Hollow electron beam collimation at CERN

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High Luminosity LHC

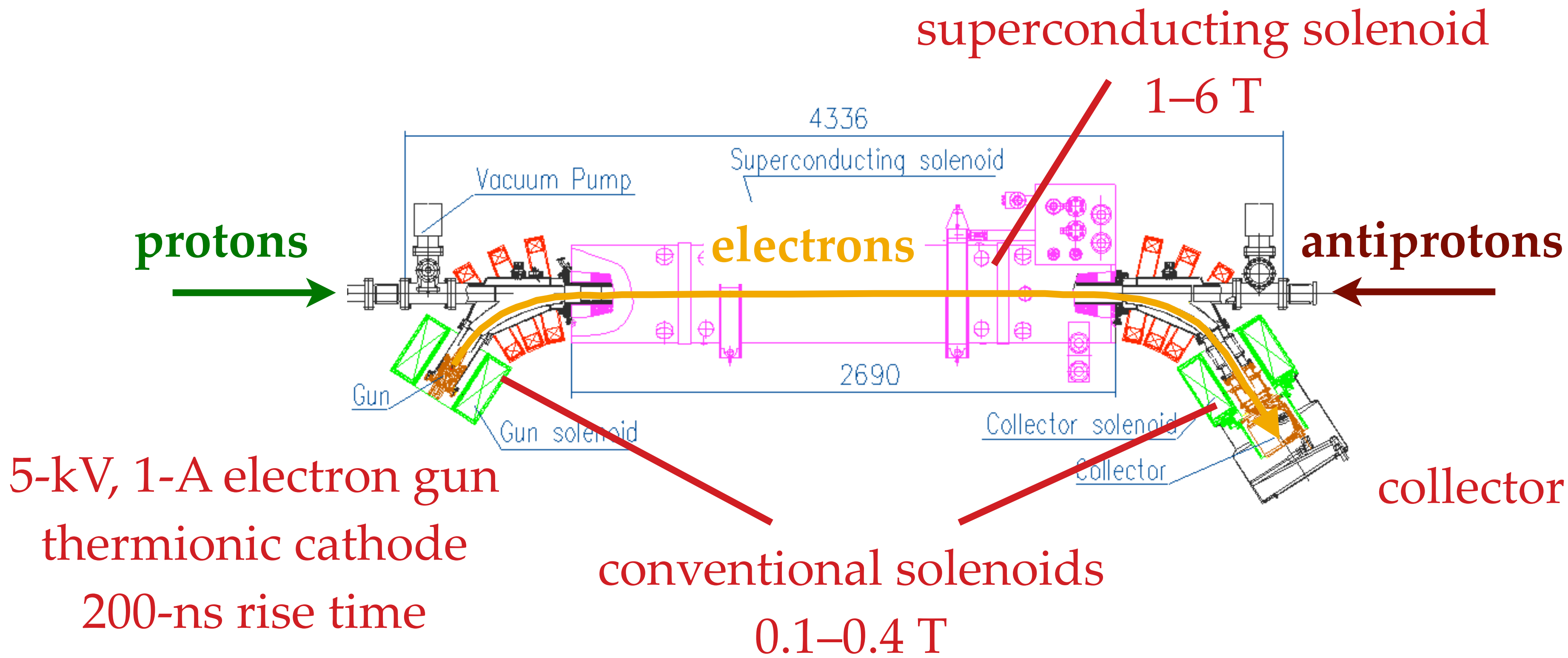
LARP

Outline

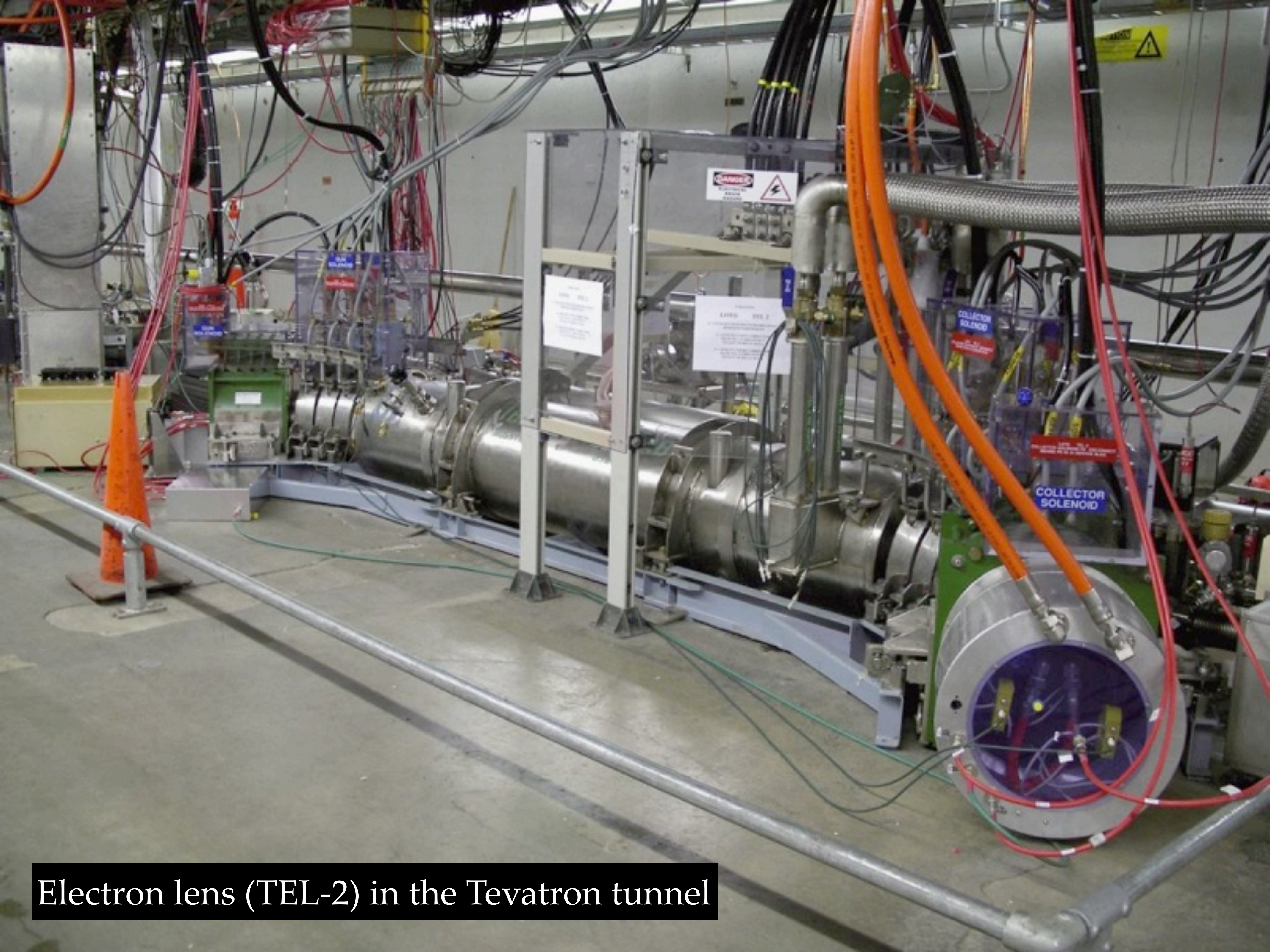
- Hollow beam collimation at CERN
  - Motivation
  - Tevatron experience
  - Numerical simulations
  - Integration
  - Alternative schemes
  - Tests of new 1-in electron gun

