Halo dynamics and control with hollow electron beams

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- ***Halo dynamics and accelerator performance***
- ***Measurements of halo diffusion with collimator scans***
- ***The hollow electron beam collimator***
- ***Effect of the hollow beam collimator on halo diffusion***

52nd ICFA Advanced Beam Dynamics Workshop on
High Intensity and High Brightness Hadron Beams (HB2012)
Beijing, China, 17-21 September 2012

Part I: Halo diffusion measurements

Halo dynamics and accelerator performance

Halo dynamics influences global accelerator performance

- beam lifetime
- emittance growth
- dynamic aperture
- collimation efficiency

intrabeam scattering

lattice resonances

beam-gas scattering

coupling

It depends on a multitude of effects, some of which are stochastic in nature

ground motion

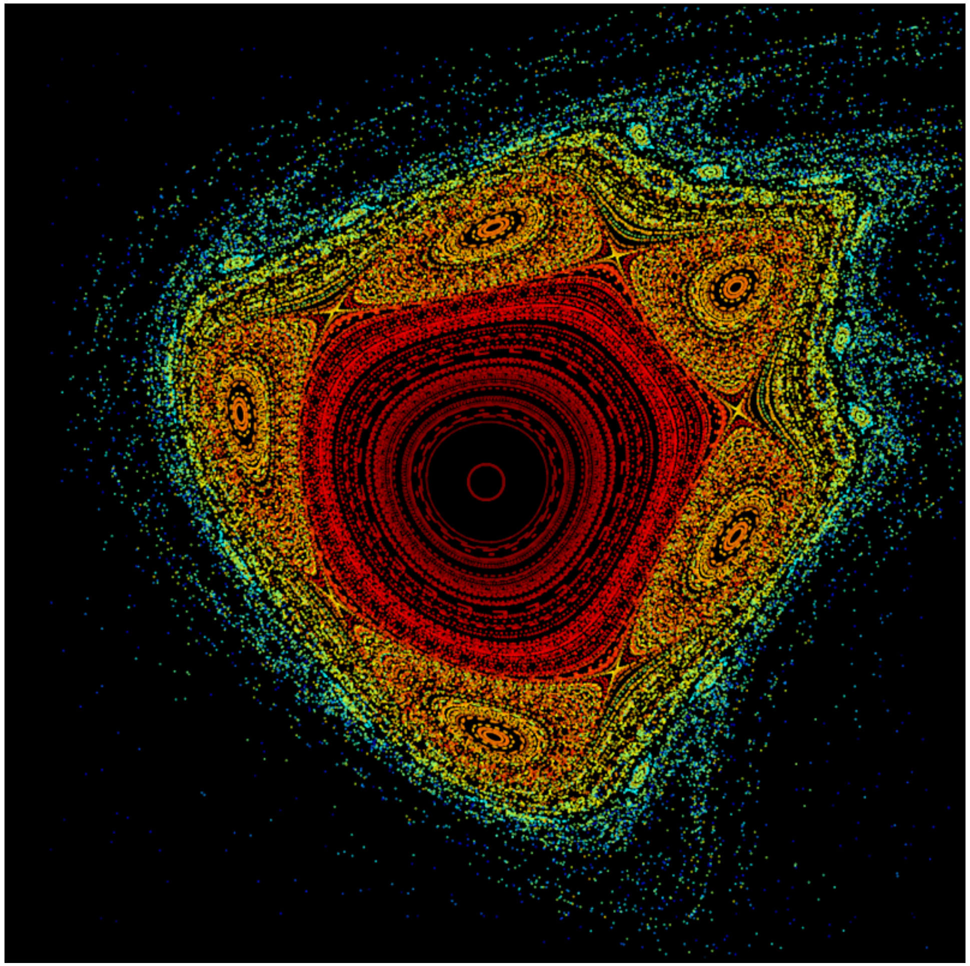
lattice nonlinearities

power-supply ripple

beam-beam forces

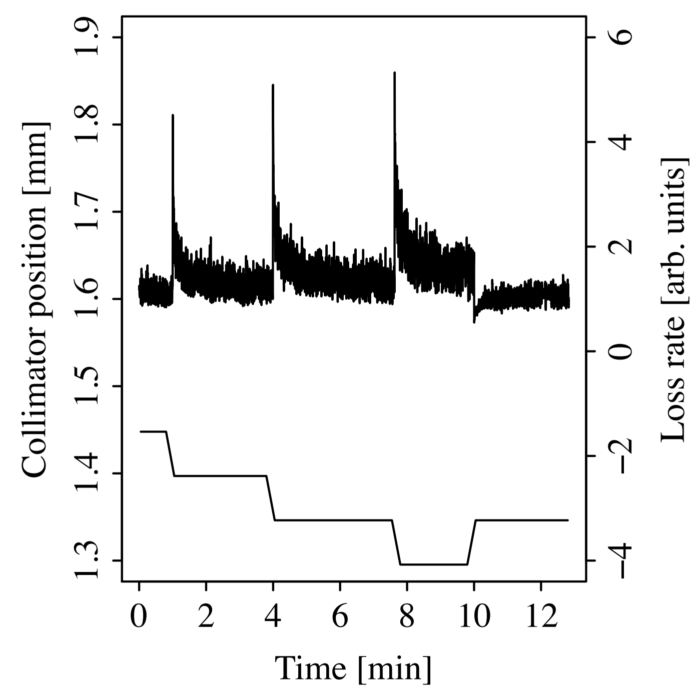
Stochastic character of halo dynamics

Dynamics is in general very rich

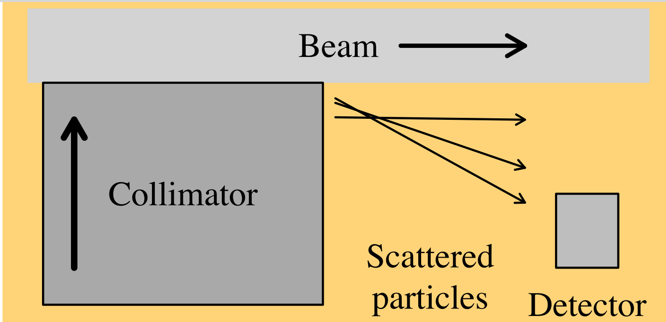


Superposition of many effects (some random) can make halo dynamics stochastic

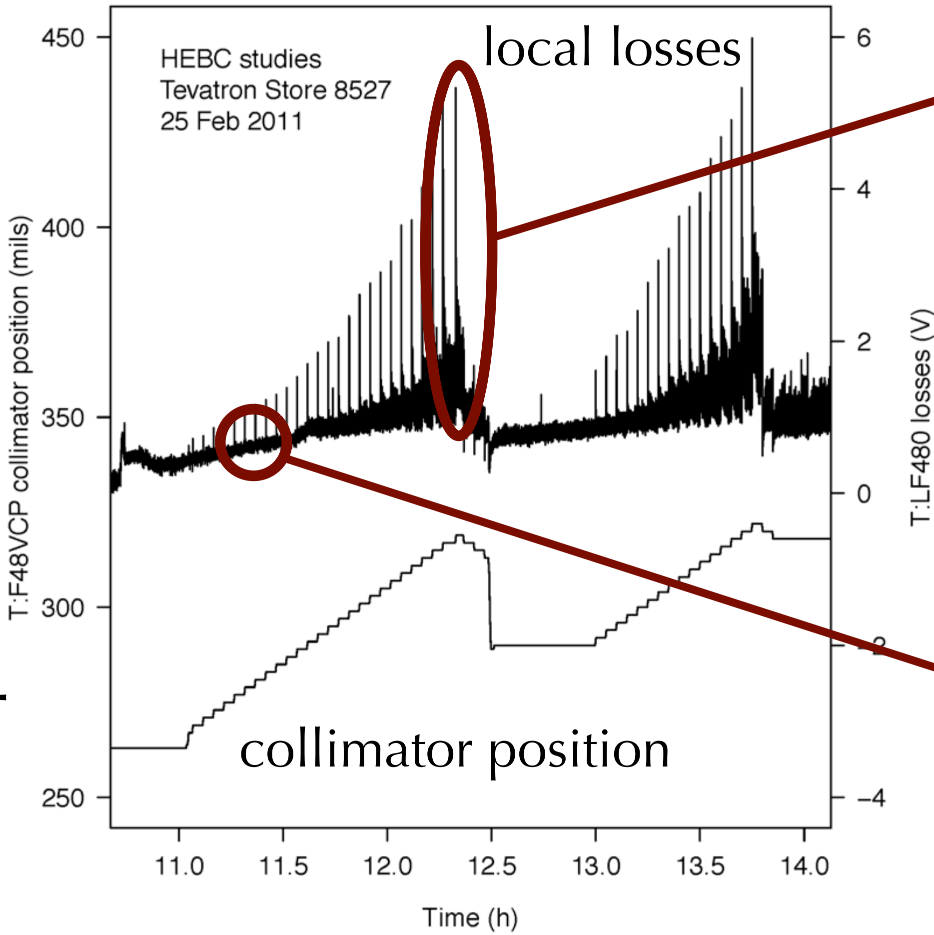
This is often empirically confirmed by relaxation of losses ~ 1/sqrt(t) during collimator setup



