# Plans for deployment of hollow electron lenses at the Large Hadron Collider for enhanced beam collimation

S. Redaelli, A. Bertarelli, R. Bruce, D. Perini, A. Rossi, B. Salvachua – CERN, Geneva, Switzerland

G. Stancari, A. Valishev – FNAL, Batavia, IL, USA

Research supported by FP7 HiLumi LHC, Grant Agreement 284404 and by the US DOE through the US-LARP program. Fermilab is operated by Fermi Research Alliance, LLC under Contract DE-AC02-07CH11359 with the US DOE.

# Outline

- Introduction: Need for halo control in the LHC
- Halo control using hollow electron lens
- Design of a hollow electron lens for the LHC
- Present status and timeline
- Summary

# LHC collimation challenge

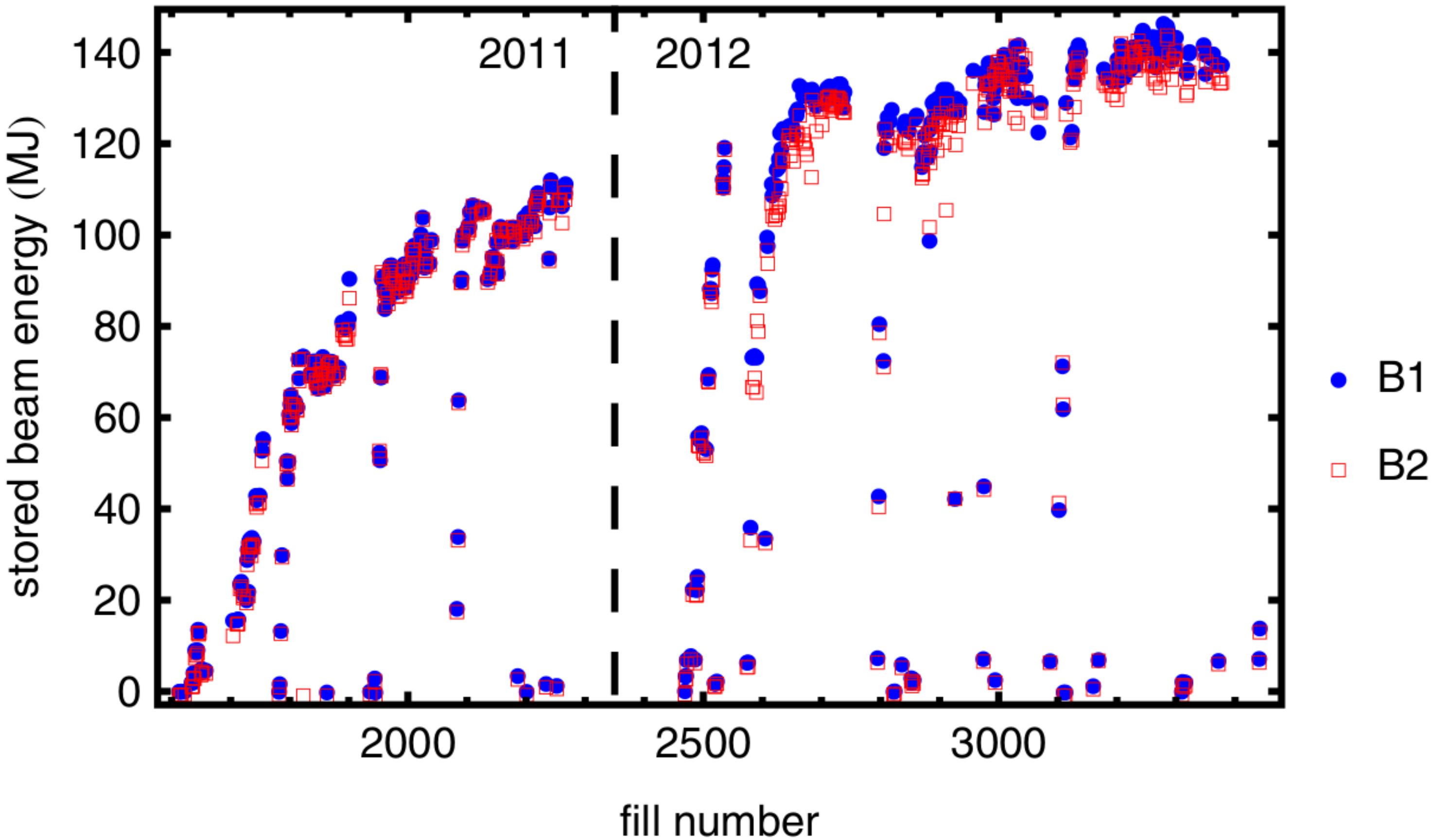
- LHC: 27 km ring, designed to collide 7 TeV proton beams
- Huge stored energy per beam : 362 MJ for nominal configuration, 675 MJ for planned upgrade HL-LHC


675 MJ = kinetic energy of USS Harry S. Truman cruising at 7 knots

- Several MJ found above 3 σ (7 MJ for Gaussian, in reality more)
- Beams could be highly destructive if not controlled well => collimation plays an essential role to prevent dangerous losses

