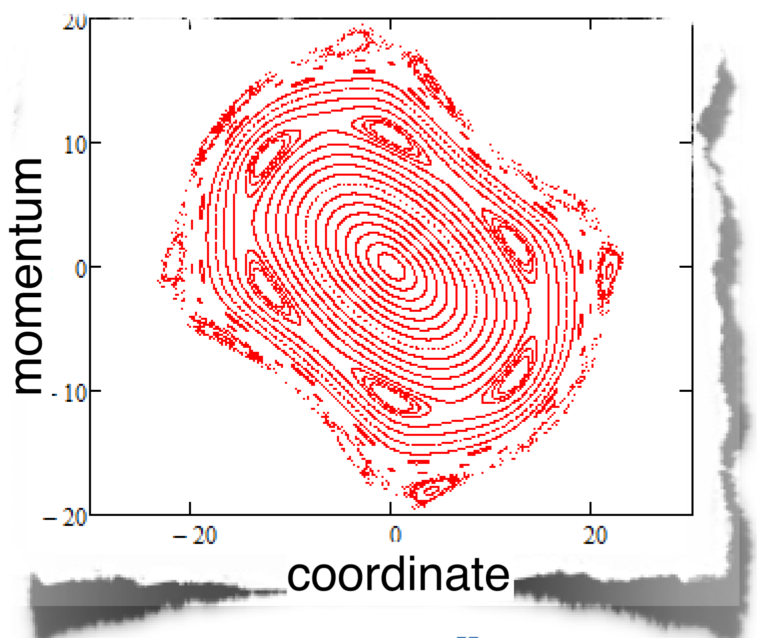
- **Conventional strong-focusing accelerators** are **based upon linear elements** (dipoles and quadrupoles). Same design betatron frequency for all particles. In the ideal case, the Courant-Snyder invariant is conserved
- **Nonlinear elements are necessary** (e.g., sextupoles for chromaticity, octupoles 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 (Liouville-Arnold) integrable, i.e. with *n* independent conserved quantities for *n*-dimensional dynamics, then it is bounded and therefore stable

An example of nonlinear integrable map

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]

$$\left.\begin{aligned} x' &= y \\ y' &= -x + f(y) \end{aligned}\right\}$$

with $f(x) = -\dfrac{Bx^2 + Dx}{Ax^2 + Bx + C}$.

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

It can be **extended to 2D** in an **uncoupled symmetric lattice**. The **axially symmetrical kick** can be generated by a charge distribution (e.g., an electron lens)

Practical implementations of nonlinear (quasi-)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 (Shwartz, NA-PAC13)

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

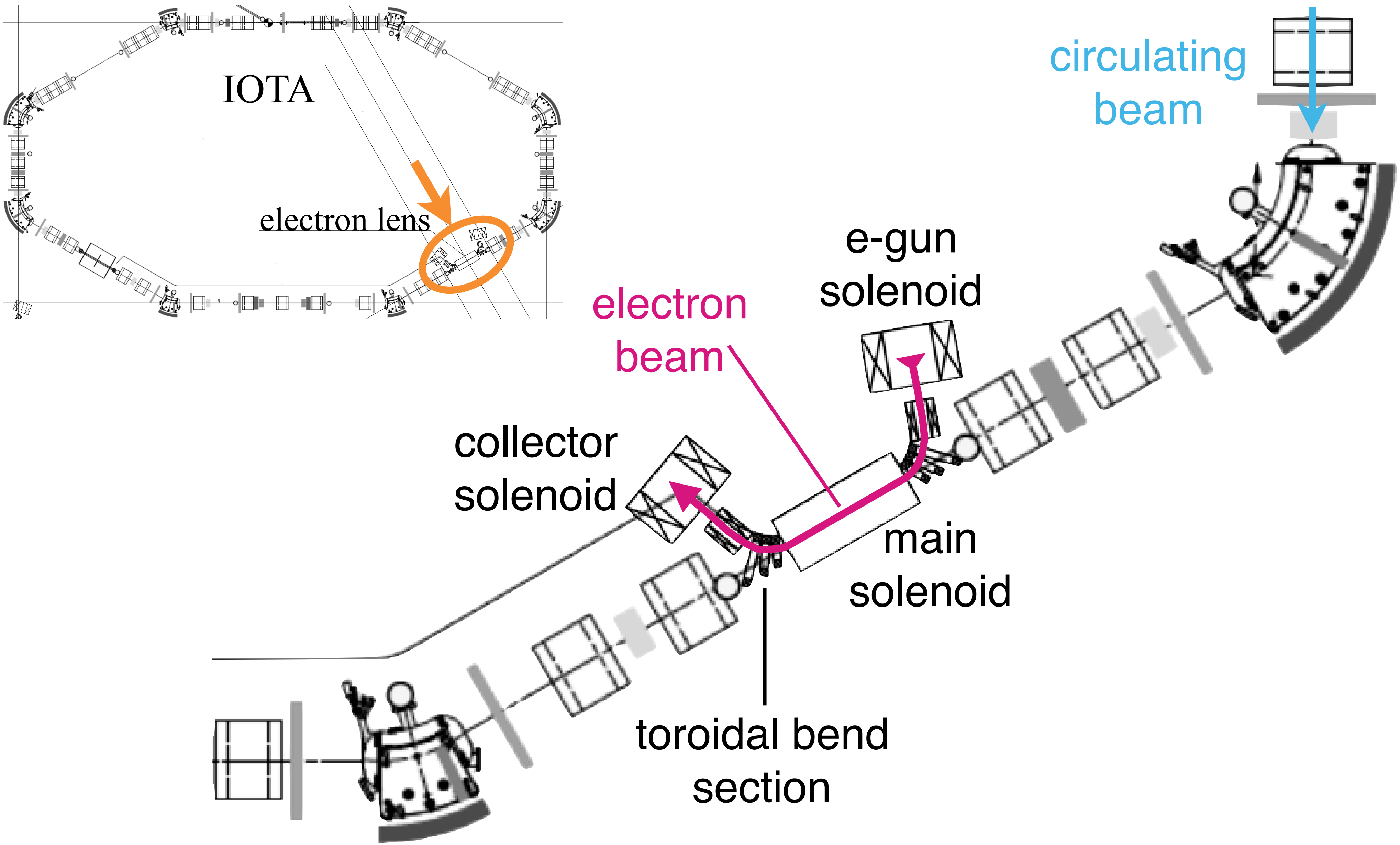
2. Axially symmetric kick in long solenoid

