Measured effects of depleted halo population with hollow electron lens in the Tevatron and relevance for HL-LHC

or

What can a hollow electron lens do?

Giulio Stancari
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Review of the needs for a hollow electron lens for the HL-LHC
CERN, October 6-7, 2016

Contributors and collaborators

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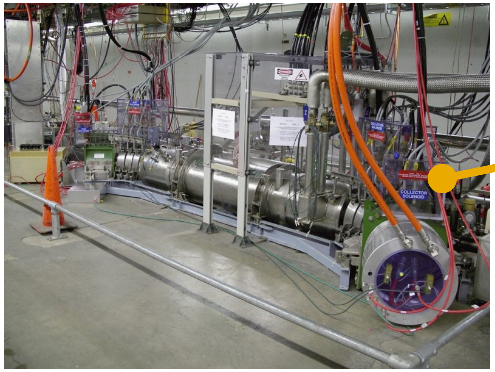
Collimation and electron lenses in the Tevatron



TEL-2

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

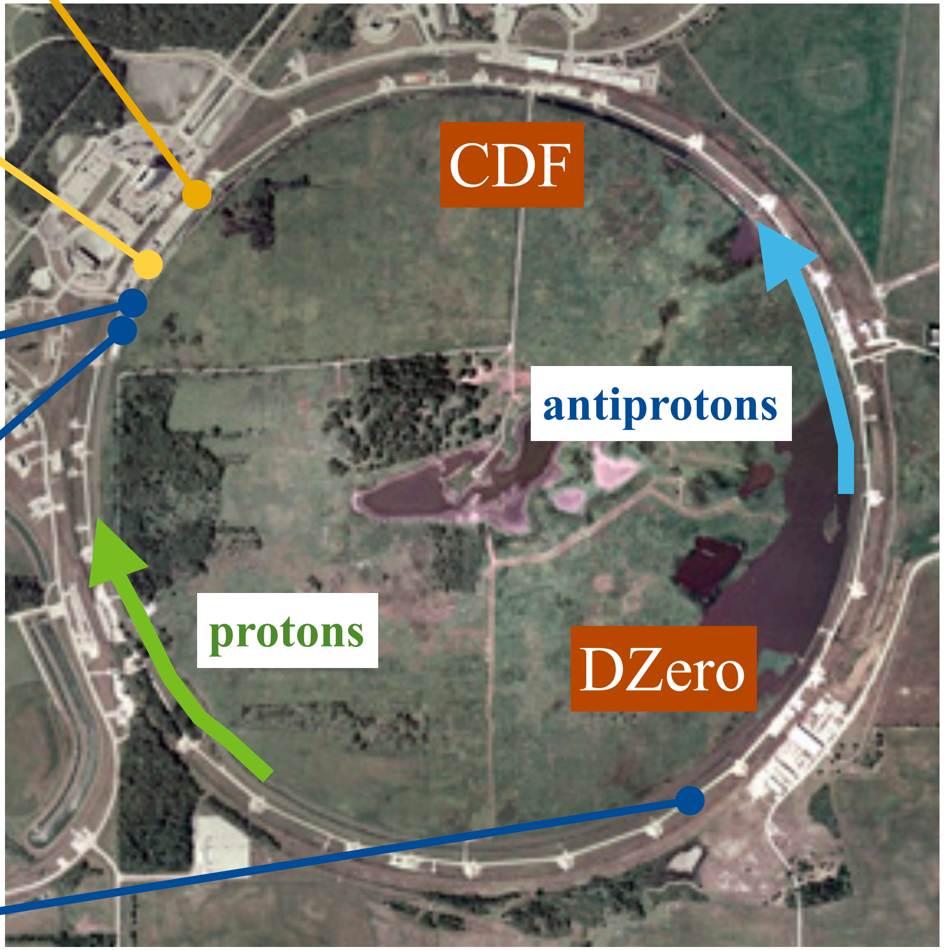
TEL-1

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

Primary (F49)

Secondary (F48)

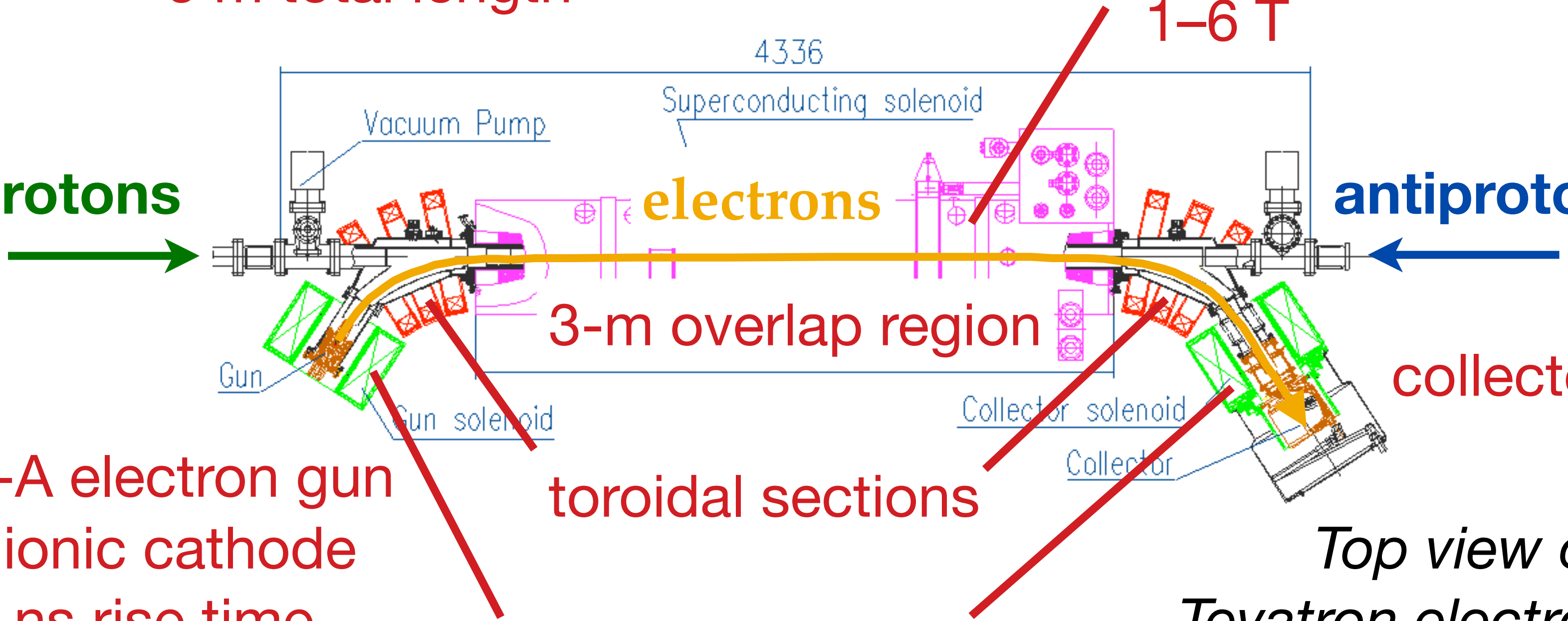
Secondary (D17)



Antiproton collimators
L-shaped
5-mm tungsten primaries at 5 sigma
1.5-m steel secondaries at 6 sigma

Electron-lens apparatus and beam layout

- Pulsed, magnetically confined, low-energy electron beam
- Circulating beam 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

3-m overlap region

collector

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

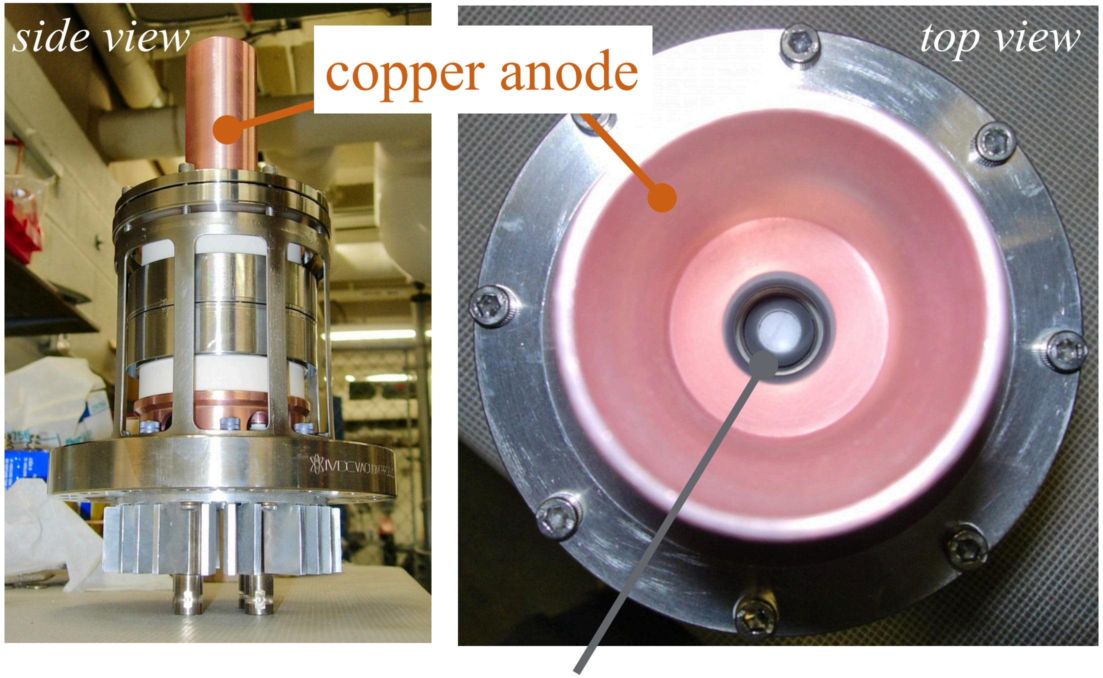
toroidal sections

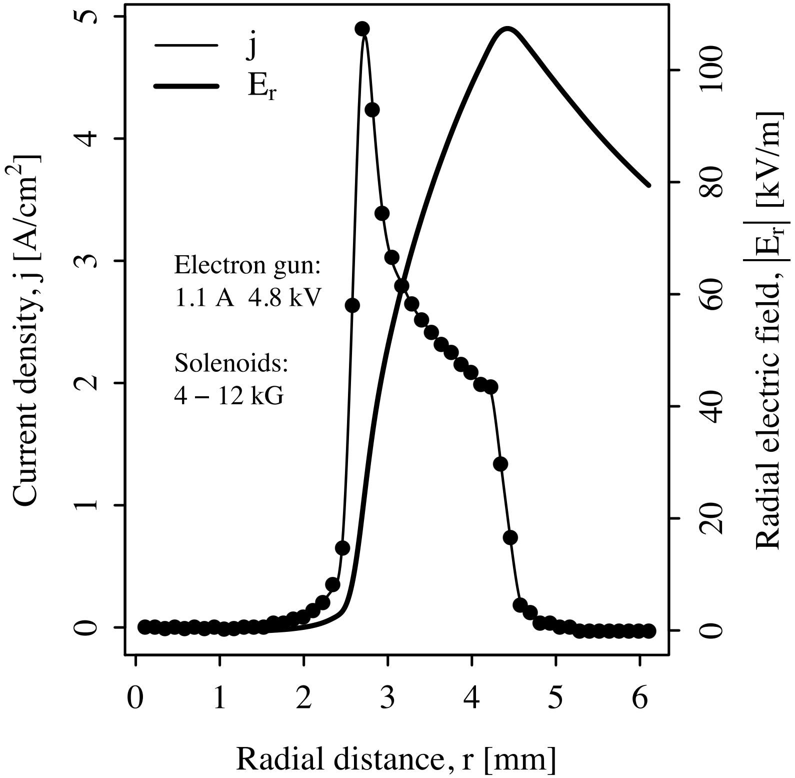
conventional solenoids
0.1–0.4 T

Top view of
Tevatron electron lens
(TEL-2)

