Electron lenses for the Large Hadron Collider

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Contributors

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High Luminosity LHC

LARP

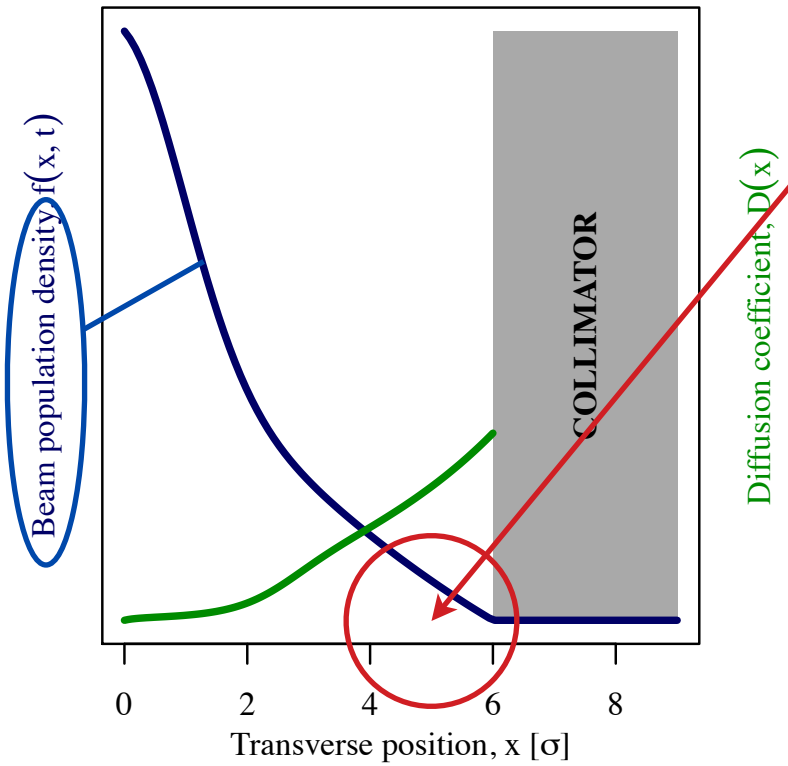
Collimation and beam halo are critical for HL-LHC (1/2)

- LHC and HL-LHC represent **huge leaps in stored beam energy**

	Tevatron	LHC 2012	LHC nominal	HL-LHC
Stored energy per beam	2 MJ	140 MJ	**362 MJ**	**692 MJ**

- The collimation system has performed very well so far (6σ half gaps, 140 MJ @ 4 TeV): efficiency, robustness. Signs of impedance limitations. Minimum design HL-LHC lifetimes (e.g., slow losses during squeeze/adjust) are close to plastic deformation of primary and secondary collimators: (692 MJ) / (0.2 h) = 1 MW

Collimation and beam halo are critical for HL-LHC (2/2)

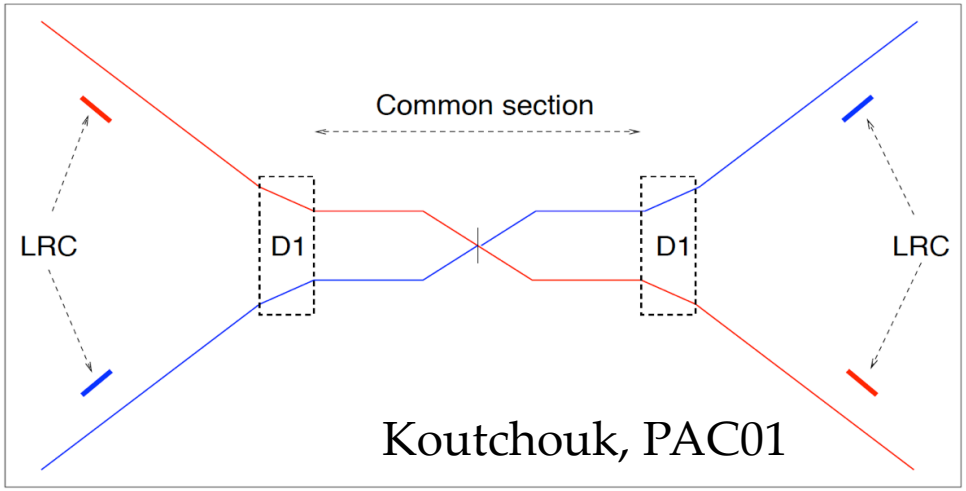


- **Halo populations** (e.g., 4σ to 6σ) in LHC are poorly known. Collimator scans and van-der-Meer scans indicate 0.1-5% of total energy, which translates to 0.7 MJ to 35 MJ at 7 TeV.
- **Quench limits**, **magnet damage**, or even **collimator deformation** will be reached with fast crab-cavity failures (~2σ orbit shift) or other fast losses

- Hence the **need to measure and monitor the halo, and to remove it at controllable rates**. Beam halo monitoring and control are **one of the major risk factors for HL-LHC** and for **safe operation with crab cavities**
- **Hollow electron lenses are the most established and flexible tool for controlling the halo of high-power beams**

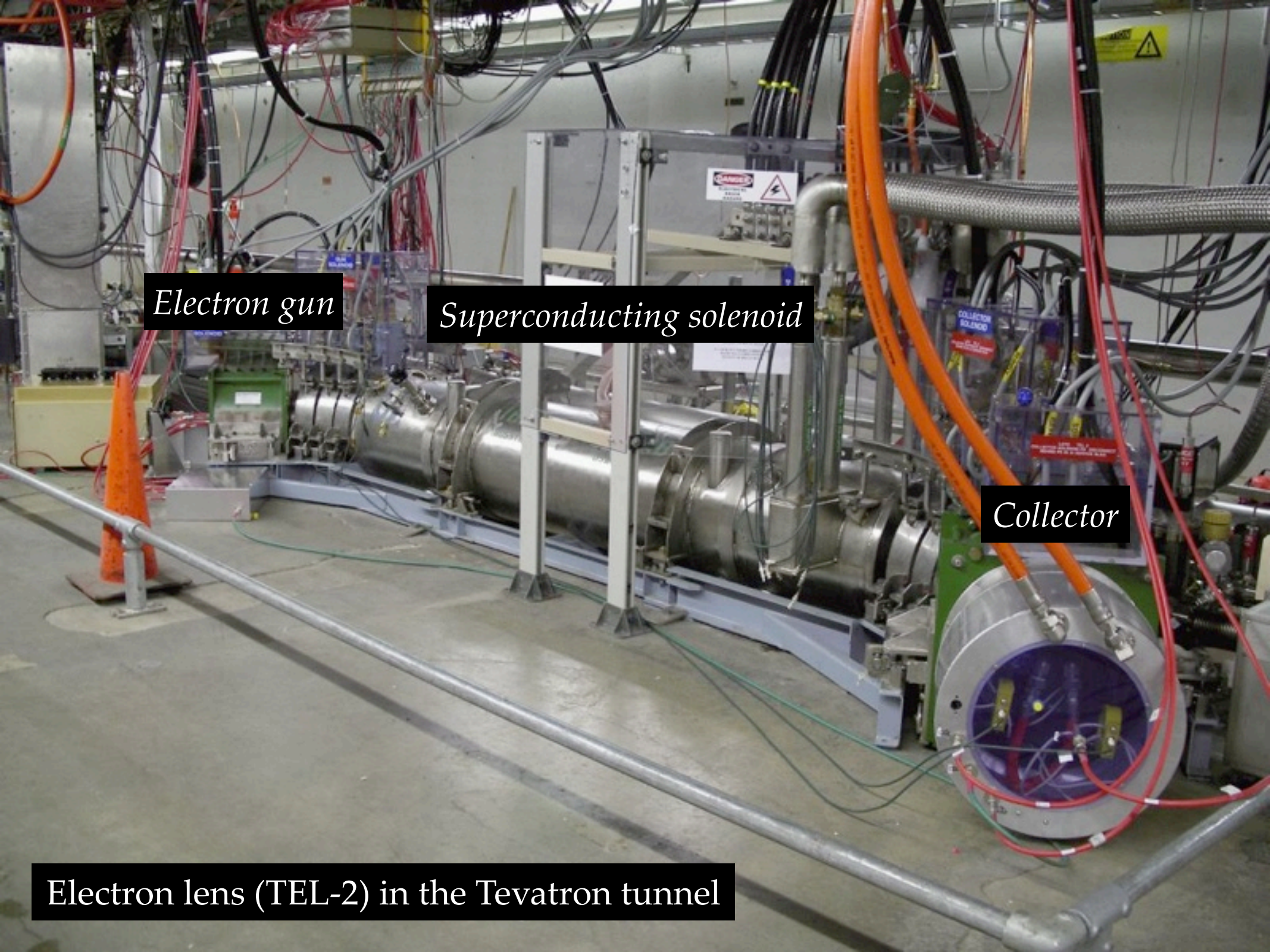
Long-range beam-beam compensation is essential for HL-LHC Plan B

- HL-LHC Plan B:
  - flat optics at collisions: (10, 50) cm β^* $\Rightarrow$ no IP1/5 compensation
  - no crab cavities required (crab crossing/kissing improve performance)
  - **a long-range beam-beam compensation scheme is needed** to achieve luminosity



- Wire compensators at 10σ to be tested after LS1: technically challenging (378 A required) and a risk for collimation and machine protection
- **Electron lenses for long-range beam-beam compensation are a safer, less demanding alternative, with pulsing option**
  - (21 A) × (3 m) required for HL-LHC, any transverse shape

[Valishev and Stancari, arXiv:1312.1660]



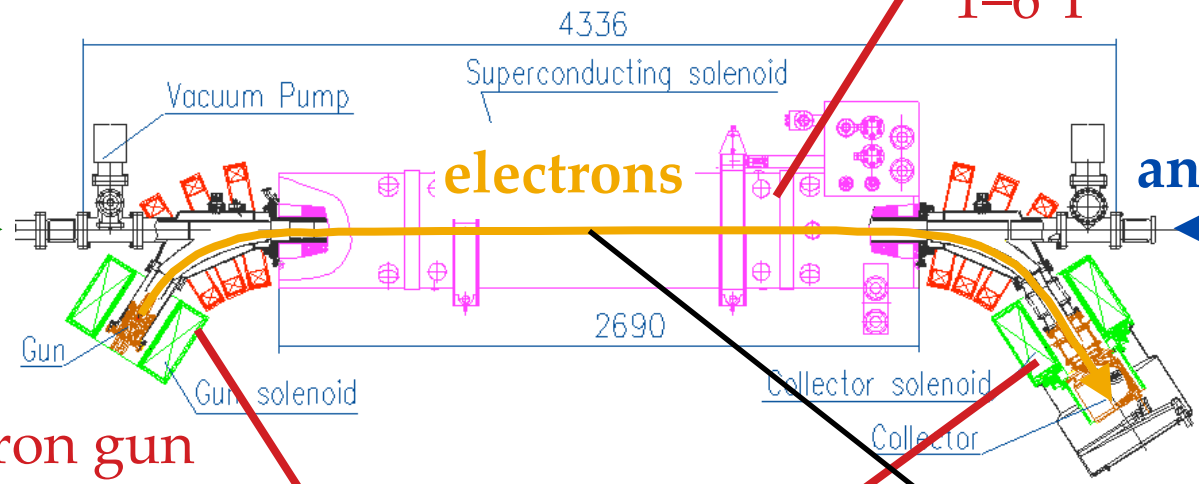
Electron lens (TEL-2) in the Tevatron tunnel

Hollow beam collimation with Tevatron electron lenses

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

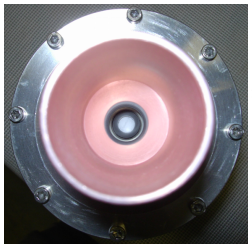
electrons

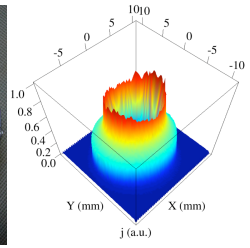
antiprotons

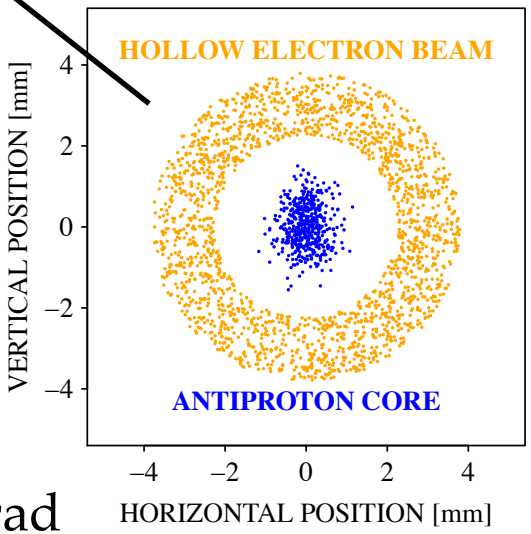
collector

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

Hollow electron lenses for halo scraping

- **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)

Goals of US LARP electron-lens project

General goals exploit the unique expertise developed at Fermilab over a decade of work on electron lenses for the Tevatron collider

- Main focus: to develop hollow electron lenses as unique tool for beam halo scraping and control in the LHC
- Also, investigate other uses of electron lenses to improve LHC performance:
  - long-range beam-beam compensation
  - tune-spread generation to suppress instabilities observed before collisions

Specific technical goals of work on hardware development, numerical simulations, data analysis, and documentation:

- to provide a solid experimental basis
- to develop accurate design tools
- to assess the technical feasibility
- to establish readiness for construction

Strategy and plans defined with CERN

- **Collimation needs** will be reassessed and **decisions** will be taken after gaining operational experience at 6.5 TeV (presumably late 2015)
  - Uncertainties: cleaning efficiency, lifetimes, quench limits, impedances, halo pop.
- Meanwhile, **proceed with design of 2 devices** within HL-LHC and LARP:
  - conceptual design drafted (FERMILAB-TM-2572-APC)
  - technical design in 2014/2015
    - in collaboration with CERN LHC collimation team, BE/BI, and EN/MME
  - ready for construction in 2015-2017
  - installation during 2018 long shutdown or 2023 if limited by resources
- **Build electron lens expertise at CERN**: simulations, test stand
- **Investigate alternative halo scraping schemes** with simulations and experiments
  - tune modulation, damper excitation, beam-beam wire compensators
- **Collaborate on** nondestructive, direct **halo diagnostics**
- If possible, **extend Tevatron experience with beam tests at RHIC** to explore specific LHC scenarios: operation during ramp, pulsing patterns, ...

Recent progress

- **Built and characterized 1-in hollow electron gun prototype (5 A @ 10 keV) for the LHC**
  - S. Li and G. Stancari, FERMILAB-TM-2542-APC (August 2012)
  - V. Moens, FERMILAB-MASTERS-2013-02, CERN-THESIS-2013-126 (September 2013)
- **Implemented electron-lens layouts in Warp 3D particle-in-cell code, as a new comprehensive tool for electron lens design**
  - V. Moens, FERMILAB-MASTERS-2013-02, CERN-THESIS-2013-126 (September 2013)
- **Calculated halo removal rates and effects on core in various operating scenarios by numerical tracking**
  - V. Previtali et al., FERMILAB-TM-2560-APC (July 2013) [SixTrack]
  - A. Valishev [Lifetrac]
- **Drafted conceptual design report of LHC hollow electron lenses**
  - Stancari, Valishev, Redaelli et al., FERMILAB-TM-2572-APC (February 2014)
- **Developed concept of electron lenses as long-range beam-beam compensators for HL-LHC**
  - Valishev and Stancari, arXiv:1312.1660 (December 2013)

Researcher training and transfer of knowledge

- *S. Li* (U. Chicago) undergraduate Lee Teng internship (summer 2012)
- *J. S. Kim*, *Y. H. Cho*, *B. S. Yang* (students of Prof. Hae June Lee, Pusan National University, Korea) visited Fermilab in 2013
- Positive experience with joint EPFL-CERN-Fermilab Master student
  - *V. Moens* graduated September 2013
  - plan to accept new Master/PhD student in 2014
- *V. Previtali*'s Toohig fellowship completed July 2013
- *R. Rossi* just started as CERN technical student on beam halo dynamics
- Synergies with electron-cooler test stand being built for low-energy ELENA antiproton ring (G. Tranquille, R. Jones, BE/BI, CERN)
- Post-doc / CERN fellow / Toohig fellow needed as point of contact at CERN: numerical studies, electron-lens test stand hardware, diagnostics

Proposed goals for the rest of Fiscal Year 2014

- Complete **numerical studies of electron-lens imperfections** and their impact on proton core
- Organize **visit of collimation team, BE/BI and EN/MME representatives to Fermilab** for electron lenses and test stand
- Demonstrate use of **Warp code as design tool** for electron lenses in various configurations
- Complete and publish study of **effect of measured halo diffusion** in LHC **on impact parameters**
- **Present project status and results** at IPAC14
- Set up new **joint** EPFL/CERN/Fermilab Master/PhD **thesis project**
- Analyze and **publish more Tevatron measurements** on hollow electron beam collimation
- Visit CERN to draft **technical design** report and develop **electron-lens test stand**

Proposed involvement of US LARP (till decision on construction)

Plan is based on LARP / HL-LHC common strategy and unique Fermilab competences:

- **Contribute to technical design report**
  - electron-lens design, numerical tracking simulations
- **Participate in LHC beam studies** on halo dynamics and alternative halo-scraping schemes
  - Example: G. Valentino et al., PRSTAB **16**, 021003 (2013) on first halo diffusion measurements in LHC; proposed experiment, analyzed data
- **Contribute to CERN electron-lens test stand** design and implementation
- **Maintain working Fermilab electron-lens test stand**, the *only* operational lab of this kind in the world
- If it is decided to proceed with construction of 2 devices (~10 M$/each, US accounting), roles of Fermilab / BNL / CERN are to be negotiated

Requested LARP resources (till decision on construction)

Continued support at this year's level would be appropriate for the proposed involvement:

- 1 FTE/year (partial support of 2 Fermilab scientists)
- 15 k$/year for travel to CERN (about 4 x 1 week) for technical design report, test stand work, and beam studies
- Occasional support for joint Master/PhD student at Fermilab and electron-lens test stand hardware

