Fermilab
Fermi National Accelerator Laboratory
Office of Science / U.S. Department of Energy
Managed by Fermi Research Alliance, LLC

LARP

Collimation with Hollow Electron Beams

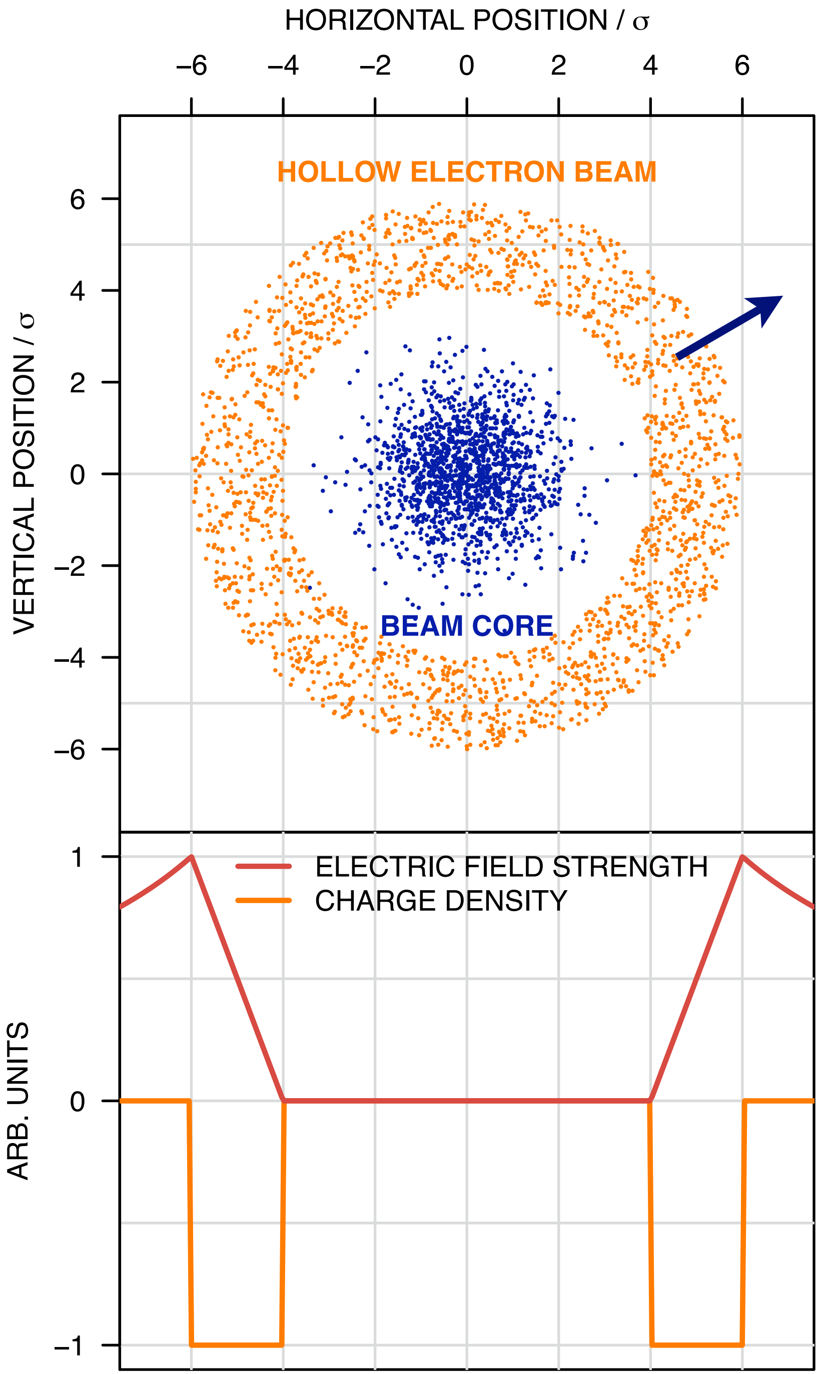
Giulio Stancari
Fermi National Accelerator Laboratory

in collaboration with
A. Valishev, J. Annala, A. Didenko, T. Johnson, I. Morozov, V. Previtali,
G. Saewert, V. Shiltsev, D. Still, L. Vorobiev

Thanks to LHC collimation experts.
In particular: R. Assmann, R. Bruce, S. Redaelli, A. Rossi

1st Joint HiLumi LHC / LARP Collaboration Meeting
CERN, 16-18 November 2011

Concept of hollow electron beam collimator (HEBC)



Halo experiences nonlinear transverse kicks:

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

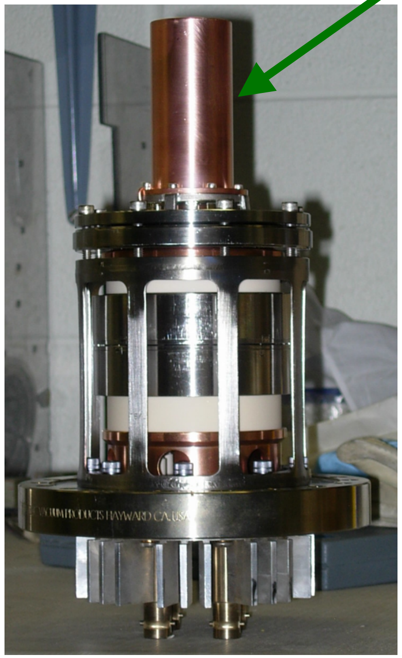
About **0.2 μrad** in TEL2 at 980 GeV

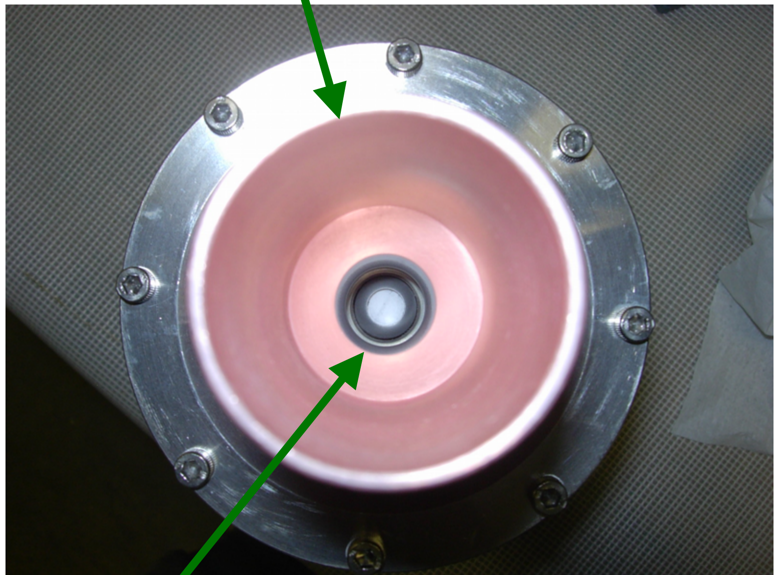
For comparison: multiple scattering in Tevatron collimators $\theta_{\rm rms} = 17\ \mu{\rm rad}$

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

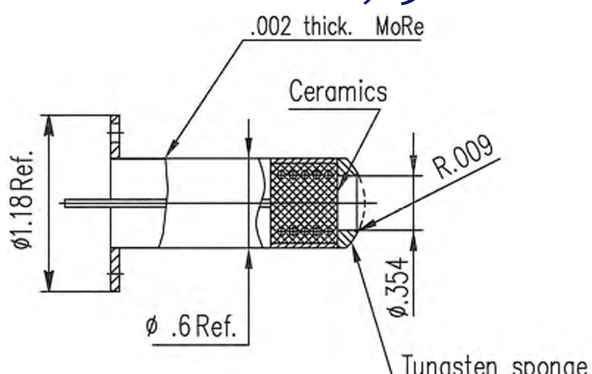
The 15-mm hollow electron gun

side view Copper anode *top view*



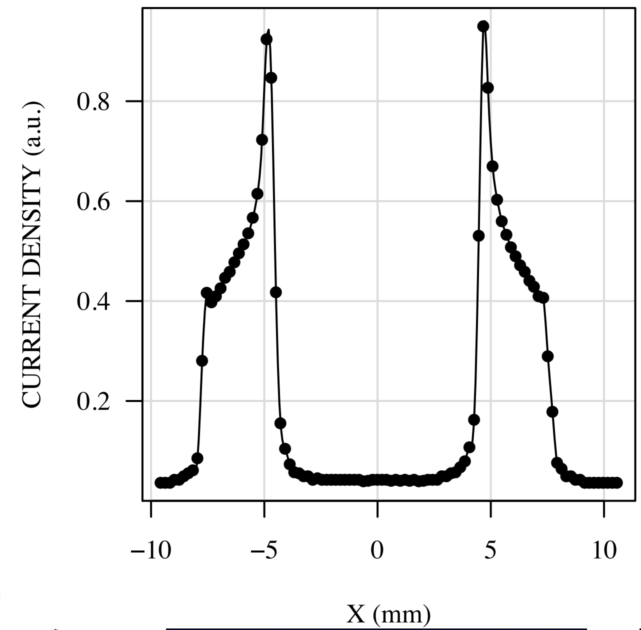


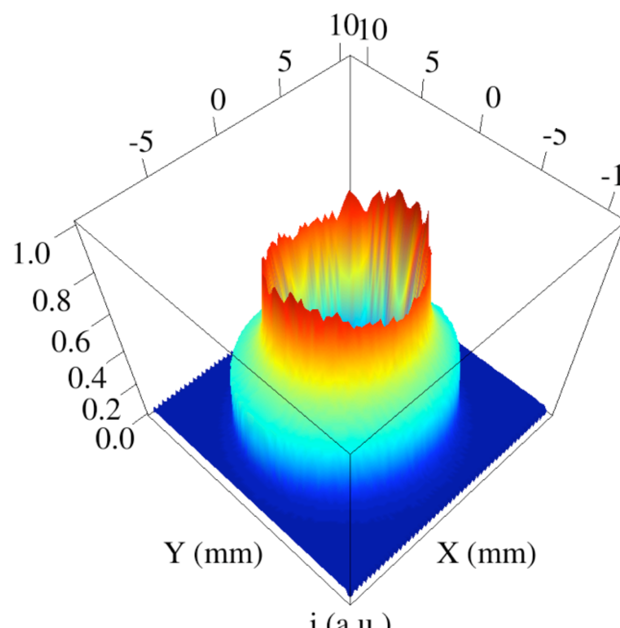
Tungsten dispenser cathode
with convex surface
15-mm diameter, 9-mm hole

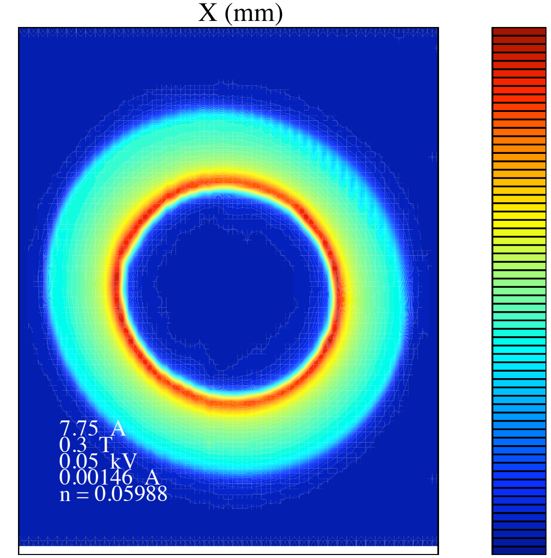


Yield: **1.1 A** at 4.8 kV

Profile measurements

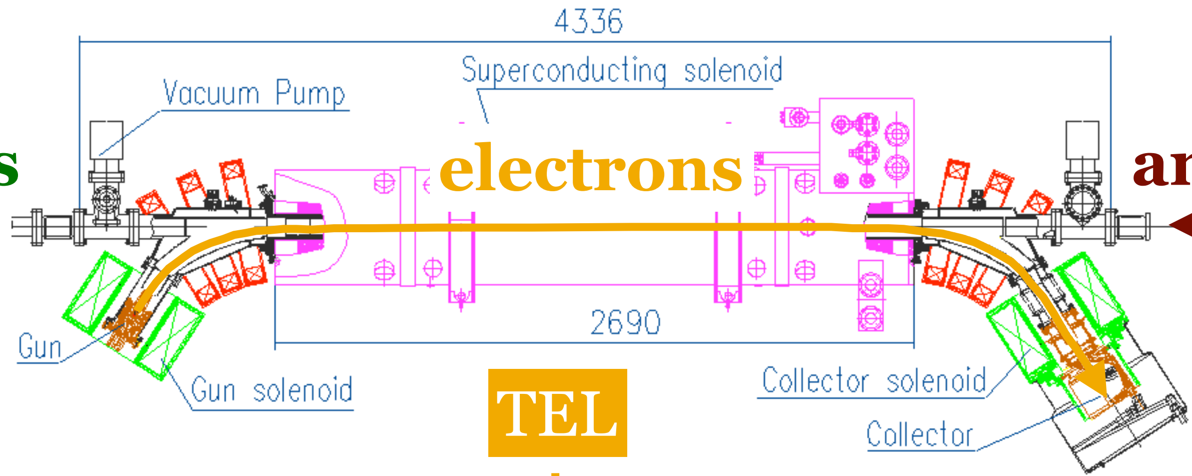






Layout of the beams in the Tevatron

protons



antiprotons

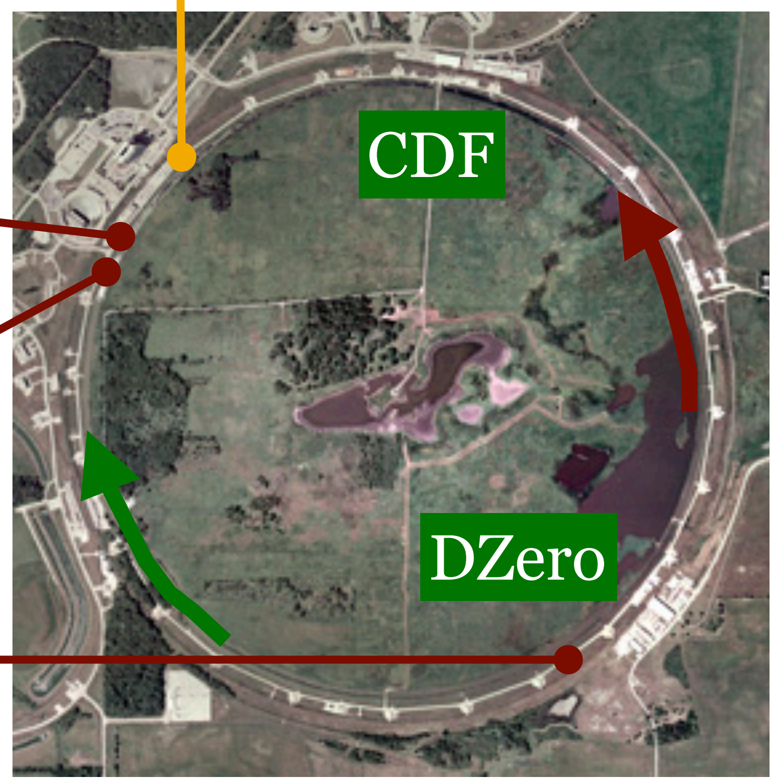
TEL

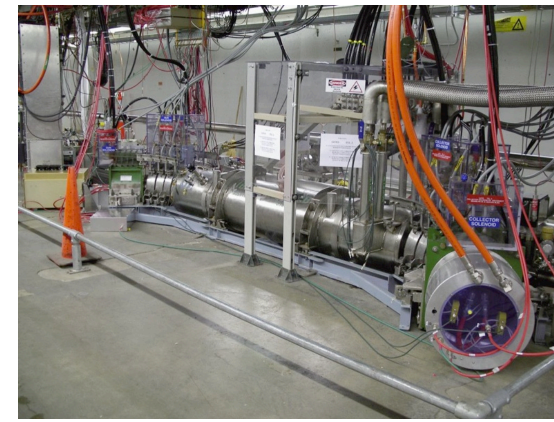
Antiproton collimators:

Primary (F49)

Secondary (F48)

Secondary (D17)

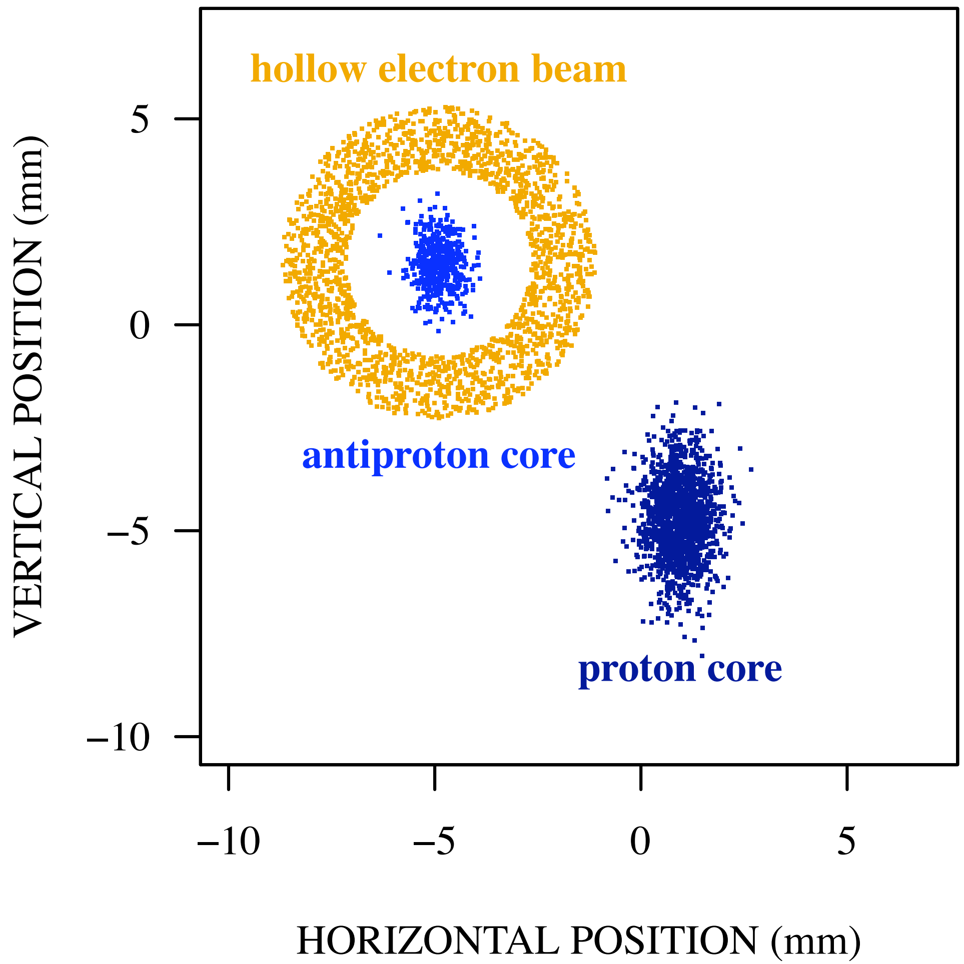


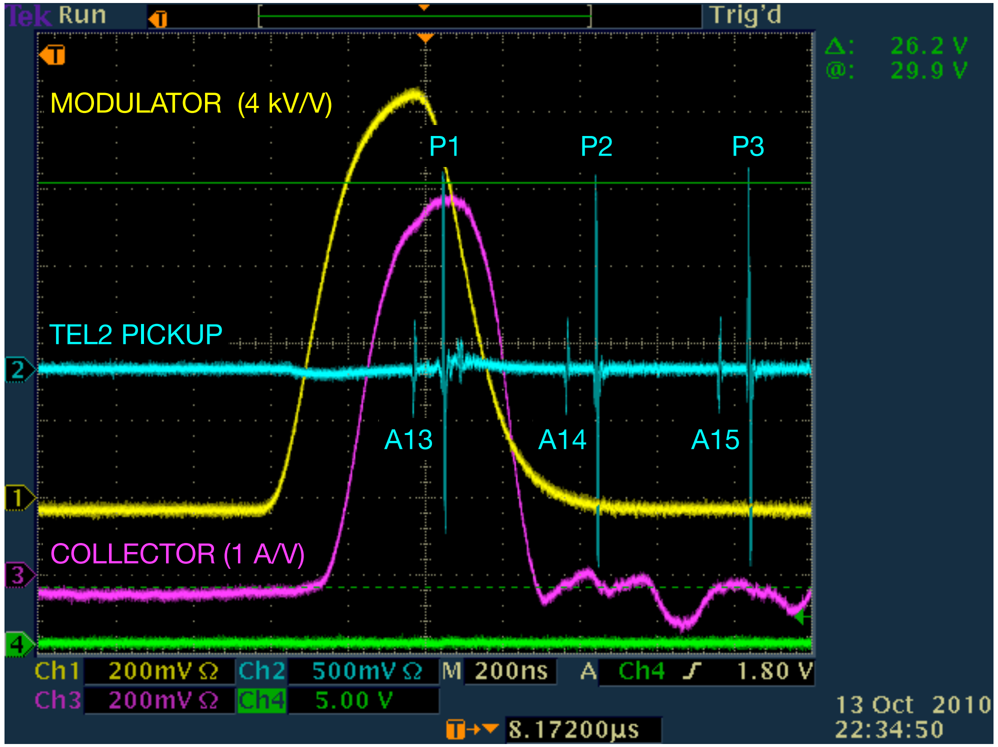


Tevatron electron lens

Layout of the beams in the Tevatron electron lens

Transverse separation is 9 mm





Pulsed electron beam can be synchronized with any group of bunches

Brief project history up to LARP CM 16 (May 2011)

- **Summer '09**: Hollow gun design
- **August '09**: Hollow gun manufactured and delivered
- **Fall/winter '09**: Hollow beam dynamics studies in test stand
- **August '10**: Hollow gun installed in Tevatron electron lens (TEL2)
- **October '10**: First Tevatron experiments
- **January '11**: A. Didenko (contractor engineer) joins to work on new electron gun design and assembly
- **February '11**: I. Morozov (student / guest scientist) joins for 1 year to work on numerical calculations
- **March '11**: gated loss monitors installed in Tevatron

