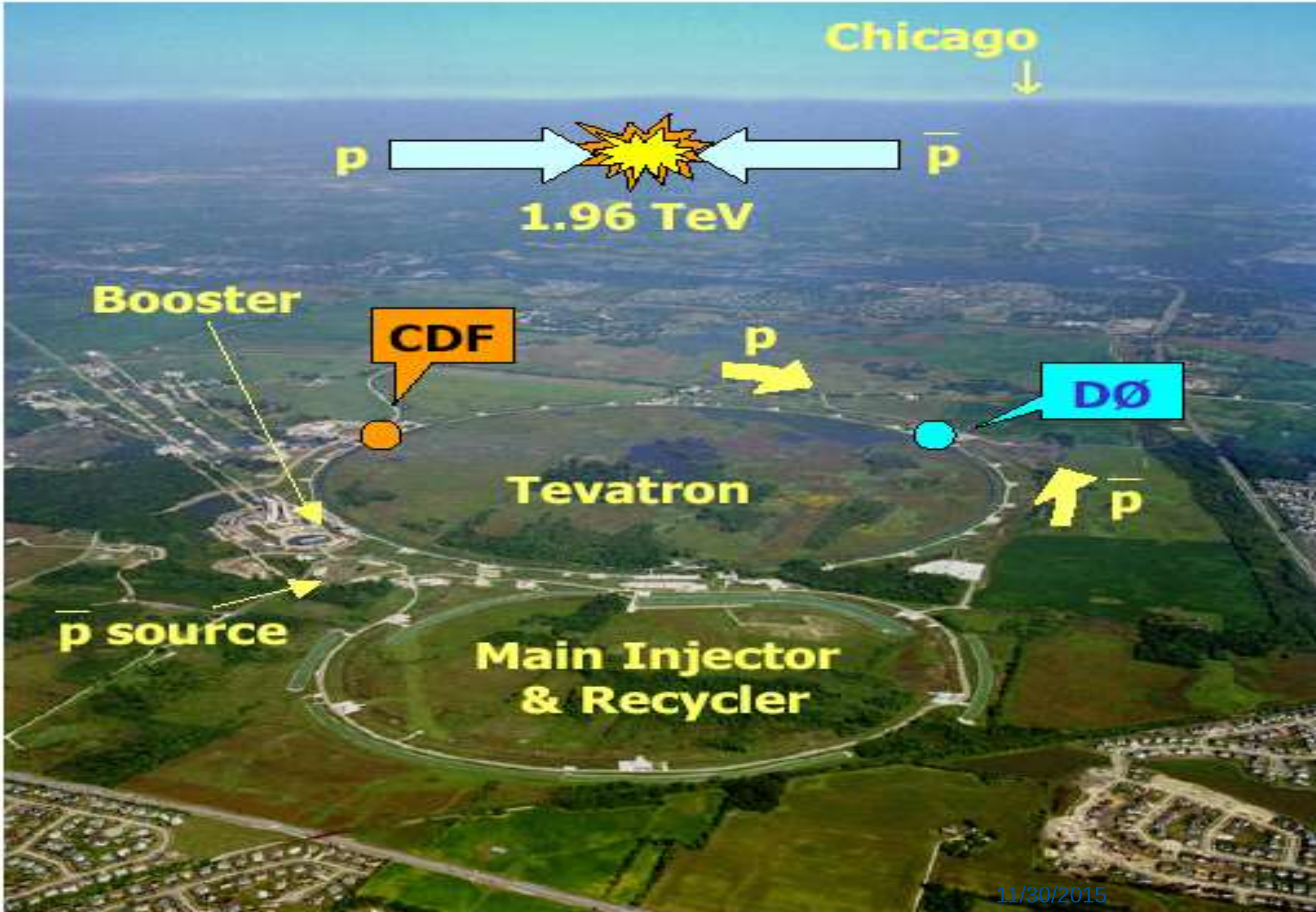
Tevatron Collider at Fermilab (Oct. 13, 1985 - Sep.30, 2011)



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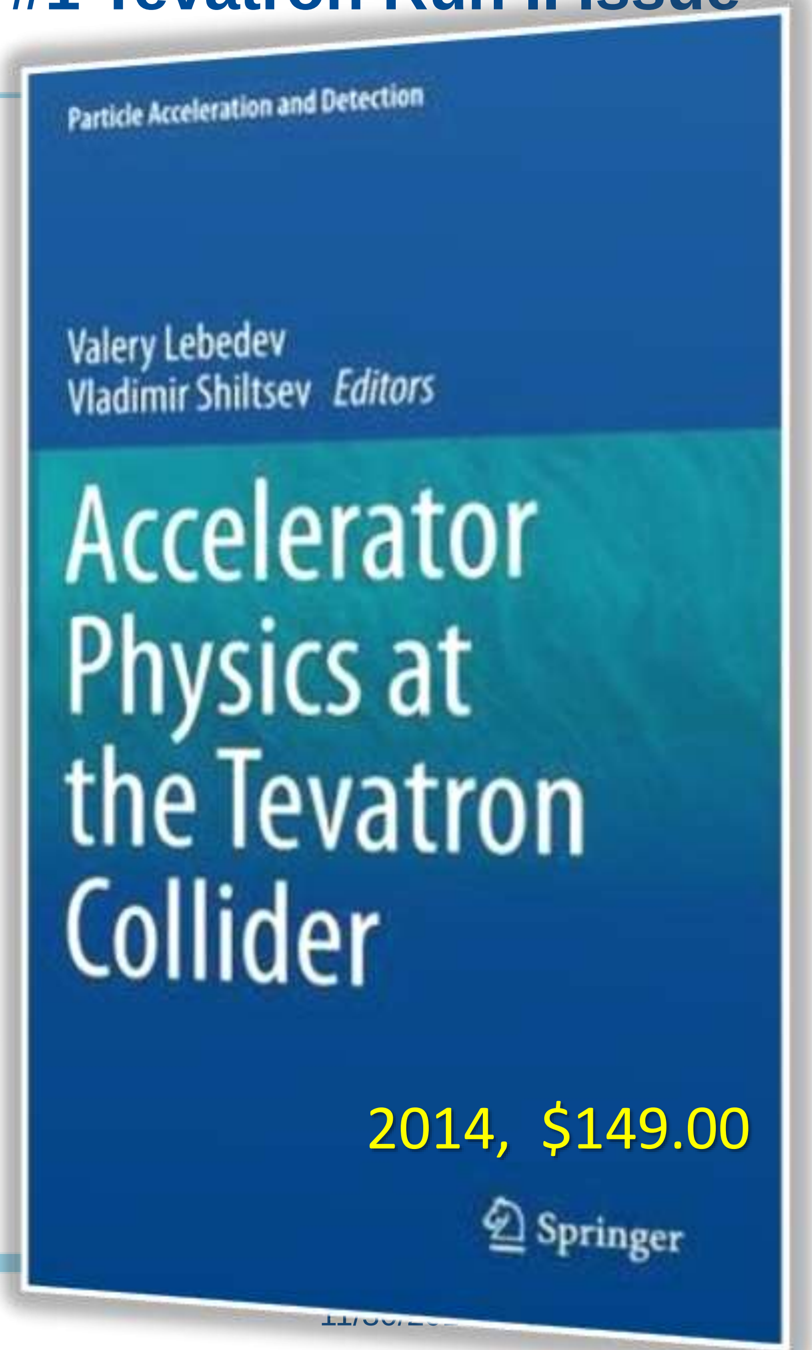
Long Range Beam-Beam Effects in the Tevatron *p-pbar* Collider Run II: Operational Realities & Corrections/TELs