Diffusion rate vs. amplitude from collimator scans

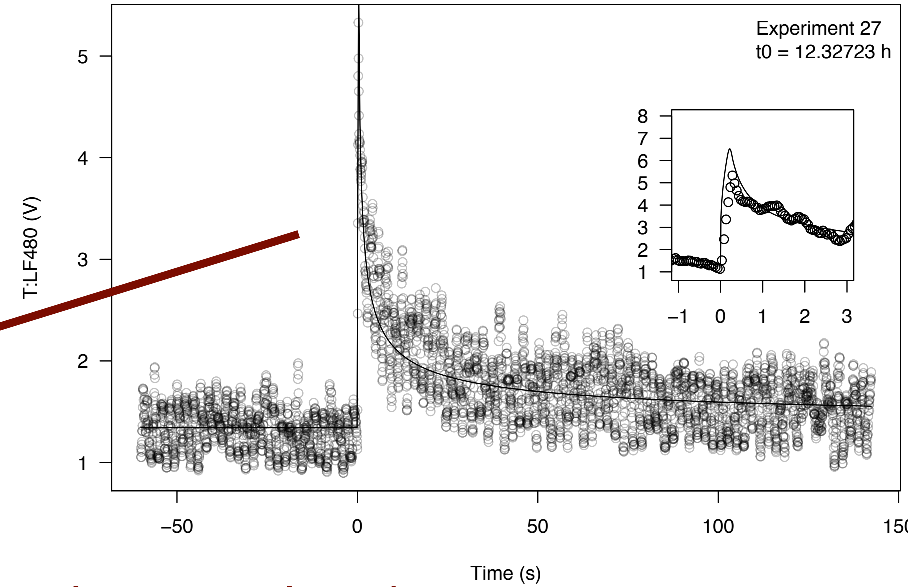


up towards beam axis

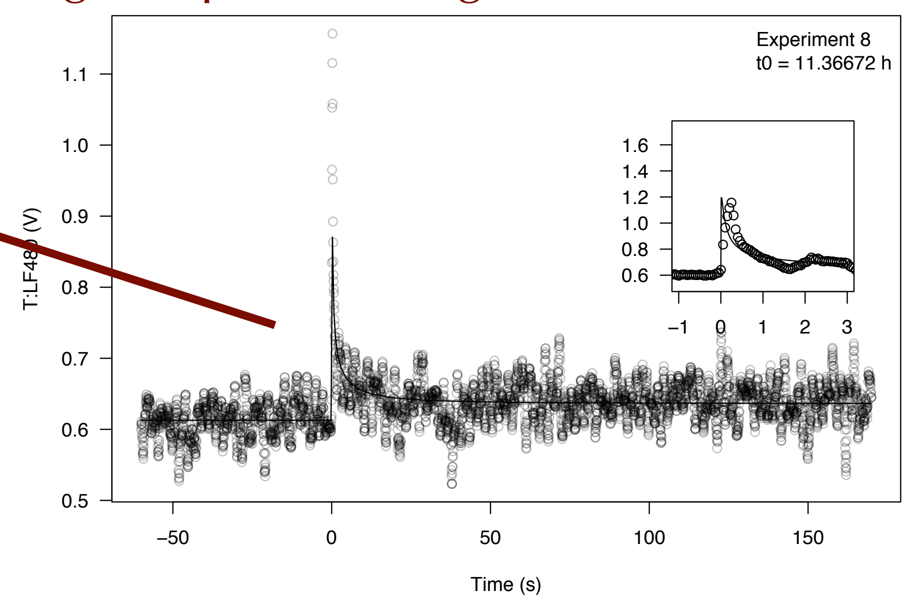


IPAC11, p. 1882
arXiv:1108.5010 [physics.acc-ph]

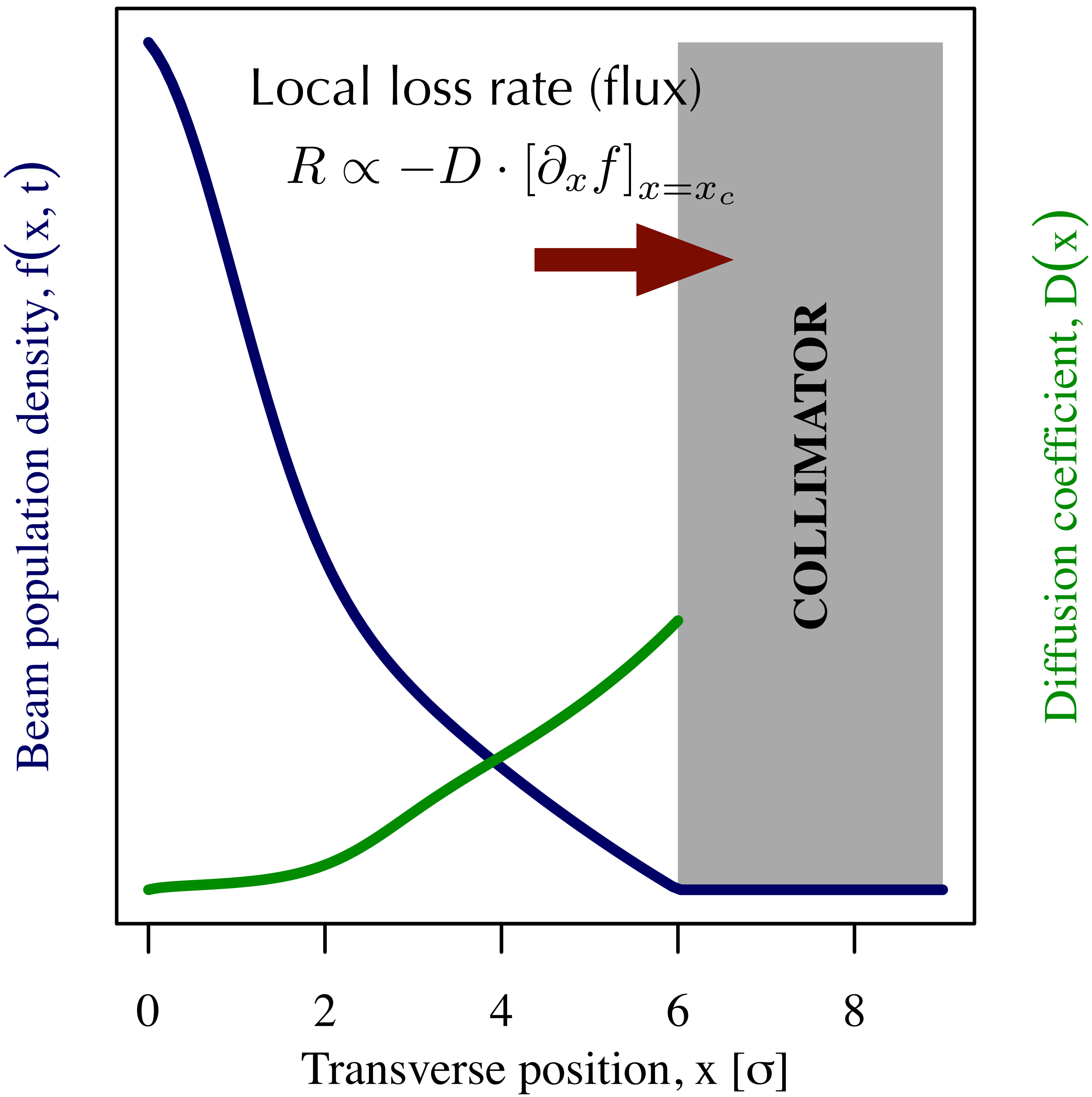
Mess and Seidel, NIMA **351**, 279 (1994)



Tails repopulate faster at large amplitudes (higher diffusion rate)



