Hollow electron lenses for the LHC: status of the conceptual design report

Giulio Stancari
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LHC Collimation Upgrade Specification Meeting
CERN, 27 March 2014

Contributors

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High Luminosity LHC

LARP

The report

FERMILAB-TM-2572-APC

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

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(Dated: DRAFT: February 4, 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.

Draft available at <https://cdcvs.fnal.gov/redmine/documents/683>
To be published as FERMILAB-TM-2572-APC, CERN document, and arXiv

Outline of the report

- Introduction
- Motivation and strategy
- Expected performance
  - principles, halo removal, effects on core, experimental studies
- Hardware specifications and integration studies
  - physical and mechanical features; hollow electron guns; vacuum; electrical; cryogenics; diagnostics; impedance
- Resources and schedule
- Alternative halo-removal schemes
  - tune modulation with warm quads, damper excitations, beam-beam wires
- Conclusions

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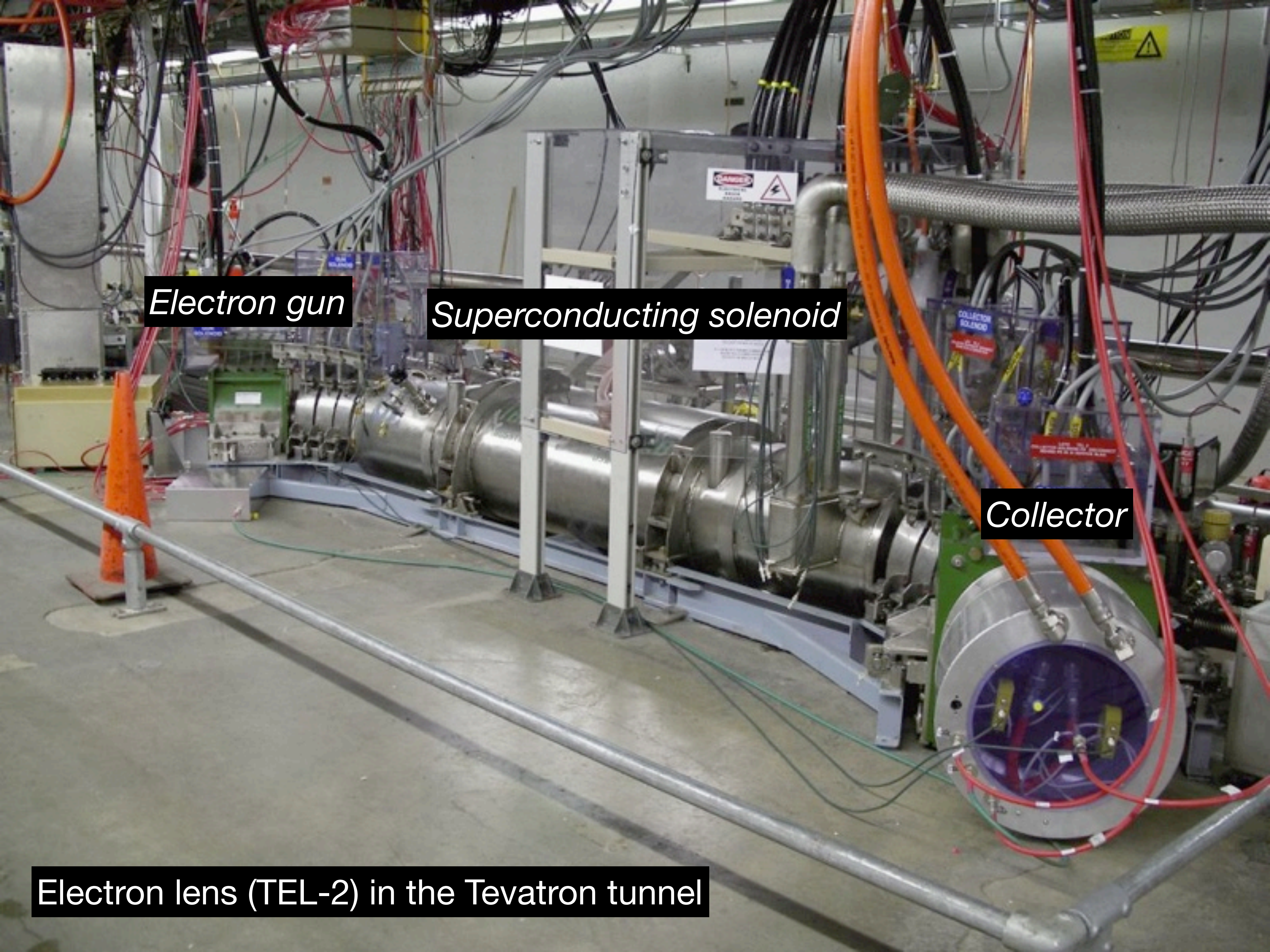
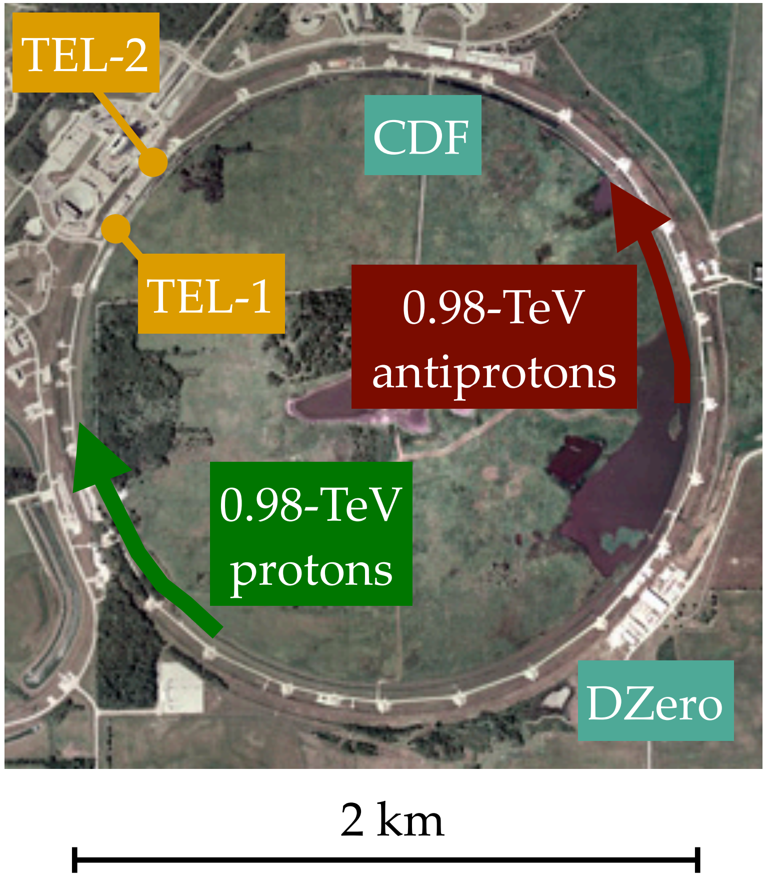

Electron gun
Superconducting solenoid
Collector
Electron lens (TEL-2) in the Tevatron tunnel

Electron lenses in the Fermilab Tevatron collider

- ***long-range beam-beam compensation***
  - Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)
- ***abort-gap cleaning during 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
- ***collimation with hollow electron beams***
  - Stancari et al., Phys. Rev. Lett. **107**, 084802 (2011)

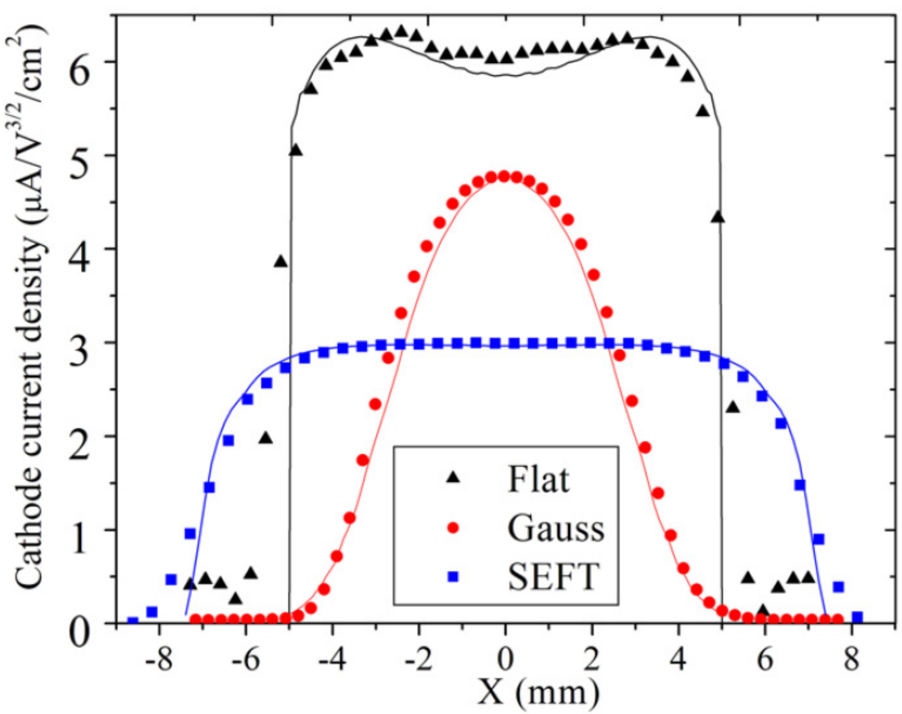
Electron lenses for beam-beam compensation are currently being commissioned in the Relativistic Heavy Ion Collider at Brookhaven National Laboratory



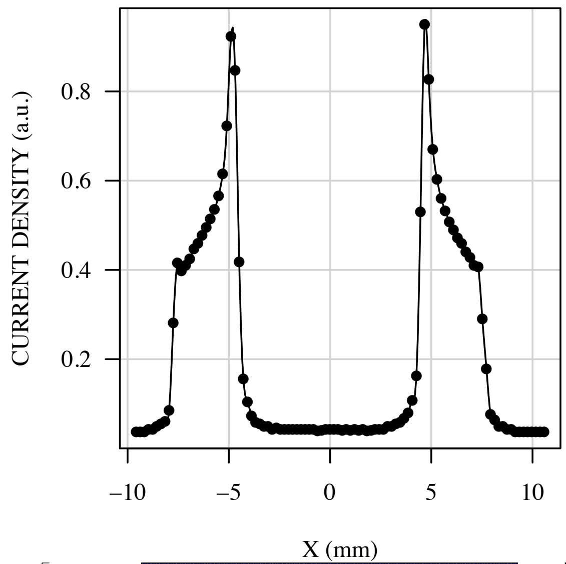
Control of electron beam profile

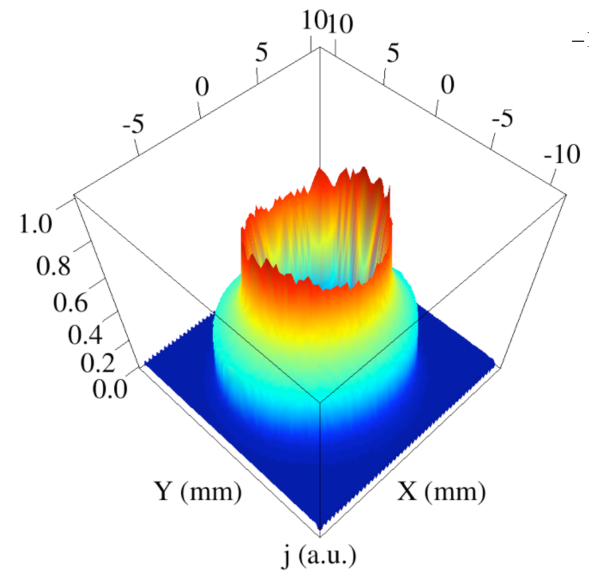
Current density profile of electron beam is shaped by cathode and electrode geometry and maintained by strong solenoidal fields

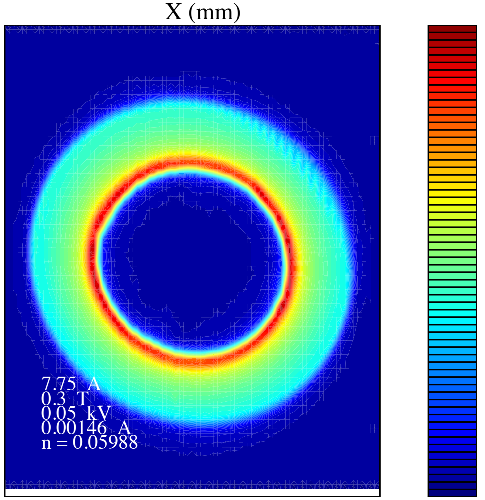
Flat profiles for bunch-by-bunch betatron tune correction



Hollow profile for halo scraping







Gaussian profile for compensation of nonlinear beam-beam forces

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Hollow beam collimation with Tevatron electron lenses