Summary and conclusions

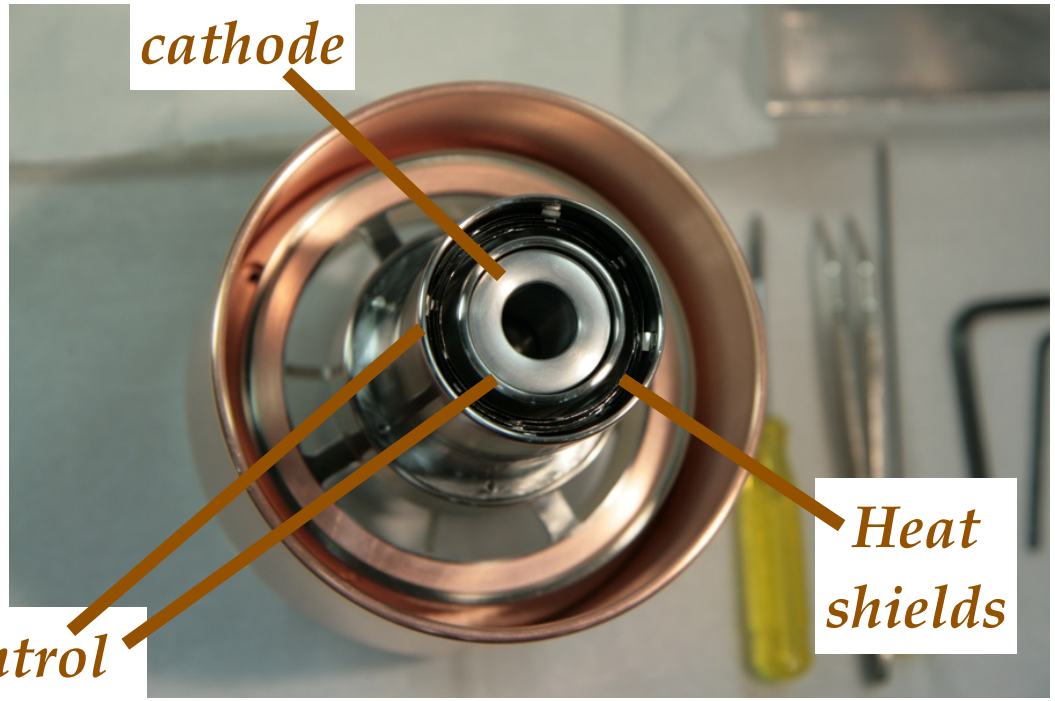
- Unique Fermilab expertise on electron lenses was used to develop
  - tunable **beam halo scraping** for high-power hadron beams and
  - a concept for **long-range beam-beam compensation**

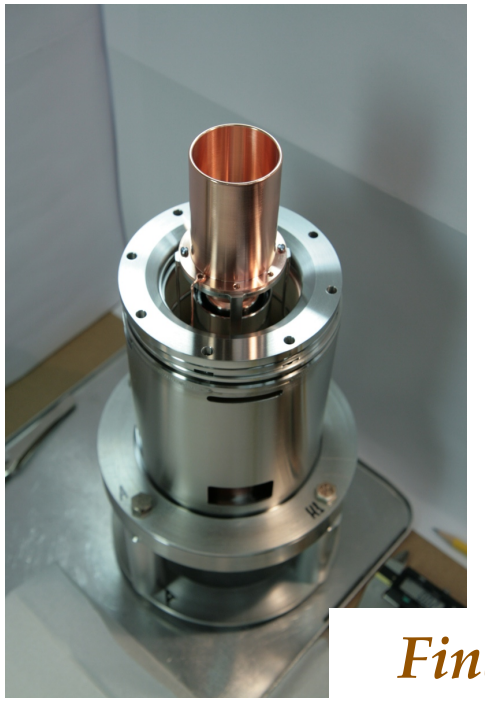
  to **improve the performance of the LHC** and to **address some of the main risk factors for HL-LHC**
- An **implementation strategy** for hollow electron lenses was developed by LARP and the LHC collimation team to prepare for HL-LHC challenges
  - conceptual design now
  - technical design in 2014-2015
  - transfer electron-lens expertise to CERN (hardware and modeling)
  - investigate alternative schemes (simulations and beam studies)
  - propose further experiments at RHIC in 2015
  - reassess collimation requirements and needs at 6.5 TeV (2015)
    - if needed, build 2 devices (in 3 years) to install in 2018 or 2023 with LARP and CERN contributions to be determined
- Small fraction of LARP budget, with **high potential impact**

Thank you for your attention!

Backup slides

25-mm hollow electron gun, LHC prototype





- 25 mm outer diameter, 13.5 inner diameter
- Built and characterized at Fermilab electron-lens test stand
- Yields up to 5 A at 10 kV

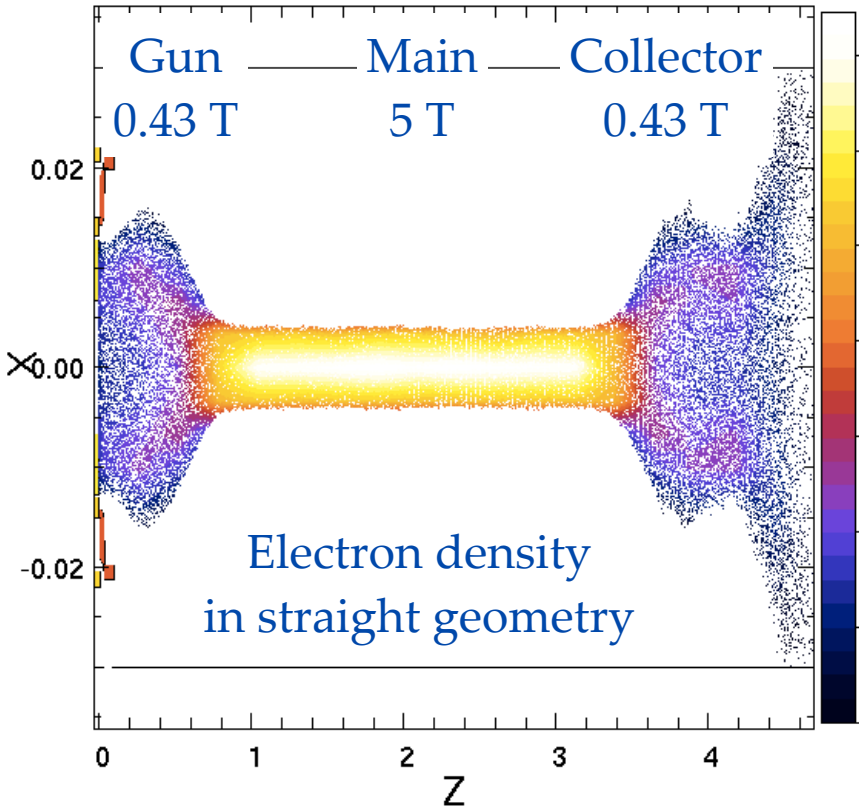
Main goals of numerical simulations

- **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**
  - Warp particle-in-cell code
  - 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

Dynamics of the magnetically confined electron beam

3D simulation of electron beam propagation in electron lens with Warp particle-in-cell code [V. Moens]:

- Injection: space-charge limited e-gun or arbitrary particle coordinates
- Layout: straight (test stand) or with bends (TEL-2 and LHC e-lens)
- Computing resources
  - up to 1 m propagation calculable on multi-core laptop
  - working parallel version installed on Fermilab cluster

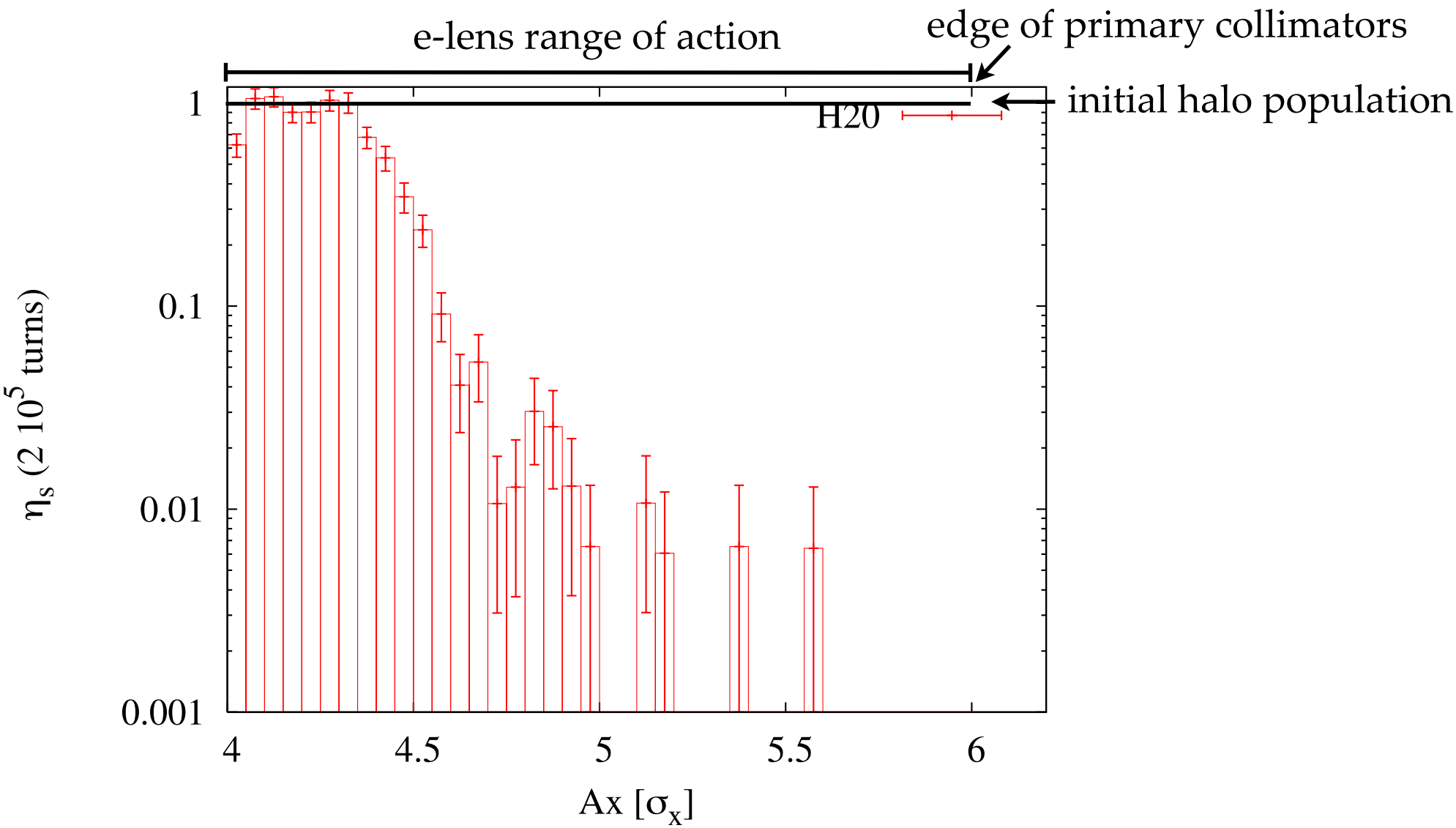


Results of numerical tracking simulations

- 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, even with asymmetries/bends
    - in resonant mode in ideal case
    - effect of imperfections in resonant mode under study

Example of simulated halo scraping (SixTrack, LHC lattice)

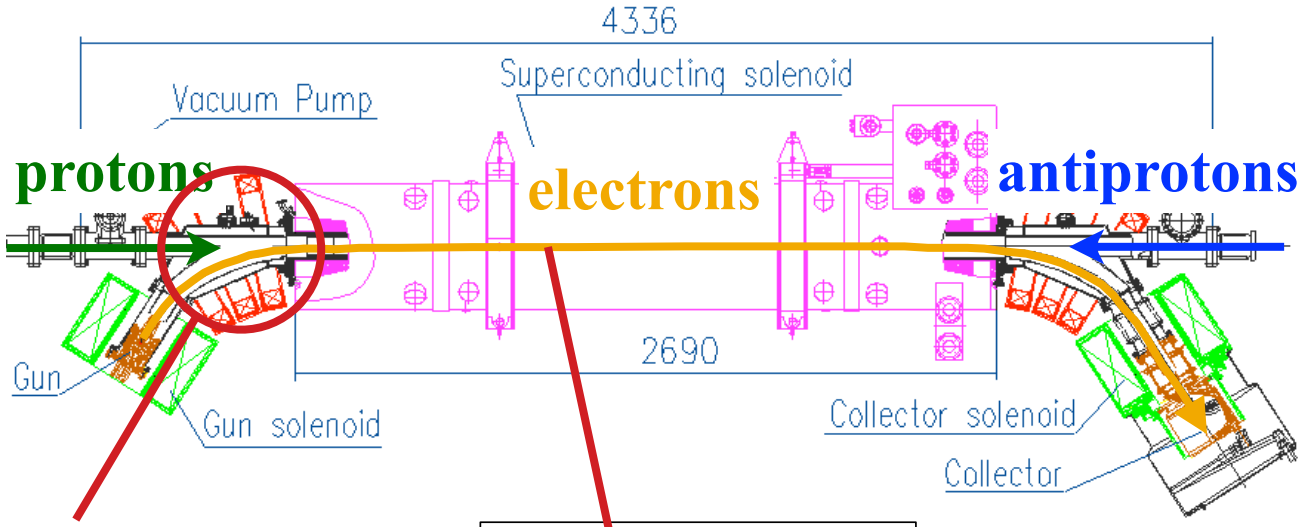
Residual halo population vs. betatron amplitude after 18 s of resonant scraping



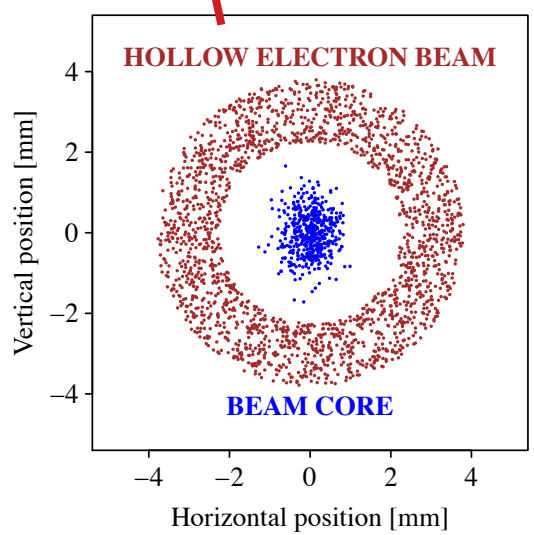
Previtali et al., FERMILAB-TM-2560-APC (2013)

Effect of asymmetries in electron distribution on circulating beam

No adverse effects were observed at the Tevatron in continuous operation, but application to the LHC may require higher beam currents and different pulsing patterns. We studied two sources of asymmetry:



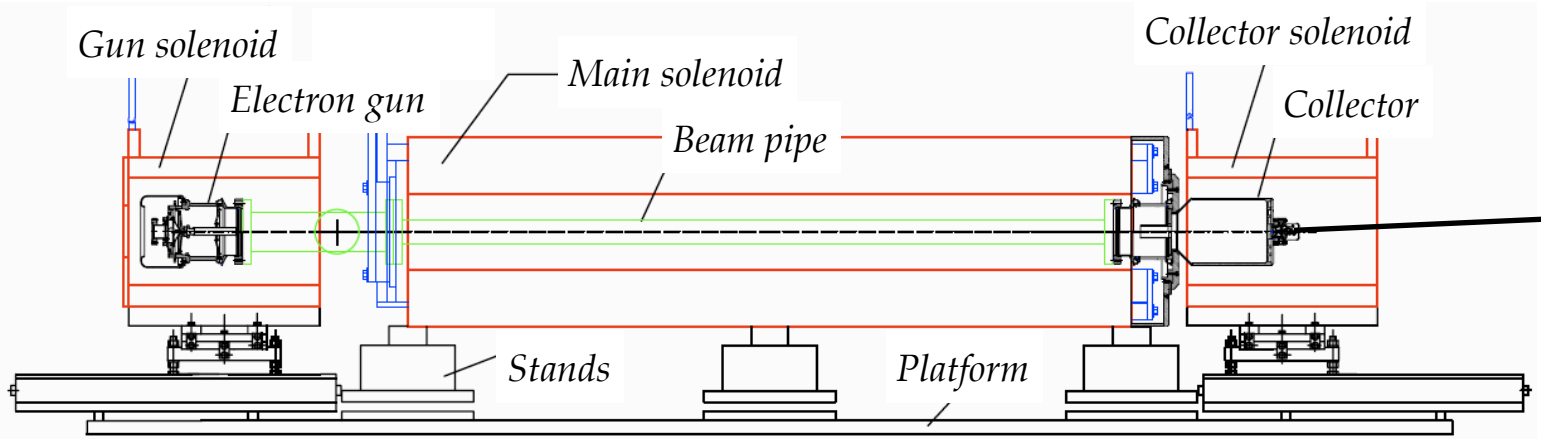
1. bends for injection/extraction



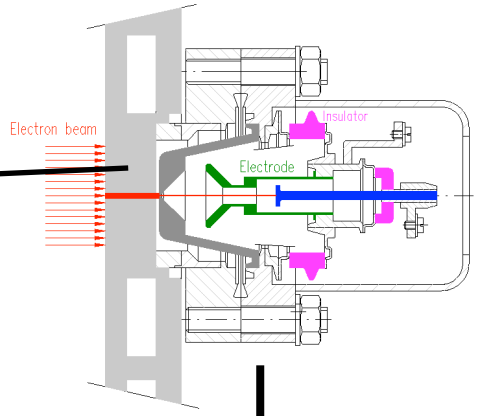
2. azimuthal asymmetries in overlap region