Tevatron electron lenses (TEL)

Proposed in 1990s for beam-beam compensation in colliders
Based on electromagnetic field generated by electron beam
Stability provided by strong axial magnetic fields



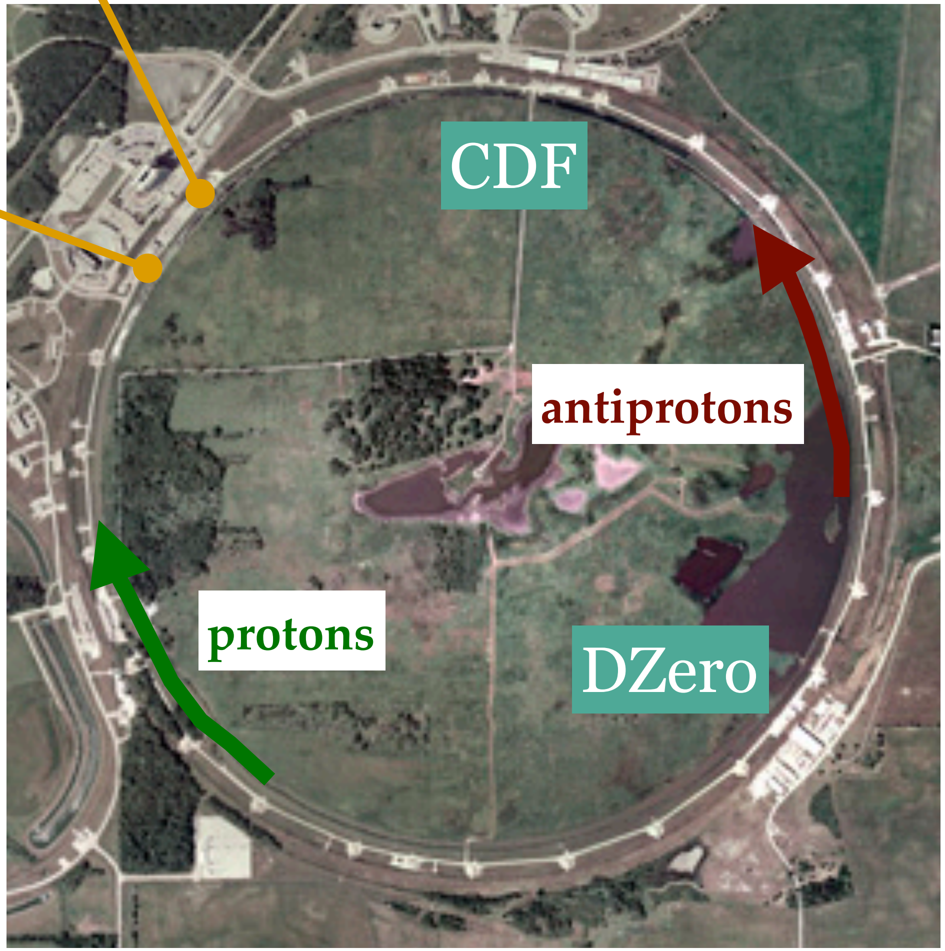
Shiltsev et al., Phys. Rev. ST Accel. Beams **2**, 071001 (1999)
Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)
Shiltsev et al., Phys. Rev. ST Accel. Beams **11**, 103501 (2008)
Shiltsev et al., New J. Phys. **10**, 043042 (2008)

