Electron lenses: hollow beam scraper design report and preliminary studies on long-range compensators

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Contributors

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O. Aberle, A. Bertarelli, F. Bertinelli, O. Brüning, G. Bregliozzi, P. Chiggiato, S. Claudet, R. Jones, Y. Muttoni, L. Rossi, B. Salvant, H. Schmickler, G. Tranquille, G. Valentino (CERN), V. Moens (EPFL), G. Annala, G. Apollinari, M. Chung, T. Johnson, I. Morozov, E. Prebys, V. Previtali, G. Saewert, V. Shiltsev, D. Still, L. Vorobiev (Fermilab), R. Assmann (DESY), M. Blaskiewicz (BNL), D. Grote (LLNL), H. J. Lee (Pusan National U., Korea), S. Li (Stanford U.), A. Kabantsev (UC San Diego), T. Markiewicz (SLAC), and D. Shatilov (BINP).

Young researcher contributions

- *S. Li* (U. Chicago) undergraduate Lee Teng internship (summer 2012): hollow electron gun characterization
- *J. S. Kim*, *Y. H. Cho*, *B. S. Yang* (students of Prof. Hae June Lee, Pusan National University, Korea) visited Fermilab in 2013: space-charge dynamics of hollow beam
- *V. Moens* (joint EPFL-CERN-Fermilab Master student) graduated September 2013: hollow electron gun performance, simulations of electron beam dynamics
- plan to accept new Master/PhD student in 2014
- *V. Previtali*'s Toohig fellowship completed July 2013: numerical tracking simulations
- *R. Rossi* recently started as CERN technical student on beam halo dynamics
- Post-doc / CERN fellow / Toohig fellow needed as point of contact at CERN: numerical studies, electron-lens test stand hardware, diagnostics

Outline

- Introduction
- **Design of hollow electron beam scrapers for the LHC**
  - 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
- **Long-range beam-beam compensation with electron lenses**
  - Motivation, preliminary considerations, integration issues
- Conclusions

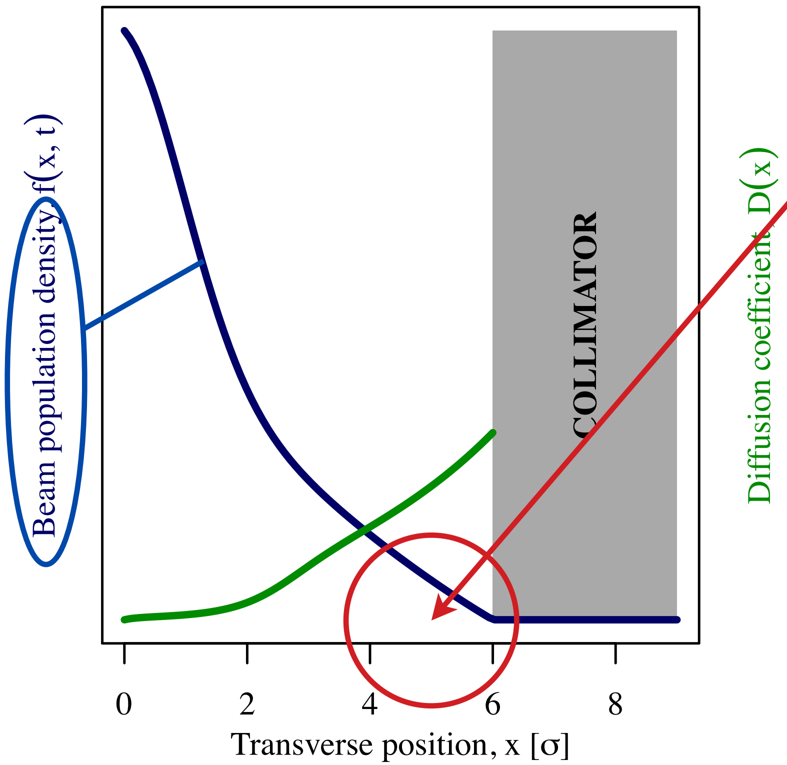
Collimation and beam halo are critical for HL-LHC

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

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

- The collimation system has performed very well so far (6σ half gaps, 140 MJ @ 4 TeV): efficiency, robustness. Signs of impedance limitations. 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

Collimation and beam halo are critical for HL-LHC



- **Halo populations** (e.g., 4σ to 6σ) in LHC are poorly known. Collimator scans and van-der-Meer 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** and for **safe operation with crab cavities**
- **Hollow electron lenses are the most established and flexible tool for controlling the halo of high-power beams**

Strategy for electron lenses and halo control

[see Redaelli, LARP CM20, April 2013]

- Final collimation needs and decisions can only be defined after gaining operational experience at 7 TeV (2015)
  - uncertainties: cleaning efficiency, lifetimes, quench limits, impedances
- Proceed with design of 2 devices:
  - conceptual design completed
  - technical design in 2014-2015
  - construction 2015-2017, if needed
  - installation during 2018 long shutdown (2022 if limited by resources)
- Investigate proposed alternative schemes
  - damper excitation, tune modulation, beam-beam wire compensators
- Exchange electron lens hardware/software expertise with CERN
- Develop noninvasive, direct halo diagnostics (see Alan Fisher's talk)
- If possible, extend Tevatron experience with beam tests at RHIC

The conceptual design 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

Hollow beam collimation with Tevatron electron lenses

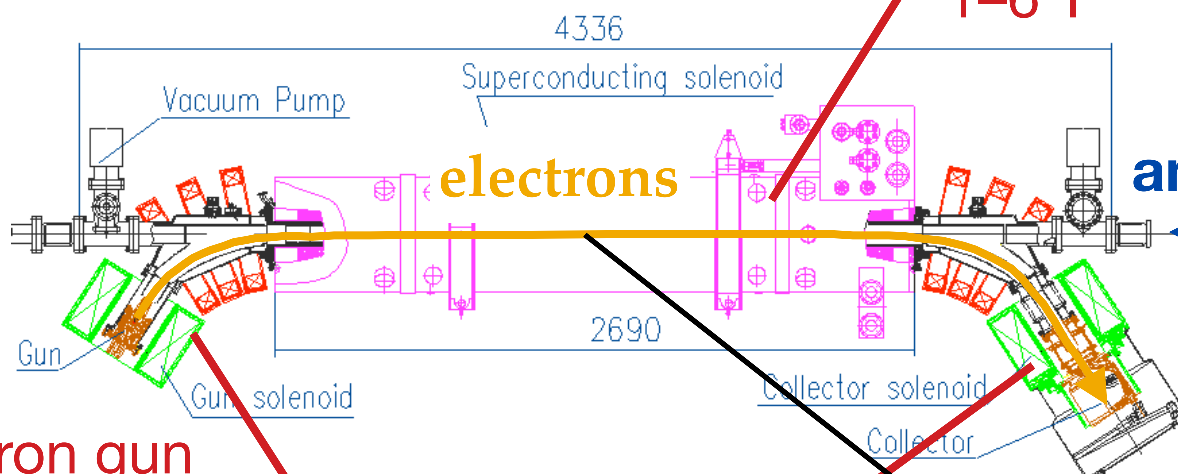
Circulating beams affected by electromagnetic fields generated by electrons
Stability provided by strong axial magnetic fields

6 m total length

superconducting solenoid
1–6 T

protons

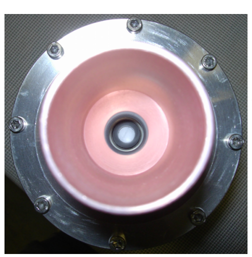
antiprotons

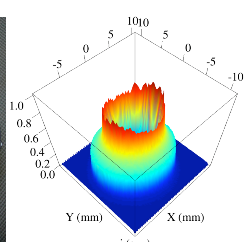


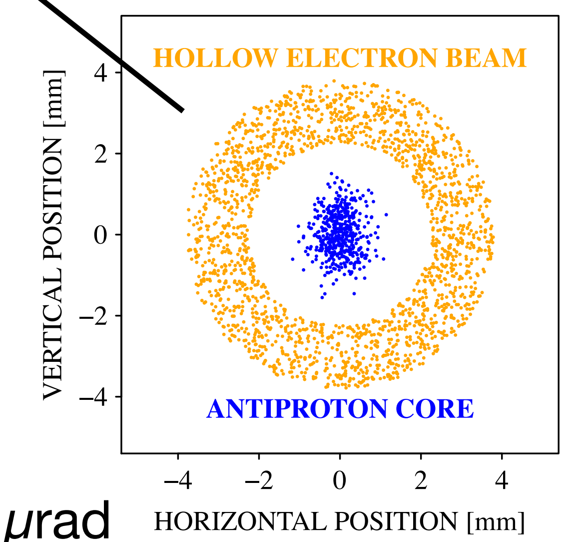
collector

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

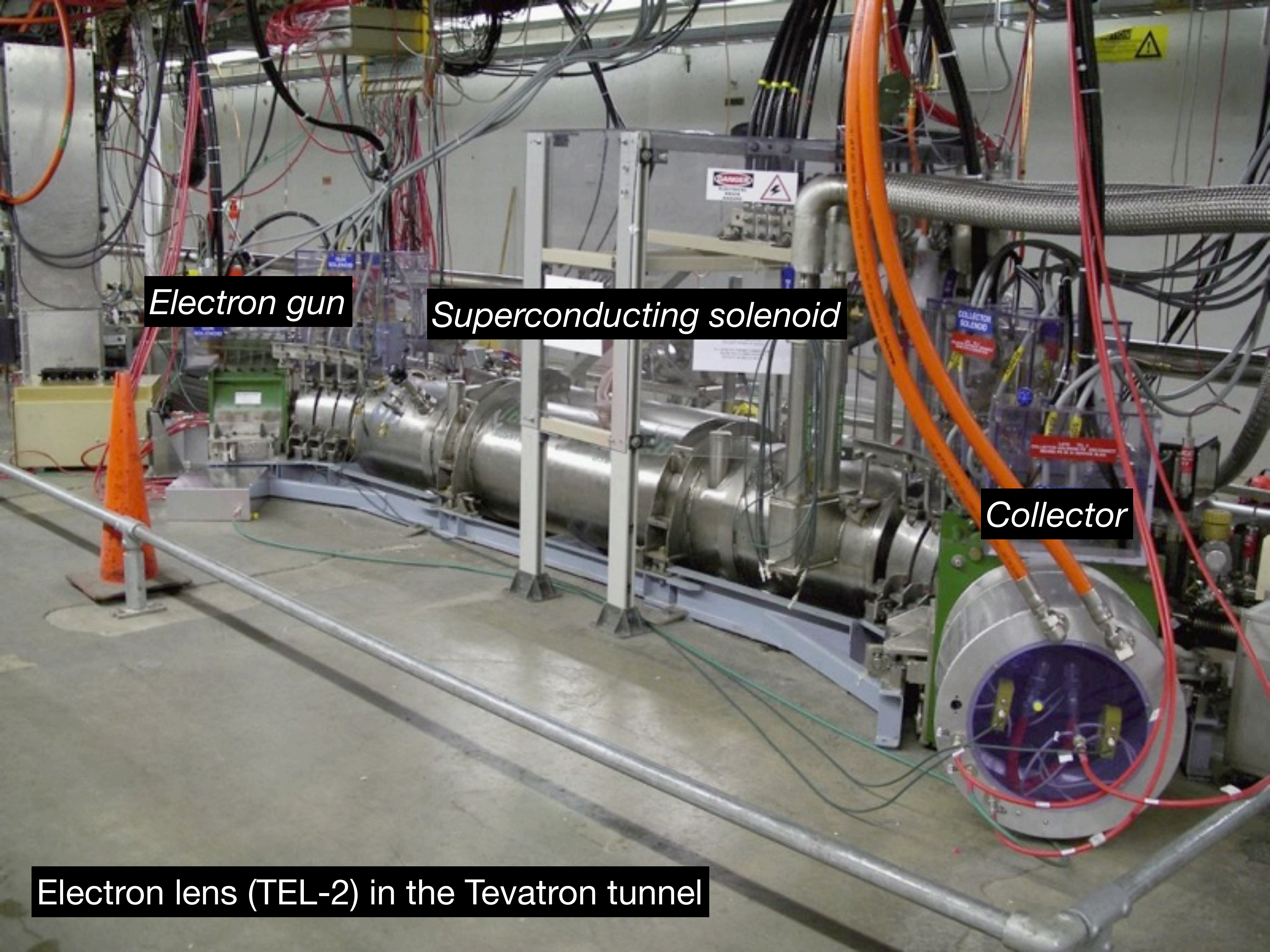
conventional solenoids
0.1–0.4 T





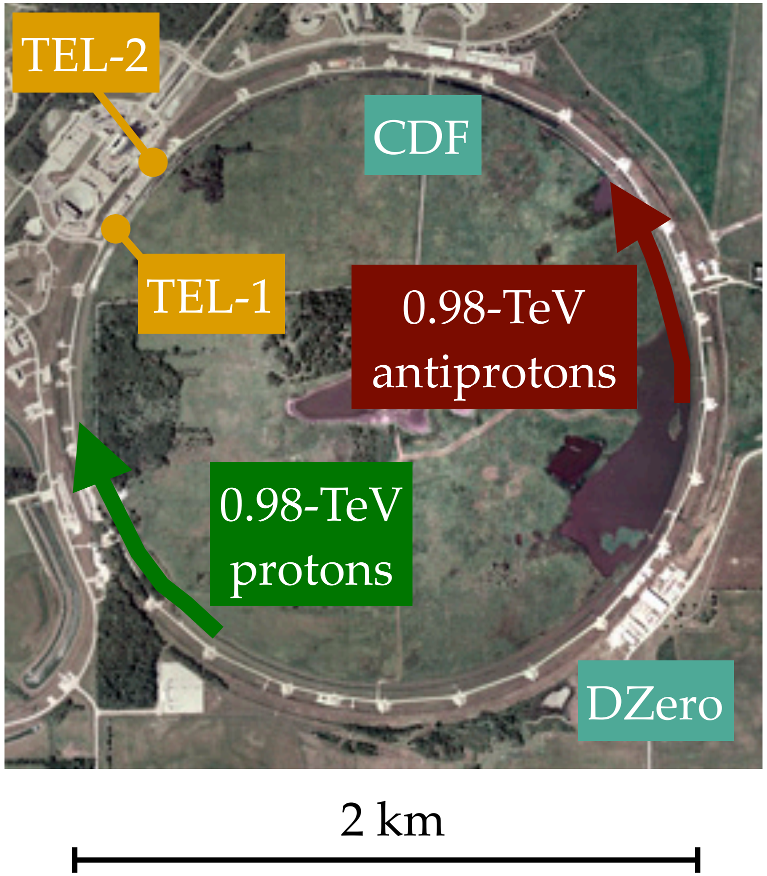


Tunable transverse halo kicks ~0.1 μrad


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 (tune shift)***
  - 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)