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

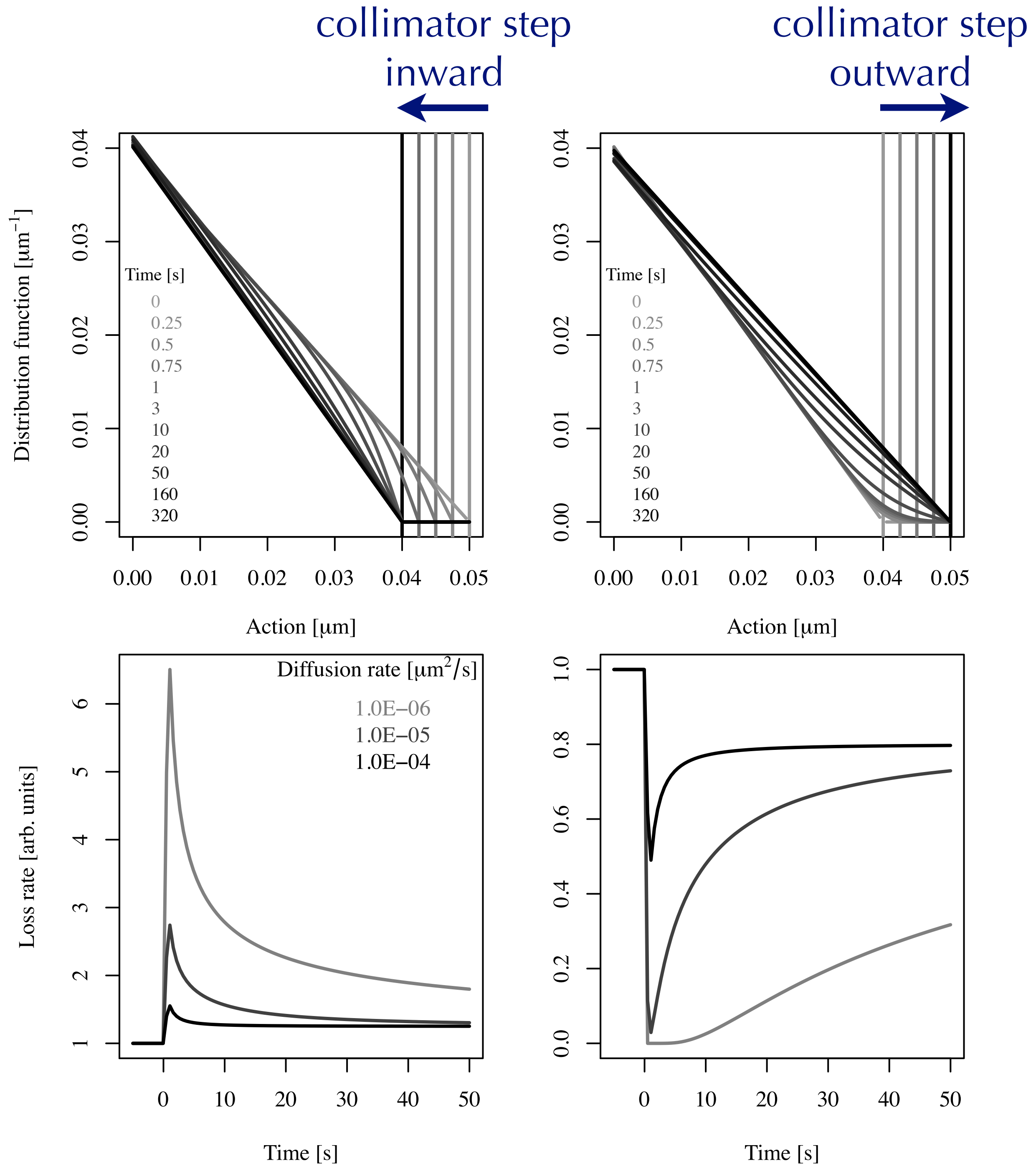
$$\partial_t f = \partial_J \left(D \cdot \partial_J f \right)$$

Instantaneous loss rate is proportional to slope of distribution function

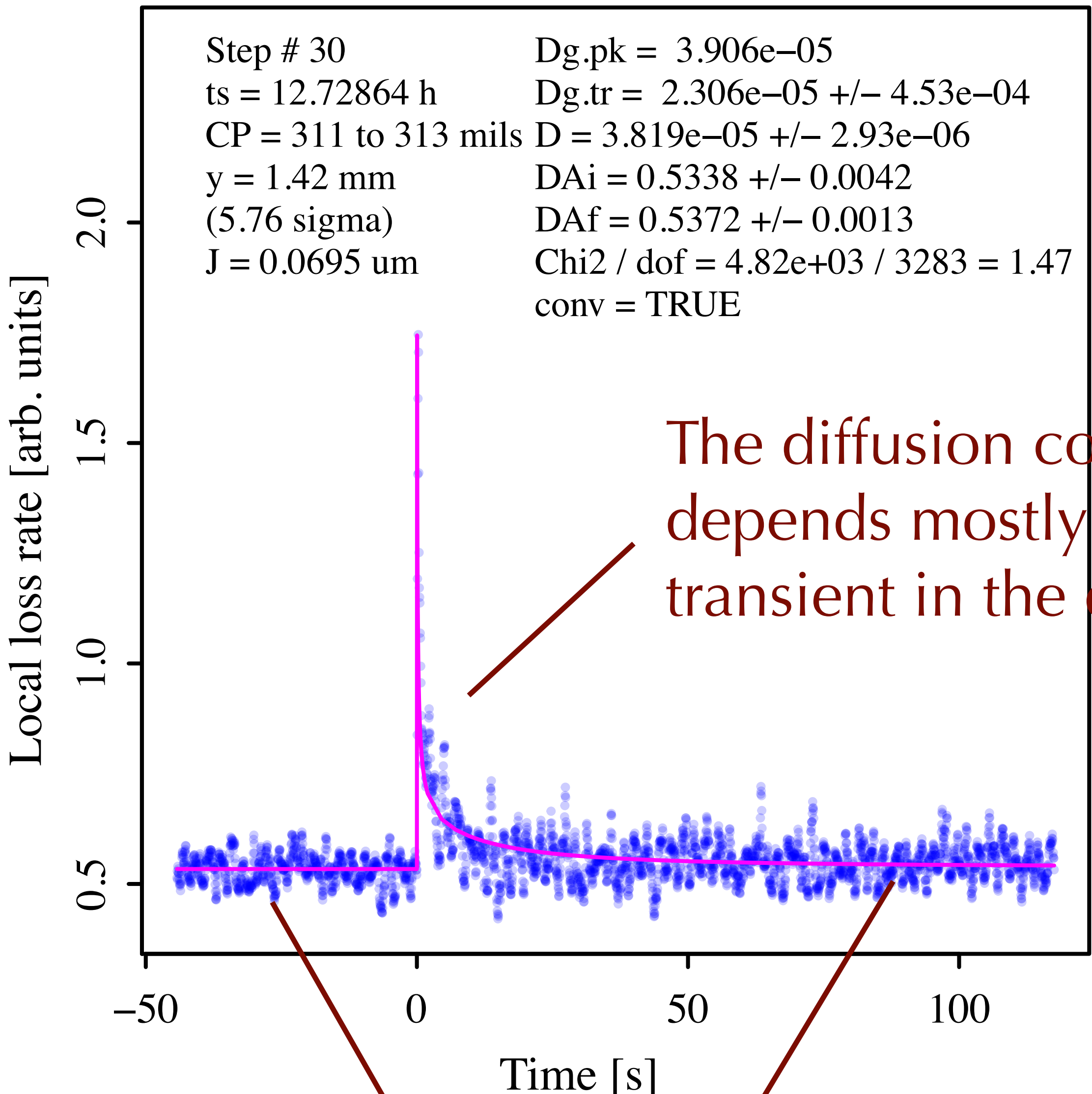
$$R = -k \cdot D \cdot [\partial_J f]_{J=J_c} + B$$

loss monitor calibration (k)

background rate (B)