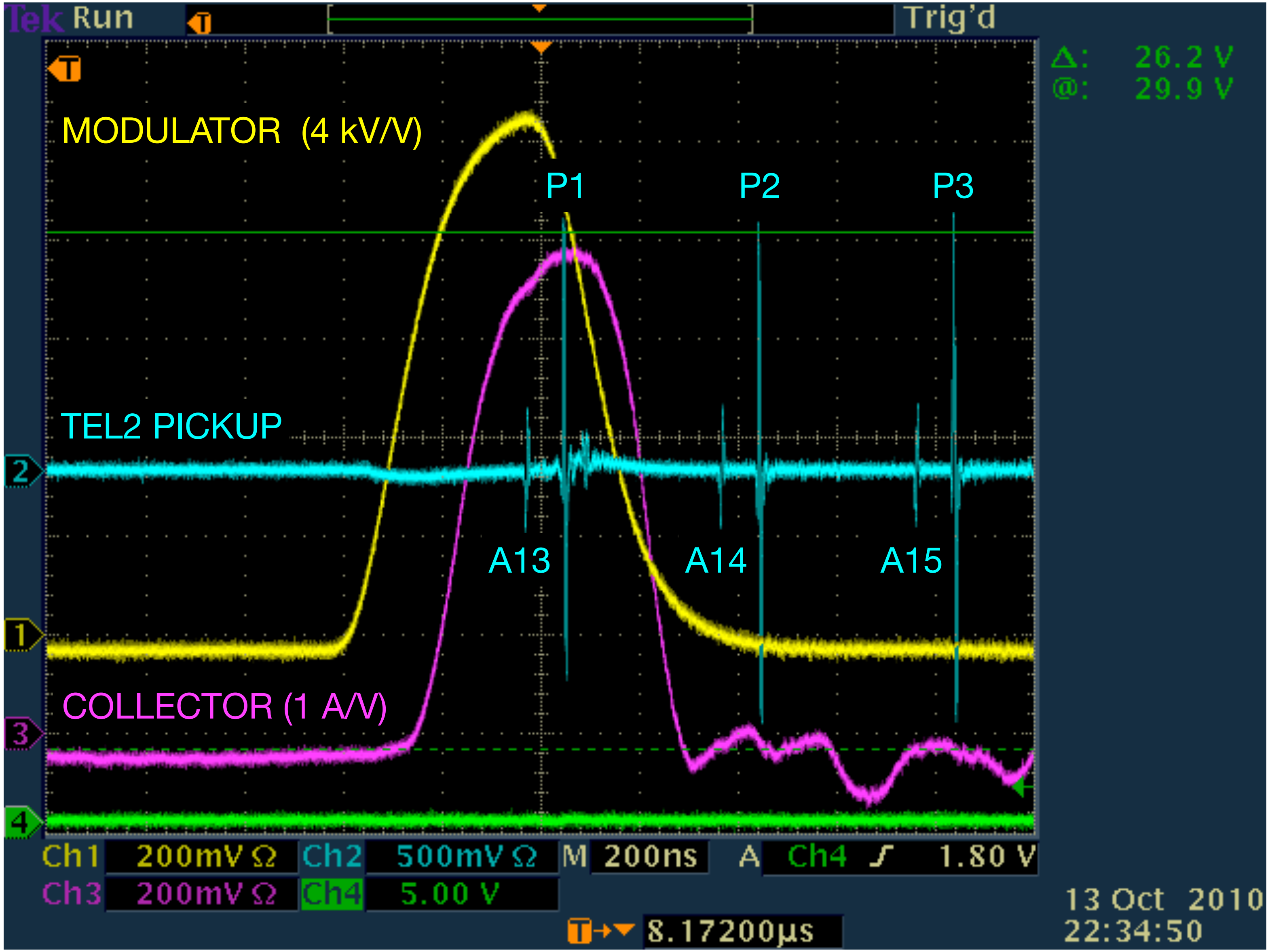


Electron lens (TEL-2) in the Tevatron tunnel

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

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

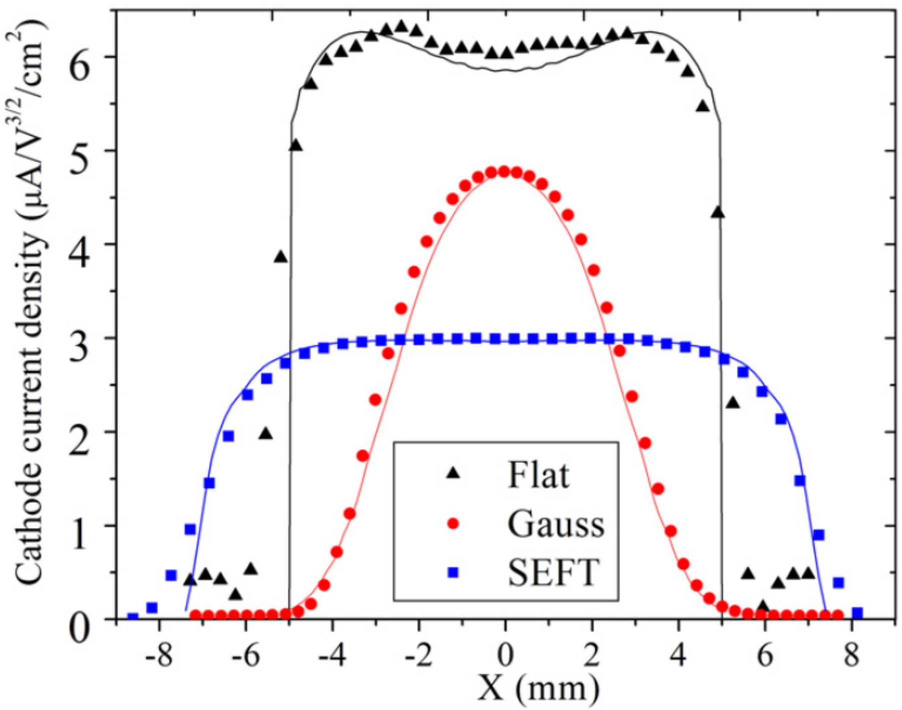




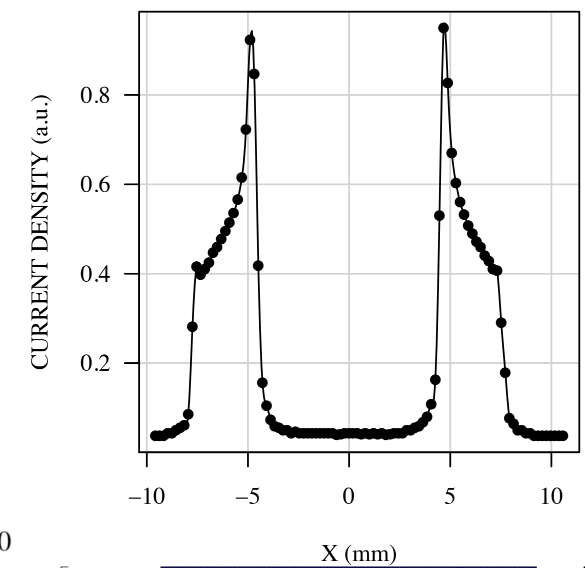
Pulsed electron beam could be **synchronized** with any group of bunches

