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# Beam-beam effects, electron lenses and the Tevatron experience

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Summary:

- Beam-beam and electron lenses in the Tevatron
- The "electron wire" for long-range compensation in HL-LHC

*ICFA Mini-Workshop on Beam-Beam Effects in Circular Colliders*

*Lawrence Berkeley National Laboratory*

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# Contributors and collaborators

Many invaluable contributions from the whole Fermilab Accelerator Division, Tevatron Department and electron-lens team

For this talk, special thanks to

G. Annala, V. Shiltsev, D. Still, A. Valishev (Fermilab)

W. Fischer, X. Gu, C. Montag (BNL)

S. White (ESRF)

A. Rossi, H. Schmickler, F. Zimmermann (CERN)

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# Electron lenses and beam-beam effects in the Fermilab Tevatron collider

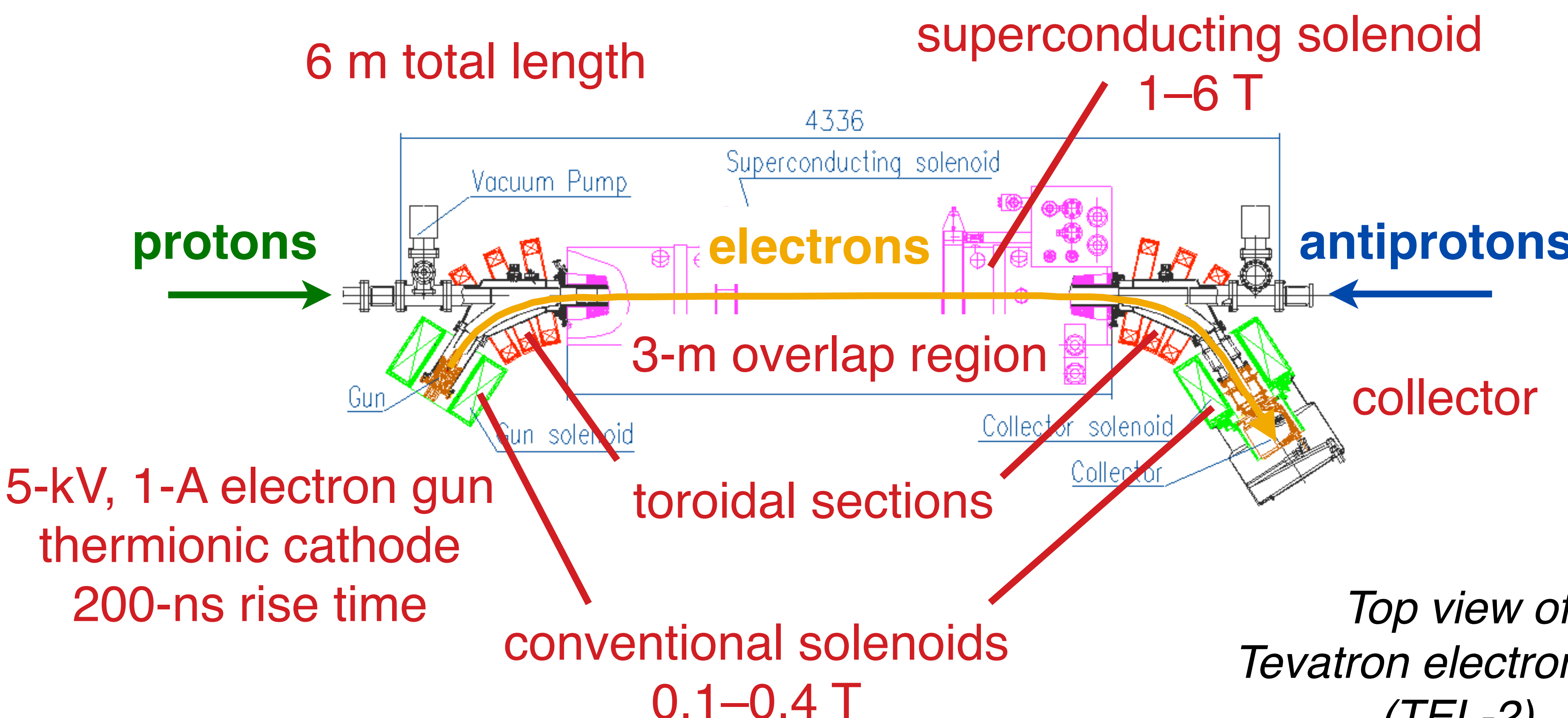
# Characteristic beam-beam features in the Tevatron collider

- Protons and antiprotons circulated in the same beam pipe
- Smaller antiproton beam sizes (factor 2), from beam cooling, significantly affected proton lifetime through nonlinear head-on beam-beam forces
- Long-range beam-beam interactions affected luminosity lifetime mainly through antiproton emittance growth
- The collider operated along the diagonal $Q_x = 20.583$, $Q_y = 20.585$

Lebedev and Shiltsev (eds.), *Accelerator Physics at the Tevatron Collider* (Springer, 2014)
Shiltsev, *Electron Lenses for Super-Colliders* (Springer, 2016)

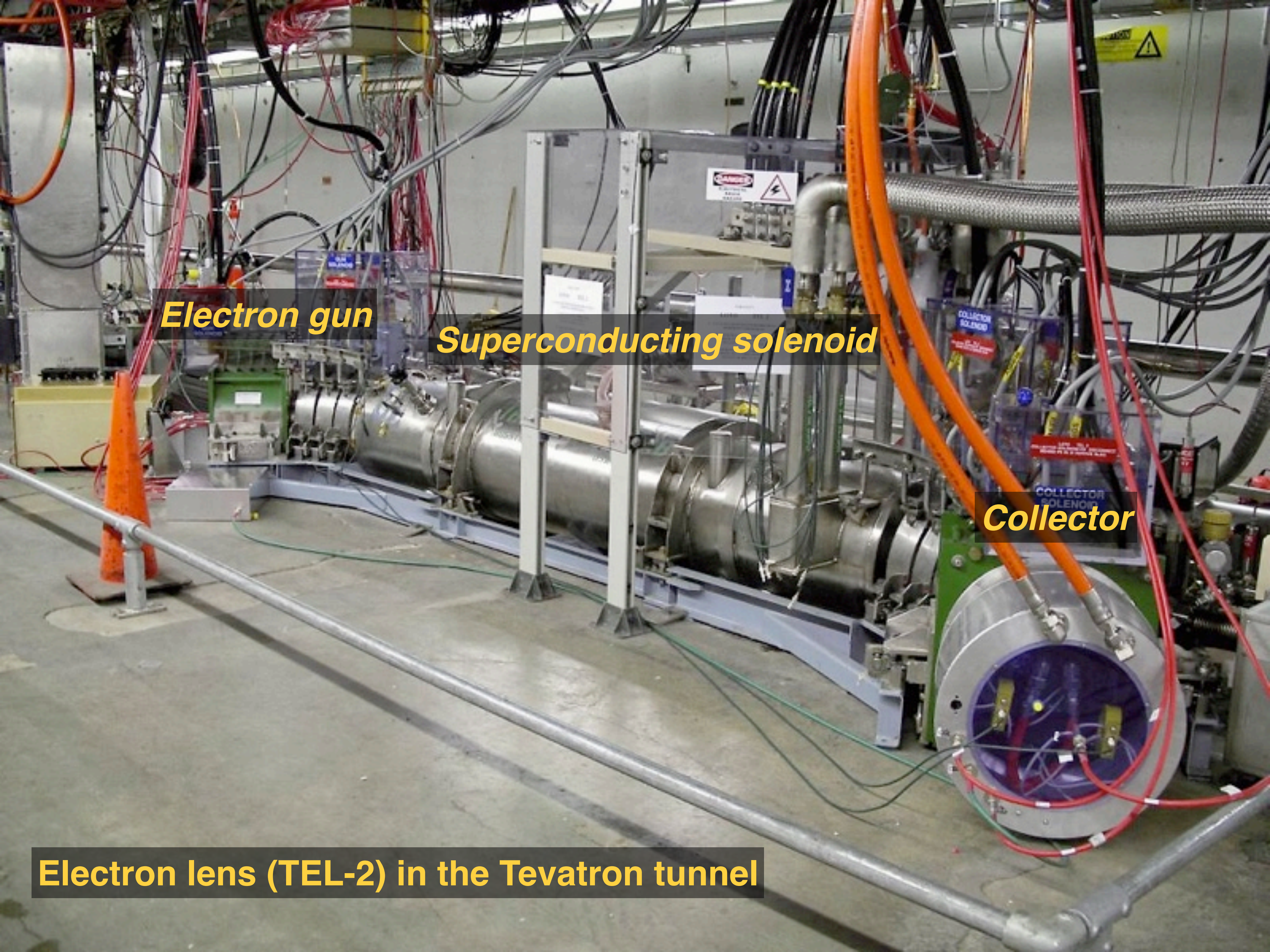
# Electron-lens apparatus and beam layout

- Pulsed, magnetically confined, low-energy electron beam
- Circulating beam affected by electromagnetic fields generated by electrons
- Stability provided by strong axial magnetic fields




*Top view of Tevatron electron lens (TEL-2)*

Shiltsev et al., Phys. Rev. ST Accel. Beams **11**, 103501 (2008)




Electron lens (TEL-2) in the Tevatron tunnel

# Applications of electron lenses

## In the Fermilab Tevatron collider (2001-2011)

- ***long-range beam-beam compensation (tune shift of individual bunches)***
  - Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)
- ***abort-gap cleaning during regular collider 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
- ***demonstration of halo scraping with hollow electron beams***
  - Stancari et al., Phys. Rev. Lett. **107**, 084802 (2011)

## In RHIC at BNL (2015-present)

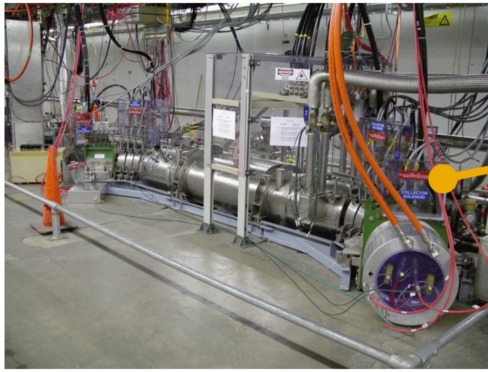
- ***head-on beam-beam compensation for luminosity improvement***
  - Gu et al., Nucl. Instrum. Methods A **637**, 190 (2011)
  - Luo et al., Phys. Rev. ST Accel. Beams **15**, 051004 (2012)
  - Gu et al., Nucl. Instrum. Methods A **743**, 56 (2014)
  - Fischer et al., Phys. Rev. Lett. **115**, 264801 (2015)
  - Luo et al., Phys. Rev. Accel. Beams **19**, 021001 (2016)
  - Thieberger et al., Phys. Rev. Accel. Beams **19**, 041002 (2016)
  - Gu et al., Phys. Rev. Accel. Beams **20**, 023501 (2017)
  - Fischer et al., Phys. Rev. Accel. Beams **20**, 091001 (2017)

# Applications of electron lenses

## Current areas of research

- ***nonlinear integrable lattices*** *in the Fermilab Integrable Optics Test Accelerator (IOTA)*
  - Nagaitsev, Valishev et al., IPAC12
  - Stancari, arXiv:1409.3615
  - Antipov et al., JINST **12**, T03002 (2017)
- ***hollow electron beam scraping*** *of protons in LHC*
  - Stancari et al., CERN-ACC-2014-0248
  - Bruce et al., IPAC15
  - Oct. '16 review: <https://indico.cern.ch/event/567839>
  - Zanoni et al., J. Phys. Conf. Series **874**, 012102 (2017)
- ***long-range beam-beam compensation*** *as charged, current-carrying "wires" for LHC*
  - Valishev and Stancari, arXiv:1312.5006
  - Fartoukh et al., Phys. Rev. ST Accel. Beams **18**, 121001 (2015)
- ***tune-spread generation for beam stability (Landau damping)*** *in HL-LHC or FCC*
  - Shiltsev et al., Phys. Rev. Lett. **119**, 134802 (2017)
- **space-charge compensation** of high-intensity hadron beams (IOTA, SIS18 at GSI)
  - Antipov et al., JINST **12**, T03002 (2017)
  - Park et al., NAPAC16
  - Stem and Boine-Frankenheim, IPAC17