Azimuthal asymmetries in overlap region from measured profiles

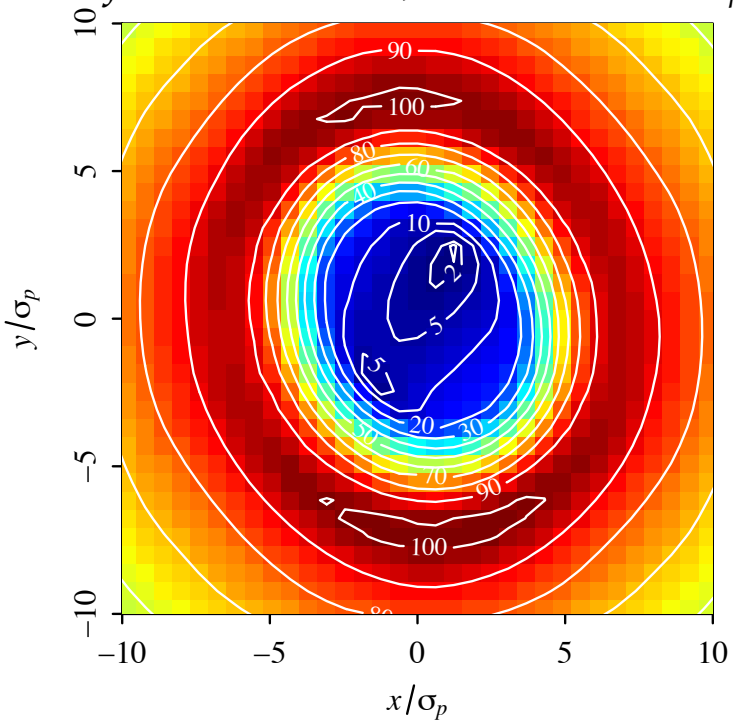
Fermilab electron-lens test stand



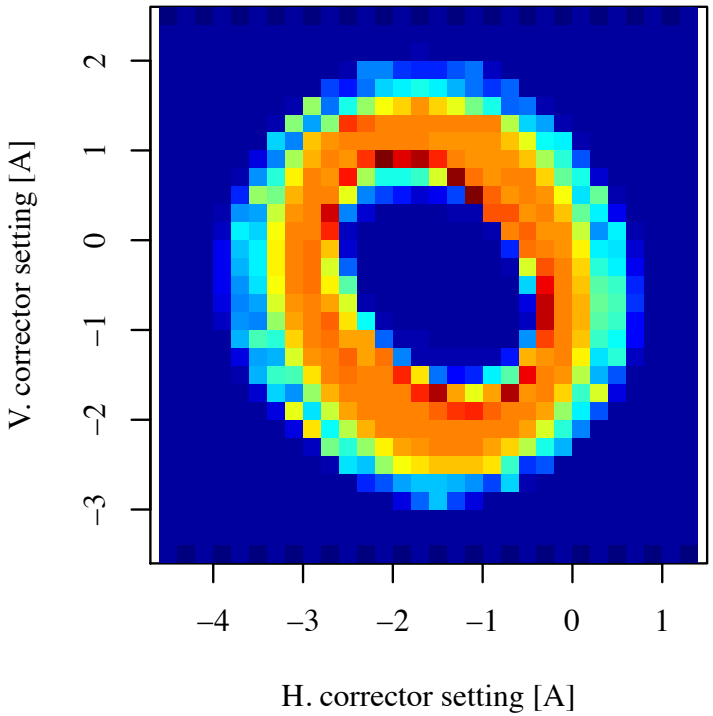
Pinhole for current-density measurements



Calculated electric field [kV/m] for 1-A current, inner radius $4\sigma_p$



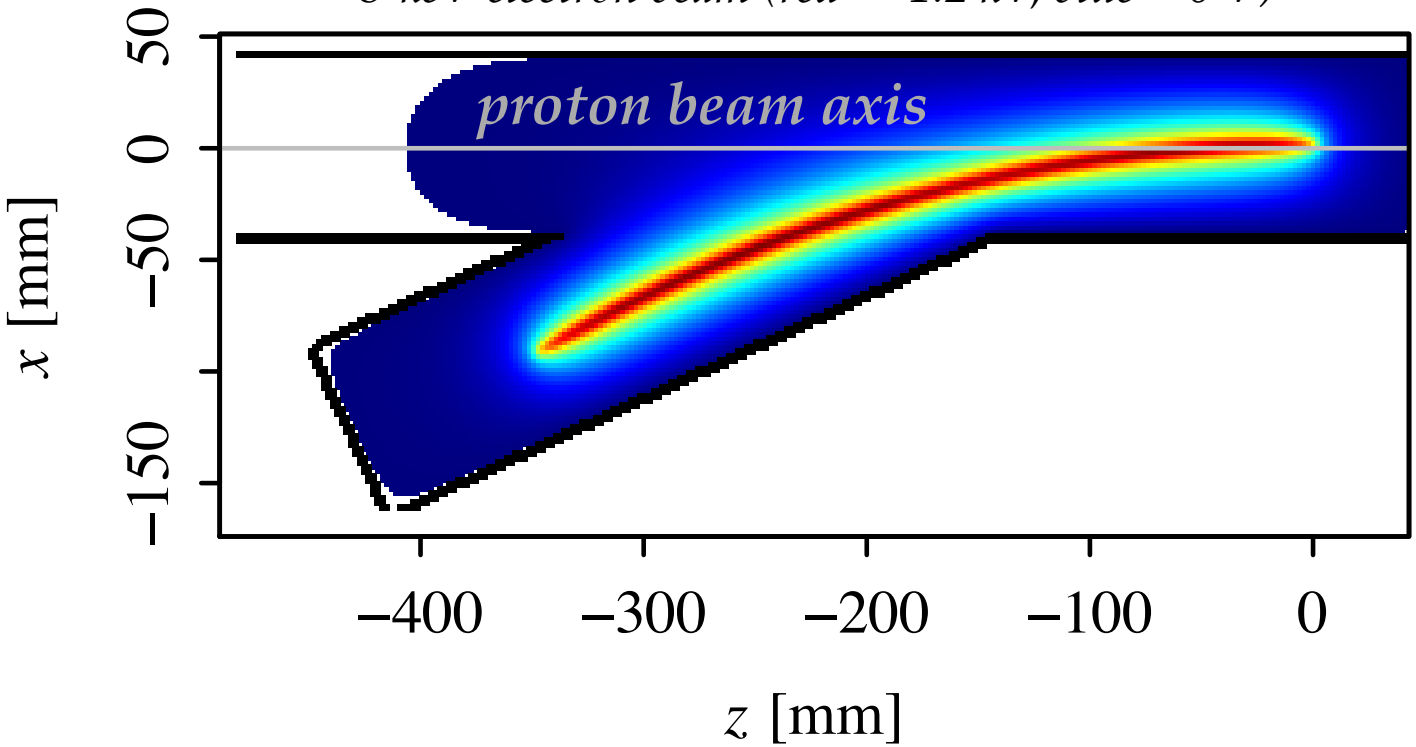
Example of measured profile



Kick maps from injection and extraction bends: simplified approach

3D calculation of electric fields generated by a static, hollow charge distribution inside cylindrical beam pipes using Warp particle-in-cell code

Electrostatic potential on the plane of the bend for 1 A, 5-keV electron beam (red = -1.2 kV, blue = 0 V)



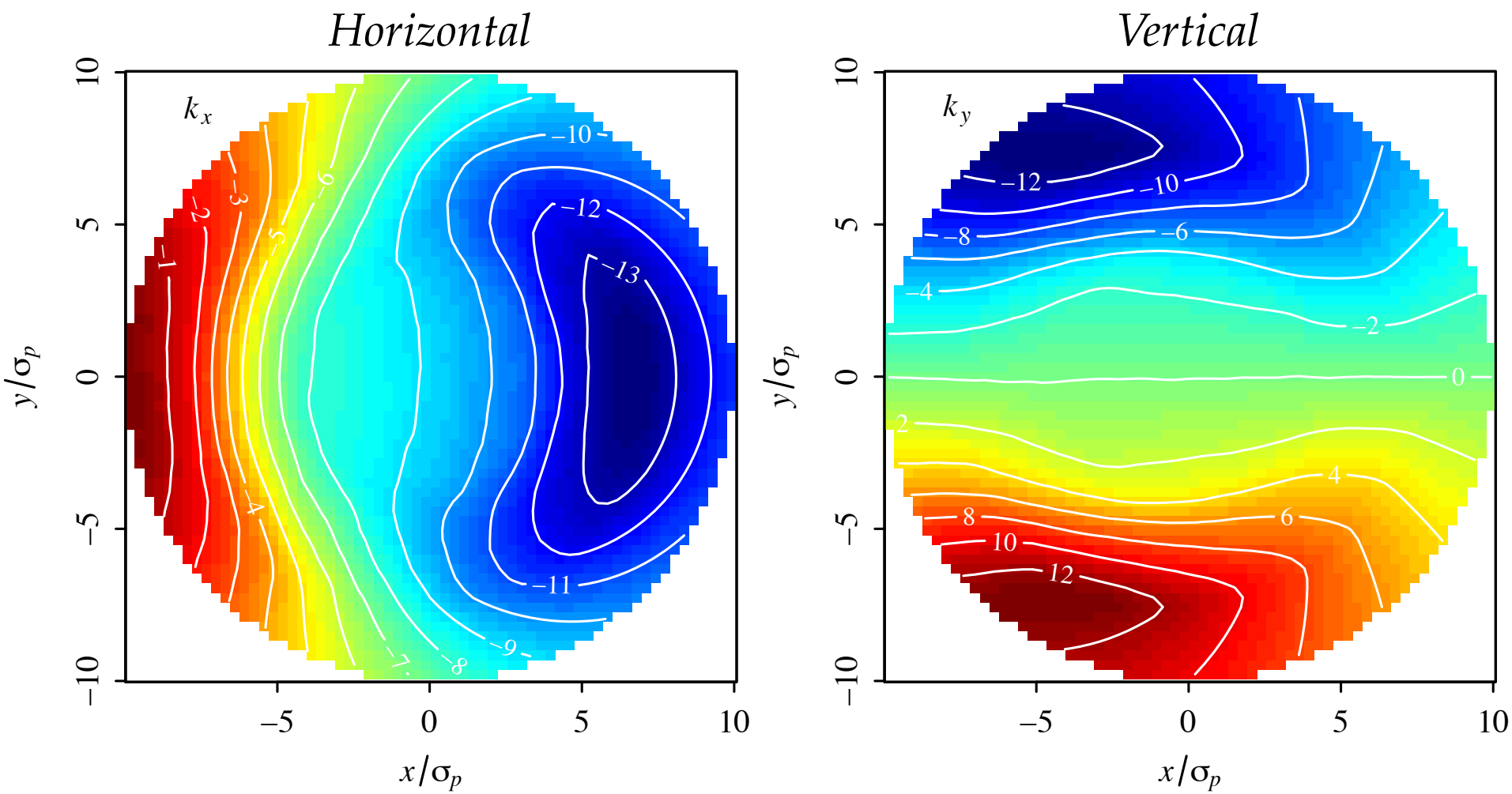
Kick maps are calculated by integrating electric fields over straight proton trajectories

$$k_{x,y} \equiv \int_{z_1}^{z_2} E_{x,y}(x, y, z)\, dz$$

Stancari, FERMILAB-FN-0972-APC (2013)

Kick maps from injection and extraction bends

Integrated fields ('kicks') [kV] vs. transverse proton position



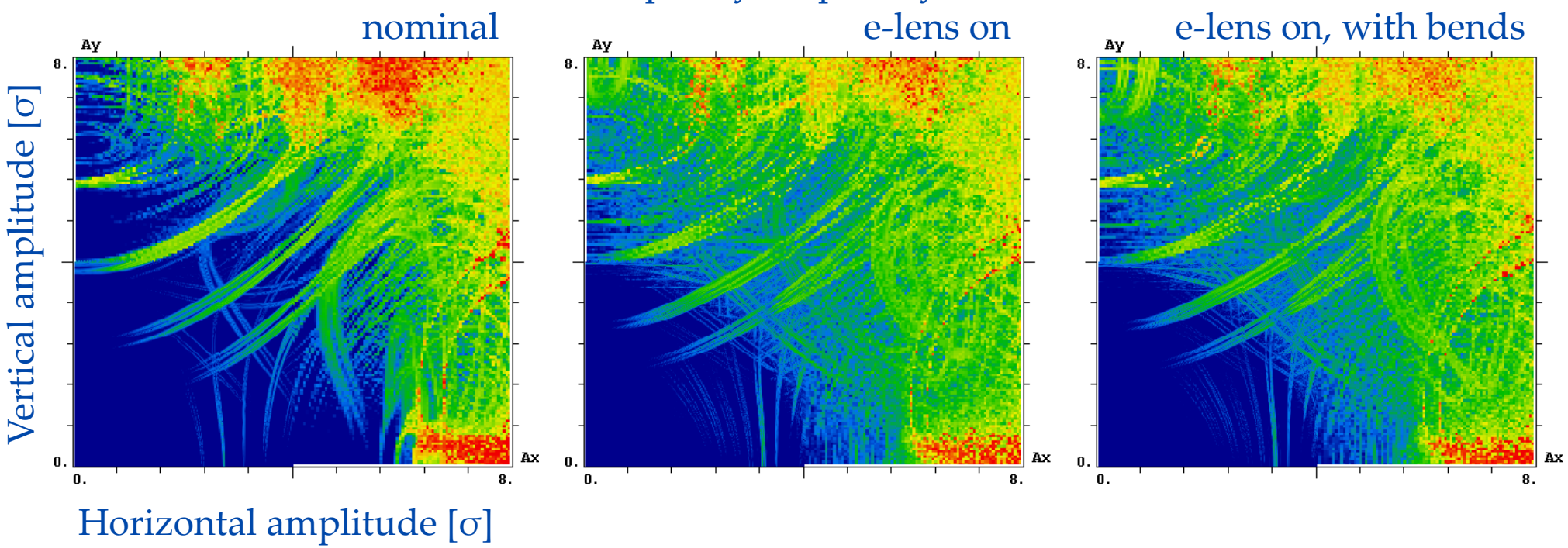
For 7-TeV protons, 10 kV ⇒ 1.4 nrad

Core and halo beam dynamics including imperfections

Evaluation of core lifetimes, emittance growth rates, and frequency maps with Lifetrac tracking code [A. Valishev]

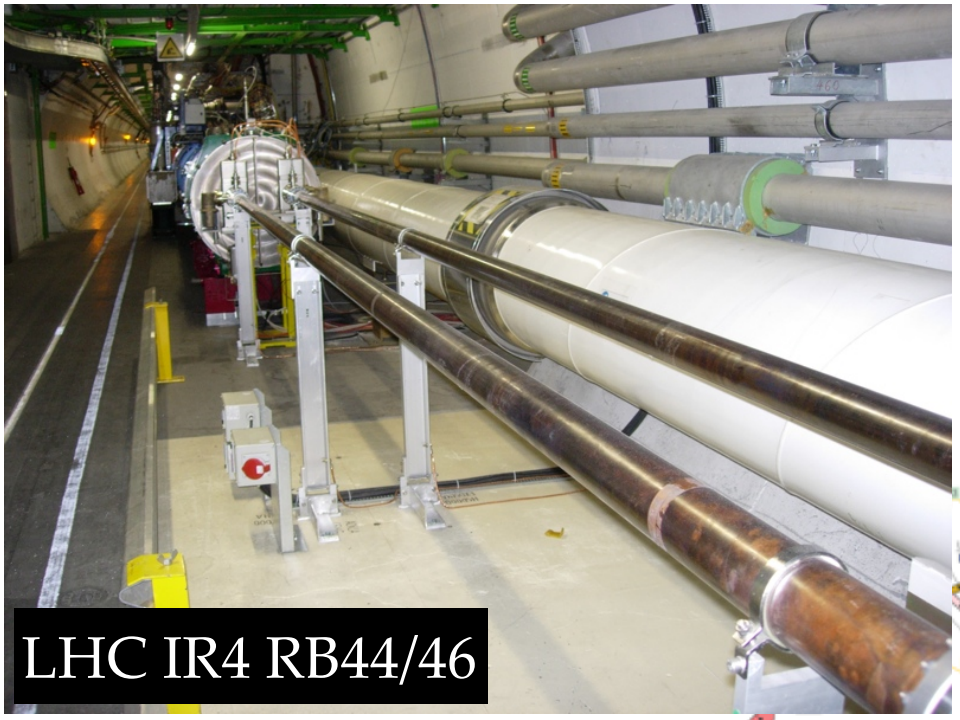
- LHC **lattice** V6.503 at 7 TeV, no multipole errors, <u>collisions on</u>
- 6D **halo**, 4-6σ transverse, Gaussian longitudinal
- Hollow **e-lens** 1.2 A at 4σ at IR4/RB46, <u>continuous</u> operation

Frequency-map analysis

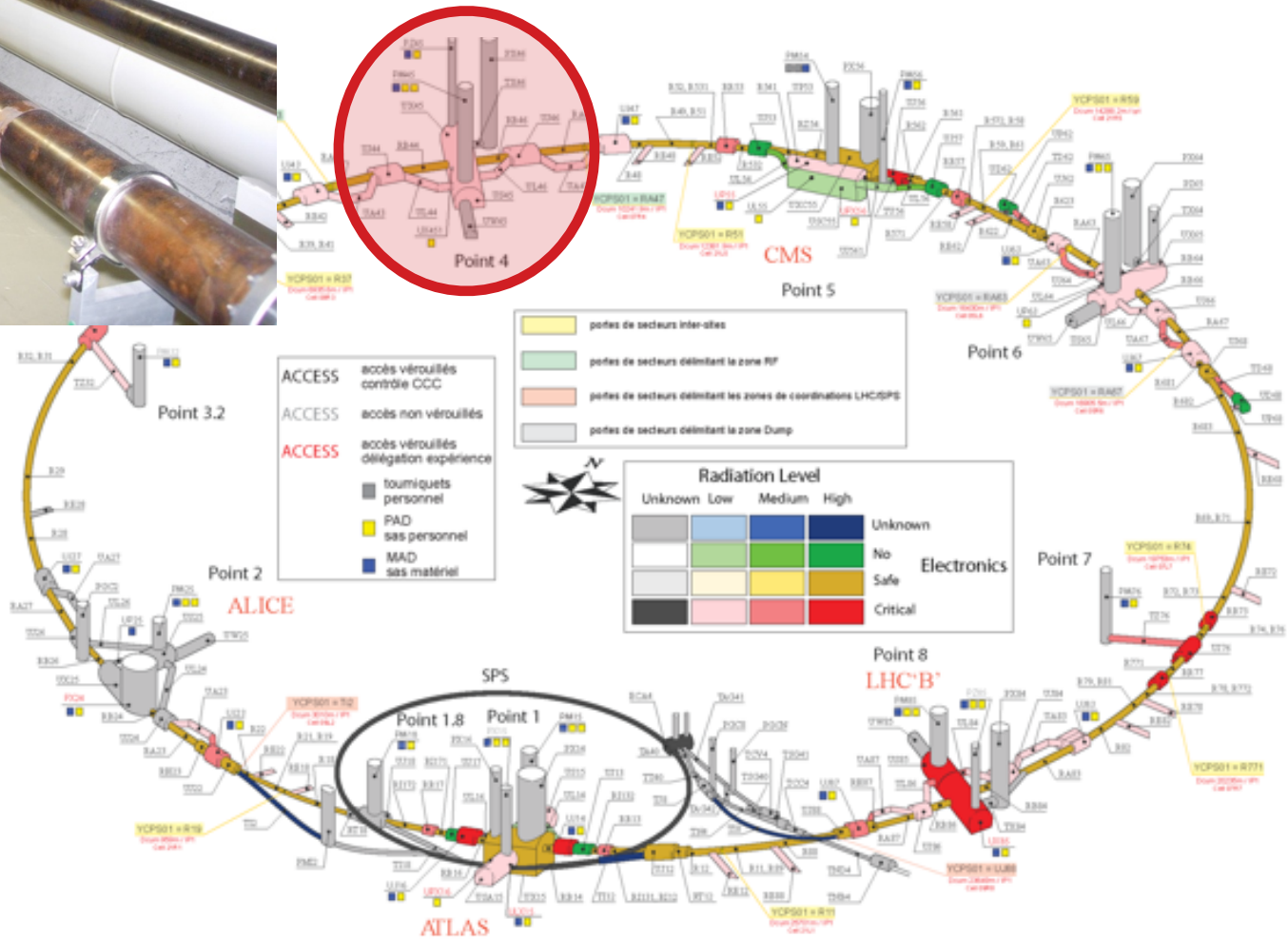


- Negligible effects on core lifetimes, emittances, and luminosity
- Smooth halo scraping (4% of halo population / minute)

Candidate locations for electron lenses in the LHC



Upstream or downstream of rf cavities



Some aspects of LHC integration

- Some **Tevatron components** may be reused (ie, superconducting coil) - to be determined

- **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?

