Hollow electron beam collimation: Tevatron experiments

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LARP

Fermilab

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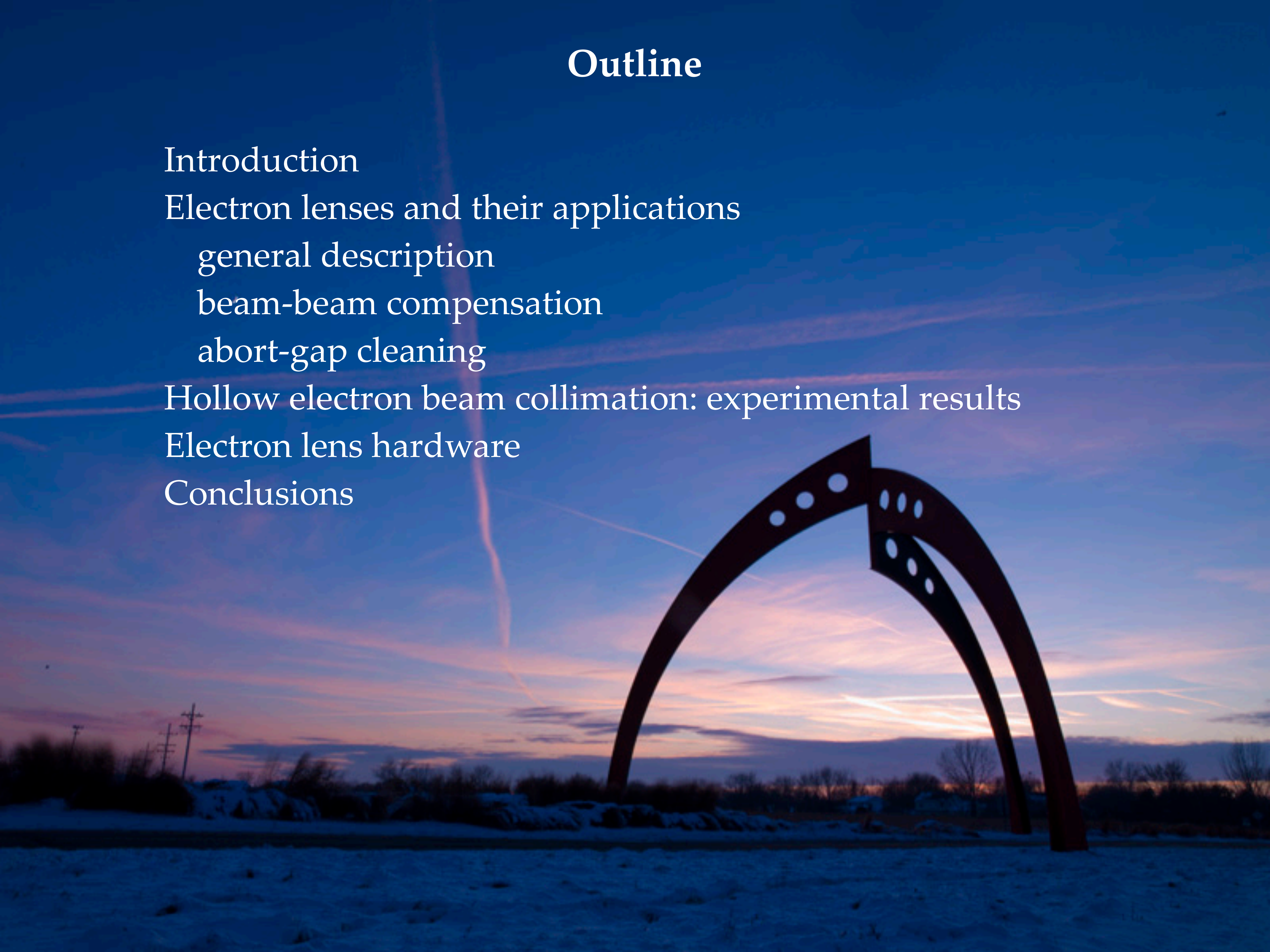
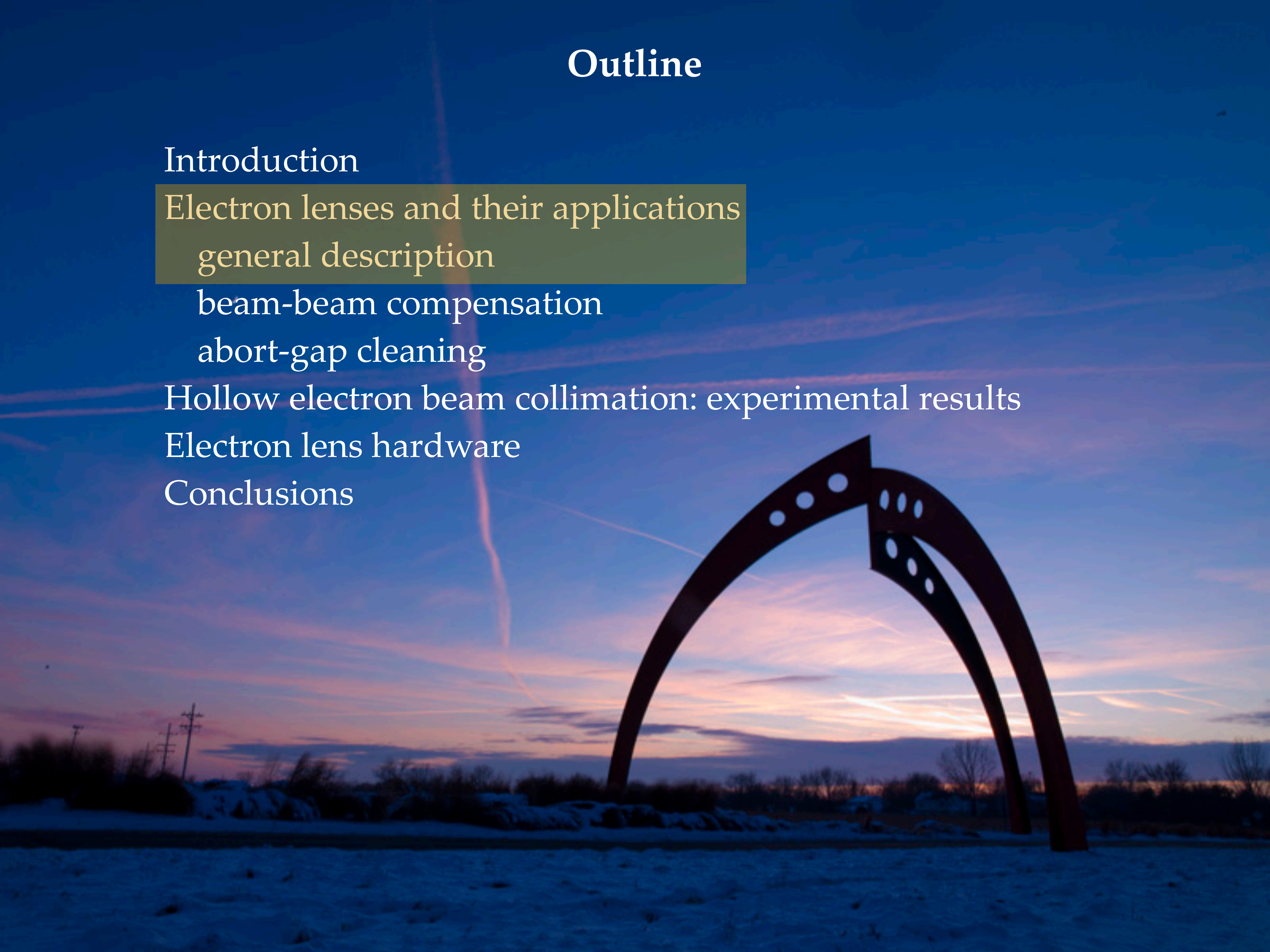
Outline



- Introduction
- Electron lenses and their applications
    - general description
    - beam-beam compensation
    - abort-gap cleaning
- Hollow electron beam collimation: experimental results
- Electron lens hardware
- Conclusions

Outline



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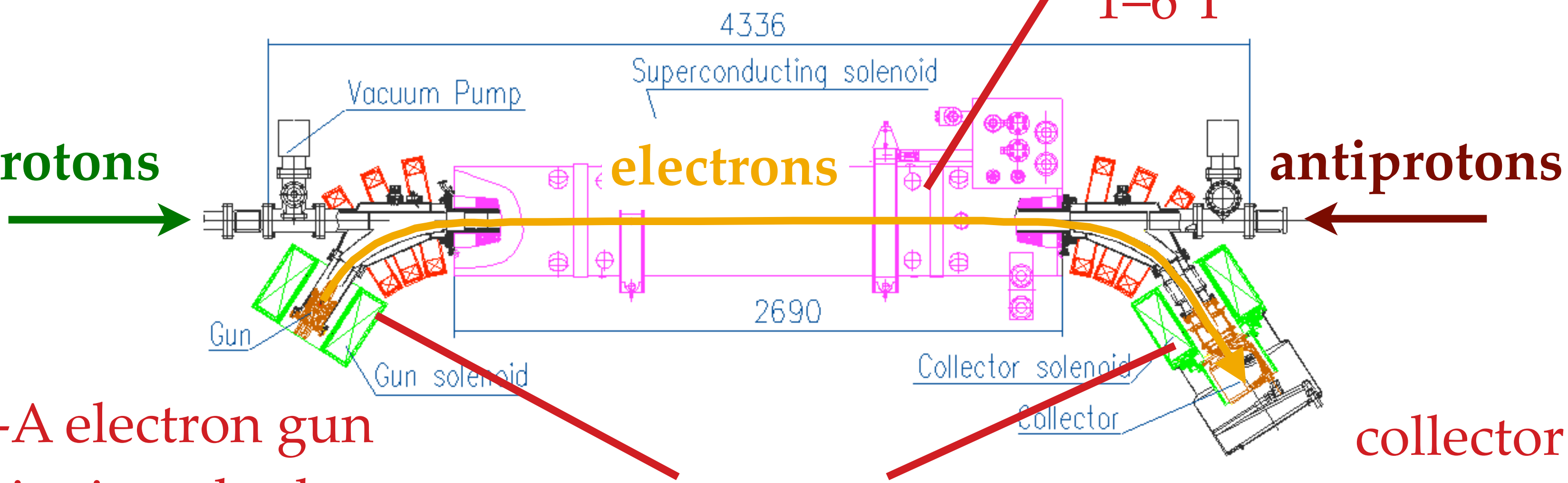
Tevatron electron lenses (TEL)

Proposed in 1990s for use in colliders

Based on electromagnetic field generated by electron beam

Stability provided by strong axial magnetic fields



superconducting solenoid
1–6 T

protons

electrons

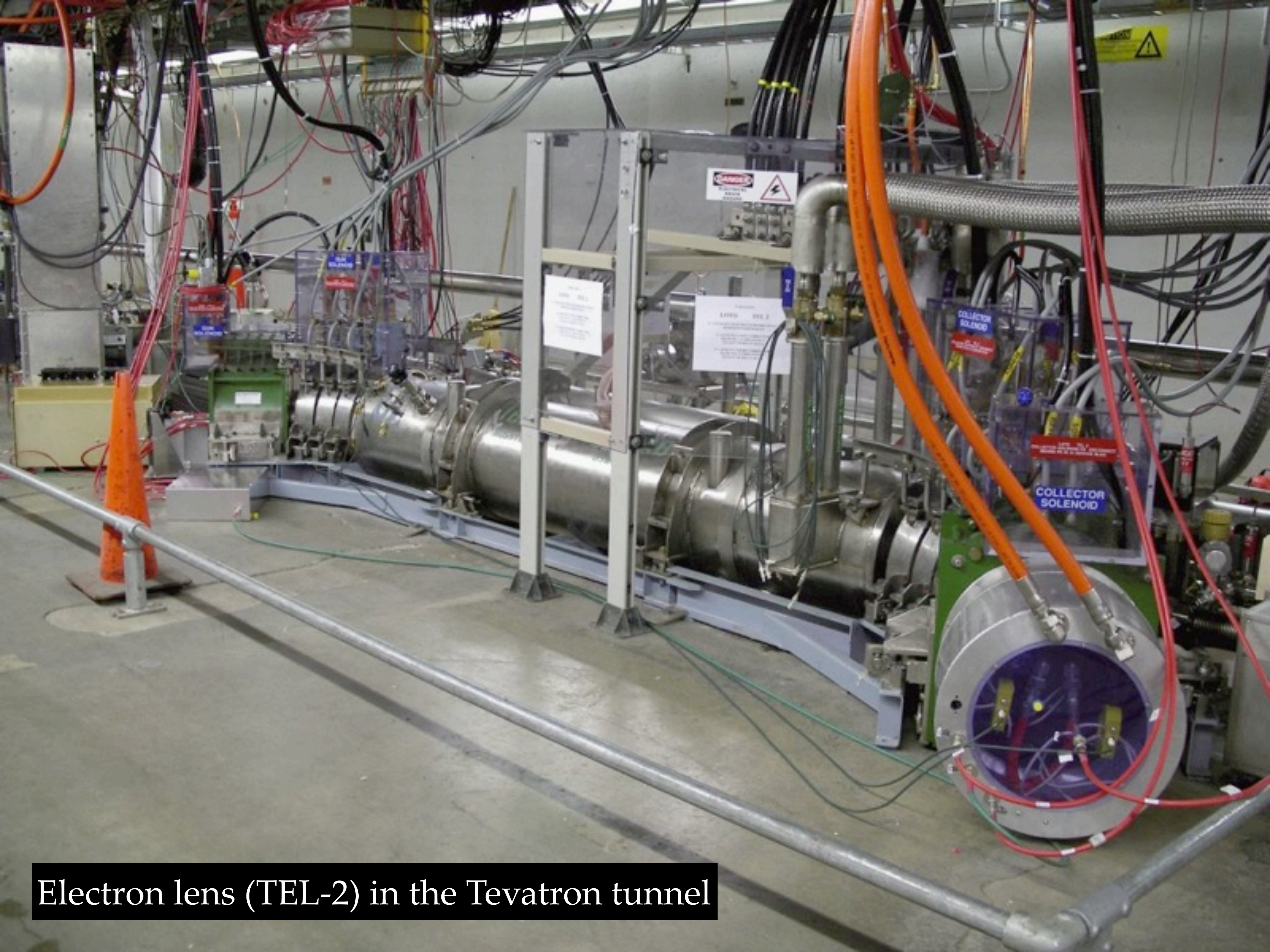
antiprotons

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

conventional solenoids
0.1–0.4 T

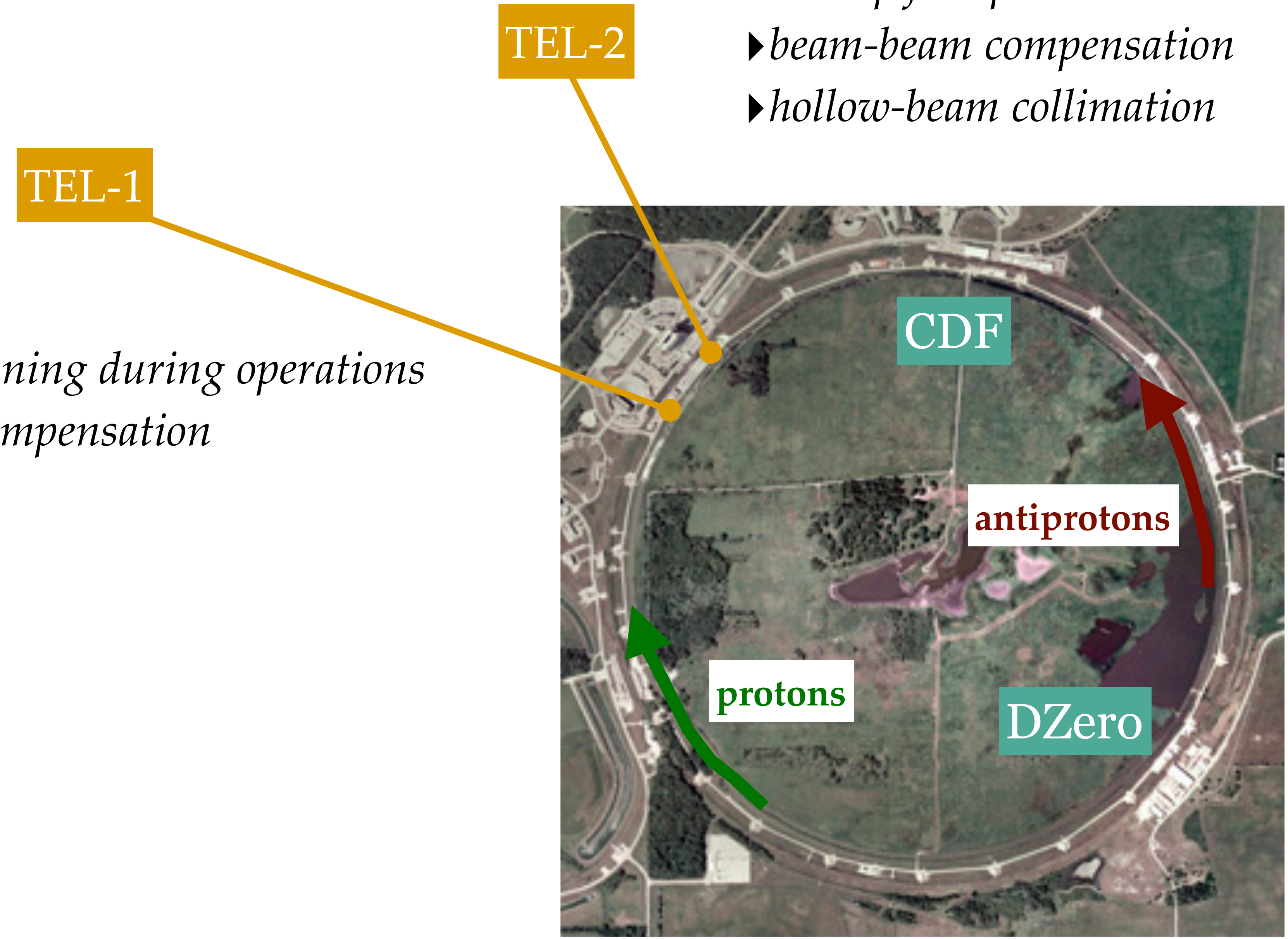
collector

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

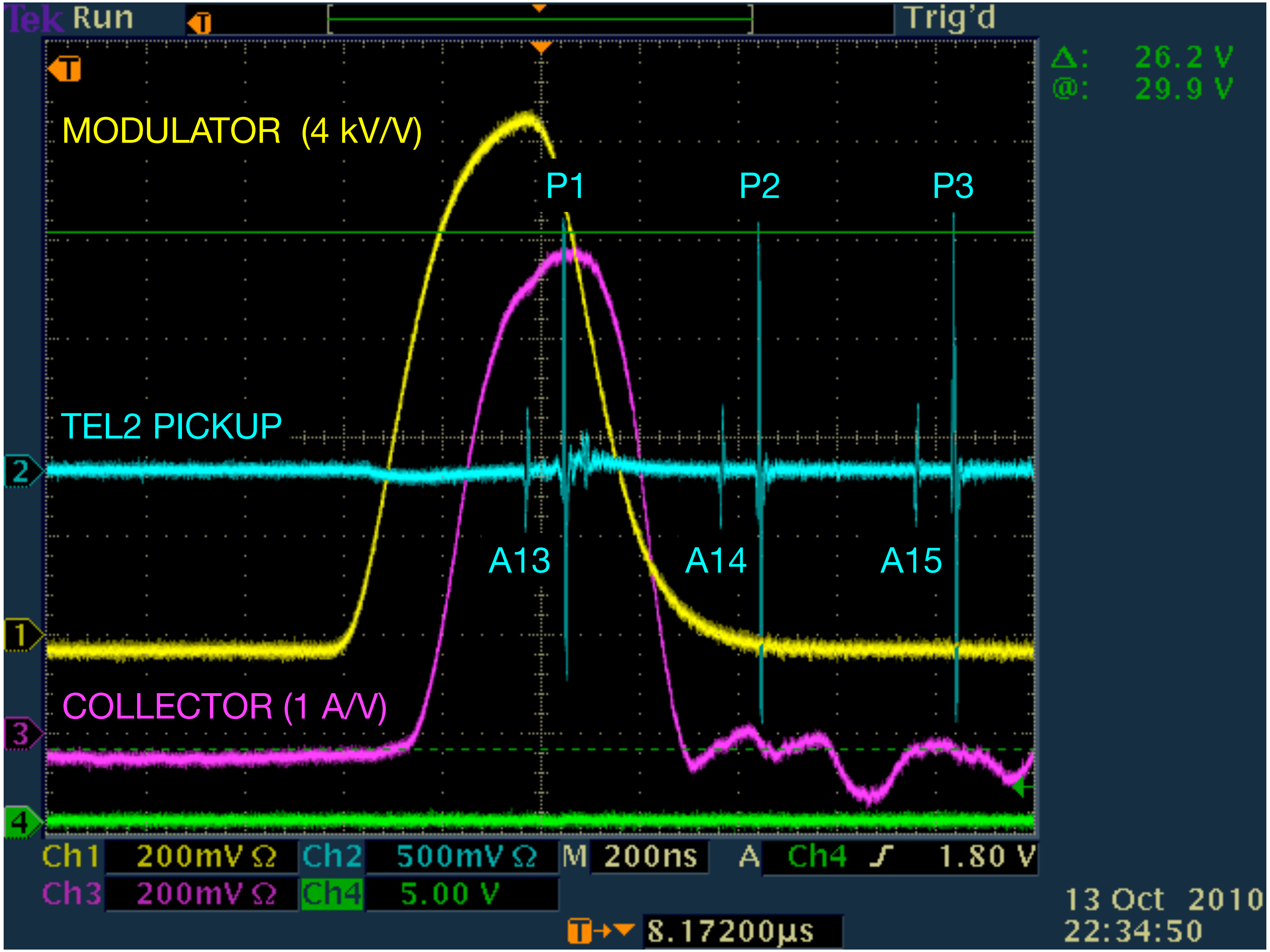
Electron lenses in the Fermilab Tevatron collider



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

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

Pulsed operation of the electron lens

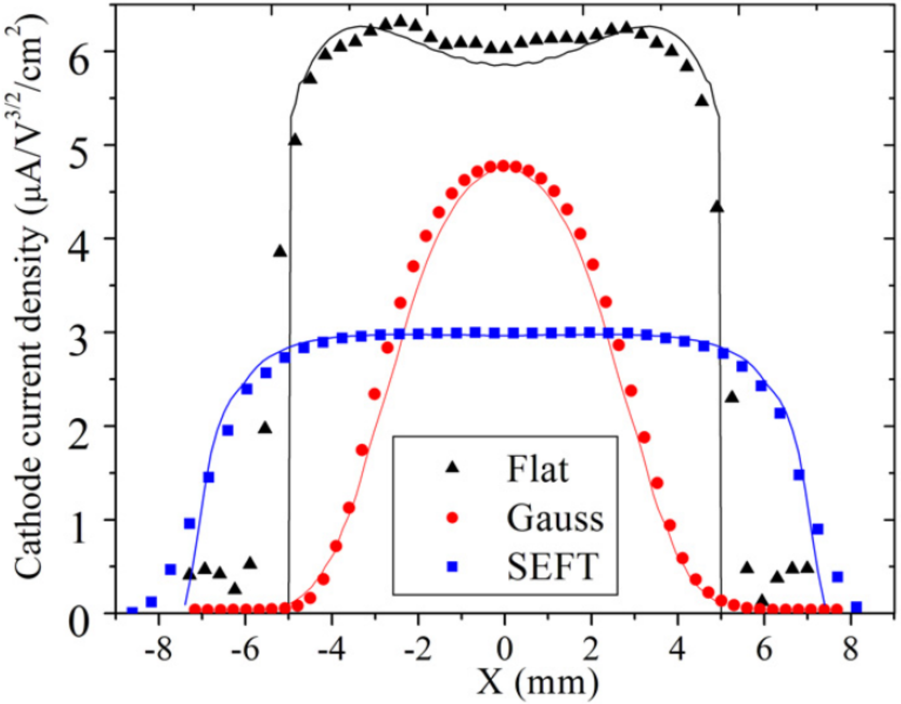


Pulsed electron beam could be **synchronized** with any group of bunches

Profile control

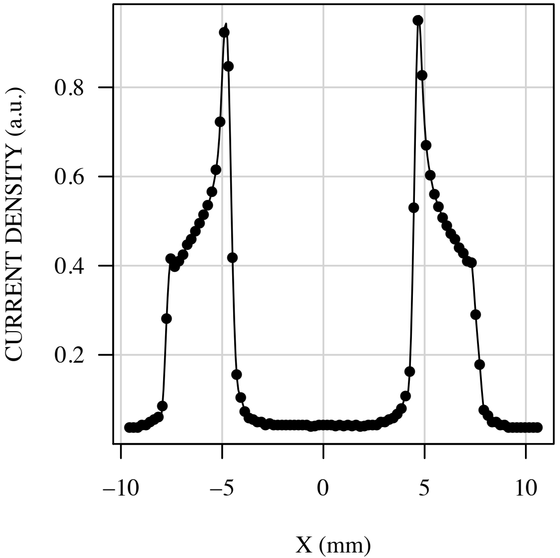
Current density profile of electron beam is shaped by electrode geometry and maintained by strong solenoidal fields