Vladimir Shiltsev
Accelerator Physics Center, Fermilab
November 30, 2015

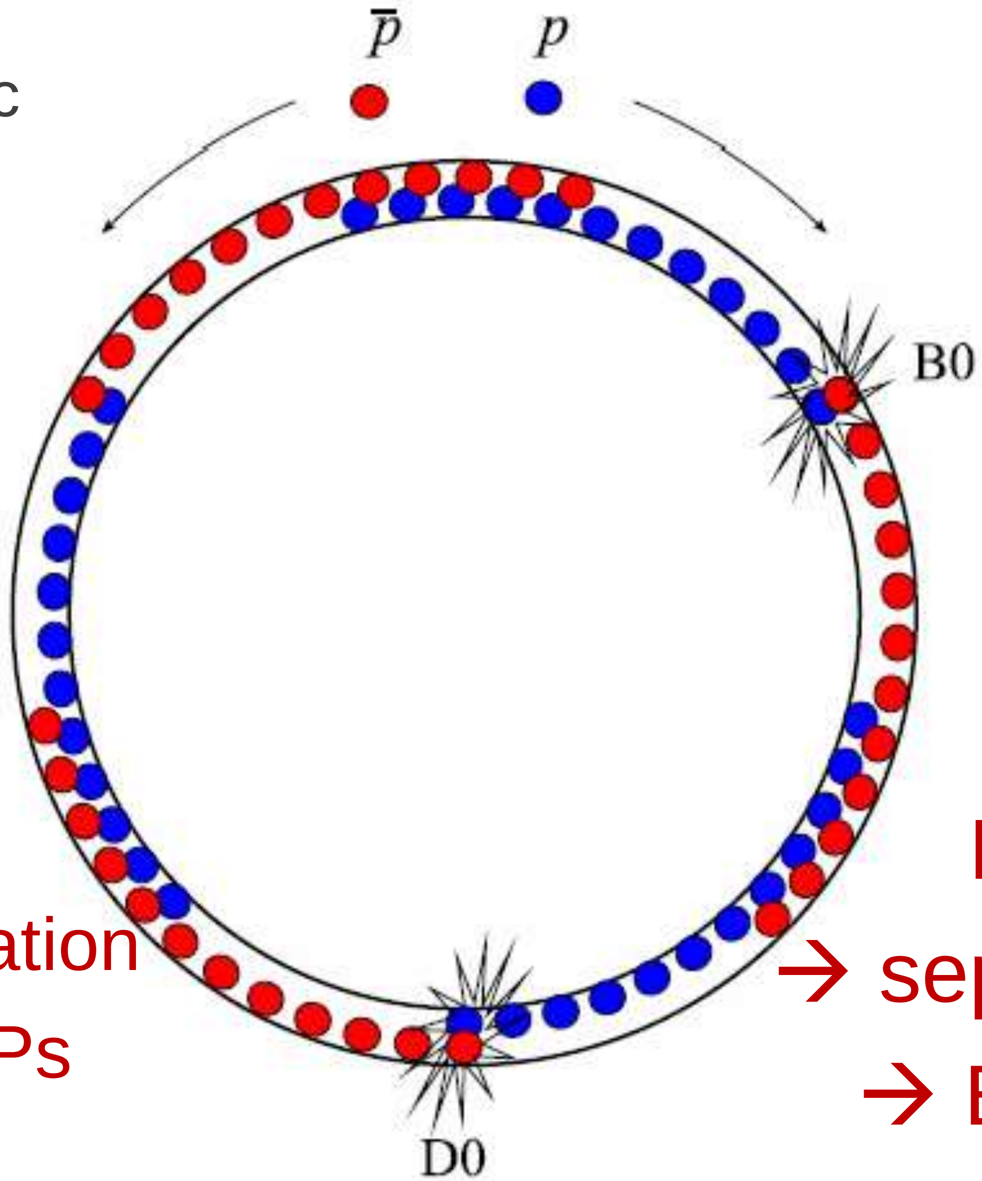
Long-range beam-beam – arguably, #1 Tevatron Run II Issue

- Many people studied the effects (operations, theory, studies, analysis)
  - Y.Alexahin, J.Annala, T.Bolshakov, V.Boocha, H.Cheung, B.Erdely, P.Garbincius, B.Hanna, P.Ivanov, J.Johnstone, A.Kabel, V.Lebedev, P.Lebrun, M.Martens, R.Moore, J.Qiang, T.Sen, F.Schmidt, D.Shatilov, V.Shiltsev, J.Slaughter, E.Stern, D.Still, G.Stancari, A.Tollestrup, A.Valishev, M.Xiao, X.L.Zhang, F.Zimmermann