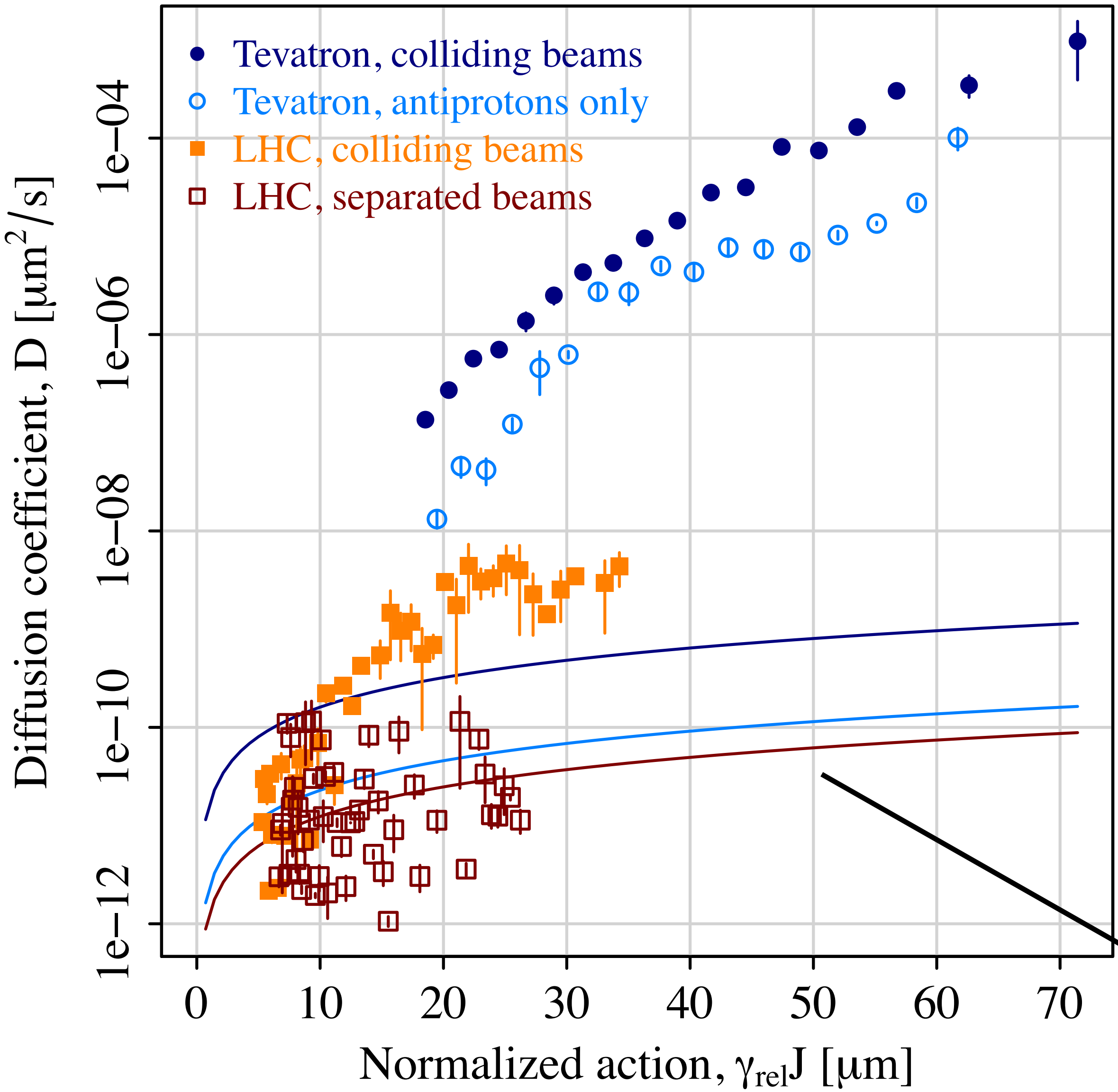
Diffusion model fit to loss rate data



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

Comparison of beam halo diffusion in the Tevatron and in the LHC



Effect of beam-beam is 1-2 orders of magnitude

Very low noise and nonlinearities in LHC

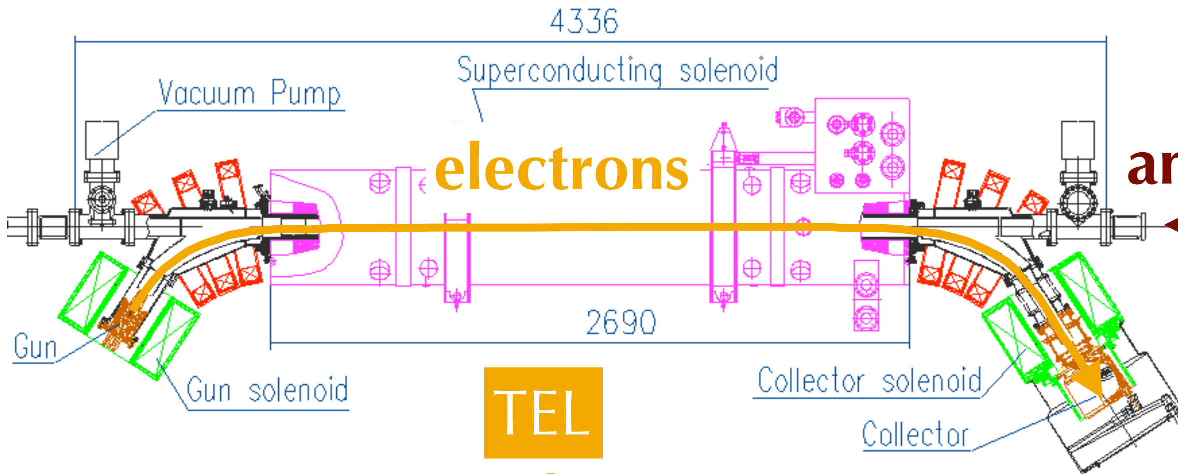
curves from measured core emittance growth

$$D(J) = \dot{\varepsilon} \cdot J$$

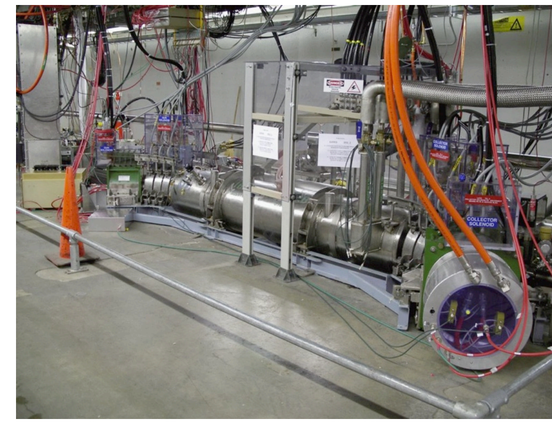
Part II: The hollow electron beam collimator and halo diffusion

Hollow beam collimation in the Tevatron: layout of the beams

protons



antiprotons



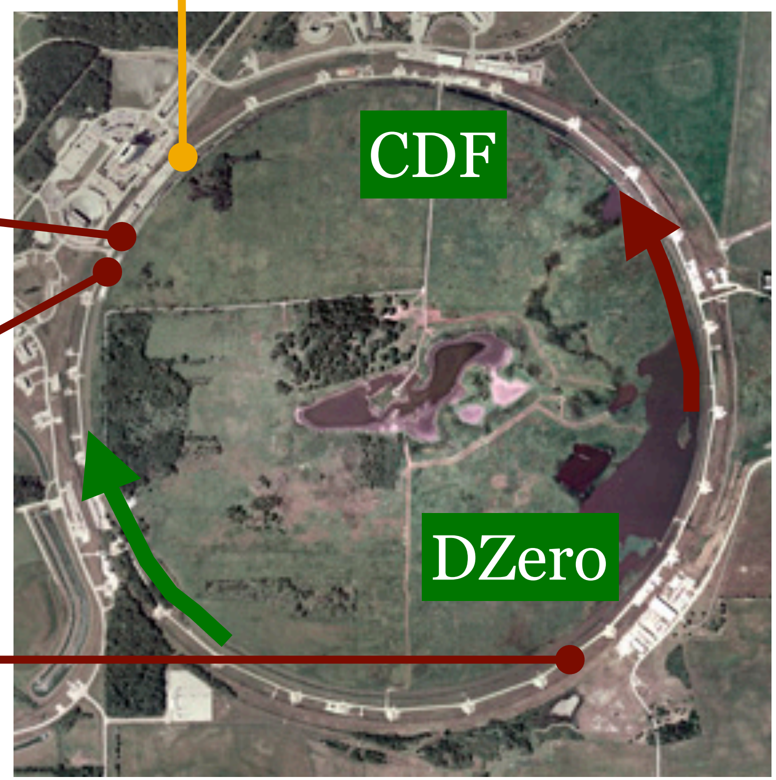
Tevatron electron lens (TEL2)

Antiproton collimators:

Primary (F49)

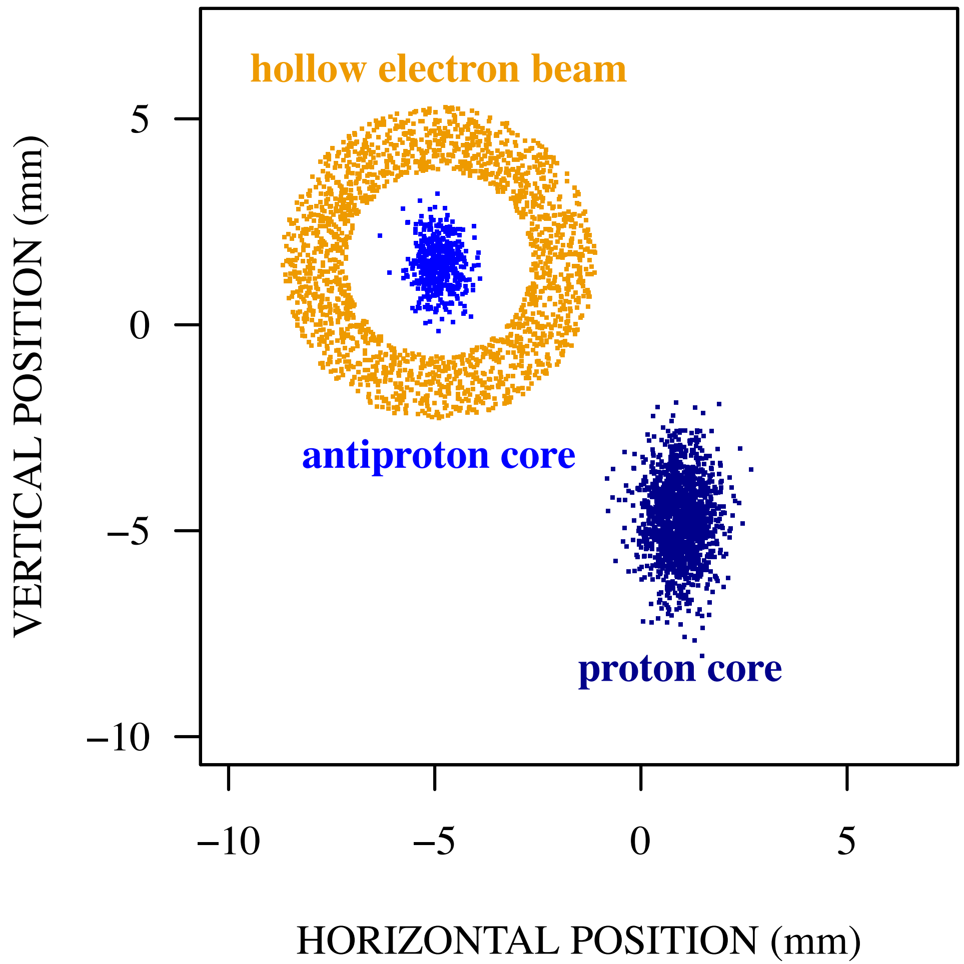
Secondary (F48)

