New Methods of Particle Collimation in Colliders

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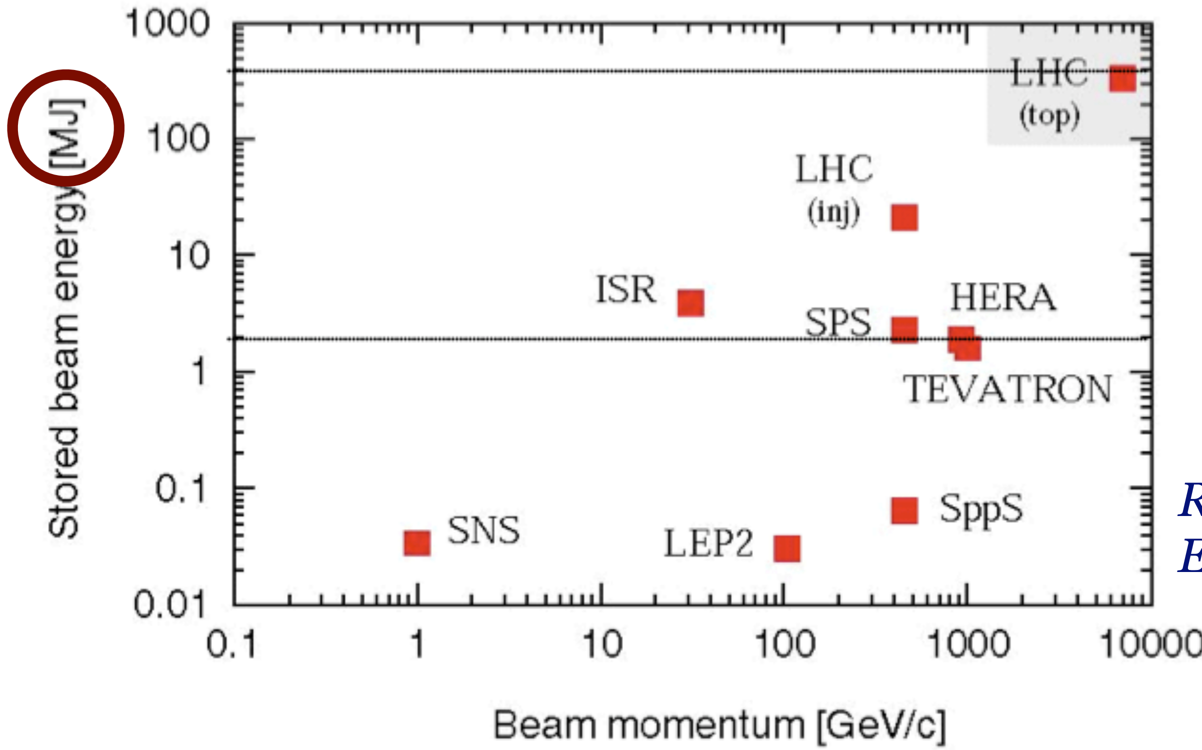
- ➡ Introduction to collimation systems
- ➡ The hollow electron beam collimator
- ➡ Tevatron experiments and results
- ➡ Conclusions and outlook

Meeting of the Division of Particles and Fields of the American Physical Society
Providence, Rhode Island, August 9, 2011

The need for collimation

- In high-power machines, **stored beam energy** can be large

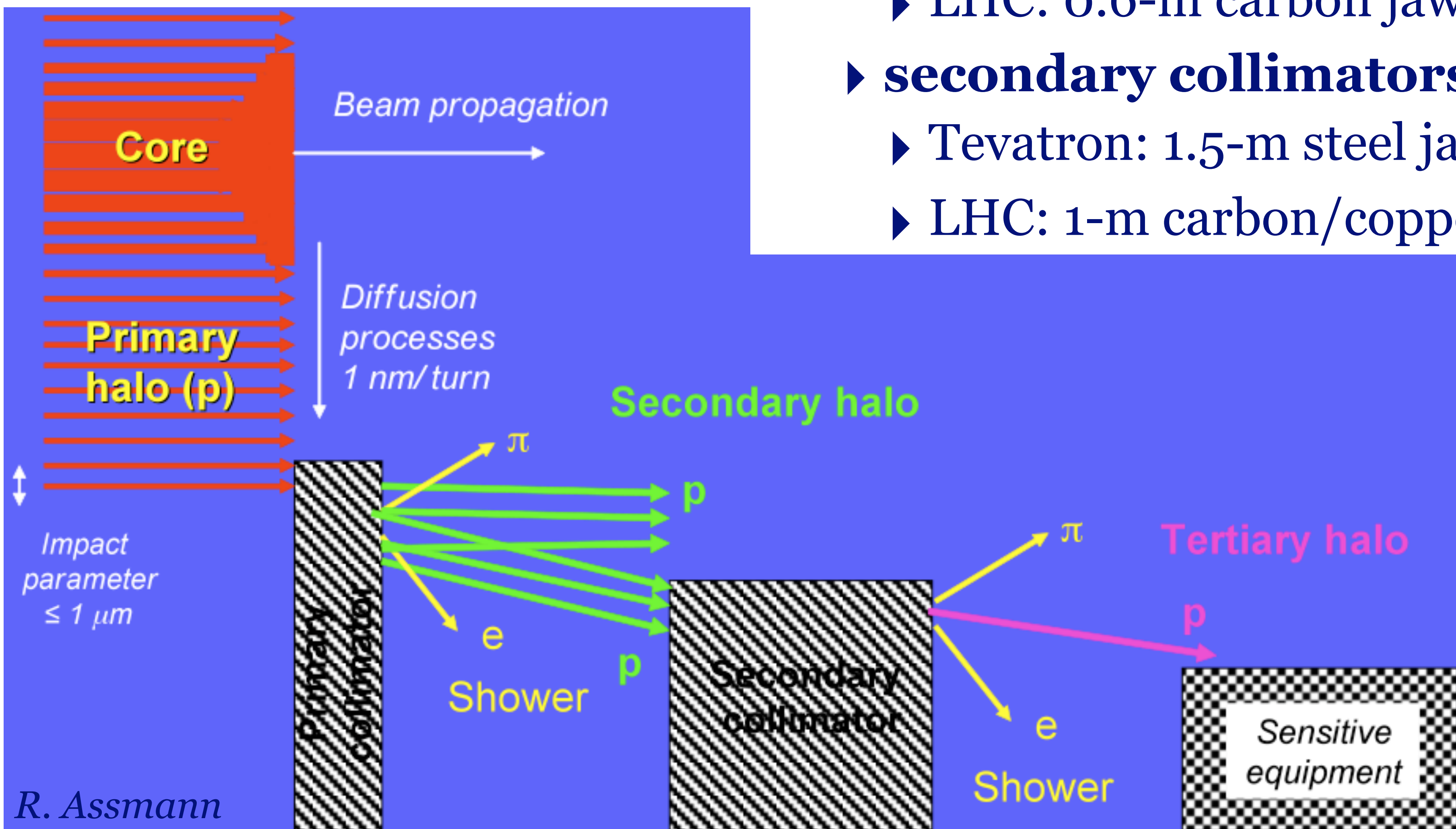


R. Assmann et al. EPAC02

- Beam-gas and intrabeam scattering, rf noise, ground motion, resonances, beam-beam effects cause formation of **beam halo**
- Uncontrolled particle **losses** can damage components, cause magnets to lose superconductivity, and increase experimental backgrounds

The conventional two-stage collimation system

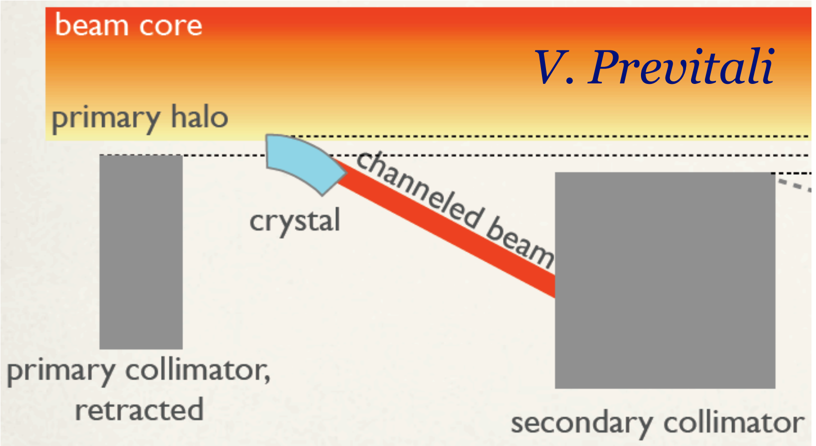
- Goals of collimation:
  - reduce beam halo
  - direct losses towards absorbers
- Conventional schemes:
  - **primary collimators**
    - Tevatron: 5-mm W at 5σ
    - LHC: 0.6-m carbon jaws at 6σ
  - **secondary collimators**
    - Tevatron: 1.5-m steel jaws at 6σ
    - LHC: 1-m carbon/copper at 7σ



Advanced collimation concepts

Limitations of multi-stage approach

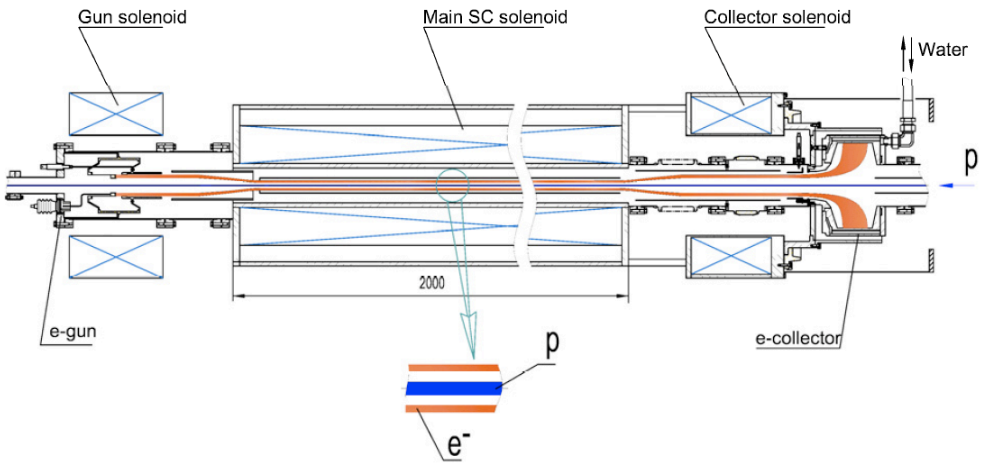
- **leakage**
- **impedance**
- **loss spikes during setup**
- **losses due to beam jitter**



▸ Channeling and volume reflection in **bent crystals**: reduce leakage by directing halo particles deeper into absorbers in a single-pass

