Beam-beam compensation studies at the Tevatron with electron lenses

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Outline

Introduction

General features of electron lenses

Beam-beam compensation studies

Other electron lens applications

- abort-gap clearing
- hollow electron beam collimation

Conclusions

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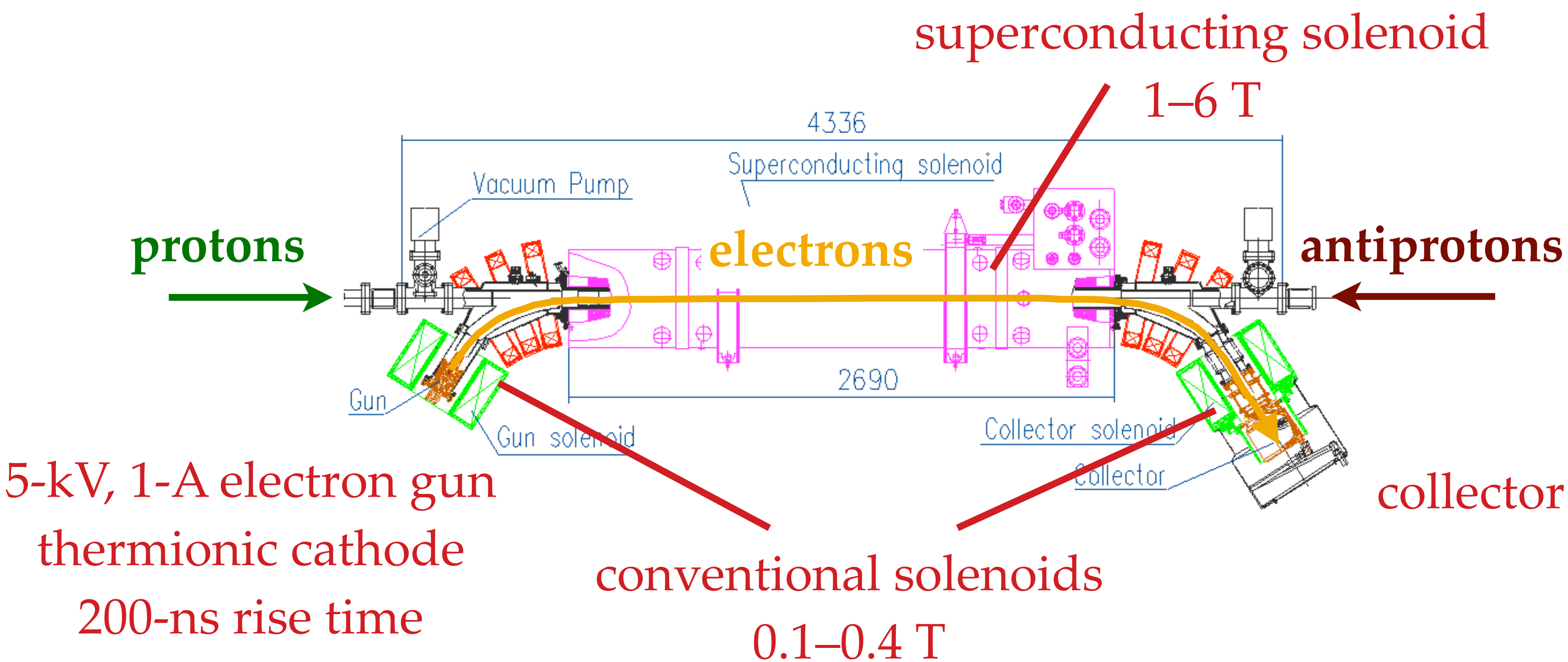
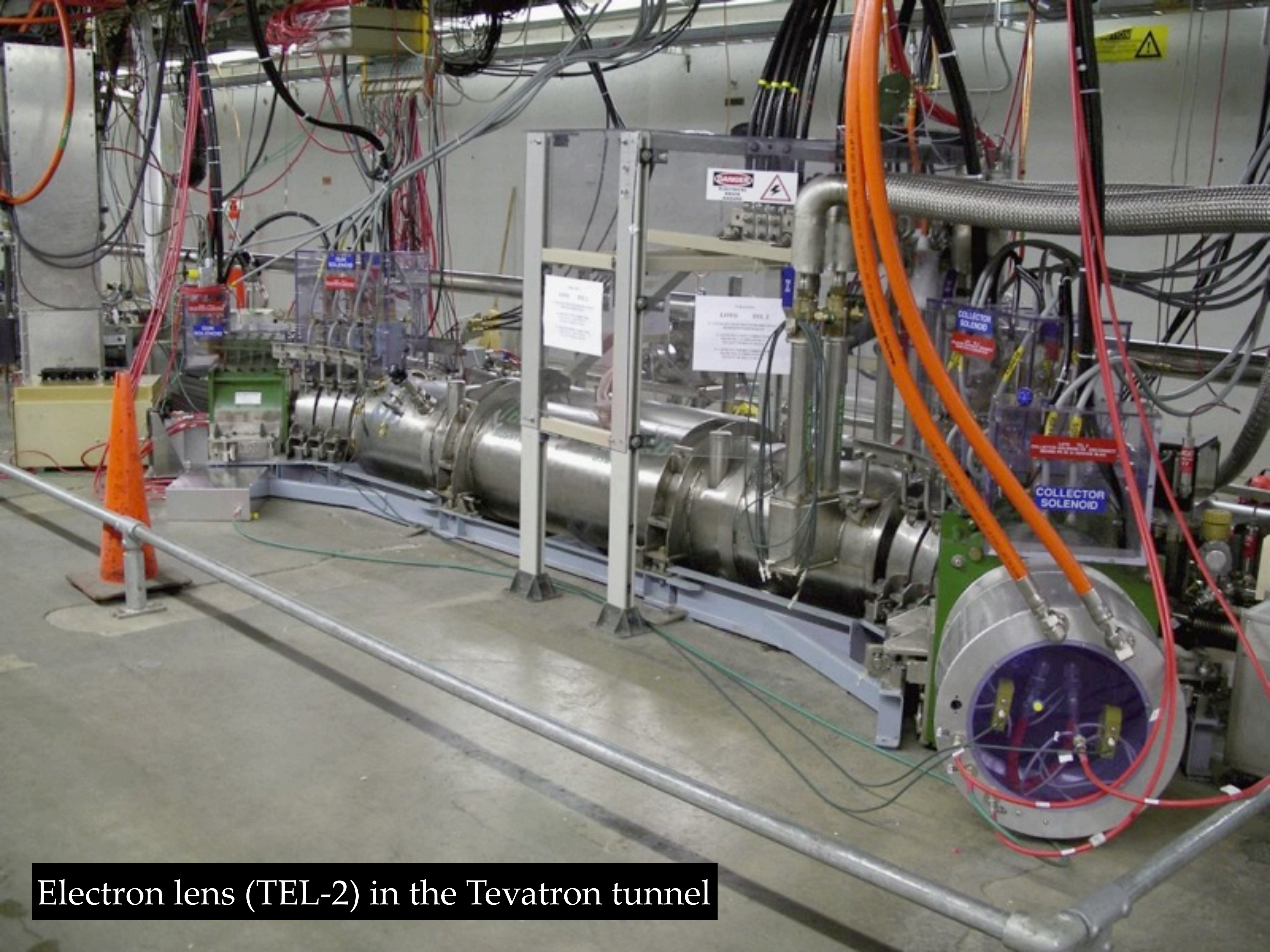
Tevatron electron lenses (TEL)

Proposed in 1990s for beam-beam compensation in colliders
Based on electromagnetic field generated by electron beam
Stability provided by strong axial magnetic fields



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

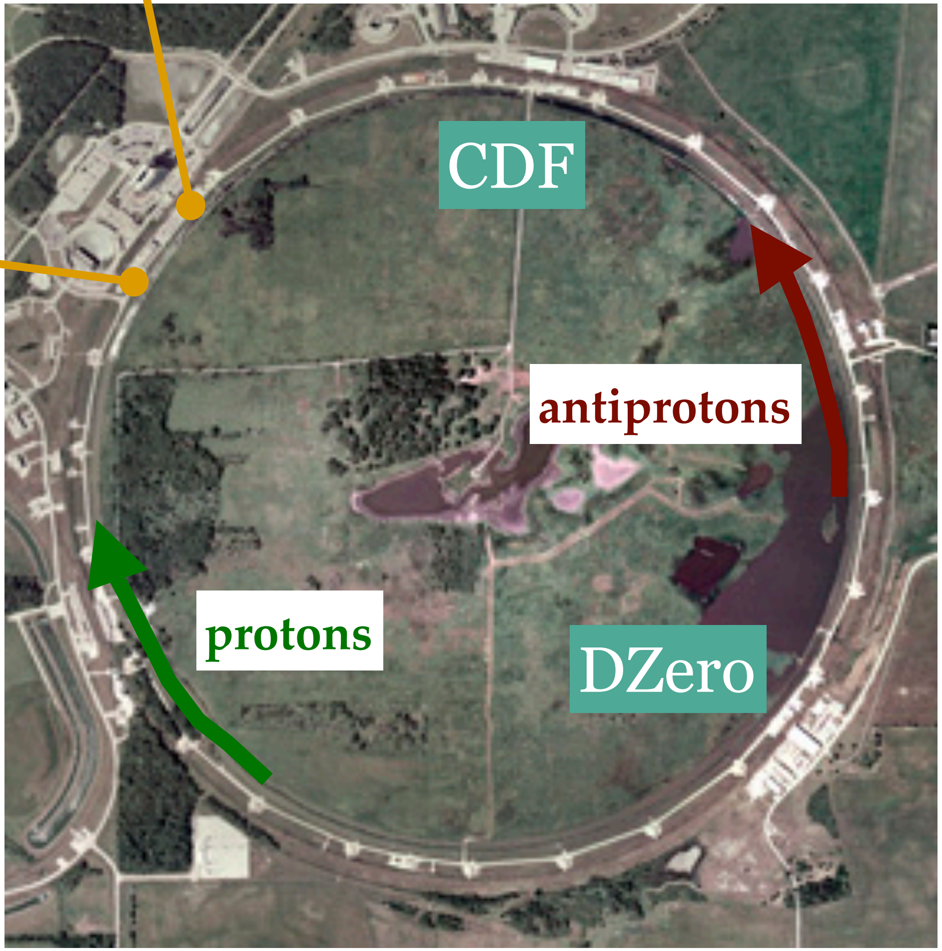
Electron lenses in the Fermilab Tevatron collider