# Electron lenses in the Tevatron

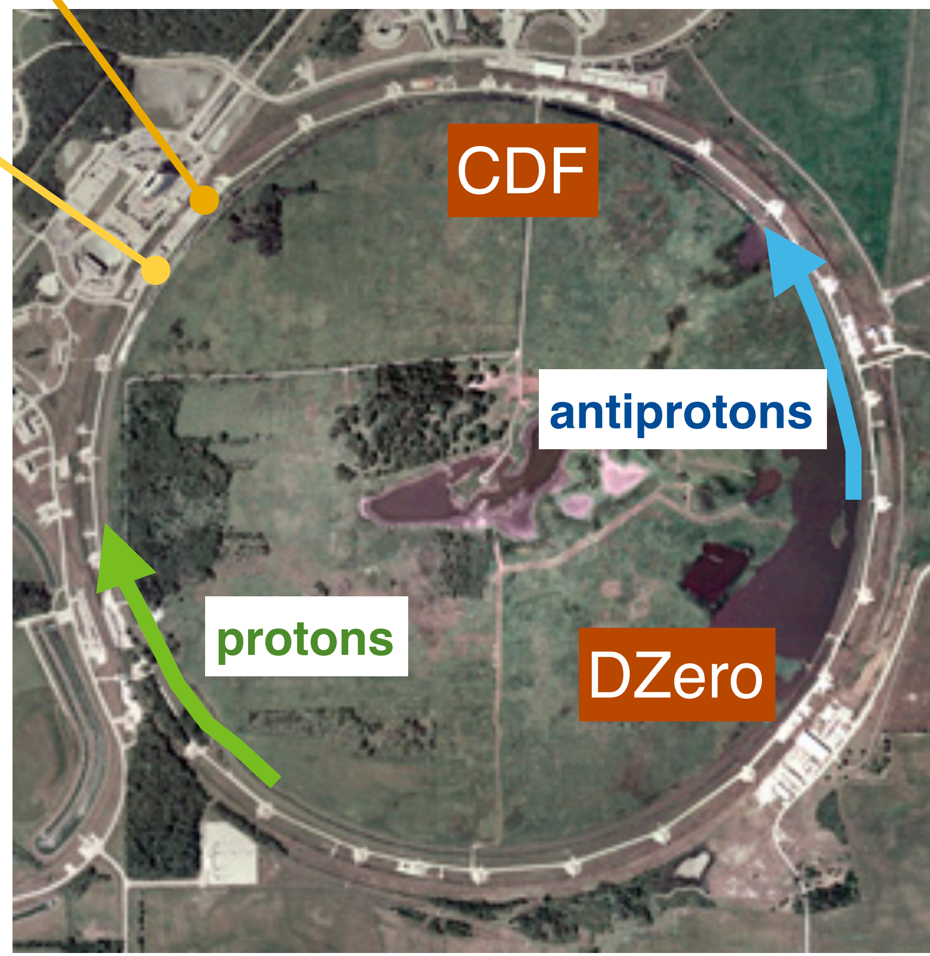


TEL-2

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

TEL-1

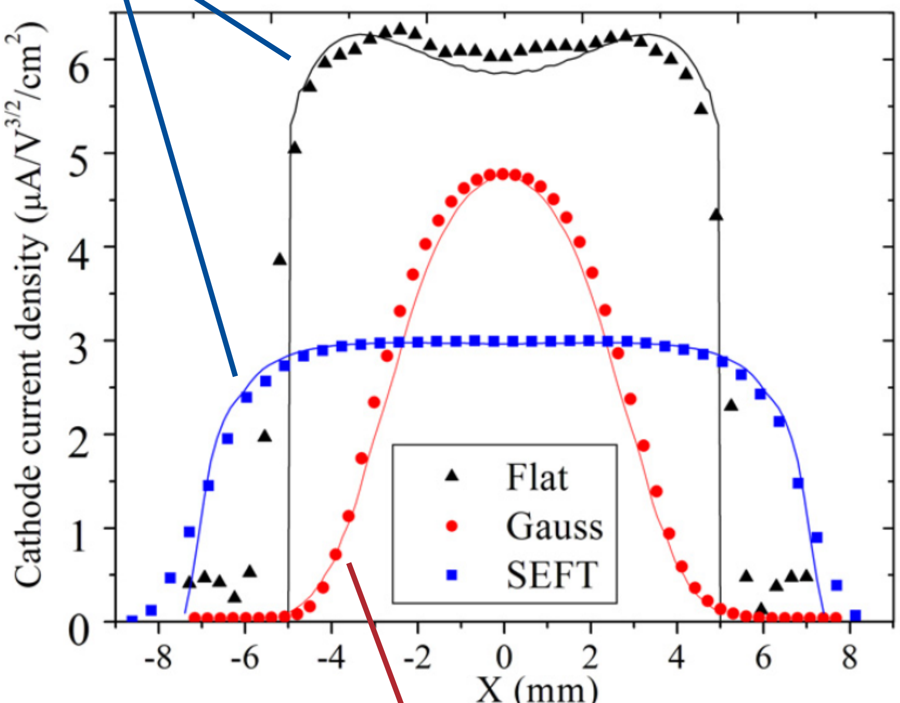
- *abort-gap cleaning during operations*
- *beam-beam compensation studies*

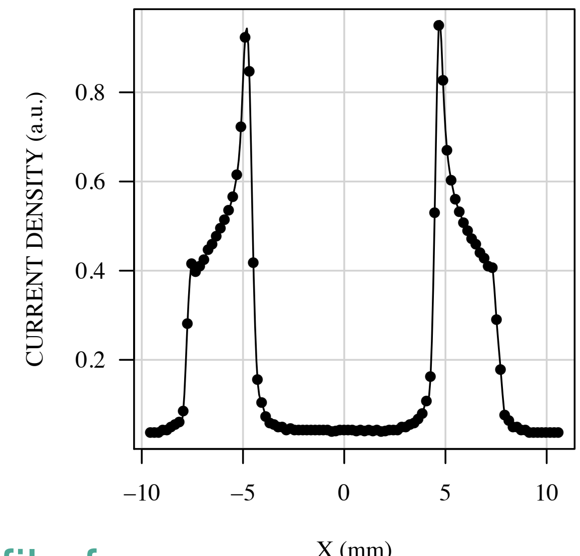


# Control of the electron beam current-density profile

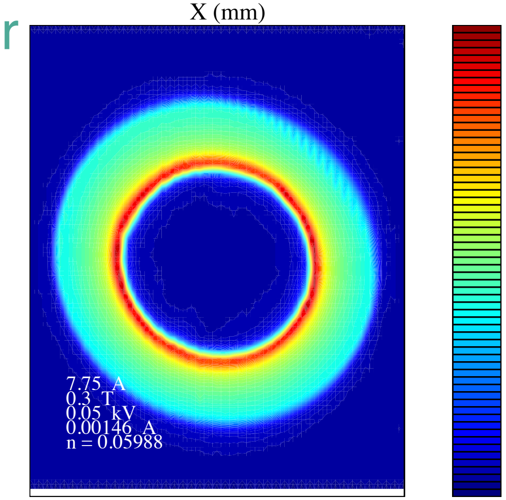
**Current density profile of electron beam** is shaped by cathode and electrode geometry and maintained by strong solenoidal fields