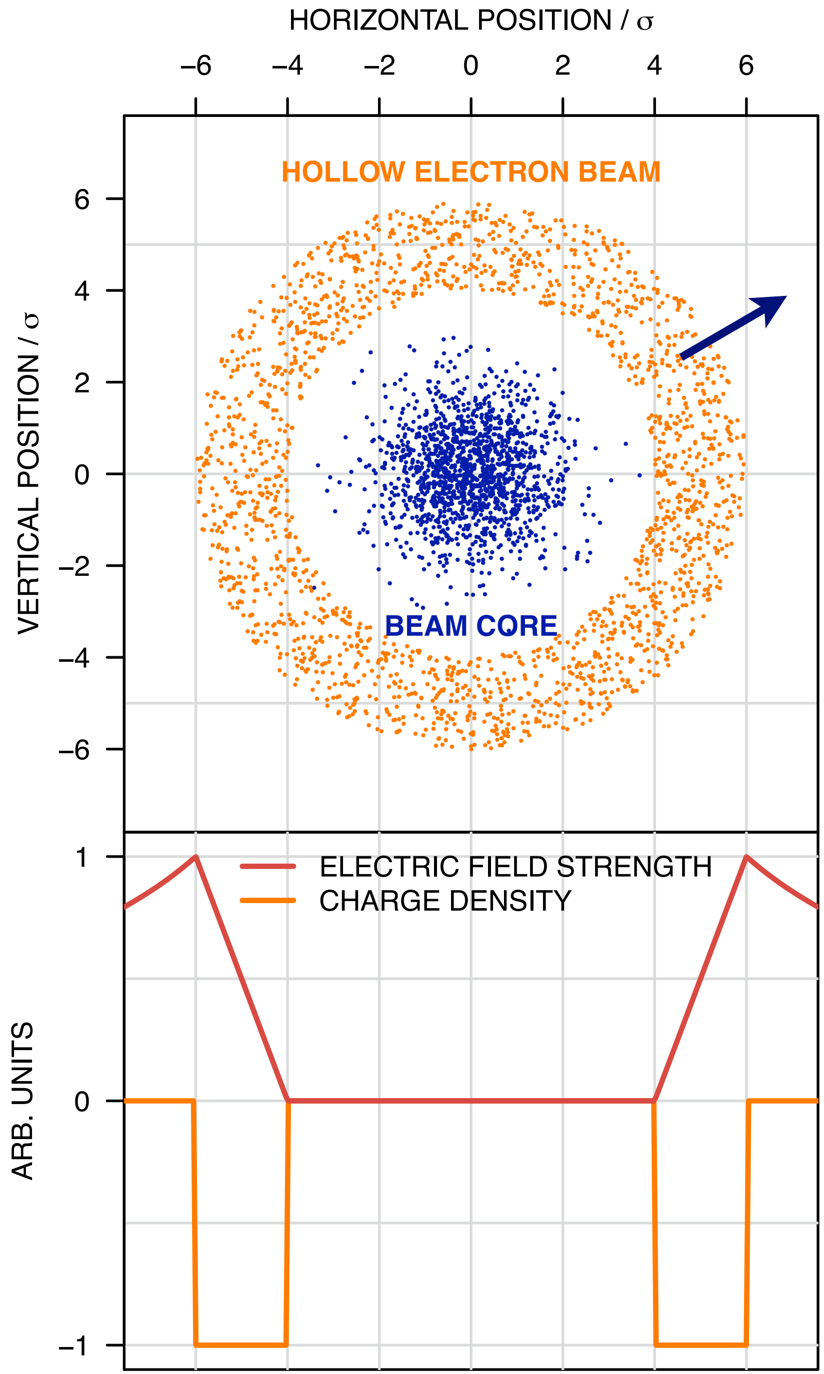
Tsyganov, FERMILAB-TM-682 (1976), Maslov et al., SSCL-484 (1991), Zvoda et al., PAC11, Scandale et al., Phys. Rev. Lett. ***102****, 084801 (2009)*

▸ **Hollow electron beam collimator**: cylindrical, hollow, magnetically confined, pulsed electron beam overlapping with halo, as soft halo scraper and tunable halo diffusion enhancer



focus of this talk

Concept of hollow electron beam collimator



Halo experiences nonlinear transverse kicks:

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

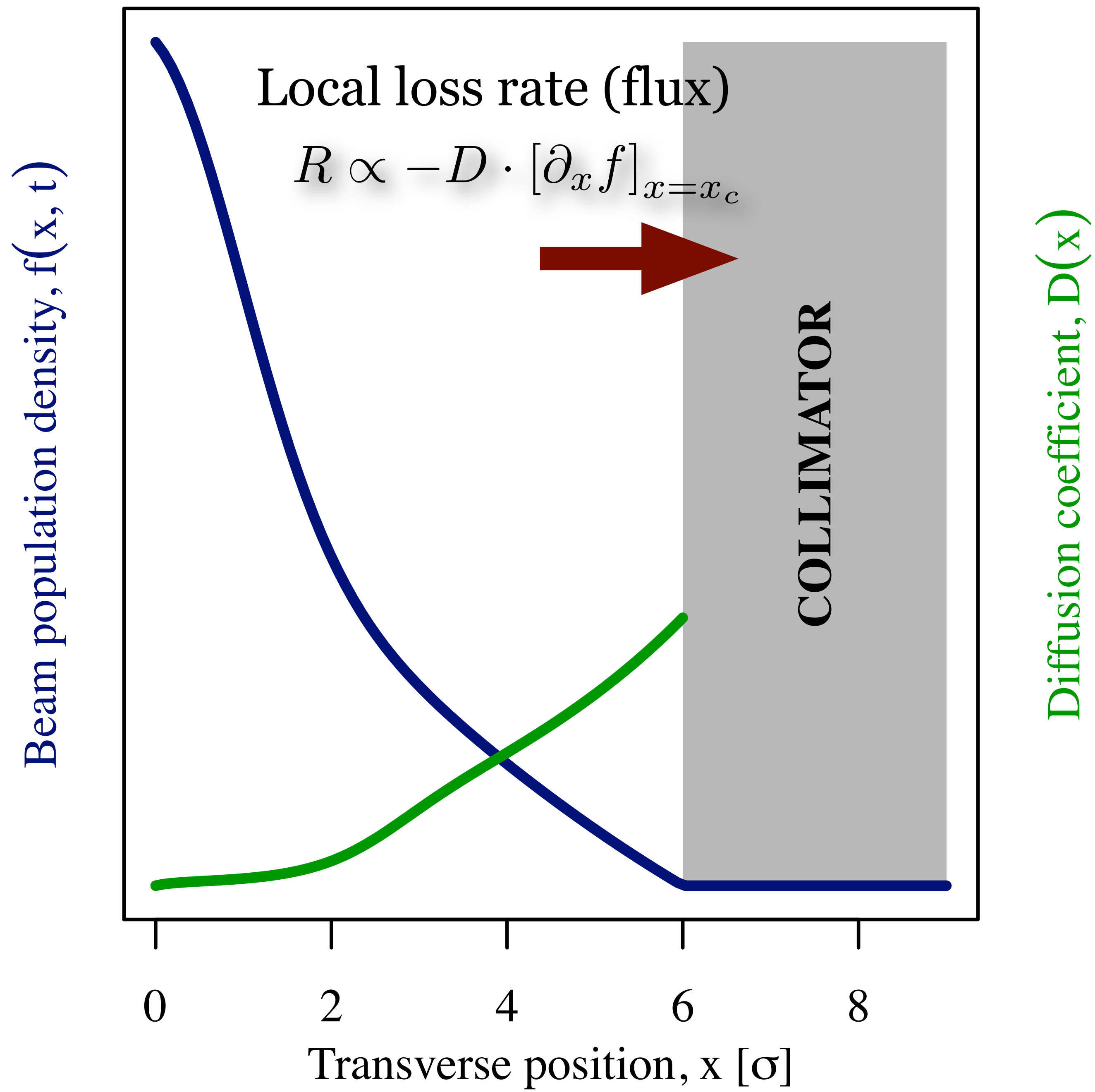
About **0.2 µrad** in TEL2 at 980 GeV

For comparison:
multiple scattering
in Tevatron collimators

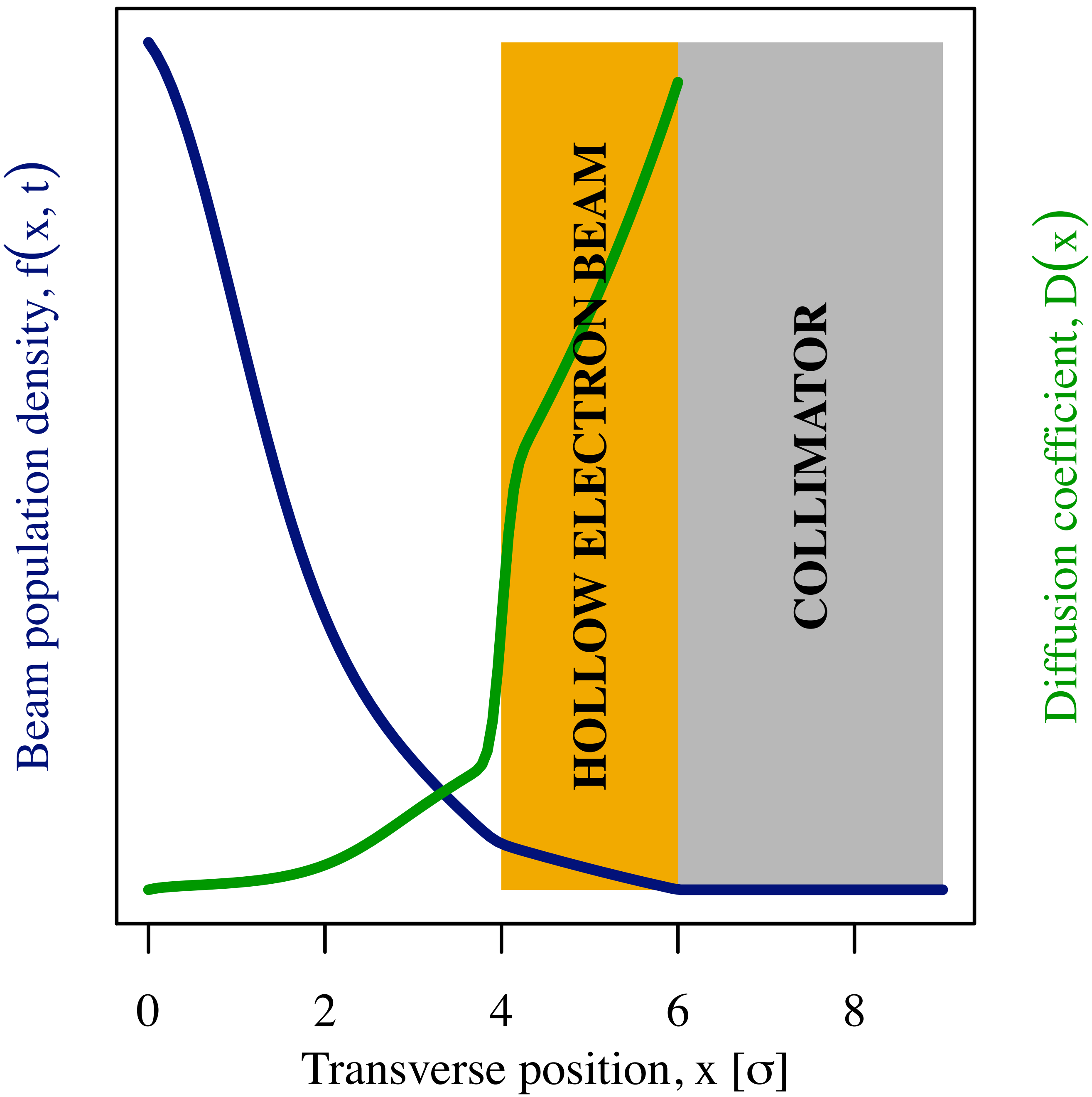
$$\theta_{\rm rms} = 17\ \mu\text{rad}$$

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

1-dimensional diffusion cartoon of collimation



1-dimensional diffusion cartoon with hollow electron beam



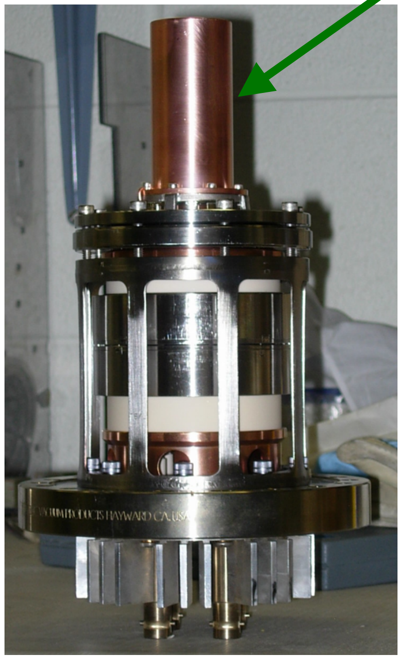
A good complement to a two-stage system for high intensities?