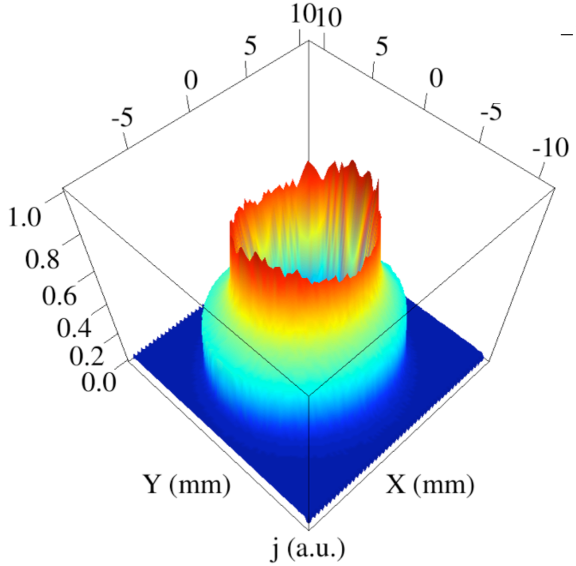
Flat profiles for bunch-by-bunch betatron tune correction

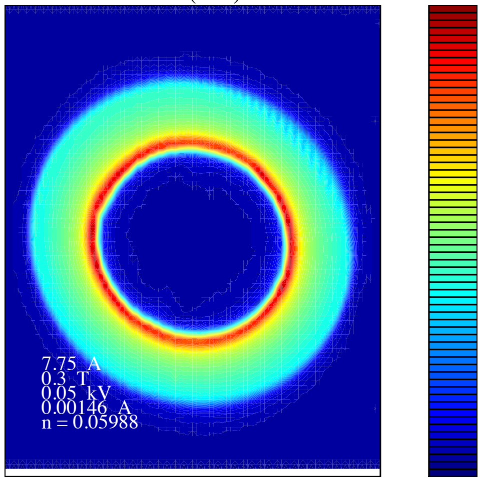


Gaussian profile for compensation of nonlinear beam-beam forces

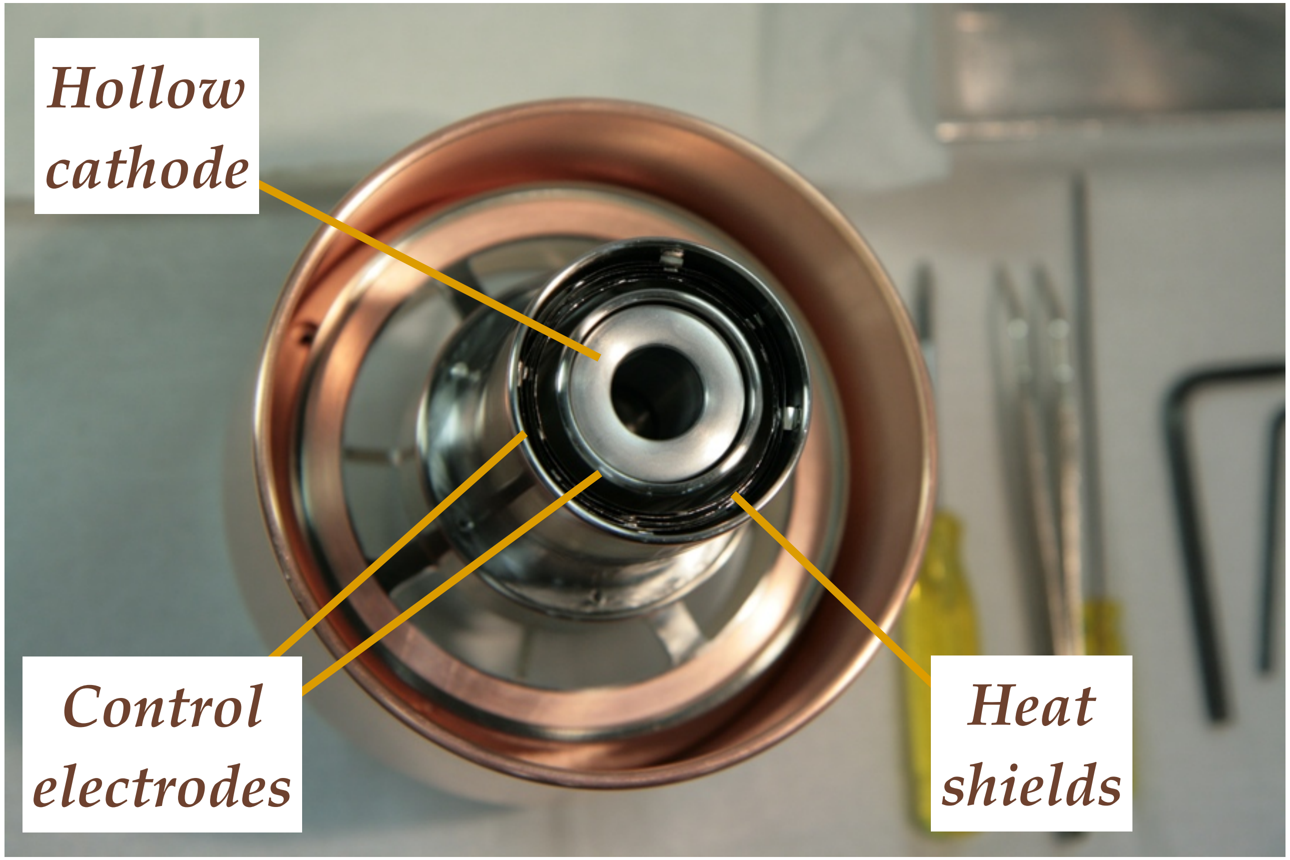
Hollow profile for halo scraping





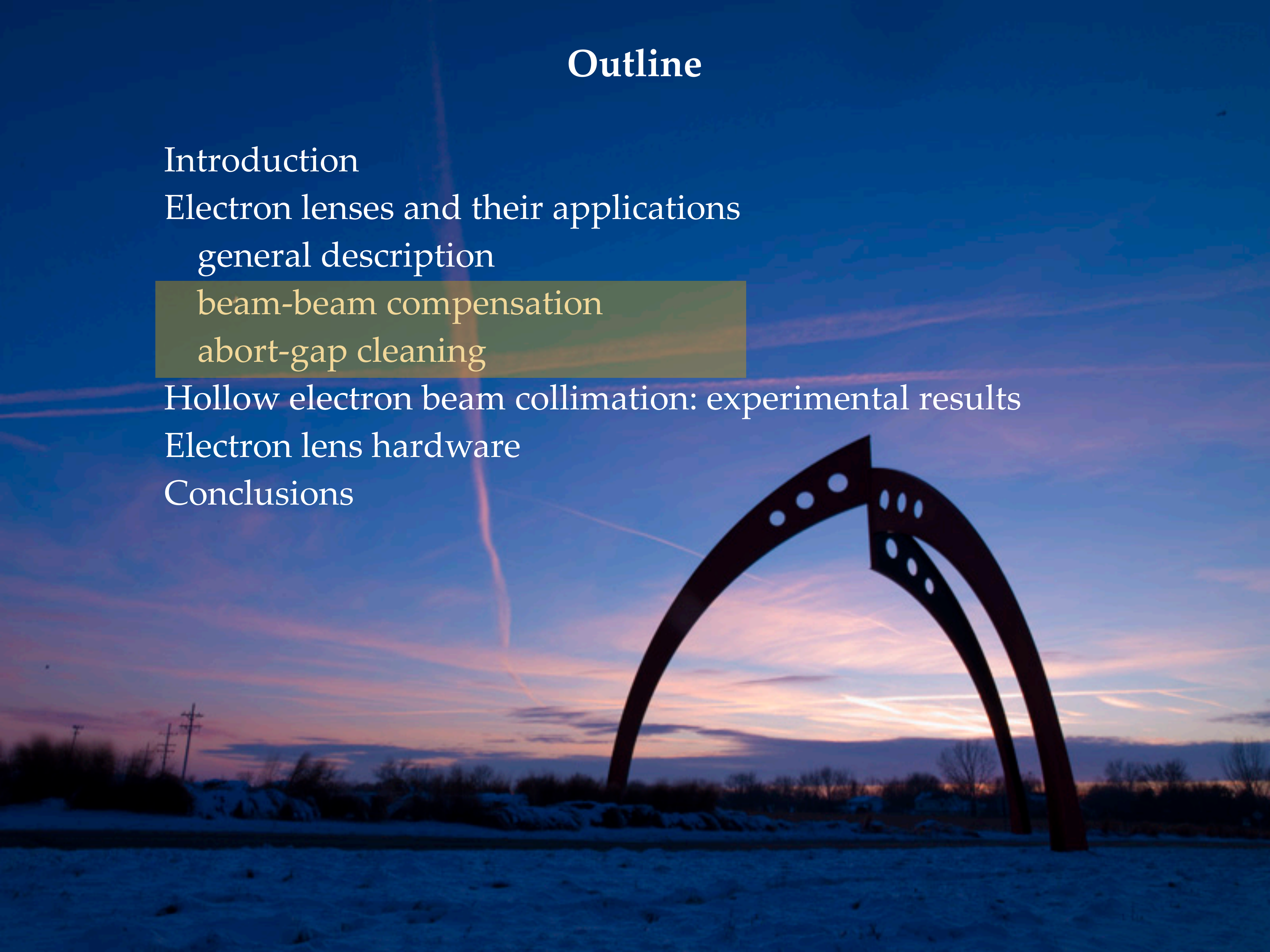


Example of electron gun with hollow cathode



Final assembly

Outline



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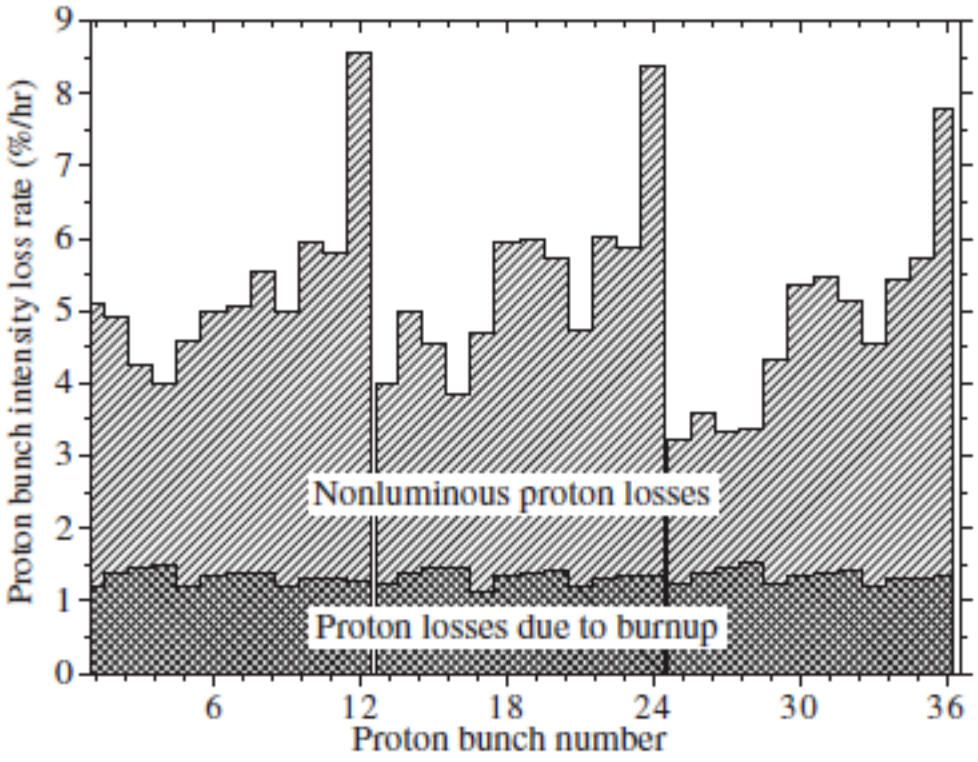
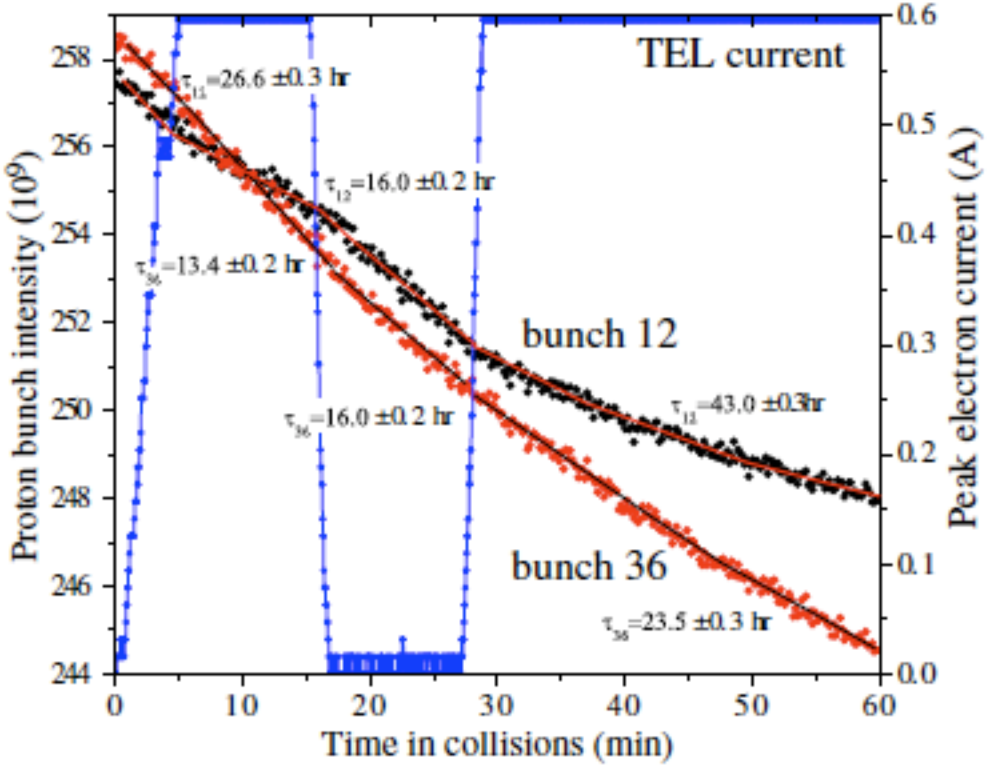
Tevatron electron lenses for long-range beam-beam compensation

- 36 (3x12) proton bunches collide with 36 (3x12) antiproton bunches
- Because of collision pattern, beam-beam tune shift and losses depend on position in bunch train



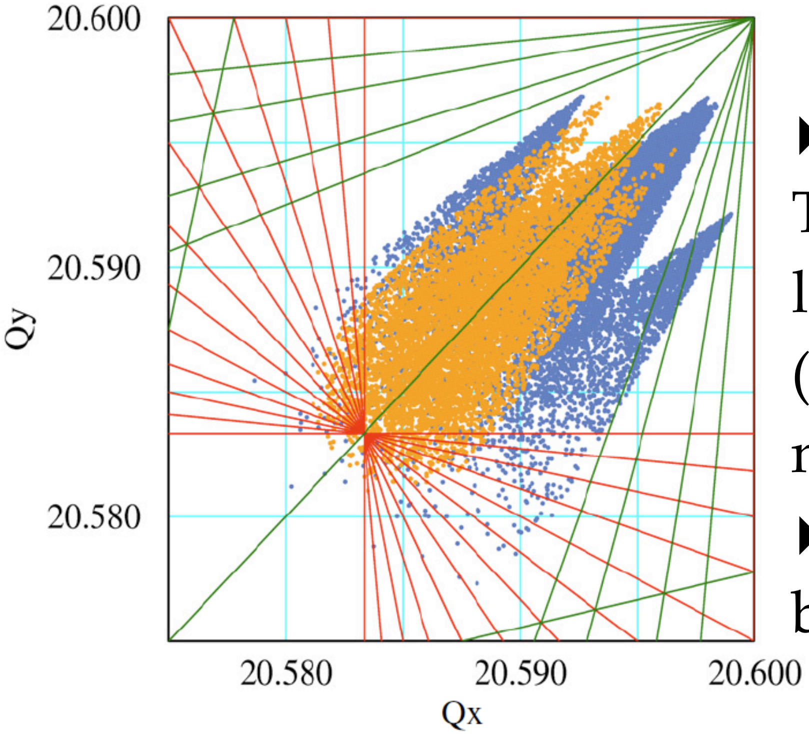


Electron lens with flat profile improves lifetime of chosen bunch

Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)

Tevatron electron lenses for head-on beam-beam compensation

Can a Gaussian electron profile mitigate the nonlinear head-on beam-beam forces acting on antiprotons? Can the tune footprint be reduced?



- ▸Only preliminary studies possible at the Tevatron: technical feasibility; effects on lifetime, tunes, and losses; code benchmarking. (Because of electron cooling, head-on nonlinearities were weak for antiprotons.)
- ▸Electron lenses for beam-beam compensation being installed in RHIC at BNL

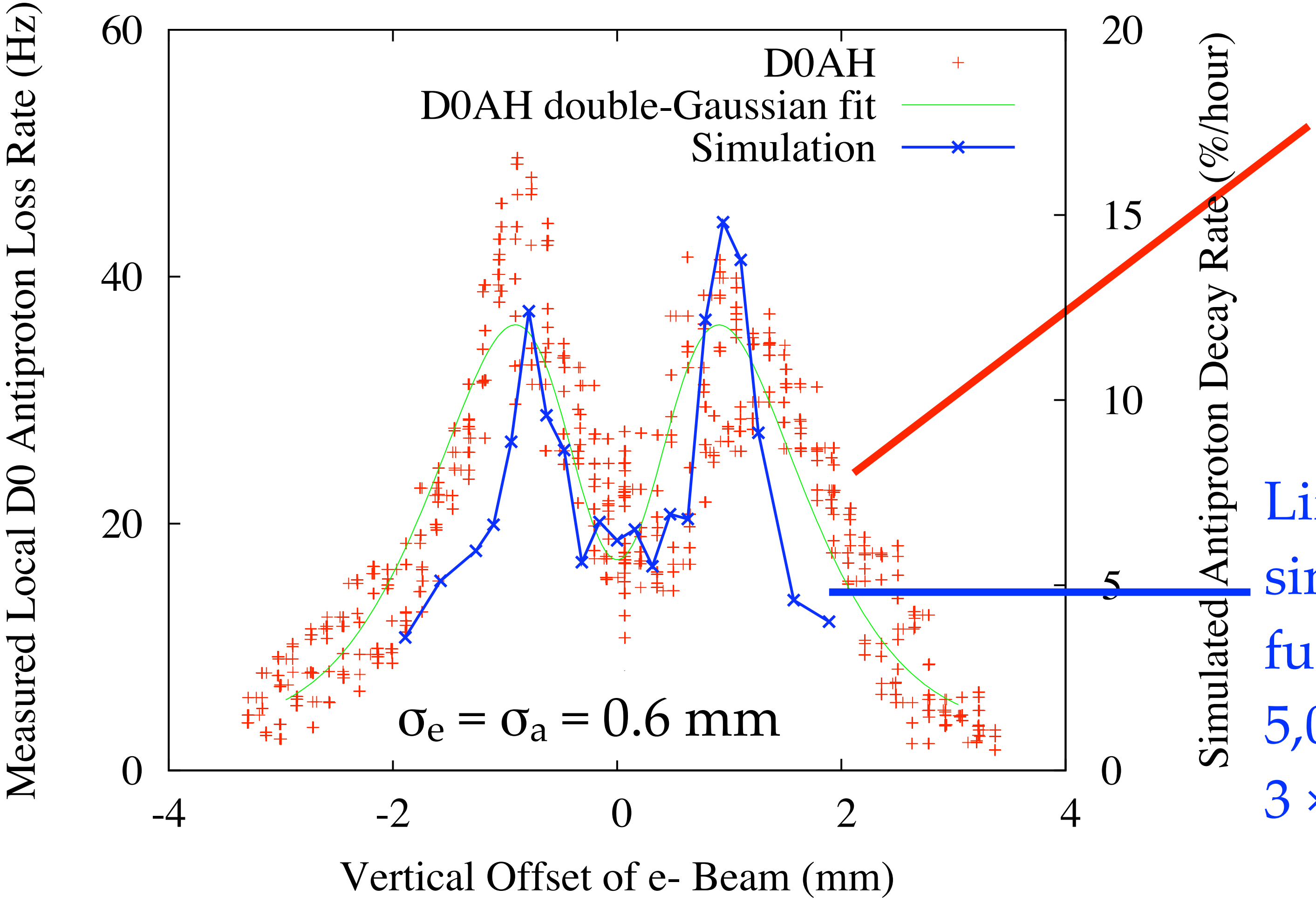
Stancari and Valishev, PAC11 (2011)

Observations in electron beam position scan

(1) No increase in losses with nominal tunes

(2) With tunes lowered by 0.003 (towards 7th order resonance):

- good BPM alignment and no e^-/p^- systematic difference
- double hump structure



measured loss rate

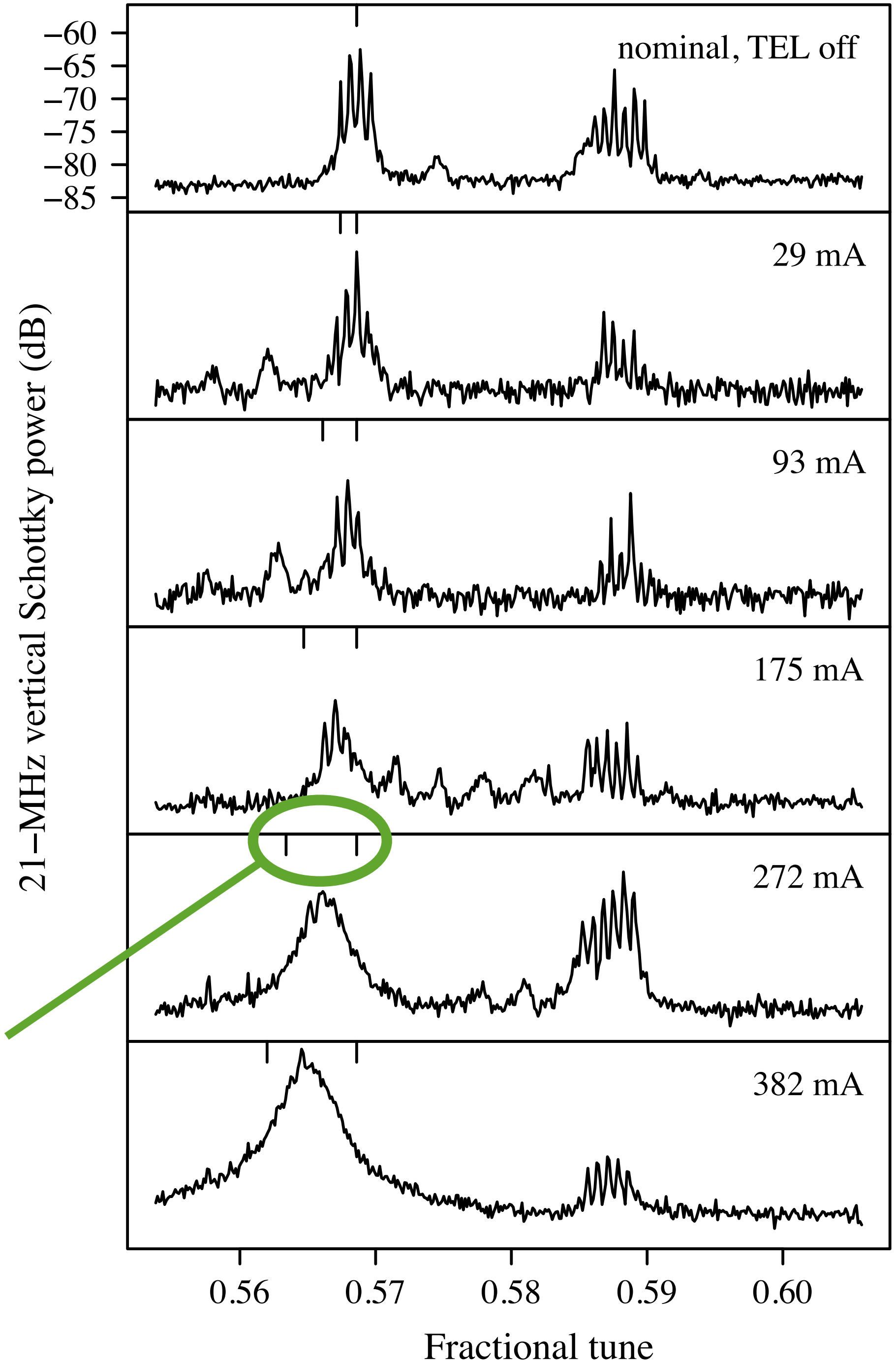
Lifetrac weak-strong simulation:
full collision pattern,
5,000 macroparticles,
3×10^6 turns

(3) Lifetrac simulation reproduces both (1) and the double hump

Incoherent tune spectrum vs. electron beam current

Schottky spectra during dedicated antiproton-only store.