TEL-2

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

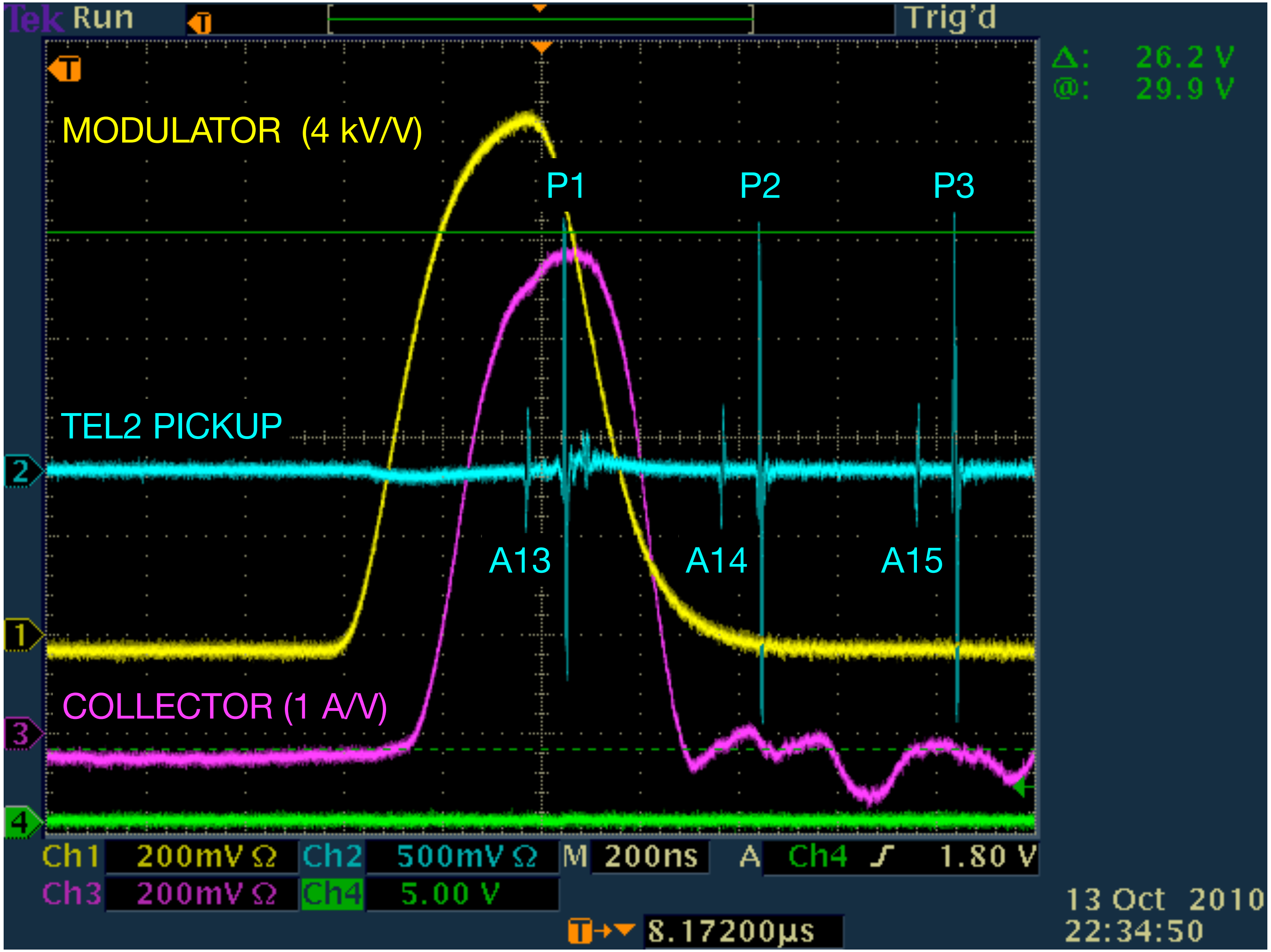
TEL-1

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



Pulsed operation of the electron lens

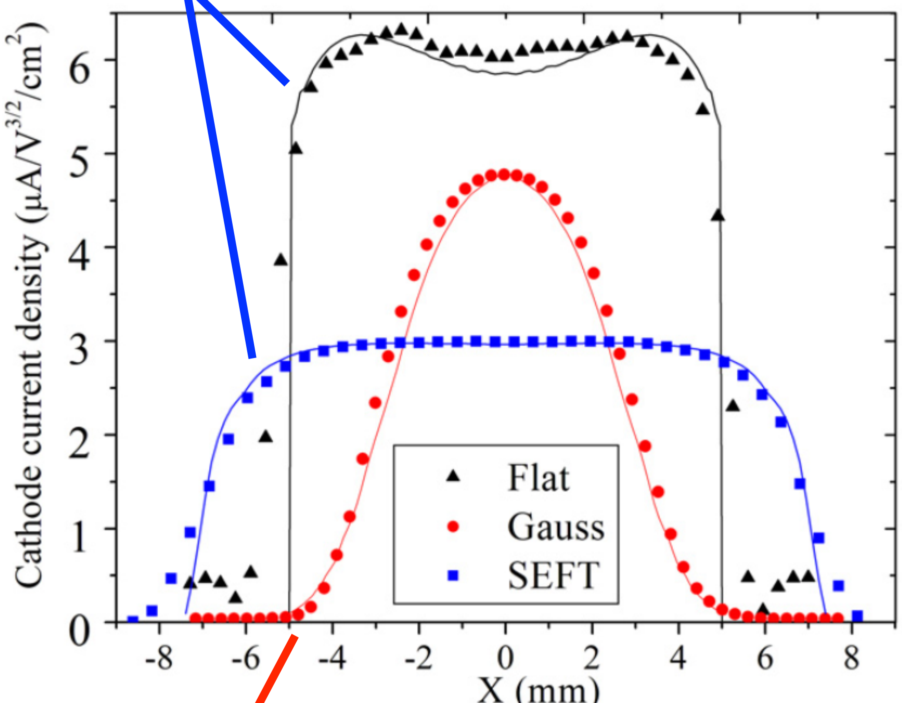
Pulsed electron beam could be **synchronized** with any group of bunches



Profile control of the electron beam

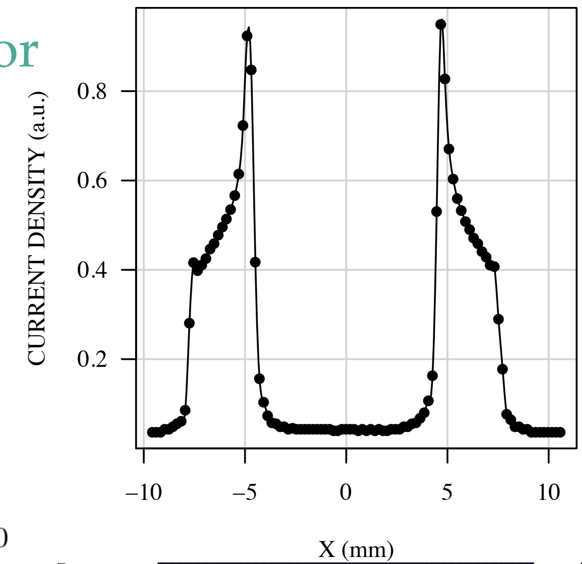
- Current density profile shaped by electrode geometry/potentials
- Maintained during transport by strong solenoidal fields
- Different electron guns for different purposes

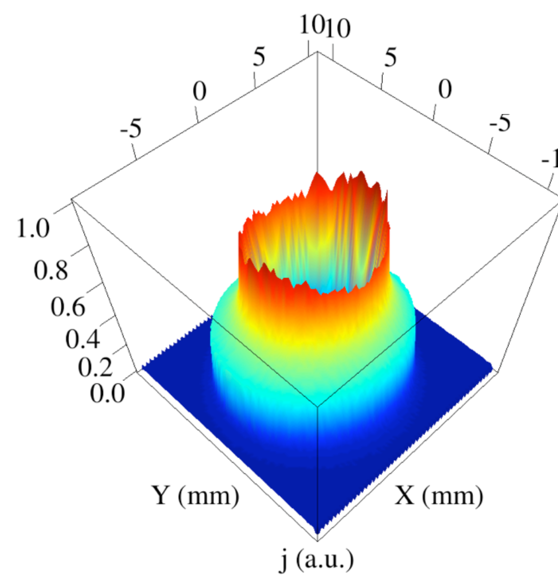
Flat profiles for bunch-by-bunch betatron tune correction