Any axially-symmetric current distribution

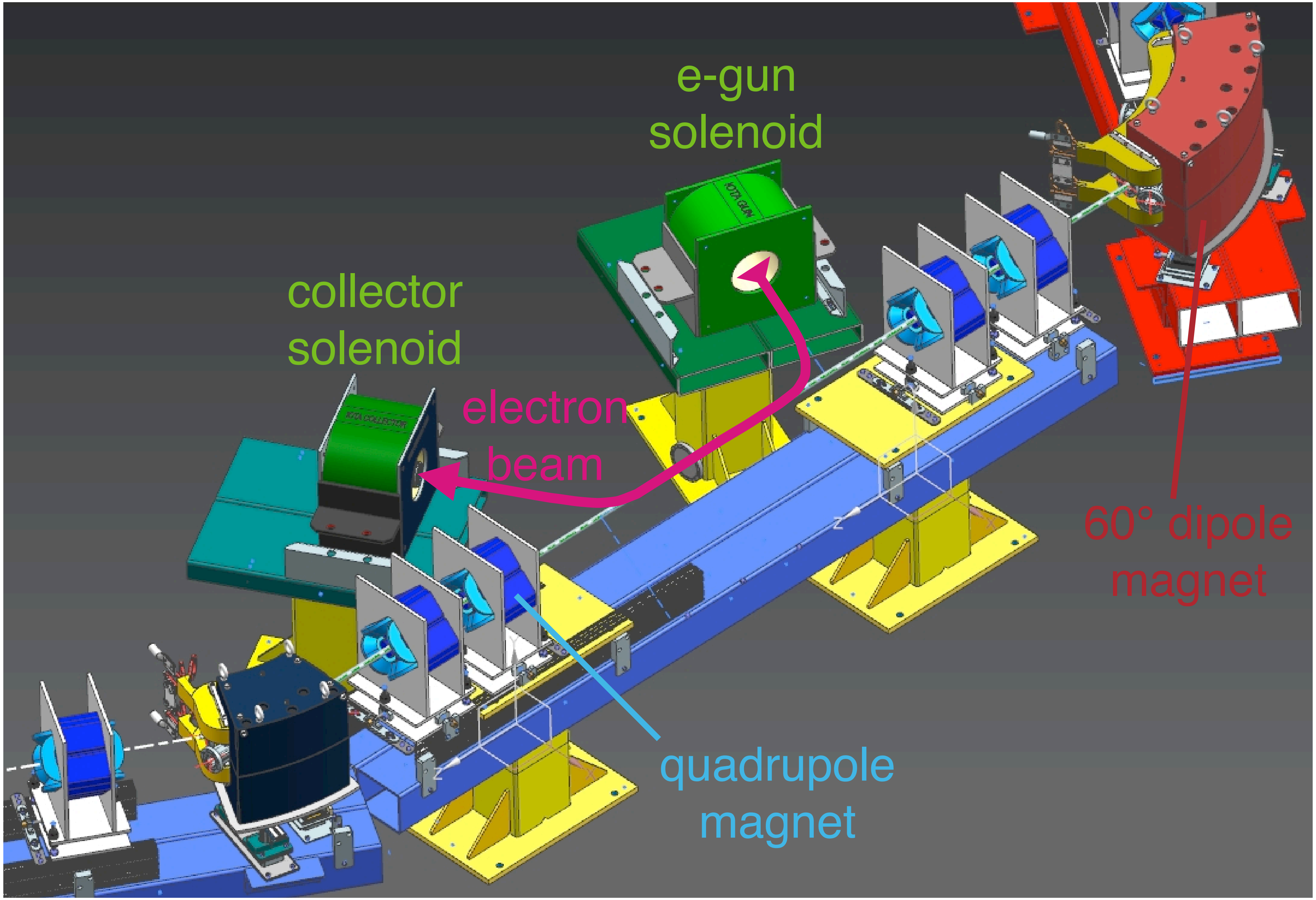
$$\sim \frac{L}{2\pi\beta} = \frac{L B_z}{4\pi(B\rho)}$$