- 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
- 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
- Control of hollow beam profile
- Beam stability at high intensity
- Cost

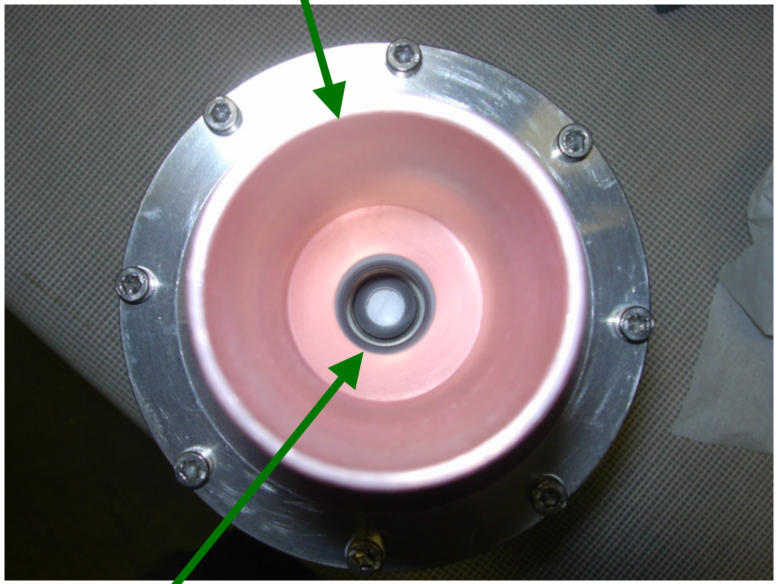
The 15-mm hollow electron gun

Copper anode

side view

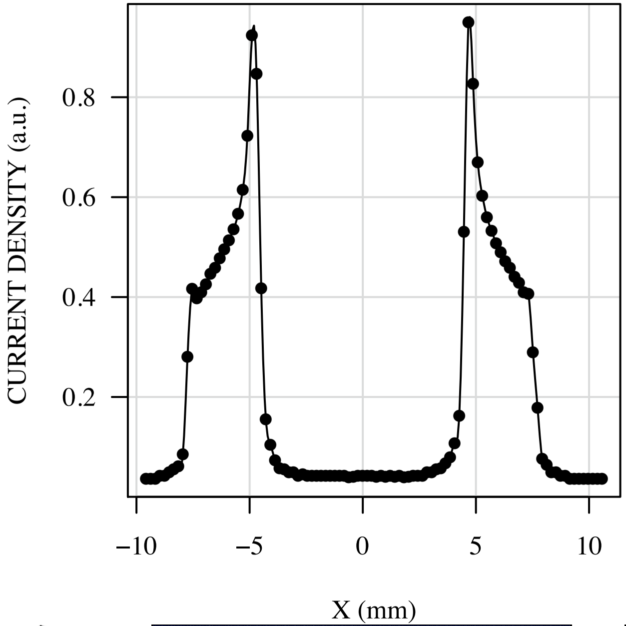


top view

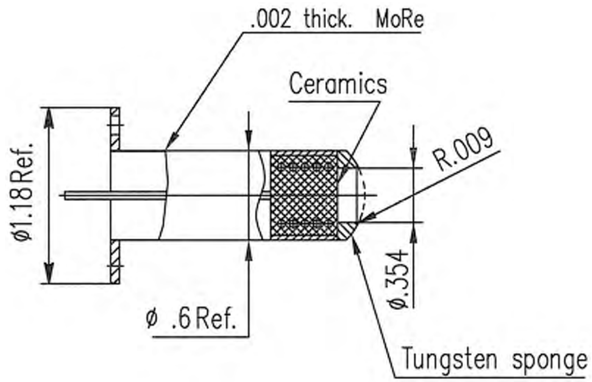


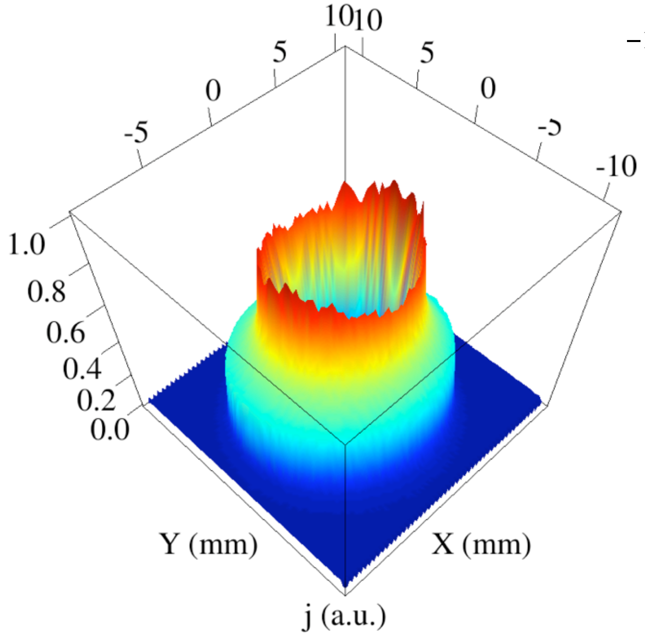
Yield: **1.1 A** at 4.8 kV

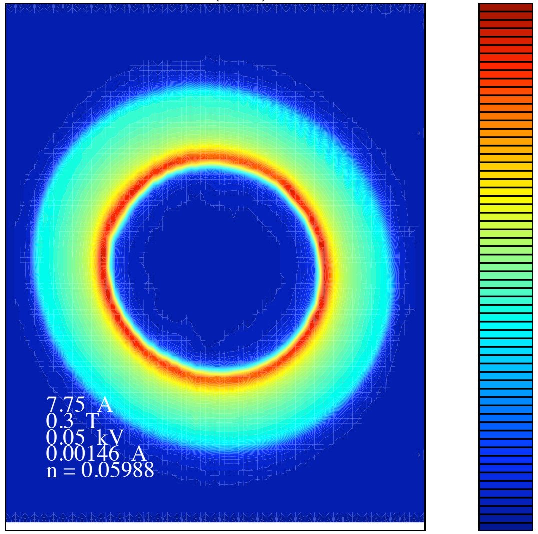
Profile measurements



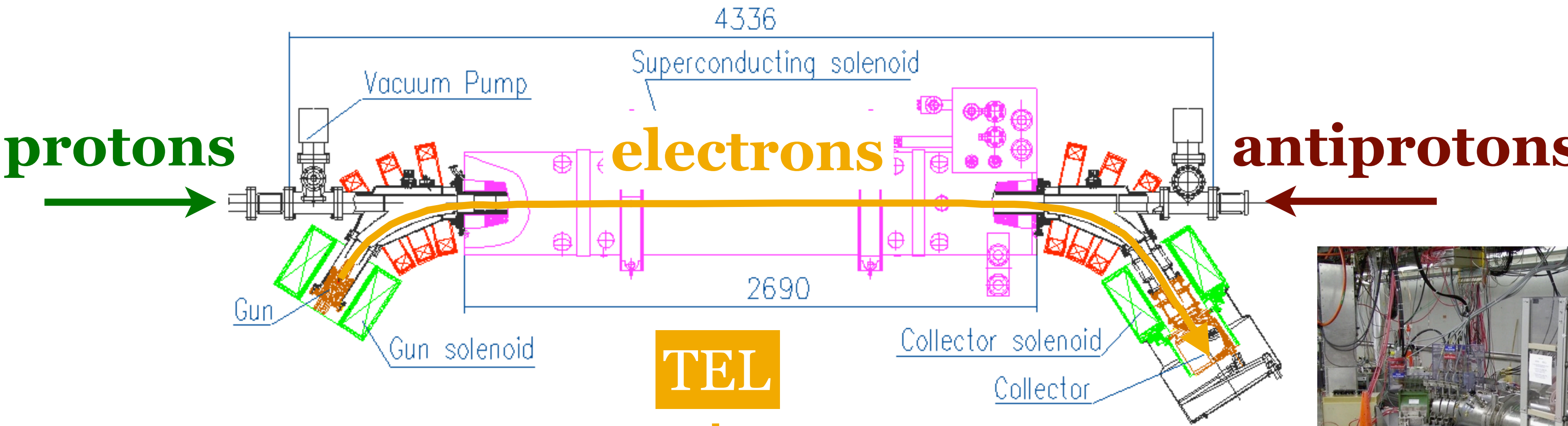
Tungsten dispenser cathode
with convex surface
15-mm diameter, 9-mm hole

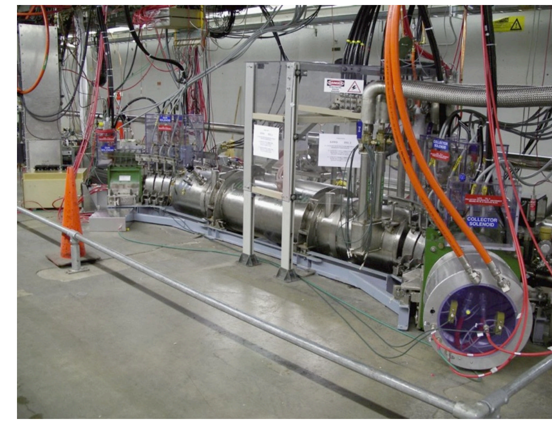






Layout of the beams in the Tevatron





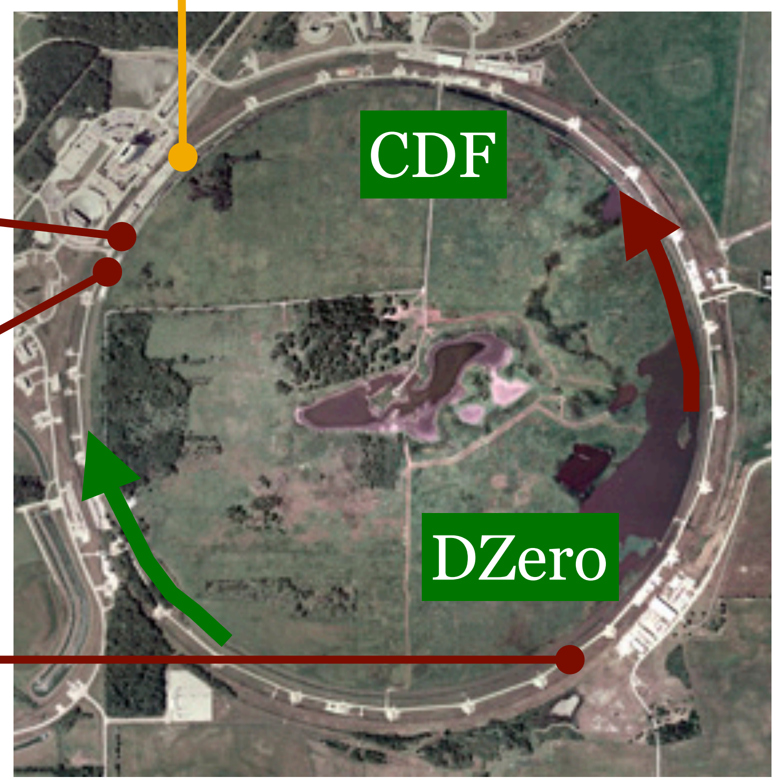
Tevatron electron lens

Antiproton collimators:

Primary (F49)

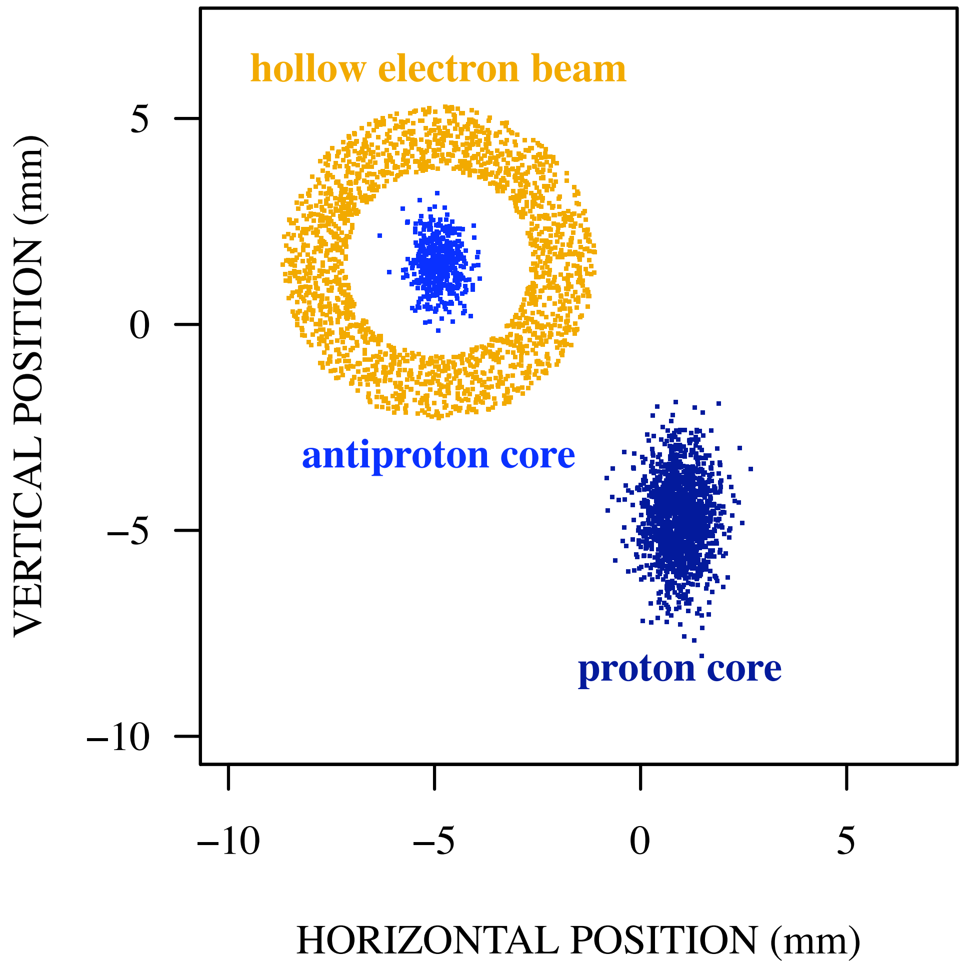
Secondary (F48)

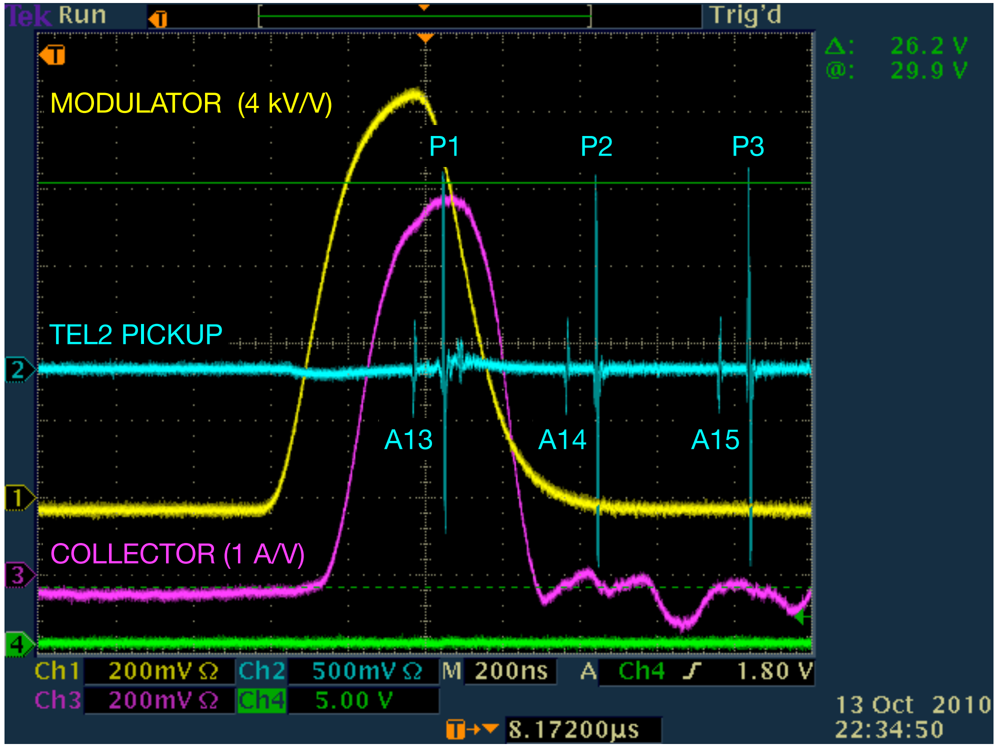
Secondary (D17)



Layout of the beams in the Tevatron

Transverse separation
is 9 mm at TEL





Pulsed electron beam
can be synchronized with
any group of bunches

Brief project history

- **Summer ’09**: Hollow gun design
- **August ’09**: Hollow gun manufactured and delivered
- **Fall/winter ’09**: Hollow beam dynamics studies in test stand
- **August ’10**: Hollow gun installed in Tevatron electron lens
- **October ’10 - now**: Tevatron experiments
- **March ’11**: new gated train-by-train antiproton loss monitors

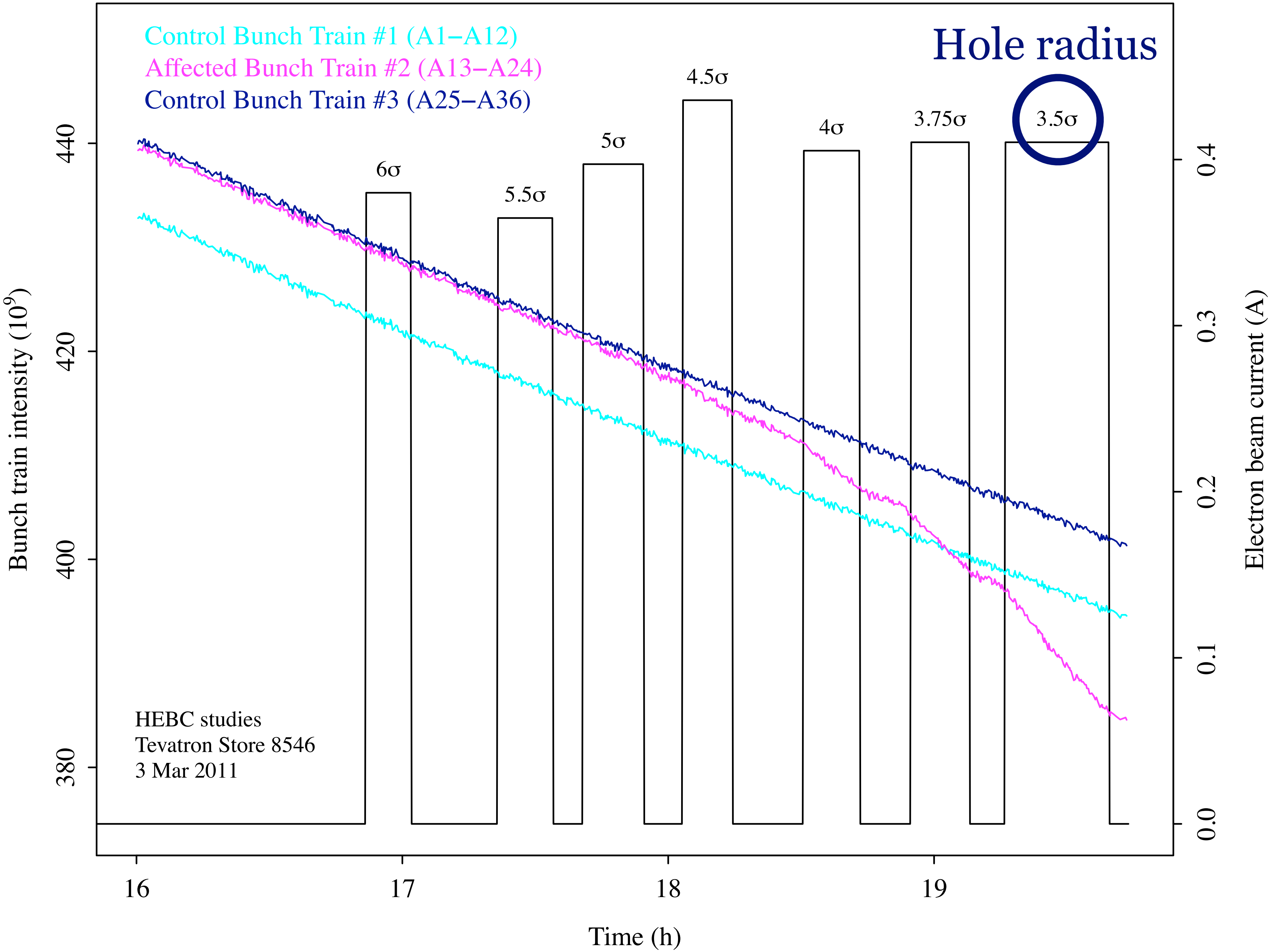
installed near Tevatron secondary collimators

First results will appear soon in Phys. Rev. Lett. (August 2011):
G. Stancari et al., arXiv:1105:3256