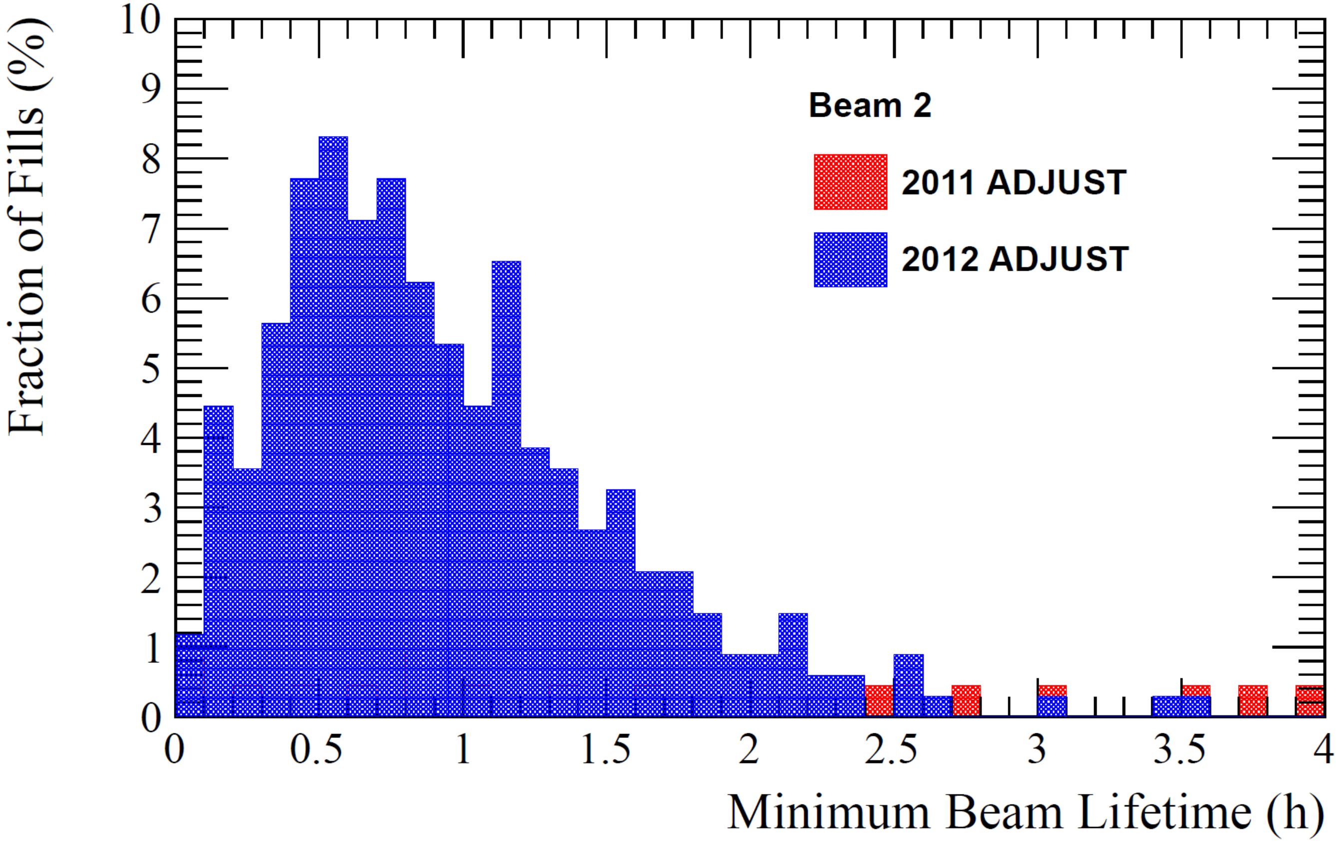
# Stored energy in Run 1

- LHC collimation worked very well in Run I at 4 TeV (2010-2013)
- Routinely stored ~140 MJ beams over hours



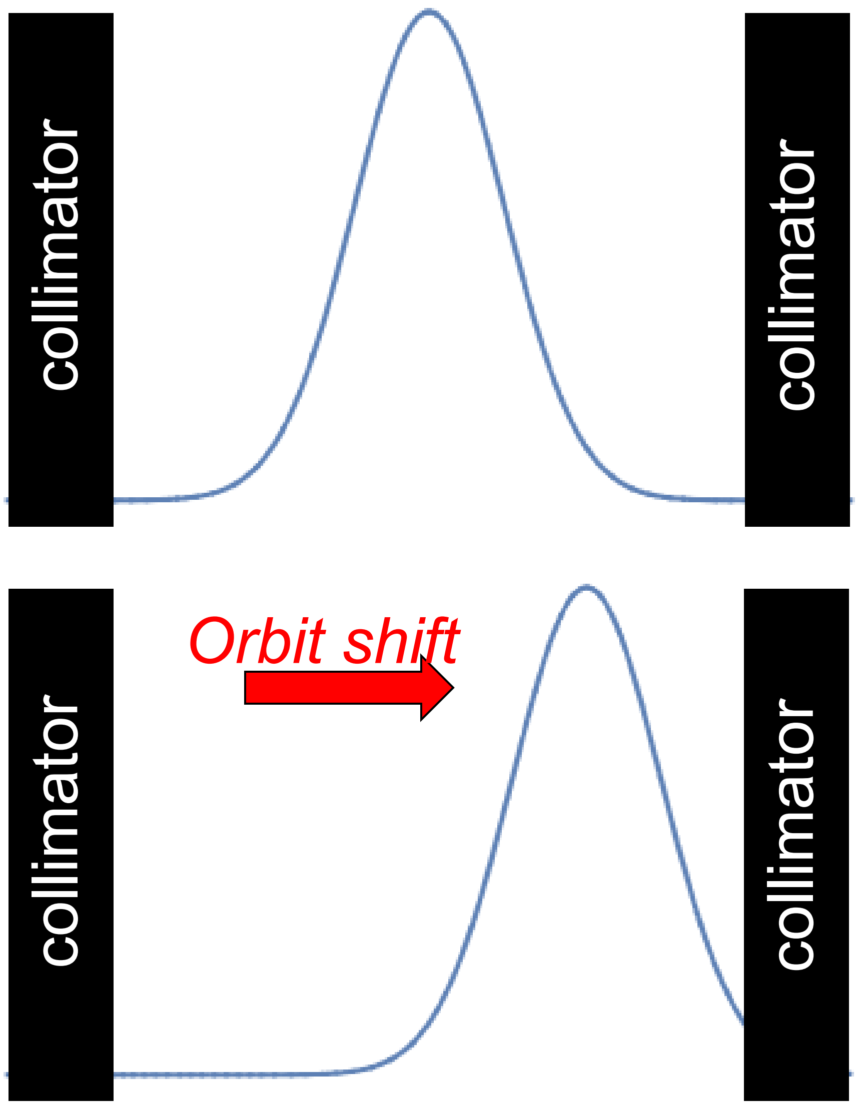
# Run 1 lifetime drops

- Operation sometimes perturbed by sudden losses => beam dumps



# Halo removal

- Halo scraped on collimators when orbit moves
- Expect higher losses in the future (higher stored energy)
- HL-LHC: phase failure of crab cavity => beam gets a ~1-σ kick which causes scraping
- Possible mitigation: limit peak loss by actively depleting halo in controlled way

