Applications of electron lenses: scraping of high-power beams, beam-beam compensation, and nonlinear optics

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Contributors

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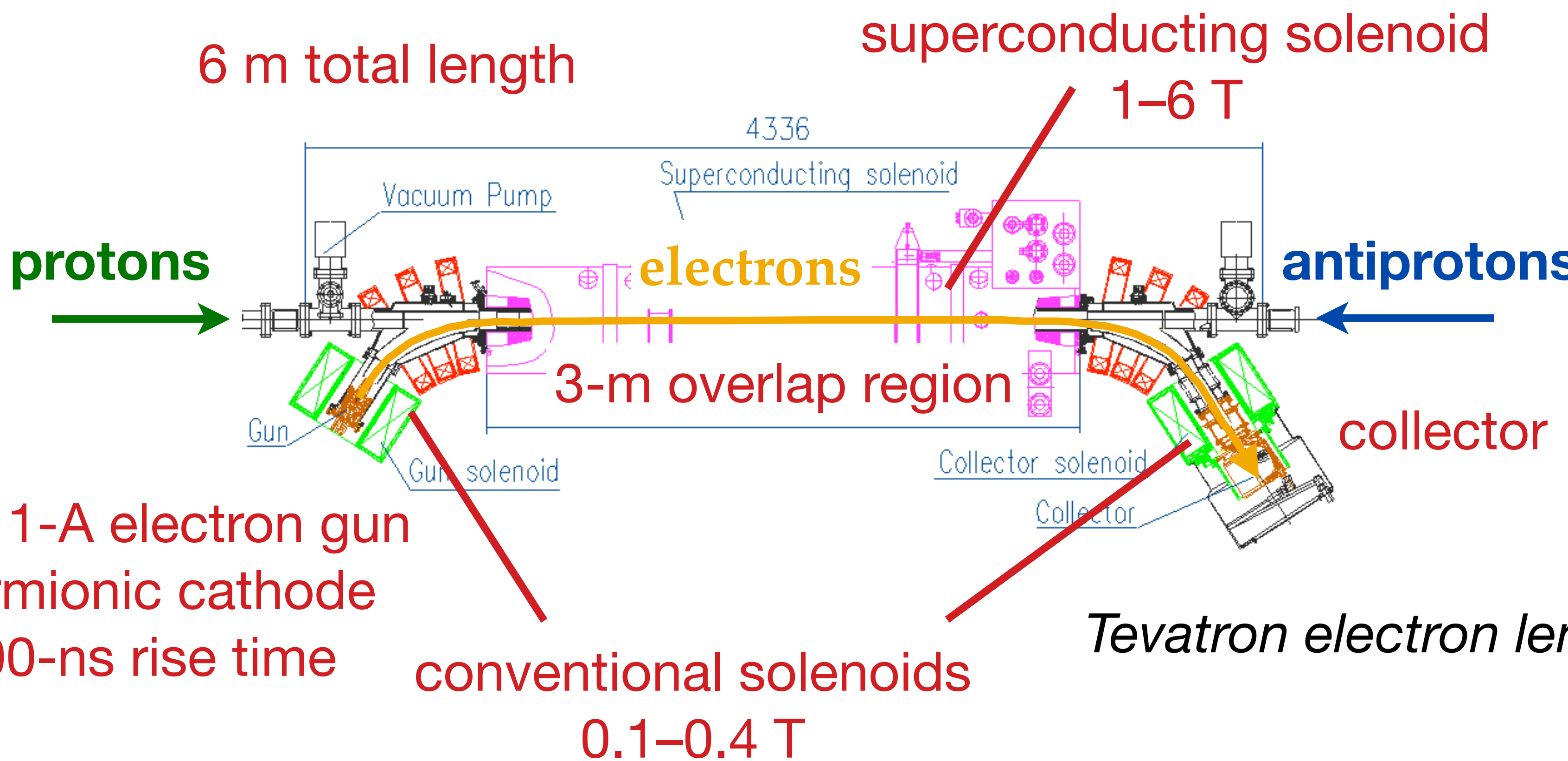
Outline

- **Introduction**
  - What's an electron lens? What can it be used for?
- **Hollow electron beam collimation**
  - Concept and experimental demostration at the Tevatron
  - Proton halo in the LHC
  - A design of hollow electron beam scraper for the LHC
    - parameters, simulations, hardware, integration
- **Long-range beam-beam compensation** for the LHC upgrades
  - Motivation, preliminary considerations, integration
- **Nonlinear dynamics** in the Fermilab Integrable Optics Test Accelerator (IOTA)
- **Conclusions**

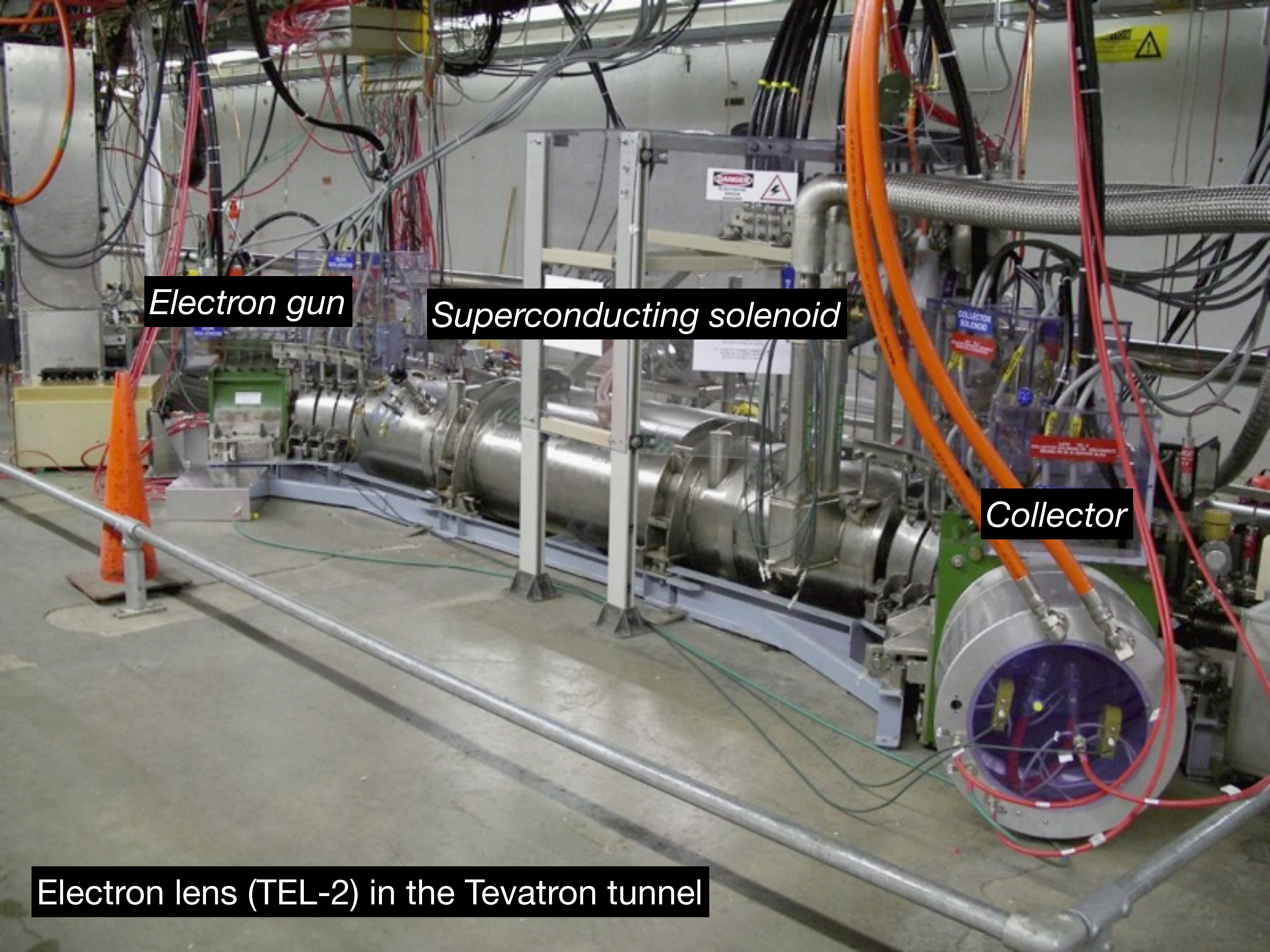
What's an electron lens?

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



Tevatron electron lens

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

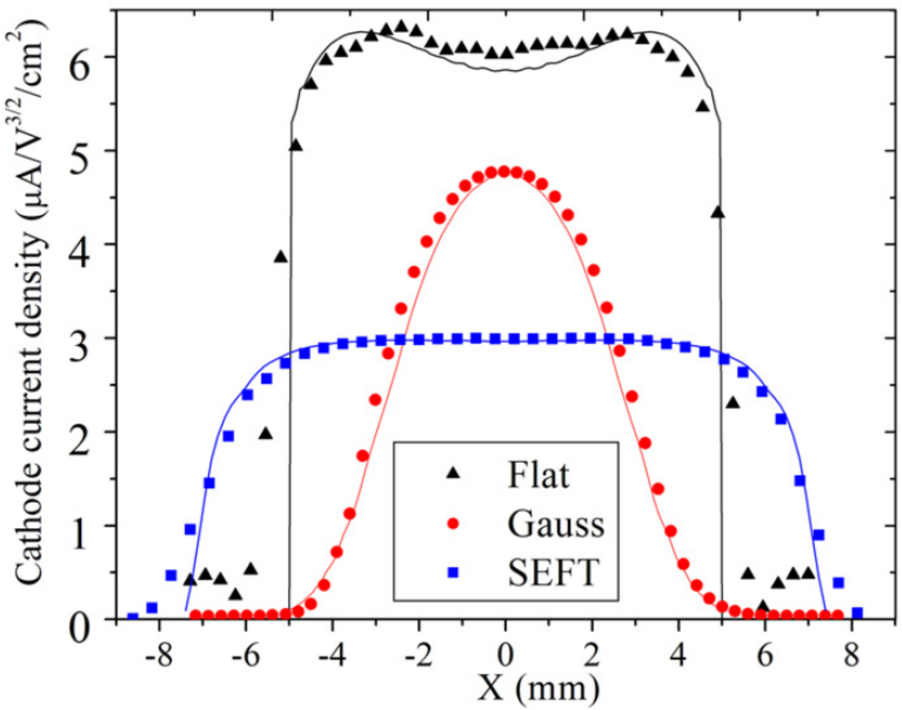


Electron lens (TEL-2) in the Tevatron tunnel

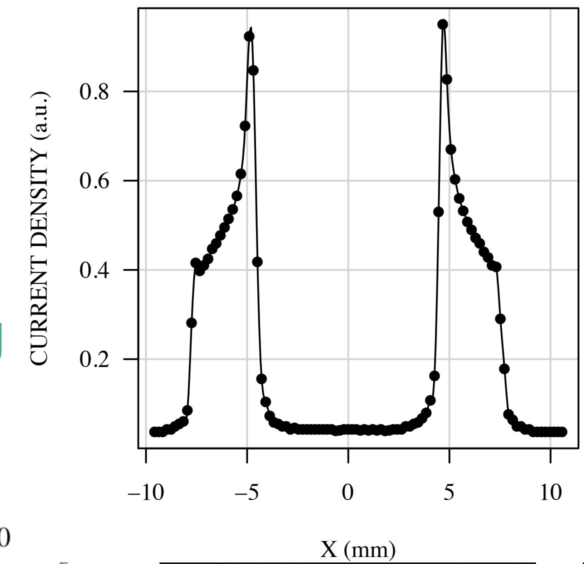
First main feature: control of electron beam profile

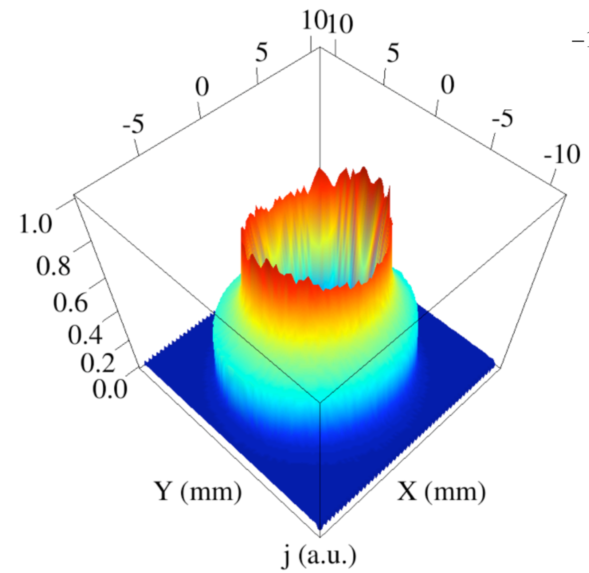
Current density profile of electron beam is shaped by cathode and electrode geometry and maintained by strong solenoidal fields

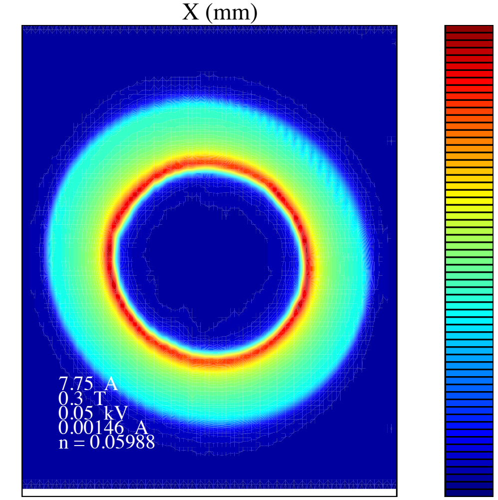
Flat profiles for bunch-by-bunch betatron tune correction



Hollow profile for halo scraping



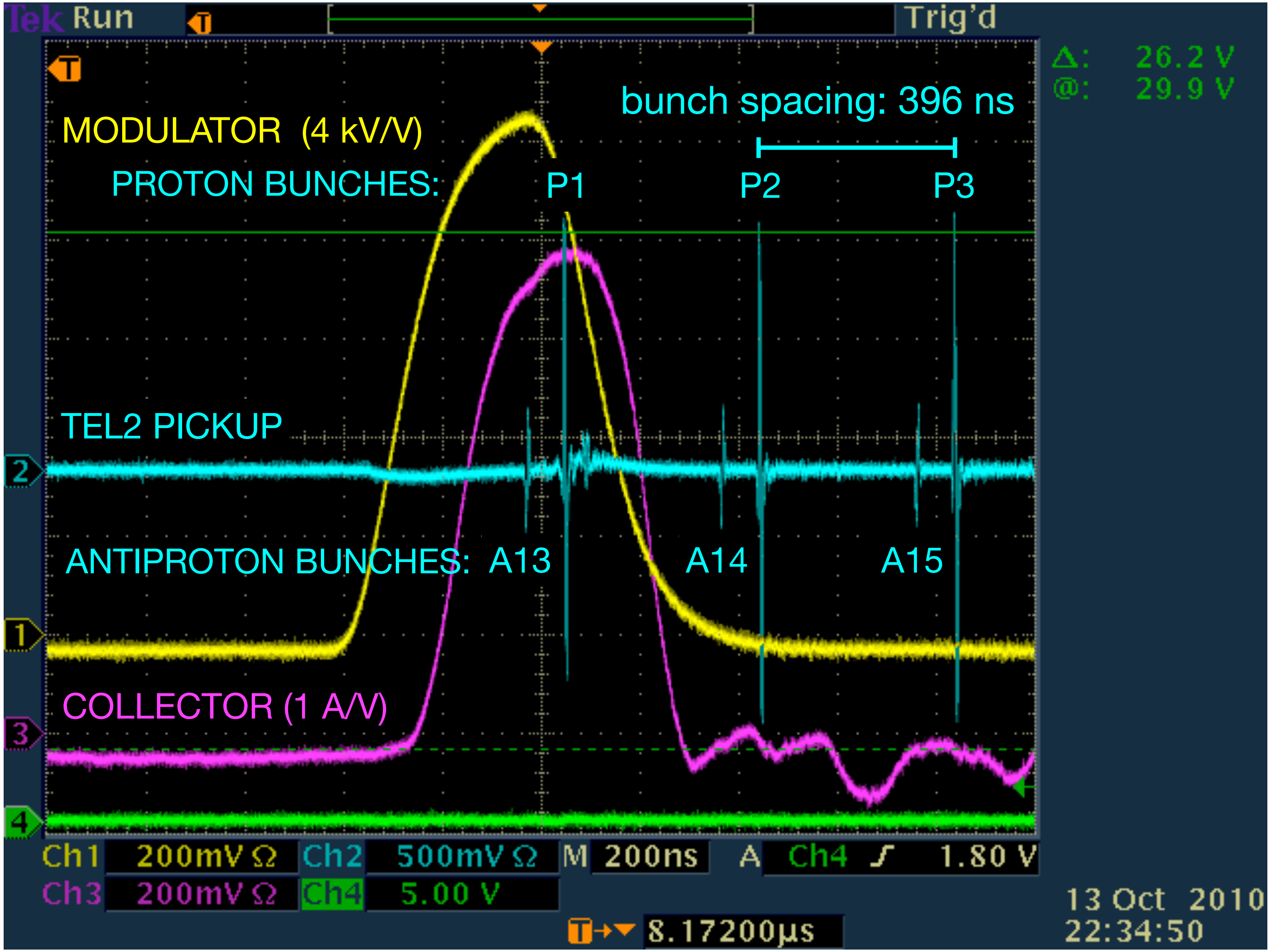




Gaussian profile for compensation of nonlinear beam-beam forces

Second main feature: pulsed electron beam operation

Beam synchronization in the Tevatron



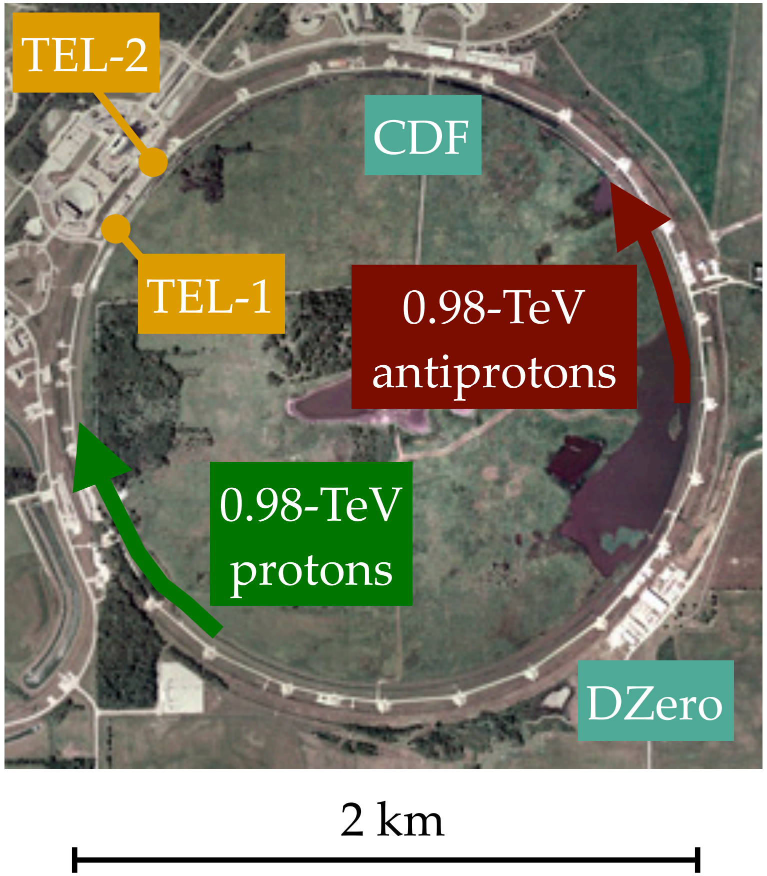
Pulsed electron beam could be **synchronized with any group of bunches**, with a different intensity for each bunch