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

15-mm hollow electron gun: geometry and fields



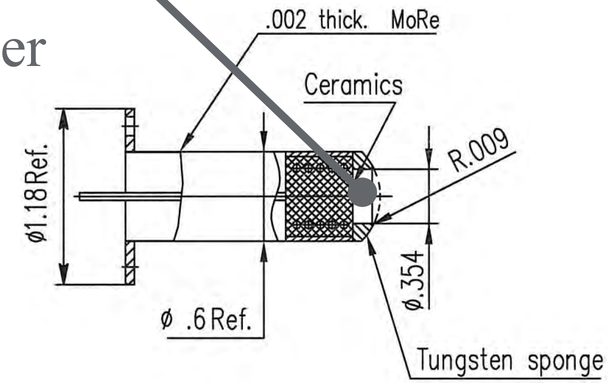


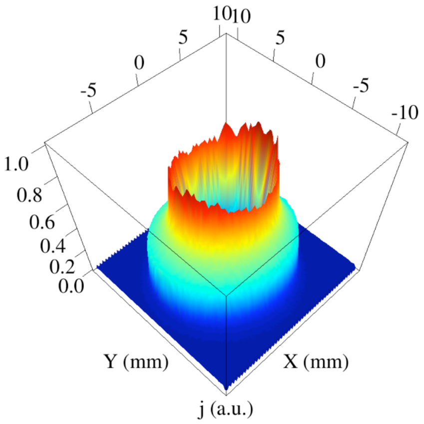
tungsten dispenser cathode

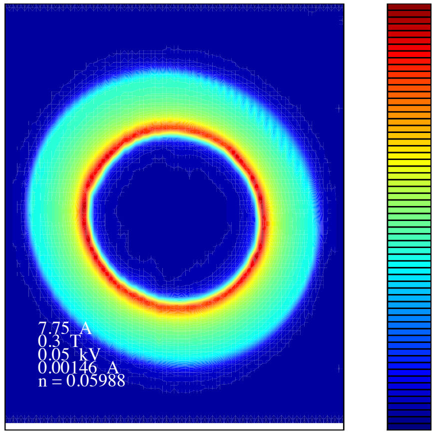
convex surface

15-mm outer diameter

9-mm hole diameter

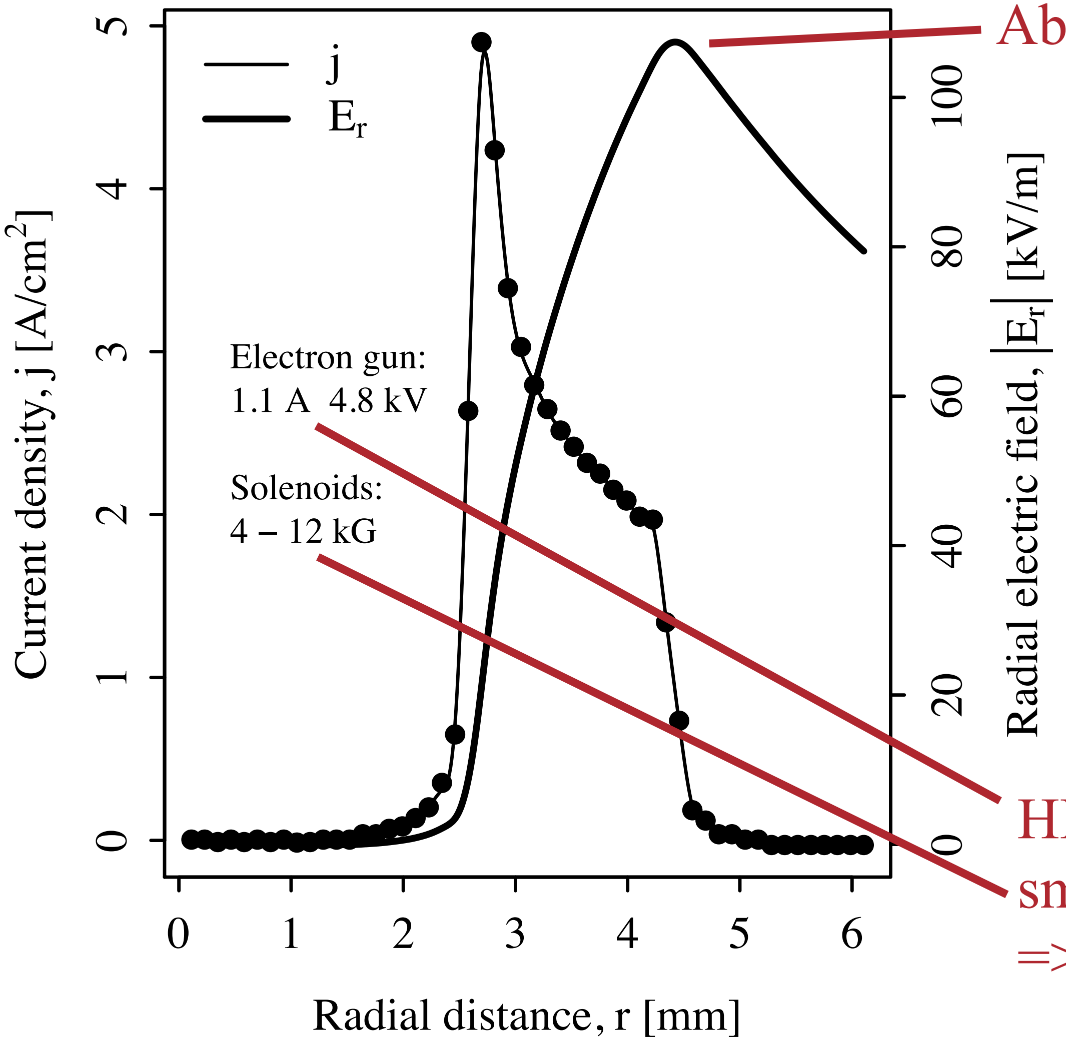






Current densities, fields, and kicks

Nonlinear transverse kick depends on current density at e-gun, magnetic compression in solenoids, and (anti)proton magnetic rigidity

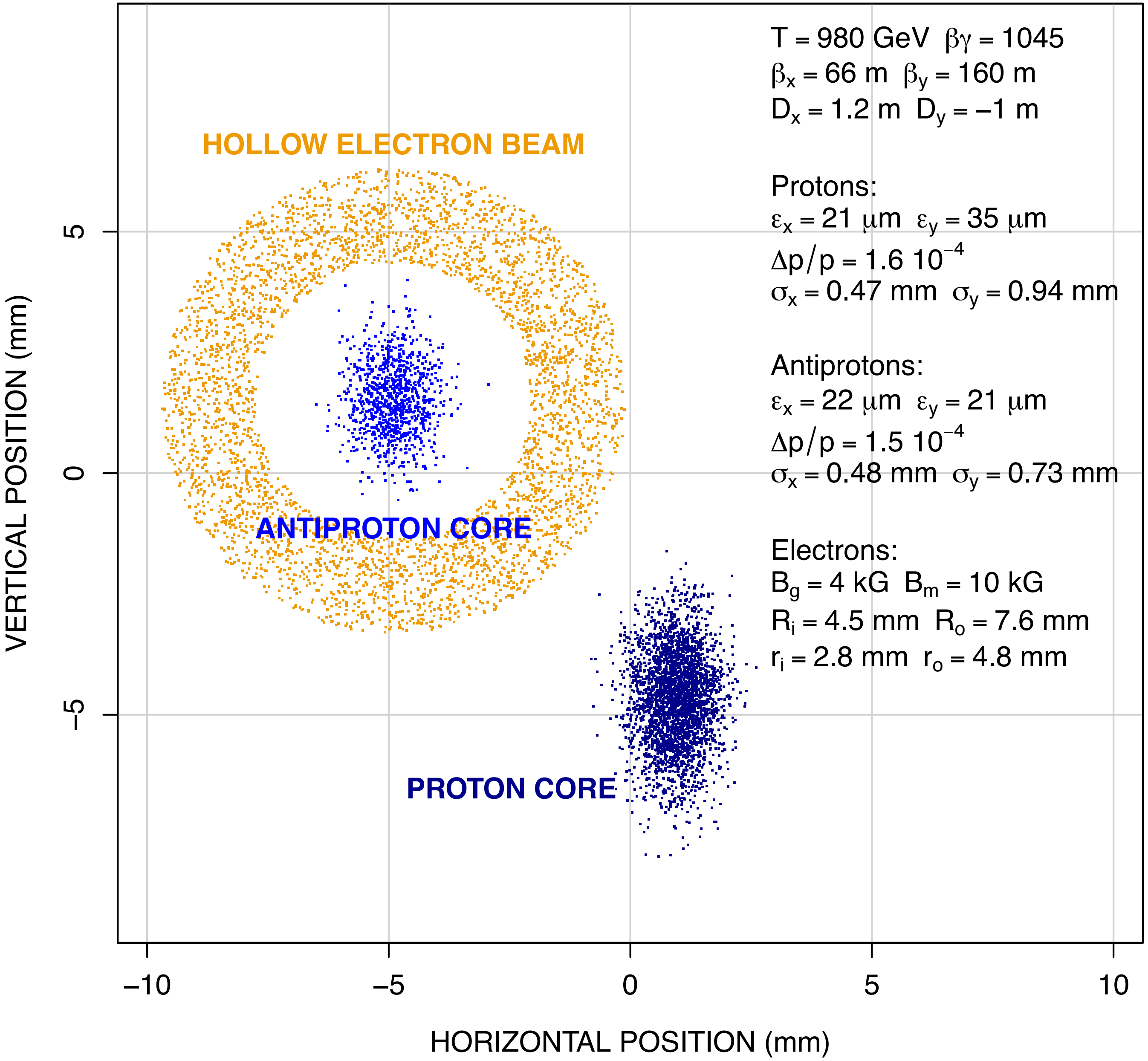


About **0.3 μrad** max in TEL-2 at 980 GeV

Nonlinear deterministic kicks are complementary (i.e., small and tunable) to random multiple scattering in primary collimators (17 μrad rms in Tevatron)

HL-LHC e-gun prototype reached 5 A + smaller beam sizes in HL-LHC => similar transverse kicks

Typical transverse layout of the beams



$T = 980$ GeV $\beta\gamma = 1045$
$\beta_x = 66$ m $\beta_y = 160$ m
$D_x = 1.2$ m $D_y = -1$ m

Protons:
$\varepsilon_x = 21$ µm $\varepsilon_y = 35$ µm
$\Delta p/p = 1.6\ 10^{-4}$
$\sigma_x = 0.47$ mm $\sigma_y = 0.94$ mm

Antiprotons:
$\varepsilon_x = 22$ µm $\varepsilon_y = 21$ µm
$\Delta p/p = 1.5\ 10^{-4}$
$\sigma_x = 0.48$ mm $\sigma_y = 0.73$ mm

Electrons:
$B_g = 4$ kG $B_m = 10$ kG
$R_i = 4.5$ mm $R_o = 7.6$ mm
$r_i = 2.8$ mm $r_o = 4.8$ mm

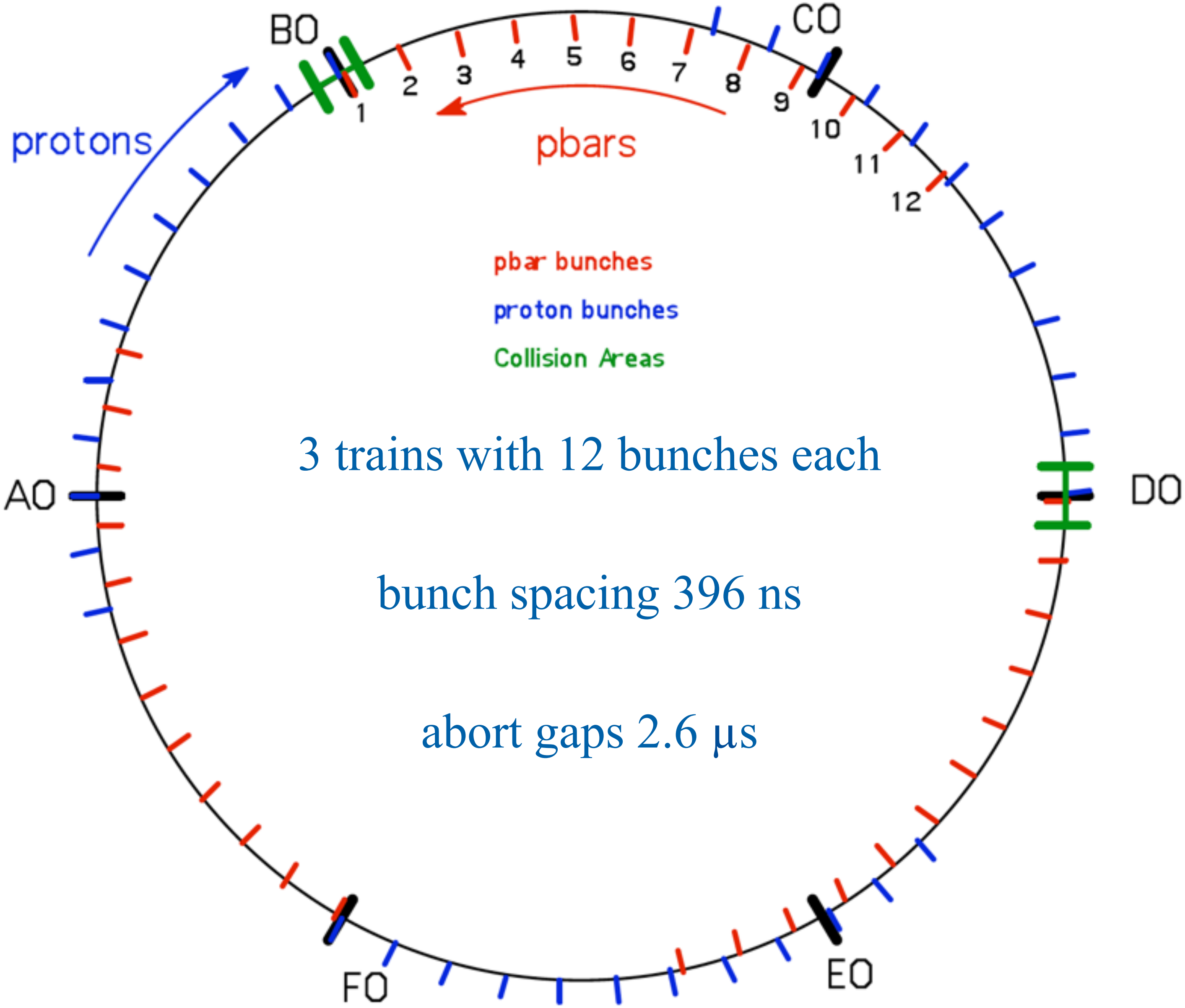
9-mm separation between proton and antiproton beams in common beam pipe

hole radius controlled by ratio of solenoid fields

$$r = r_{\text{egun}}\sqrt{\frac{B_{\text{egun}}}{B_{\text{main}}}}$$

[Normalized 95% emittances]

Tevatron bunch structure

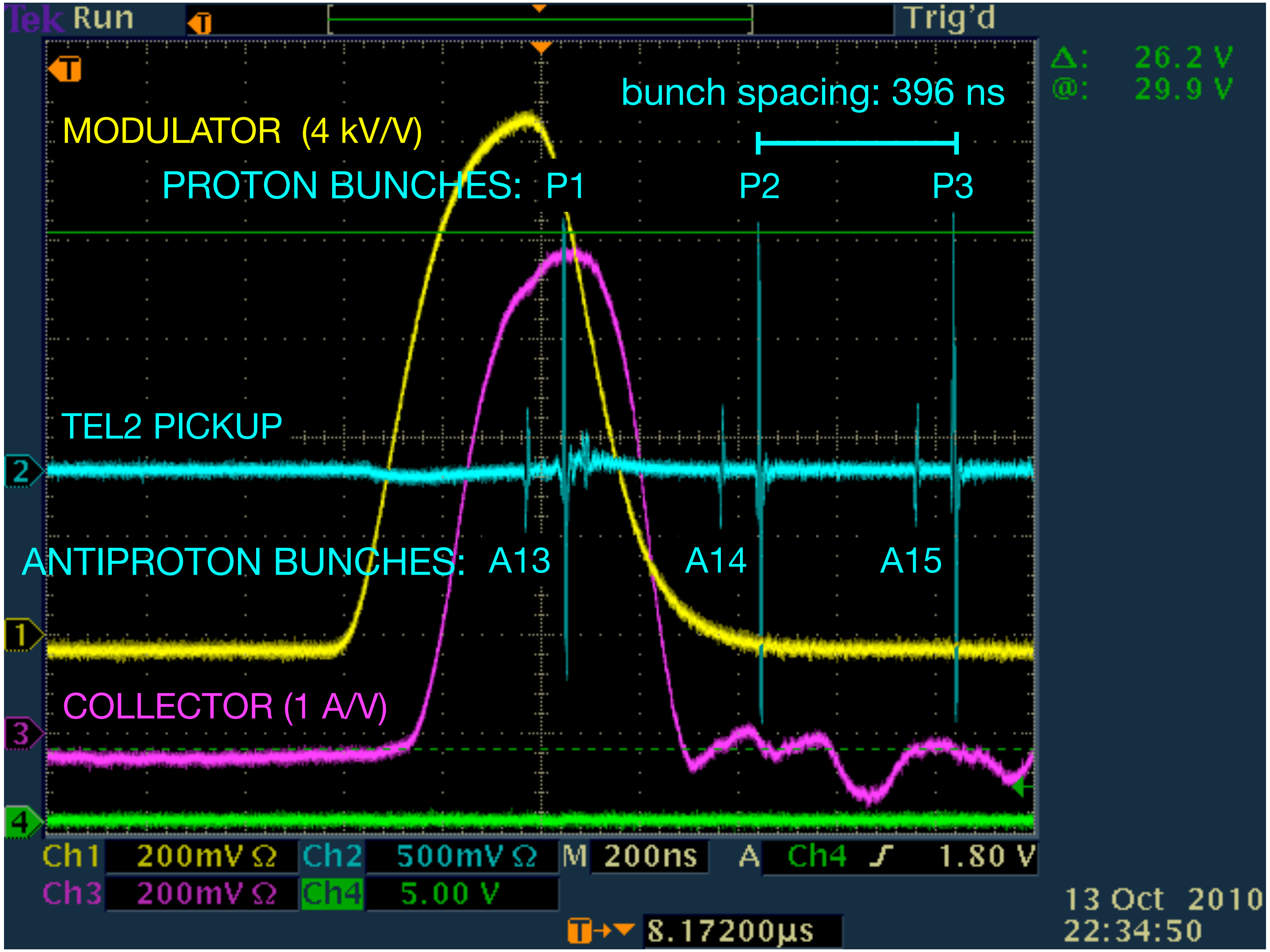


3 trains with 12 bunches each

bunch spacing 396 ns

abort gaps 2.6 µs

Time structure and synchronization of the beams



The high-voltage modulator allowed the pulsed electron beam to be **synchronized with any group of bunches**, with a different intensity for each bunch