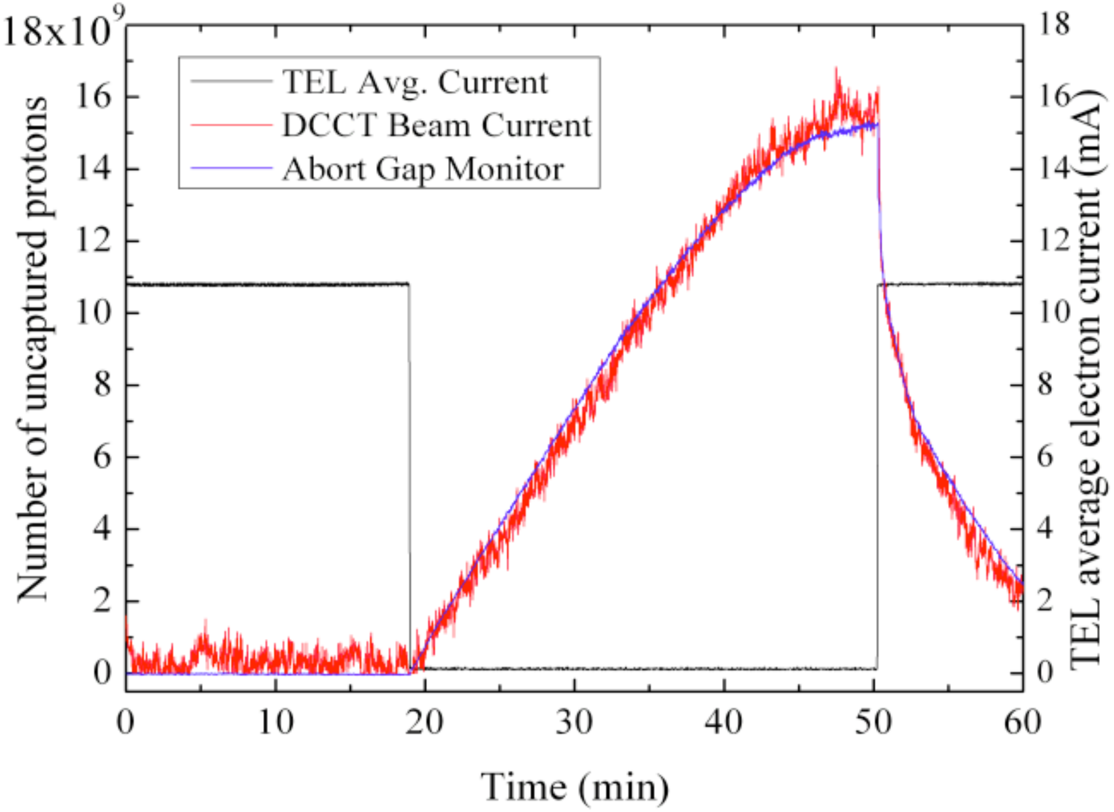
As expected, collisions with electrons widen the tune spectrum.



Calculated linear beam-beam tune shift due to electrons

Tevatron electron lenses for abort-gap cleaning

- Due to intrabeam scattering, instabilities, rf noise, etc. the amount of beam outside the rf bucket increases with time
- Uncaptured beam fills the abort gap (empty space between bunch trains), endangering superconducting magnets in case of beam abort

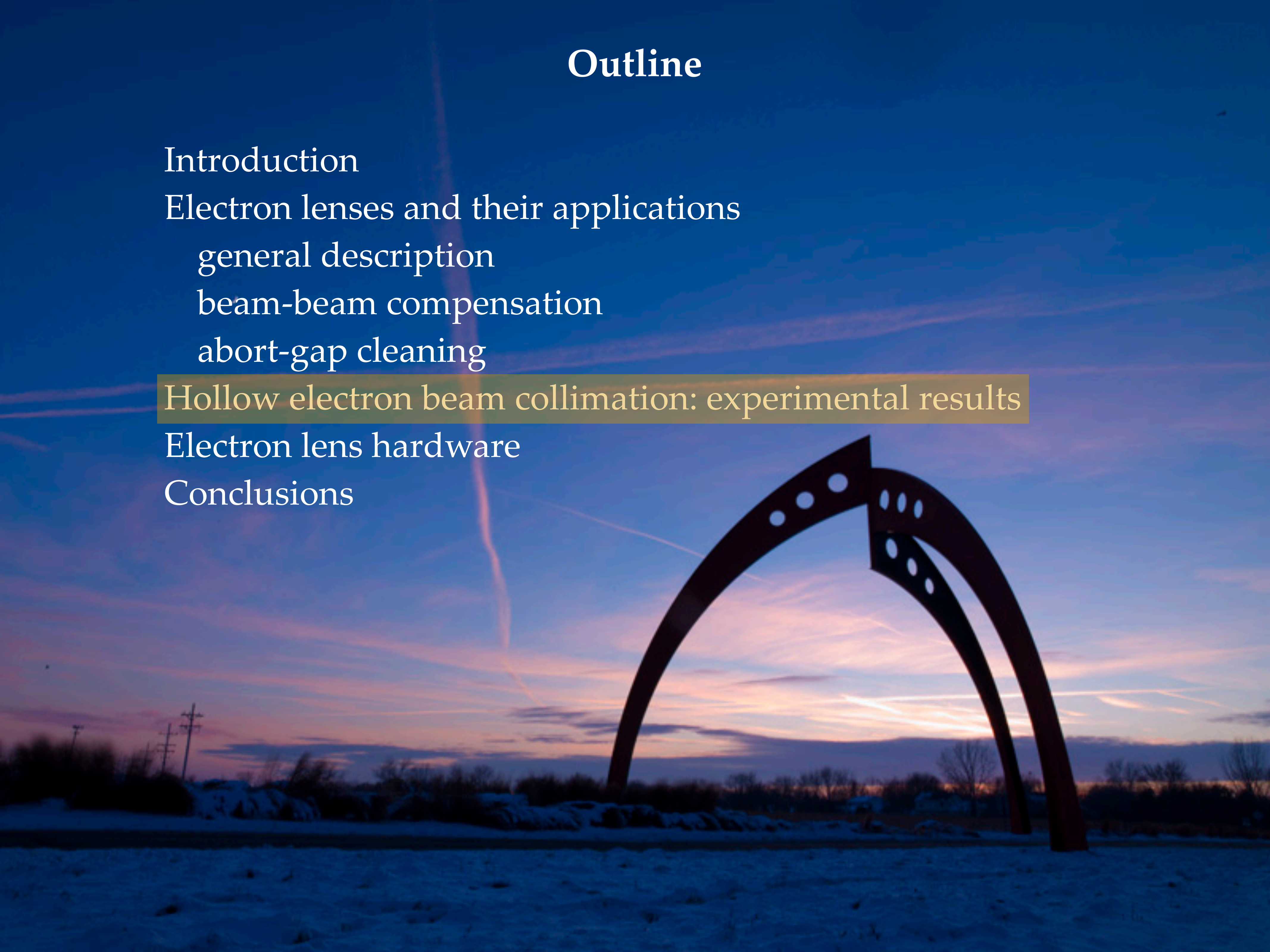


Electron lens was routinely used during operations to smoothly clear the abort gap by resonantly exciting uncaptured particles

Reliable operation from 2003 until Tevatron shutdown in 2011

Zhang et al., Phys. Rev. ST Accel. Beams **11**, 051002 (2008)

Outline



Introduction

Electron lenses and their applications
- general description
- beam-beam compensation
- abort-gap cleaning

Hollow electron beam collimation: experimental results

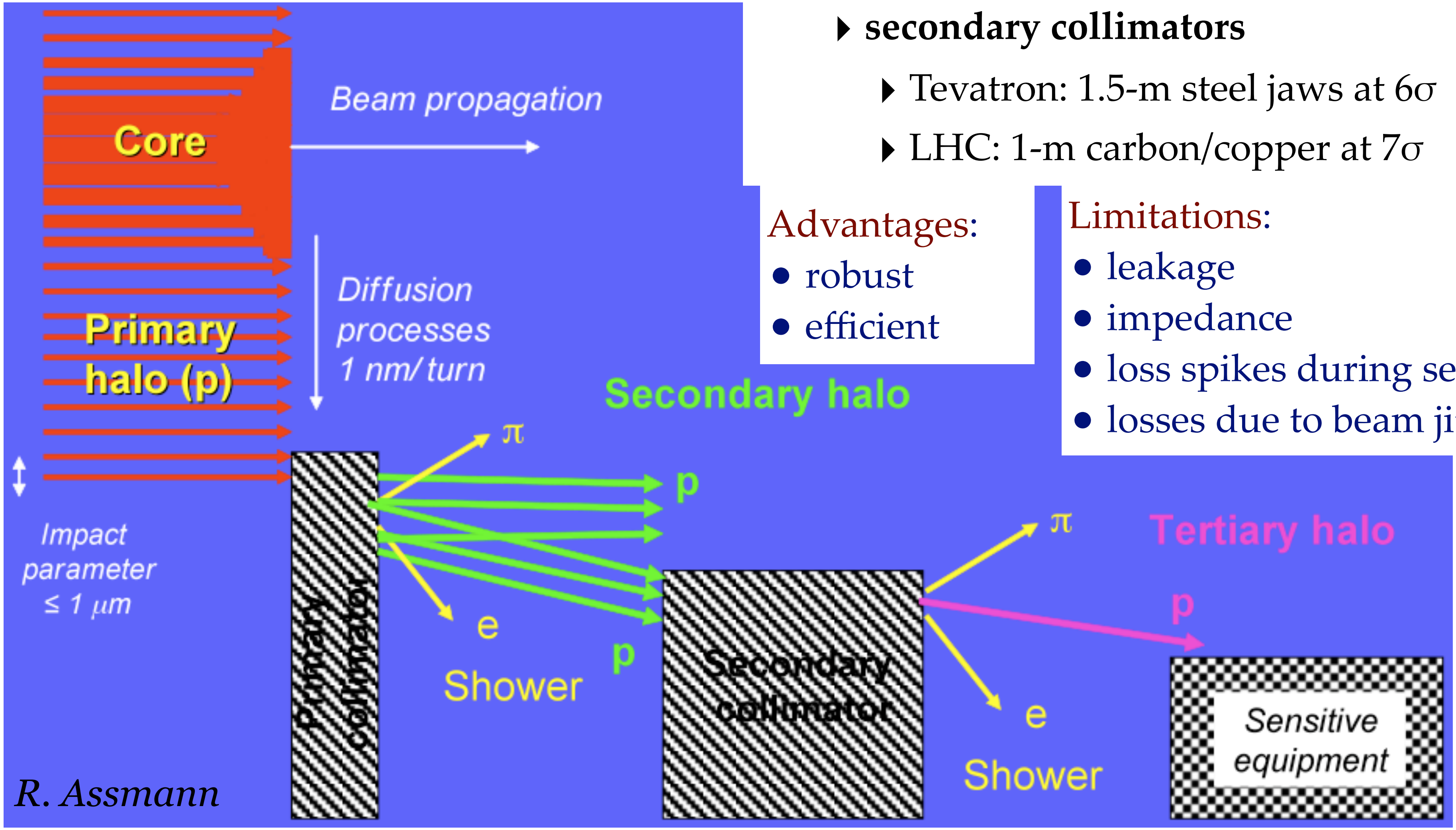
Electron lens hardware

Conclusions

The conventional multi-stage collimation system

- Goals of collimation:
  - reduce beam halo
  - direct losses towards absorbers

- Conventional schemes:
  - **primary collimators**
    - Tevatron: 5-mm W at 5σ
    - LHC: 0.6-m carbon jaws at 6σ
  - **secondary collimators**
    - Tevatron: 1.5-m steel jaws at 6σ
    - LHC: 1-m carbon/copper at 7σ

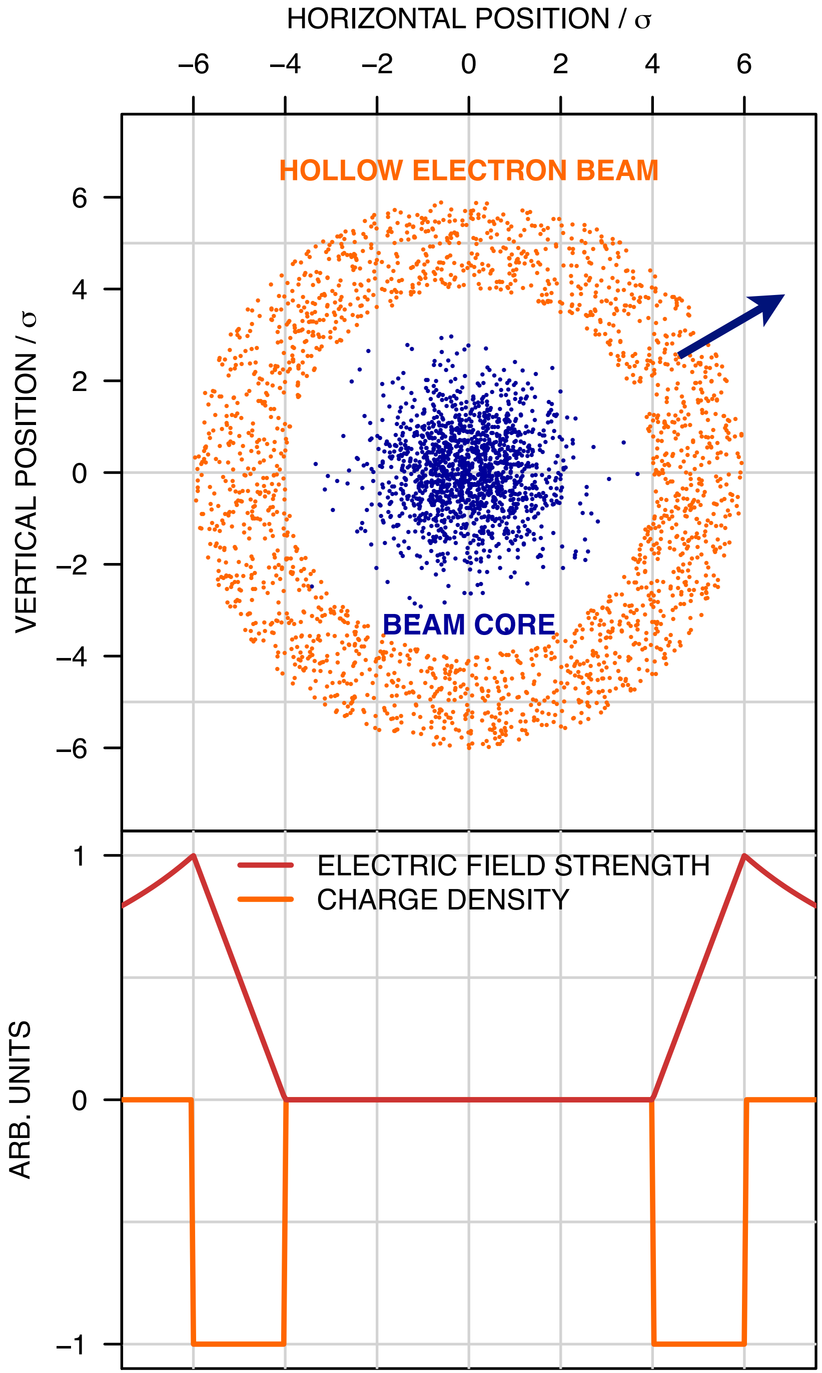


Advantages:
- robust
- efficient

Limitations:
- leakage
- impedance
- loss spikes during setup
- losses due to beam jitter

R. Assmann

Concept of hollow electron beam collimator (HEBC)



Halo experiences nonlinear transverse kicks:

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

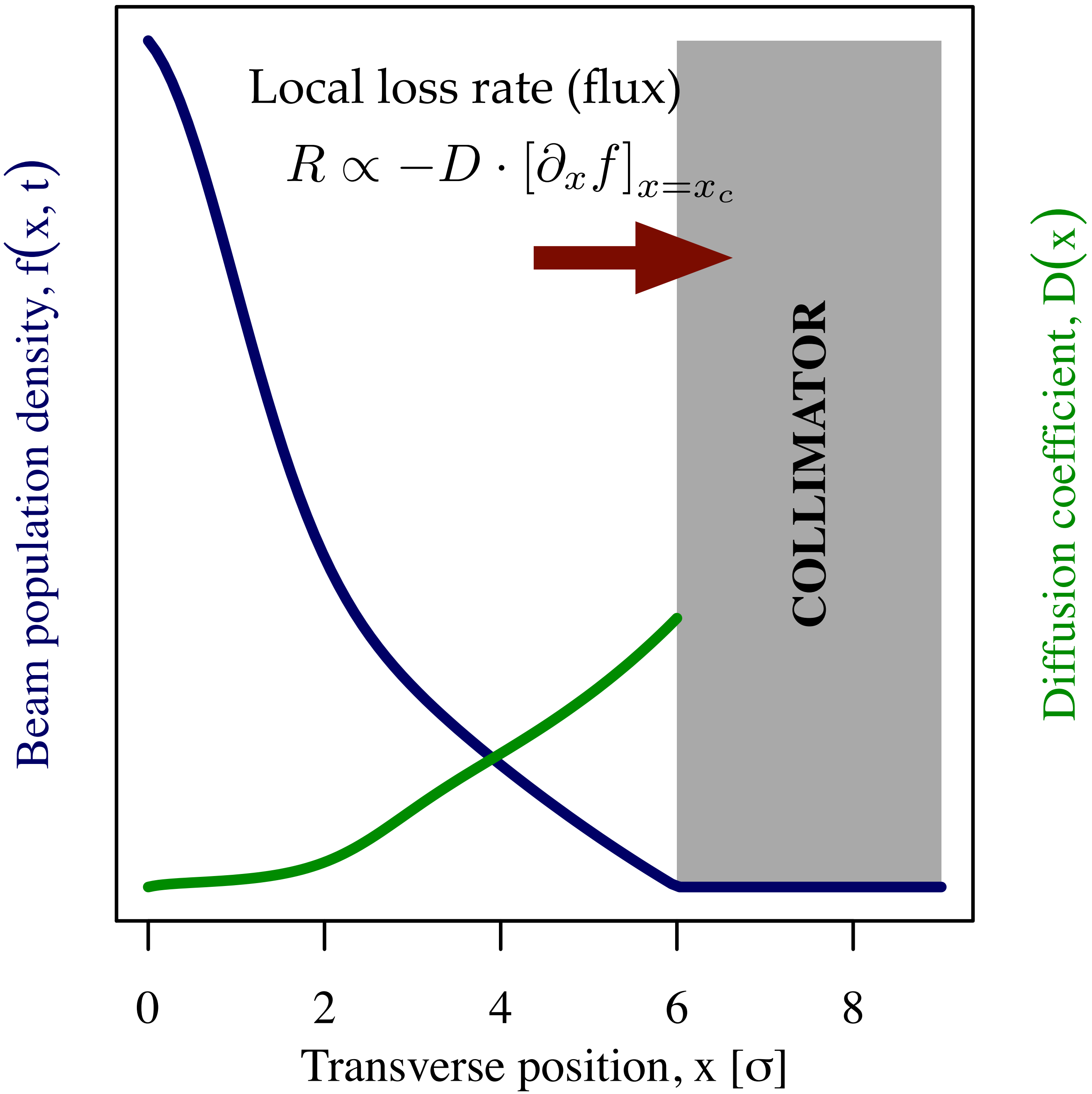
About **0.2 μrad**
in TEL2 at 980 GeV

For comparison:
multiple scattering
in Tevatron collimators

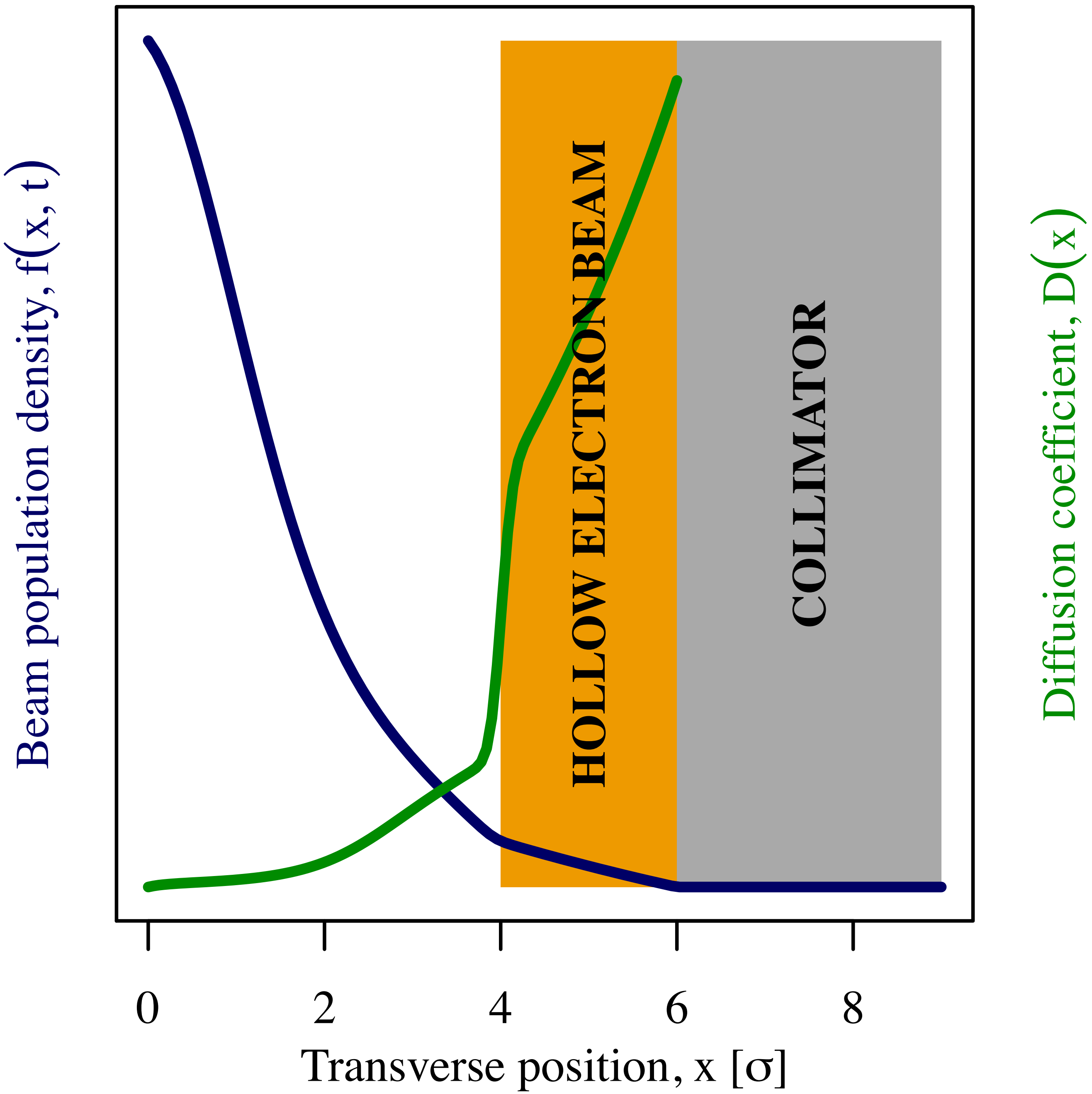
$$\theta_{\mathrm{rms}} = 17\ \mu\mathrm{rad}$$

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

1-dimensional diffusion cartoon of collimation



1-dimensional diffusion cartoon with hollow electron beam



A good complement to a two-stage system 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

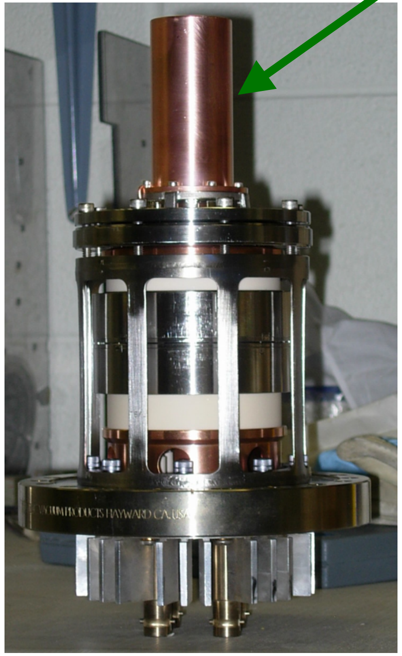
- Critical beam alignment
- Space-charge evolution of hollow beam profile
- Stability of beams at high intensity
- Cost