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)

Tevatron electron lenses



Presently, being commissioned in RHIC at BNL

- ***head-on beam-beam compensation***
  - X. Gu's talk at this workshop

Current areas of research

- ***generation of nonlinear integrable lattices*** in the Fermilab Integrable Optics Test Accelerator
- ***hollow electron beam scraping*** of protons in LHC
- ***long-range beam-beam compensation*** as charged, current-carrying "wires" for LHC
- to ***generate tune spread for Landau damping*** of instabilities before collisions in LHC

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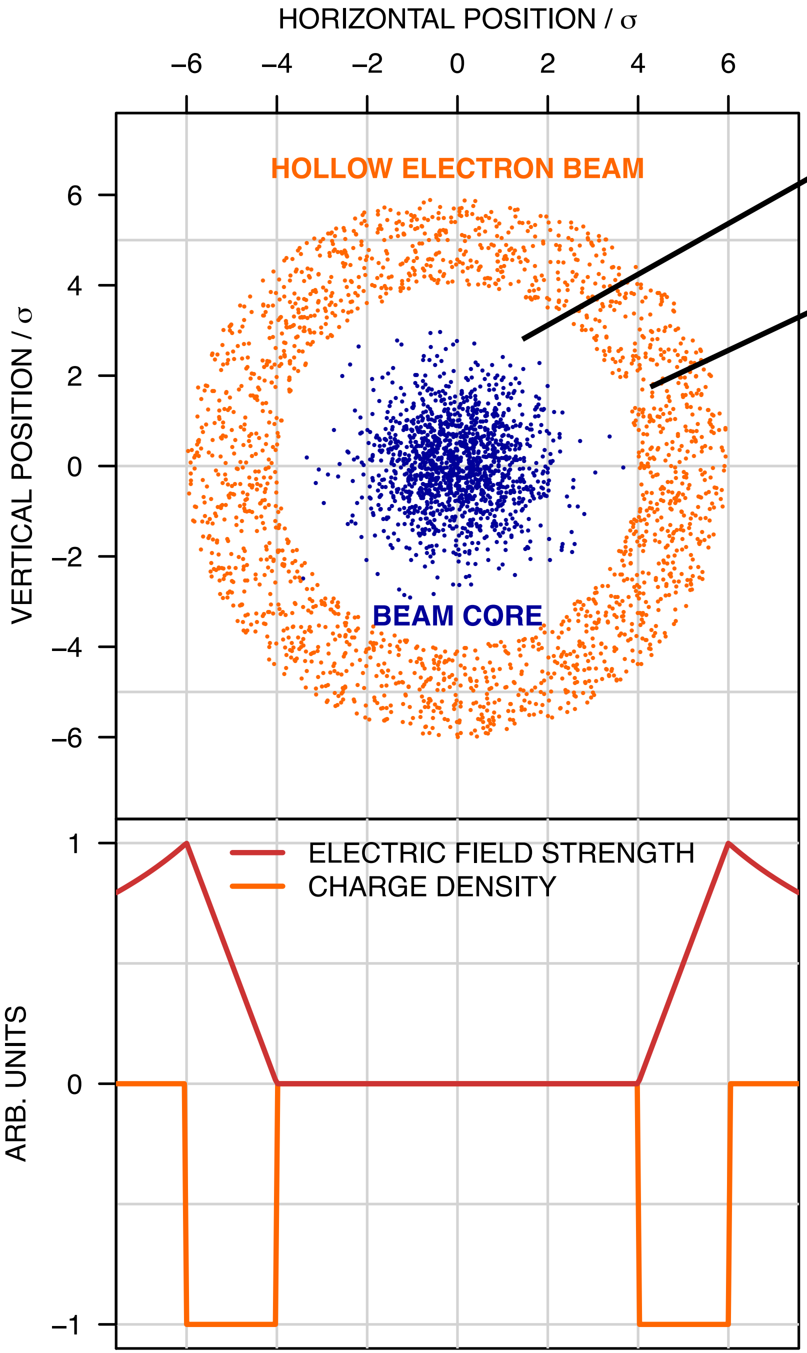
Concept of hollow electron beam collimator or scraper



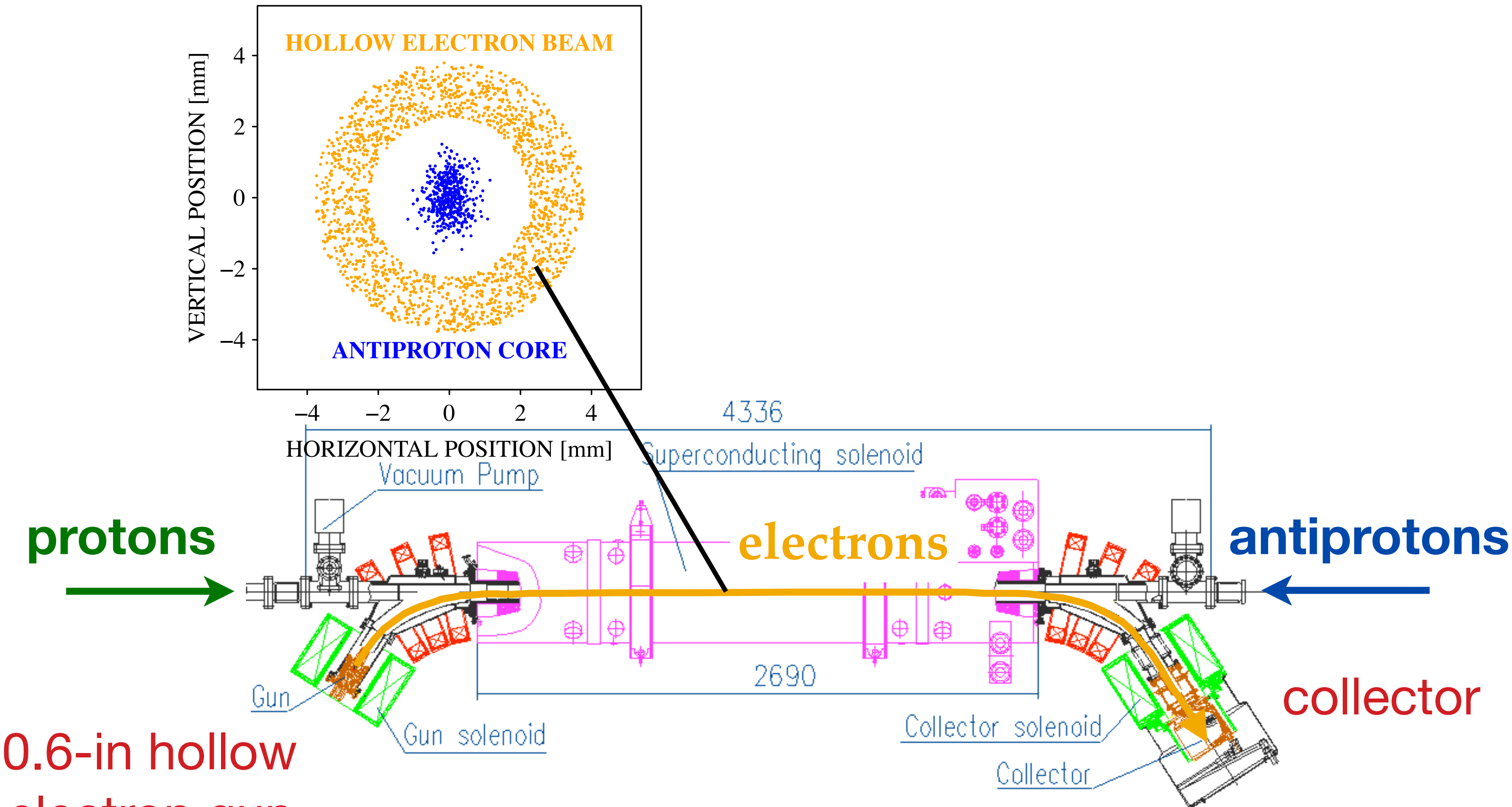
- **Beam core** is unaffected (field-free region)
- **Halo** experiences nonlinear, tunable, possibly pulsed transverse kicks:

$$\theta_r = \frac{2\, I_r\, L\, (1 \pm \beta_e \beta_p)}{r\, \beta_e\, \beta_p\, c^2\, (B\rho)_p} \left(\frac{1}{4\pi\epsilon_0} \right)$$

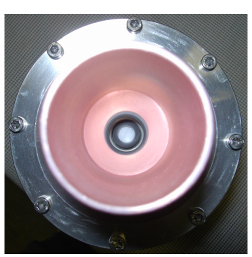
No metal close to the high-power beam: no material damage or impedance

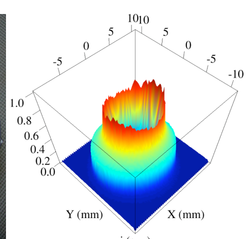
Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08

Hollow beam collimation with Tevatron electron lenses



0.6-in hollow electron gun
1.2 A at 5 kV





Tunable transverse halo kicks ~0.1 μrad

Hollow electron beam collimation studies in the Tevatron

- Tevatron studies (Oct. '10 - Sep. '11) provided experimental foundation
- Main results:
  - **compatible with collider operations**
  - **beam alignment** is **reliable** and **reproducible**
  - **halo removal** is **controllable**, **smooth**, and **detectable**
  - **negligible particle removal** or **emittance growth in the core**
  - **loss spikes** due to beam jitter and tune adjustments **are suppressed**
  - effect of electron beam on **halo fluxes and diffusivities vs. amplitude can be directly measured** with collimator scans

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

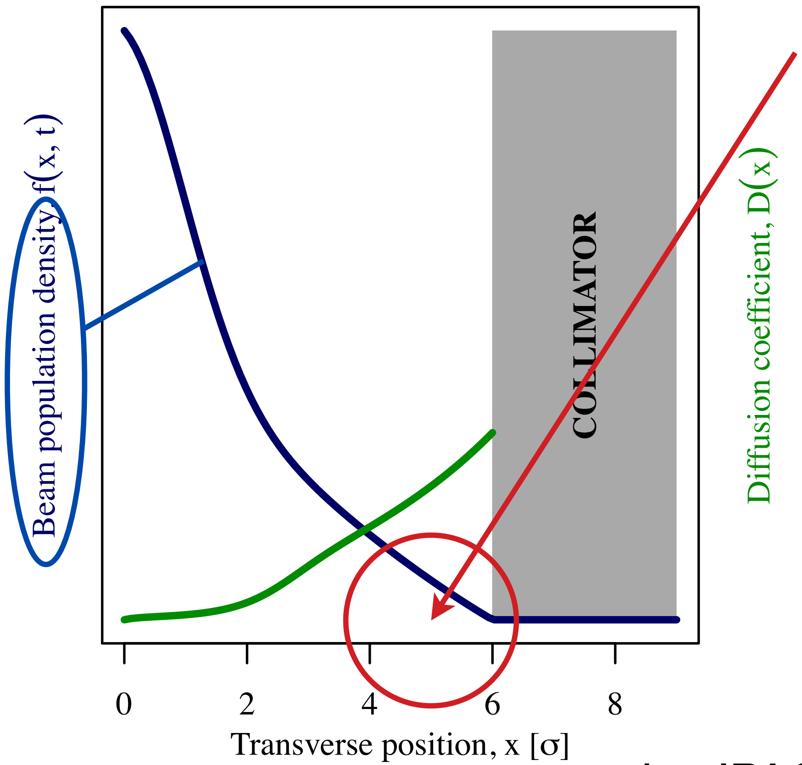
Collimation and beam halo are critical for LHC

- LHC and HL-LHC represent **huge leaps in stored beam energy**

	Tevatron	LHC 2012	LHC nominal	HL-LHC
Stored energy per beam	2 MJ	140 MJ	**362 MJ**	**692 MJ**

- **No scrapers exist** in LHC for full beam at top energy
- The collimation system has performed very well so far (6σ half gaps, 140 MJ @ 4 TeV): efficiency, robustness
- About 40 **fills lost** in 2012 due **to instabilities** (interplay of *collimator impedance* and beam-beam effects?)
- **Minimum design HL-LHC lifetimes** (e.g., slow losses during squeeze/adjust) **are close to plastic deformation** of primary and secondary collimators: (692 MJ) / (0.2 h) = 1 MW
- Significant program of collimation system upgrades under way

Collimation and beam halo are critical for LHC



- **Halo populations** (e.g., 4σ to 6σ) in LHC are **poorly known**. Collimator scans and van-der-Meer luminosity scans indicate 0.1%-5% of total energy, which translates to 0.7 MJ to 35 MJ at 7 TeV.
- **Quench limits**, **magnet damage**, or even **collimator deformation** will be reached with fast crab-cavity failures (~2σ orbit shift) or other fast losses

see also IPAC14: R. Schmidt, TUPRO016; B. Yee-Rendon, TUPRO003

- Hence the **need to measure and monitor the halo, and to remove it at controllable rates**. Beam halo monitoring and control are **one of the major risk factors for HL-LHC** and for **safe operation with crab cavities**
- **Hollow electron lenses are the most established and flexible tool for controlling the halo of high-power beams**

A plan for electron lenses and halo control in LHC

- Developed with **LHC collimation team**, **US LHC Accelerator Research Program (LARP)** and **HL-LHC Project**
- Final **collimation needs and decisions** can only be defined after gaining operational experience at 7 TeV (end of 2015)
  - uncertainties: cleaning efficiency, lifetimes, quench limits, impedances
- Meanwhile, proceed with **design** of 2 electron lenses, 1 per beam:
  - conceptual design completed (arXiv:1405.2033)
  - technical design in 2014-2015
- **Construction** 2015-2017, if needed; **installation** during 2018 long shutdown (2022 if limited by resources)
- Investigate proposed **alternative schemes** (R. Bruce). Cheaper, available sooner?
  - transverse damper excitation (W. Hofle)
  - tune modulation [Brüning and Willeke, Phys. Rev. Lett. **76**, 3719 (1996)]
  - both work in tune space, halo not necessarily separated
- Exchange electron lens **hardware/software expertise** with CERN; synergies with ELENA electron cooler?
- Develop noninvasive, direct **halo diagnostics**: synchrotron light (A. Fisher); backscattered electrons in e-lens (*à la* RHIC)?
- If possible, extend Tevatron experience with **beam tests** at RHIC

The conceptual design report

FERMILAB-TM-2572-APC

Conceptual design of hollow electron lenses for beam halo control in the Large Hadron Collider*

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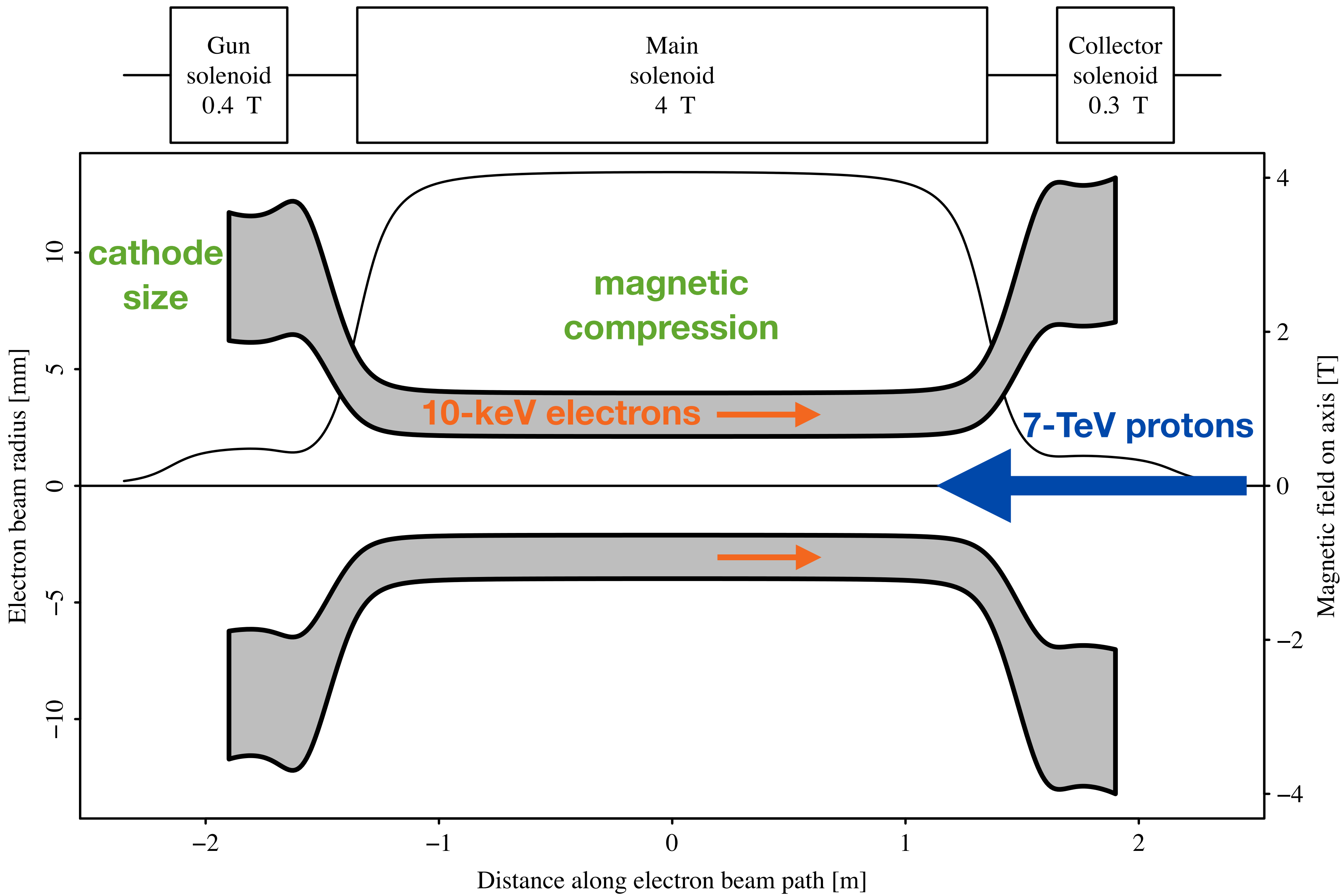
(Dated: May 9, 2014)