Smaller tune spreads in IOTA
More robust

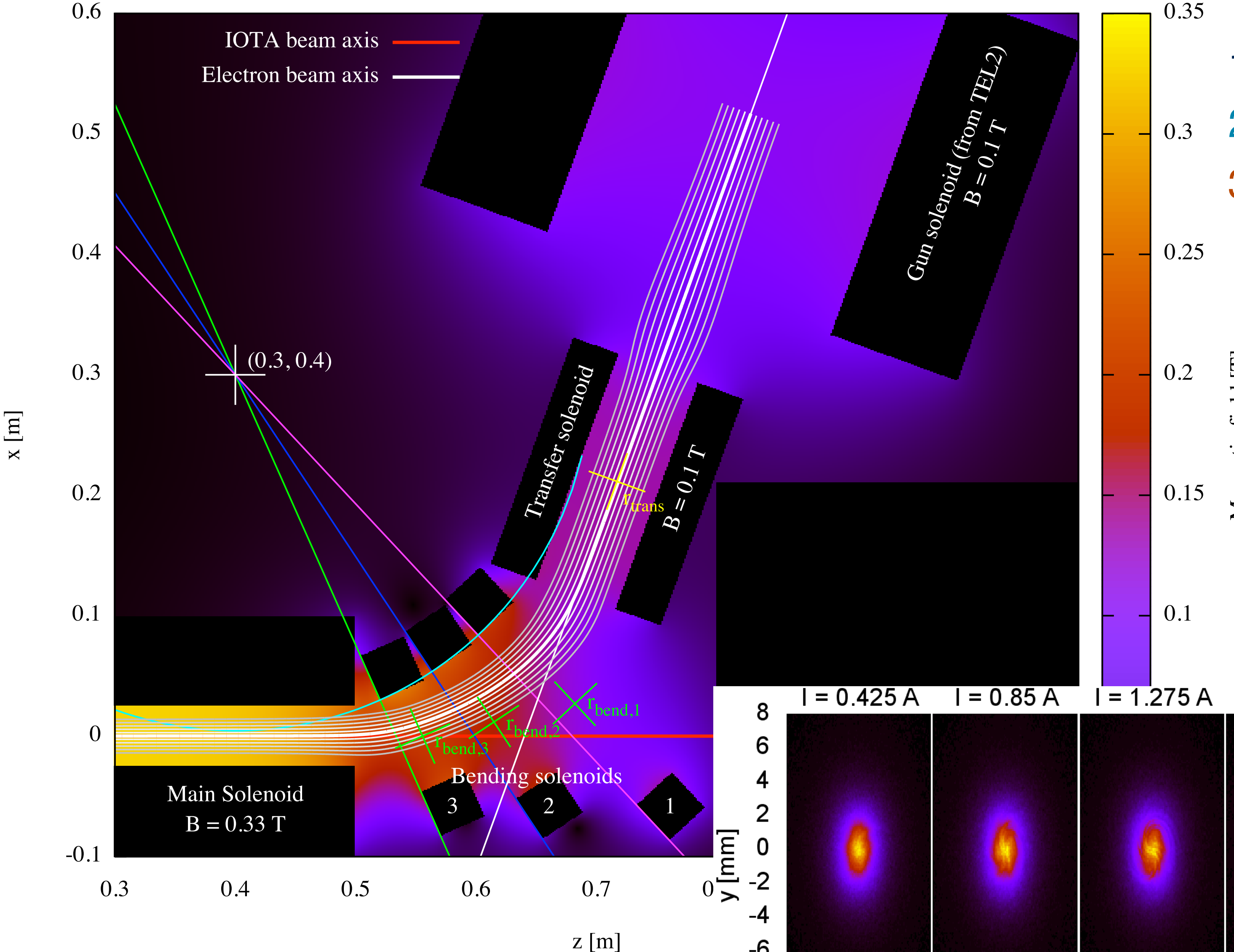
Electron lens layout in IOTA (top view)