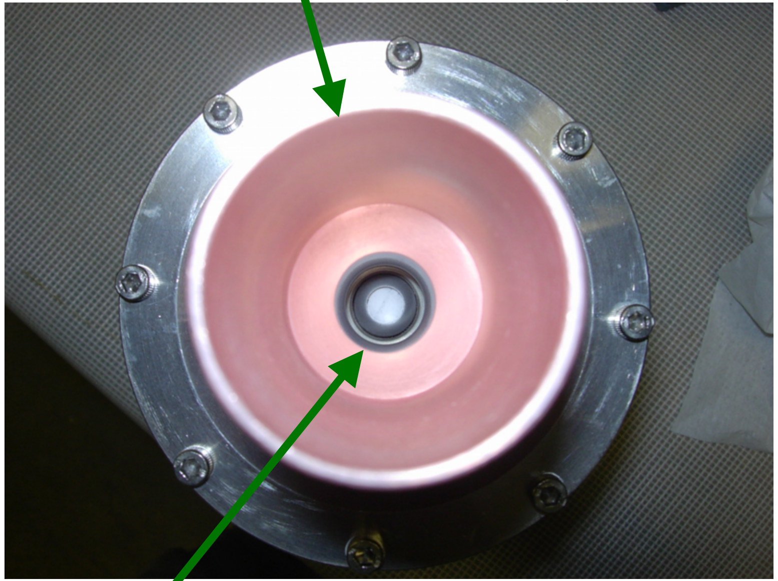
The 15-mm hollow electron gun

side view

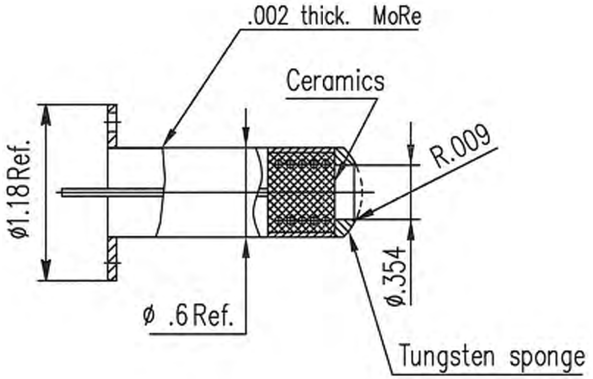
Copper anode

top view



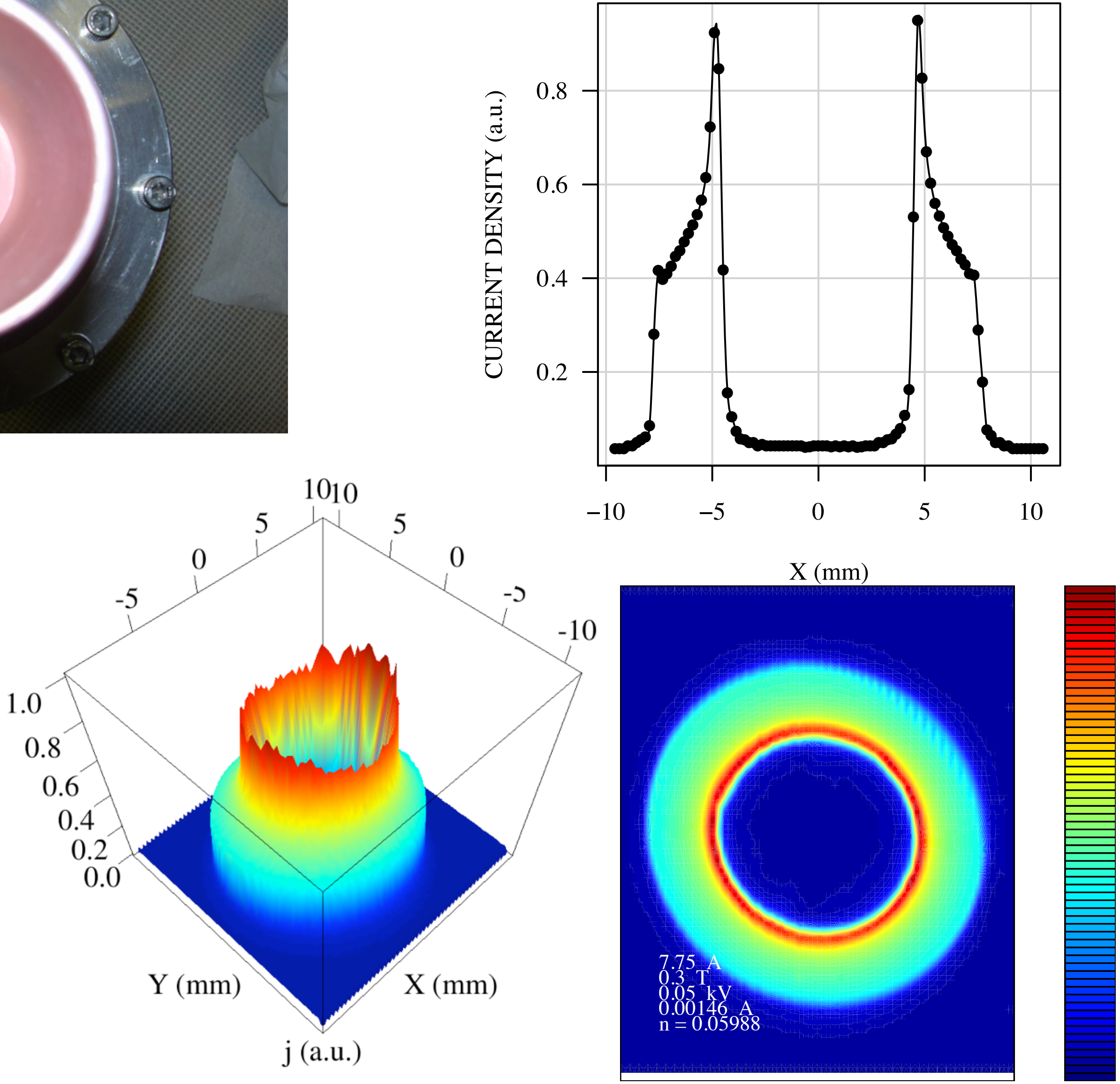


Tungsten dispenser cathode
with convex surface
15-mm diameter, 9-mm hole

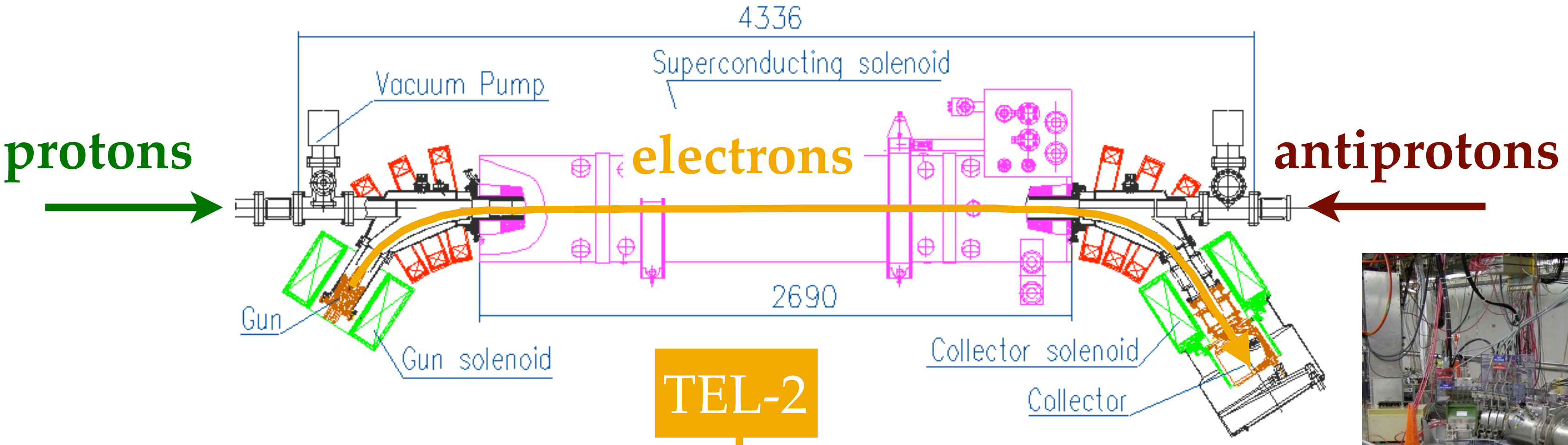


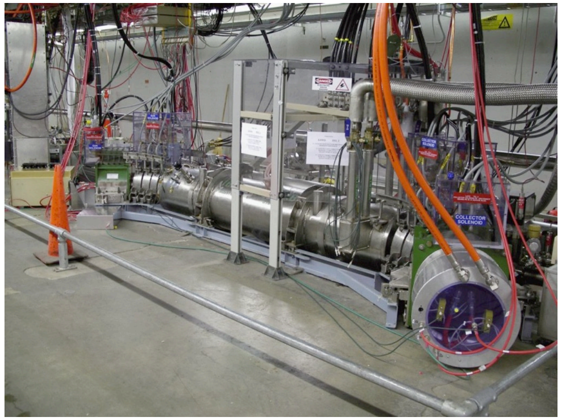
Yield: **1.1 A** at 4.8 kV

Profile measurements



Layout of the beams in the Tevatron





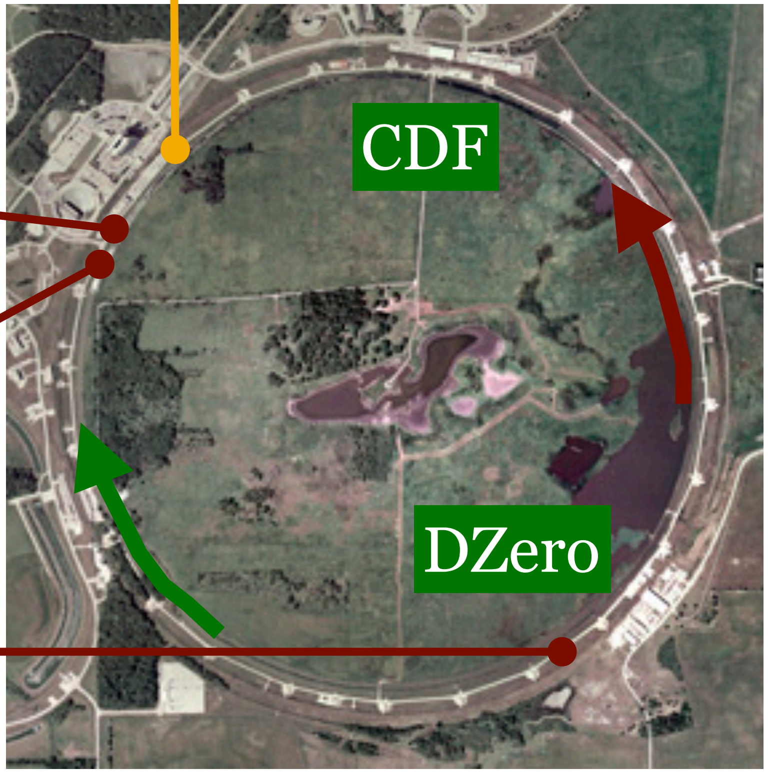
Tevatron electron lens

Antiproton collimators:

Primary (F49)

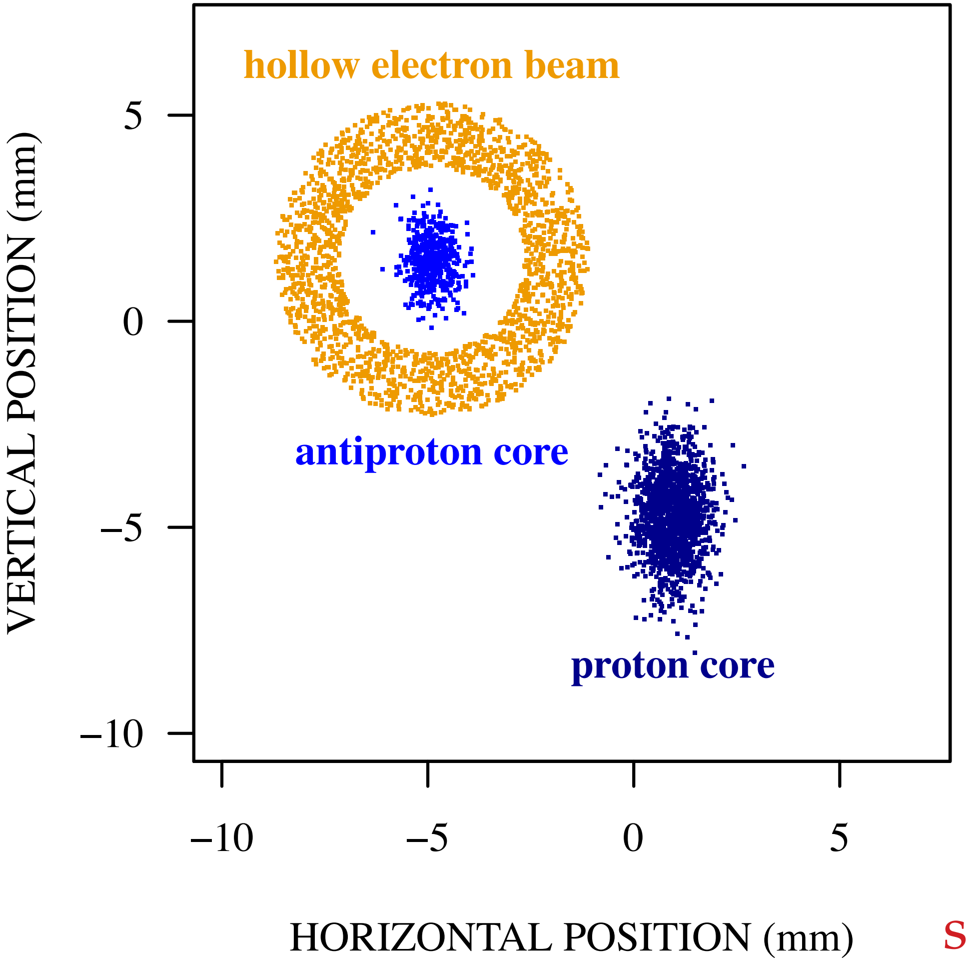
Secondary (F48)

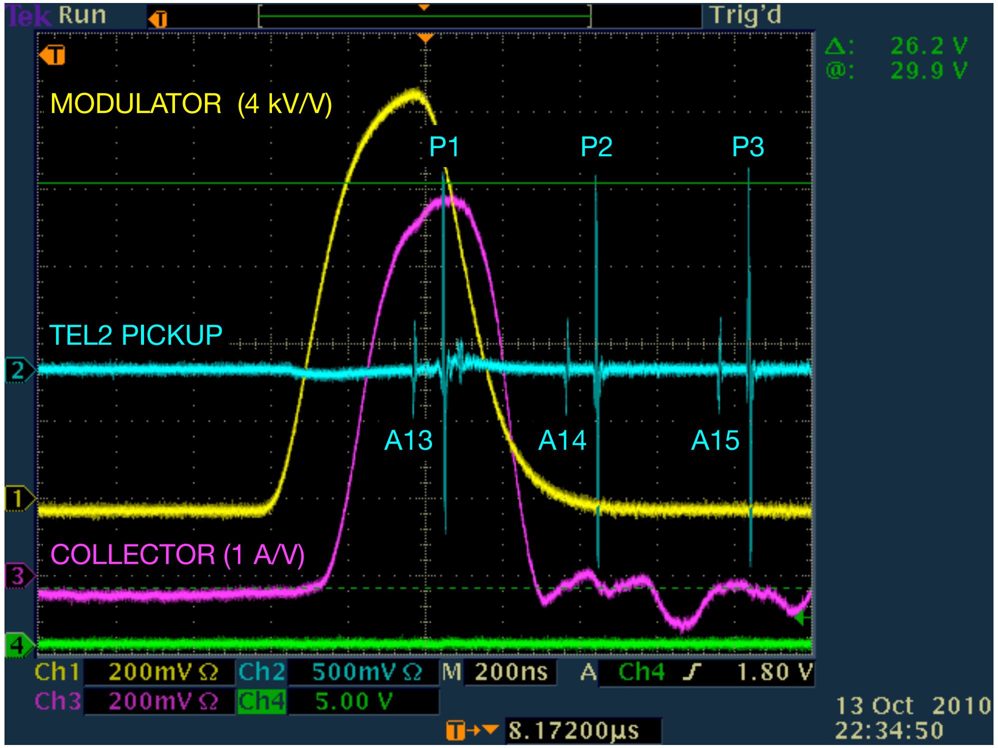
Secondary (D17)



Layout of the beams in the Tevatron

Transverse separation was 9 mm at TEL





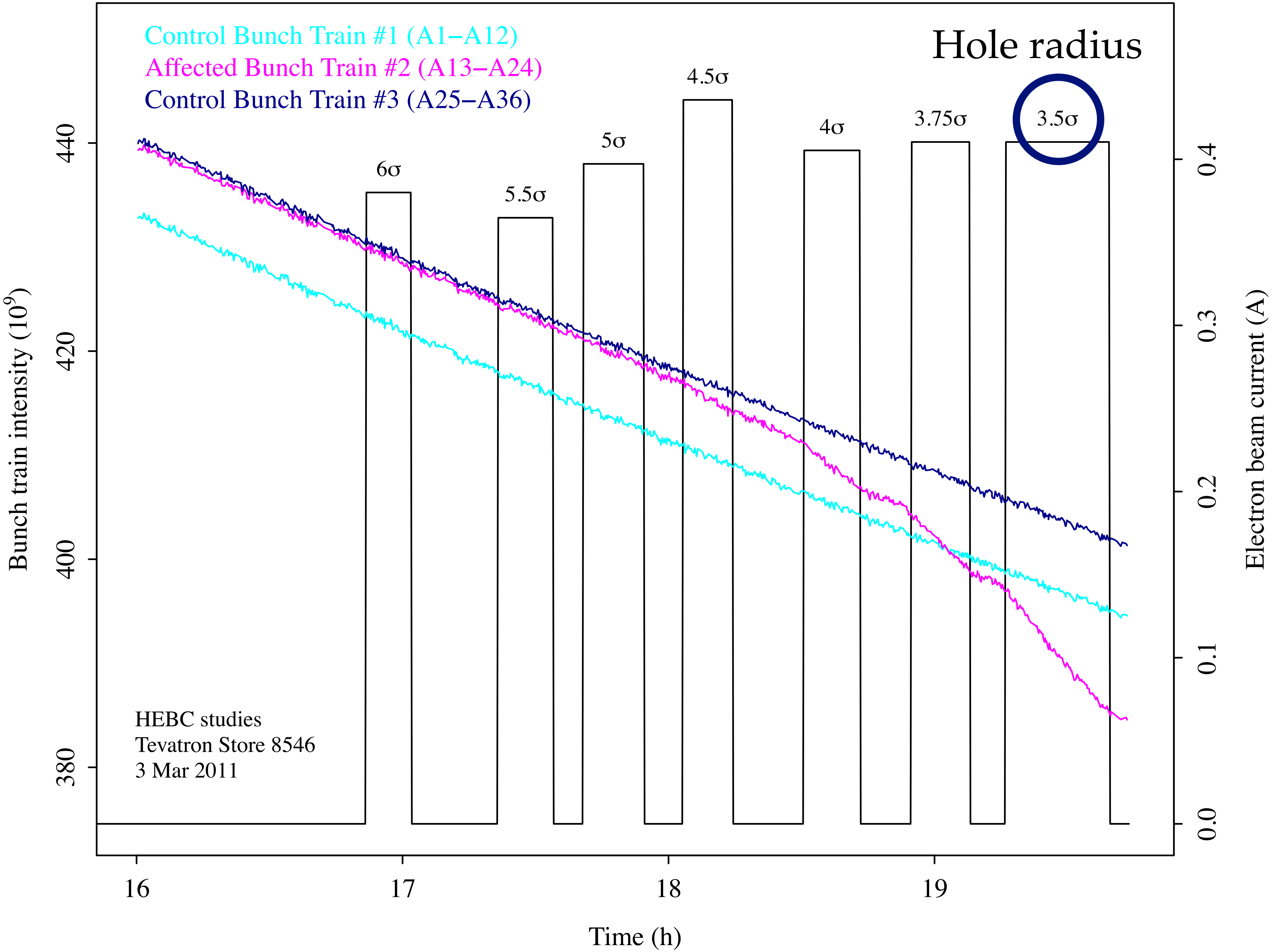
Pulsed electron beam could be synchronized with any group of bunches

Experimental studies of hollow electron beam collimation

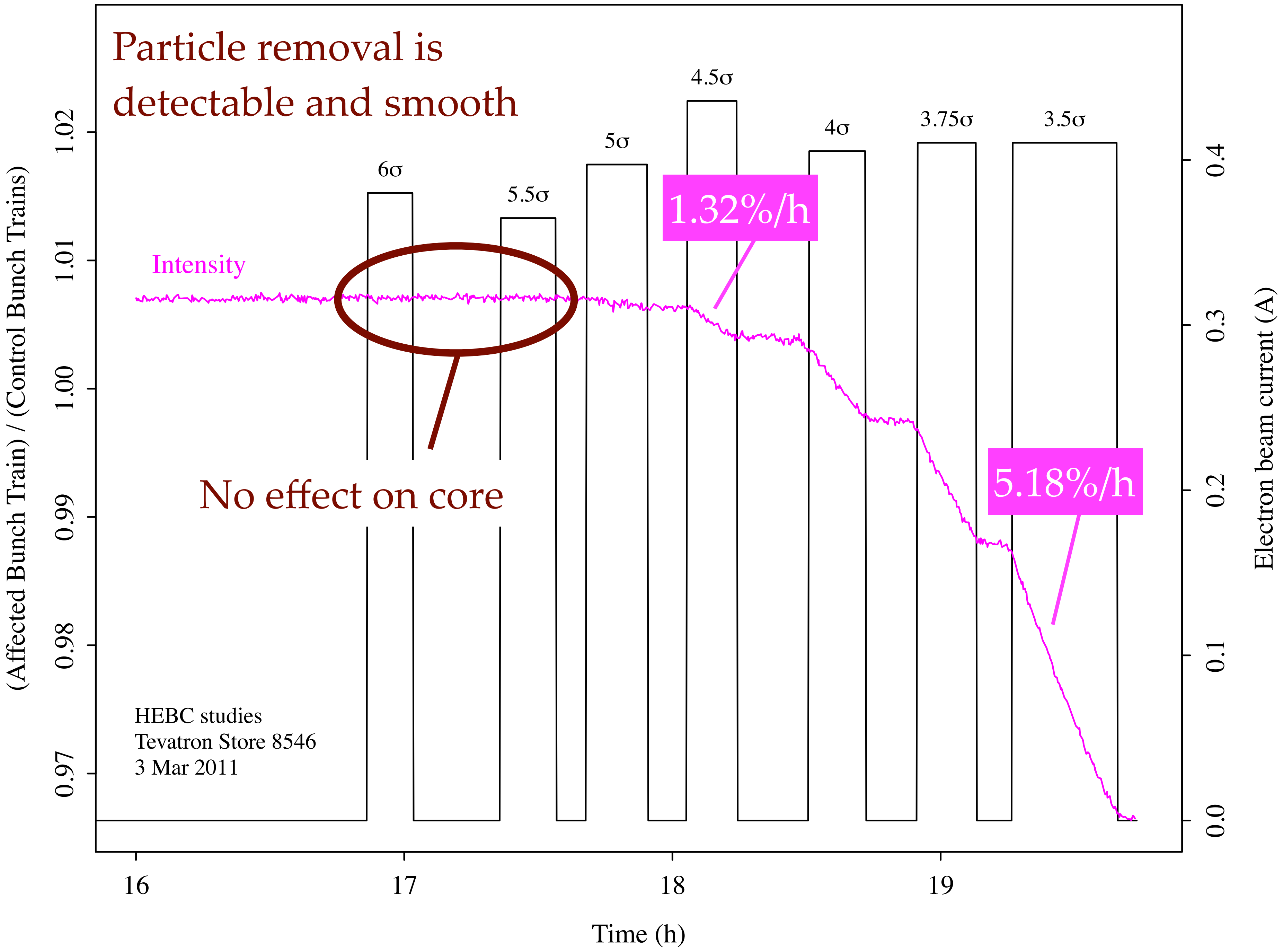
- Tevatron experiments (Oct. ‘10 - Sep. ’11) provided experimental foundation
- Main results
  - **compatibility with collider operations**
  - **alignment** is reliable and reproducible
  - **smooth halo removal**
  - **removal rate vs. particle amplitude**
  - **negligible effects on the core** (particle 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]

Electrons acting on 1 antiproton bunch train (#2, A13-A24)



Removal rate: affected bunch train relative to other 2 trains



Is the core affected? Are particles removed from the halo?

