Electron lens studies at the Tevatron

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Fermilab
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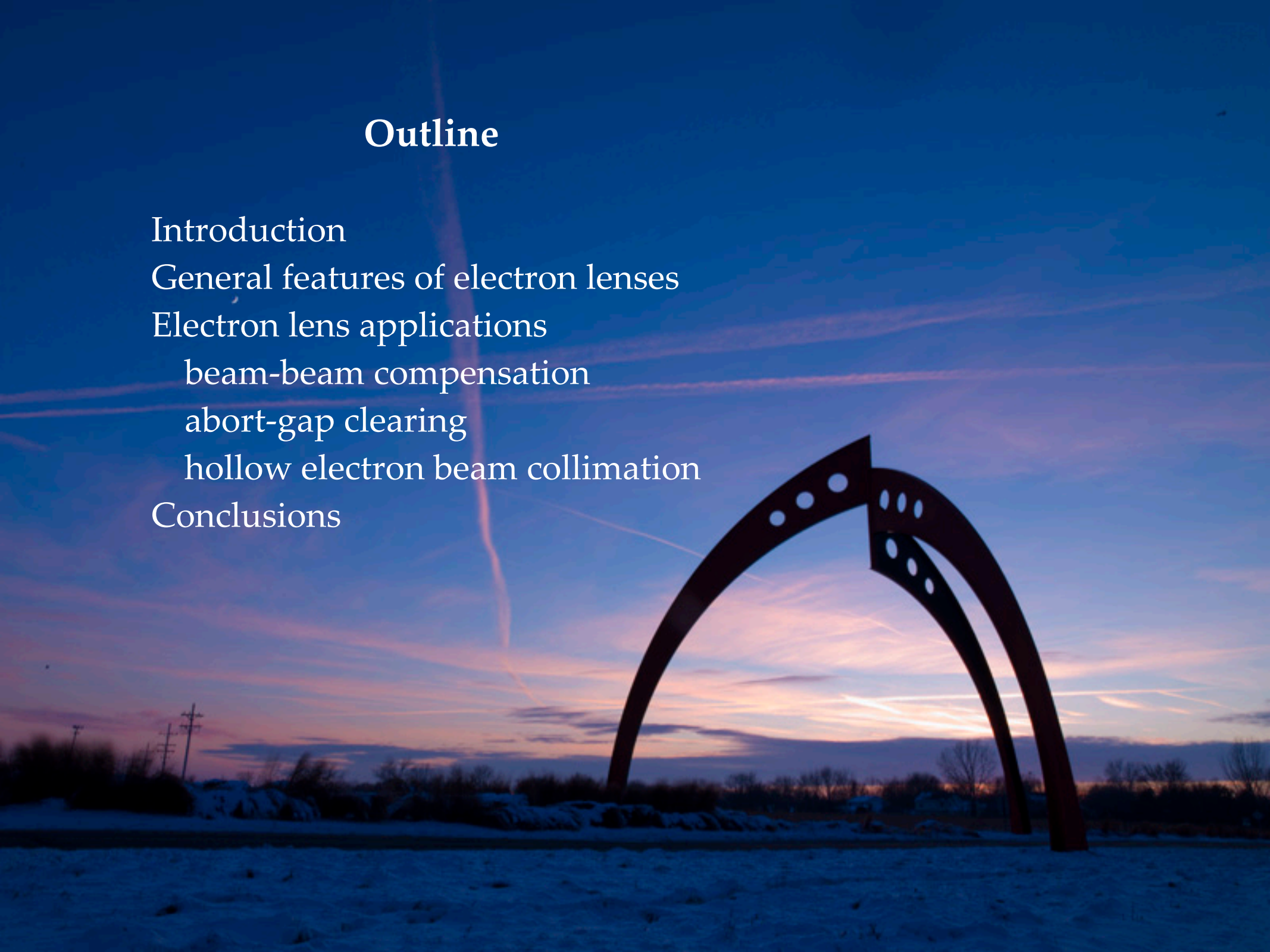
Outline

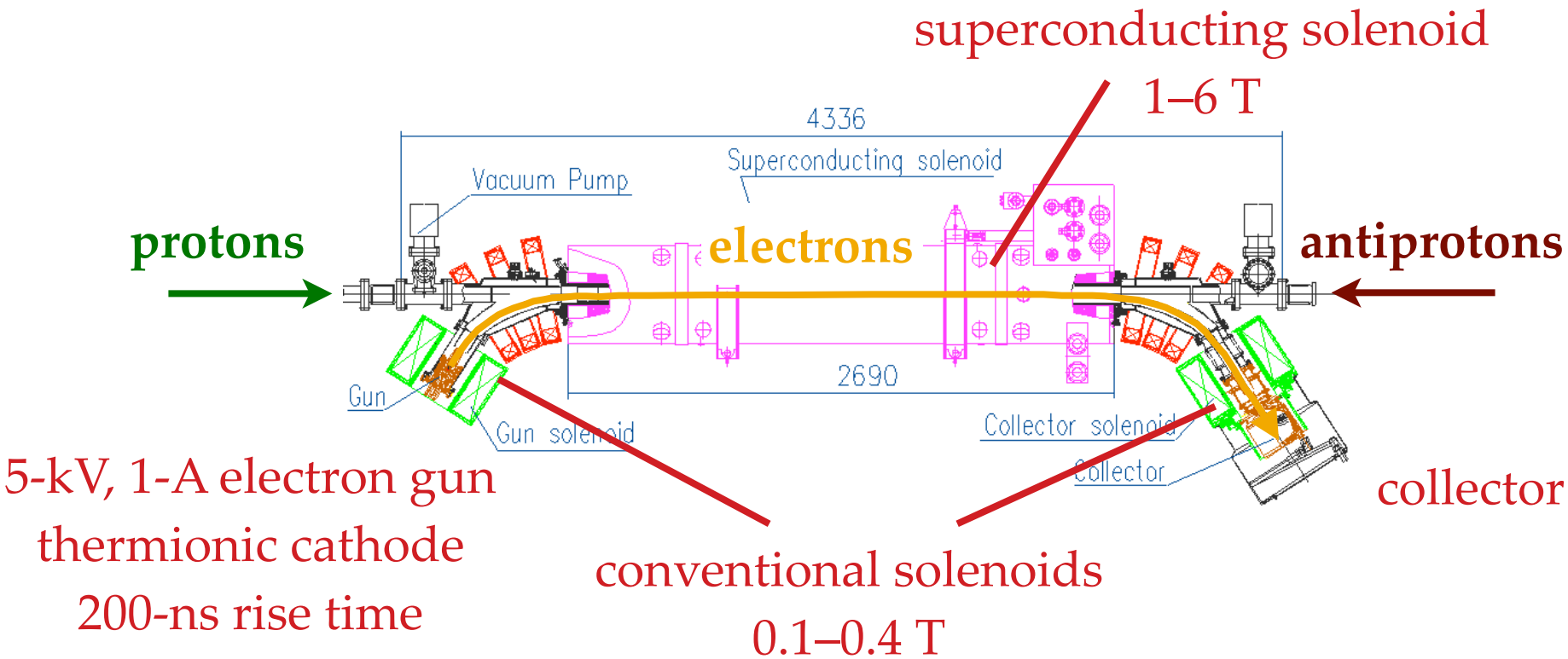
Introduction
General features of electron lenses
Electron lens applications
- beam-beam compensation
- abort-gap clearing
- hollow electron beam collimation

Conclusions

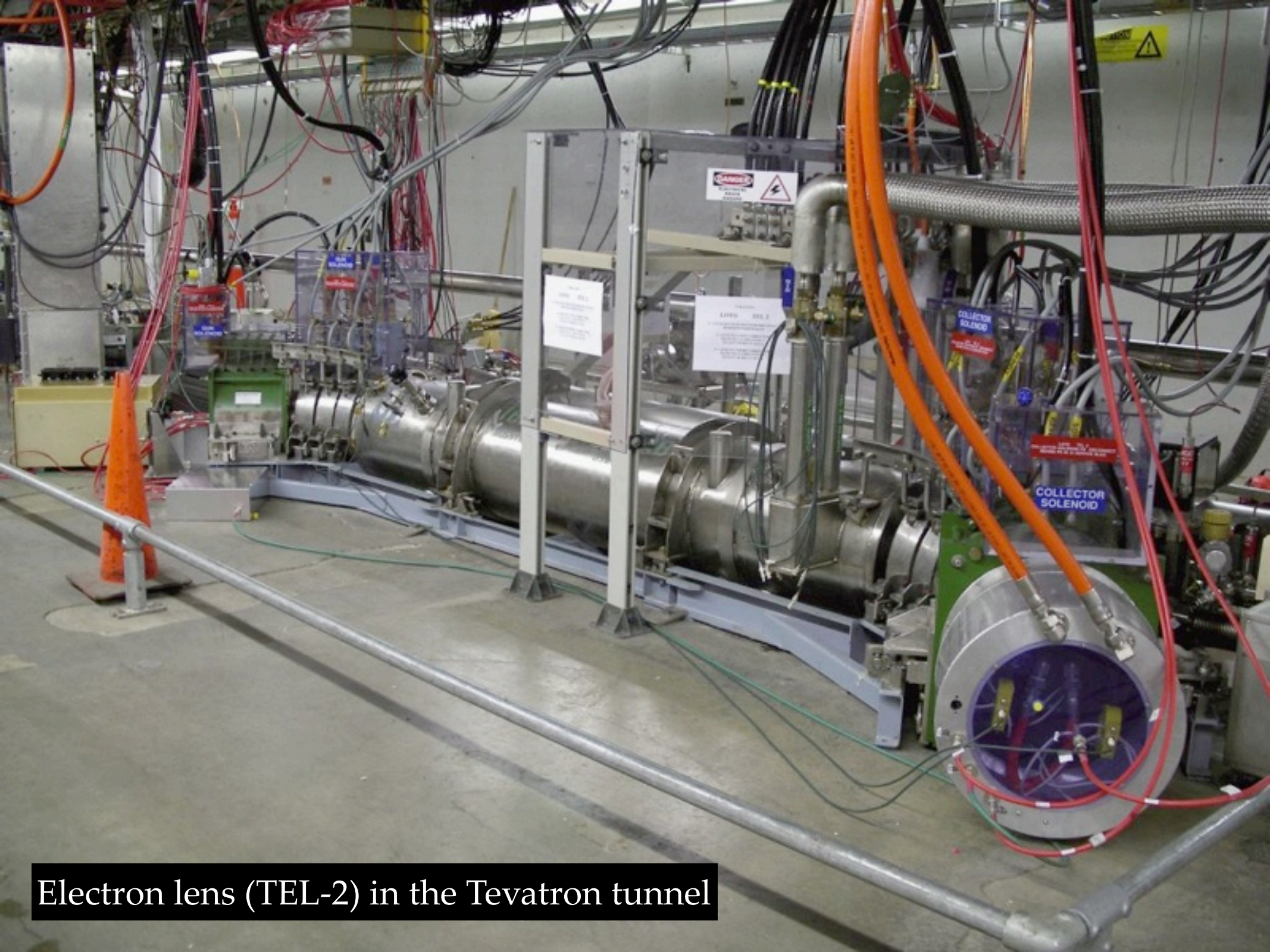


Tevatron electron lenses (TEL)

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

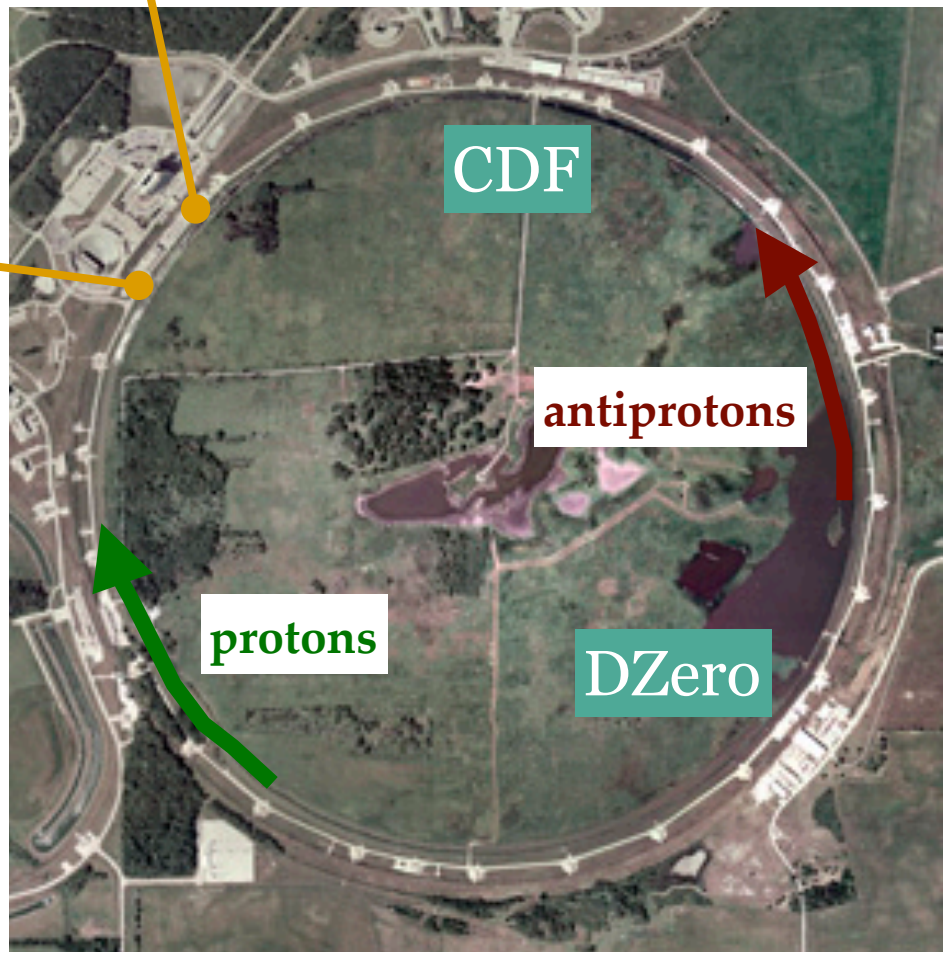
Electron lenses in the Fermilab Tevatron collider