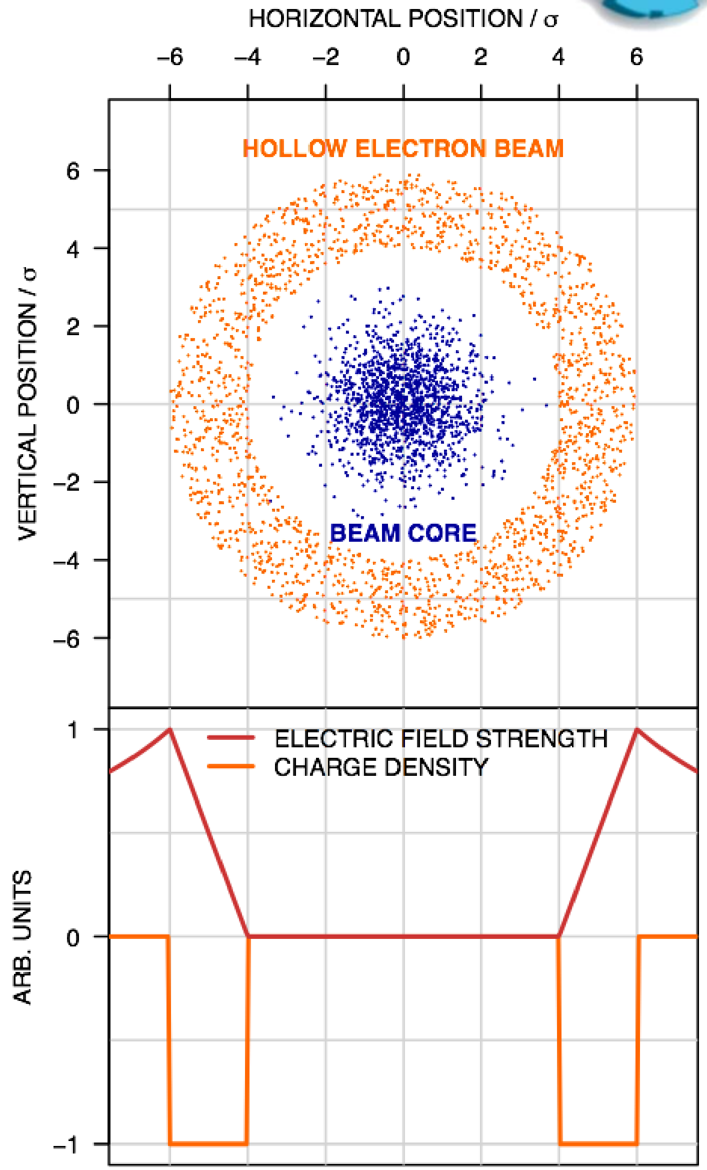


# Methods for halo control

- Hollow electron lens
  - Subject of this talk
  - Requires new hardware
- Alternatives under parallel study:
  - Put halo on resonance using a tune ripple or transverse damper
  - Relies on very good knowledge of tune and detuning with amplitude – not evident!
  - Does not require new hardware

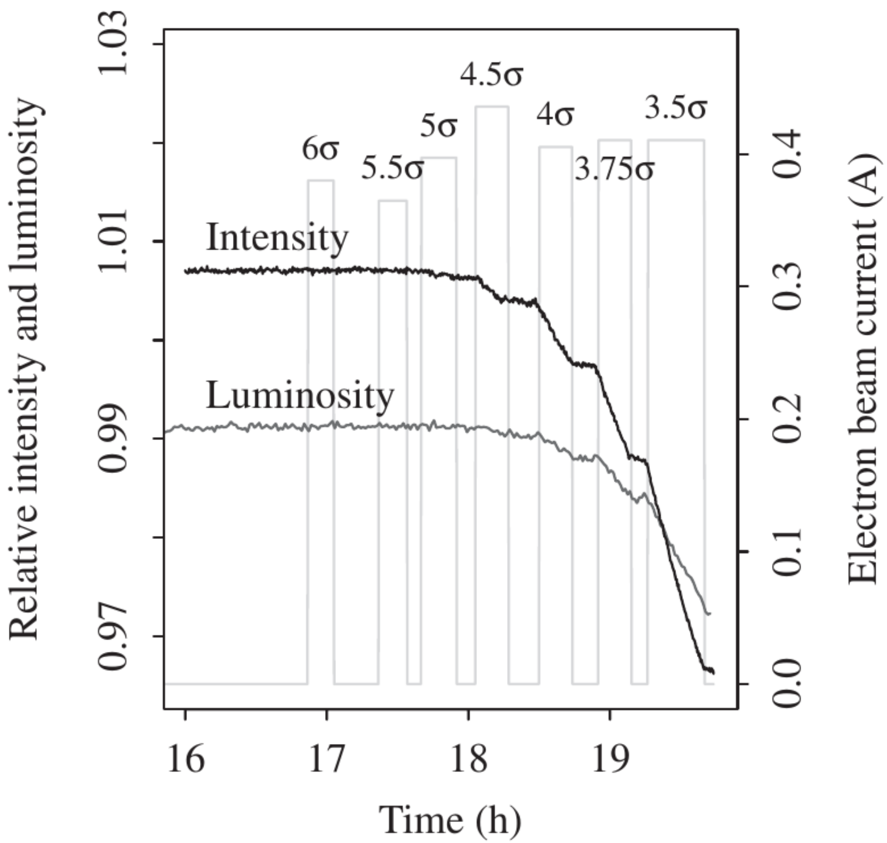
# Principle of hollow e-lens

- Main beam travelling inside a hollow electron beam (cylindrical shell) over a short distance
- Halo particles kicked to higher amplitudes by electromagnetic field of electron beam (slow process)
  - Eventually hit collimators
- Electron beam hollow => core not affected (in field-free region)



# Experimental studies at Tevatron

- Operating the e-lens at inner radius 4-4.5σ has no effect on luminosity while the intensity goes down =>
  halo is scraped
- Loss spikes due to beam jitter and tune adjustments suppressed