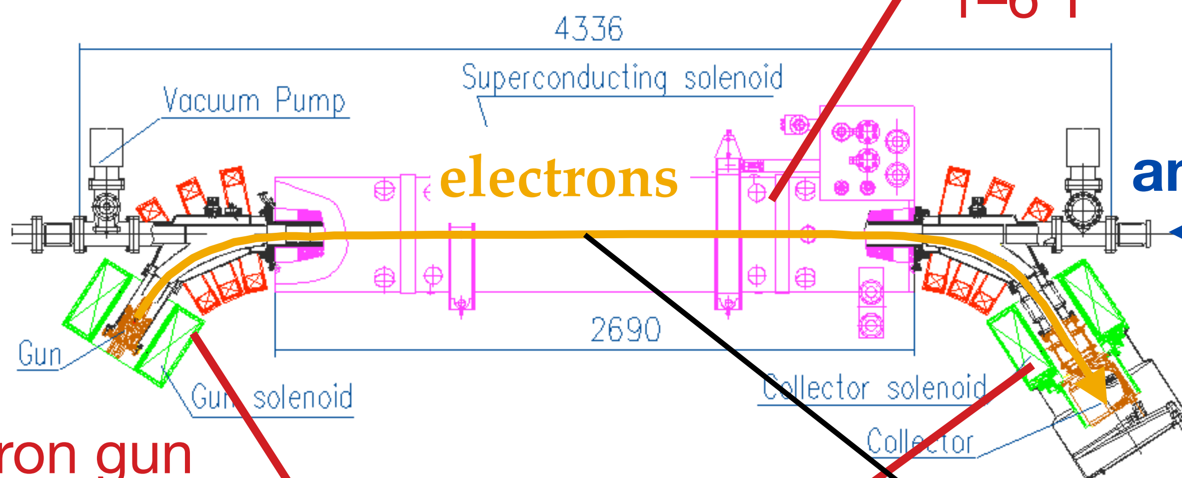
Circulating beams affected by electromagnetic fields generated by electrons
Stability provided by strong axial magnetic fields

6 m total length

superconducting solenoid
1–6 T

protons

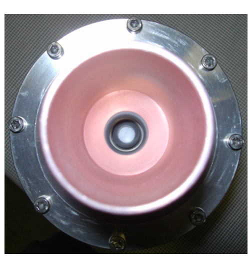
antiprotons

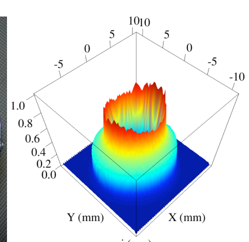


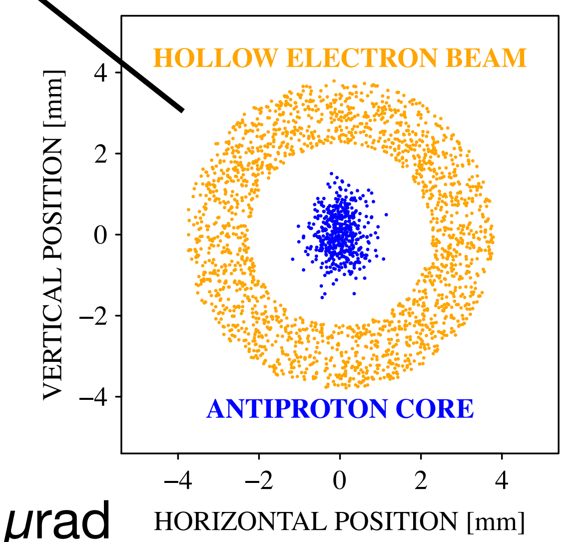
collector

5-kV, 1-A electron gun
thermionic cathode
200-ns rise time

conventional solenoids
0.1–0.4 T

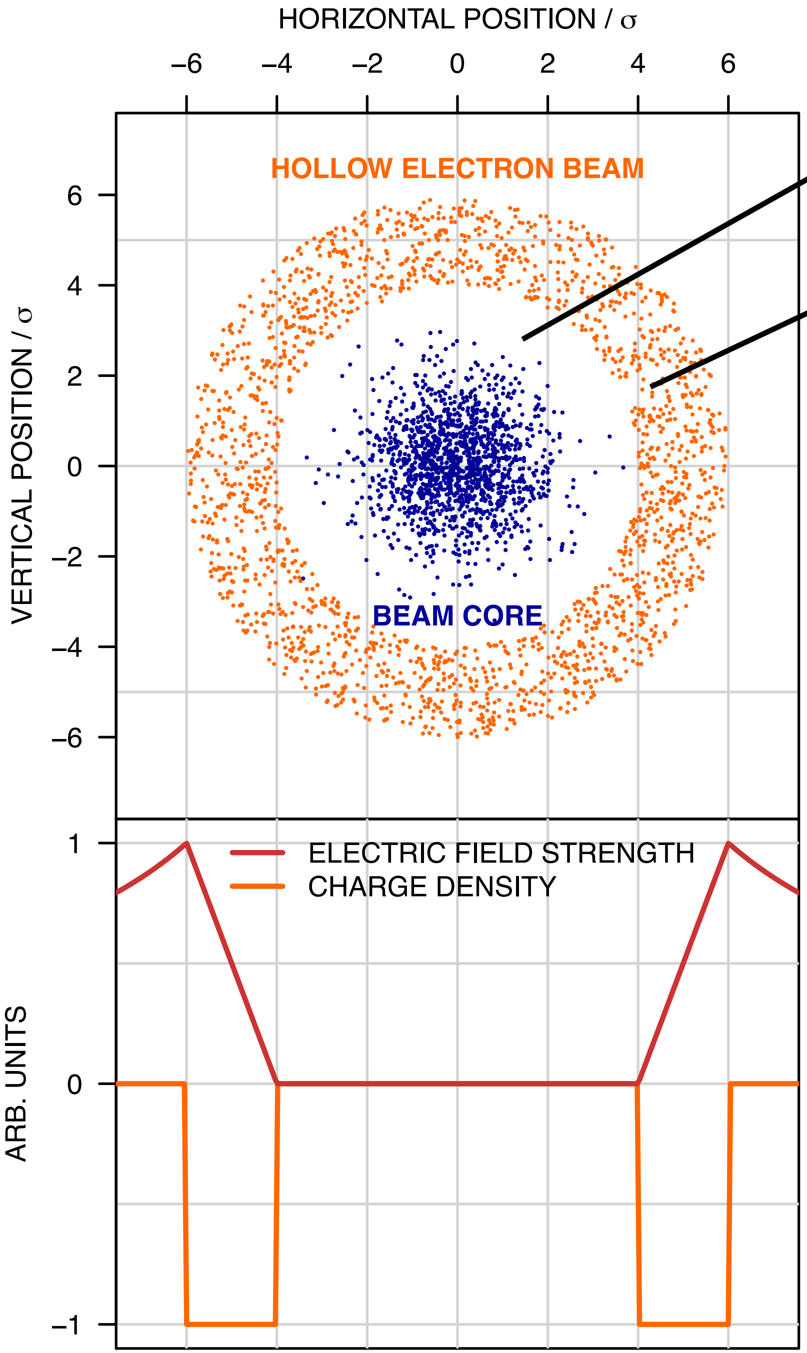






Tunable transverse halo kicks ~0.1 μrad

Concept of hollow electron beam collimator or scraper

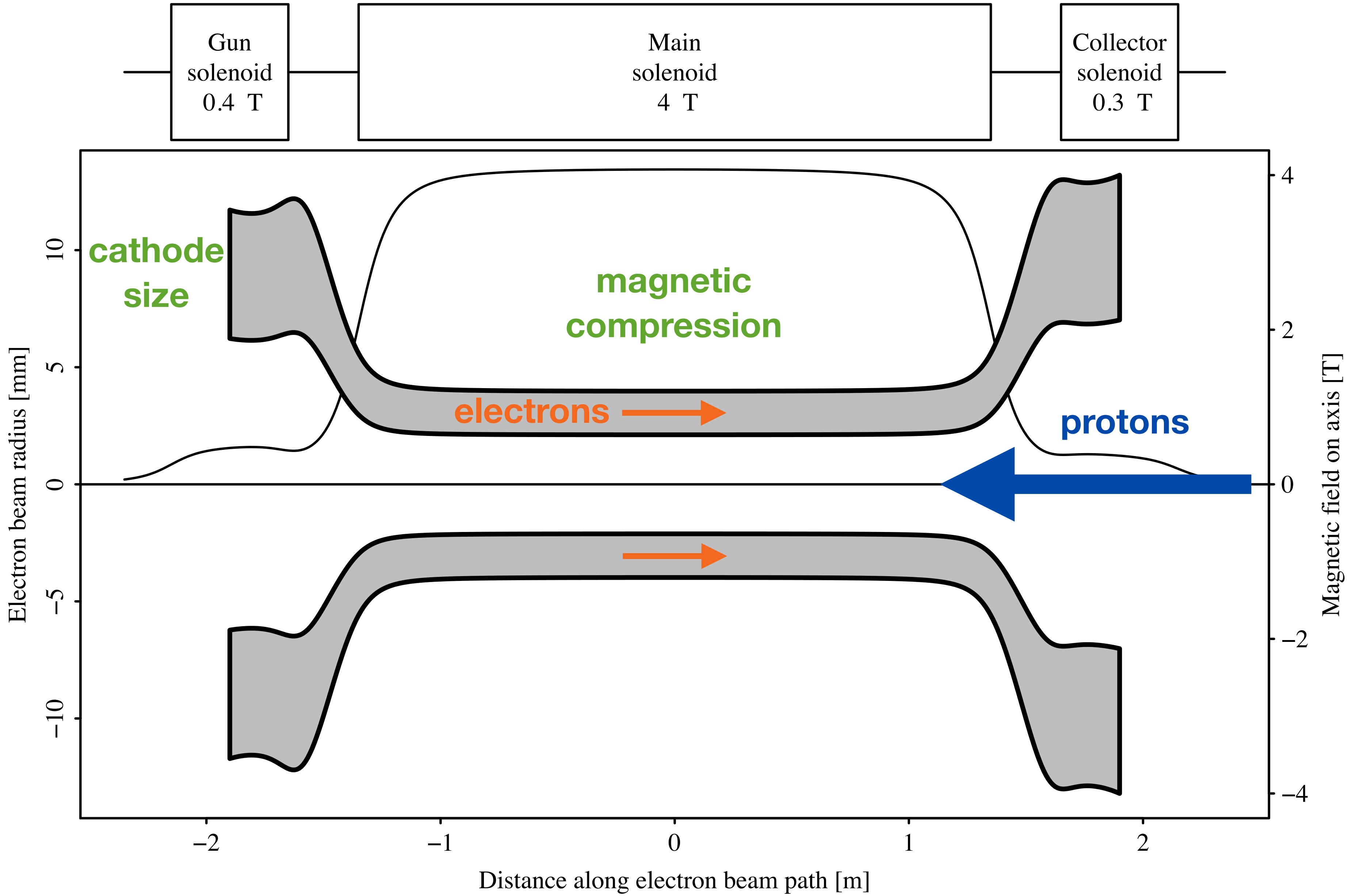


- **Beam core** is unaffected (field-free region)
- **Halo** experiences nonlinear transverse kicks:

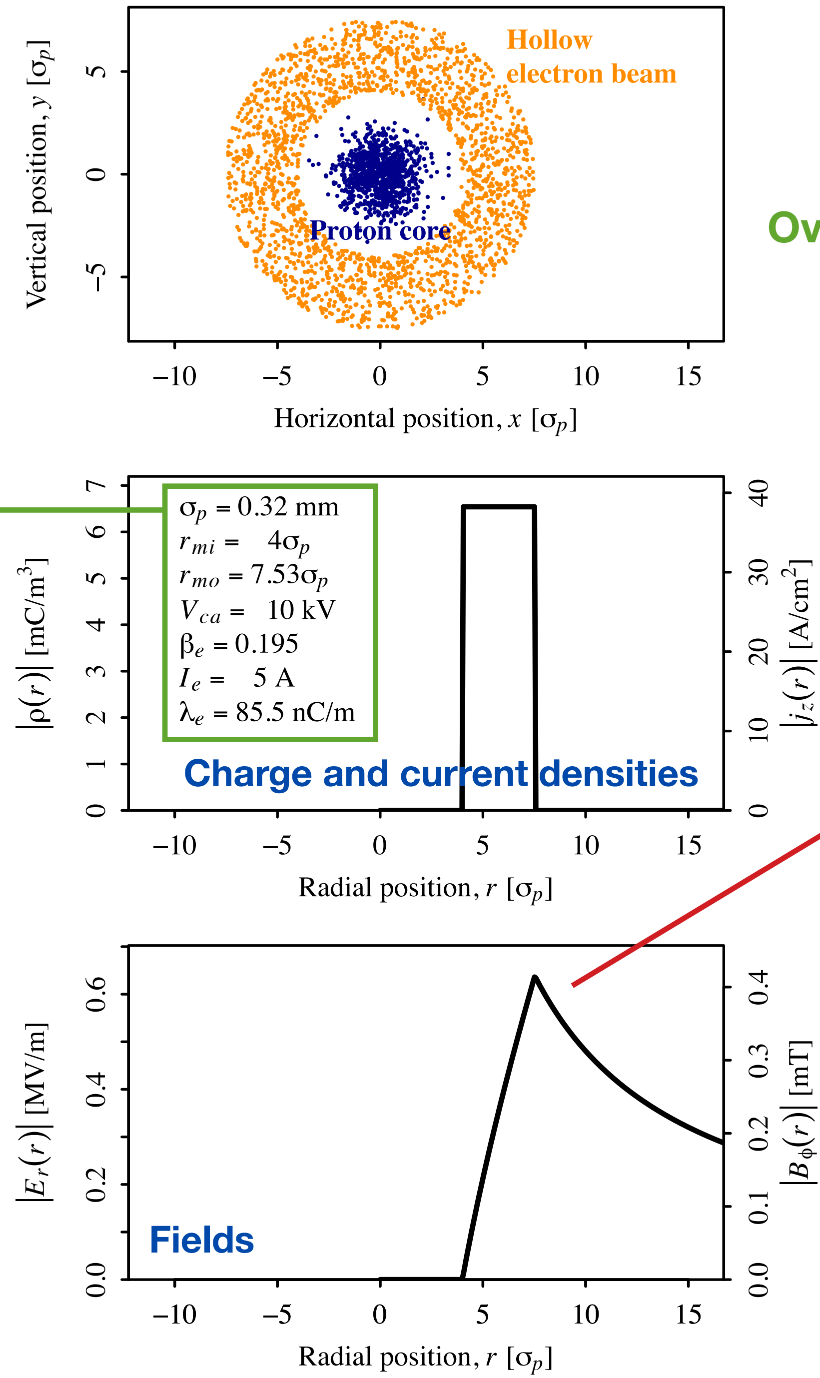
$$\theta_r = \frac{2\, I_r\, L\, (1 \pm \beta_e \beta_p)}{r\, \beta_e\, \beta_p\, c^2\, (B\rho)_p} \left(\frac{1}{4\pi\epsilon_0} \right)$$