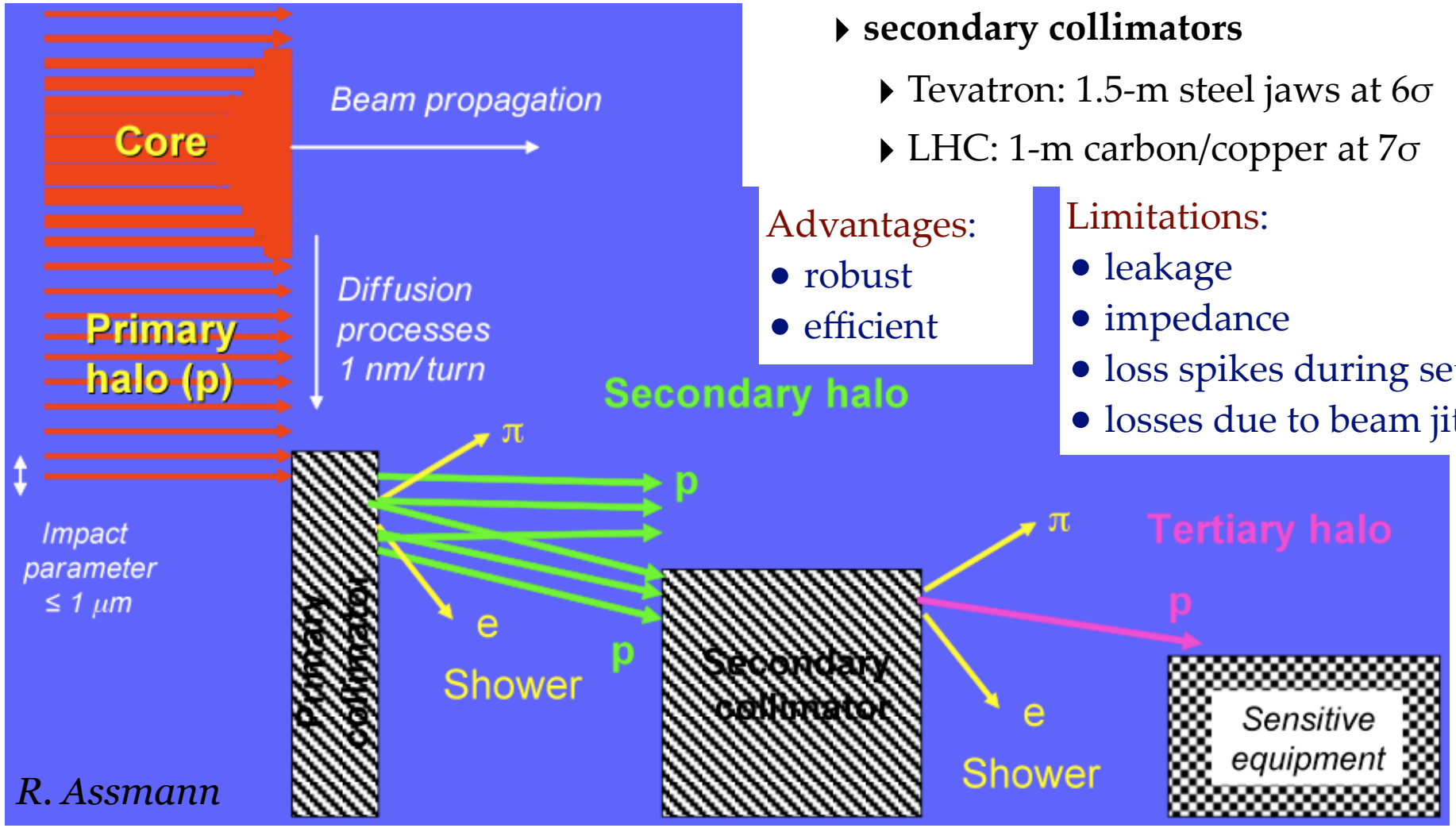
The conventional multi-stage collimation system

- 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

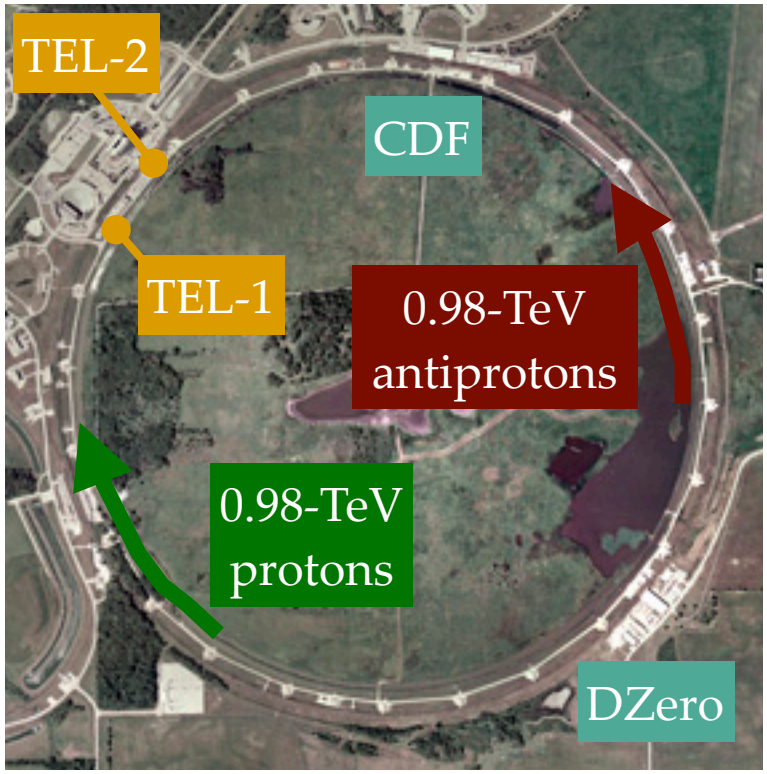
Limitations:
- leakage
- impedance
- loss spikes during setup
- losses due to beam jitter



Electron lenses in the Fermilab Tevatron collider

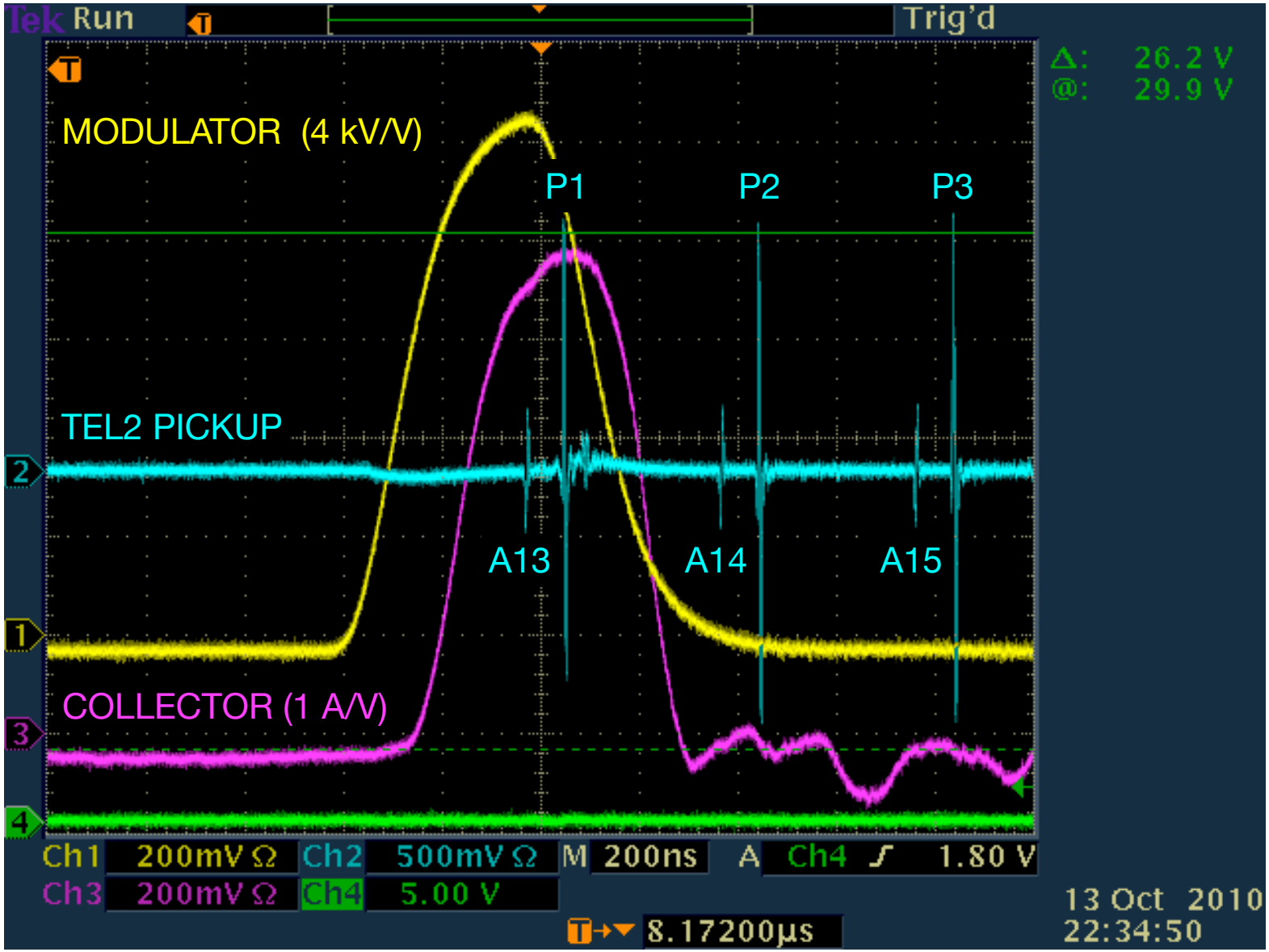
- *long-range beam-beam compensation*
  - Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)
- *abort-gap cleaning during operations*
  - Zhang et al., Phys. Rev. ST Accel. Beams **11**, 051002 (2008)
- *studies of head-on beam-beam compensation*
  - Stancari and Valishev, FERMILAB-CONF-13-046-APC
- *collimation with hollow electron beams*
  - Stancari et al., Phys. Rev. Lett. **107**, 084802 (2011)

Electron lenses for beam-beam compensation are currently being commissioned in the Relativistic Heavy Ion Collider at Brookhaven National Laboratory



2 km

Pulsed operation of the electron lens

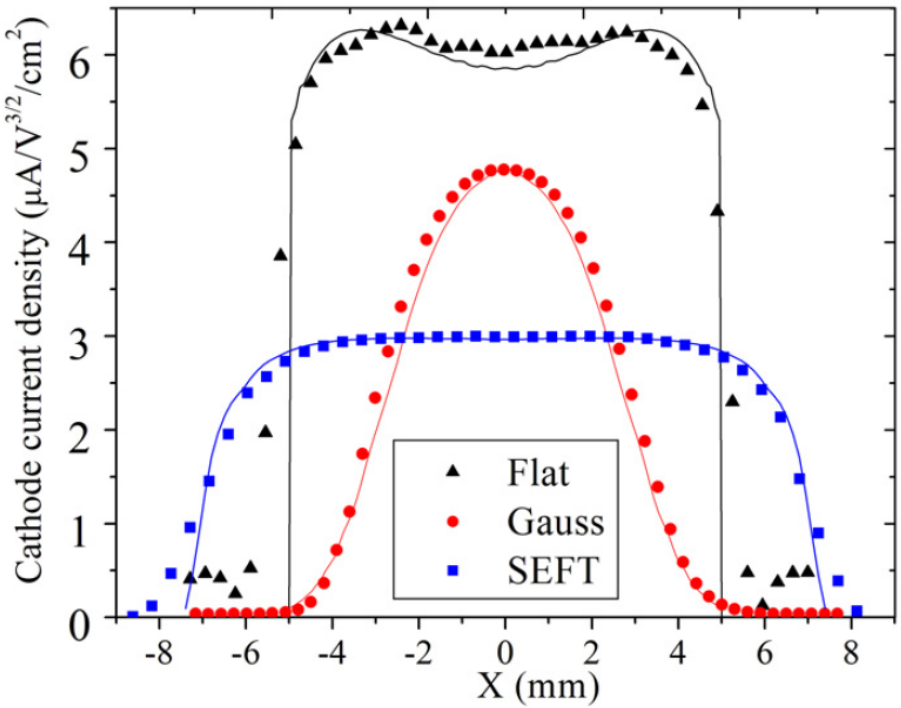


Pulsed electron beam could be **synchronized** with any group of bunches

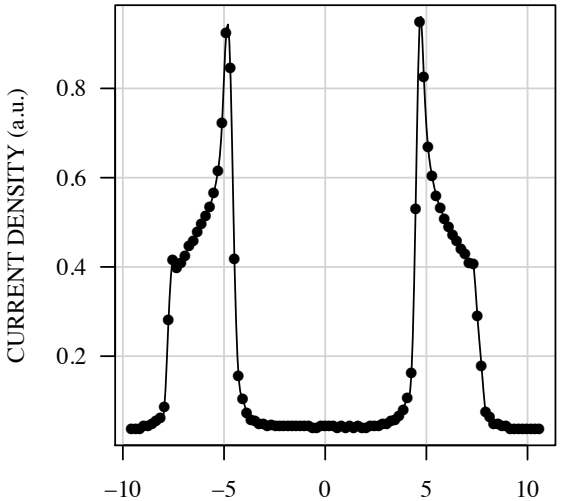
Profile control

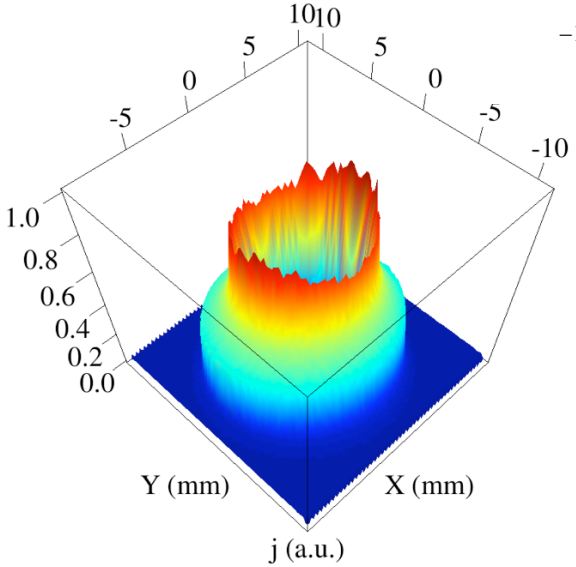
Current density profile of electron beam is shaped by cathode and electrode geometry and maintained by strong solenoidal fields

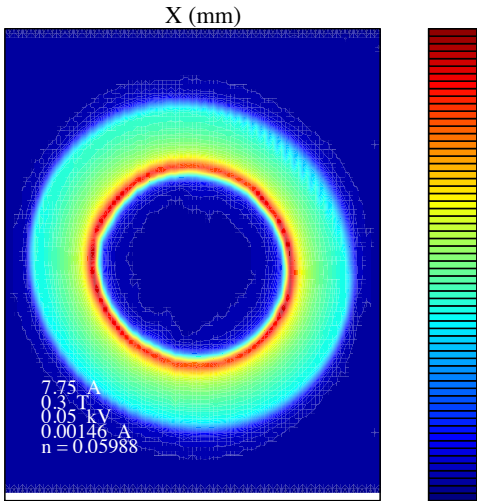
Flat profiles for bunch-by-bunch betatron tune correction



Hollow profile for halo scraping

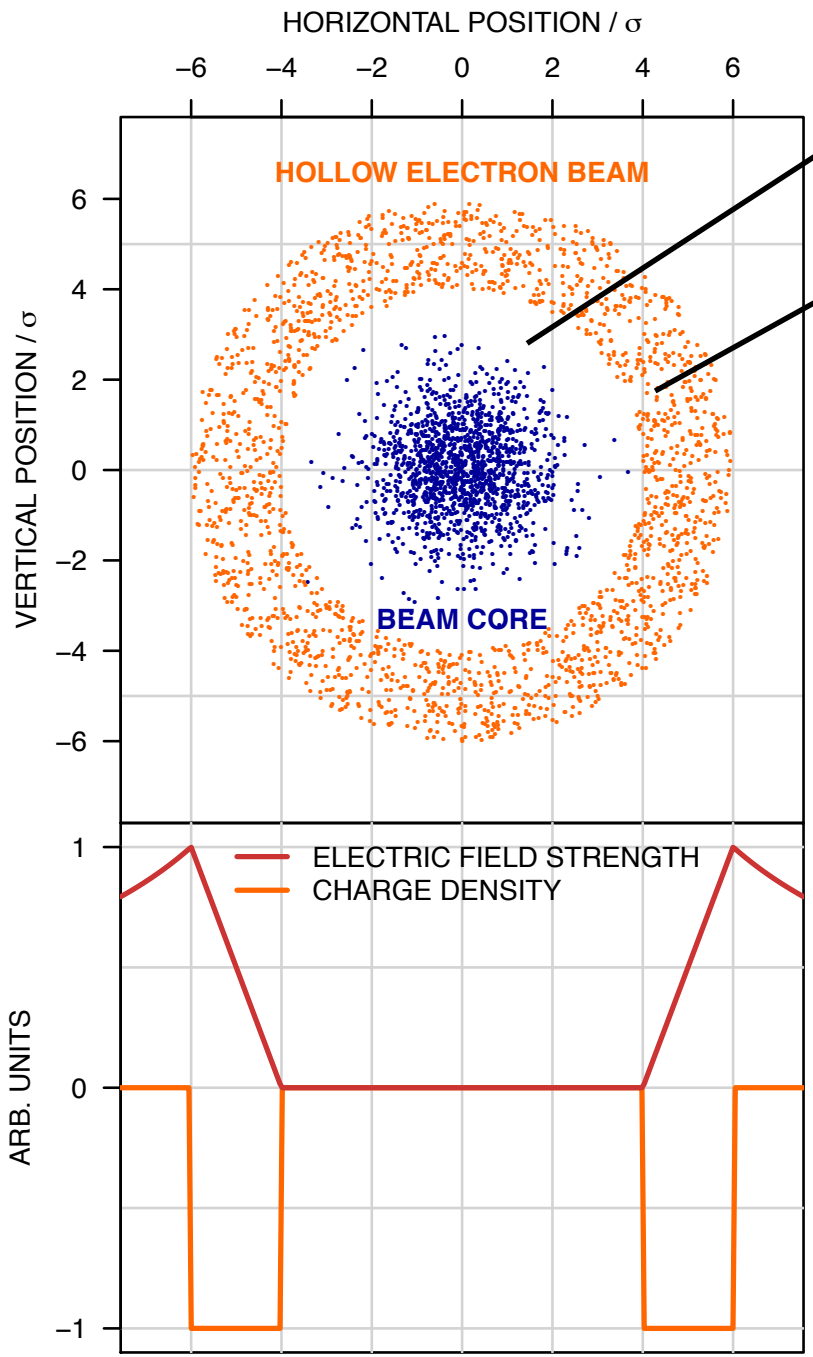






Gaussian profile for compensation of nonlinear beam-beam forces

Concept of hollow electron beam collimator



- **Beam core** is unaffected (field-free region)
- **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 0.98 TeV