Experimental studies with hollow electron beams

- Conducted in the Fermilab Tevatron collider with hollow gun installed in electron lens (TEL-2)
- Started Oct. 2010, ended Jun. 2011 (collider run ended Sep. 2011)
- Mostly at top energy (980 GeV) because of availability, stable conditions, and collimator configuration
- Chose to act on antiprotons because of lower emittances and intensities, smaller beam sizes (therefore larger solenoid fields for stability), and collimator positions

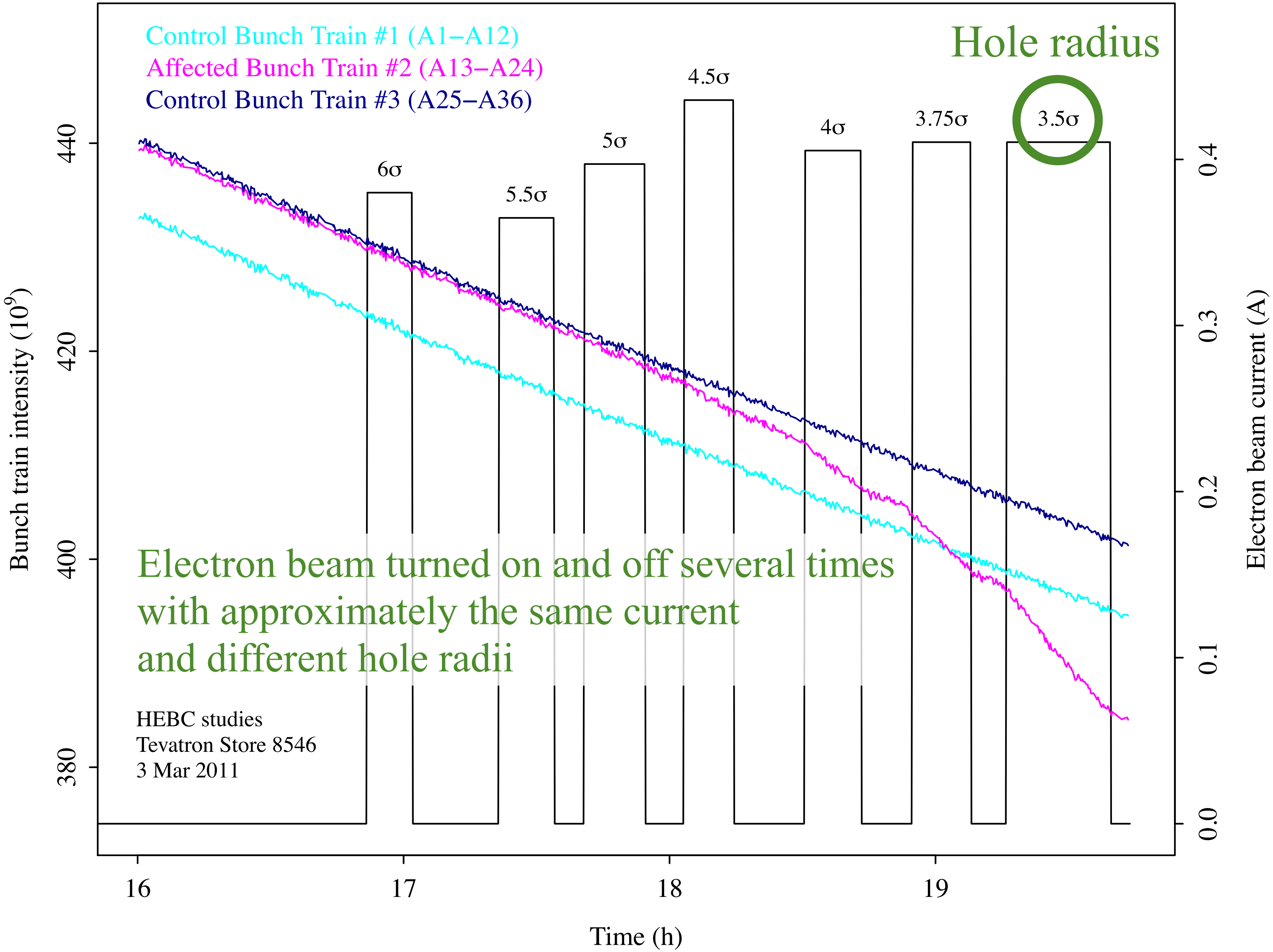
Experimental studies with hollow electron beams

Main goals and observables

- basic compatibility with collider operations
- particle removal
- removal rate vs. amplitude
- effects on the core
- effects on transverse beam diffusion
- effects on loss-rate fluctuations (beam jitter, tune changes)

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

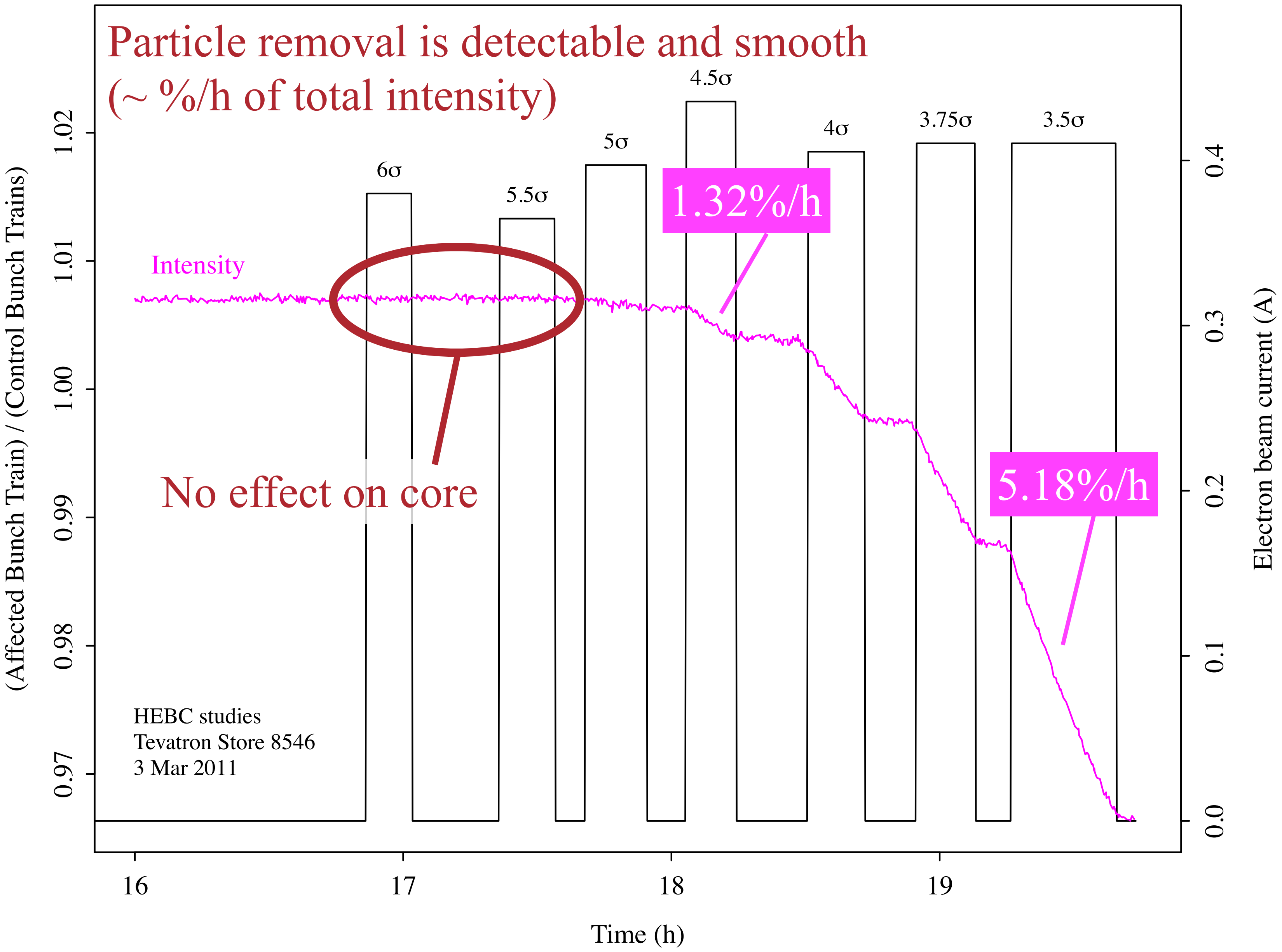
Electron lens on antiproton bunch train #2



Electron beam turned on and off several times with approximately the same current and different hole radii

HEBC studies
Tevatron Store 8546
3 Mar 2011

Relative removal rate of affected bunch train



Particle removal is detectable and smooth (~ %/h of total intensity)

No effect on core

1.32%/h

5.18%/h

Which particles are removed?

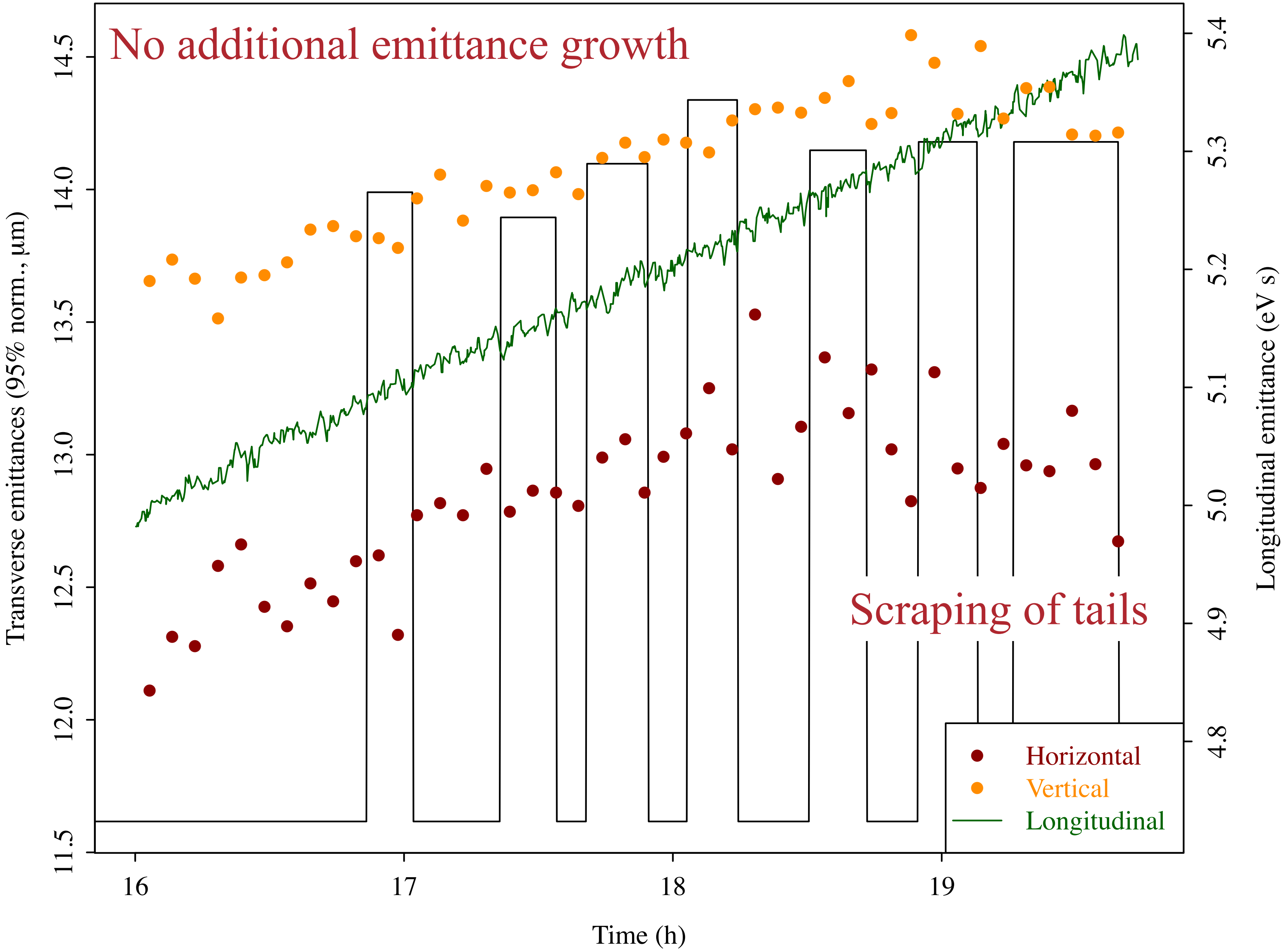
Several strategies:

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

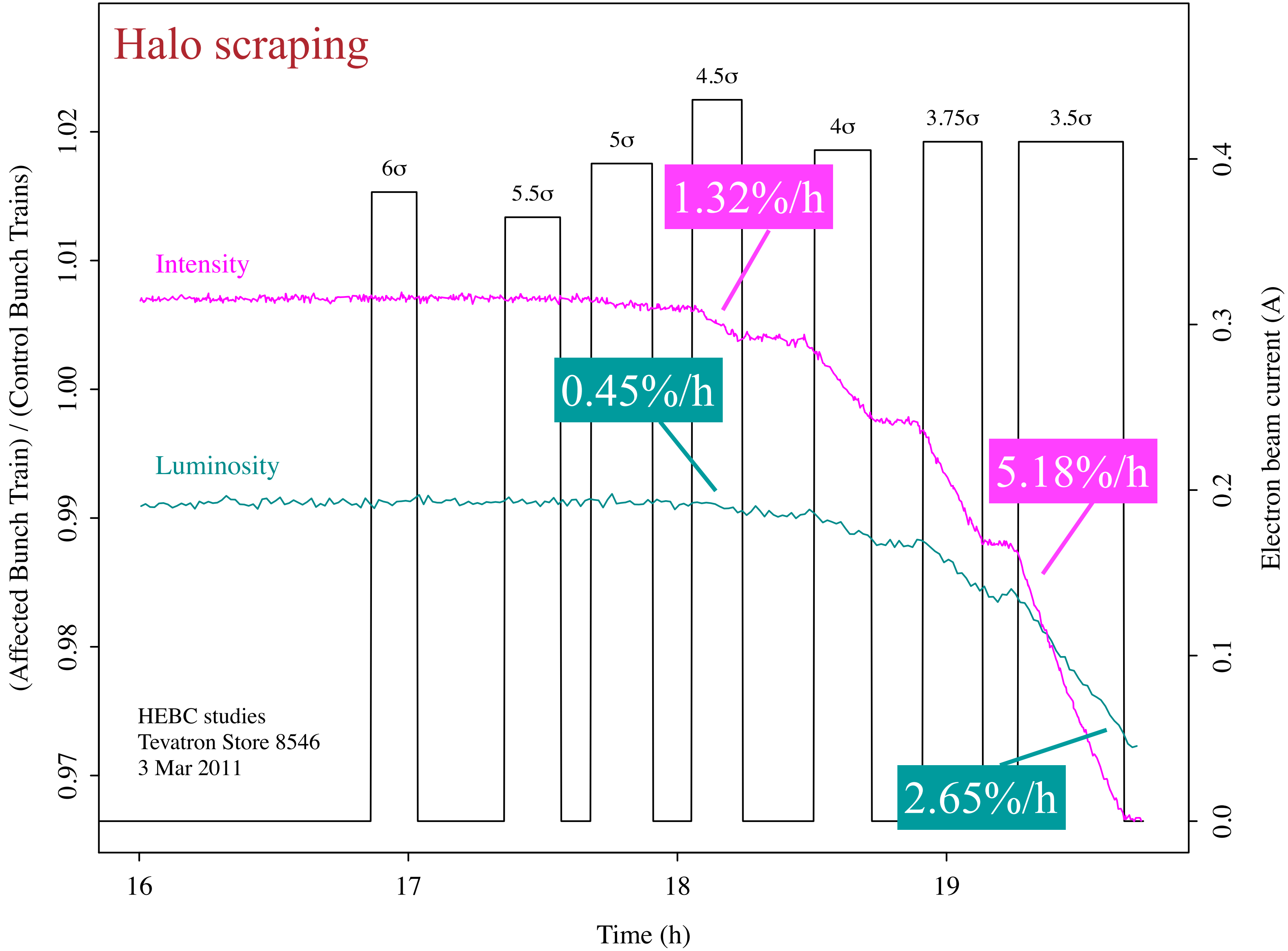
$$\mathcal{L} = \left(\frac{f_{\mathrm{rev}} N_b}{4\pi} \right) \frac{N_p N_a}{\sigma^2} \qquad \frac{\Delta \mathcal{L}}{\mathcal{L}} = \frac{\Delta N_p}{N_p} + \frac{\Delta N_a}{N_a} - 2 \frac{\Delta \sigma}{\sigma}$$

  - 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

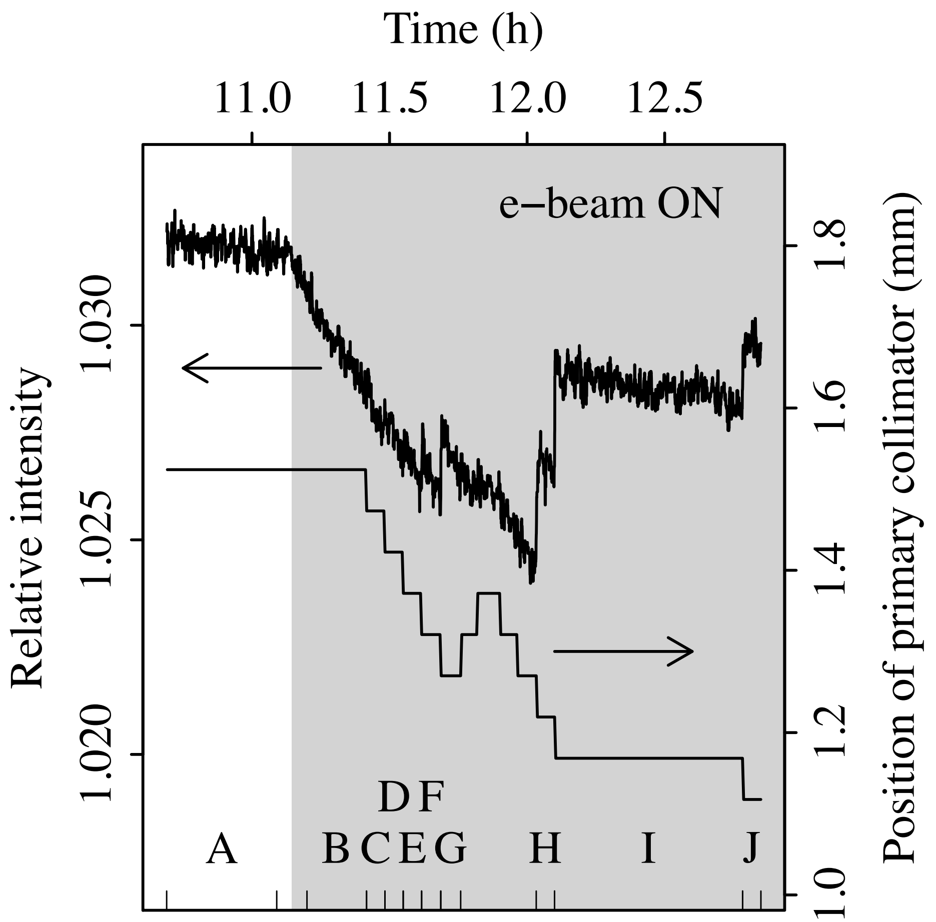


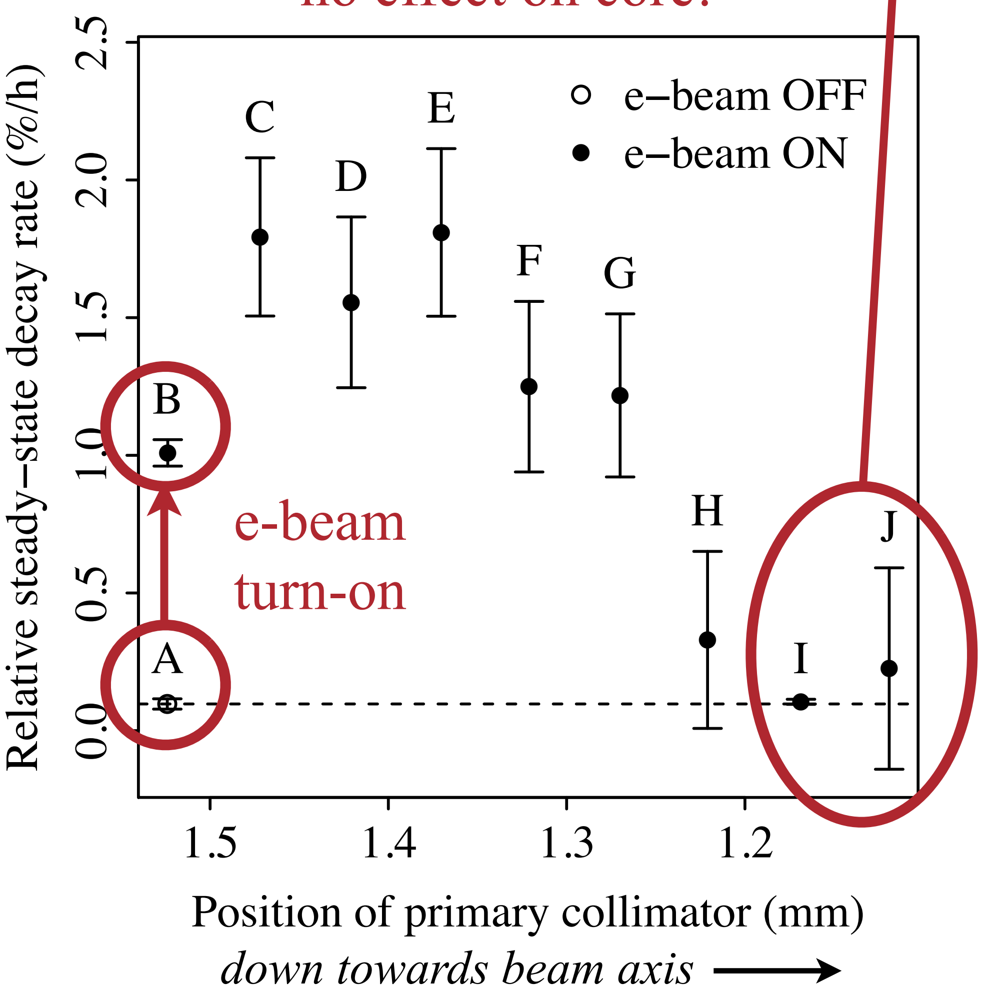
Relative intensity and luminosity



Removal rate vs. amplitude (collimator scan)

Electrons (0.15 A) on antiproton train #2, 3.5σ hole radius (1.3 mm at collimator)
Vertical scan of primary collimator (others retracted)

