LARP

HiLumi HL-LHC PROJECT

Design Considerations for an Electron-Lens Test Stand at CERN

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Motivation

Several new applications of electron lenses may benefit the CERN program

A test stand at CERN is essential to

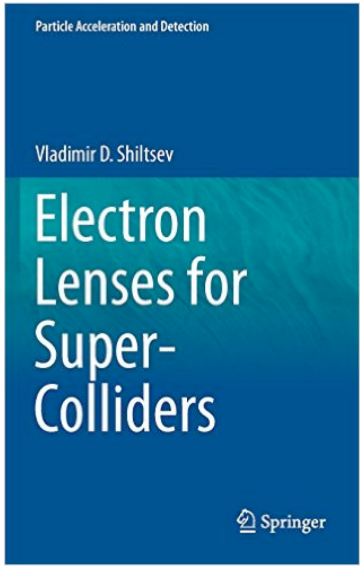
- transfer past experience and know-how
- develop new techniques and extend the reach of applications

Applications of electron lenses

In the Fermilab Tevatron collider

- ***long-range beam-beam compensation (tune shift of individual bunches)***
  - Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)
- ***abort-gap cleaning (for years of regular 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)

PAST



Presently, used in RHIC at BNL for head-on beam-beam compensation, luminosity improvements

- Fischer et al., Phys. Rev. Lett. **115**, 264801 (2015)