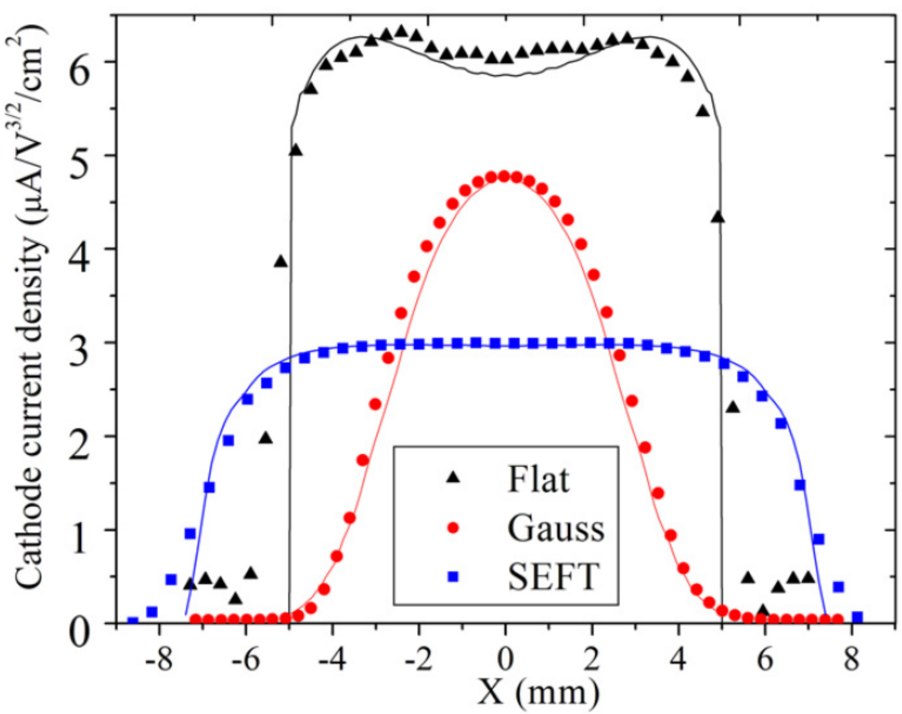


Electron lenses for head-on beam-beam compensation are currently being commissioned in the Relativistic Heavy Ion Collider at Brookhaven National Laboratory

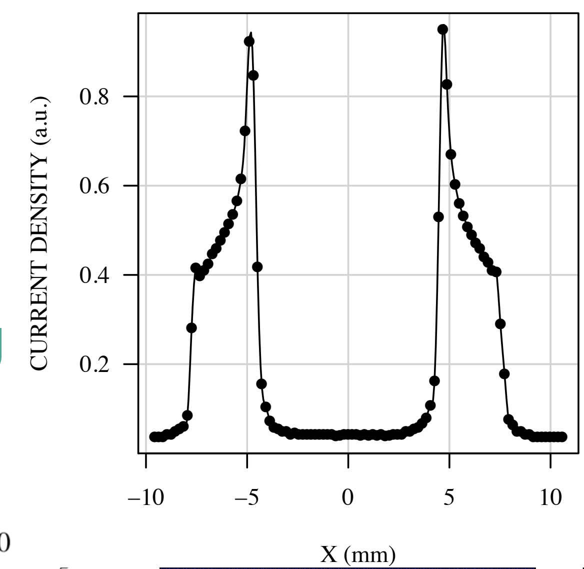
Control of electron beam profile

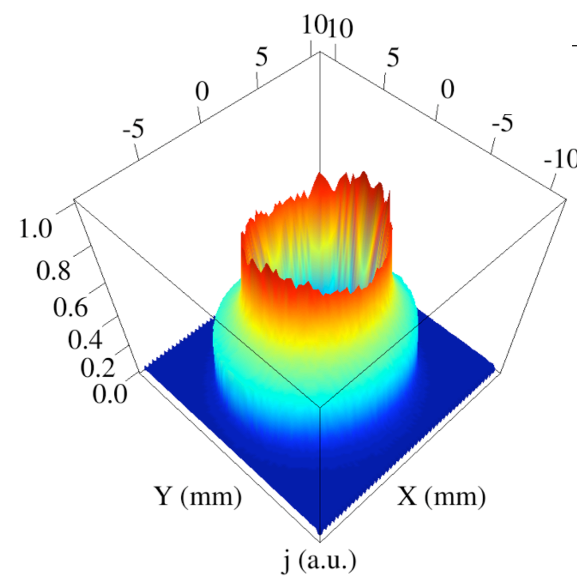
Current density profile of electron beam is shaped by cathode and electrode geometry and maintained by strong solenoidal fields

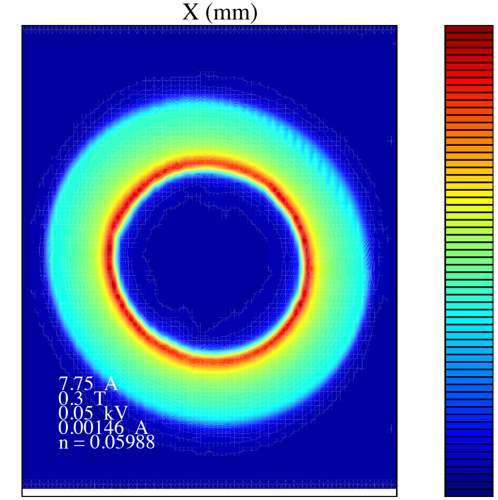
Flat profiles for bunch-by-bunch betatron tune correction



Hollow profile for halo scraping

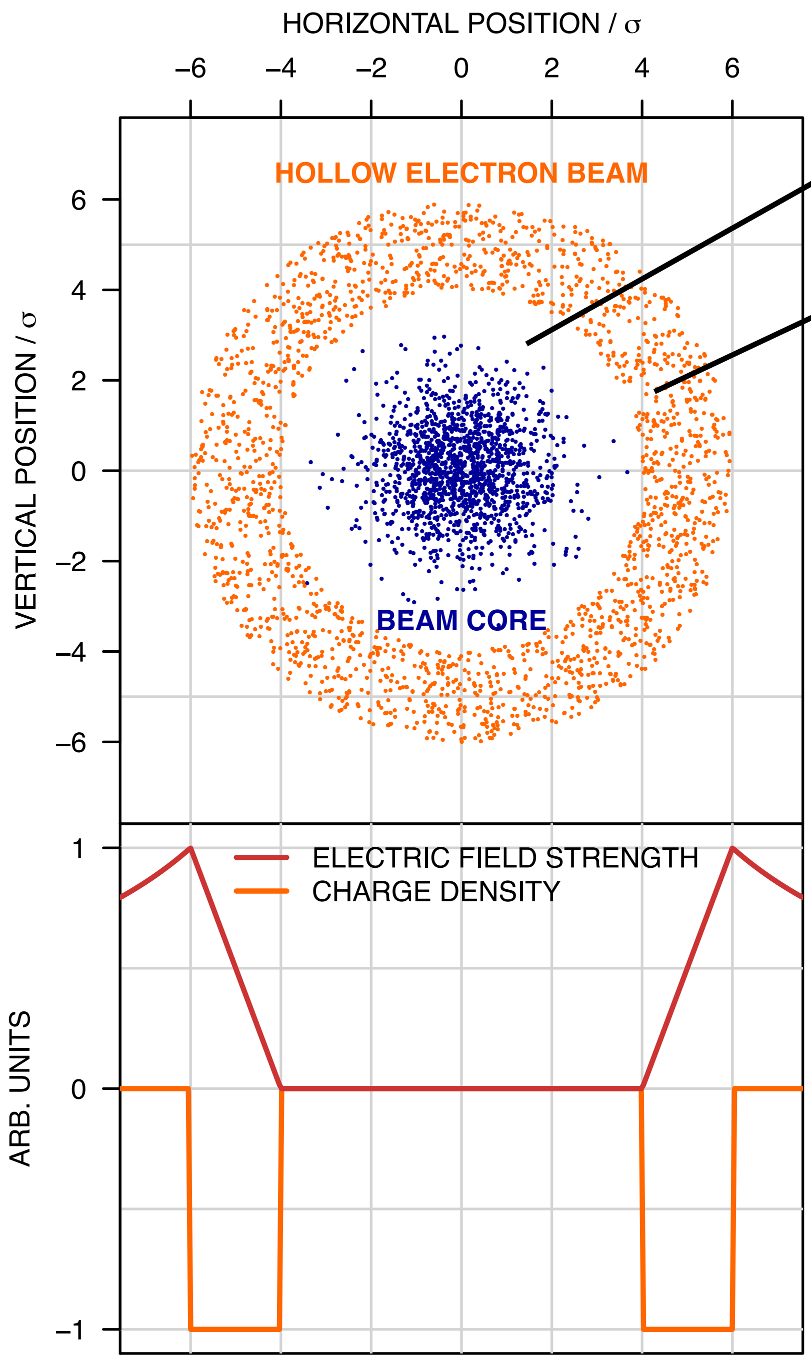






Gaussian profile for compensation of nonlinear beam-beam forces

Concept of hollow electron beam collimator or scraper

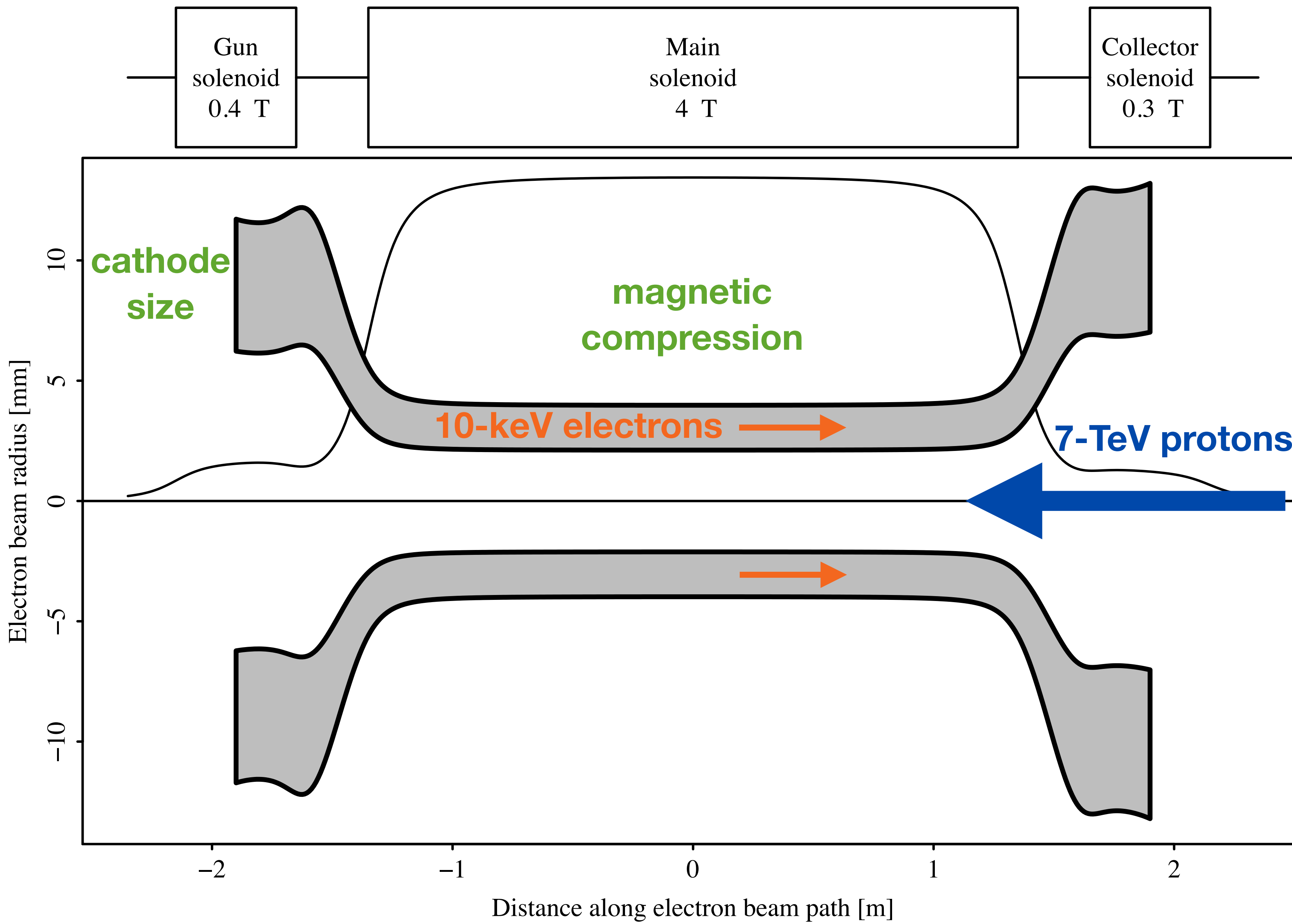


- **Beam core** is unaffected (field-free region)
- **Halo** experiences nonlinear transverse kicks:

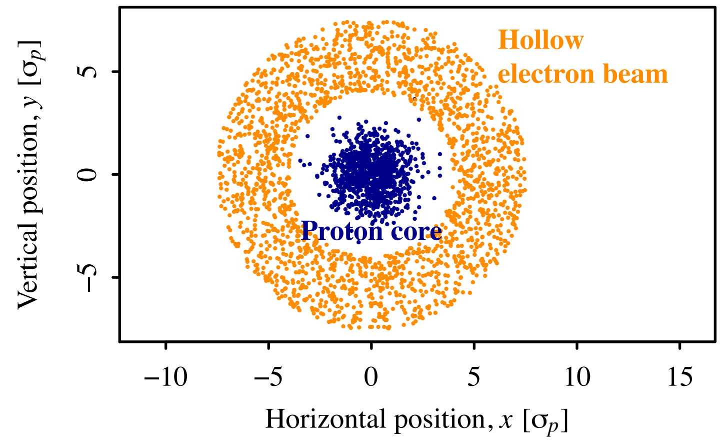
$$\theta_r = \frac{2\, I_r\, L\, (1 \pm \beta_e \beta_p)}{r\, \beta_e\, \beta_p\, c^2\, (B\rho)_p} \left(\frac{1}{4\pi\epsilon_0} \right)$$