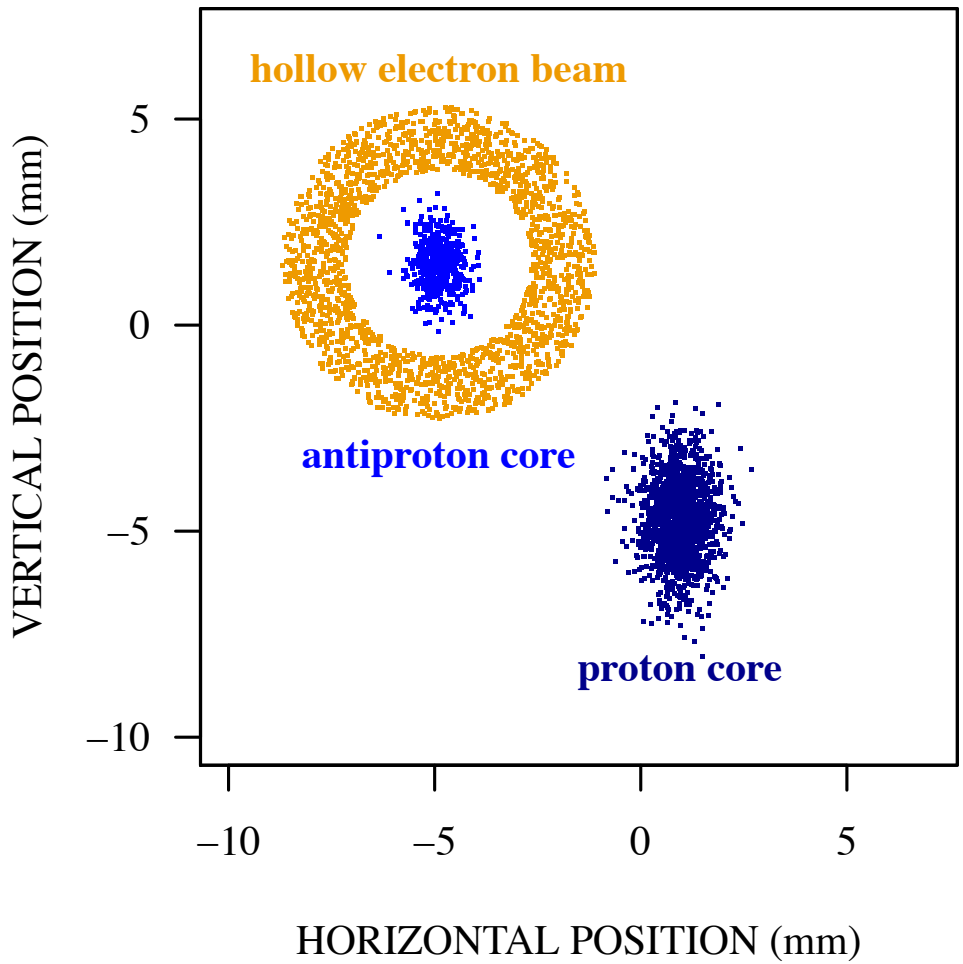
For comparison: multiple Coulomb scattering in Tevatron collimators generates random kicks $\theta_{\rm rms} = 17\ \mu{\rm rad}$

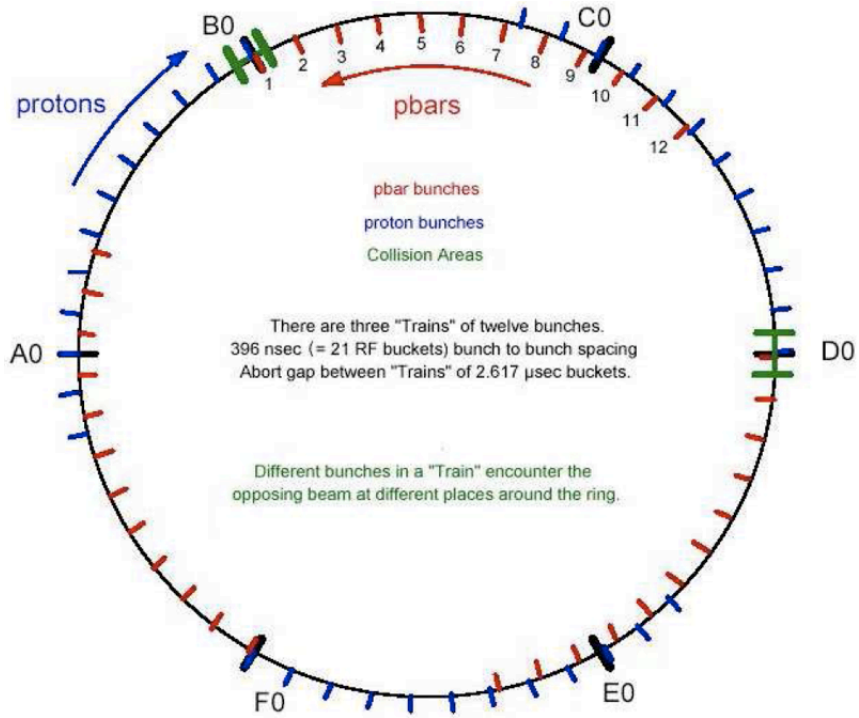
Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08

Layout of the beams in the Tevatron

Proton and antiproton beams in the same vacuum pipe

Transverse separation was 9 mm in electron lens





3 trains of 12 bunches each

396 ns bunch separation

Features of hollow electron beam collimation

ADVANTAGES

- 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
- Resonant excitation is possible for faster removal (pulsed operation)
- Low impedance
- No ion breakup
- Position control by magnetic fields (no motors or bellows)
- Established electron-cooling / electron-lens technology

POTENTIAL ISSUES

- Critical
  - beam alignment
  - symmetry of electron beam profile
- Stability of beams at high intensity
- Cost

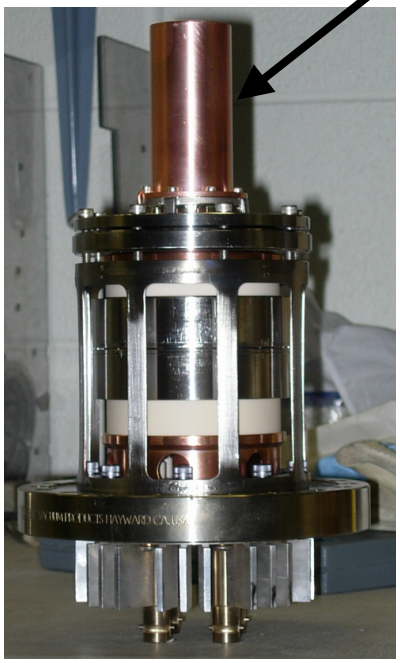
Experimental studies of hollow electron beam collimation

- 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]

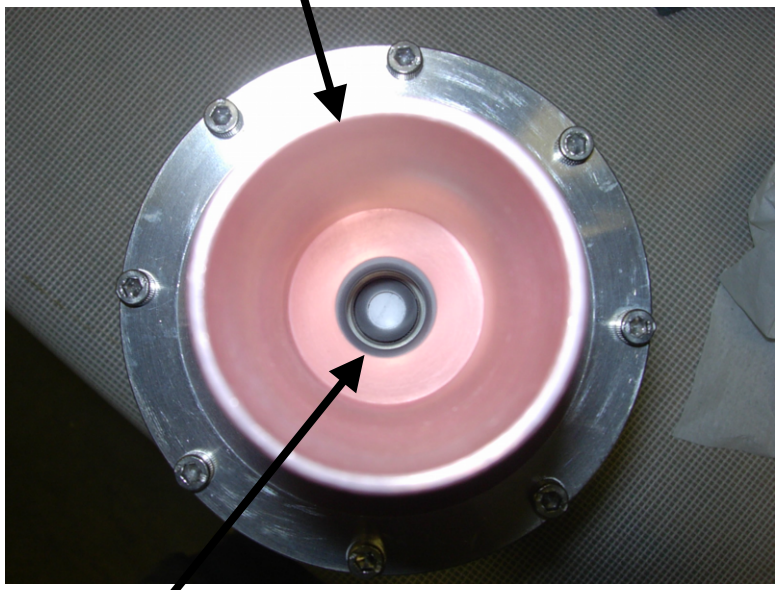
The 15-mm hollow electron gun

side view



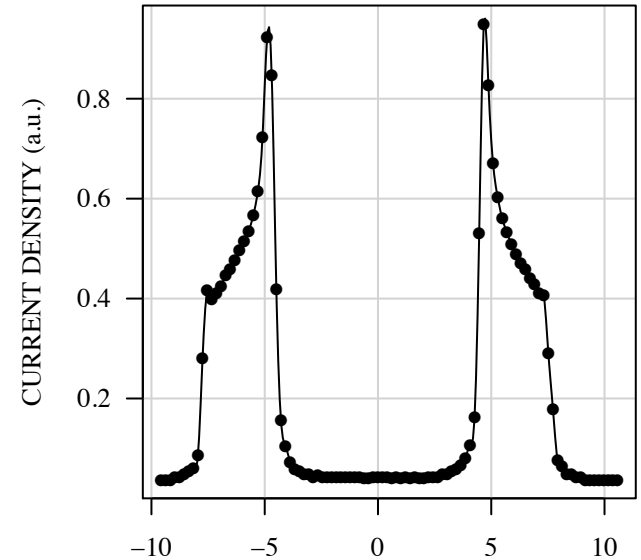
Copper anode

top view

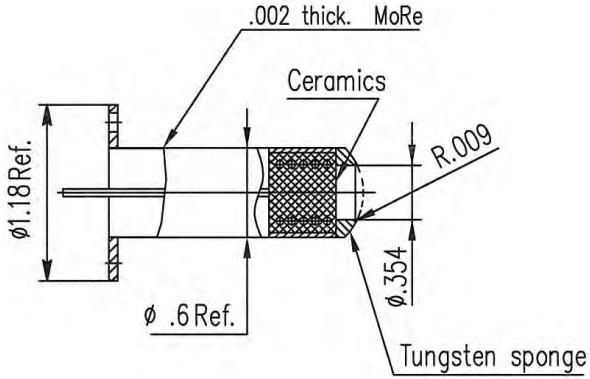


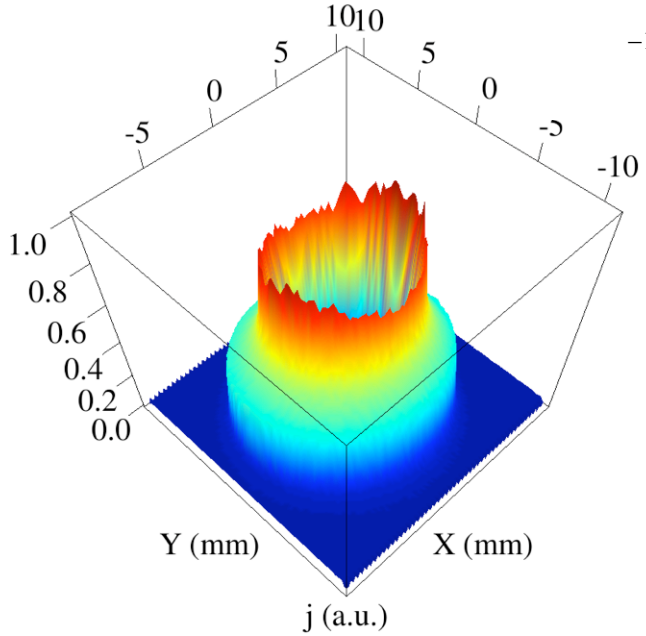
Peak yield: **1.1 A** at 4.8 kV

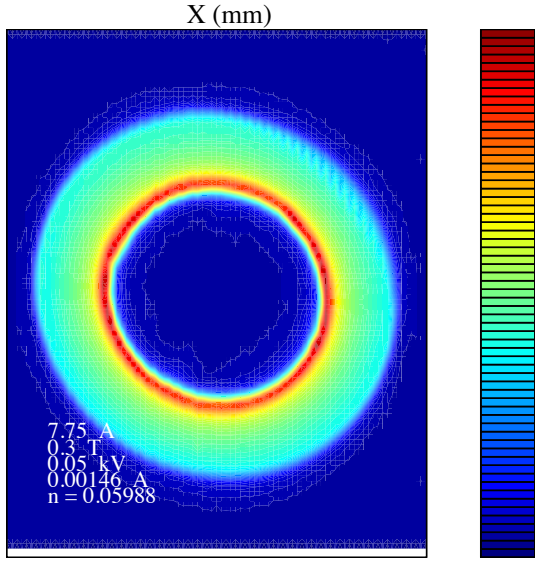
Profile measurements



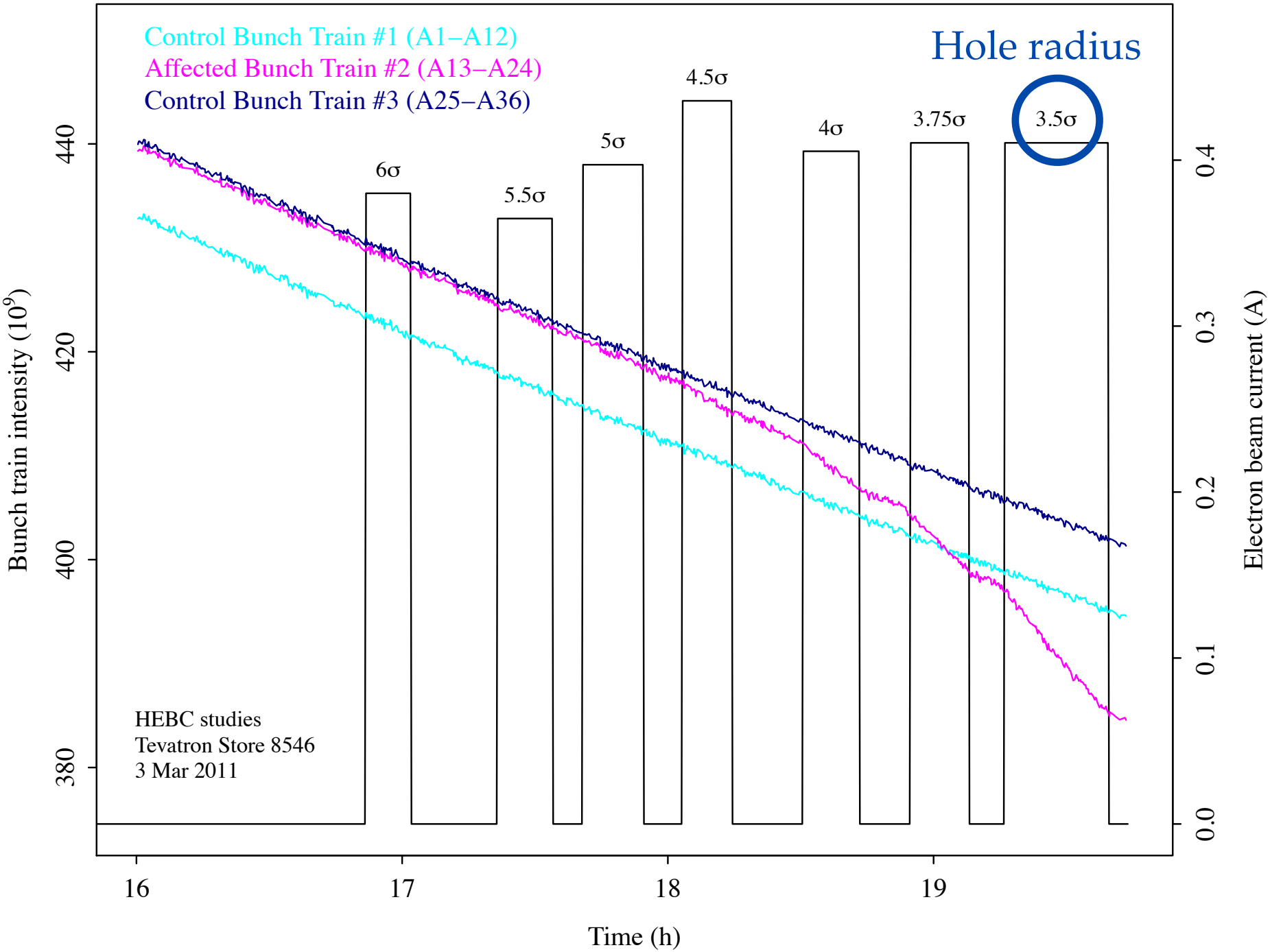
Tungsten dispenser cathode
with convex surface
15-mm diameter, 9-mm hole