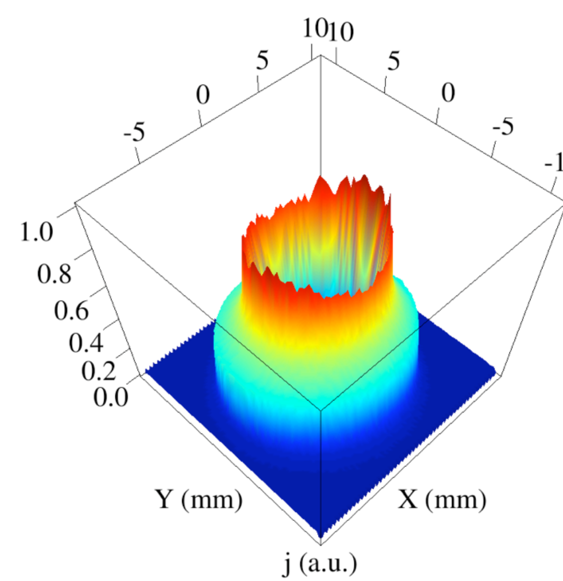
Current density profile of electron beam is shaped by electrode geometry and maintained by strong solenoidal fields

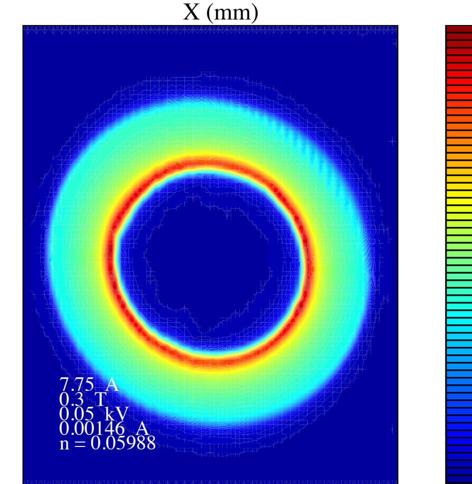
Flat profiles for bunch-by-bunch betatron tune correction



Hollow profile for halo scraping





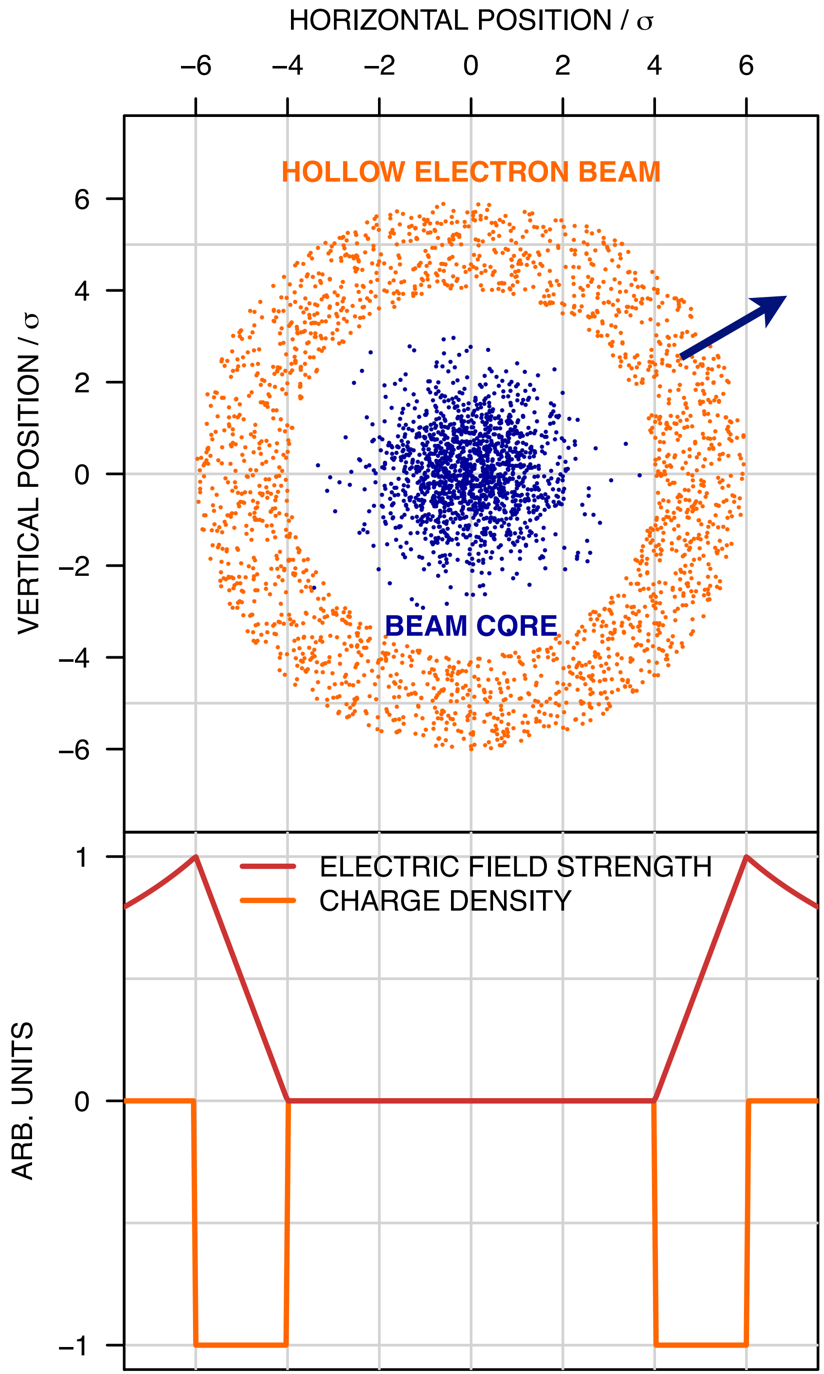


Gaussian profile for compensation of nonlinear beam-beam forces

Principal subsystems

- **Electrical**
  - 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: ~5-10 kV
  - stacked-transformer modulator, anode pulsing: 5 kV, 150 kHz, 200 ns rise time
- **Vacuum**
  - beam vacuum: 10^{-9} mbar typical, 4 ion pumps, 255 l/s nominal total
  - insulating vacuum between cold mass and warm beam pipe: 10^{-6} mbar
  - bake out with heat tape (accessible parts) and heating foils (inside)
- **Cryogenics**
  - static heat load: 12 W (helium vessel at 4 K), 25 W (nitrogen shield)
  - Tevatron magnet string cooling system: 90 l/s of liquid He
  - cryo bypass allows isolation of system
  - quench protection
- **Cooling water** for collector
- **Diagnostics**
  - 6 corrector magnets inside main solenoid
  - 2 BPMs (each one both horizontal and vertical)

Concept of hollow electron beam collimator (HEBC)



Halo experiences nonlinear transverse kicks:

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

About **0.2 μrad**
in TEL2 at 980 GeV

For comparison:
multiple scattering
in Tevatron collimators
$\theta_{\mathrm{rms}} = 17\ \mu\mathrm{rad}$

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

Good complement to conventional collimation for high intensities?