Progress since LARP CM 16 (May 2011)

- **June ’11**: Recommendations from U.S. DOE LARP and LHC Collimation reviews
- **July ’11**: first results accepted for publication in Physical Review Letters
- **August ’11**: V. Previtali (Toohig fellow) joins Fermilab group to lead effort on applicability at CERN
- **September ’11:** Tevatron studies completed
- **October ’11**: Assembly and installation of new 25-mm gun in test stand
- **November ’11**: initiated preliminary integration studies of TEL2 at CERN
- Ongoing simulations and Tevatron data analysis

June 2011 Reviews

U.S. DOE LARP Review Committee*: [...] We support the fabrication of a <u>new hollow electron gun</u> with a 1-inch cathode that will be capable of delivering up to 3 A of beam at 5 kV. This follows a successful proof-of-principle demonstration at the Tevatron. [...] The committee is encouraged by the results of the hollow electron beam lens used as a scraper. We encourage LARP to proceed with discussions of how to <u>transfer the hardware</u> to CERN to continue the effort. [...]*

LHC Collimation Review Committee*: [...] Another option under discussion in the past involves the concept of a hollow electron beam collimator (Fermilab). Since no material must be placed close to the beam, there exists no damage risk with this scheme. Beyond a certain betatron amplitude the hollow e-beam would generate high diffusion rates for the protons. It can be expected that this mechanism also smoothens out spiky loss rates in time. With high intensity and primary collimators placed close to the beam, such non-uniformly distributed loss rates can be an operational problem. [...]*

Tevatron beam studies

- October 2010 - September 2011
- 19 experiments: both parasitic and dedicated
- 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)
  - transverse beam **diffusion enhancement**
  - **suppression of loss-rate fluctuations** (beam jitter, tune changes)
  - effects on **collimation efficiency**

First Tevatron results appeared in PRL:

PRL **107,** 084802 (2011) PHYSICAL REVIEW LETTERS week ending 19 AUGUST 2011

Collimation with Hollow Electron Beams

G. Stancari,* A. Valishev, G. Annala, G. Kuznetsov,† V. Shiltsev, D. A. Still, and L. G. Vorobiev

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA

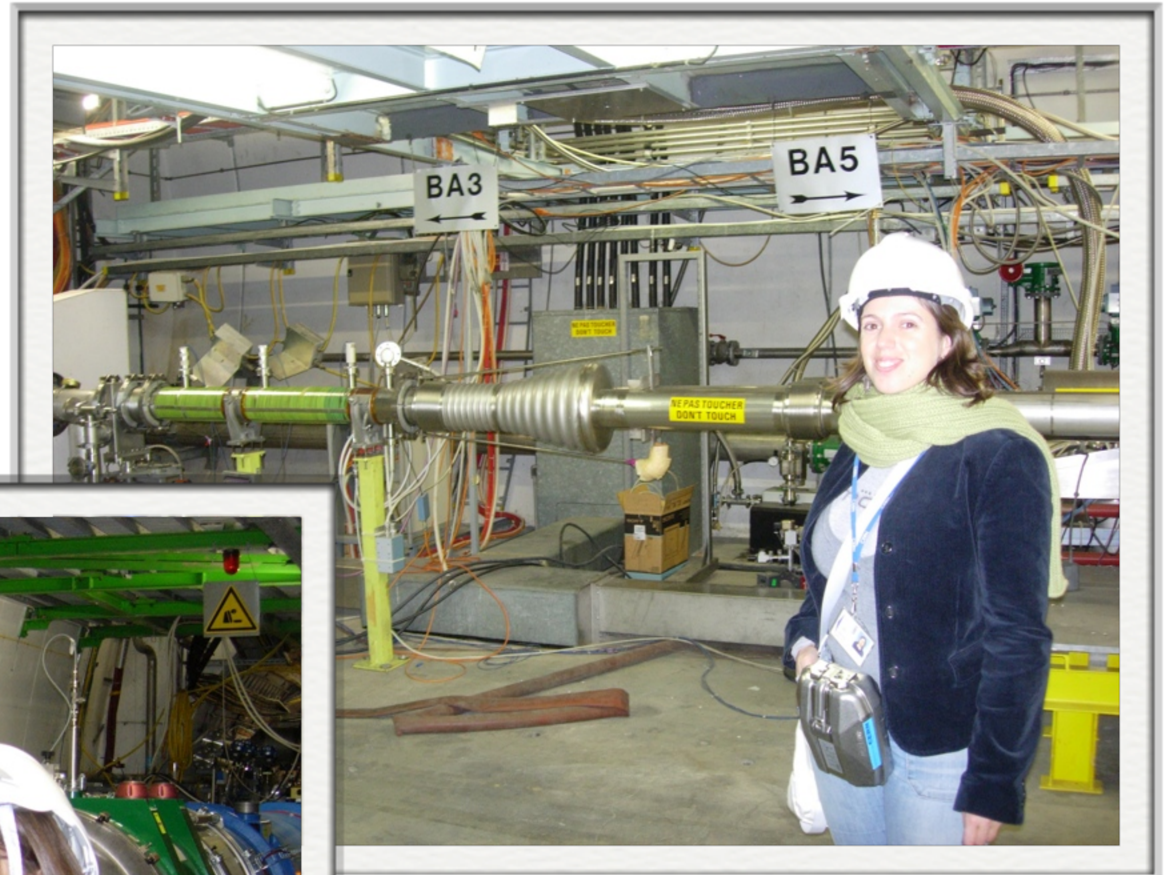
(Received 16 May 2011; published 17 August 2011)

A novel concept of controlled halo removal for intense high-energy beams in storage rings and colliders is presented. It is based on the interaction of the circulating beam with a 5-keV, magnetically confined, pulsed hollow electron beam in a 2-m-long section of the ring. The electrons enclose the circulating beam, kicking halo particles transversely and leaving the beam core unperturbed. By acting as a tunable diffusion enhancer and not as a hard aperture limitation, the hollow electron beam collimator extends conventional collimation systems beyond the intensity limits imposed by tolerable losses. The concept was tested experimentally at the Fermilab Tevatron proton-antiproton collider. The first results on the collimation of 980-GeV antiprotons are presented.

DOI: 10.1103/PhysRevLett.107.084802 PACS numbers: 29.27.−a, 41.85.Si

Detailed PRSTAB paper in preparation

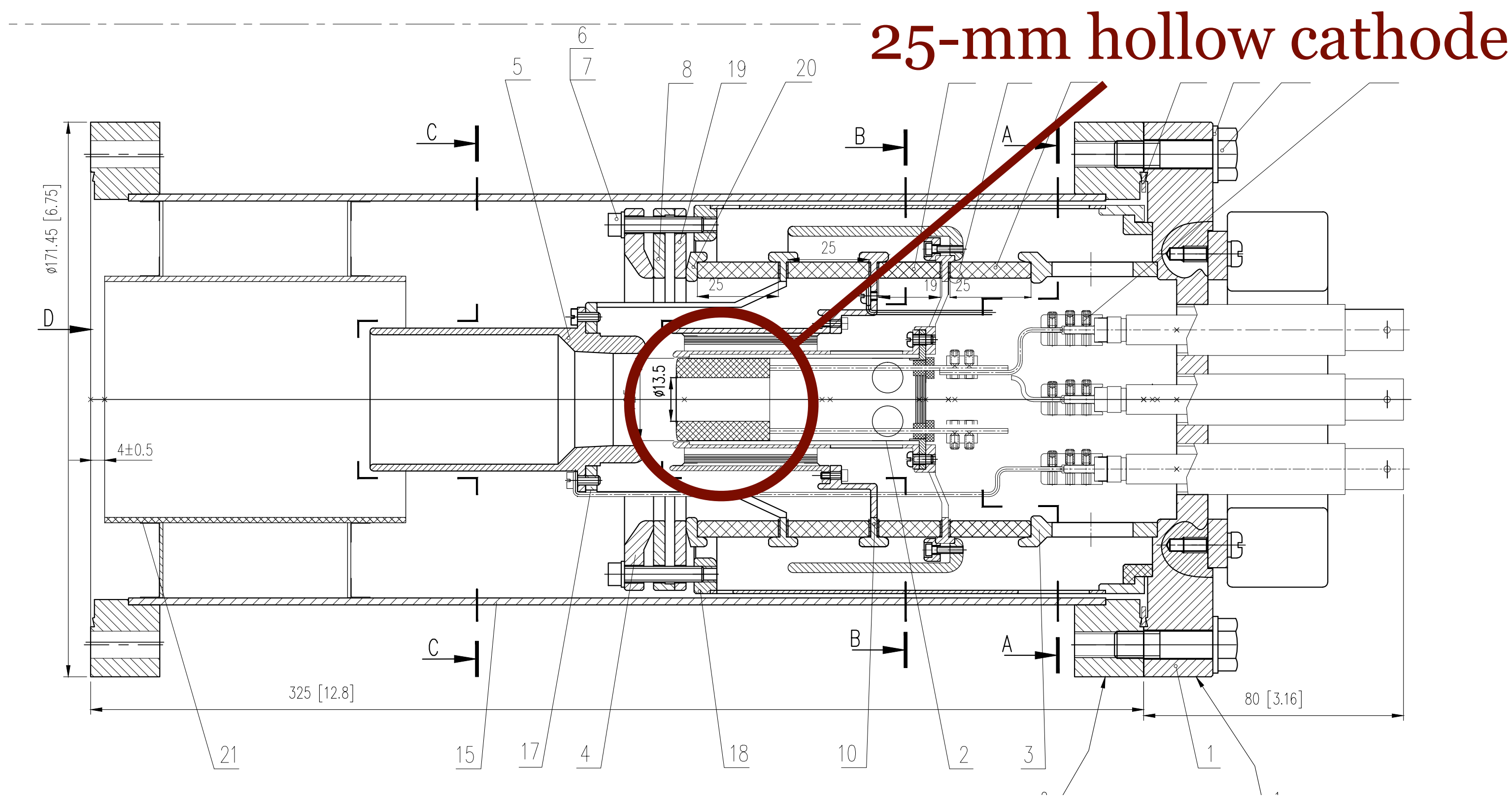
In August, Valentina Previtali joined the Fermilab group as Toohig fellow



She will lead the study on applicability of hollow electron lenses at CERN

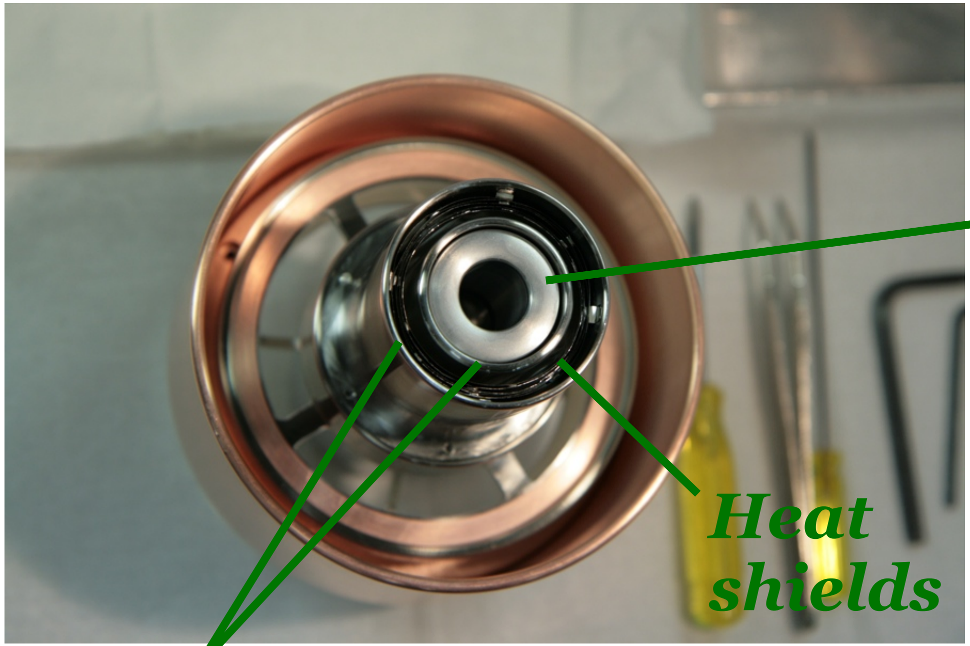
New 25-mm hollow gun

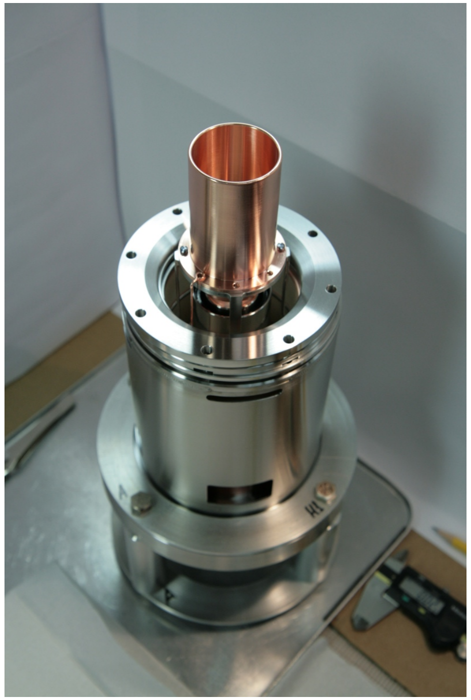
- 25 mm outer diameter, 13.5 mm inner diameter
- Designed to deliver 3 A at 5 kV (8 A at 10 kV)



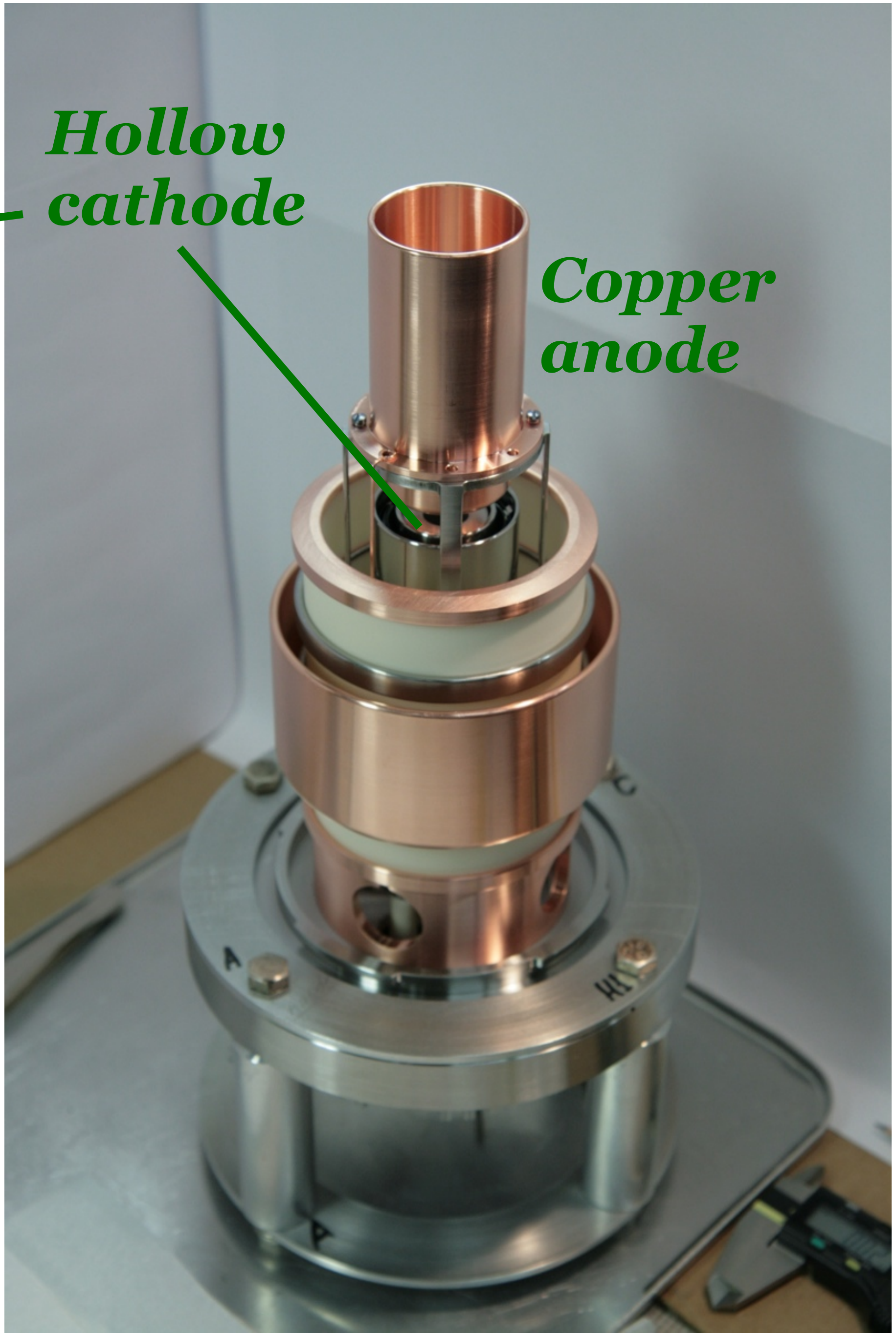
- Goal: To test technical feasibility of stronger scraper
- Installed in Fermilab electron-lens test stand
- Characterization under way

