Collimation with hollow electron beams: a proposed design for the LHC upgrade

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Context and motivation

- Hollow electron lenses can be used for collimation and scraping of high-power hadron beams when radiation damage and impedance limit the use of conventional collimators
  - Shiltsev, BEAM06, CERN-2007-002
  - Shiltsev et al., EPAC08
- Concept demonstrated experimentally at the Fermilab Tevatron collider
- Measured halo removal rates, effects on the core, enhancement of diffusion, mitigation of loss transients from beam jitter and tune adjustments
  - Stancari, Valishev, et al., Phys. Rev. Lett. **107**, 084802 (2011)
  - Stancari, APS/DPF Proc., arXiv:1110.0144 [physics.acc-ph] (2011)
- Promising technique for the LHC upgrades

Hollow beam collimation in a Tevatron electron lens

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

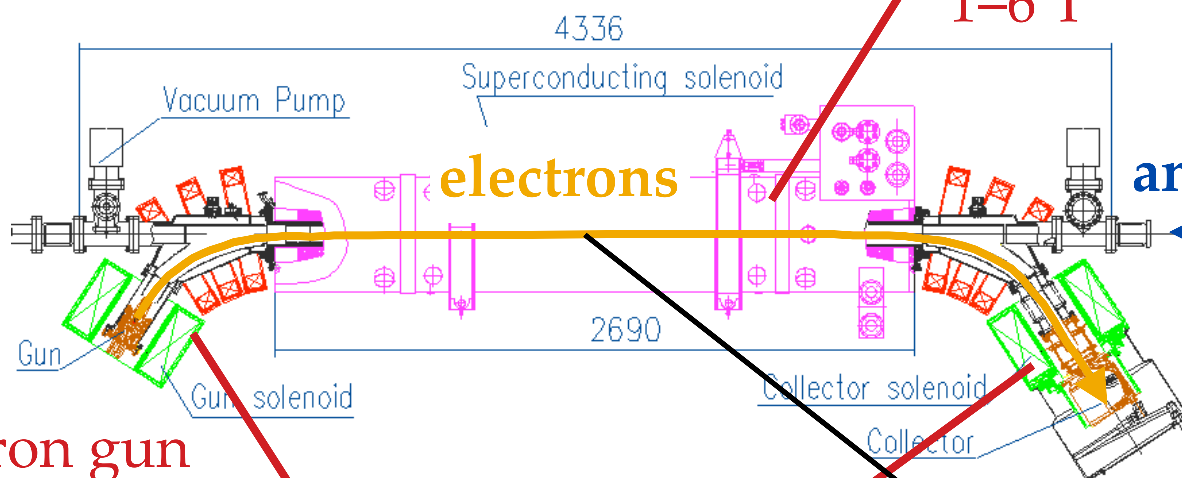
6 m total length