- 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 diffusion
- Low impedance of magnetically confined electron beam
- Resonant excitation is possible (pulsed e-beam)
- No ion breakup
- Position control by magnetic fields (no motors or bellows)
- Established electron-cooling / electron-lens technology

- Critical beam alignment
- Space-charge evolution of hollow beam profile
- Stability of beams at high intensity
- Cost

Experimental studies of hollow electron beam collimation

- Tevatron experiments (Oct. '10 - Sep. '11) provided experimental foundation
- Main results
  - **compatibility with collider operations**
  - **alignment** is reliable and reproducible
  - **smooth halo removal**
  - **removal rate vs. particle amplitude**
  - **negligible effects on the core** (particle removal or emittance growth)
  - **suppression of loss-rate fluctuations** (beam jitter, tune changes)
  - effects on **collimation efficiency**
  - transverse beam halo **diffusion enhancement**

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

Scraping in the LHC

- **Is halo scraping needed in the LHC?**
  - *Final decision may need to wait for experience at 7 TeV: lifetimes, collimator settings, quench limits*
  - *2012 operational experience with tight collimator settings suggests it would be useful in many cases*
    - *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 failures: critical for crab cavities*
- **How to scrape an when?**
  - *No dedicated scraping devices in LHC: 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*

Hollow electron beams as scrapers for high intensities

- **Is the hollow electron lens a good complement to the LHC collimation system?**
  - *Extensive operational experience at the Tevatron, mainly in collisions*
  - *Limited tests with single beams, never during ramp*
  - *Complex nonlinear halo dynamics: may work differently in different machines*
- **Can an electron lens have other uses?**
  - *Control of tune spread with Gaussian electron beams; bunch-by-bunch tune shift with flat beams; abort-gap clearing*
- **Can the existing Tevatron hardware be used at CERN?**
  - *Scale kicks from 1 TeV to 7 TeV, one device per beam*
  - *Integration issues in SPS or LHC: mechanical, electrical, vacuum, cryogenics*
- **Are there alternative and cheaper schemes for halo removal?**
  - *Tune modulation with warm quads; transverse damper excitation; AC dipole*
- **What are possible timelines for tests and installation?**

Scenarios and timelines

Goal: if electron lenses are needed, install 2 devices in the LHC during LS2

What tests are needed? What are the best options going forward?

- Install TEL2 in LHC in LS1: not feasible
- Install TEL2 in SPS in LS1, beam tests in 2015, then use for LHC
- Direct production of 1 or 2 devices for the LHC
- Preparatory work during LS1 and 2015, 2016 winter stops

Aim for a decision on next steps and action items in early 2013

Internal review of hollow electron beam collimation at CERN held Nov 9, 2012: `indico.cern.ch/event/213752`

Tests in the SPS?

PROs

- Similarities to LHC: working point, weak coupling
- Compare with Tevatron results
- Acquire operational experience
- Integrate with CERN controls
- Validate simulations
- All prototype collimators tested in SPS before LHC installation

CONs

- Lower energy than Tevatron (270 GeV coast)
- Limited collimators and diagnostics

Alternative halo removal techniques

- **Tune modulation** using warm quadrupoles
  - *used at HERA to counteract power-supply ripple*
- Excitation with **transverse dampers** or **AC dipole**
- Both methods **work in tune space**: halo not necessarily separated
- **Emittance preservation** needs to be demonstrated
- Some **beam tests** may be feasible before LS1
- **Simulations** of effects on halo and core can be set up if needed

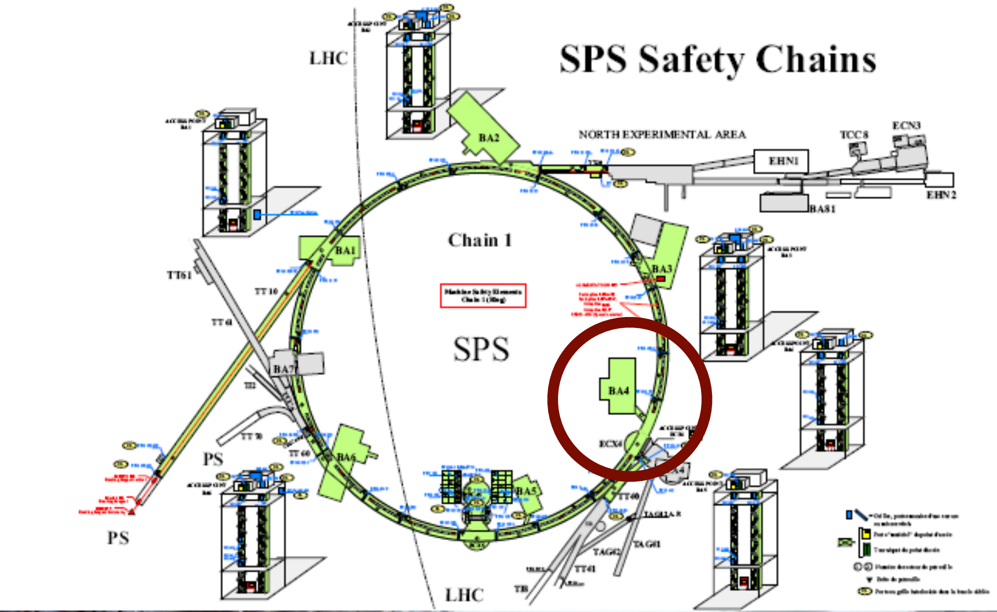
- Strong need for direct, nondestructive **halo diagnostics**
- Synchrotron light with micromirror arrays is being pursued; dynamic range may be limited by stray light
- Beam-induced N_2 luminescence detected by APDs looks very promising