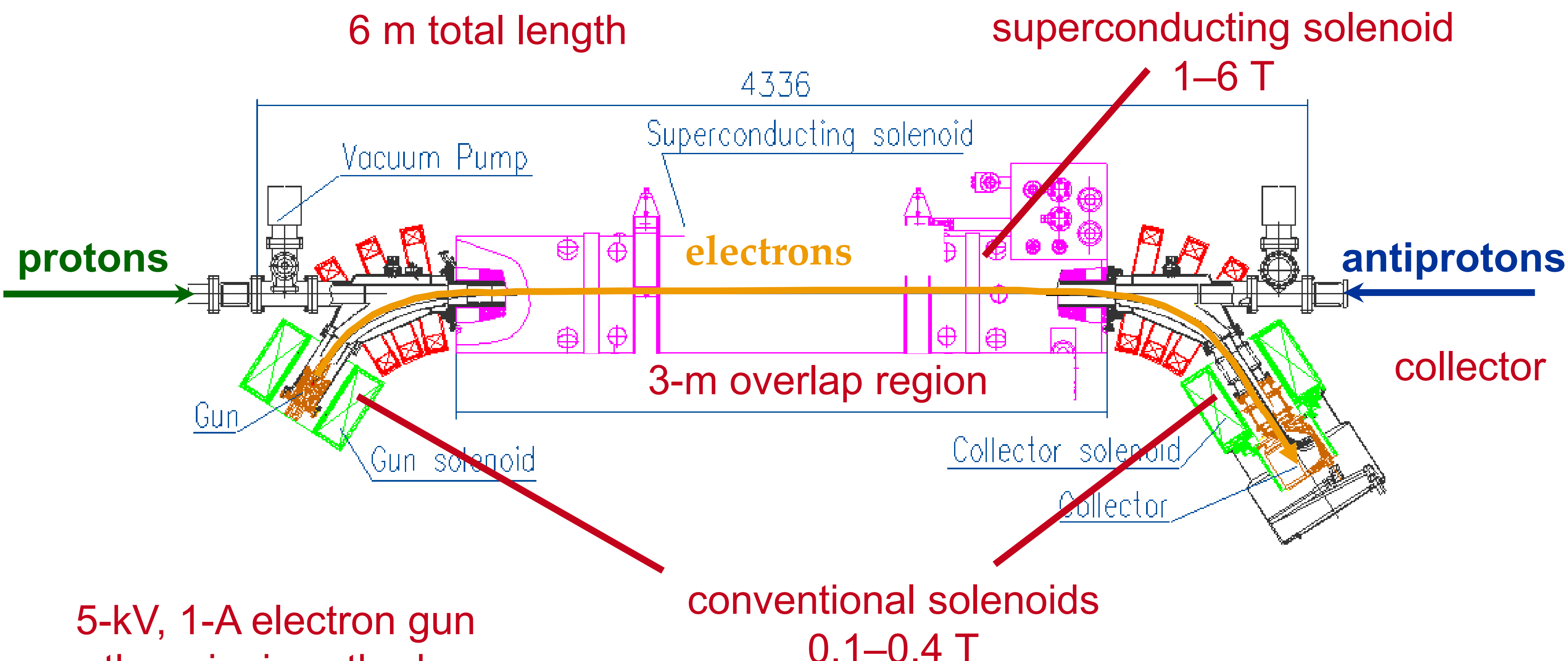



*Stancari et al., Phys. Rev. Lett. 107, 084802 (2011)*

*See also*
*Shiltsev, BEAM06, CERN-2007-002*
*Shiltsev et al., EPAC08*
*Shiltsev et al., Phys. Rev. STAB11, 103501 (2008)*

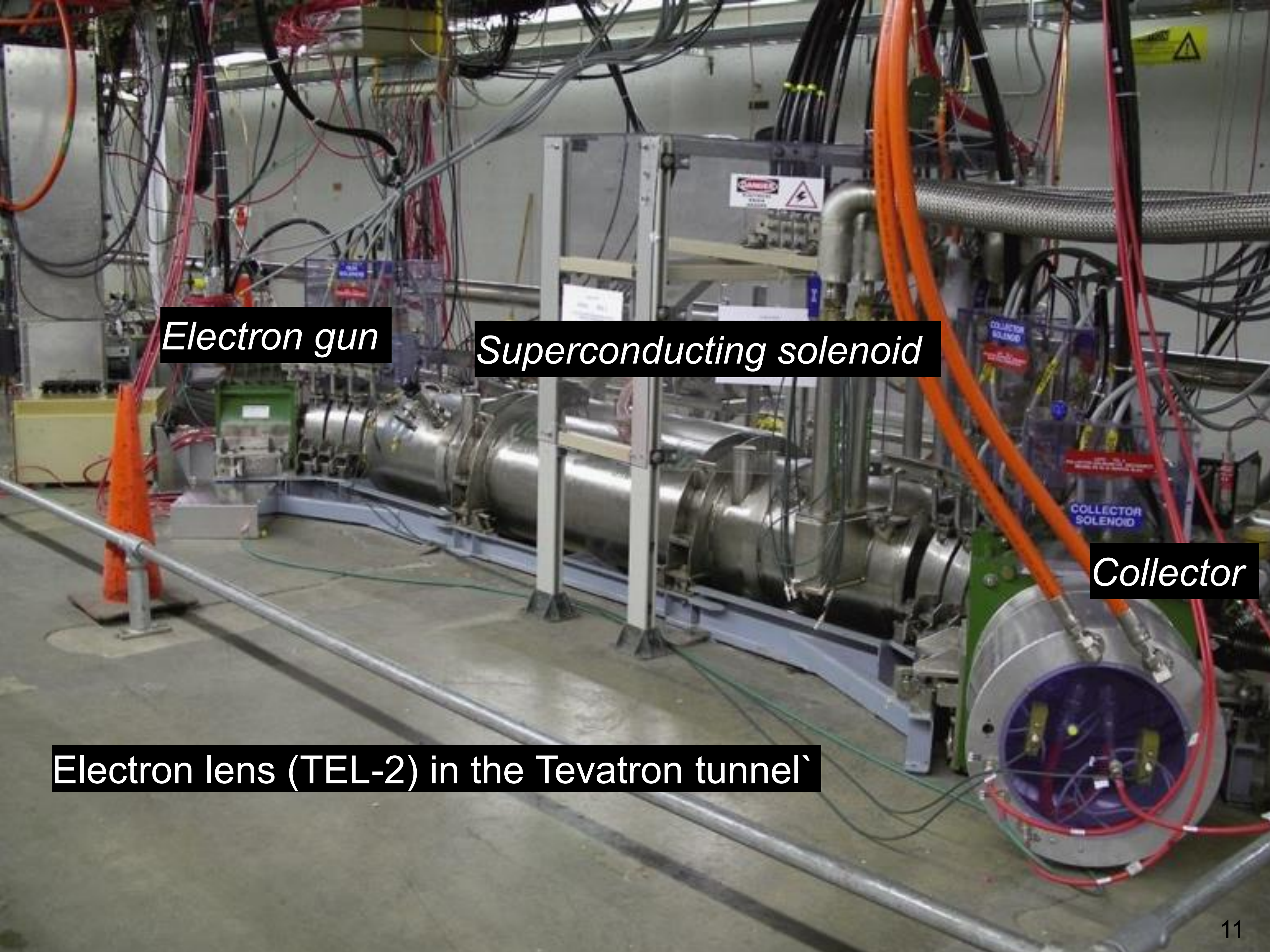
# Tevatron electron lens layout

- Pulsed, magnetically confined, low-energy electron beam
- Tunable transverse halo kicks ~0.1 μrad