TEL-2

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

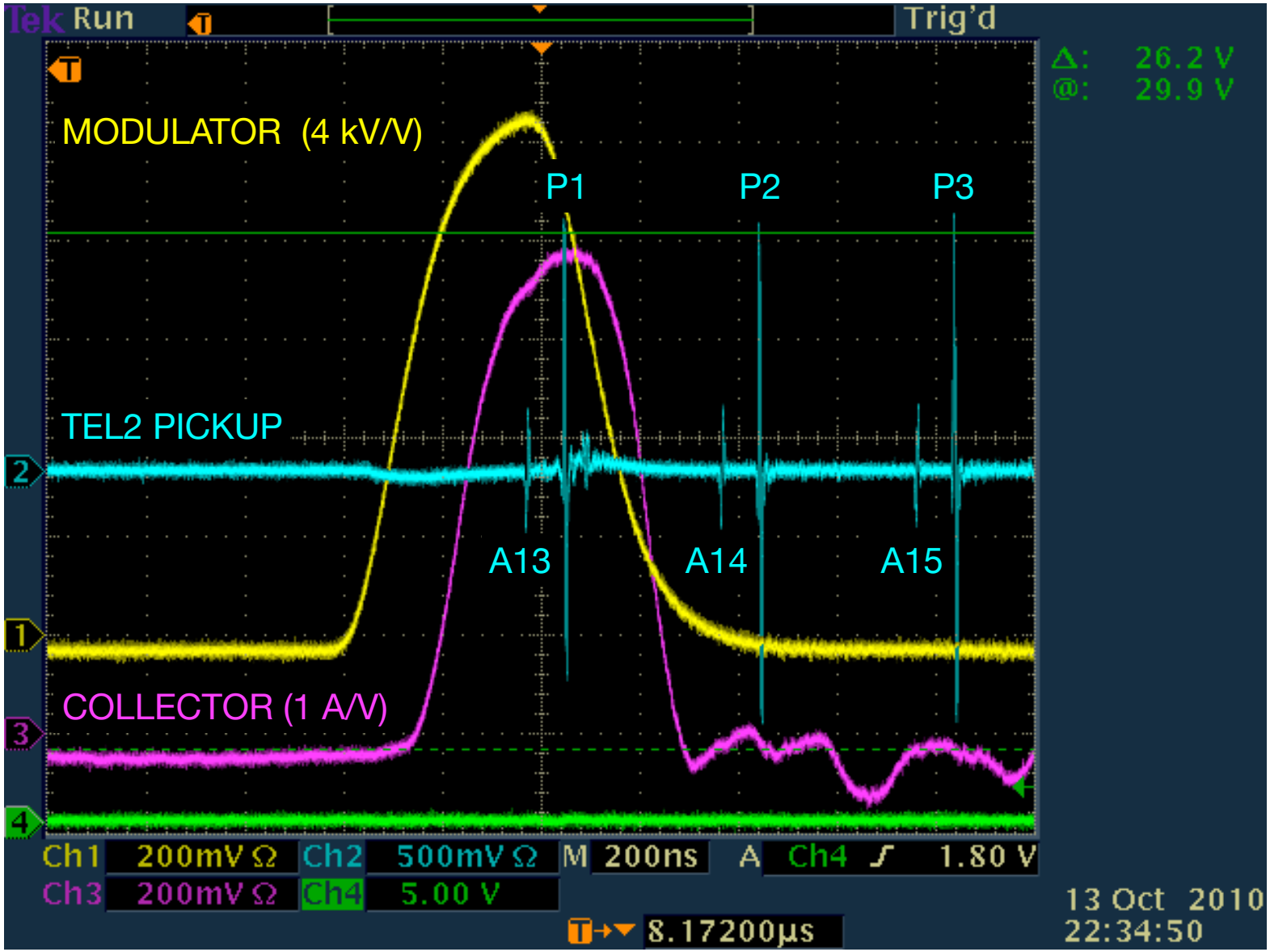
TEL-1

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



Pulsed operation of the electron lens

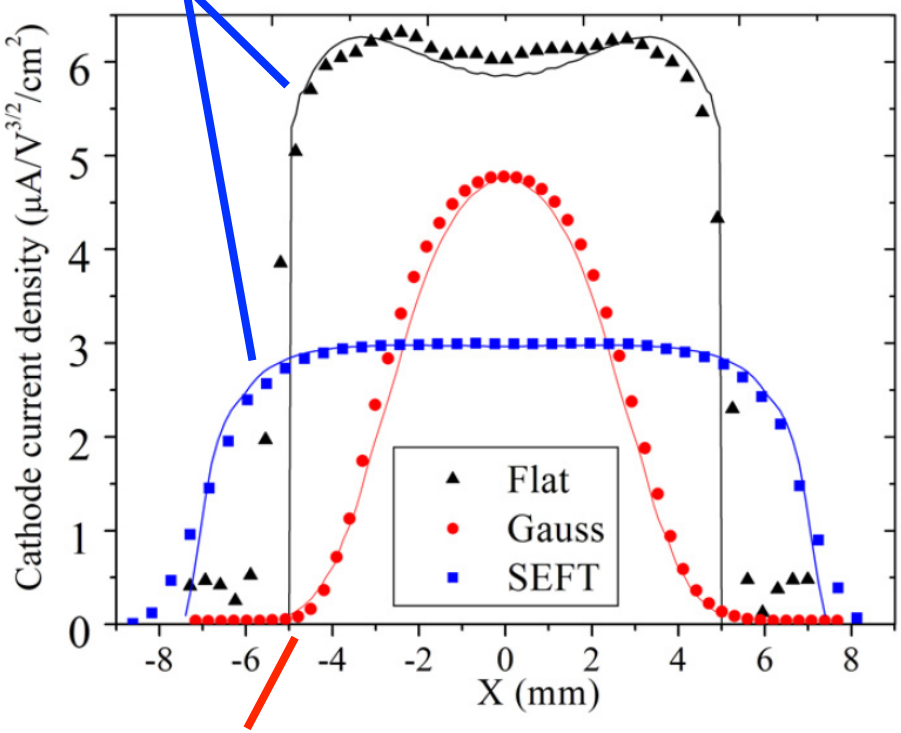
Pulsed electron beam could be **synchronized** with any group of bunches



Profile control of the electron beam

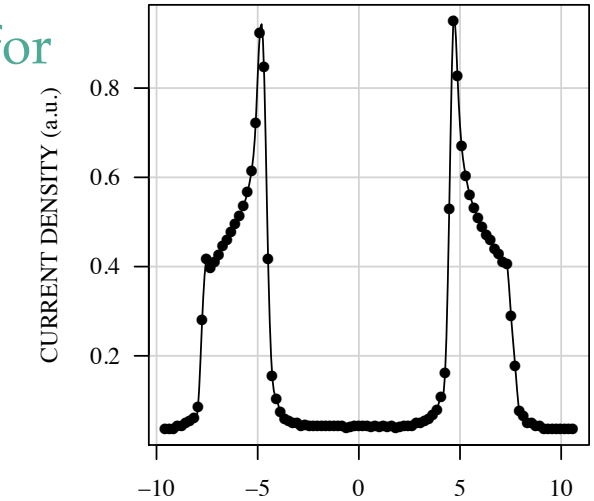
- Current density profile shaped by electrode geometry/potentials
- Maintained during transport by strong solenoidal fields
- Different electron guns for different purposes

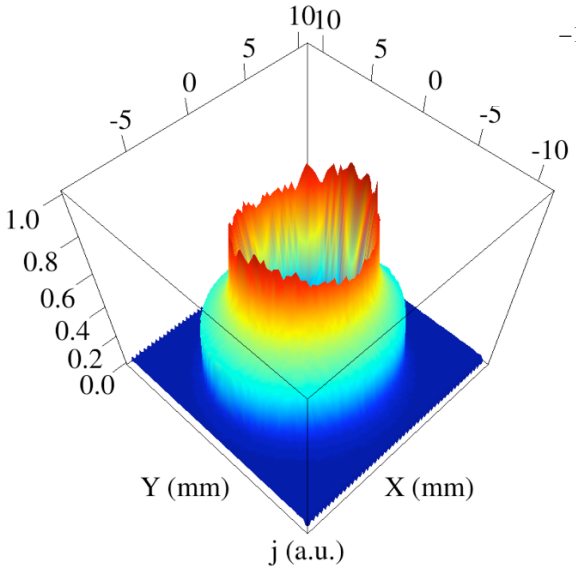
Flat profiles for bunch-by-bunch betatron tune correction

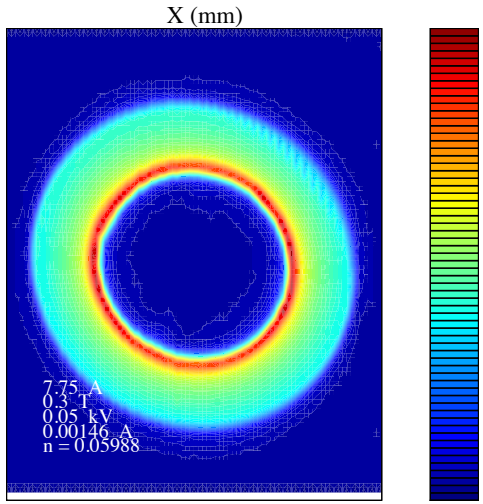


Gaussian profile for compensation of nonlinear beam-beam forces

Hollow profile for halo scraping

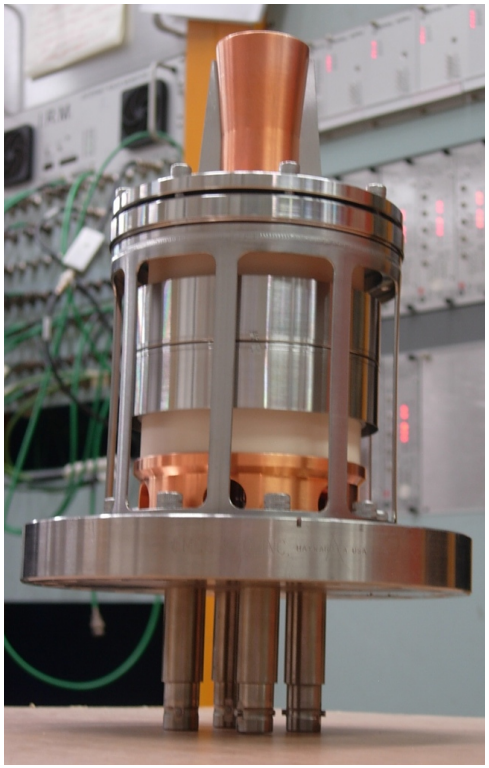






The 10.2-mm Gaussian electron gun

side view

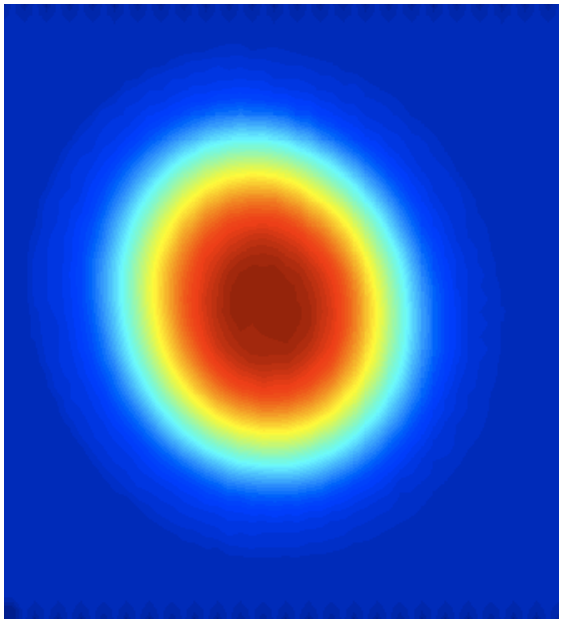


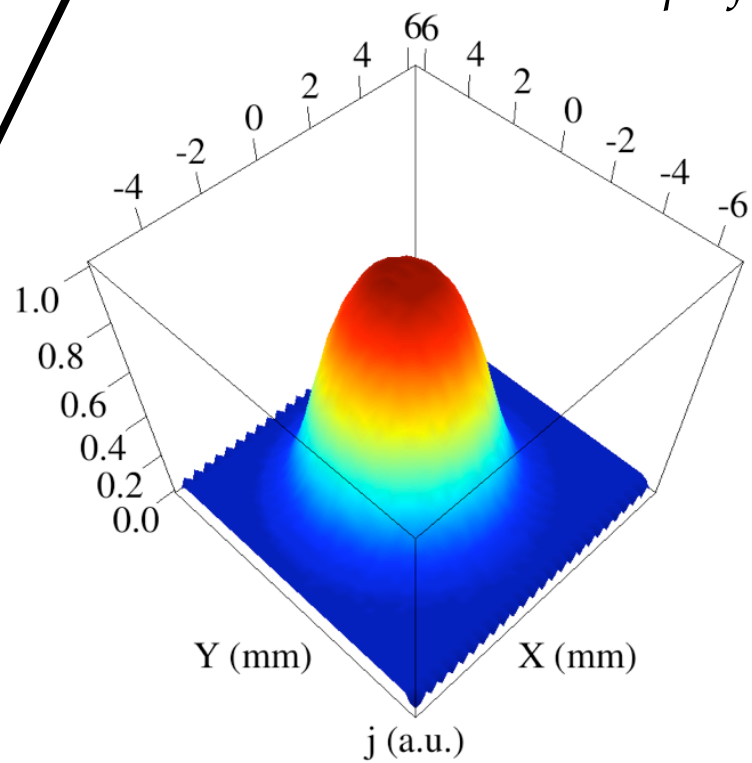
top view

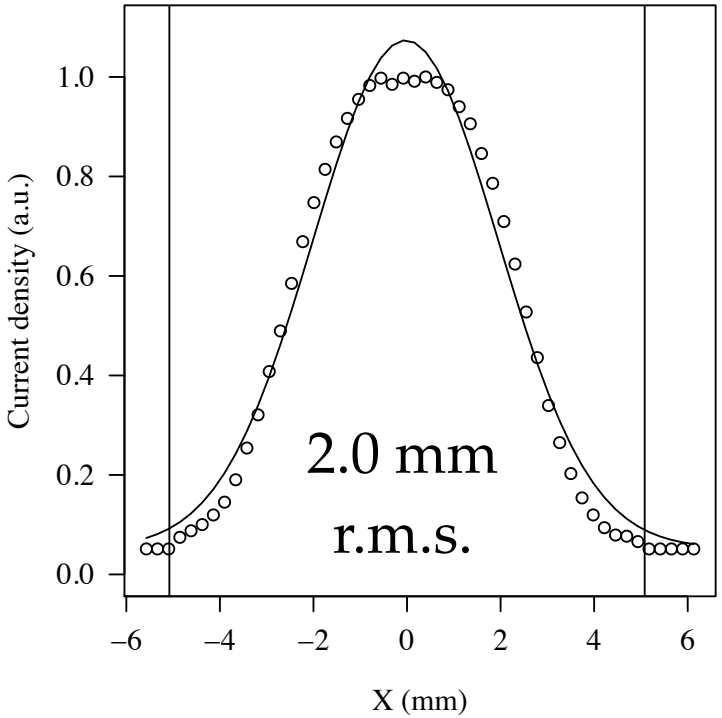
Tungsten dispenser cathode with convex surface operating at 1100°C