PRESENT

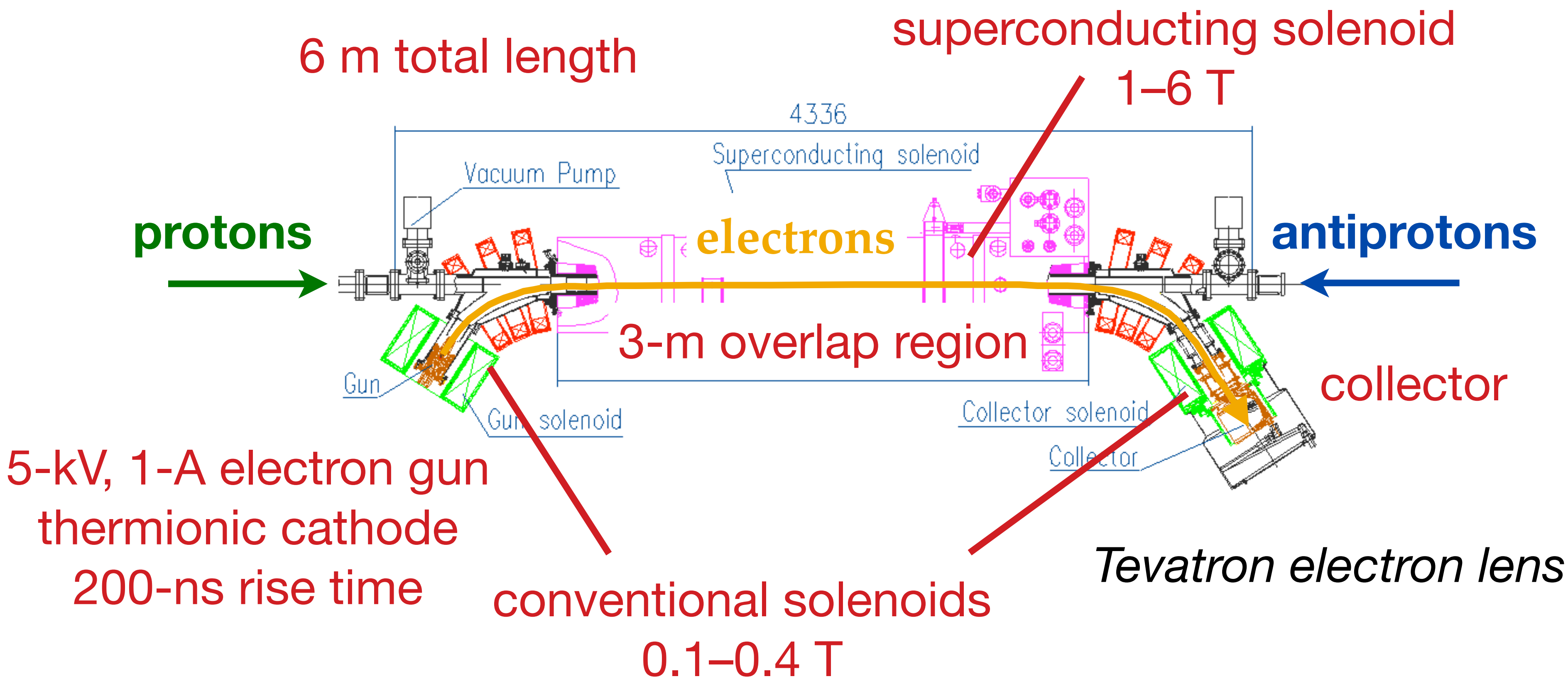
Current areas of research

- ***generation of nonlinear integrable lattices*** in the Fermilab Integrable Optics Test Accelerator
  - Nagaitsev, Valishev et al., IPAC12; Stancari, arXiv:1409.3615, Stancari et al., IPAC15
- ***hollow electron beam scraping*** of protons in LHC
  - Stancari et al., CERN-ACC-2014-0248; Bruce et al., IPAC15
- ***long-range beam-beam compensation*** as charged, current-carrying "wires" for LHC
  - Valishev and Stancari, arXiv:1312.5006; Fartoukh et al., PRSTAB **18**, 121001 (2015)
- to ***generate tune spread for Landau damping*** of instabilities before collisions in LHC and for Fermilab Recycler

FUTURE

What's an electron lens?

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



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

Fermilab electron-lens test stand

Built in late 1990s to support the Tevatron program

It's the only operational e-lens test stand in the world

Currently used

- to test the performance of electron guns
- to study dynamics of intense, magnetically confined electron beams