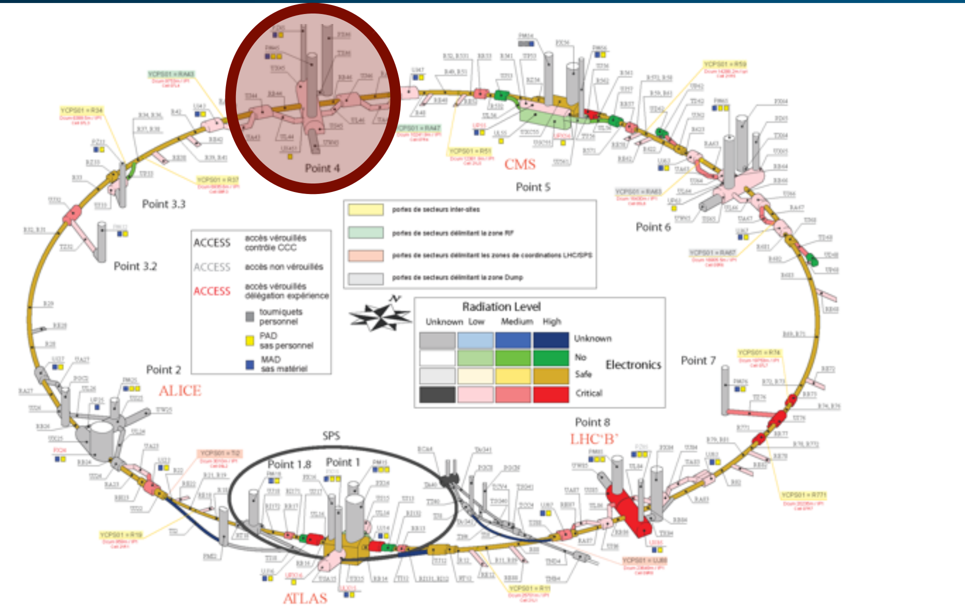
see H. Schmickler's presentation at last week's internal review

Numerical simulations

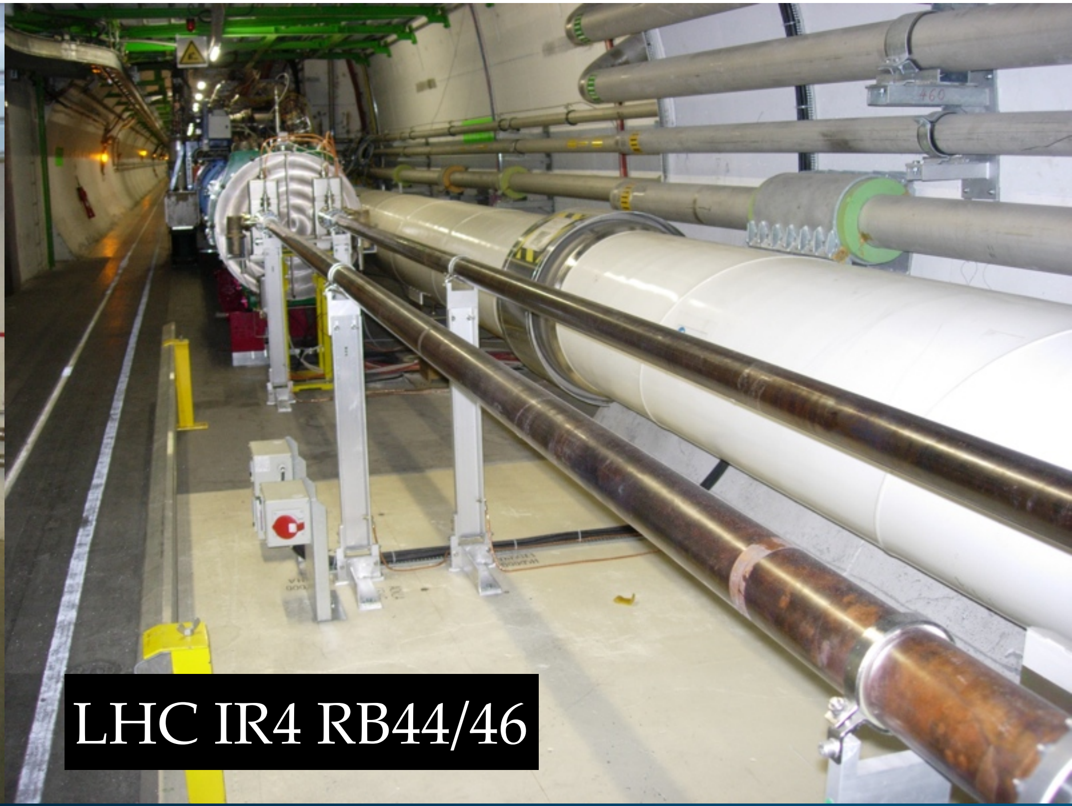
- **Is hollow electron beam collimation effective in the LHC? What tests can be done in the SPS?**
- Methods
  - Lifetrac and SixTrack codes
  - Machine models with some nonlinearities
  - Uniform halo population, no replenishing mechanisms (i.e., diffusion)
  - Ideal electron lens, profile imperfections
- Results
  - Observable effects in time scales of seconds/minutes
  - Smooth scraping with electron pulsed every turn
  - Enhanced effects with resonant or random pulsing
- Details in talk by Valentina Previtali this afternoon