Yield: **0.5 A** at 4.6 kV

Measured profiles





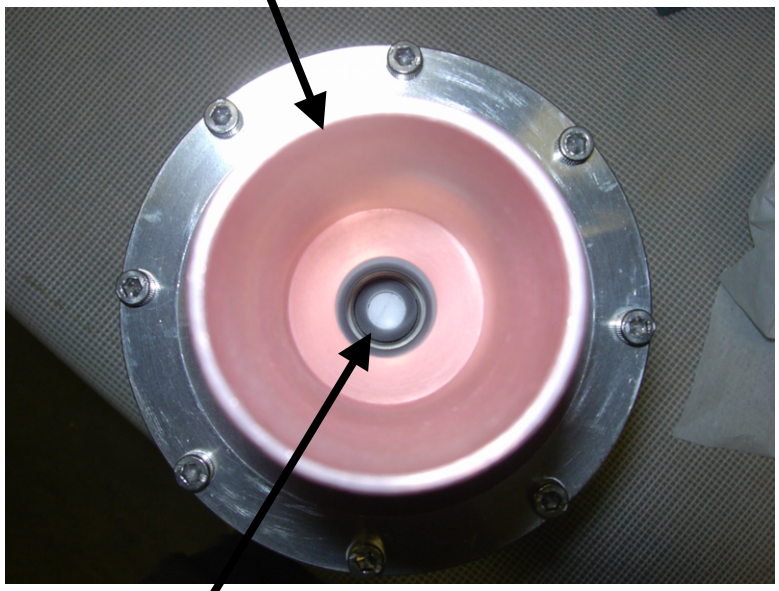


The 15-mm hollow electron gun

side view

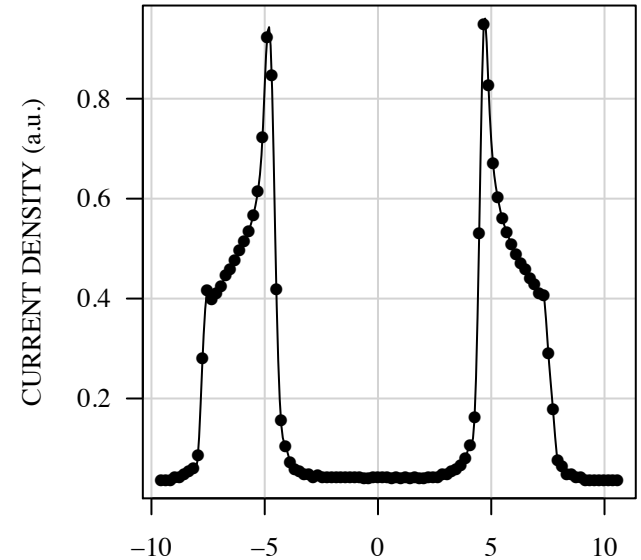
Copper anode

top view

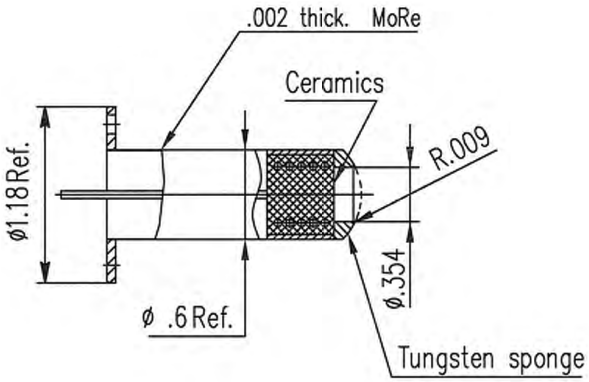


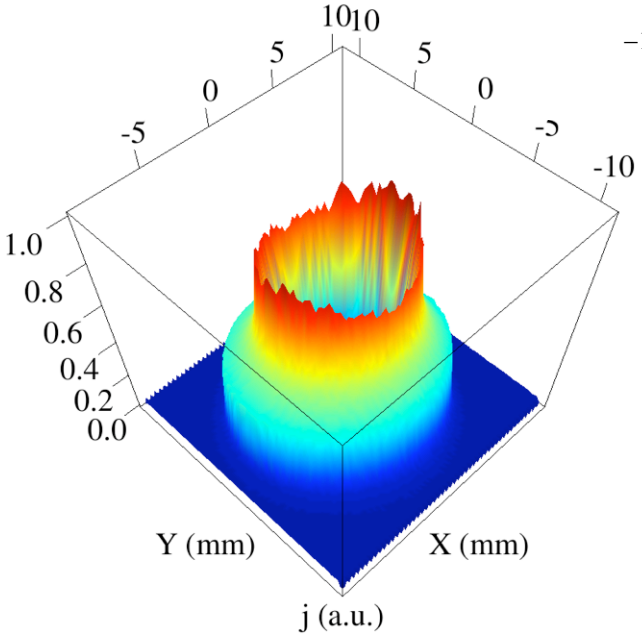
Yield: **1.1 A** at 4.8 kV

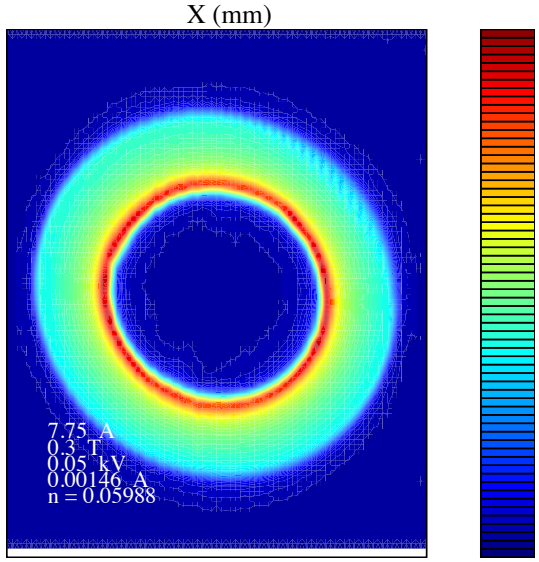
Profile measurements



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



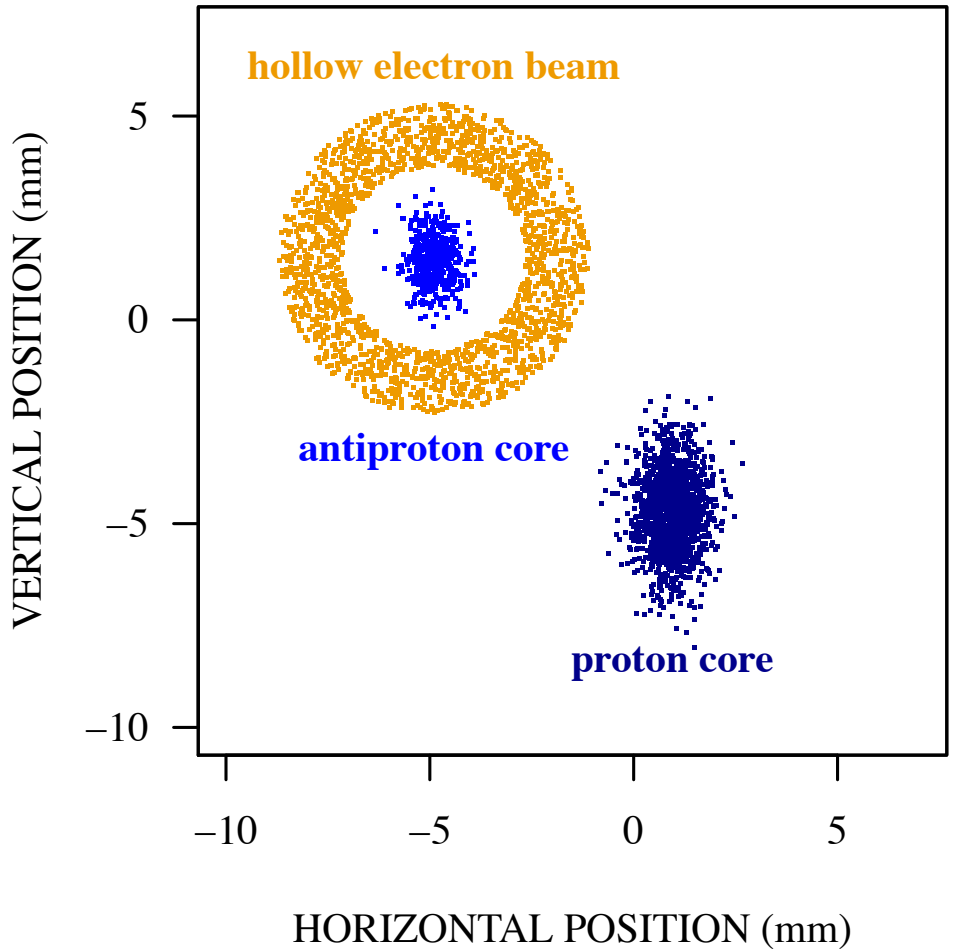


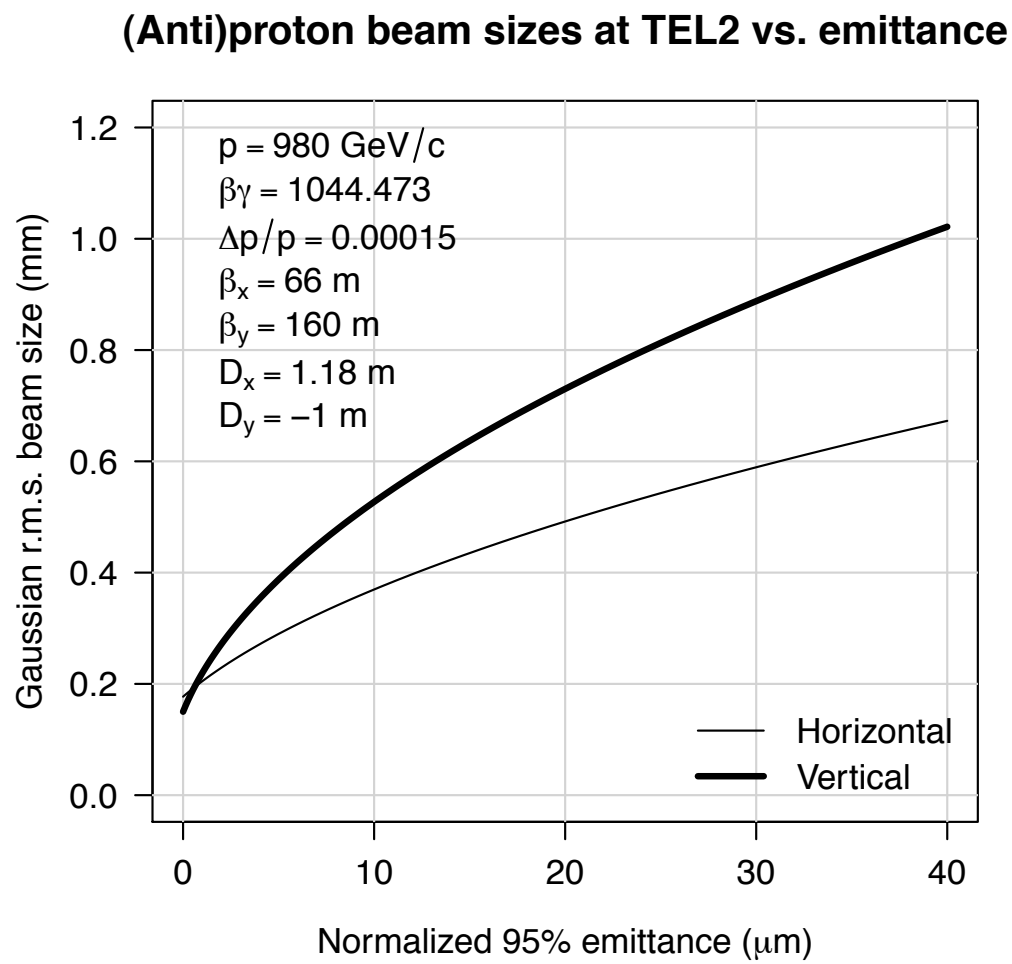


Beam layout in the Tevatron

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

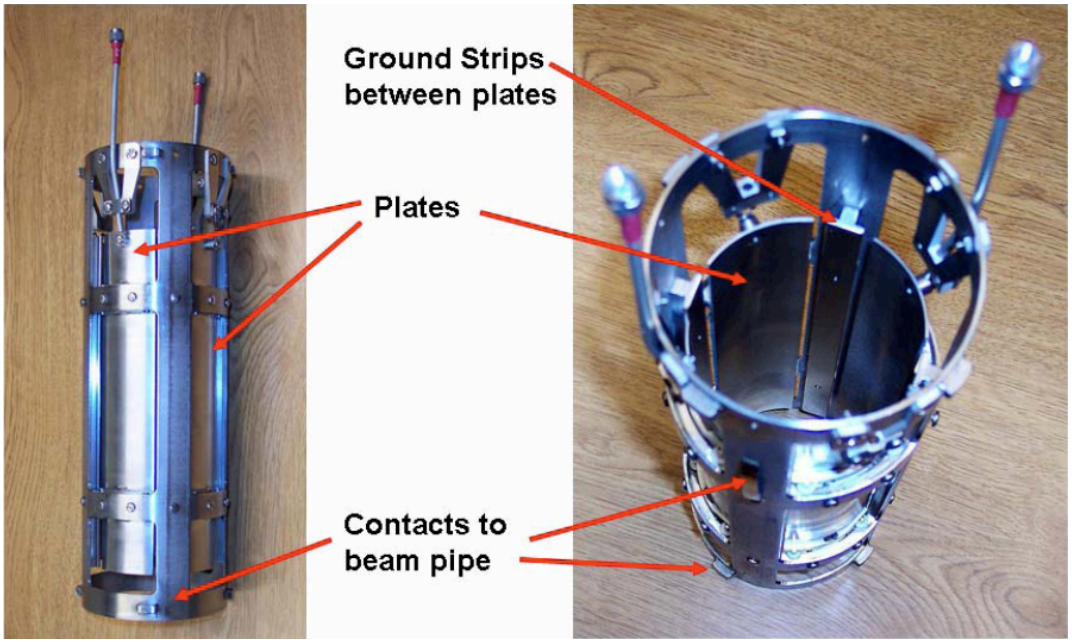
Lattice parameters	CDF IP	DZero IP	TEL2
Amplitude functions [m]	0.30, 0.30	0.50, 0.50	68, 153
Dispersion [m]	0, 0	0, 0	1.2, -1.0
Betatron phase [2π]	6.84	13.85	3.22