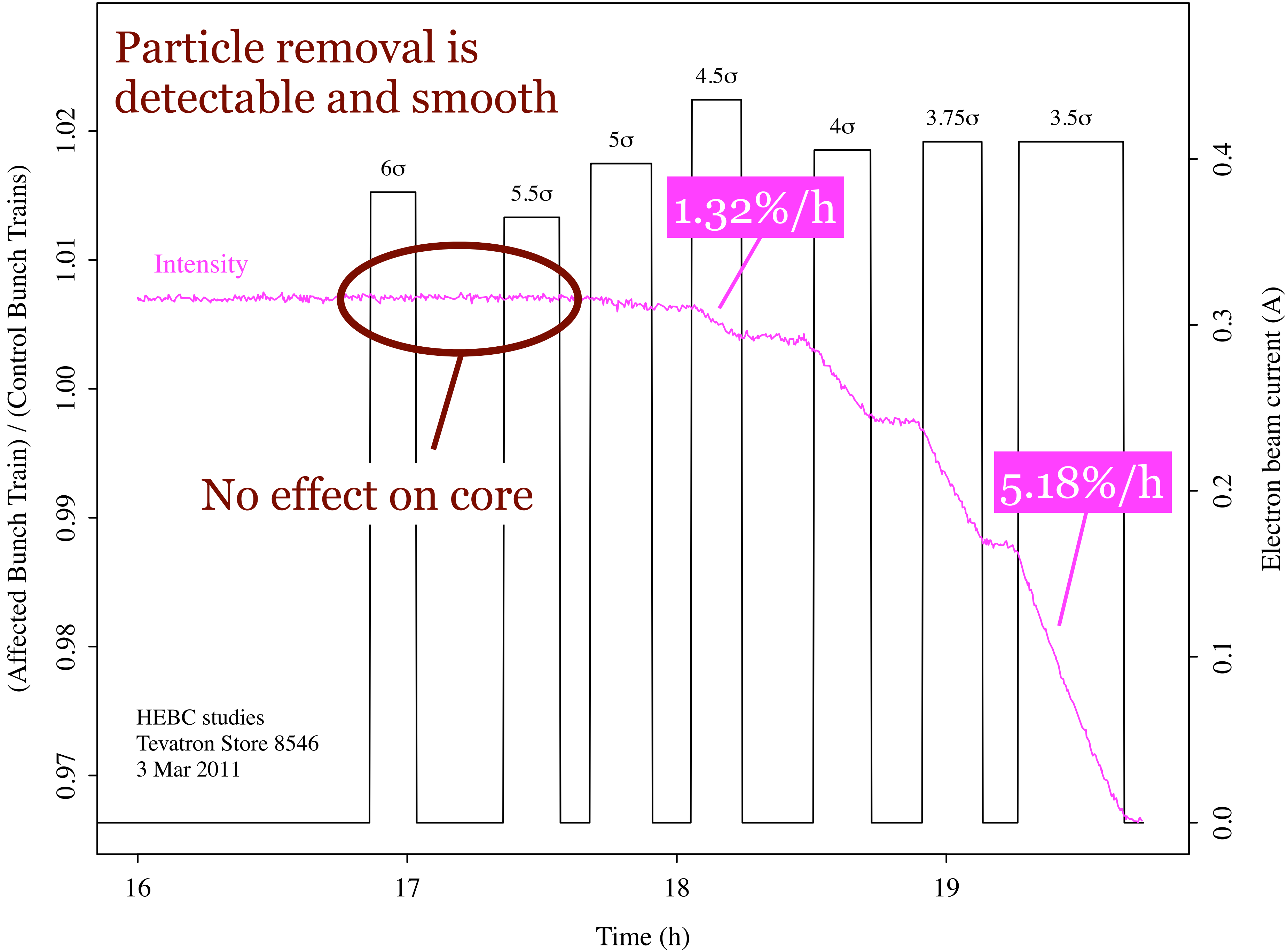
Tevatron beam studies

- Measured **main observables** vs. beam current, relative alignment, hole size, pulsing pattern, collimator configuration:
    - overall particle **removal rate**
    - **effects on the core** and on unaffected bunches
    - **removal rate vs. particle amplitude**
    - enhancement of transverse beam **diffusion**
    - **collimation efficiency**
    - **fluctuations** in loss rates
- A few examples shown below

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?

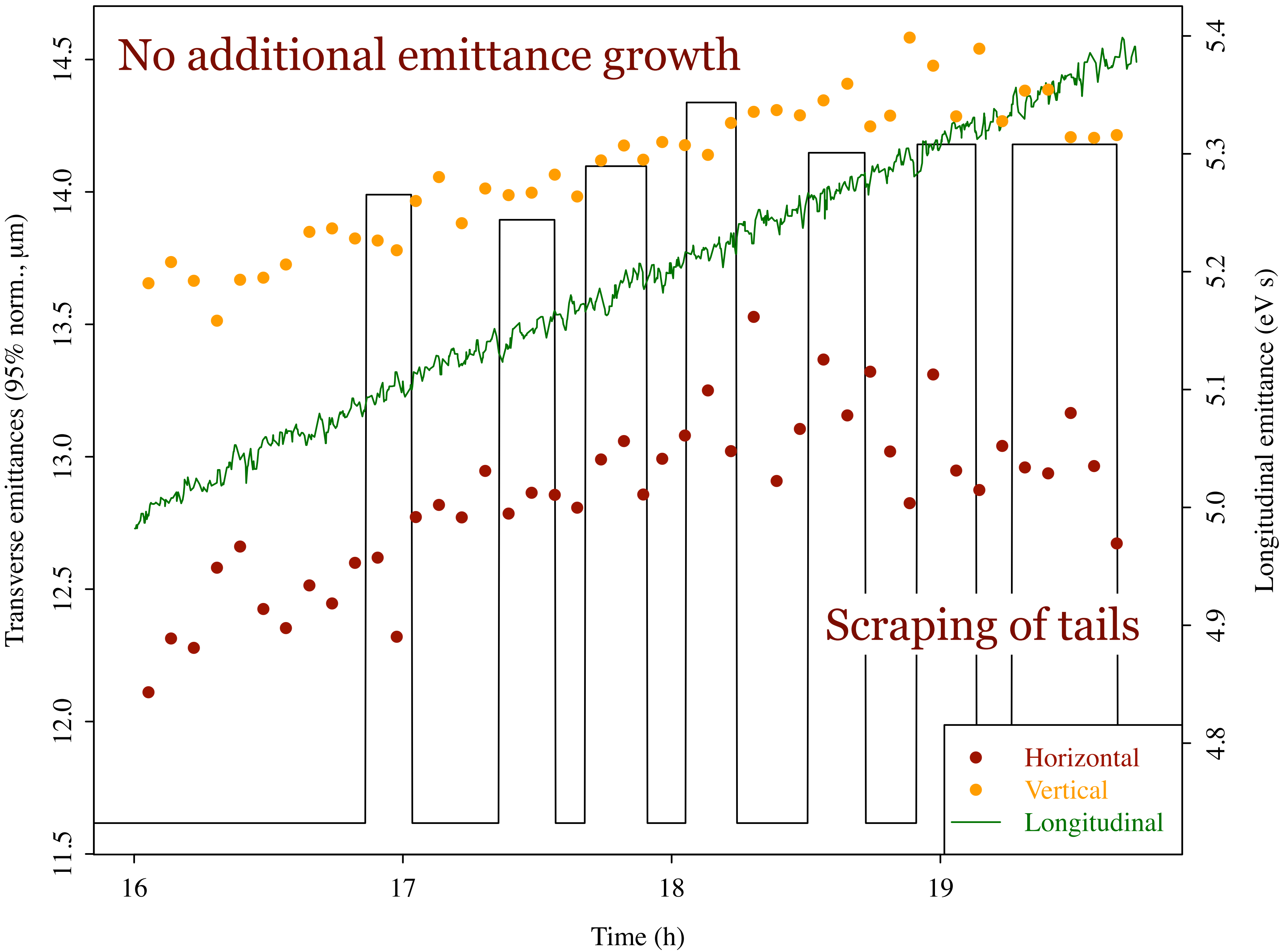
Several strategies:

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

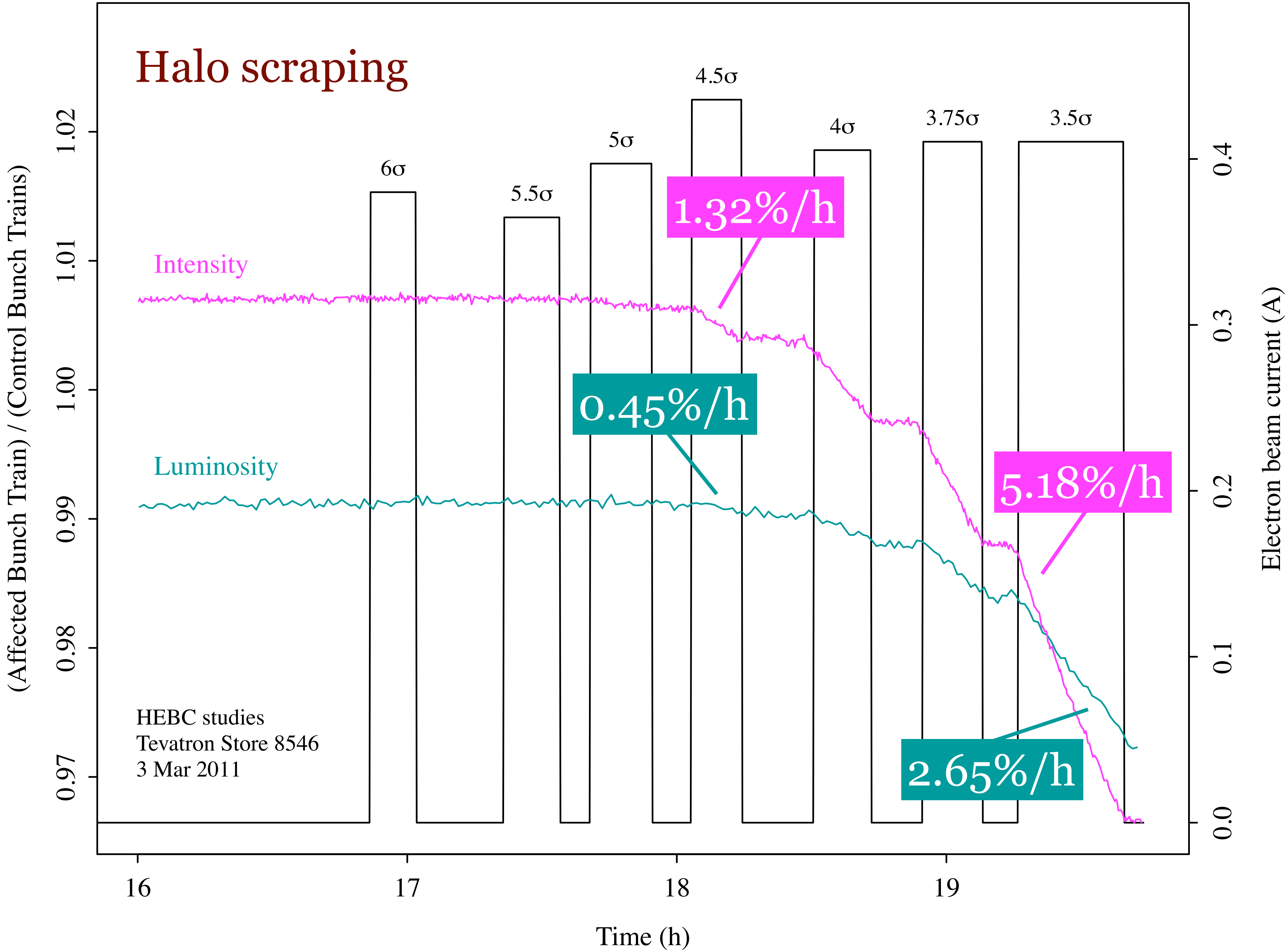
$$\mathcal{L} = \left(\frac{f_{\text{rev}} N_b}{4\pi} \right) \frac{N_p N_a}{\sigma^2} \qquad \frac{\Delta \mathcal{L}}{\mathcal{L}} = \frac{\Delta N_p}{N_p} + \frac{\Delta N_a}{N_a} - 2 \frac{\Delta \sigma}{\sigma}$$

  - 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)