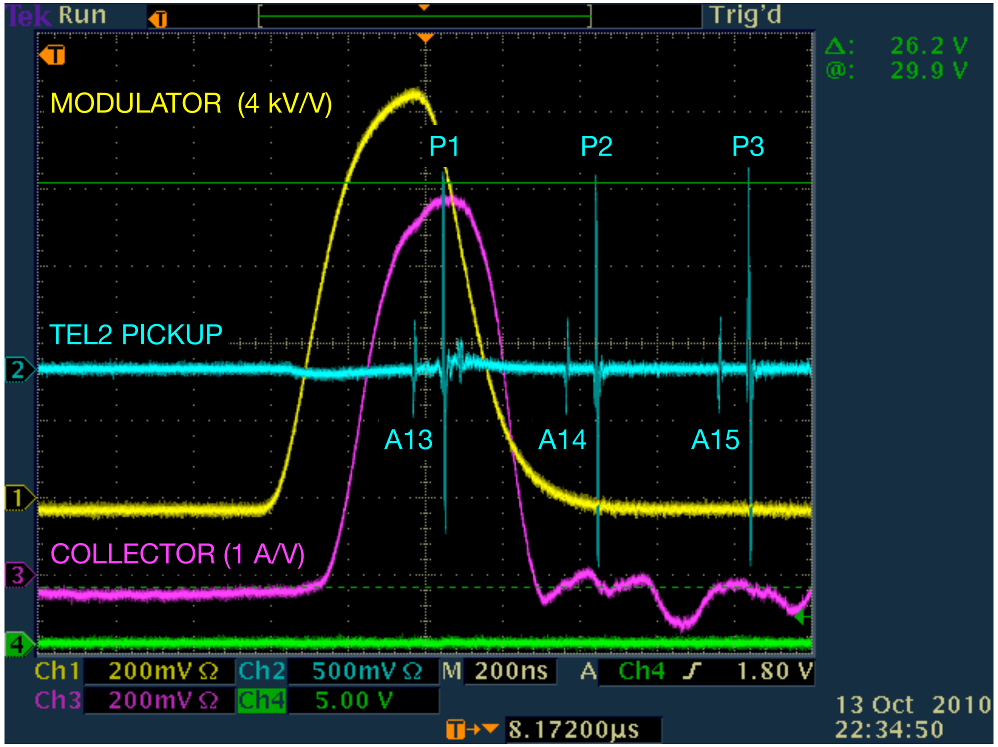
Secondary (D17)



Hollow beam collimation in the Tevatron: layout of the beams

Transverse view





Pulsed electron beam
could be synchronized
with any group of bunches

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

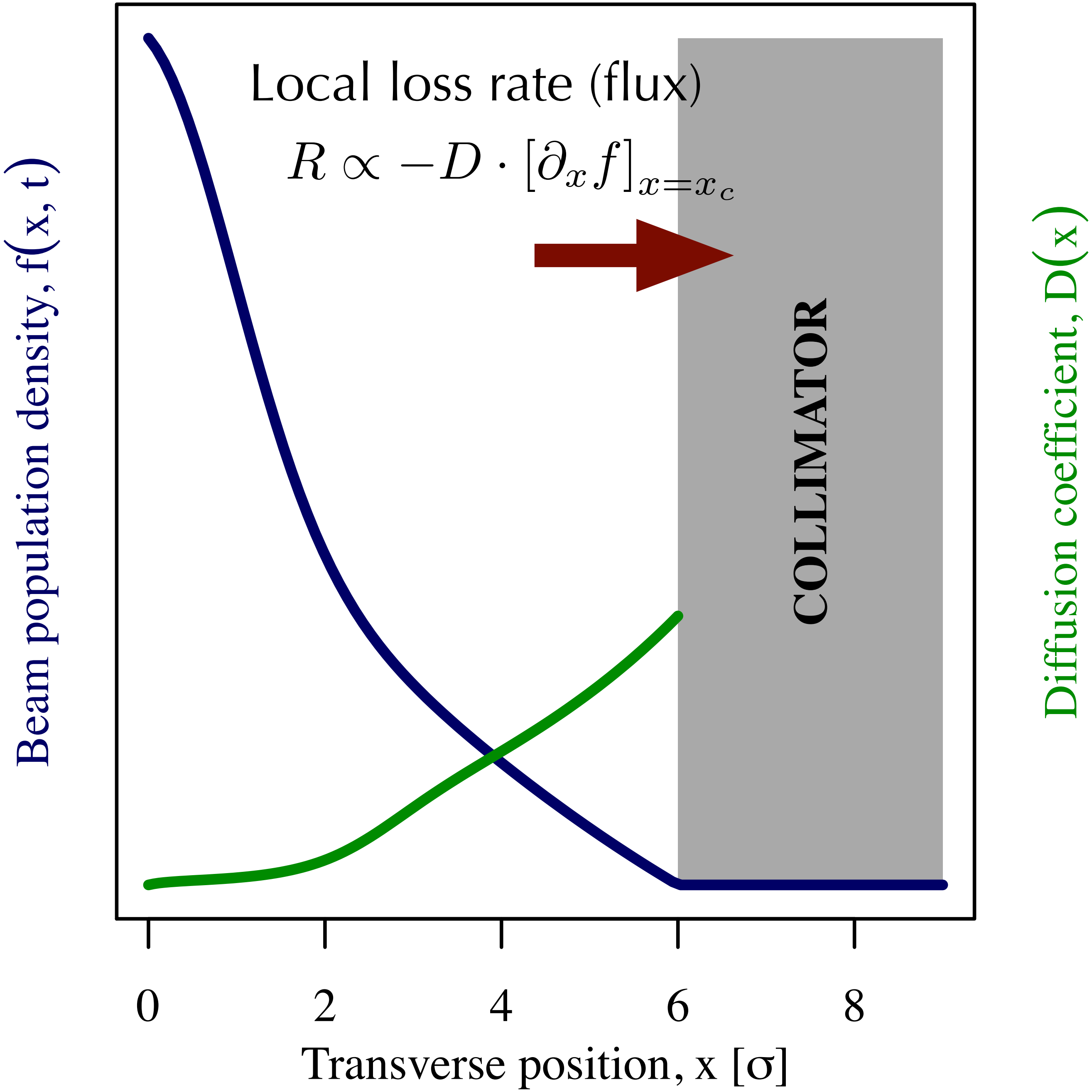
- Can be close to or even overlap with the main beam
  - no material damage
  - tunable strength (“variable thickness”)
- Works as “soft scraper” by enhancing diffusion
- Low impedance
- Resonant excitation is possible (pulsed e-beam)
- No ion breakup
- Position control by magnetic fields (no motors or bellows)
- Established electron-cooling / electron-lens technology

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

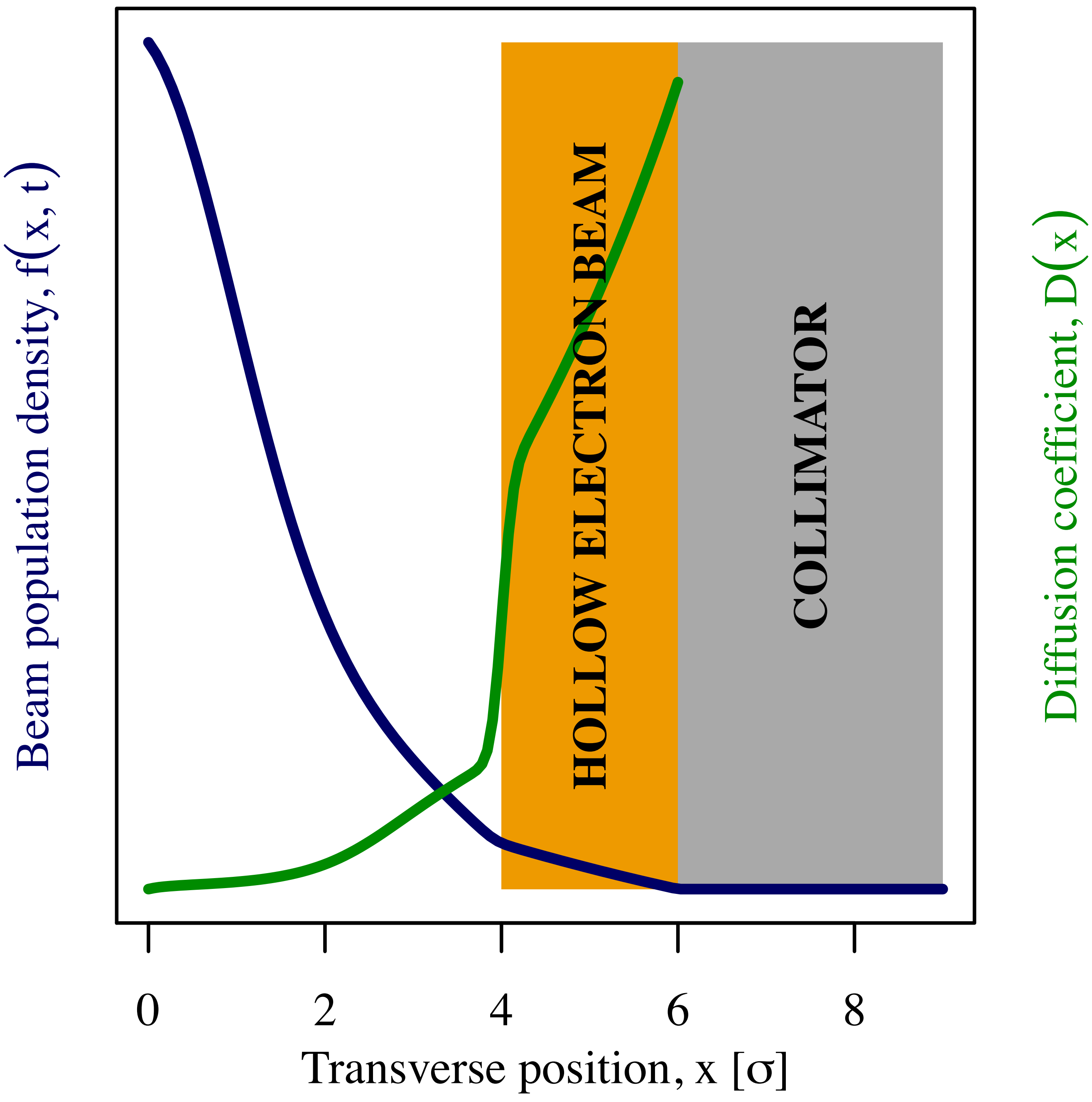
Experimental studies of hollow electron beam collimation