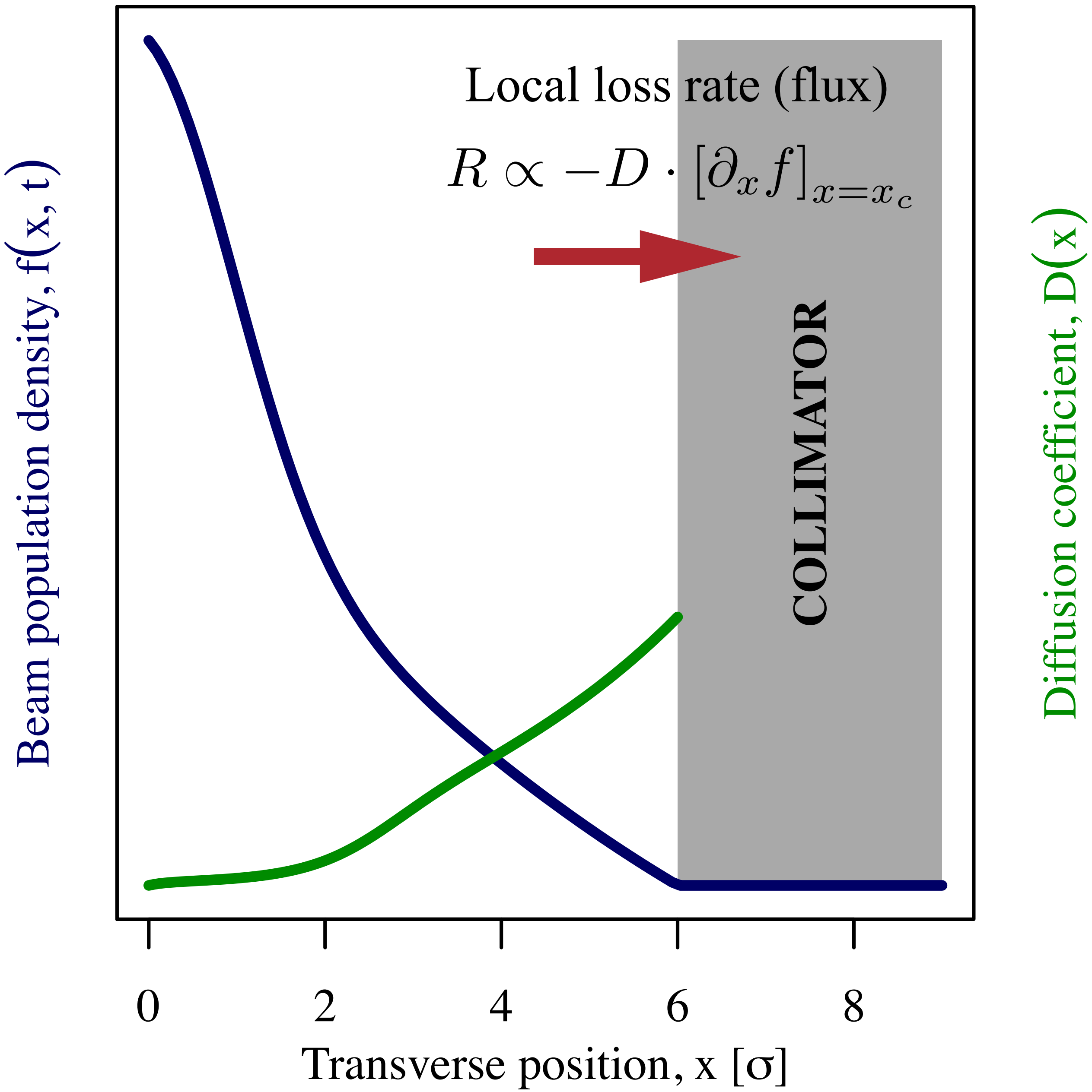




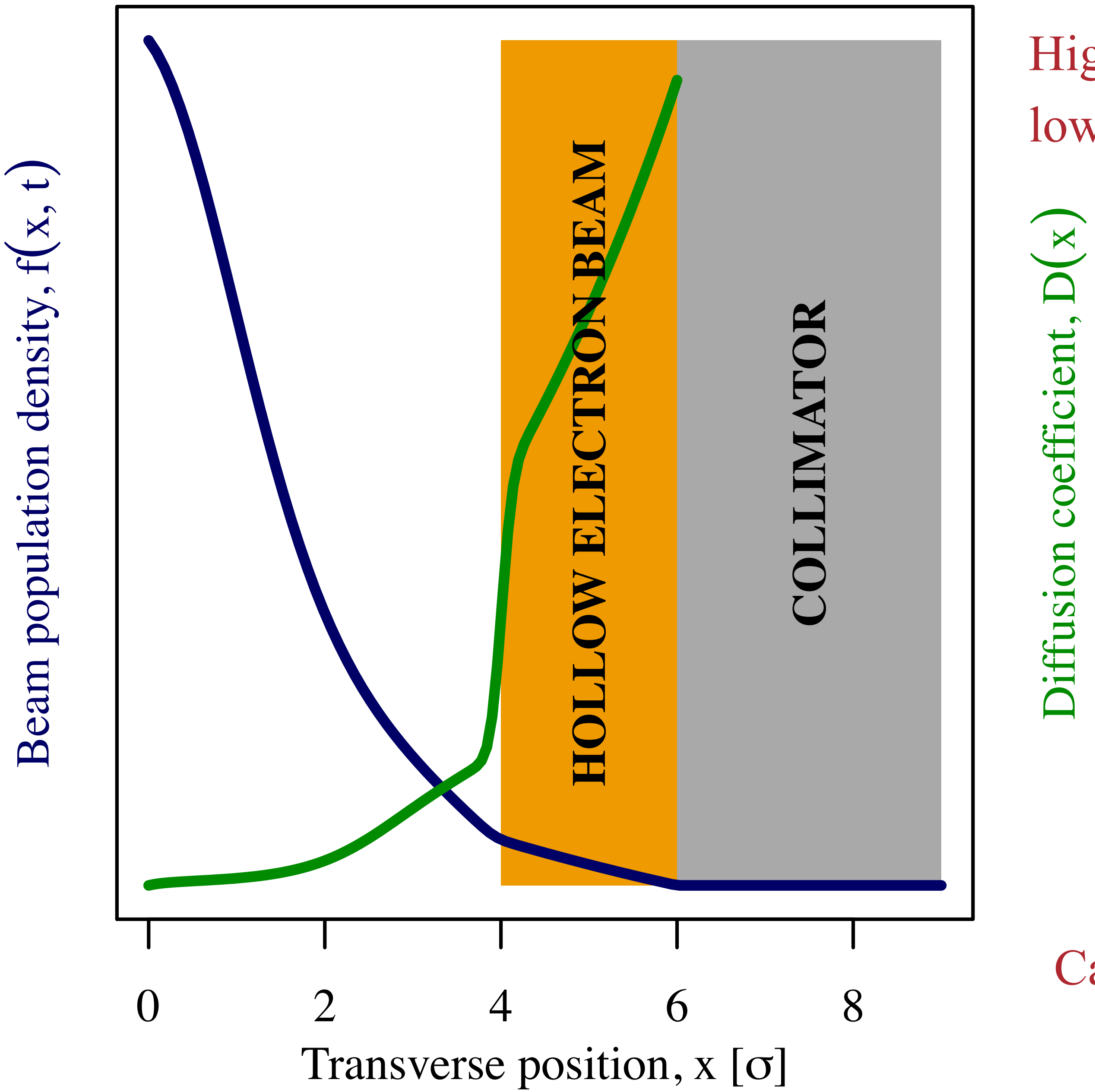
e-beam shadowed by primary, no effect on core!

e-beam turn-on

Diffusion model of hollow e-lens effect



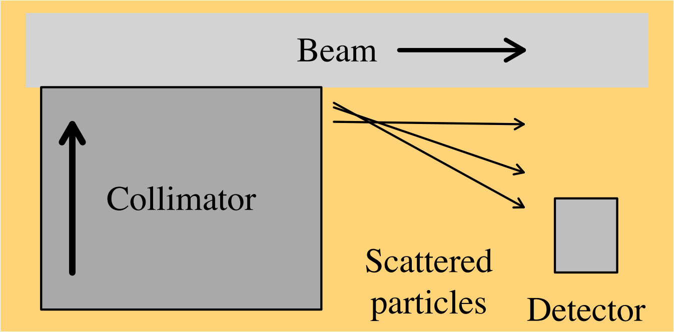
Diffusion model of hollow e-lens effect

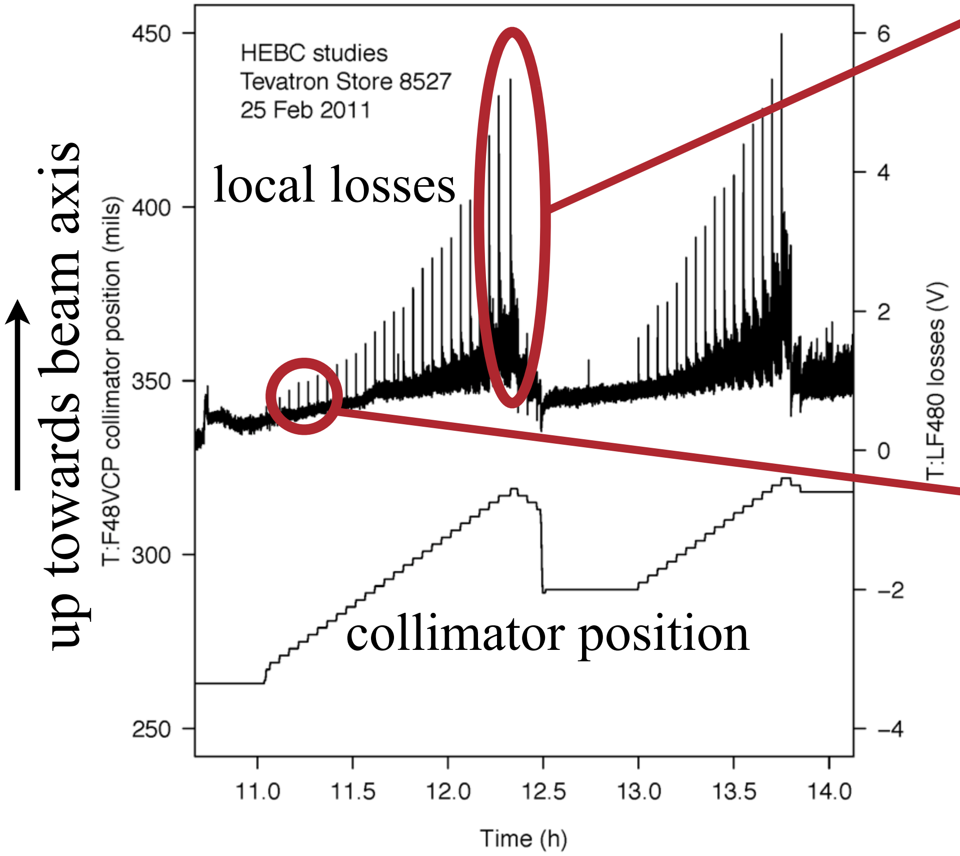


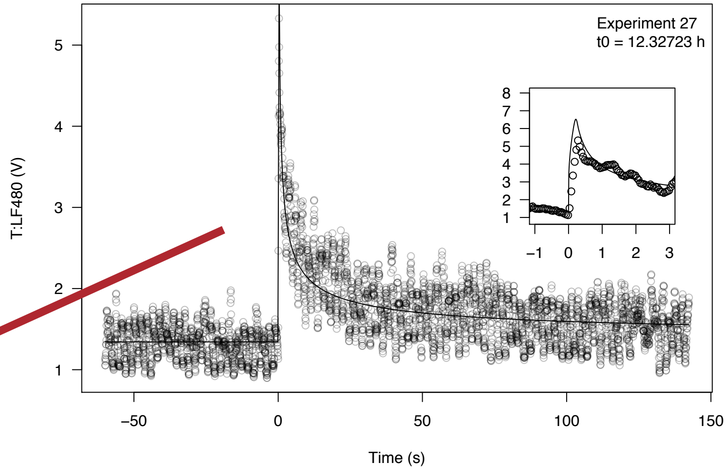
Higher diffusion =>
lower steady-state population

Can this effect be measured?

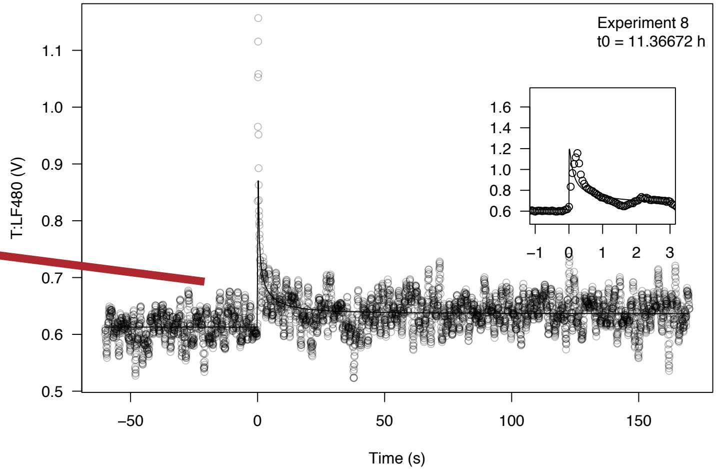
Diffusion rate vs. amplitude (collimator scan)







Losses equilibrate faster at large amplitudes (higher diffusion rate)



Mess and Seidel, NIMA **351**, 279 (1994)
Stancari et al., IPAC11
Valentino et al., PRSTAB **16**, 021003 (2013)

Diffusion model of loss-rate evolution

Distribution function evolves under diffusion with boundary condition at collimator

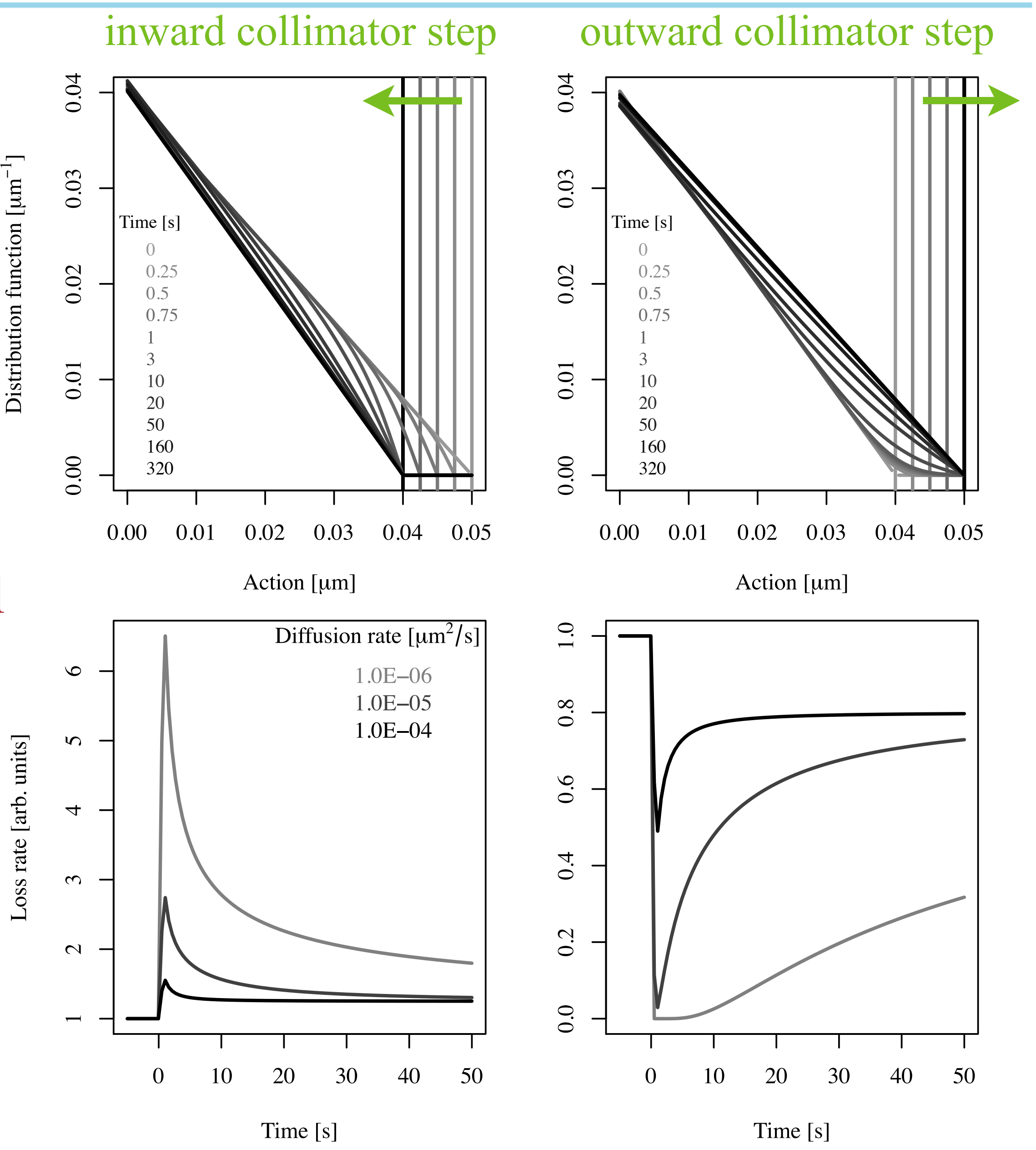
$$\partial_t f = \partial_J \left(D \cdot \partial_J f \right)$$