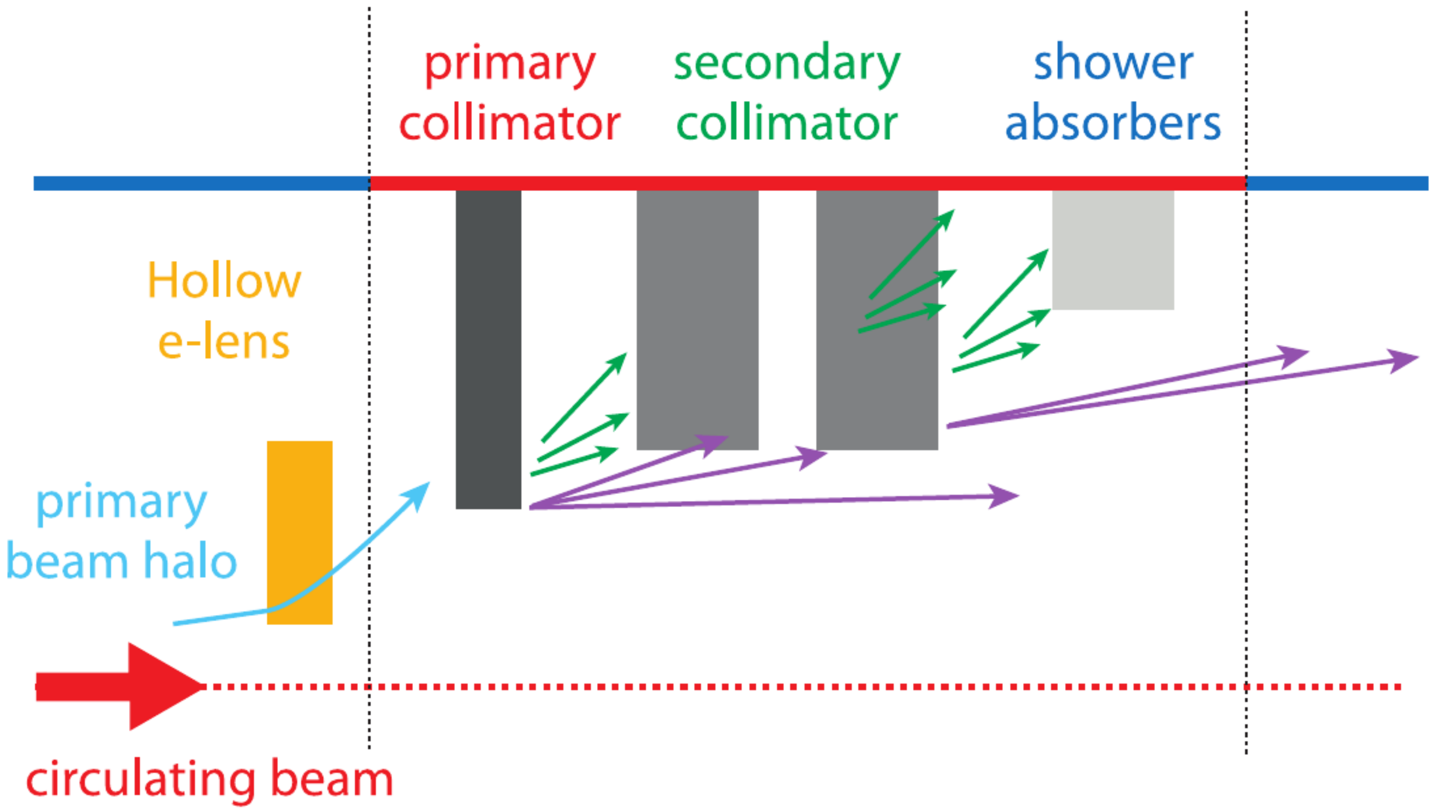

5-kV, 1-A electron gun
thermionic cathode
200-ns rise time

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


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

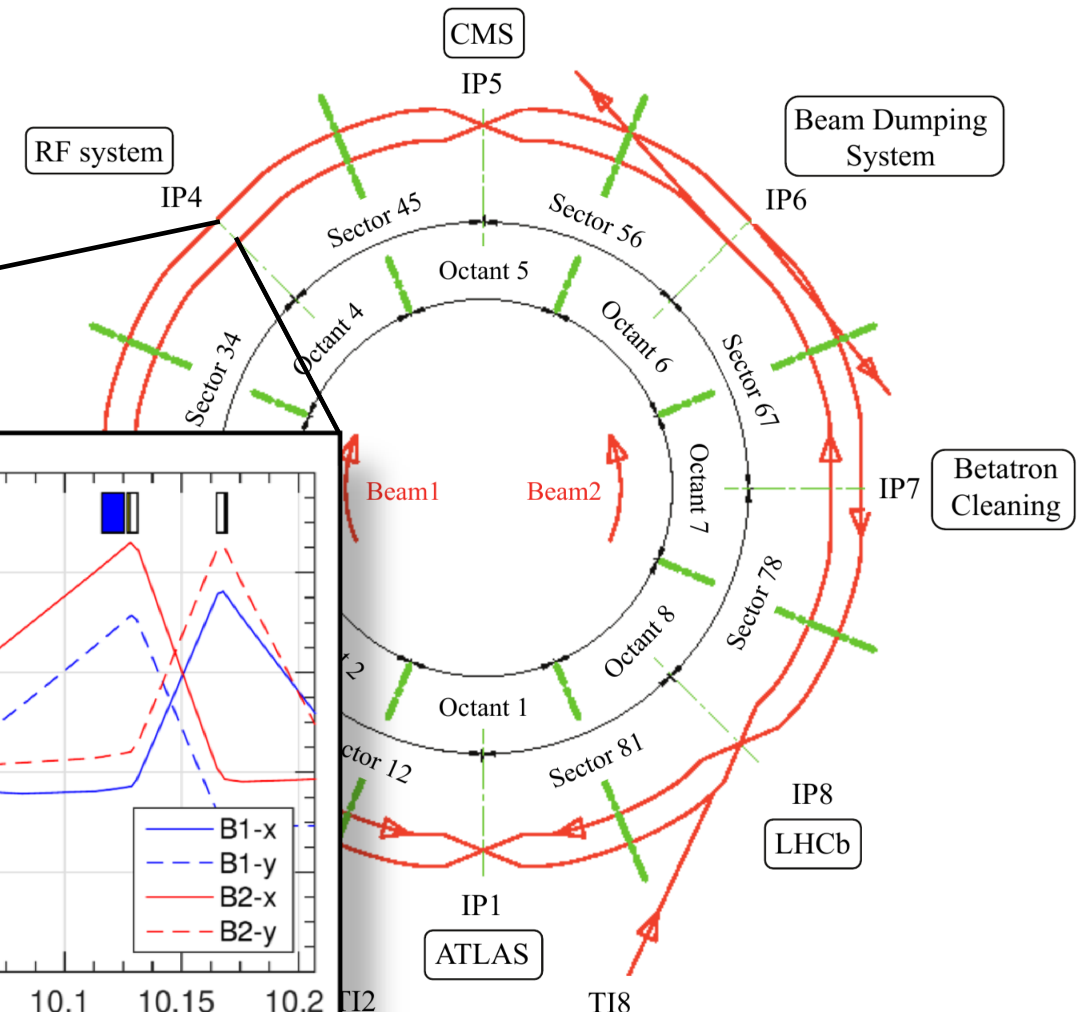
# Hollow electron lens for the LHC

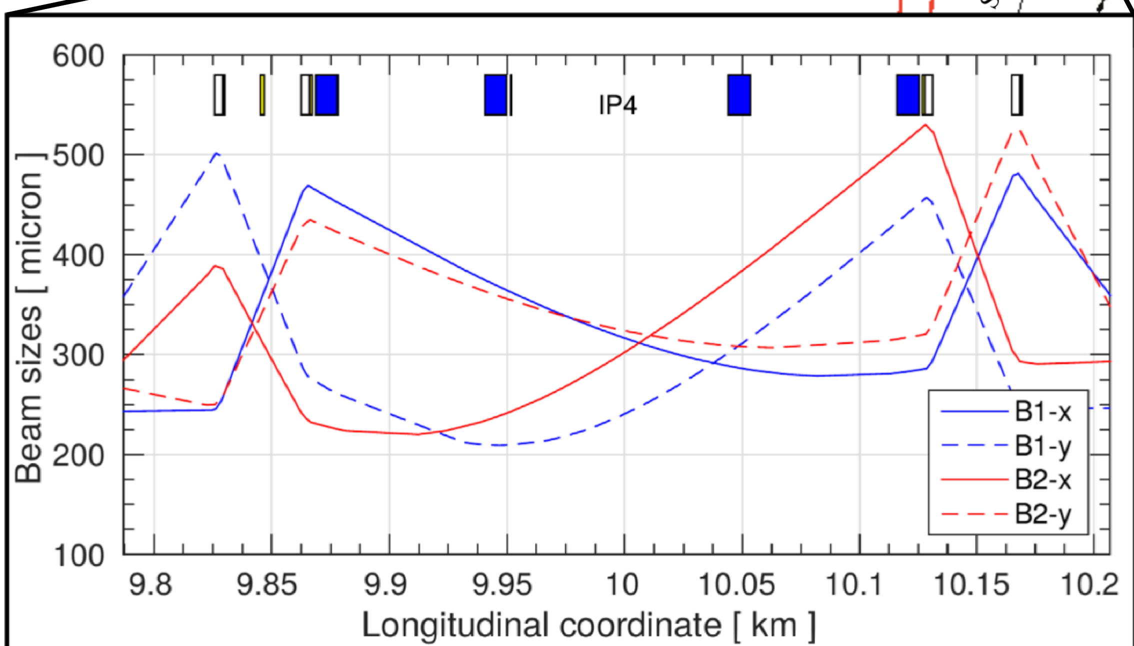
- Should be integrated in existing collimation system



# Proposed location in the LHC

- Best place found: IP4
  - Space available and $\beta_x \approx \beta_y$



# Required parameters

- Kick given by electron lens

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

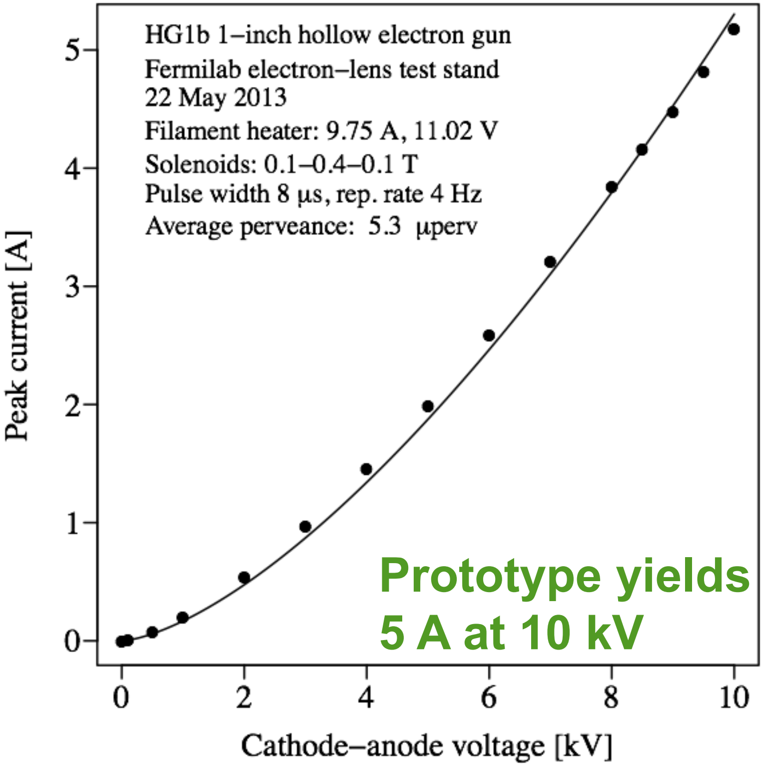
- Keeping the Tevatron hardware, kicks given to protons would be factor ~7 less from magnetic rigidity
  - Increase electron current to compensate (or length – less attractive)
- Halo removal rate depends not only on kick but also on lattice non-linearities
  - Simulations (LifeTrack and SixTrack) demonstrate desired halo depletion with 5A current and stochastic excitation mode

*A. Valishev, FERMILAB-TM-2584-AP (2014)*

# Hollow electron gun (1)

- New gun needed for higher current and adjusted electron beam size
- First prototype built and tested at Fermilab.
- Tungsten dispenser cathode with BaO:CaO:Al2O3 impregnant, 1400 K