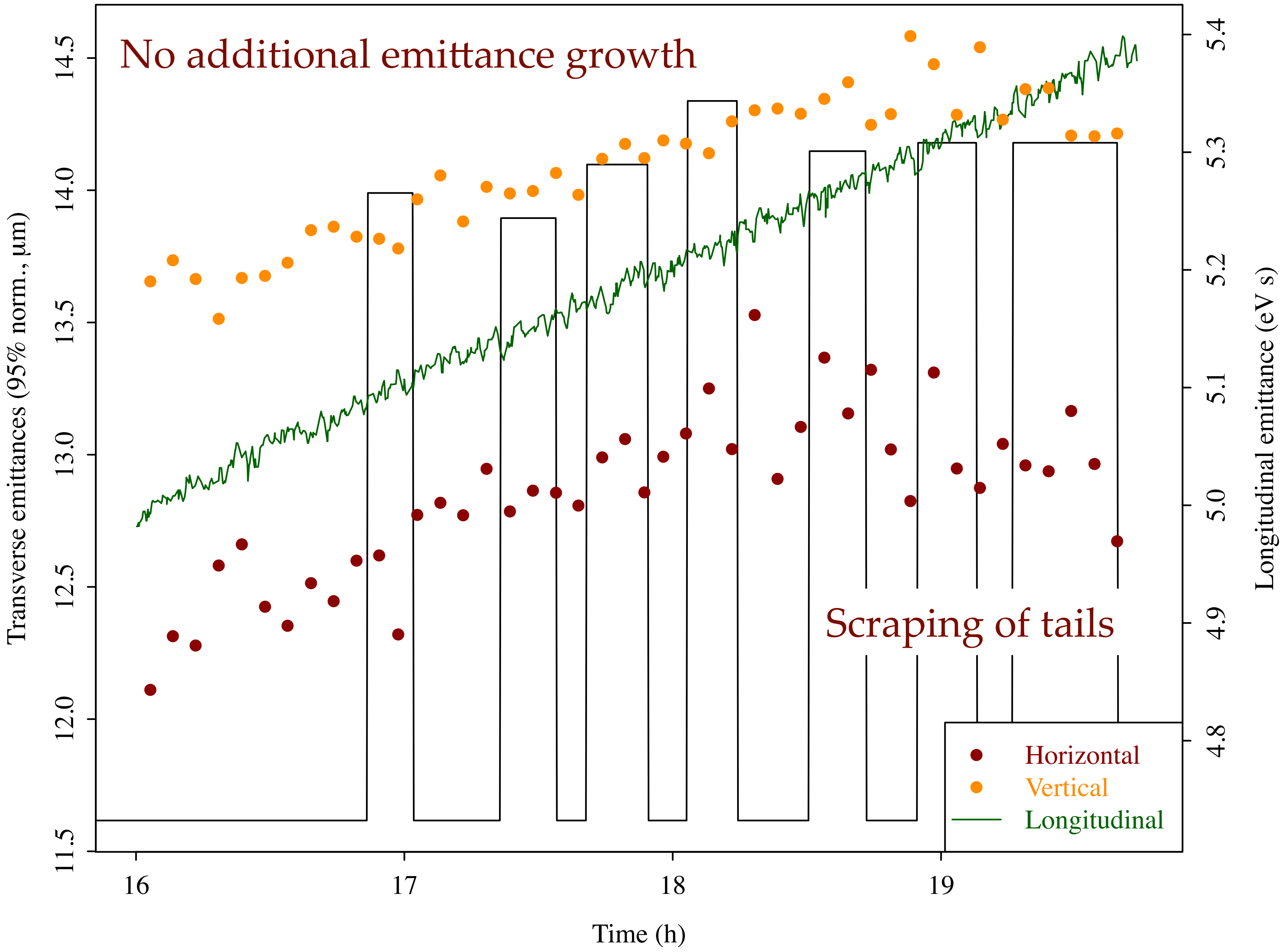
Several strategies:

- **No removal** when e-beam is shadowed by collimators (previous slide)
- Check **emittance** evolution
- Compare **intensity** and **luminosity** change when scraping antiprotons:

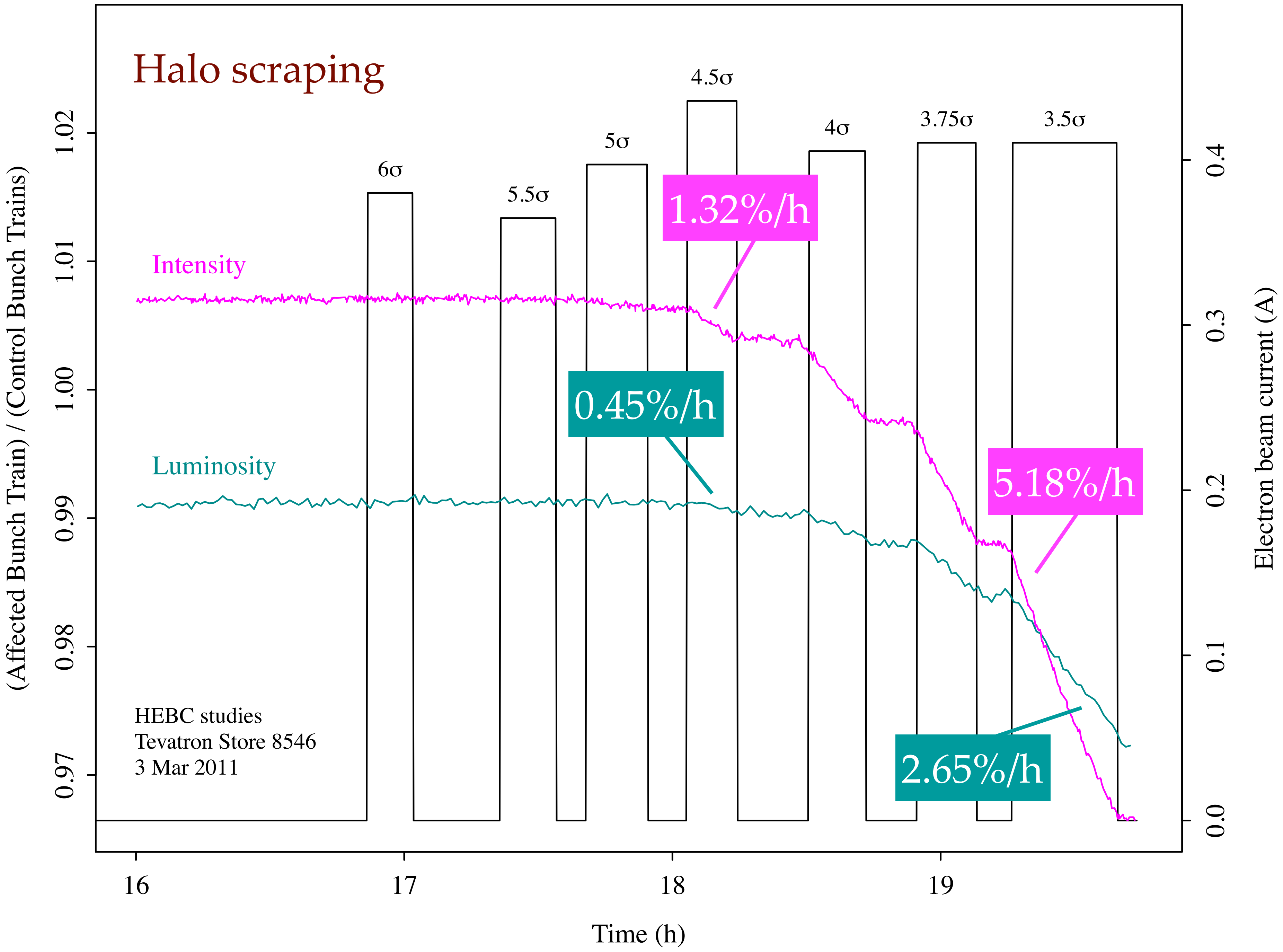
$$\mathcal{L} = \left(\frac{f_{\text{rev}} N_b}{4\pi}\right) \frac{N_p N_a}{\sigma^2} \qquad \frac{\Delta\mathcal{L}}{\mathcal{L}} = \frac{\Delta N_p}{N_p} + \frac{\Delta N_a}{N_a} - 2\frac{\Delta\sigma}{\sigma}$$

  - same fractional variation if other factors are constant
  - luminosity decreases more if there is emittance growth or proton loss
  - luminosity decreases less if removing halo particles (smaller relative contribution to luminosity)
- **Removal rate** vs. amplitude (collimator scan, steady state)
- **Diffusion rate** vs. amplitude (collimator scan, time evolution of losses)

Emittances of affected bunch train



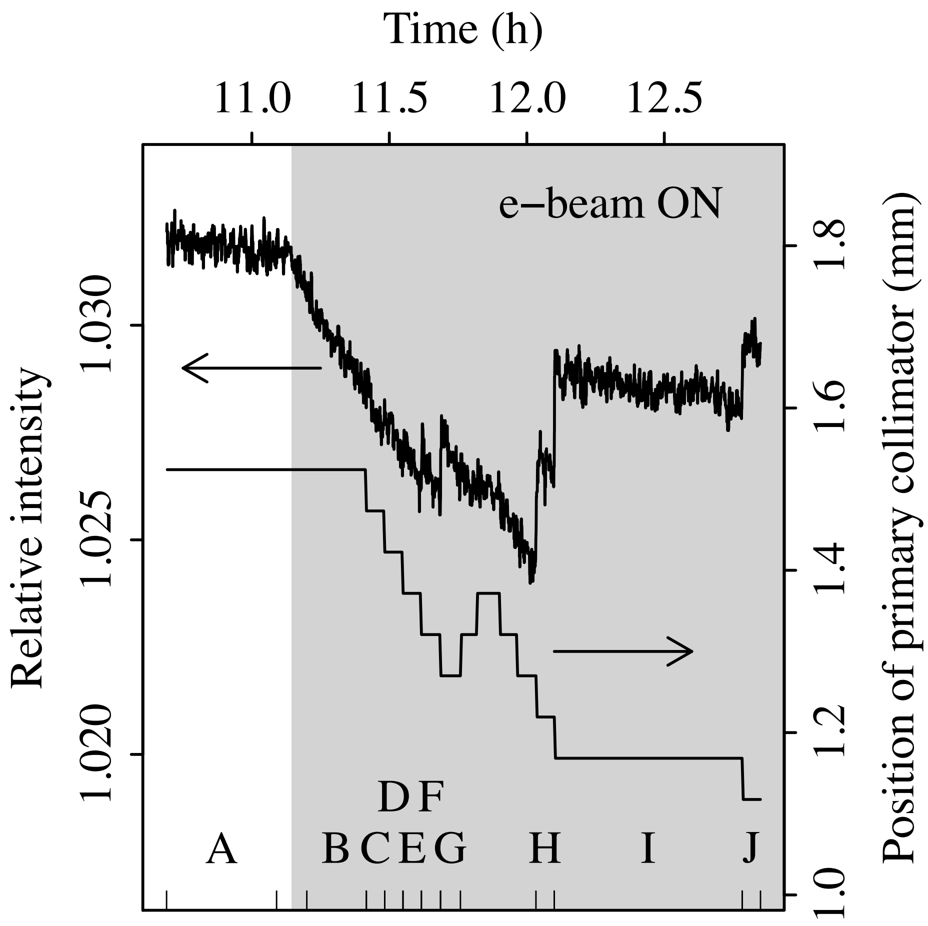
Luminosity of affected bunch train relative to other 2 trains



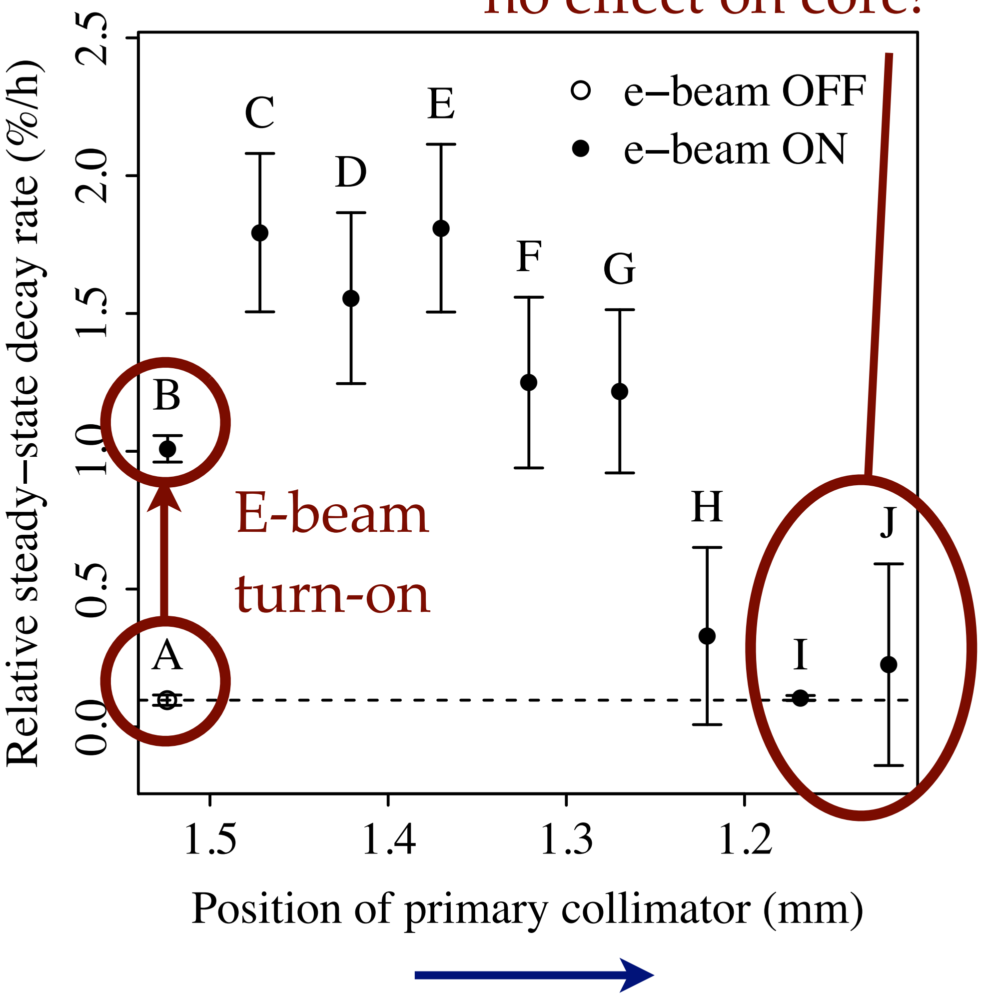
Removal rate vs. amplitude from collimator scan

Electrons (0.15 A) on pbar train #2, 3.5σ hole (1.3 mm at collimator)

Vertical scan of primary collimator (others retracted)



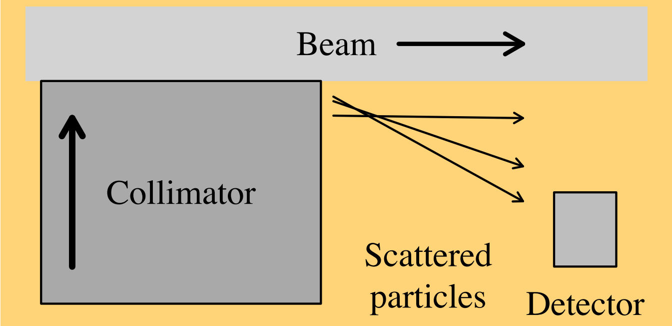
E-beam shadowed, no effect on core!



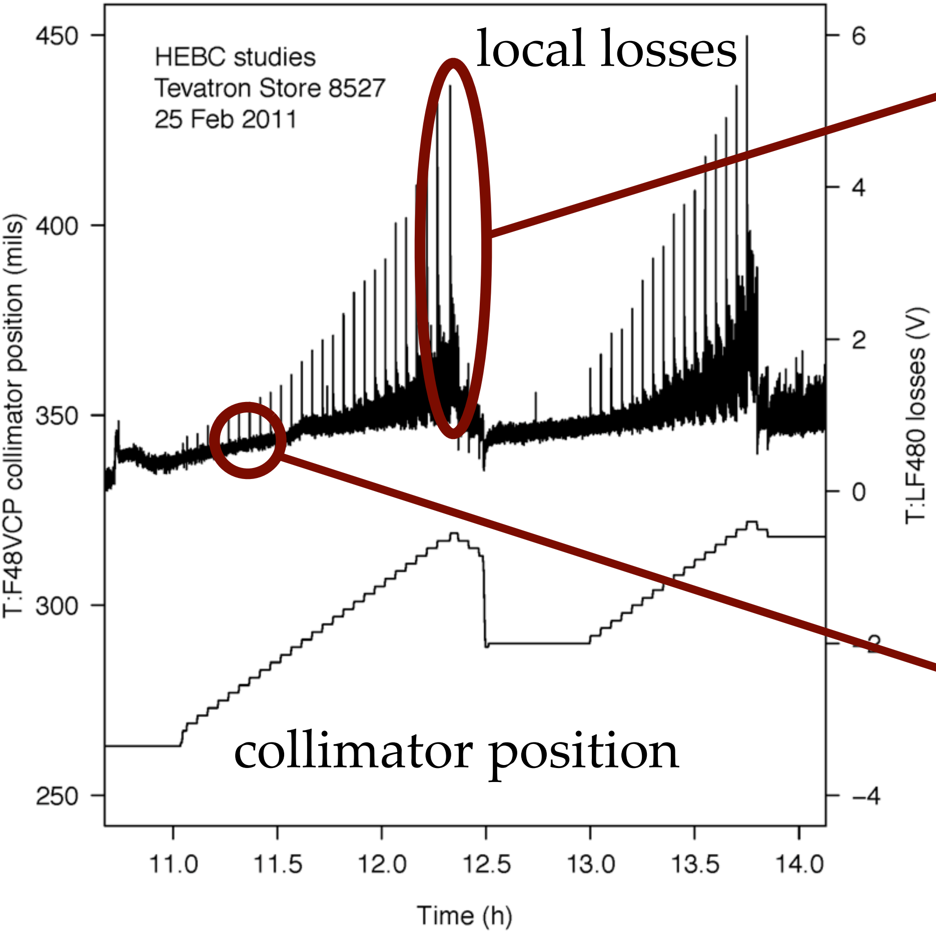
E-beam turn-on

down towards beam axis

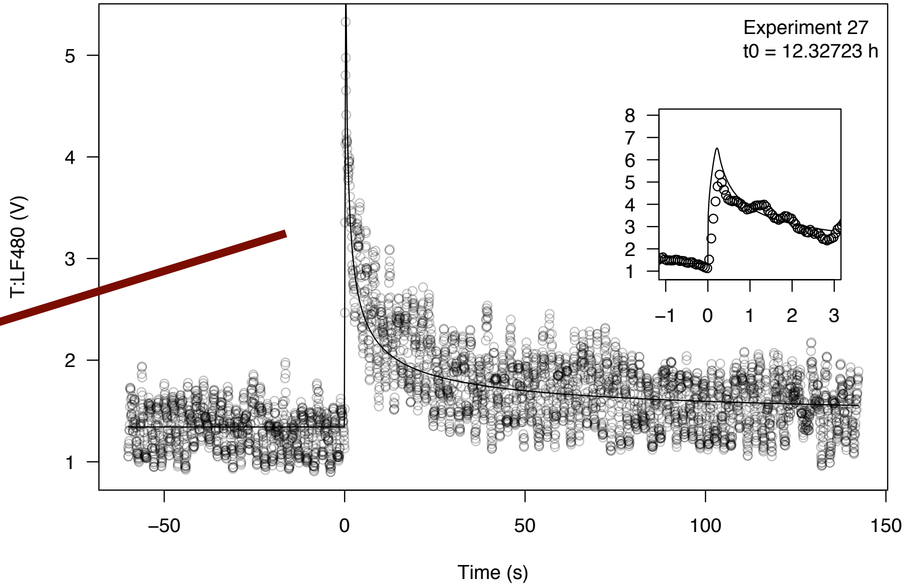
Diffusion rate vs. amplitude from collimator scans



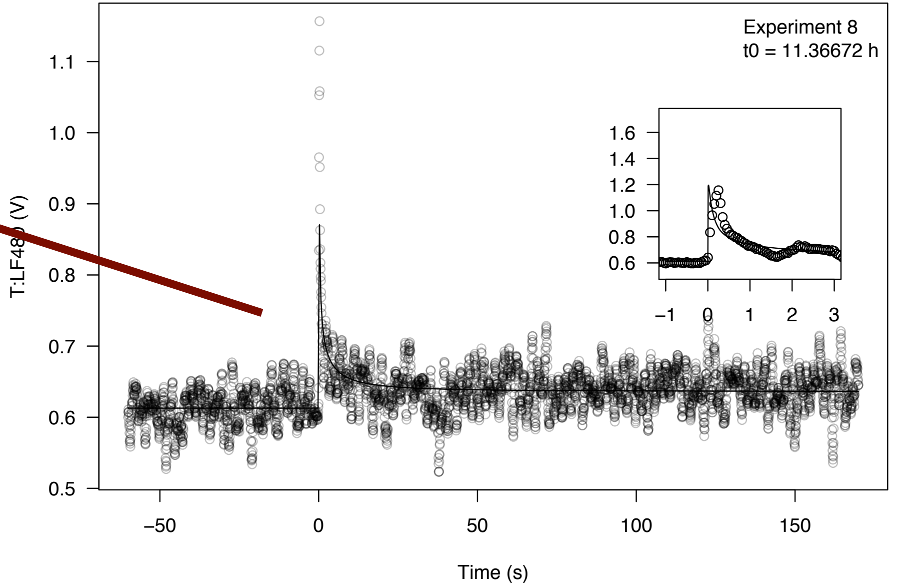
up towards beam axis



Mess and Seidel, NIMA **351**, 279 (1994)

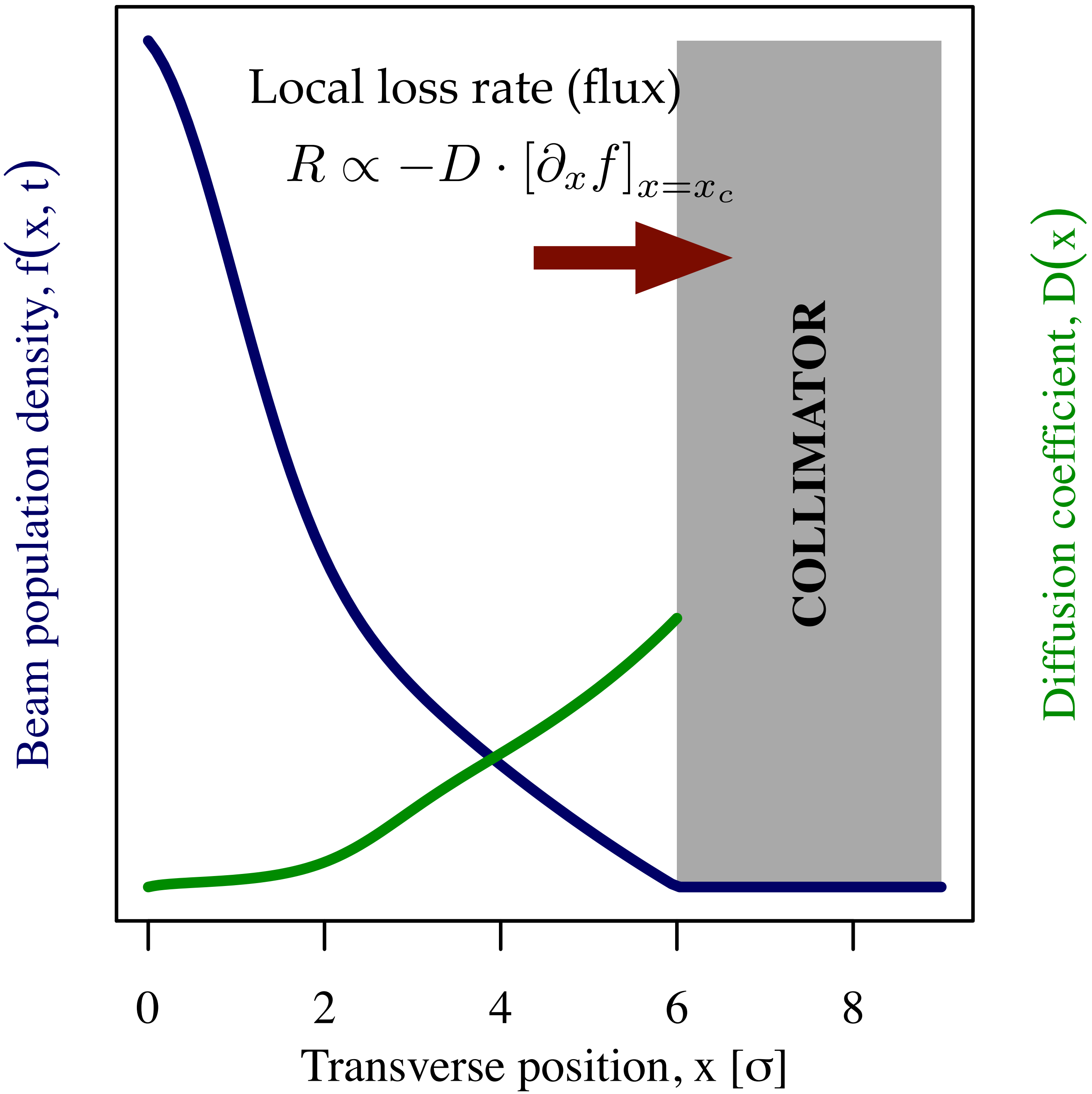


Tails repopulate faster at large amplitudes (higher diffusion rate)



IPAC11, p. 1882
arXiv:1108.5010 [physics.acc-ph]

1-dimensional diffusion cartoon of collimation



Diffusion model of loss rate evolution in collimator scans

Distribution function evolves under diffusion with boundary condition at collimator