36 proton x 36 antiproton bunches

Same magnetic fields → same orbits → 72 IPs



396 ns bunch separation → 59 m btw IPs

Need only 2 → separate at 70 → Electric field

Tevatron: Helical Orbits

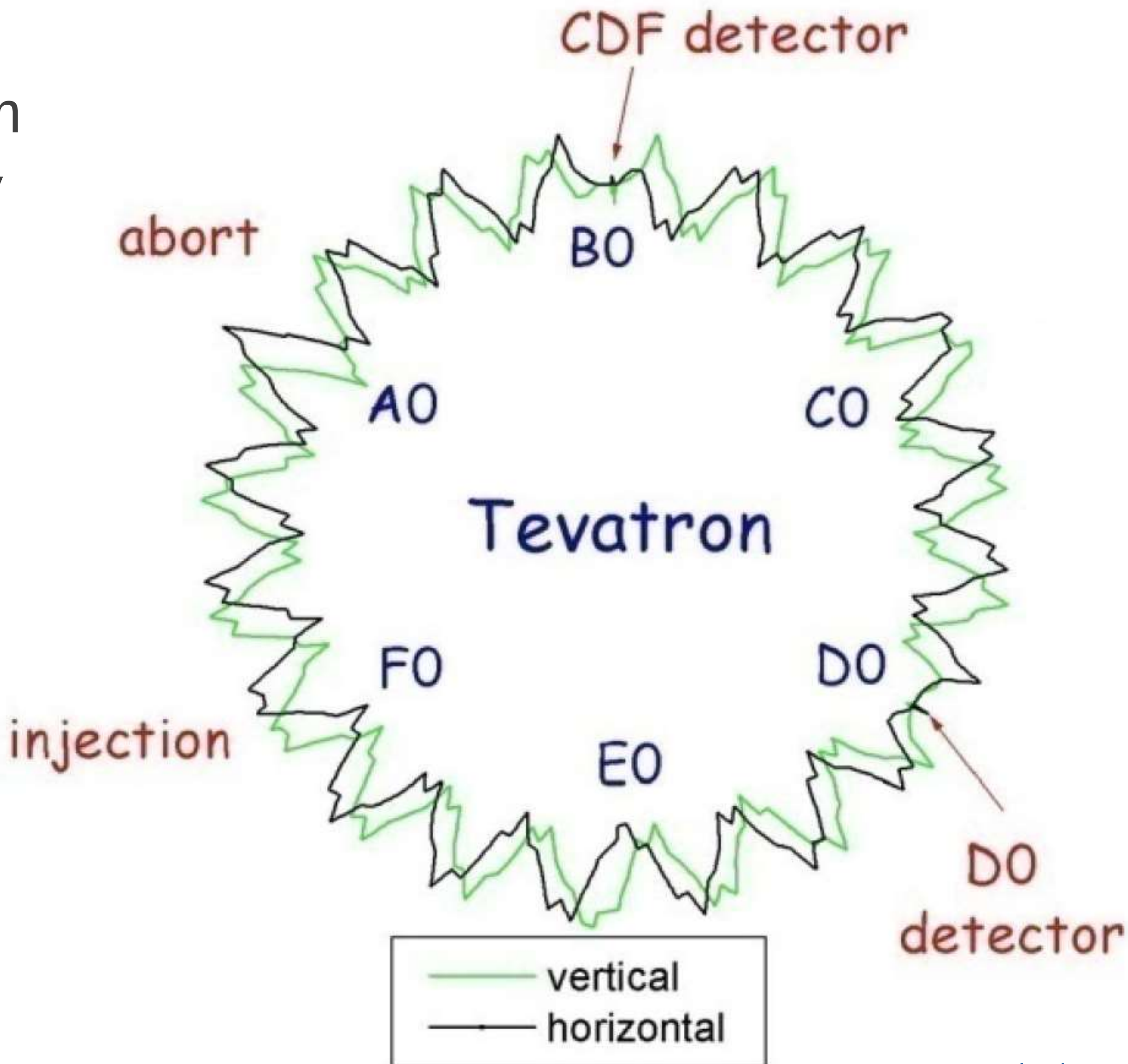
separation

~ 12-15 mm

at 150 GeV

6-8 mm

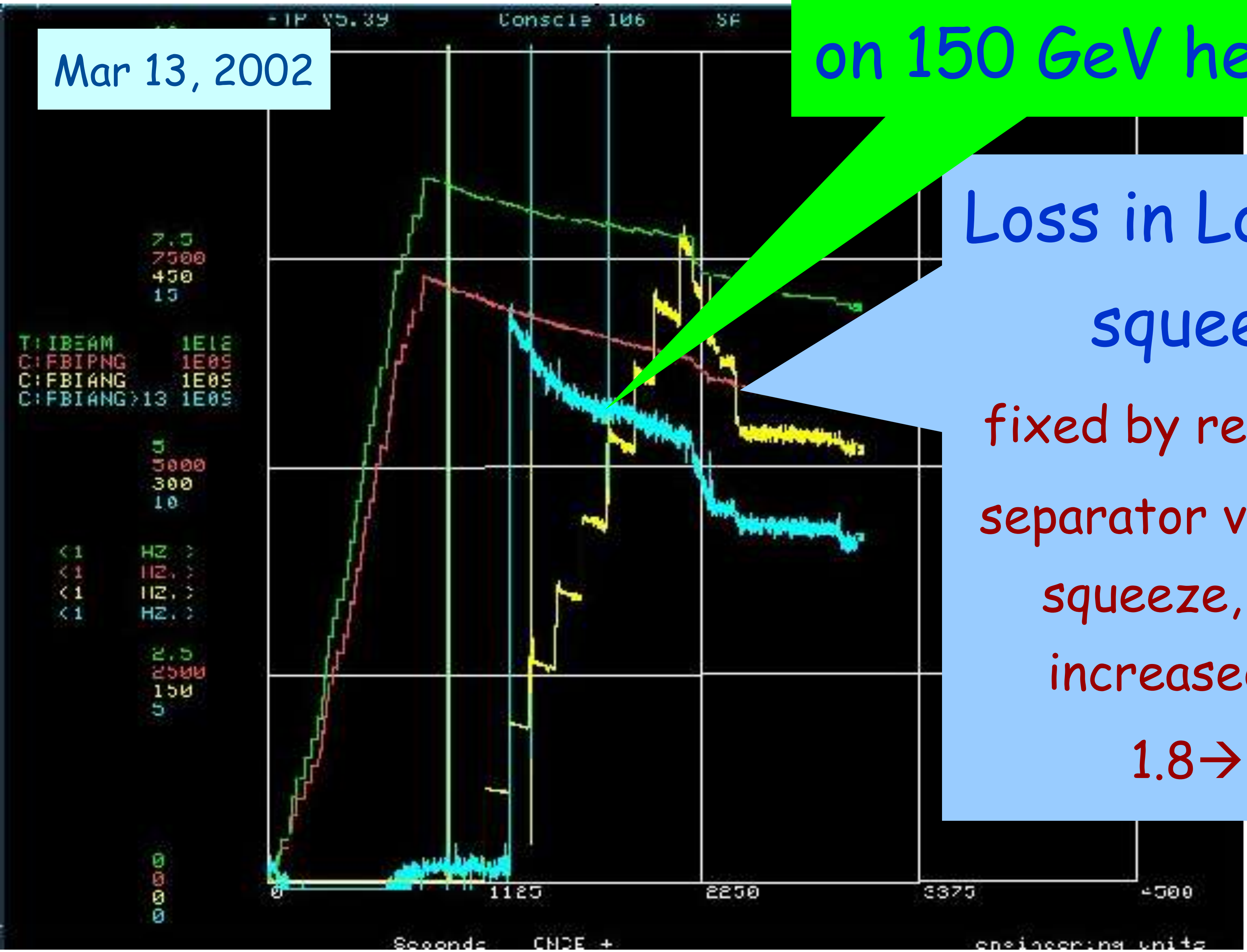
at LB



LR-Beam-Beam Effects in Tevatron (early Run II)