New 25-mm hollow gun

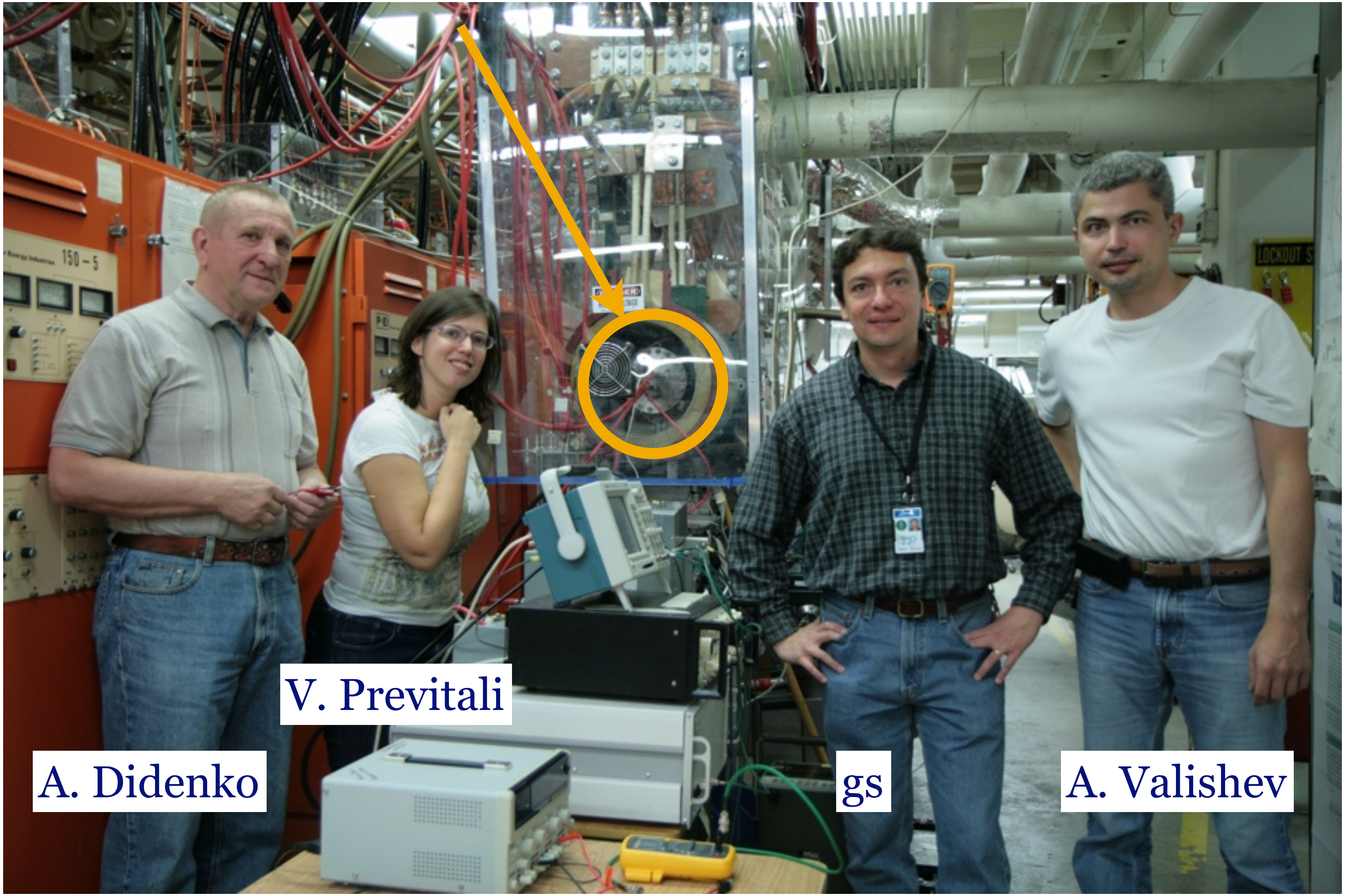




Final
assembly

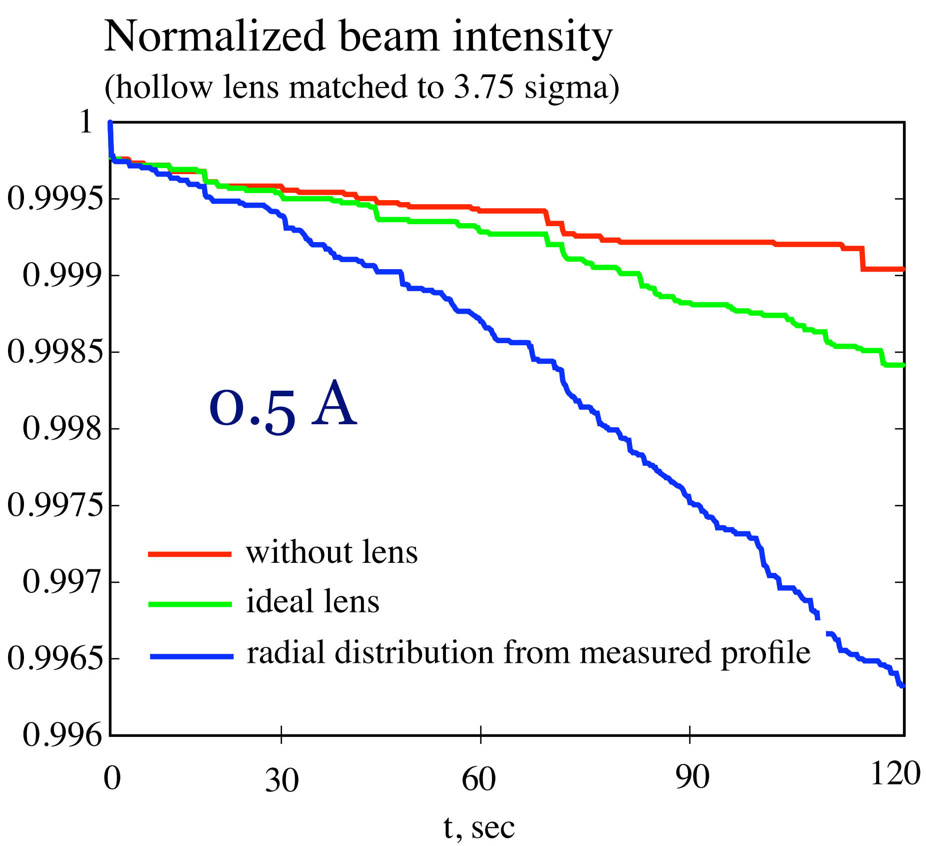


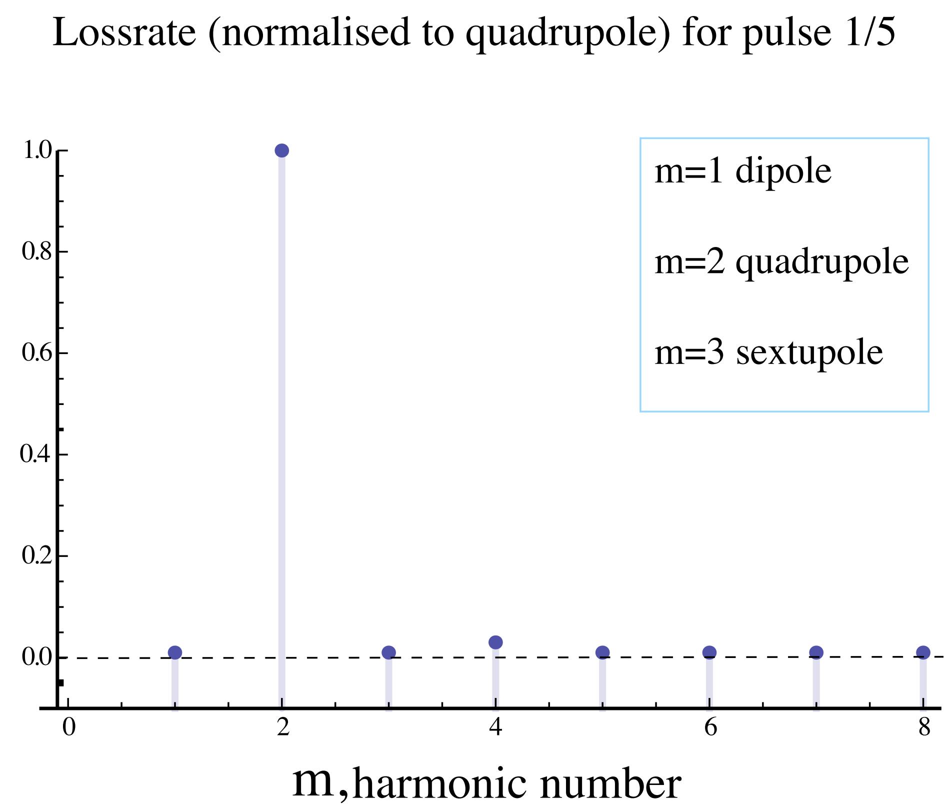
New 25-mm electron gun in Fermilab test stand



Lifetrac calculations of electron profile effects on removal rates

- Halo removal rates are consistent with observations

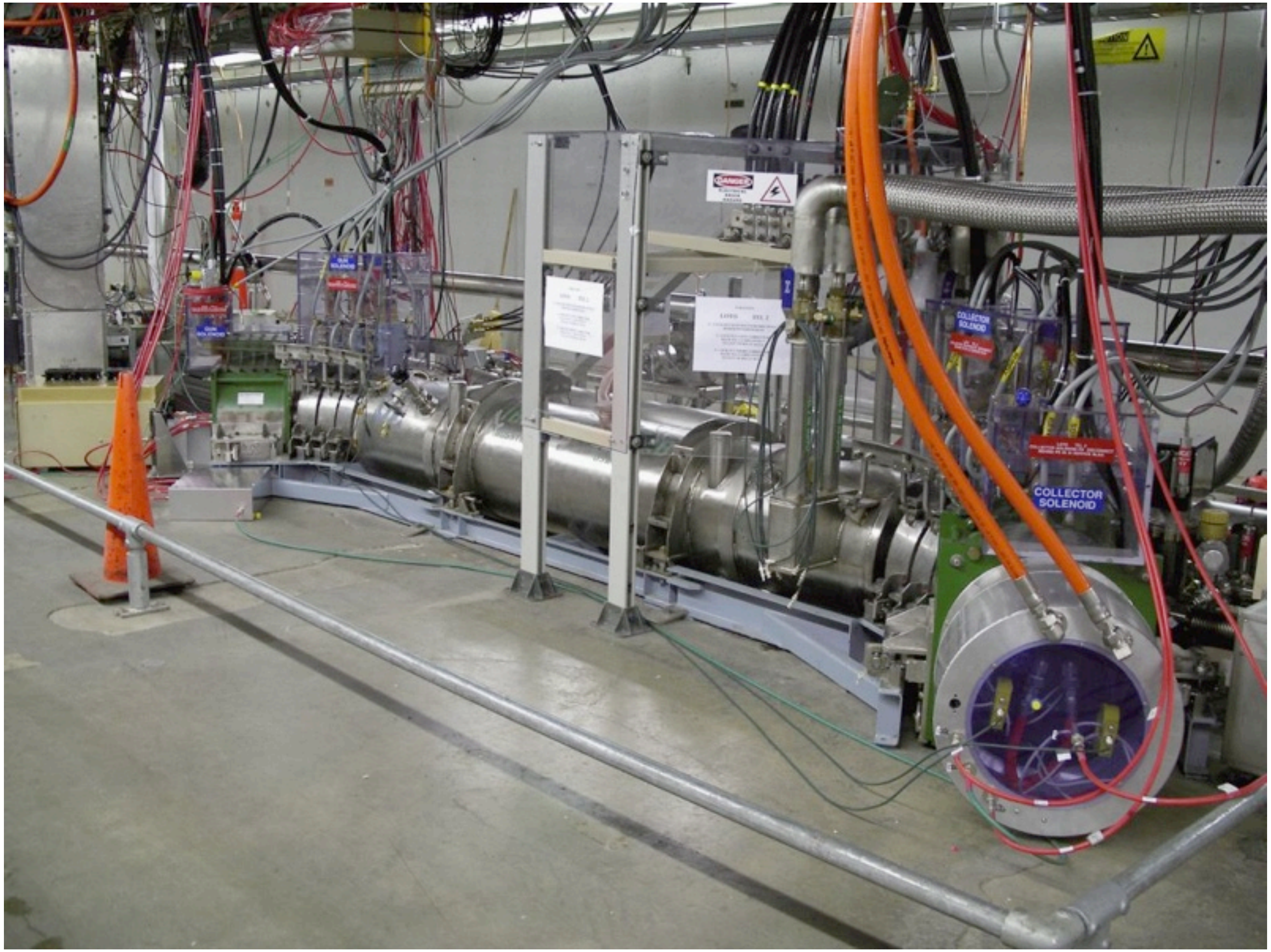




- Azimuthal quadrupole dominates halo losses in pulsed mode
- Effect is tune dependent

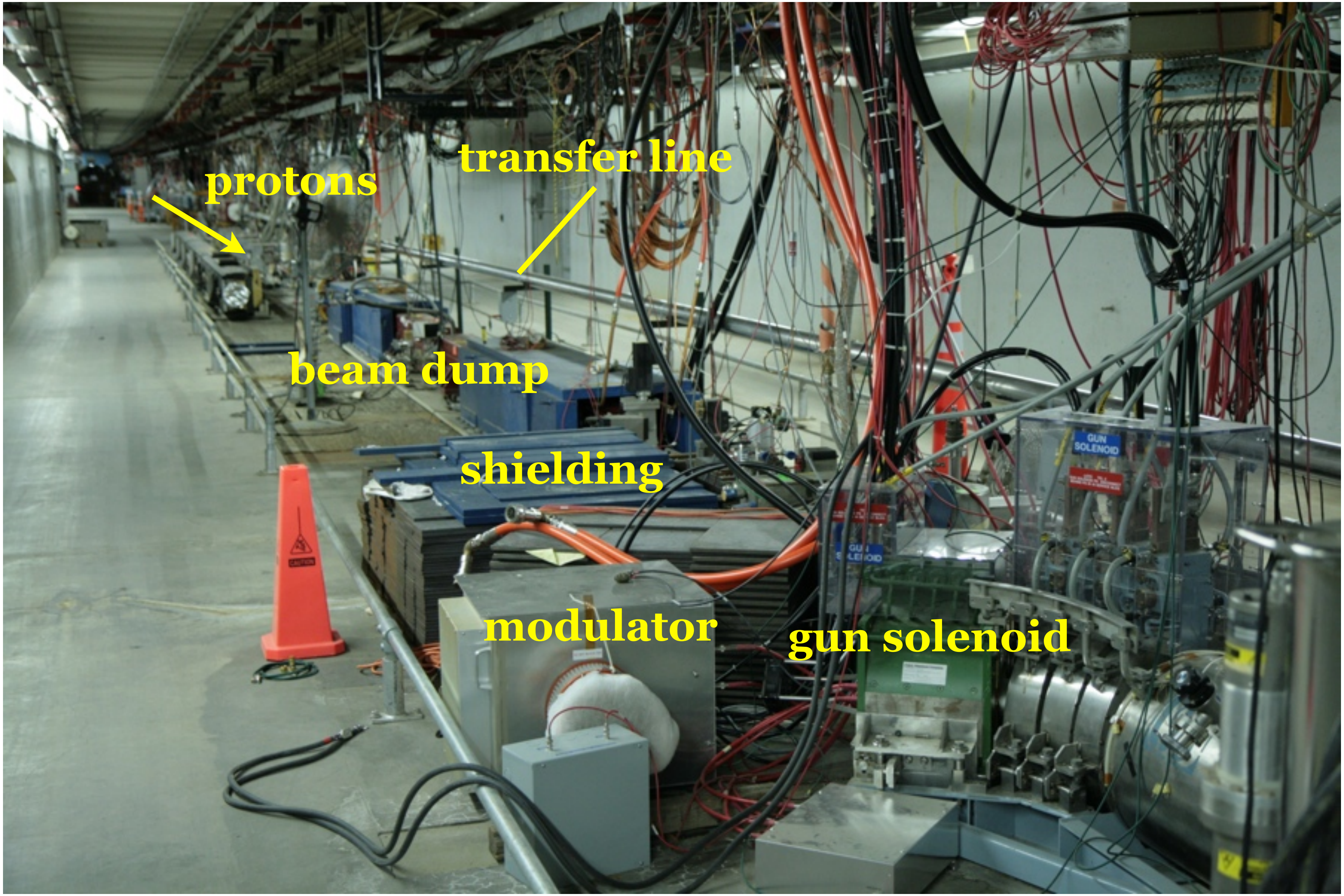
I. Morozov

Electron lens hardware to CERN?

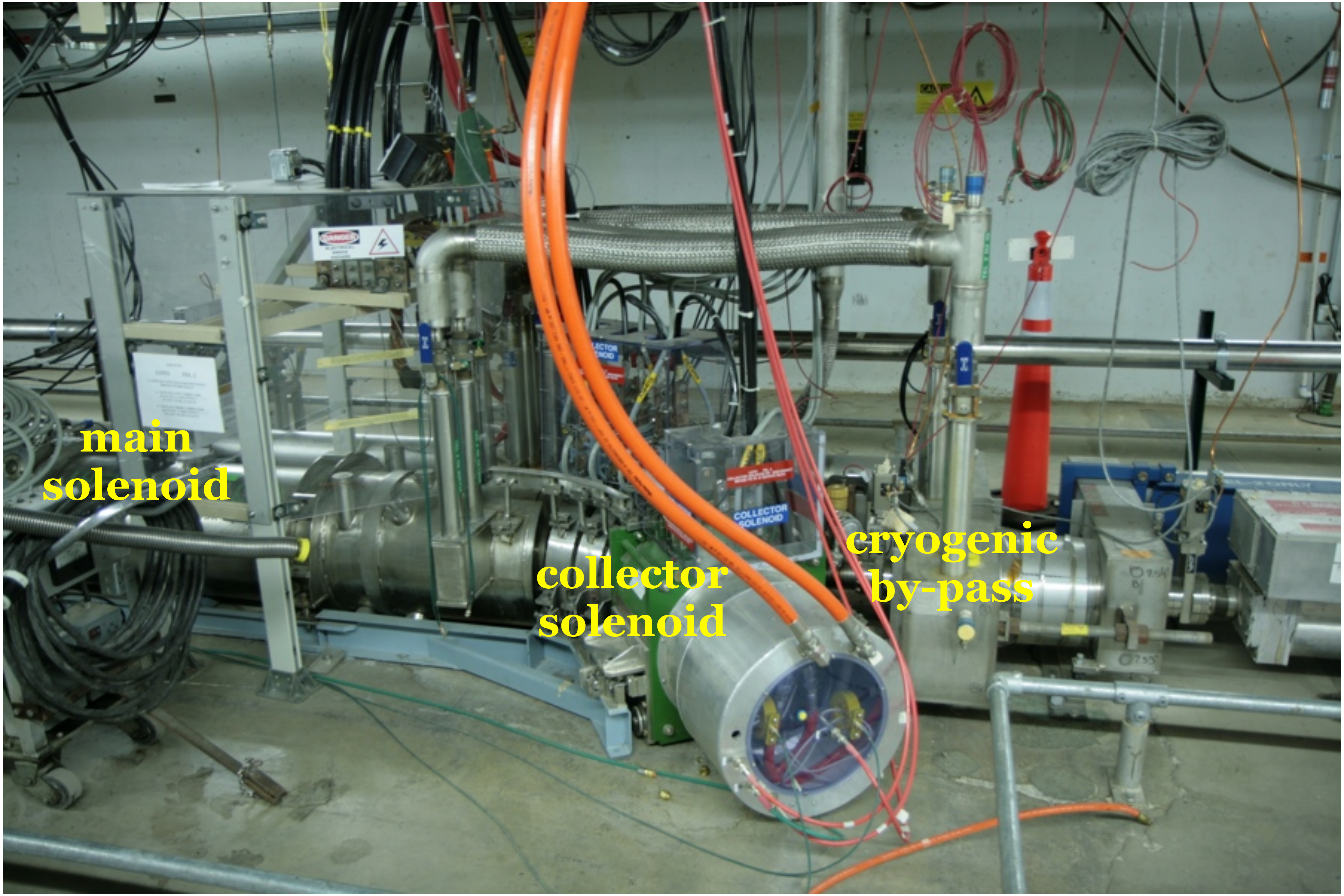


- TEL2 hardware has become available after Tevatron shutdown, including power supplies
- Investigating its possible use at CERN with LHC Collimation Group

TEL2 photographs: gun side



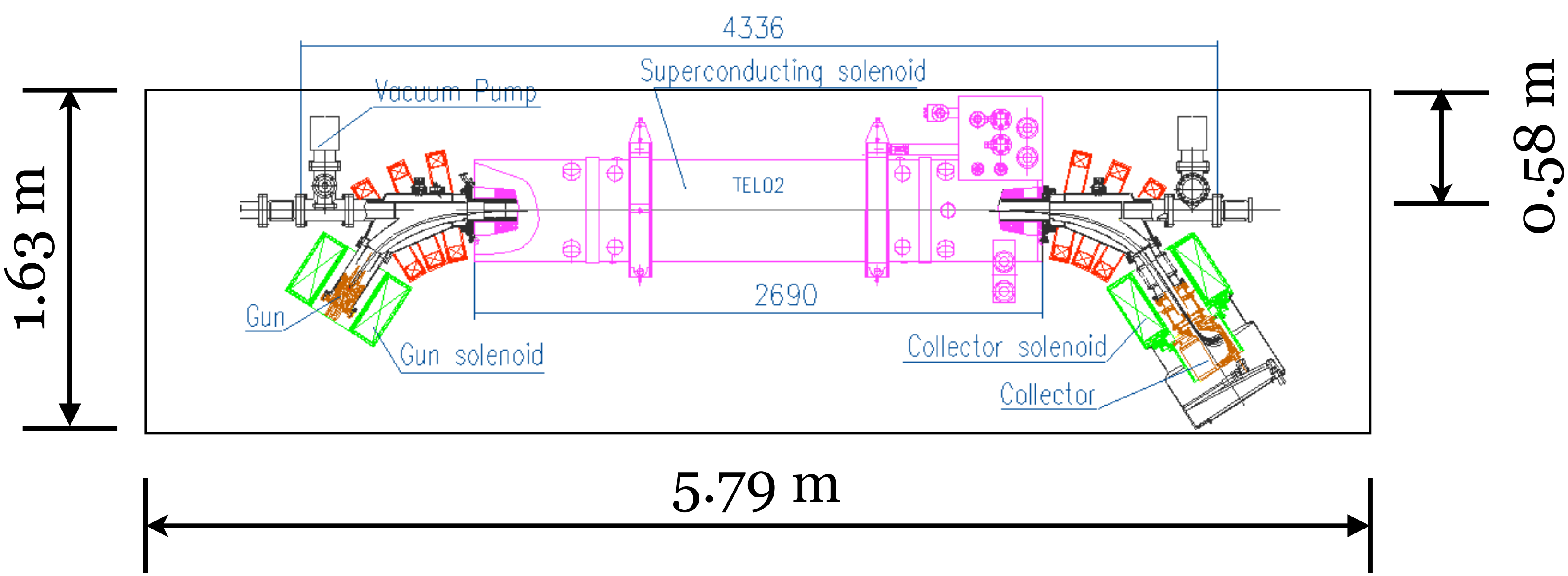
TEL2 photographs: collector side



Application of hollow-beam collimation at CERN

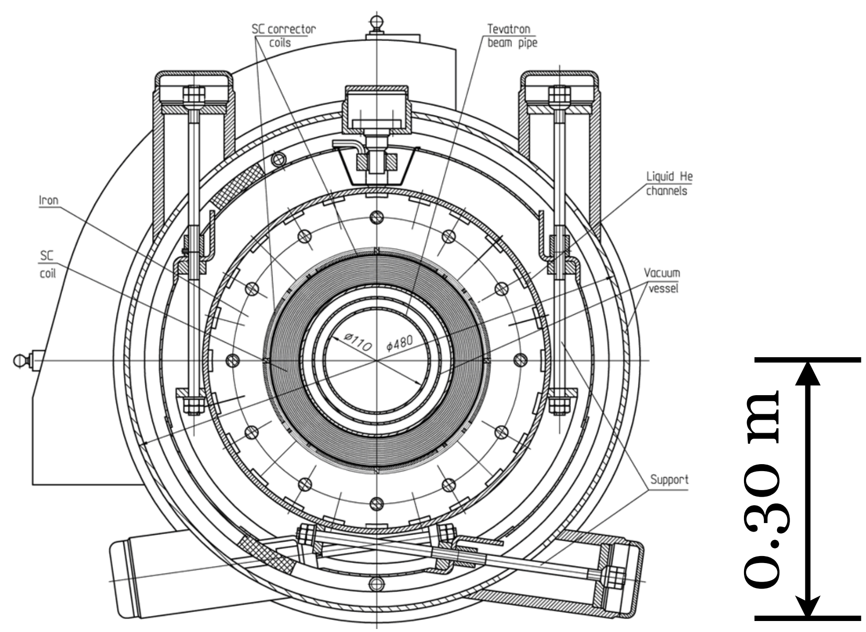
- Purpose:
  - complement primary collimators
  - flexible halo control (synergy with tune modulation? → O. Brüning)
- Possible benefits:
  - faster and safer collimator setup
  - scraping before collisions
  - protection against beam jitter and orbit drifts
  - improve capture efficiency for protons and ions
- Where?
  - Is TEL2 compatible with SPS or LHC requirements?
  - If not, use TEL2 as prototype for final system?
- Design considerations:
  - beam sizes → cathode size, magnetic field strength and straightness
  - pulsing patterns → modulator complexity
  - kick strength → cathode size and operating voltage