Flat profiles for bunch-by-bunch betatron tune correction



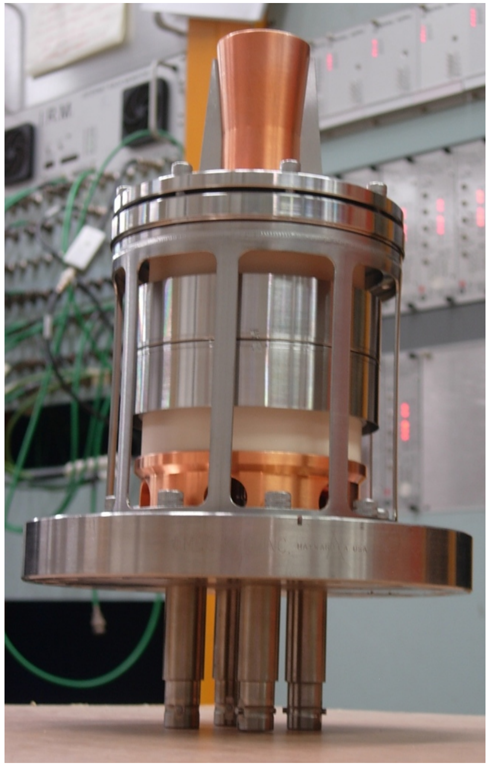

Hollow profile for halo scraping




Gaussian profile for compensation of nonlinear beam-beam forces

# The 0.6-in (10-mm) Gaussian electron gun

*side view*

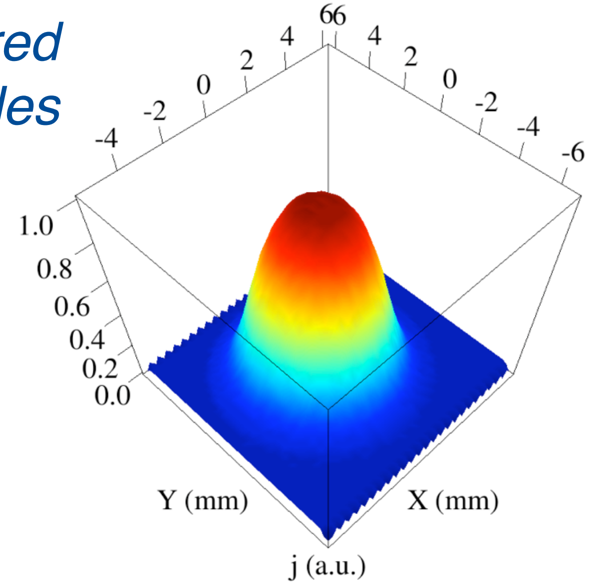


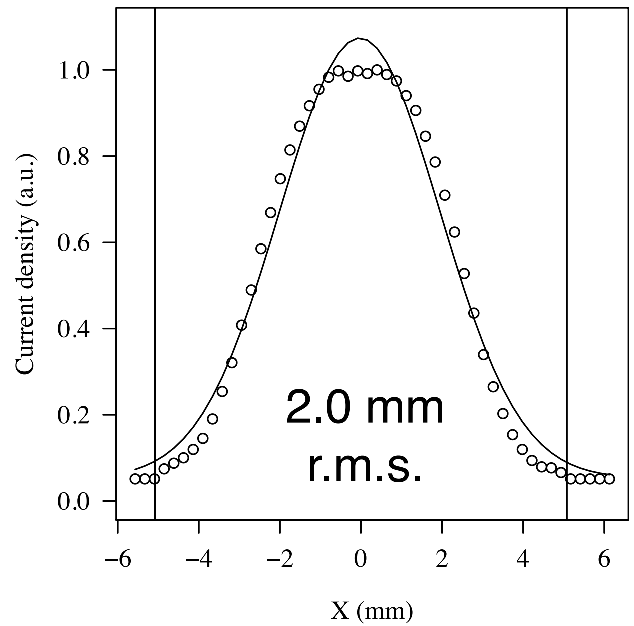
*top view*

*Tungsten dispenser cathode with convex surface operating at 1100°C*

Yield: **0.5 A** at 4.6 kV

*Measured profiles*



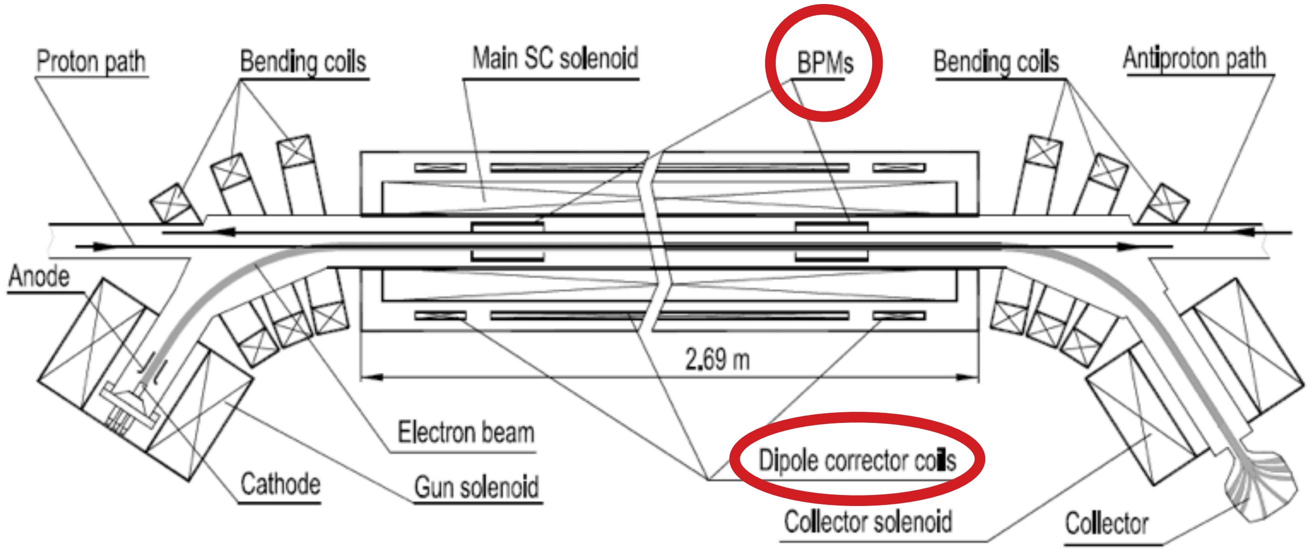



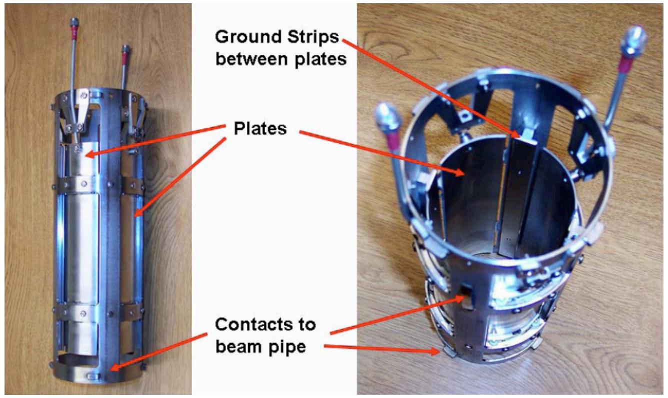
# Alignment of electron beam with circulating beams

Electron position and angle aligned with (anti)proton beam using 6 H/V dipole correctors in main solenoid

Systematic difference in stripline BPM response between fast (anti)proton and slow electron pulse < 0.2 mm. Corrected with independent calibrations.

First alignment done manually: time consuming, but reproducible



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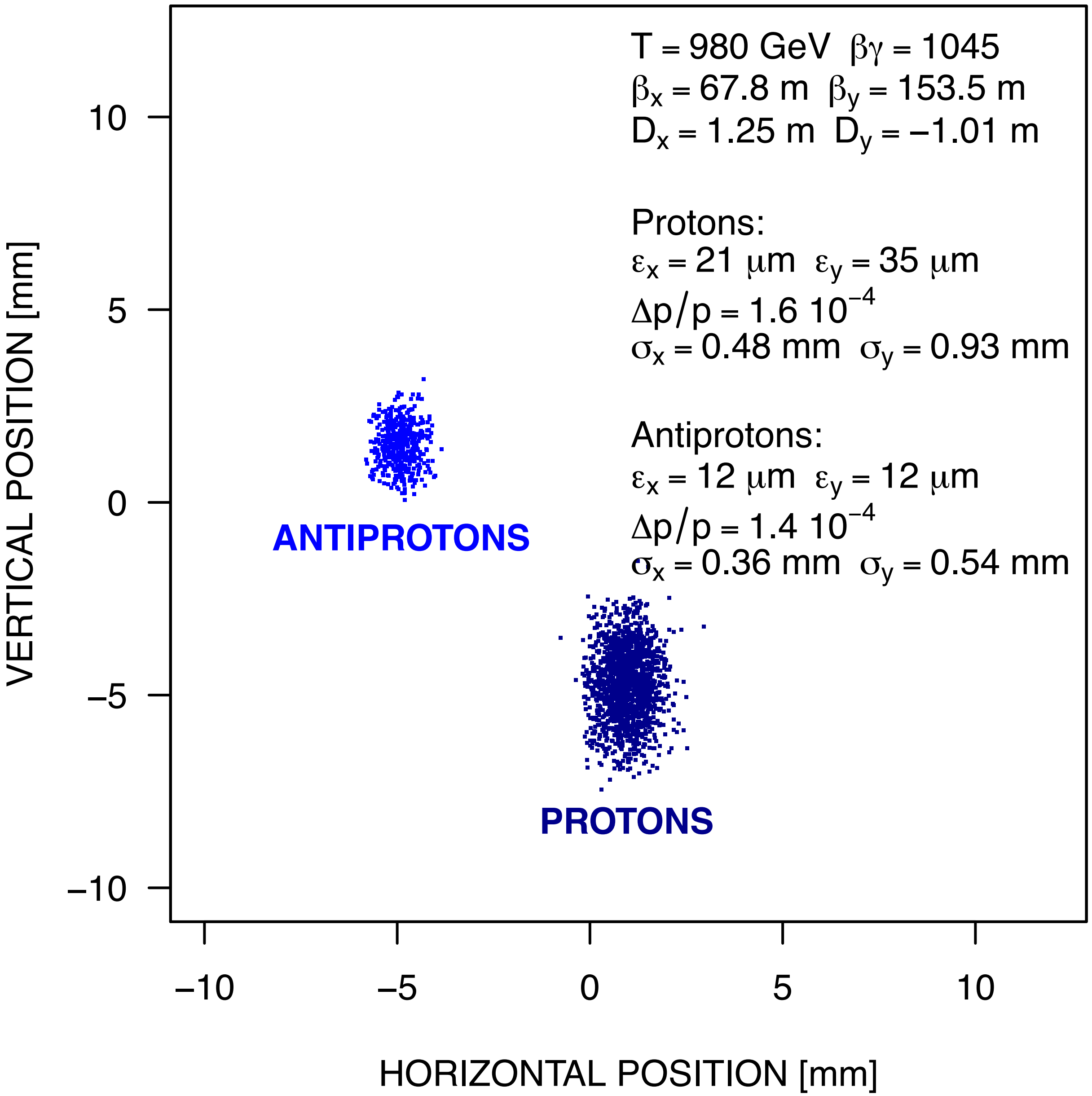
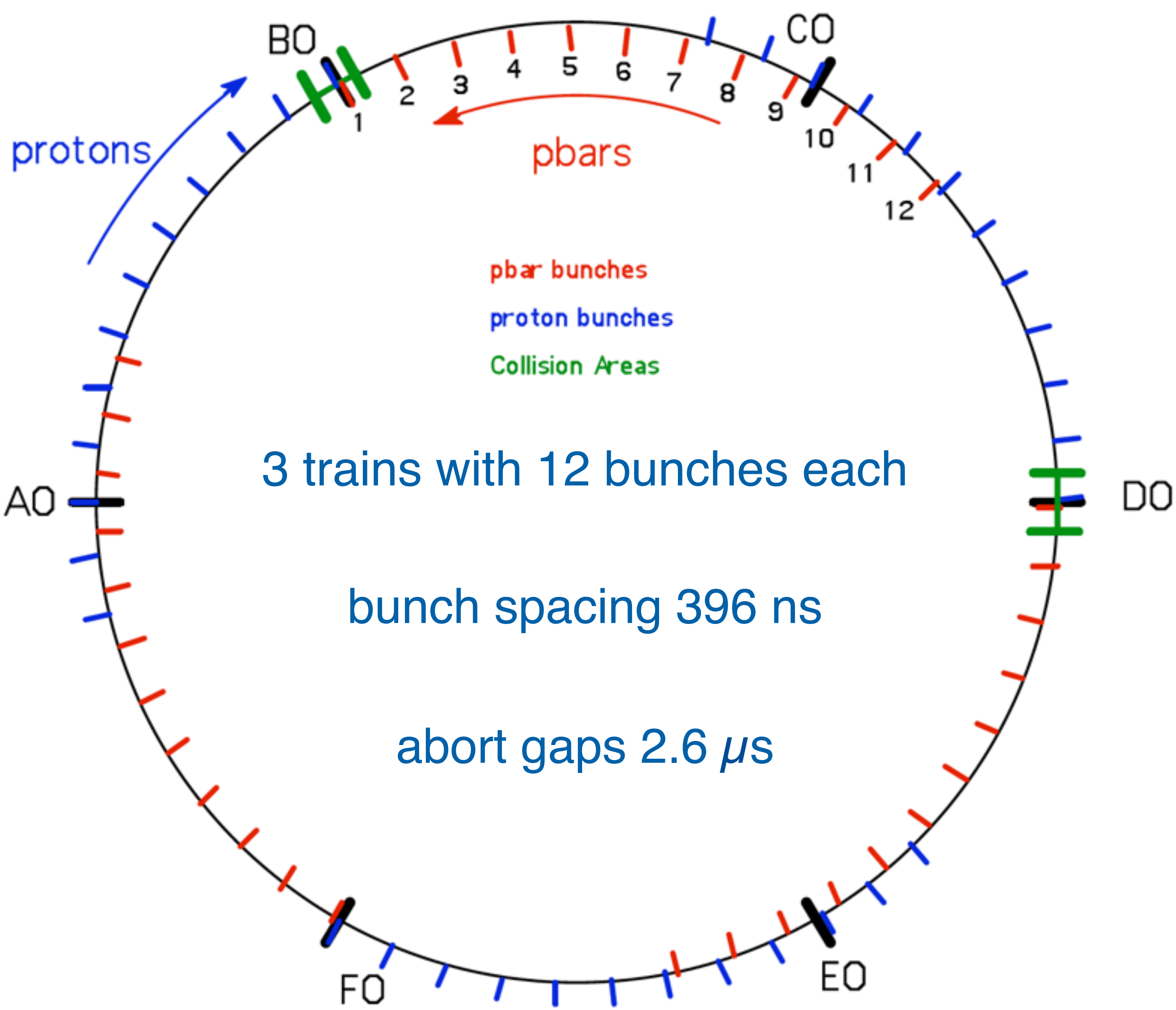
# Transverse layout of the beams in the Tevatron at the e-lens




9-mm separation between proton and antiproton beams in common beam pipe

[Normalized 95% emittances]