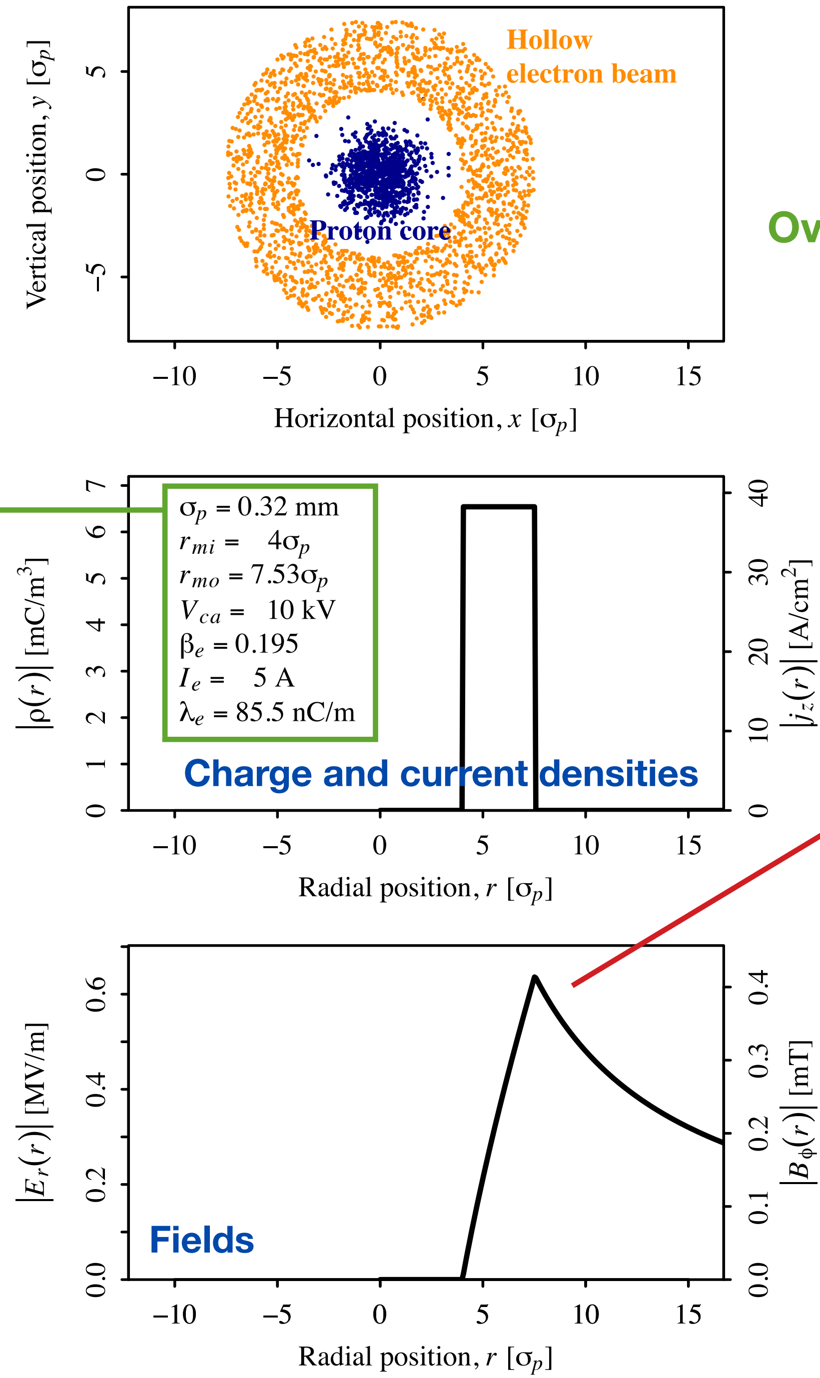
Collimation with hollow electron beams is a technique for halo control in high-power hadron beams. It is based on an electron beam (possibly pulsed or modulated in intensity) guided by strong axial magnetic fields which overlaps with the circulating beam in a short section of the ring. The concept was tested experimentally at the Fermilab Tevatron collider using a hollow electron gun installed in one of the Tevatron electron lenses. Within the US LHC Accelerator Research Program (LARP) and the European FP7 HiLumi LHC Design Study, we are proposing a conceptual design for applying this technique to the Large Hadron Collider at CERN. A prototype hollow electron gun for the LHC was built and tested. The expected performance of the hollow electron beam collimator was based on Tevatron experiments and on numerical tracking simulations. Halo removal rates and enhancements of halo diffusivity were estimated as a function of beam and lattice parameters. Proton beam core lifetimes and emittance growth rates were checked to ensure that undesired effects were suppressed. Hardware specifications were based on the Tevatron devices and on preliminary engineering integration studies in the LHC machine. Required resources and a possible timeline were also outlined, together with a brief discussion of alternative halo-removal schemes and of other possible uses of electron lenses to improve the performance of the LHC.

Available as **FERMILAB-TM-2572-APC** and as **arXiv:1405.2033**

Electron beam size is matched to proton beam size by solenoids



Example of numerical parameters for the LHC



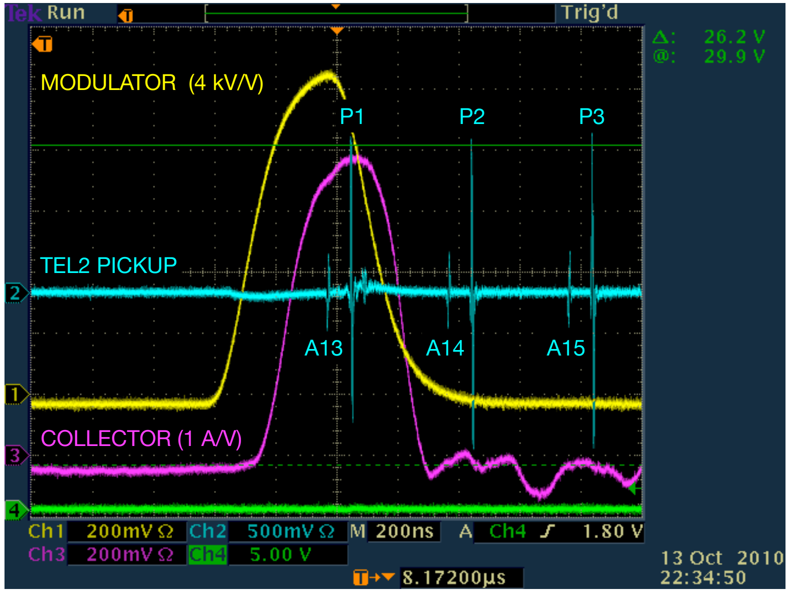
Proton rms size
Inner radius
Outer radius
Accelerating voltage
Velocity
Peak current
Linear current density

Overlap region *L* = 3 m

Max. kick **0.3 μrad** for 7-TeV protons

For comparison: multiple Coulomb scattering in LHC primaries generates *random* kicks with spread θ_{rms} = 1.3 μrad

Pulsed operation of the electron lens in the LHC



Current state of the art of electron-lens modulator rise time (10%-90%) is 200 ns at 5 kV

Pfeffer and Saewert, JINST **6**, P11003 (2011)

This enables

- turn-by-turn current modulation to enhance halo removal, if needed
- train-by-train (900 ns separation), or possibly batch-by-batch (225 ns), operation
    - to **preserve halo on a subset of bunches for machine protection**
    - to **compare different electron-lens settings** for diagnostics

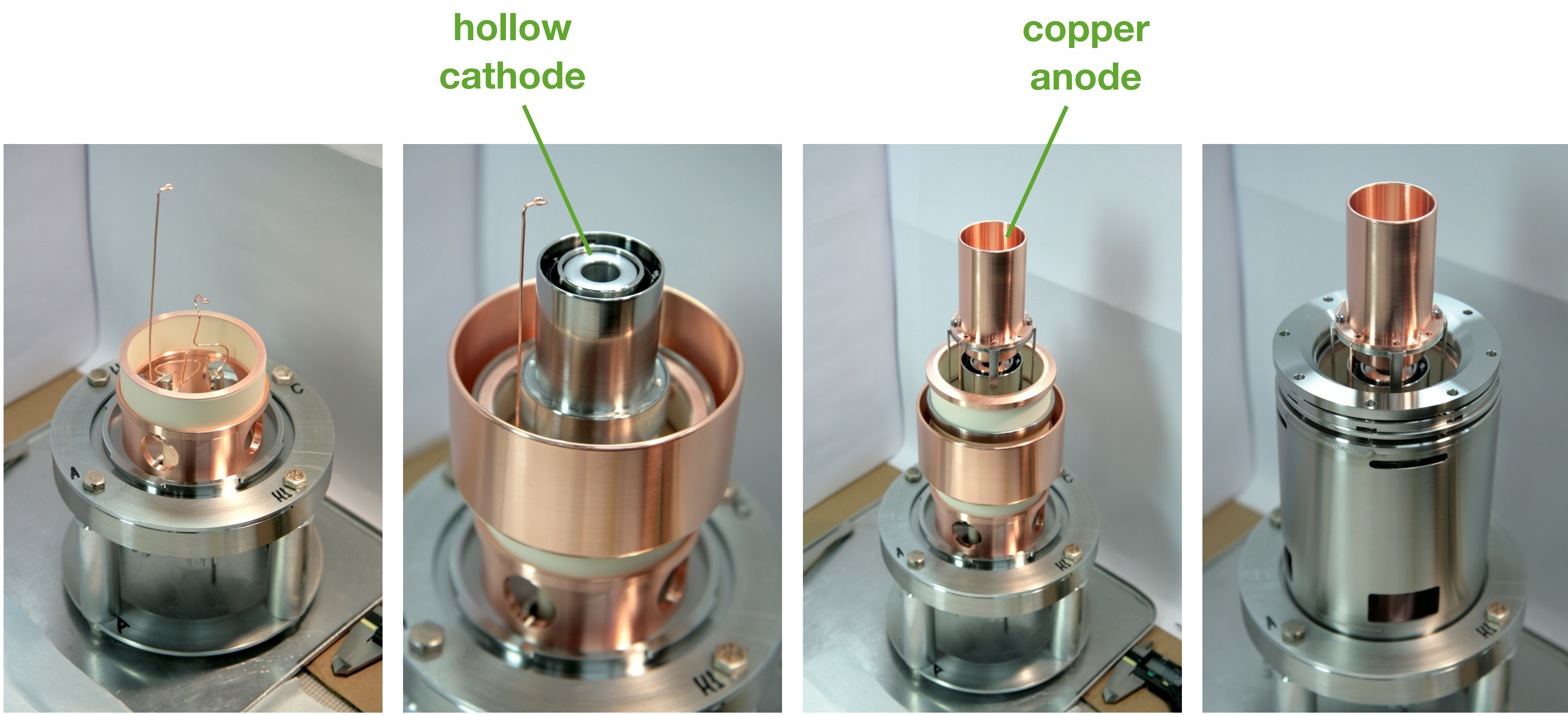
Bunch-by-bunch operation (25 ns or 50 ns) is not necessary for collimation

Summary of specifications in conceptual design report

Parameter	Value or range
Beam and lattice	
Proton kinetic energy, T_p [TeV]	7
Proton emittance (rms, normalized), ϵ_p [μm]	3.75
Amplitude function at electron lens, $\beta_{x,y}$ [m]	200
Dispersion at electron lens, $D_{x,y}$ [m]	≤ 1
Proton beam size at electron lens, σ_p [mm]	0.32
Geometry	
Length of the interaction region, L [m]	3
Desired range of scraping positions, r_{mi} [σ_p]	4–8
Magnetic fields	
Gun solenoid (resistive), B_g [T]	0.2–0.4
Main solenoid (superconducting), B_m [T]	2–6
Collector solenoid (resistive), B_c [T]	0.2–0.4
Compression factor, $k \equiv \sqrt{B_m/B_g}$	2.2–5.5
Electron gun	
Inner cathode radius, r_{gi} [mm]	6.75
Outer cathode radius, r_{go} [mm]	12.7
Gun perveance, P [μperv]	5
Peak yield at 10 kV, I_e [A]	5
High-voltage modulator	
Cathode-anode voltage, V_{ca} [kV]	10
Rise time (10%–90%), τ_{mod} [ns]	200
Repetition rate, f_{mod} [kHz]	35

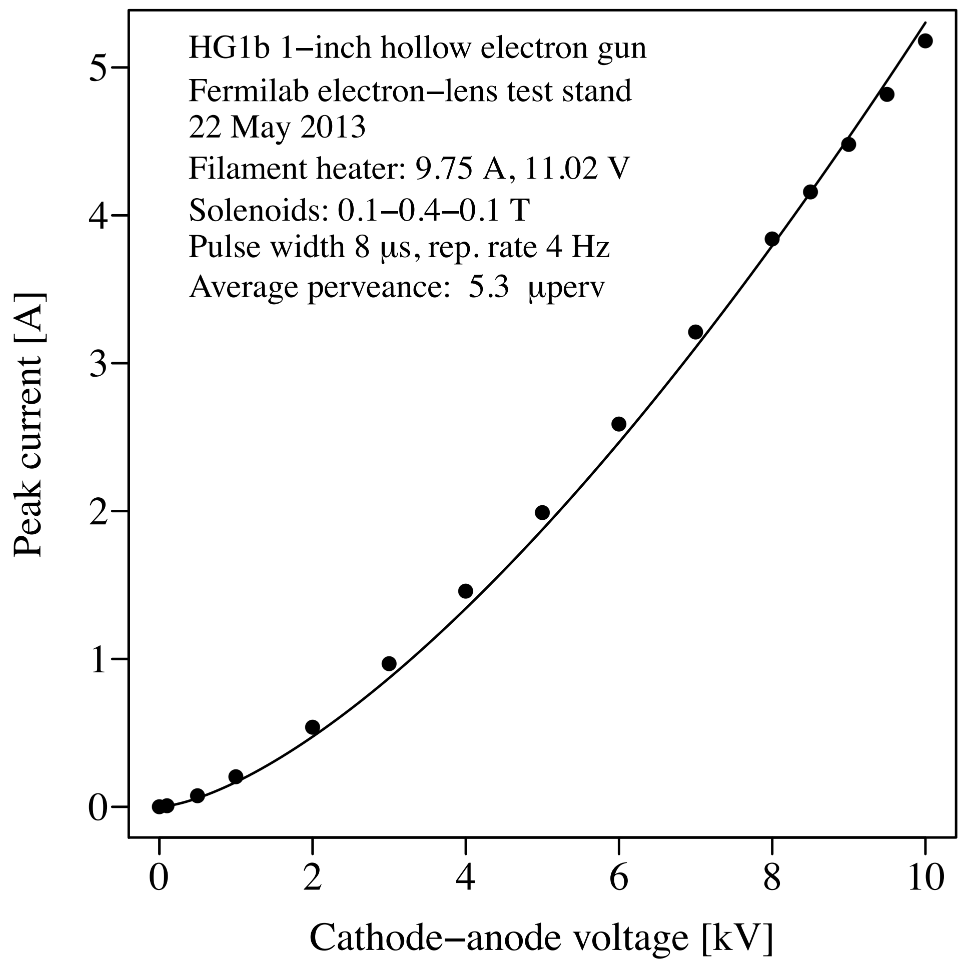
All technical parameters are currently achievable

Hollow electron gun prototype for the LHC



- 25 mm outer diameter, 13.5 mm inner diameter
- Built and characterized at Fermilab electron-lens test stand

Performance of hollow electron gun prototype



Yields 5 A at 10 kV

Numerical simulations: goals

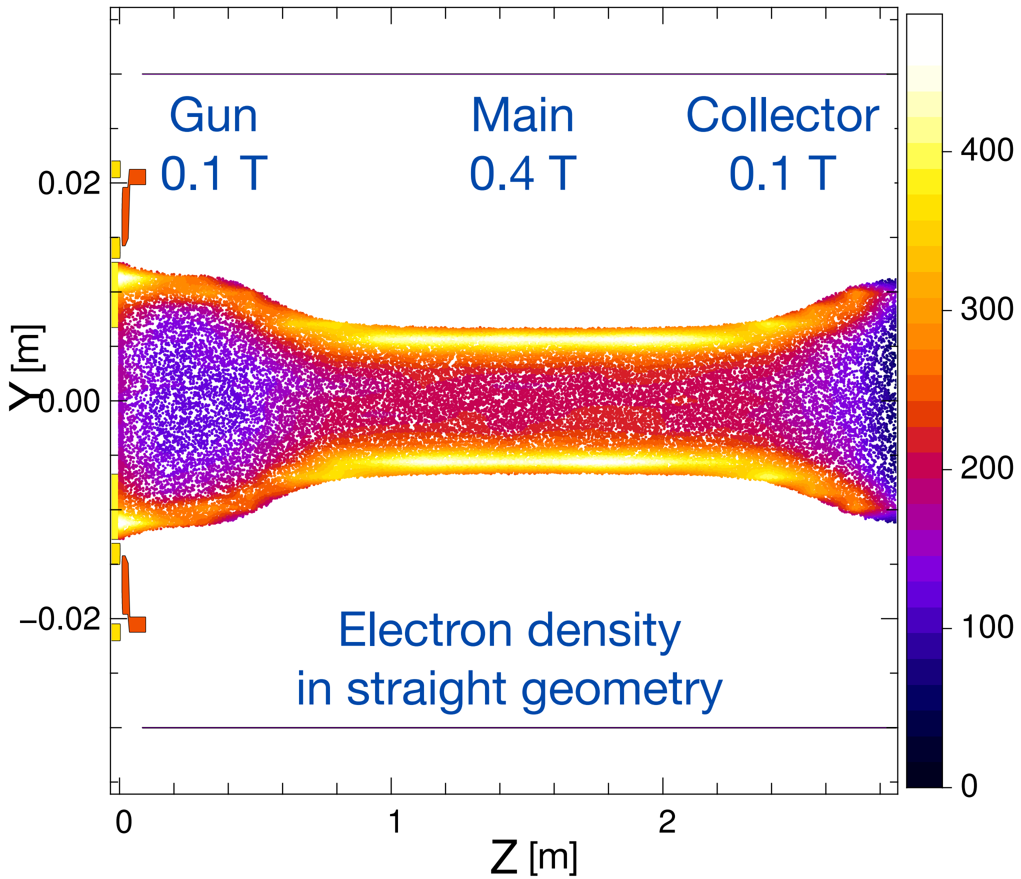
- **Would hollow electron beam collimation be effective in the LHC?**
  - The kicks are nonlinear, with a small random component. Halo removal rates are expected to depend on magnetic rigidity of the beam, machine lattice, and noise sources. Nontrivial extrapolation from Tevatron to LHC.
- **Which modes of operation would be useful?**
  - *continuous*: same electron current every turn
    - most of Tevatron experiments done in this mode
  - *resonant*: current modulated to excite betatron oscillations (sinusoidal or skipping turns)
    - used for clearing abort gap in Tevatron
  - *stochastic*: random on/off, or constant with random component
- **Would there be any adverse effects on the core, such as lifetime degradation or emittance growth?**
  - No effects were seen in the Tevatron in continuous mode. Effects of asymmetries in resonant operation?