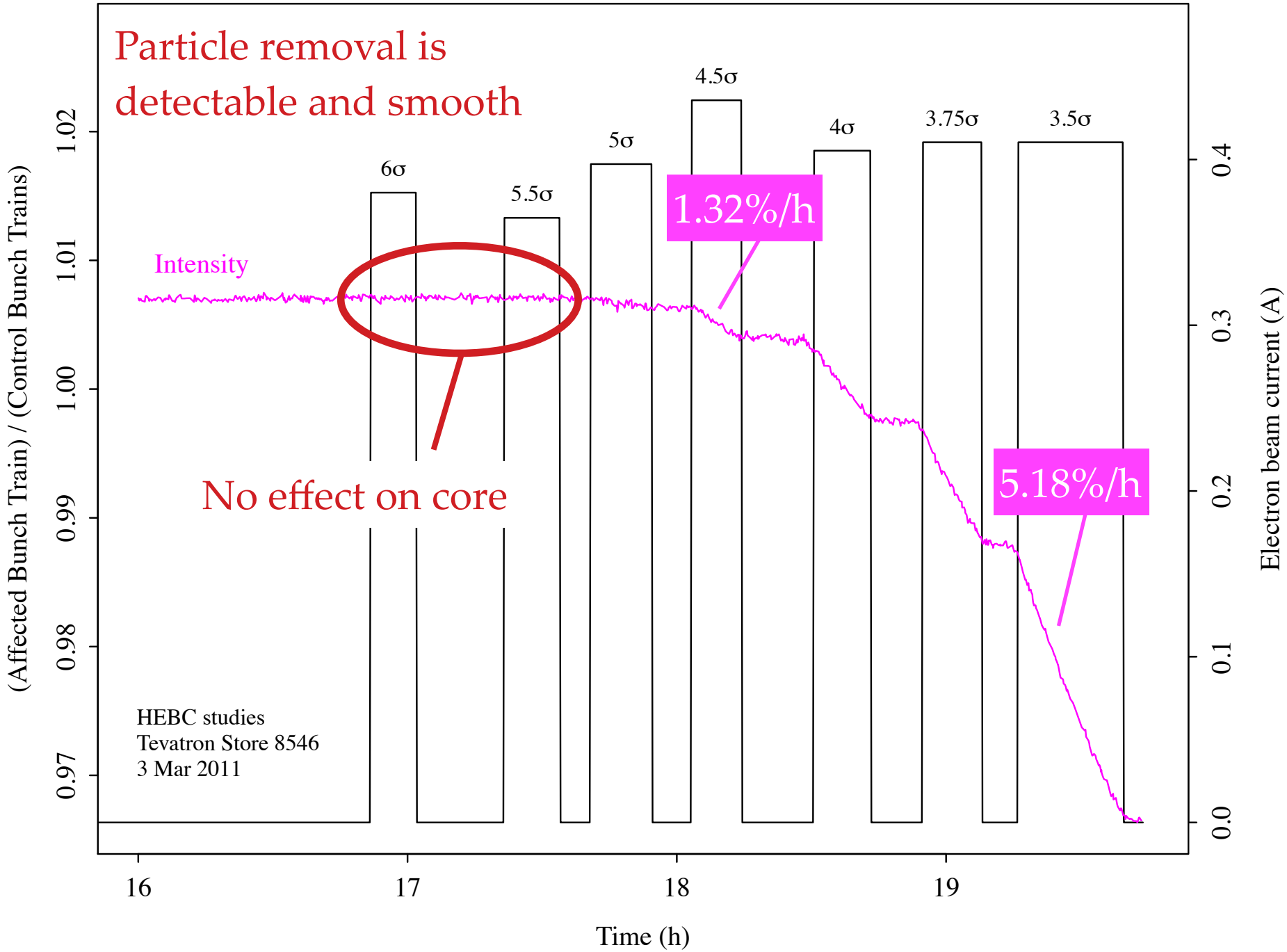




Scraping of 1 antiproton bunch train



Removal rate: affected bunch train relative to other 2 trains



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

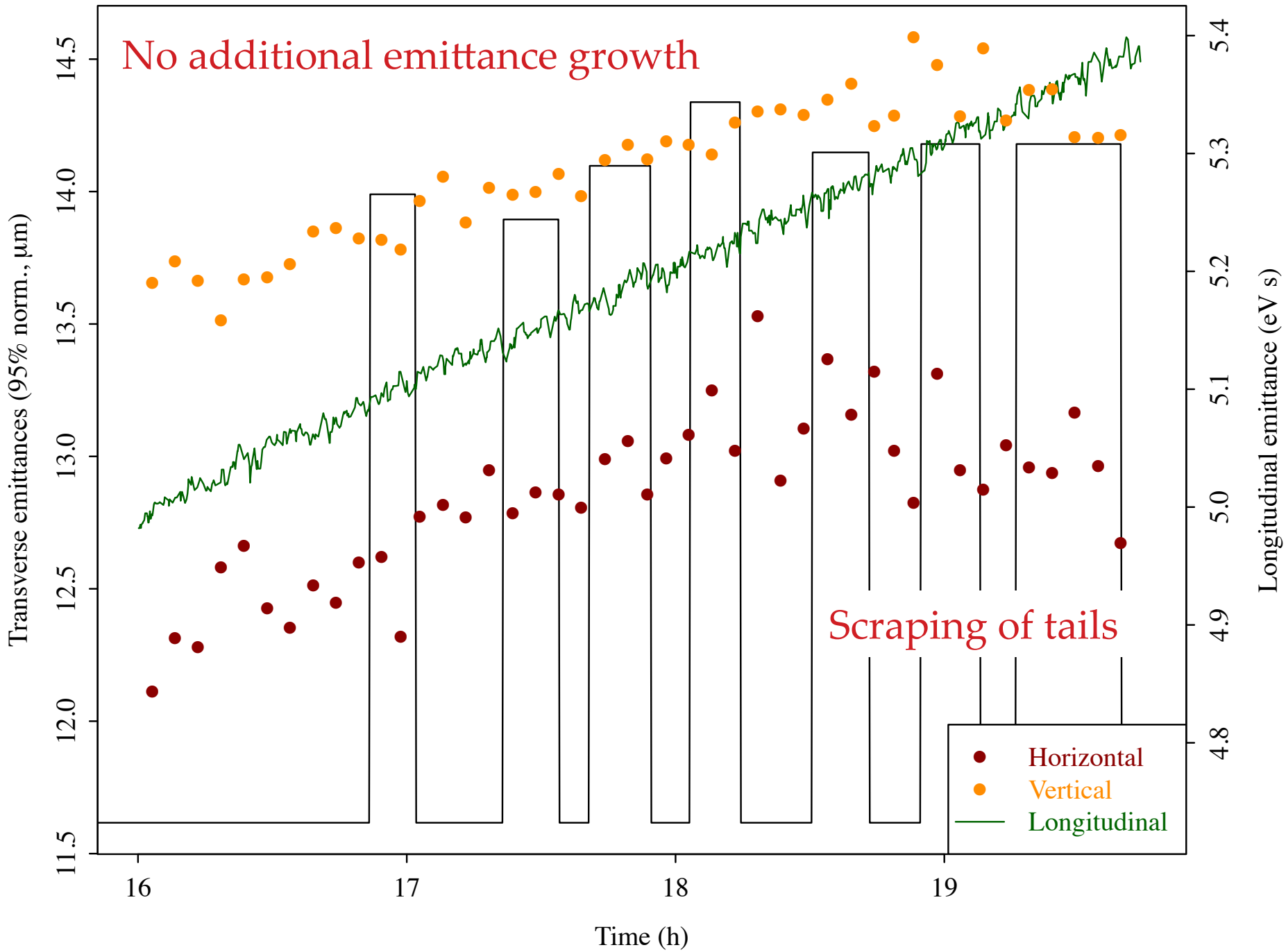
Several strategies:

- **No removal** with large electron beam inner radius (previous slide)
- Check **emittance** evolution
- Compare **intensity** and **luminosity** change when scraping antiprotons:

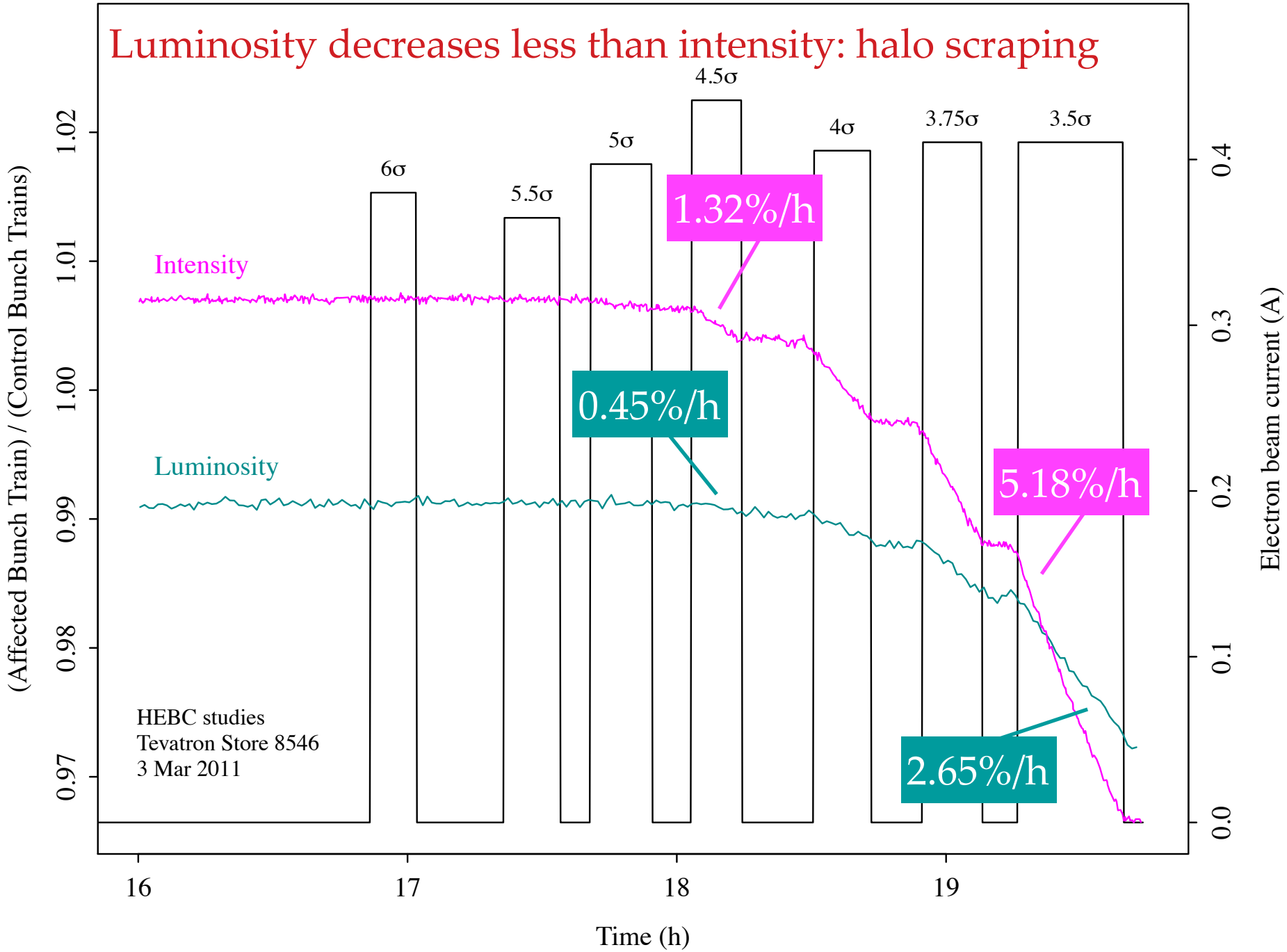
$$\mathcal{L} = \left(\frac{f_{\mathrm{rev}} N_b}{4\pi}\right) \frac{N_p N_a}{\sigma^2} \qquad \frac{\Delta\mathcal{L}}{\mathcal{L}} = \frac{\Delta N_p}{N_p} + \frac{\Delta N_a}{N_a} - 2\frac{\Delta\sigma}{\sigma}$$

  - 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

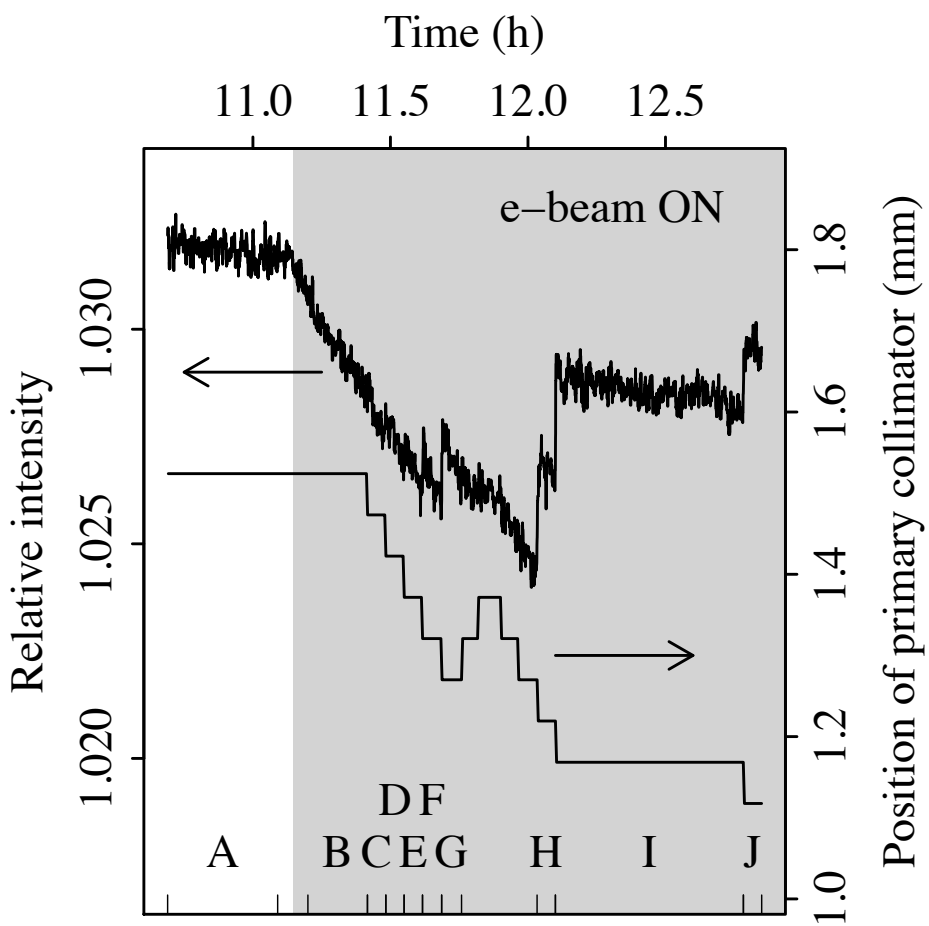


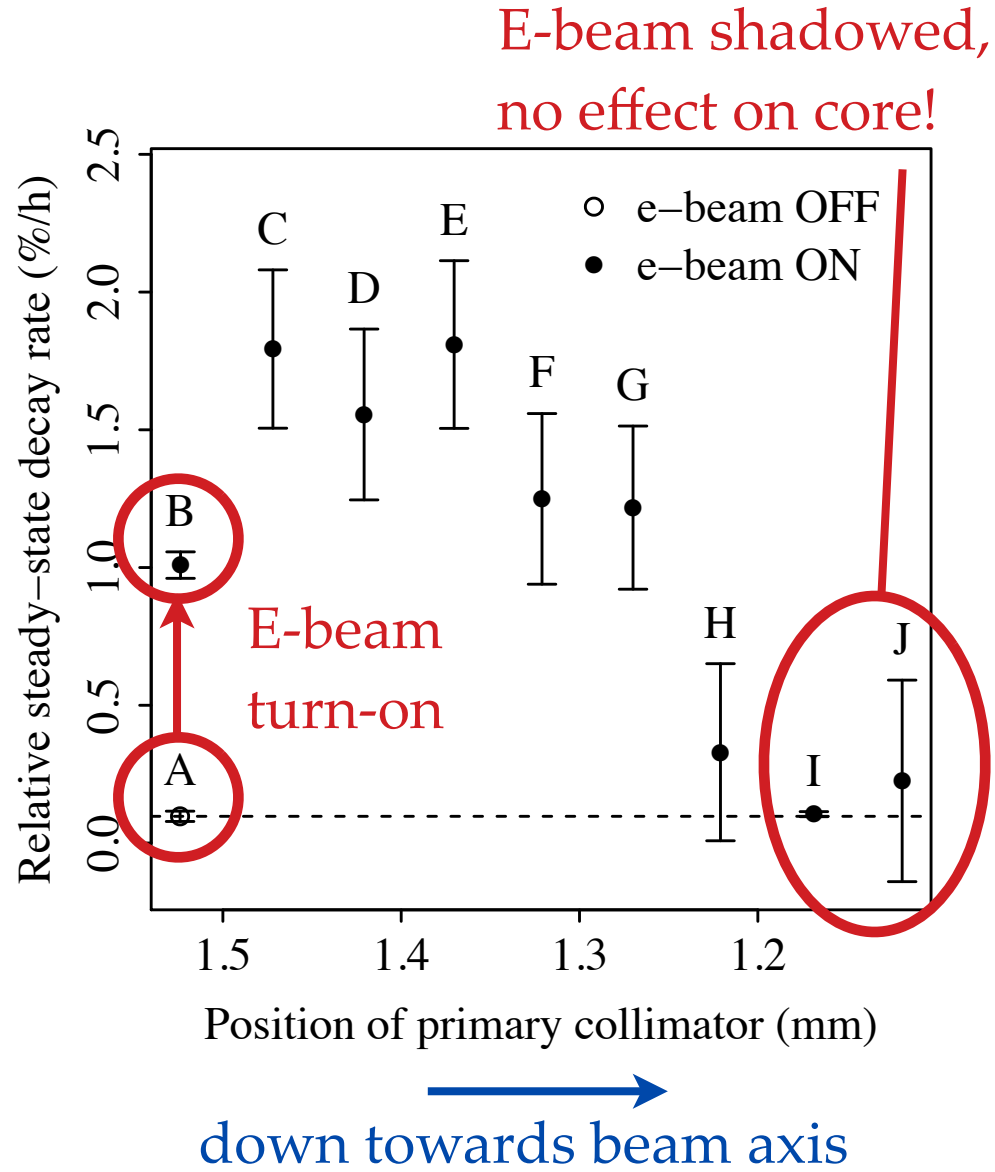
Relative intensity and luminosity of affected bunch train