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

Electron beam size is matched to proton beam size by solenoids



Example of numerical parameters for the LHC



Overlap region L = 3 m

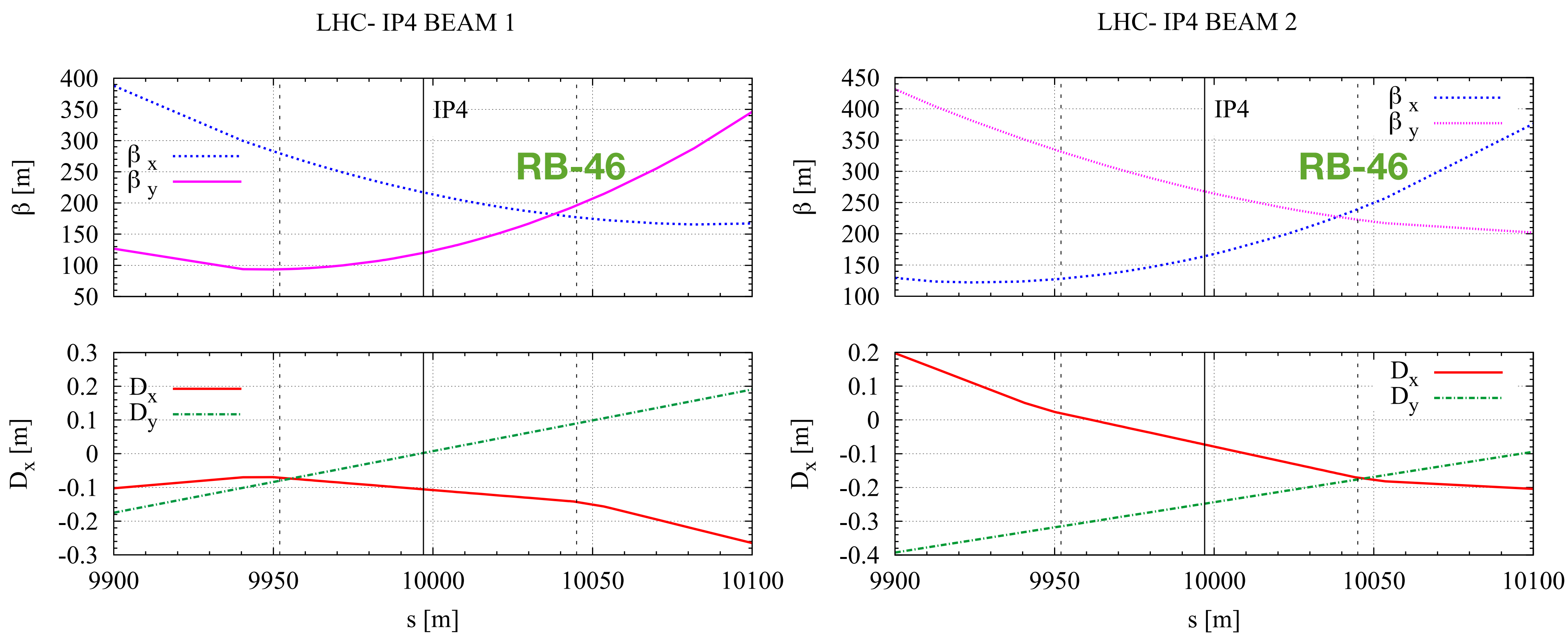
Proton rms size
Inner radius
Outer radius
Accelerating voltage
Velocity
Peak current
Linear current density

Max. kick **0.3 μrad** for 7-TeV protons

For comparison: multiple Coulomb scattering in LHC primaries generates random kicks with spread θ_{rms} = ... μrad

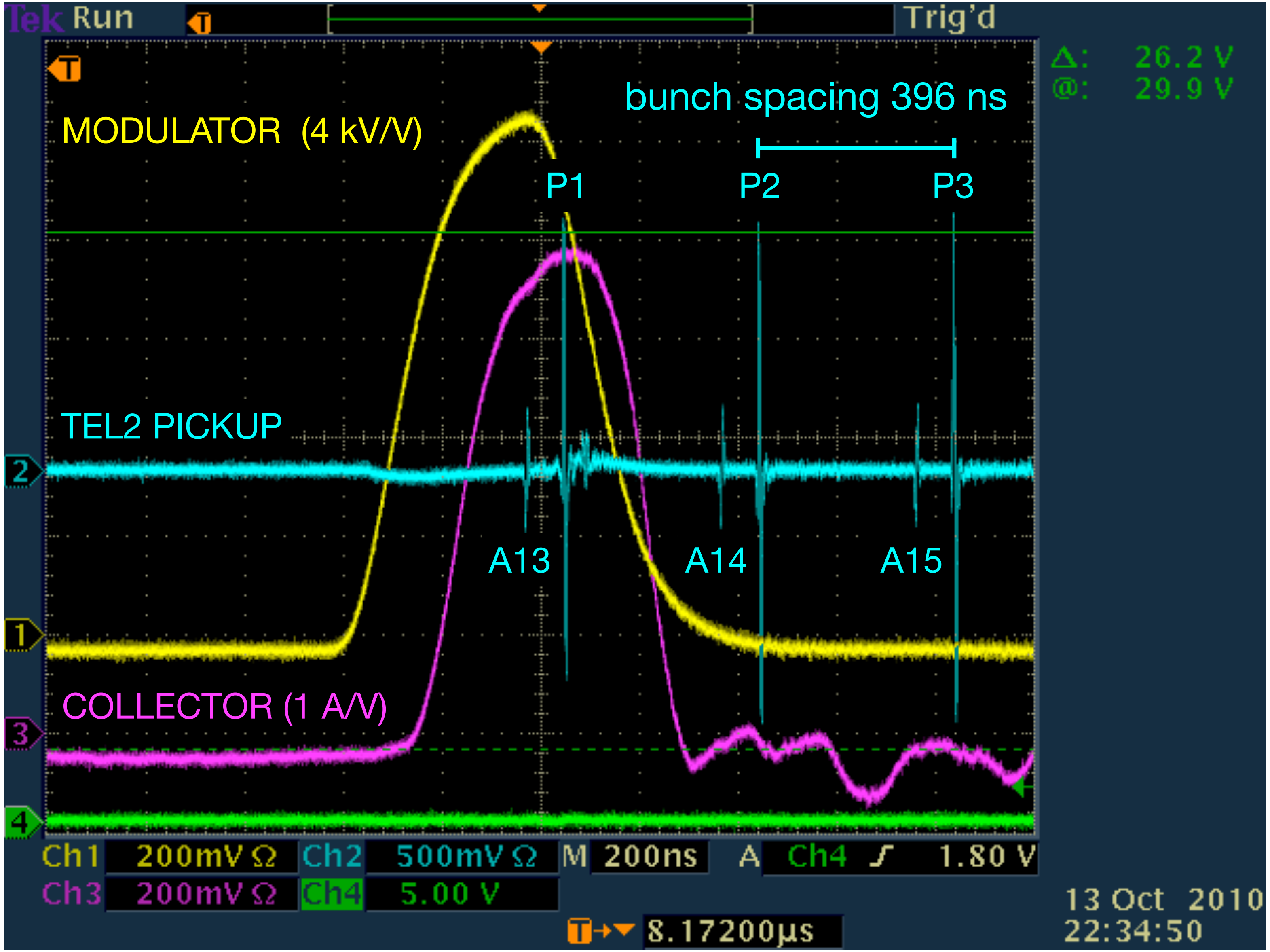
Beam optics at candidate locations (LHC v6.503)

Round beams, β ~ 200 m, low dispersion



Check HL-LHC lattices and evaluate impact on e-lens parameters

Pulsed operation of the electron lens in the Tevatron



Pulsed electron beam could be **synchronized** with any group of bunches

Pulsed operation of the electron lens in the LHC

Current state of the art of electron-lens modulator is a rise time (10%-90%) of 200 ns at 5 kV. Pfeffer and Saewert, JINST 6, P11003 (2011)

This enables

- turn-by-turn current modulation (stochastic or resonant) to enhance halo removal, if needed
- train-by-train (900 ns separation), or possibly batch-by-batch (225 ns), operation
  - to preserve halo on a subset of bunches for machine protection
  - to compare different electron-lens settings for diagnostics

Bunch-by-bunch operation is not necessary for collimation

Summary of specifications

Parameter	Value or range
Beam and lattice	
Proton kinetic energy, T_p [TeV]	7
Proton emittance (rms, normalized), ε_p [μm]	3.75
Amplitude function at electron lens, $\beta_{x,y}$ [m]	200
Dispersion at electron lens, $D_{x,y}$ [m]	≤ 1
Proton beam size at electron lens, σ_p [mm]	0.32
Geometry	
Length of the interaction region, L [m]	3
Desired range of scraping positions, r_{mi} [σ_p]	4–8
Magnetic fields	
Gun solenoid (resistive), B_g [T]	0.2–0.4
Main solenoid (superconducting), B_m [T]	2–6
Collector solenoid (resistive), B_c [T]	0.2–0.4
Compression factor, $k \equiv \sqrt{B_m/B_g}$	2.2–5.5
Electron gun	
Inner cathode radius, r_{gi} [mm]	6.75
Outer cathode radius, r_{go} [mm]	12.7
Gun perveance, P [μperv]	5
Peak yield at 10 kV, I_e [A]	5
High-voltage modulator	
Cathode-anode voltage, V_{ca} [kV]	10
Rise time (10%–90%), τ_{mod} [ns]	200
Repetition rate, f_{mod} [kHz]	35

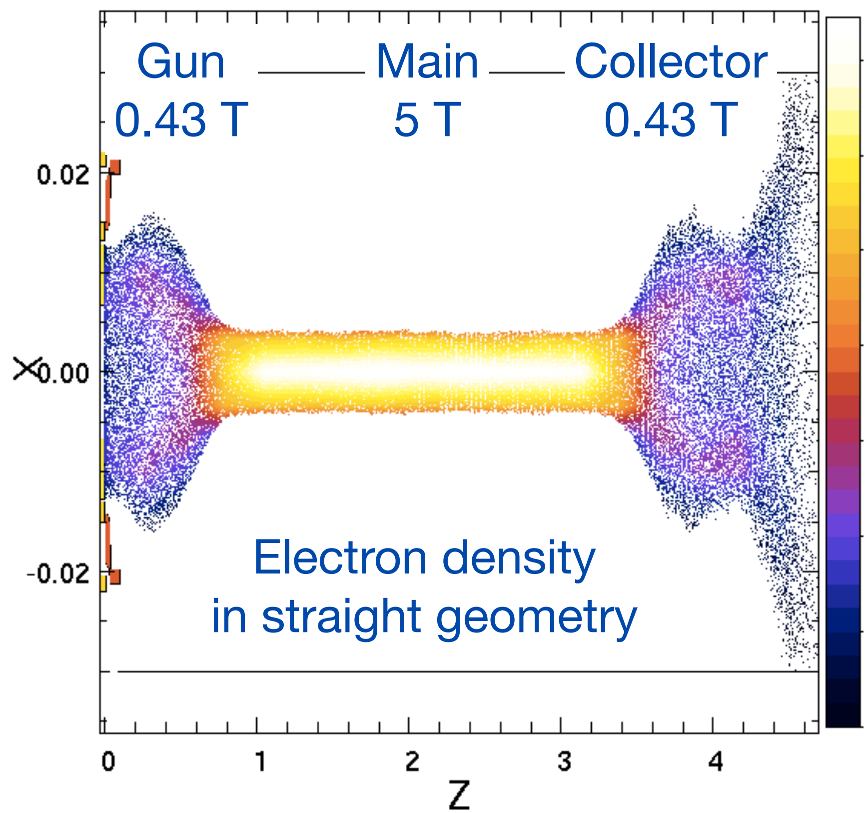
Main goals of numerical simulations

- **Would hollow electron beam collimation be effective in the LHC?**
  - The kicks are nonlinear, with a small random component. Halo removal rates are expected to depend on magnetic rigidity of the beam, machine lattice, and noise sources. Nontrivial extrapolation from Tevatron to LHC.
- **Would there be any adverse effects on the core, such as lifetime degradation or emittance growth?**
  - No effects were seen in the Tevatron in continuous mode. Effects of asymmetries in resonant operation?
- **Methods**
  - Warp particle-in-cell code for electron beam dynamics
  - Lifetrac and SixTrack for numerical tracking
  - Machine models with nonlinearities
  - Uniform halo population, replenishing mechanisms to be implemented
    - Diffusion was measured in both Tevatron and LHC
  - Ideal electron lens, profile imperfections, injection/extraction bends