Electron-lens layout in IOTA

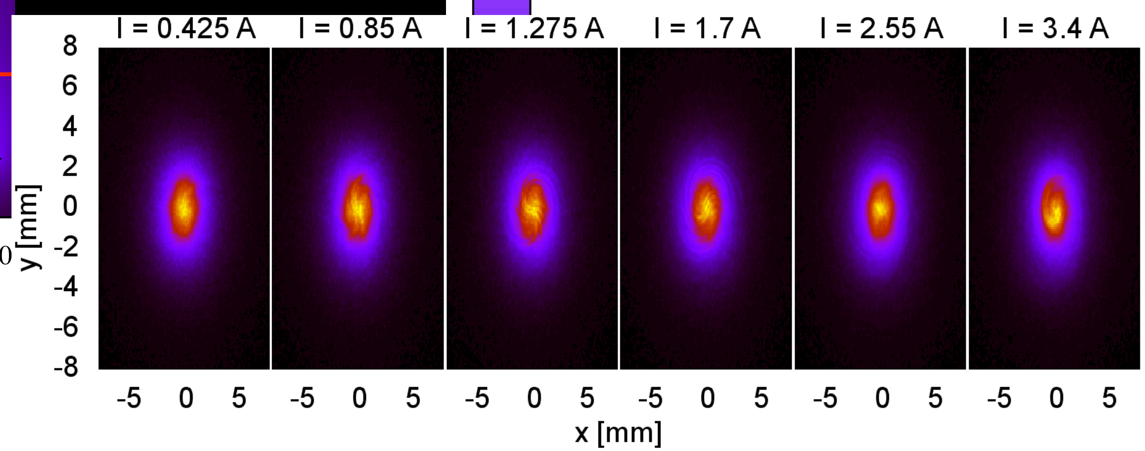


Design of beam transport in electron lens



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

Design of McMillan e-gun

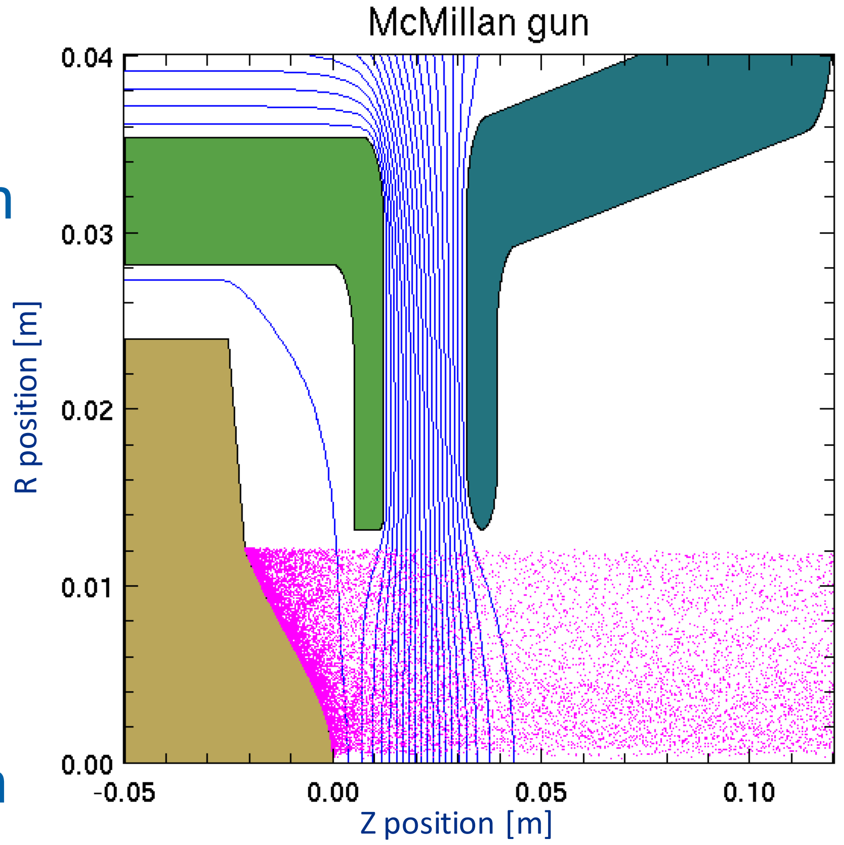
Is it possible to generate the required current-density profile? $$j(r) = \frac{j_0 a^4}{(r^2 + a^2)^2}$$

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



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

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

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

Does nonlinear integrable optics combined with cooling enable higher brightnesses?