Resistive solenoids < 0.4 T
Total length 2.8 m (straight configuration)
10 keV, 5 A electron beam
200 kW electrical power

Example of electron gun testing

New hollow electron gun (25 mm diam.) prototype designed at Fermilab/ CERN, built at CERN. Shipped to Fermilab for testing. Now installed in test stand.

Research objectives for a CERN test stand

General research topics, mainly driven by applications for long-range beam-beam compensation, space-charge compensation, and hollow e-beam collimation

- demonstrate magnetized electron beams with currents up to 20 A
- develop new cathodes with higher current densities and controllable current-density profiles
- modulate the electron beam with frequencies up to 10 MHz
- develop new instrumentation and diagnostics

  imaging of electrons and protons through gas fluorescence, ...
- test propagation of elliptical electron beams

Test-stand design questions

What cathode size is needed?

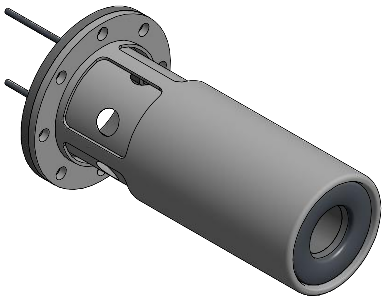
What electron beam energy is required?

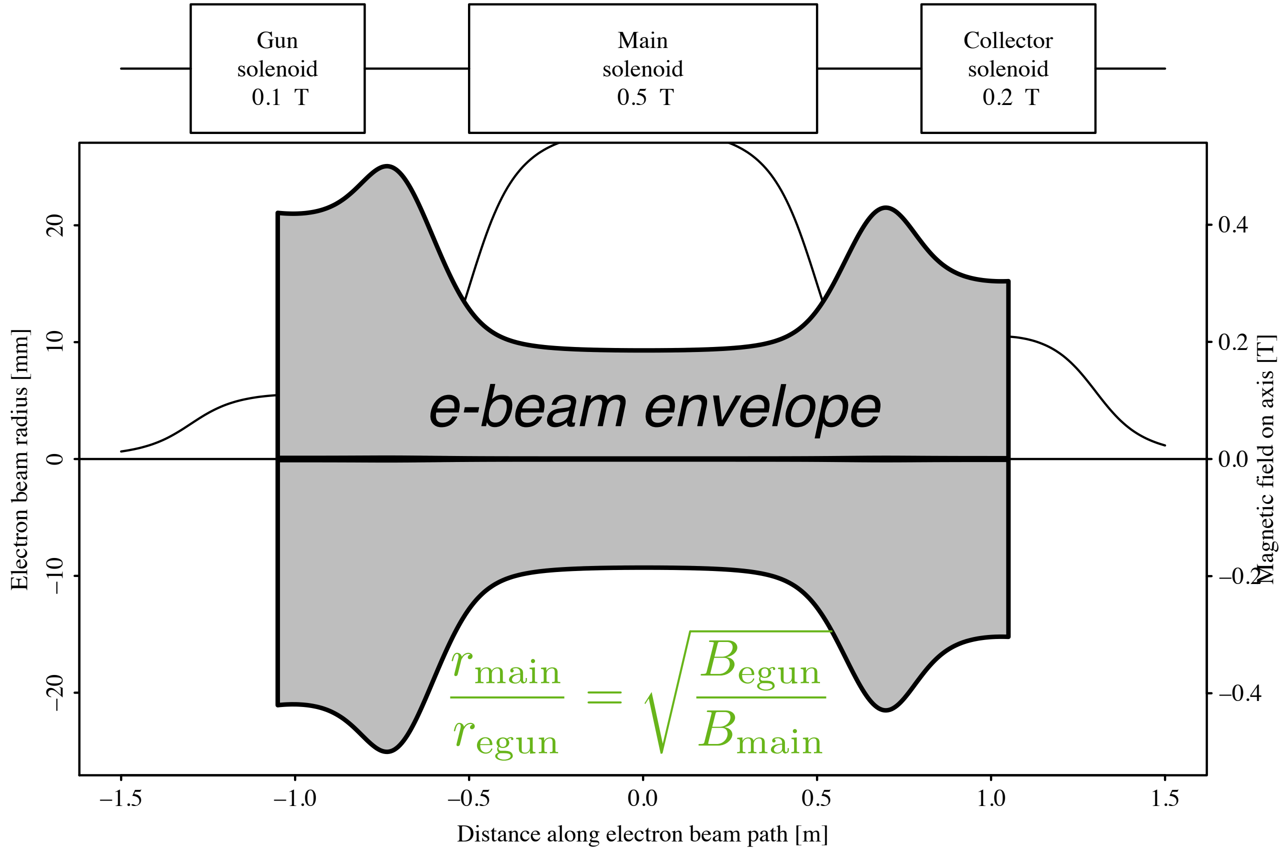
Resistive or superconducting solenoids?