superconducting solenoid
1–6 T

protons

electrons

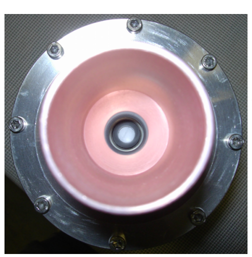
antiprotons

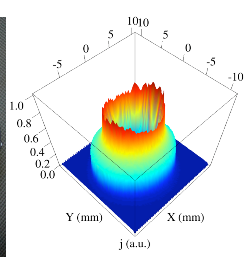


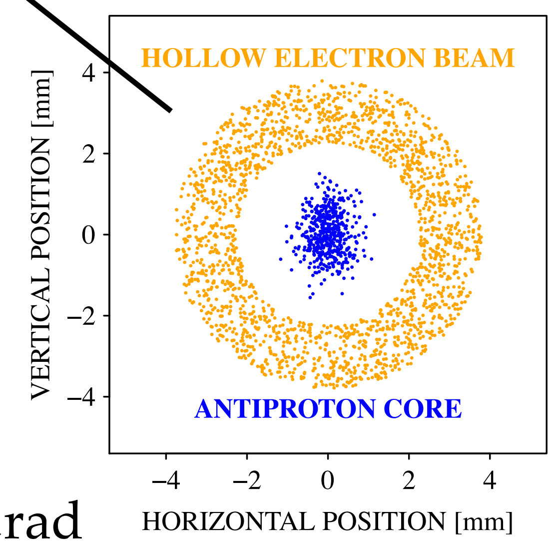
collector

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

conventional solenoids
0.1–0.4 T

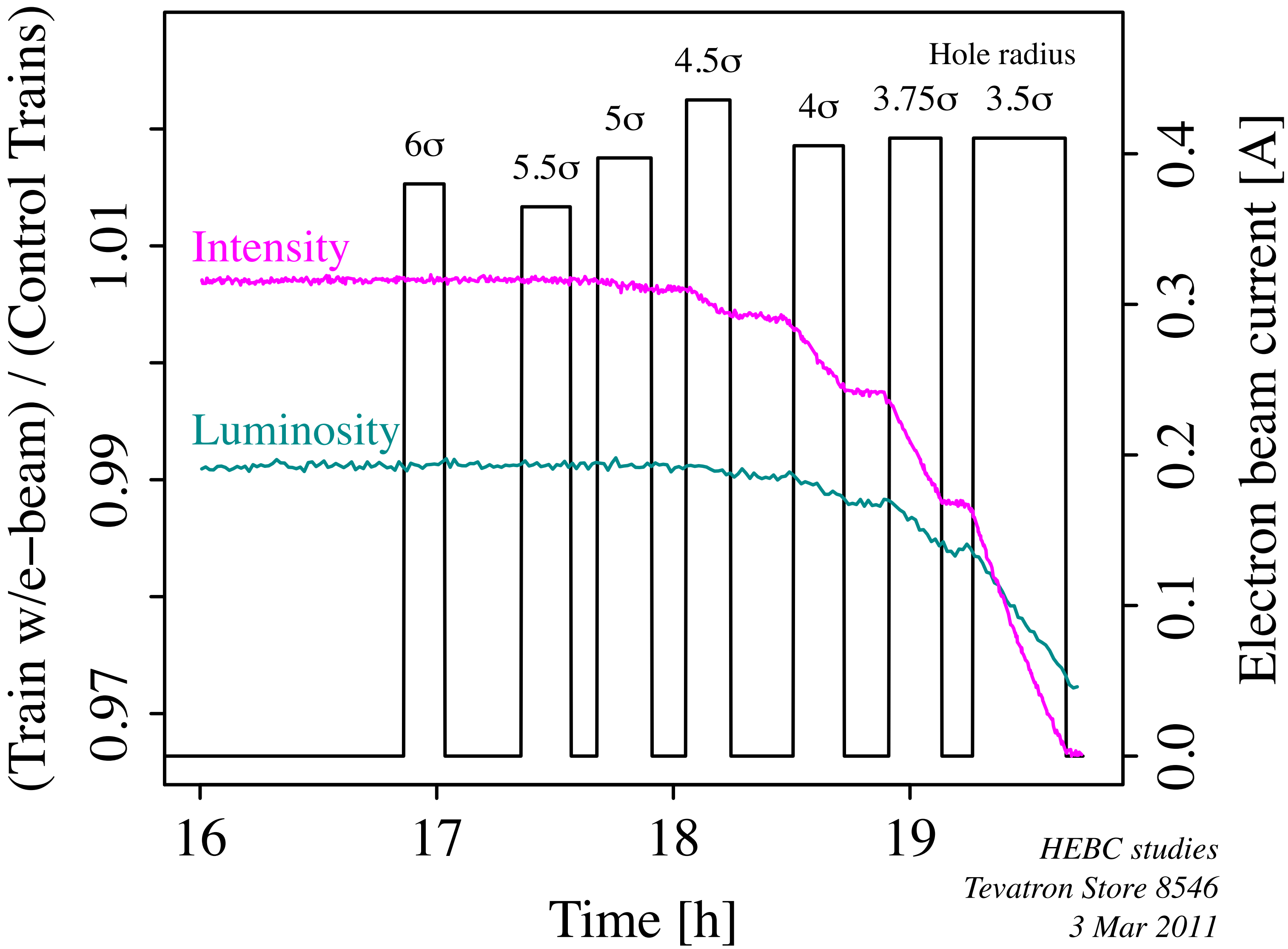






Tunable transverse halo kicks ~0.1 μrad

Example of smooth halo scraping



HEBC studies
Tevatron Store 8546
3 Mar 2011

Main features of hollow electron beam collimation

- Can be close to or even overlap with the main beam
  - no material damage
- Continuously variable strength (“variable thickness”)
- Works as “soft scraper” by enhancing drift and diffusion
- Low impedance of magnetically confined electron beam
- Resonant excitation is possible (pulsed electron beam)
- No ion breakup
- Position control by magnetic fields (no motors or bellows)
- Established electron-cooling / electron-lens technology