Stancari et al., COOL15

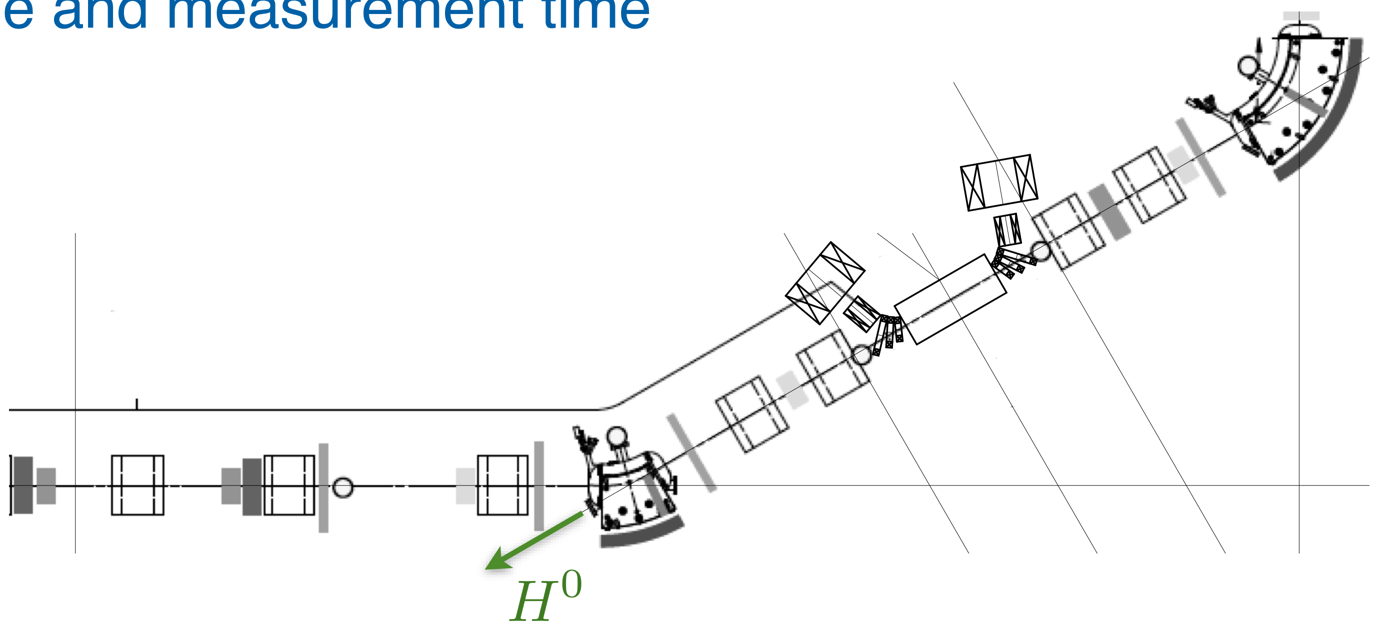
Antipov et al., JINST **12**, T03002 (2017)

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; good compromise between beam lifetime and measurement time



A critical diagnostic tool for cooling and proton beam evolution

Space-charge compensation in rings

Space-charge compensation routinely used in linacs, rf photoinjectors

In rings, it would enable higher intensities

A challenging subject: local correction of global effect possible?

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

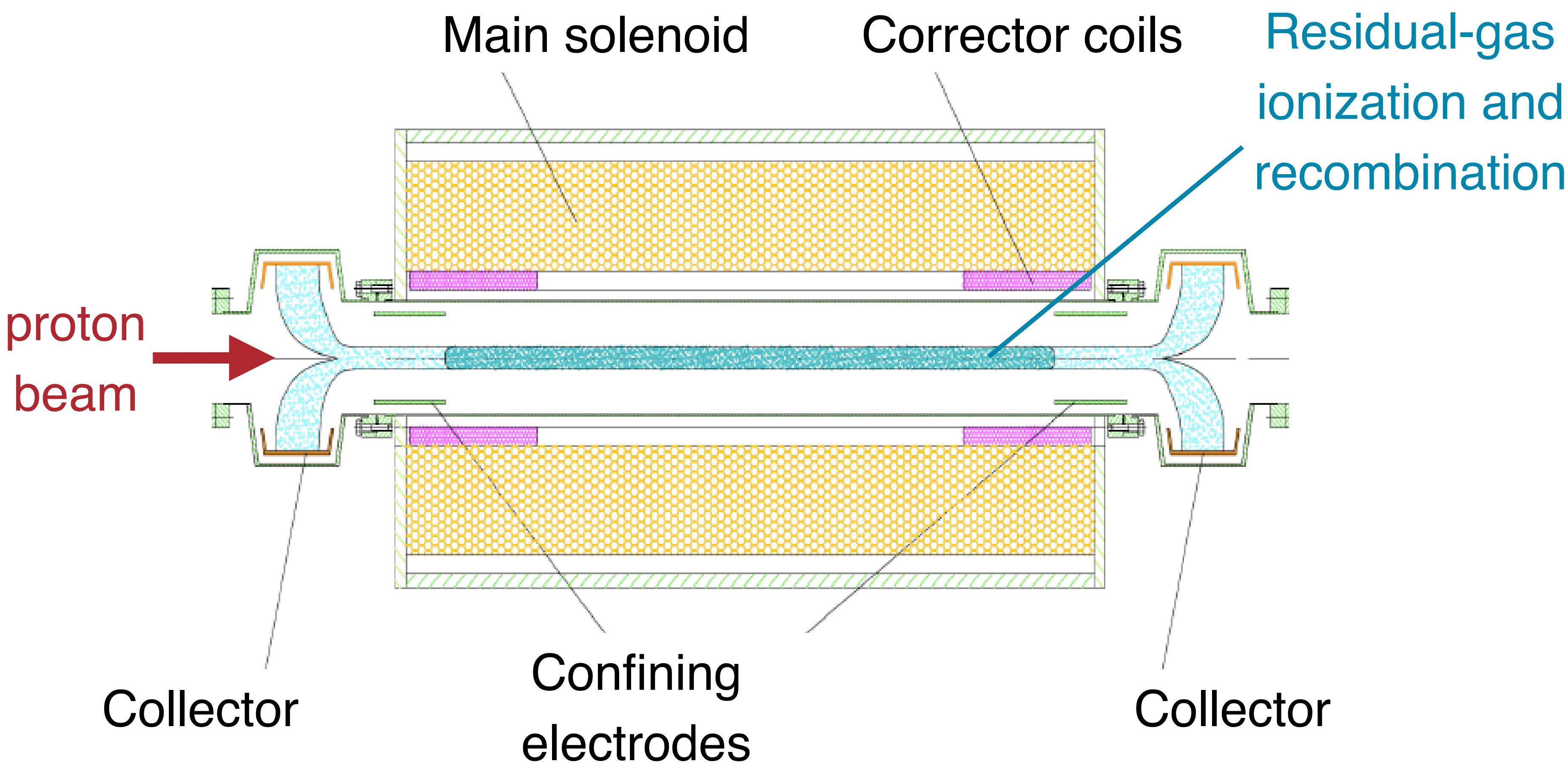
Implementation with electron lens has advantage of magnetic confinement for stability