# Tevatron bunch structure

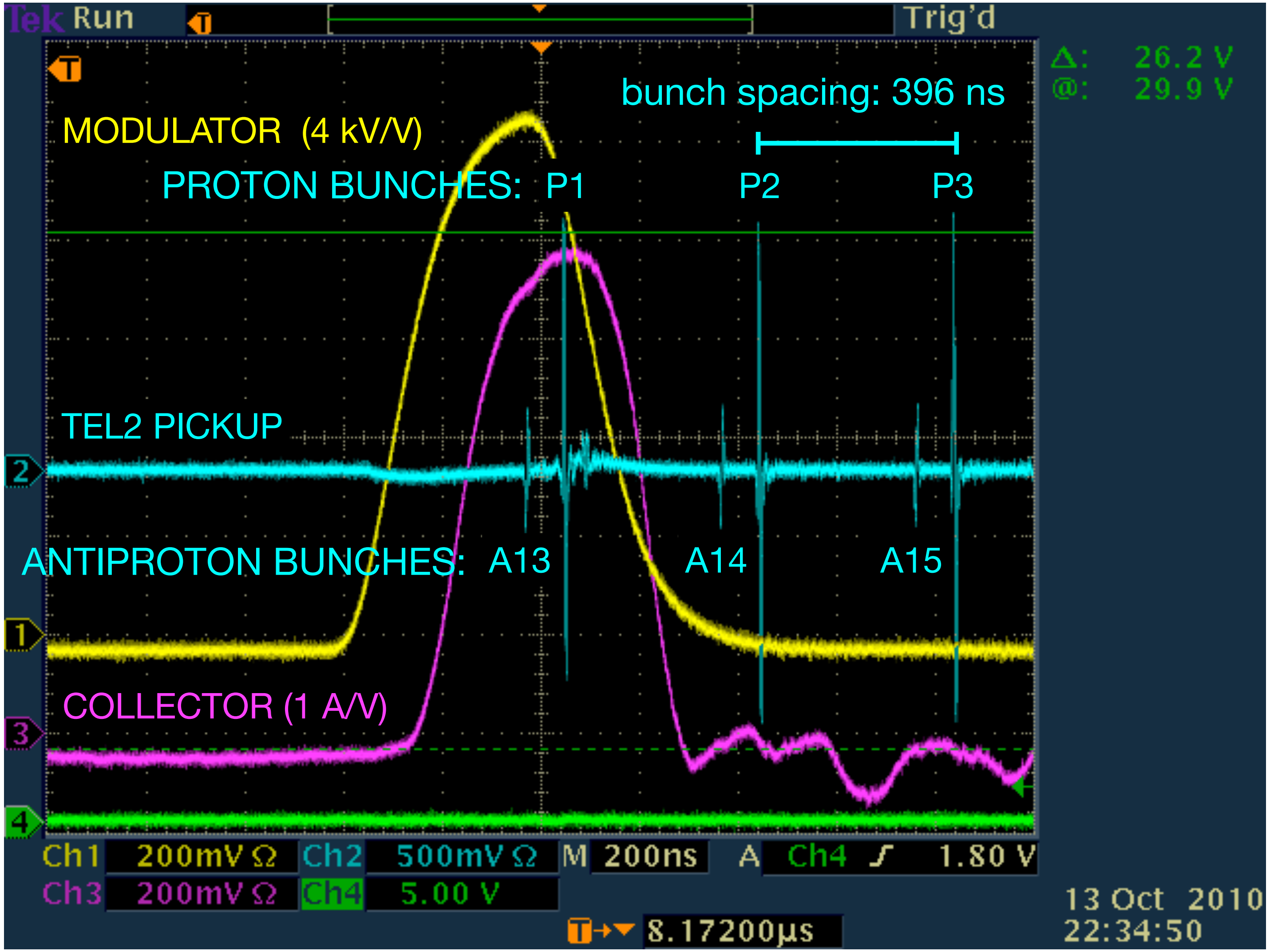



3 trains with 12 bunches each

bunch spacing 396 ns

abort gaps 2.6 $\mu$s

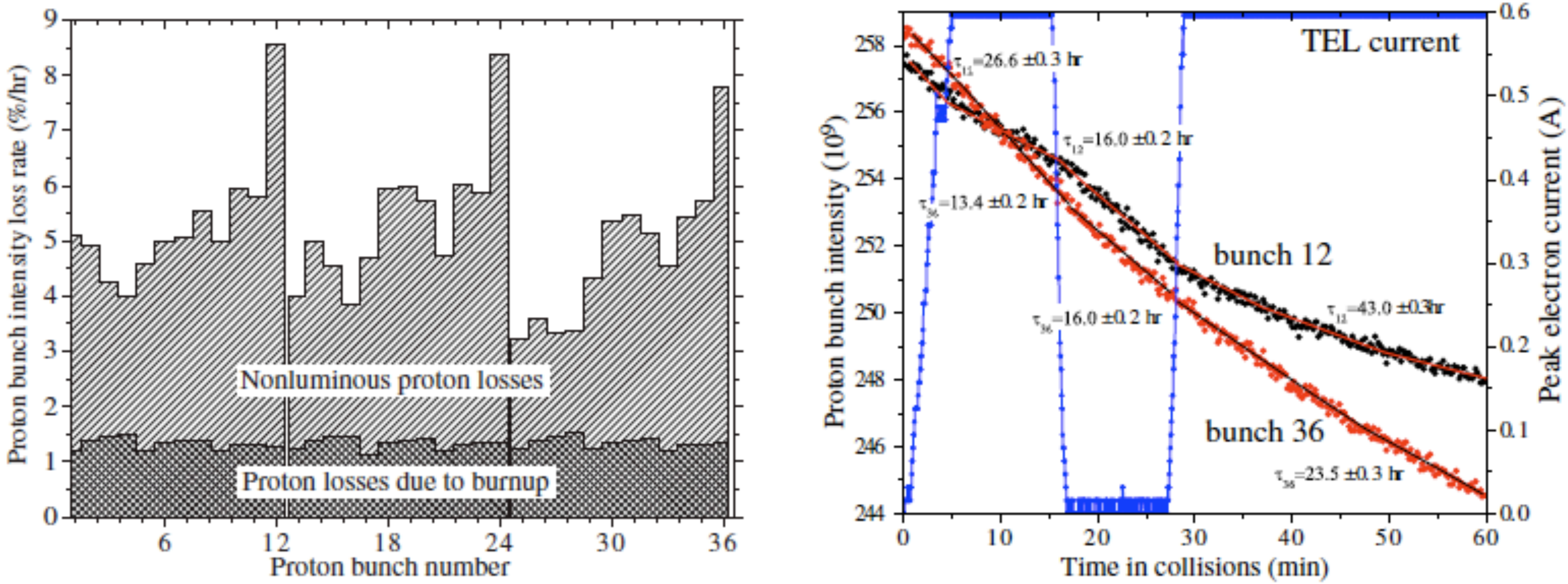
# Time structure and synchronization of the beams




Pulsed electron beam could be **synchronized with any group of bunches**, with a different intensity for each bunch, or **with the abort gap**

# Long-range compensation by tune shifting

Due to collision pattern, beam-beam tune shift and losses depend on position in bunch train

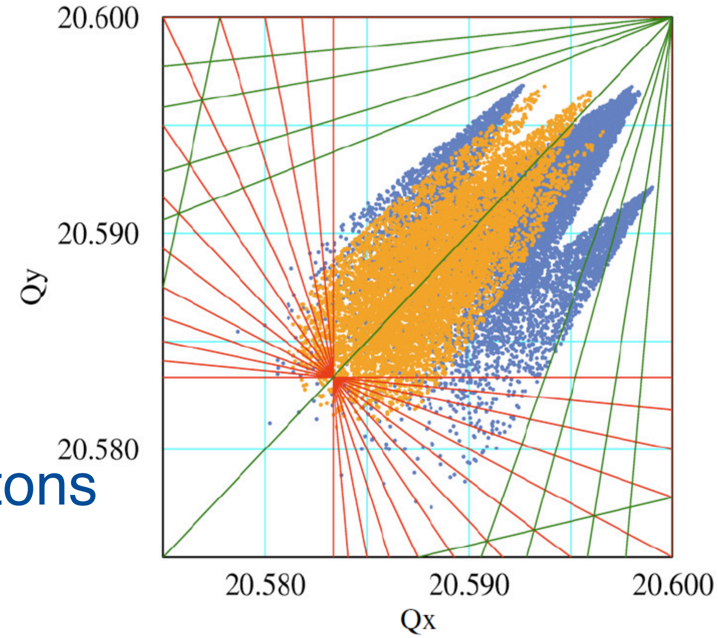



E-lens with flat profile improves lifetime by tune shifting chosen bunch

Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)

# Head-on beam-beam compensation with e-lens?

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, in collaboration with BNL

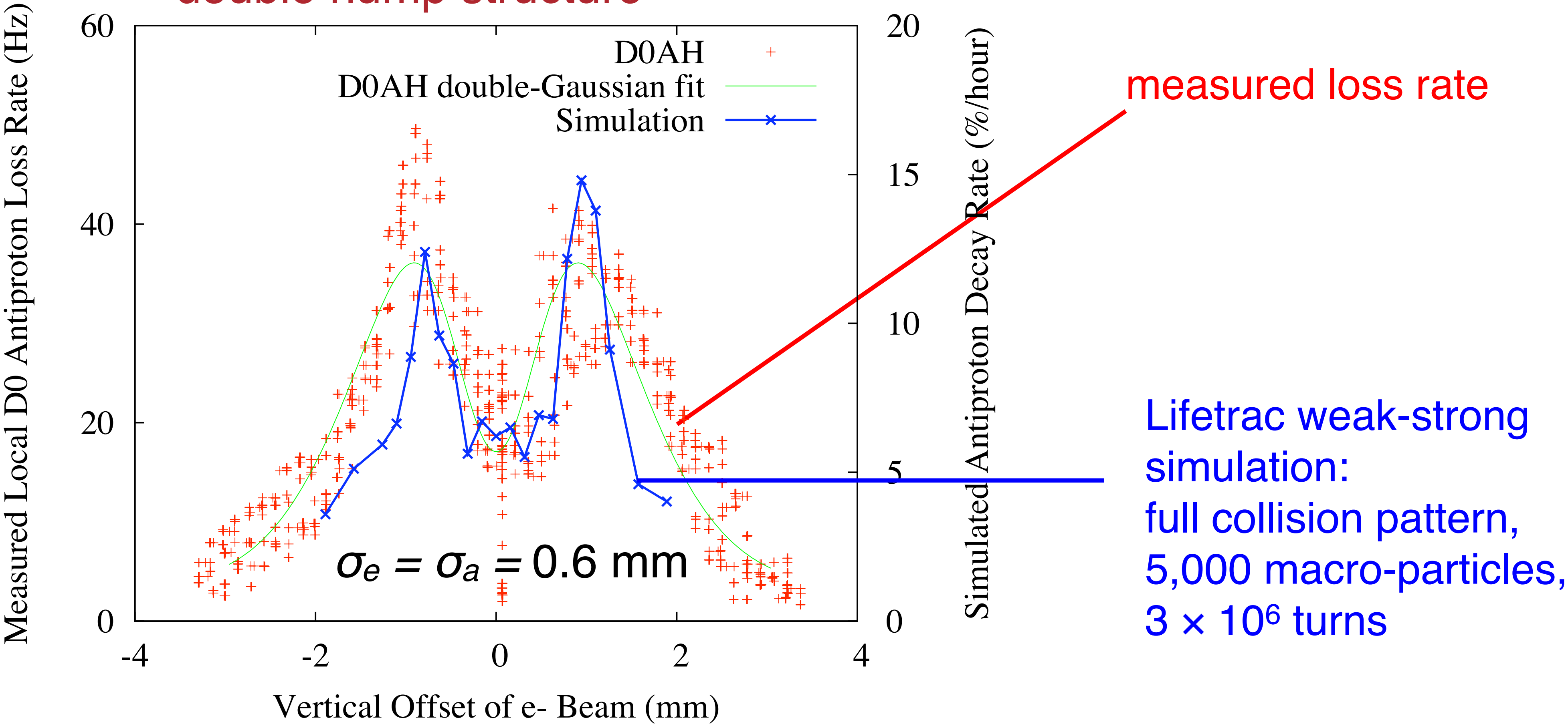
Linear beam-beam parameter for antiprotons due to electrons