Previtali et al., FERMILAB-TM-2560-APC (2013)
Valishev, FERMILAB-TM-2584-APC (2014)

Dynamics of the magnetically confined electron beam

3D simulation of electron beam propagation in electron lens with Warp particle-in-cell code

- Injection: space-charge limited e-gun or arbitrary particle coordinates
- Layout: straight (test stand) or with bends (TEL-2 and LHC e-lens)
- Computing resources
  - tests on multi-core laptops
  - parallel version on Fermilab Accelerator Simulations Wilson Cluster

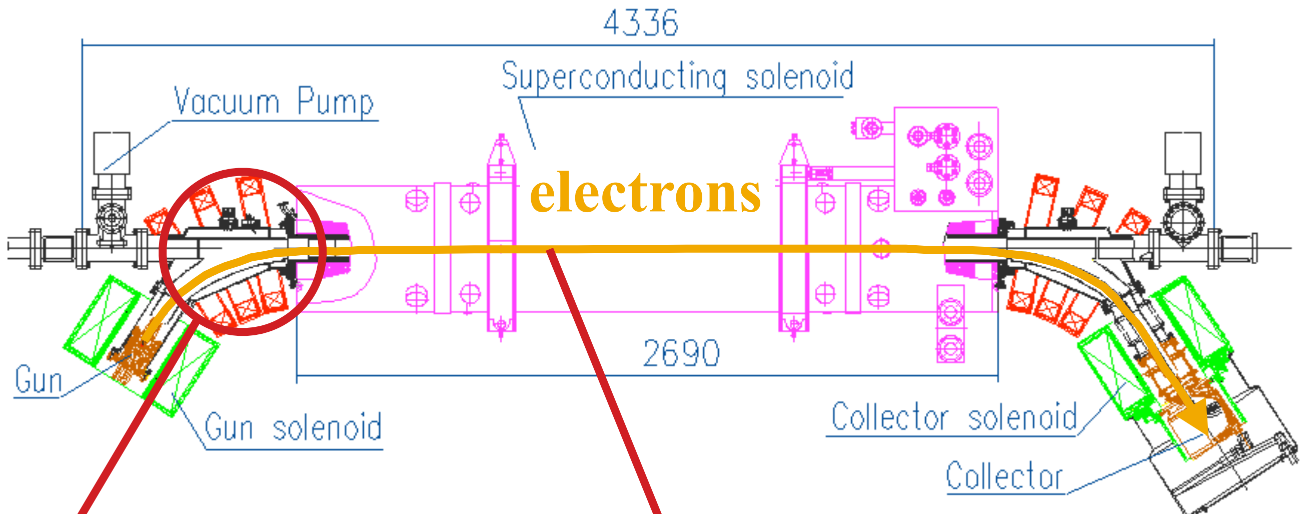


First use of particle-in-cell codes for electron-lens design

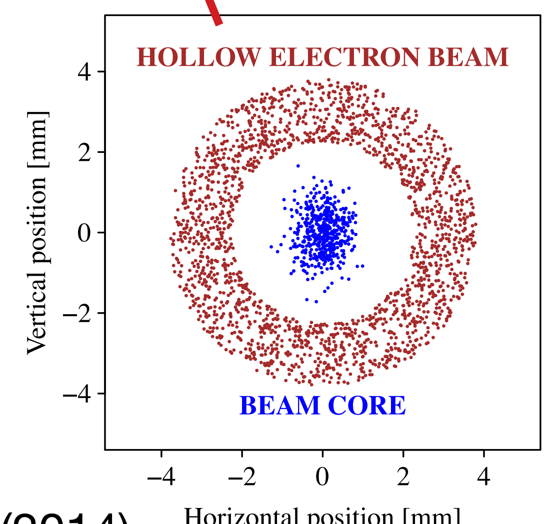
Moens, CERN-THESIS-2013-126
Stancari, NA-PAC13
➡IPAC14 poster MOPME033

Effect of asymmetries in electron distribution on circulating beam

No adverse effects were observed at the Tevatron in continuous operation, but application to the LHC may require higher beam currents and different pulsing patterns. We studied two sources of asymmetry:



1. bends for injection/extraction



2. azimuthal asymmetries in overlap region

Morozov et al., IPAC12

Stancari, FERMILAB-FN-0972-APC, arXiv:1403.6370 (2014)

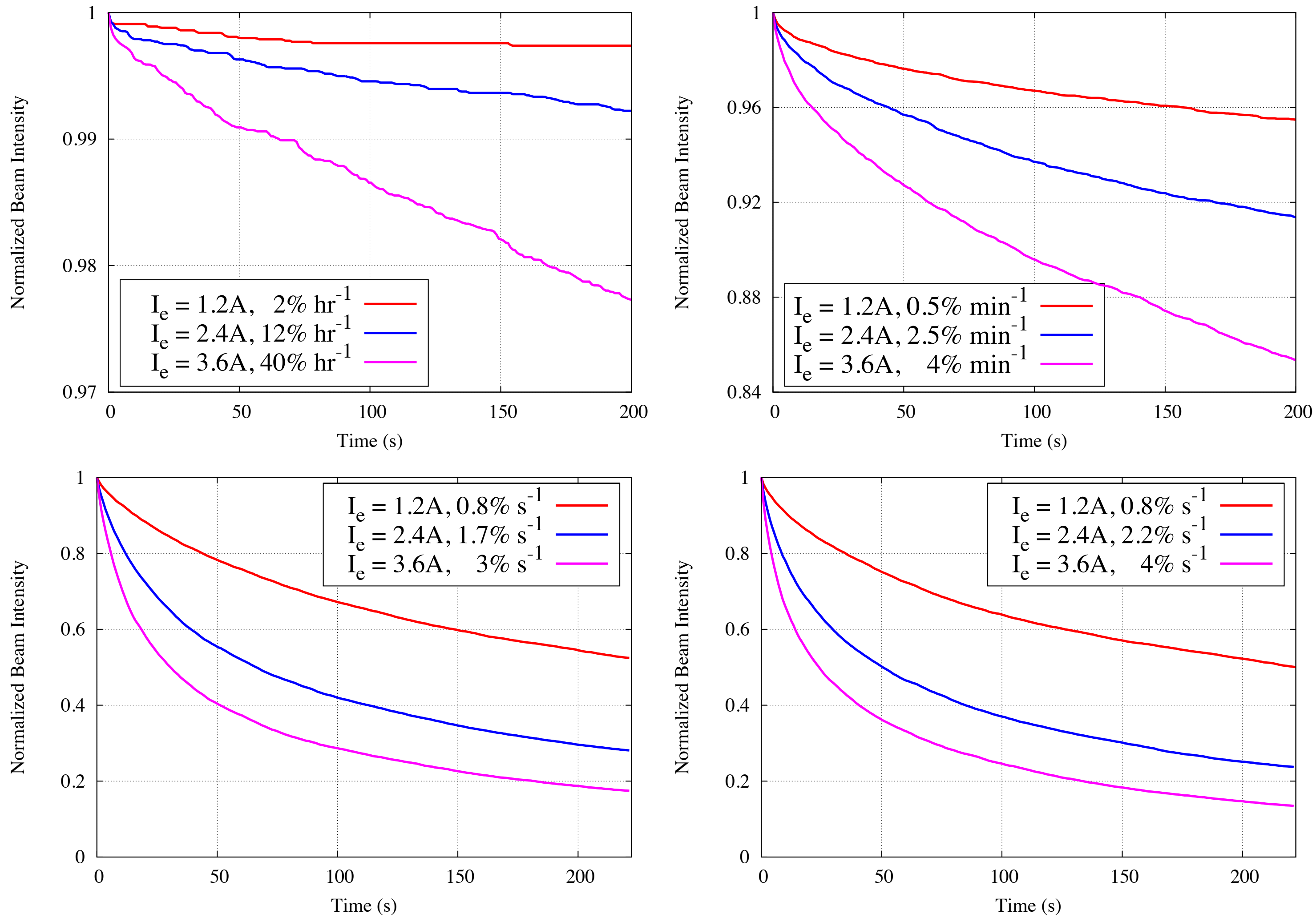
Valishev, FERMILAB-TM-2584-APC (2014)

Lifetrac calculations of halo removal rates vs. electron current

without collisions | with collisions

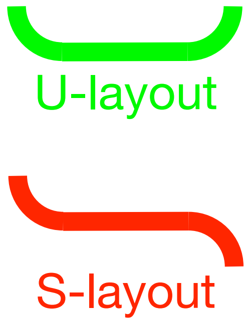
continuous mode

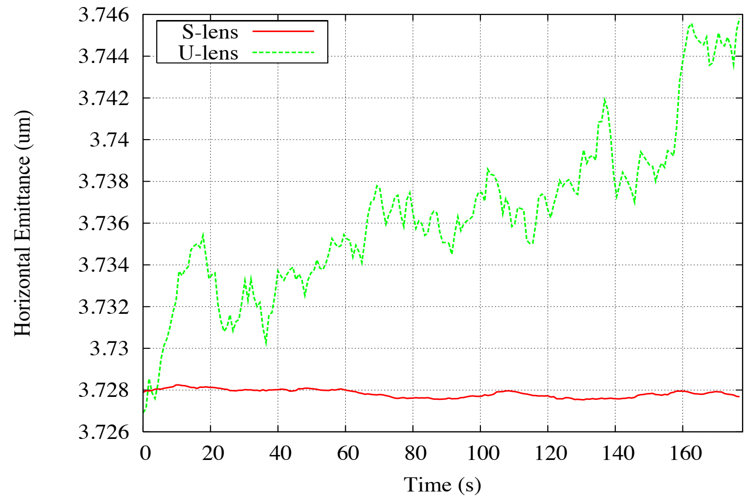
stochastic mode

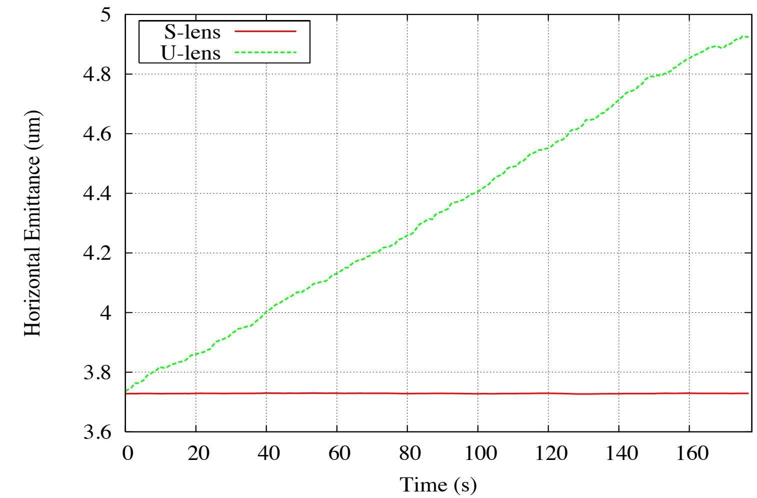


- A wide range of removal rates is possible
- Continuous mode useful for smooth cleaning
- Stochastic mode can be used for faster scraping

Lifetrac calculation of the effect of injection/extraction bends



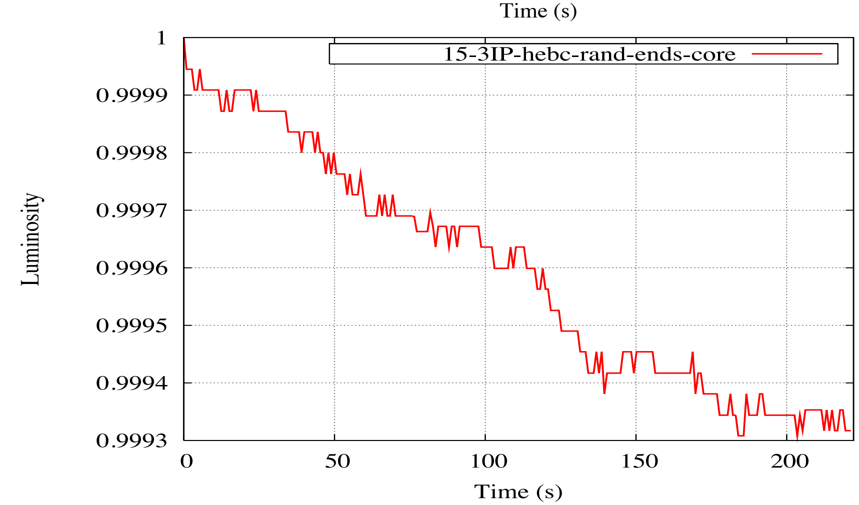




- In continuous mode, no impact on emittances or luminosity

- In stochastic mode, with U-layout (gun and collector on same side), dipole kick generates emittance growth (e.g., 10% modulation, 0.3 um/h)

- In stochastic mode, with S-layout (gun and collector on opposite sides of ring), small contribution to luminosity lifetime (90 h, or 1%/h)



If pulsed operation is required, then S-layout is necessary

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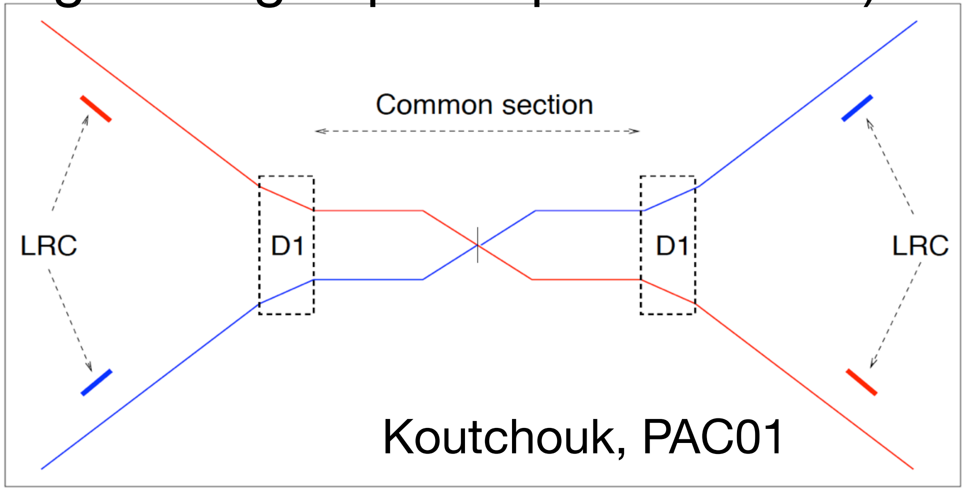
Long-range compensation is essential for HL-LHC flat optics schemes

- A possible HL-LHC luminosity scheme:
  - flat optics at collisions: (10, 50) cm β^* $\Rightarrow$ no IP1/5 compensation
  - no crab cavities required (crab crossing/kissing improve performance)
  - **a long-range beam-beam compensation scheme is needed** to achieve luminosity



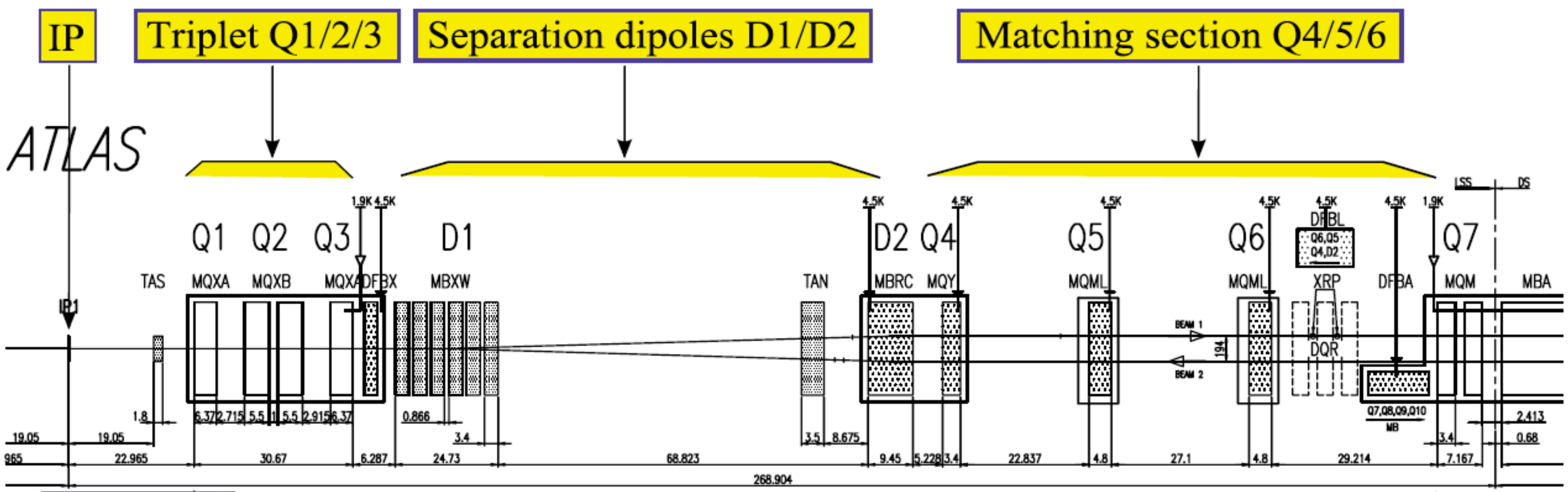
- Wire compensator devices at 10σ to be tested after current shutdown: technically challenging (378 A required) and a risk for collimation and machine protection
- **Electron lenses for long-range beam-beam compensation may be a safer, less demanding alternative, with pulsing option**
  - (21 A) × (3 m) required for HL-LHC, any transverse shape

Valishev and Stancari, arXiv:1312.1660

Long-range beam-beam compensation with electron lenses

Preliminary work proceeding in parallel:

- **beam physics**: expected performance, sensitivity to location
  - 2 options under study:
    - between D1 and D2 dipoles (challenging layout and integration)
    - beyond D2 dipole



LHC IR layout [CERN-2004-003; Fartoukh, Phys. Rev. ST Accel. Beams **16**, 111002 (2013)]

- **energy deposition** (superconducting solenoid) and **radiation to electronics** (anode high-voltage modulator) in both locations
- **integration**