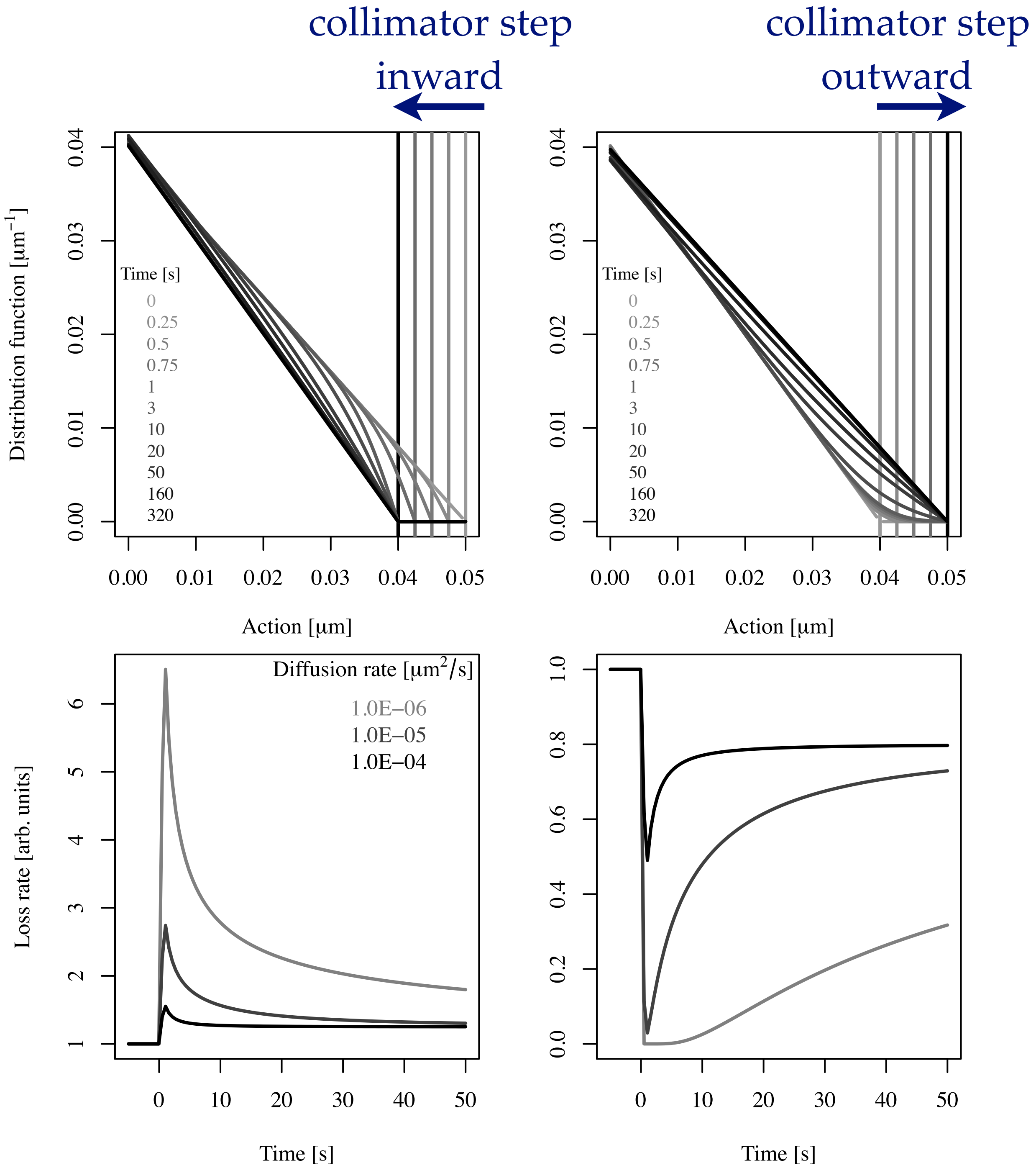
$$\partial_t f = \partial_J \left(D \cdot \partial_J f \right)$$

Instantaneous loss rate is proportional to slope of distribution function

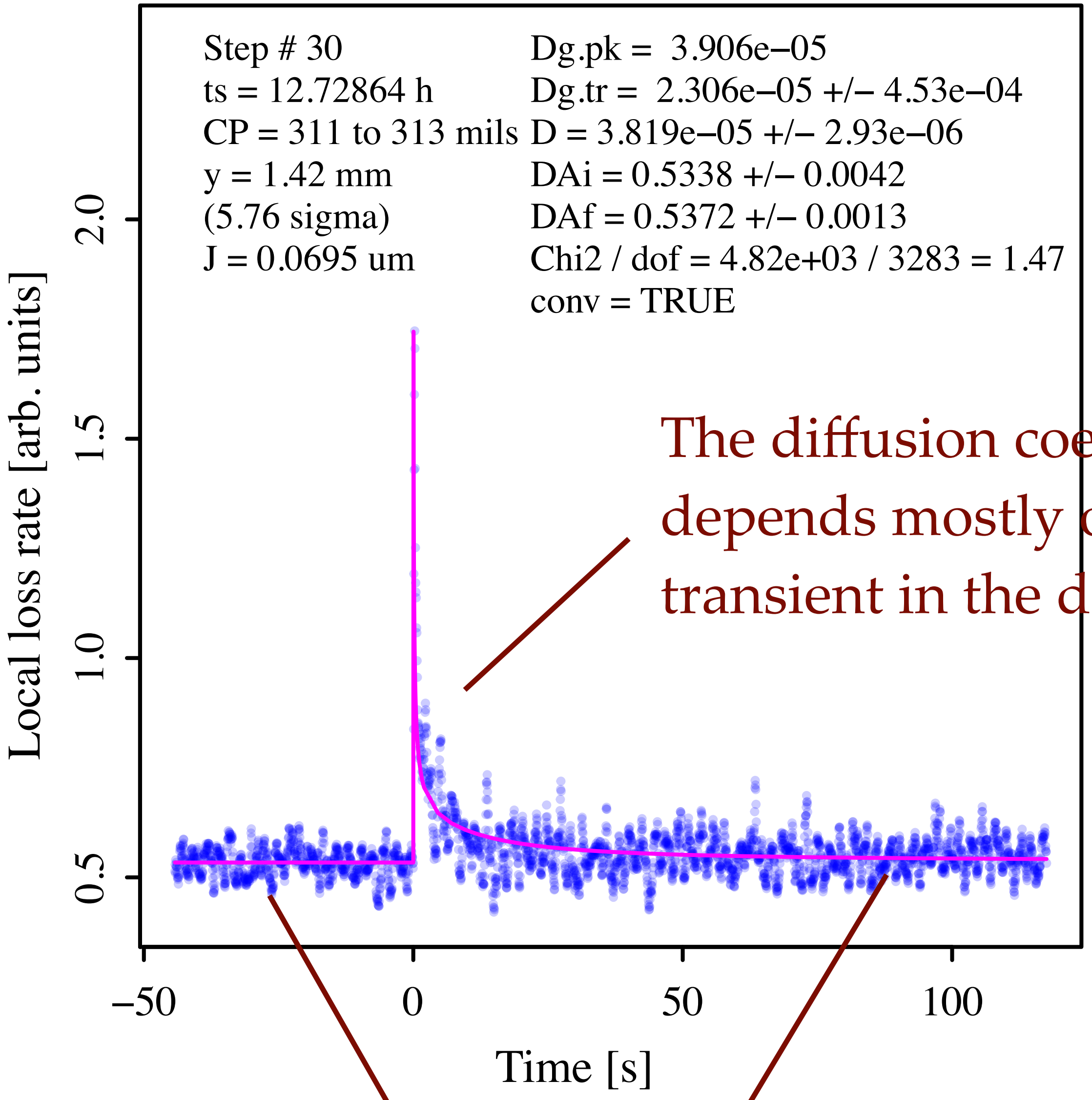
$$R = -k \cdot D \cdot \left[\partial_J f \right]_{J=J_c} + B$$

loss monitor calibration

background rate



Diffusion model fit to loss rate data



The diffusion coefficient depends mostly on the transient in the data

Particle fluxes before and after the step are determined by the steady-state loss levels

Gated antiproton loss monitors

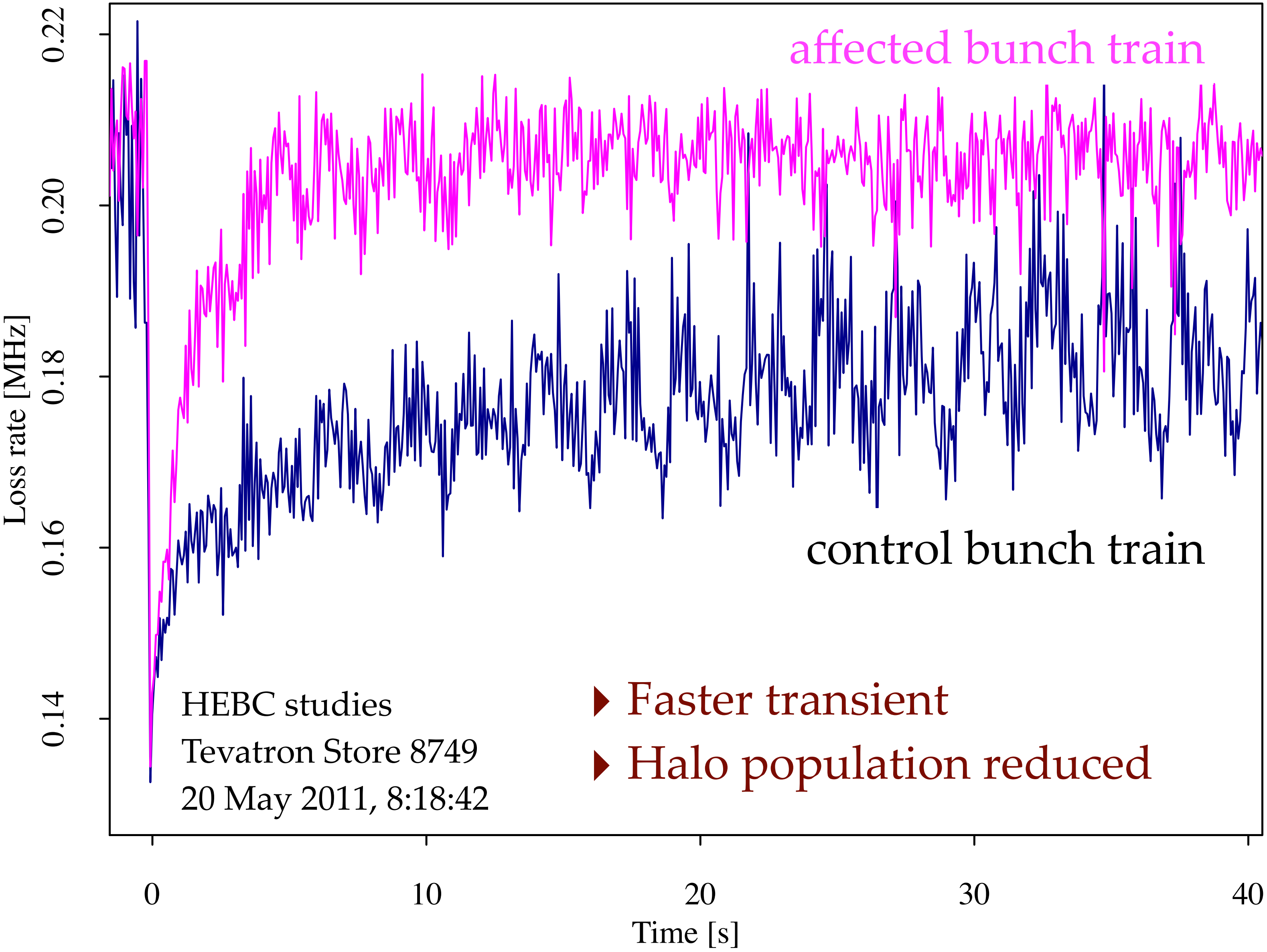
- Scintillator paddles installed near F49 antiproton absorber (Mar '11)
- Gated to individual bunch trains
- Recorded at 15 Hz

Simultaneous measurements of **diffusion rates**, **collimation efficiency**, and **loss spikes** on affected and control bunch trains at maximum electron currents

Measured effect of the hollow electron lens on diffusion in the Tevatron

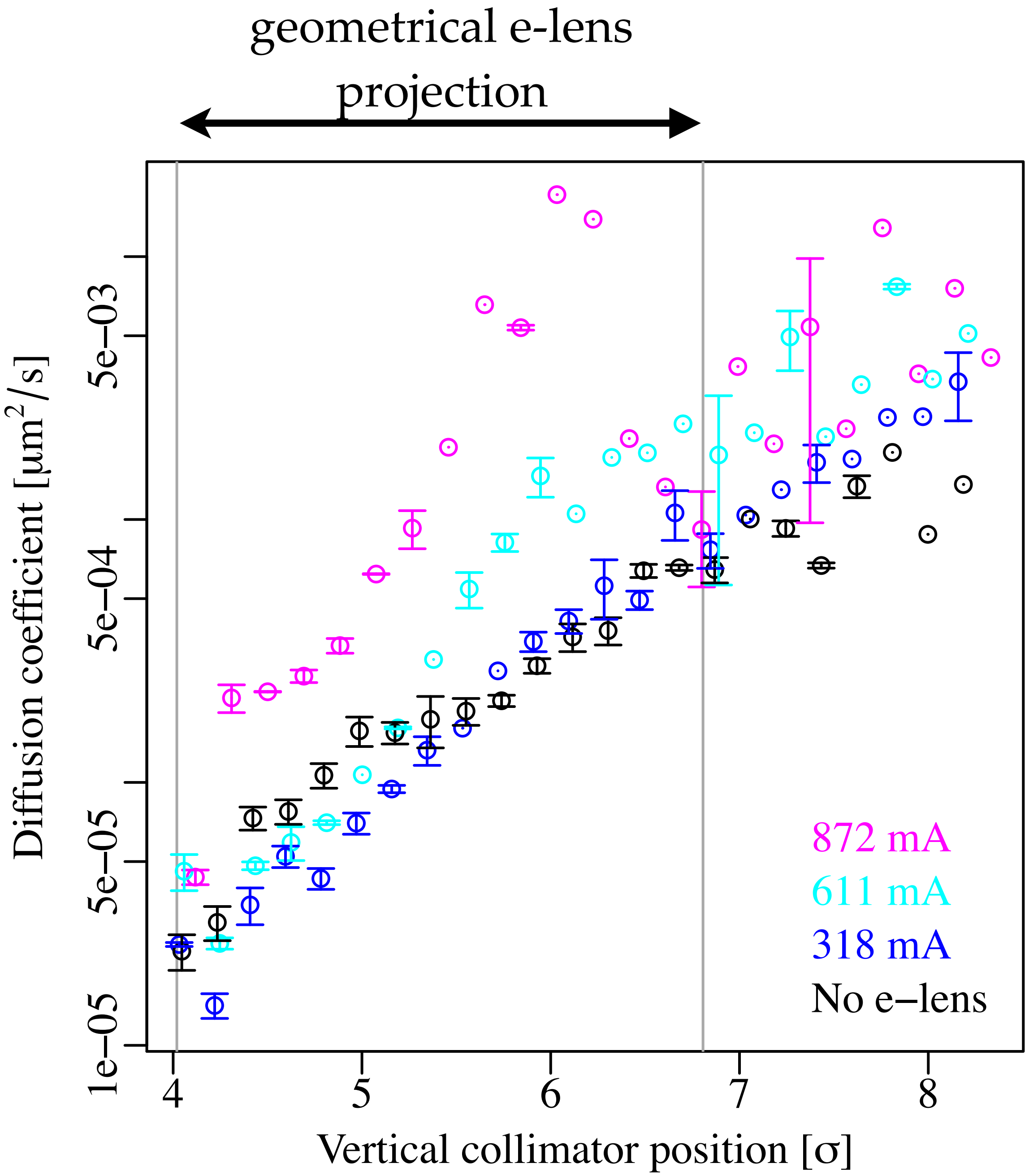
Electrons (0.9 A) on pbar train #2, 4.25σ hole

Example of **vertical collimator step out**, 50 μm



- Faster transient
- Halo population reduced

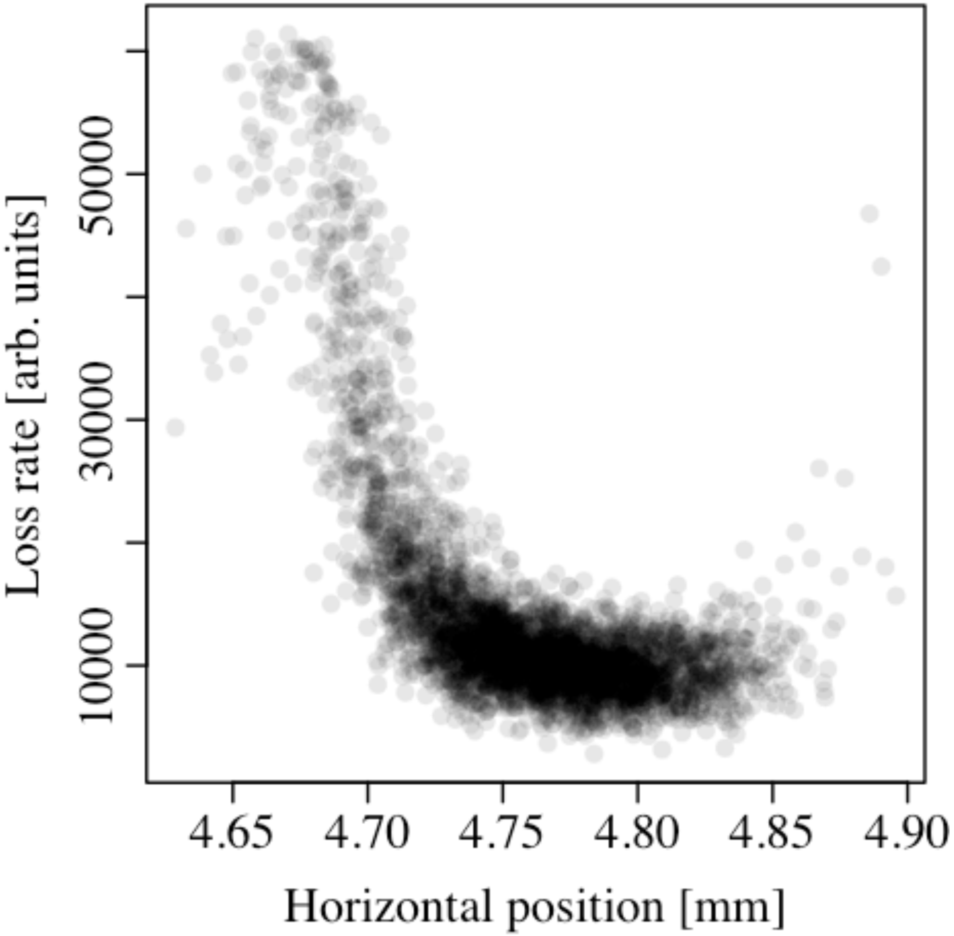
Measured effect of the hollow electron lens on diffusion in the Tevatron



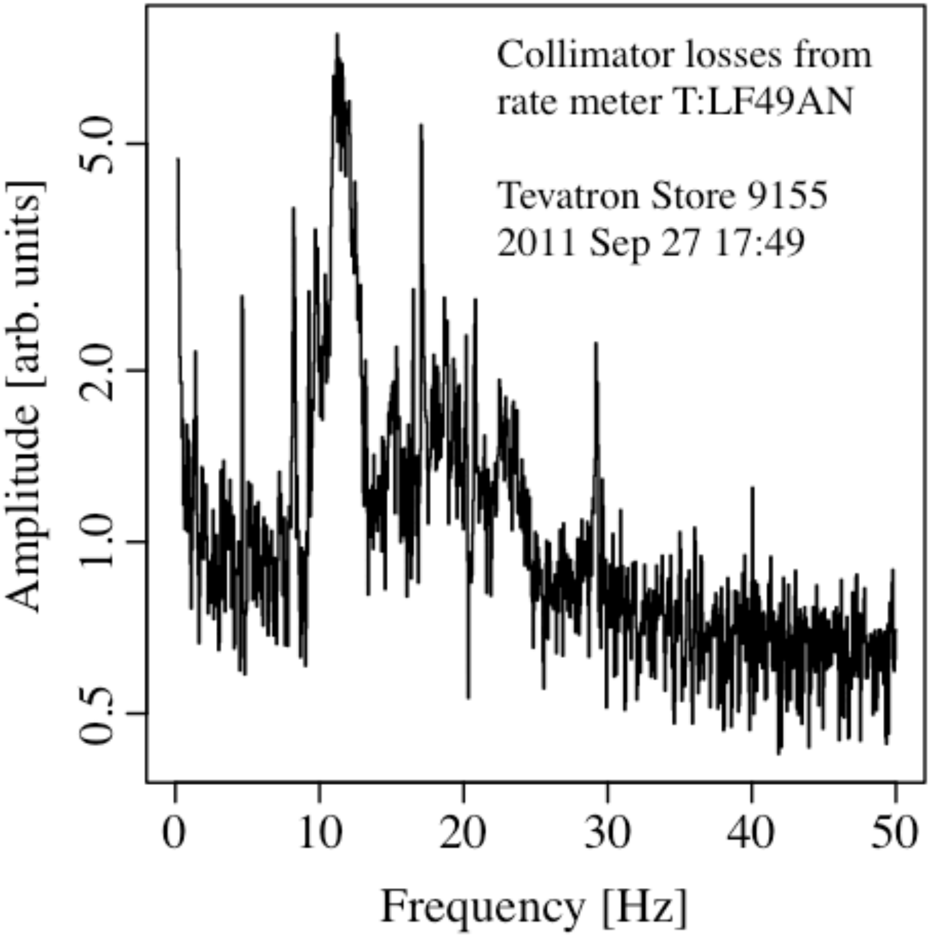
Large diffusion enhancement in halo region