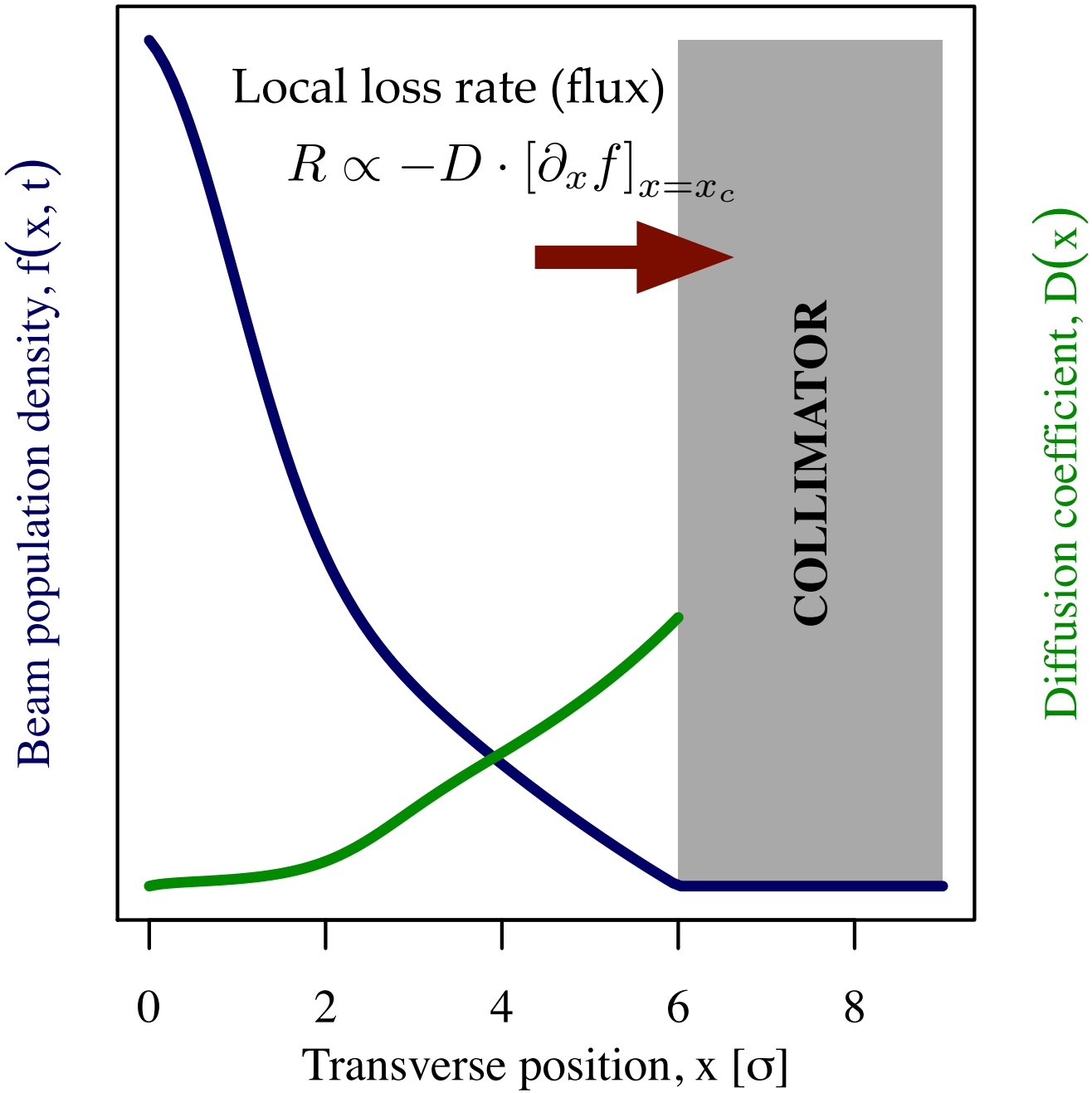
Removal rate vs. amplitude from collimator scan

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

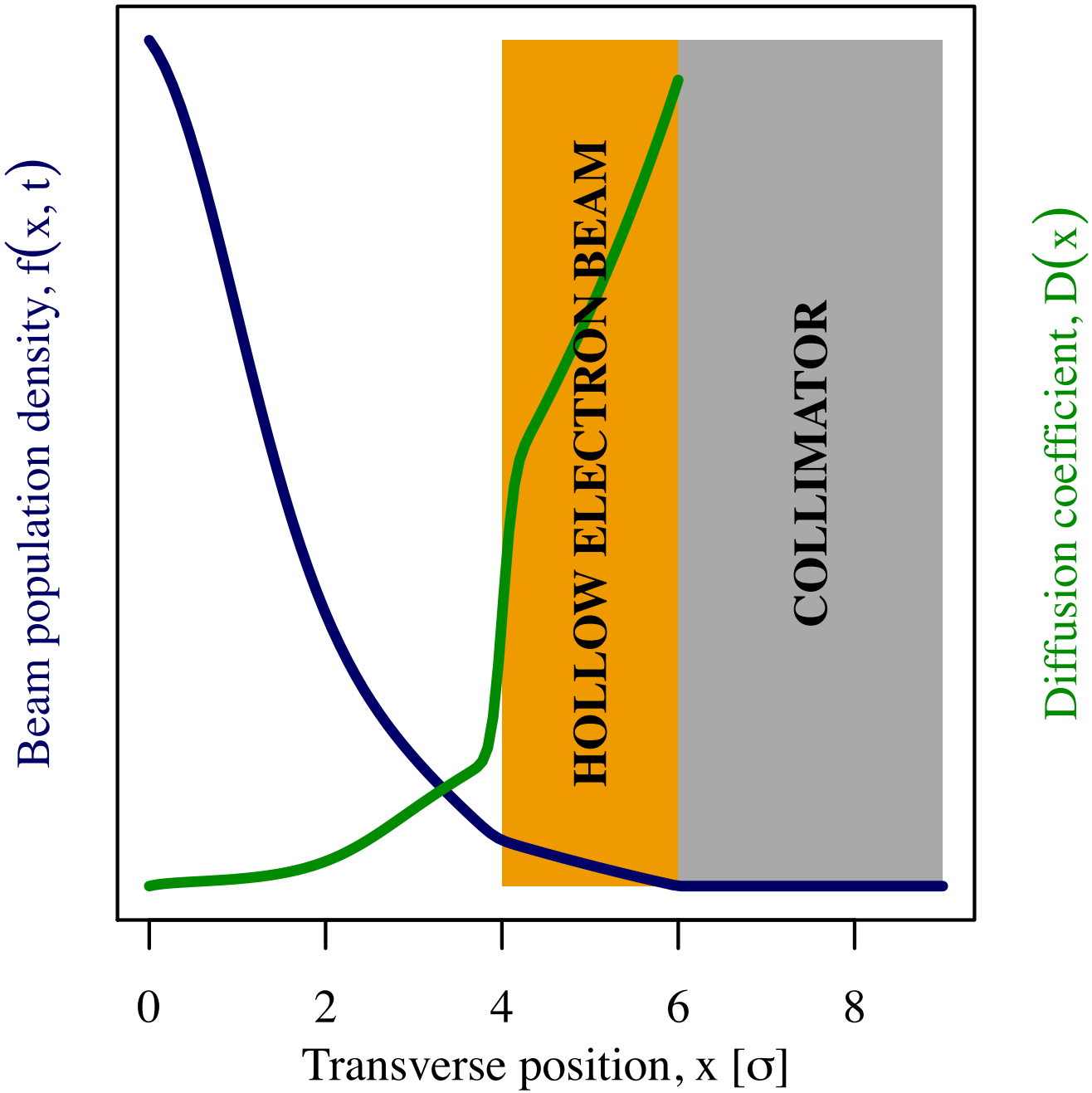




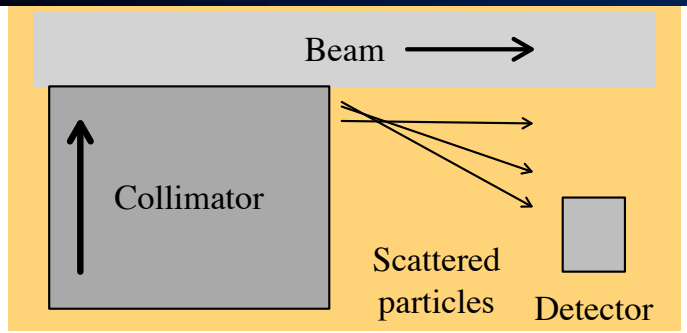
1-dimensional diffusion cartoon of collimation



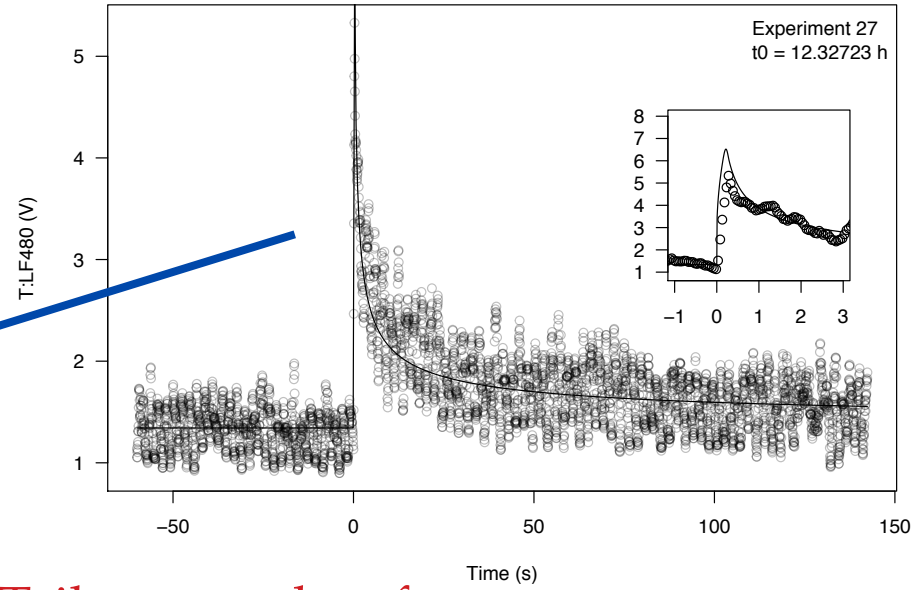
1-dimensional diffusion cartoon with hollow electron beam

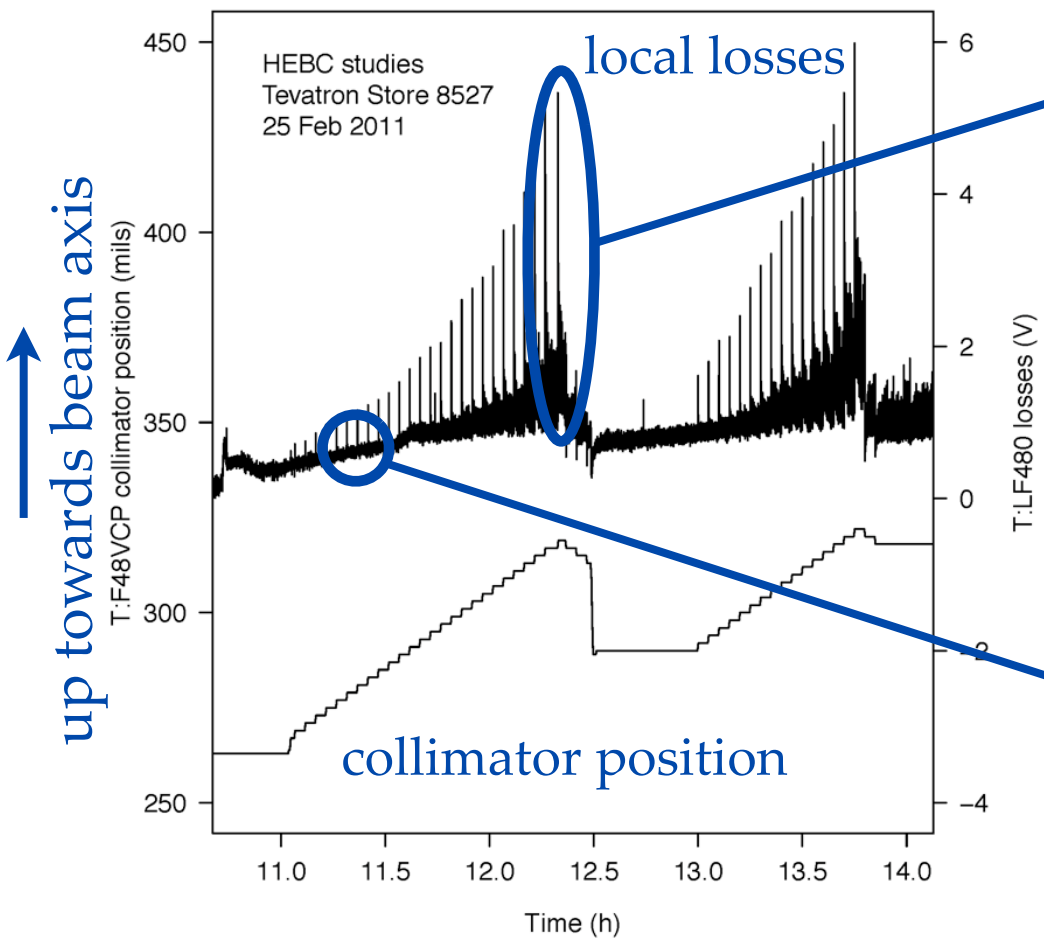


Measurement of diffusion rate vs. amplitude with collimator scans

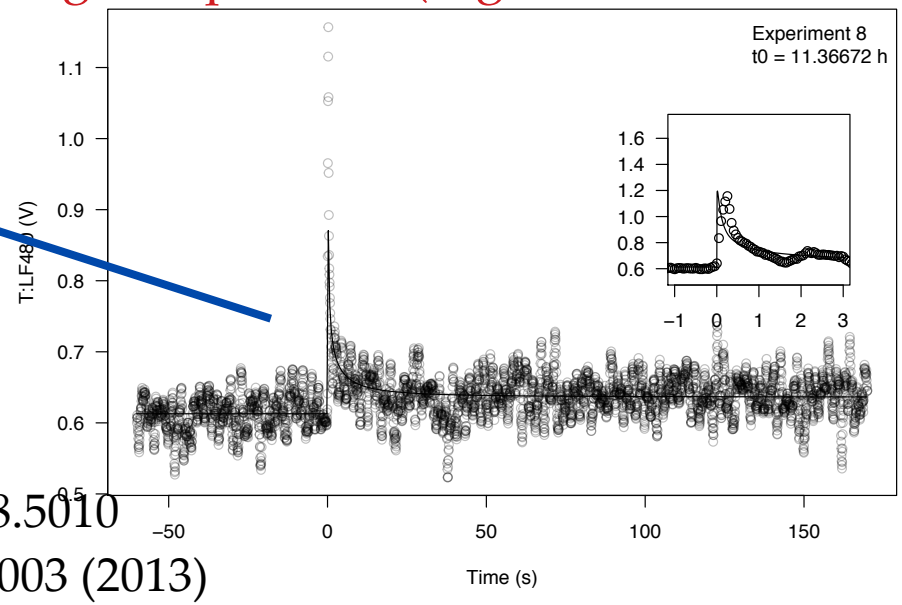


Mess and Seidel, NIMA **351**, 279 (1994)





Tails repopulate faster at large amplitudes (higher diffusion rate)



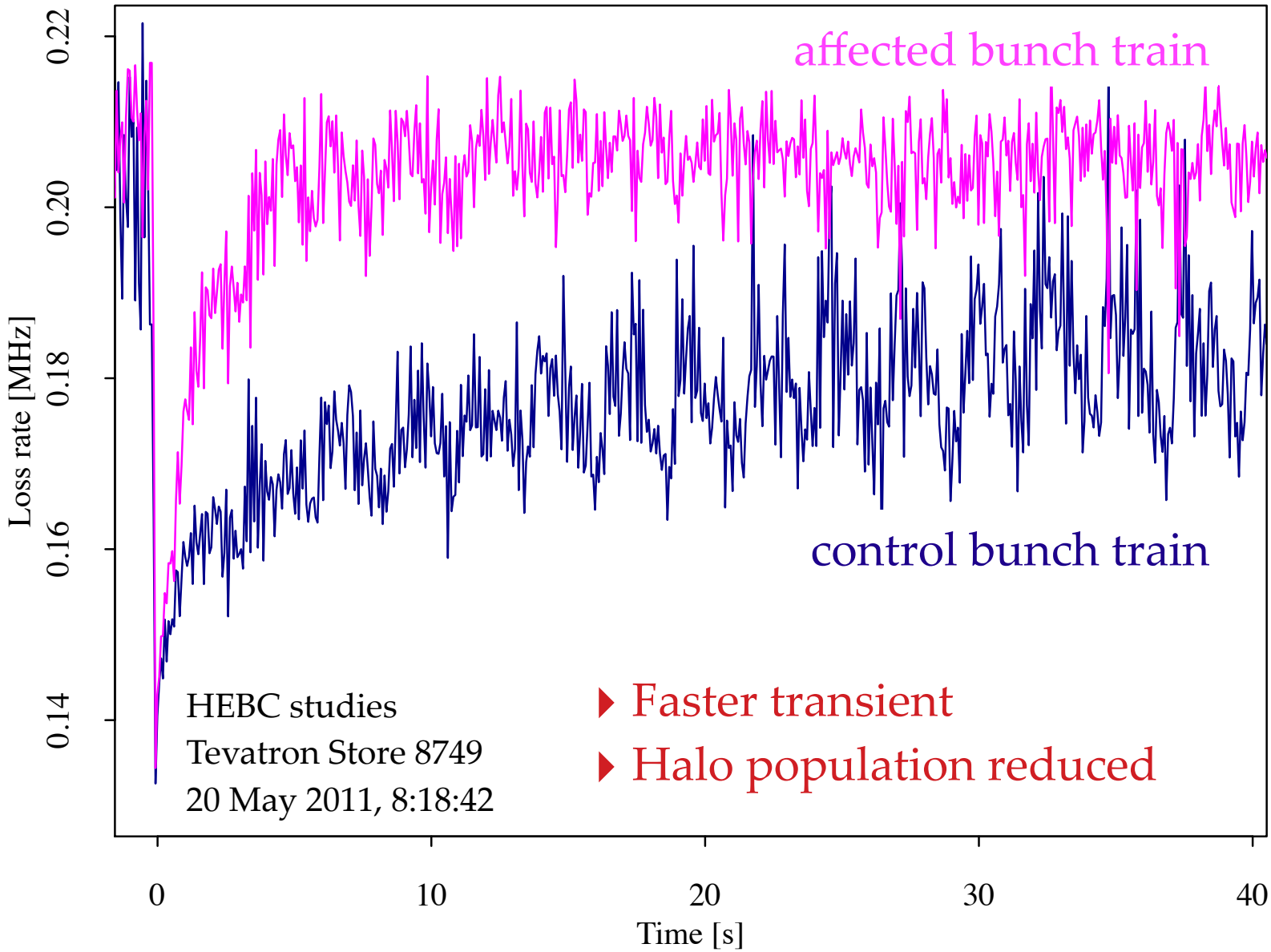
Stancari et al., IPAC11, HB2012, BB2013, arXiv:1108.5010

Valentino et al., Phys. Rev. ST Accel. Beams **16**, 021003 (2013)

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



Diffusion model of loss rate evolution in collimator scans

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

Distribution function evolves under diffusion with boundary condition at collimator