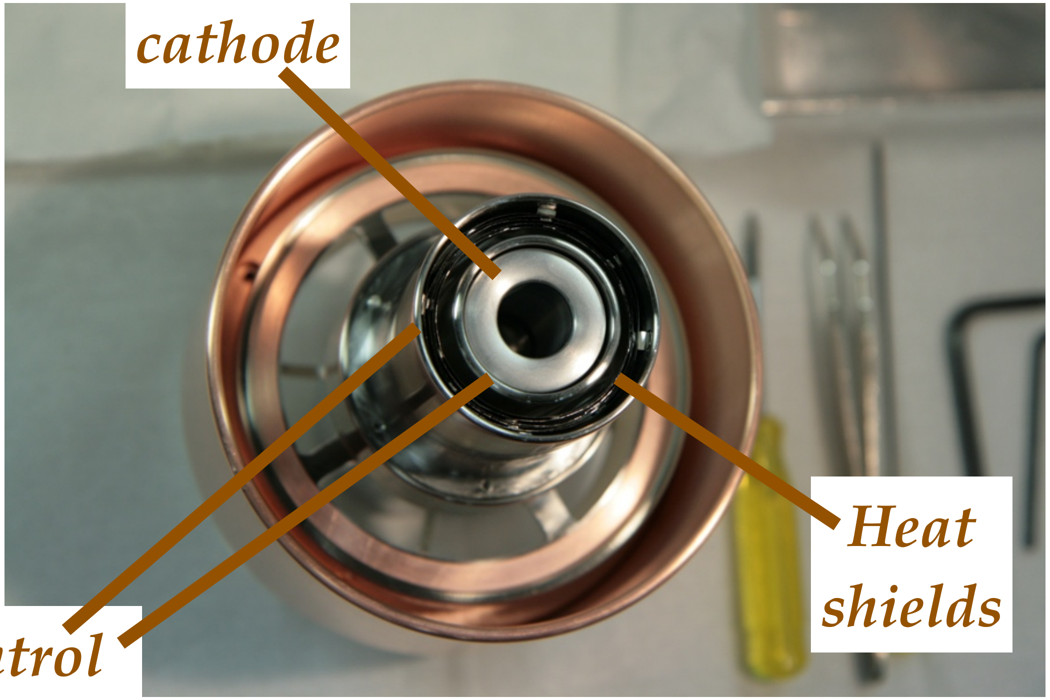
A good complement to the LHC collimation system?

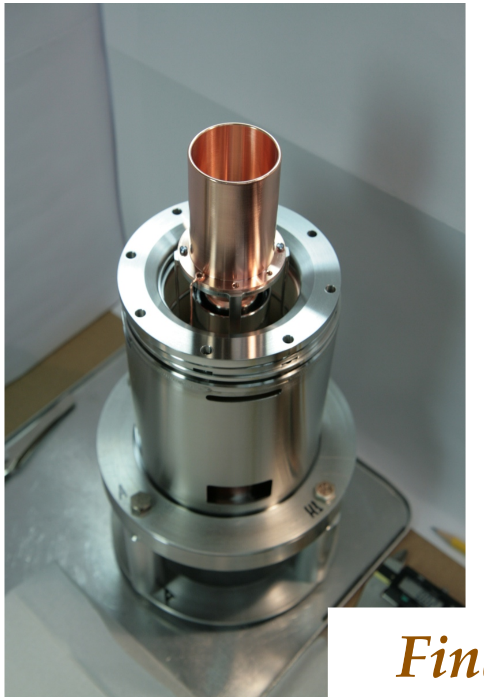
- Scraping in the LHC
  - No dedicated scraping devices; primaries currently best option
  - Scraping with primaries limited in speed and range; almost excluded at top energy and full intensity
  - Scraping at injection is not effective because of continuous tail repopulation
- Possible uses of hollow electron lenses suggested by 2012 operations
  - Control losses during all phases: ramp, squeeze, adjust
  - Reduce sensitivity to orbit drifts during squeeze
  - Remove tails before they are lost in collisions
  - Limit halo during physics run
  - Machine protection for single-turn crab-cavity failures
- Other uses of electron lenses (with different current profiles)?
  - flexible tune-spread control to mitigate instabilities, ...