Beam jitter in the Tevatron

Beam losses at collimator and beam centroid positions recorded at 100 Hz

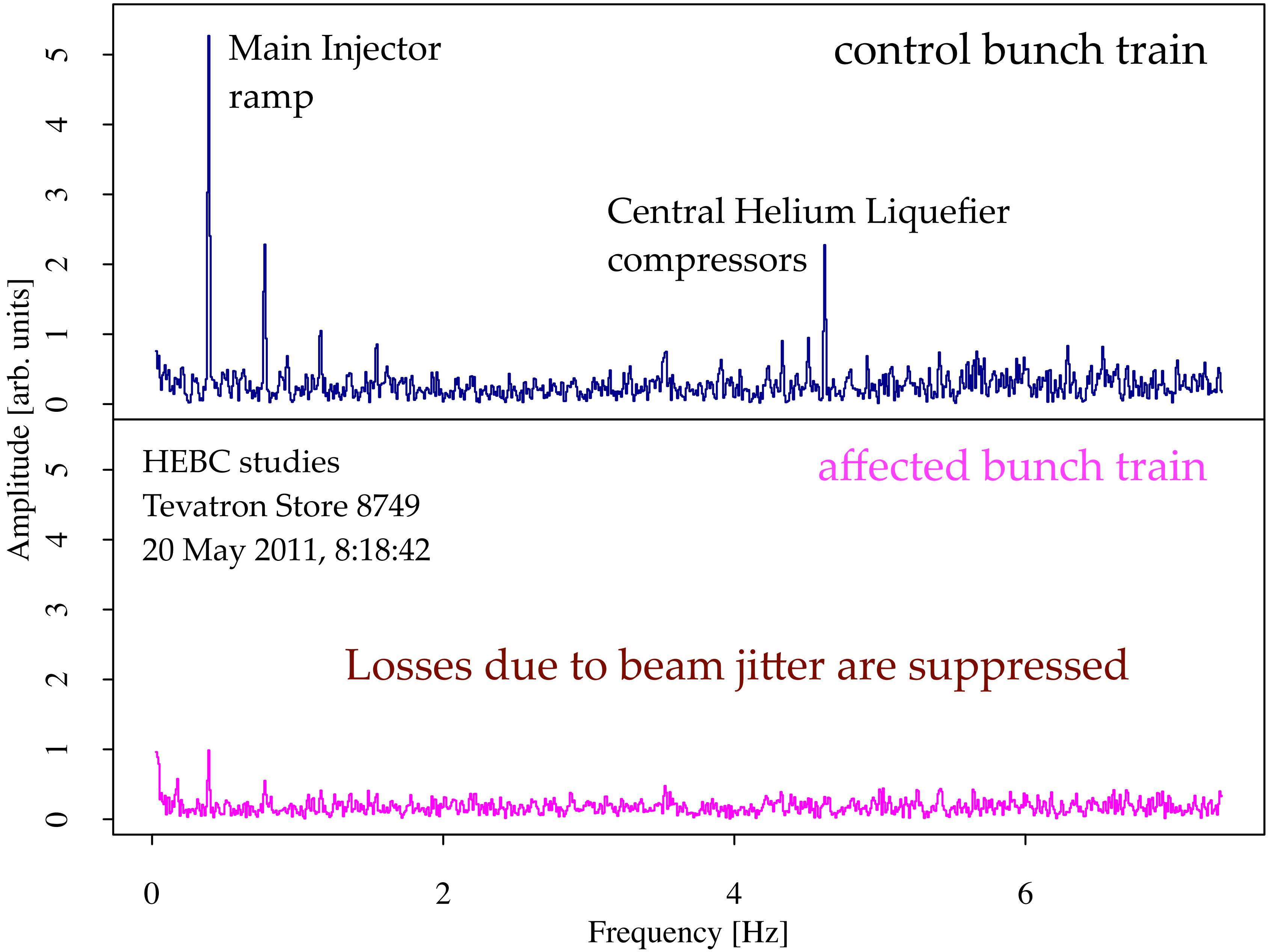


Frequency spectrum of losses

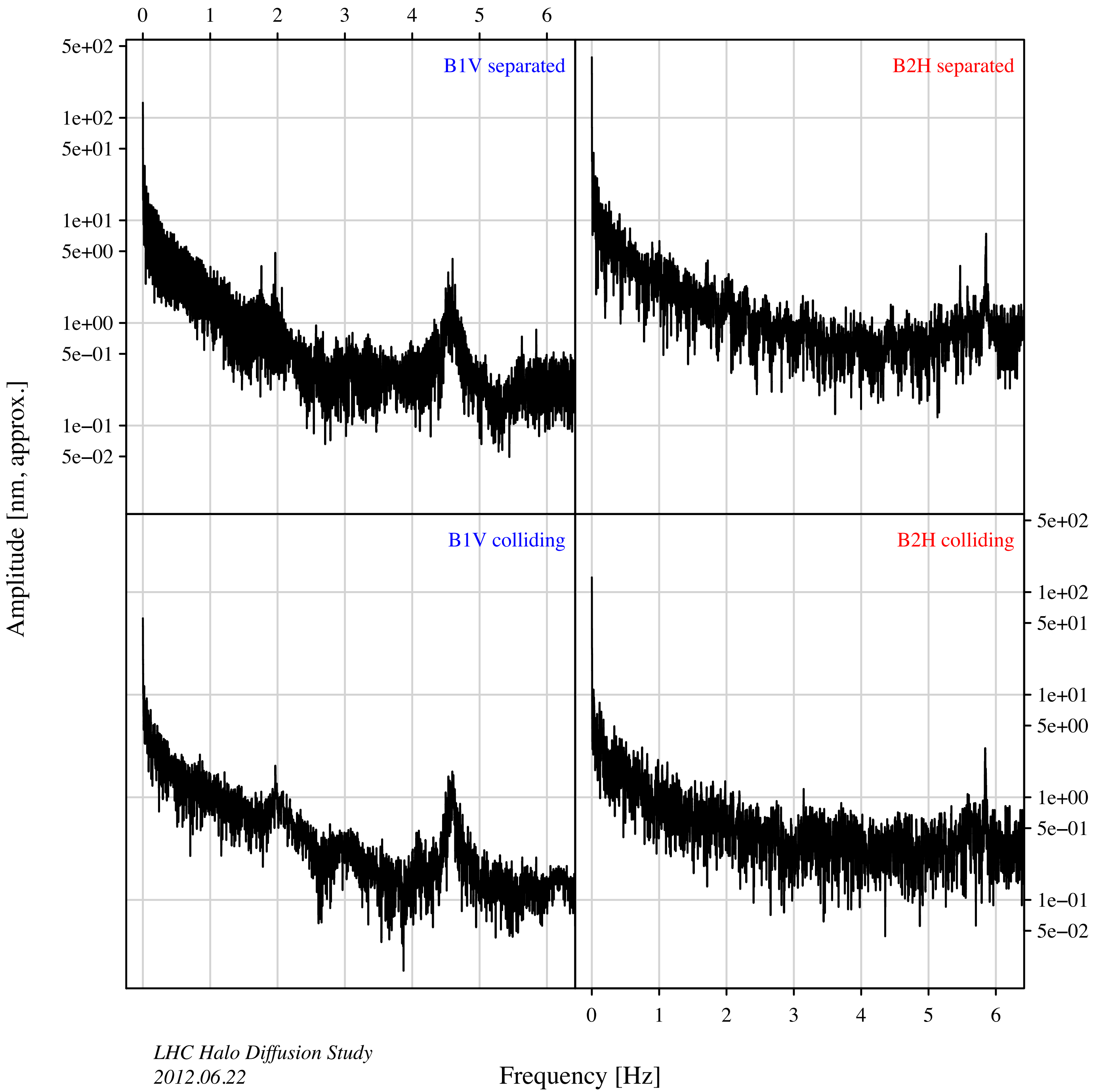


Beam vibrates at low frequency with amplitudes of a few tens of microns: ground motion, mechanical vibrations, ...

Fourier analysis of losses



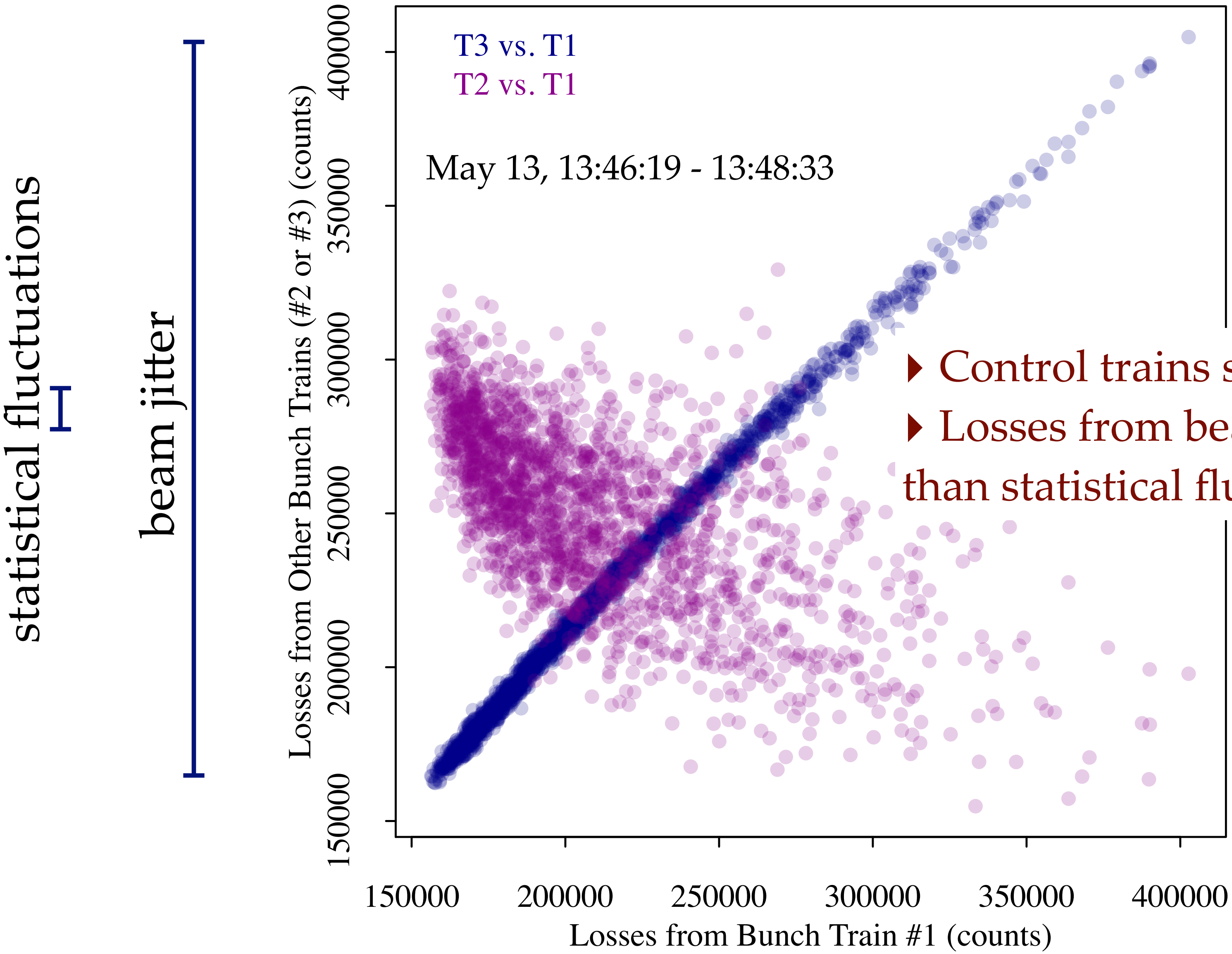
Beam jitter in the LHC at 4 TeV



Loss rate spectra in LHC with tight collimators show low-frequency vibrations

Preliminary calibration suggests sub-micron amplitudes at the primary

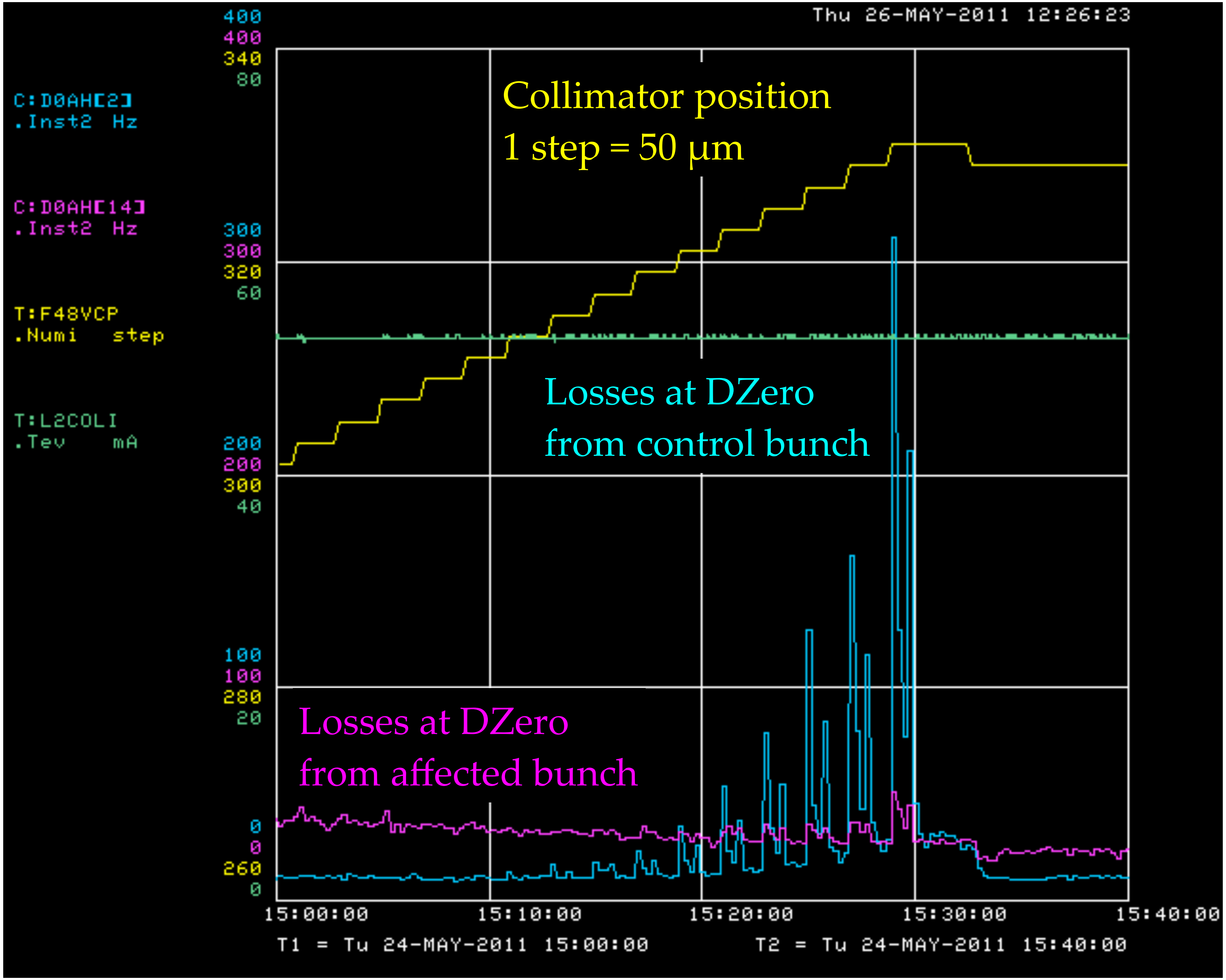
Correlation of steady-state losses



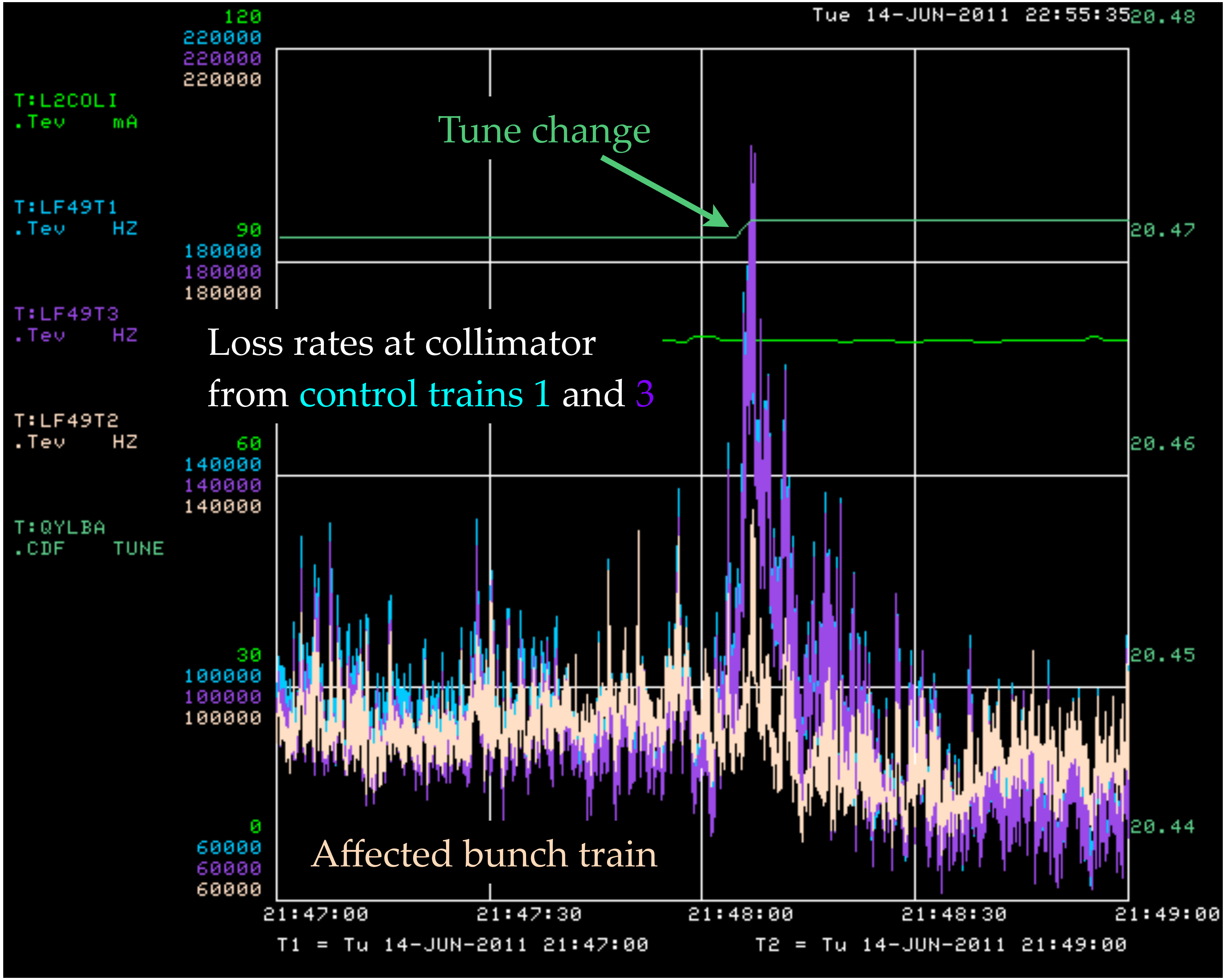
- Control trains strongly correlated
- Losses from beam jitter much larger than statistical fluctuations

- Hollow beam eliminates correlations among trains
- Interpretation: larger diffusion rate, lower tail population, less sensitive to jitter

Suppression of loss spikes during collimator steps



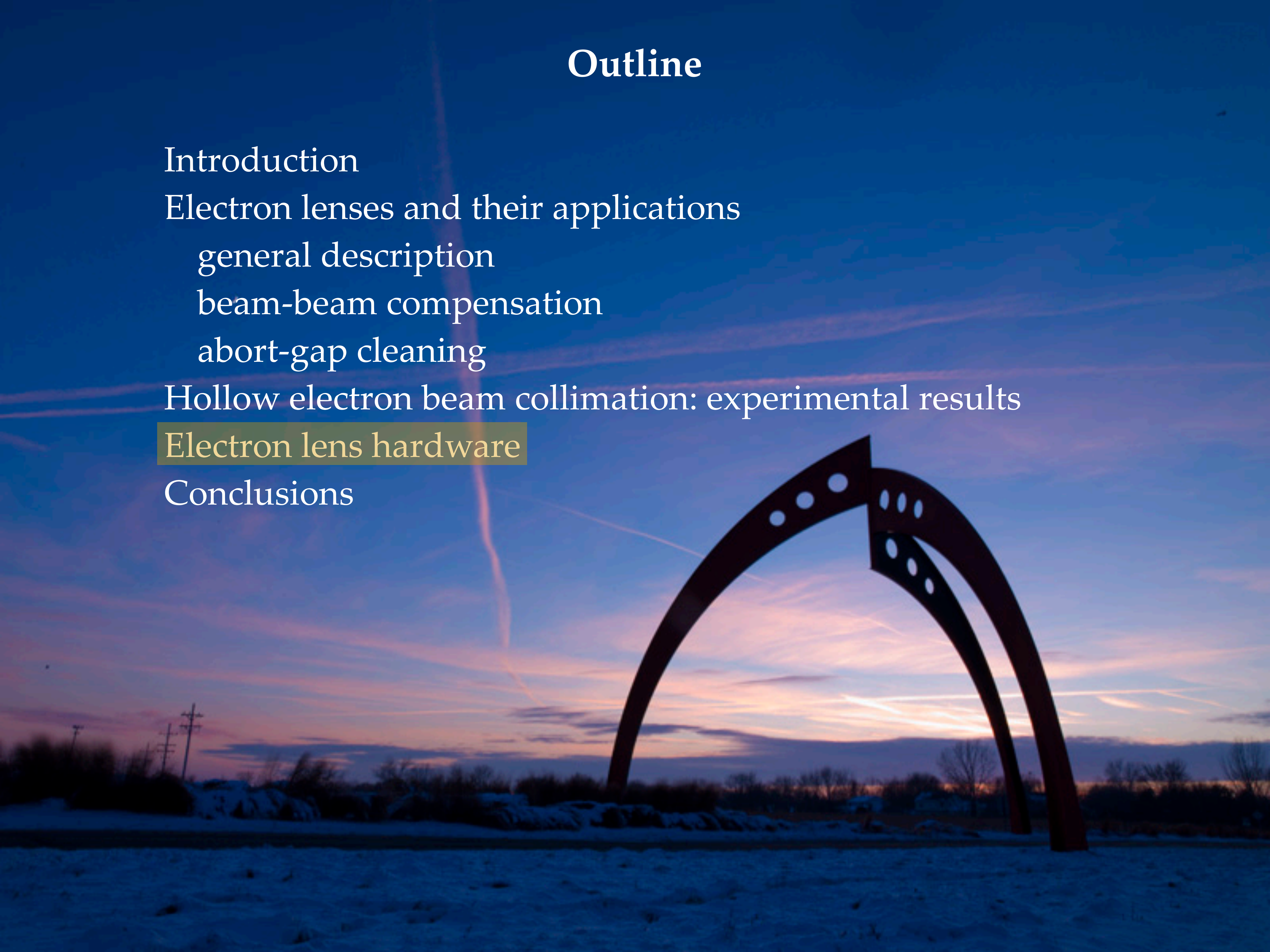
Suppression of loss spikes during tune change



Tune change

Loss rates at collimator from control trains 1 and 3

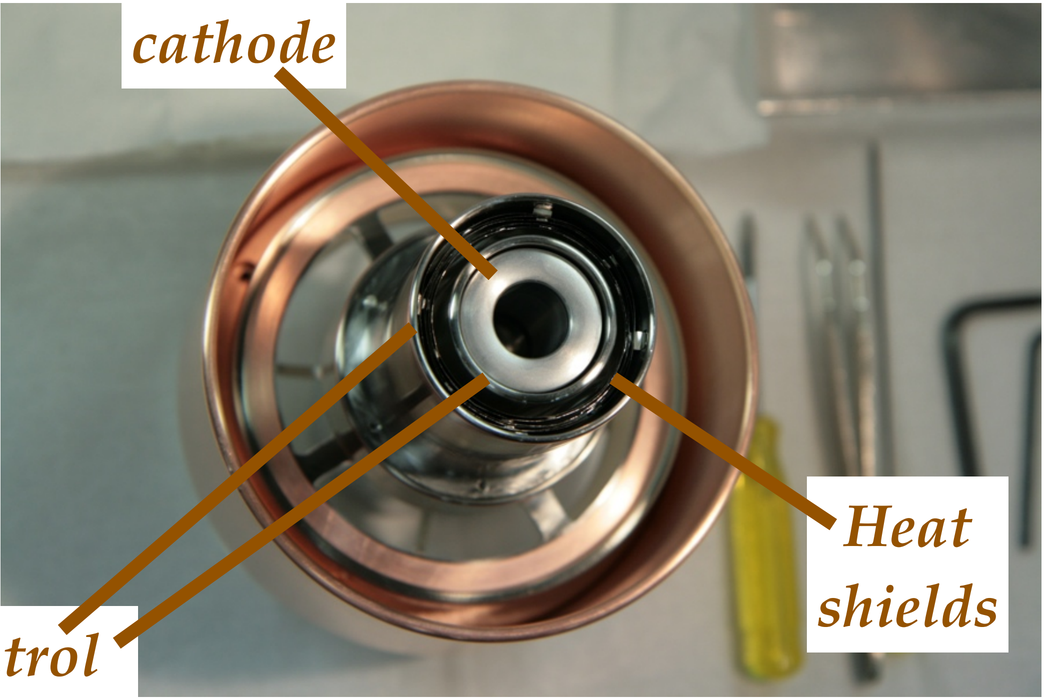
Affected bunch train



Outline

- Introduction
- Electron lenses and their applications
    - general description
    - beam-beam compensation
    - abort-gap cleaning
- Hollow electron beam collimation: experimental results
- Electron lens hardware
- Conclusions