Mar 13, 2002

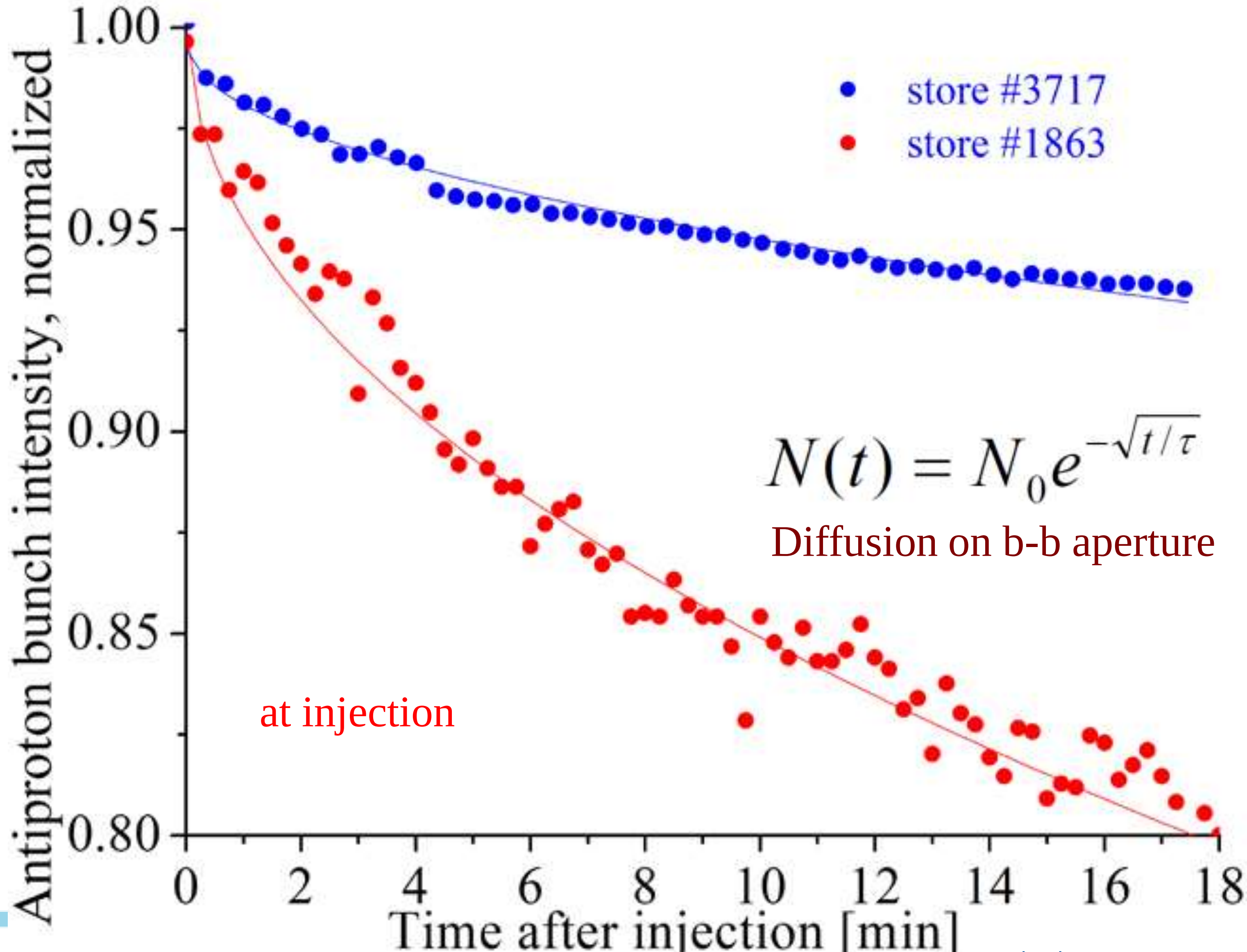
on 150 GeV helix



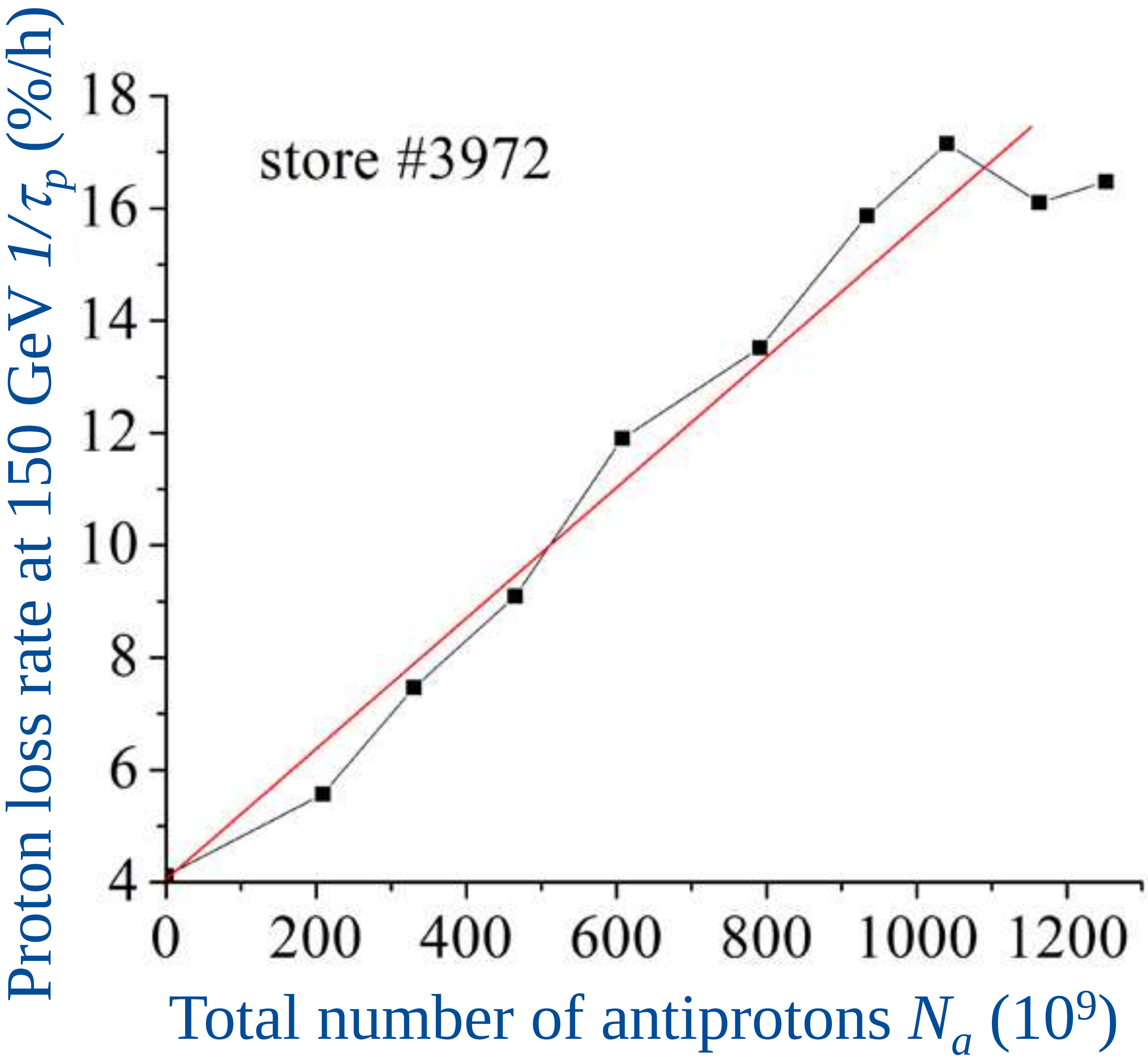
Loss in Low-Beta squeeze:

fixed by rearranging separator voltages in squeeze, so d/σ increased from $1.8 \rightarrow 2.7$

Separated beams – Long-range effects at injection, ramp, squeeze



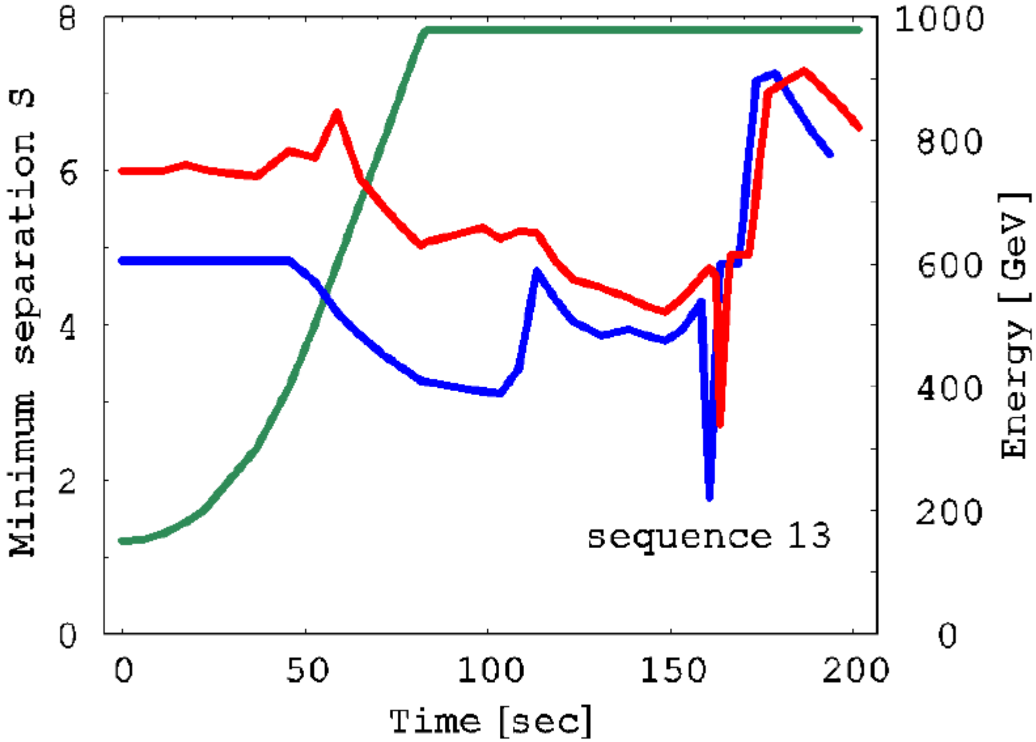
Losses Driven by Opposite Beam



Empirically Found Dependencies

- Losses were dependent on :

$$\frac{\Delta N_{a,p}}{N_{a,p}} = 1 - \frac{N(t)}{N(t=0)} \propto \sqrt{t} \cdot \varepsilon^2_{a,p} \frac{N_{p,a}}{\varepsilon_{p,a}} Q'^2_{a,p} \cdot F(\varepsilon_L, Q_{x,y}, S_{a-p})$$