Two concepts:

- given profile (transverse/longitudinal?) from electron gun <u>or</u>
- electrons from residual-gas ionization trapped in Penning-Malmberg configuration ("electron column")

Numerical simulation studies necessary to guide experiments in IOTA

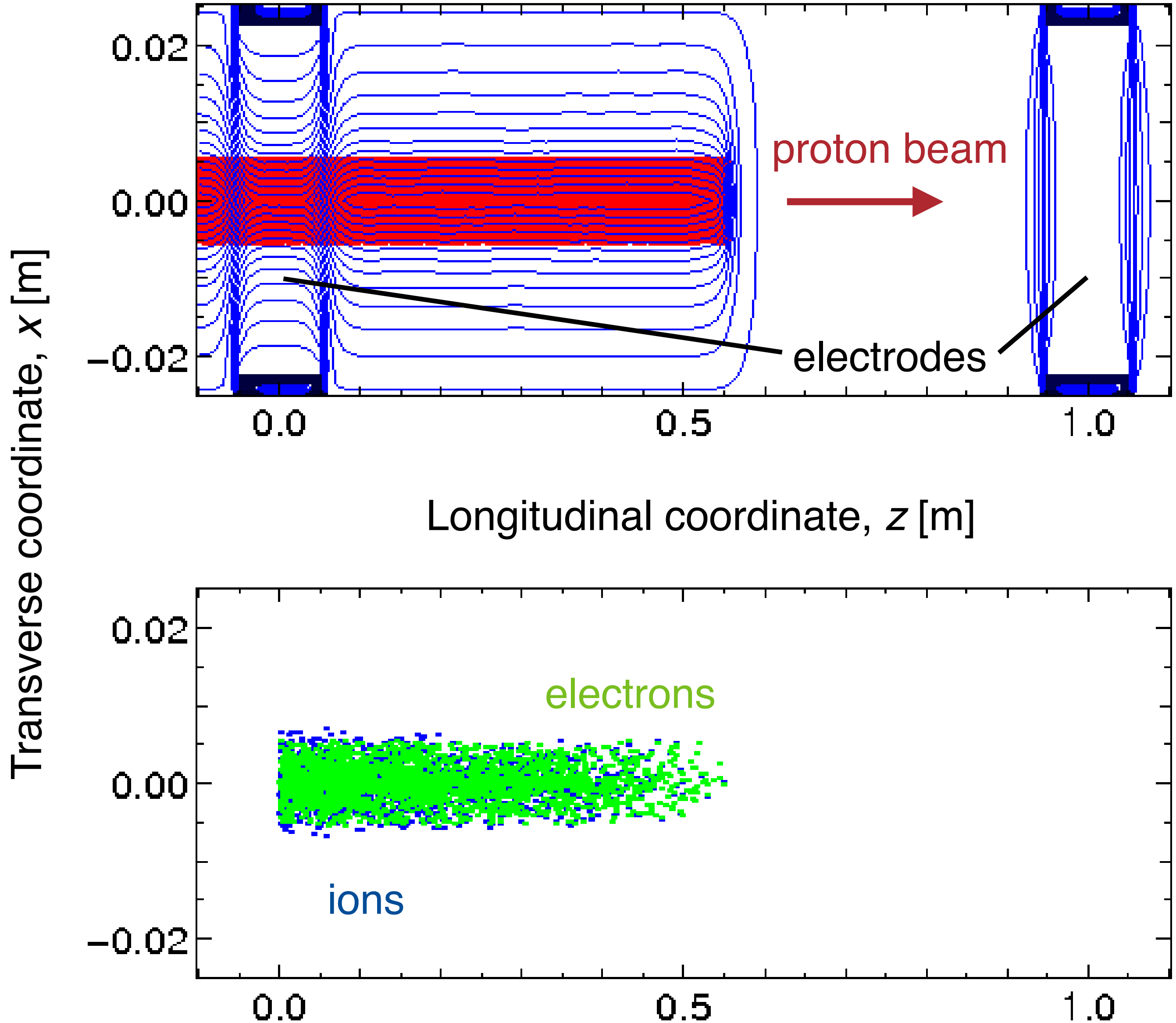
Concept of electron column



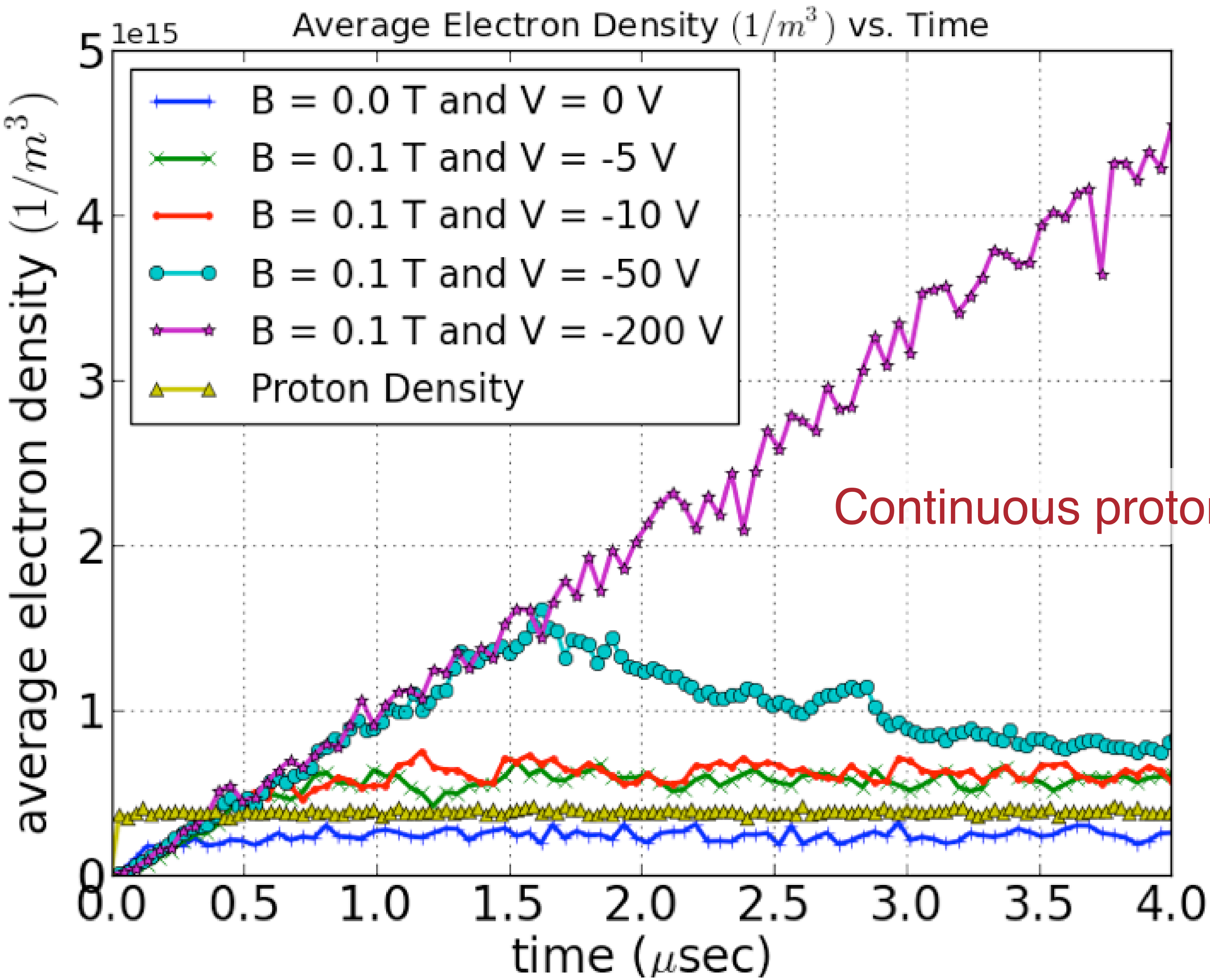
In strong field, ionization electrons mirror transverse profile of protons

How does the e-column evolve?