Dynamics of the magnetically confined electron beam

3D simulation of electron beam propagation in electron lens with Warp particle-in-cell code [V. Moens]:

- Injection: space-charge limited e-gun or arbitrary particle coordinates
- Layout: straight (test stand) or with bends (TEL-2 and LHC e-lens)
- Computing resources
  - up to 1 m propagation calculable on multi-core laptop
  - working parallel version installed on Fermilab cluster

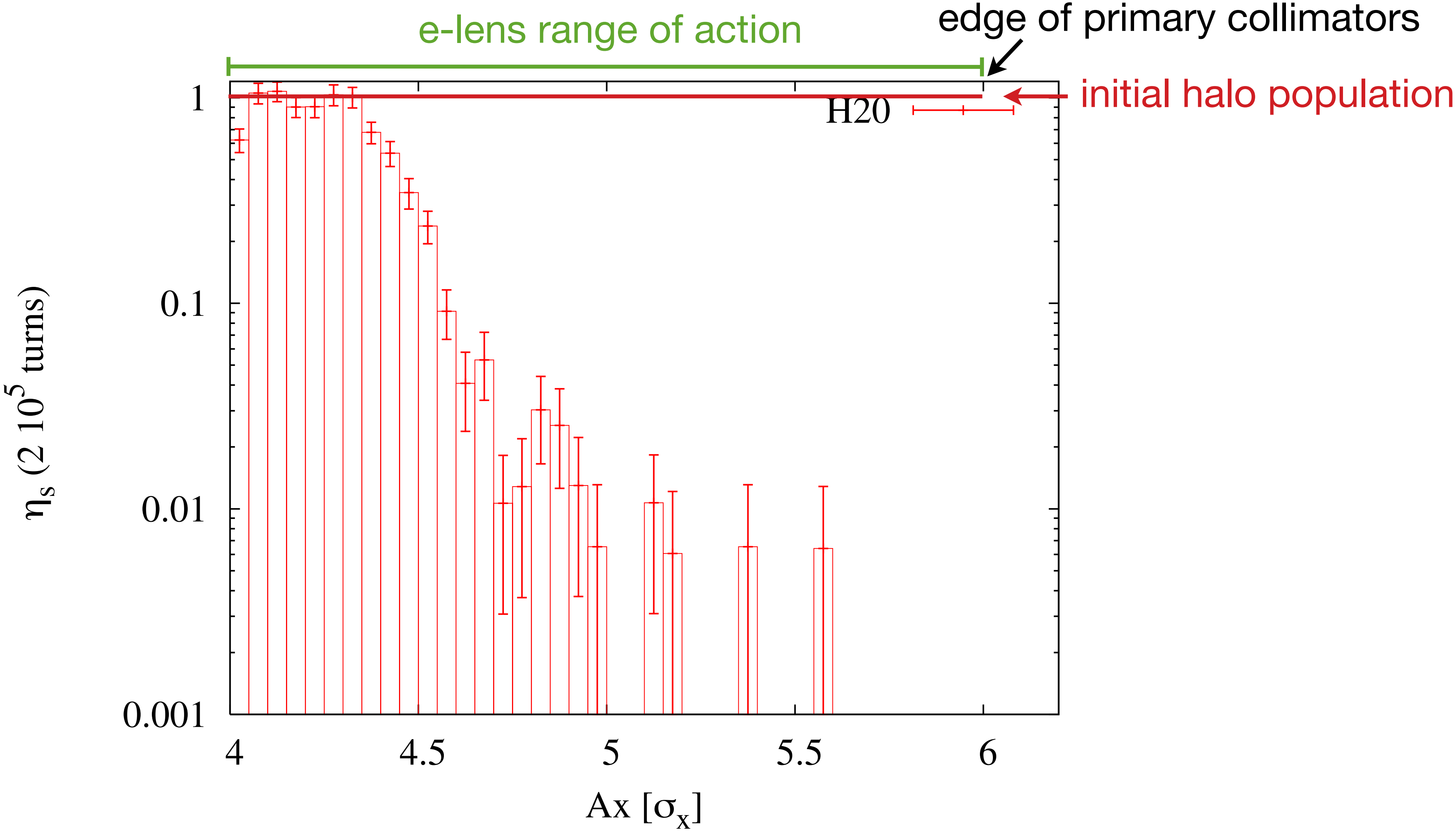


Results of numerical tracking simulations

- Flexibility of high-voltage modulator enables different modes of operation:
  - *continuous*: same electron current every turn
    - *Most of Tevatron experiments done in this mode*
  - *resonant*: current modulated to excite betatron oscillations (sinusoidal or skipping turns)
    - *Used for clearing abort gap in Tevatron*
  - *stochastic*: random on/off, or constant with random component
- **Observable effects** in time scales of seconds/minutes
- **Smooth scraping** with electron pulsed every turn
- **Enhanced removal rates** with resonant or stochastic modes
  - Resonant mode depends on details of tune distribution
  - Stochastic mode is very robust
- **No adverse effects on core**
  - in continuous mode, even with asymmetries/bends
  - in resonant mode in ideal case
  - effect of imperfections in resonant mode under study

Example of simulated halo scraping (SixTrack, LHC lattice)

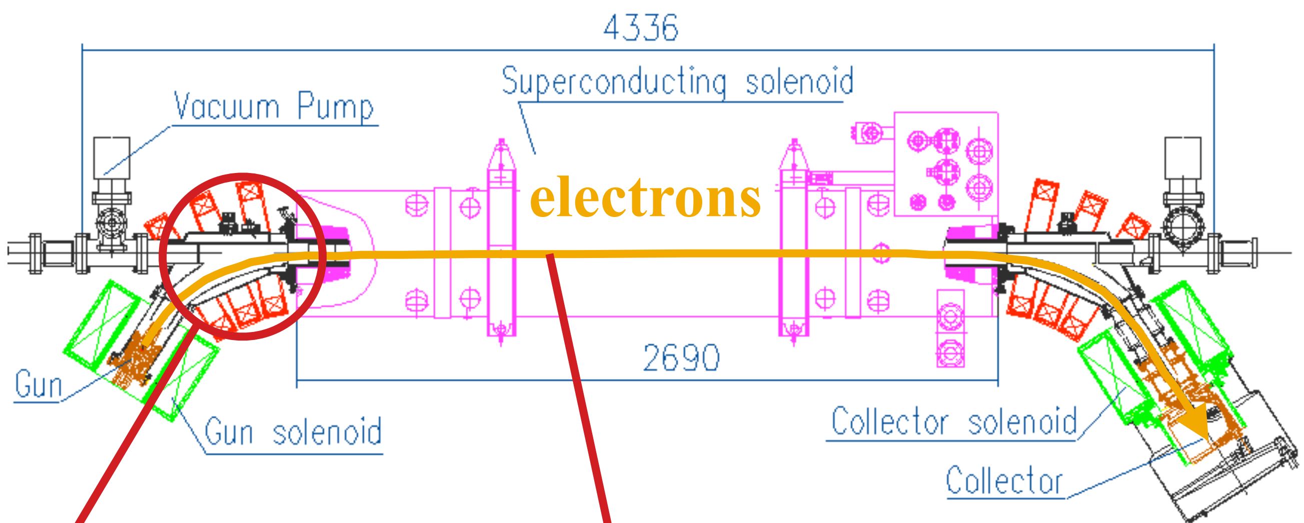
Residual halo population vs. betatron amplitude after 18 s of resonant scraping



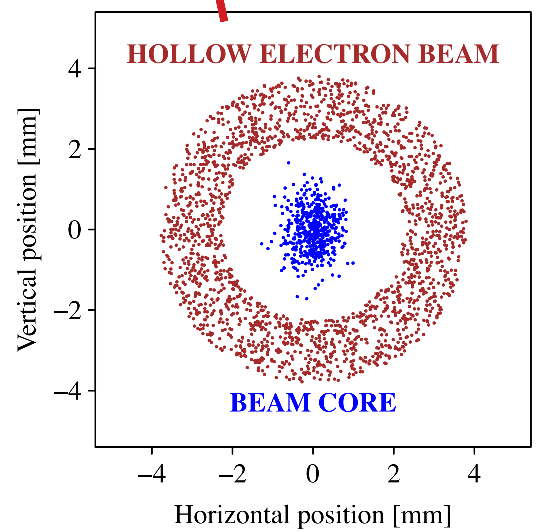
Previtali et al., FERMILAB-TM-2560-APC (2013)

Effect of asymmetries in electron distribution on circulating beam

No adverse effects were observed at the Tevatron in continuous operation, but application to the LHC may require higher beam currents and different pulsing patterns. We studied two sources of asymmetry:



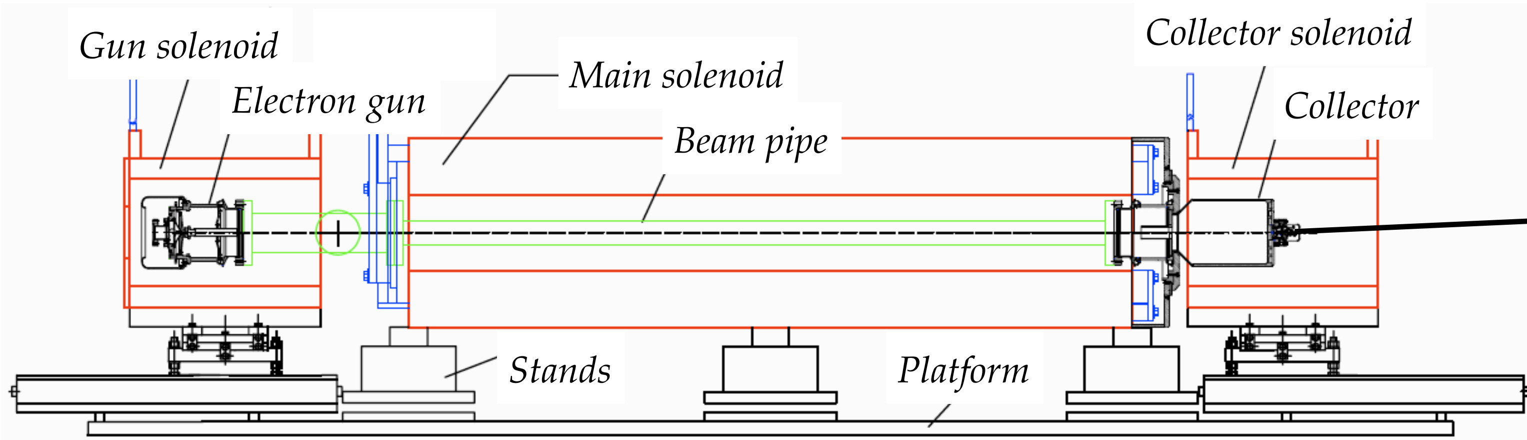
1. bends for injection/extraction



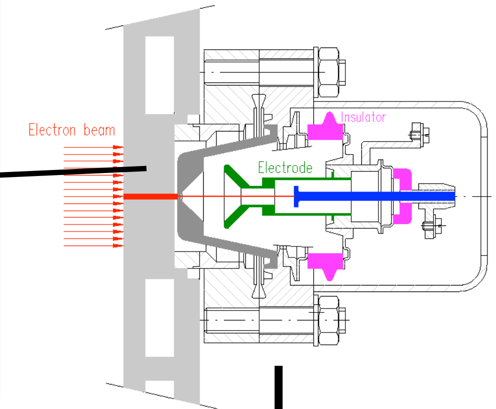
2. azimuthal asymmetries in overlap region