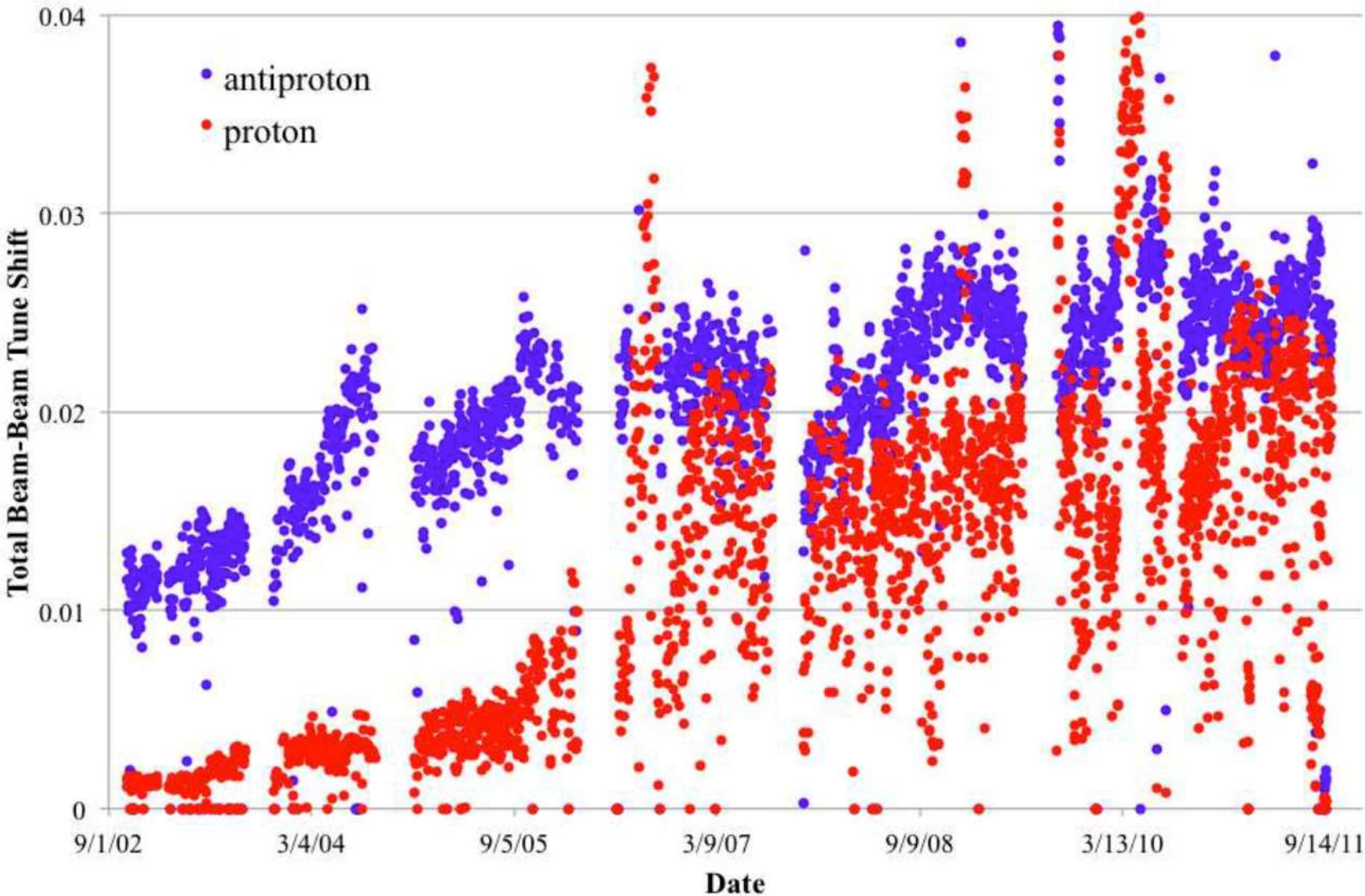
$$S = \sqrt{(\Delta x / \sigma_{x\beta})^2 + (\Delta y / \sigma_{y\beta})^2}$$

less than 5-6σ separation causes unsatisfactory losses

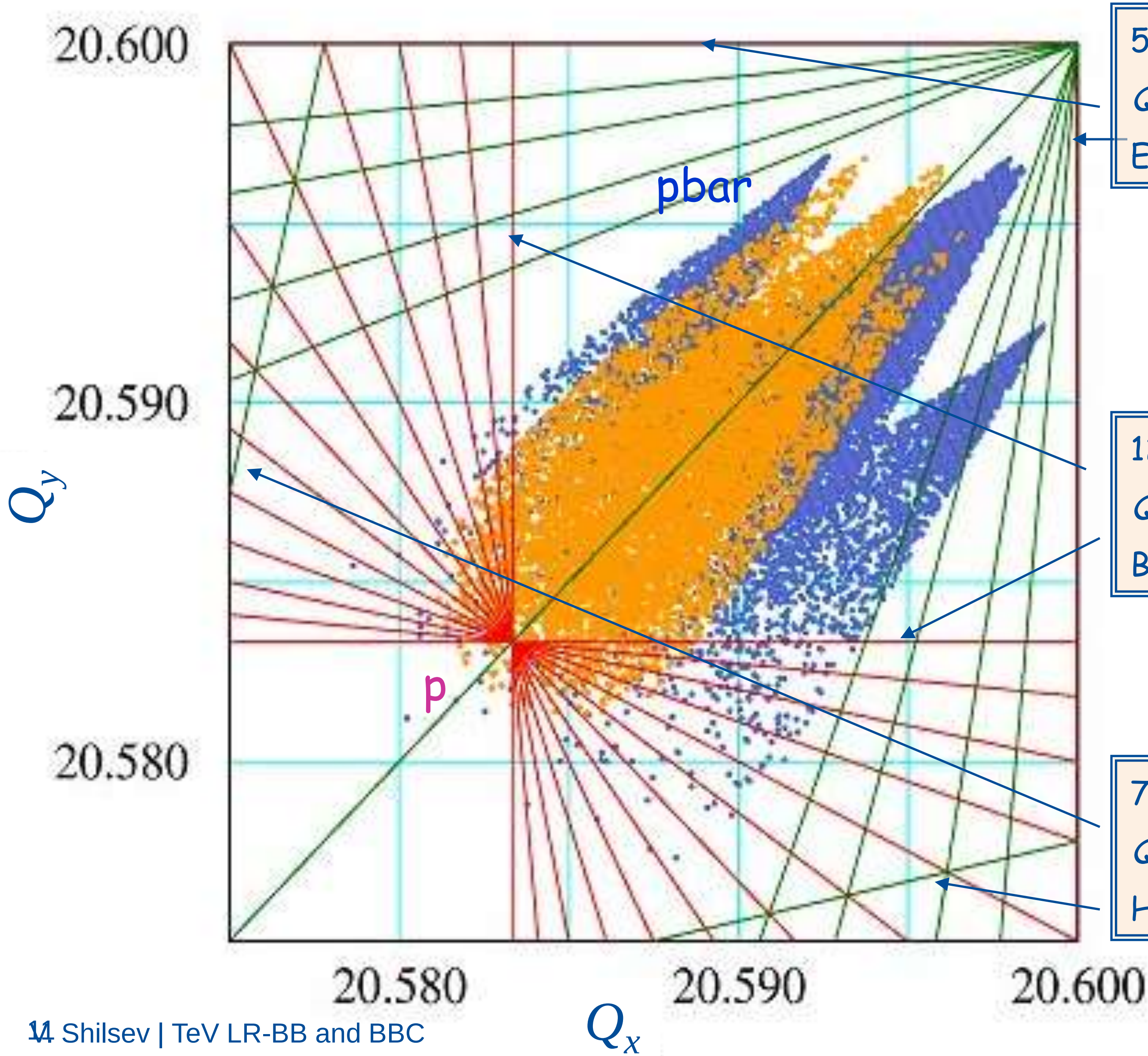
$$Q_x/Q_y = 20.584/20.576$$

Decreased Q' to ~3 and then to ~0 (new octupole circuits

Beam-beam During Collisions



Situation at Low-beta: Confinement



5th order resonances:
Q=3/5=0.600 –
EMITTANCE BLOWUP

protons
antiprotons

12th order resonances:
Q=7/12=0.583 -
Bad lifetime

7th order resonances:
Q=4/7=0.571 -
HIGH LOSSES

Luminosity Lifetime Constituents

$$\tau_L^{-1} = \tau_\varepsilon^{-1} + \tau_a^{-1} + \tau_p^{-1} + \tau_H^{-1}$$

(9-11) + (16-18) +(25-45)+(70-80) =(5-5.5) hrs

- Emittance growth = >90% IBS + <10% Beam-Beam
- Pbar lifetime = (80-85)% burnup + ~15% LRBB
- Proton lifetime = >50% Beam-Beam + <50 % burnup
- Hougrlass lifetime = >90% IBS + <10% Beam-Beam