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

Electron beam size is matched to proton beam size by solenoids

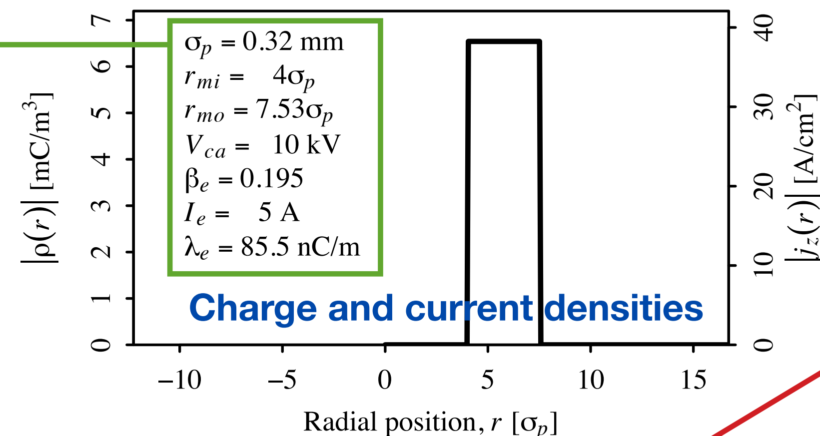


Example of numerical parameters for the LHC

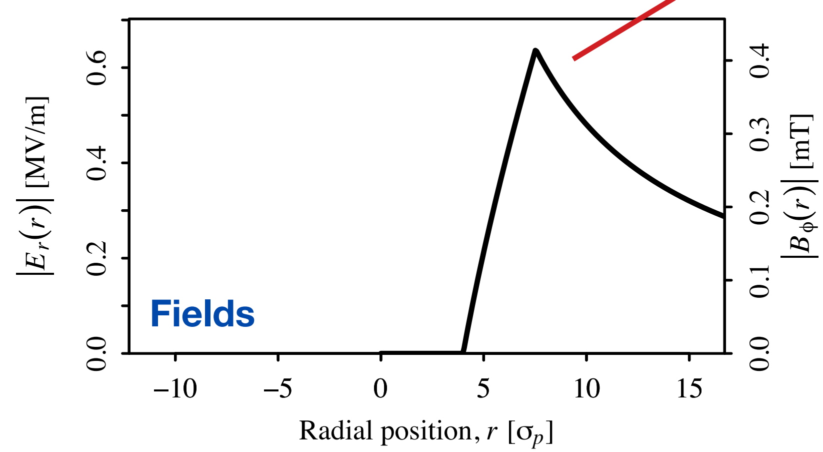


Overlap region L = 3 m

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



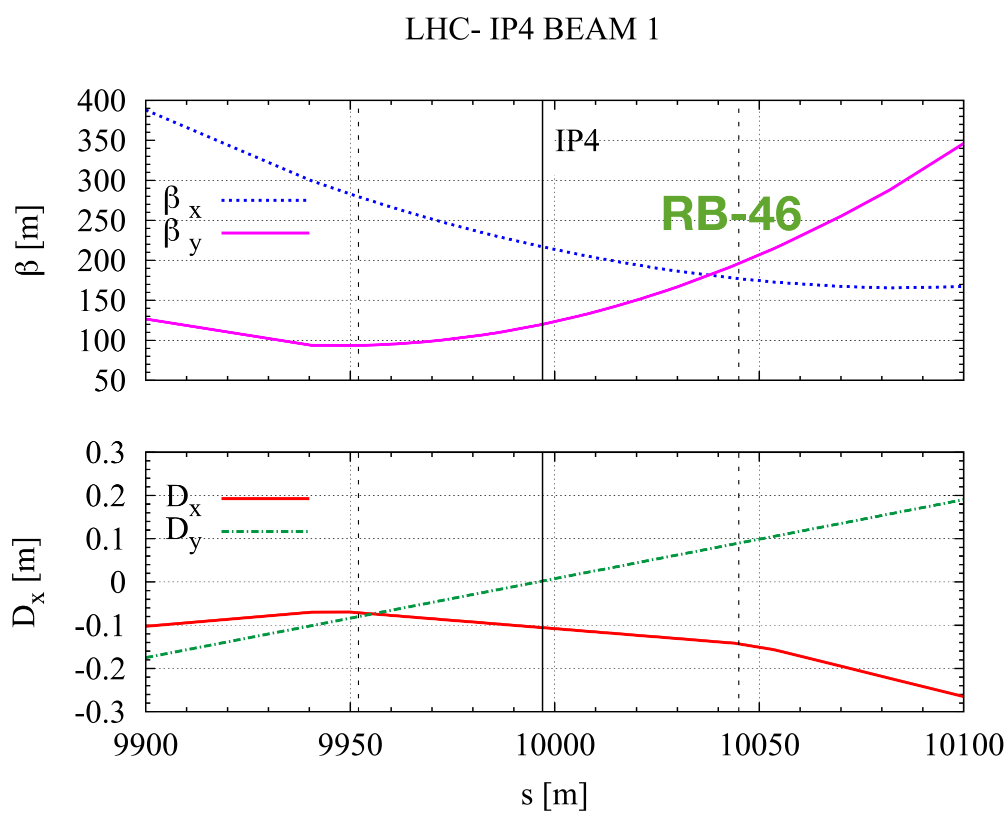
Max. kick **0.3 μrad** for 7-TeV protons

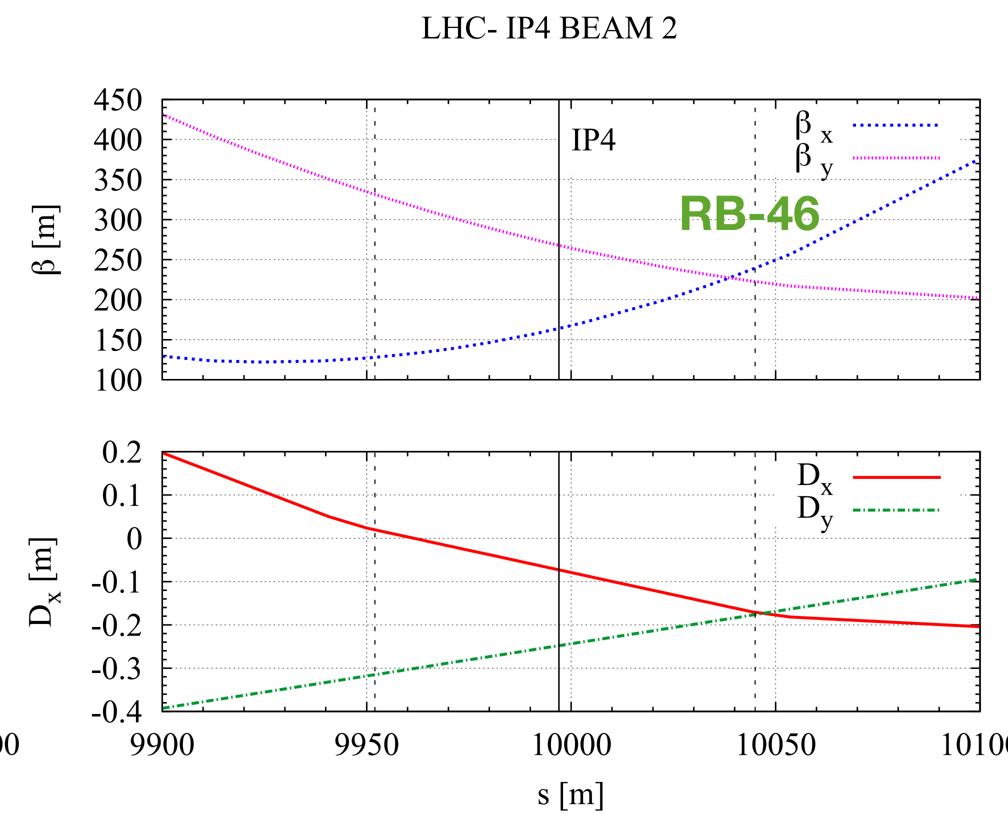


For comparison: multiple Coulomb scattering in LHC primaries generates random kicks with spread θ_{rms} = 1.3 μrad

Beam optics at candidate locations (LHC v6.503)

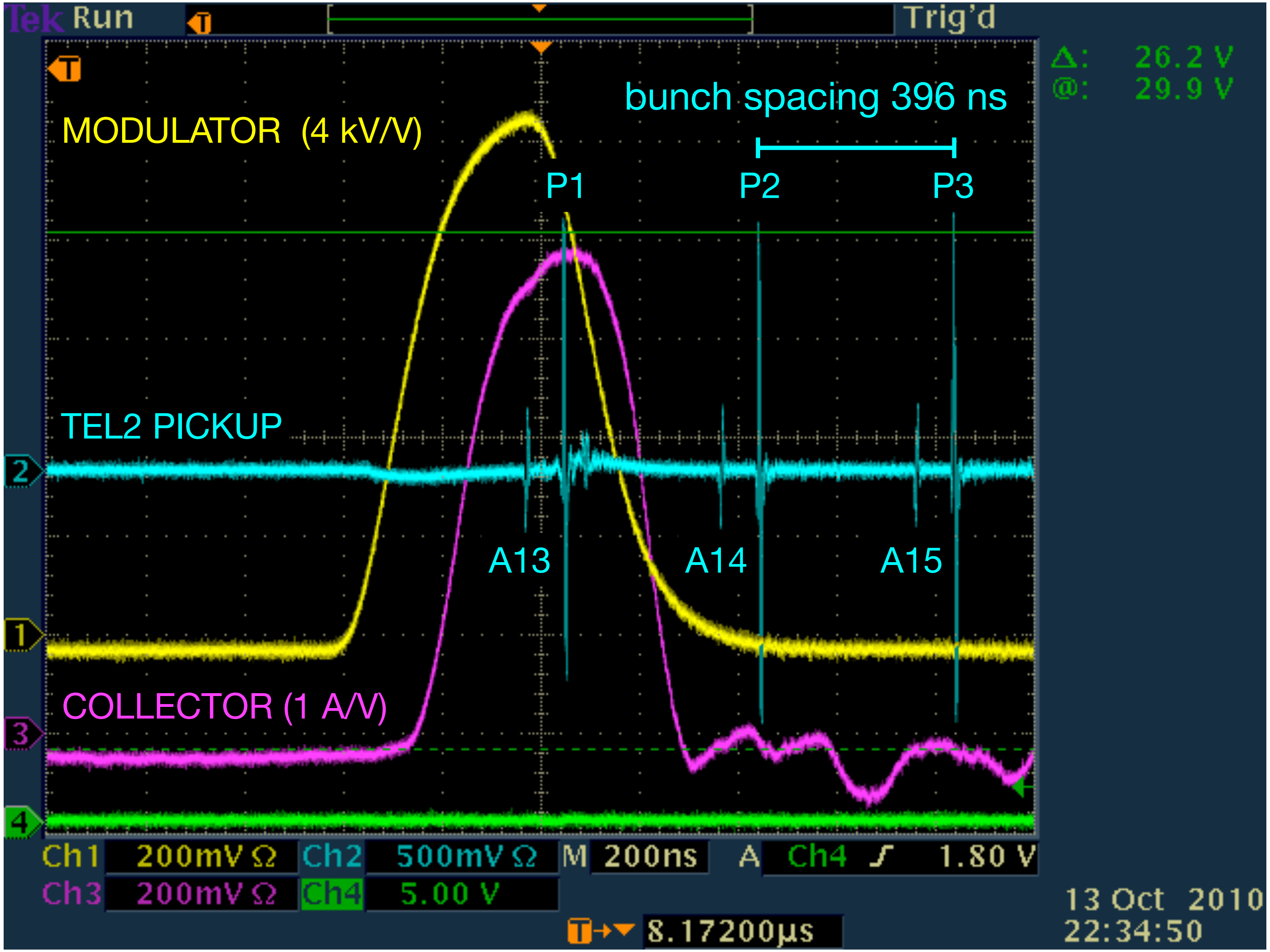
Round beams, β ~ 200 m, low dispersion





HL-LHC lattice used in recent simulations

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

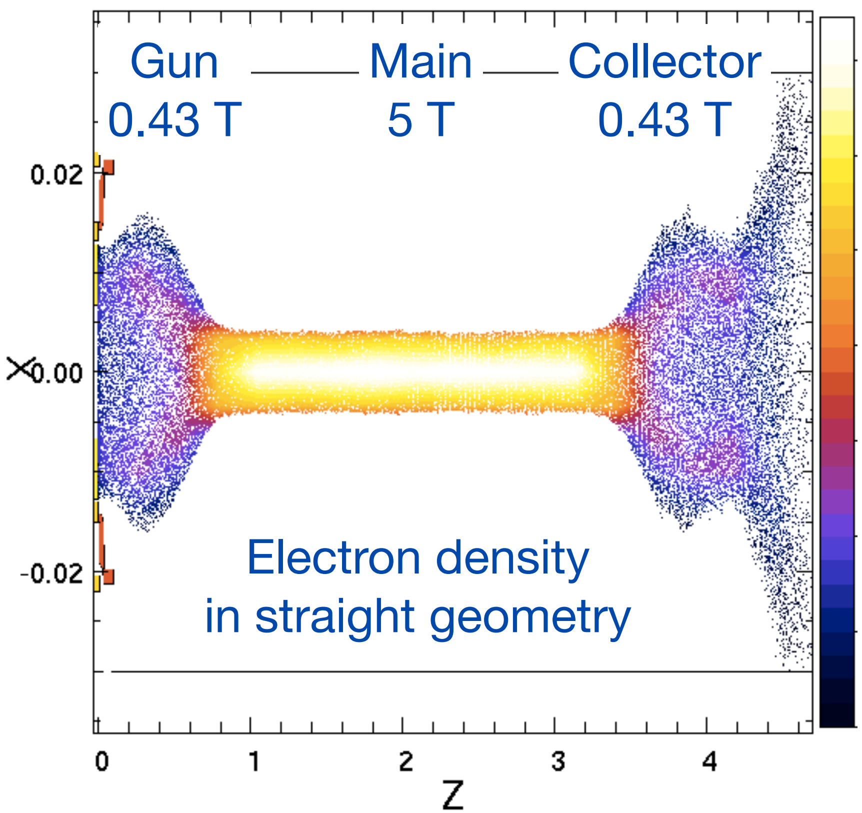
Main goals of numerical simulations

- **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 with space charge
  - Lifetrac and SixTrack for numerical tracking
  - Machine models with nonlinearities
  - Uniform halo population, replenishing mechanisms to be implemented
    - Note: Diffusion was measured in both Tevatron and LHC
    [Stancari et al., FERMILAB-CONF-13-054-APC, arXiv:1312.5007]
  - Ideal electron lens + imperfections (profile asymmetries, 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