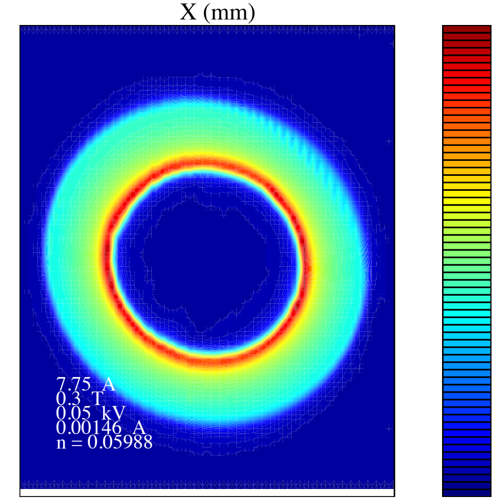


Gaussian profile for compensation of nonlinear beam-beam forces

Hollow profile for halo scraping

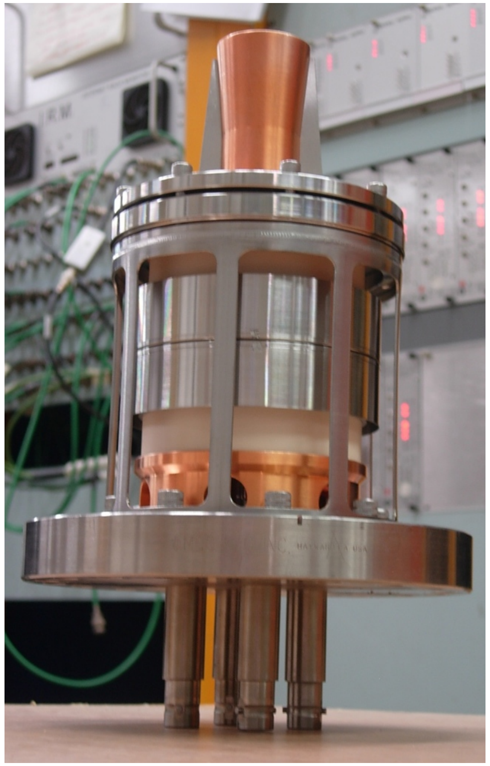




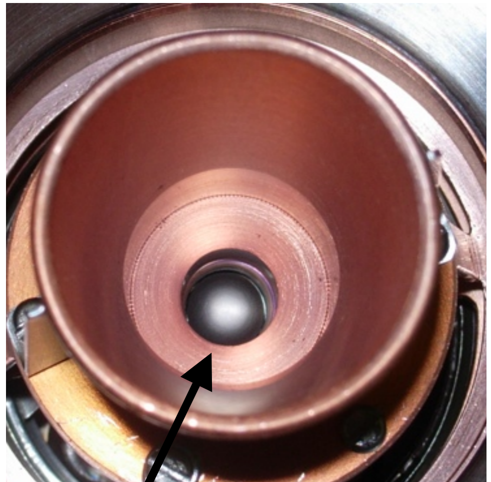


The 10.2-mm Gaussian electron gun

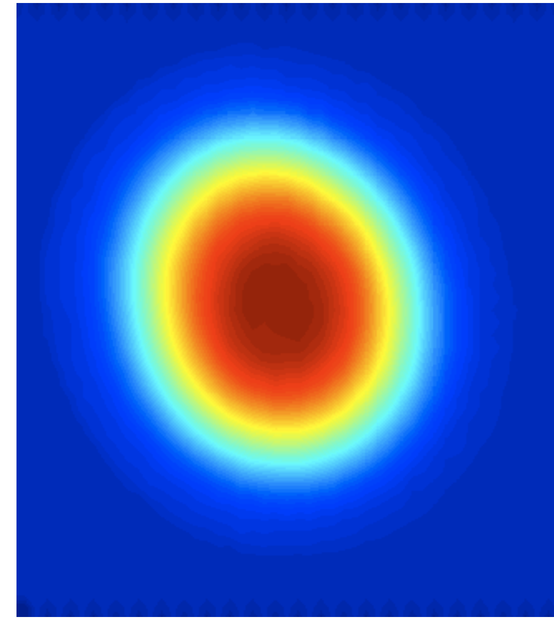
side view



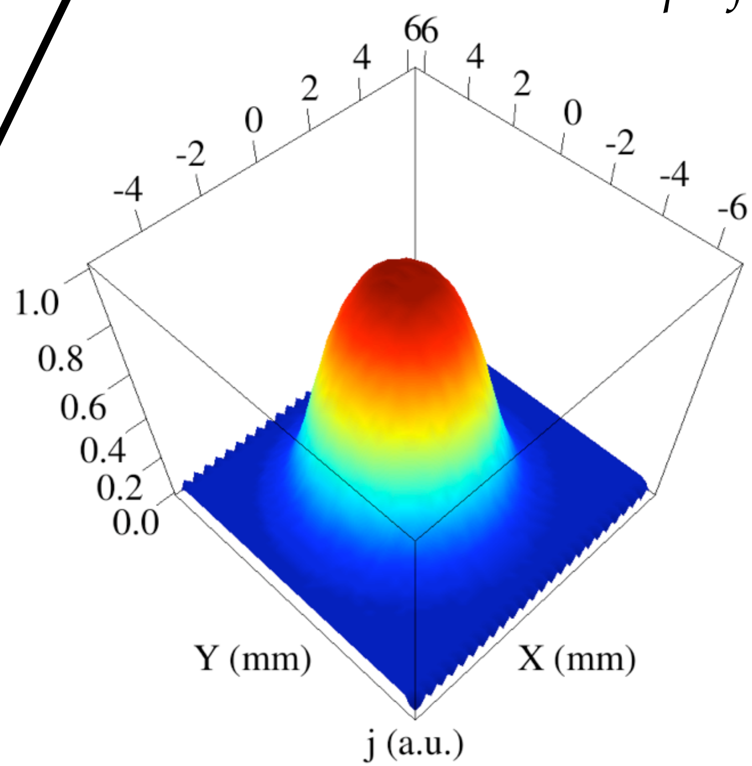
top view

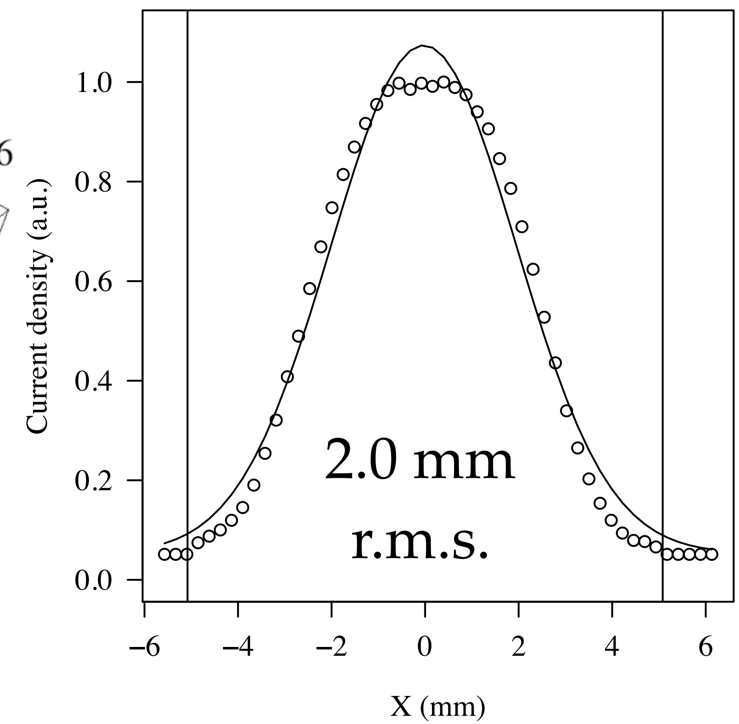


Tungsten dispenser cathode with convex surface operating at 1100°C



Measured profiles

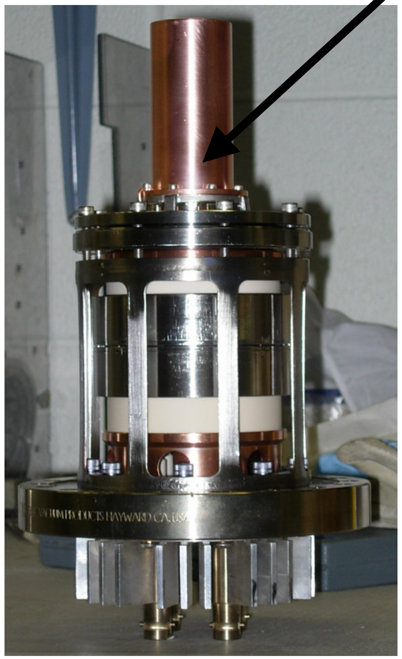


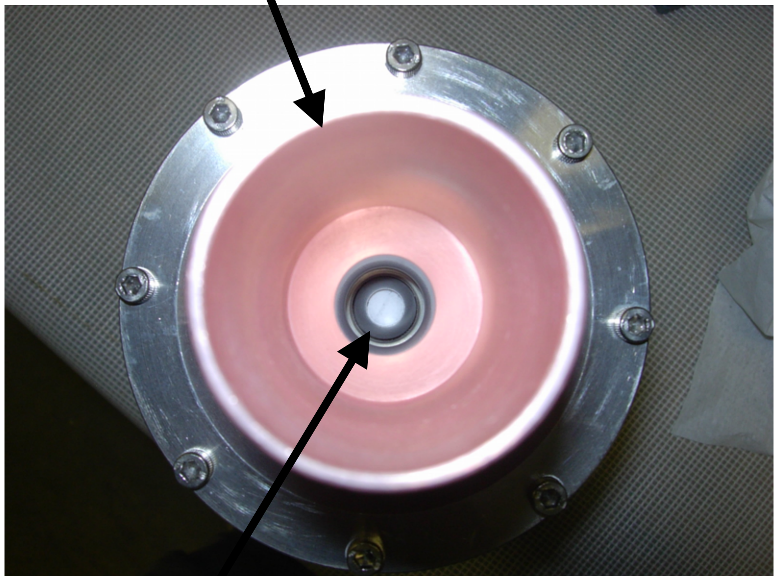


Yield: **0.5 A** at 4.6 kV

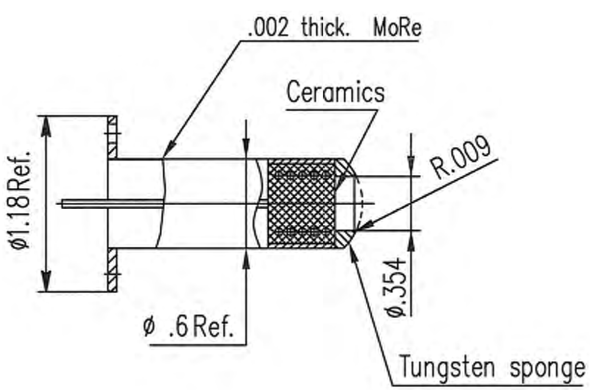
The 15-mm hollow electron gun

side view Copper anode *top view*



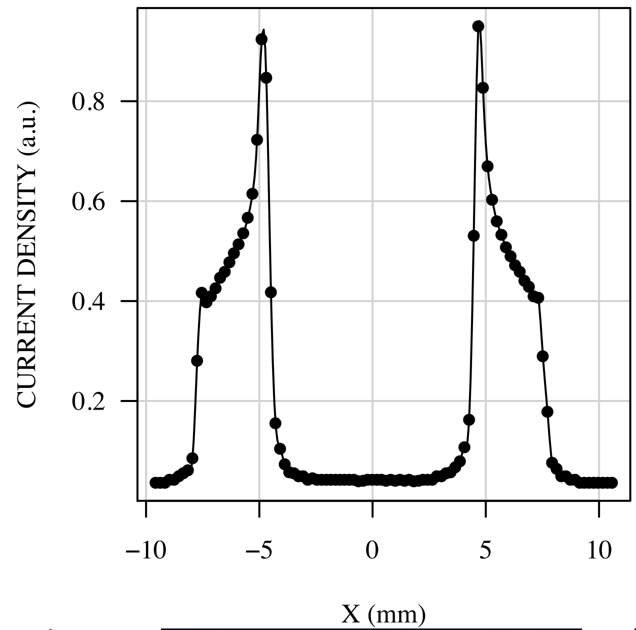


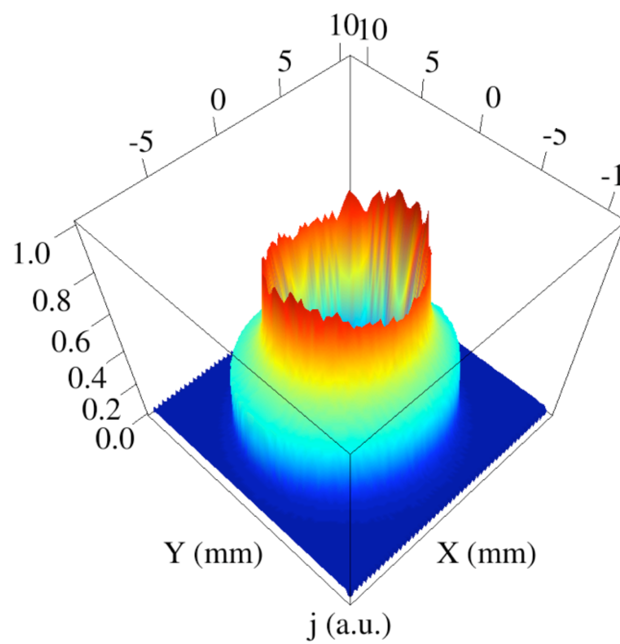
Tungsten dispenser cathode
with convex surface
15-mm diameter, 9-mm hole