Strategy and plans

- Final **collimation needs and decisions** can only be defined after gaining operational experience at 7 TeV (2015)
  - cleaning efficiency, lifetimes, quench limits, impedances
- **Proceed with design** of 2 devices within the U.S. LHC Accelerator Research Program (LARP) and European HiLumi LHC Design Study:
  - conceptual design Nov. 2013
  - technical design in 2014
  - construction 2015-2017
  - installation during 2018 long shutdown (2022 if limited by resources)
- Investigate proposed **alternative schemes**
  - damper excitation, tune modulation, beam-beam wire compensators
- Build **electron lens competence at CERN**
- Develop nondestructive, direct **halo diagnostics**
- If possible, extend Tevatron experience with **beam tests at RHIC**?

1-inch hollow gun, LHC prototype





- Thermionic dispenser cathode (tungsten, barium oxide)
- 25 mm outer diameter, 13.5 inner diameter
- Built and characterized at Fermilab electron-lens test stand
- Yields over 5 A at 10 kV

Moens, FERMILAB-MASTERS-2013-02

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**
  - Lifetrac and SixTrack codes
  - 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

see also Stancari et al., poster **TUPAC15**

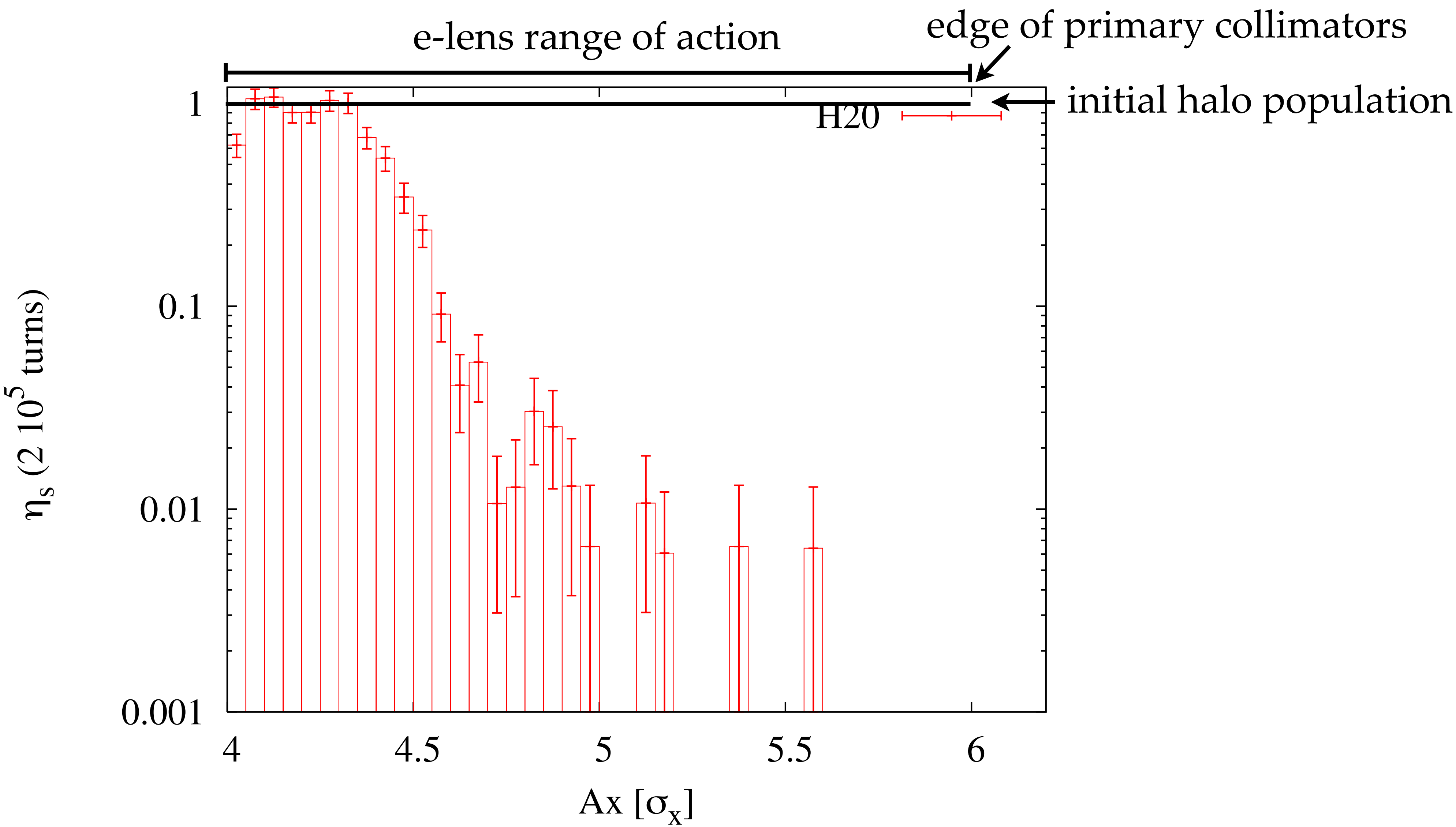
Results of numerical simulations

- 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
  - in resonant mode in ideal case
  - effect of imperfections (profile asymmetries, injection/extraction bends) under study

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

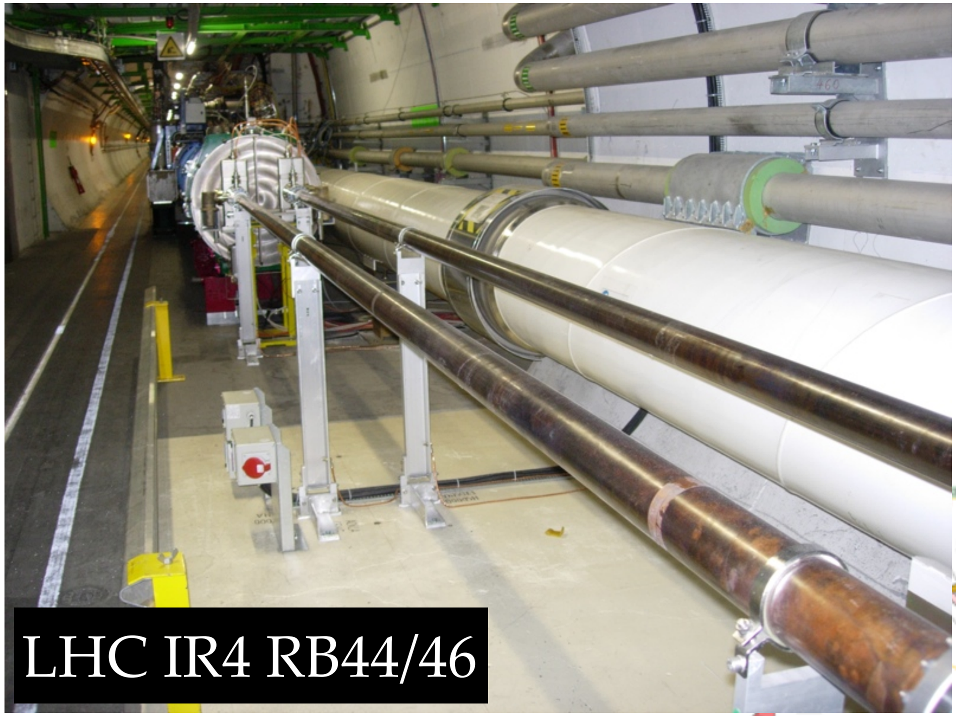
Example of simulated halo scraping (SixTrack, LHC lattice)