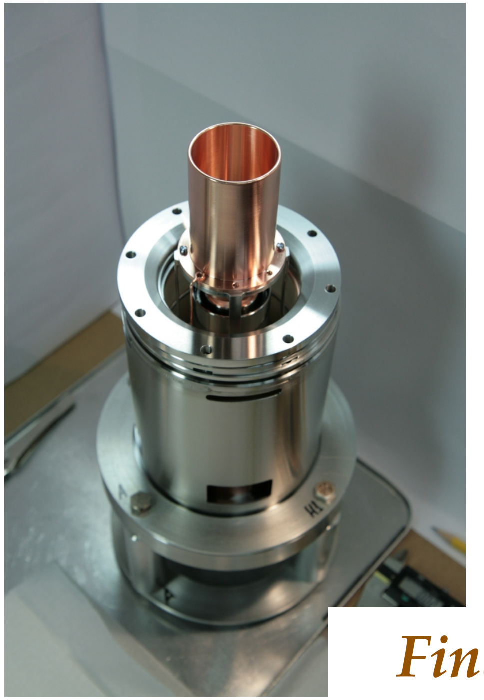
New 25-mm hollow gun



Hollow cathode

Heat shields

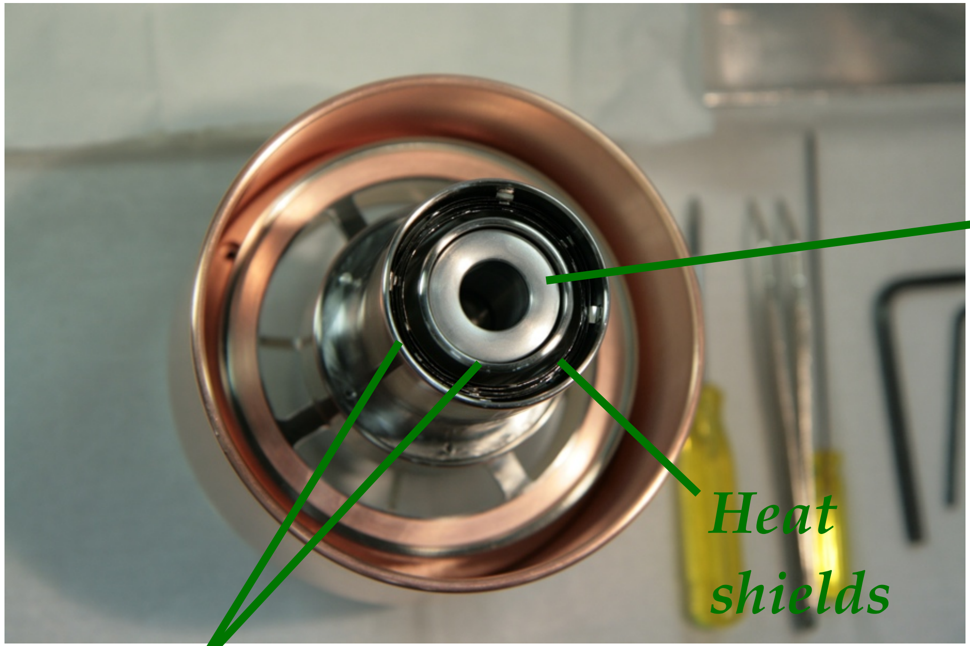
Control electrodes



Final assembly

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

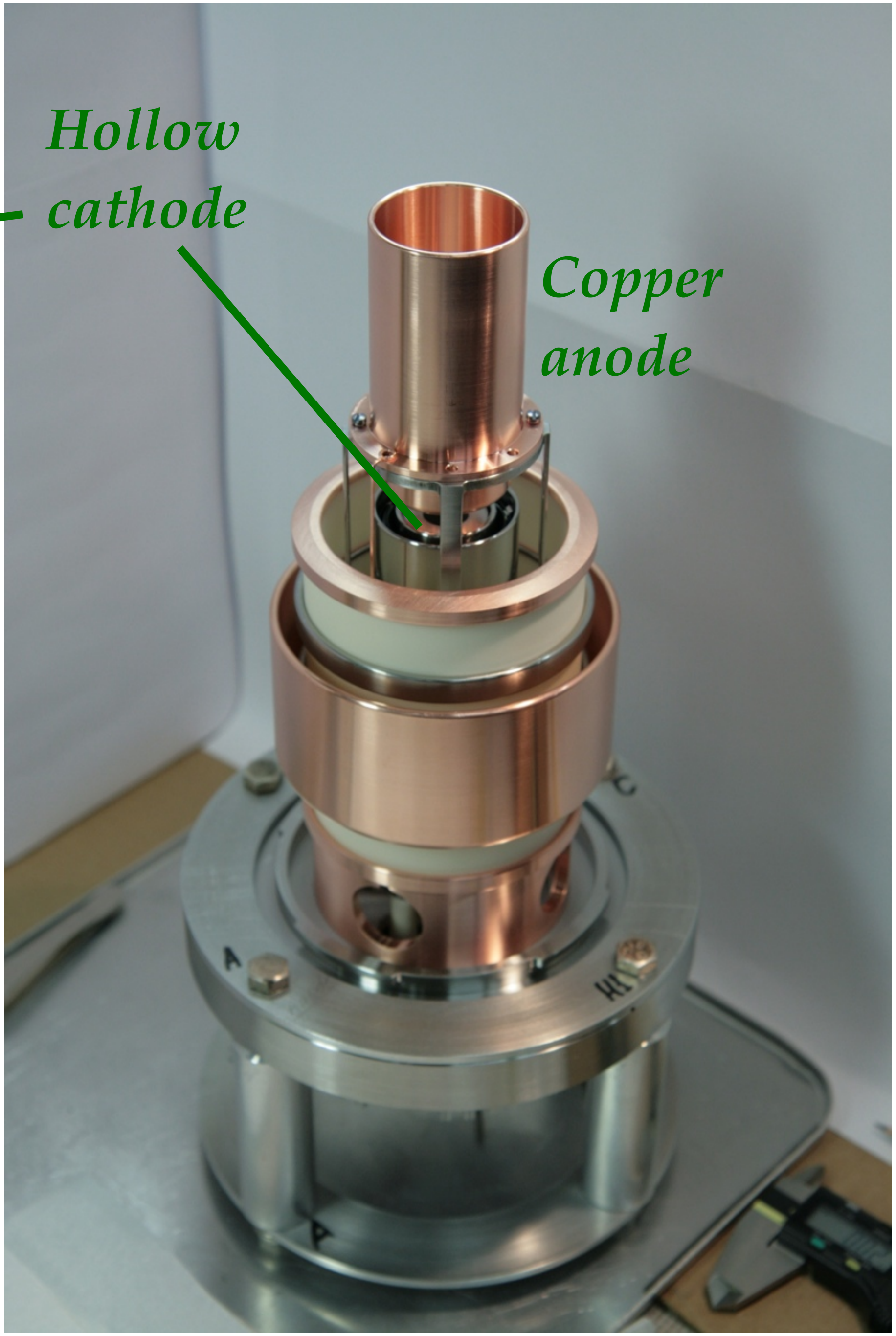
New 25-mm hollow gun



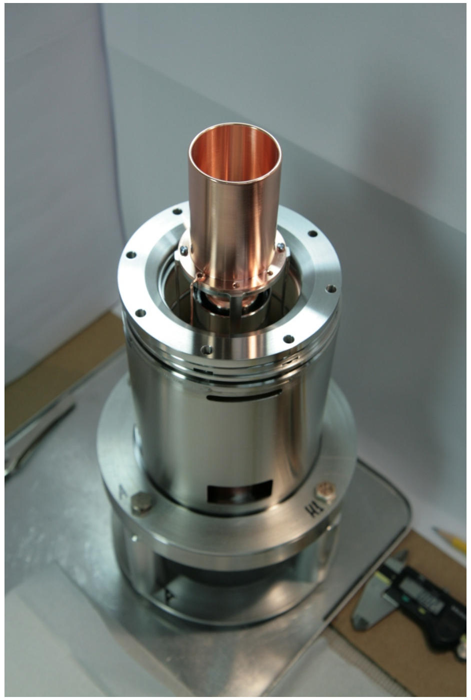
Heat shields

Profile-control electrodes

Hollow cathode



Copper anode



Final assembly

Achievable range of hole radii in overlap region

inner or outer radius
in overlap region
(main solenoid)

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

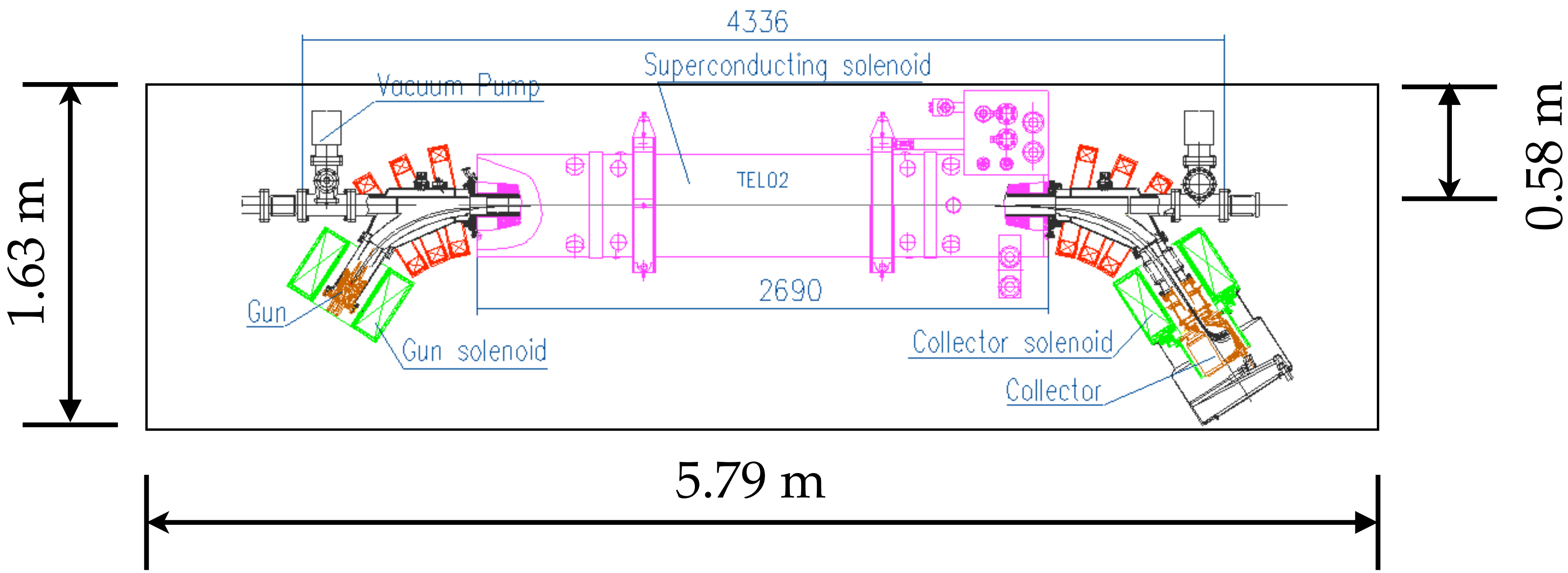
inner or outer radius
at electron gun

field in gun solenoid
0.1 – 0.4 T

field in main solenoid
1 – 6 T

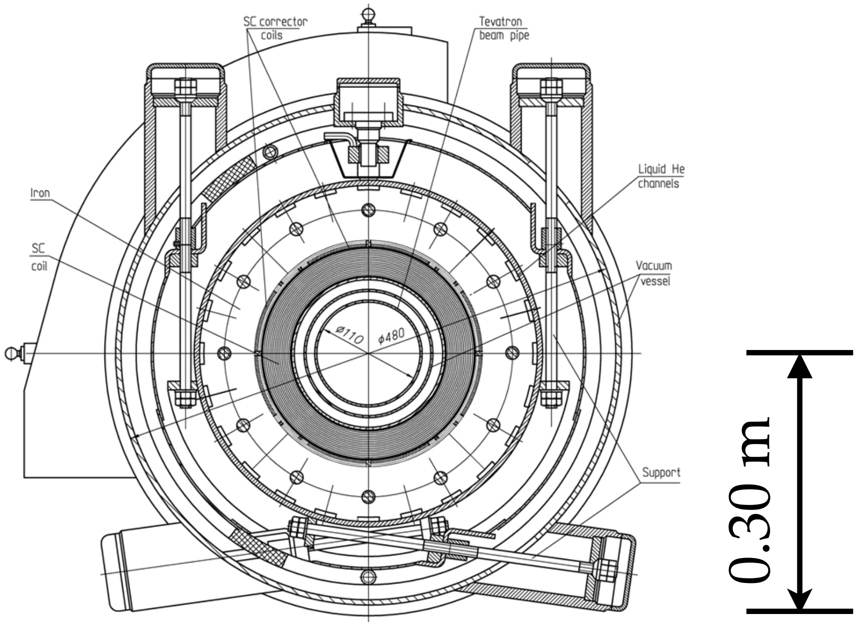
	Gun radii [mm]		Yield @ 8 kV [A]	Radii in overlap region [mm]			
				minimum		maximum	
	$(r_i)_g$	$(r_o)_g$		$(r_i)_m$	$(r_o)_m$	$(r_i)_m$	$(r_o)_m$
original 0.6-in gun	4.5	7.62	2.2	0.58	0.98	2.8	4.8
new 1-in gun	6.75	12.7	2.9	0.87	1.6	4.3	8.0

TEL2 dimensions

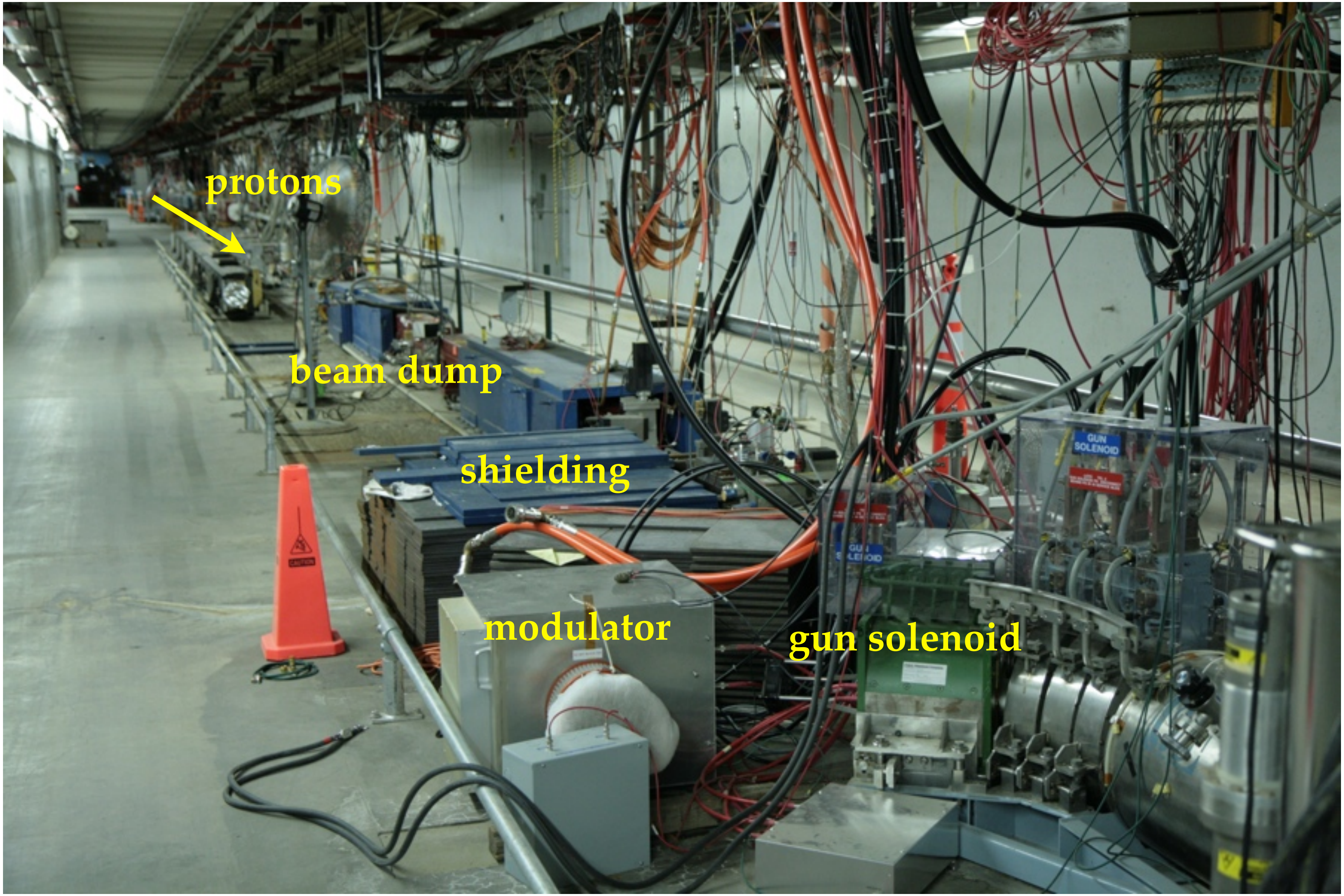


Height (including current and cryo leads): 1.47 m

Weight: about 2 t



TEL2 photographs: gun side

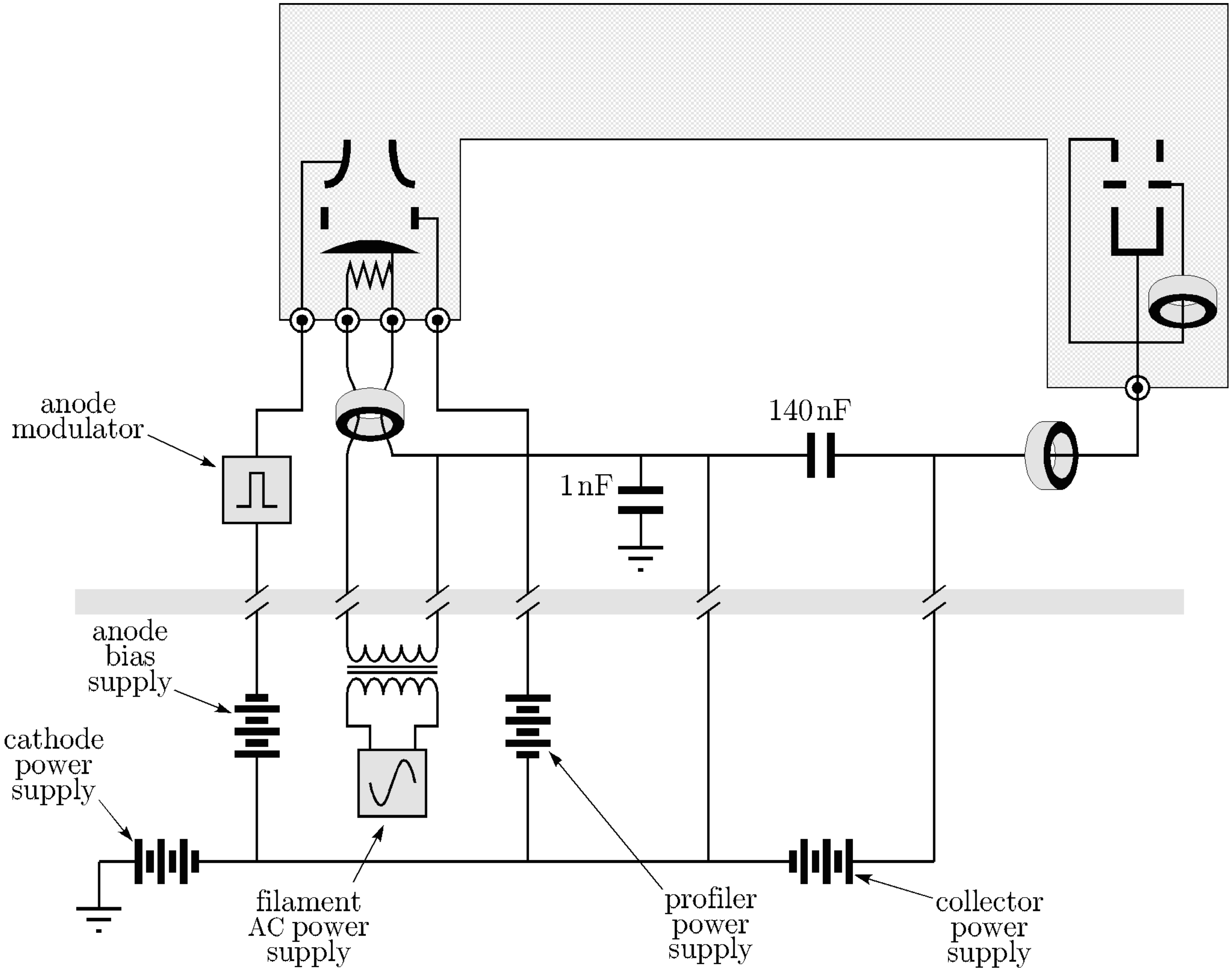


TEL2 photographs: collector side

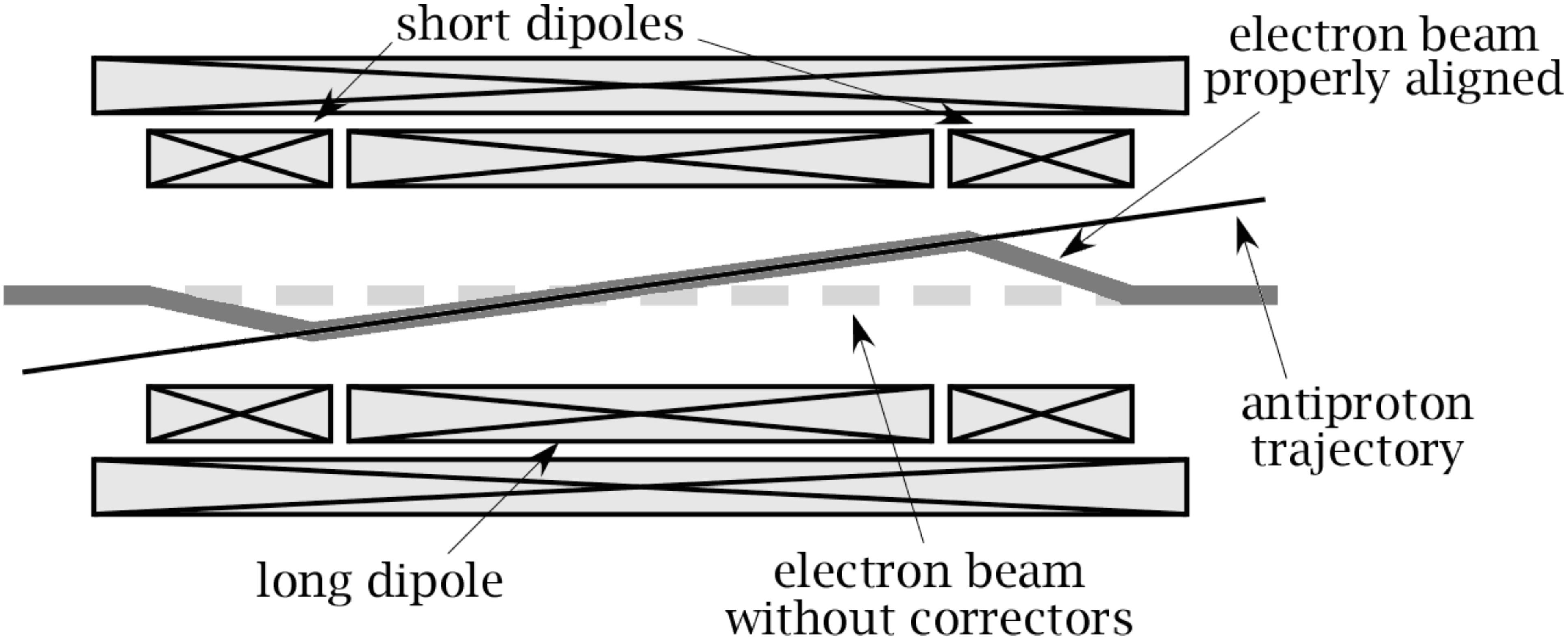
Principal subsystems

- **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)

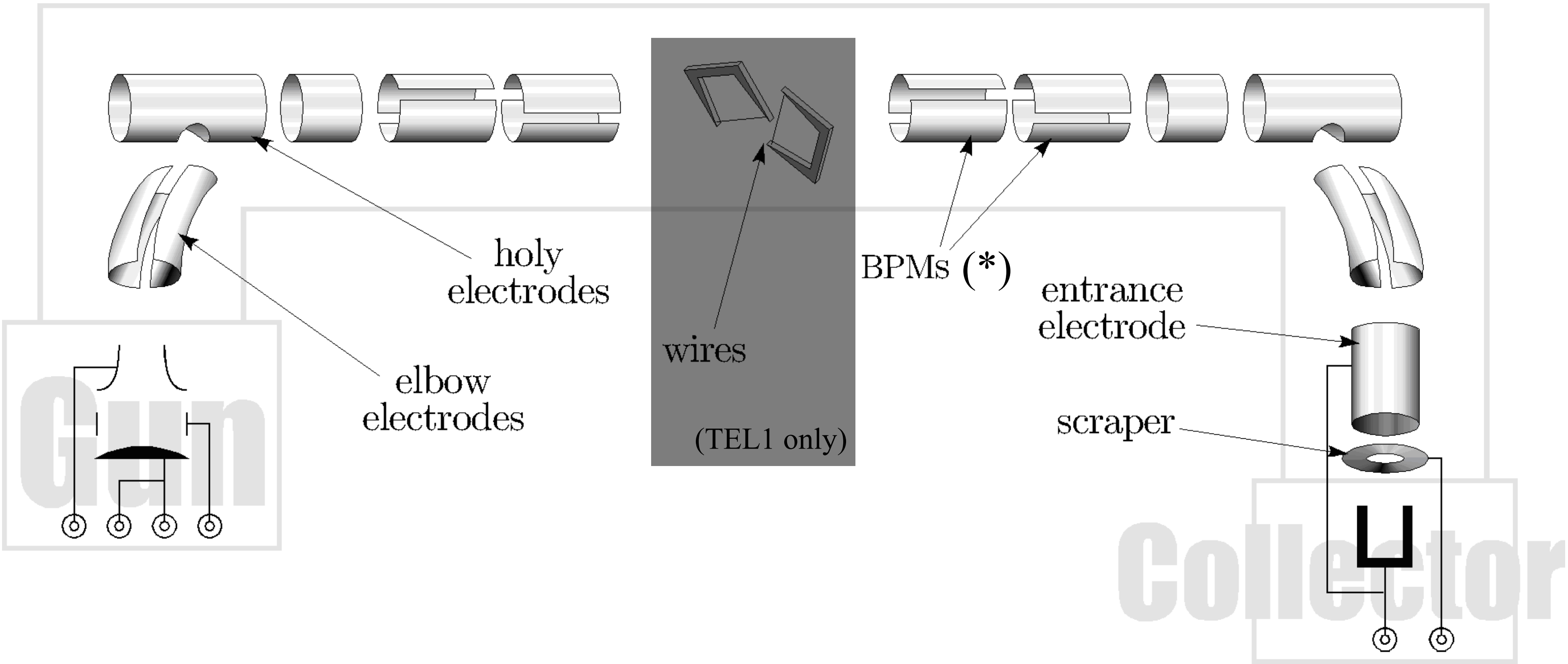
Tevatron electron lens: electrical schematic diagram



Tevatron electron lens: corrector dipoles



Tevatron electron lens: electrodes



(*) H and V BPMs combined in TEL2

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

- **Electron lenses** are a mature technique for beam manipulation in circular machines:
  - **bunch-by-bunch betatron tune shifts** with flat electron profiles
  - **nonlinear beam-beam compensation** with Gaussian profiles: Tevatron experimental studies, RHIC installation under way
  - **abort gap clearing** at the Tevatron reliable over many years of operation
- A novel technique for **collimation** of high-power hadron beams with **hollow electron beams** was developed at the Tevatron; promising technique for the LHC
- The Tevatron electron lens hardware is available for use at CERN

Thank you