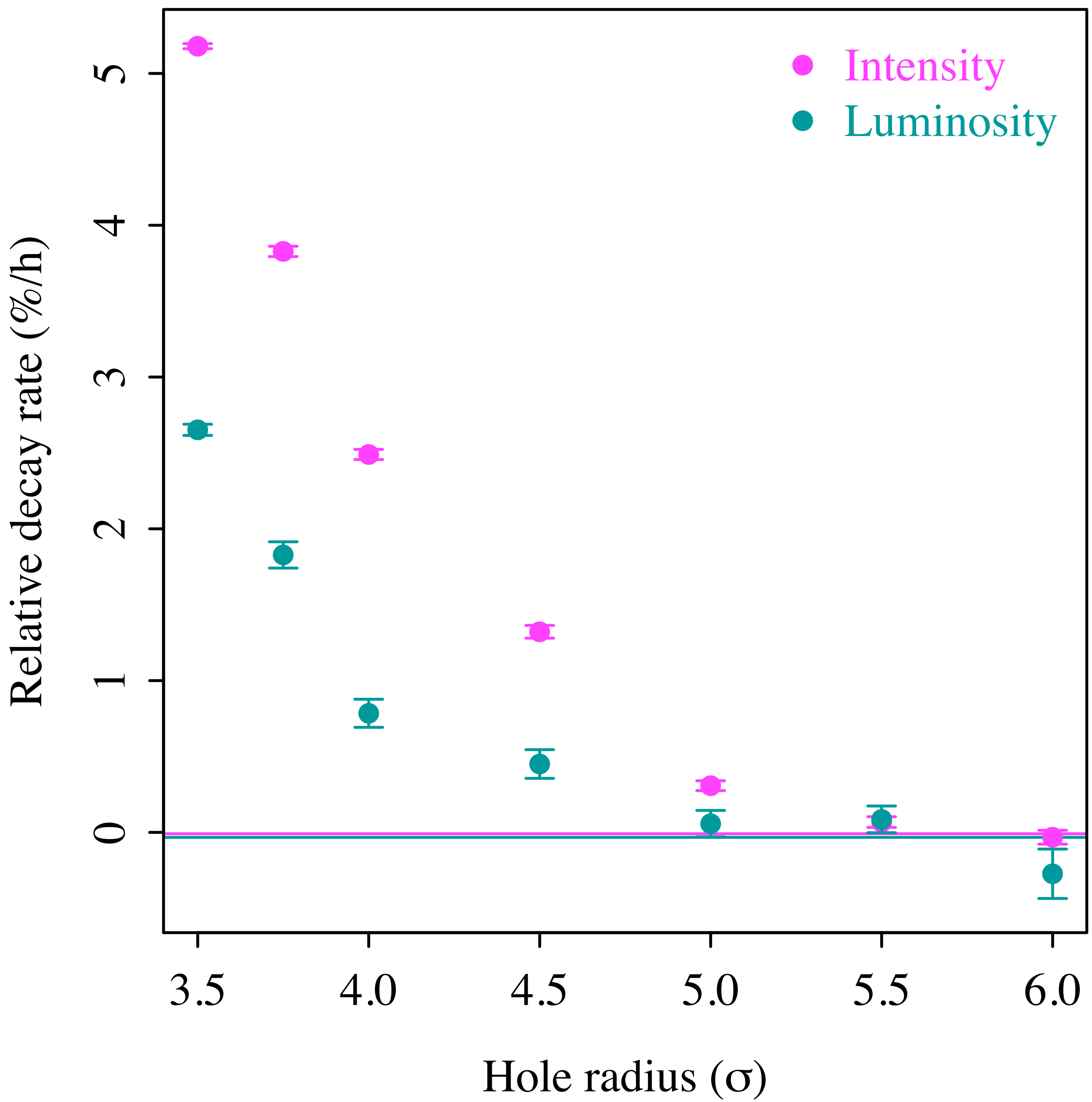
Emittances of affected bunch train



Luminosity of affected bunch train relative to other 2 trains

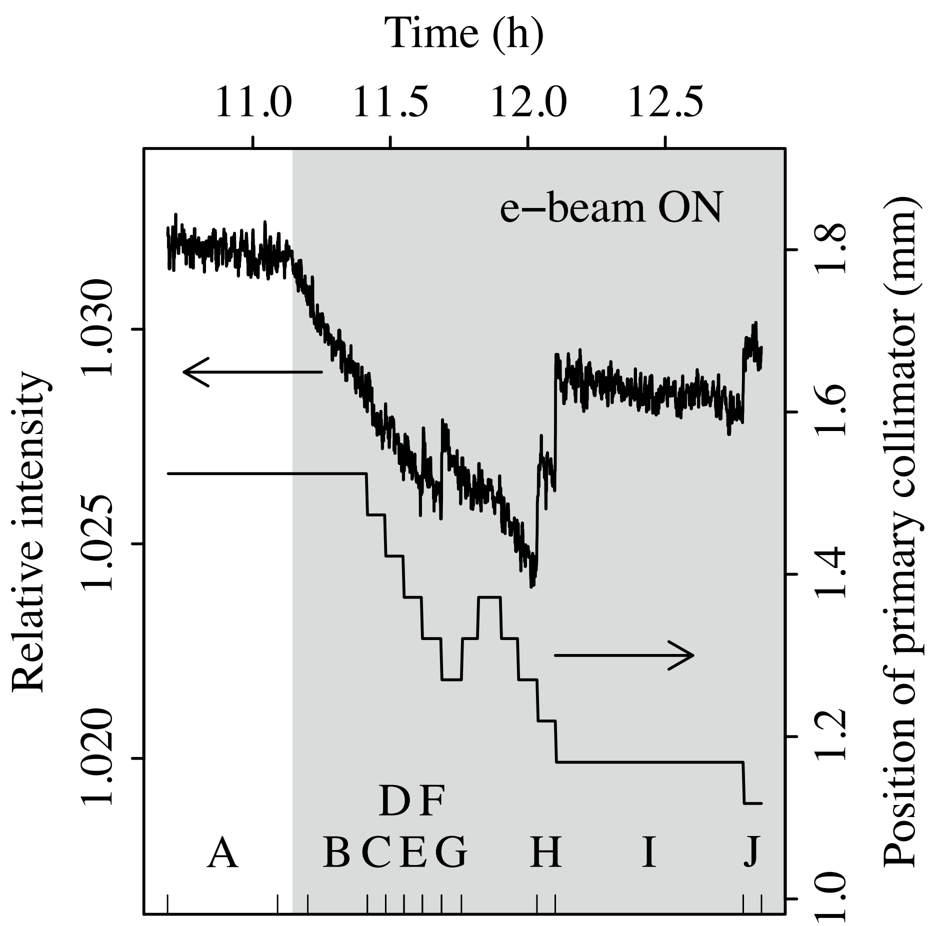


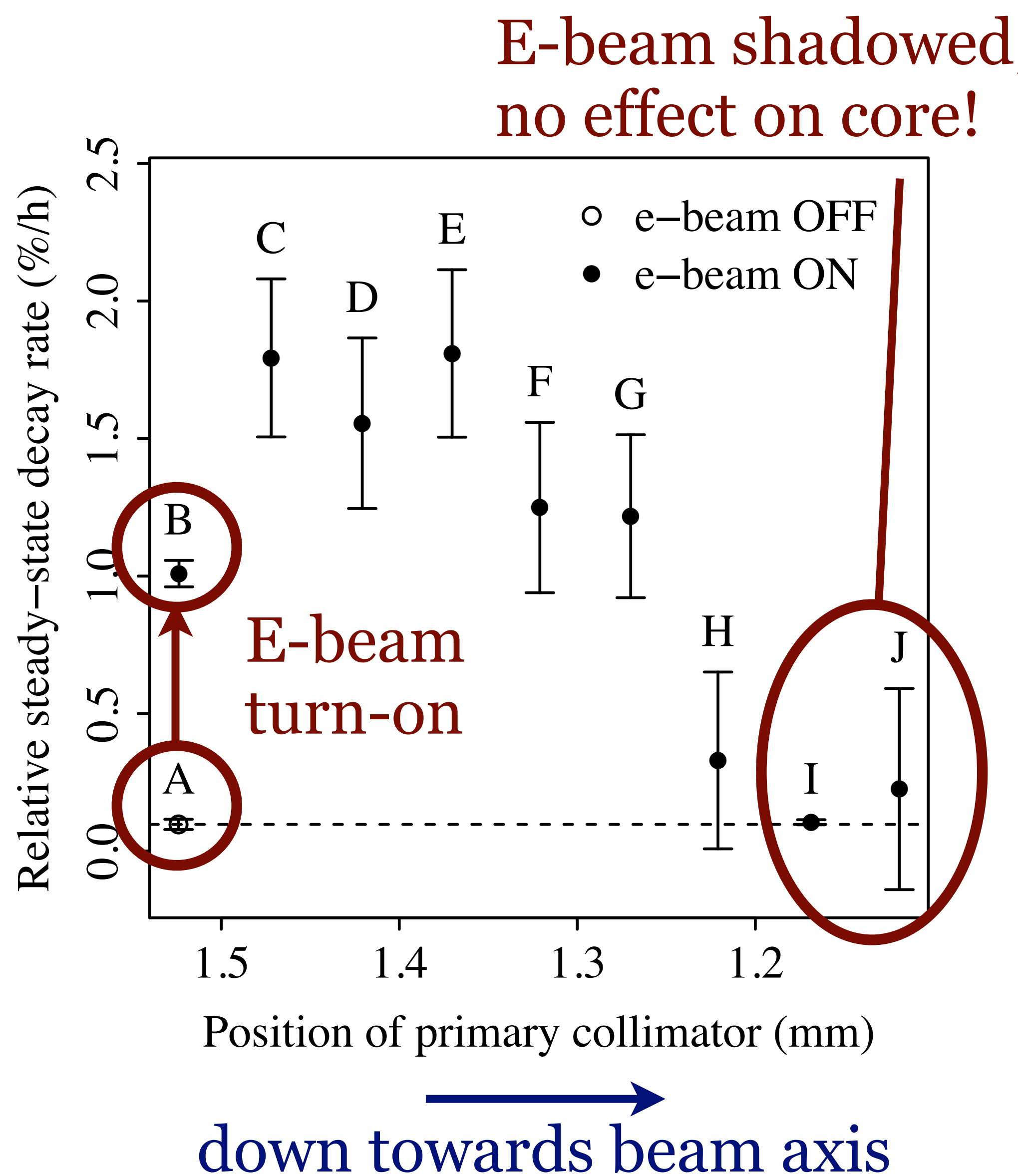
Relative decay rates



Removal rate vs. amplitude from collimator scan

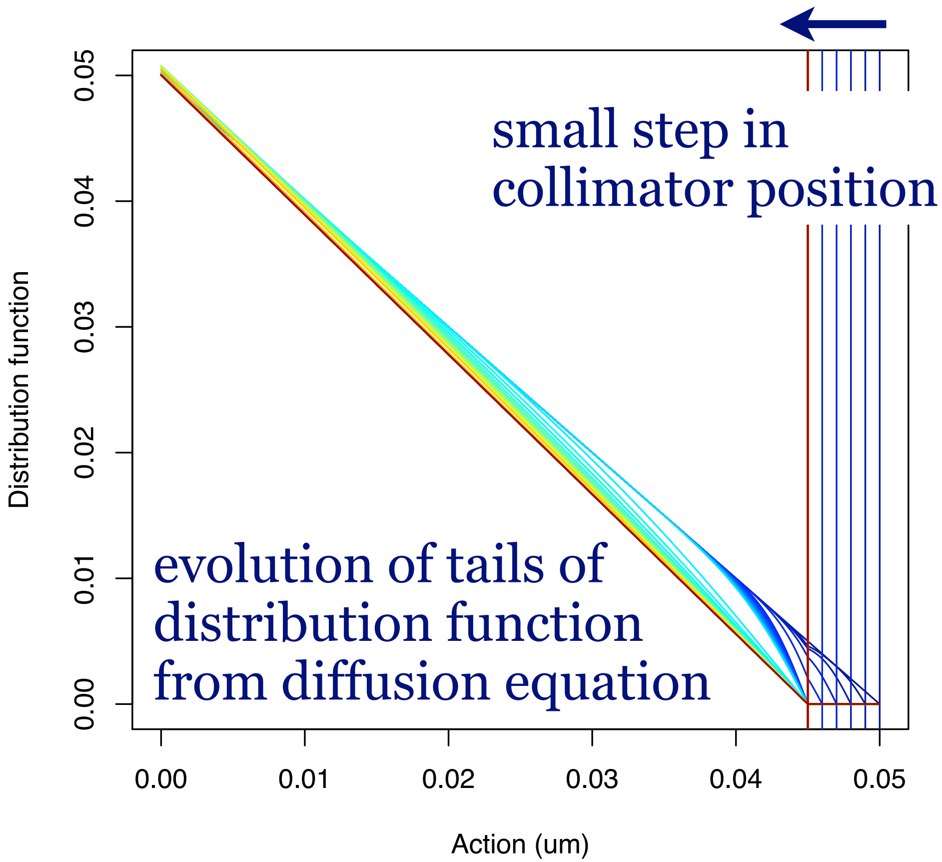
Electrons (0.15 A) on pbar train #2, 3.5σ hole (1.3 mm at collimator)
Vertical scan of primary collimator (others retracted)