- 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** ← focus of this part of the talk
- First results:
  - Phys. Rev. Lett. **107**, 084802 (2011)
  - IPAC11, p. 1939
  - APS/DPF Proceedings, arXiv:1110.0144 [physics.acc-ph]

1-dimensional diffusion cartoon of collimation



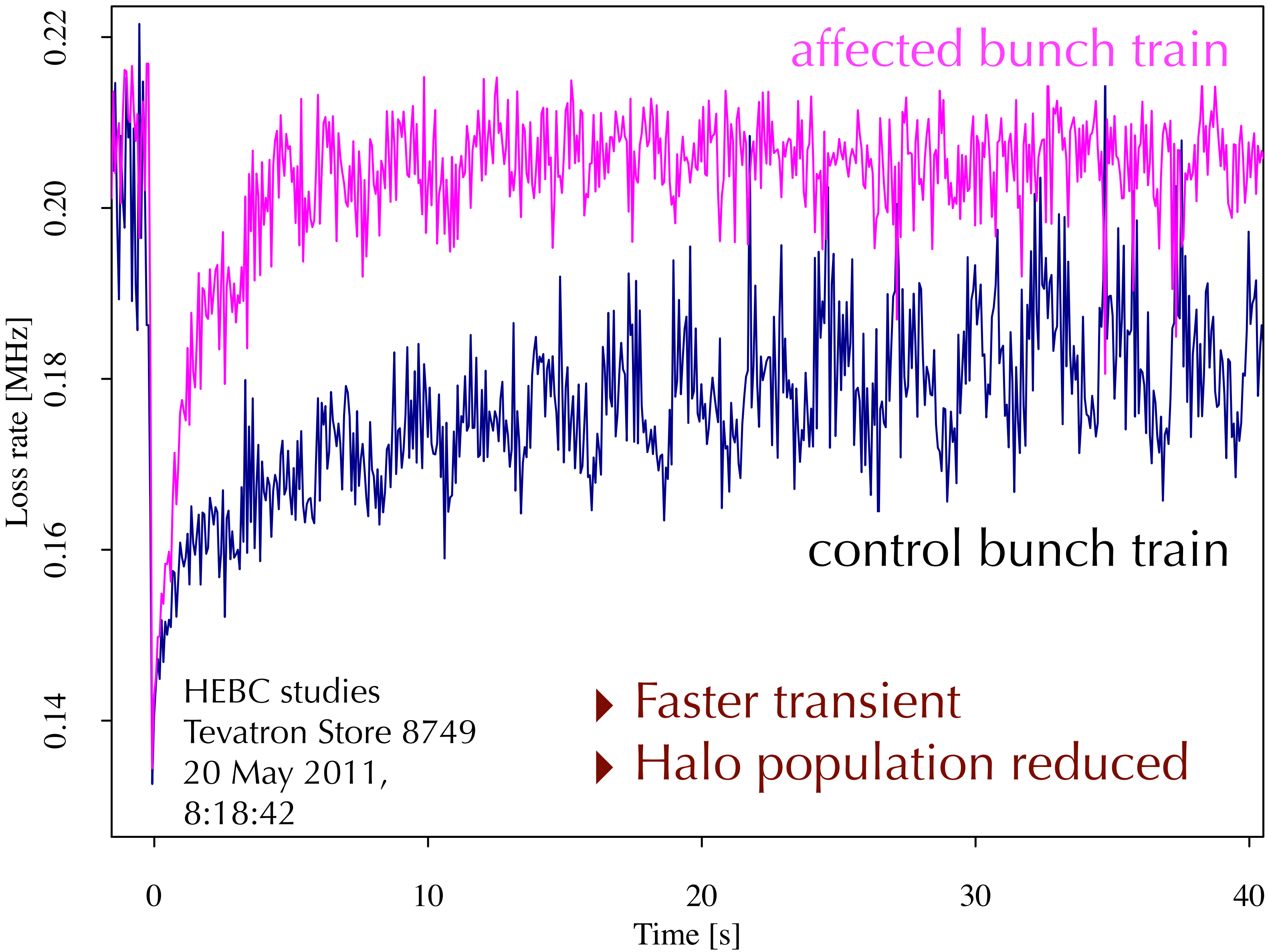
1-dimensional diffusion cartoon with hollow electron beam



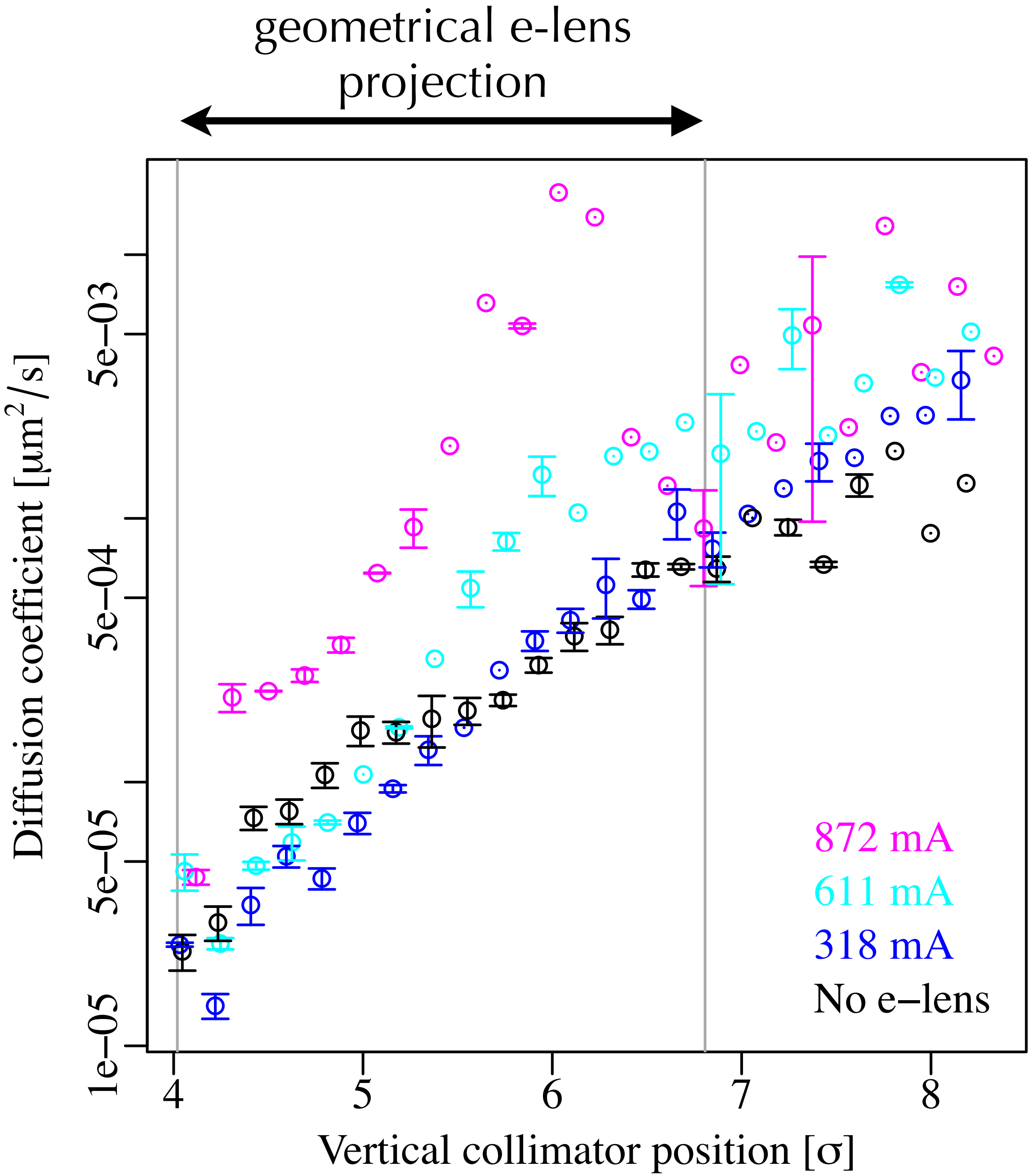
Measured effect of the hollow electron lens on diffusion in the Tevatron

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

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



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



Large diffusion enhancement in halo region

Application to the LHC and other facilities?