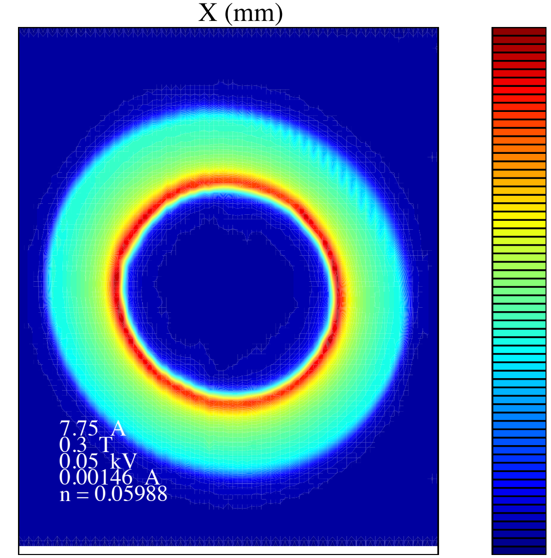


Yield: **1.1 A** at 4.8 kV

Profile measurements



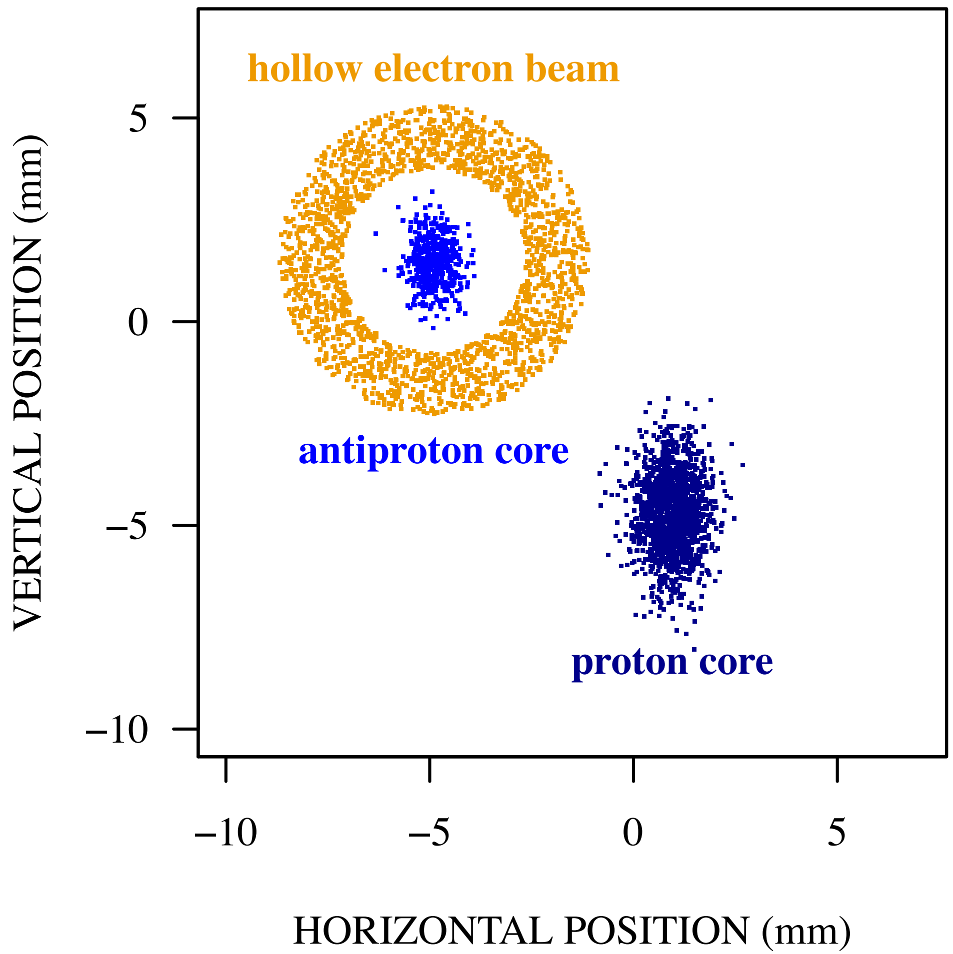


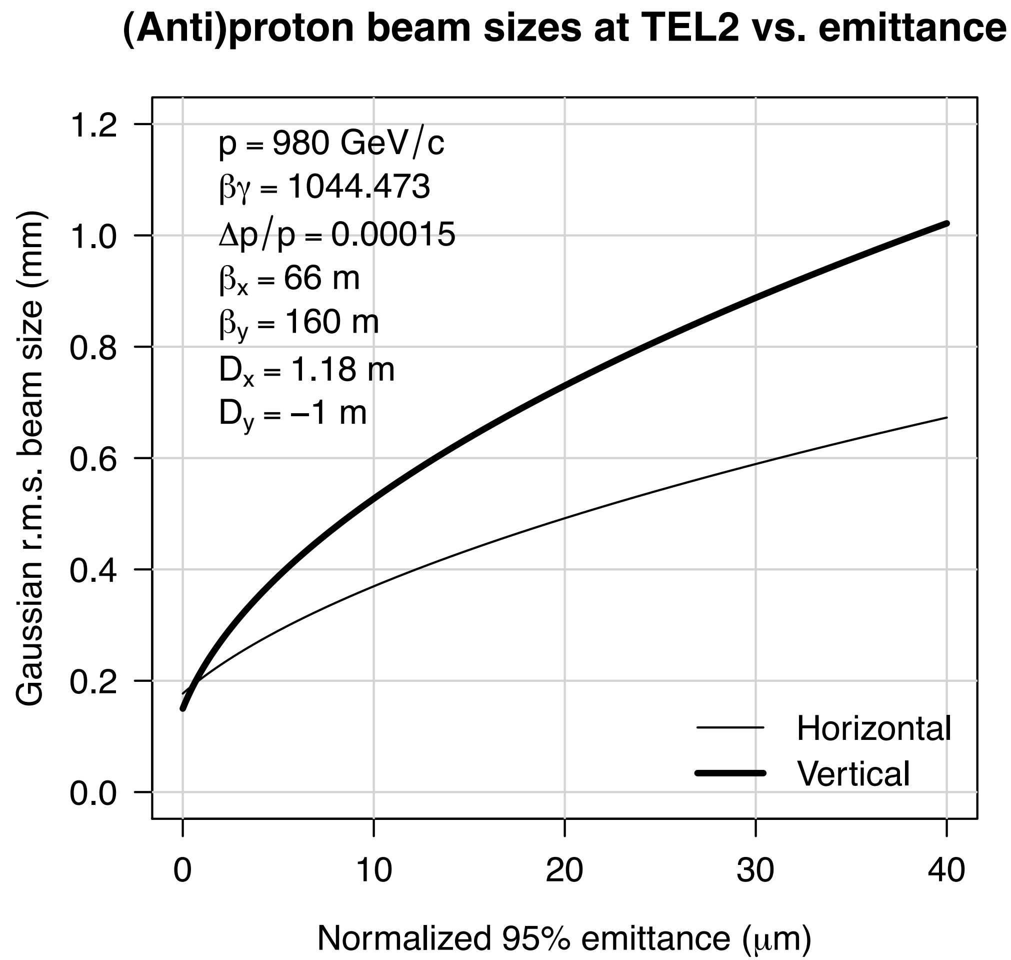


Beam layout in the Tevatron

- Proton and antiproton beams circulated in same beam pipe
- Separation of 9 mm at TEL-2

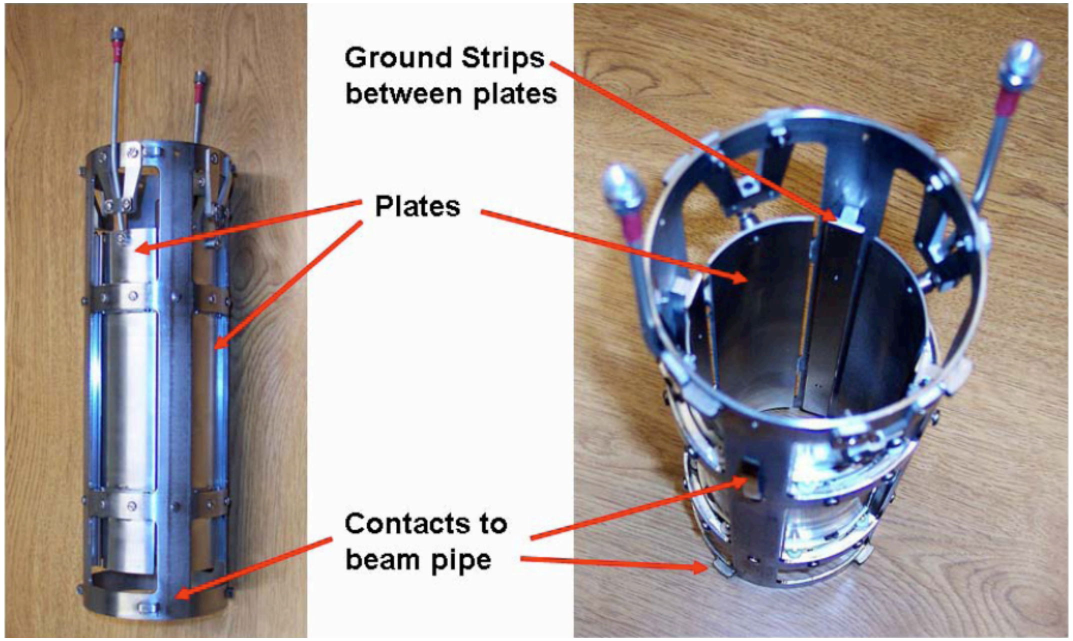
Lattice parameters	CDF IP	DZero IP	TEL2
Amplitude functions [m]	0.30, 0.30	0.50, 0.50	68, 153
Dispersion [m]	0, 0	0, 0	1.2, -1.0
Betatron phase [2π]	6.63, 6.85	13.77, 13.85	3.17, 3.22