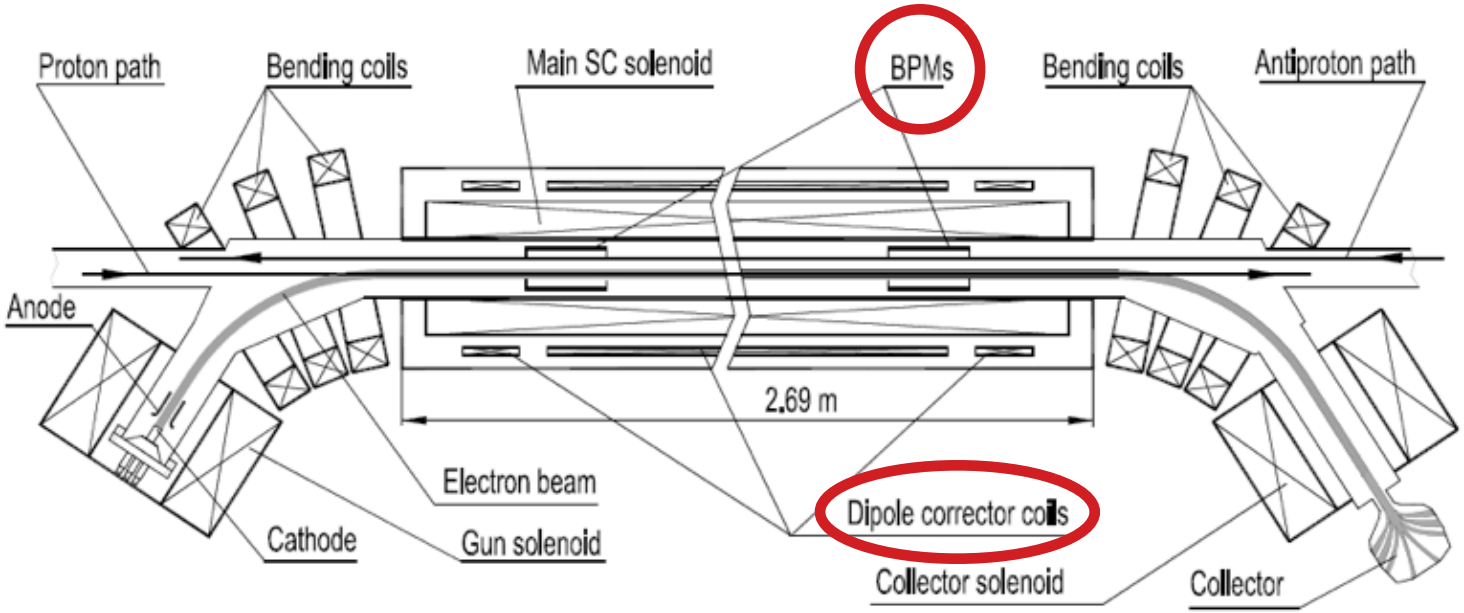


Alignment of electron beam with circulating beam

- 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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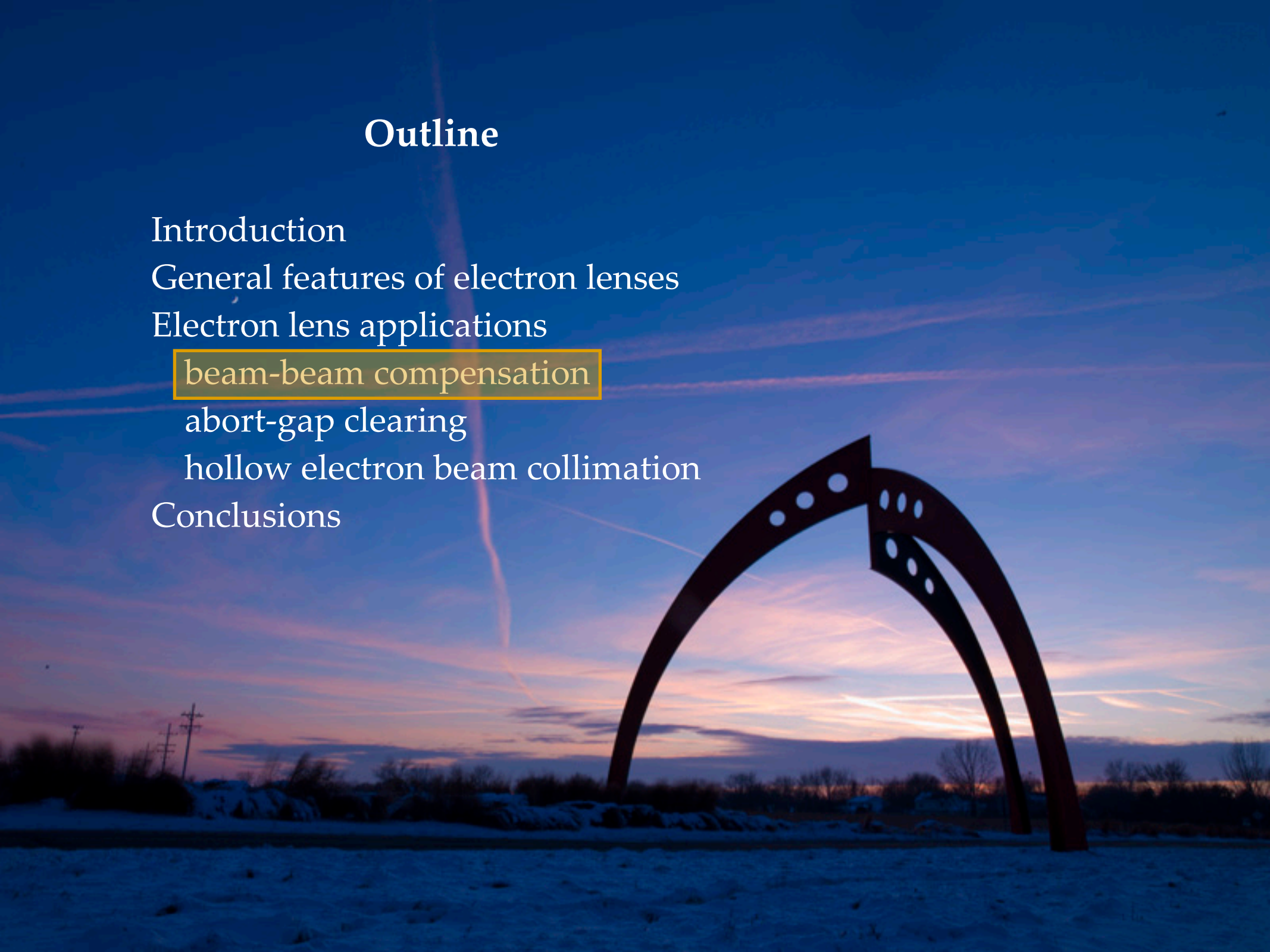
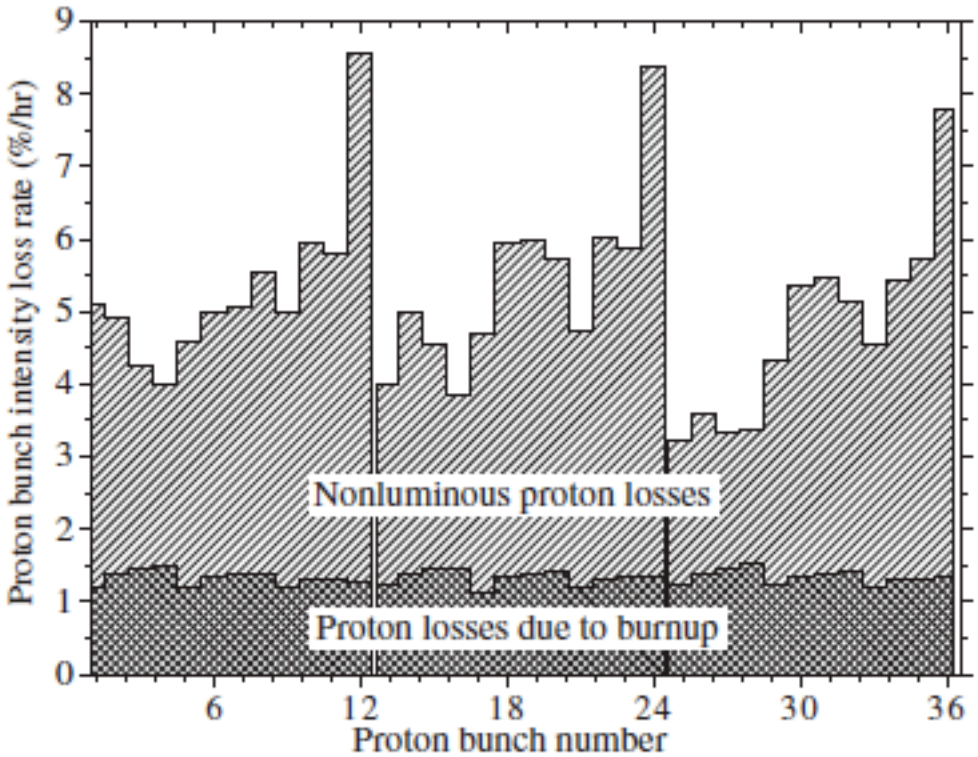
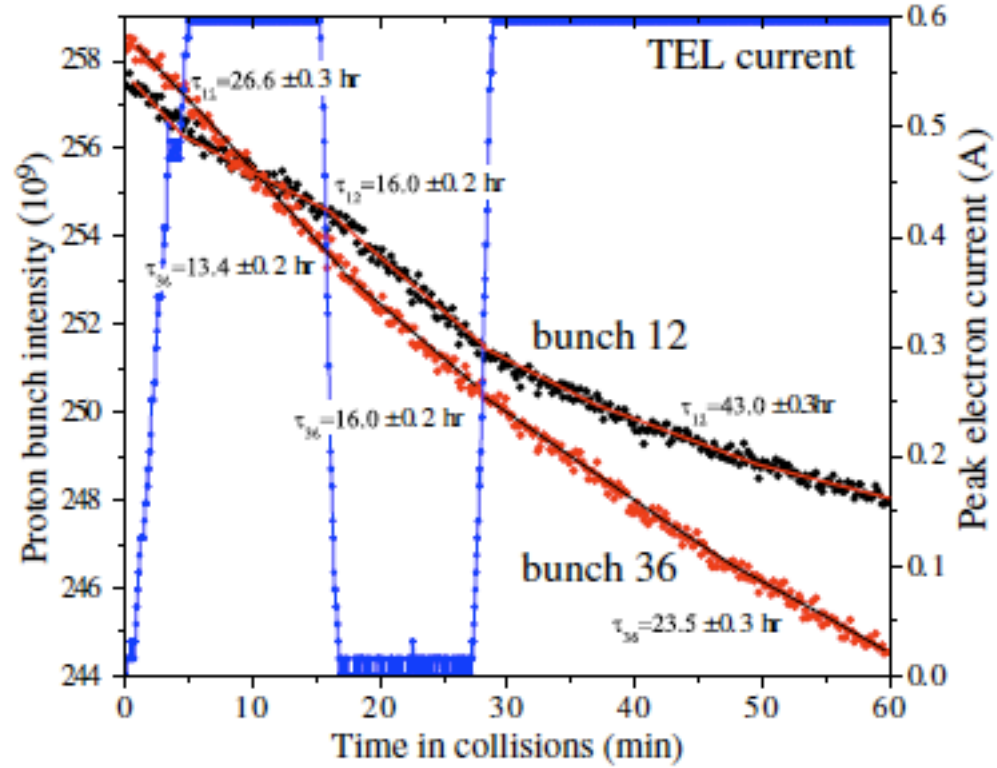