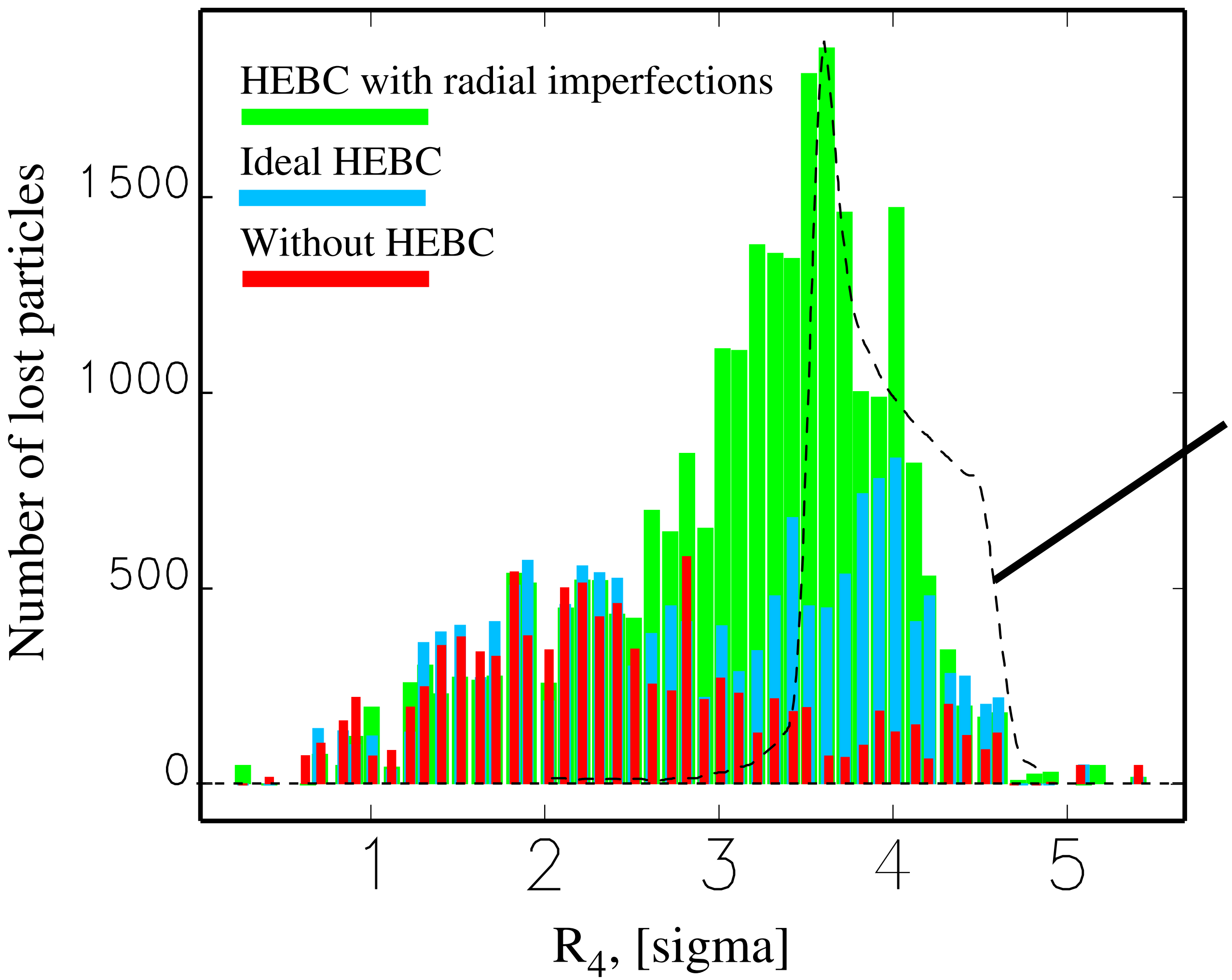
Numerical simulations
- Understanding of Tevatron observations
- Predictions for SPS and LHC
- Main observables
  - halo removal rates
  - diffusion enhancement

Development of **hollow electron guns**
- Improve design/testing technology
- Produce prototypes for LHC

Study possible TEL2 **integration in LHC or SPS**
- Preparatory work at FNAL
- Scientific and technical aspects

Lifetrac simulation of removal rates in the Tevatron

Which particles are removed?

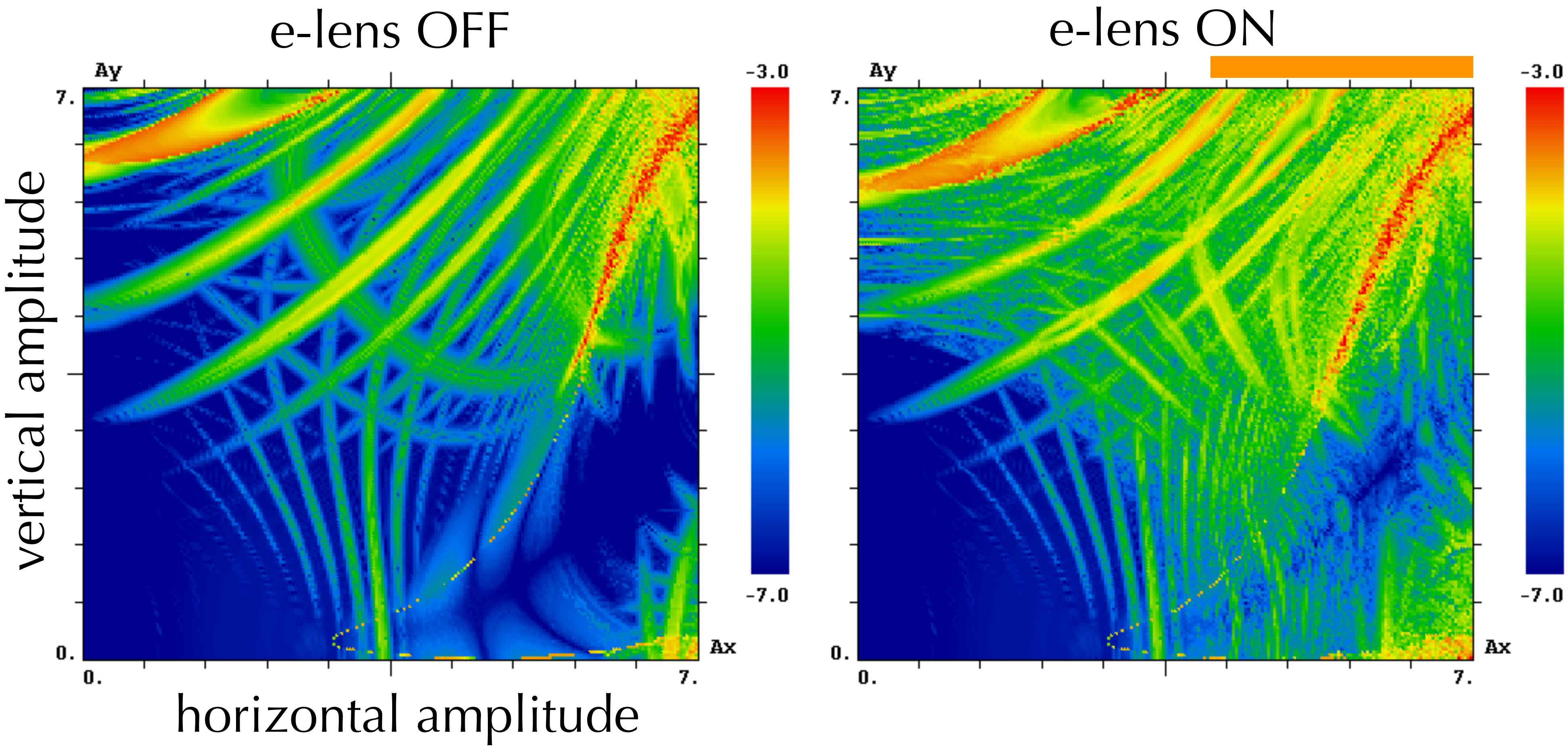


Initial 4D amplitude of lost particles

Particles removed from halo

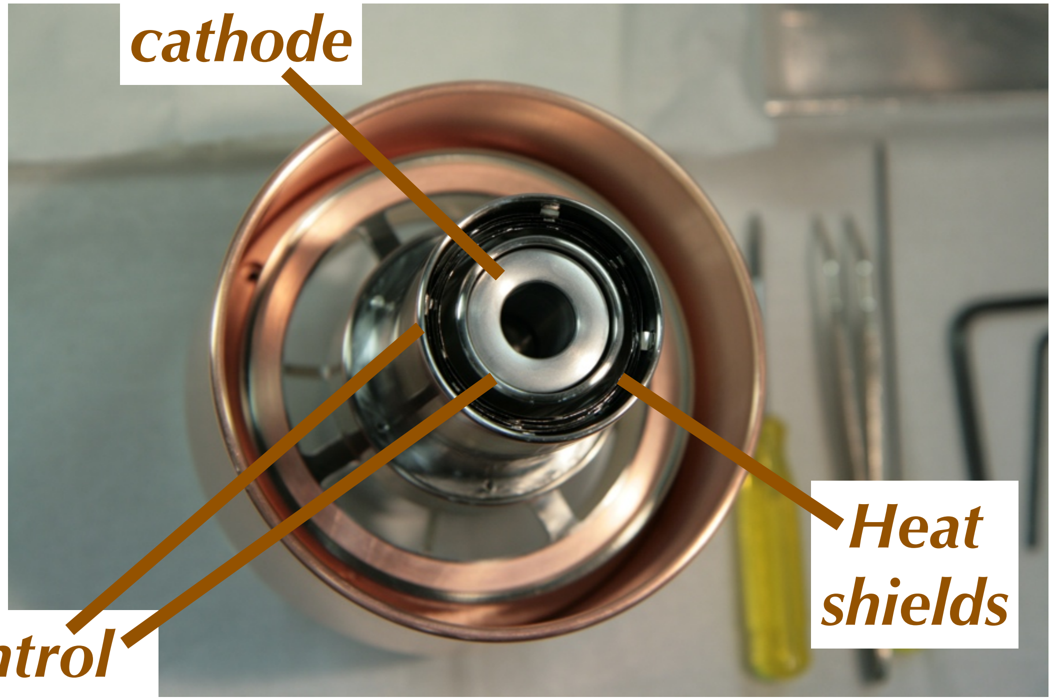
Halo removal sensitive to radial profile and halo population, which are hard to measure