Candidate locations for electron lens





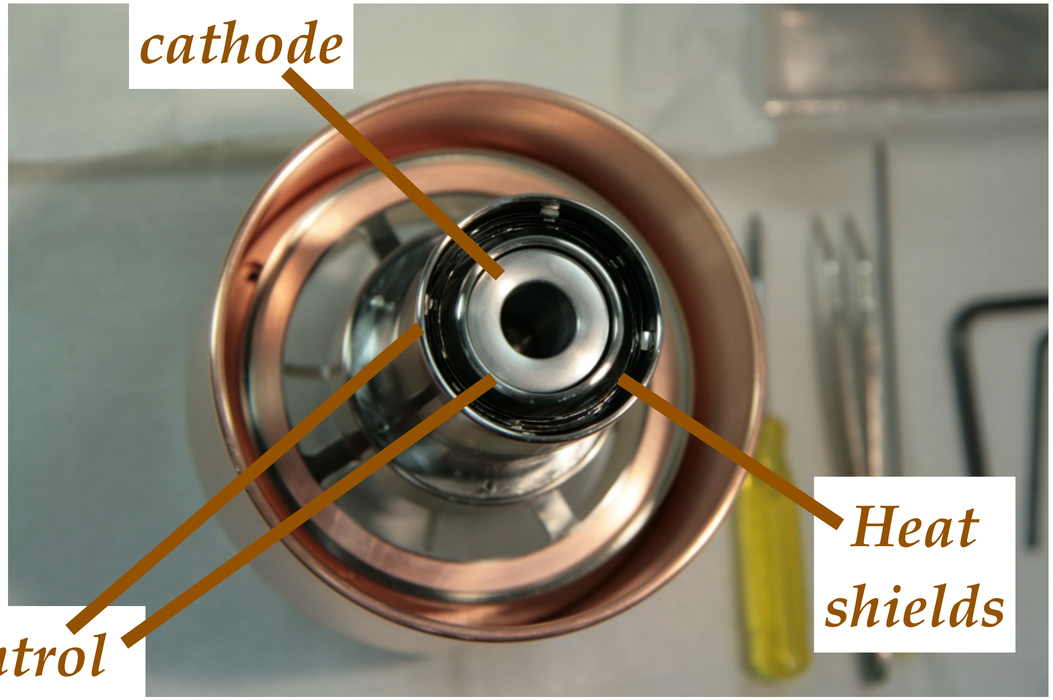
SPS BA4 COLDEX installation

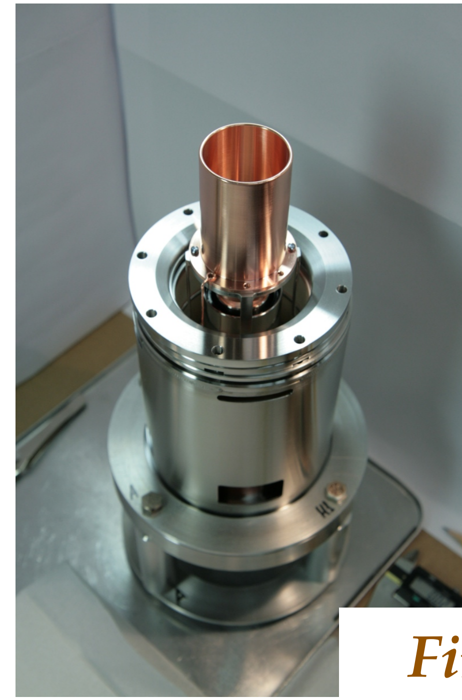

LHC IR4 RB44/46

Integration of existing Tevatron electron lens at CERN

- Two possible **locations** were identified
  - BA4 (Coldex) in SPS
  - IR4/RB46 in LHC
- **Vacuum** will require additional NEG cartridges, surface tests, electrode bake-out
- **Cryogenics**
  - In SPS, system cannot cool both e-lens and crab cavities at the same time
  - In LHC, can be treated as stand-alone magnet; easier integration if dedicated RF refrigerator is confirmed for LS2
- Preliminary **impedance** studies suggest some modifications may be required for longitudinal fields; transverse impedance looks OK
- To be addressed: location of power supplies, cabling, cooling water, integration of quench protection, e-cloud when solenoids are off