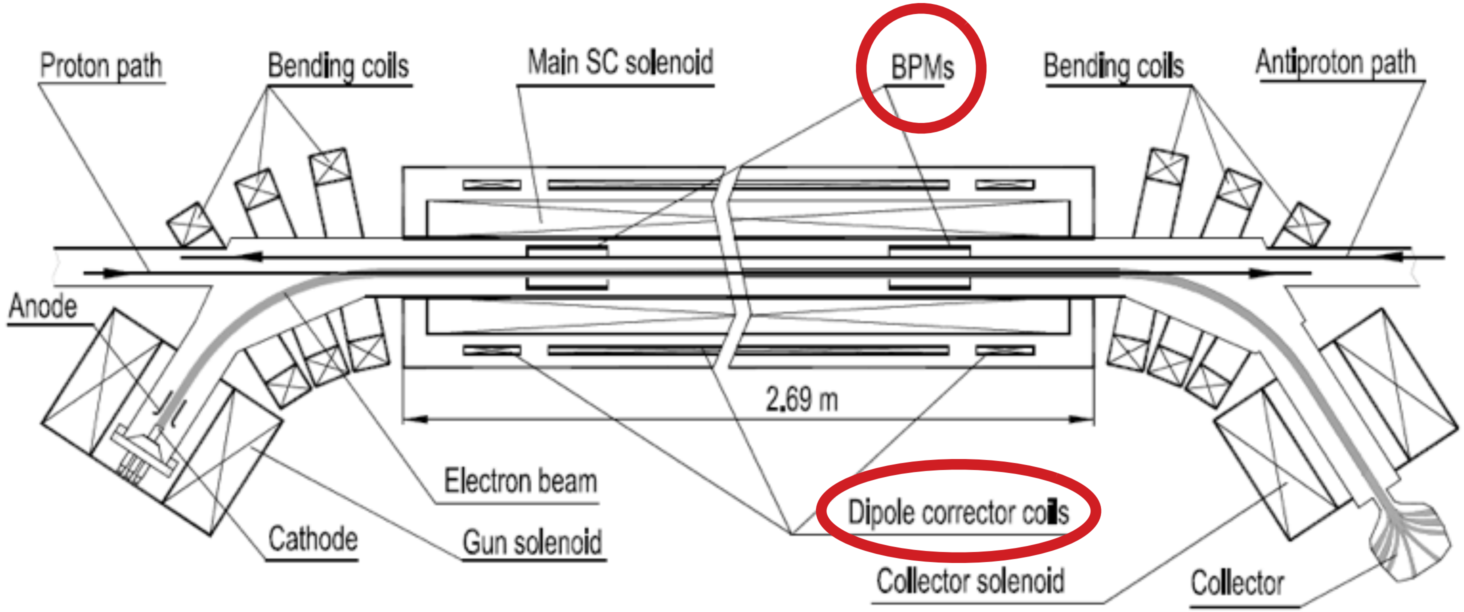


Alignment of electron beam with circulating beam

- BPMs accurate (<0.1 mm) for both (slow) electron and (fast) proton/antiproton bunches
- Electron beam alignment done manually with magnetic correctors
- Reproducible from store to store; depends on solenoidal fields



Combined horizontal/vertical BPMs



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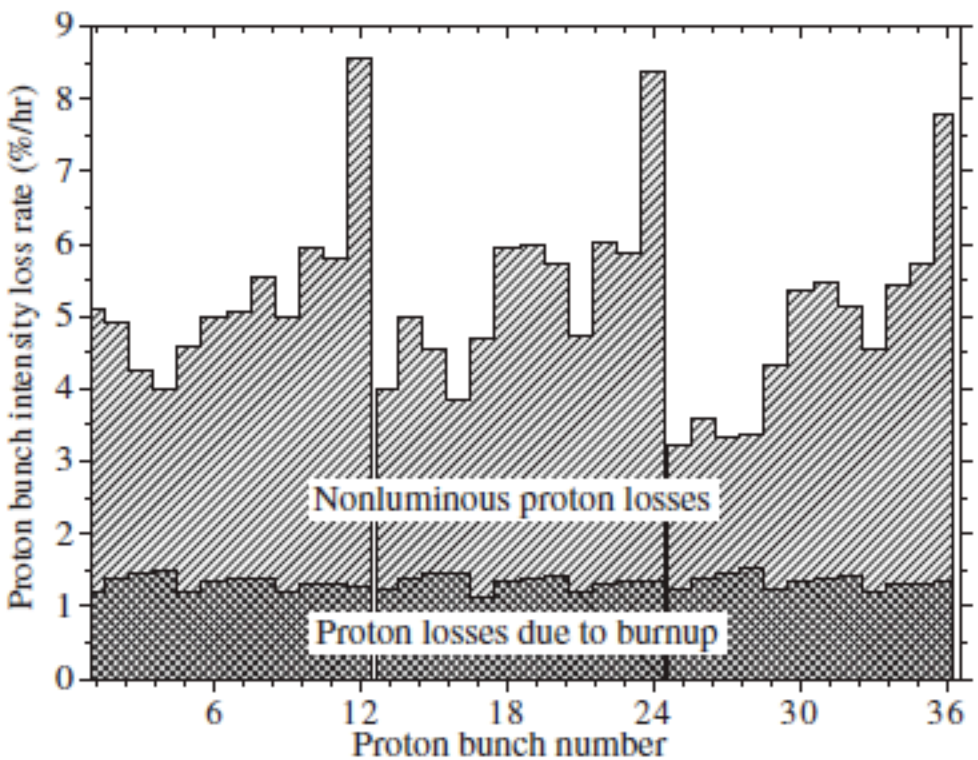
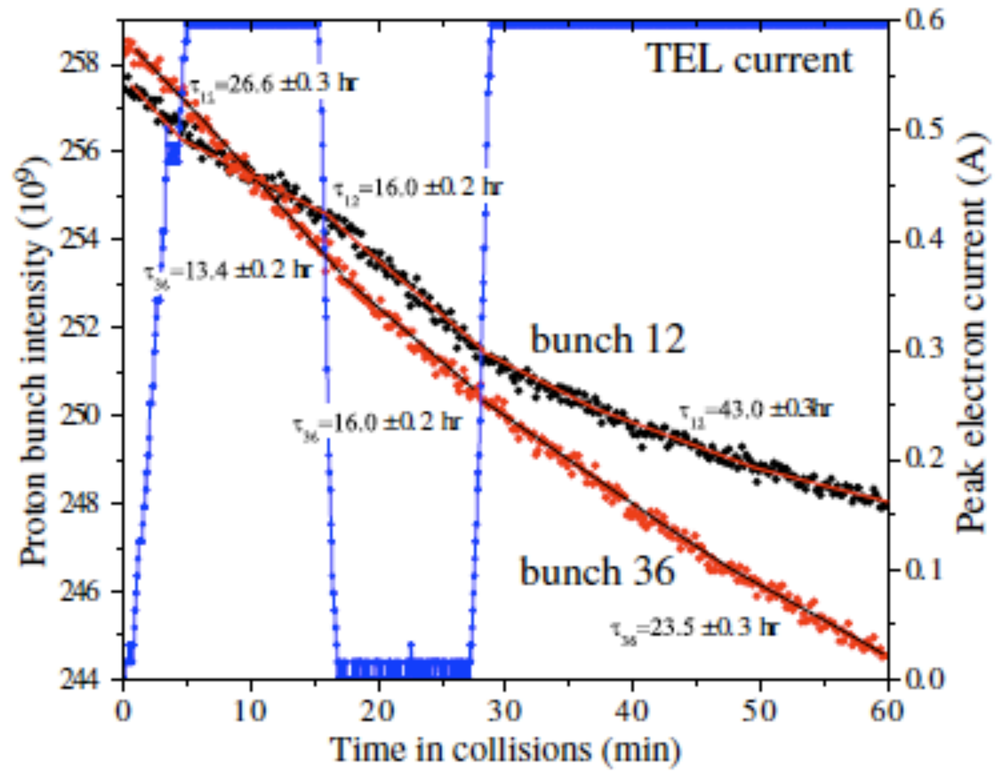
- 36 (3x12) proton bunches collide with 36 (3x12) antiproton bunches
- Because of collision pattern, beam-beam tune shift and losses depend on position in bunch train



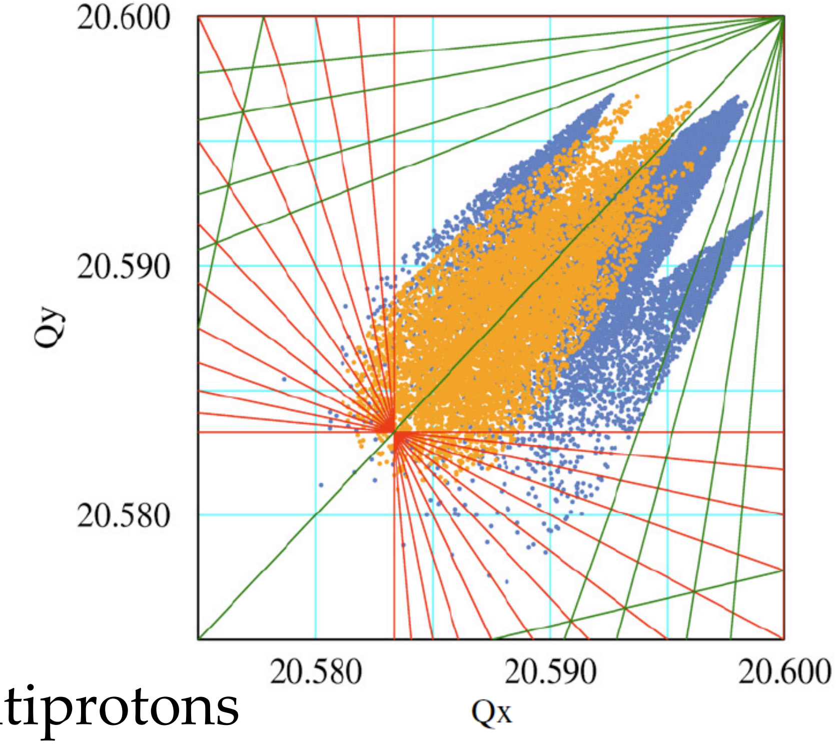


Electron lens with flat profile improves lifetime of chosen bunch

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?