TEL2 dimensions



Height (including current and cryo leads): 1.47 m

Weight: about 2 t

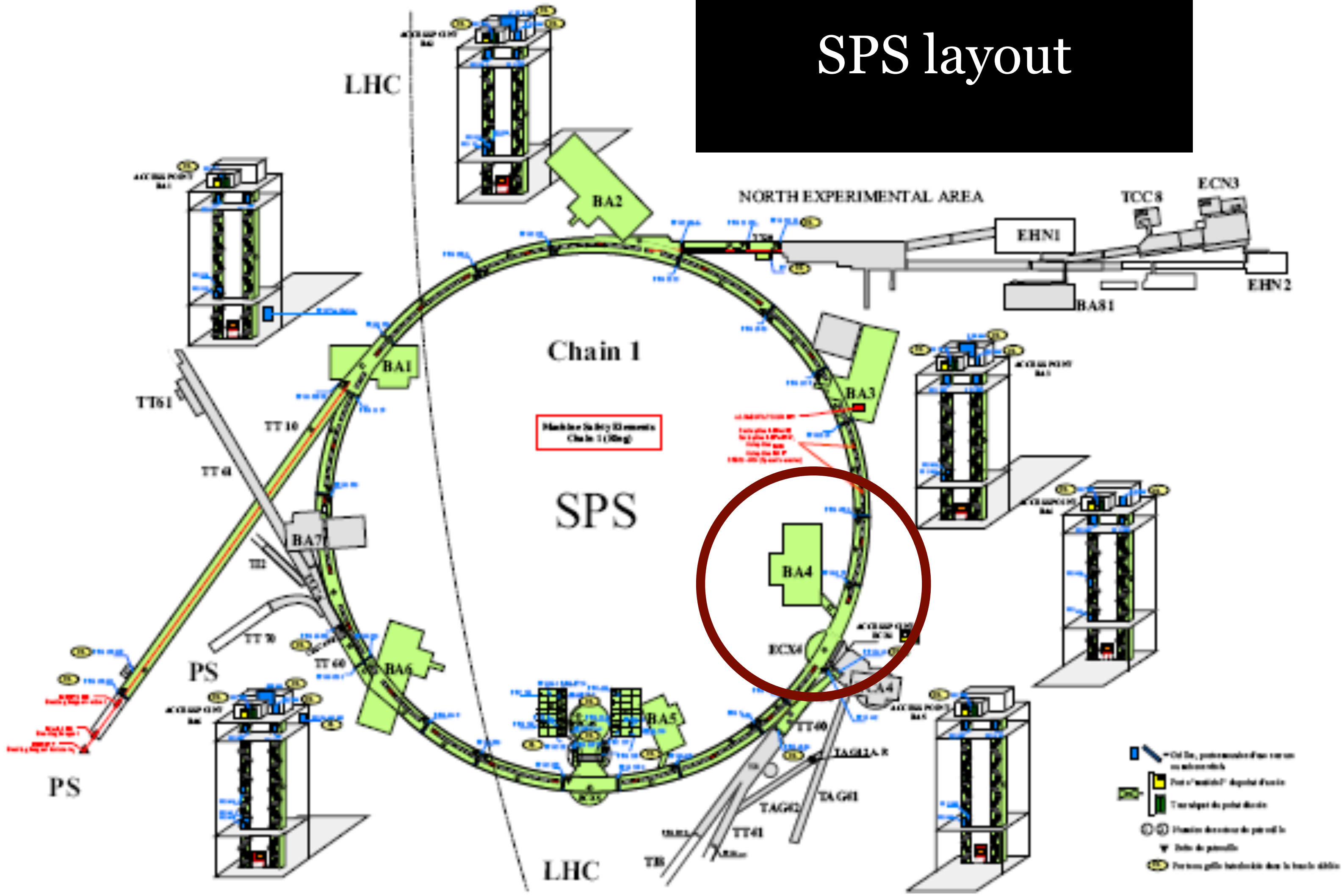


Candidate locations at CERN

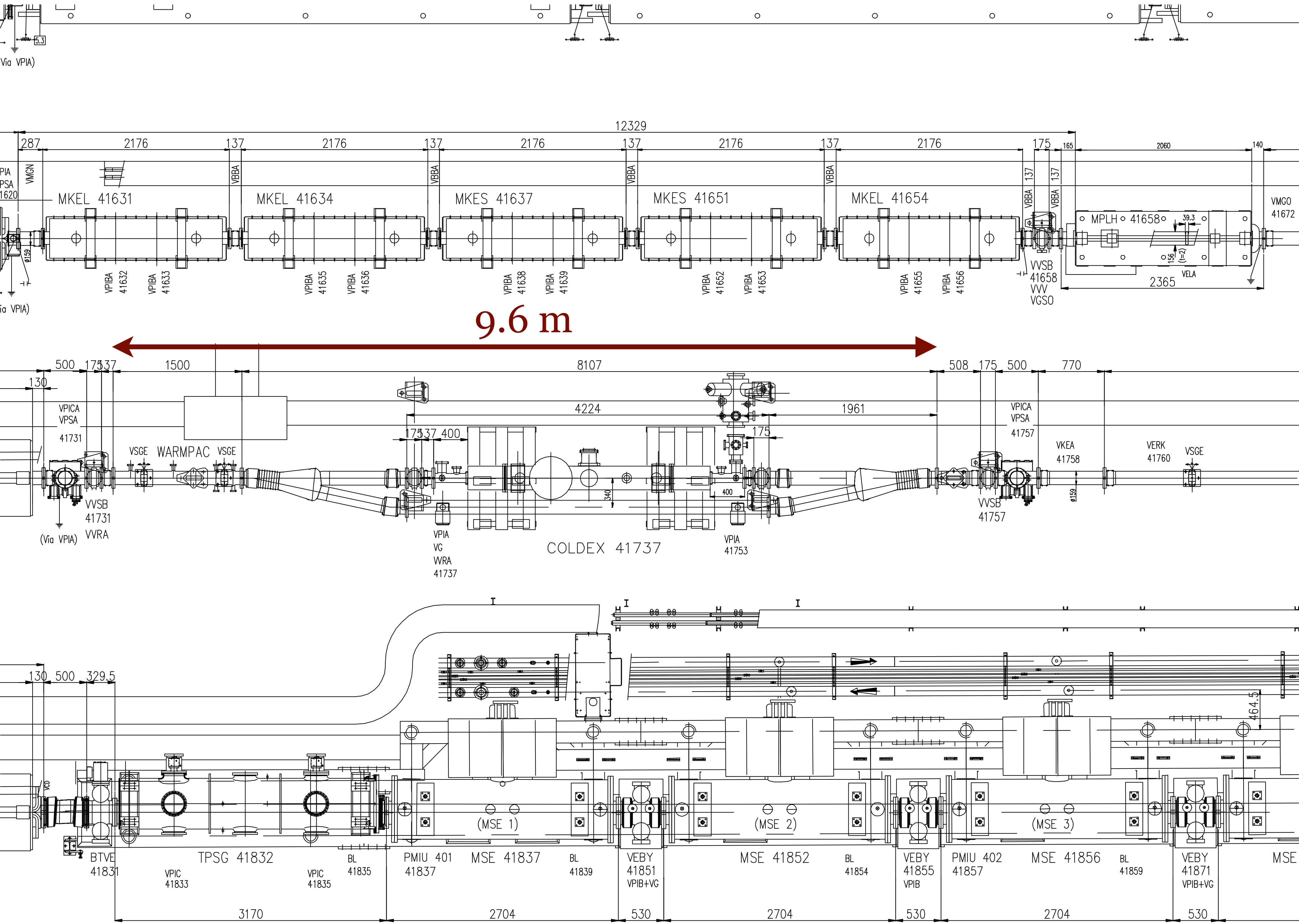
- BA4 in SPS:
  - R&D purpose:
    - test device and integrate controls
  - physical space
  - cryogenics
  - beam size
- storage ring operation
- candidate location for crab cavities
- RB 44 or RB 46 at IR4 in LHC:
  - final goal:
    - complement collimation system
  - longitudinal space
  - large beam-axis separation (42 cm)
  - beam size
- challenging integration
- scarce study time
- IR3 or IR7 in LHC?
- others?

Thanks to CERN staff for arranging tunnel visits!
In particular: A. Rossi (BE-ABP), B. Jenninger (TE-VSC), and E. Bravin (BE-BI)

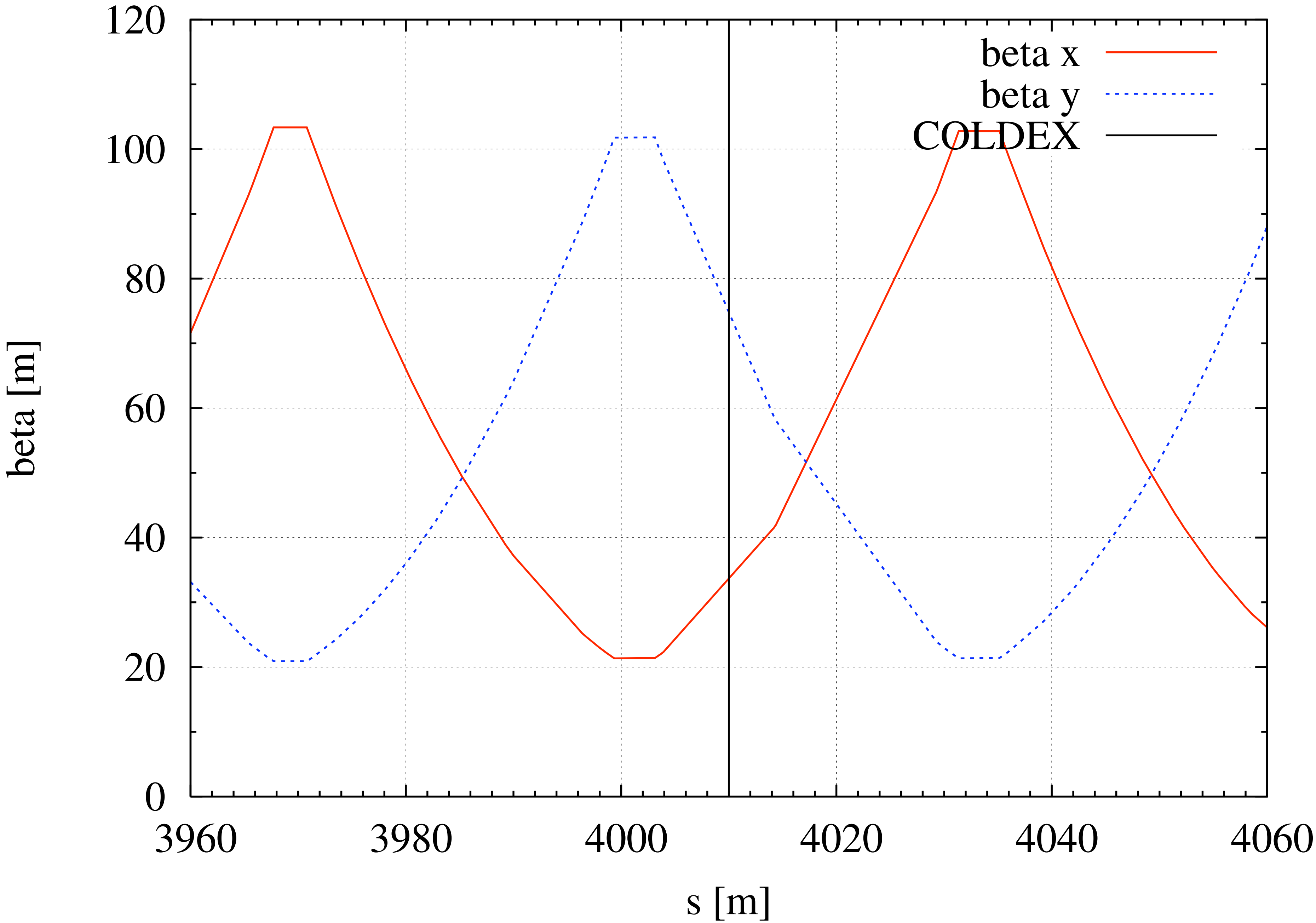
SPS layout



LHC
NORTH EXPERIMENTAL AREA
TCC8
ECN3
EHN1
EHN2
BA81
BA2
BA1
BA3
BA4
BA5
BA6
BA7
Chain 1
SPS
TT61
TT10
TT 60
TT 70
TT40
TT41
TAG61
TAG62
ECX4
PS
PS
LHC

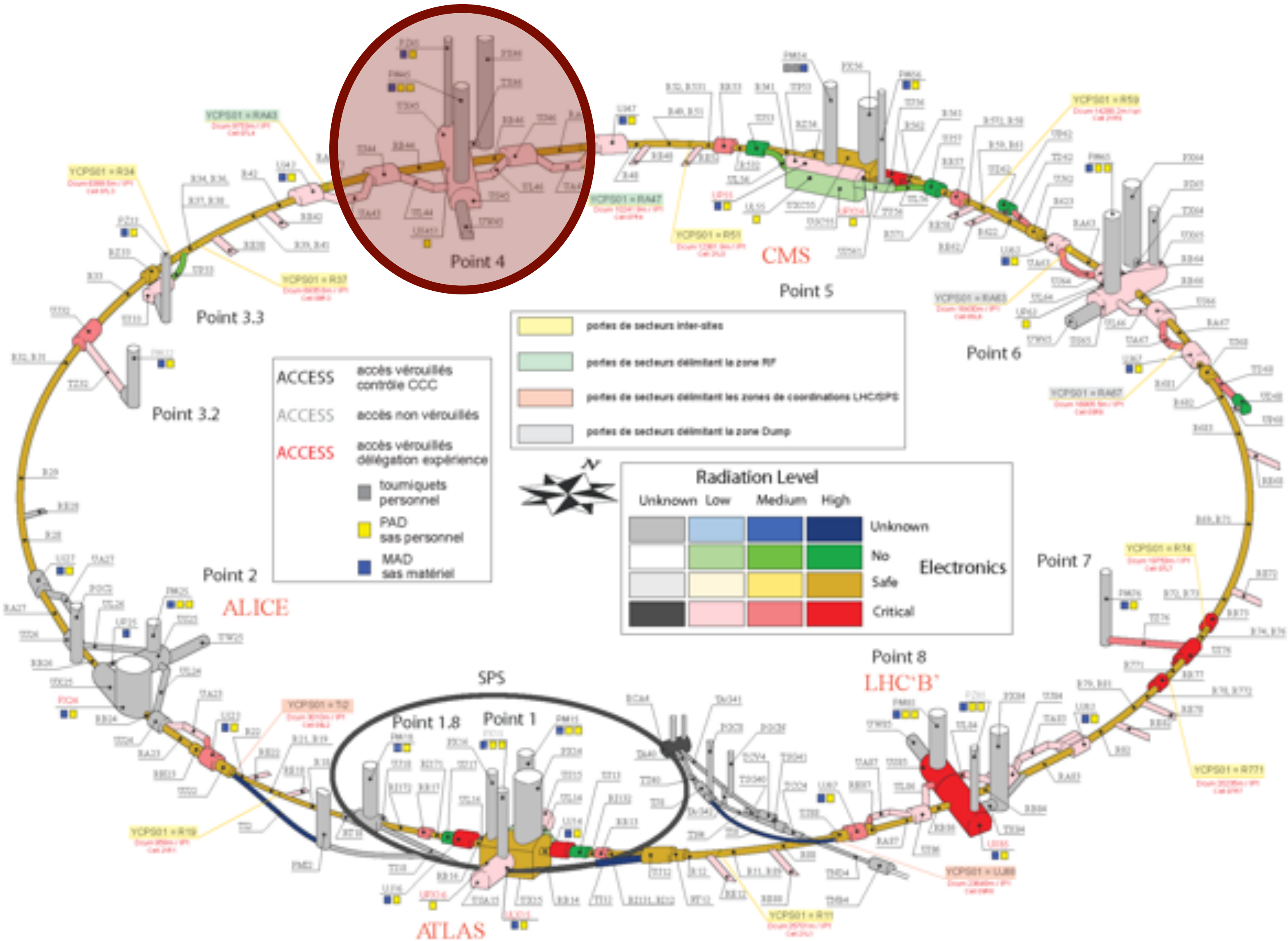

9.6 m
12329
287
2176
137
175
165
2060
140
VMGN
VBBA
MKEL 41631
MKEL 41634
MKES 41637
MKES 41651
MKEL 41654
MPLH 41658
VMGO
41672
VPIBA 41632
VPIBA 41633
VPIBA 41635
VPIBA 41636
VPIBA 41638
VPIBA 41639
VPIBA 41652
VPIBA 41653
VPIBA 41655
VPIBA 41656
VVSB
41658
VVV
VGSO
VELA
2365
(Via VPIA)
500
175
137
1500
8107
508
770
130
4224
1961
400
VPICA
VPSA
41731
VSGE
WARMPAC
VVSB
41731
VVRA
VPIA
VG
VRA
41737
COLDEX 41737
VPIA
41753
VPICA
VPSA
41757
VKEA
41758
VERK
41760
VVSB
41757
329.5
464.5
BTVE
41831
TPSG 41832
VPIC
41833
VPIC
41835
BL
41835
PMIU 401
41837
MSE 41837
(MSE 1)
BL
41839
VEBY
41851
VPIB+VG
MSE 41852
(MSE 2)
BL
41854
VEBY
41855
VPIB
PMIU 402
41857
MSE 41856
(MSE 3)
BL
41859
VEBY
41871
VPIB+VG
MSE
3170
2704
530

Amplitude functions at BA4 in SPS

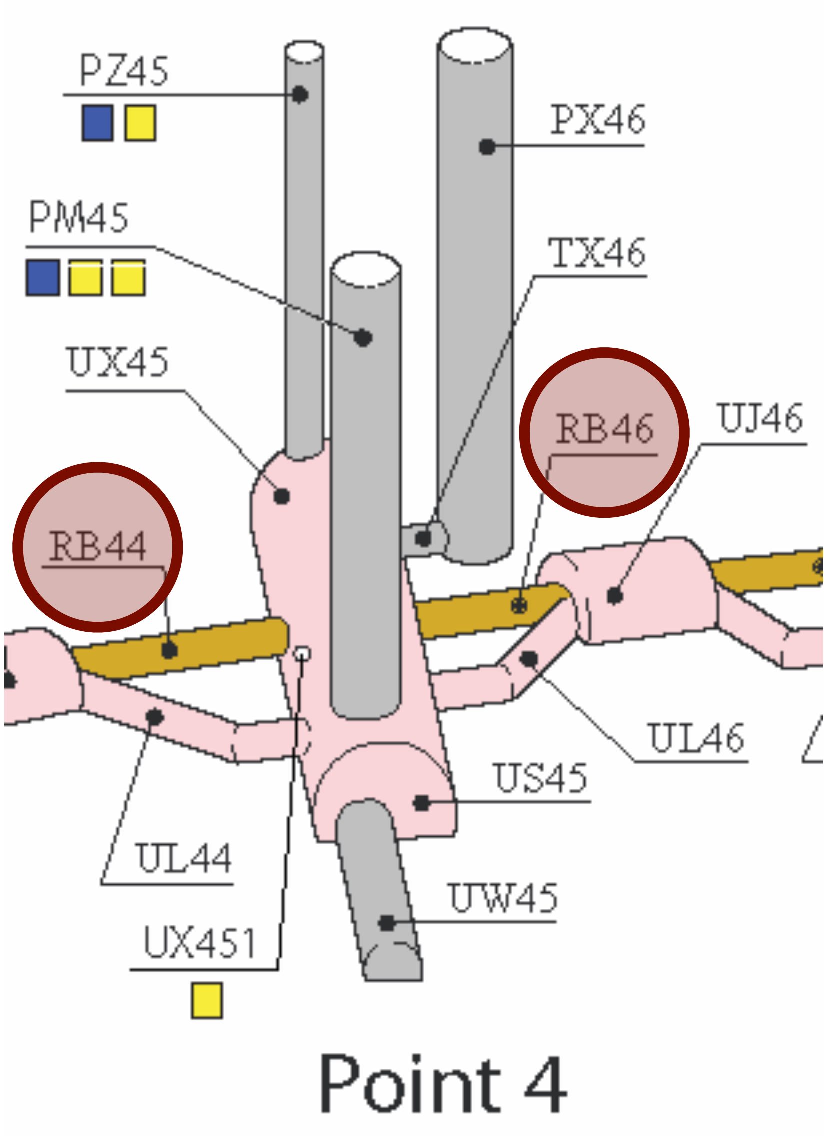


COLDEX installation overview looking downstream

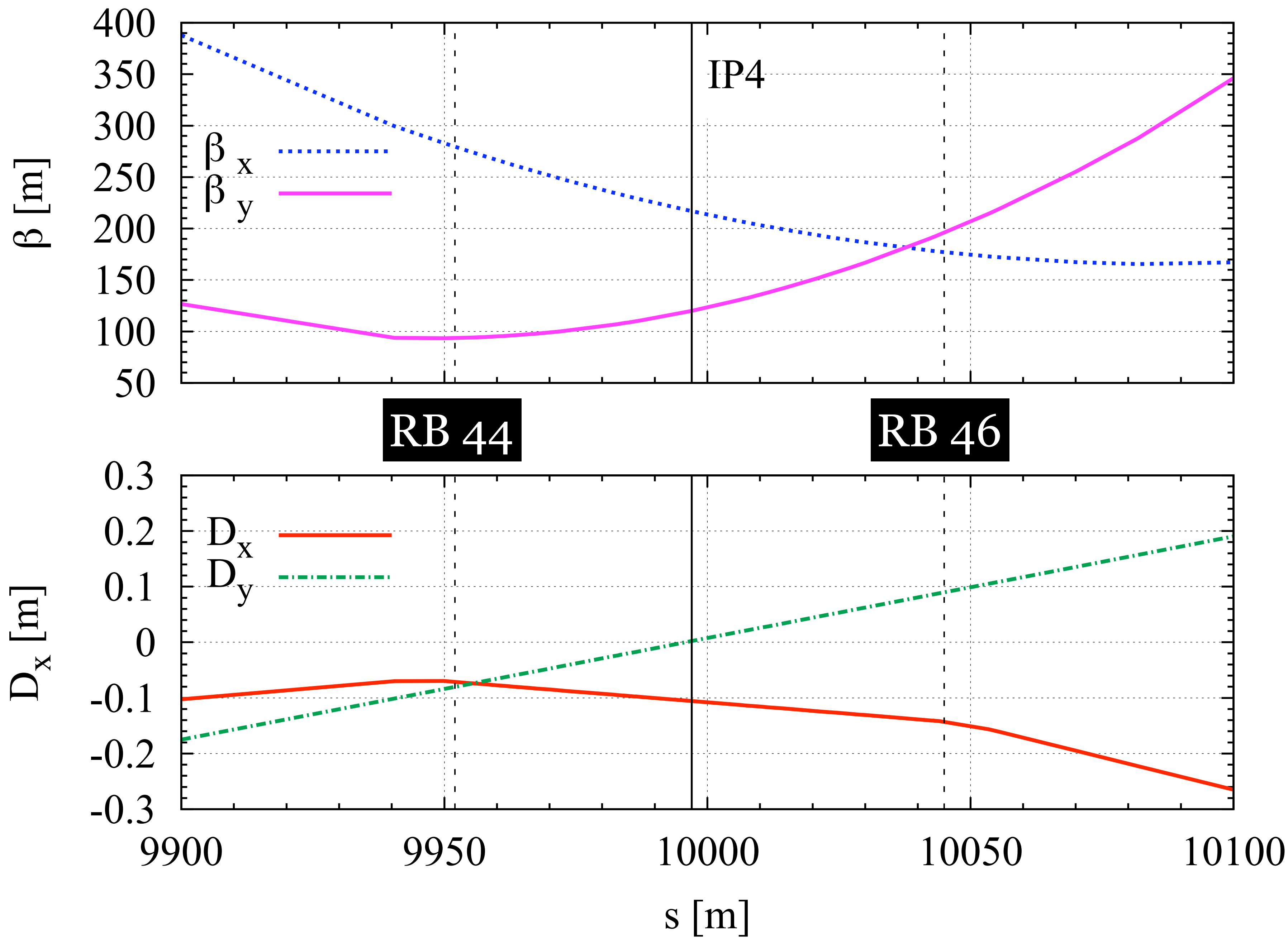
LHC IR4 candidate location



Detail of IR4 in LHC



LHC IR4 beam-1 optics v6.503




RB 44 location looking upstream

CERN-Fermilab collaboration on hollow beam scraper

- Our group is interested in collaboration on hollow-beam collimation at CERN through U.S. LARP
- Of course, project is to be led by CERN
- Available resources at Fermilab:
  - TEL2 hardware
  - physicists (~2 FTEs)
    - Tevatron data analysis
    - modeling and simulations for Tevatron and LHC
    - experimental beam studies
  - technicians and engineers (~2 FTEs)
    - TEL documentation, shipping, installation
    - design and construction of new components

Further information

- **Papers**
  - Ageev et al., PAC 01, p. 3630 [TEL magnets and cryogenics]
  - Shiltsev et al., PRL **99**, 244801 (2007) [beam-beam compensation]
  - Shiltsev et al., PRSTAB **11**, 103501 (2008) [TEL design and operation]
  - Stancari et al., IPAC 10, TUPEB076 [hollow gun design and performance]
  - Stancari et al., PRL **107**, 084802 (2011) [hollow beam collimation]
  - Stancari et al., arXiv:1110.0144 [hollow beam collimation]
- **Web pages**
  - https://cdcvs.fnal.gov/redmine/projects/elens/wiki [new e-lens wiki]
  - http://www-bd.fnal.gov/lug/tev33/ebeam_comp [original e-lens pages]

Summary and outlook

- Hollow electron beams open up new options for beam scraping in high-intensity storage rings and colliders
- Many observations at the Tevatron: compatibility with collider operations, halo removal rates, effects on core, diffusion, fluctuations in losses, collimation efficiencies, ...
- New 25-mm electron gun assembly; characterization under way
- Validate Tevatron simulations against collected data
- TEL2 hardware now available
- Transfer experimental program to CERN? Support from DOE LARP Review and LHC Collimation Review (June 2011).
- Study applicability at CERN in collaboration with LHC Collimation Working Group: benefits, feasibility, locations

Thank you!