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

Stancari and Valishev, PAC11 (2011)

# Observations in position scan of Gaussian e-beam

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

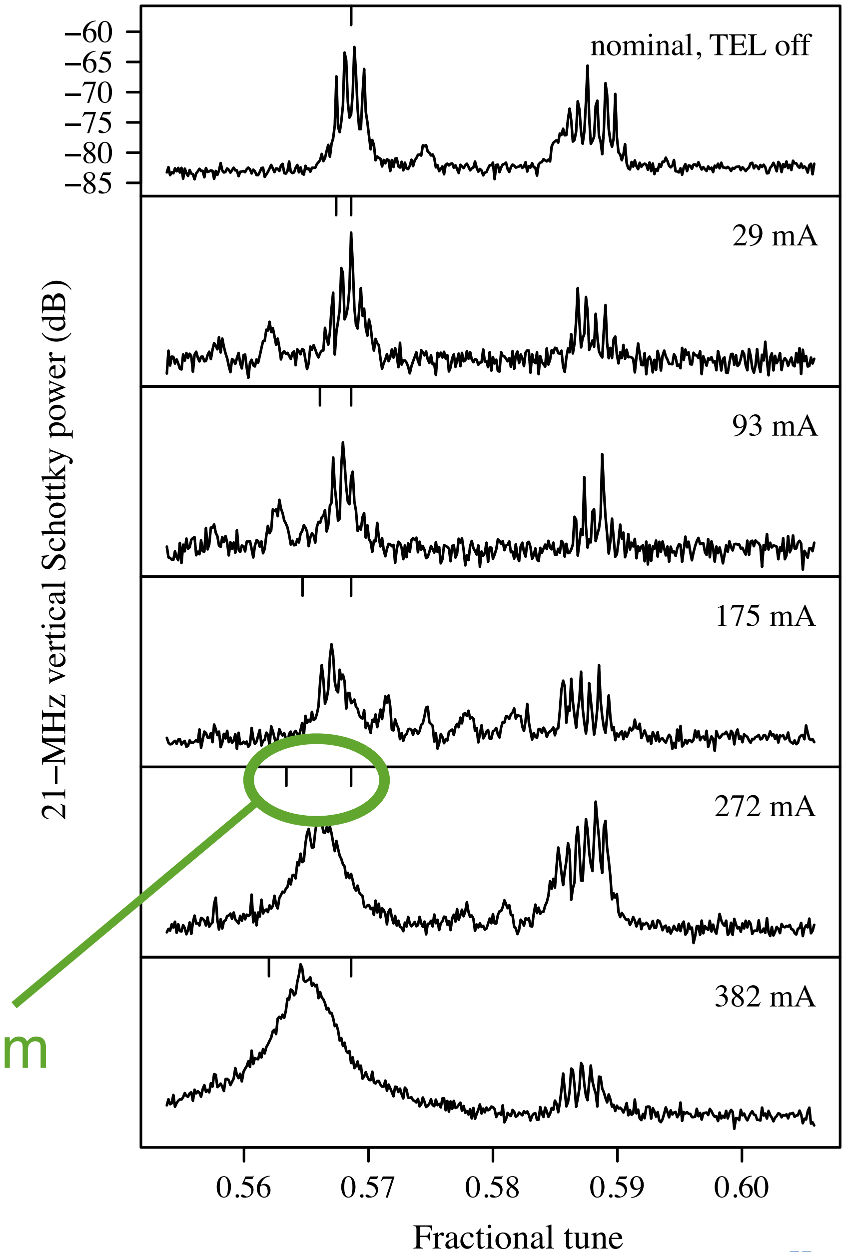



3. Lifetrac simulation reproduces both (1) and the double hump

# Incoherent tune spectrum vs. e-beam current

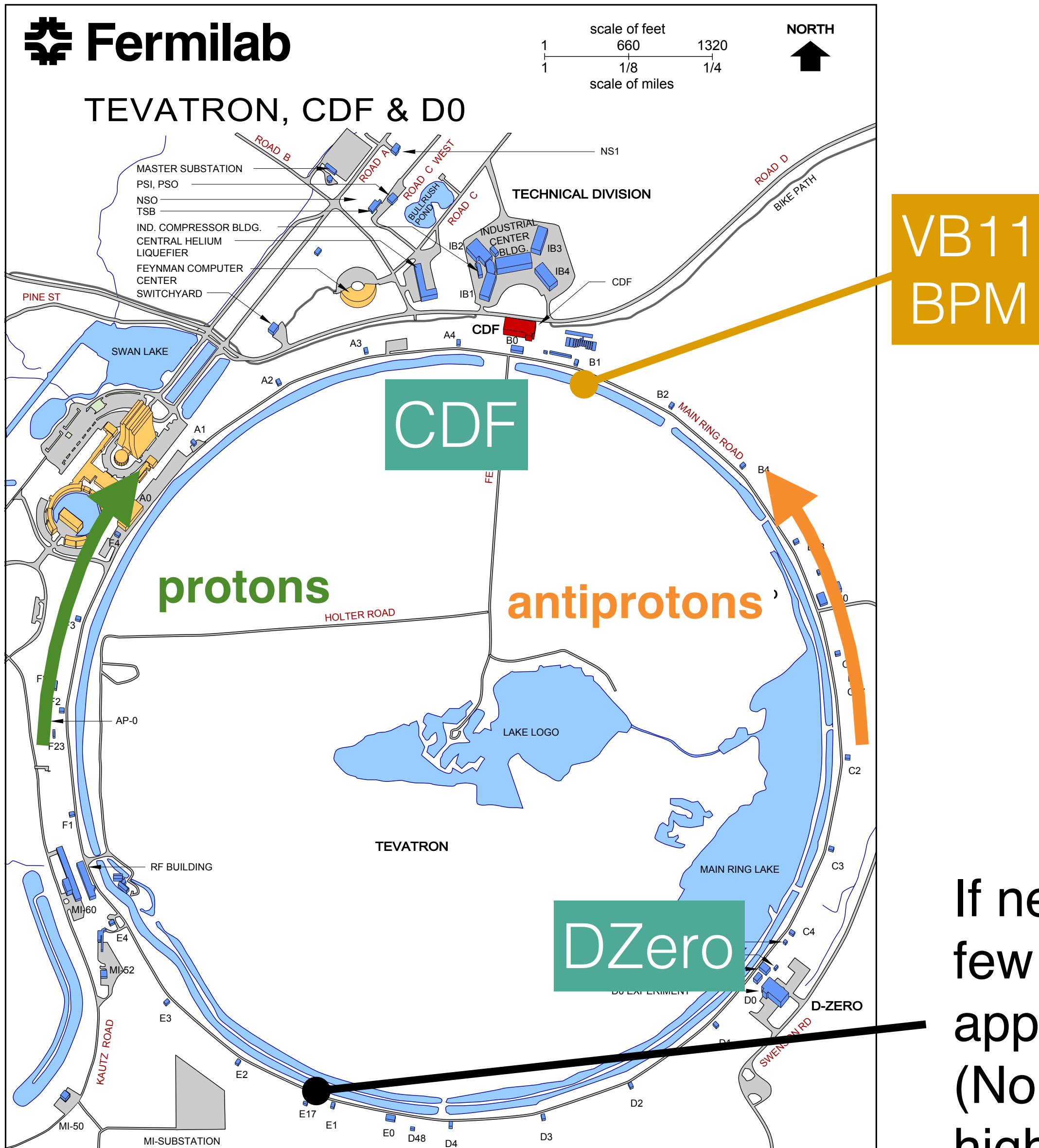
*Schottky spectra measured during dedicated **antiproton-only store***