- Tevatron not ideal for direct demonstration
  - weak head-on nonlinearities for cooled antiprotons
  - Nonzero dispersion, phase advance 1.2π
- Preliminary feasibility studies possible
  - operational issues, alignment
  - effects on lifetimes, tunes, and losses
  - code benchmarking
- Gaussian gun installed in Tevatron in June 2009
- Beam experiments between September 2009 and July 2010

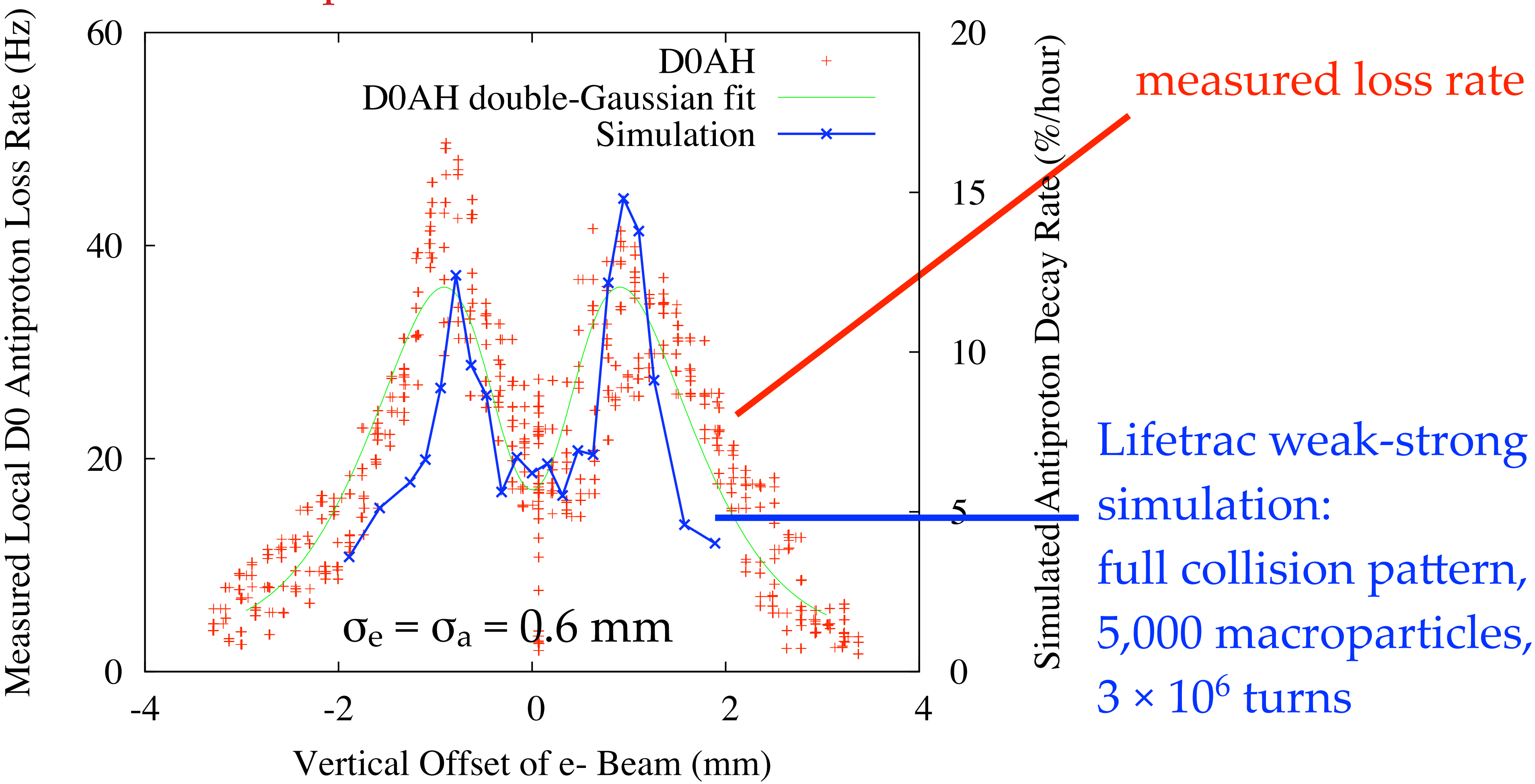
Linear beam-beam parameter for antiprotons due to electrons

$$\xi_e = -\frac{N_e r_p \beta (1+\beta_e)}{4\pi\gamma_p\sigma_e^2}$$

Stancari and Valishev, PAC11 (2011)

Observations in electron beam position scan

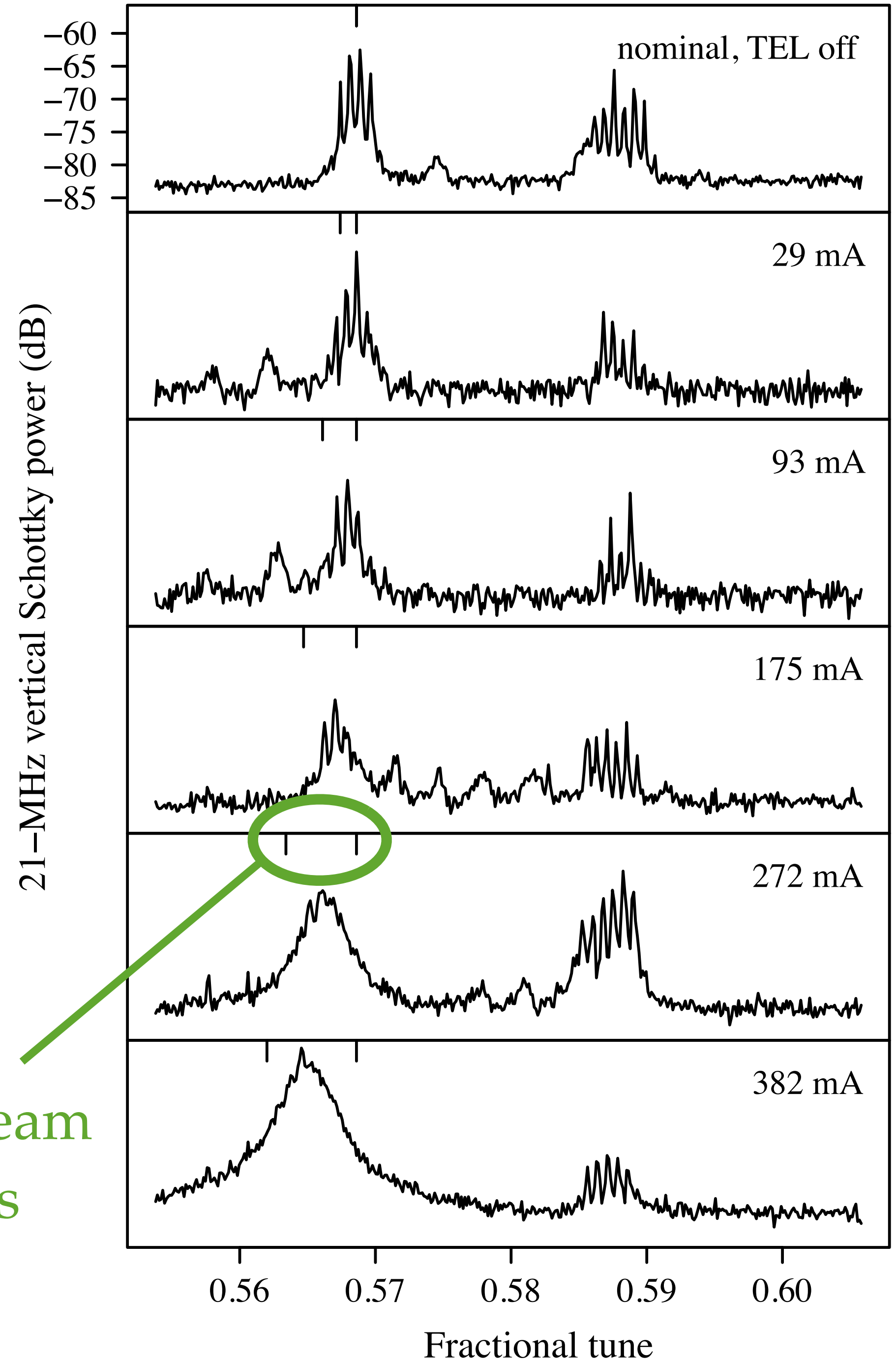
1. No increase in losses with nominal tunes (Q_x=0.575, Q_y=0.581)
2. With tunes lowered by 0.003 (towards 7th order resonance):
   - good BPM alignment and no e^-/p^- systematic difference
   - double hump structure