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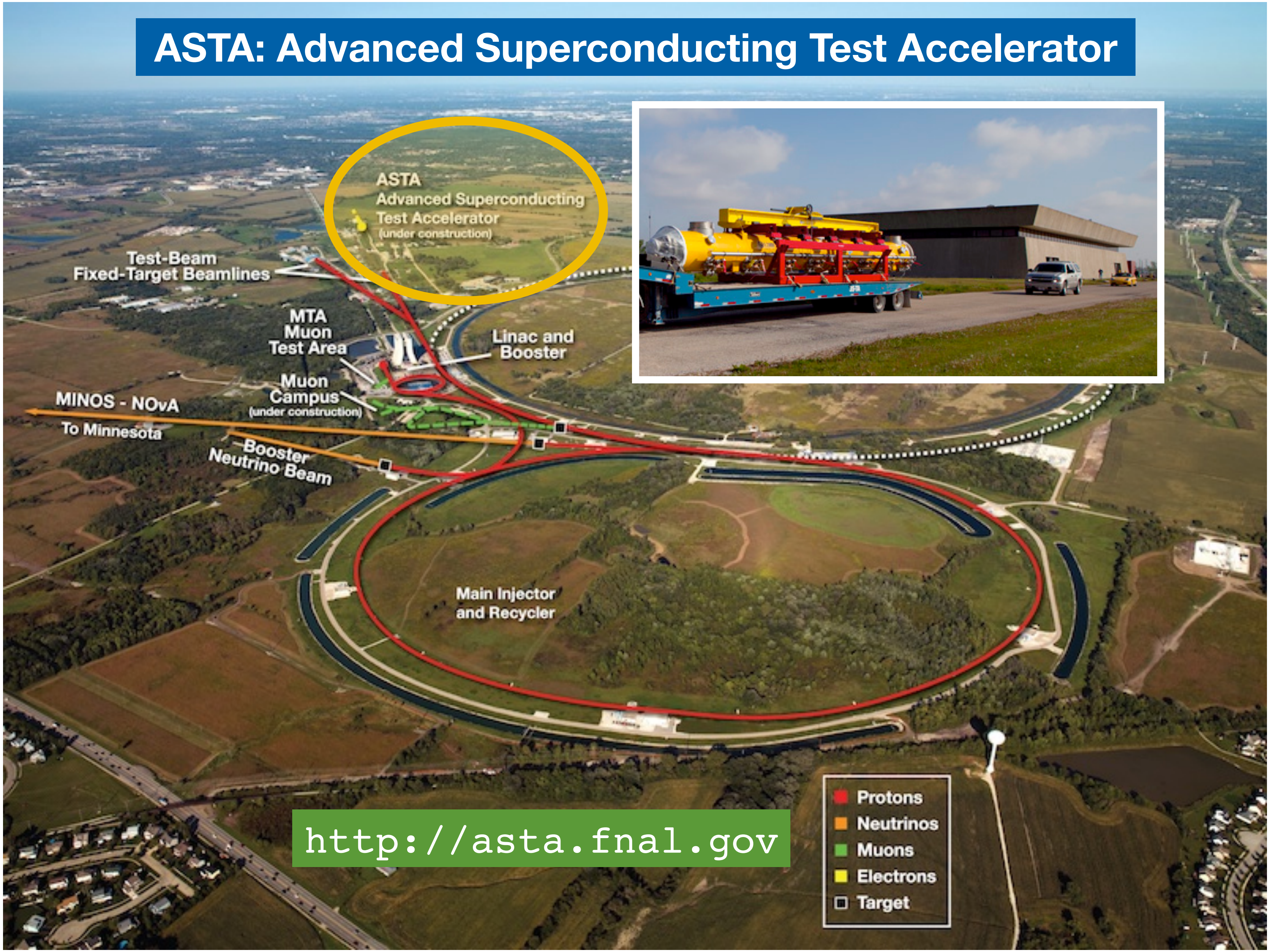
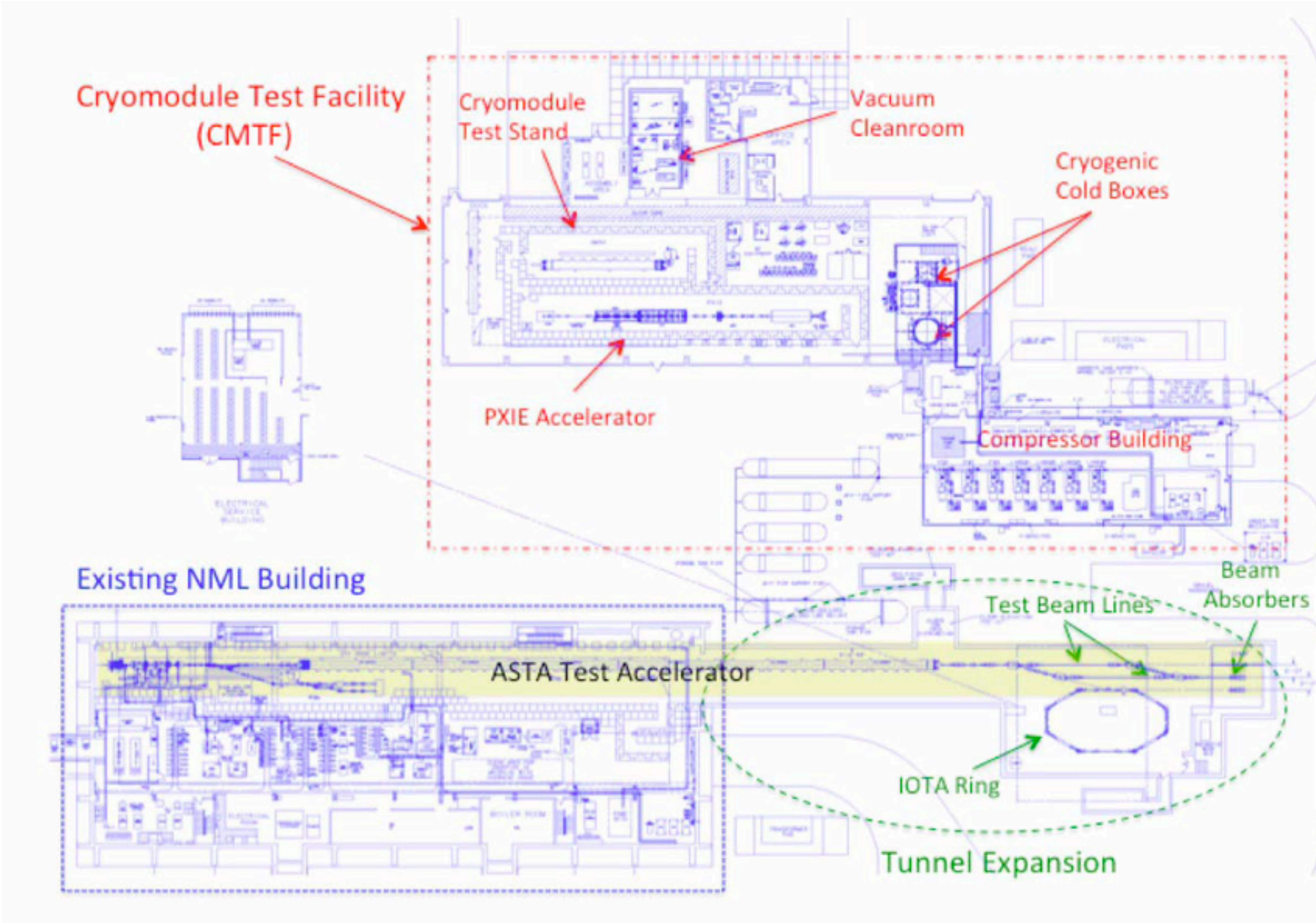
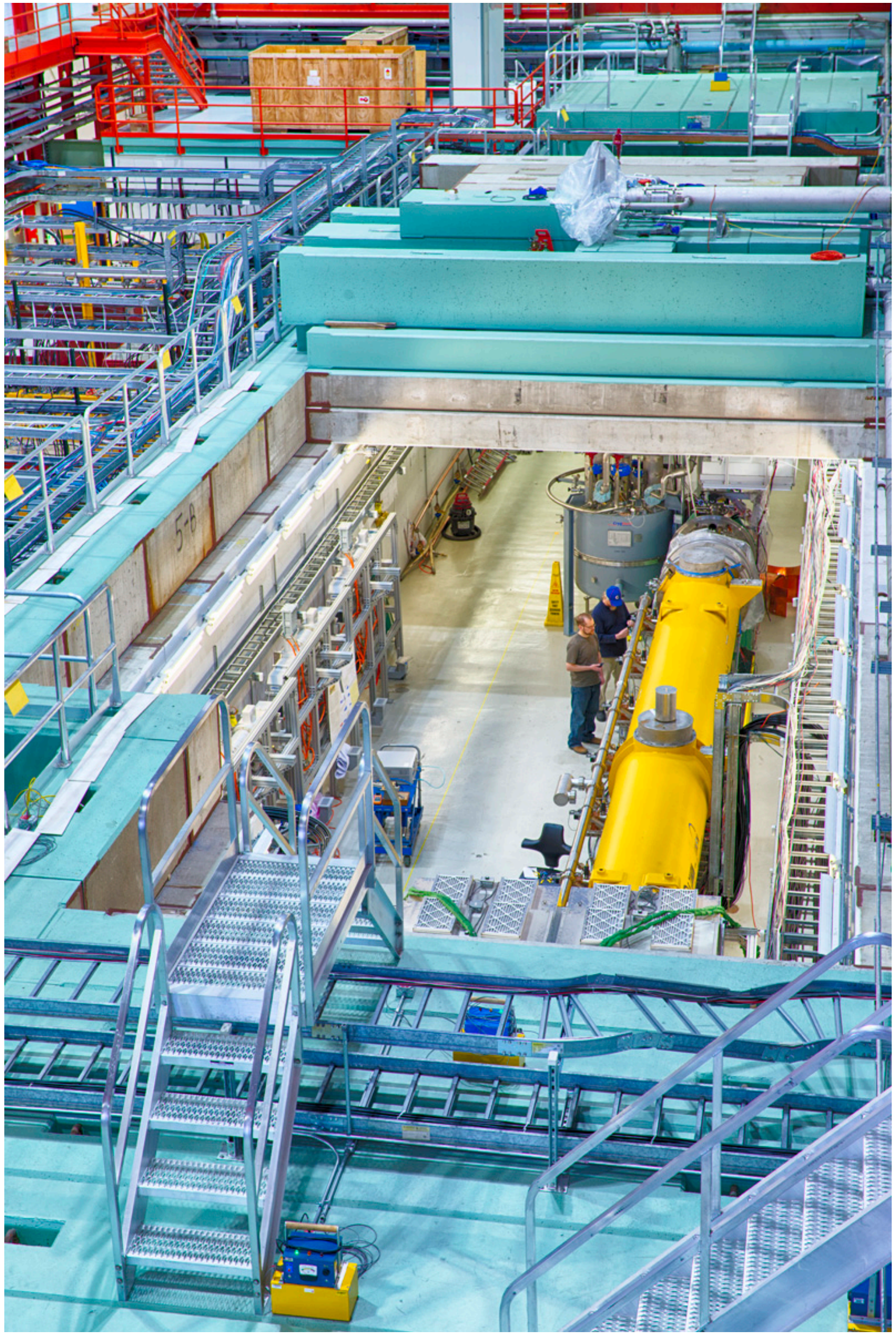
The new beam physics research center at Fermilab



Floor plan of the facility



Interior of the facility

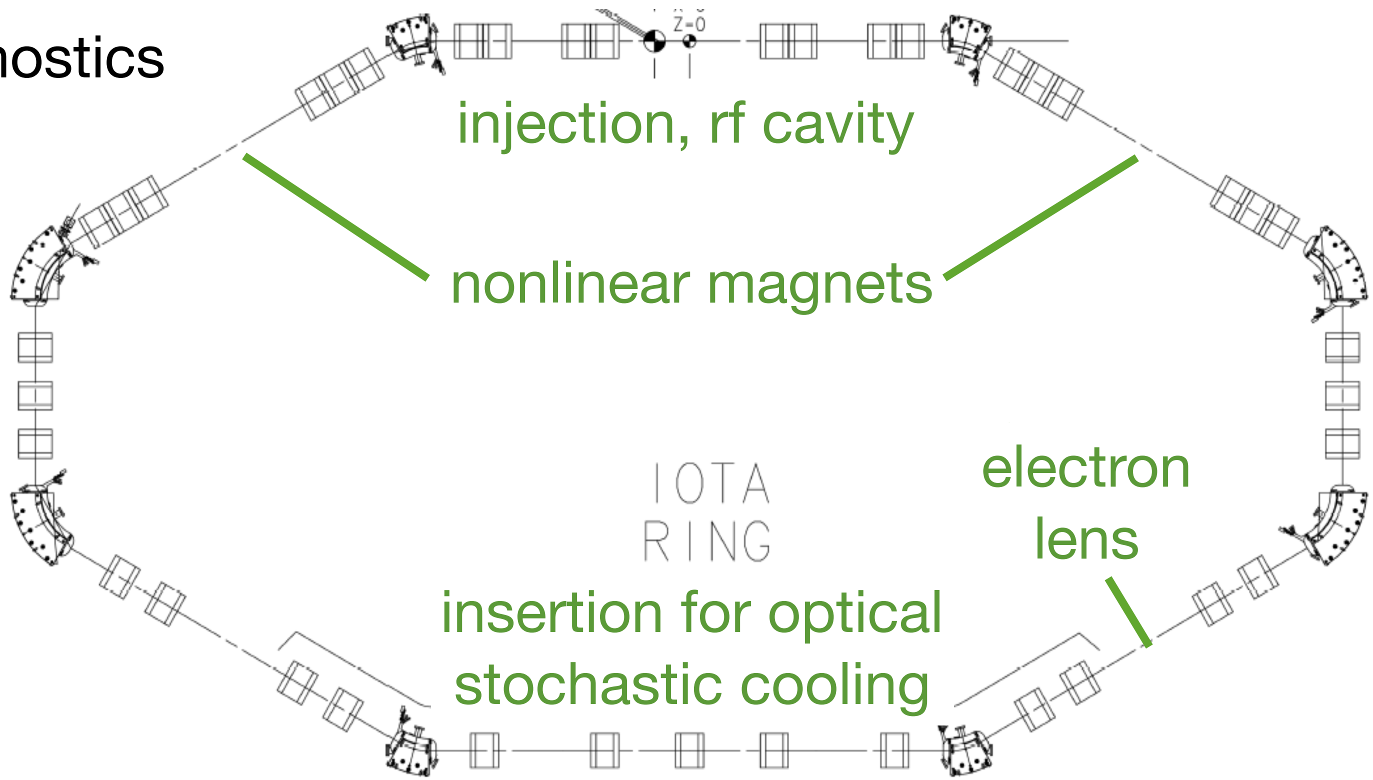


Integrable Optics Test Accelerator (IOTA)

Is it possible to design a highly nonlinear lattice with large dynamic aperture and a correspondingly wide tune spread to avoid instabilities?

IOTA project goal: demonstrate ~0.25 nonlinear tune spread without loss of dynamic aperture in a real machine

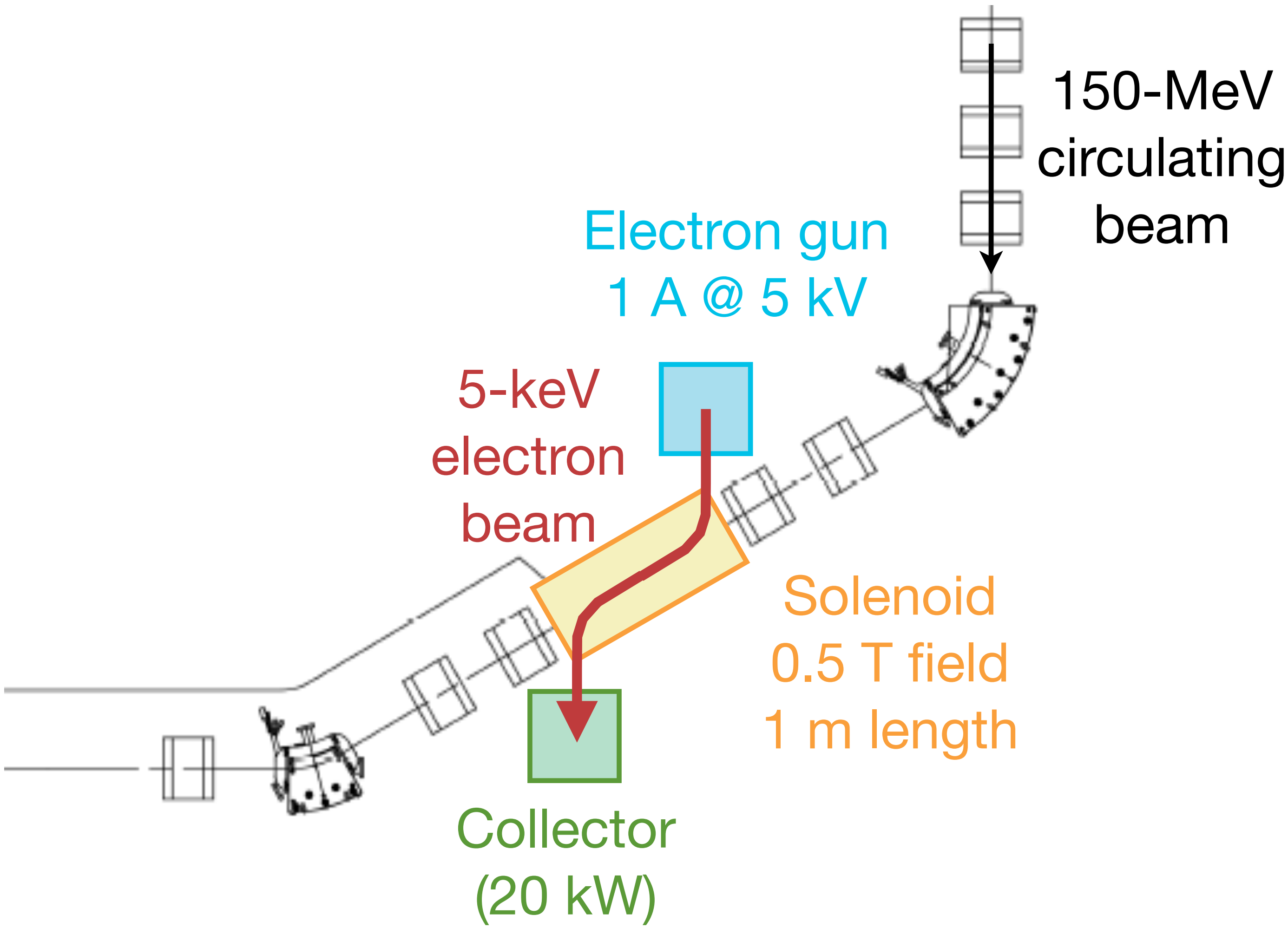
50 – 150 MeV e^- beams; 10^9 e^-/bunch
40 m circumference
flexible lattice and diagnostics



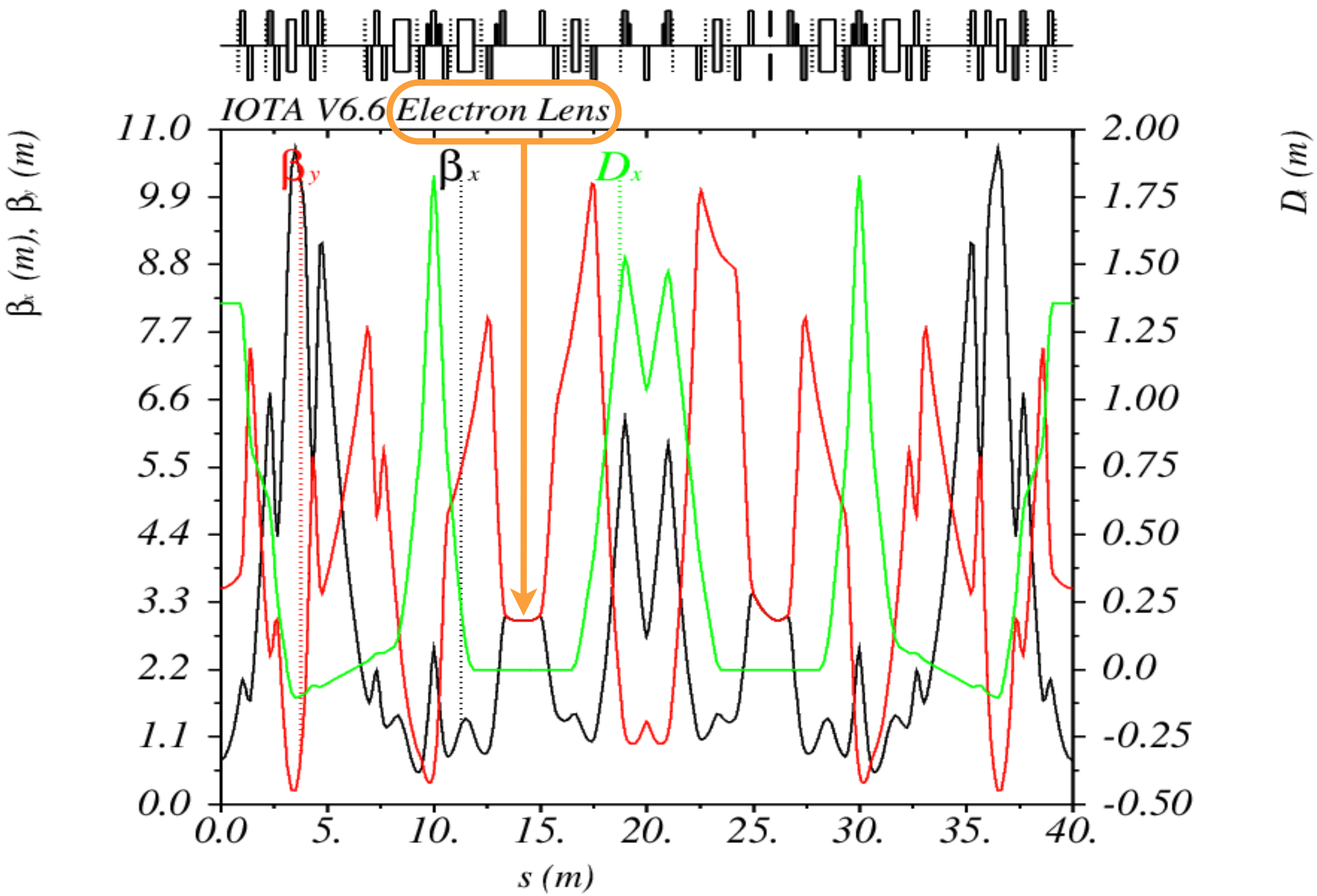
S. Nagaitsev plenary talk
at this workshop

Danilov and Nagaitsev, Phys. Rev. ST Accel. Beams **13**, 084002 (2010)
Valishev, Nagaitsev, Danilov, and Shatilov, IPAC12 (2012)

Electron-lens preliminary parameters



IOTA lattice with electron lens



G. Kafka
A. Valishev

Nonlinear integrable optics with electron lenses

Use the electromagnetic field generated by the electron distribution to provide the desired nonlinear field