Tevatron electron lenses for long-range beam-beam compensation

- 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



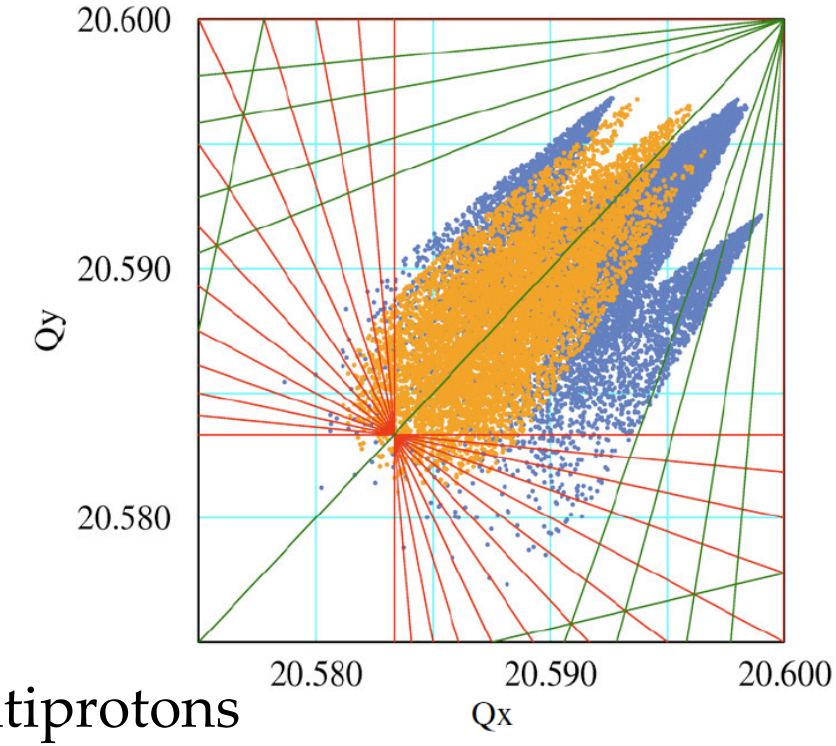


Electron lens with flat profile improves lifetime of chosen bunch

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

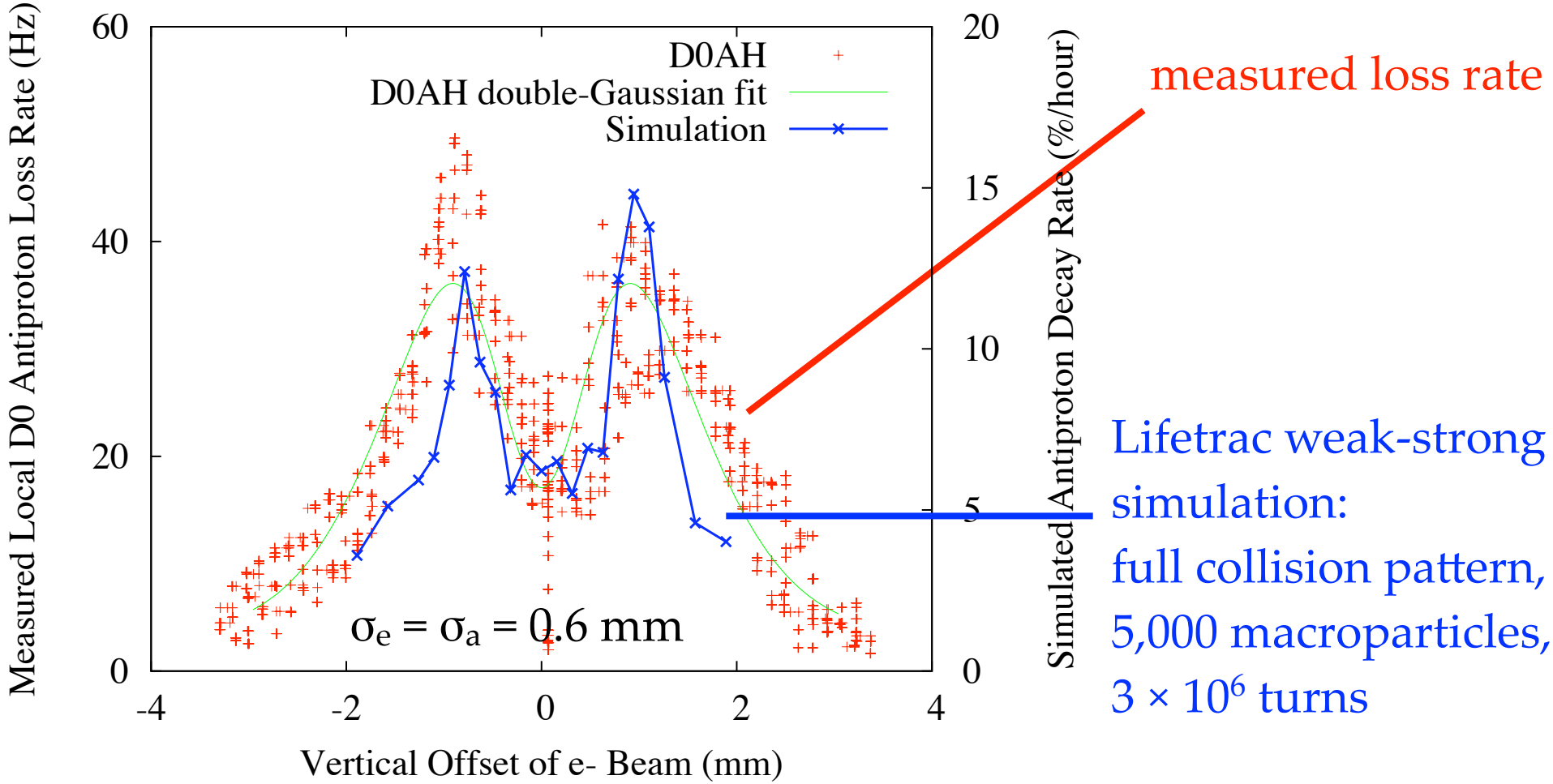
Linear beam-beam parameter for antiprotons due to electrons

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

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

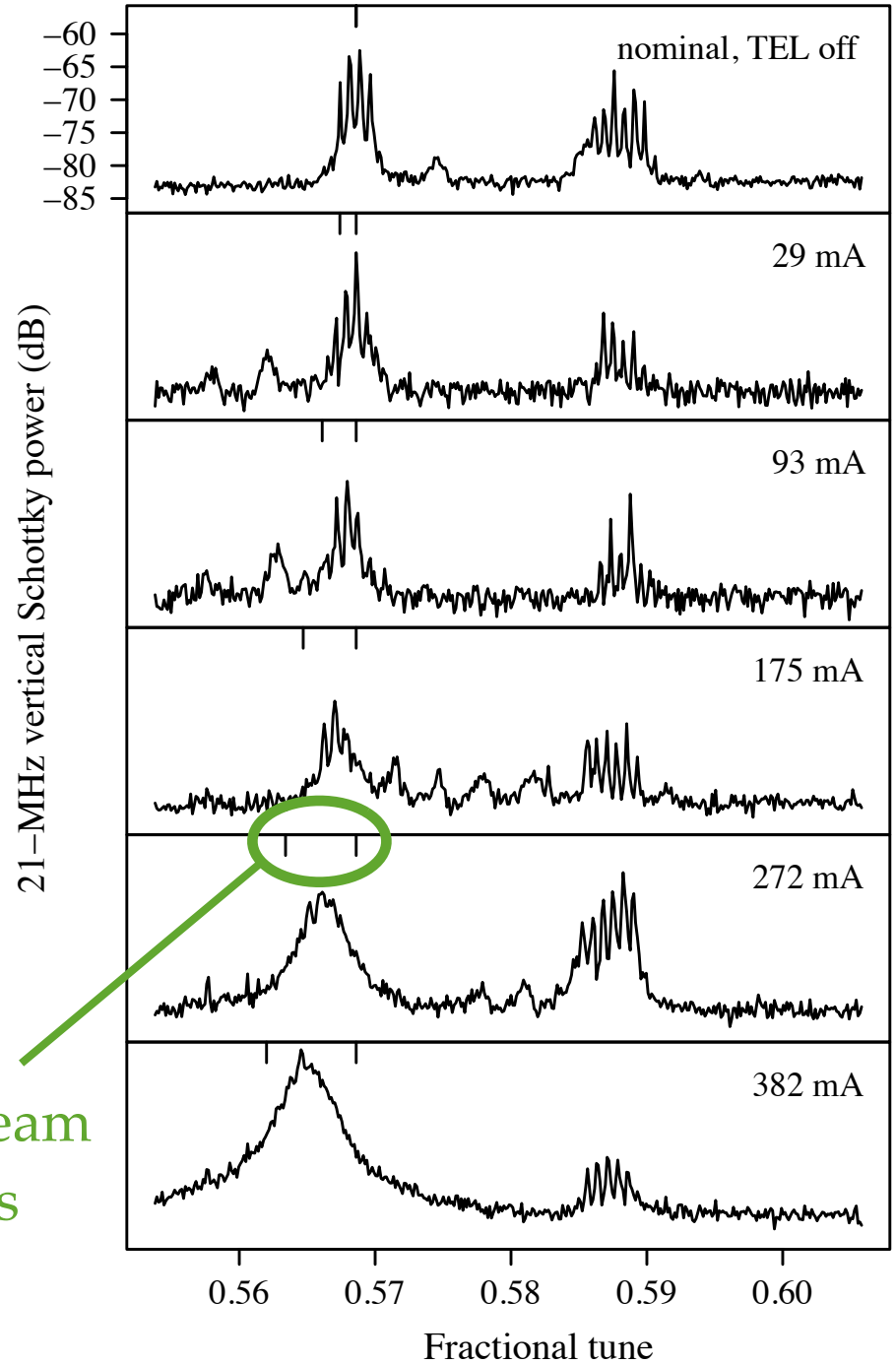


3. Lifetrac simulation reproduces both (1) and the double hump

Incoherent tune spectrum vs. electron beam current

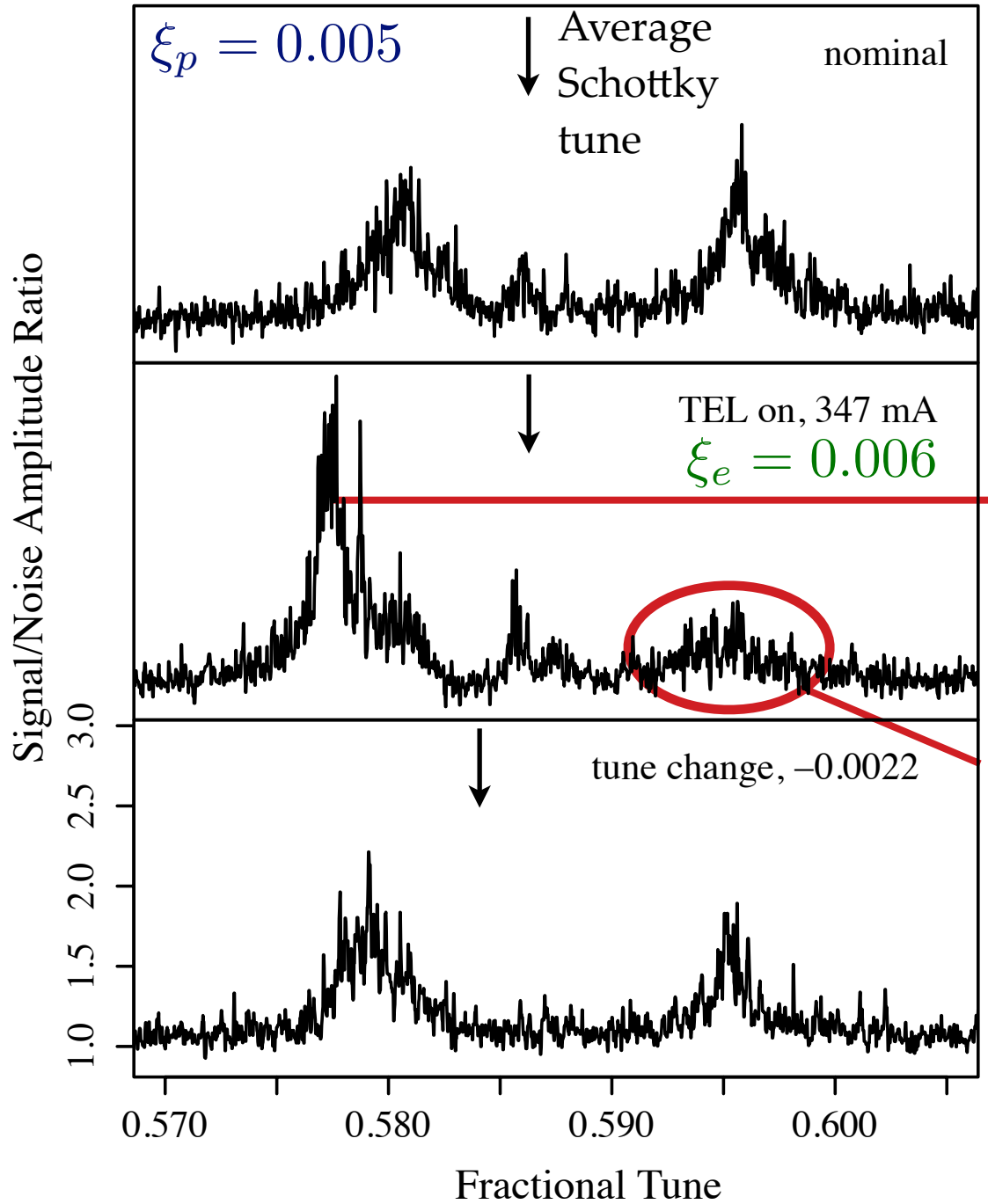
Schottky spectra measured during dedicated ***antiproton-only store***

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

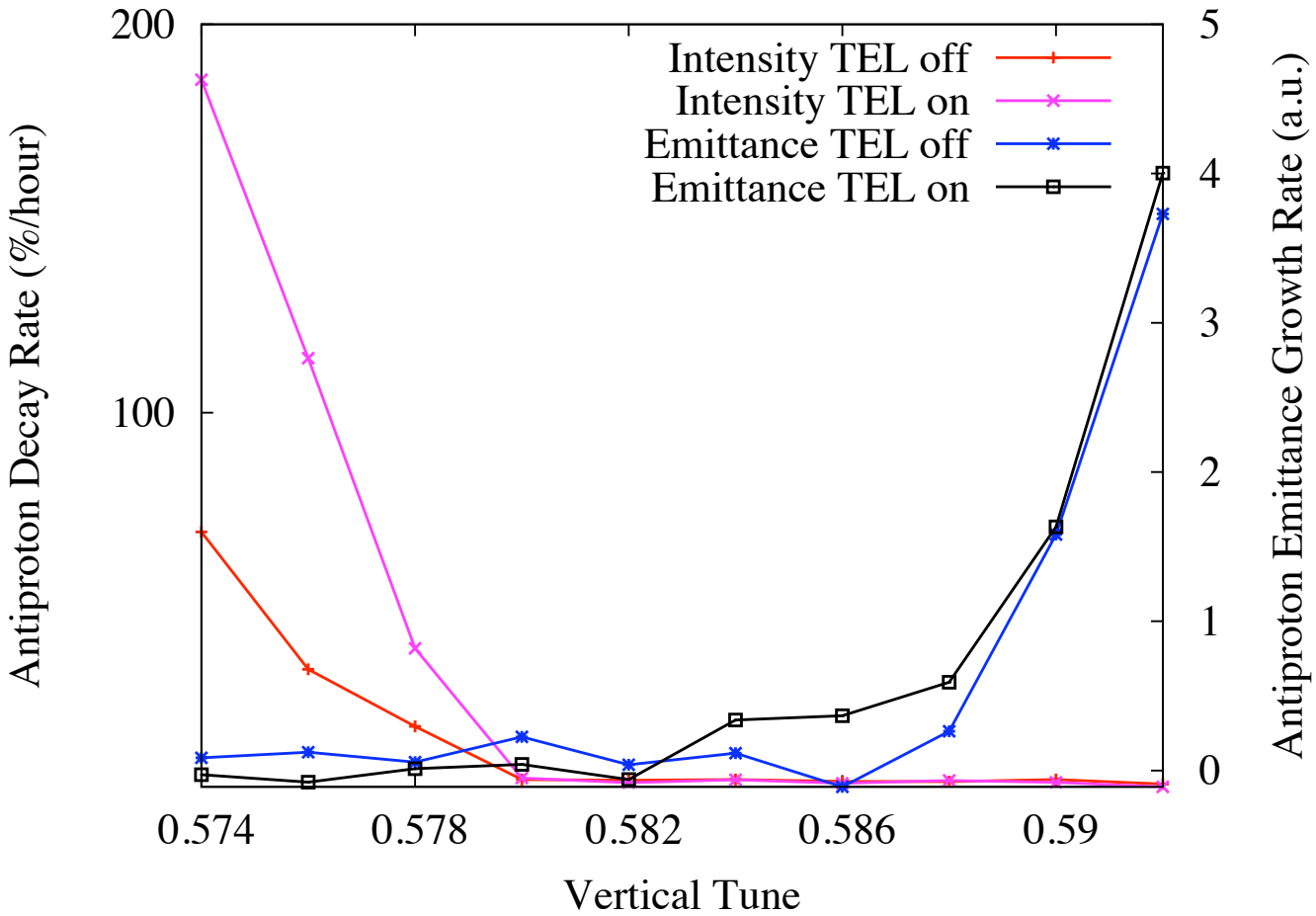
Interpretation requires calculation of mode strengths and widths