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

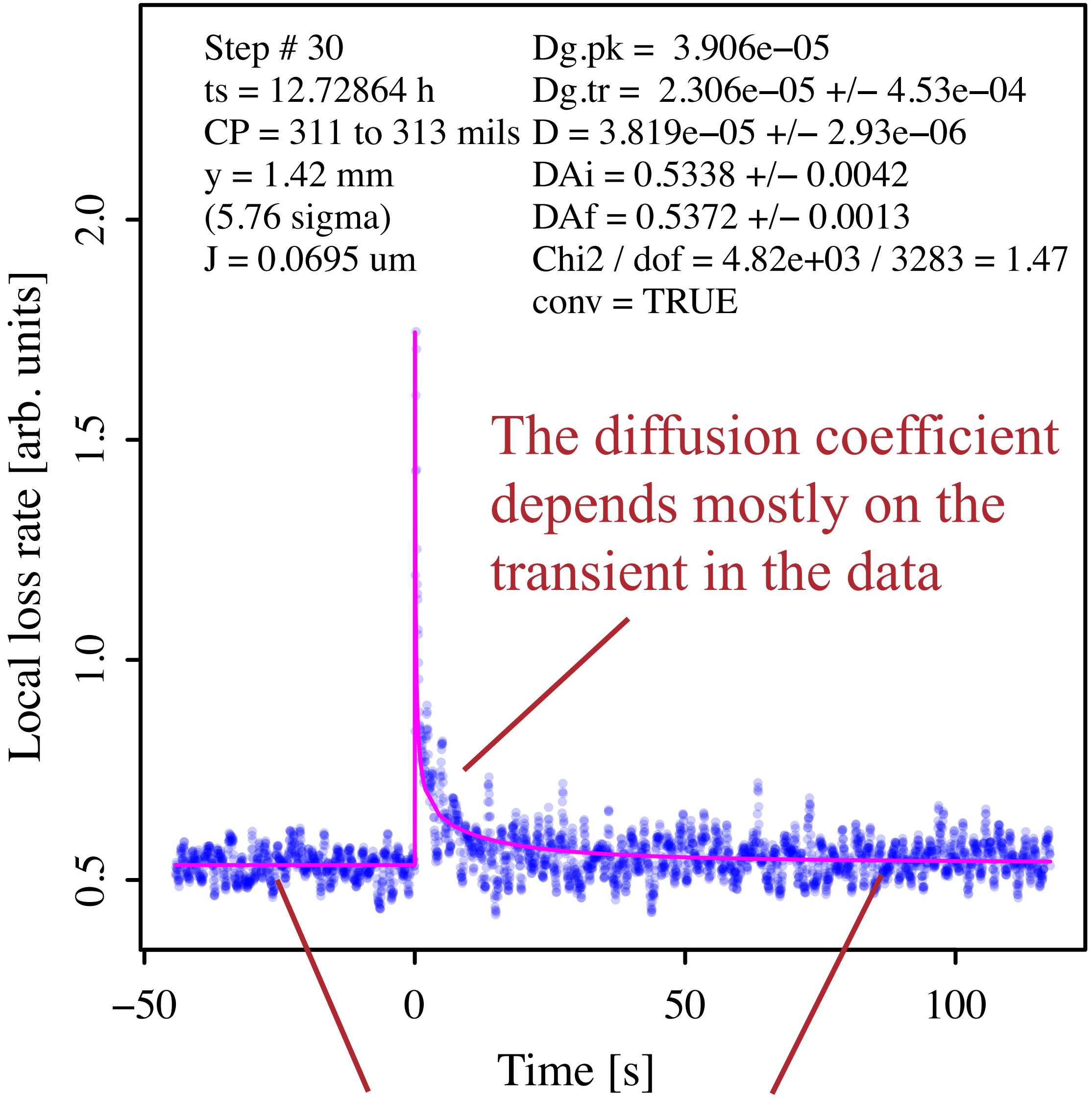
background rate


inward collimator step

outward collimator step

Stancari, arXiv:1108.5010 [physics.acc-ph]

Diffusion model applied to collimator steps

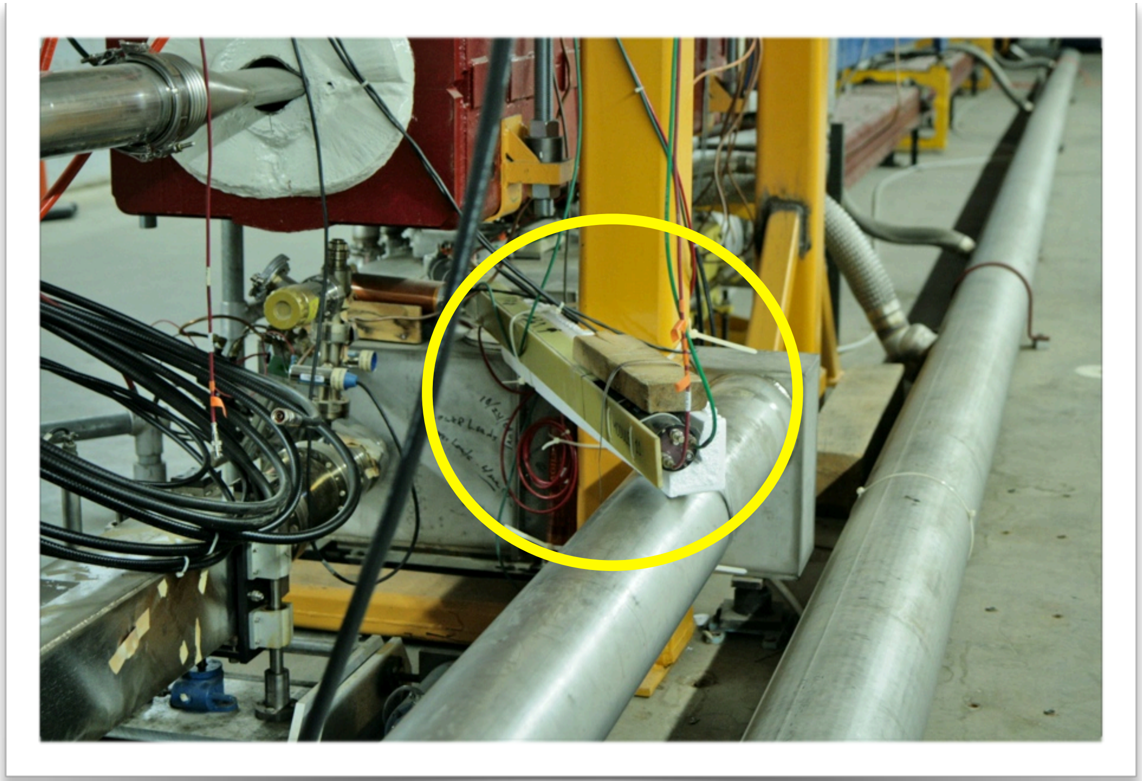


The diffusion coefficient depends mostly on the transient in the data

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

Gated antiproton loss monitors

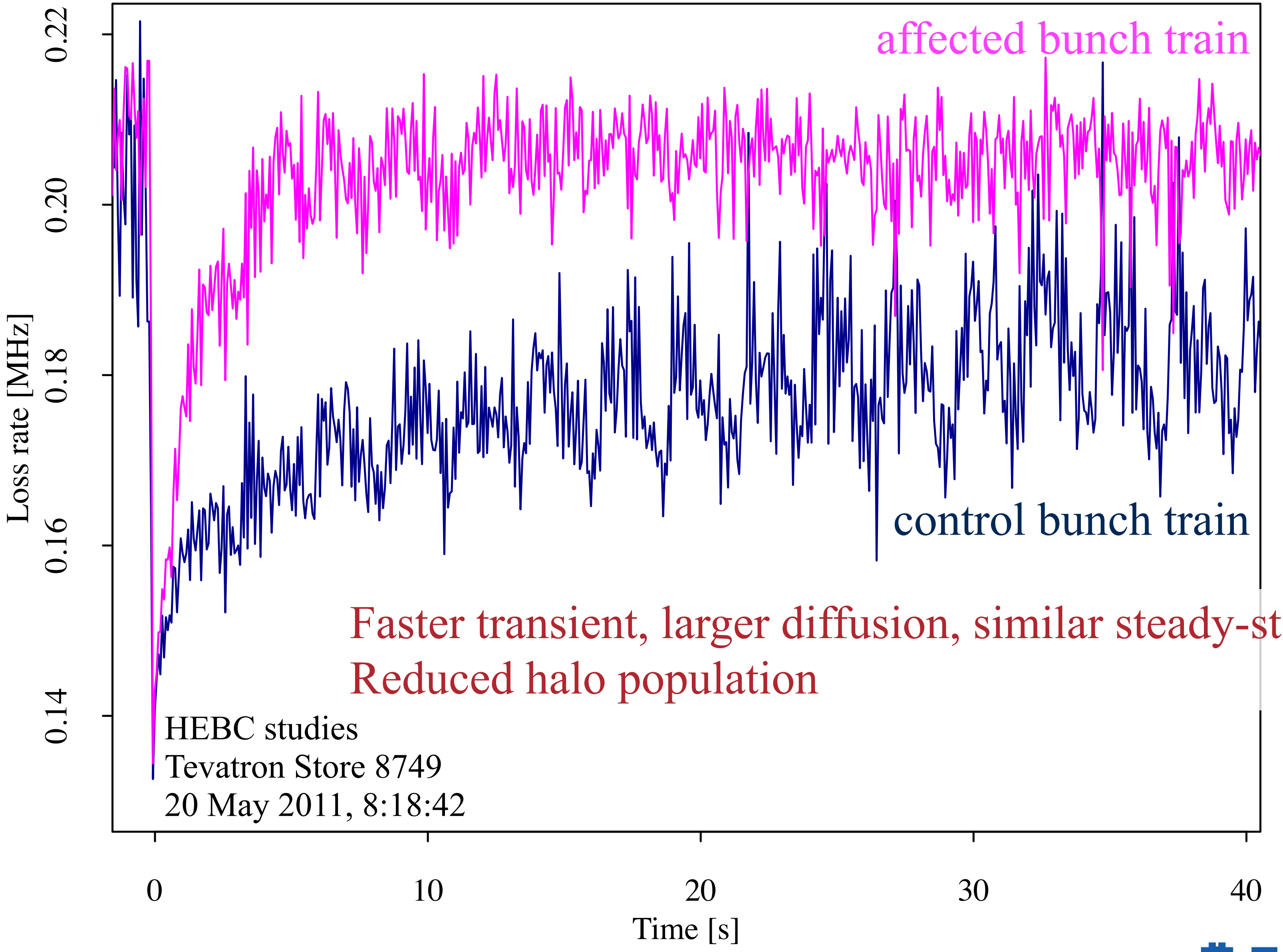
- Scintillator paddles installed near F49 antiproton absorber (March 2011) for hollow electron beam studies
- Gated to individual bunch trains
- Recorded at 15 Hz



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

Observed effect on equilibration time after step

Electrons (0.9 A) on pbar train #2, 4.25σ hole. **Vertical collimator step out**, 50 µm