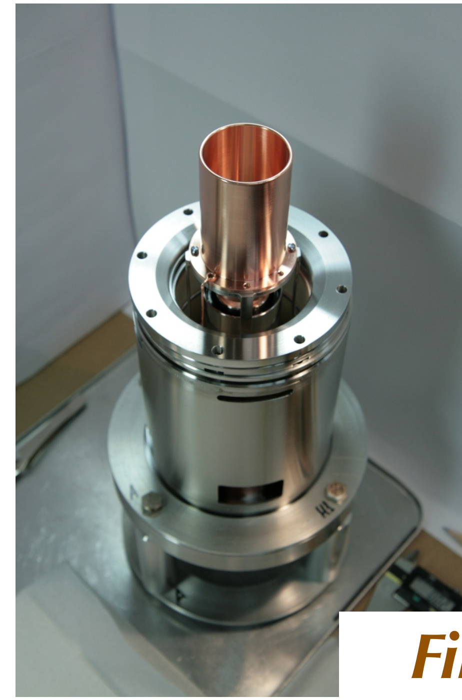
Lifetrac simulation: example of effects of hollow electron beam in LHC



Frequency map analysis (FMA) shows new resonances and increased tune jitter for particles between 4 and 6 sigma

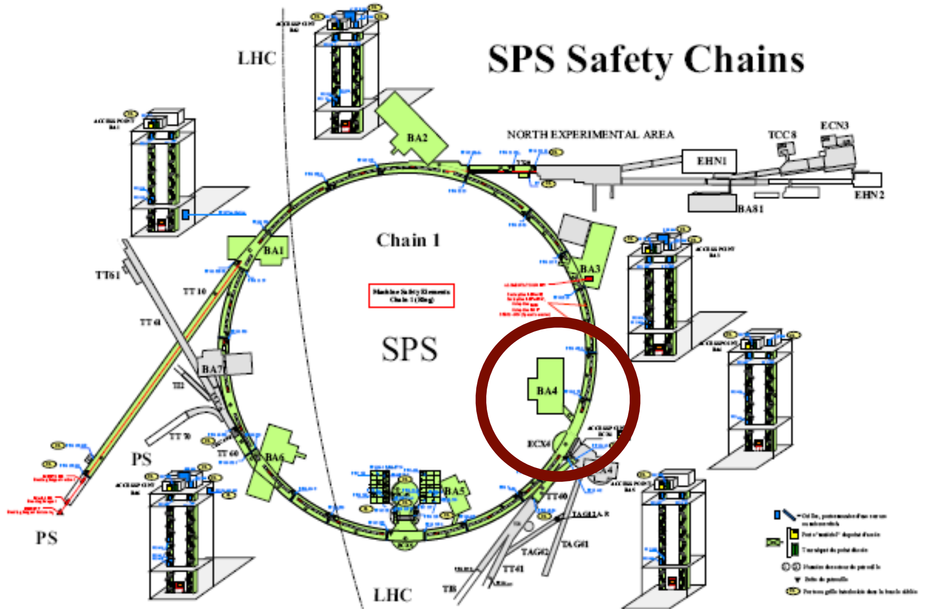
New 25-mm hollow gun

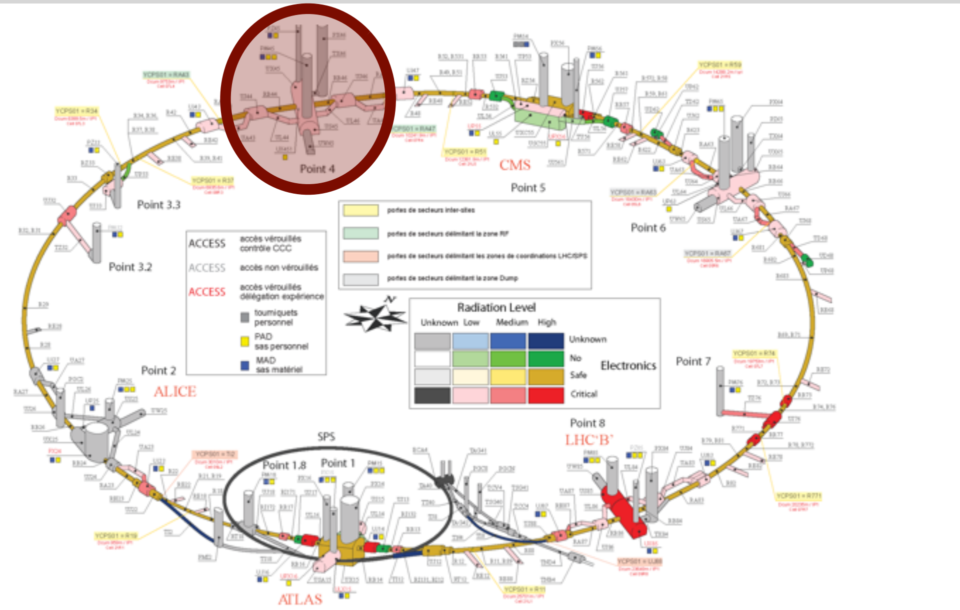




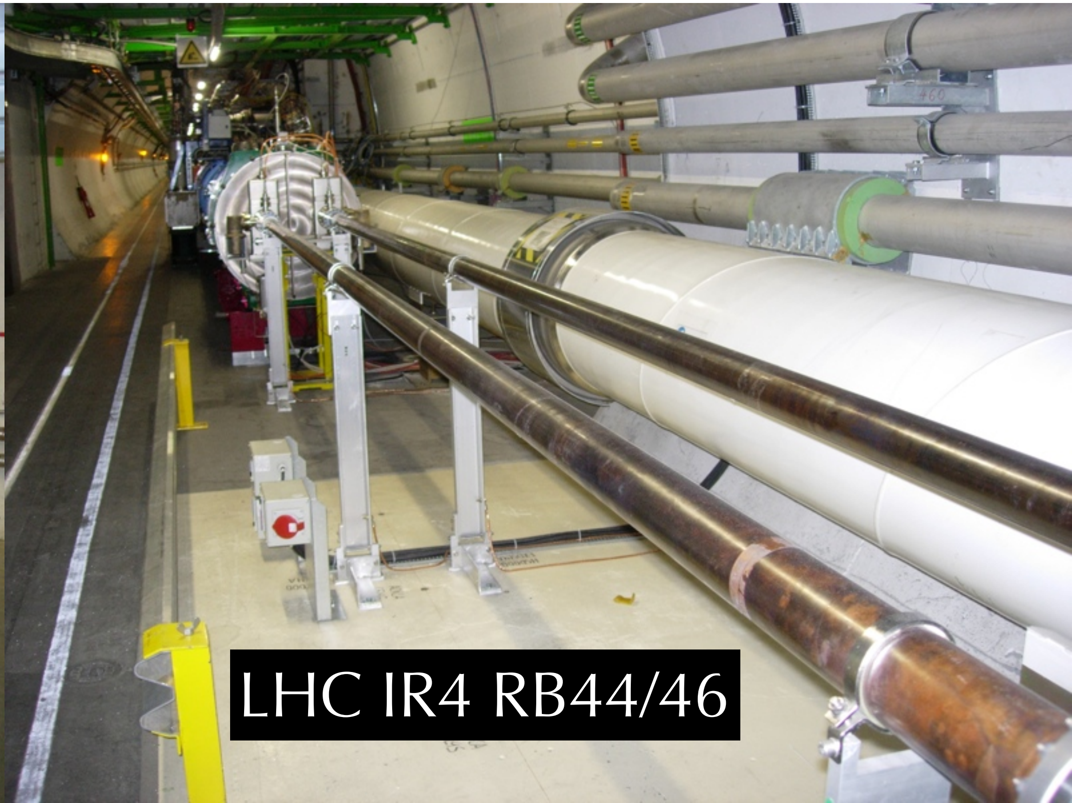
- 25 mm outer diameter, 13.5 inner diameter
- Designed with LHC in mind: 2.2 A at 5 kV, 6.3 A at 10 kV
- Goal: test technical feasibility of larger and stronger scraper
- Characterized at Fermilab electron-lens test stand

Candidate locations for electron lens in SPS and LHC





SPS BA4 COLDEX installation


LHC IR4 RB44/46

Conclusions

- **Halo dynamics** is often **stochastic**, due to the nature and number of effects in real machines
- **Collimator scans** are a sensitive tool for the study of **halo diffusion vs. amplitude**:
  - diffusion coefficients
  - beam populations
  - lifetimes/fluxes
  - impact parameters
  - collimation efficiencies
- **Magnetically confined hollow electron beams** are a safe and flexible technique for **halo control in high-power accelerators**
  - Tevatron experiments provided experimental foundation
  - diffusion enhancement presented here
  - application to LHC being investigated
  - benefits for other facilities?

Thank you!