First prototype of hollow cathode

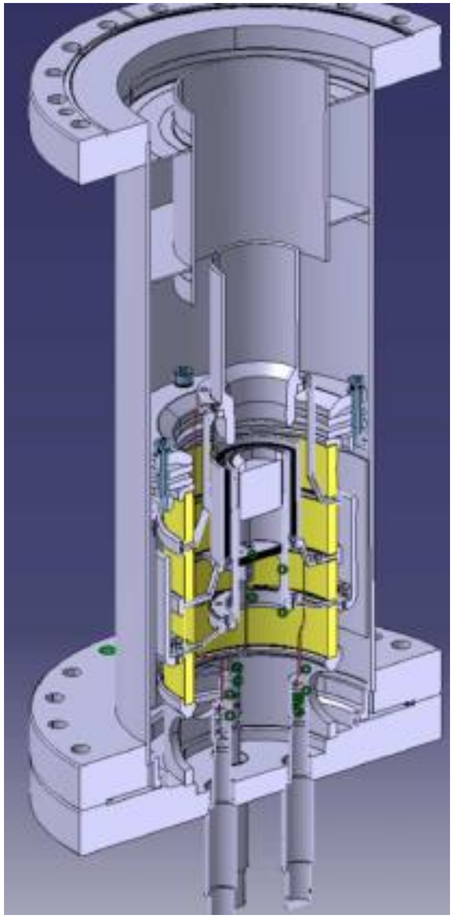



Prototype yields 5 A at 10 kV

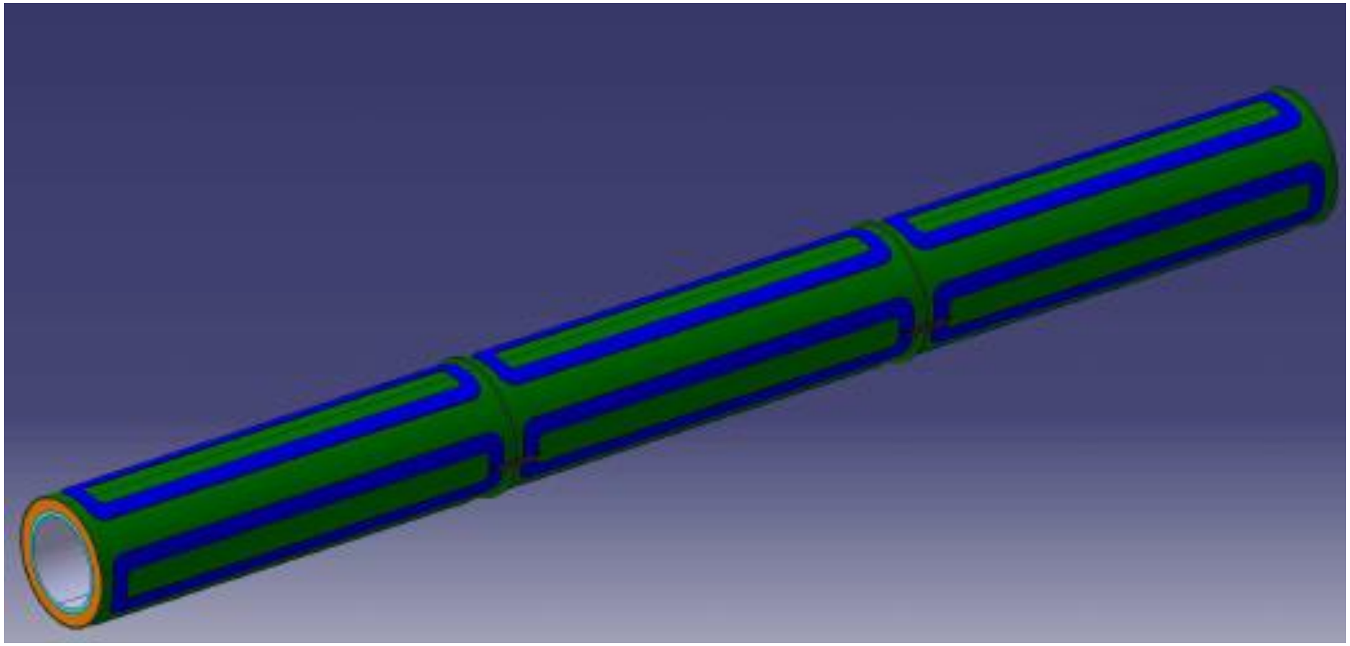
# Hollow electron gun (2)

- Powering
  - 10 kV modulator used to power the gun
  - If we want to act on a subset of bunches: Need fast rise time of 200 ns
- Next gun to be built at CERN
  - Test stand planned to be set up at CERN