Observed effect of electron beam on antiproton tune spectrum




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

# Detection of coherent oscillations with single BPM




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

Vertical strip-line pickup

$\beta_y = 880\ \mathrm{m}$

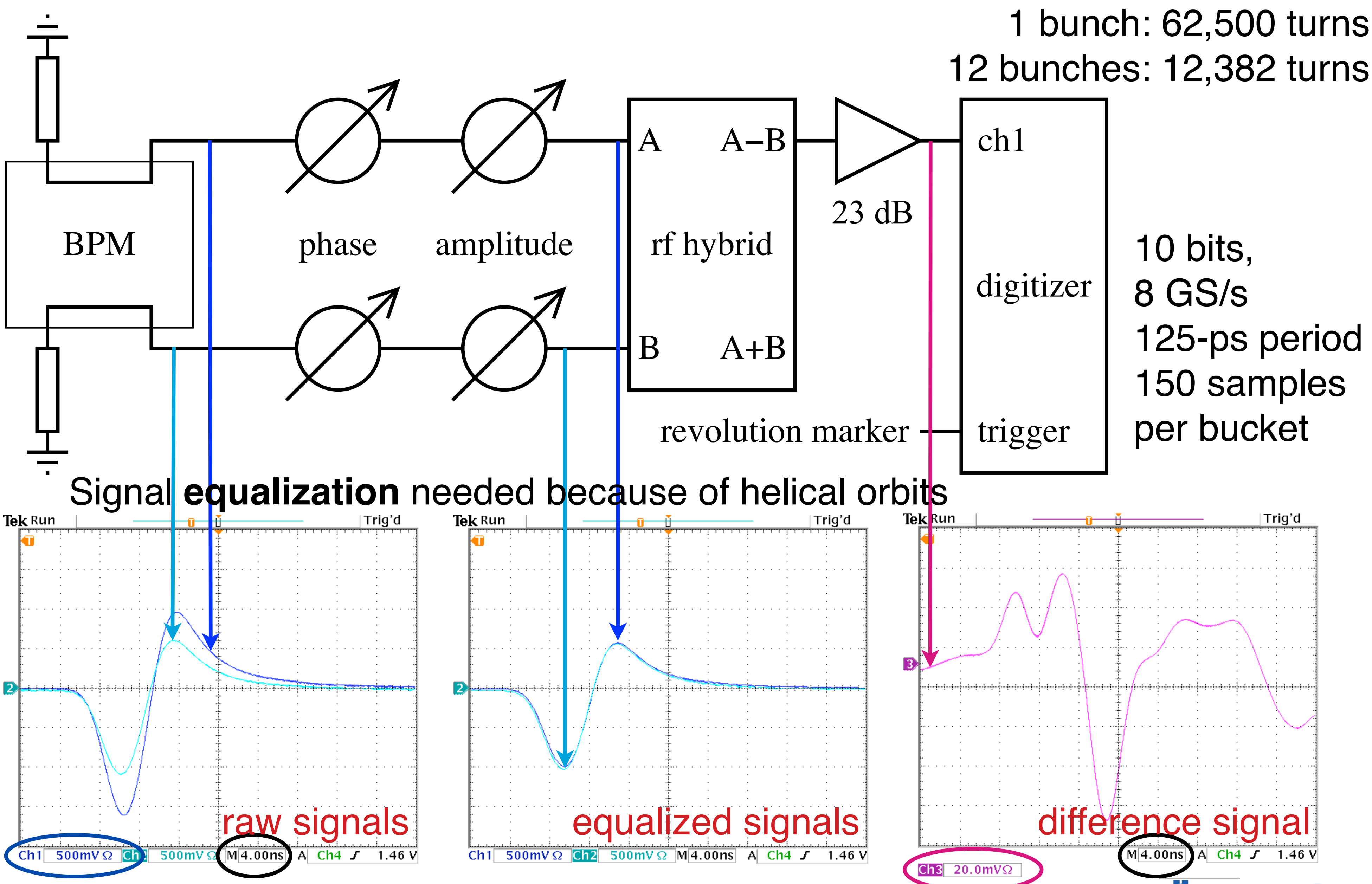
Osc. amplitude ~50 um

Sensitivity ~10 nm

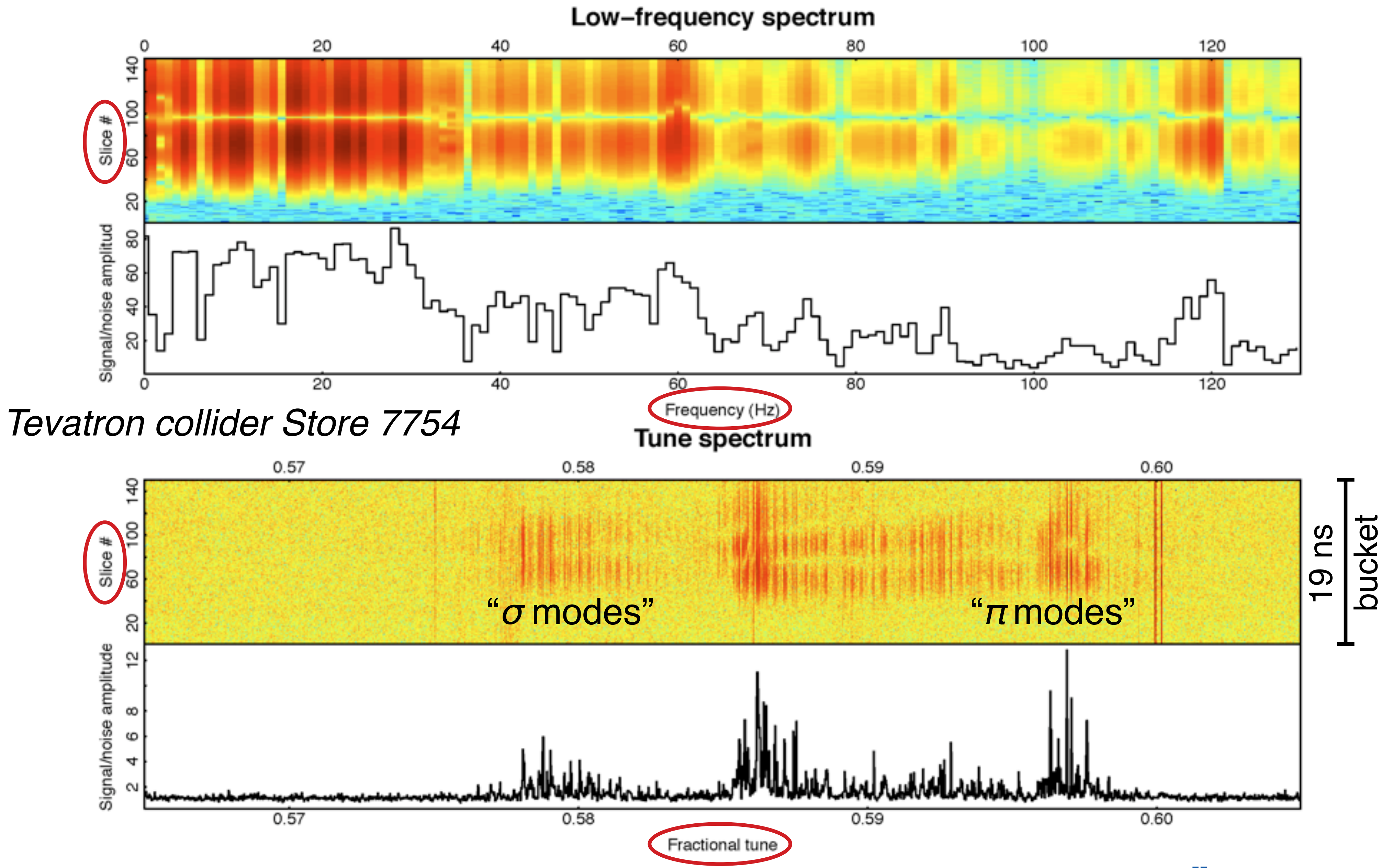
If necessary, signal enhanced by a few watts of band-limited noise applied for 1 s

(No adverse effects on beams even at high luminosity)

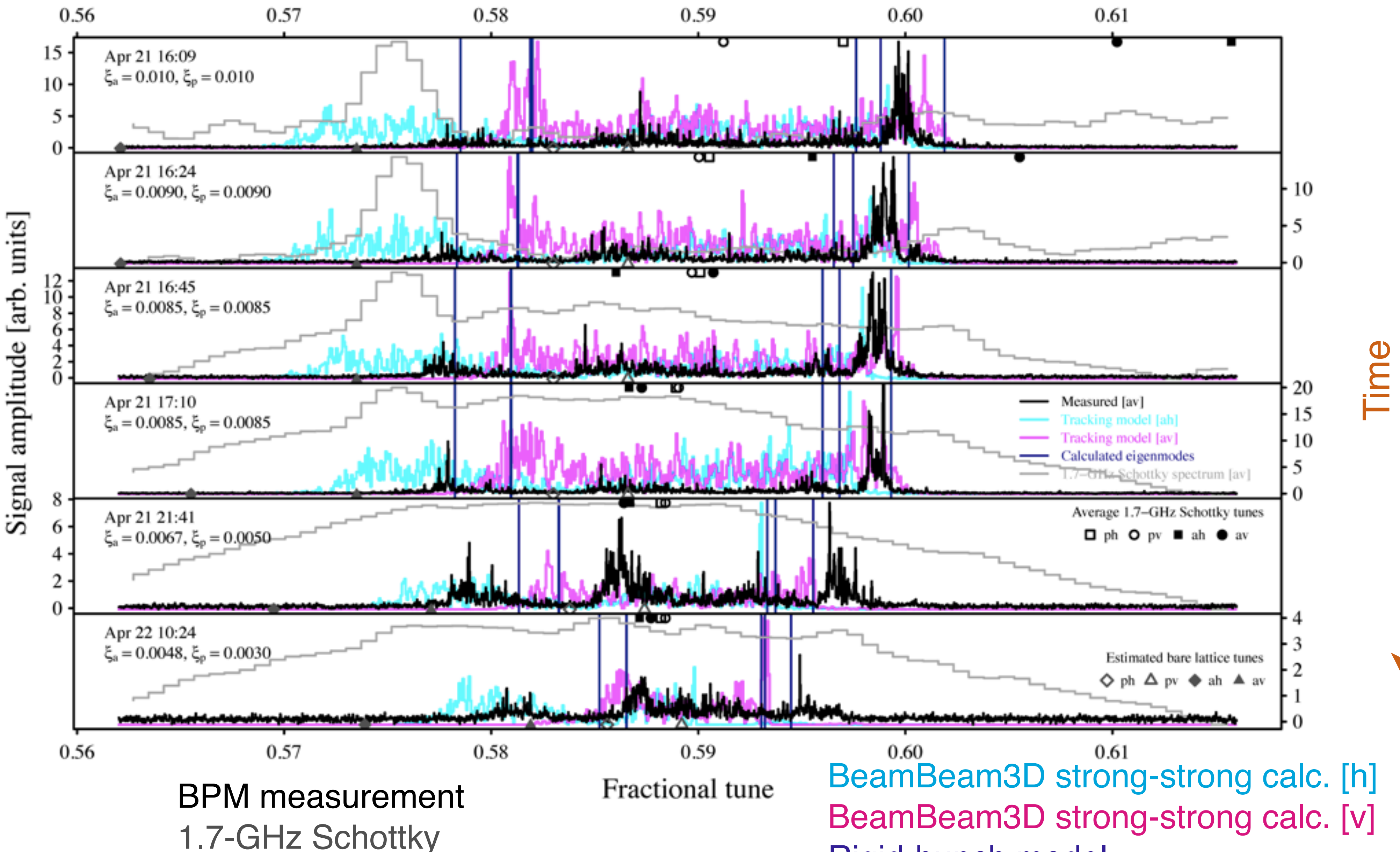
# Apparatus for detection of coherent oscillations



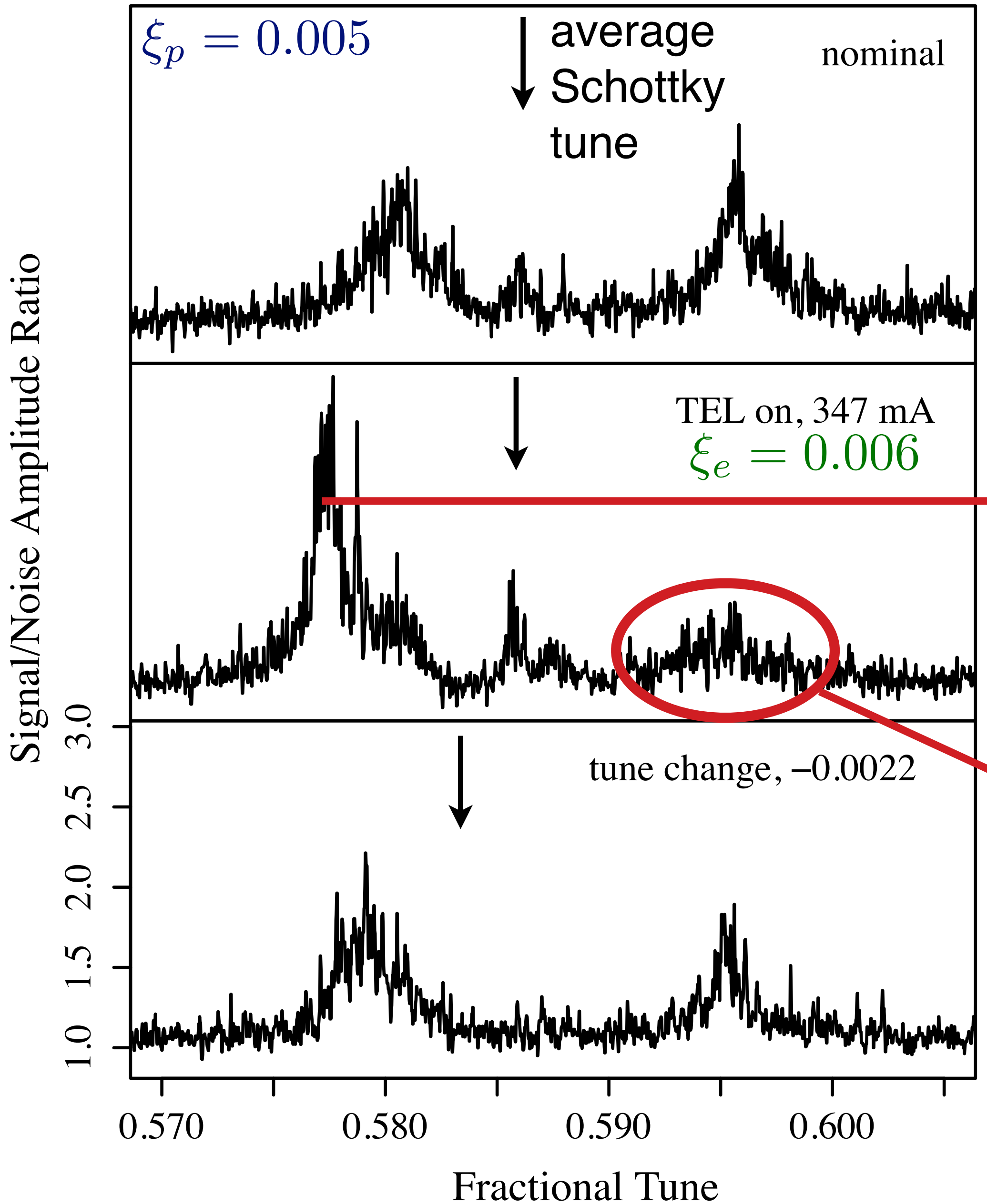
# Spectrum of coherent oscillations within a bunch



# Evolution of coherent modes during collider store



# Effect of electron lens on transverse coherent modes




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

Tune shift of first eigenmode
Change in tune spread?