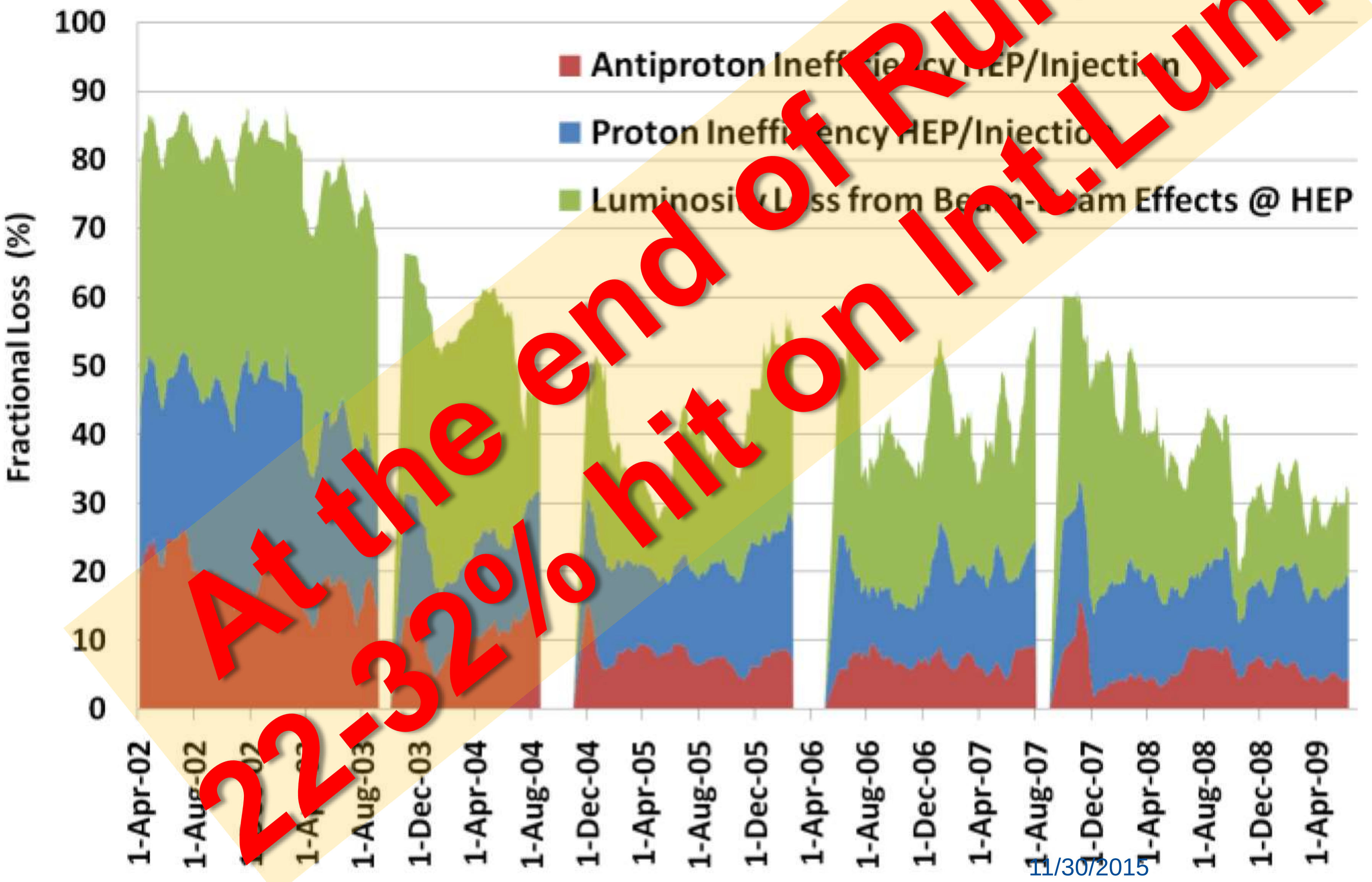
$$\left(\frac{1}{\tau_a}\right)_{BB} = \left(\frac{dN_a}{N_a dt}\right)_{BB} \propto N_p \frac{\varepsilon_a^2}{S^3}$$