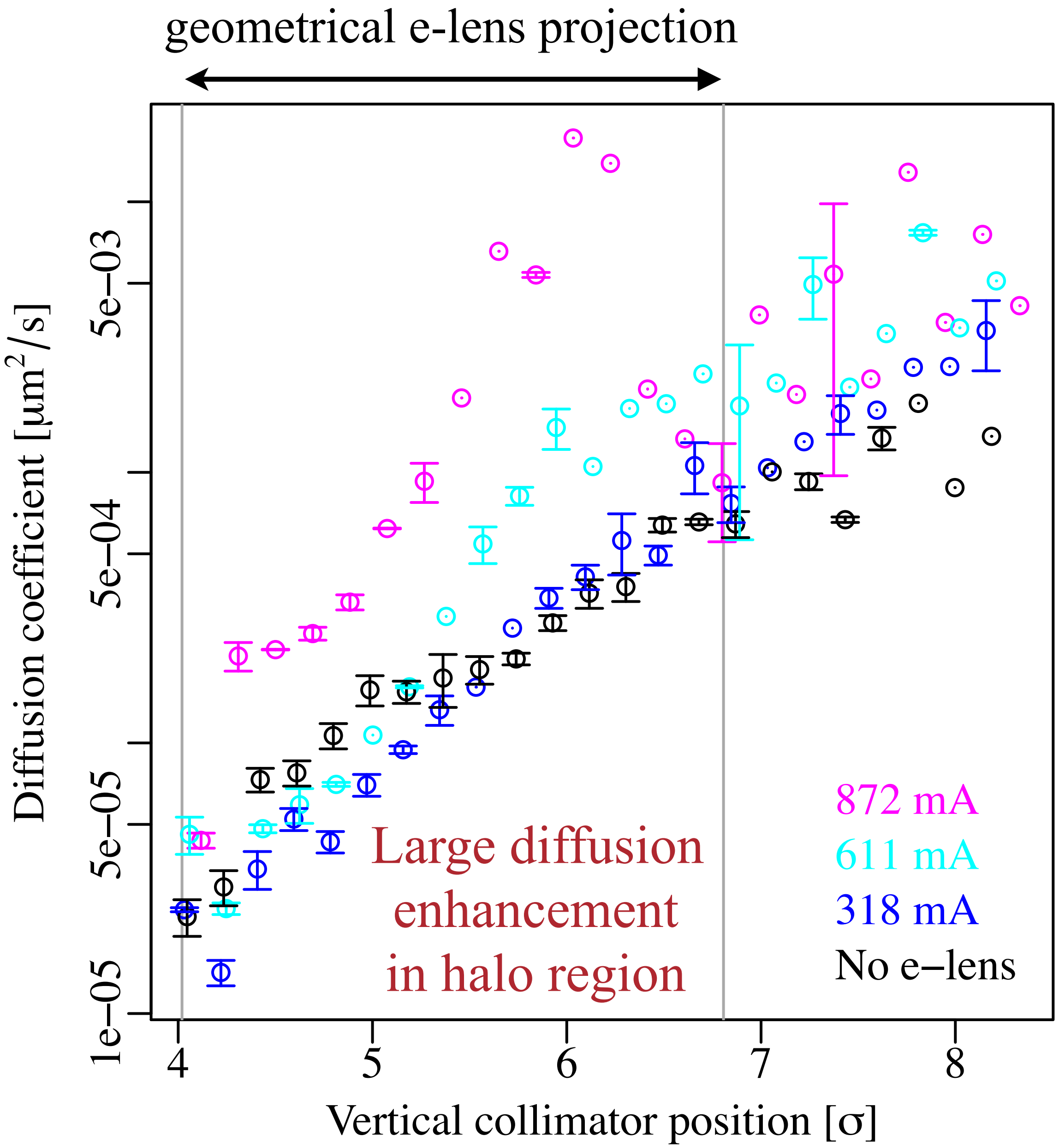


Faster transient, larger diffusion, similar steady-state flux

Reduced halo population

HEBC studies
Tevatron Store 8749
20 May 2011, 8:18:42

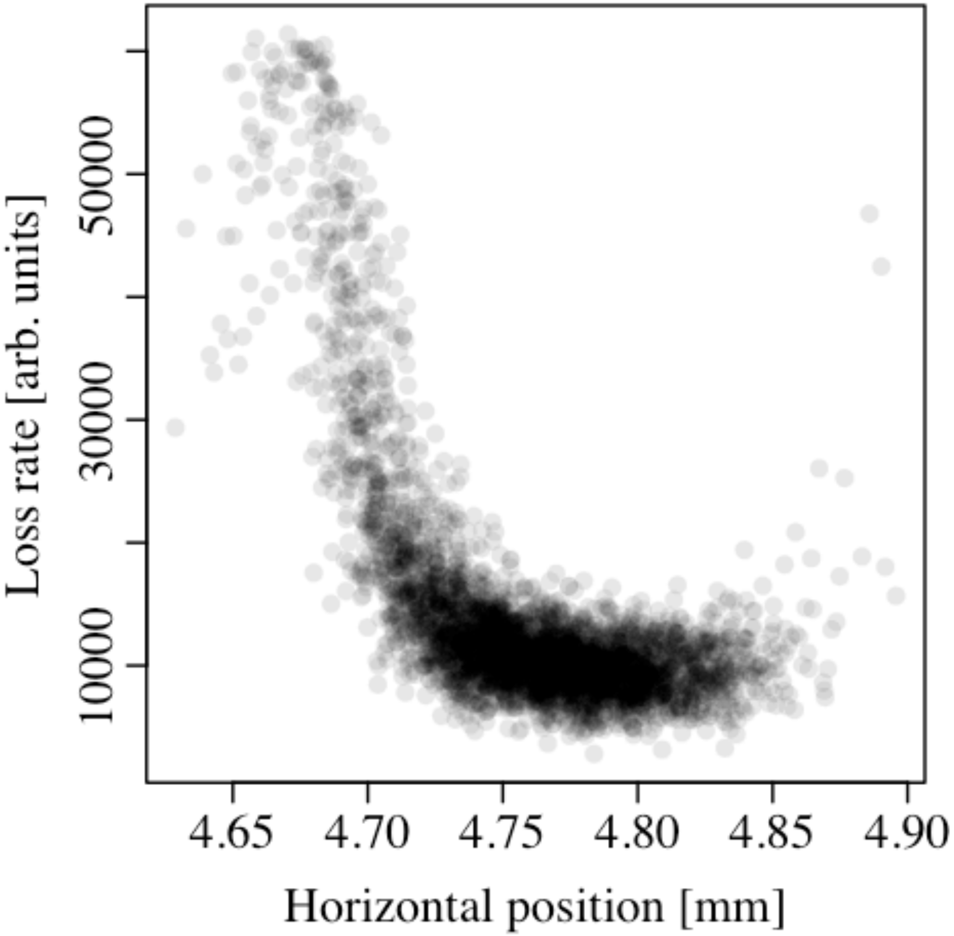
Effect on diffusion rate vs. e-beam current



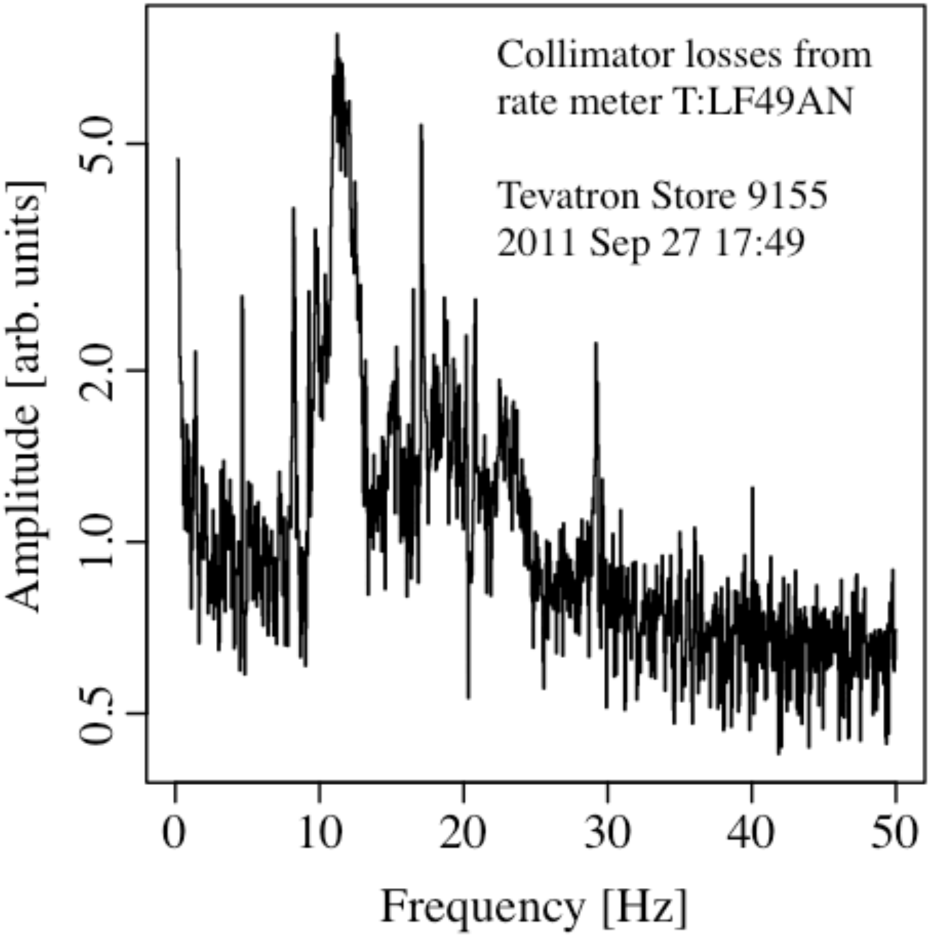
Large diffusion enhancement in halo region

Beam jitter in the Tevatron

Beam losses at collimator vs. beam centroid positions, recorded at 100 Hz

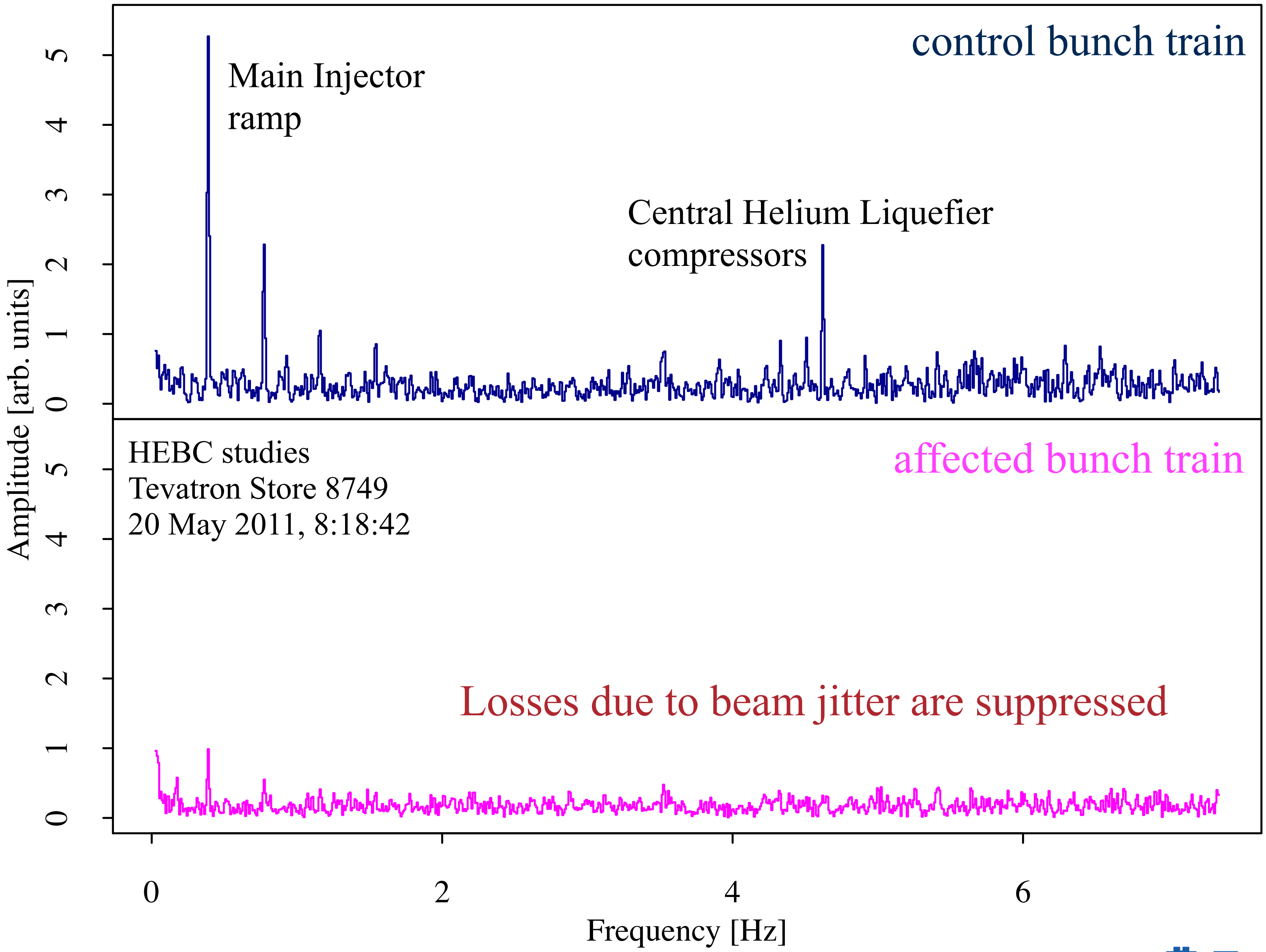


Frequency spectrum of losses

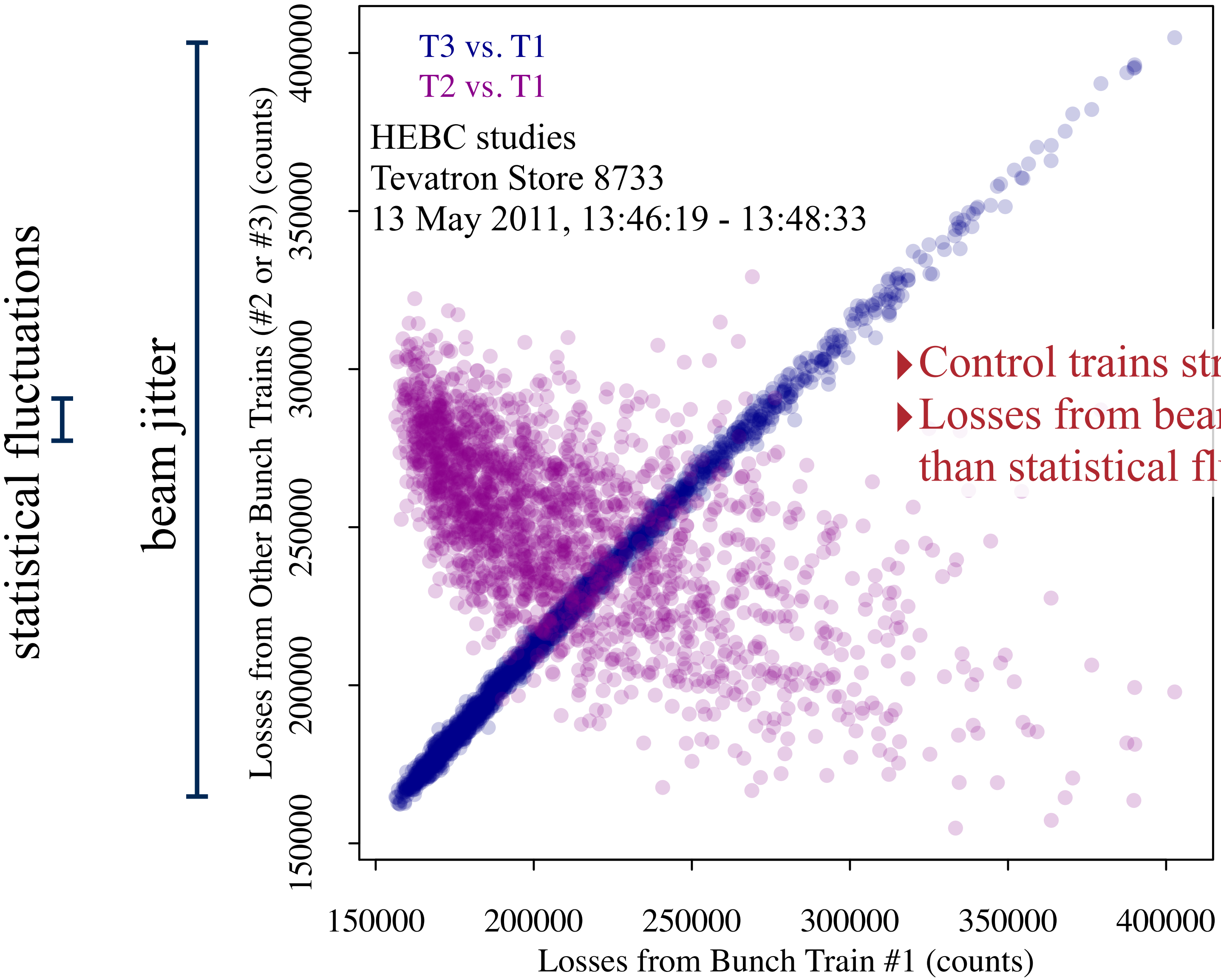


Beam vibrates at low frequency with amplitudes of a few tens of microns: ground motion, mechanical vibrations, ...