Straight beam path, or are toroidal sections (bends) necessary?

Cathode size

Depends on mechanical constraints, achievable current density of the material, geometry, and required beam size in the overlap region (through the achievable compression factor from the solenoid fields)





For 20 A and a 50% active area, a radius of 32 mm is required with barium-oxide dispenser cathodes

Electron beam energy

Determined by

- voltage required to extract current (e-gun perveance)
- space-charge potential to be overcome
- finite propagation time in overlap region
- enhancement factor for LRBB compensation

General considerations of required beam power and radiation protection (X-ray production) also apply

For 20 A and typical beam sizes, a kinetic energy **> 25 keV** is necessary

Solenoid fields

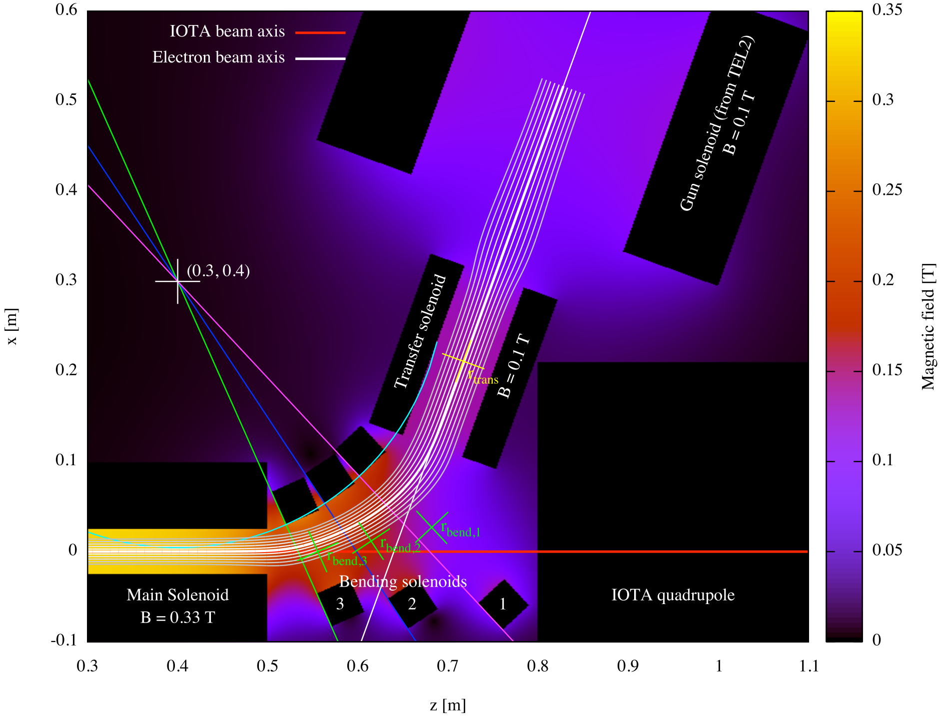
0.1 T is sufficient for the beams to be magnetically confined (i.e., small Larmor radius compared to the transverse beam size)