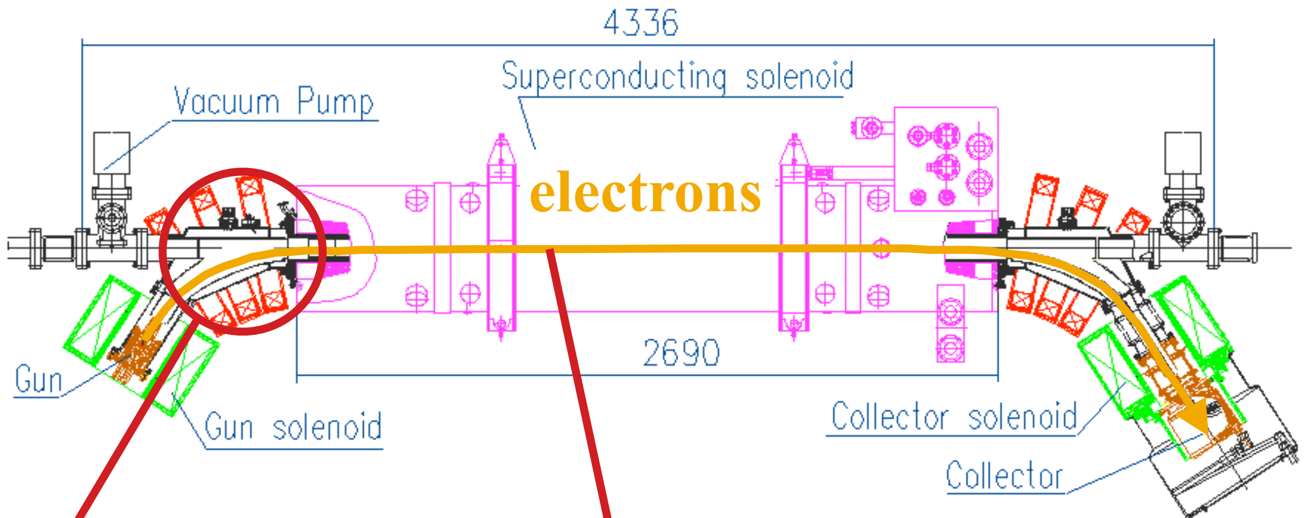


Simulations with straight geometry completed

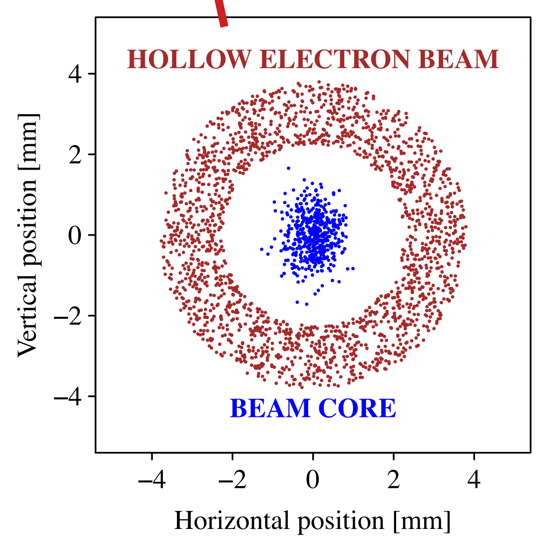
Looking for student / post-doc to lead this effort

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:



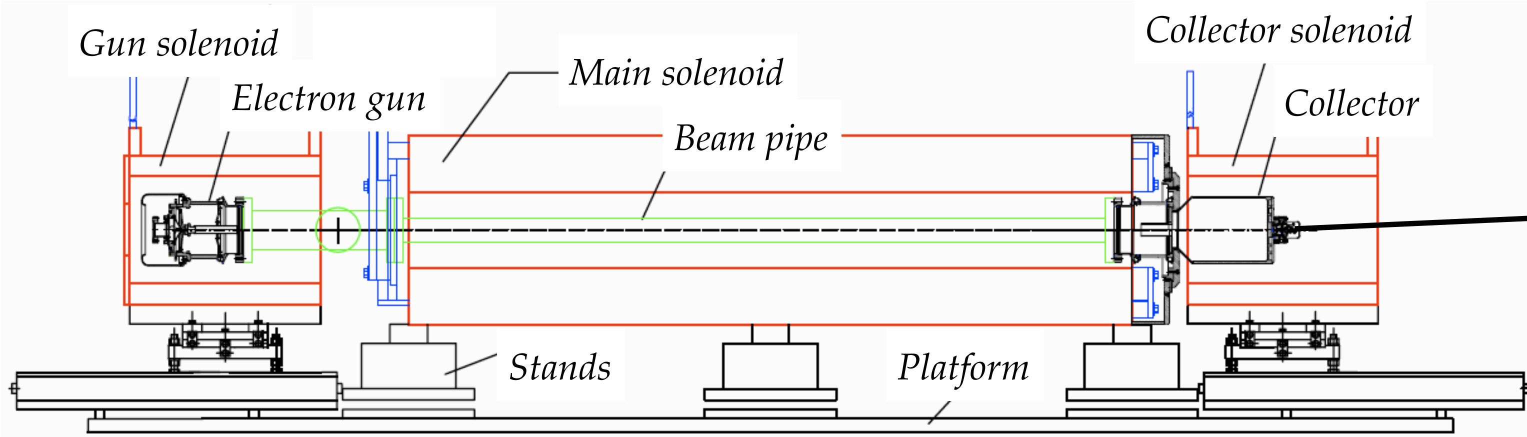
1. bends for injection/extraction



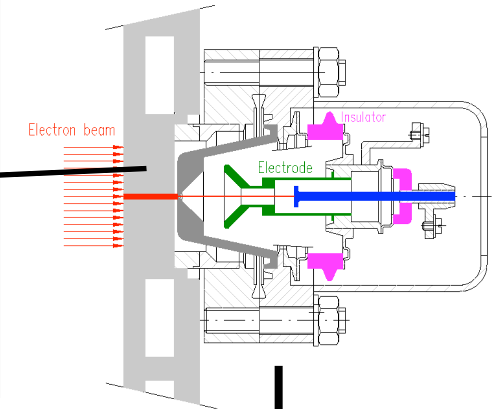
2. azimuthal asymmetries in overlap region

Azimuthal asymmetries in overlap region from measured profiles

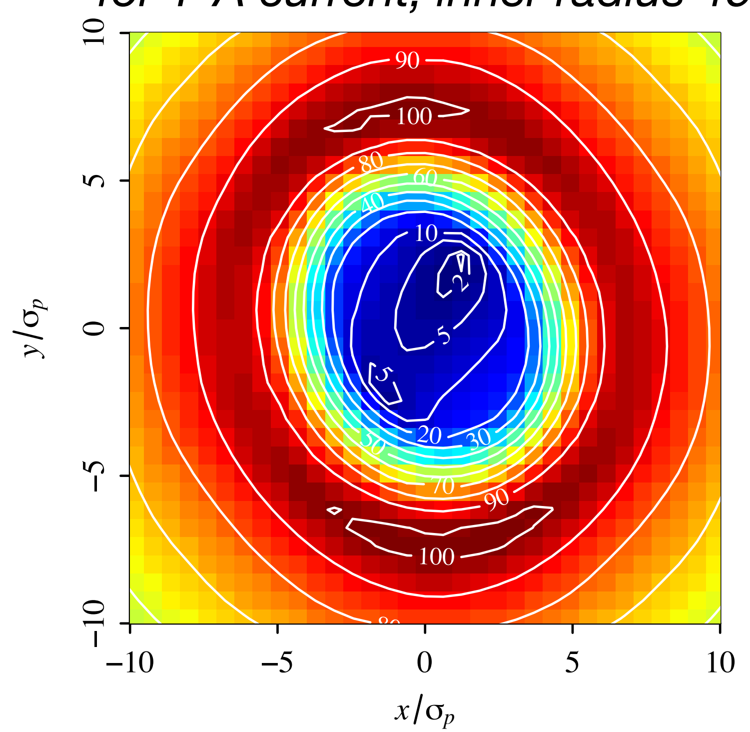
Fermilab electron-lens test stand



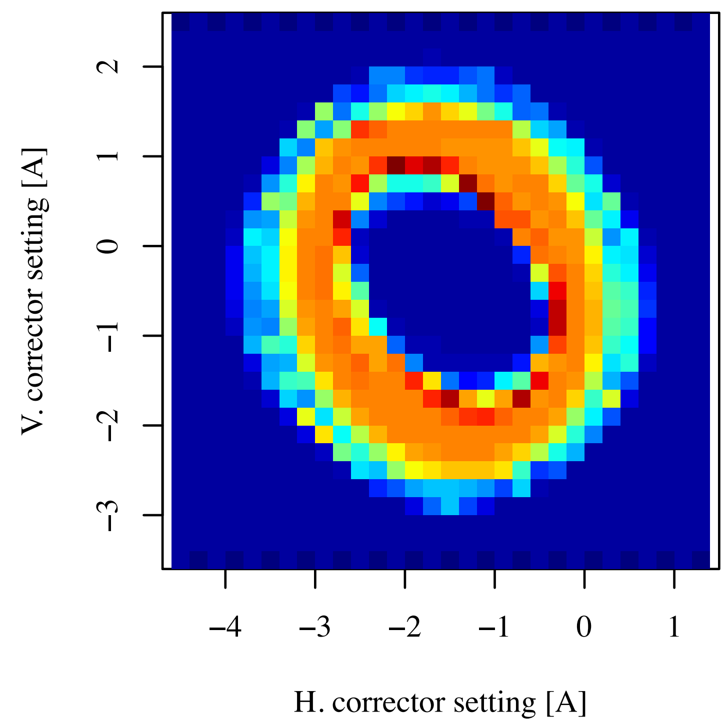
Pinhole for current-density measurements



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



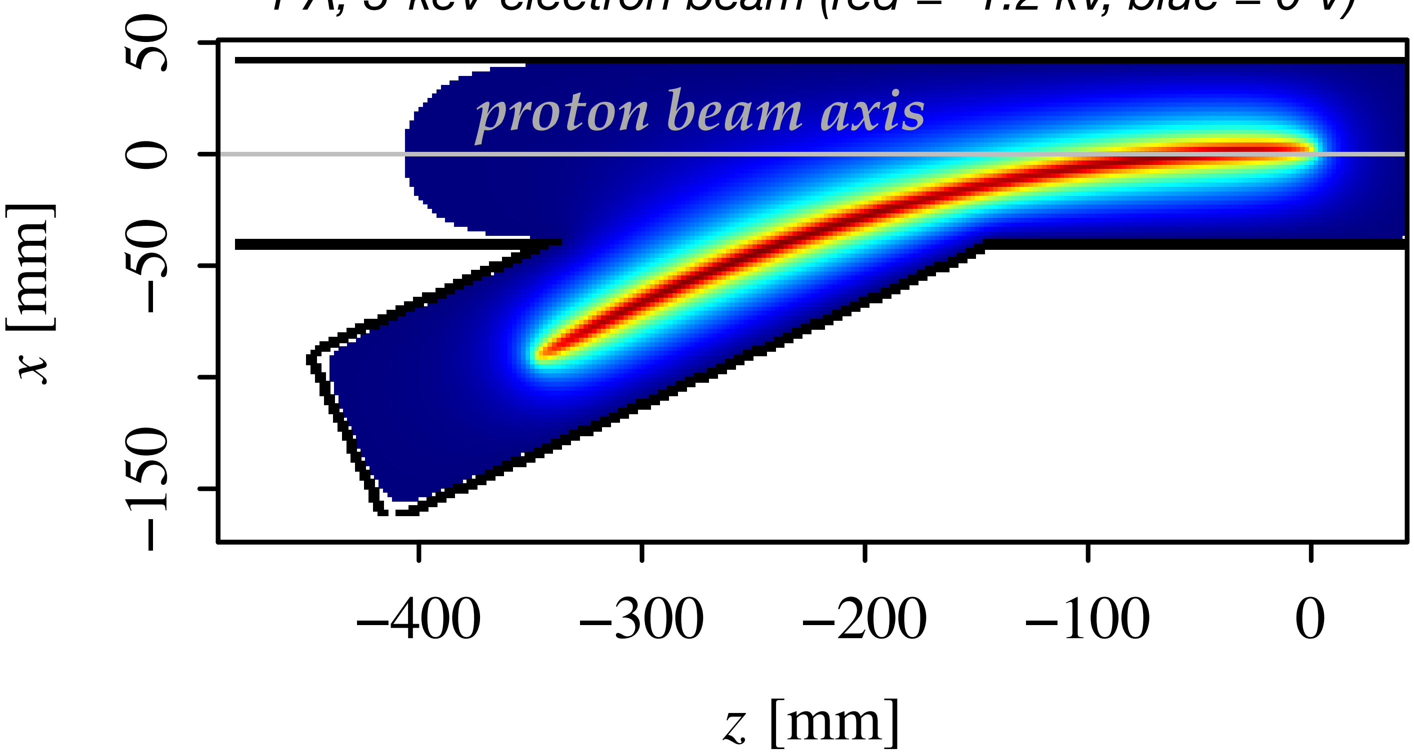
Example of measured profile



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

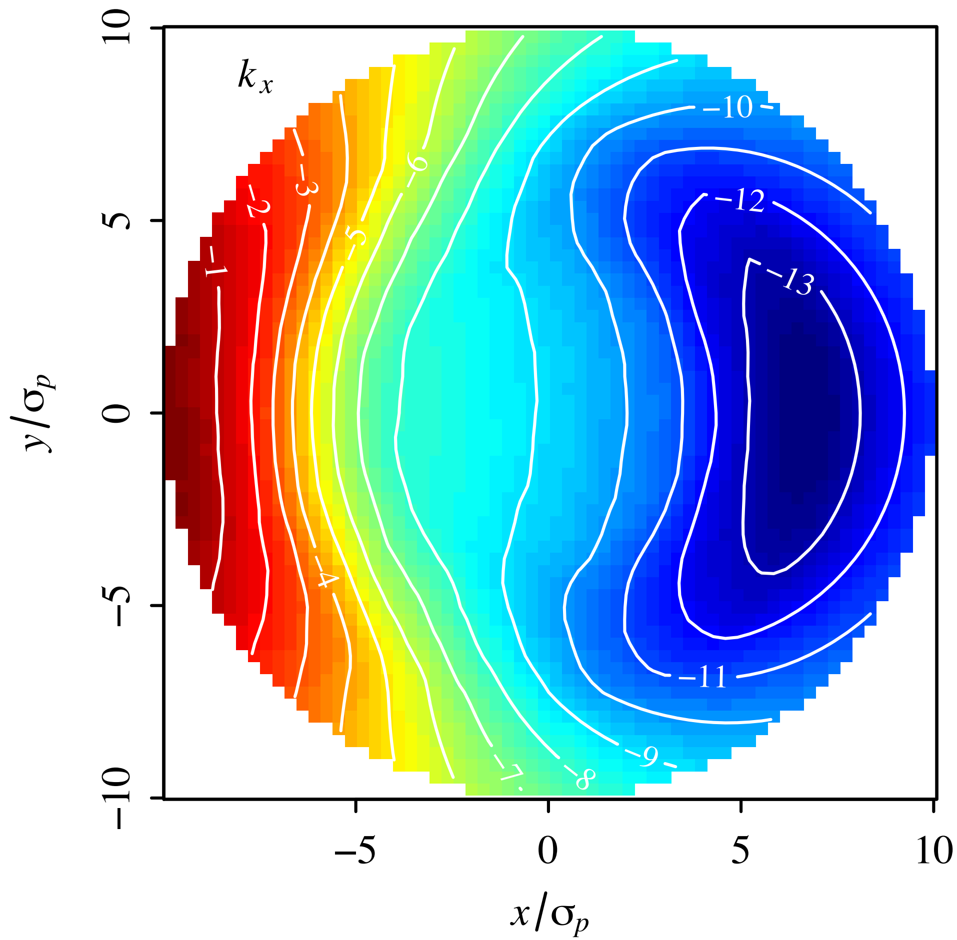
$$k_{x,y} \equiv \int_{z_1}^{z_2} E_{x,y}(x,y,z)\, dz$$