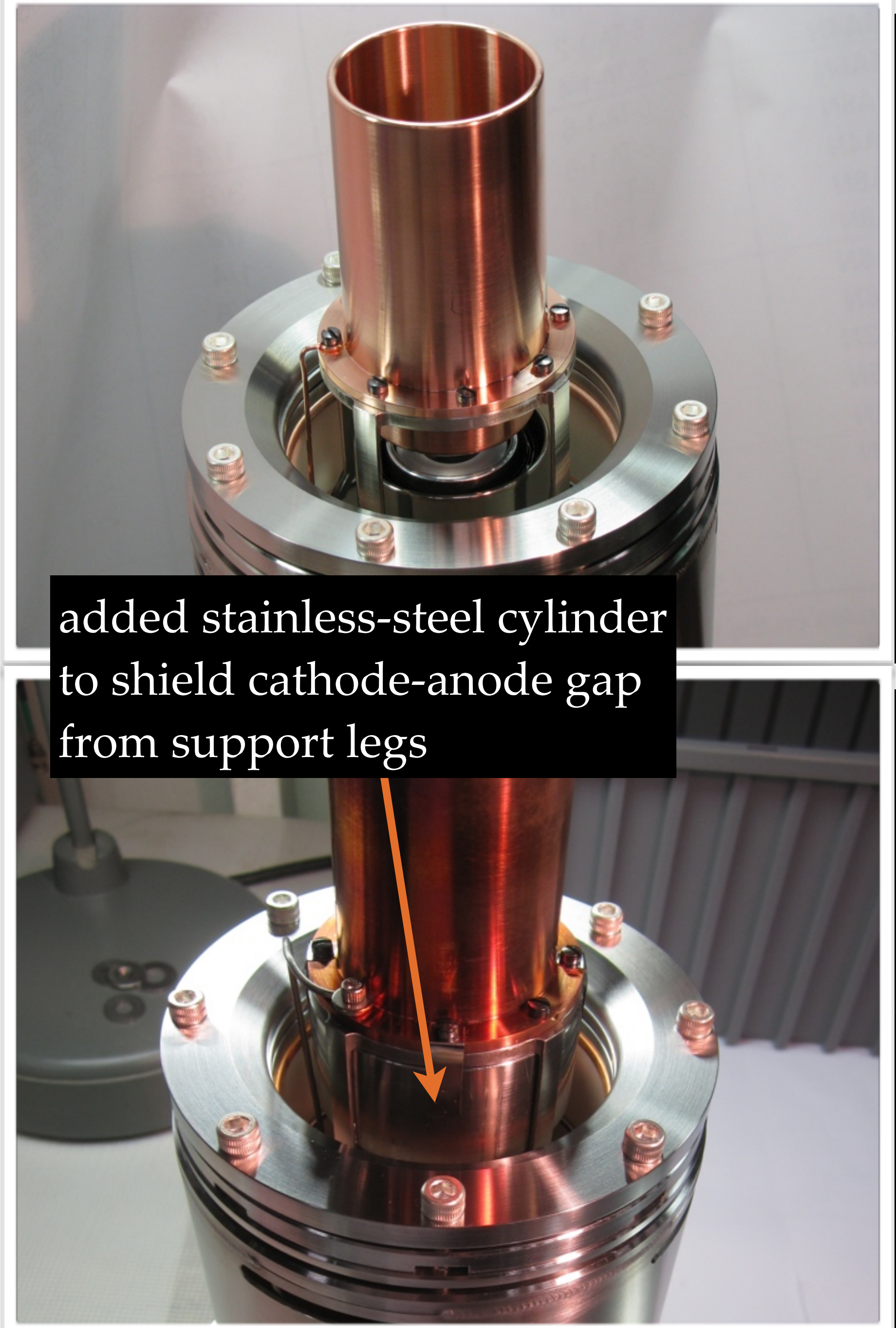
New 25-mm hollow gun

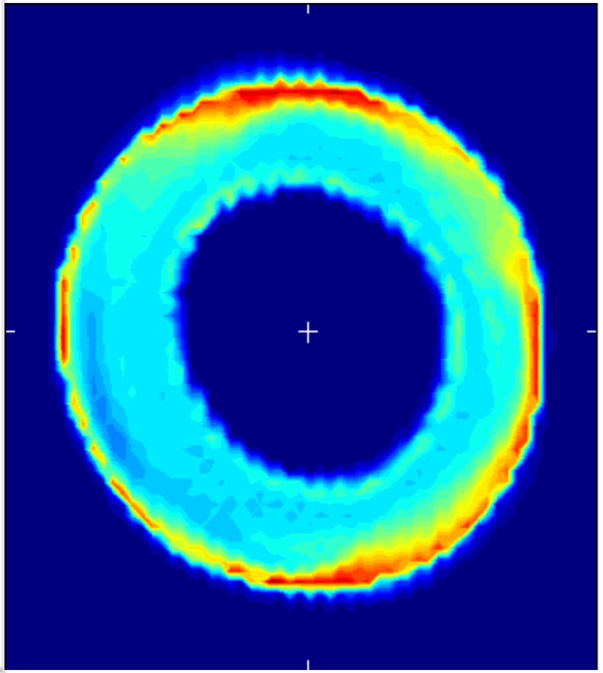


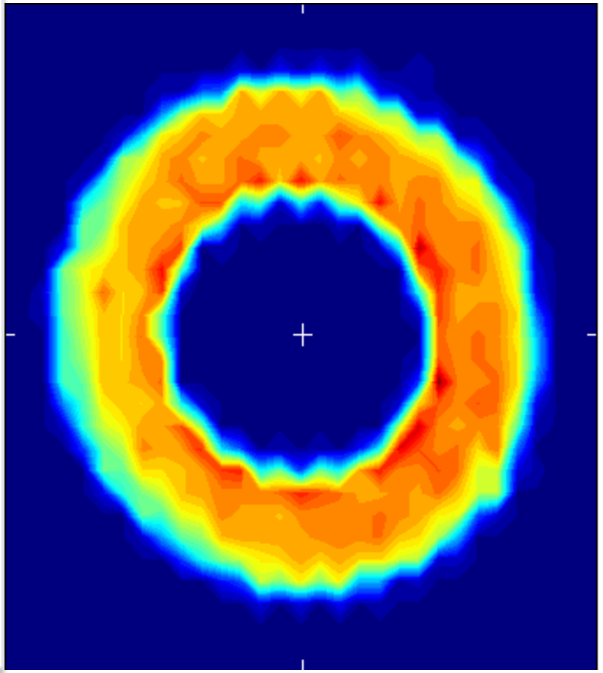


- 25 mm outer diameter, 13.5 inner diameter
- Tested technical feasibility of larger and stronger scraper
- Characterized at Fermilab electron-lens test stand

Electron gun modifications







- Improved profile uniformity
- Extensive characterization will continue in the next few weeks

Achievable range of hole radii in overlap region

$$(r_{i,o})_m = (r_{i,o})_g \sqrt{\frac{B_g}{B_m}}$$

inner or outer radius in overlap region (main solenoid)

inner or outer radius at electron gun

field in gun solenoid 0.1 – 0.4 T

field in main solenoid 1 – 6 T

	Gun radii [mm]		Yield @ 8 kV [A]	Radii in overlap region [mm]			
				minimum		maximum	
	$(r_i)_g$	$(r_o)_g$		$(r_i)_m$	$(r_o)_m$	$(r_i)_m$	$(r_o)_m$
original 0.6-in gun	4.5	7.62	2.2	0.58	0.98	2.8	4.8
new 1-in gun	6.75	12.7	2.9	0.87	1.6	4.3	8.0

Further information

- **Papers**
  - Ageev et al., PAC 01, p. 3630 [TEL magnets and cryogenics]
  - Shiltsev et al., PRL **99**, 244801 (2007) [beam-beam compensation]
  - Shiltsev et al., PRSTAB **11**, 103501 (2008) [TEL design and operation]
  - Stancari et al., IPAC 10, p. 1698 [hollow gun design and performance]
  - Stancari et al., PRL **107**, 084802 (2011) [hollow beam collimation]
  - Stancari et al., IPAC11, p. 1939 (2011) [hollow beam collimation]
  - Stancari et al., APS/DPF Proc., arXiv:1110.0144 [hollow beam collimation]
- **Web pages**
  - https://cdcvs.fnal.gov/redmine/projects/elens/wiki [new e-lens wiki]
  - http://www-bd.fnal.gov/lug/tev33/ebeam_comp [original e-lens pages]

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
- Study of hollow electron beam production and dynamics continues
- The Tevatron electron lens hardware is available for use at CERN
- Application of hollow electron lenses as scrapers for the LHC was internally reviewed last week (indico.cern.ch/event/213752)
  - motivation, requirements, other uses (tune-shift and tune-spread control)
  - Tevatron experience
  - integration in SPS and LHC
  - numerical simulations
  - alternative methods (tune modulation, transverse dampers, AC dipole)
  - summary, minutes, and action items in preparation

Thank you