Suppression of second eigenmode

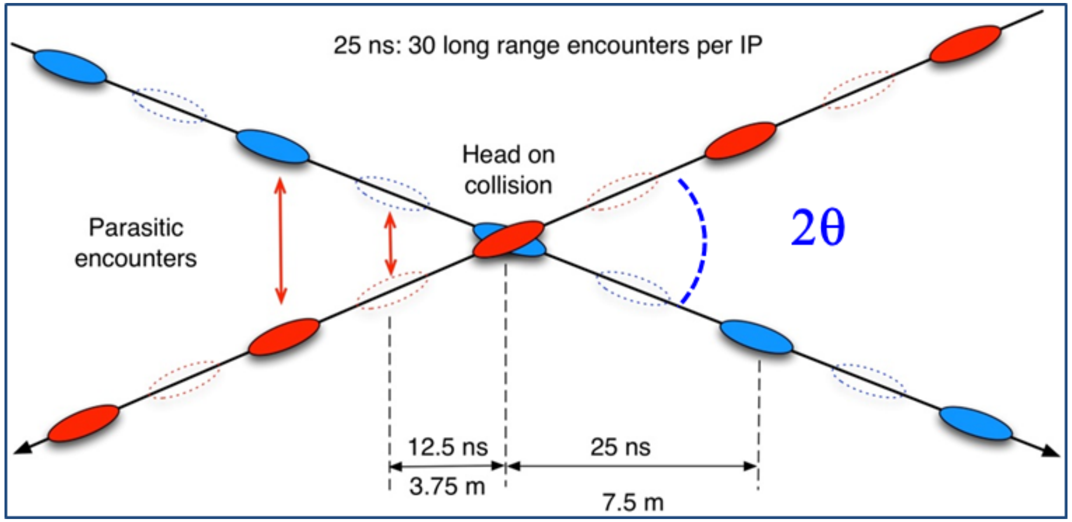
Interpretation requires calculation of mode strengths and widths

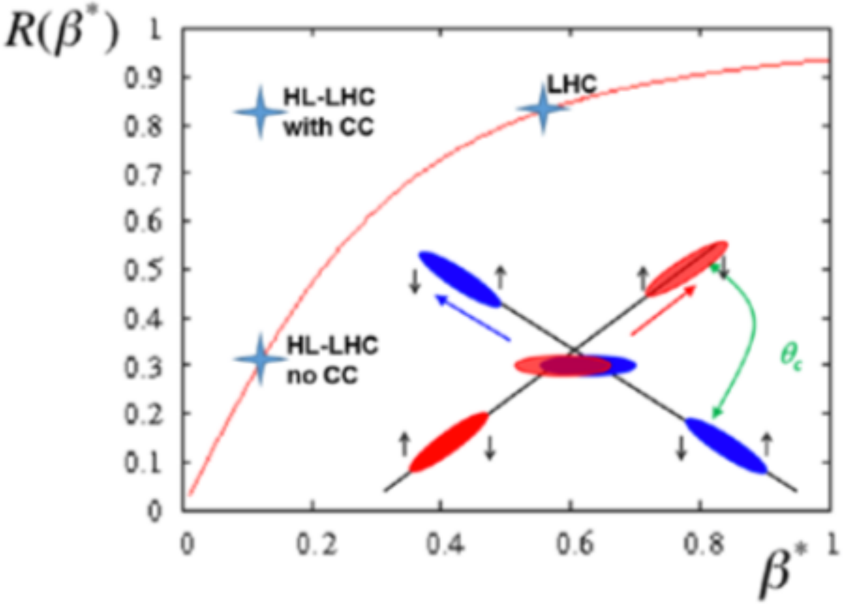
# The “e-wire”?
# Electron lenses as wires for long-range beam-beam compensation in HL-LHC

# Luminosity scenarios in HL-LHC

Luminosity increase in HL-LHC achieved by:

- increased bunch intensity
- smaller beam sizes
- larger crossing angle (to avoid long-range interactions), with geometrical overlap recovered through crab cavities



# Luminosity scenarios in HL-LHC

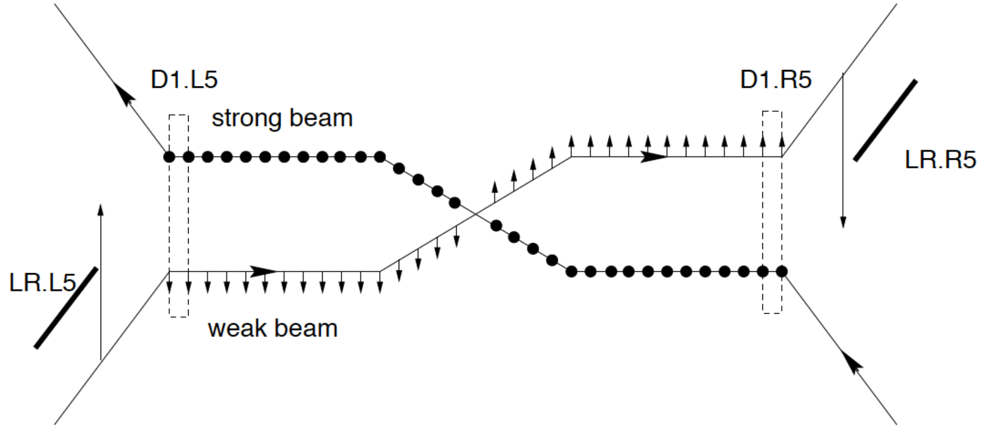
An alternative scenario is possible, in case crab cavities do not perform as expected:

- Considers **round** (0.15 m / 0.15 m beta*) or **flat** (0.1 m / 0.4 m) **optics**
- Assumes **a long-range beam-beam compensation scheme** (wires, e-wires, ...), needed mostly at end of beta* leveling, when separation decreases to ~10 sigma, a few hours into the store, when $N_p = 1.5e11$
- Optimal compensation strength requirements:
  - 131 A m (round)
  - 105 A m (flat)

Fartoukh, Papaphilippou, Shatilov, and Valishev, PRSTAB **18**, 121001 (2015)

# Long-range compensation schemes

A **current-carrying wire** appropriately positioned on each side of the interaction regions can compensate the long-range effects [Koutchouk, LHC-Note-223 (2000)]

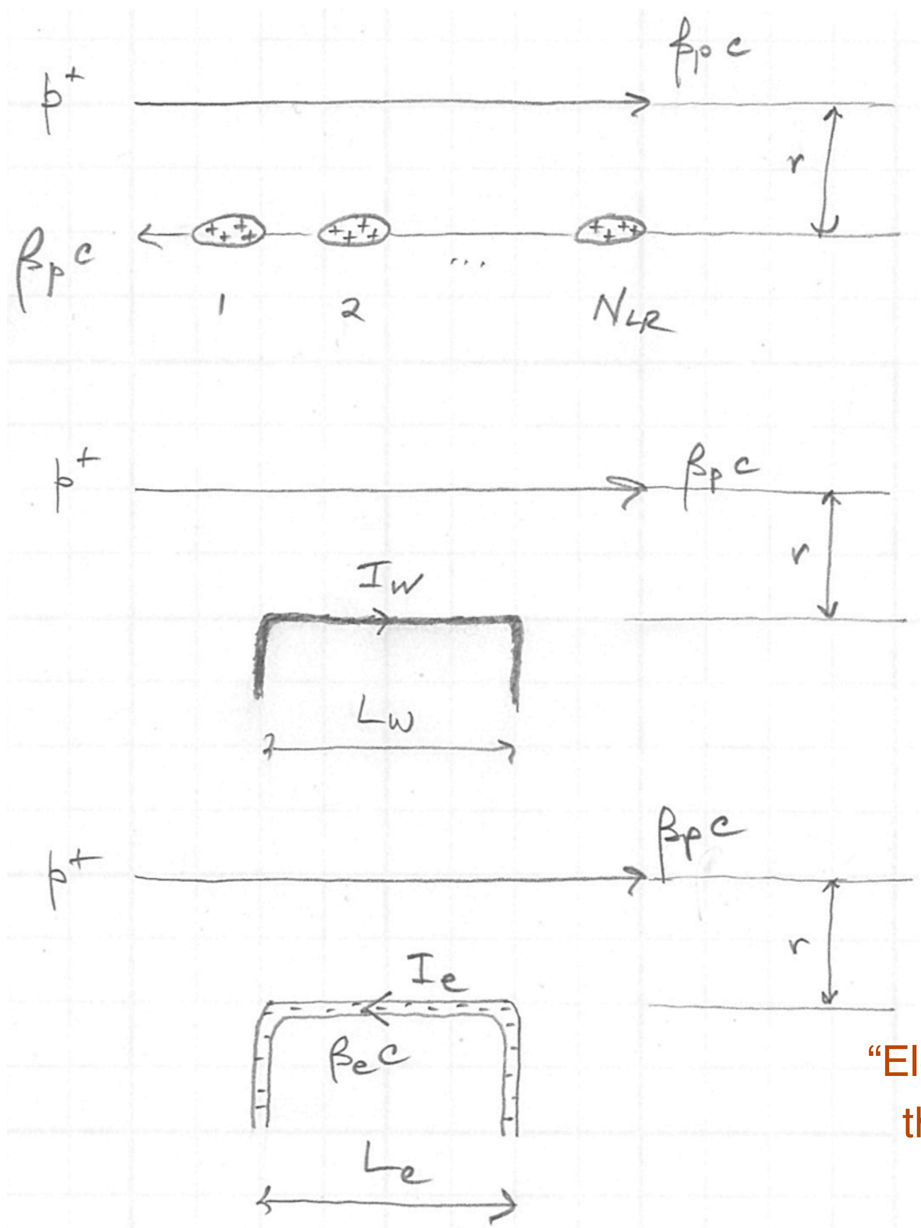



Wire-in-jaw collimators are being used for experiments in LHC [see previous talks]

An **electron beam ("e-wire")** has several advantages over a metal wire:

- no material close to the beam
- lower current: wire is charged, magnetic and electric fields add up
- electron current can be tailored bunch-by-bunch to match the number of long-range encounters (mitigation of Pacman effect)
  [Valishev and Stancari, FERMILAB-TM-2571-APC]

# Comparison of long-range compensation schemes




momentum transfer $\Delta p_{\perp}$

## Long-range beam-beam

$$N_{\mathrm{LR}} N_p e c \frac{1+\beta_p^2}{2\beta_p} \left(\frac{\mu_0 e}{2\pi r}\right)$$

Beam-beam kick is proportional to bunch charge *($N_p$ e)* and to number of interactions *$N_{LR}$*

## Wire

$$L_w I_w \left(\frac{\mu_0 e}{2\pi r}\right)$$

Wire strength is characterized by current times length

## Electron beam

$$L_e I_e \frac{1 \pm \beta_e \beta_p}{\beta_e \beta_p} \left(\frac{\mu_0 e}{2\pi r}\right)$$