Azimuthal asymmetries in overlap region from measured profiles

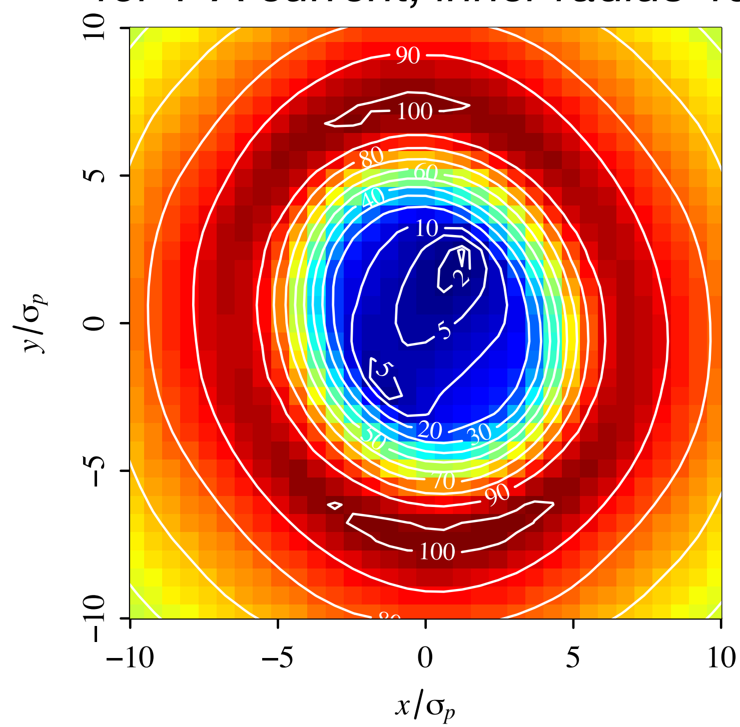
Fermilab electron-lens test stand



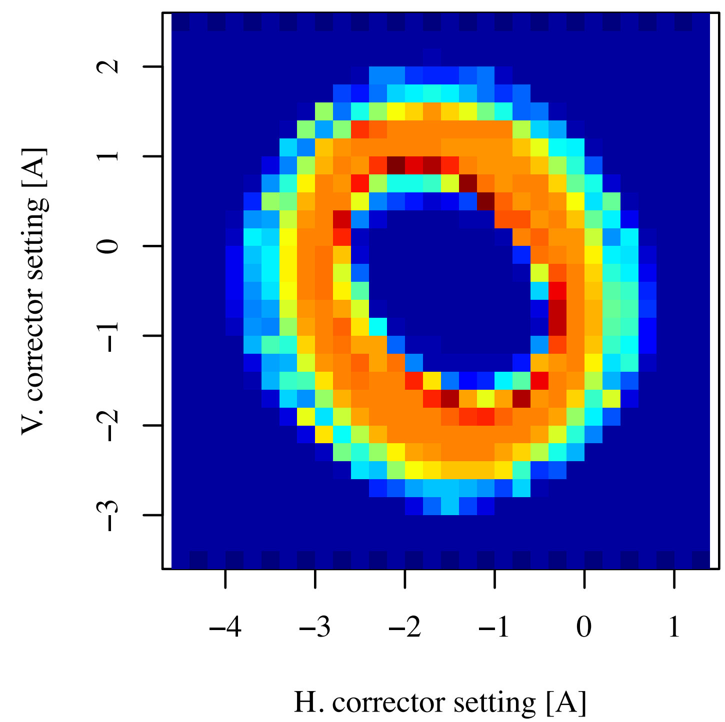
Pinhole for current-density measurements



Calculated electric field [kV/m] for 1-A current, inner radius $4\sigma_p$



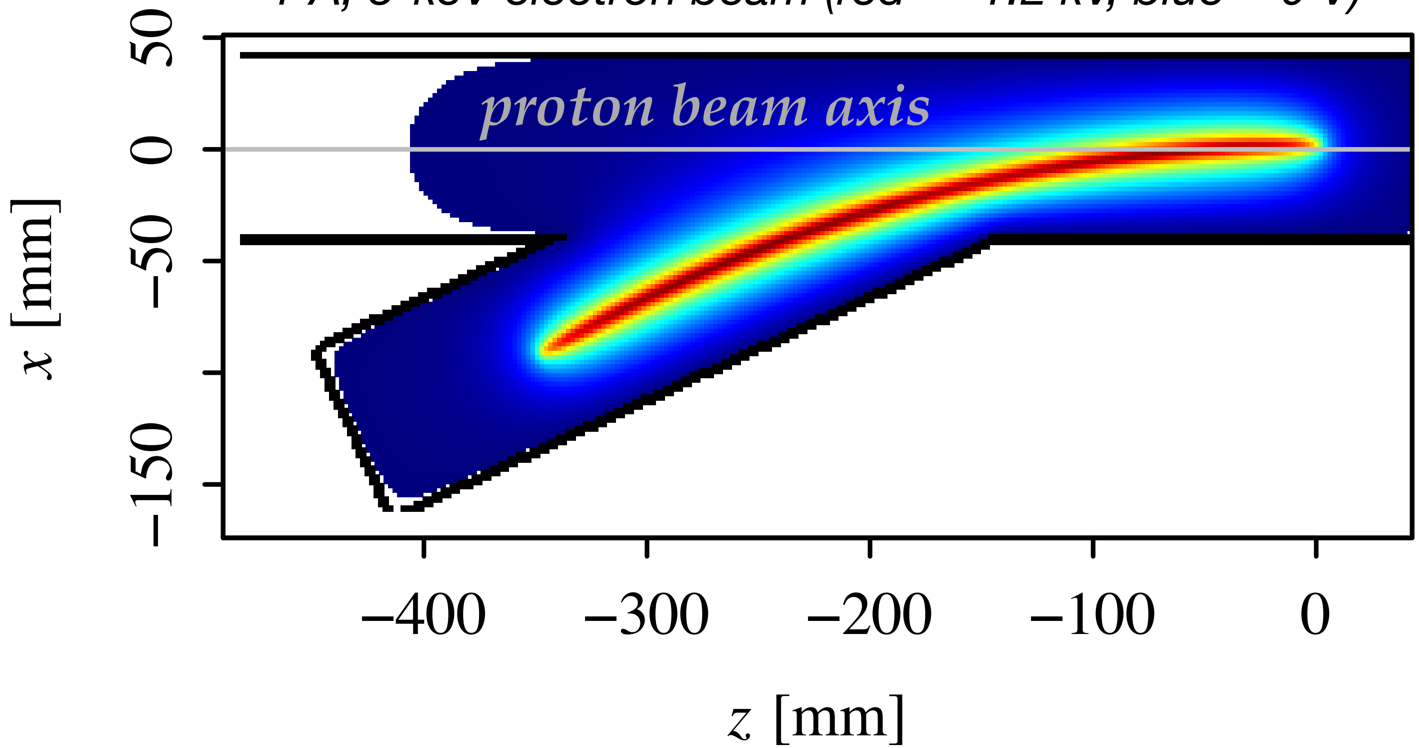
Example of measured profile



Kick maps from injection and extraction bends: simplified approach

3D calculation of electric fields generated by a static, hollow charge distribution inside cylindrical beam pipes using Warp particle-in-cell code

Electrostatic potential on the plane of the bend for 1 A, 5-keV electron beam (red = -1.2 kV, blue = 0 V)



Symplectic kick maps are calculated by integrating electric fields over straight proton trajectories

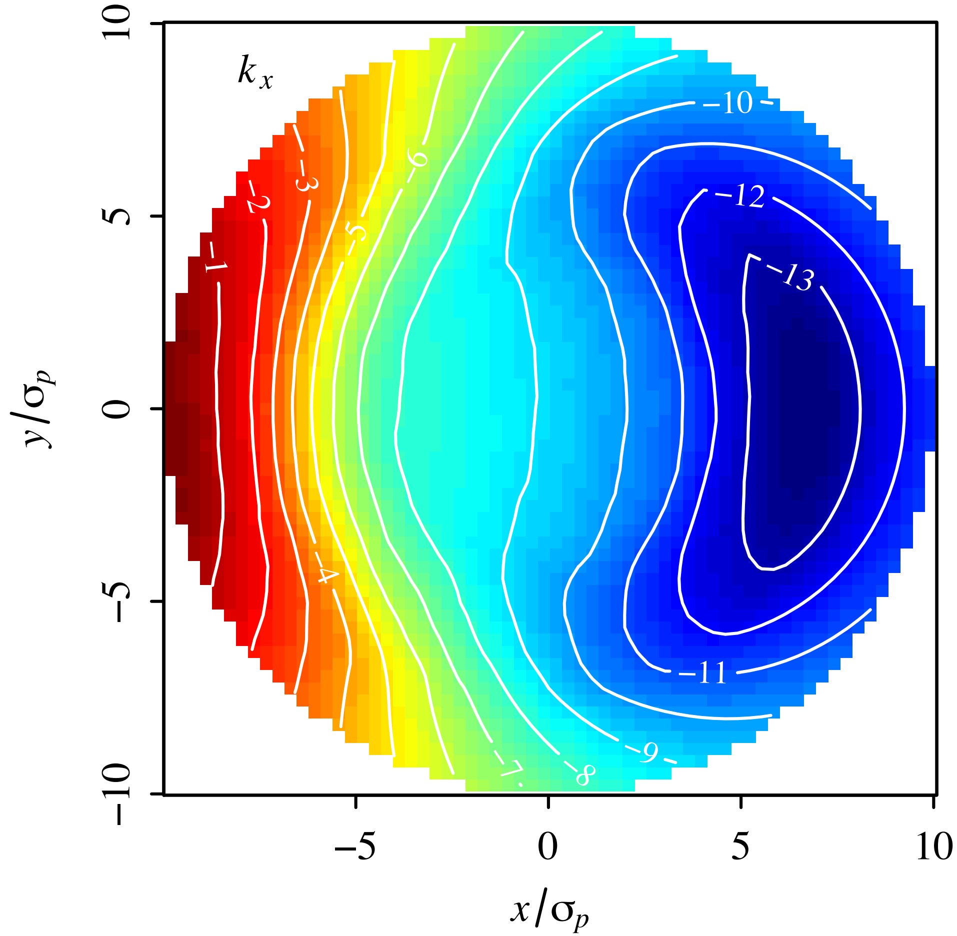
$$k_{x,y} \equiv \int_{z_1}^{z_2} E_{x,y}(x, y, z)\, dz$$

Stancari, FERMILAB-FN-0972-APC, arXiv:1403.6370 (2014)

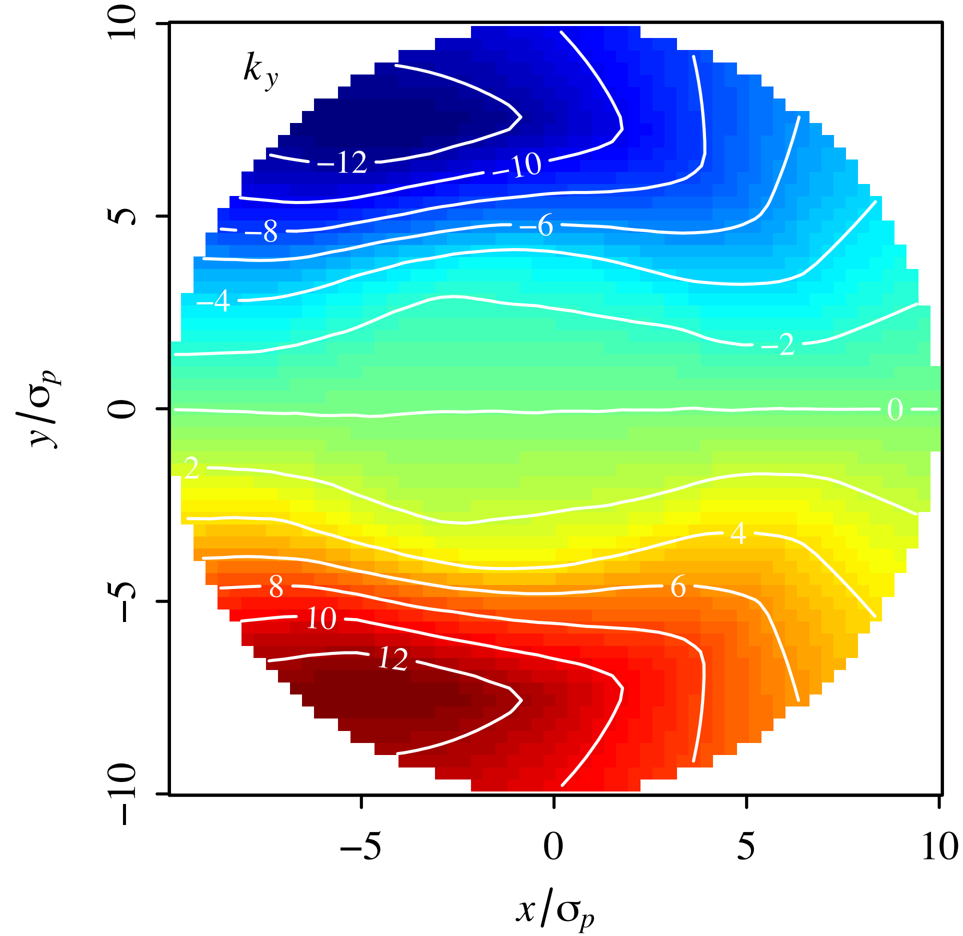
Kick maps from injection and extraction bends