Measured effect on Fourier spectrum of losses



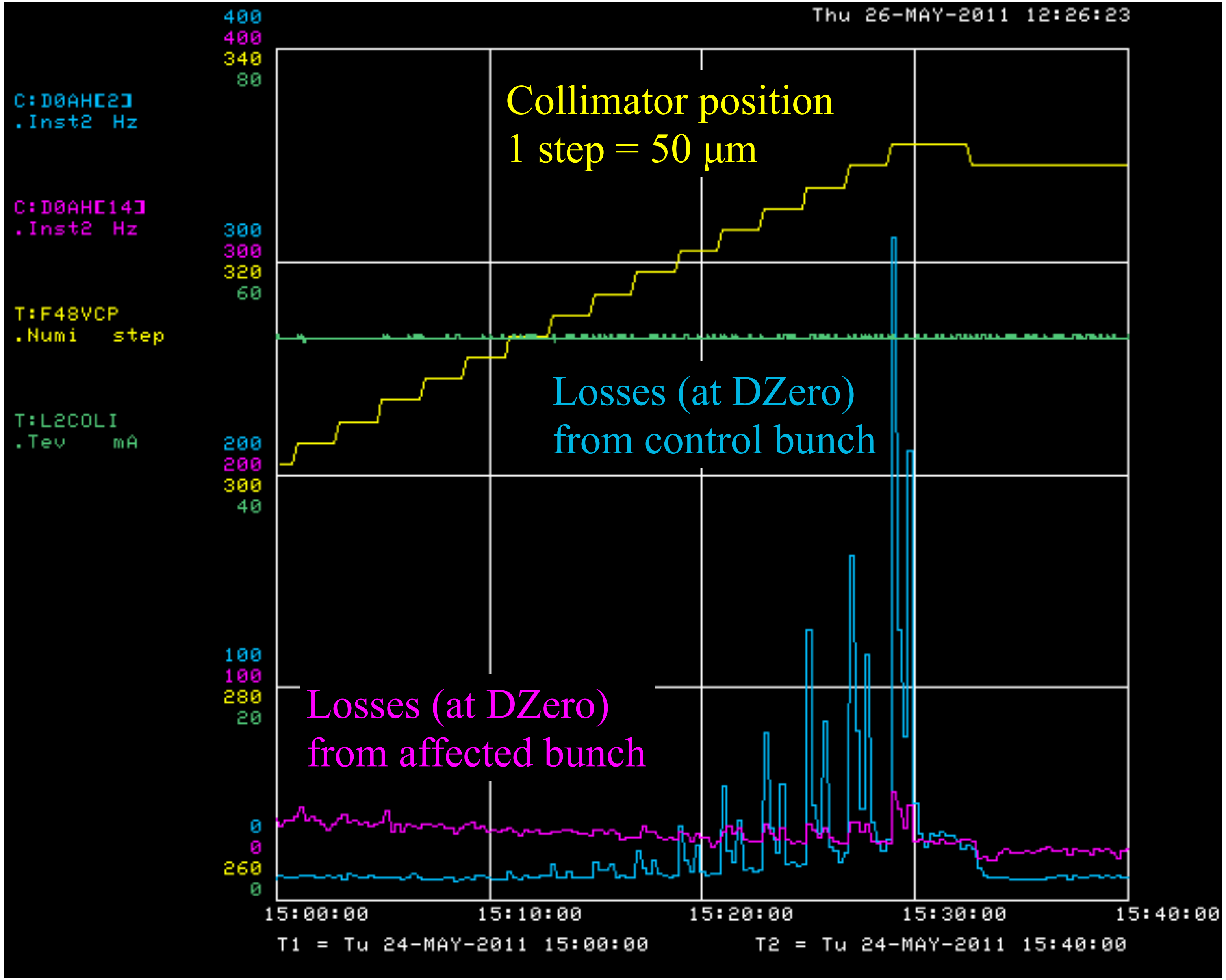
Correlation of steady-state losses



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

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

Suppression of loss spikes during collimator steps



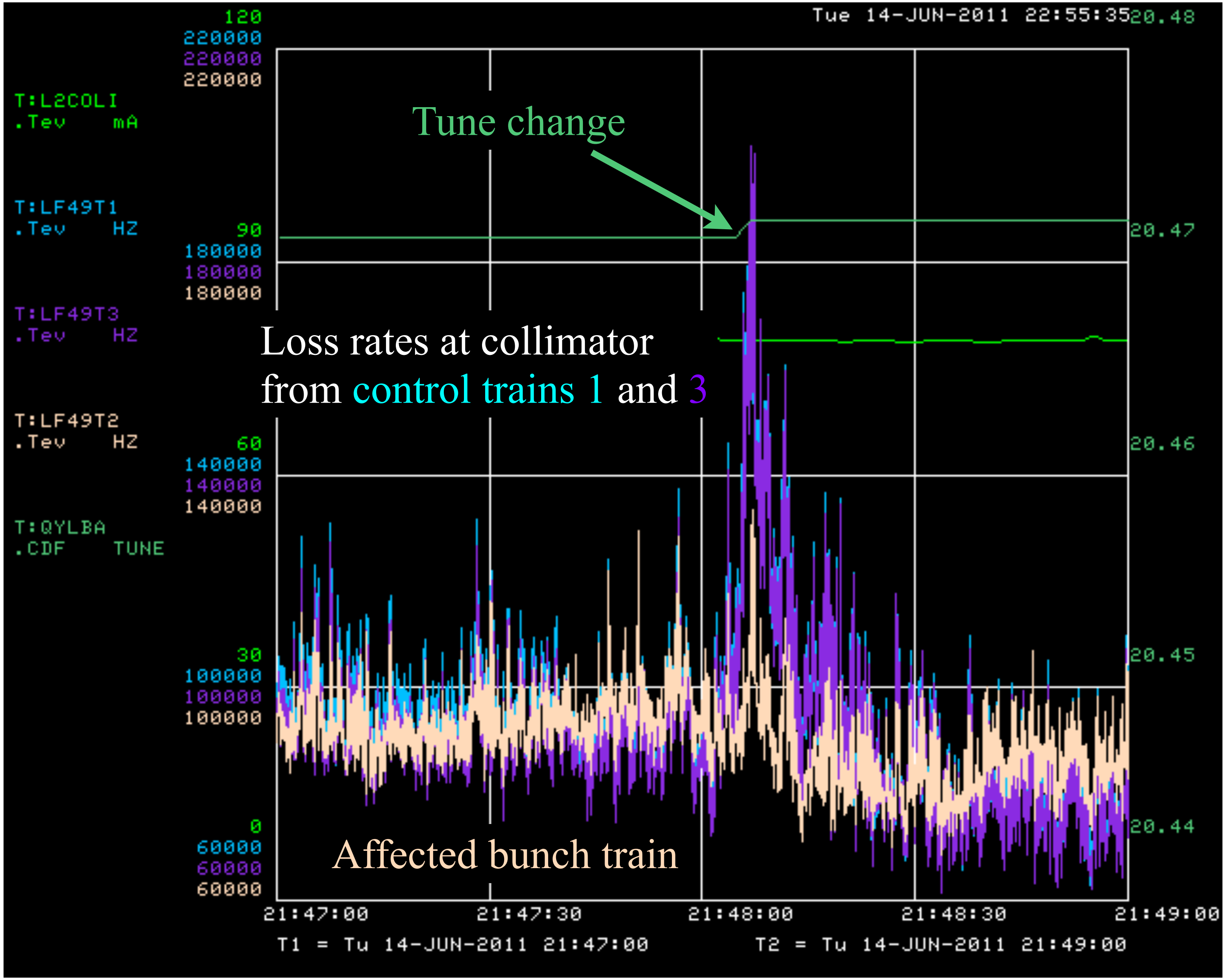
Collimator position
1 step = 50 µm

Losses (at DZero)
from control bunch

Losses (at DZero)
from affected bunch

LARP

Suppression of loss spikes after tune change



Tune change

Loss rates at collimator from control trains 1 and 3

Affected bunch train

Main experimental results (1/2)

Basics

- removal rates were clearly detectable
- no effect on other bunches
- parasitic experiments were possible
- alignment was reliable and reproducible
- orbit bump with fixed e-beam was a viable scraping option
- stable conditions during whole store
- operation by bunch trains was possible

Removal rates

- particle removal was smooth and tunable
- small differences observed between separated and colliding beams
- measured removal rates vs. amplitude

Diffusion

- diffusion model reproduced transients during collimator steps
- enhancement of diffusion rate was significant
- sensitive tool to estimate halo population complementary to intensity decay

Main experimental results (2/2)

Loss fluctuations

- loss spikes to due beam jitter and tune adjustments were suppressed

Adverse effects on the core

- no direct core removal
- compared intensity and luminosity decay
- no additional emittance growth

Resonant excitation (i.e. different e-beam currents for different turns)

- limited experimental data
- much higher removal rates
- very sensitive to tunes and chromaticity
- caused coherent spikes in Schottky spectrum
- observed negative effects on luminosity

Open experimental questions

- Are there resonant excitation schemes that enhance halo removal without affecting the core? (In simulations, yes)
- Are there differences between the removal rates of protons and antiprotons?
- Are there alternative methods that are as effective and flexible?

A wide range of complementary studies is being conducted or planned:

- *Measurements of beam halo population and diffusion in LHC at 6.5 TeV*
  Valentino et al., CERN-ACC-Note-2016-0010 + recent studies with multiple bunches
- *Alternative halo control methods: narrow-band excitation and tune ripple*
  Bruce, Wagner et al., IPAC16 Proc. + recent studies
- *Effects of resonant excitation on core to simulate e-lens pulsing patterns*
  Fitterer et al., FERMILAB-TM-2635-AD, NA-PAC16

- *Extend Tevatron observations with experiments with e-lenses in RHIC*
  p-p collider, effect on protons, pulsing schemes; only possible in 2018

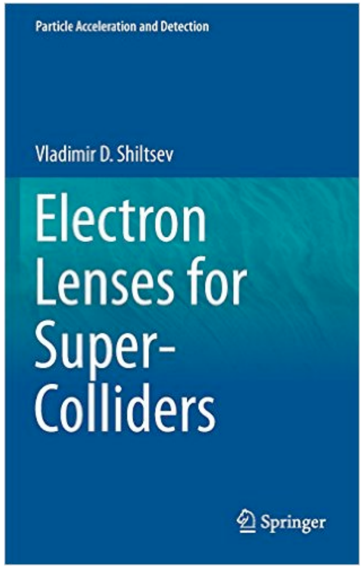
Thank you for your attention

Backup slides

Applications of electron lenses

In the Fermilab Tevatron collider

- ***long-range beam-beam compensation (tune shift of individual bunches)***
  - Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)
- ***abort-gap cleaning (for years of regular 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
- ***demonstration of halo scraping with hollow electron beams***
  - Stancari et al., Phys. Rev. Lett. **107**, 084802 (2011)



Particle Acceleration and Detection

Vladimir D. Shiltsev

Electron Lenses for Super-Colliders

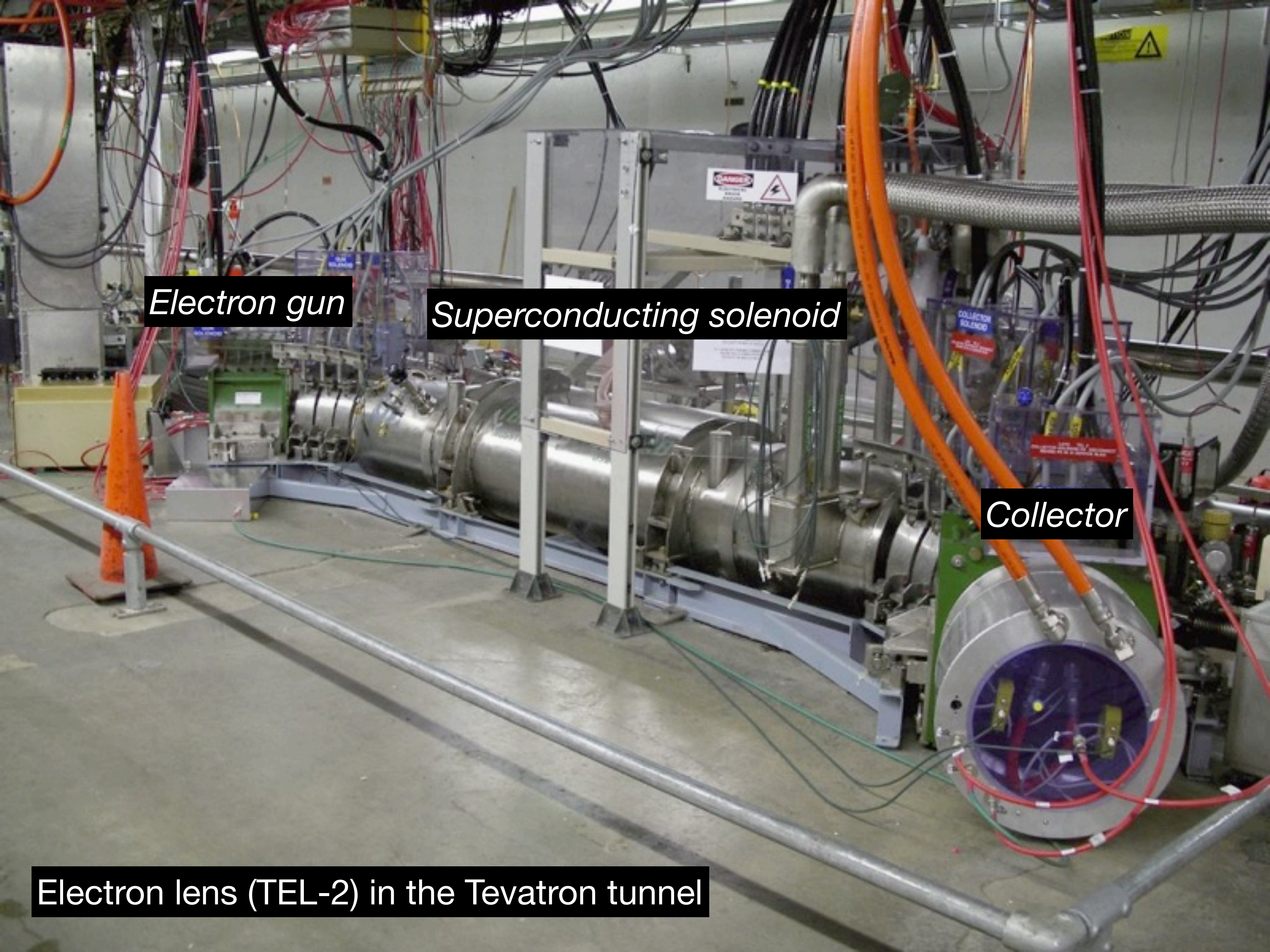
Springer

Presently, used in RHIC at BNL for head-on beam-beam compensation, luminosity improvements

- Fischer et al., Phys. Rev. Lett. **115**, 264801 (2015)

Current areas of research

- ***generation of nonlinear integrable lattices*** in the Fermilab Integrable Optics Test Accelerator
  - Nagaitsev, Valishev et al., IPAC12; Stancari, arXiv:1409.3615, Stancari et al., IPAC15
- ***hollow electron beam scraping*** of protons in LHC
  - Stancari et al., CERN-ACC-2014-0248; Bruce et al., IPAC15
- ***long-range beam-beam compensation*** as charged, current-carrying “wires” for LHC
  - Valishev and Stancari, arXiv:1312.5006; Fartoukh et al., PRSTAB **18**, 121001 (2015)
- to ***generate tune spread for Landau damping*** of instabilities before collisions in LHC and for Recycler



Electron lens (TEL-2) in the Tevatron tunnel