IBS determined ~50-55% of lifetime

Burnup due to luminosity – another 30-35%

Beam-Beam reduces lumi-lifetime@LowBeta by 12-17 %

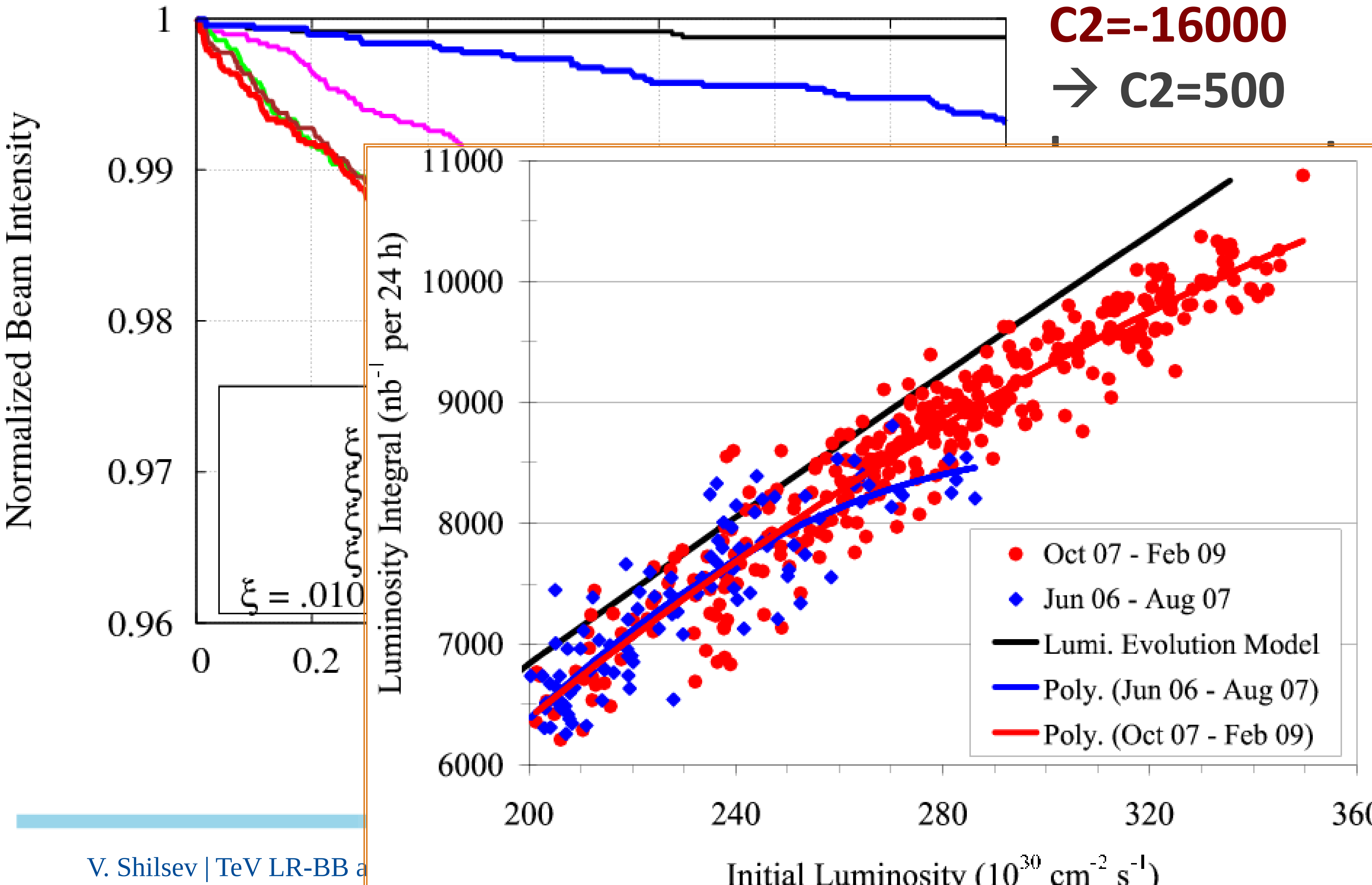
Total Luminosity Loss due to Beam-Beam



Effect of β* Chromaticity: Simulation → Practical Implementation

C2=-16000

→ C2=500

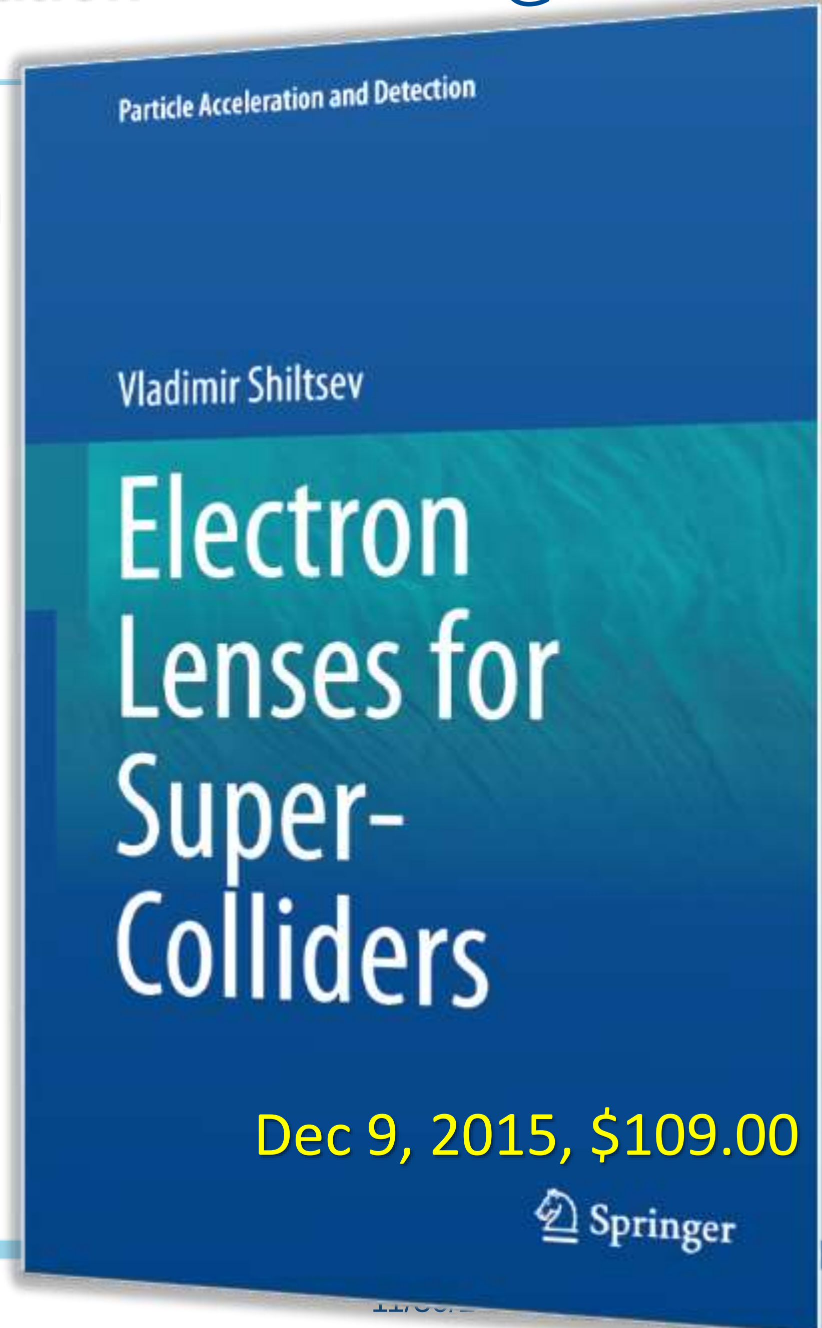


What helped us to reduce LRBB-*effects*

- Injection, ramp, low-beta squeeze:
  - Opened apertures (replaced magnets), increased helix
  - *Q'* reduced: Transverse Dampers & Octupoles
  - Emittances improved (thanks to injectors)
- At low beta (in collision stores)
  - Use new separators, helix optimized (1st LR IPs >6 sigma)
  - Lower Q', pbar blowup, tune stabilization
  - Chromatism of beta-function (*Q"*) greatly reduced
- Operational Machine Stabilization:
  - Stable intensities and emittances from injectors
  - Drastically stabilized Tevatron (orbits, tunes, chromaticities)
- Outstanding development of beam diagnostics
  - Tunes (3 instruments), emm (3), Intensity (3), lumi (2), BPMs
- (First ever?) **trustable beam-beam simulations**
- **First ever (!) operational electron lenses !**

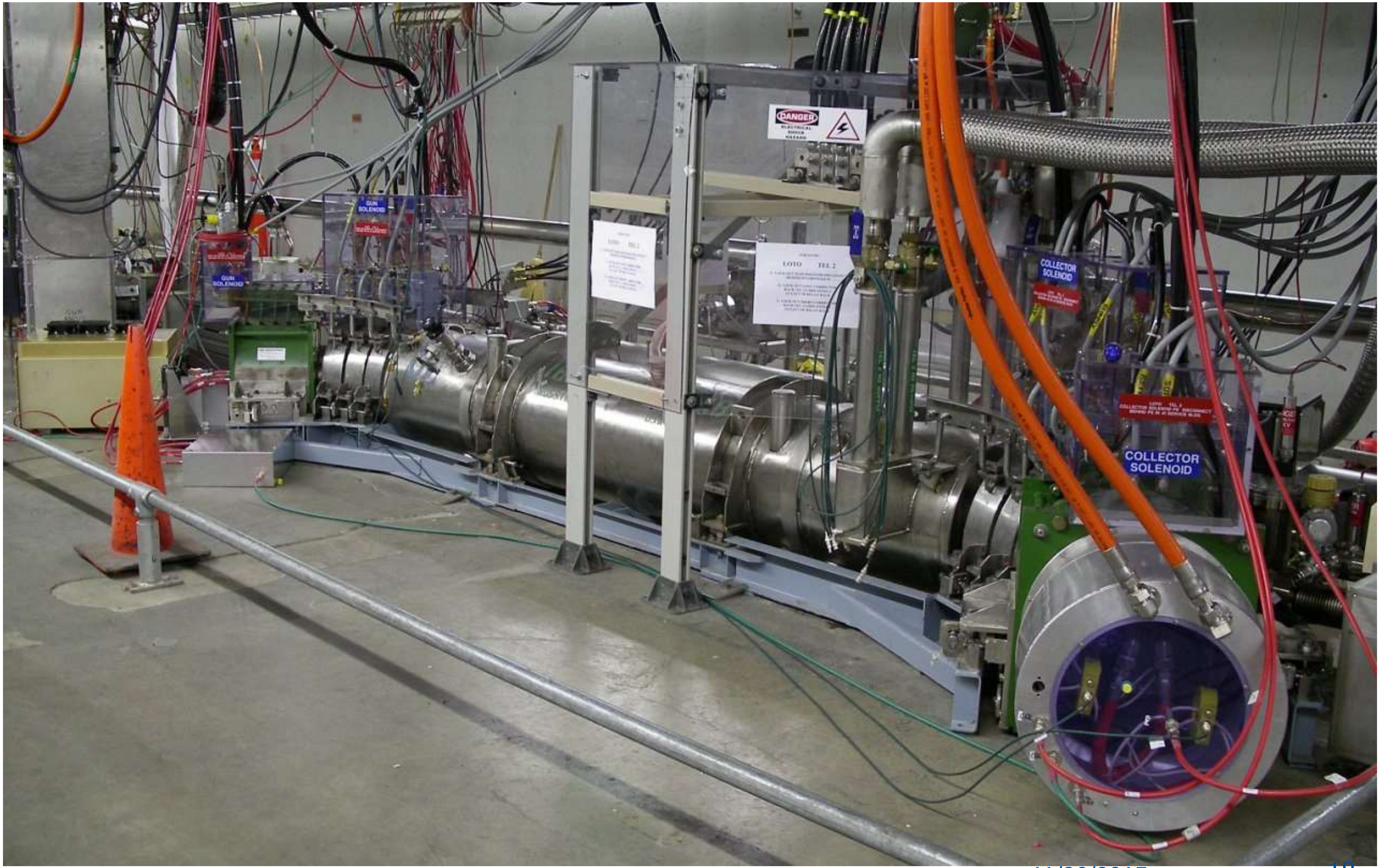
Electron Lenses for BB-Compensation – First time@Tevatron