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

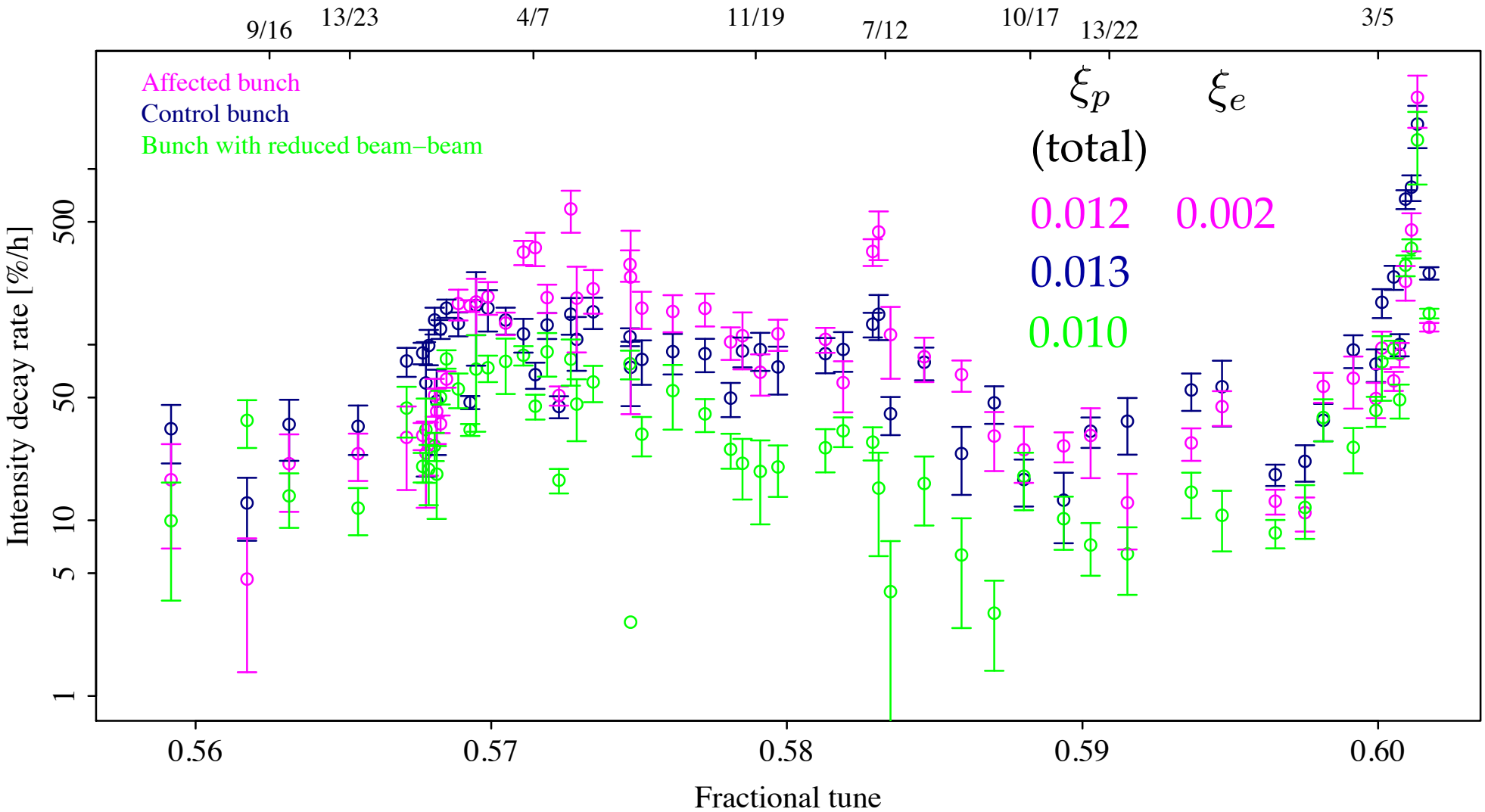
2nd attempt: smaller proton blowup, large electron size to match protons => negligible benefit expected, used for tune scans and code benchmarking



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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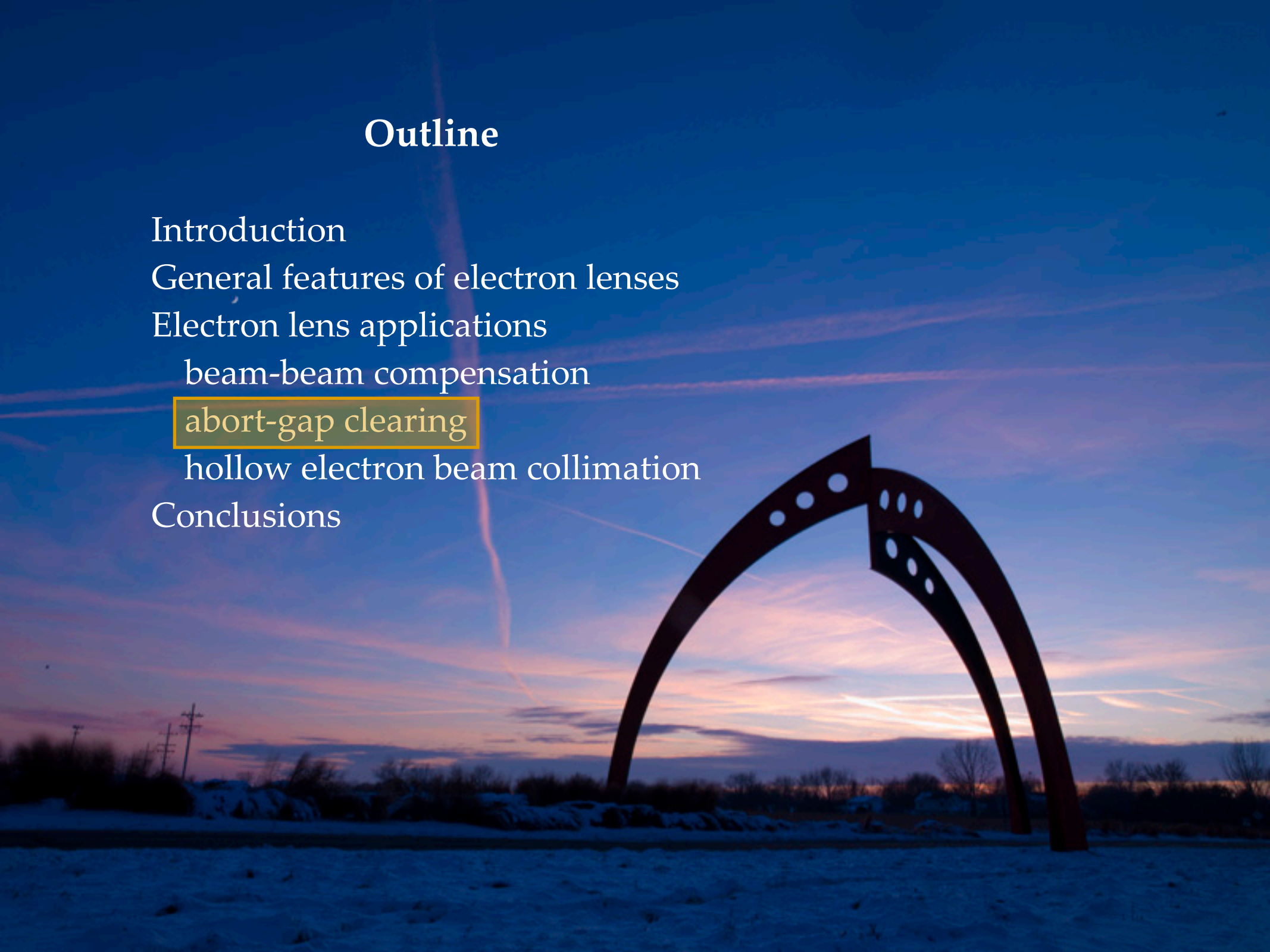
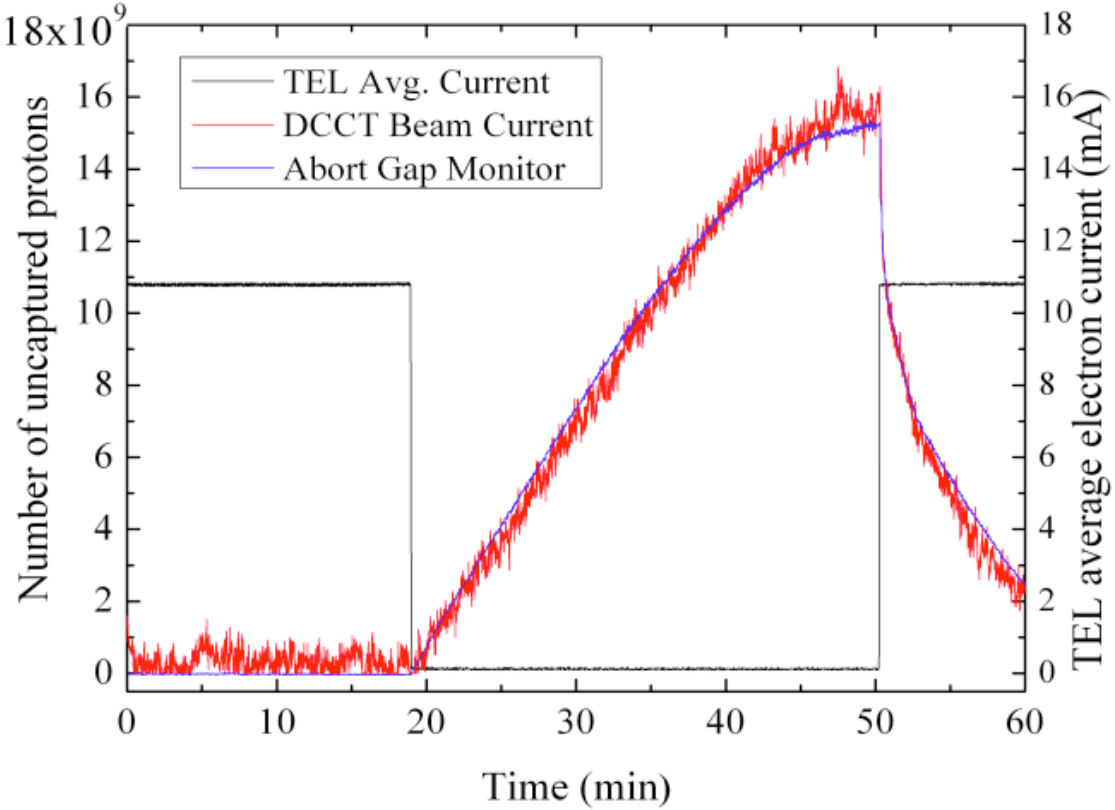