Combined axial magnetic fields and radial self electric fields induce azimuthal distortion of the current-density profiles (*ExB drift*), to be mitigated with high solenoidal fields. **> 0.6 T** is the preliminary estimate for typical beam parameters

Toroidal sections (bends)

Bends introduce electron trajectory drifts and profile distortions due to the nonuniform magnetic field strength and gradient

Because the test stand is meant to explore new intensity regimes, it is important to verify these effects experimentally



Bend design
(synergy with Fermilab IOTA e-lens)

Noll, PhD thesis
Noll and Stancari, arXiv:1511.04507

Conclusions

A preliminary design study for a CERN electron-lens test stand was completed [FERMILAB-TM-2629-APC, in preparation]. Estimates depend on required electron beam intensity, shape and size.

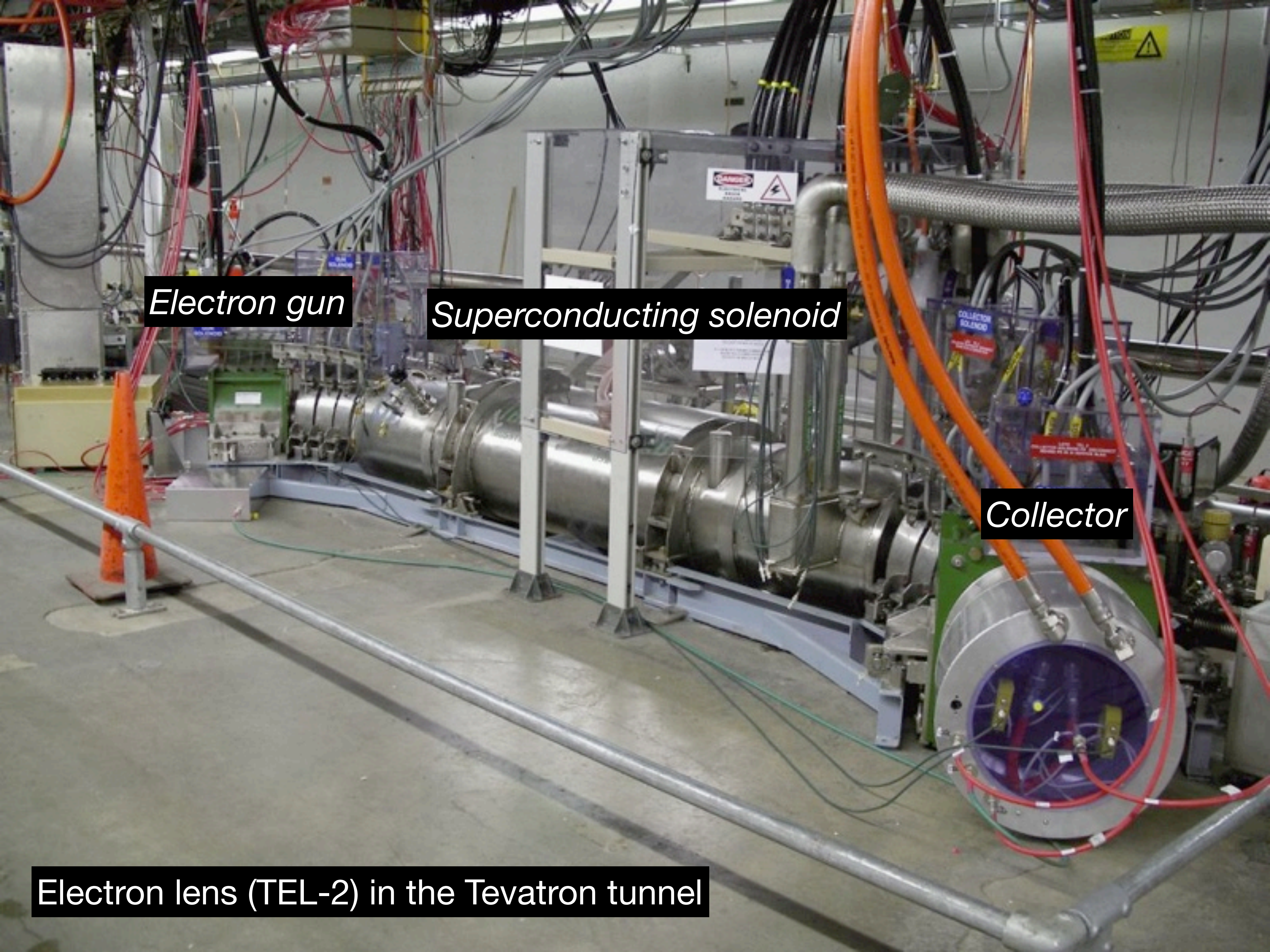
Barium oxide dispenser cathodes are appropriate but bulky. Scandium-based cathodes or other new designs are worth exploring for higher current densities.