Backup

The conventional multi-stage collimation system

Goals of collimation:

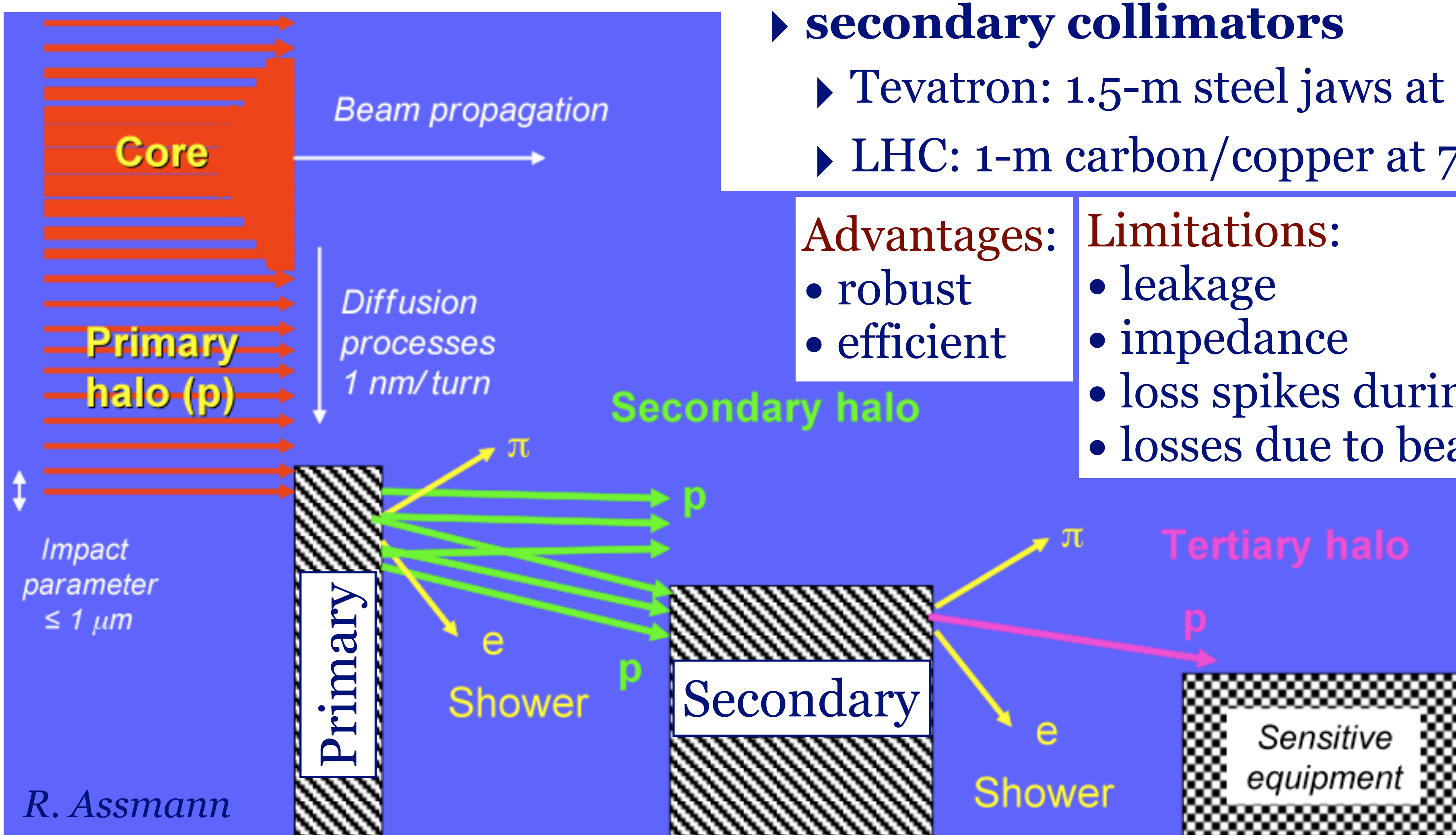
- reduce beam halo
- direct losses towards absorbers

Implementations:

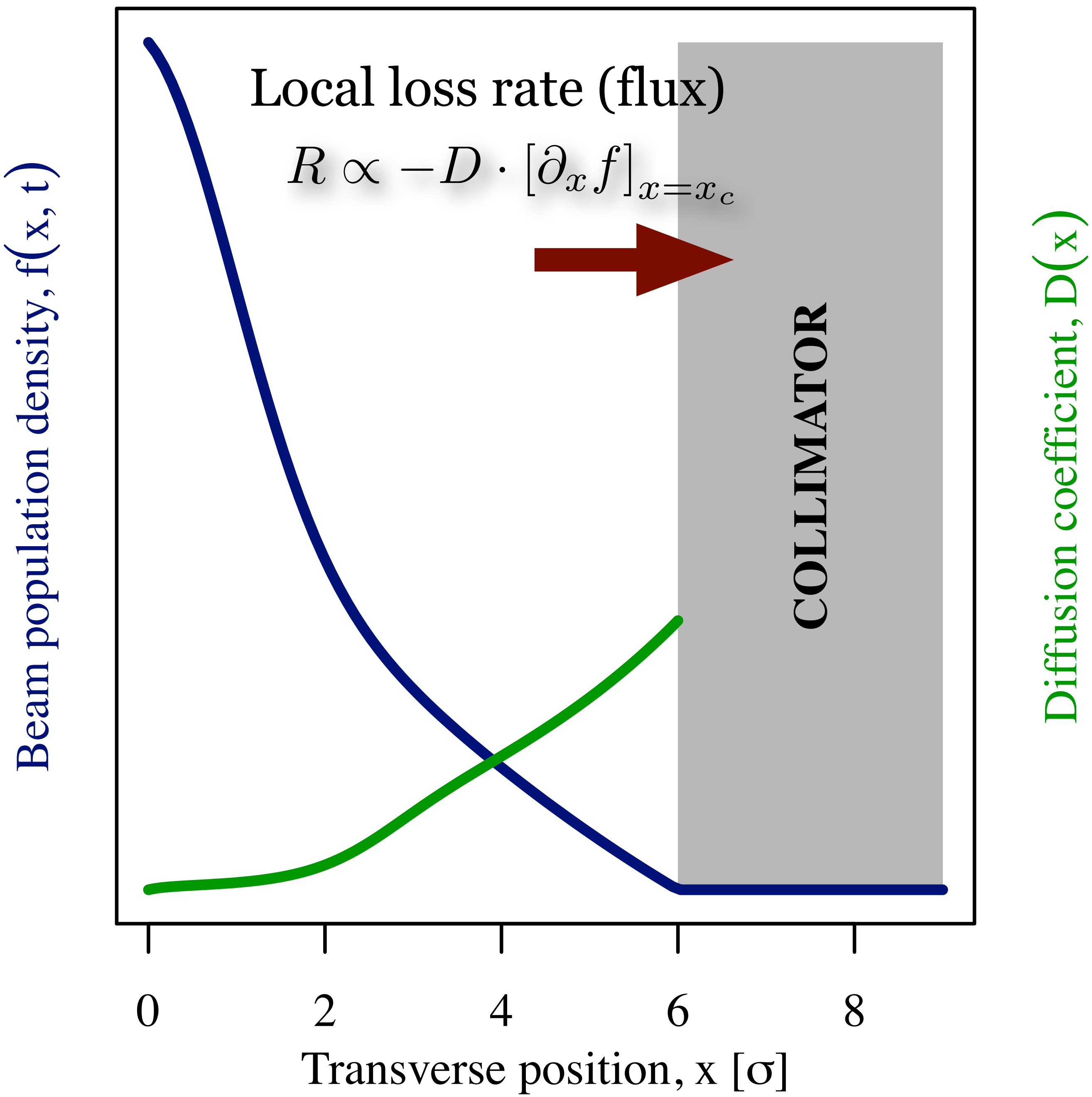
- **primary collimators**
  - Tevatron: 5-mm W at 5σ
  - LHC: 0.6-m carbon jaws at 6σ
- **secondary collimators**
  - Tevatron: 1.5-m steel jaws at 6σ
  - LHC: 1-m carbon/copper at 7σ

Advantages:
- robust
- efficient

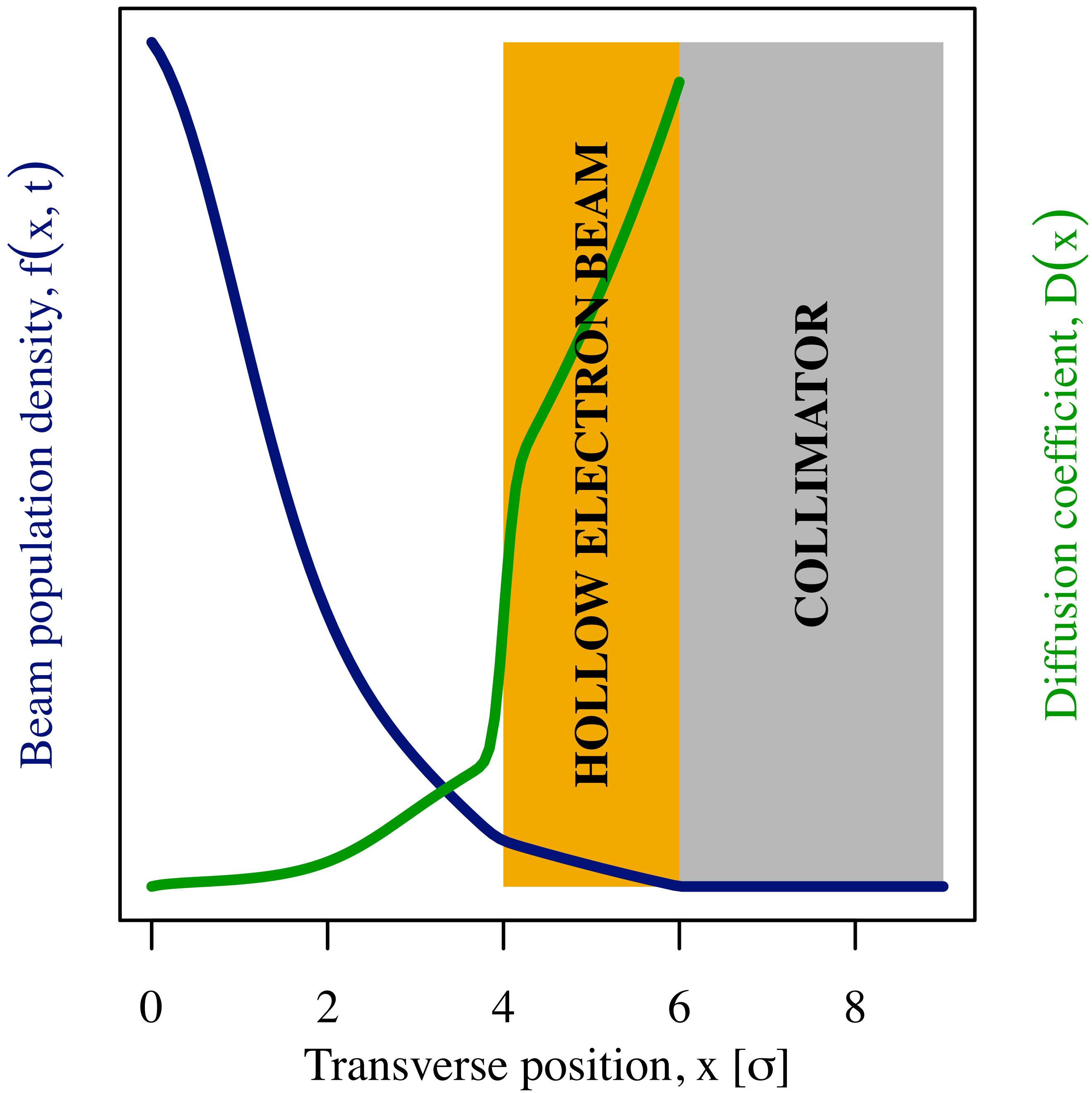
Limitations:
- leakage
- impedance
- loss spikes during setup
- losses due to beam jitter



1-dimensional diffusion cartoon of collimation



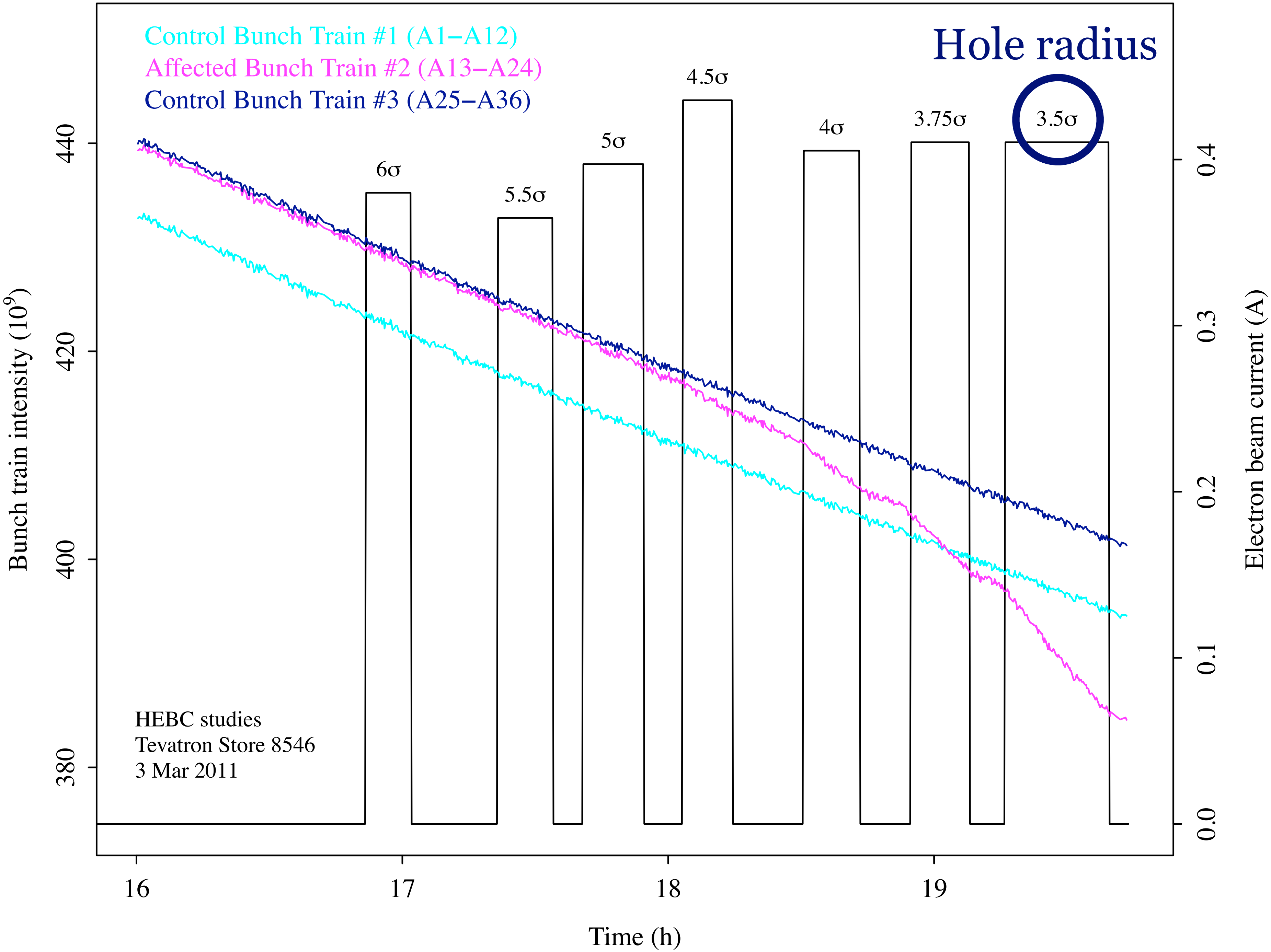
1-dimensional diffusion cartoon with hollow electron beam



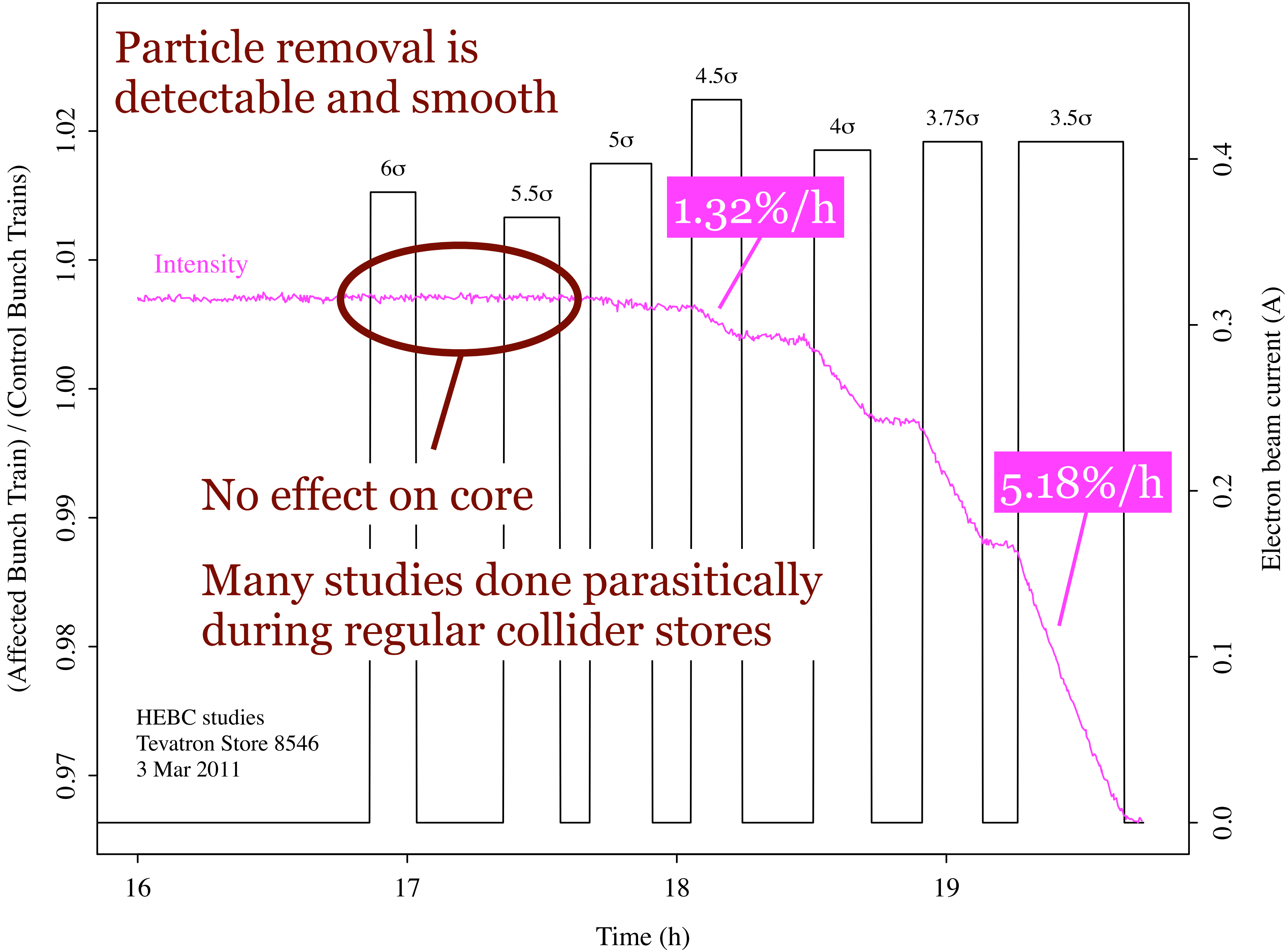
A good complement to a two-stage system for high intensities?