Tevatron electron lenses for abort-gap cleaning

- 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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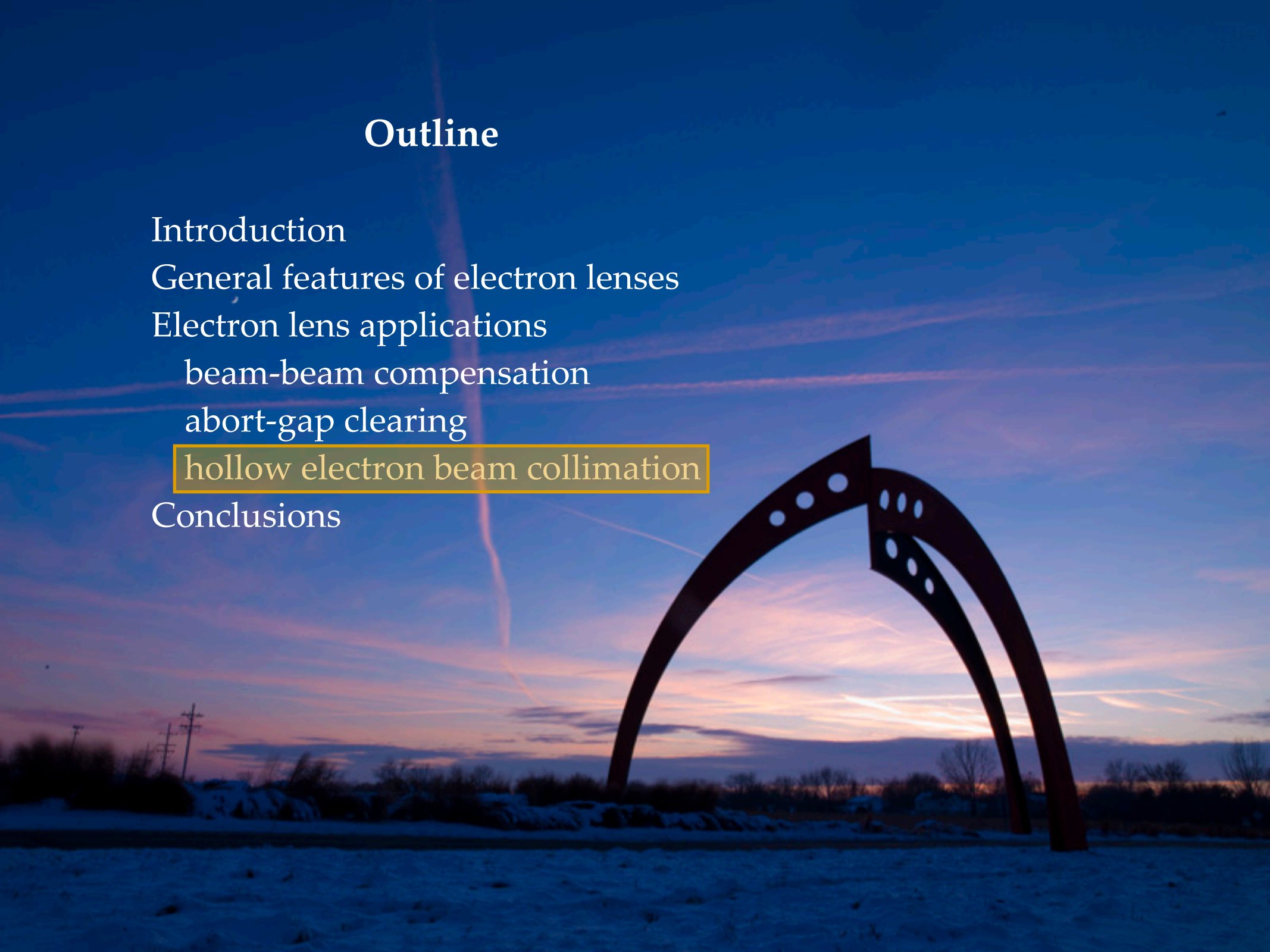
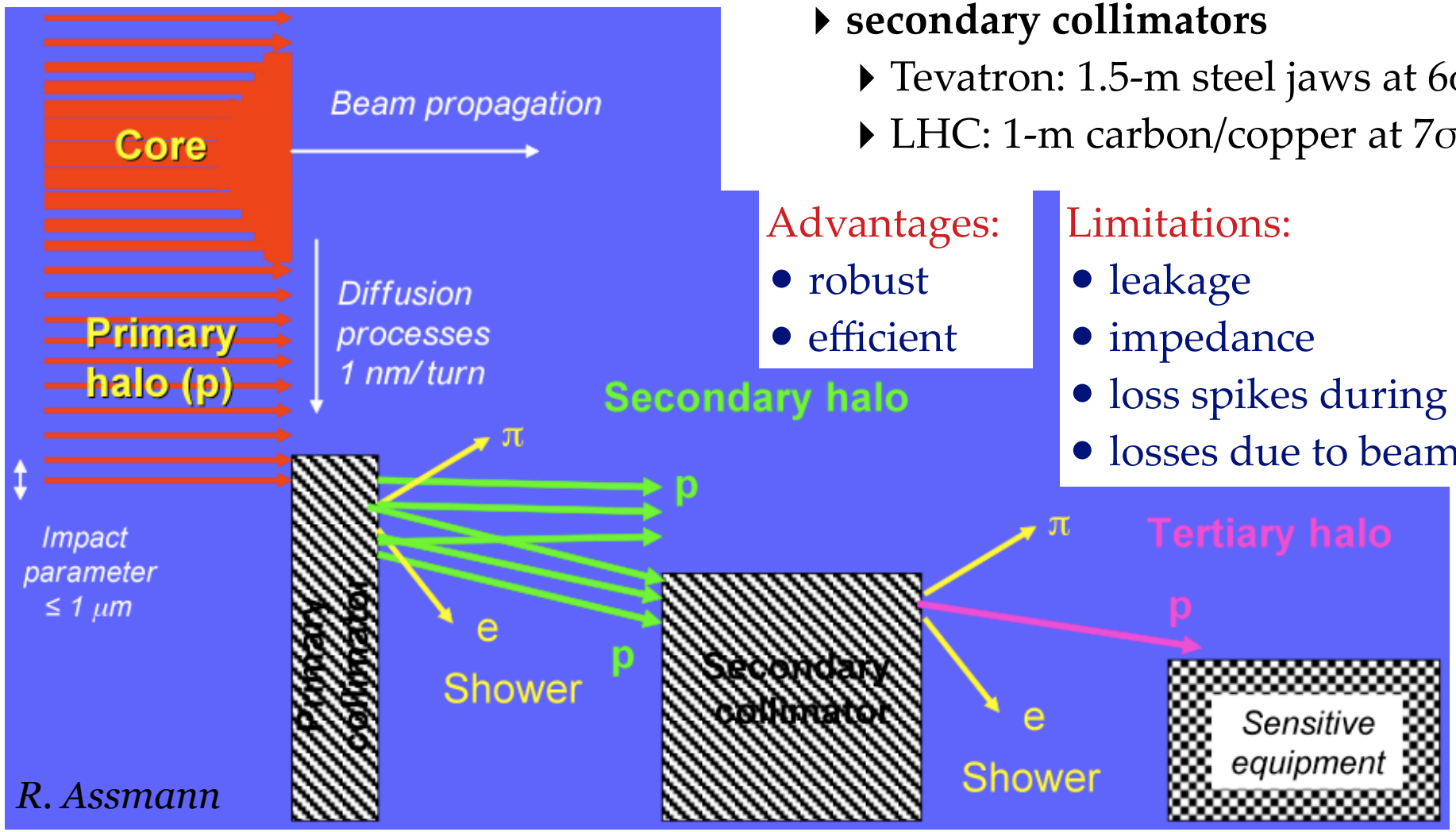


The conventional multi-stage collimation system

- Goals of collimation:
  - reduce beam halo
  - direct losses towards absorbers

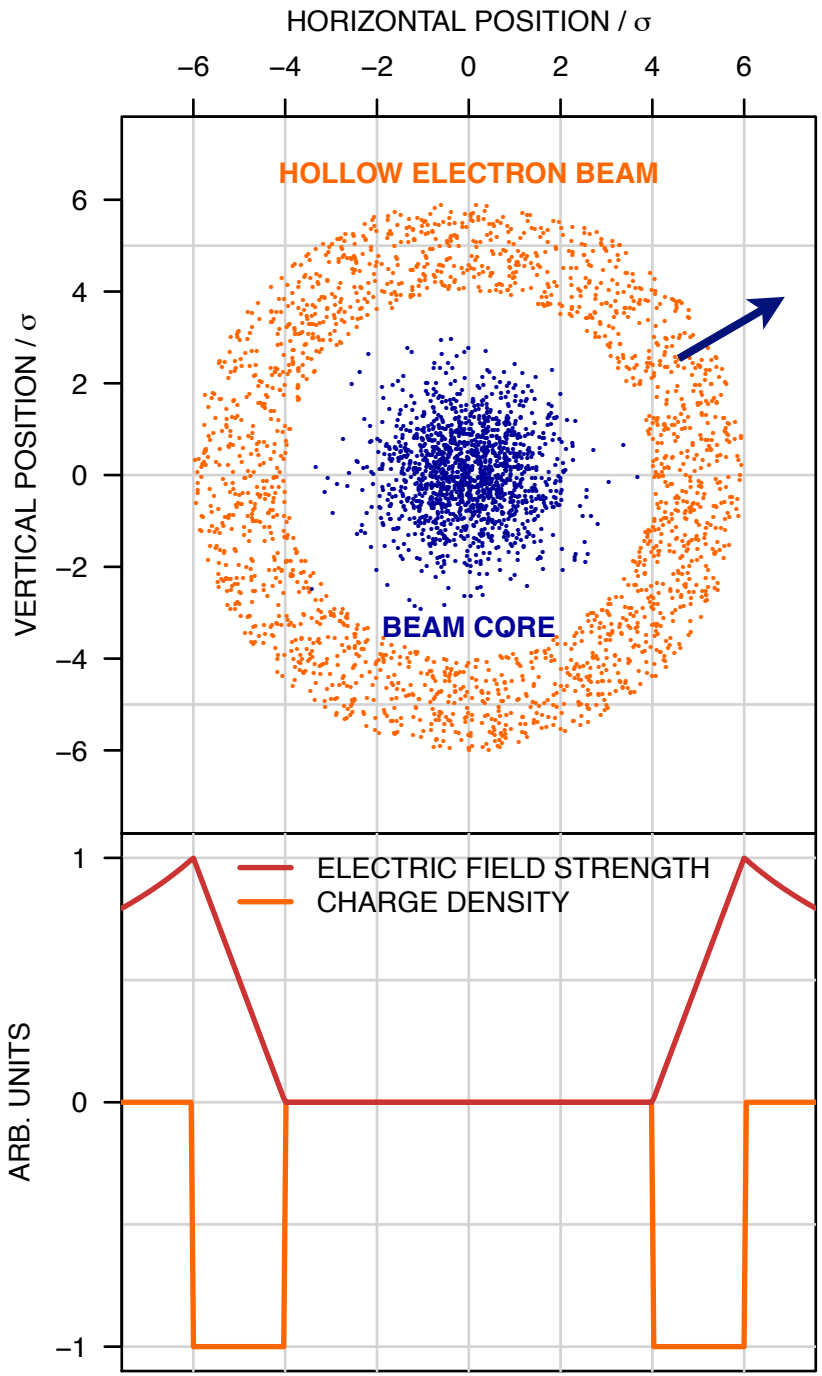
- Conventional schemes:
  - **primary collimators**
    - Tevatron: 5-mm W at 5σ
    - LHC: 0.6-m carbon jaws at 6σ
  - **secondary collimators**
    - Tevatron: 1.5-m steel jaws at 6σ
    - LHC: 1-m carbon/copper at 7σ



Advantages:
- robust
- efficient

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

Concept of hollow electron beam collimator (HEBC)



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

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

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 of magnetically confined electron beam
- 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

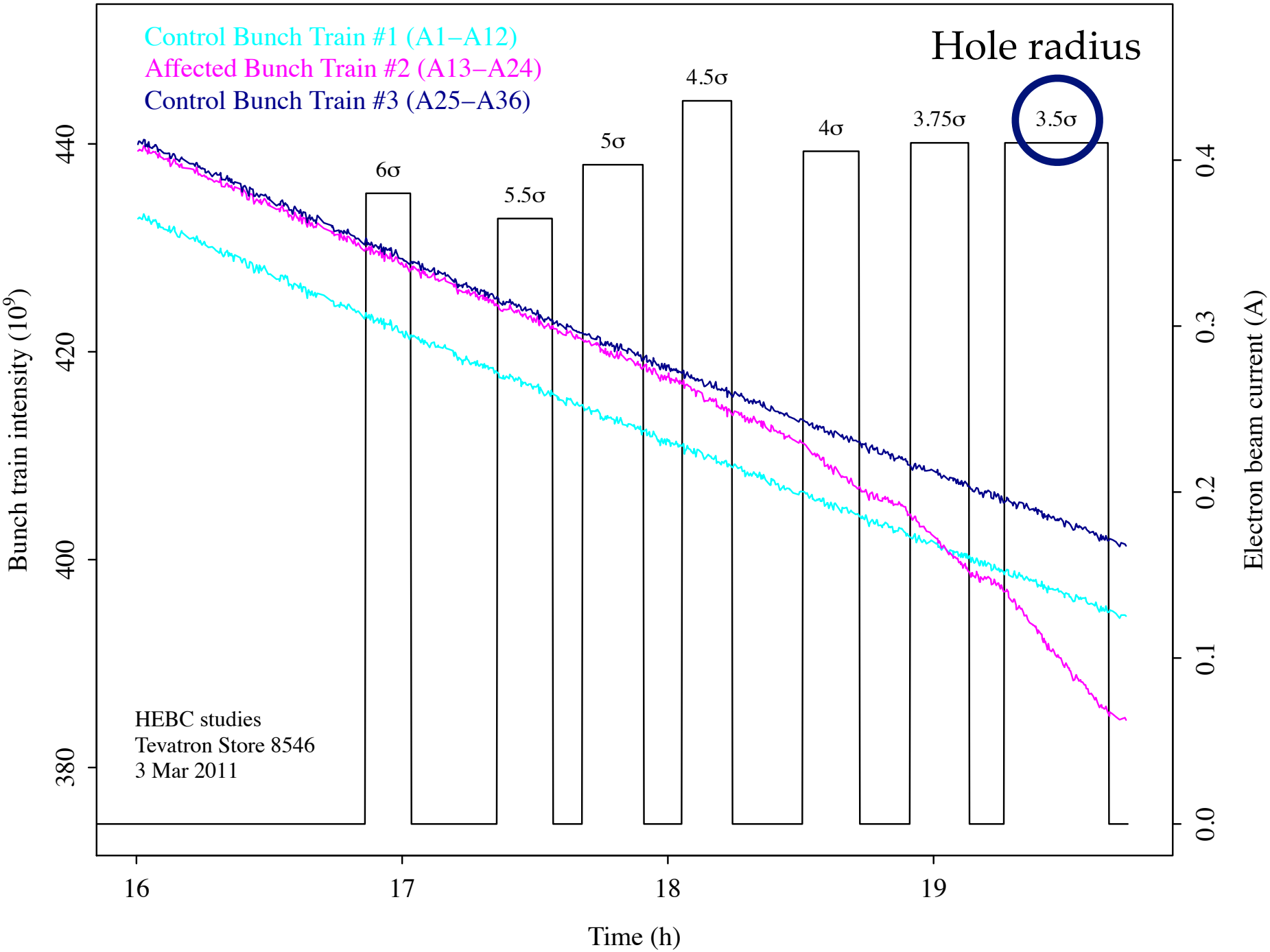
- Critical beam alignment
- Space-charge evolution of hollow beam profile
- Stability of beams at high intensity
- Cost

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]

Electrons acting on 1 antiproton bunch train (#2, A13-A24)