The required electron beam kinetic energy is > 25 keV.

Some research topics may be studied with a resistive setup (<1 T), but with a limited range of beam sizes. A superconducting main solenoid (6 T) is necessary to explore the effects of magnetic compression.

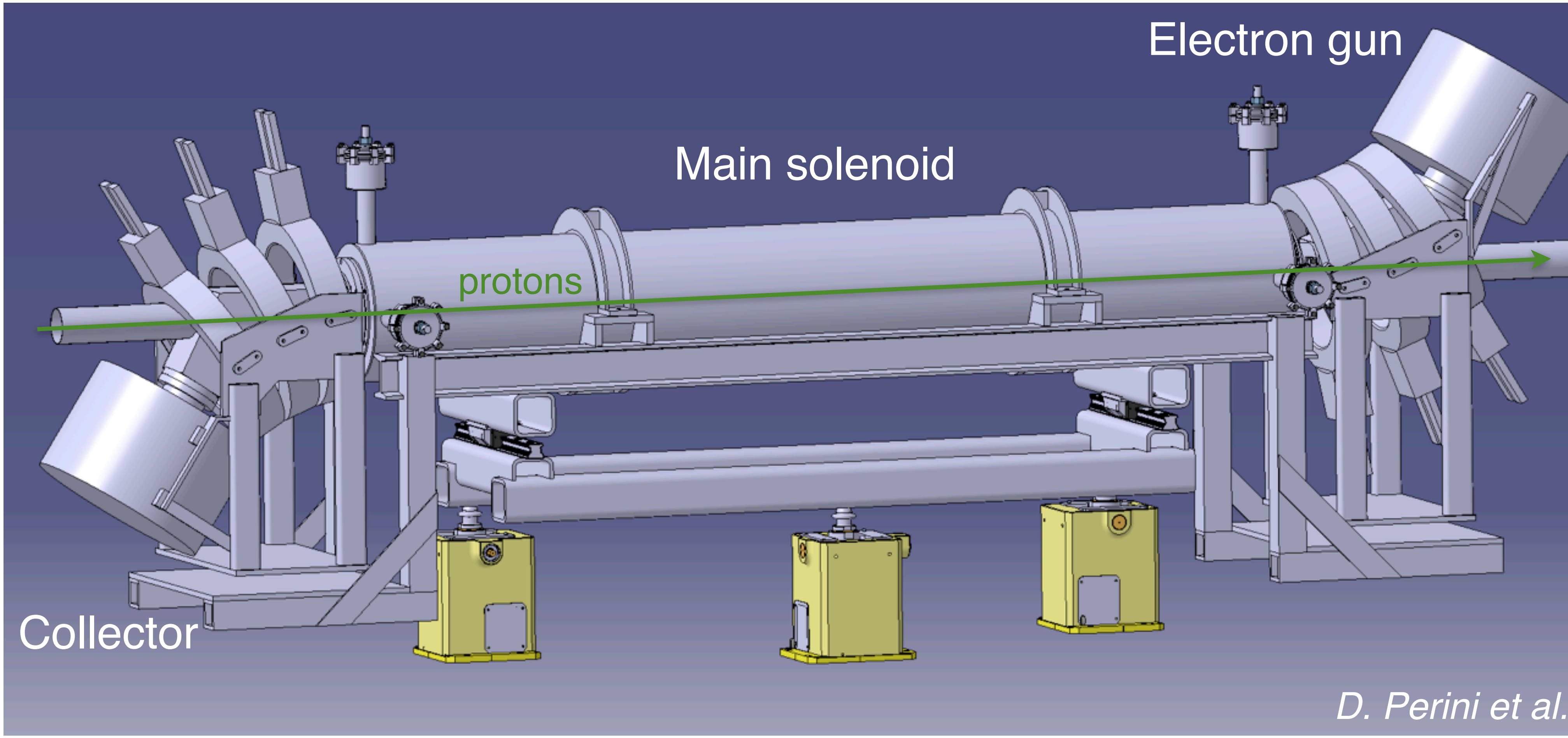
A configuration with at least one bend between gun and main solenoids is recommended. A progressive approach, with a straight configuration first and subsequent addition of bends, is discouraged because of the cost of reconfiguration.