Integrated fields ('kicks') [kV] vs. transverse proton position

Horizontal



Vertical



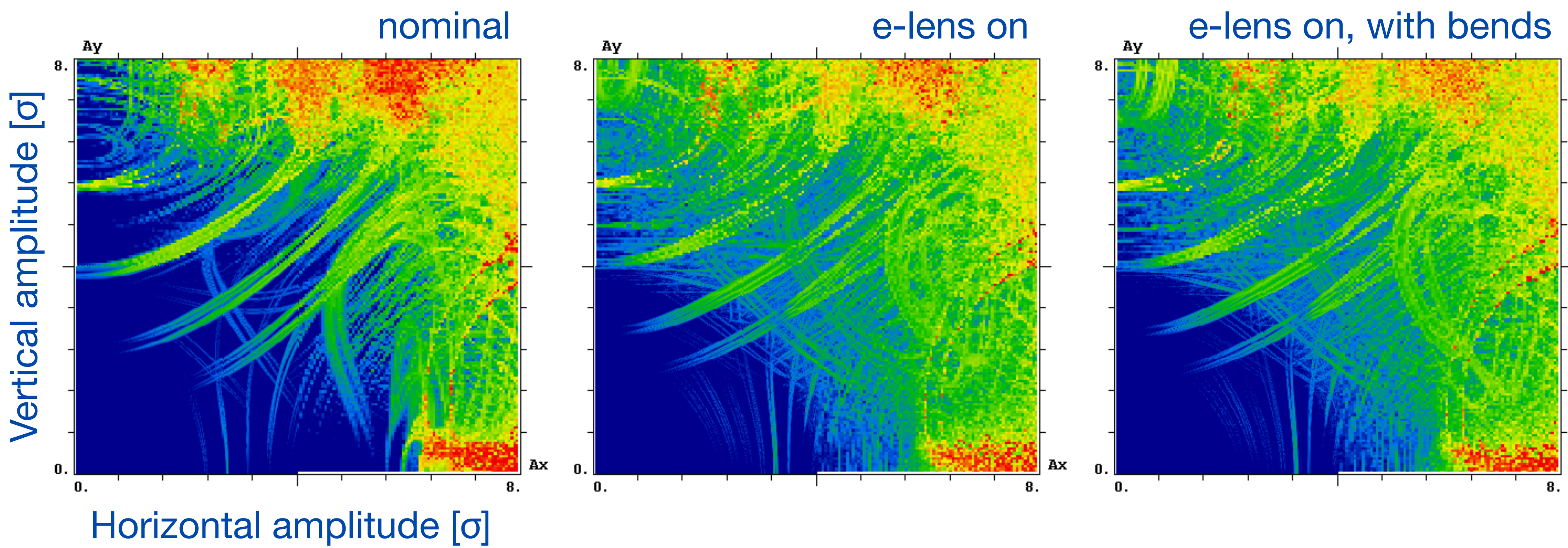
For 7-TeV protons, 10 kV ⇒ 1.4 nrad

Core and halo beam dynamics including imperfections

Evaluation of core lifetimes, emittance growth rates, and frequency maps with Lifetrac tracking code [A. Valishev]

- LHC **lattice** V6.503 at 7 TeV, no multipole errors, <u>collisions on</u>
- 6D **halo**, 4-6σ transverse, Gaussian longitudinal
- Hollow **e-lens** 1.2 A at 4σ at IR4/RB46, <u>continuous</u> operation

Frequency-map analysis



- Negligible effects on core lifetimes, emittances, and luminosity
- Smooth halo scraping (4% of halo population / minute)

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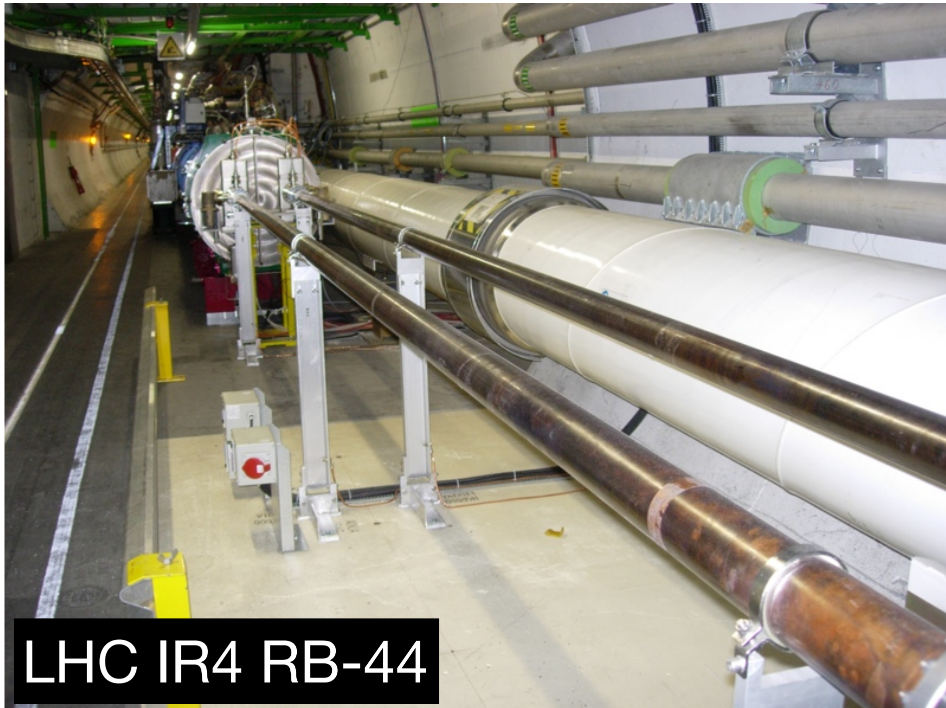
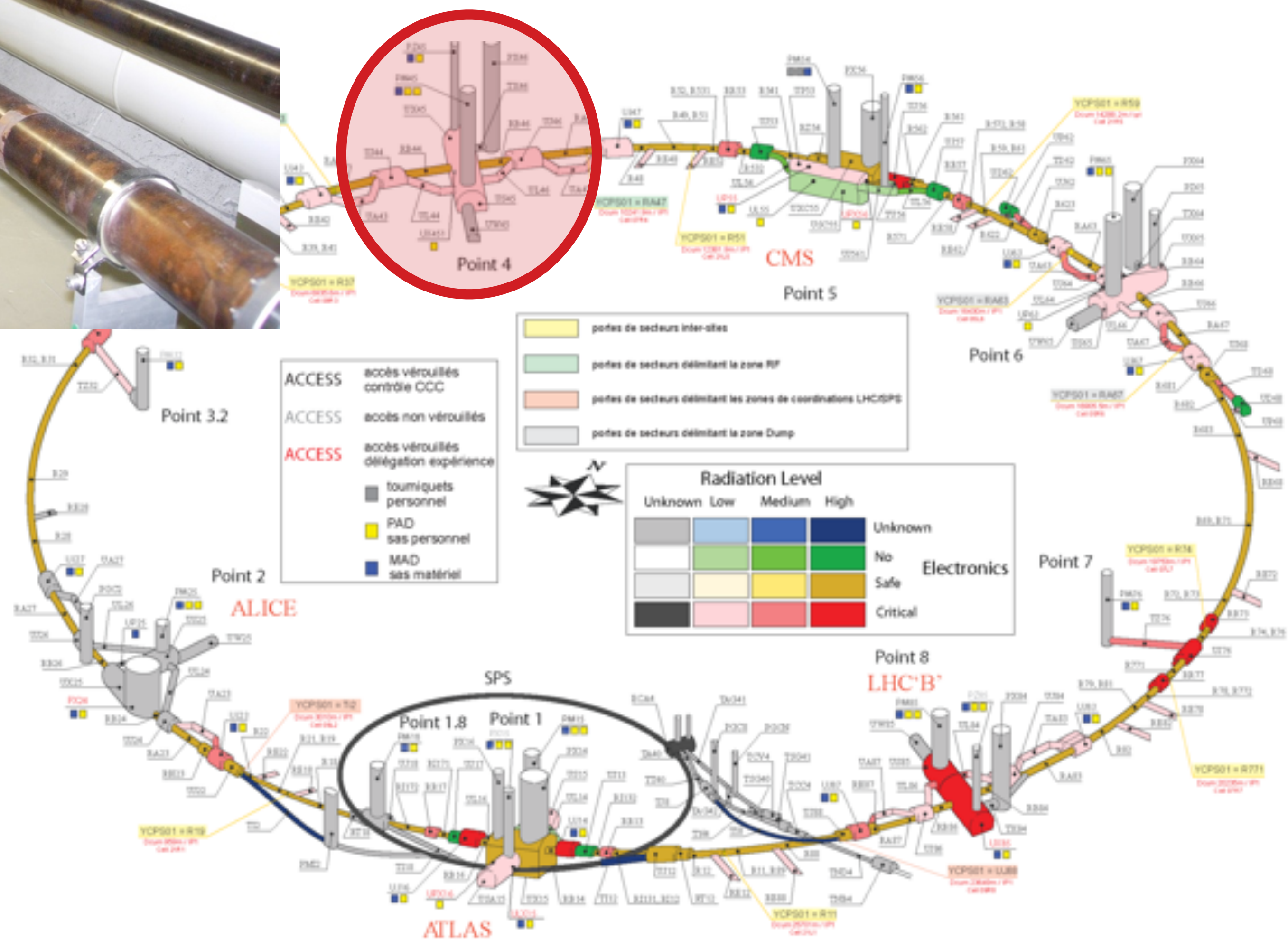
Starting point for technical design

Candidate locations for electron lenses in the LHC

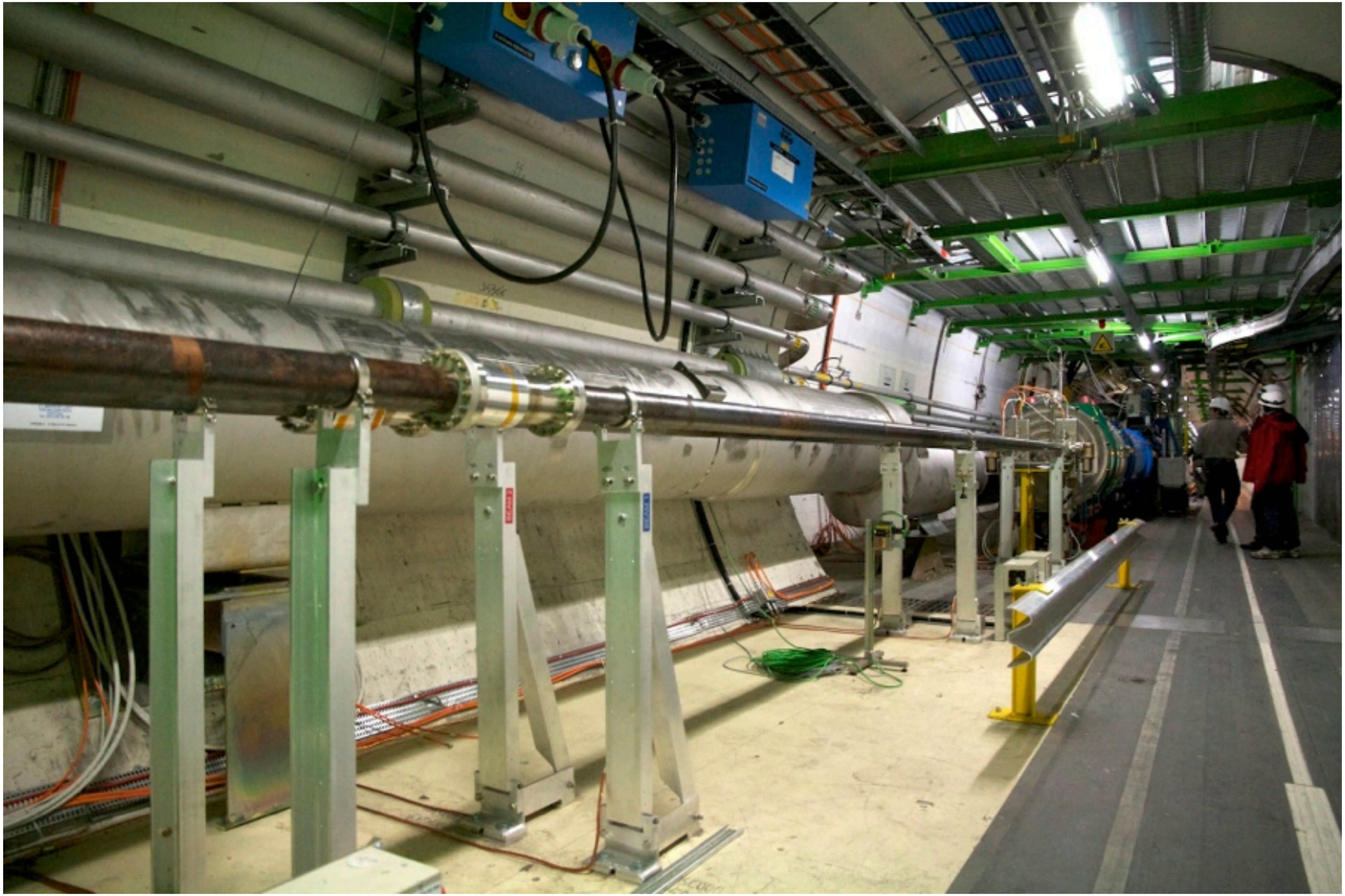


Upstream or downstream of Point 4:

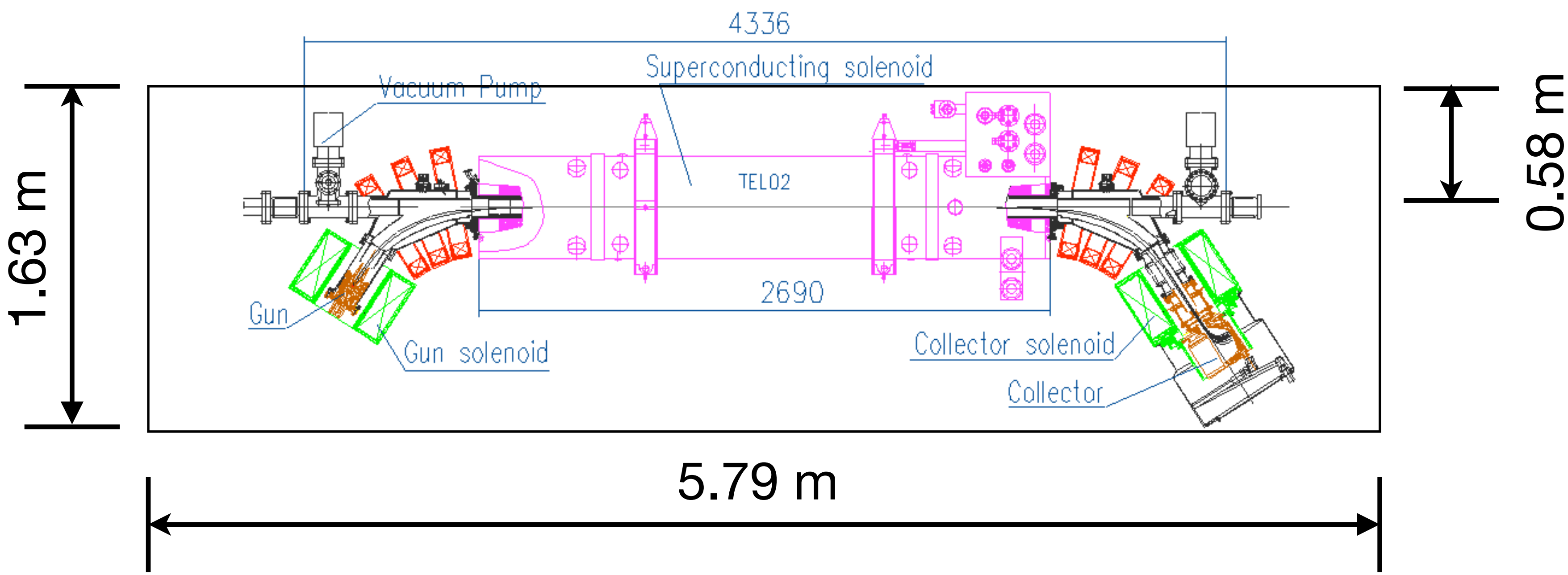
- Available longitudinal space
- Separation of beam axes: 420 mm
- Cryogenic infrastructure
- Lattice functions



Candidate location RB-46

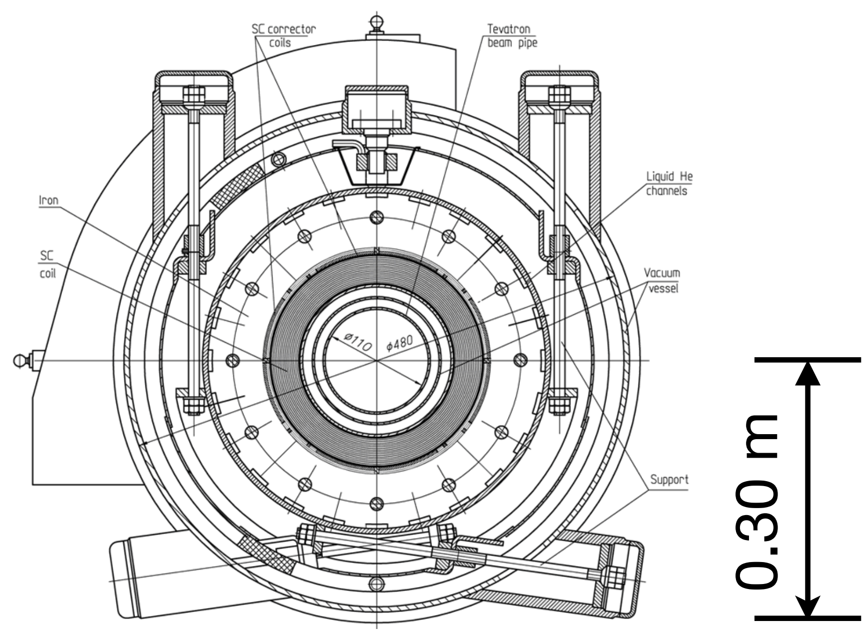


TEL2 dimensions for reference

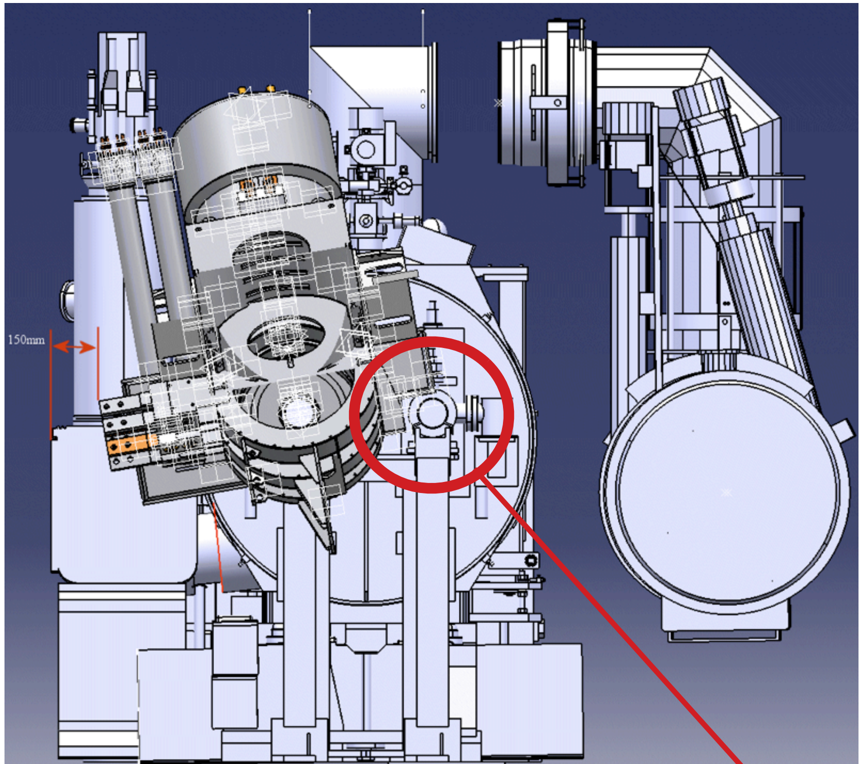


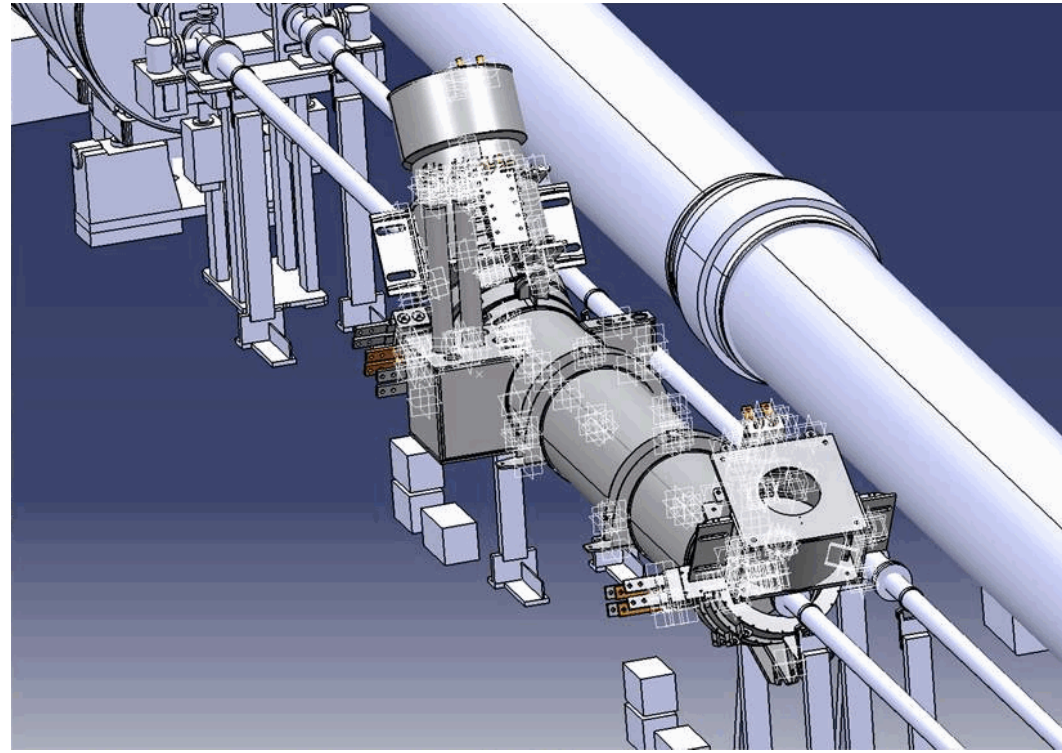
Height (including current and cryo leads): 1.47 m