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

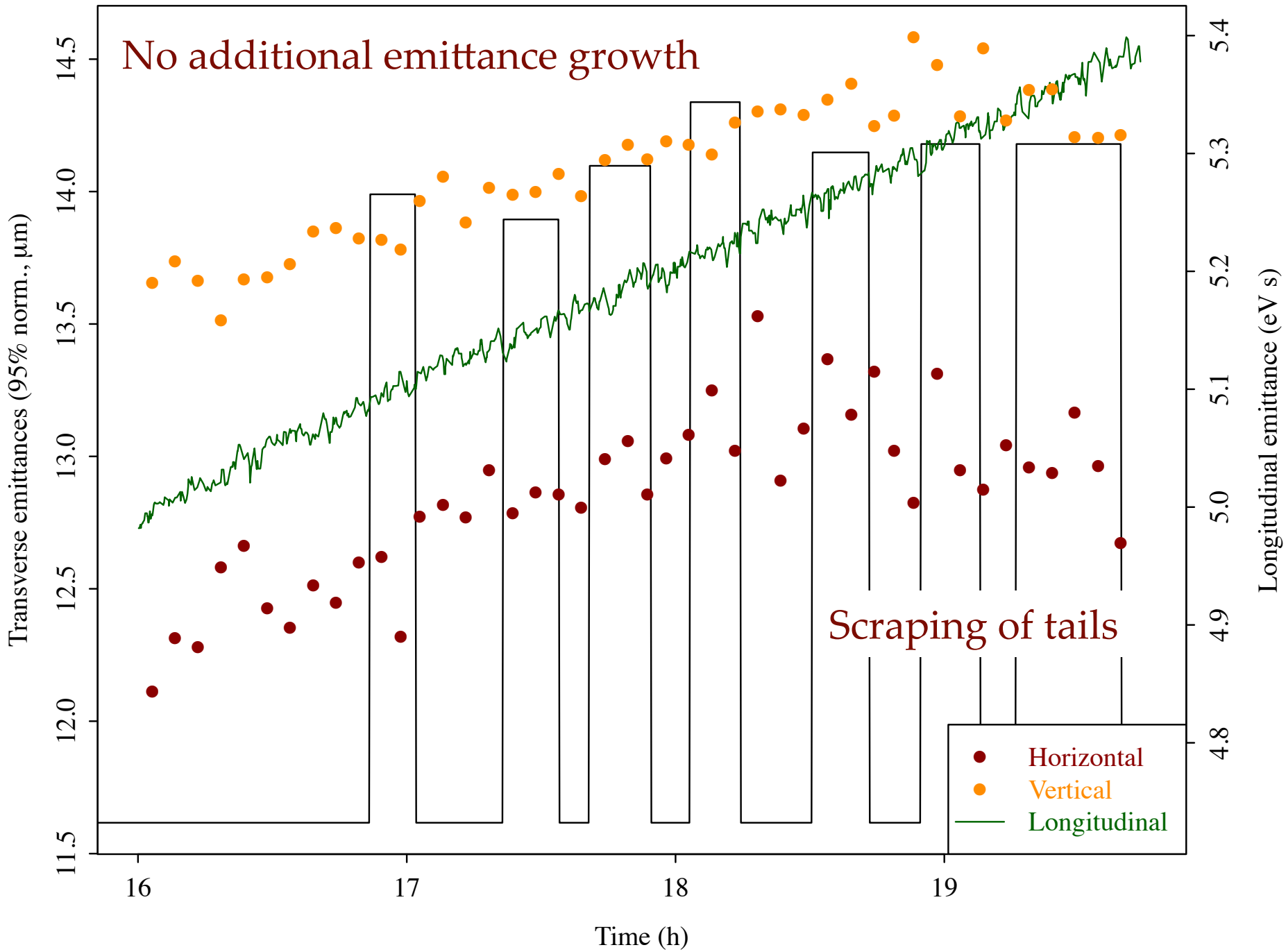
Several strategies:

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

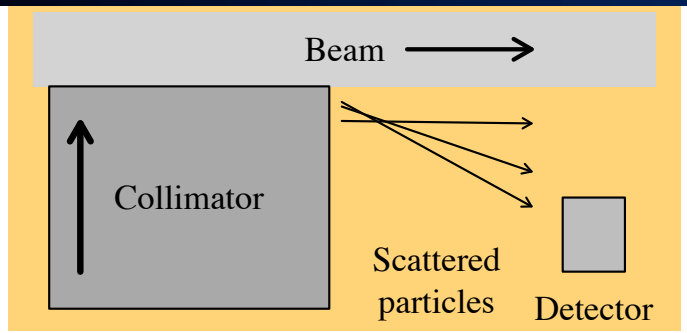
$$\mathcal{L} = \left(\frac{f_{\mathrm{rev}} N_b}{4\pi}\right) \frac{N_p N_a}{\sigma^2} \qquad \frac{\Delta\mathcal{L}}{\mathcal{L}} = \frac{\Delta N_p}{N_p} + \frac{\Delta N_a}{N_a} - 2\frac{\Delta\sigma}{\sigma}$$

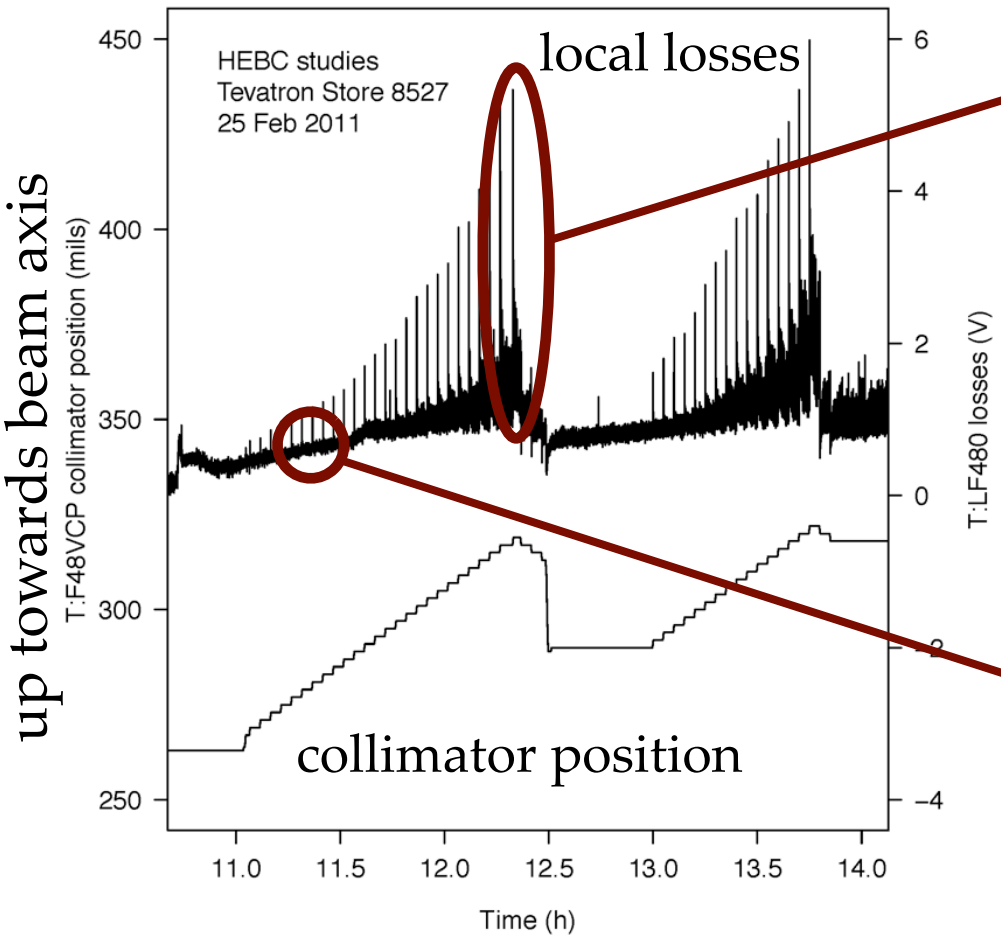
  - <u>same fractional variation</u> if other factors are constant
  - luminosity decreases <u>more</u> if there is emittance growth or proton loss
  - luminosity decreases <u>less</u> if removing halo particles (smaller relative contribution to luminosity)
- **Removal rate** vs. amplitude (collimator scan, steady state)
- **Diffusion rate** vs. amplitude (collimator scan, time evolution of losses)

Emittances of affected bunch train

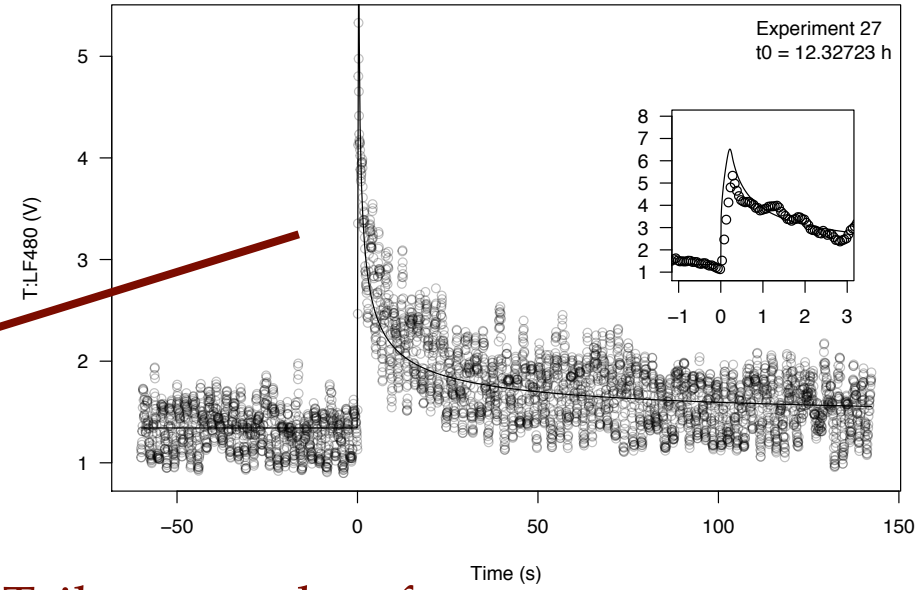


Diffusion rate vs. amplitude from collimator scans

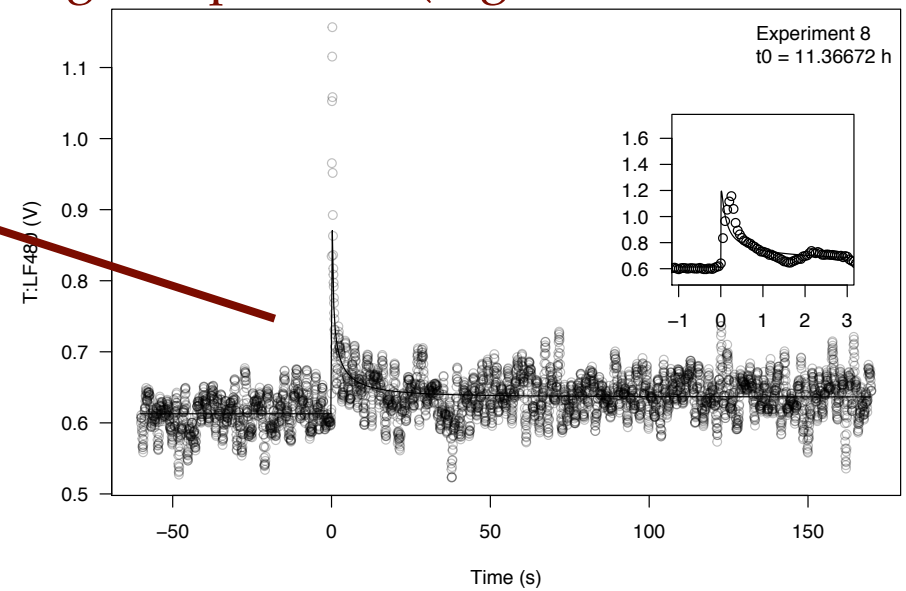




Mess and Seidel, NIMA **351**, 279 (1994)



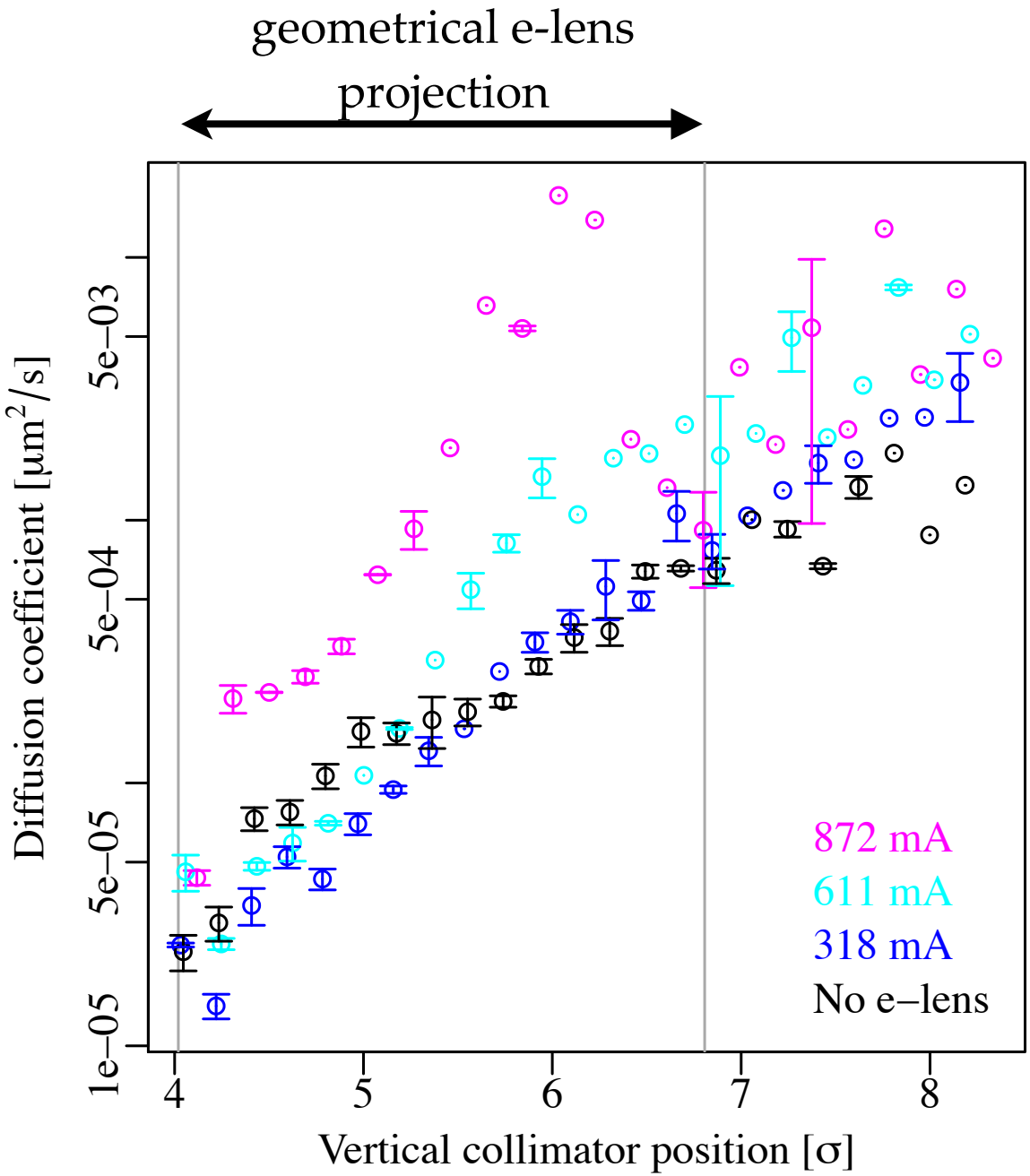
Tails repopulate faster at large amplitudes (higher diffusion rate)



IPAC11, p. 1882

arXiv:1108.5010 [physics.acc-ph]

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



Large diffusion enhancement in halo region

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 **collimation/scraping with hollow electron beams**; promising technique for the LHC
- Tevatron experience with head-on beam-beam compensation using Gaussian electron lenses
  - 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