Layout of simulations of electron column (Warp)



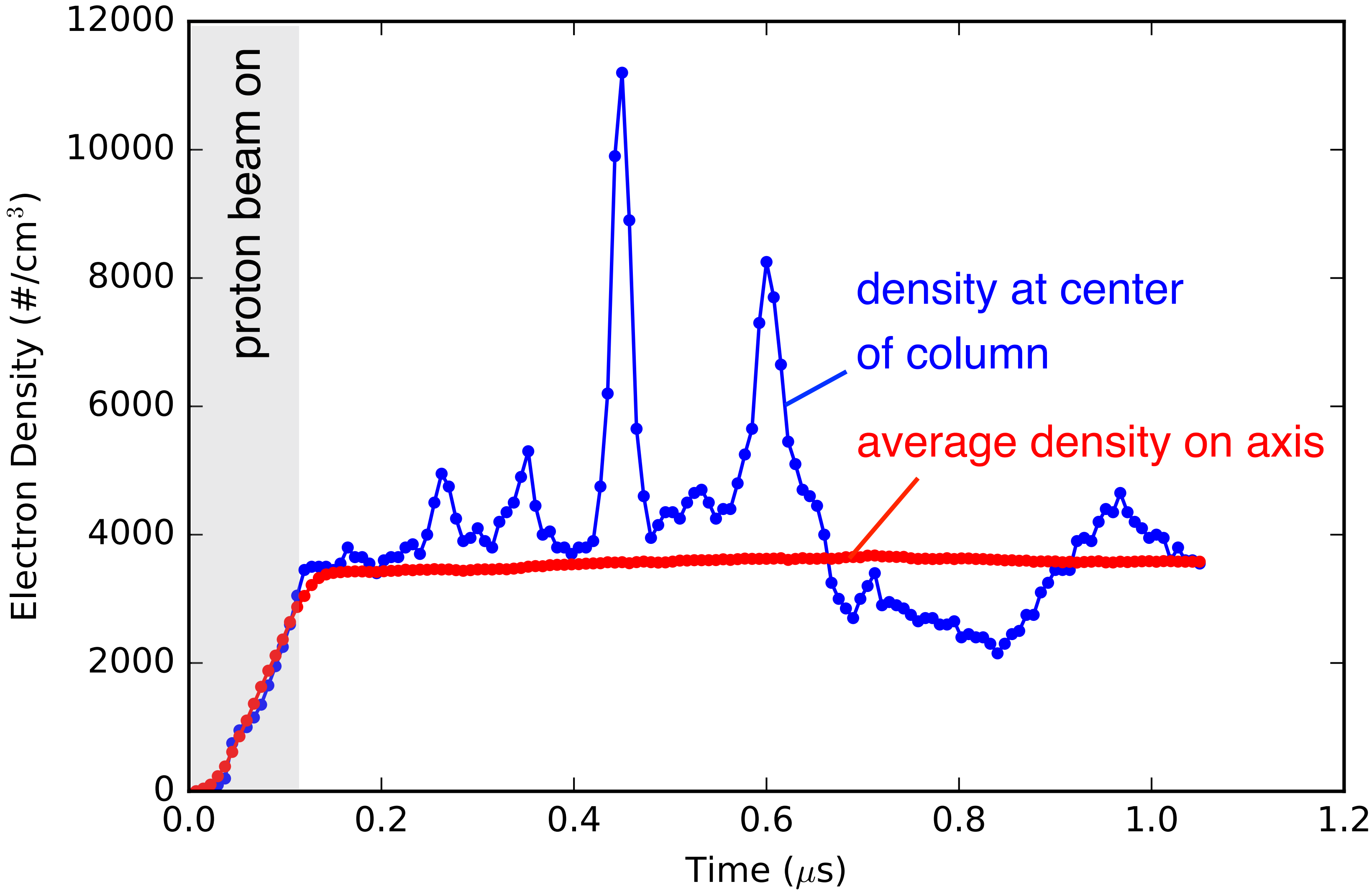
Electron density buildup vs. electrode voltage



Continuous proton beam

Park et al., NAPAC16

Evolution of electron density with pulsed proton beam



Summary of numerical calculations with pulsed proton beam

With pulsed proton beam:

- Electrons are confined transversely and oscillate longitudinally, with little loss
- Ions are lost both transversely and longitudinally
- Oscillations are determined by secondary electron velocity and by plasma frequency
- Distributed electrode voltages can help shape the charge distribution

Next step (numerically challenging): recirculation of protons around the ring, tracking the evolution of the electron column

Upcoming reports at IPAC18 and HB2018

Conclusions

Electron lenses are a mature, sophisticated, and flexible tool to control the dynamics of the circulating beam in storage rings and colliders

A rich **research program** is planned at the Fermilab IOTA/FAST facility

The **electron lens in IOTA** will enable new experiments in **nonlinear optics**, **electron cooling**, and **space-charge compensation**. Design challenges are related to the multiple functions and the limited available space.

Active halo control with hollow electron beams

- was tested in the Tevatron (2010-11); further experiments planned in RHIC in 2018
- is relevant for HL-LHC: machine protection, operational flexibility, availability, performance reach
- design is at advanced stage

Thank you for your attention

Collaborations, ideas and suggestions are always welcome!