- Can be close to or even overlap with the main beam
  - no material damage
  - tunable strength ("variable thickness")
- Works as "soft scraper" by enhancing diffusion
- Low impedance
- 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
- Control of hollow beam profile
- Beam stability at high intensity
- Cost

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



Removal rate: affected bunch train relative to other 2 trains



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

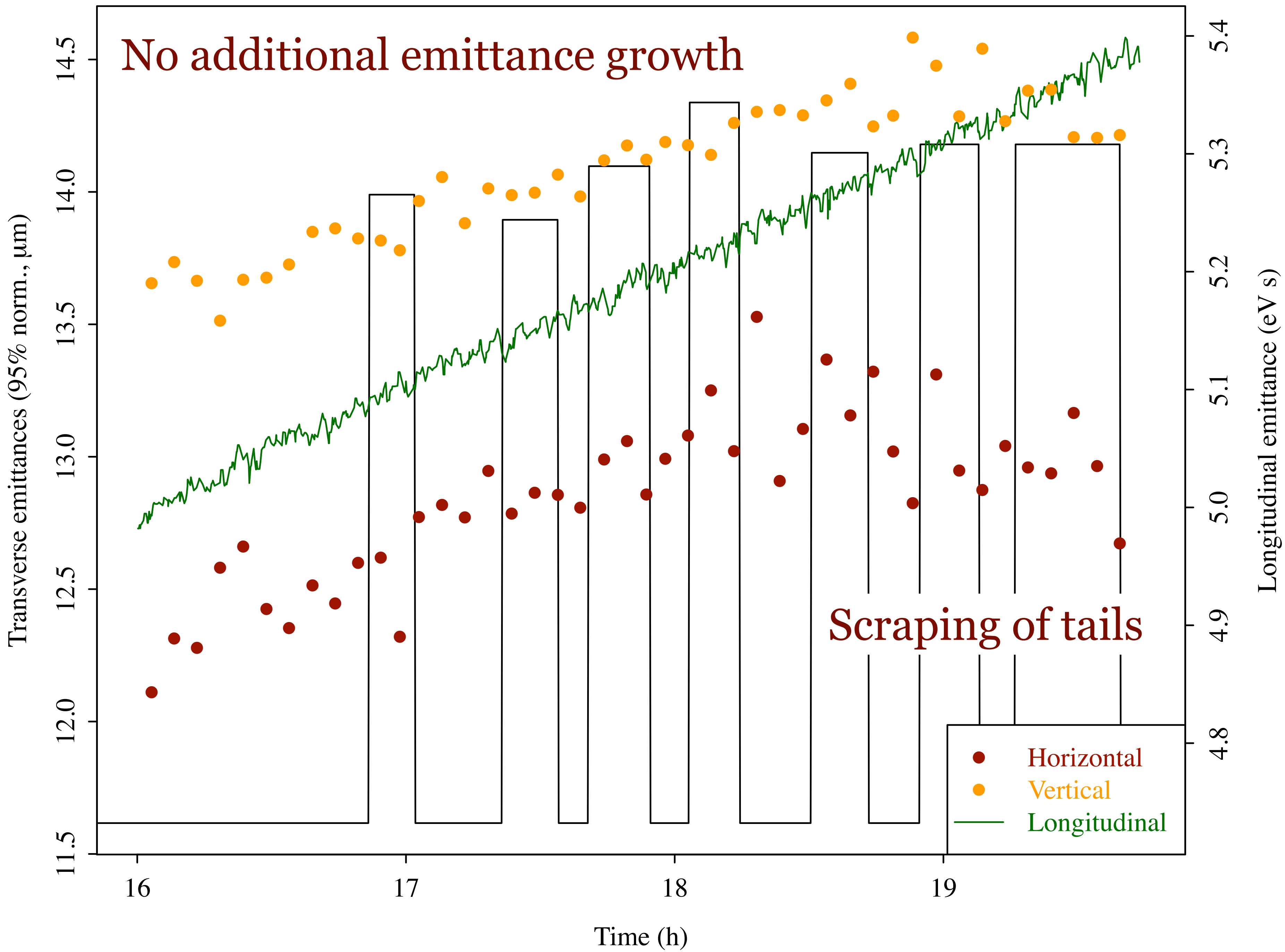
Several strategies:

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

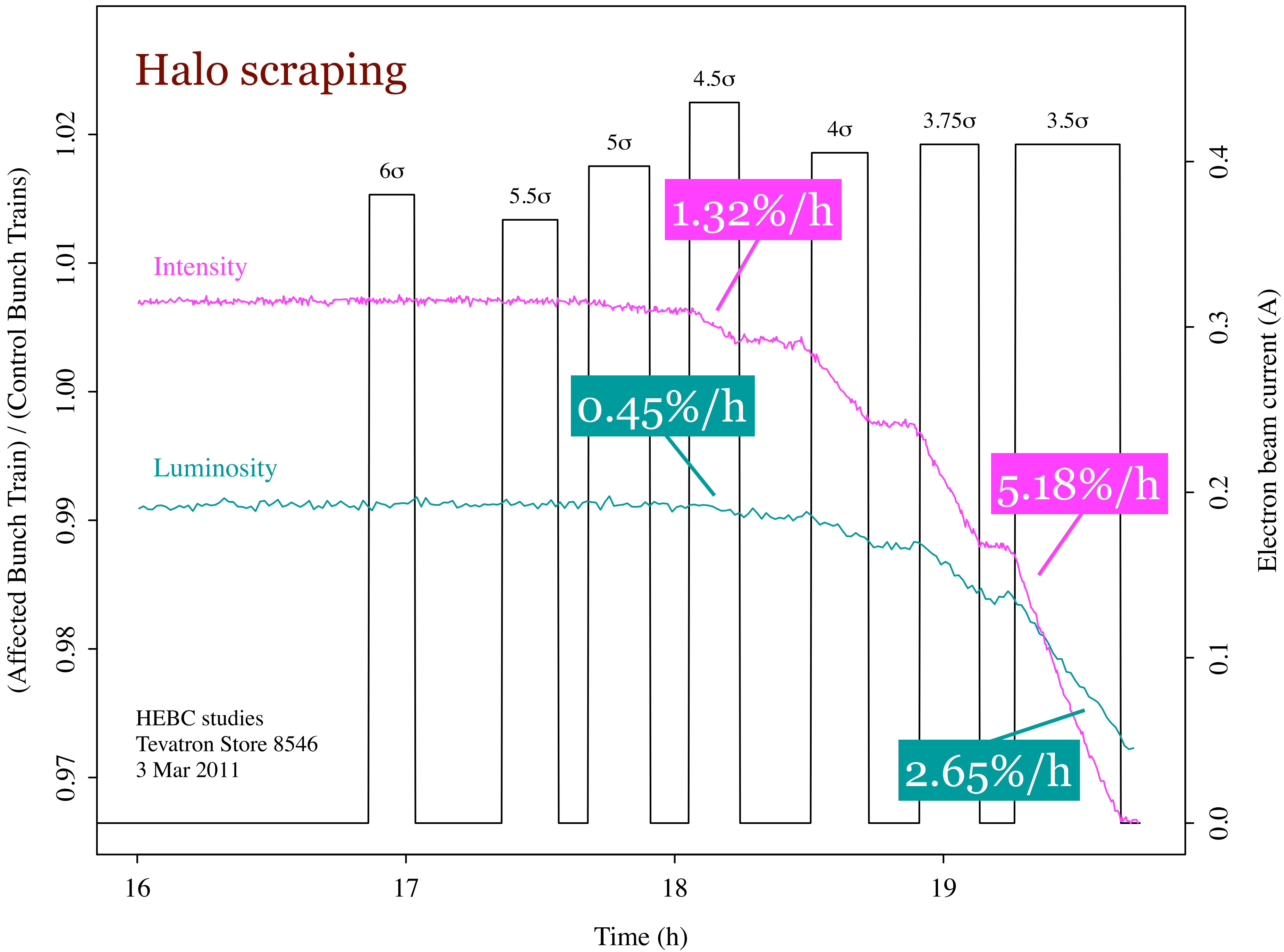
$$\mathcal{L} = \left(\frac{f_{\mathrm{rev}} N_b}{4\pi} \right) \frac{N_p N_a}{\sigma^2} \qquad \frac{\Delta \mathcal{L}}{\mathcal{L}} = \frac{\Delta N_p}{N_p} + \frac{\Delta N_a}{N_a} - 2 \frac{\Delta \sigma}{\sigma}$$

  - same fractional variation if other factors are constant
  - luminosity decreases more if there is emittance growth or proton loss
  - luminosity decreases less 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

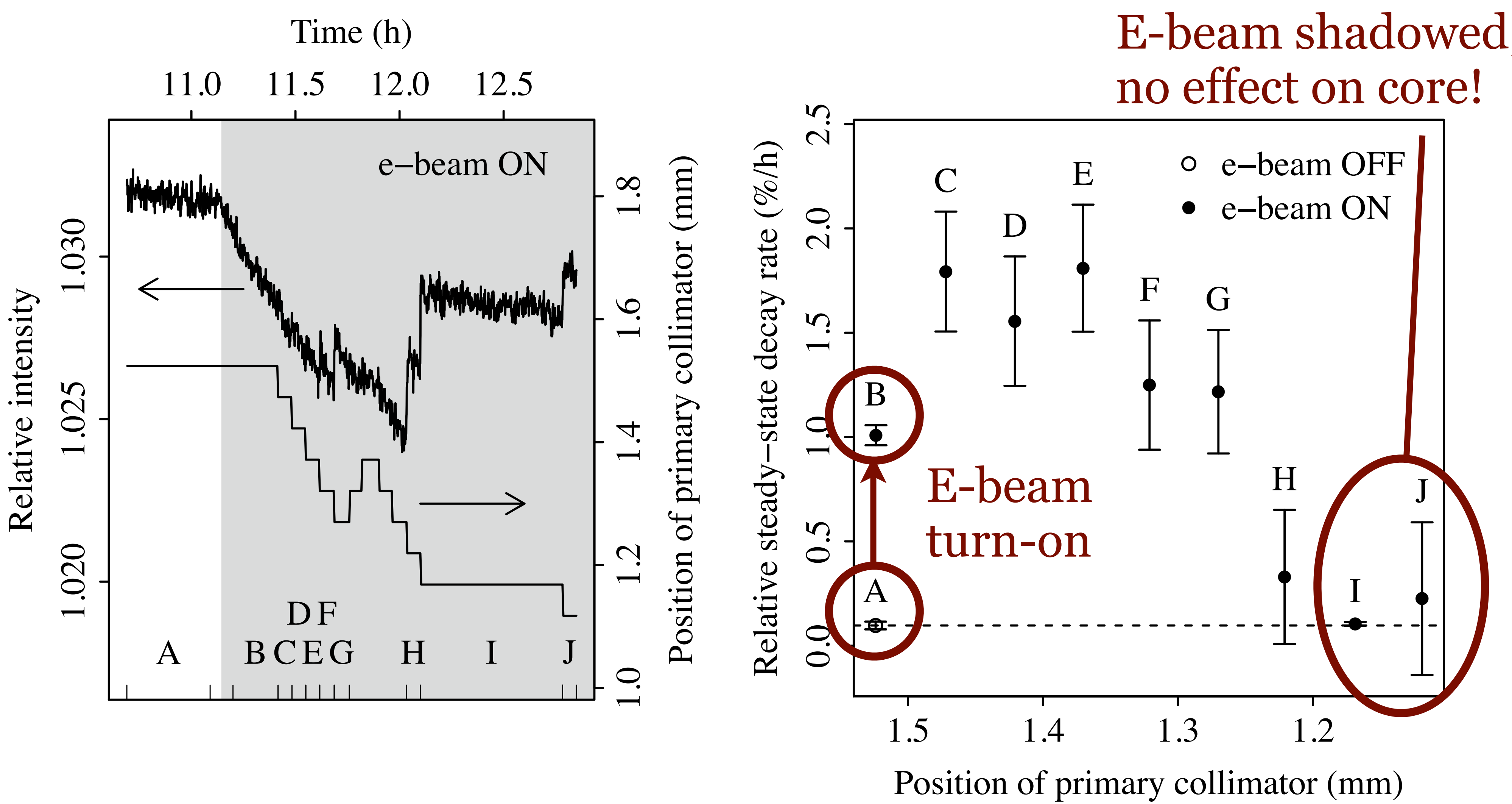


Luminosity of affected bunch train relative to other 2 trains



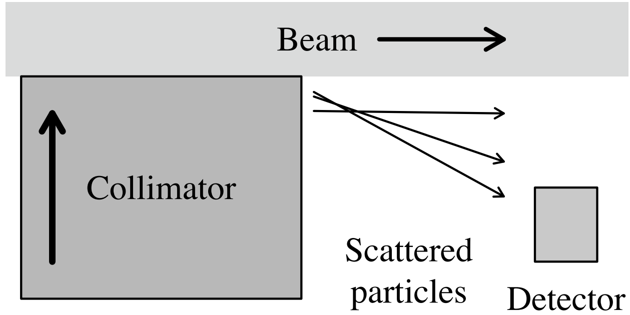
Removal rate vs. amplitude from collimator scan

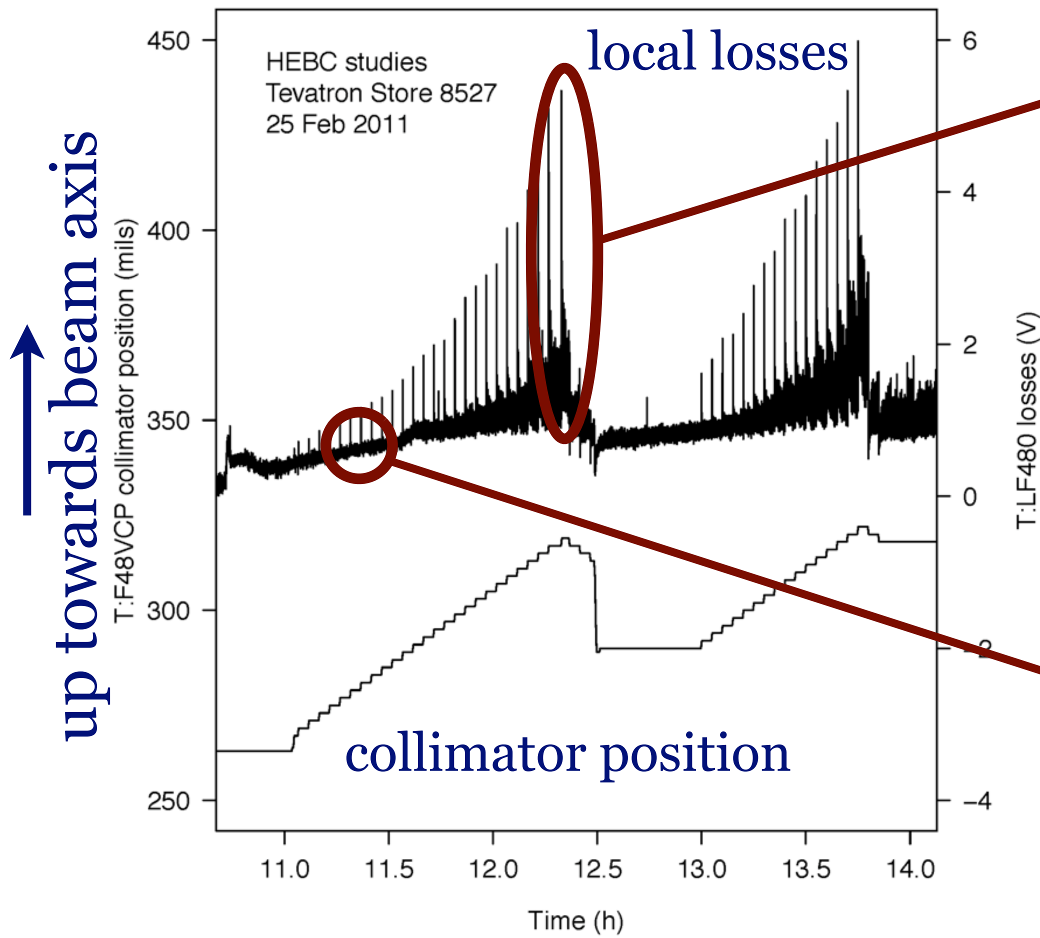
Electrons (0.15 A) on pbar train #2, 3.5σ hole (1.3 mm at collimator)
Vertical scan of primary collimator (others retracted)



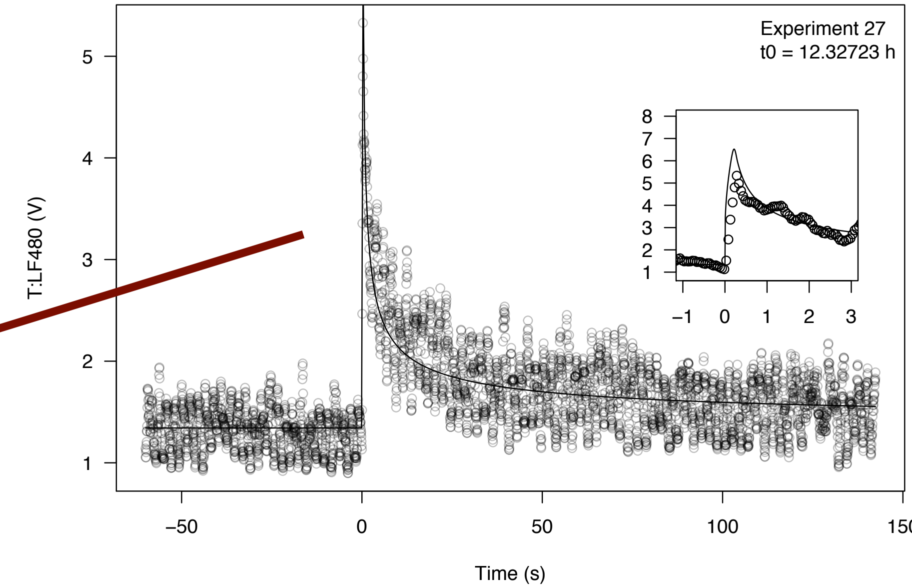
down towards beam axis

Diffusion rate vs. amplitude from collimator scans

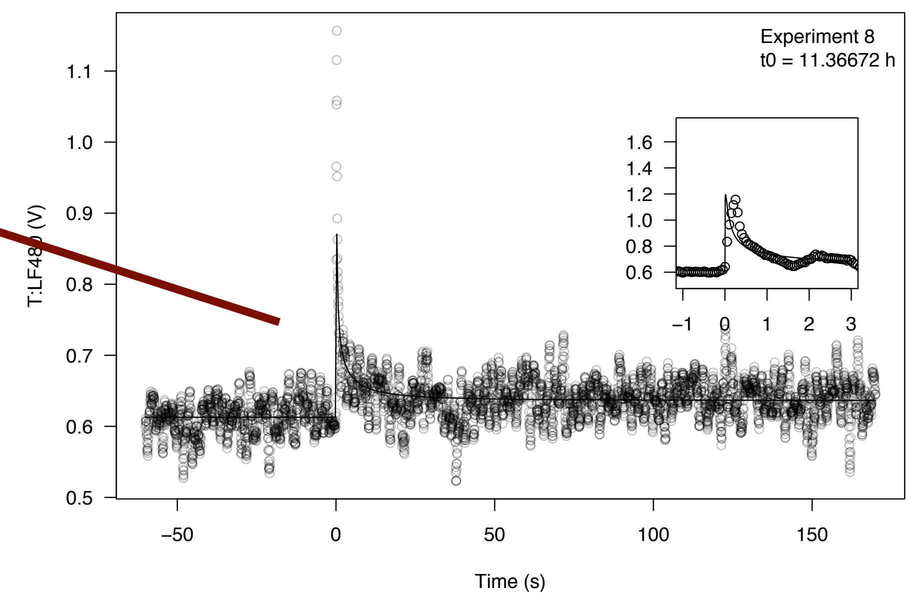




Mess and Seidel, NIMA **351**, 279 (1994)



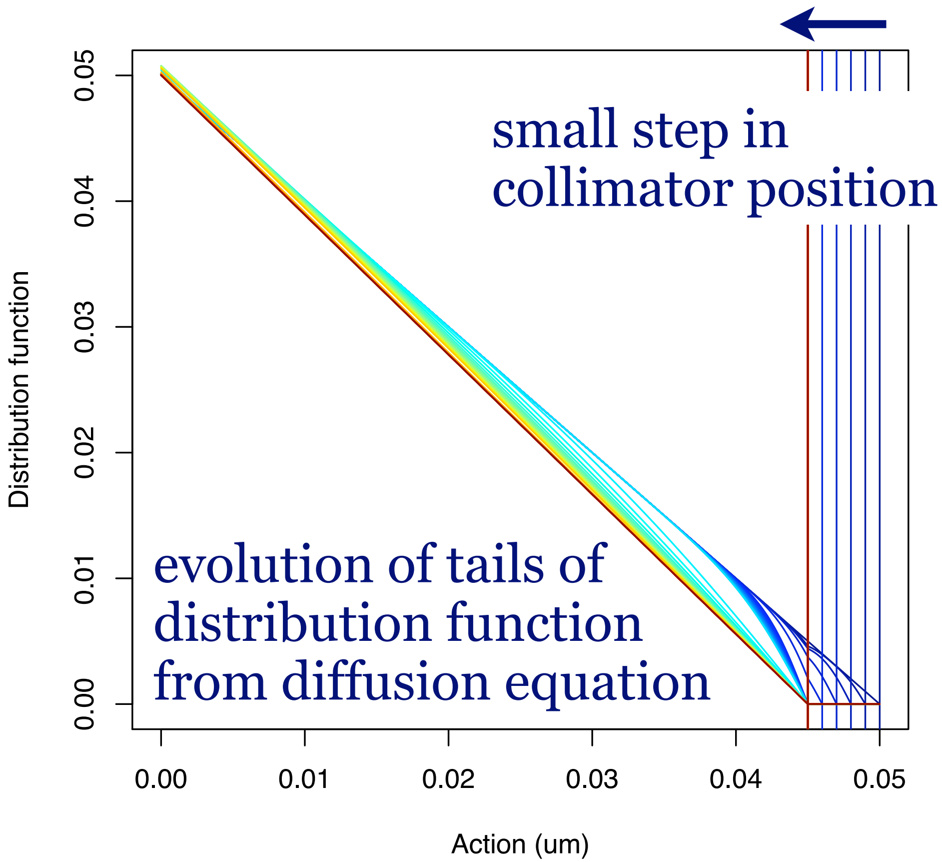
Tails repopulate faster at large amplitudes (higher diffusion rate)