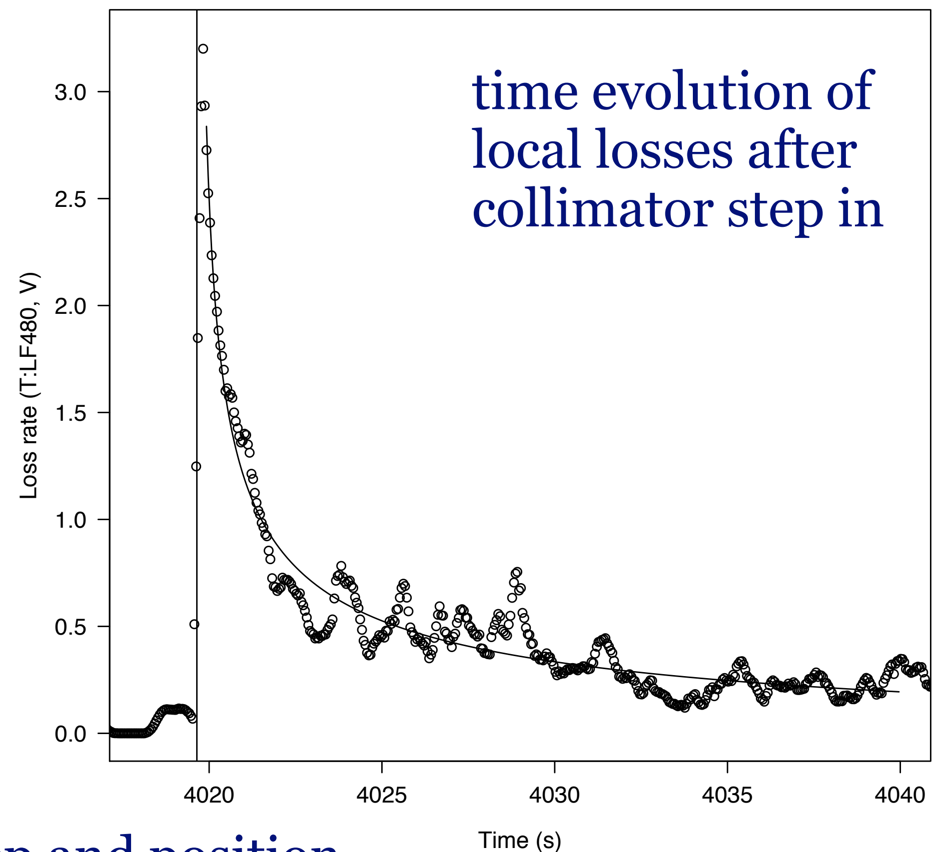




Diffusion rate vs. amplitude from collimator scans

Mess and Seidel, NIM A **351**, 279 (1994)





collimator step and position

observed loss rate

background

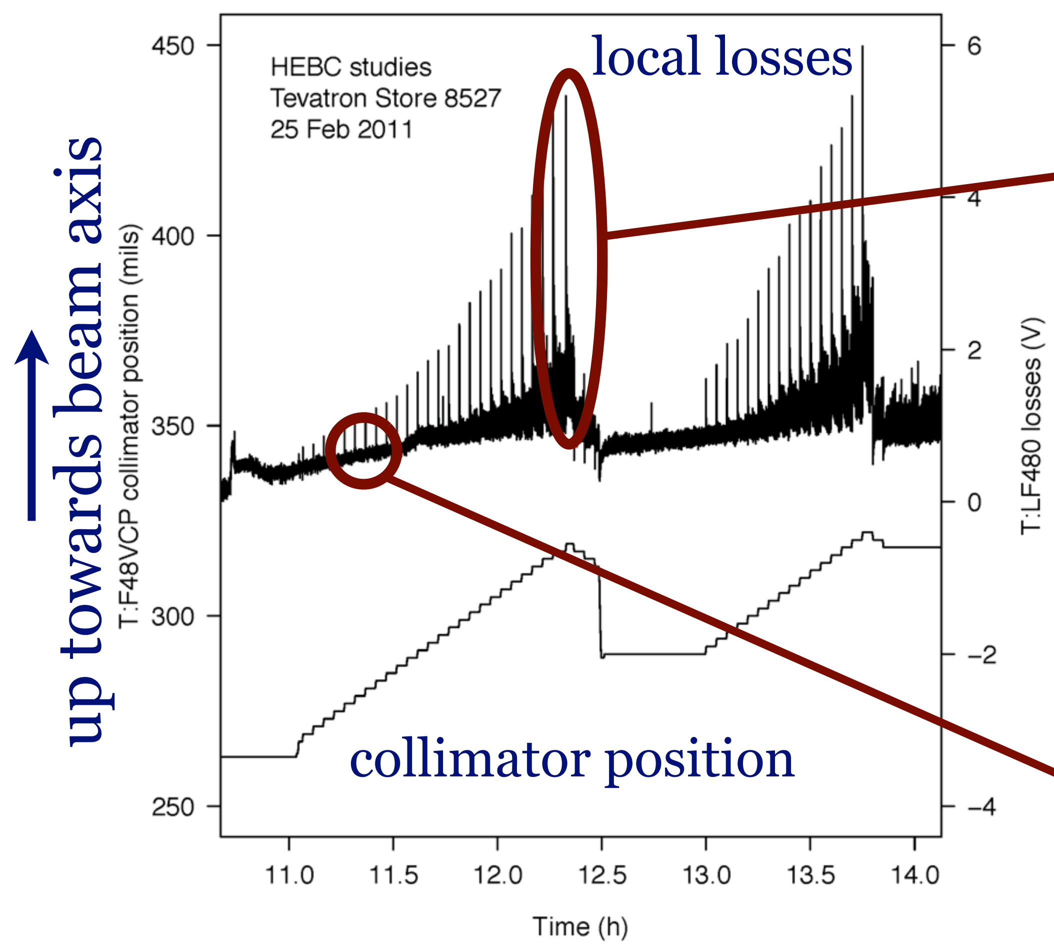
$$L(t) = a_1 \left\{ 1 + \frac{|\Delta x_c| / x_c}{\sqrt{\pi R (t - t_0)}} \right\} + a_0$$

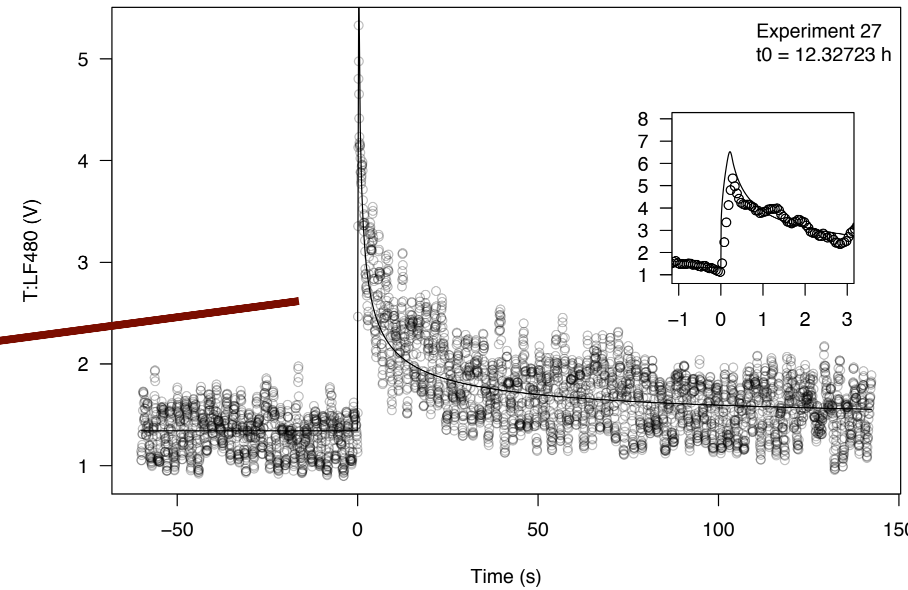
normalization (intensity, efficiency, ...)