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

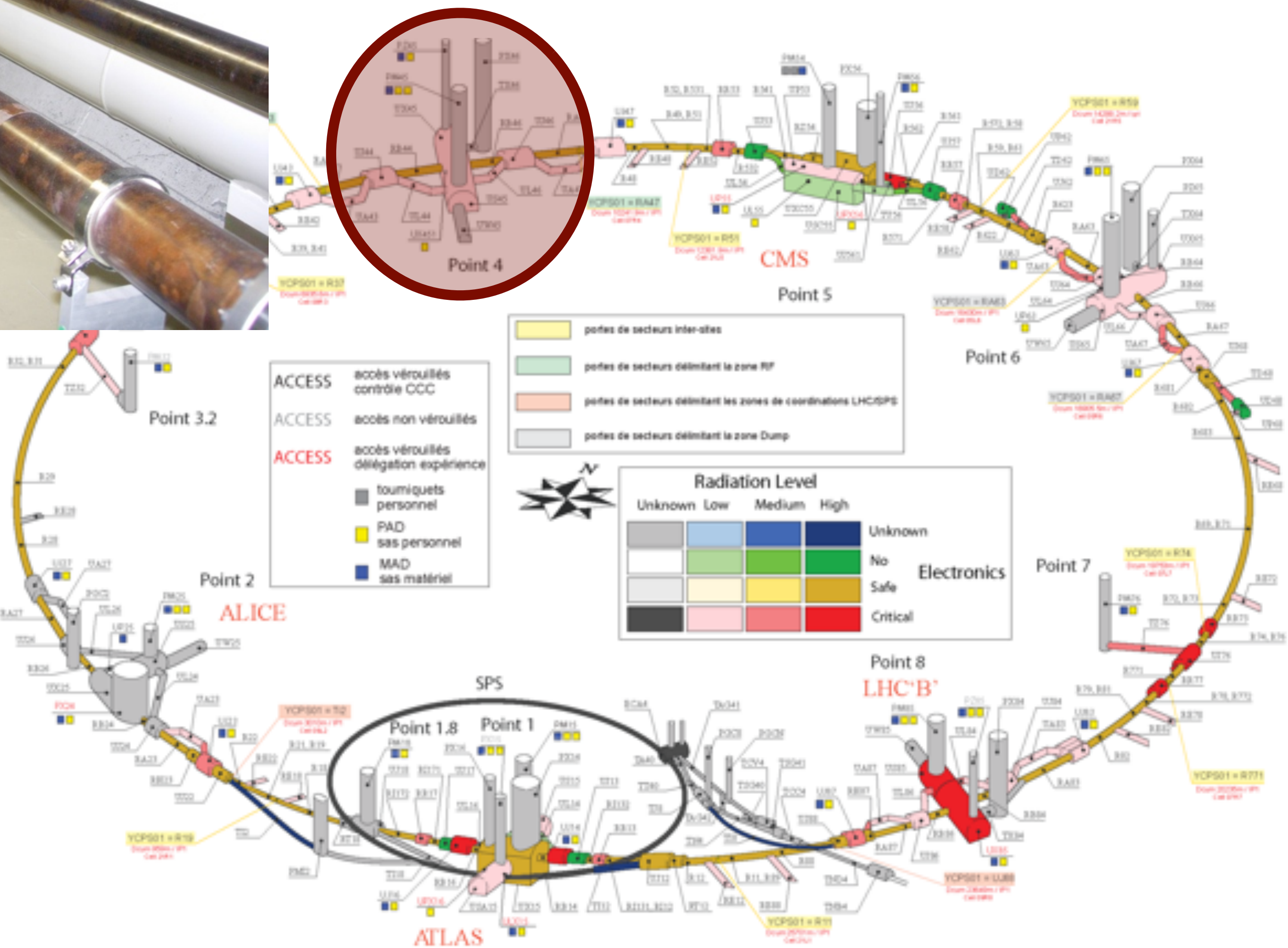


Previtali et al., FERMILAB-TM-2560-APC (2013)

Candidate locations for electron lenses in the LHC



Just upstream or downstream of rf cavities



Some aspects of LHC integration

- **Cryogenics**
  - dominates installation time: ~3 months; "long" shutdown needed
  - electron lenses can be treated as stand-alone magnets
  - may take advantage of dedicated rf refrigerator (if confirmed)

- Because of the different **bunch structure** (25 ns or 50 ns vs. 396 ns), preliminary **impedance** studies suggest that
  - modifications of Tevatron vacuum chamber and electrode designs may be required for longitudinal fields
  - transverse impedance is acceptable

Alternative halo removal techniques and halo diagnostics

- **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**
- 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)

- Strong need for direct, nondestructive **halo diagnostics**
- Synchrotron light with micromirror arrays is being pursued
  - dynamic range may be limited by stray light
- Beam-induced N_2 luminescence detected by APDs looks promising

Conclusions

- A novel technique for collimation of high-power hadron beams with hollow electron beams was developed at the Tevatron
- Promising technique for the LHC upgrade
- Conceptual design being developed within the U.S. LHC Accelerator Research Program and European HiLumi LHC Design Study
- Prototype electron gun built and tested
- Extension from Tevatron to LHC based upon experimental data and numerical simulations
- No major obstacles for mechanical and cryogenic integration
- Next steps for conceptual design:
  - complete numerical simulations of asymmetries in pulsed modes
  - compare with alternative schemes

Thank you