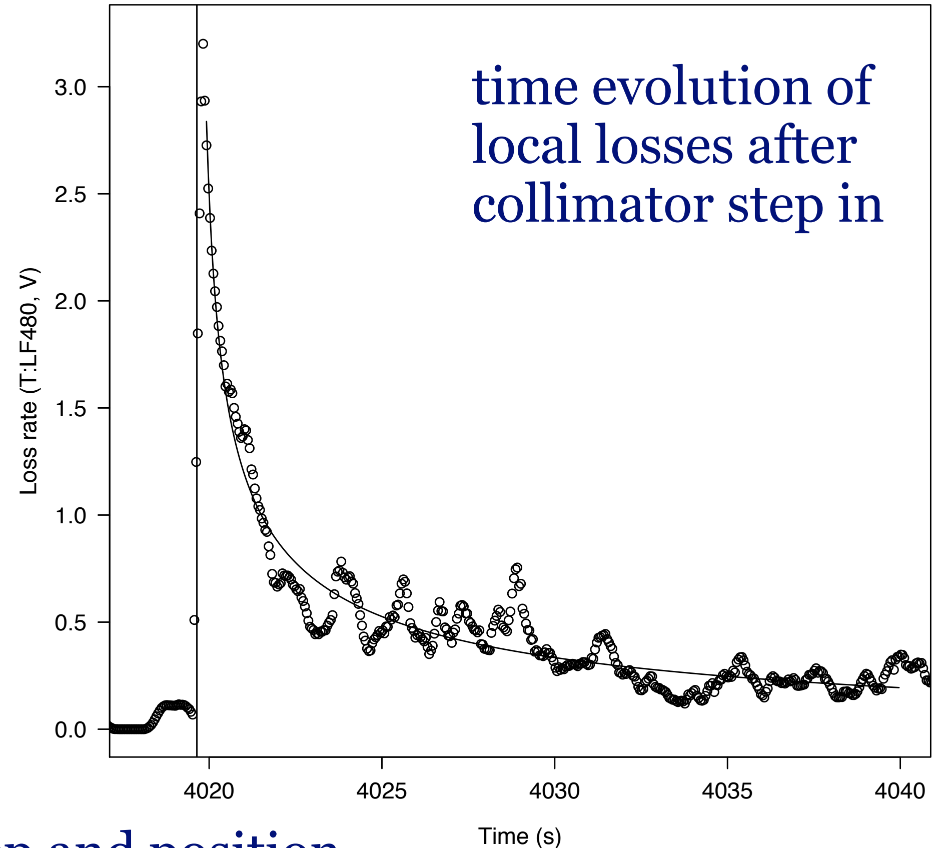


Keeping loss spikes below quench limit constrains collimator settings

Diffusion rate vs. amplitude from collimator scans

Mess and Seidel, NIM A **351**, 279 (1994)





collimator step and position

observed loss rate

background

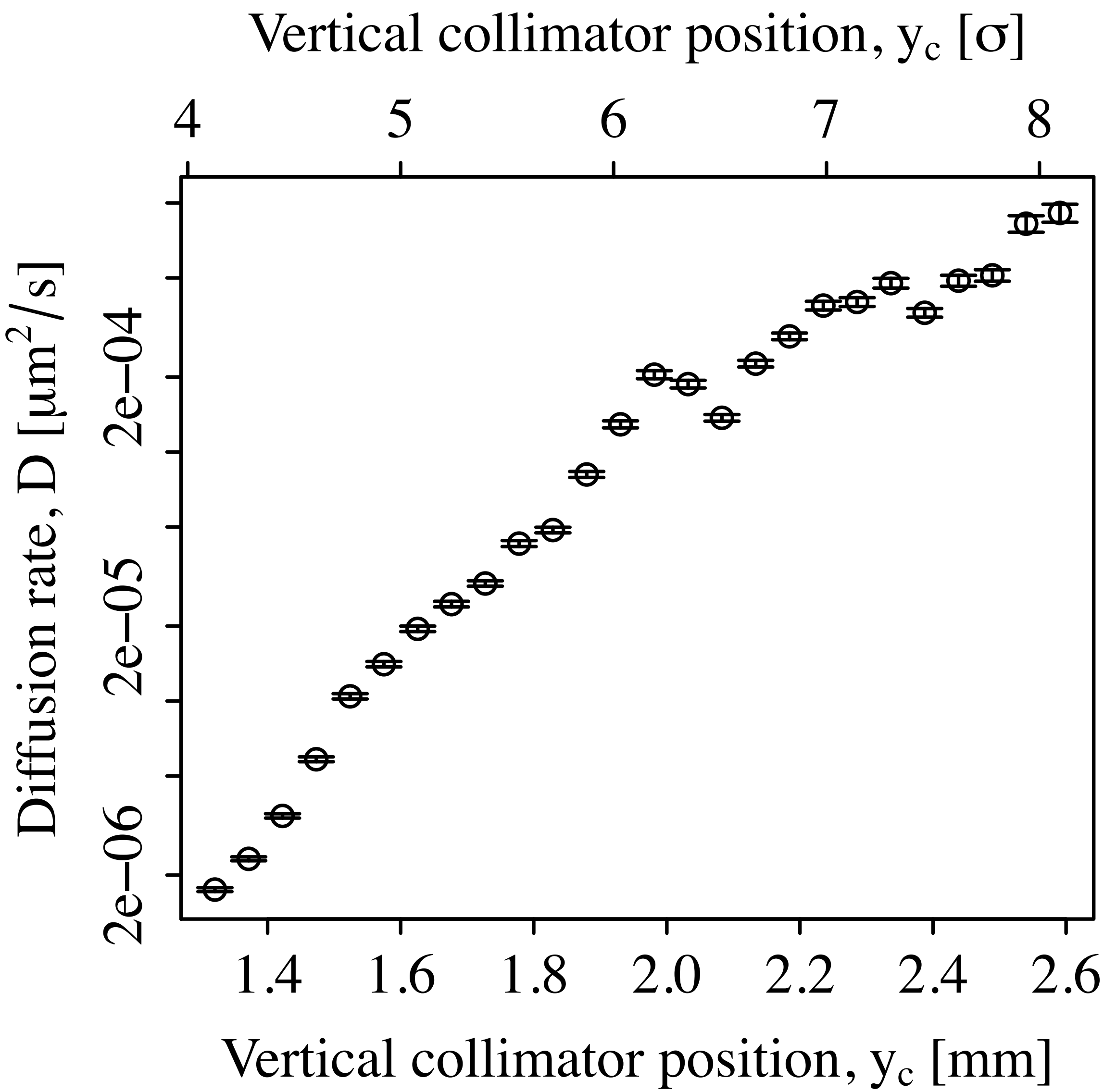
$$L(t) = a_1 \left\{ 1 + \frac{|\Delta x_c| / x_c}{\sqrt{\pi R (t - t_0)}} \right\} + a_0$$

normalization (intensity, efficiency, ...)

$D = R \cdot x_c^4 / \beta_c^2$

parameter related to diffusion rate

Diffusion rate vs. amplitude - preliminary



- First measurement of diffusion rates in Tevatron
- $D \sim J^{4.5}$

➡ see Stancari et al., IPAC11, TUPZ033
➡ arXiv:1108:5010

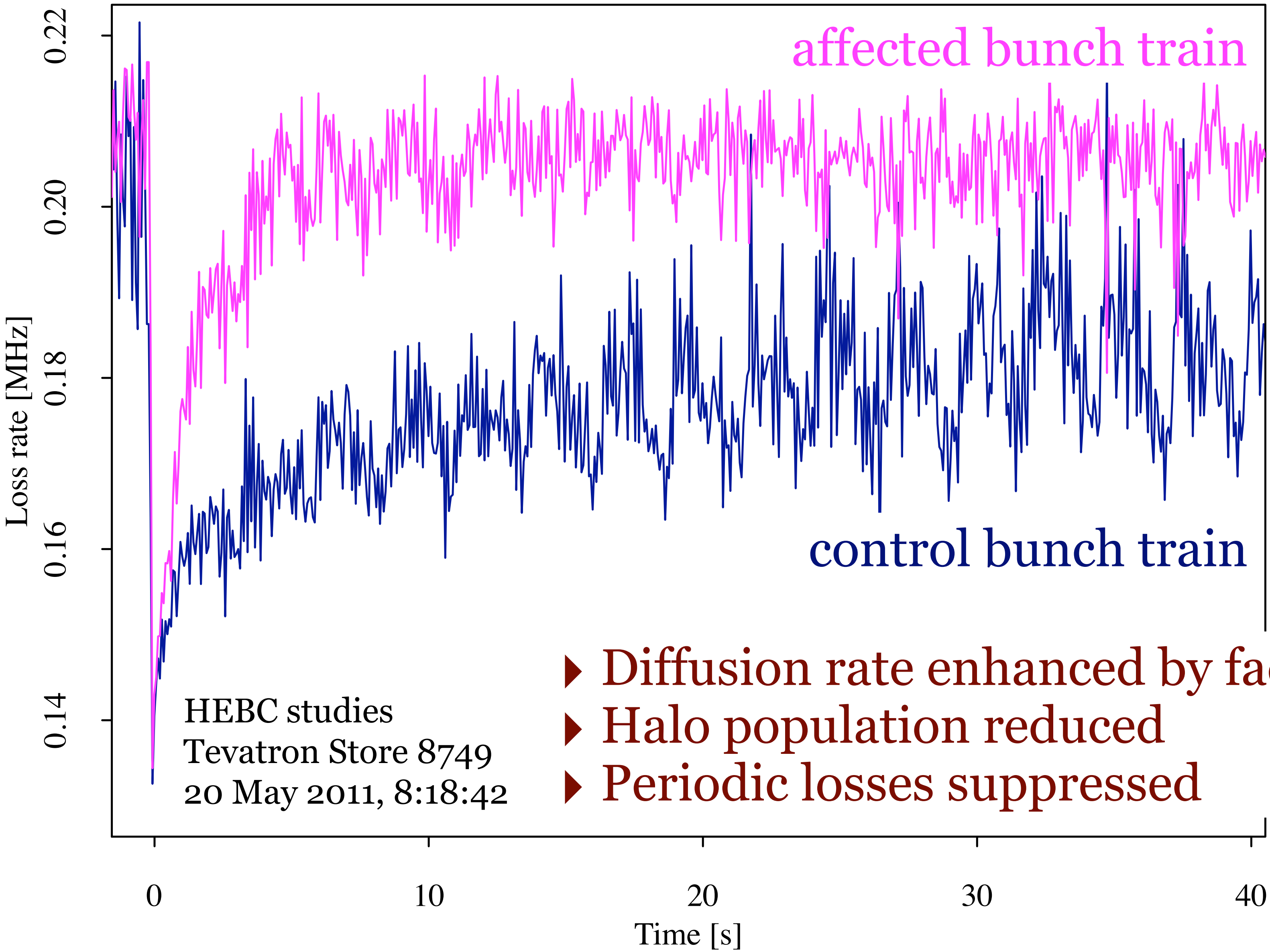
New gated antiproton loss monitors

- Scintillator paddles installed near F49 antiproton absorber (Mar '11)
- Gated to individual bunch trains
- Recorded at 15 Hz

For simultaneous measurements of **diffusion rates**, **collimation efficiency**, and **loss spikes** on affected and control bunch trains at maximum electron currents

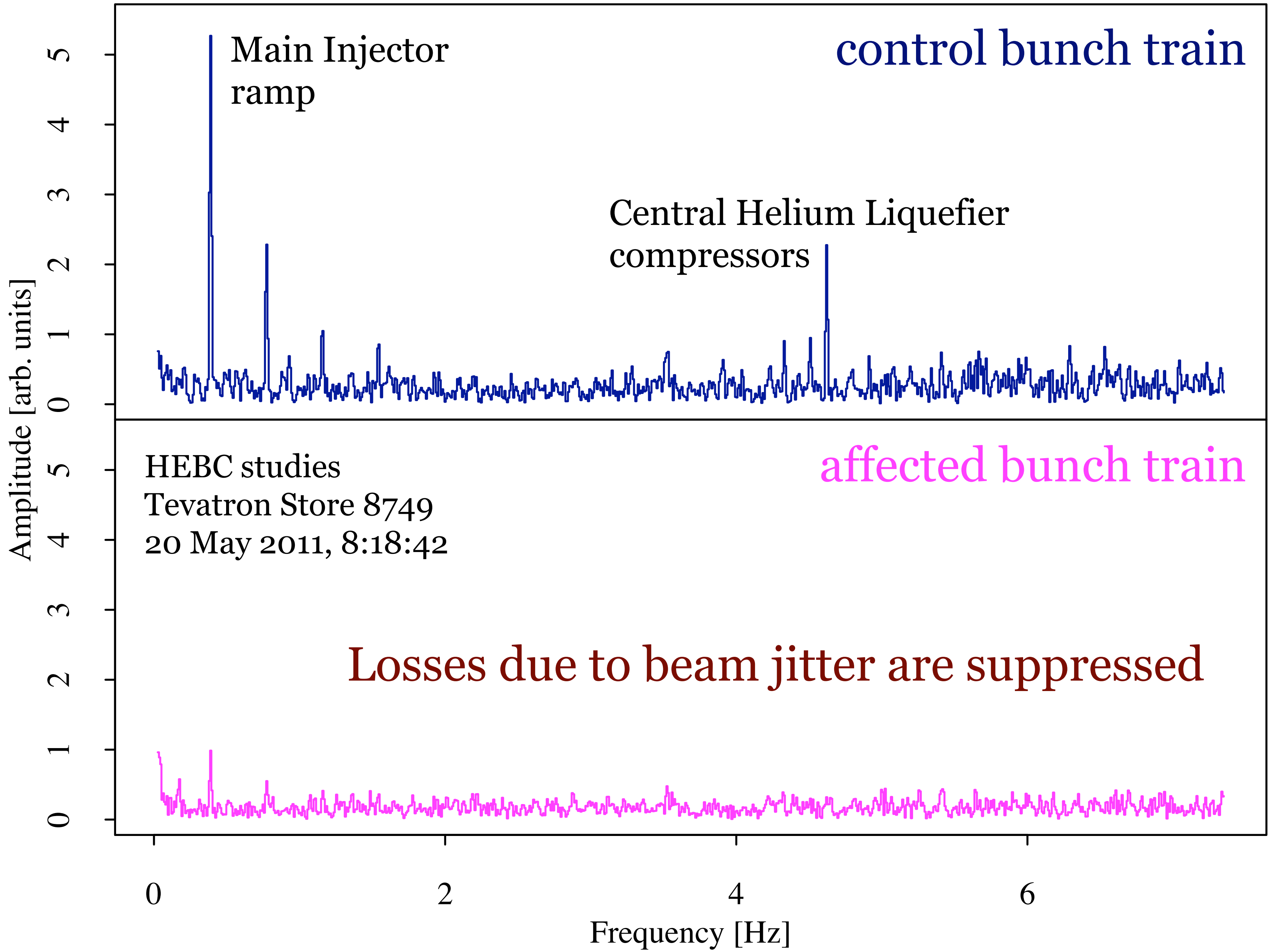
New gated loss monitors during collimator scan

Electrons (0.9 A) on pbar train #2, 4.25σ hole
Example of **vertical collimator step out**, 50 μm

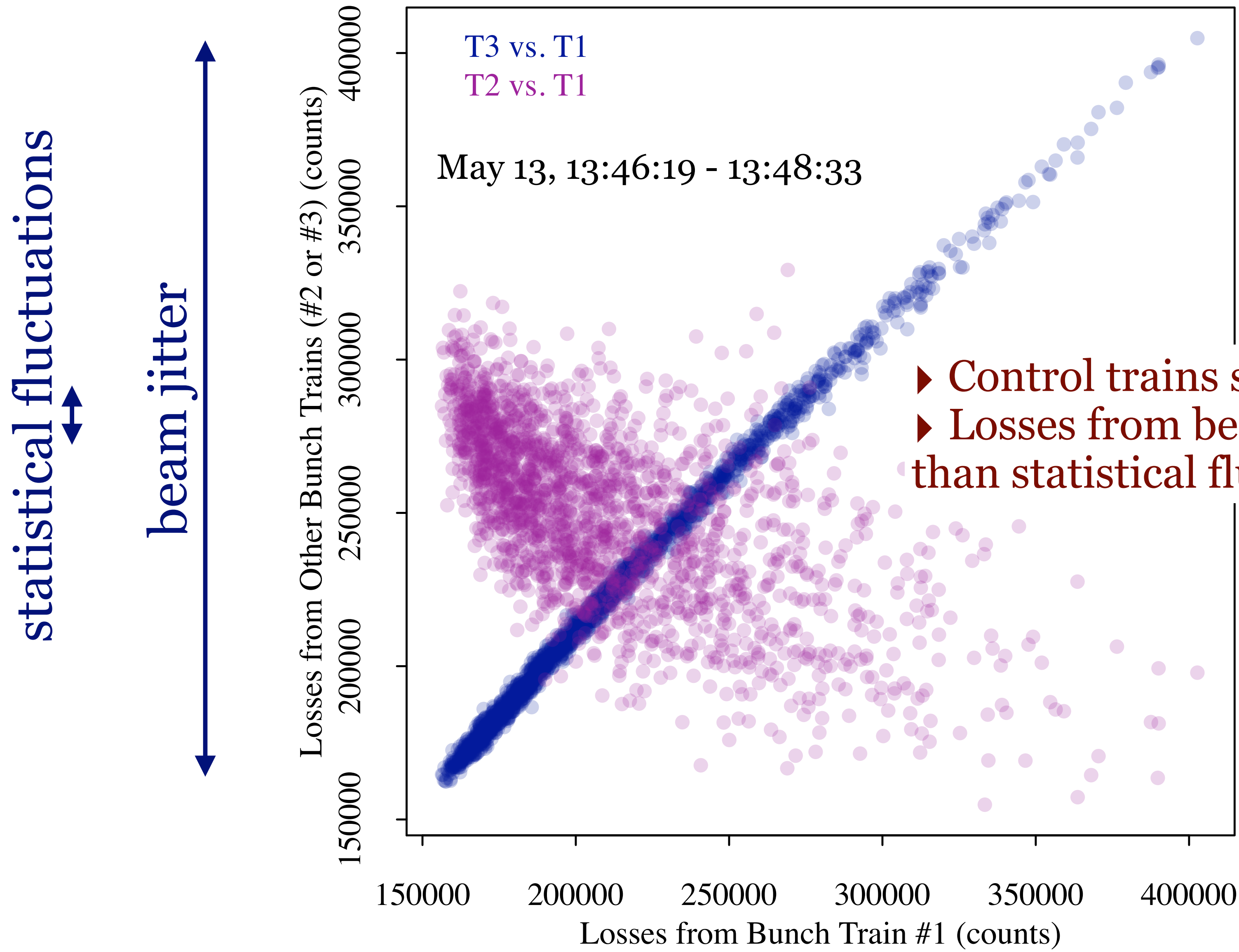


- Diffusion rate enhanced by factor ~10
- Halo population reduced
- Periodic losses suppressed