Backup slides



Electron lens (TEL-2) in the Tevatron tunnel

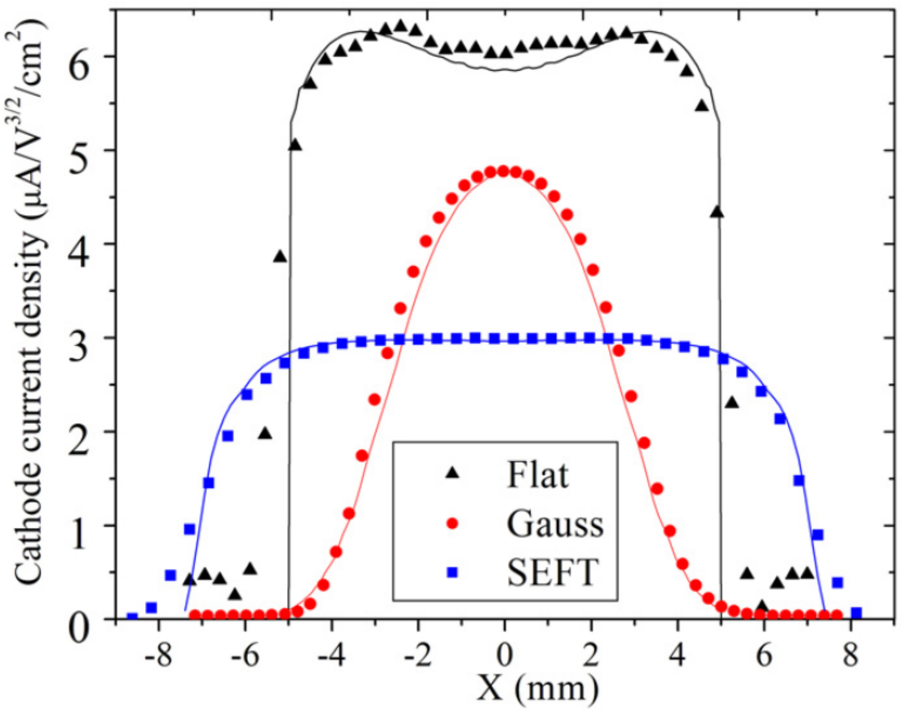
Electron-lens layout for LHC



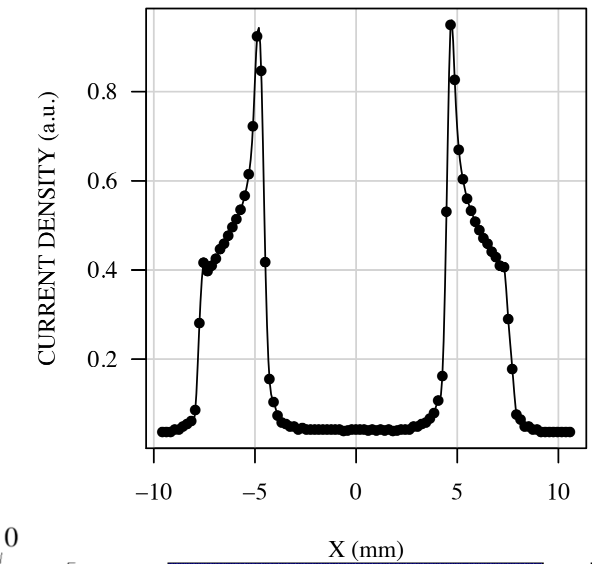
Control of electron beam profile

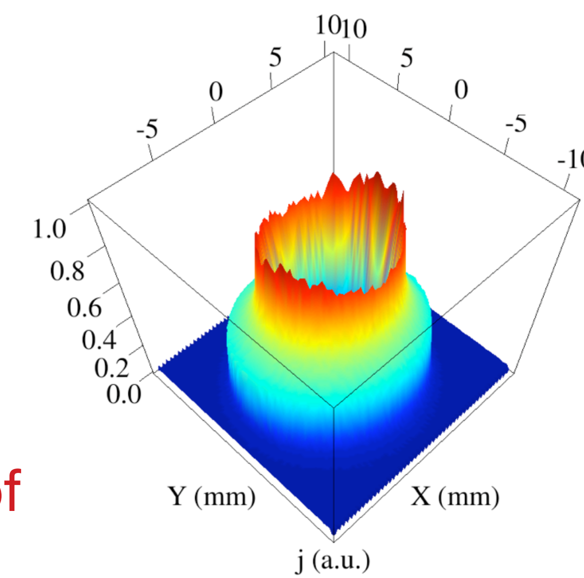
Current density profile of electron beam is shaped by cathode and electrode geometry and maintained by strong solenoidal fields