Weight: about 2 t



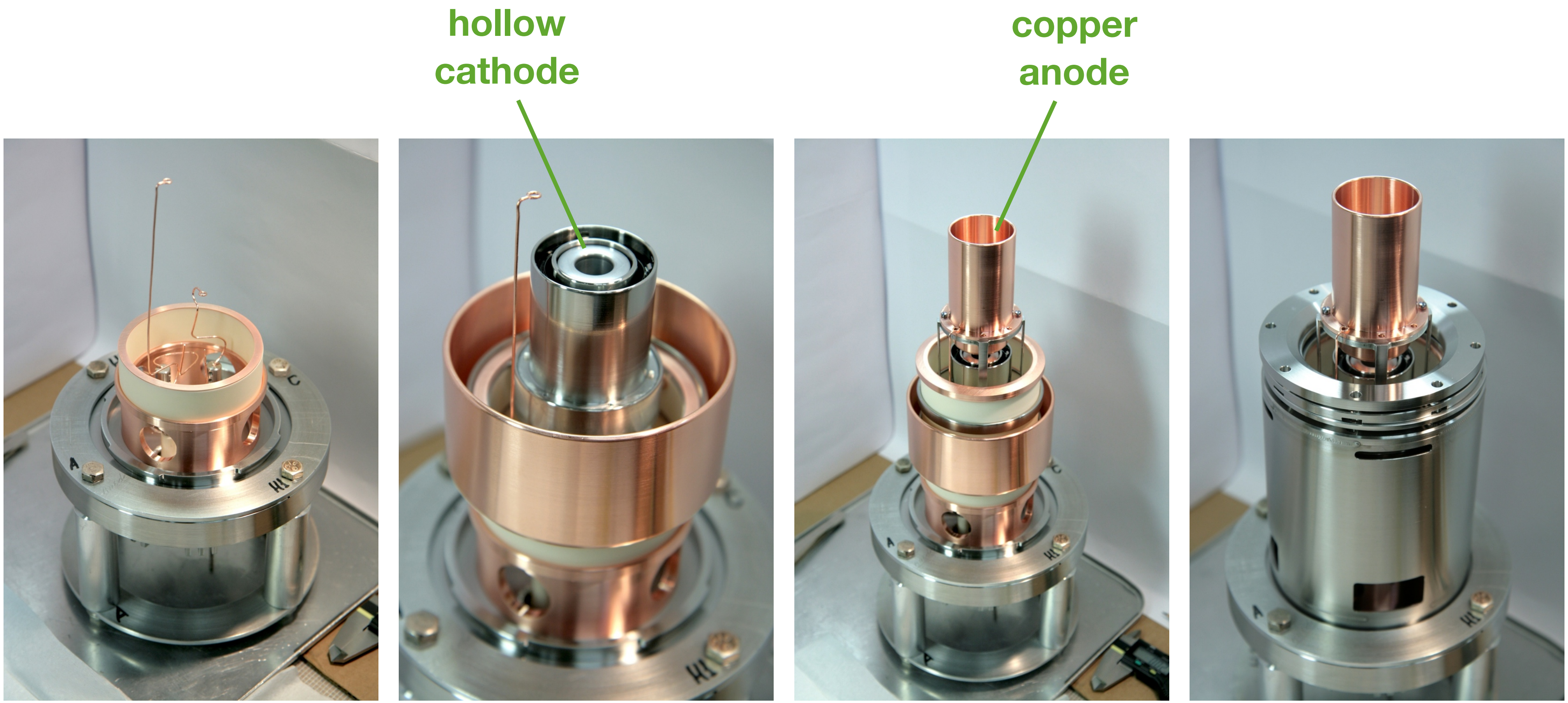
Mechanical integration studies for TEL2





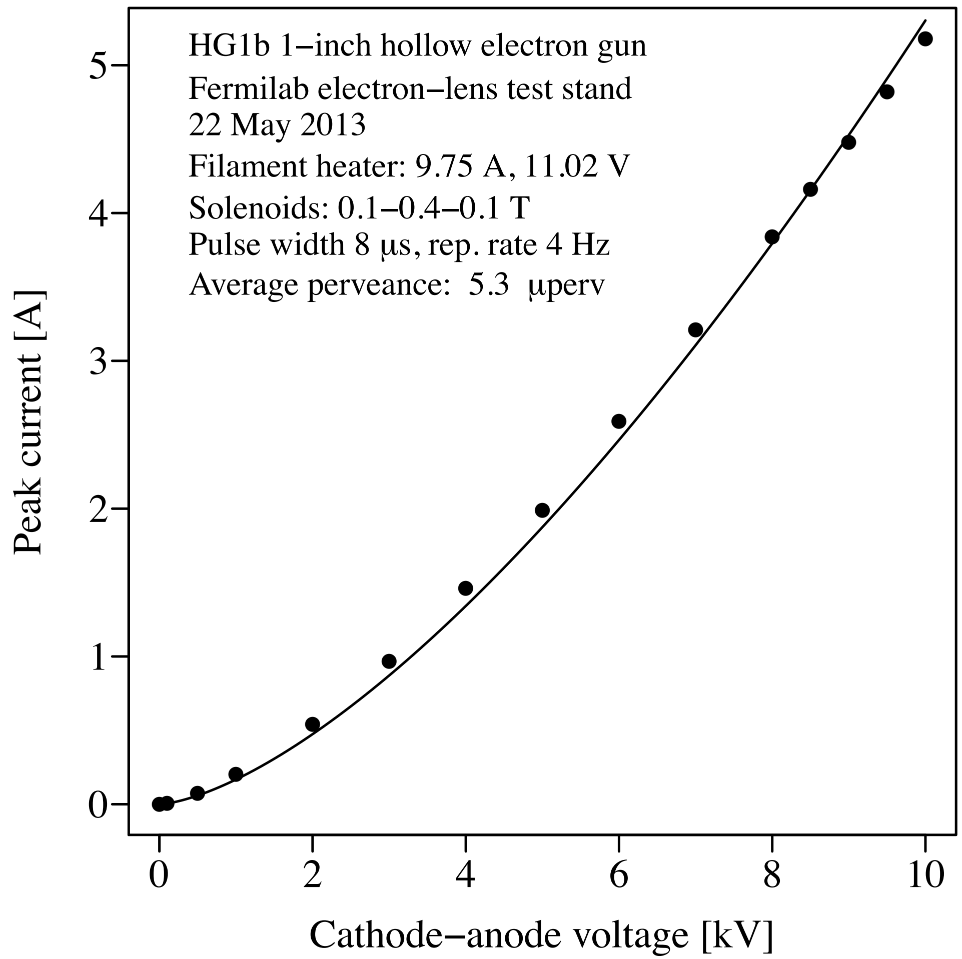
- Rotation is necessary to avoid interference
- New design of cryostat for LHC is preferable

Hollow electron gun prototype for the LHC



- 25 mm outer diameter, 13.5 mm inner diameter
- Built and characterized at Fermilab electron-lens test stand

Performance of hollow electron gun prototype



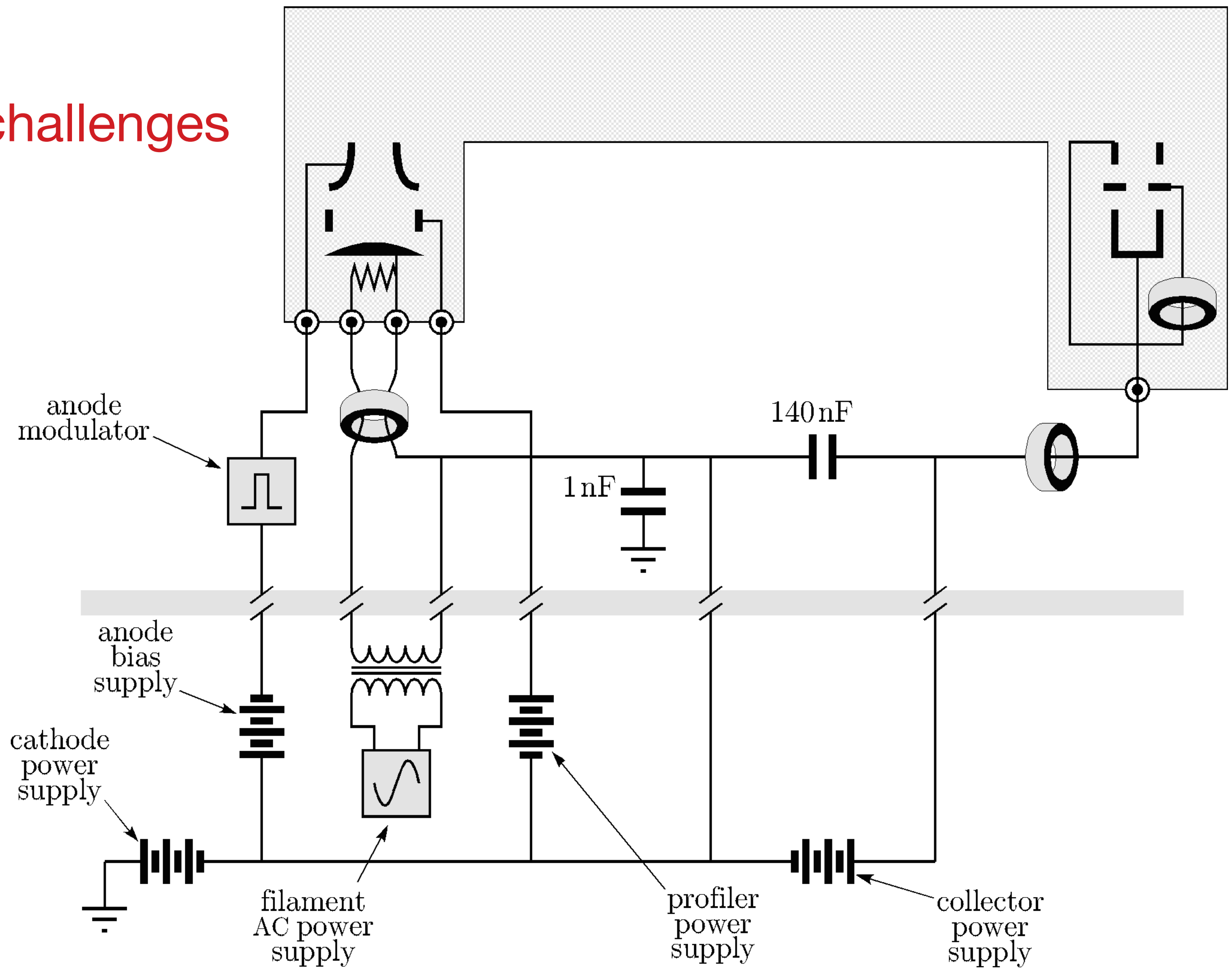
Yields 5 A at 10 kV

- Build test stand at CERN to develop electron guns and study electron beam dynamics.
- Synergies with ELENA electron cooler?

Electrical systems

- gun and collector solenoid power supplies: 340 A @ 0.4 T
- main solenoid power supply: 1780 A @ 6.5 T
- high voltage supplies for cathode, profiler, anode bias, collector: 10 kV
- stacked-transformer modulator, anode pulsing: 10 kV, 35 kHz, 200 ns rise time

No major challenges



Vacuum

- 10^{-9} mbar typical in TEL2 with 3 ion pumps + Ti sublim.
- Baking of inner surfaces
- LHC requires vacuum isolation modules on each side (0.8 m each): gate valves, NEG cartridges, pumps, gauges
- Surface certification
- E-cloud stability (enhanced with solenoids on)
- See also A. Rossi's talk at e-lens review: indico.cern.ch/event/213752

Design needs to be reviewed according to LHC specifications

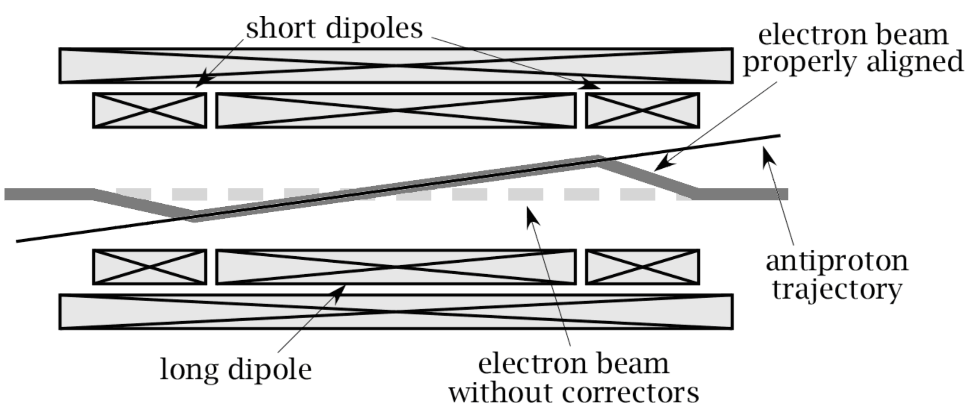
Cryogenics

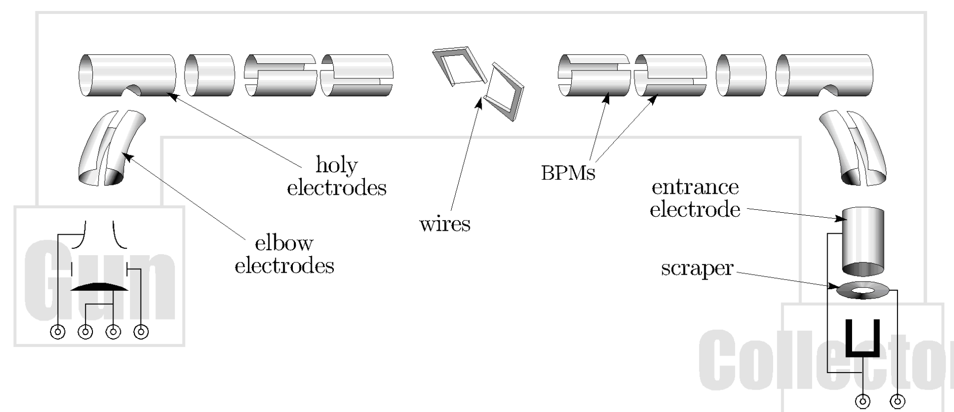
- cryogenics dominates installation time: at least 3 months required for warm-up, connections, cool-down
- electron lenses may be treated as stand-alone magnets at 4.5 K
- may take advantage of dedicated rf refrigerator for HL-LHC at IR4
- TEL2 static heat loads: 12 W for He at 4 K and 25 W for liquid N_2 shield
- Tevatron magnet string liquid He flux was 90 l/s
- N_2 not available in LHC; use gaseous He at 20 bar?
- integration of quench protection system
- See A. Rossi's talk at e-lens review: indico.cern.ch/event/213752

Likely main integration effort

Diagnostics and instrumentation

- corrector magnets for position and angle in main solenoid
- accurate BPMs for both slow electron signals and fast proton signals
- pickup and ion-clearing electrodes
- sensitive (gated) loss monitors (scintillators, diamonds, ...) at nearest aperture
  - verify e^{-}/p alignment
  - measure lifetimes, loss fluctuations, halo diffusivities vs. e-lens settings
- e-beam profiles with fluorescent screens (low current) and pinhole (high current), following BNL design
- direct noninvasive halo population measurement (synch. light, fluorescence, ...)?





Some state-of-the-art devices, some challenges
Would certainly benefit from test stand at CERN

Impedance

- Very different bunch structure in Tevatron and LHC
- Tight broad-band longitudinal impedance budget (90 mOhm)
- Preliminary studies suggest that
  - modifications of Tevatron vacuum chamber and electrodes may be required for longitudinal fields, such as rf shields to suppress trapped modes
  - transverse impedance is acceptable

More studies necessary, but no major obstacles so far

Outline of the report

- Introduction
- Motivation and strategy
- Expected performance
  - principles, halo removal, effects on core, experimental studies
- Hardware specifications and integration studies
  - physical and mechanical features; hollow electron guns; vacuum; electrical; cryogenics; diagnostics; impedance
- Resources and schedule
- Alternative halo-removal schemes
  - tune modulation with warm quads, damper excitations, beam-beam wires
- Conclusions

Resources and schedule

- Construction cost of 2 devices for the LHC (1 per beam) is about 5 M$ in materials and 6 M$ in labor
- Construction in 2015-2017 and installation in 2018 is technically feasible
- Reuse of some Tevatron equipment is possible (superconducting coil, resistive solenoids, electron guns, ...)
- Contributions to design, construction, commissioning, numerical simulations, beam studies, project management to be specified in CERN / US LARP agreement

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Alternative halo removal techniques

- **Tune modulation** using warm quadrupoles
  - used at HERA to counteract power-supply ripple
  - O. Brüning and F. Willeke, EPAC94; Phys. Rev. Lett. **76**, 3719 (1996)
- Excitation with **transverse dampers** (W. Hofle)
- Both methods **work in tune space**: halo not necessarily separated
- Beam-beam **wire compensator**
- **Emittance preservation** needs to be demonstrated
- **Simulations** of effects on halo and core were started
  - Previtali et al., FERMILAB-TM-2560-APC (2013)

Conclusions

- A concept for collimation and scraping of high-power hadron beams with hollow electron lenses was demonstrated at the Fermilab Tevatron collider
- It may be the best option in cases where material damage, localized instantaneous energy deposition, or impedance limit the use of conventional collimators
- A conceptual design of hollow electron beam scraper is being proposed for the LHC upgrades
- Expected performance is based upon experimental data and numerical simulations
- Further experimental tests may be possible at RHIC in 2015
- No major obstacles so far for integration
- Next steps
  - initiate studies for technical design
  - build electron-lens experience at CERN
    - hardware: test stand operation and diagnostics, engineering, ...
    - modeling: electron beam dynamics, particle tracking, ...
  - compare with alternative schemes

Thank you for your attention!