“Electron wire” is charged and slow, so the effect of the current is amplified



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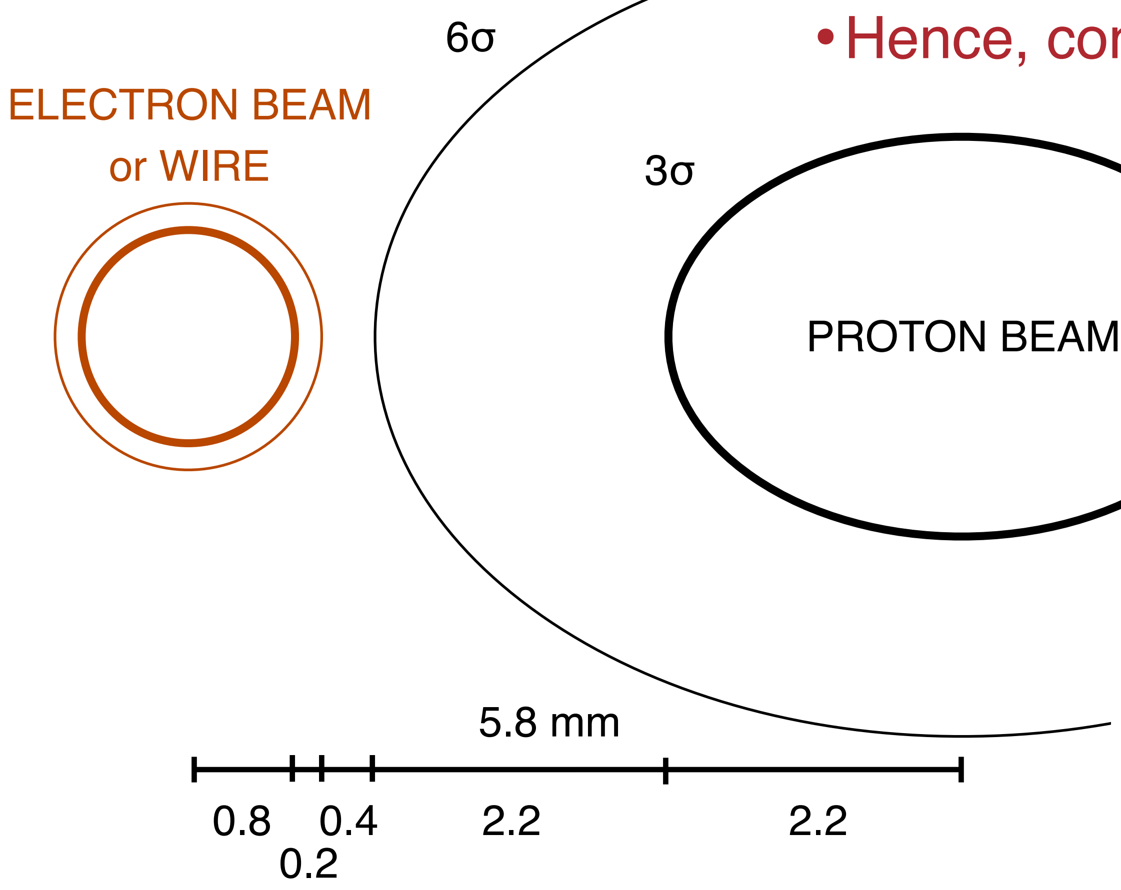
# Layout example in HL-LHC

*Beam 1, left of IP5,*
*round optics*
*(0.15 mm less margin with*
*flat optics)*

Geometrical requirements:

- Stay clear of 6$\sigma$ dynamic aperture
- Allow for reasonable ~0.2 mm straightness and alignment tolerance
- Hence, compensating wire radius ≤ 0.8 mm



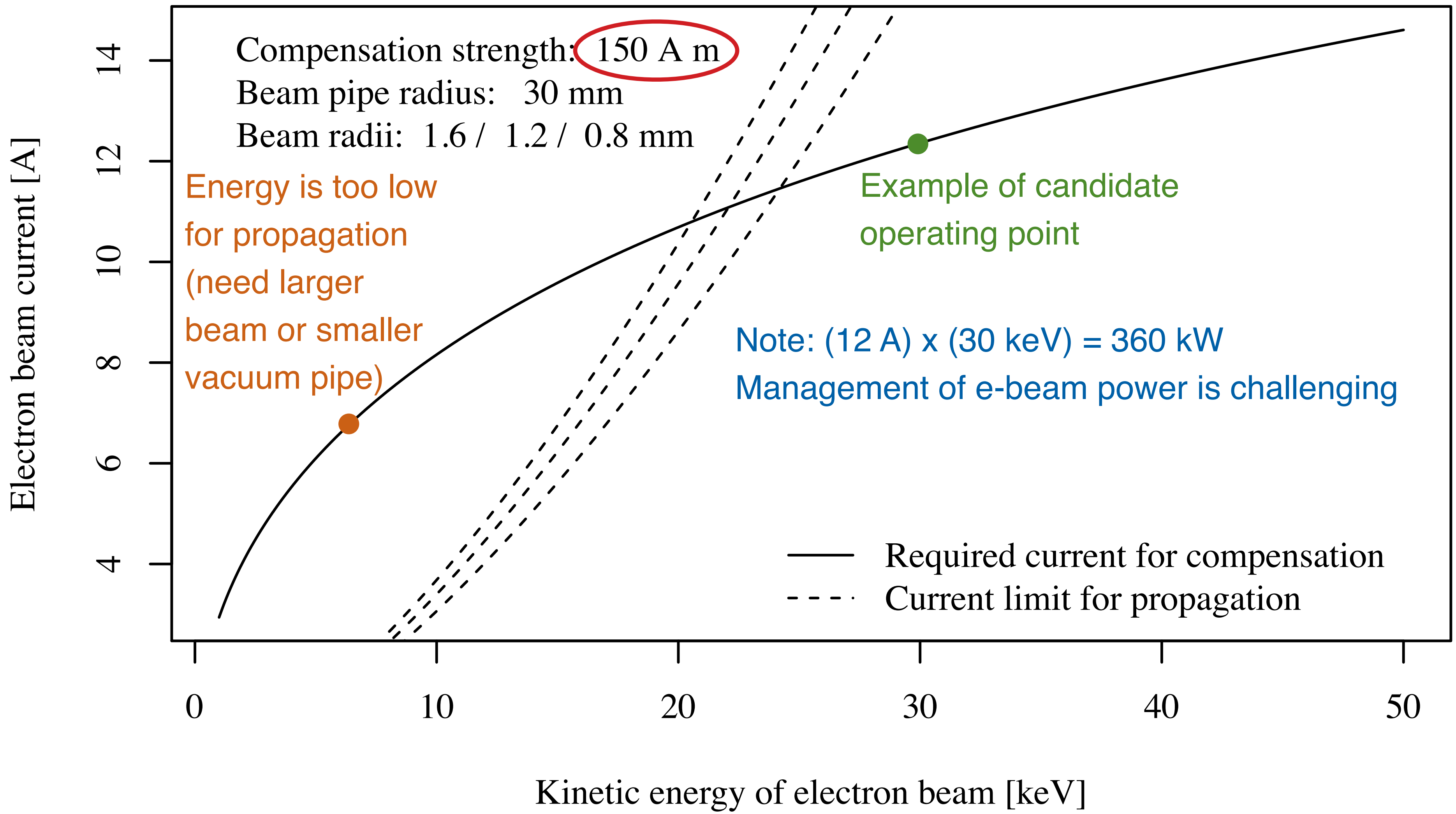

Very challenging for a metal wire

Sensitivity of configuration is under study: separation, wire size, beam shape, ...

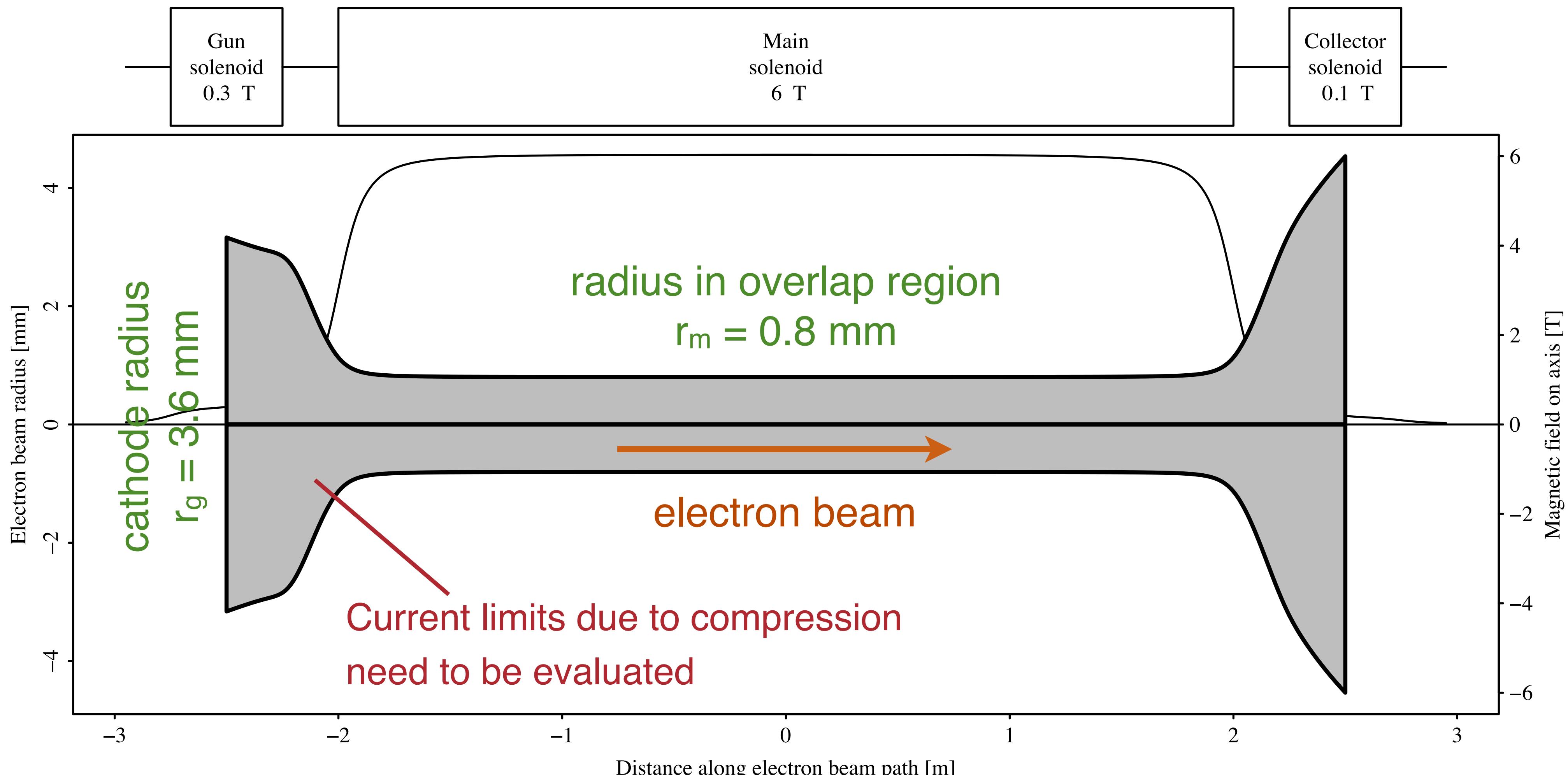
# Required e-wire compensation strength and current limits

E-beam current required for compensation decreases with e-beam energy

However, a minimum energy is required to push dense beam through vacuum pipe



# Achievable cathode current density and magnetic compression




30 A/cm² <= 600 A/cm² (12 A)

Required current density is high but achievable (e.g., with scandate cathodes)

# Conclusions (1/2)

The **Fermilab Tevatron proton-antiproton collider** had unique beam-beam features

**Electron lenses** are a flexible and mature technology to affect beam dynamics in circular machines

**Long-range beam-beam compensation by tune shifting** of individual bunches was demonstrated in the Tevatron

**Nonlinear head-on beam-beam compensation with Gaussian e-beams** was studied, in collaboration with BNL and in preparation for RHIC e-lenses:

- reproducible alignment
- no instabilities or emittance growth
- observed tune shift and tune spread generated by electron beam
- Tevatron was not suitable for direct demonstration: cold antiprotons, limited dedicated study time

# Conclusions (2/2)

## Coherent beam-beam modes

- were stable in the Tevatron (asymmetric intensities and tunes, chromaticity)
- observed evolution during collider store with low noise and high sensitivity
- measured effect of electron lens

Directly observed **diffusion** enhancement vs. amplitude from beam-beam and hollow e-lenses [BB2013 proceedings]

**"e-wire"** concept: electron lenses as pulsed, charged wires for long-range beam-beam compensation

- advantages: no material, pulsed, lower current than wire
- challenges under study: beam power, magnetic confinement
- scaled experiments possible in Fermilab and (upcoming) CERN test stands

Suggestions and collaborations always welcome

*Thank you for your attention!*

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