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

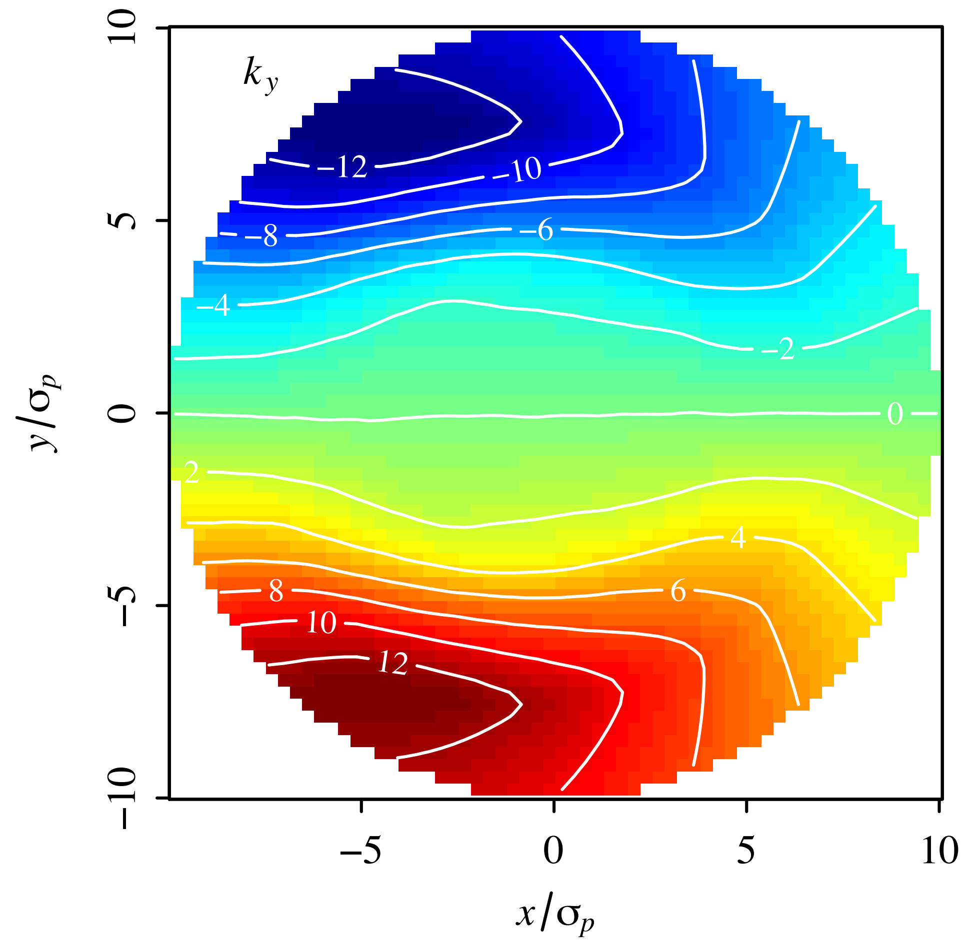
Kick maps from injection and extraction bends

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

Horizontal



Vertical



For 7-TeV protons, 10 kV ⇒ 1.4 nrad

Simulation of HEBC at LHC

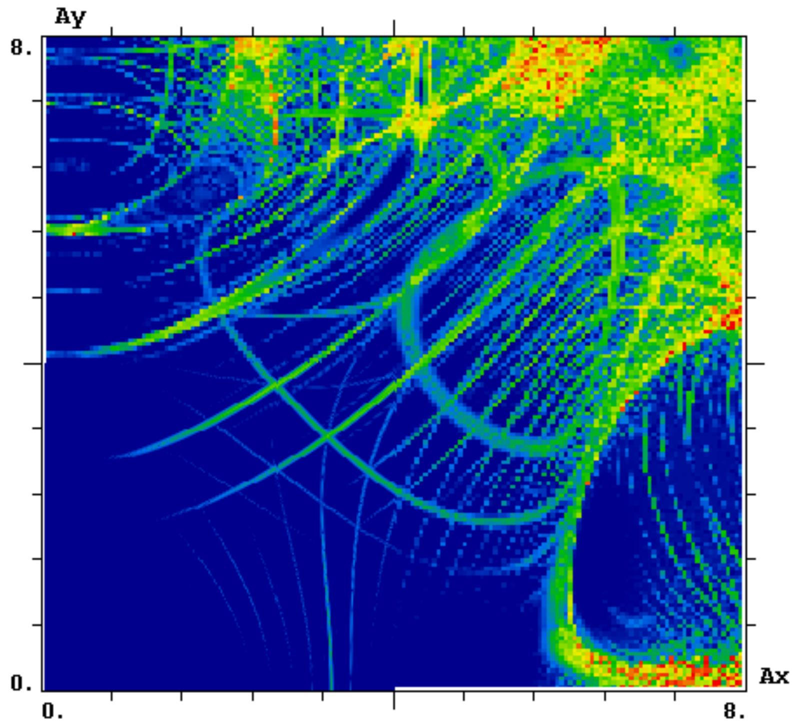
- The goal is to produce estimate of the effect of HEBC on LHC beam
  - Main question: What magnitude of the removal rate for halo particles can be expected for realistic parameters of HEBC and LHC beams?
  - What is the impact of HEBC beam imperfections on the beam core/ luminosity lifetime.
  - Both in CONTINUOUS and STOCHASTIC mode

- LHC Model
  - Lattice V6.503 with errors and beam-beam
  - HEBC element installed in RB46 at 39.26 m from IP4
  - Single aperture restriction at 6σ (both x and y)
  - 10000 macro-particles, initial distribution – a ring with $r1=4\sigma$, $r2=6\sigma$

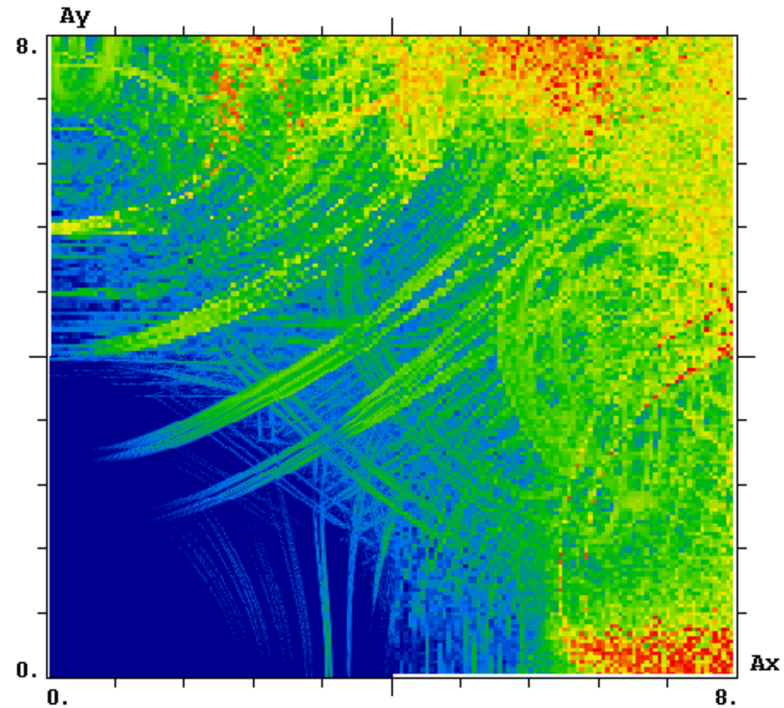
- HEBC Model
  - Constant density, Inner beam radius 4σ
  - Current up to 3.6A

Valishev, FERMILAB-TM-2584-APC (2014)

LHC HEBC Results



HEBC off



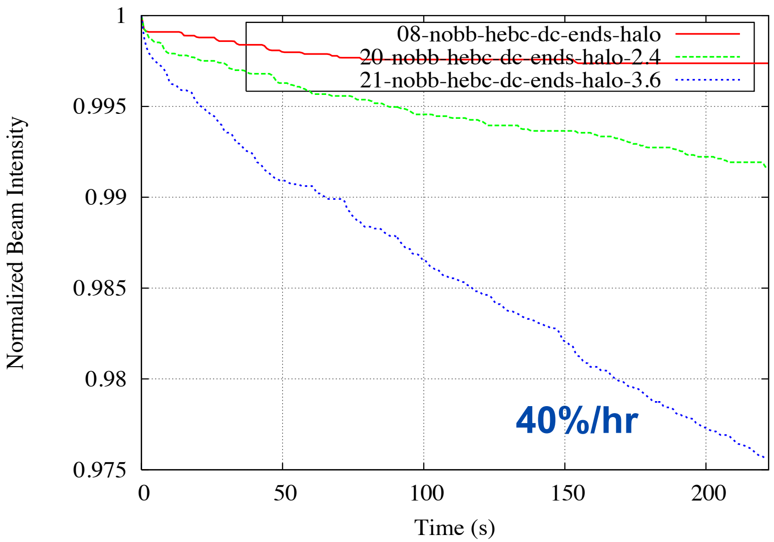
HEBC on

- **FMA shows new resonances and overall tune jitter for particles between 4 and 6 sigma**