**Present cathode design**



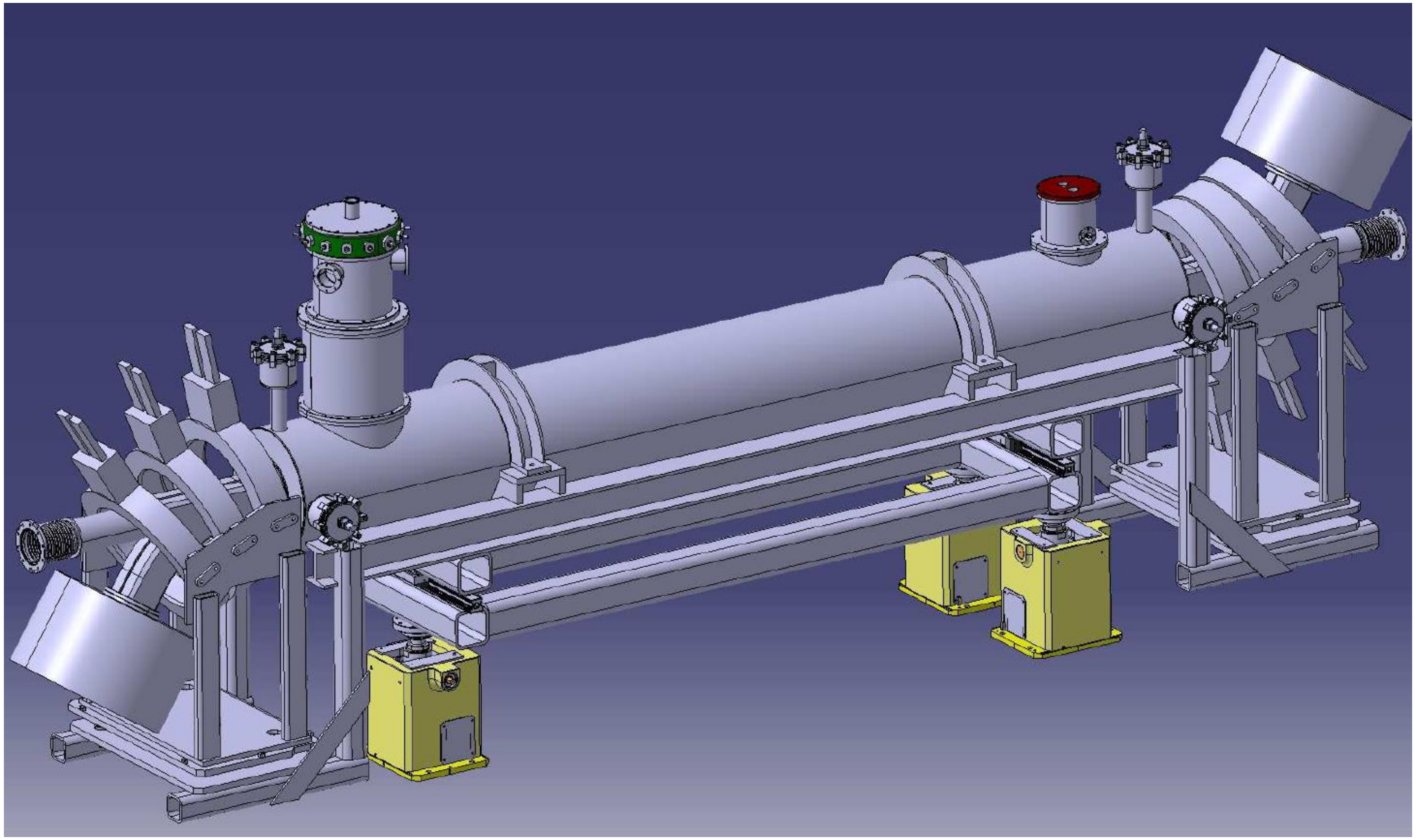
# Superconducting solenoid



- 3 m long, 250 A current, 5T field, cooled with He to 4.2 K
- Includes 6 correction coils for alignment of electron beam and pickup coil for quench protection

# Technical design

- S-shaped to compensate for the asymmetric electron beam distributions seen by the main beam
- Gun and collector stick out in vertical plane to fit in tunnel



# Instrumentation

- Detailed design of instrumentation not yet started
- Need to monitor position of electron beam and proton beam
  - Requirement: About 20 μm accuracy (0.1 σ of proton beam), good accuracy for fast (proton) and slow (electron) signals
- Need to monitor electron current at cathode and collector
- Need to monitor electron beam profile
- In addition: need halo monitor for the LHC proton beam to study halo population in various scenarios

# Summary of main parameters

| Parameter | Value or range |
|---|---|
| *Geometry* | |
| Length of the interaction region, $L$ [m] | 3 |
| Desired transverse scraping range [$\sigma$] | 4–8 |
| Inner/Outer cryostat diameter [mm] | 132 / $\approx$ 500 |
| Inner vacuum chamber diameter [mm] | 100 (80) |
| *Magnetic fields and magnet parameters* | |
| Gun and collector solenoid, $B_g$ [T] | 0.2–0.4 |
| Main solenoid (superconducting), $B_m$ [T] | 2–6 |
| Compression factor, $\sqrt{B_m/B_g}$ | 2.2–5.5 |
| Maximum current in main solenoid [A] | 250–300 |
| *Electron gun* | |
| Inner/outer cathode radius [mm] | 6.75/12.7 |
| Peak yield at 10 kV, $I$ [A] | 5 |
| *Cryogenic requirements* | |
| Static heat load [W] | $\leq$5 |
| Dynamic heat load from electric powering [W] | $\leq$0.5 |
| Dynamic heat load from beam effects | negligible |
| *High-voltage modulator* | |
| Cathode-anode voltage [kV] | 10 |
| Rise time (10%–90%) [ns] | 200 |
| Repetition rate [kHz] | 35 |

# Conceptual design

- Collaboration between US LHC Accelerator Research Program (LARP), LHC collimation team, and HL-LHC Project
- Conceptual design report finished in 2014
  - Available as **CERN-ACC-2014-0248**, **FERMILAB-TM-2572-APC** and **arXiv:1405.2033**



FERMILAB-TM-2572-APC

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

G. Stancari,[†] V. Previtali, and A. Valishev
*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.

# Strategy

- Collimation needs can only be defined in detail after gaining operational experience at 6.5 TeV (end of 2015)
  - Uncertainties: cleaning efficiency, lifetimes, quench limits, impedance
  - Final decision on installation to be taken based on Run II experience
- Meanwhile, proceed with the completion of a design for the construction of 2 devices.
  - Estimated time needed: about 3 years
  - If technical design is finalized in 2015, could aim at installation during long shutdown in 2018

# Conclusions

- Hollow electron lenses could be used at the LHC to deplete the beam halo in a controlled way, avoiding sharp loss spikes
  - Successfully tested at Tevatron
- Conceptual design finished for e-lens with LHC requirements
  - Design of key components profiting from FNAL (gun) and CERN (solenoid) experience.
- Technical design and integration studies ongoing
  - Could aim at installing 1 device per beam in 2018
- Final decision to be based on LHC beam experience at 6.5 TeV
  - Will actively monitor the LHC tails and beam lifetimes in 2015 to establish adequate action plan

# Some references


- *V. Shiltsev, in Proceedings of the 3rd CARE-HHH-APD Workshop CERN-2007-002, 2007*
- *V. Shiltsev, in Proceedings of the CARE-HHH-APDWorkshop (BEAM07), CERN-2008-005 (2008).*
- *V. Shiltsev et al., EPAC08*
- *V. Shiltsev et al., Phys. Rev. STAB11, 103501 (2008)*
- *G. Stancari et al., Phys. Rev. Lett. 107, 084802 (2011)*
- *G. Stancari et al., IPAC11*
- *G. Stancari et al., HB2012*
- *LHC Collimation Review 2013, http://indico.cern.ch/event/251588,*
- *V. Previtali et al., IPAC13*
- *G. Stancari et al., NAPAC13*
- *V. Previtali et al., FERMILAB-TM-2560-APC, 2013*
- *V. Moens, CERN-THESIS-2013-126, 2013*
- *G. Stancari, FERMILAB-FN-0972-APC, 2014*
- *A. Valishev, FERMILAB-TM-2584-APC, 2014*
- *H. Rafique et al., TUPTY069, IPAC15*