1. Axially symmetric thin-lens kick (extended McMillan case)

current density $j(r) \propto \frac{1}{(r^2 + a^2)^2}$

transverse kick $\theta(r) \propto \frac{r}{r^2 + a^2}$

McMillan, UCRL-17795 (1967)
Danilov and Perevedentsev, PAC97

2. Axially symmetric time-independent Hamiltonian with thick lens

Any axially-symmetric current density distribution

Solenoid provides
- focusing for the circulating beam, constant amplitude function
- magnetic confinement for low-energy beam

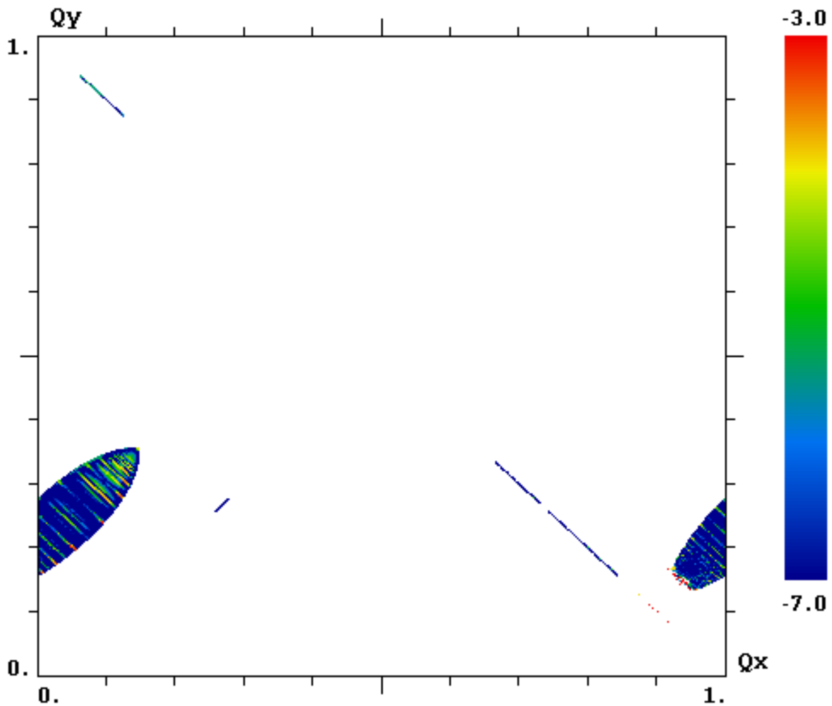
Nagaitsev and Valishev

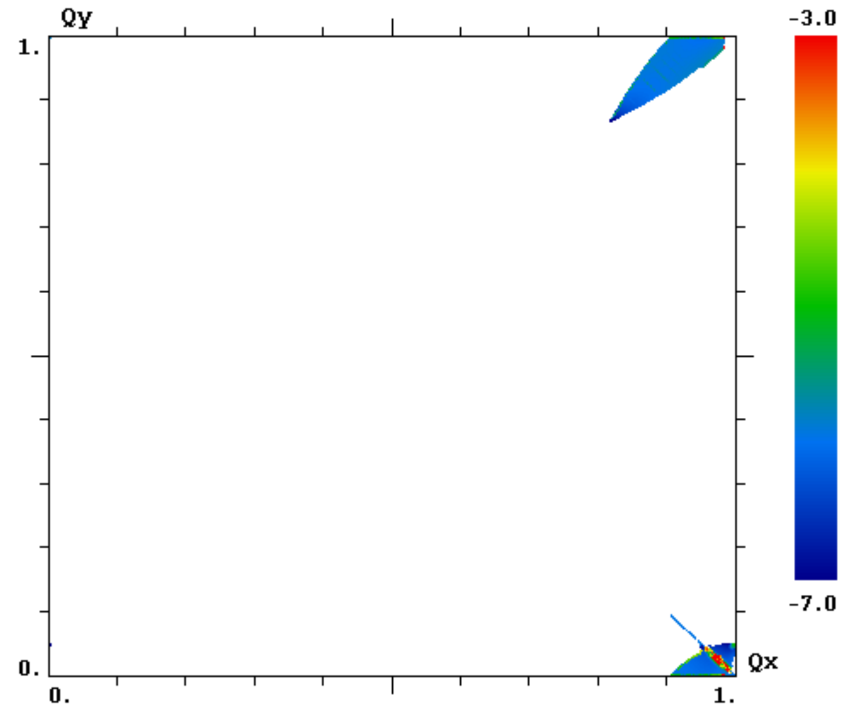
Nonlinear integrable optics with electron lenses

1. Axially symmetric thin-lens kick (extended McMillan case)

2. Axially symmetric time-independent Hamiltonian with thick lens

Frequency-map analysis (A. Valishev)





In both cases

- there are 2 transverse invariants
- nonlinear tune shifts of order -0.3 should be achievable

Summary and outlook

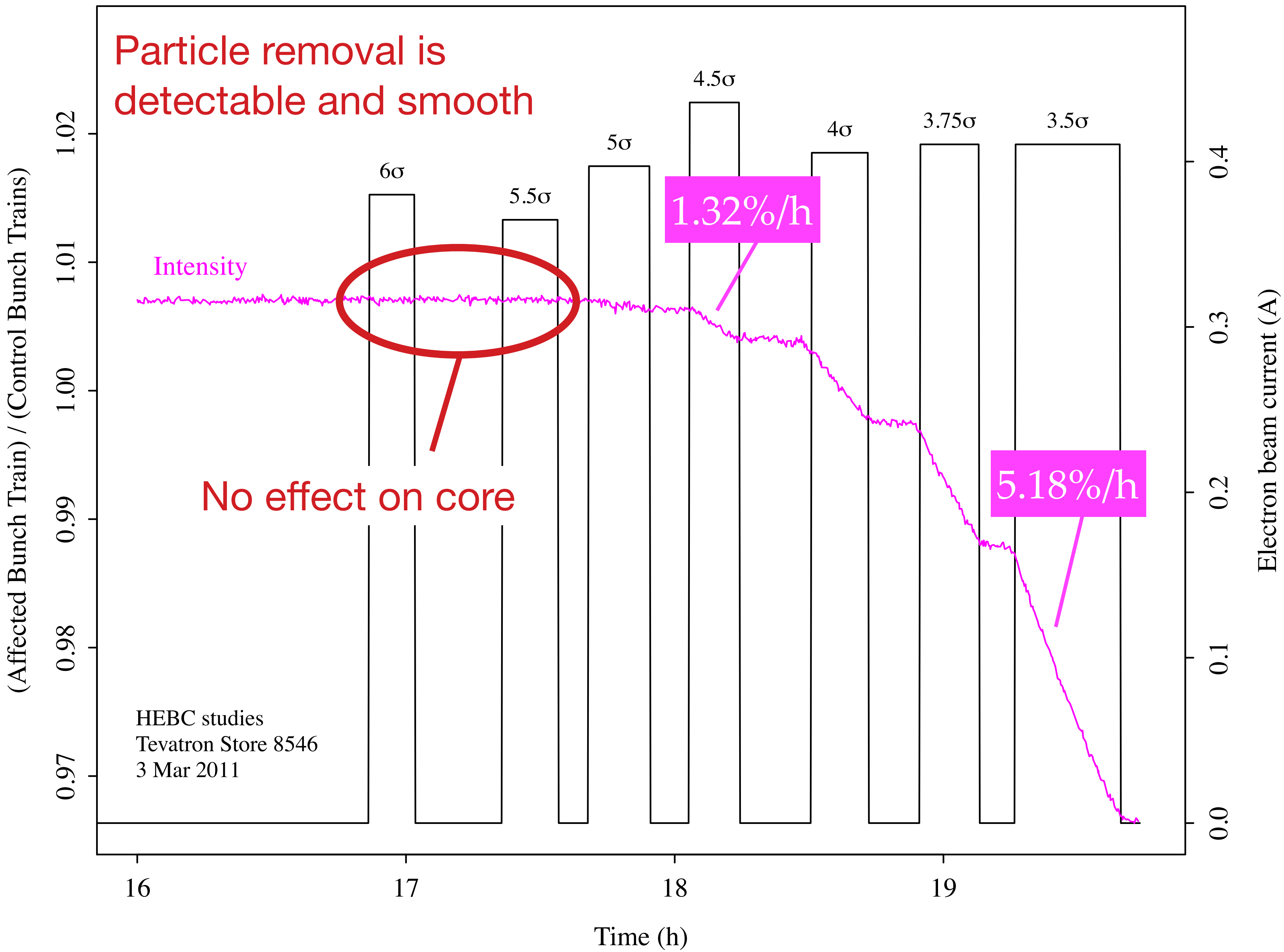
- **Electron lenses** are unique devices for active beam manipulation in accelerators, with a wide range of applications
- **Halo scraping with hollow electron beams was demonstrated** at the Fermilab Tevatron collider
- **Halo measurement and control is critical for LHC** and its upgrades
- A **conceptual design of hollow electron beam scraper for the LHC** was recently completed
  - Expected performance based upon experimental data and numerical simulations
  - Technical parameters are achievable
- Electron lenses in LHC are also a candidate for **long-range beam-beam compensation** (charged “e-wire”): preliminary concept, layout, and integration
- Near future of research on magnetized low-energy electron beams: **nonlinear integrable lattices** in the IOTA ring at the Fermilab ASTA facility

Contact:
`stancari@fnal.gov`
`<home.fnal.gov/~stancari>`

Thank you for your attention!

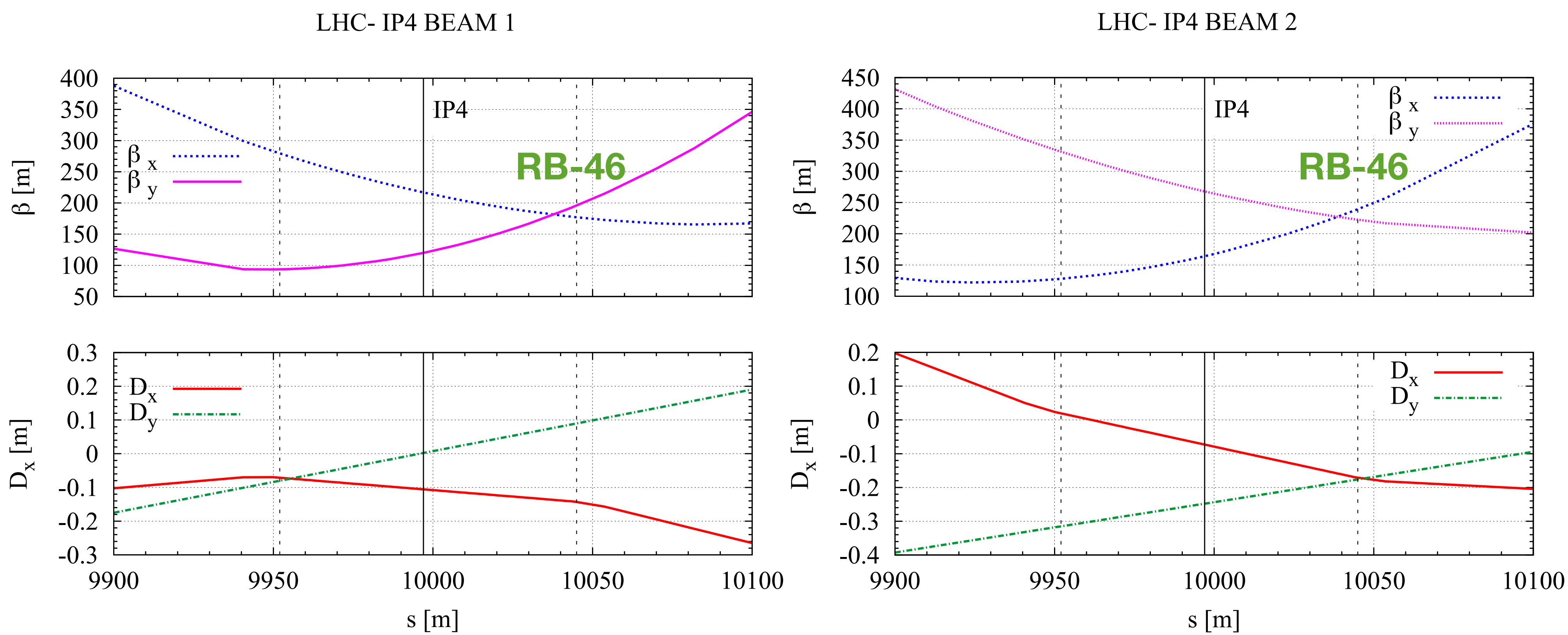
Backup slides

Relative scraping of 1 pbar bunch train vs. electron hole radius



Beam optics at candidate locations (LHC v6.503)

Round beams, β ~ 200 m, low dispersion



Numerical simulations: tools

Warp particle-in-cell code for electron beam dynamics with space charge

- charge, fields, proton kicks

Moens, CERN-THESIS-2013-126
Stancari, NA-PAC13
➡IPAC14 poster MOPME033

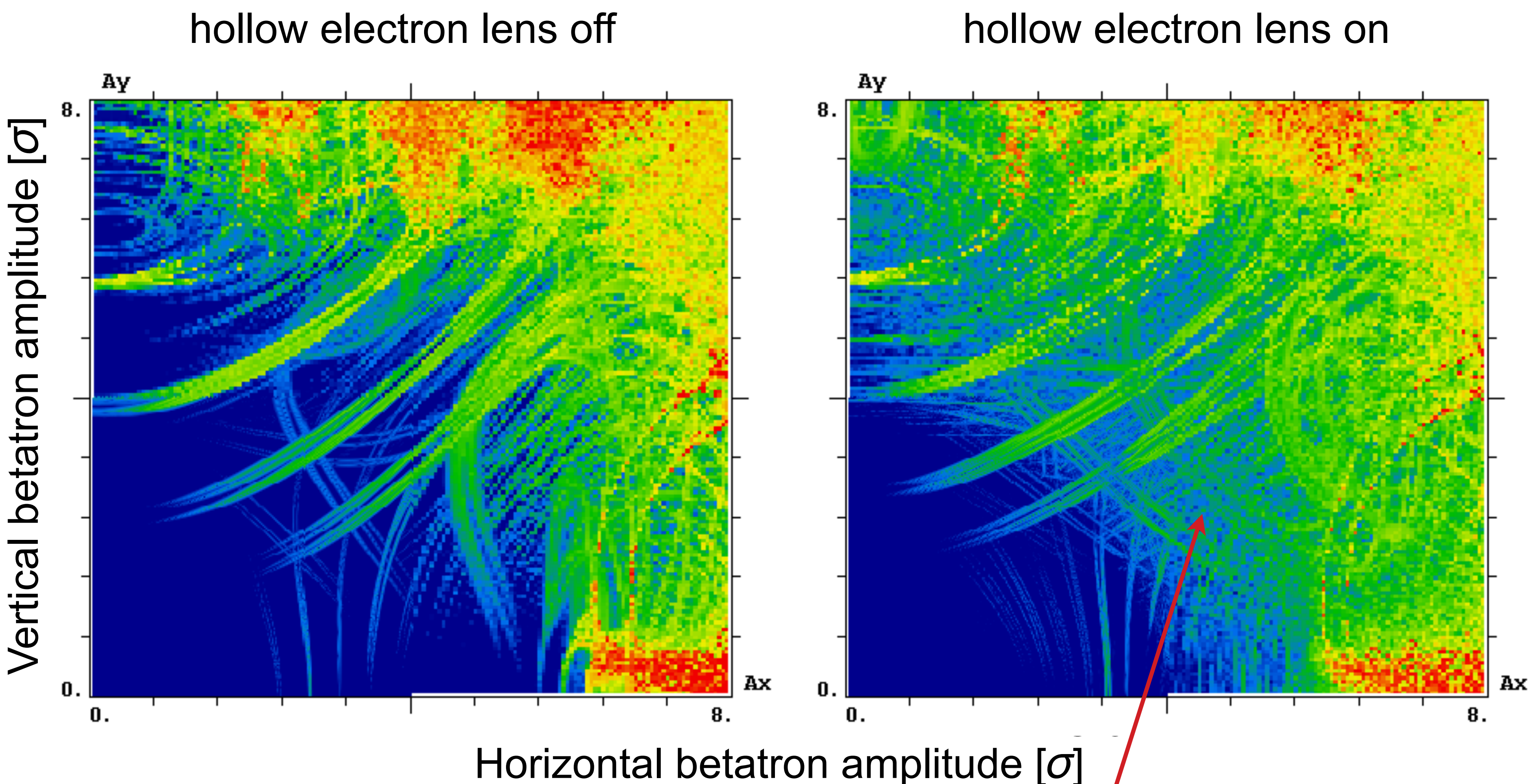
Lifetrac and SixTrack for numerical tracking

- LHC lattice V6.503 with errors, with or without collisions
- electron lens at RB-46 (near IP4), 3.6 A max. current
- single aperture restriction at 6σ
- Uniform halo population 4-6σ
  - no replenishing mechanisms, but halo diffusion was measured in both Tevatron and LHC

  Stancari et al., FERMILAB-CONF-13-054-APC, arXiv:1312.5007
  Valentino et al., Phys. Rev. ST Accel. Beams **16**, 021003 (2013)
- Ideal electron lens and imperfections
  - profile asymmetries
  - simplified model of injection/extraction bends

Previtali et al., FERMILAB-TM-2560-APC (2013)
Valishev, FERMILAB-TM-2584-APC (2014)

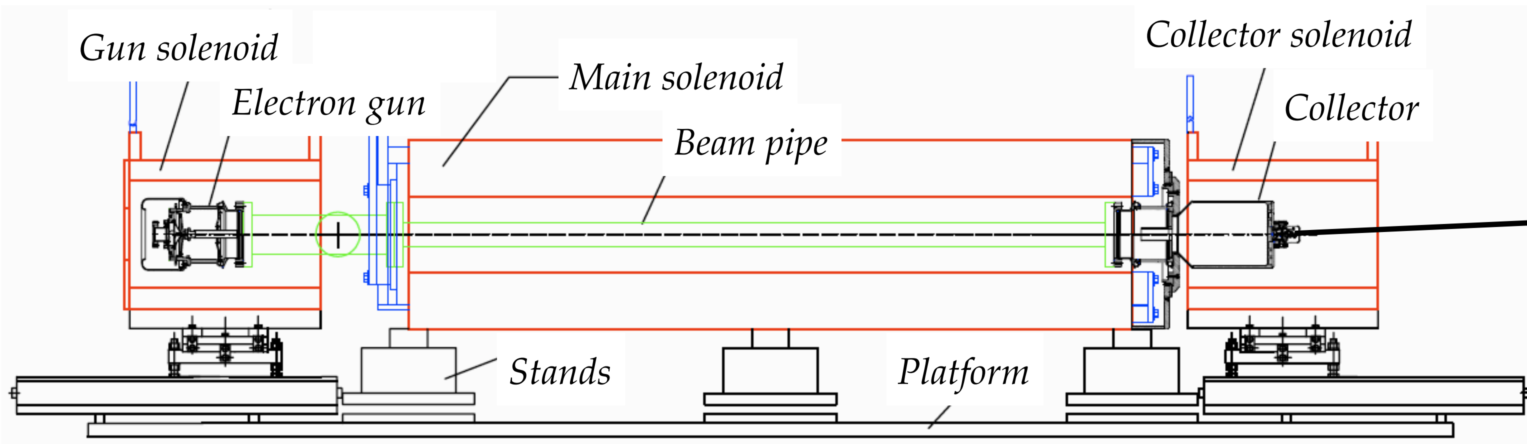
Lifetrac calculation of frequency maps vs. amplitude



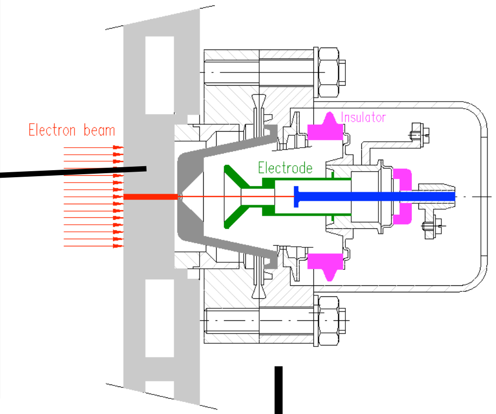
Frequency map shows new resonances and tune jitter for particles in the halo