Fourier analysis of losses



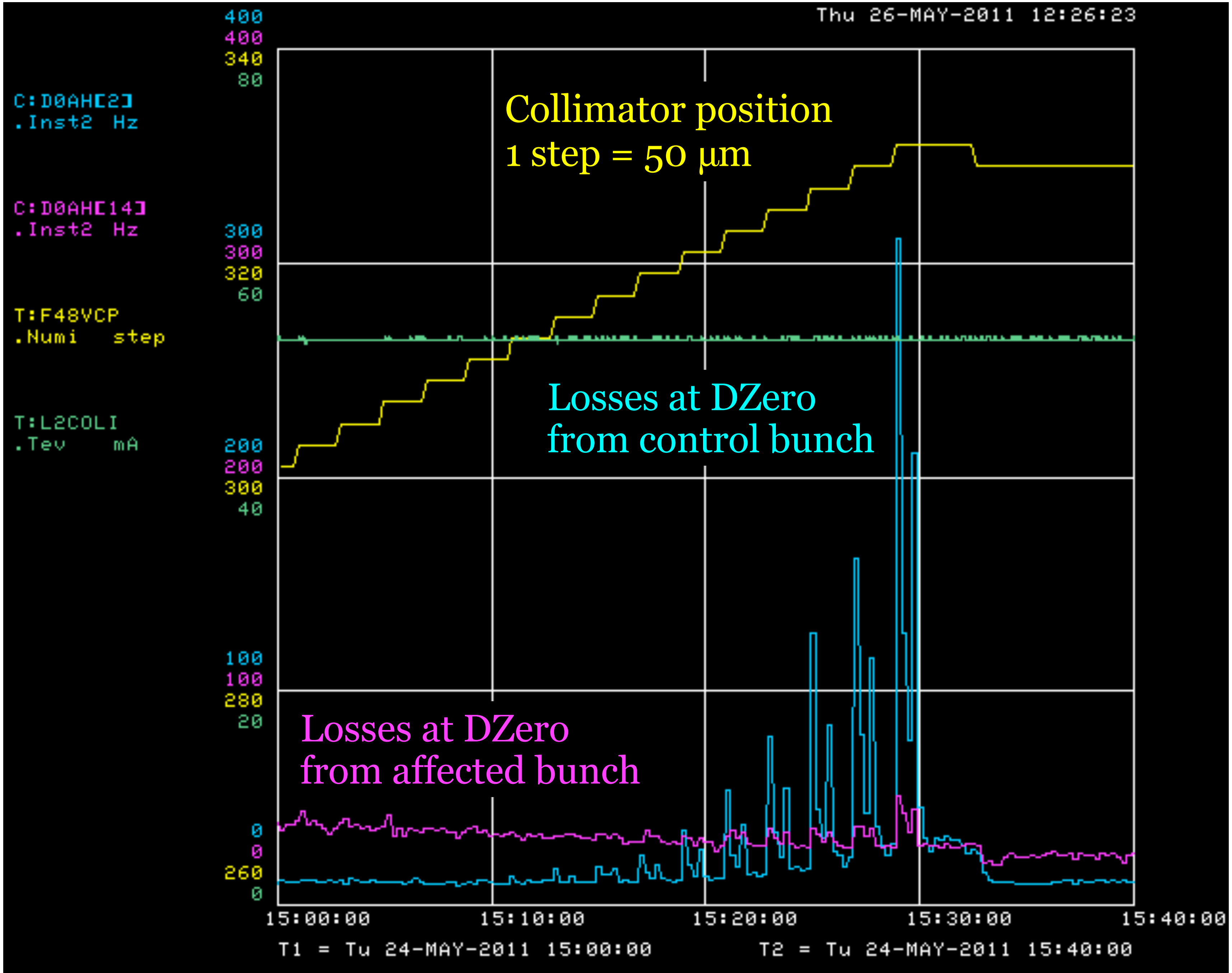
Correlation of steady-state losses



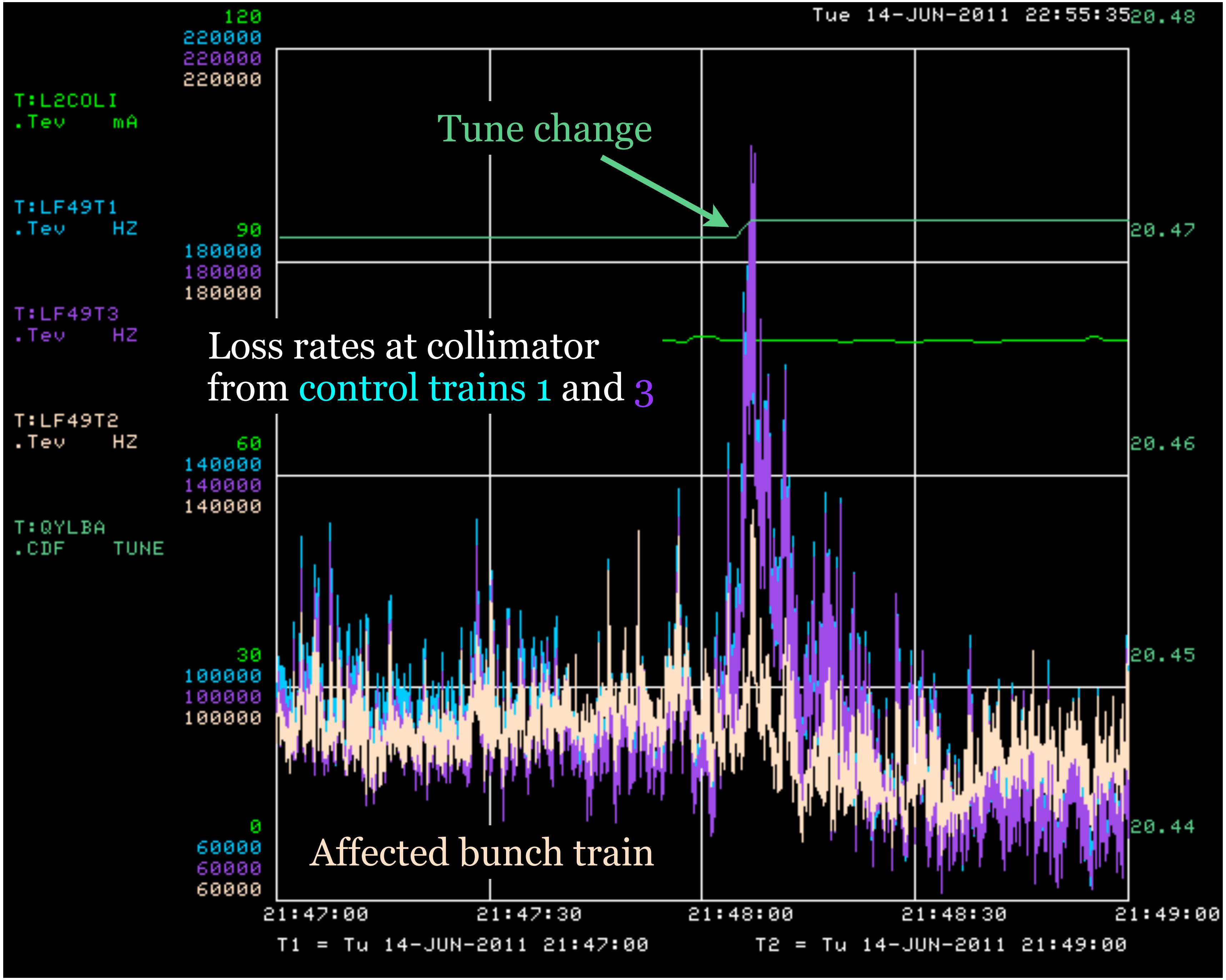
- Control trains strongly correlated
- Losses from beam jitter much larger than statistical fluctuations

- Hollow beam eliminates correlations among trains
- Interpretation: larger diffusion rate, lower tail population, less sensitive to jitter

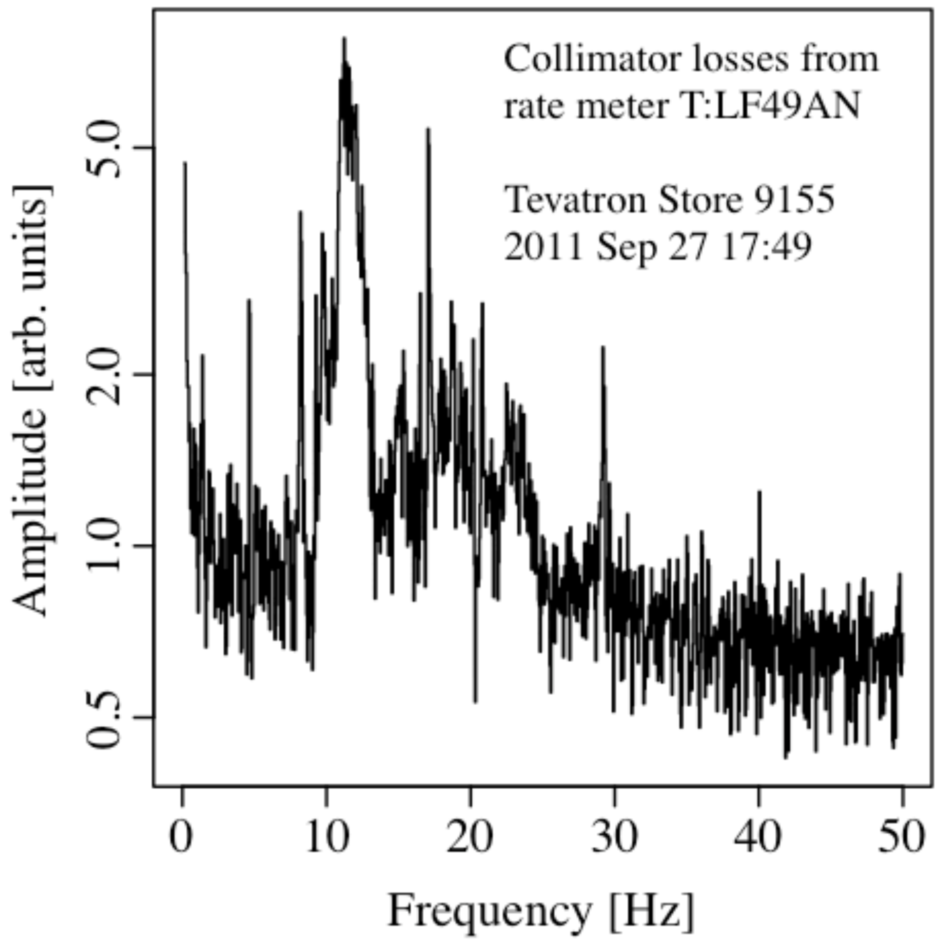
Suppression of loss spikes during collimator steps

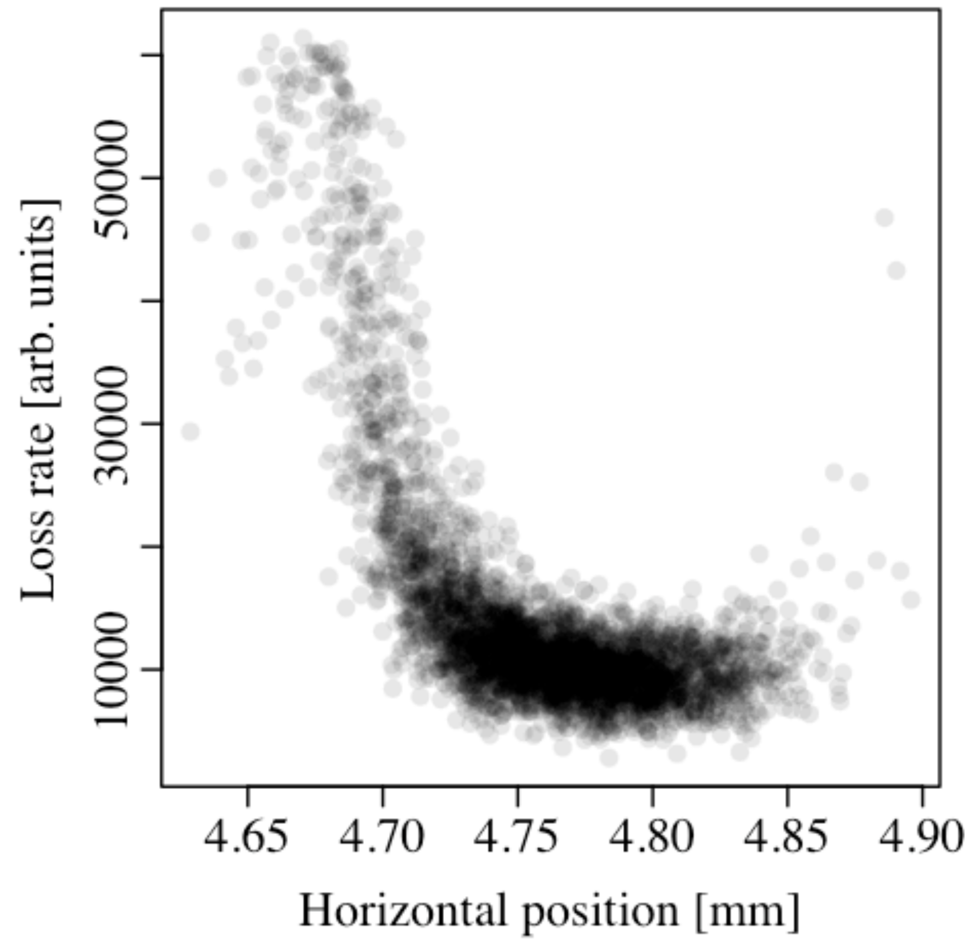


Suppression of loss spikes during tune change



Beam jitter in the Tevatron

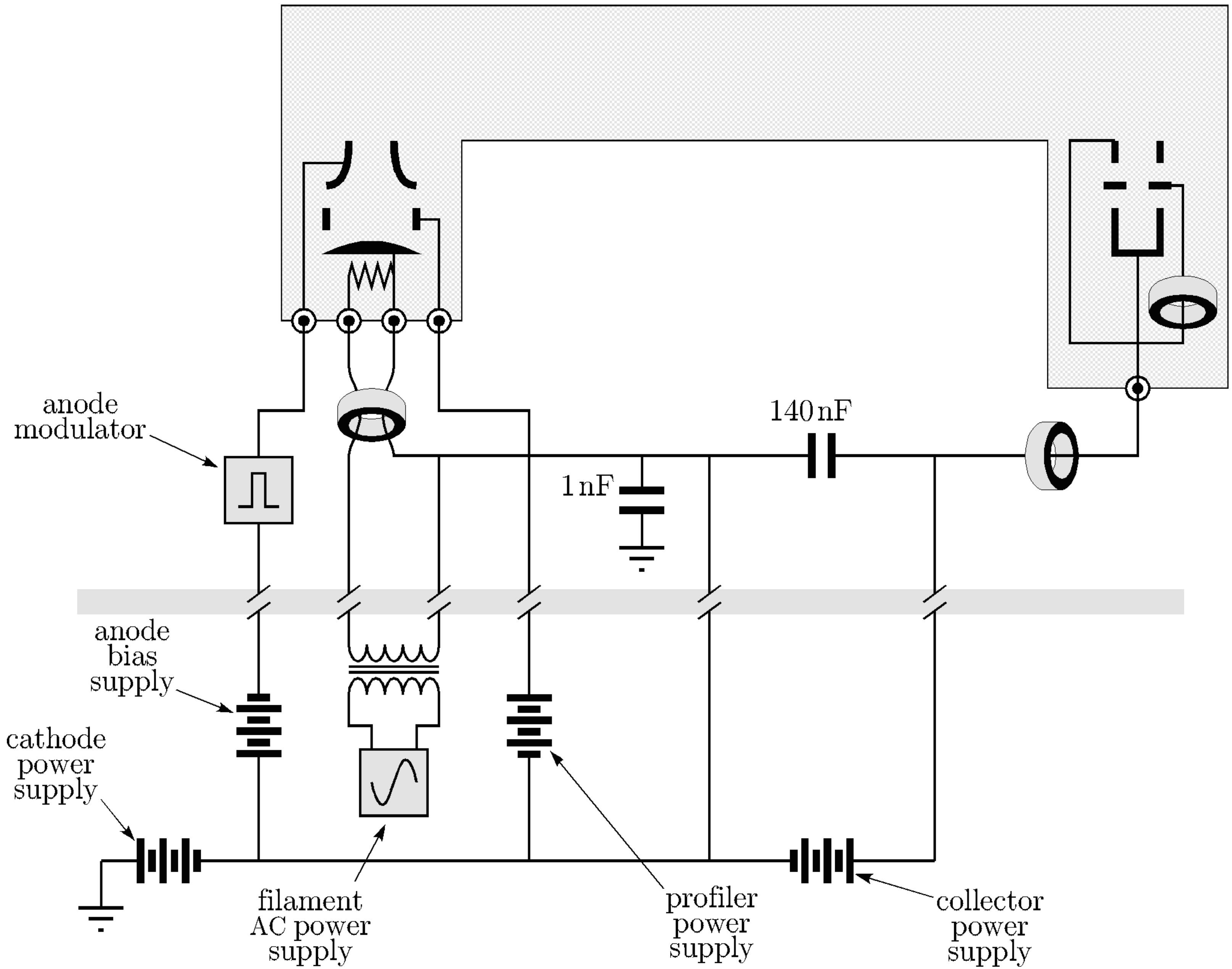




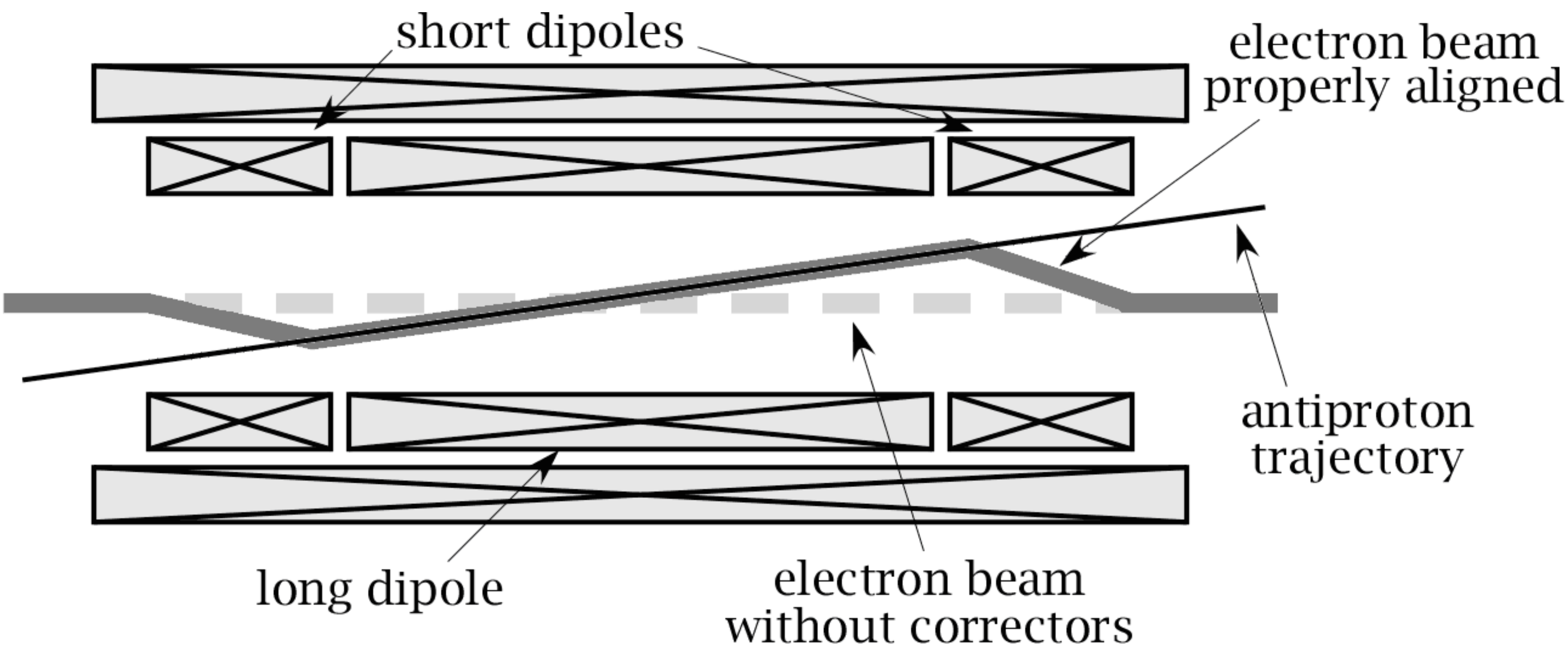
Principal subsystems

- Electrical
  - 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: ~5-10 kV
  - stacked-transformer modulator, anode pulsing: 5 kV, 150 kHz, 200 ns rise time
- Vacuum
  - 10^{-9} mbar typical
  - 3 ion pumps + Ti sublim.
- Cryogenics (4 K)
  - static heat load: 12 W (helium vessel), 25 W (nitrogen shield)
  - Tevatron magnet string cooling system: 90 l/s of liquid He
  - quench protection
- Diagnostics
  - 6 corrector magnets inside main solenoid
  - 2 BPMs (each horiz.+vert.)

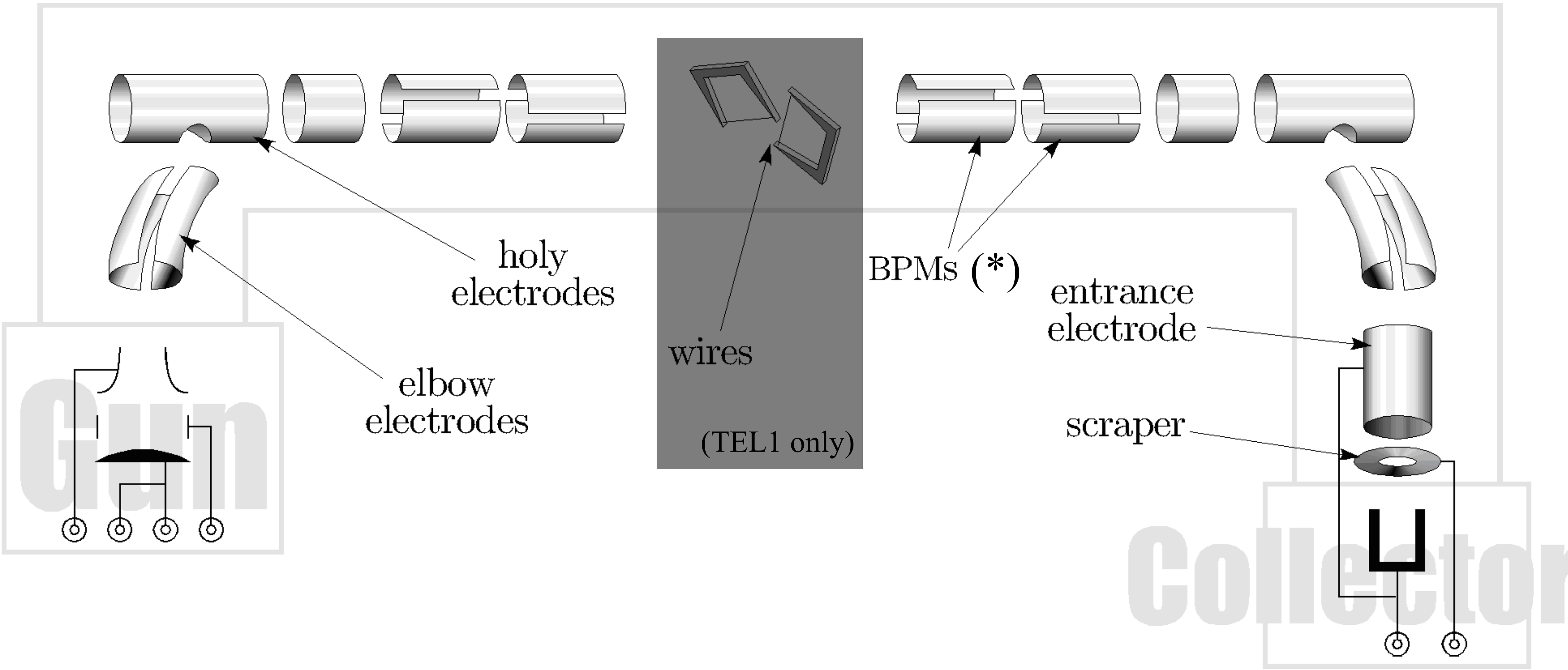
Tevatron electron lens: electrical schematic diagram



Tevatron electron lens: corrector dipoles



Tevatron electron lens: electrodes



(*) H and V BPMs combined in TEL2