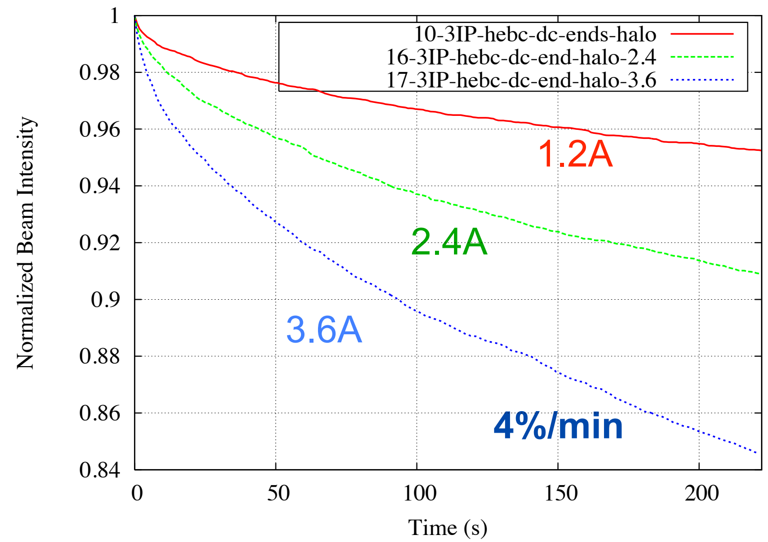
Halo Removal Rates

continuous mode

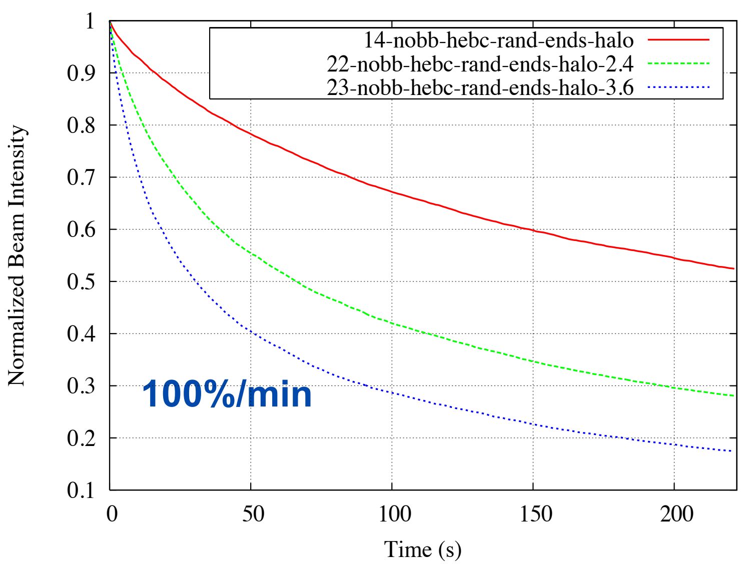
bb off

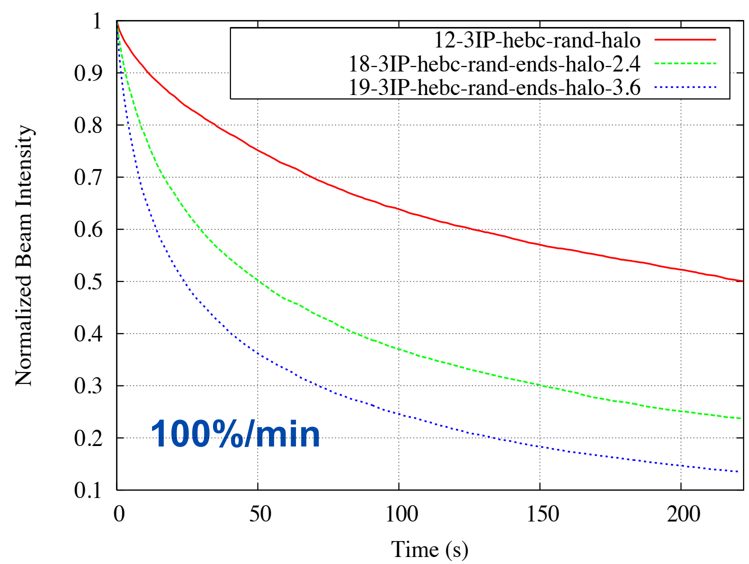


bb on



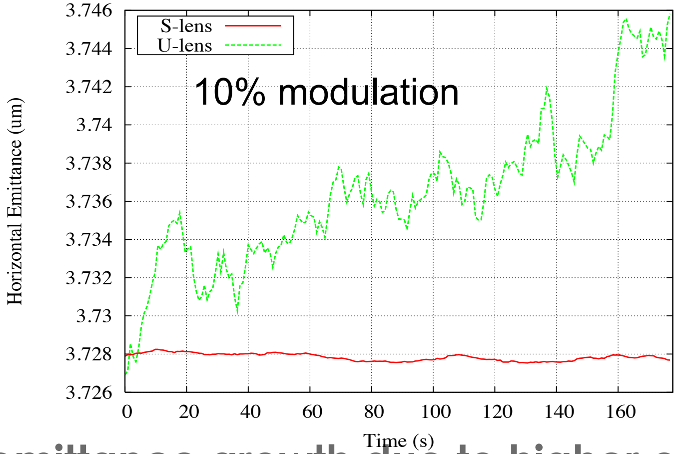
stochastic mode

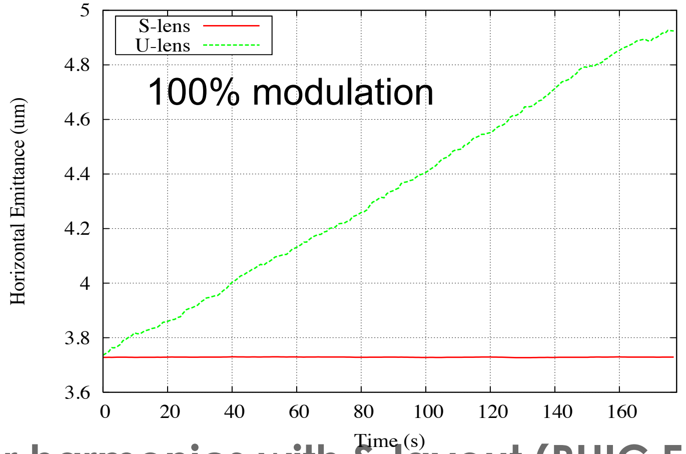




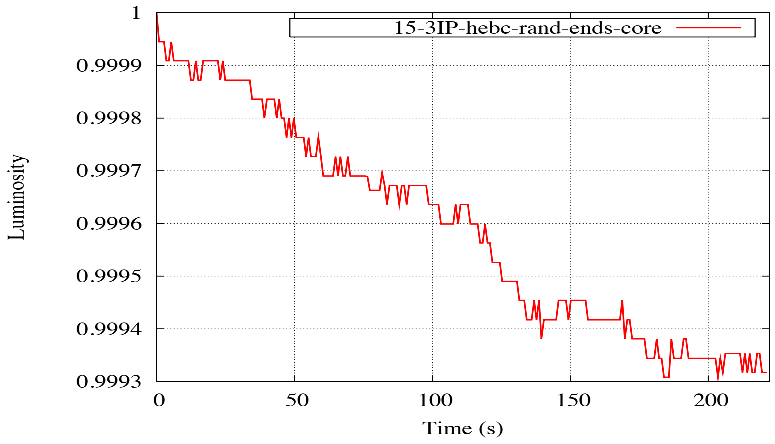
Effect of e- Bends

- No impact in continuous mode
- Stochastic mode
  - Significant horizontal emittance growth with U-layout (Tevatron EL)





  - Small emittance growth due to higher order harmonics with S-layout (RHIC EL). Luminosity lifetime 90 hours (1%/hour).



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    - 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
- **Long-range beam-beam compensation with electron lenses**
  - Motivation, preliminary considerations, integration issues
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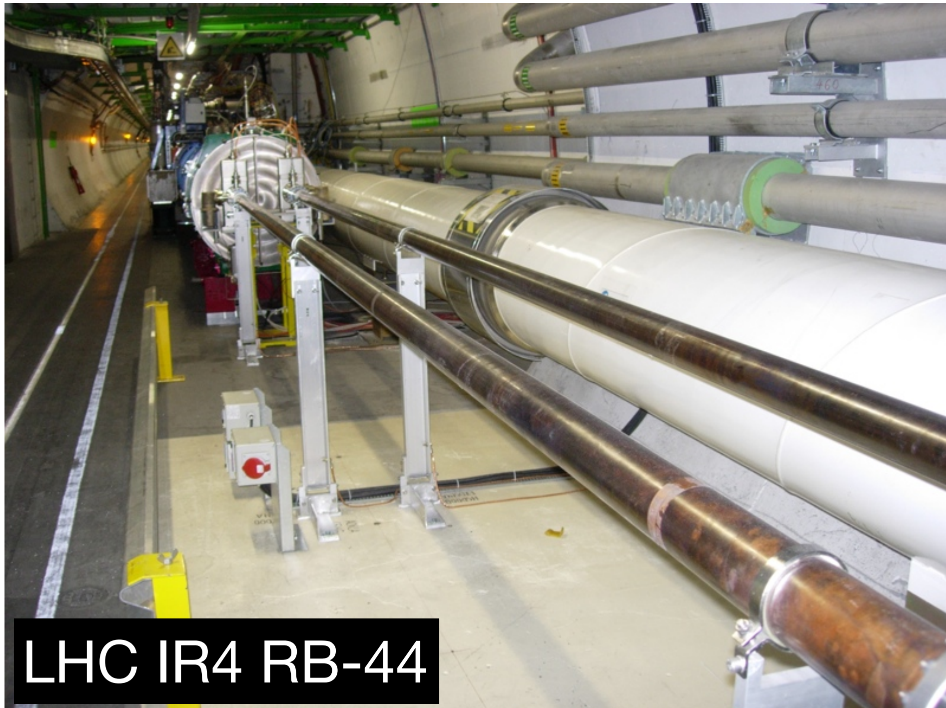
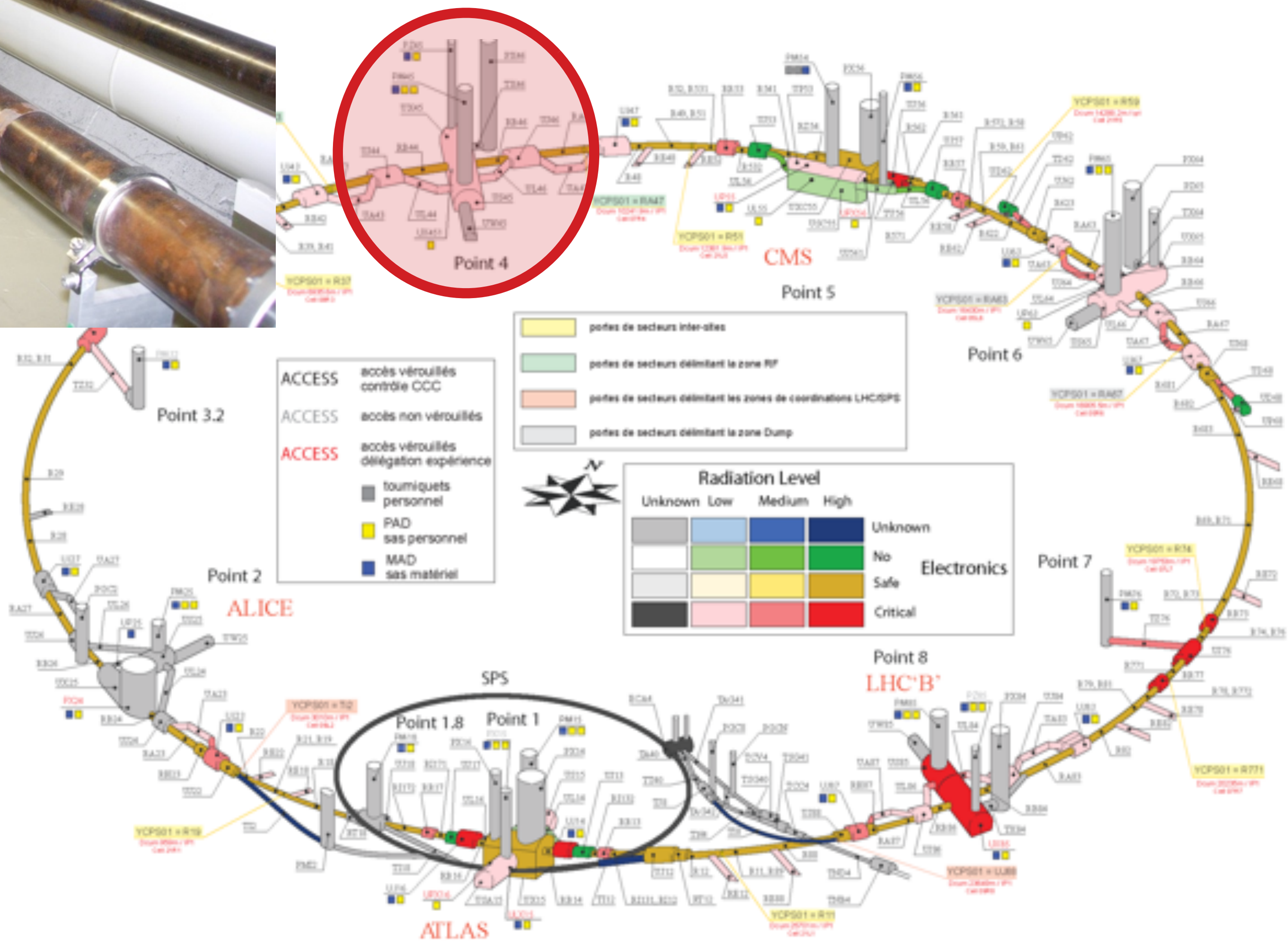
Starting point for technical design

Candidate locations for electron lenses in the LHC

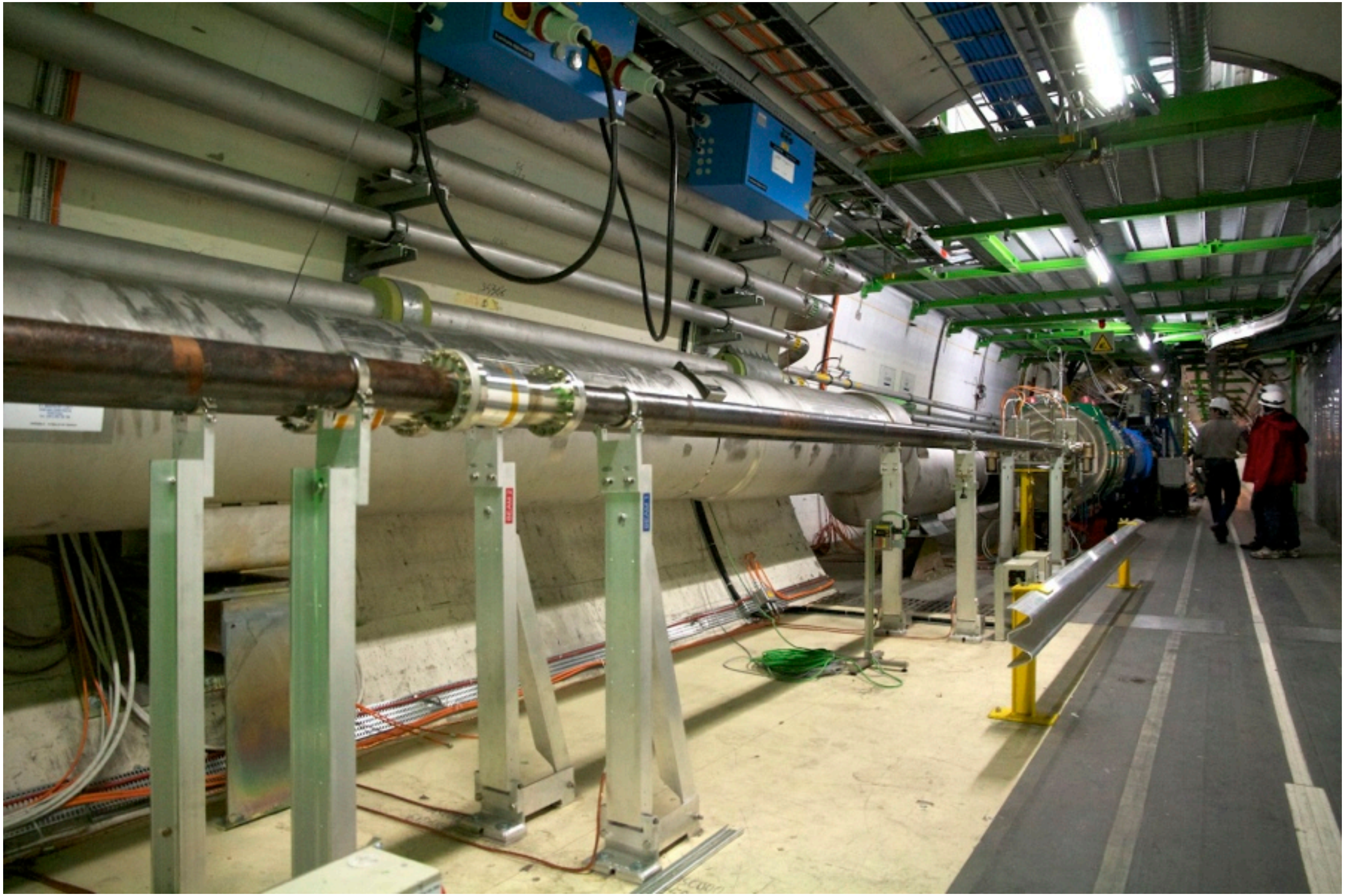


Upstream or downstream of Point 4:

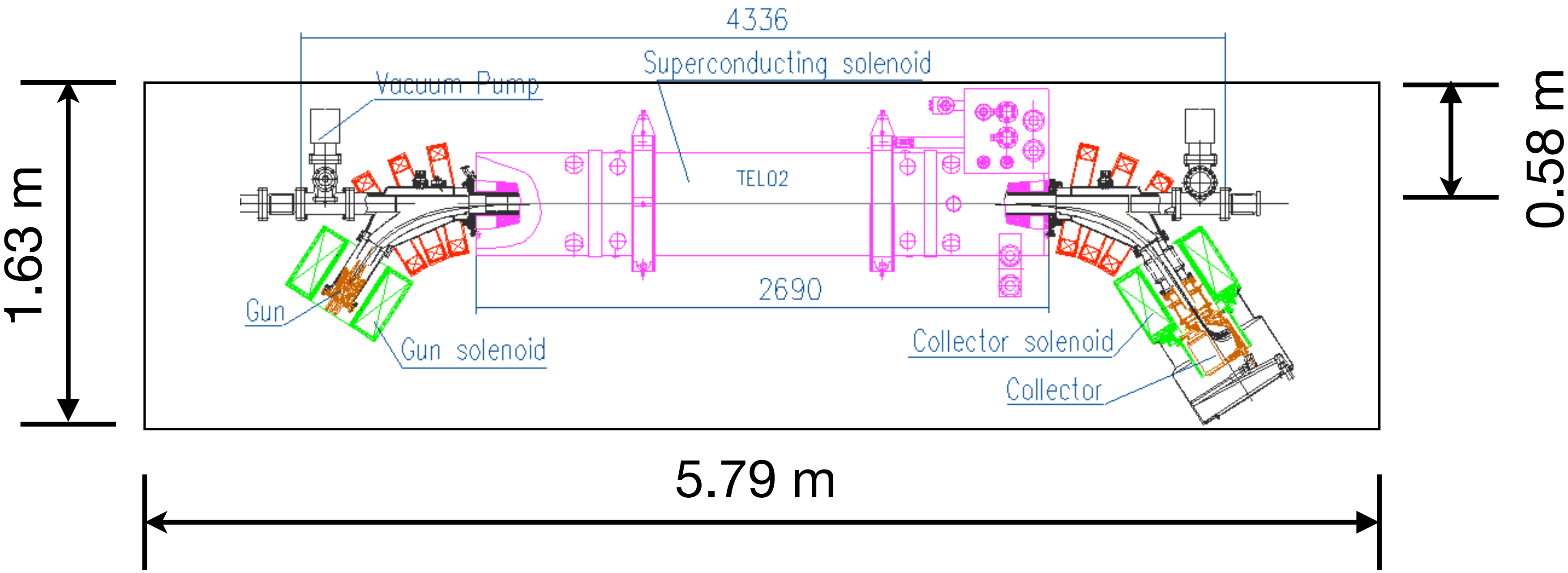
- Available longitudinal space
- Separation of beam axes: 420 mm
- Cryogenic infrastructure
- Lattice functions



Candidate location RB-46

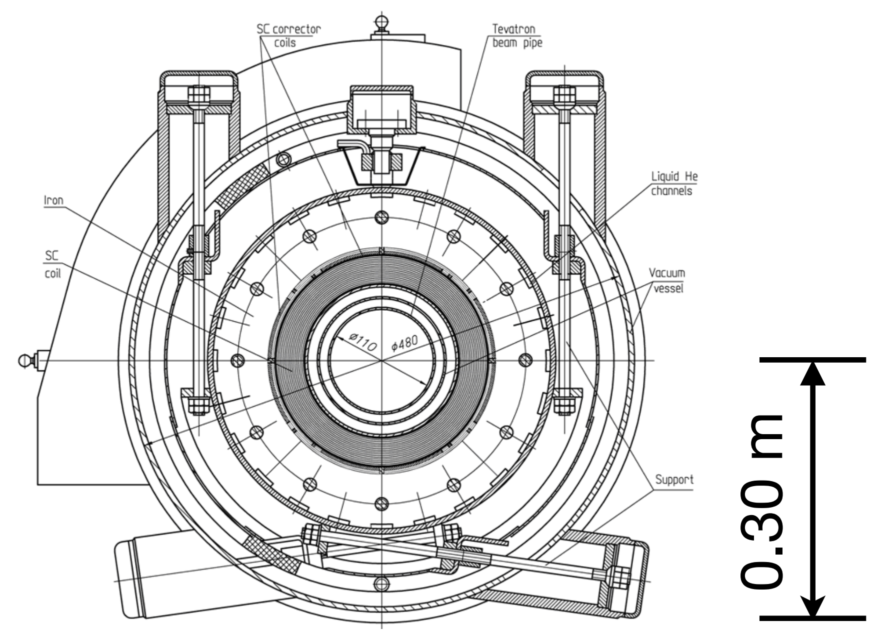


TEL2 dimensions for reference

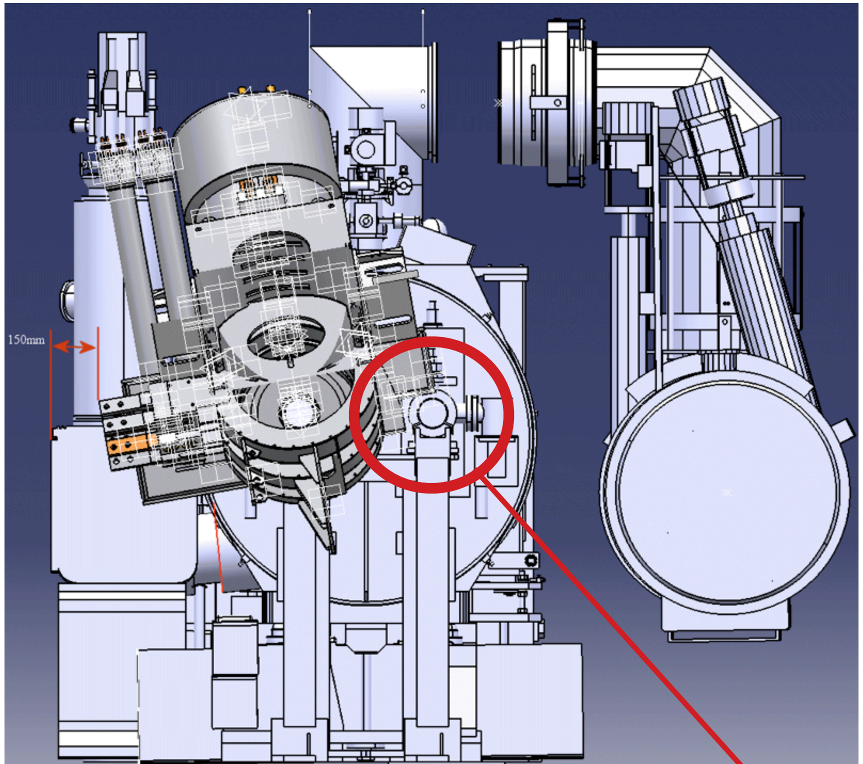


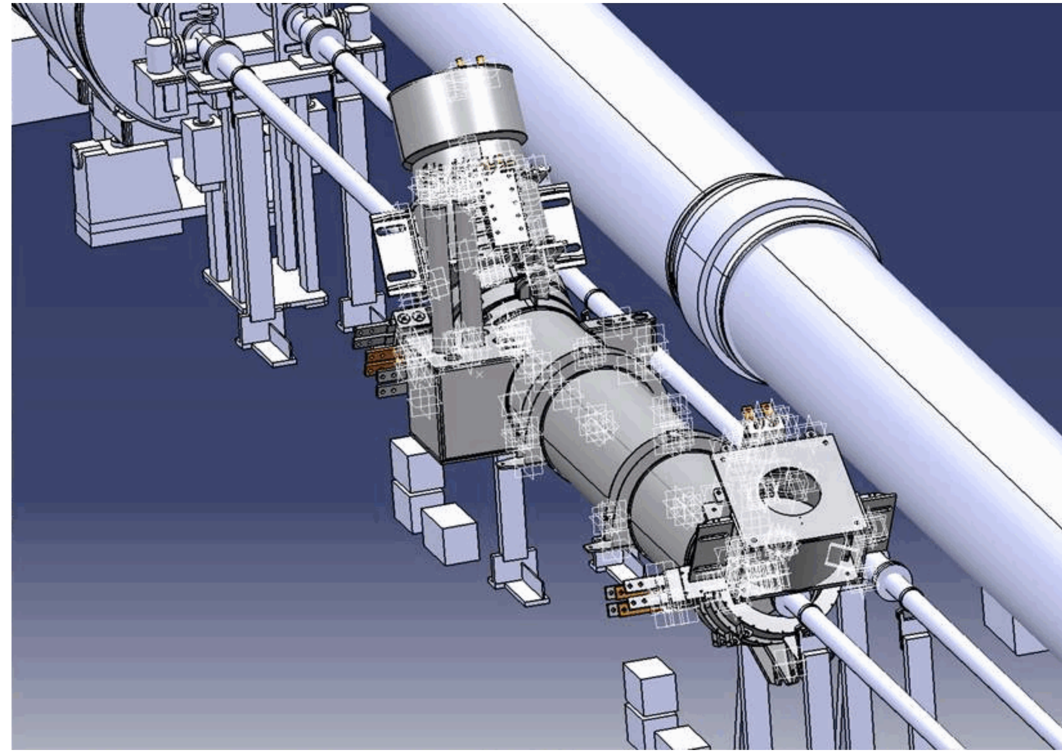
Height (including current and cryo leads): 1.47 m

Weight: about 2 t



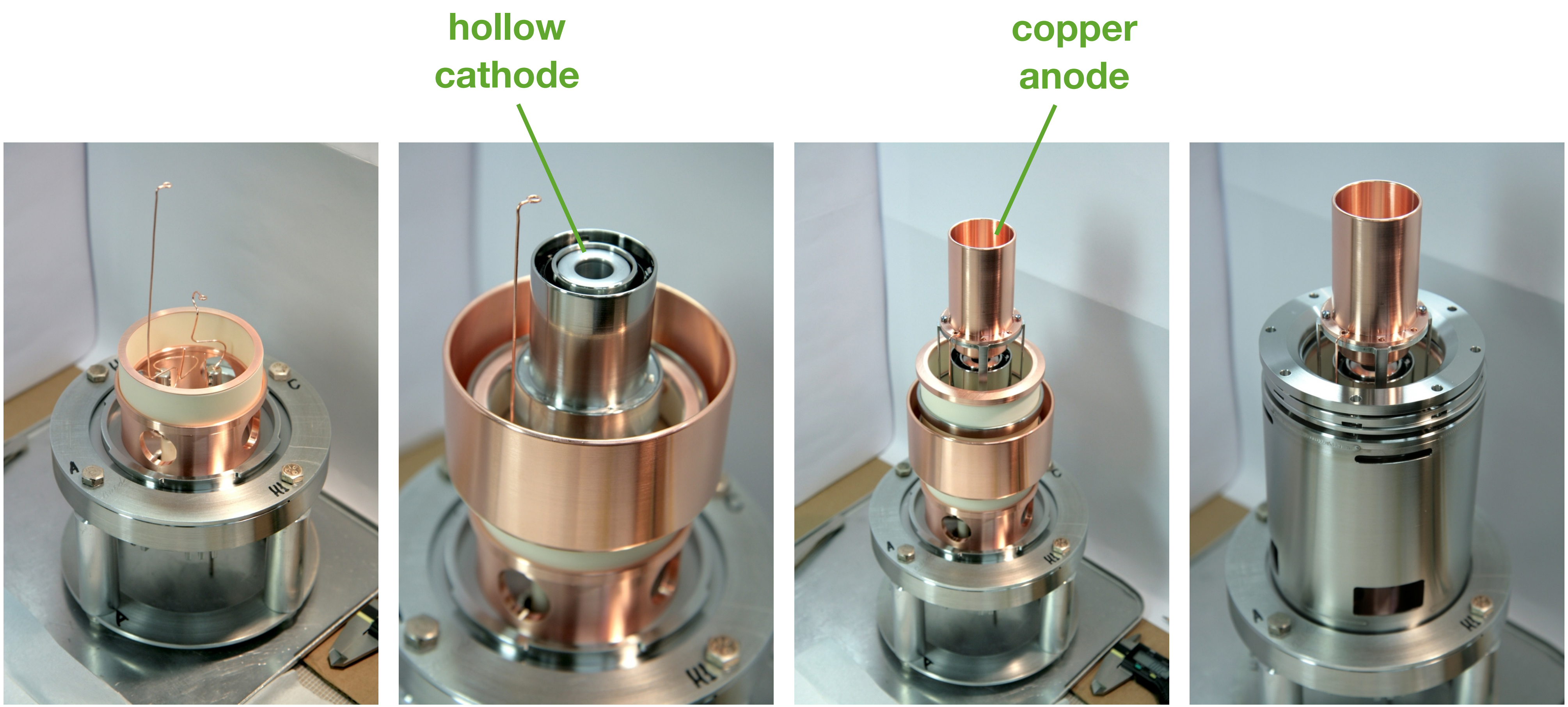
Mechanical integration studies for TEL2





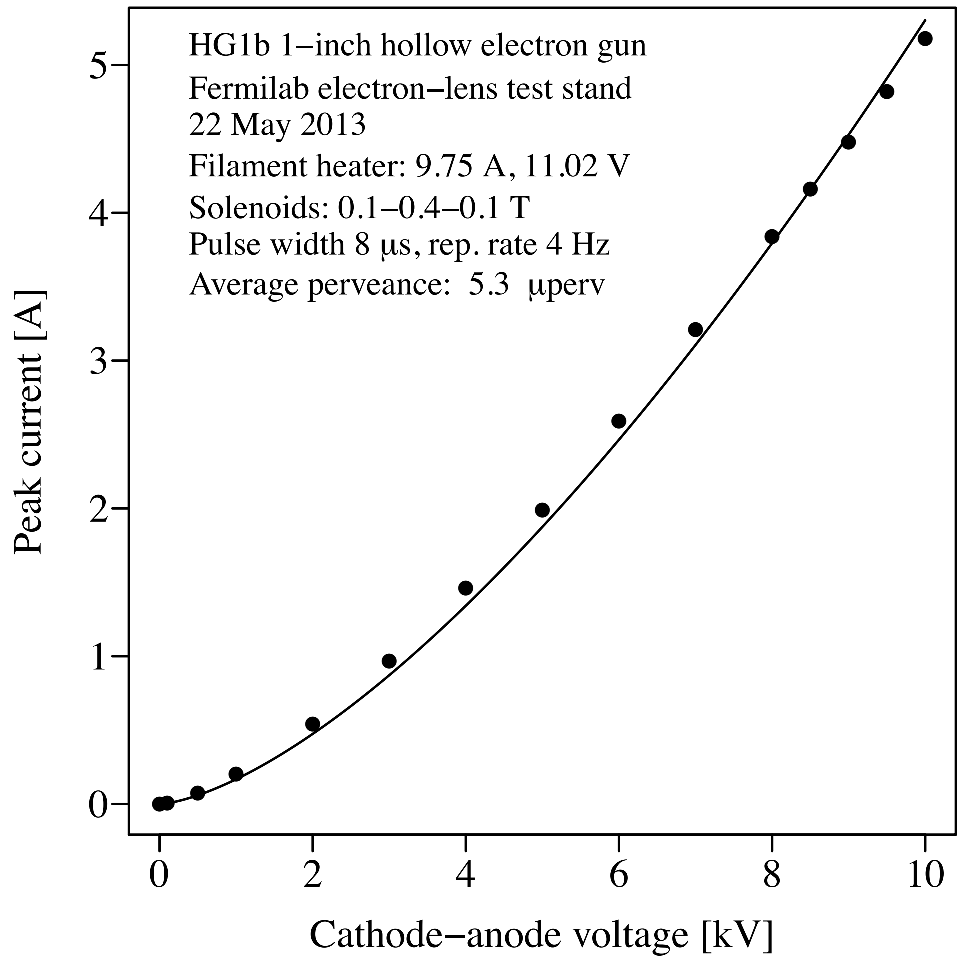
- Rotation is necessary to avoid interference
- New design of cryostat for LHC is preferable