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

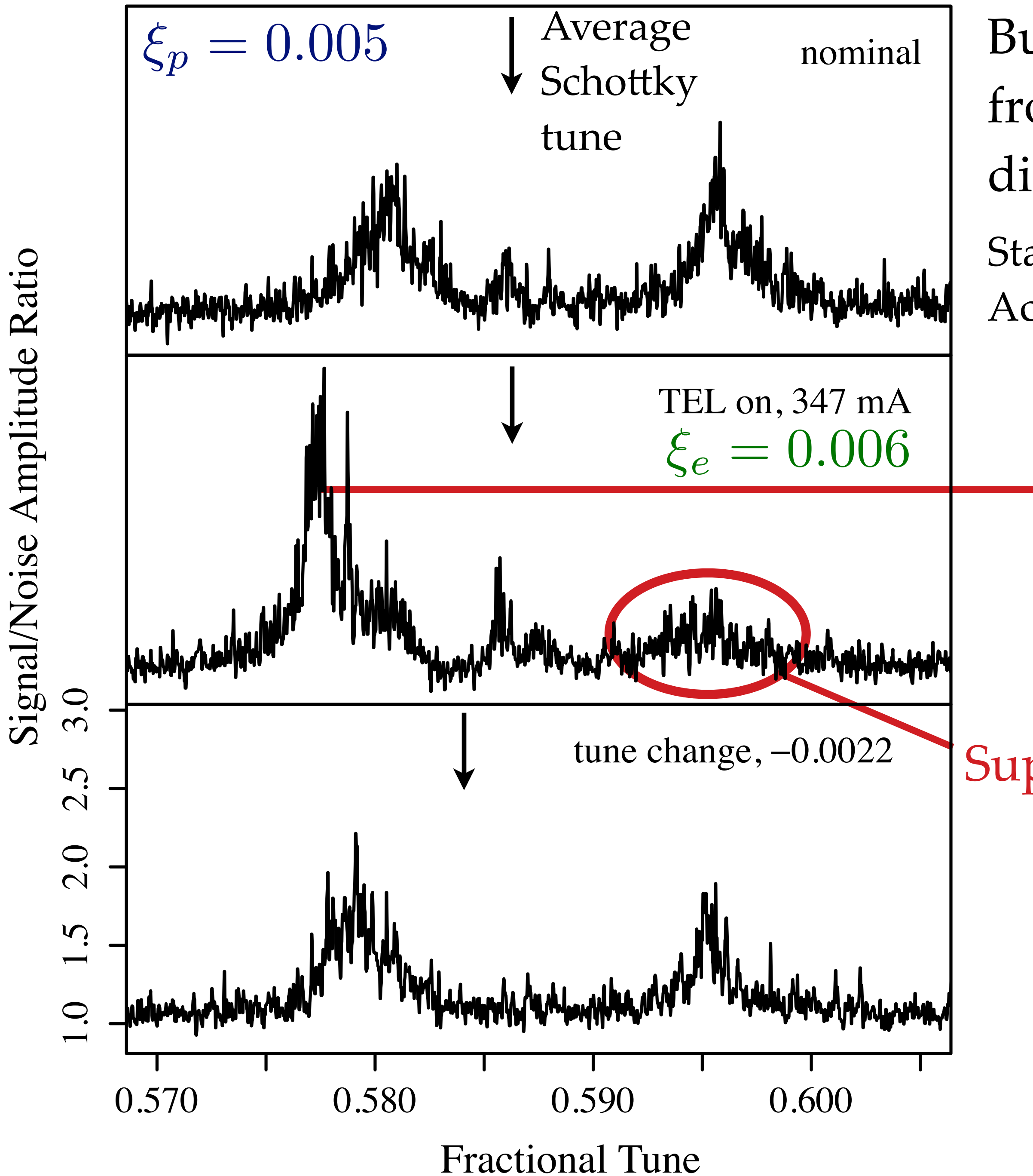
Schottky spectra measured during dedicated ***antiproton-only store***

Observed effect of electron beam on antiproton tune spectrum



Calculated linear beam-beam **tune shift** due to electrons

Effects on transverse coherent modes in regular collider store



Bunch-by-bunch signal from single vertical BPM digitized over 6×10^4 turns

Stancari and Valishev, Phys. Rev. ST Accel. Beams **15**, 041002 (2012)

Tune shift of first eigenmode
Change in tune spread?

Suppression of second eigenmode

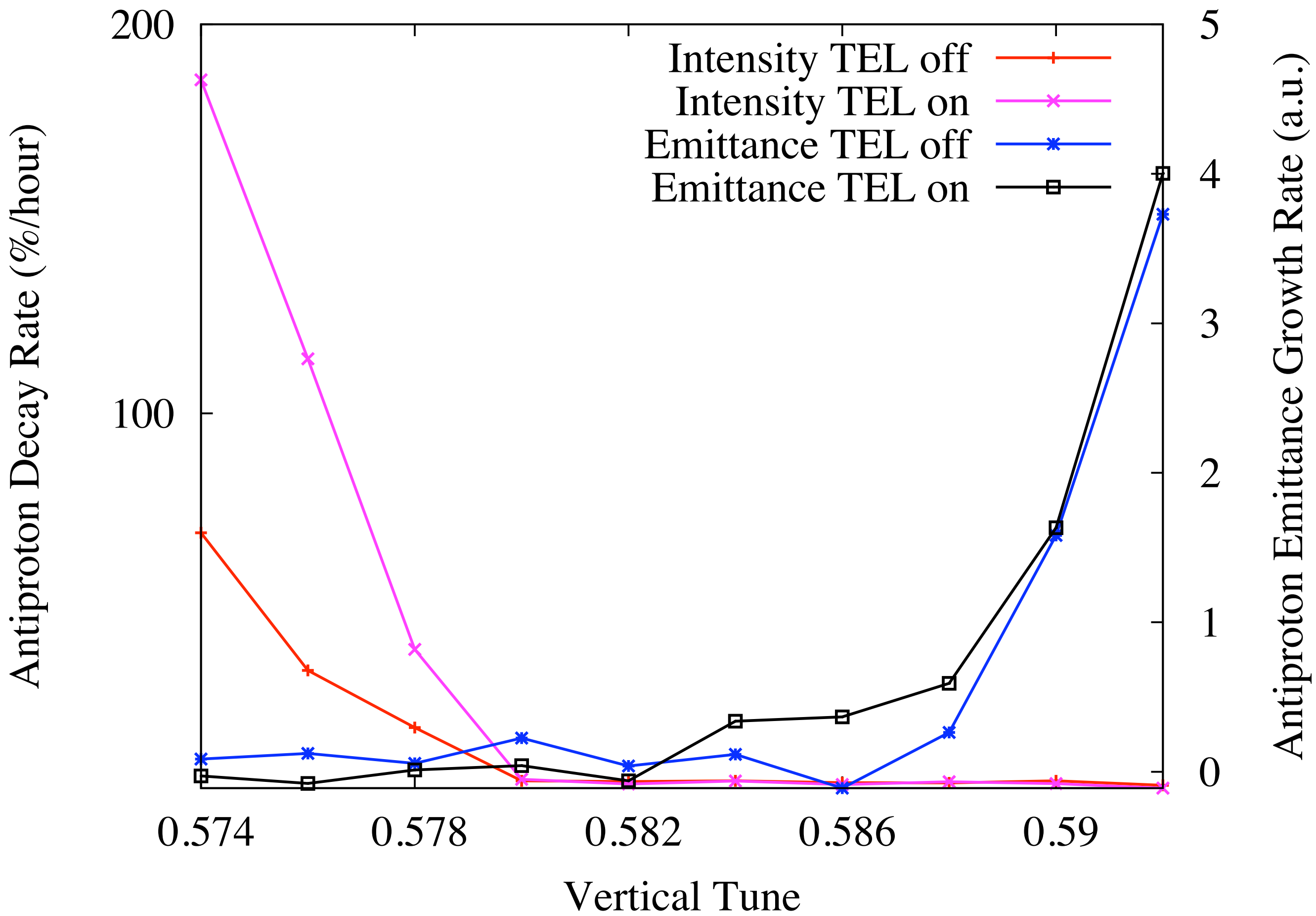
Interpretation requires calculation of mode strengths and widths

Comparison of available tune space in dedicated 3-on-3 stores

Attempted 2 special 3-on-3 stores to eliminate long-range forces: demonstration of head-on beam-beam compensation in the Tevatron?

1st attempt: proton emittance blowup at collisions before study, unusable

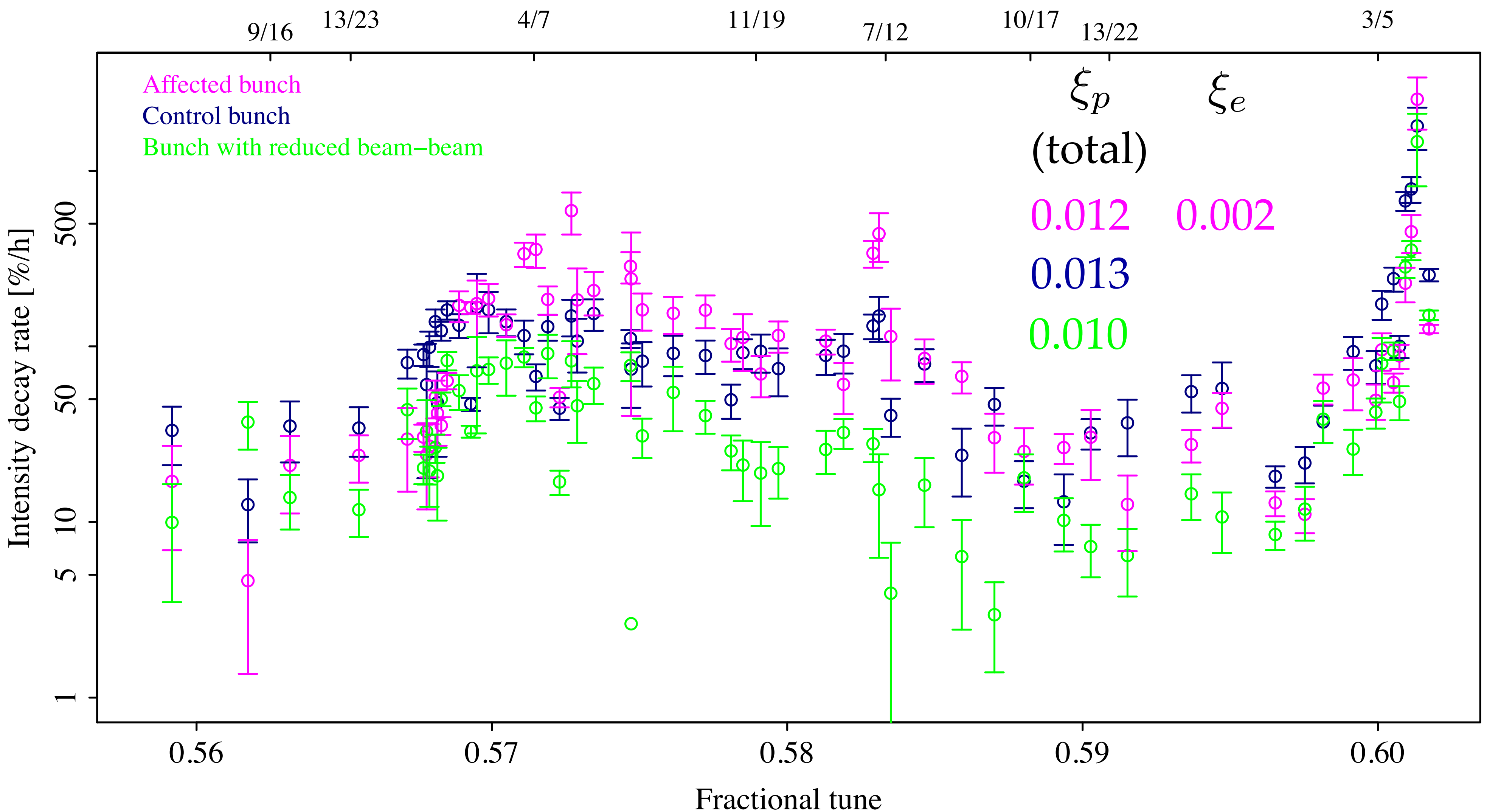
2nd attempt: smaller proton blowup, large electron size to match protons => negligible benefit expected, used for tune scans and code benchmarking