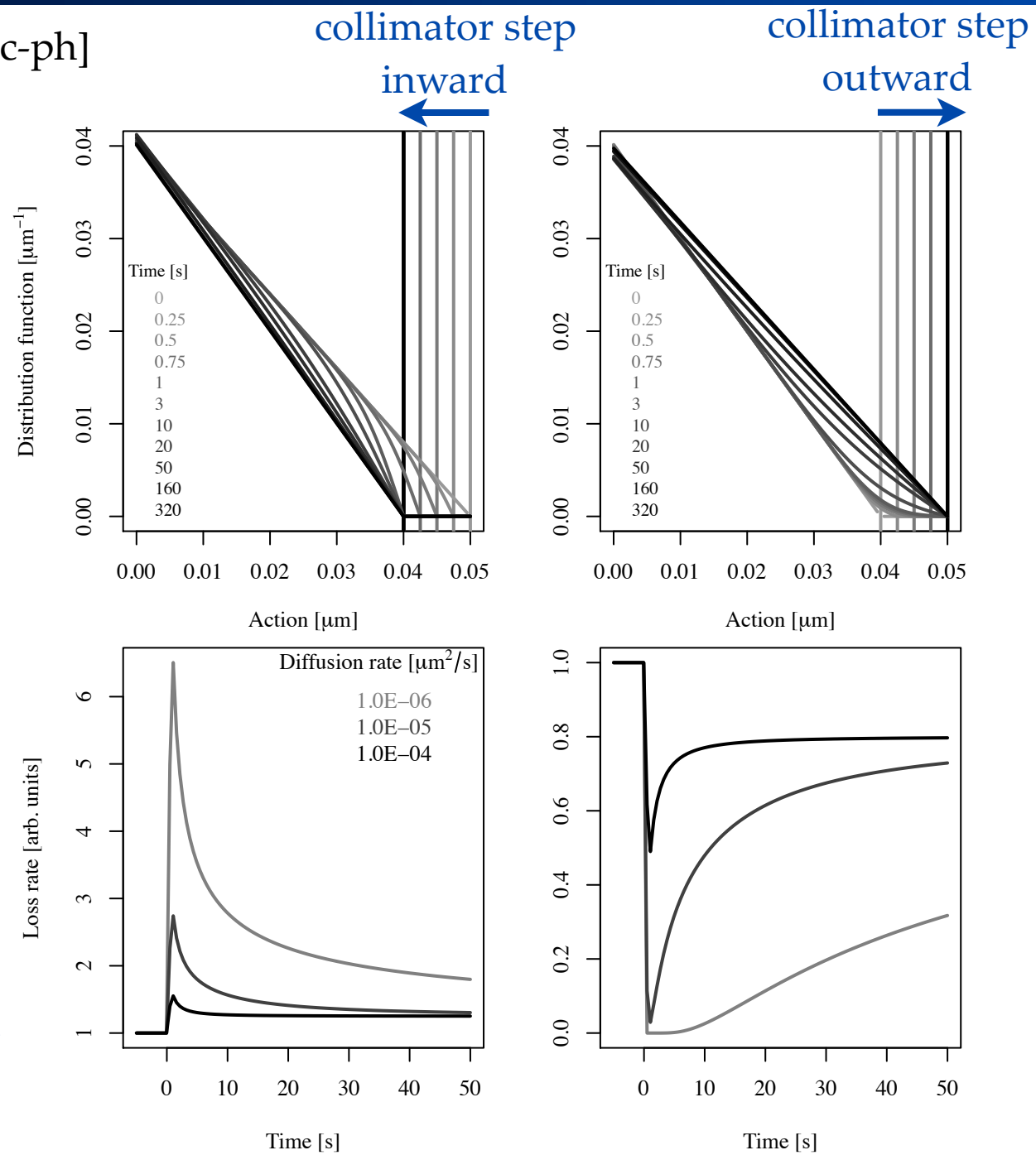
$$\partial_t f = \partial_J \left(D \cdot \partial_J f \right)$$

Instantaneous loss rate is proportional to slope of distribution function

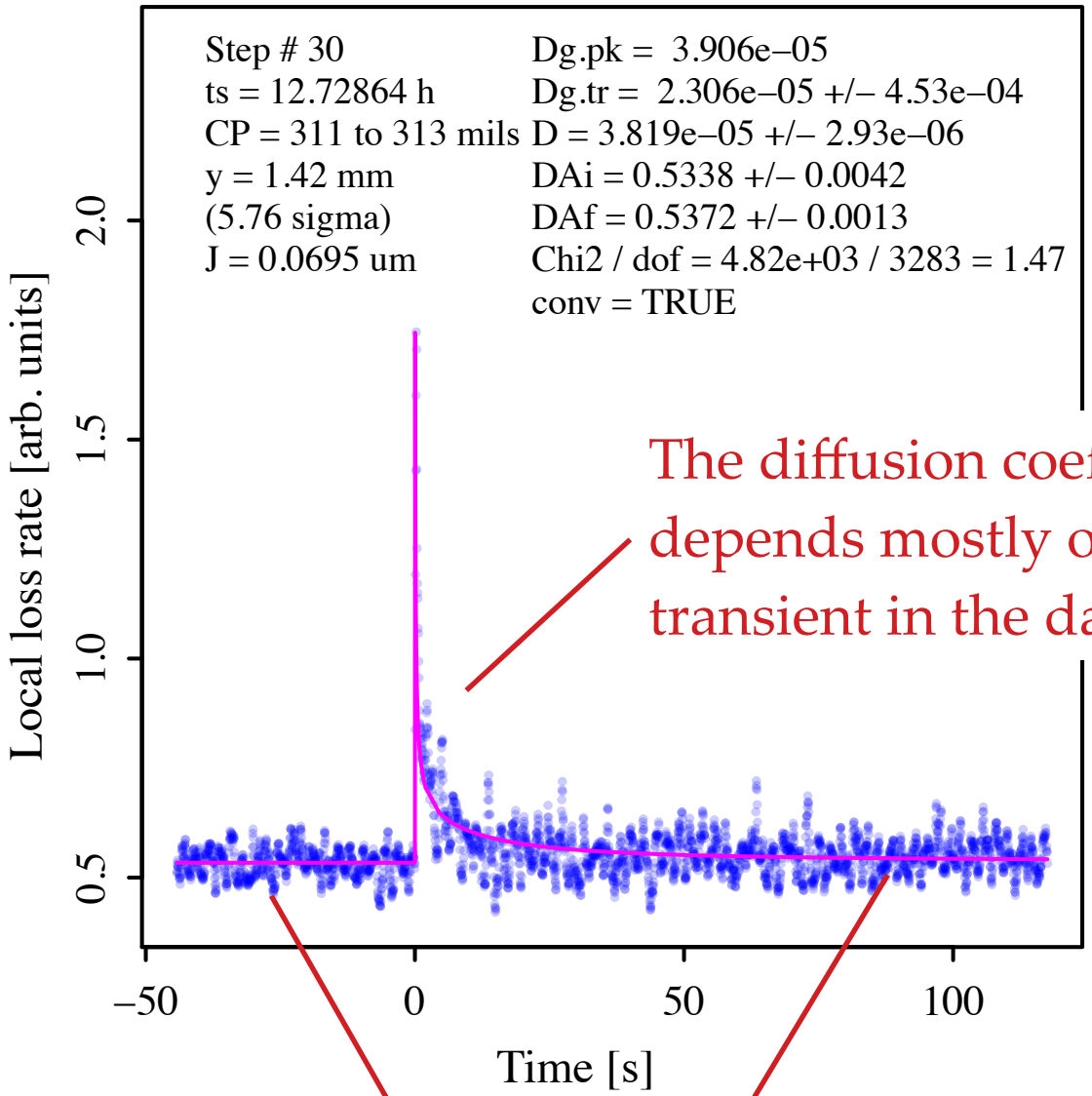
$$R = -k \cdot D \cdot \left[\partial_J f \right]_{J=J_c} + B$$

loss monitor calibration

background rate



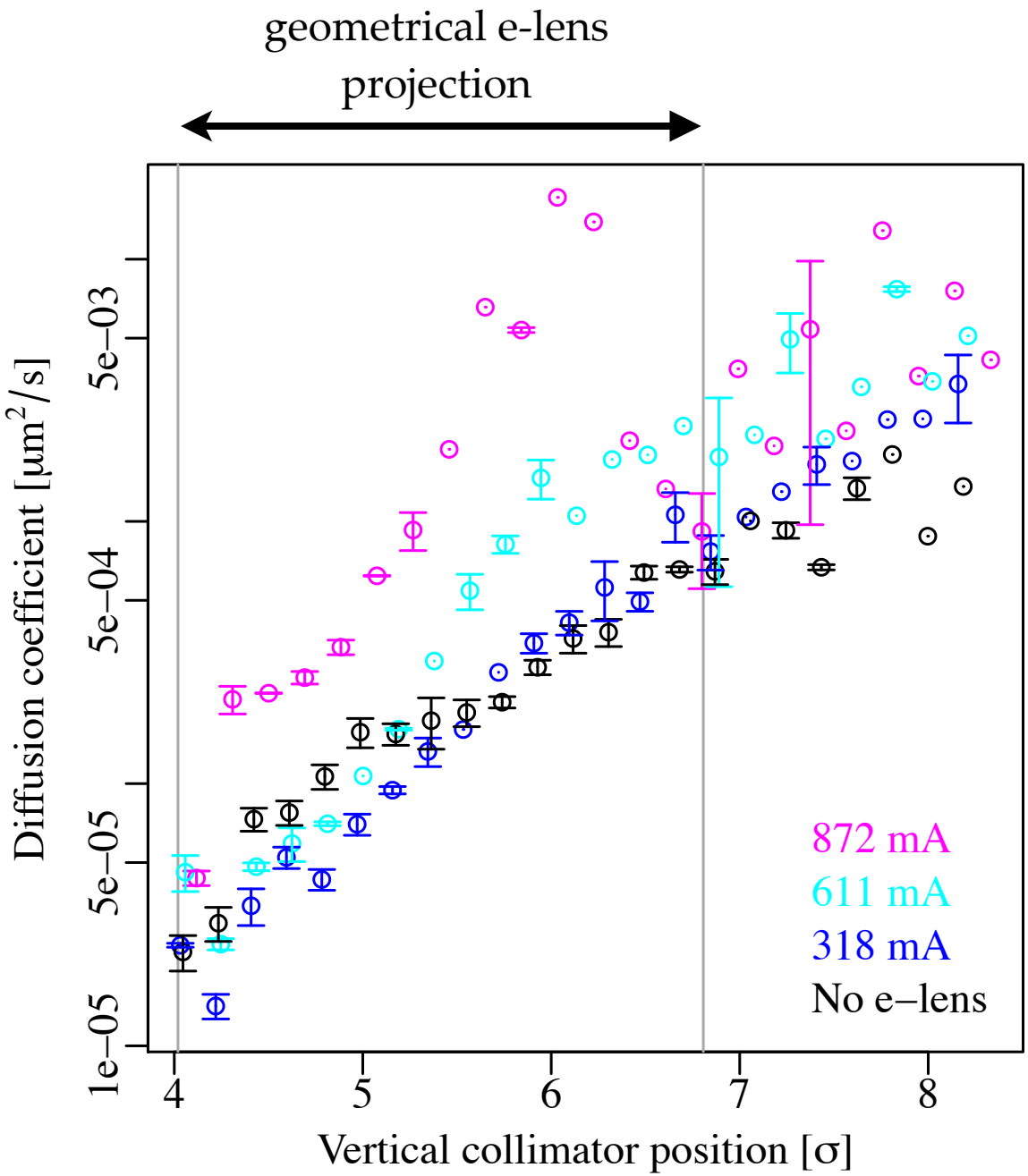
Diffusion model fit to loss rate data



The diffusion coefficient depends mostly on the transient in the data

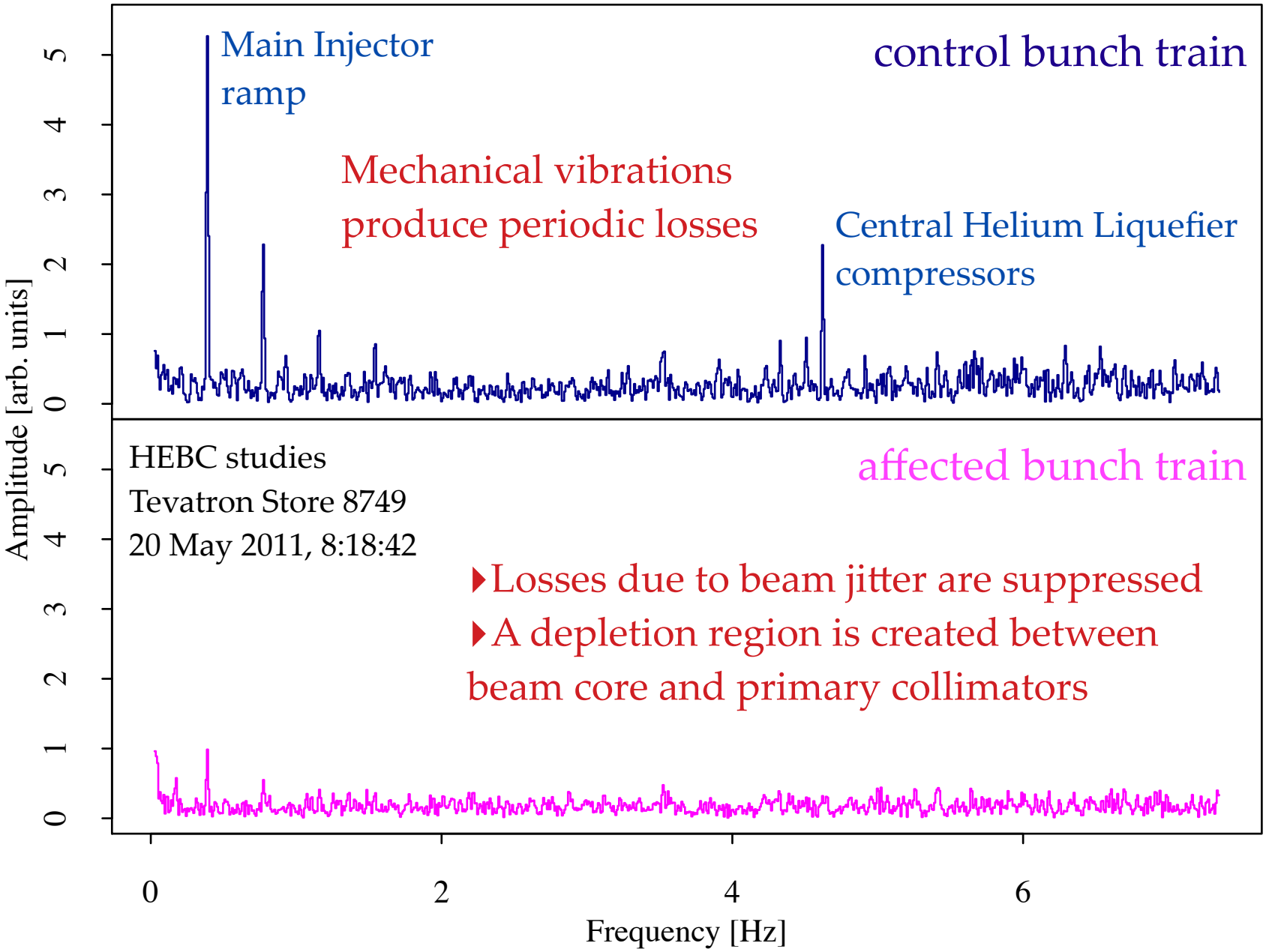
Particle fluxes before and after the step are determined by the steady-state loss levels

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



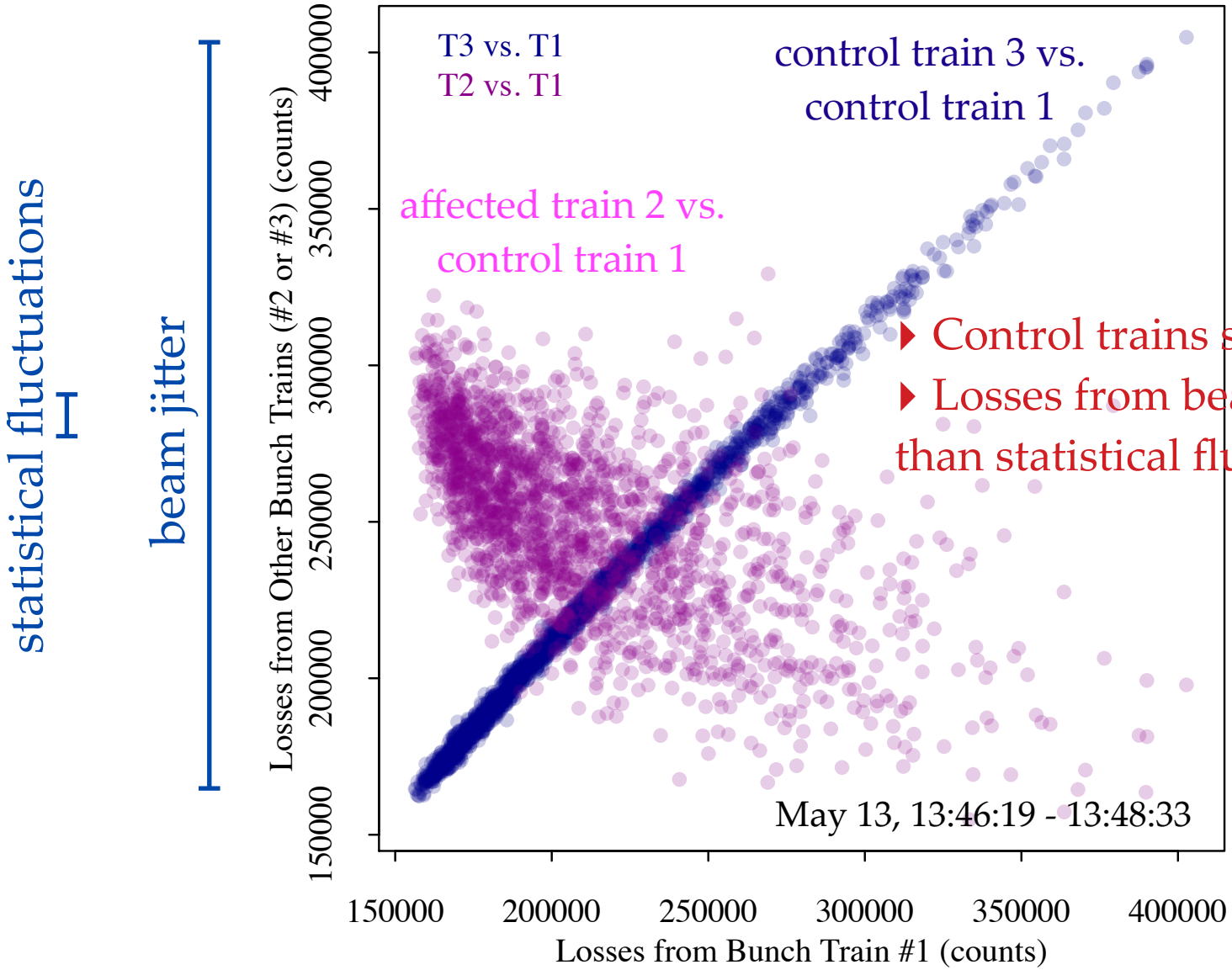
Large diffusion enhancement in halo region

Effect of hollow electron beam on periodic losses



- Losses due to beam jitter are suppressed
- A depletion region is created between beam core and primary collimators

Effect of hollow electron beam on loss correlations



- 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