Azimuthal asymmetries in overlap region from measured profiles

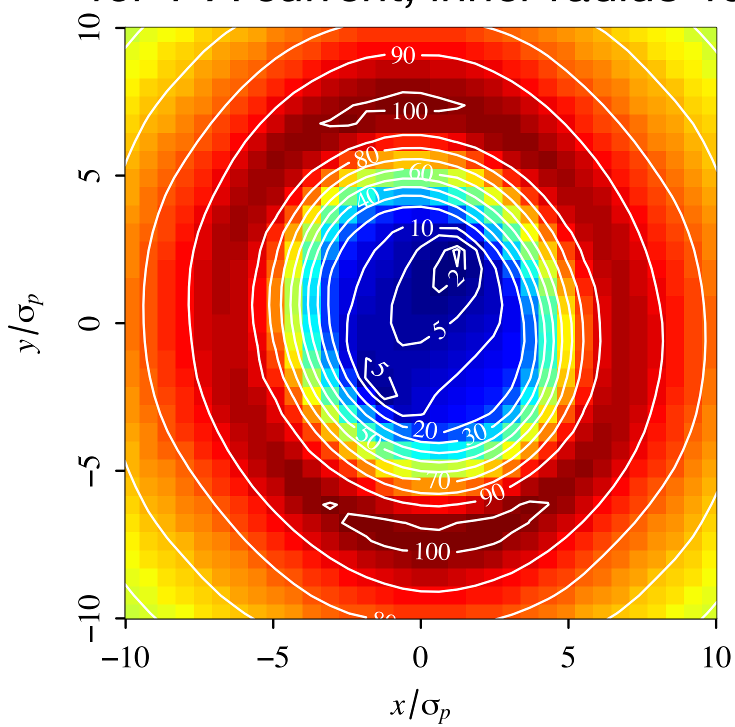
Fermilab electron-lens test stand



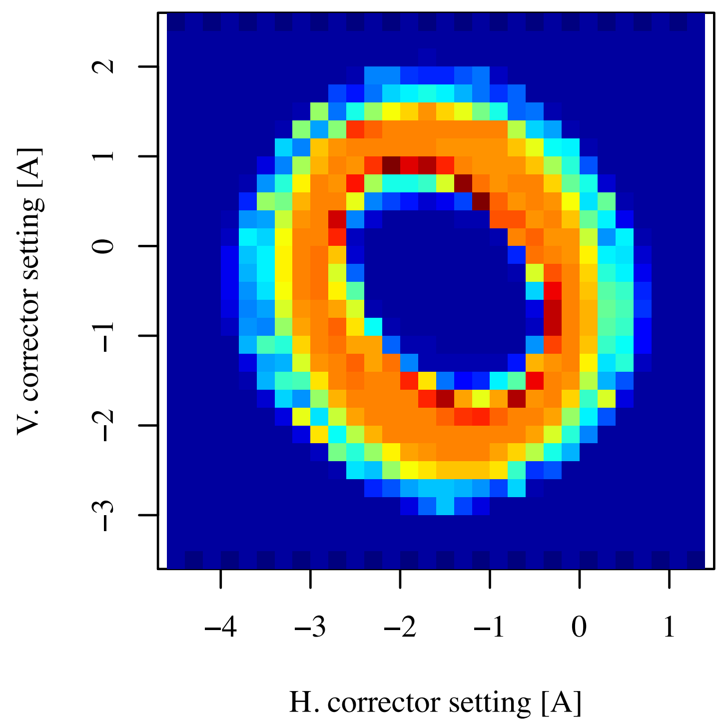
Pinhole for current-density measurements



Calculated electric field [kV/m] for 1-A current, inner radius $4\sigma_p$



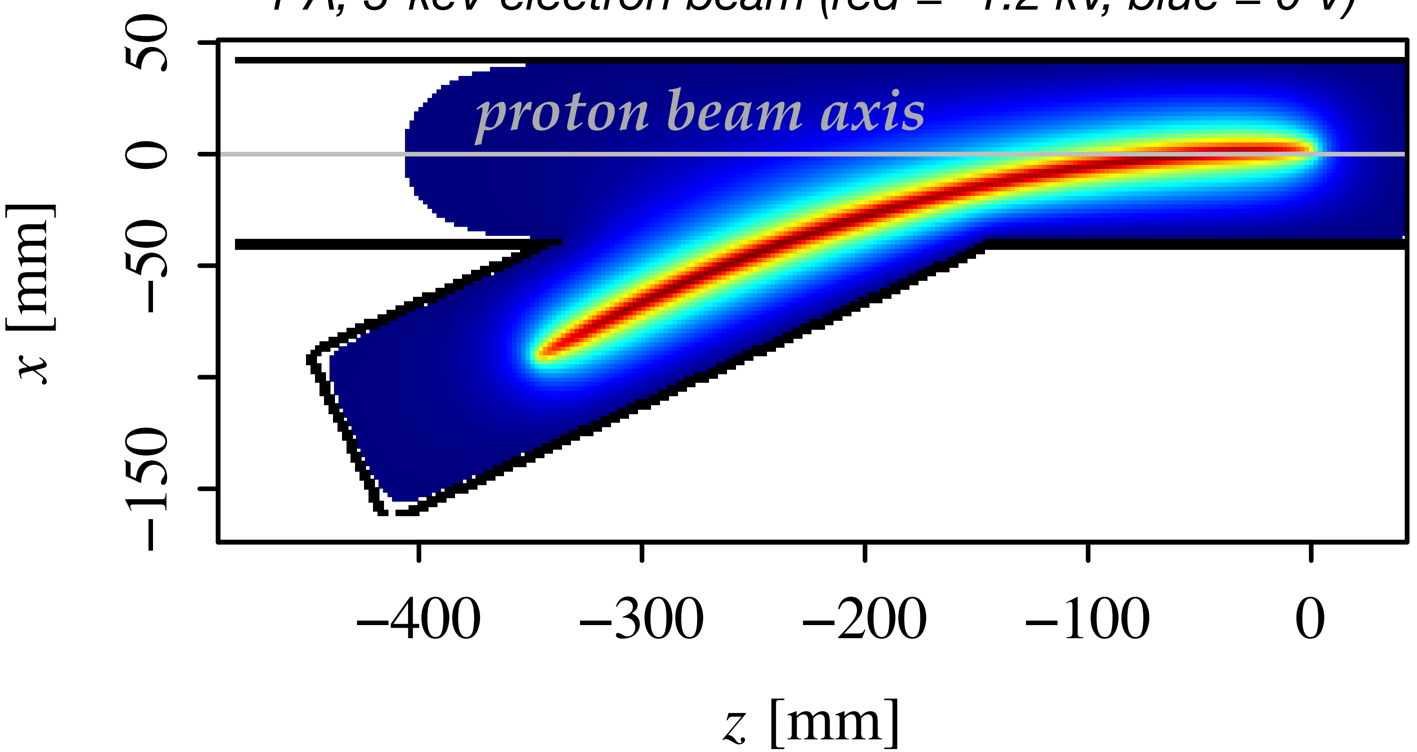
Example of measured profile



Kick maps from injection and extraction bends: simplified approach

3D calculation of electric fields generated by a static, hollow charge distribution inside cylindrical beam pipes using Warp particle-in-cell code

Electrostatic potential on the plane of the bend for 1 A, 5-keV electron beam (red = -1.2 kV, blue = 0 V)



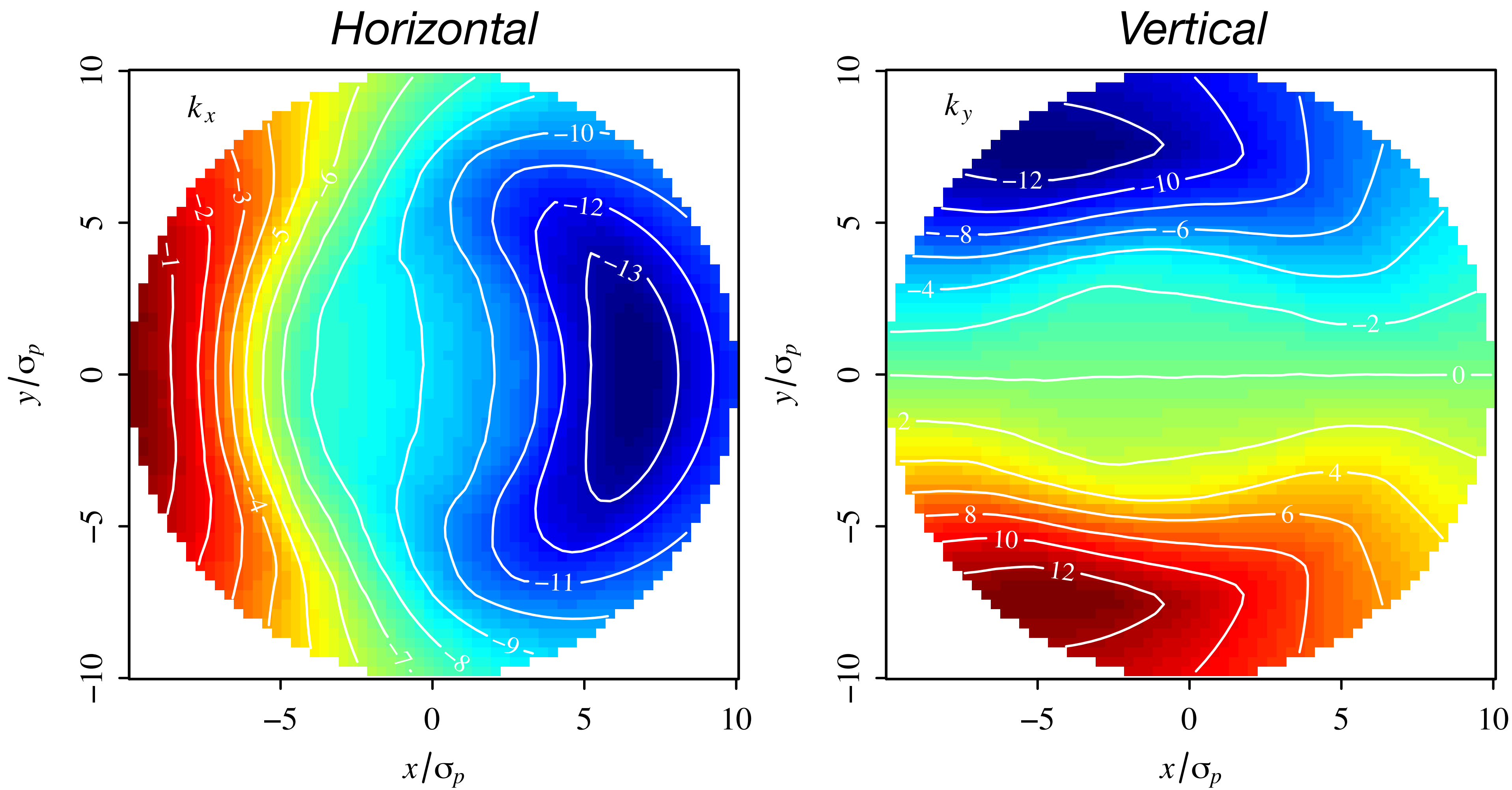
Symplectic kick maps are calculated by integrating electric fields over straight proton trajectories

$$k_{x,y} \equiv \int_{z_1}^{z_2} E_{x,y}(x,y,z)\,dz$$

Stancari, FERMILAB-FN-0972-APC, arXiv:1403.6370 (2014)

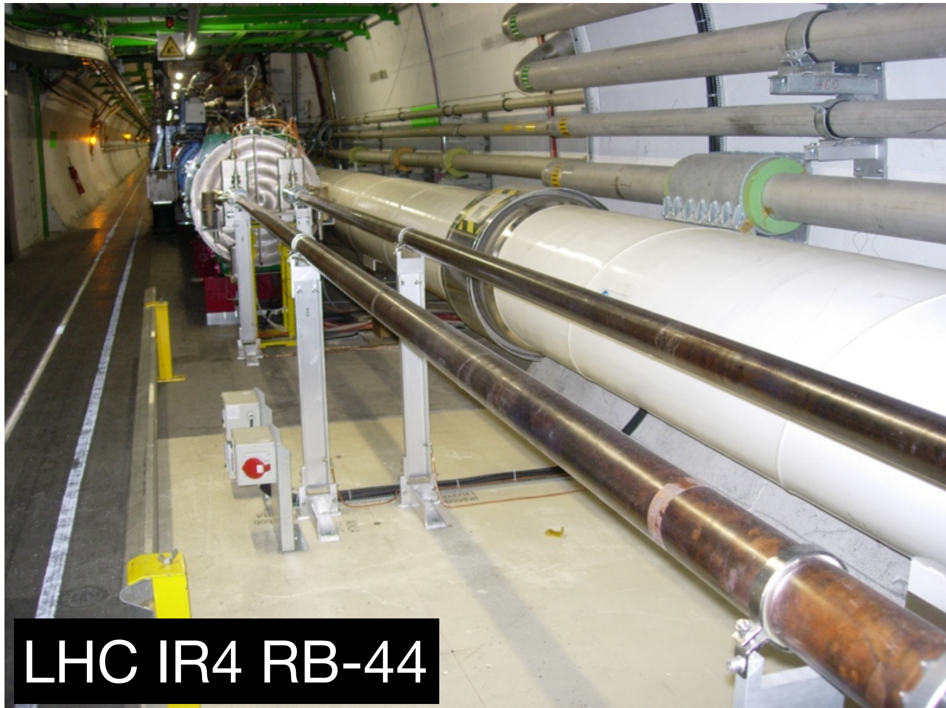
Kick maps from injection and extraction bends

Integrated fields ('kicks') [kV] vs. transverse proton position



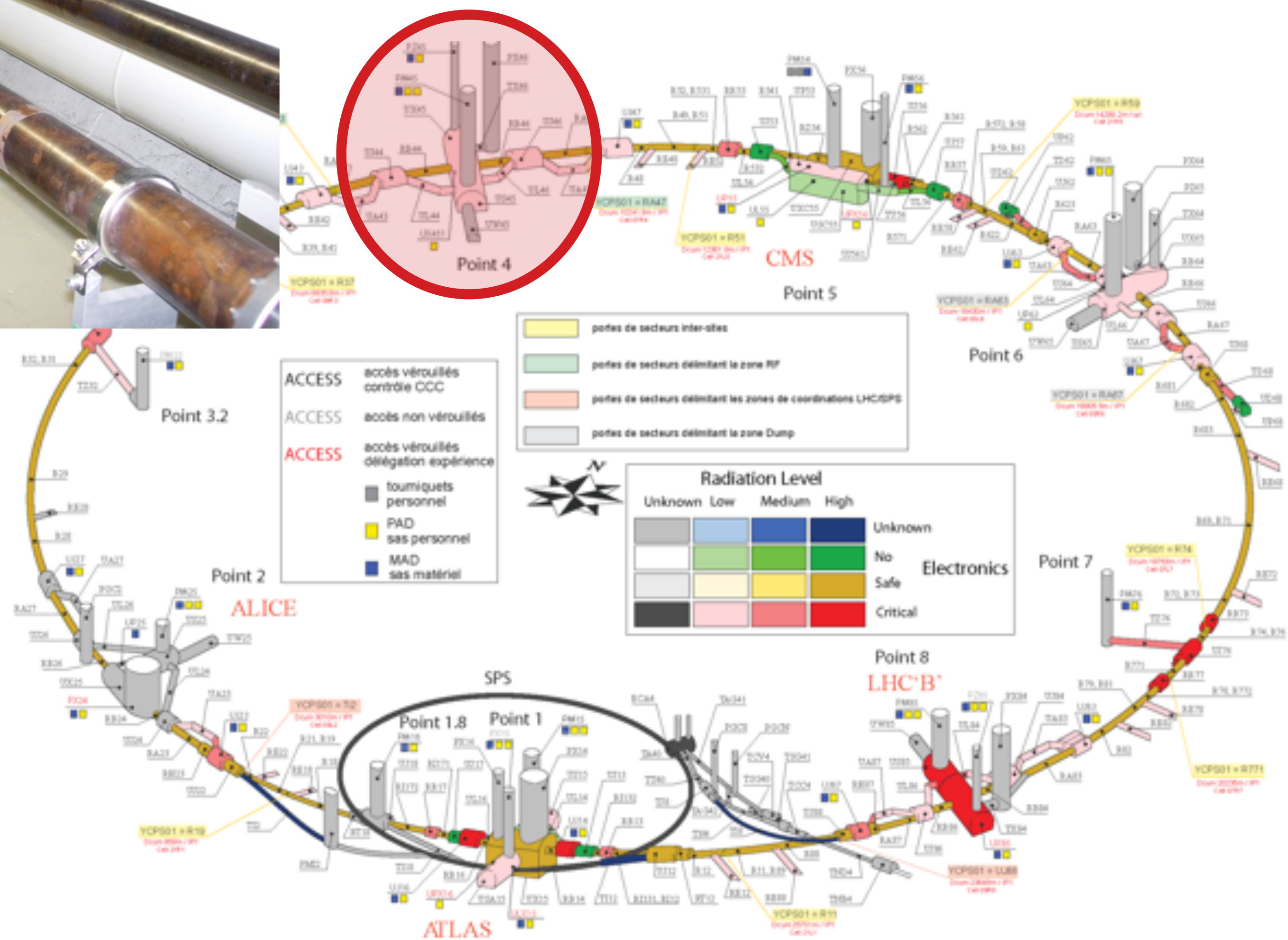
For 7-TeV protons, 10 kV ⇒ 1.4 nrad

Candidate locations for electron lenses in the LHC

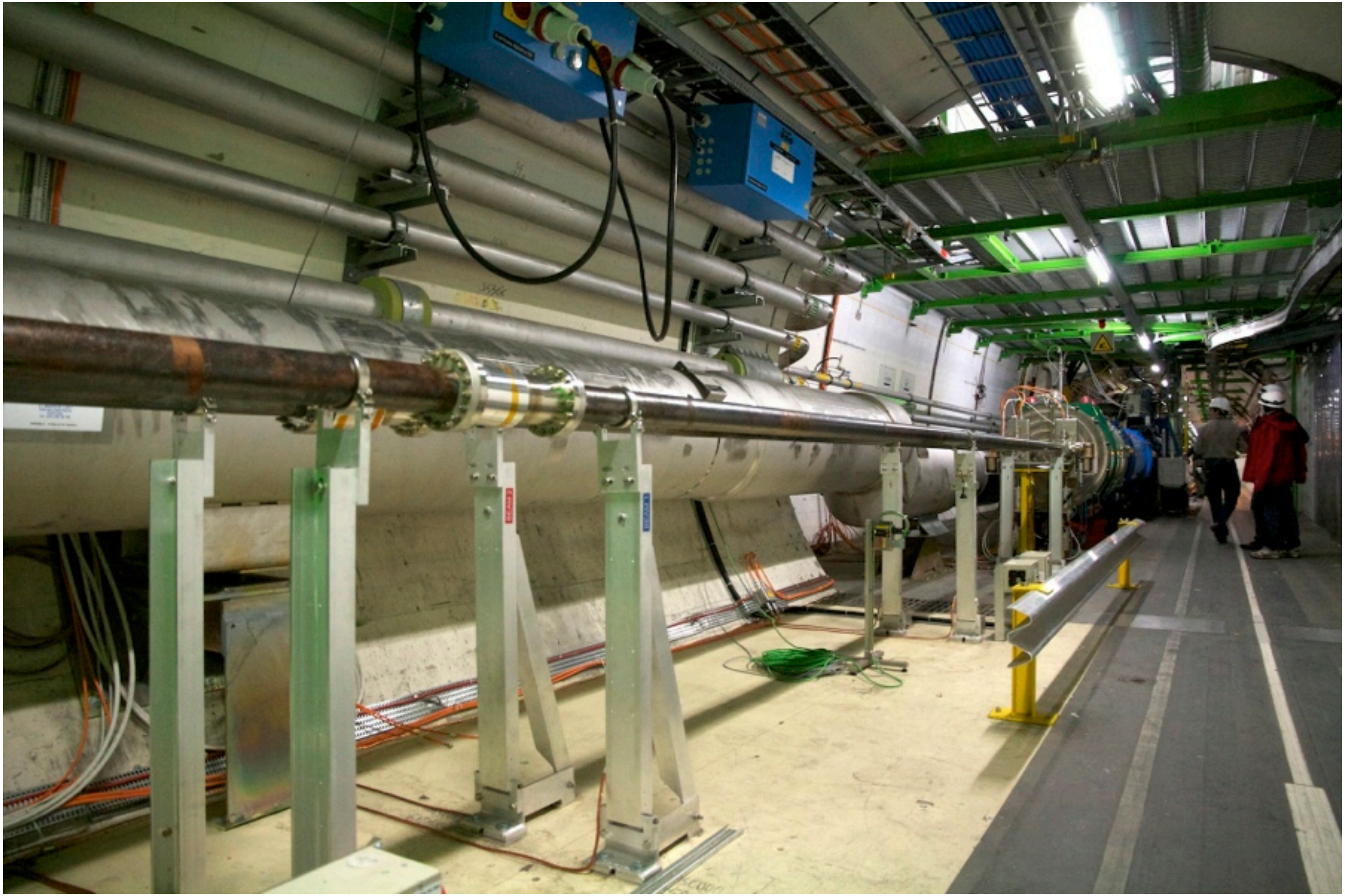


Upstream or downstream of Point 4:

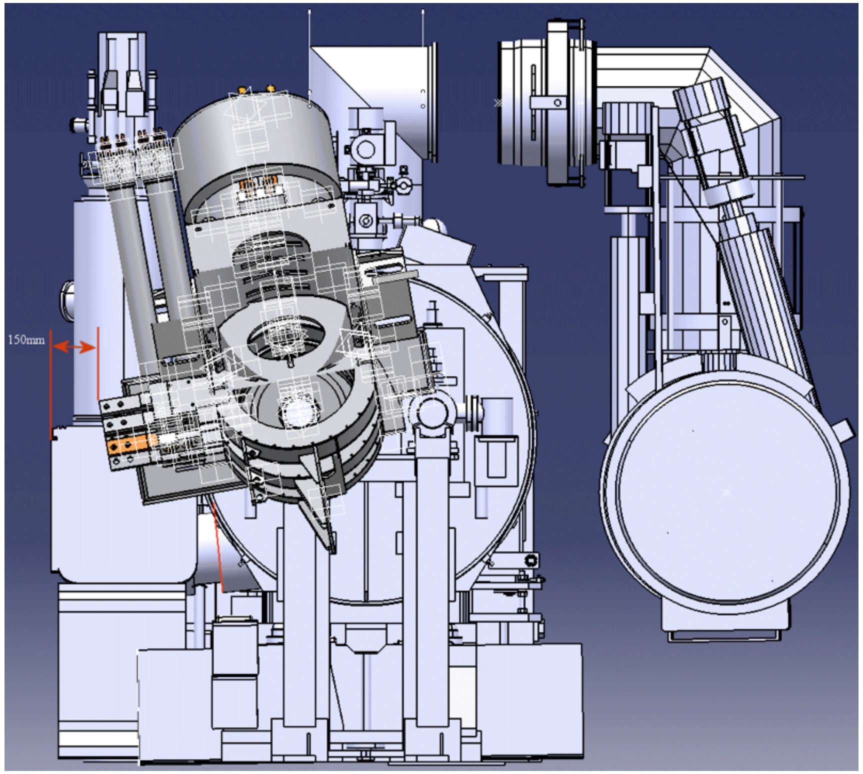
- Available longitudinal space
- Separation of beam axes: 420 mm
- Cryogenic infrastructure
- Lattice functions

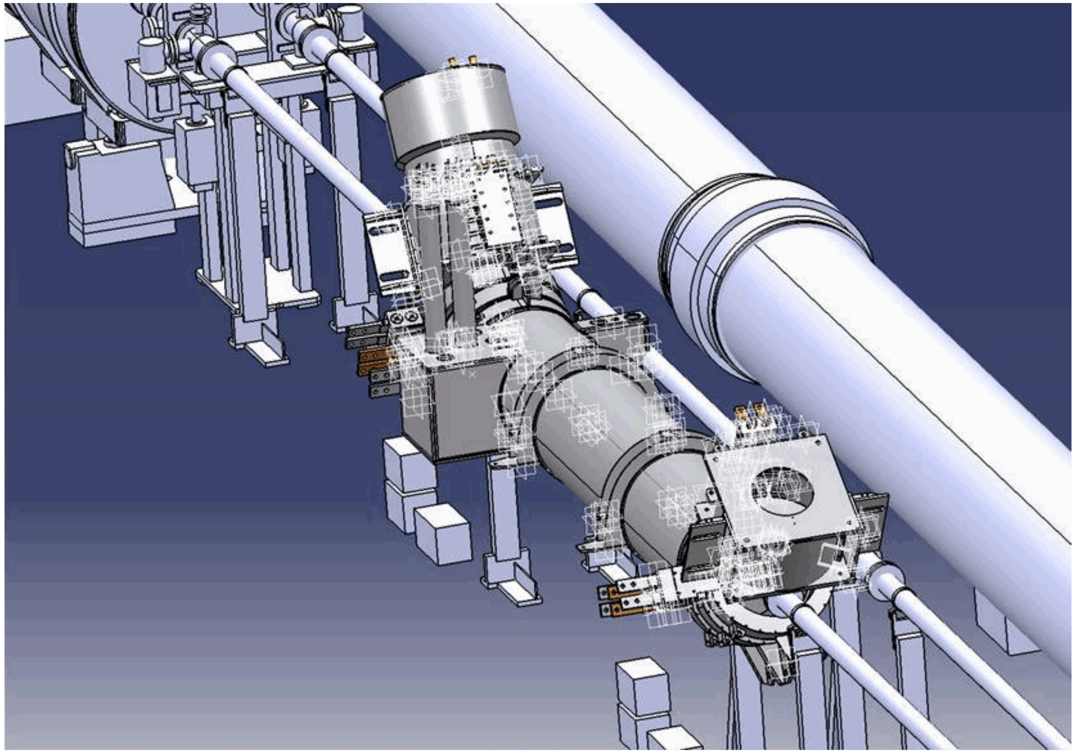


Candidate location RB-46



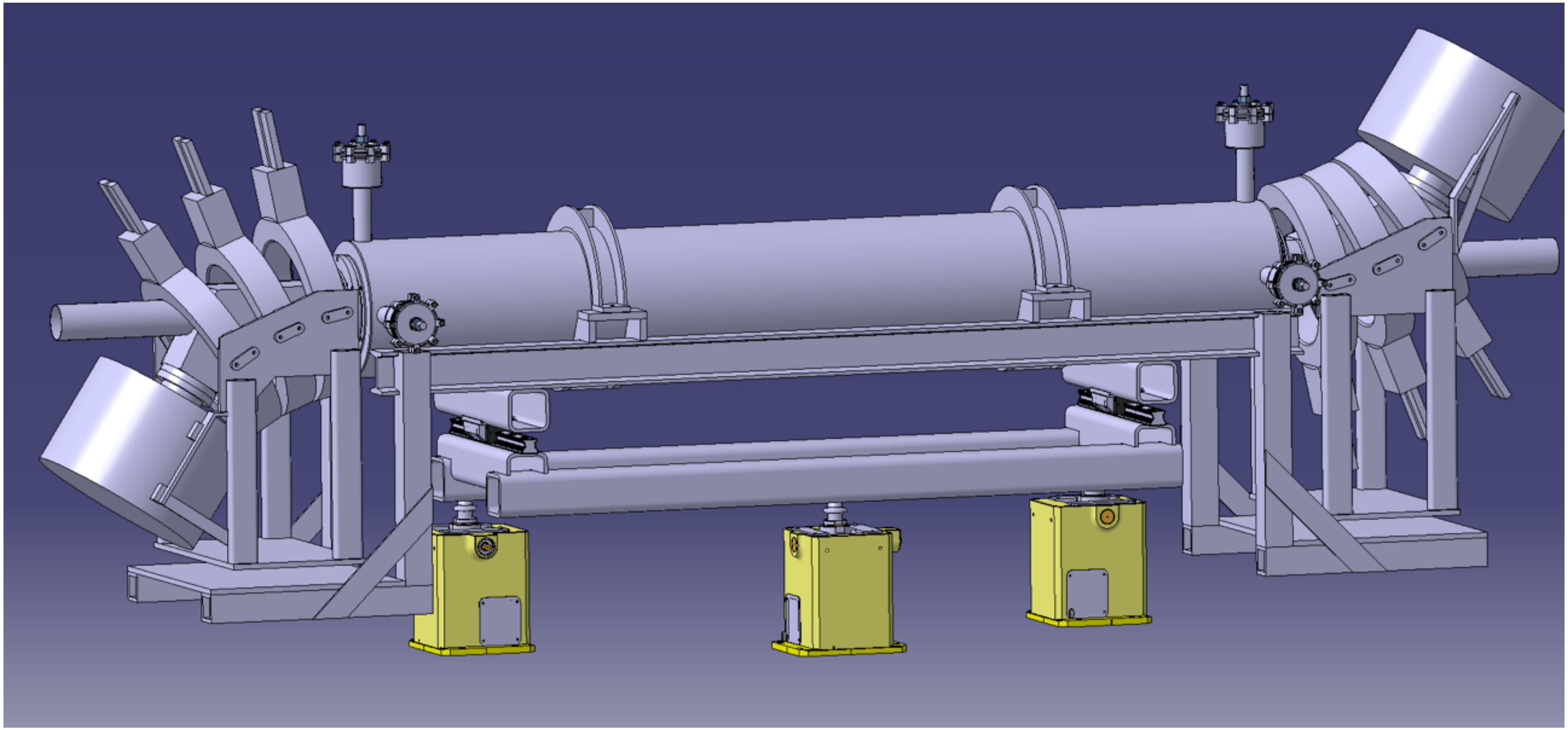
Integration studies





- Preliminary studies on cryogenics, electronics, vacuum, diagnostics, impedance
- Cryogenics will be main effort
- No major obstacles so far

Integration studies



Cryogenics

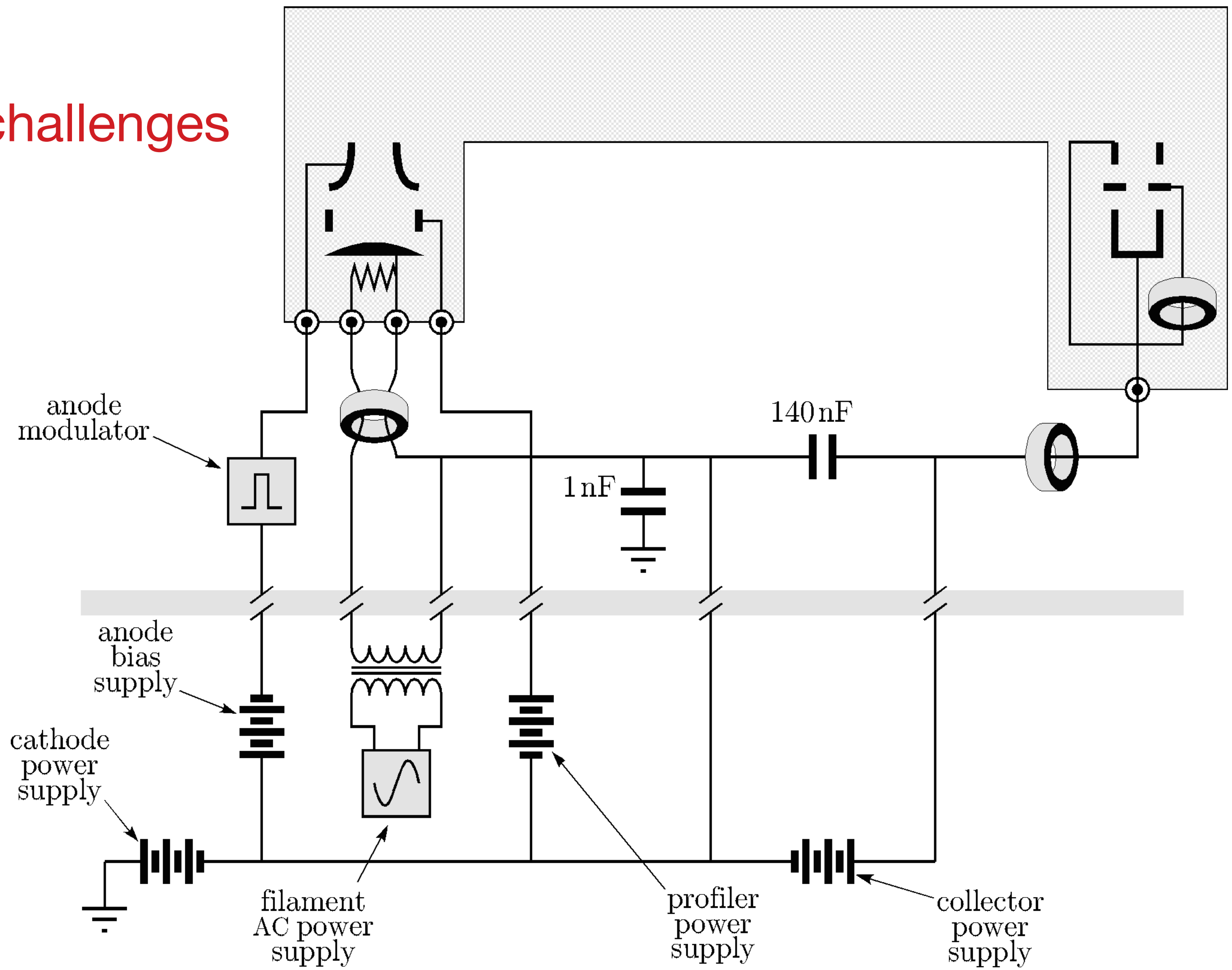
- cryogenics dominates installation time: at least 3 months required for warm-up, connections, cool-down
- electron lenses may be treated as stand-alone magnets at 4.5 K
- may take advantage of dedicated rf refrigerator for HL-LHC at IR4
- TEL2 static heat loads: 12 W for He at 4 K and 25 W for liquid N_2 shield
- Tevatron magnet string liquid He flux was 90 l/s
- N_2 not available in LHC; use gaseous He at 20 bar?
- integration of quench protection system
- See A. Rossi's talk at e-lens review: indico.cern.ch/event/213752

Likely main integration effort

Electrical systems

- gun and collector solenoid power supplies: 340 A @ 0.4 T
- main solenoid power supply: 1780 A @ 6.5 T
- high voltage supplies for cathode, profiler, anode bias, collector: 10 kV
- stacked-transformer modulator, anode pulsing: 10 kV, 35 kHz, 200 ns rise time

No major challenges



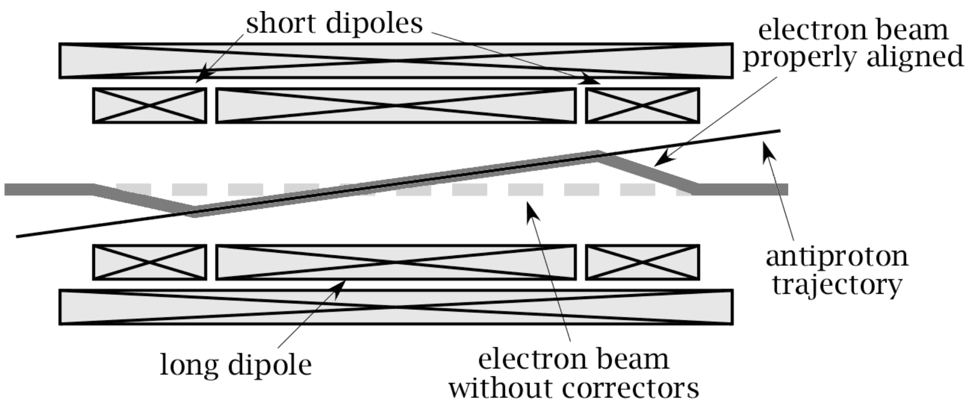
Vacuum

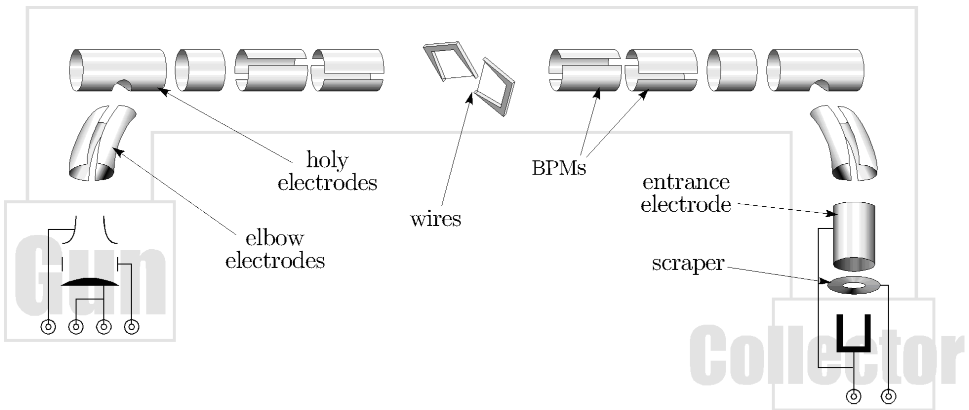
- 10^{-9} mbar typical in TEL2 with 3 ion pumps + Ti sublim.
- Baking of inner surfaces
- LHC requires vacuum isolation modules on each side (0.8 m each): gate valves, NEG cartridges, pumps, gauges
- Surface certification
- E-cloud stability (enhanced with solenoids on)
- See also A. Rossi's talk at e-lens review: indico.cern.ch/event/213752

Design needs to be reviewed according to LHC specifications

Diagnostics and instrumentation

- corrector magnets for position and angle in main solenoid
- accurate BPMs for both slow electron signals and fast proton signals
- pickup and ion-clearing electrodes
- sensitive (gated) loss monitors (scintillators, diamonds, ...) at nearest aperture
    - verify e^{-}/p alignment
    - measure lifetimes, loss fluctuations, halo diffusivities vs. e-lens settings
- electron beam diagnostics, following BNL designs
    - overlap with protons: backscattered electrons; also as sensitive halo monitor?
    - profiles with fluorescent screens (low current) and pinhole (high current)





Impedance

- Very different bunch structure in Tevatron and LHC
- Tight broad-band longitudinal impedance budget (90 mOhm)
- Preliminary studies suggest that
  - modifications of Tevatron vacuum chamber and electrodes may be required for longitudinal fields, such as rf shields to suppress trapped modes
  - transverse impedance is acceptable

More studies necessary, but no major obstacles so far

Resources and schedule

- Construction cost of 2 devices for the LHC (1 per beam) is about 5 M$ in materials and 6 M$ in labor
- Construction in 2015-2017 and installation in 2018 is technically feasible
- Reuse of some Tevatron equipment is possible (superconducting coil, resistive solenoids, electron guns, ...)
- Contributions to design, construction, commissioning, numerical simulations, beam studies, project management to be specified in CERN / US LARP agreement