Lifetrac simulation of decay rates and emittance growth in diagonal tune scan

Comparisons of available tune space in dedicated 3-on-3 stores

Measured decay rates of antiproton bunches during diagonal tune scan



- Electron sizes could not be matched with protons, beam-beam too small
- Improvement of stable region not conclusive
- Useful for comparison with numerical simulations

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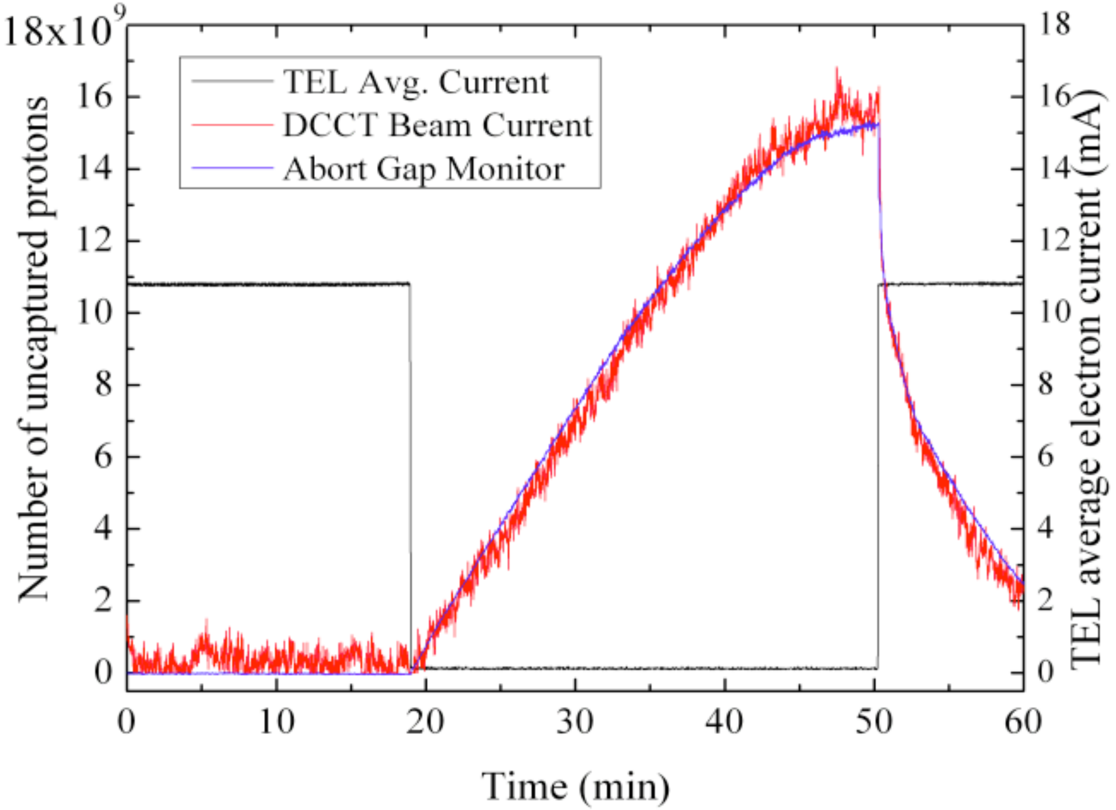
Tevatron electron lenses for abort-gap cleaning

- 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)

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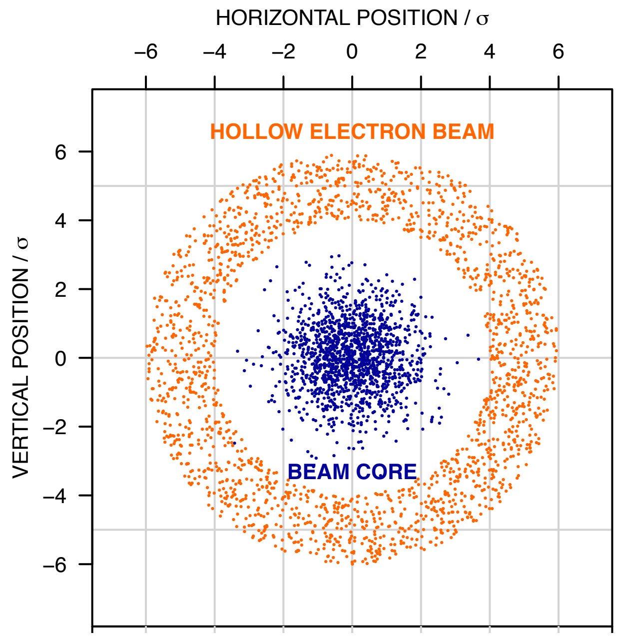
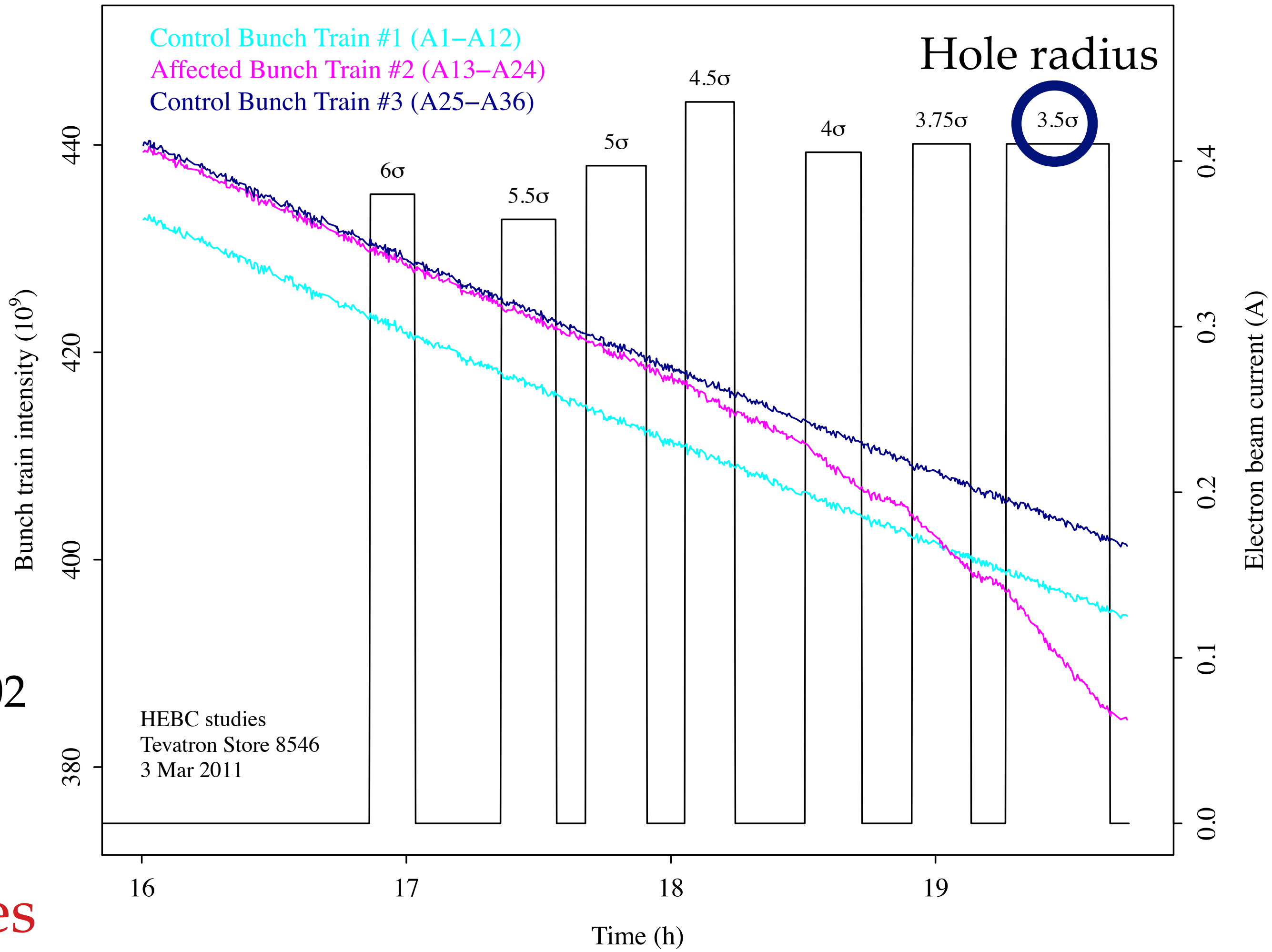
Smooth scraping and collimation with hollow electron beams

Can we use a hollow electron beam to scrape the halo when beam power or impedance limit the use of conventional collimators?



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



Yes! Extensive studies at the Tevatron:

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

Conclusions

- **Electron lenses** as a tool for beam manipulation in circular machines:
  - demonstrated **bunch-by-bunch betatron tune shifts** with flat electron profiles
  - studied **nonlinear beam-beam compensation** with Gaussian profiles
  - operated reliably for **abort gap clearing** over many years
  - developed **smooth scraping with hollow electron beams**; promising technique for the LHC
- Key observations on **head-on beam-beam compensation** using **Gaussian electron lenses** in Tevatron
  - alignment is reliable and reproducible
  - with aligned beams, no instabilities or emittance growth, even at high intensity and luminosity
  - observed tune shift and tune spread generated by electron beam
  - Tevatron not suitable for direct demonstration of concept: cold antiprotons in normal operations, limited dedicated study time

Thank you