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



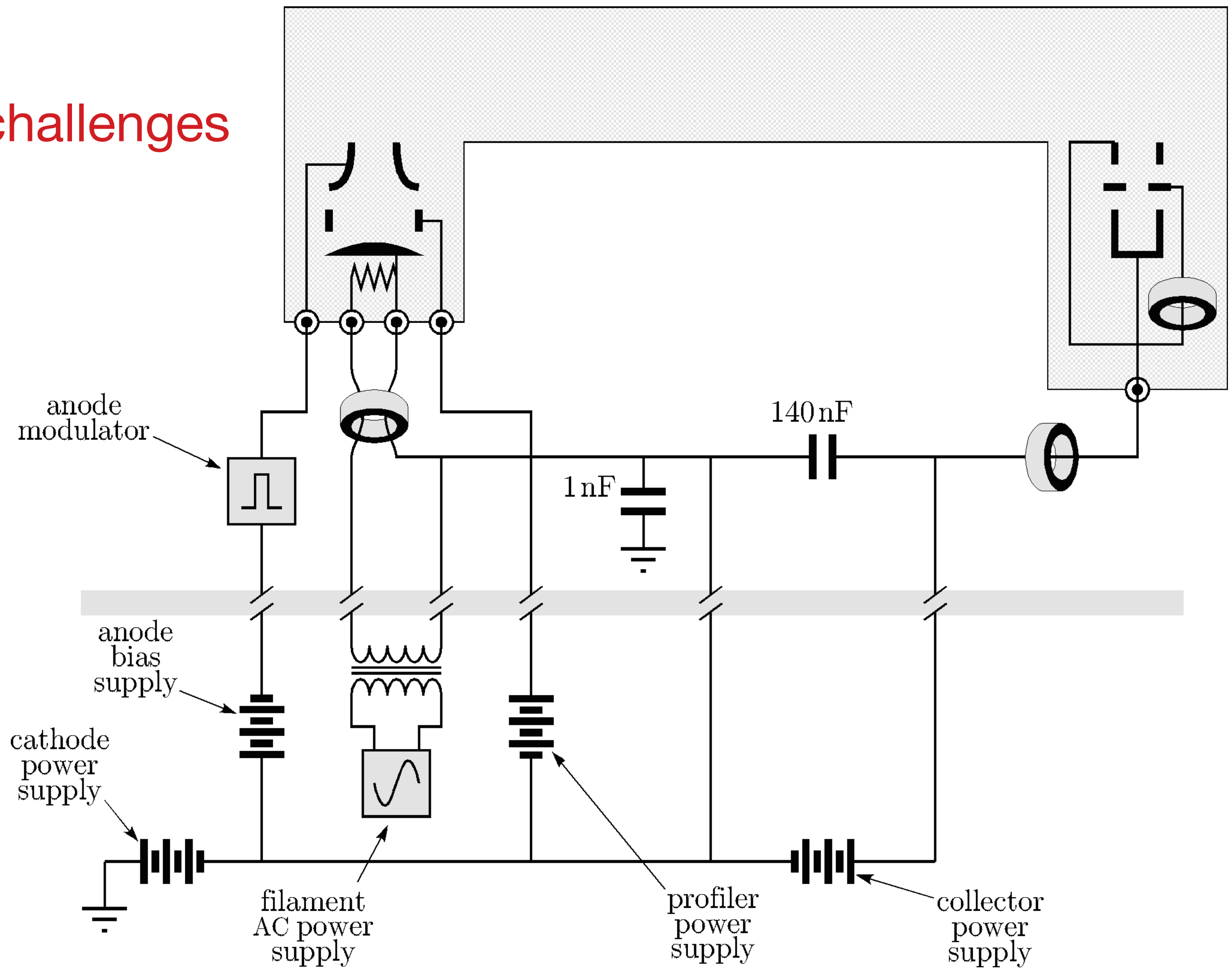
Yields 5 A at 10 kV

- 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

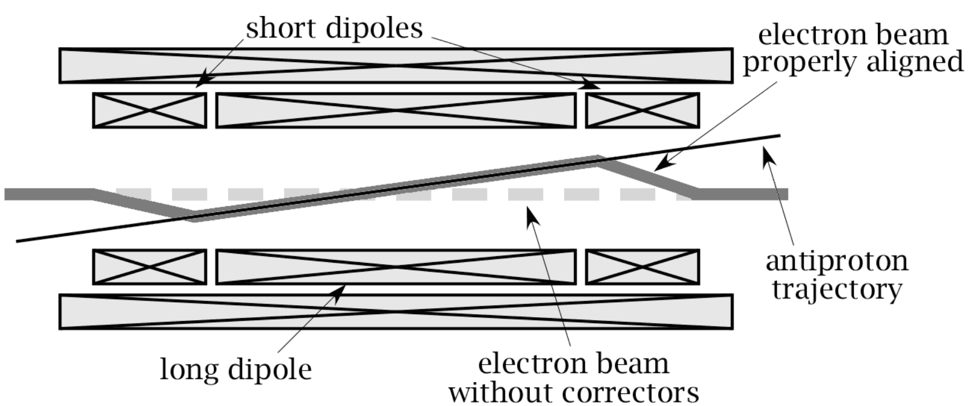
Cryogenics

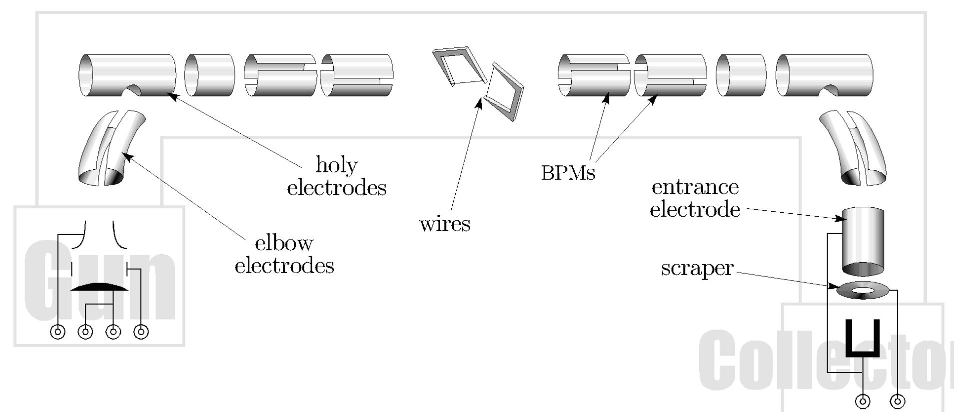
- cryogenics dominates installation time: at least 3 months required for warm-up, connections, cool-down
- electron lenses may be treated as stand-alone magnets at 4.5 K
- may take advantage of dedicated rf refrigerator for HL-LHC at IR4
- TEL2 static heat loads: 12 W for He at 4 K and 25 W for liquid 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

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

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)

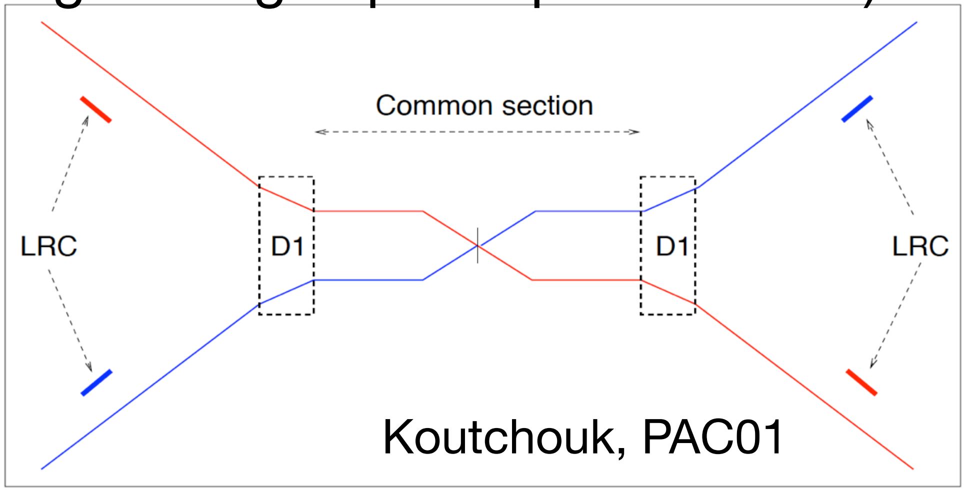
discussion and plans in Roderik Bruce's talk

Outline

- Introduction
- **Design of hollow electron beam scrapers for the LHC**
  - 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
- **Long-range beam-beam compensation with electron lenses**
  - Motivation, preliminary considerations, integration issues
- Conclusions

Long-range beam-beam compensation is essential for HL-LHC Plan B

- HL-LHC Plan B:
  - flat optics at collisions: (10, 50) cm β^* $\Rightarrow$ no IP1/5 compensation
  - no crab cavities required (crab crossing/kissing improve performance)
  - **a long-range beam-beam compensation scheme is needed** to achieve luminosity



- Wire compensators at 10σ to be tested after LS1: technically challenging (378 A required) and a risk for collimation and machine protection
- **Electron lenses for long-range beam-beam compensation are a safer, less demanding alternative, with pulsing option**
  - (21 A) × (3 m) required for HL-LHC, any transverse shape

[Valishev and Stancari, arXiv:1312.1660]

Long-range beam-beam compensation with electron lenses

Work is proceeding along two main lines:

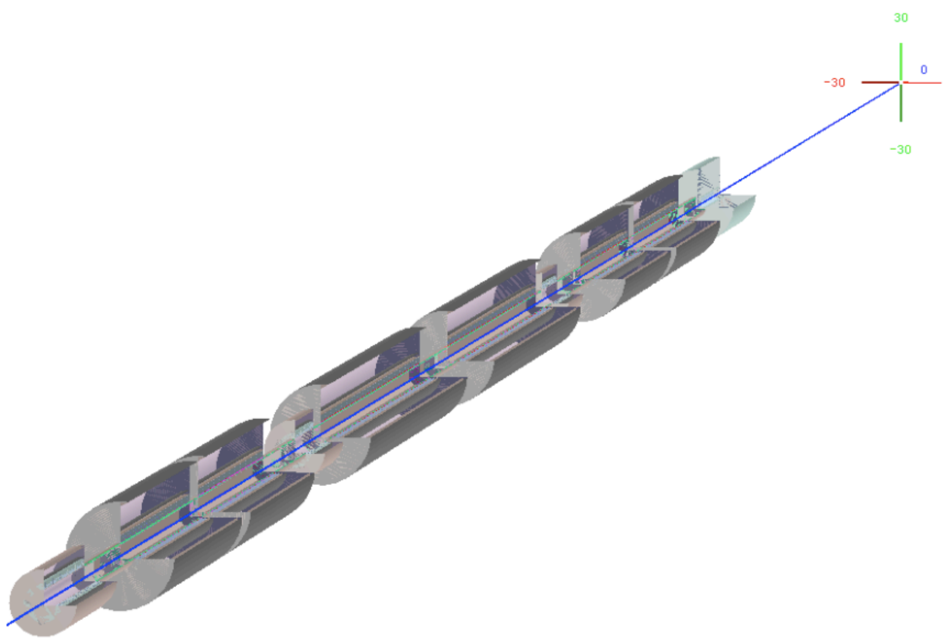
- **beam physics**: expected performance, sensitivity to location [Valishev's talk]
    - should work in both locations
        - between D1 and D2 (challenging layout and integration)
        - beyond D2
- **energy deposition** (superconducting solenoid) and **radiation to electronics** (anode high-voltage modulator) in both locations

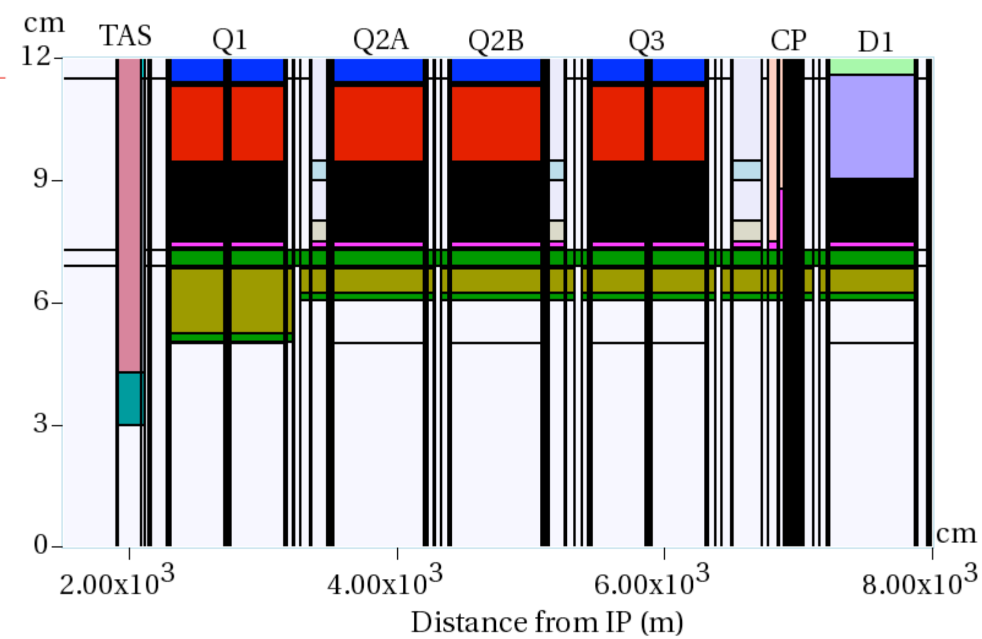
Energy deposition and radiation to electronics

I. Tropin and Mokhov's group

Integration into work flow for beam loss and machine-detector interface
in progress

MARS-MAD Beam Line Builder (MMBLB)





HL-LHC inner triplet and D1 dipole

Conclusions

- 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
- Studies for technical design were initiated
- Next steps
  - build electron-lens experience at CERN
    - hardware: test stand operation and diagnostics, engineering
    - modeling: electron beam dynamics, particle tracking
  - compare with alternative schemes
- Electron lenses are also a candidate for **long-range beam-beam compensation** (“e-wire”): concept developed, preliminary layout and integration studies

Thank you for your attention!