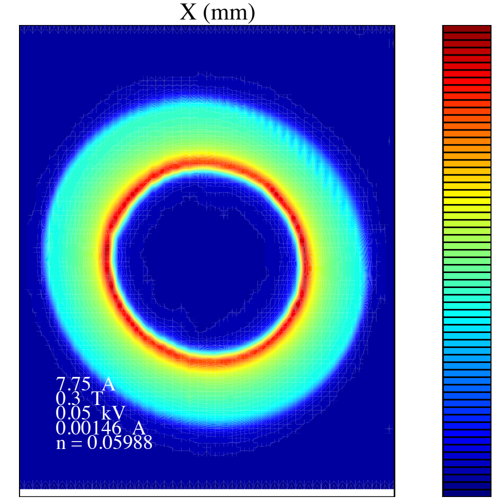
Flat profiles for bunch-by-bunch betatron tune correction



Hollow profile for halo scraping



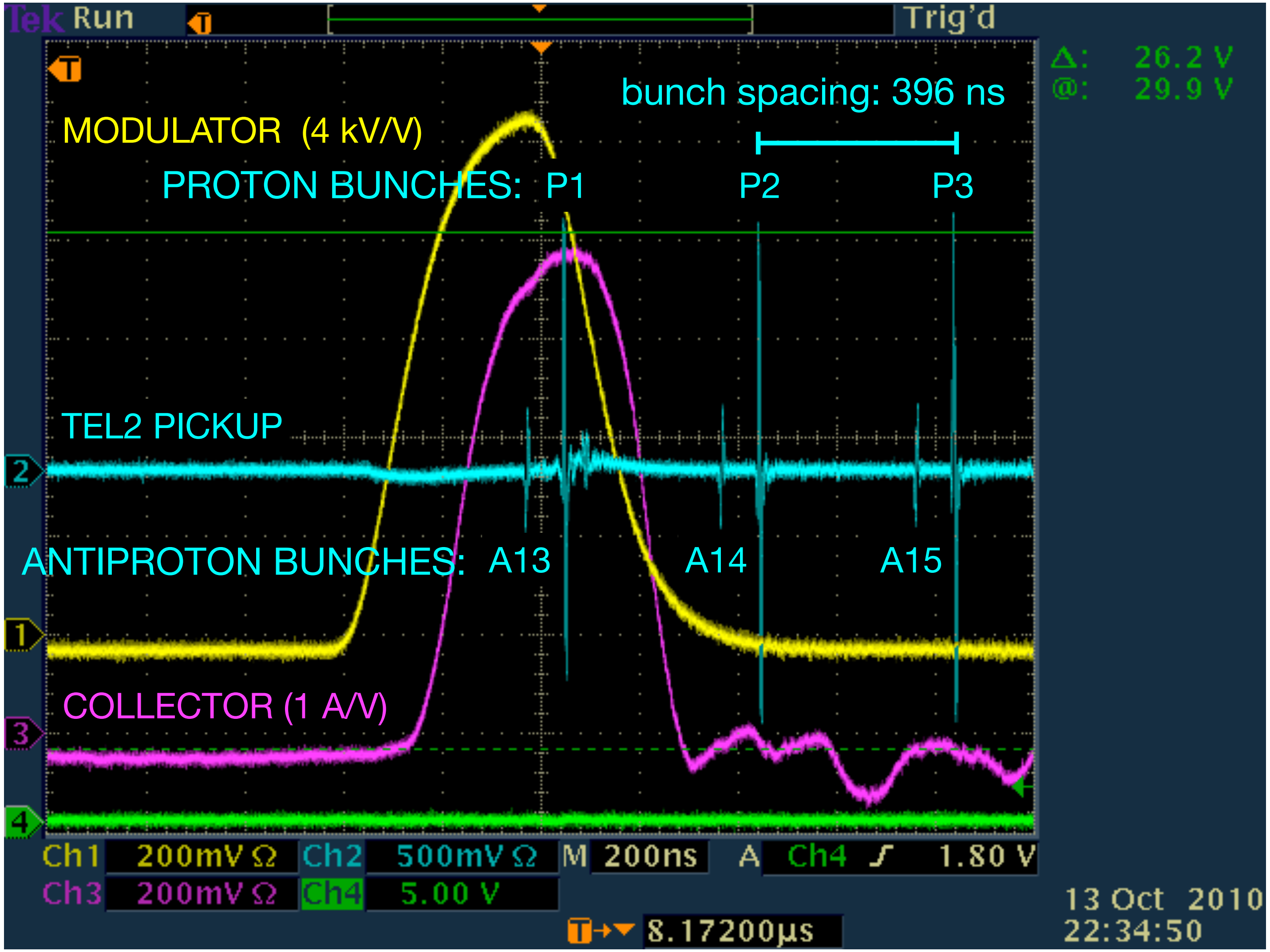




Gaussian profile for compensation of nonlinear beam-beam forces

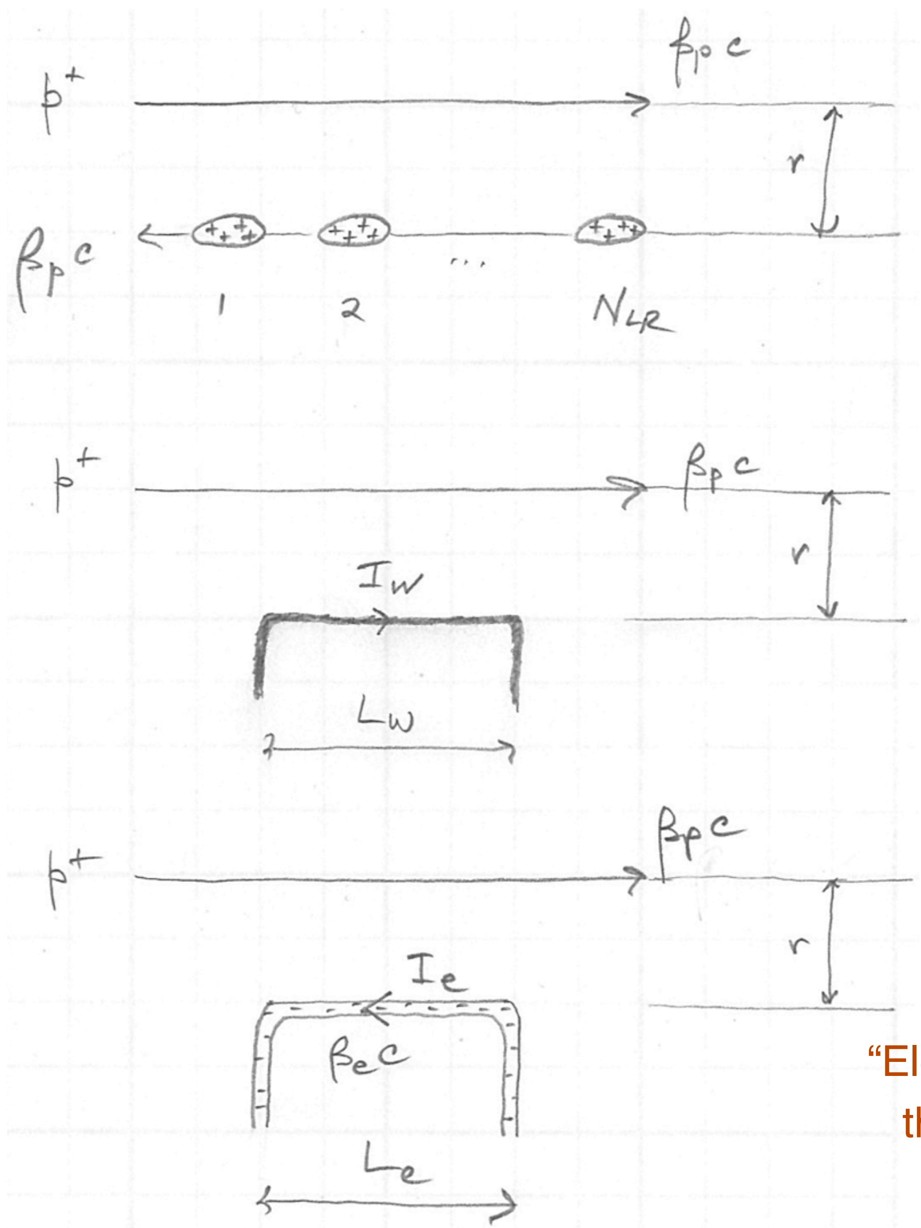
Pulsed electron beam operation

Beam synchronization in the Tevatron



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

Long-range compensation schemes



momentum transfer $\Delta p_\perp$

Long-range beam-beam

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

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