parameter related to diffusion rate

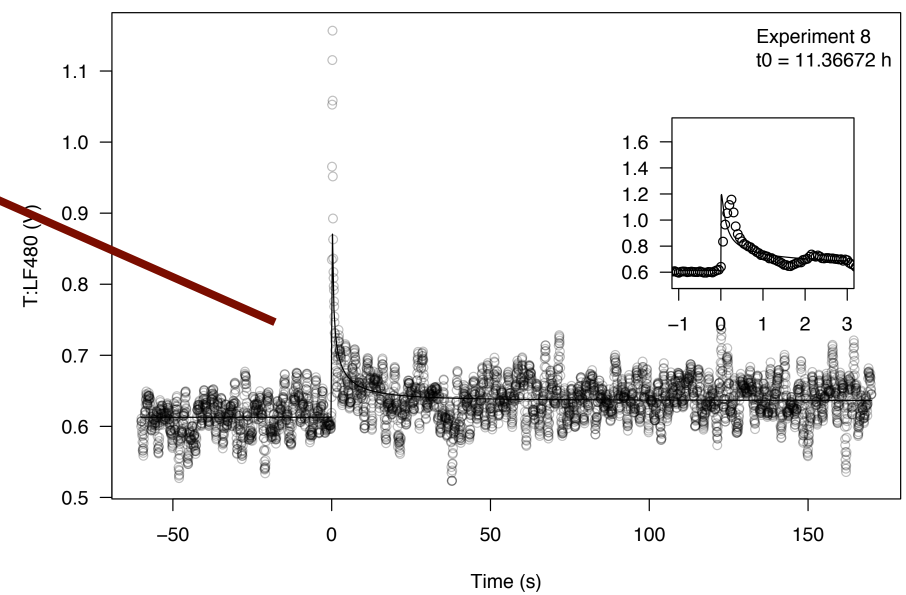
$$D = R \cdot x_c^4 / \beta_c^2$$

Vertical secondary collimator scan



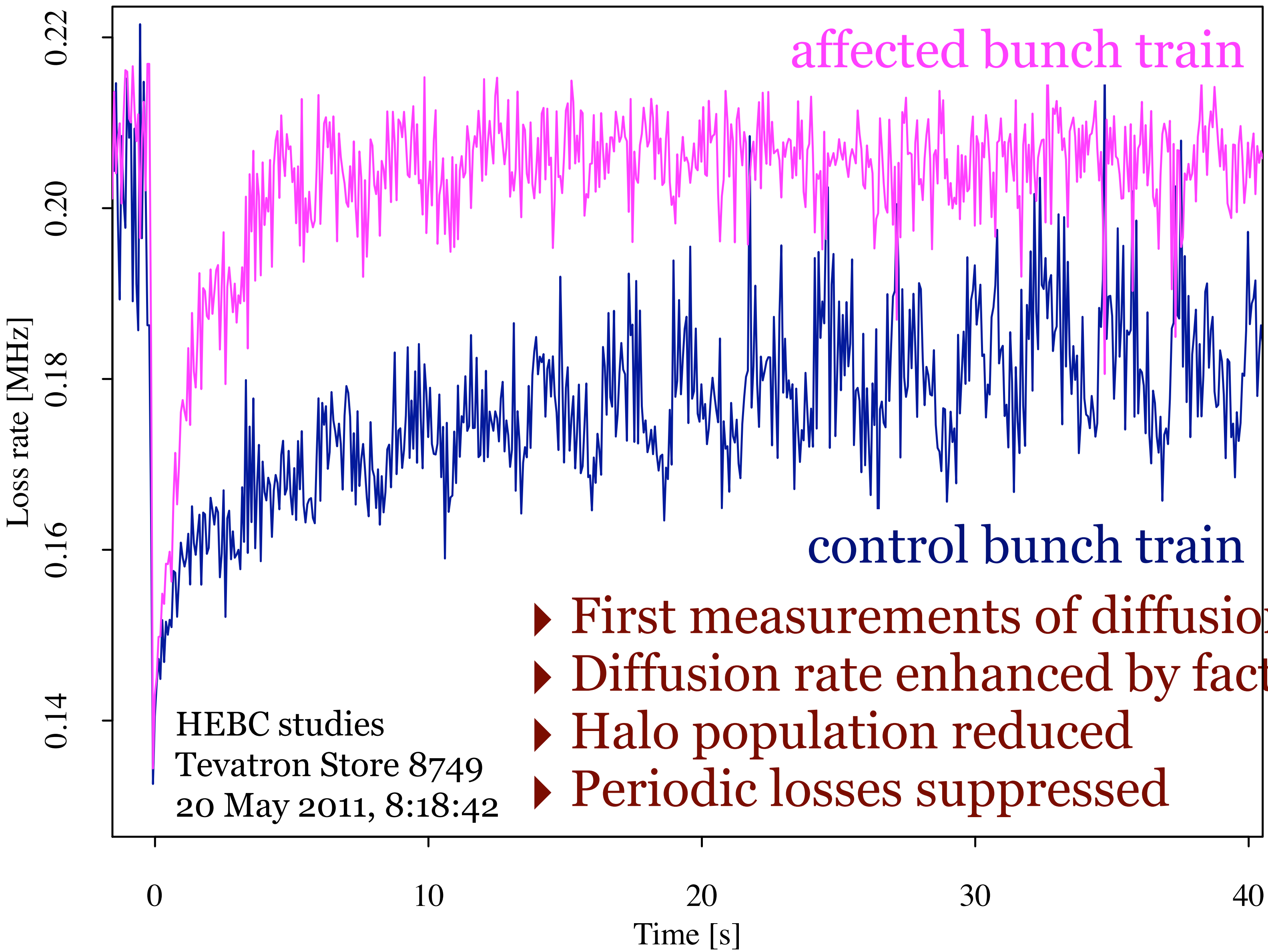


Tails repopulate faster at large amplitudes (higher diffusion rate)



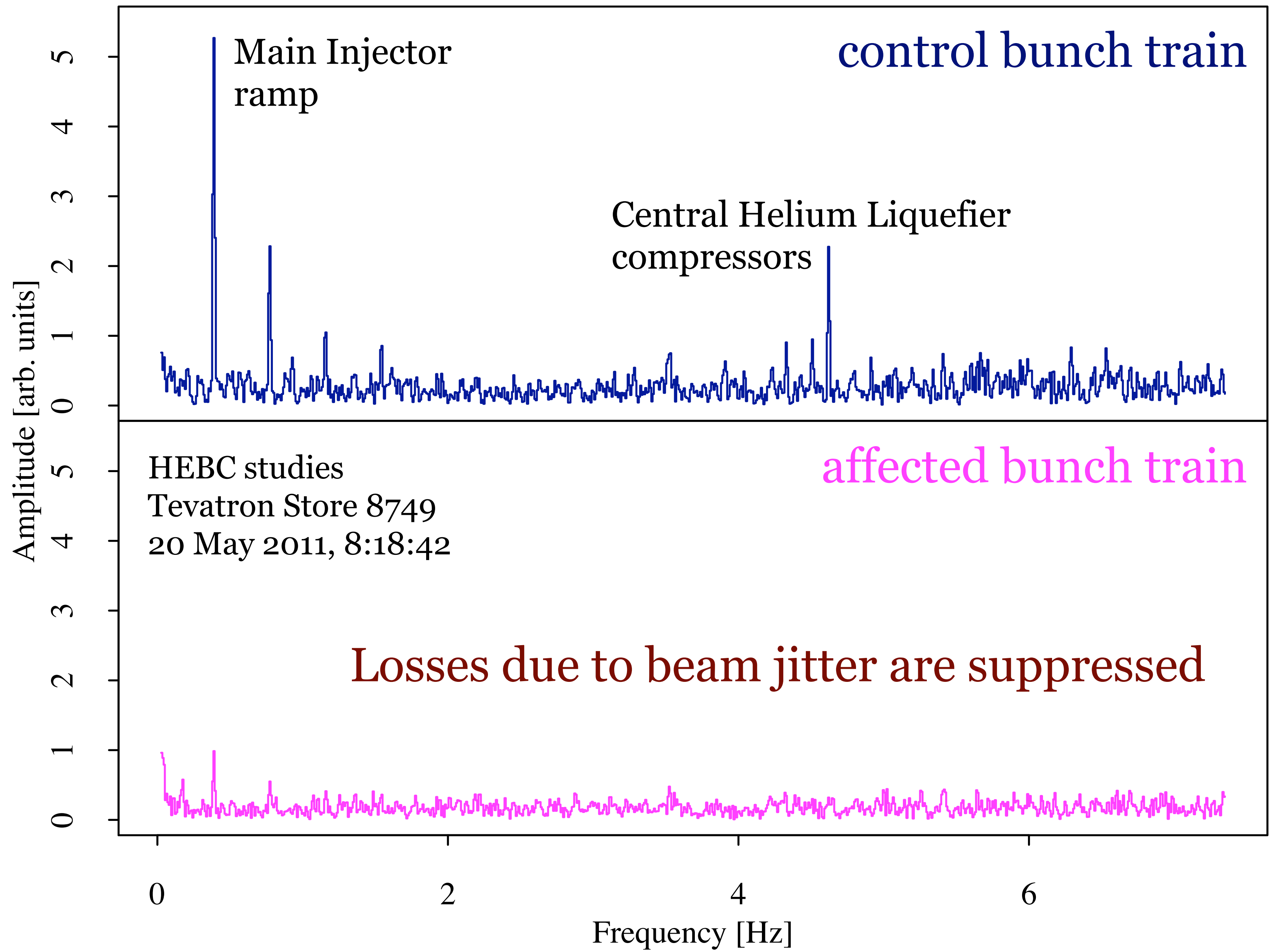
Effect of diffusion on time evolution of losses

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

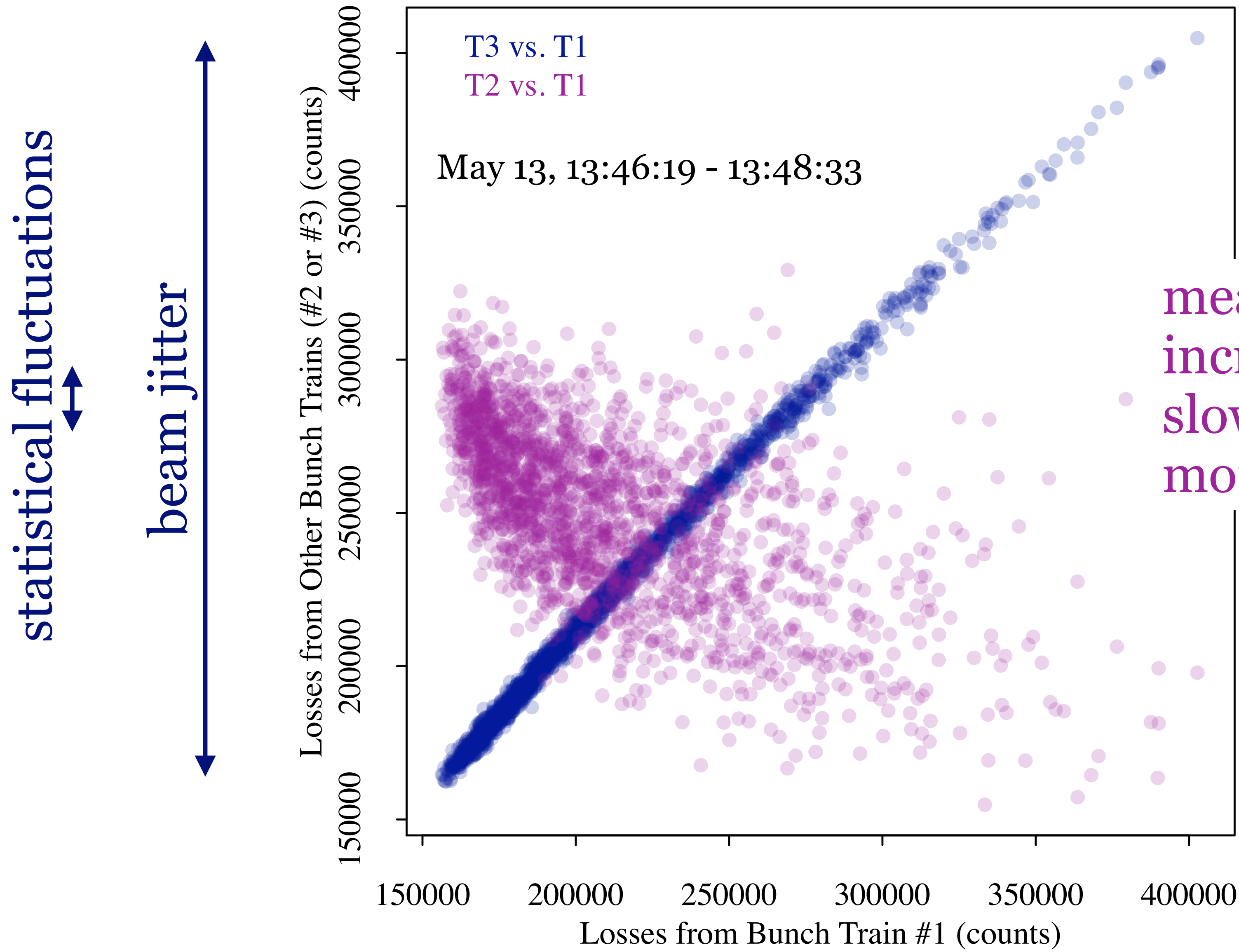


- First measurements of diffusion in Tevatron
- Diffusion rate enhanced by factor ~10
- Halo population reduced
- Periodic losses suppressed

Fourier analysis of losses



Correlation of losses



mean losses increased by 20%, slow spikes (~< Hz) more than halved

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

Summary

- Collimation system is a vital part of machine design
- Great progress in understanding of hollow beam collimation as a complement to conventional collimation systems, thanks to dedication of support staff and collaborators
- Scraping with hollow electron beams appears to be a viable option for storage rings and colliders
- Many new observations: halo removal rates, effects on core, diffusion, fluctuations in losses, collimation efficiencies
- A few more machine studies possible (now - end of August)

Outlook

- Assembly and test of larger (1-in) gun in test stand in September
- Tevatron final shutdown scheduled for September 30: electron-lens hardware will become available
- Transfer experimental program to CERN? Support from U.S. DOE LARP Review and CERN LHC Collimation Review (June 2011).
- Validate Tevatron simulations
- Study applicability to LHC: needed? feasible? Great interest from LHC Collimation Working group: scraping before collisions and collimator setup, efficiency for ions

Thanks for your attention