- Many people worked on the LRBB compensation with e-lens program (operations, theory, studies, analysis)
  - A.Alexandrov, Y.Alexahin, K.Bishofberger, A.Burov, V.Danilov, D.Finley, R.Hively, V.Kamerdzhiev, M.Kufer, G.Kuznetsov, S.Kozub, A.Martinez, M.Olson, V.Parkhomchuk, H.Pfeffer, V.Reva, G.Saewert, V.Scrapine, A.Seryi, D.Shatilov, A.Shemyakin, V.Shiltsev, N.Solyak, G.Stancari, D.Still, B.Sukhina, V.Sytnik, M.Tiunov, L.Tkachenko, A.Valishev, L.Vorobiev, D.Wildman, D.Wolff, X.L.Zhang, A.Zinchenko, F.Zimmermann



Tevatron Electron Lens #1 (F48): 24/7 operation *2001-2011*

TEL2 (A11): 24/7 operation & studies <u>2004-2011</u>



TELs: Electron Charge Distribution

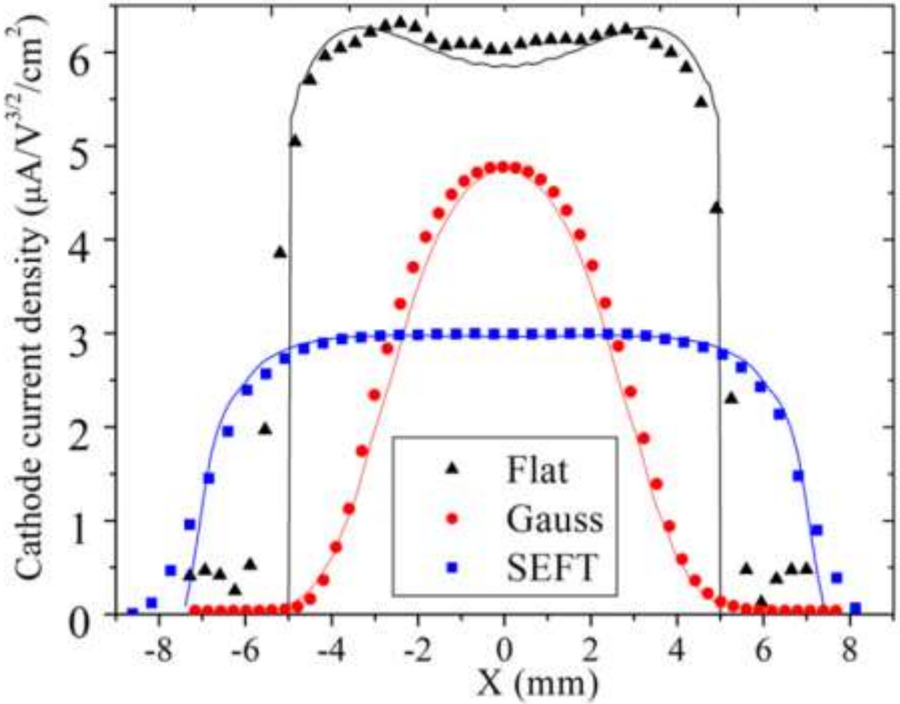
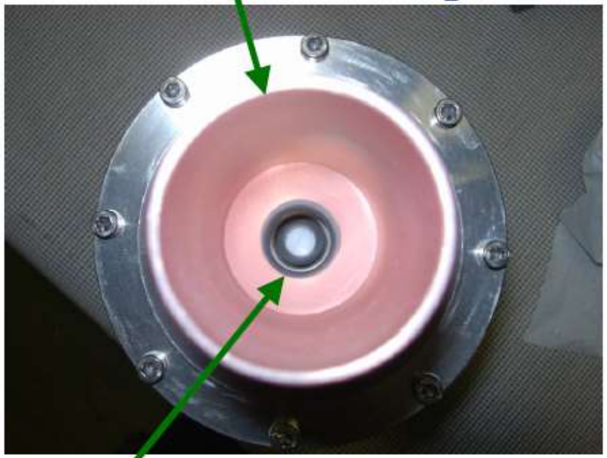
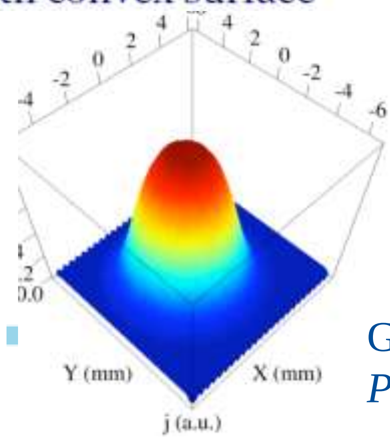


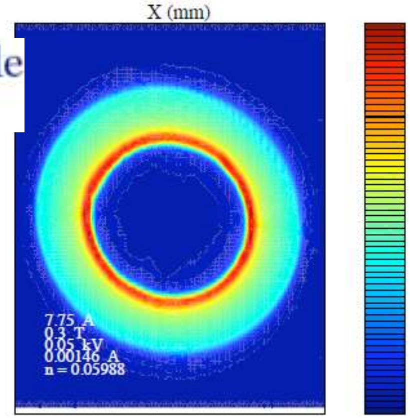
Figure 2. Three profiles of the electron current density at the electron gun cathode: black, flattop profile; red, Gaussian profile; blue, SEFT profile. Symbols represent the measured data and the solid lines are simulation results. All data refer to an anode–cathode voltage of 10 kV.

Shiltsev et al., *PRL* 99, 244801 (2007).
Shiltsev et al., NJP 10, 043042 (2008).

Electron gun



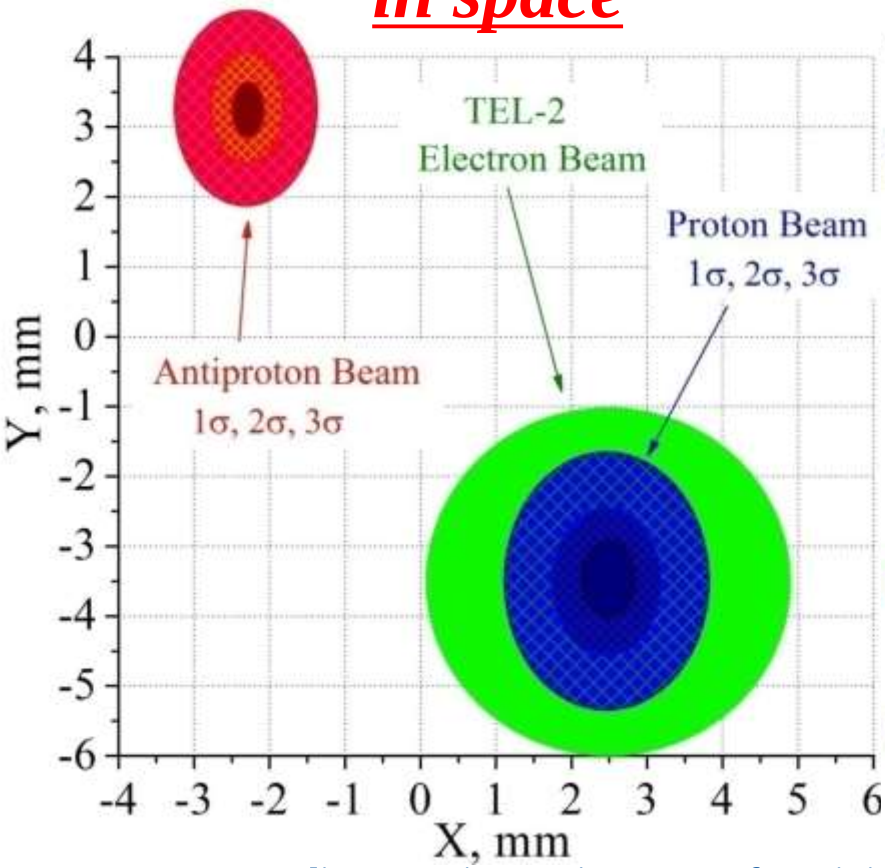


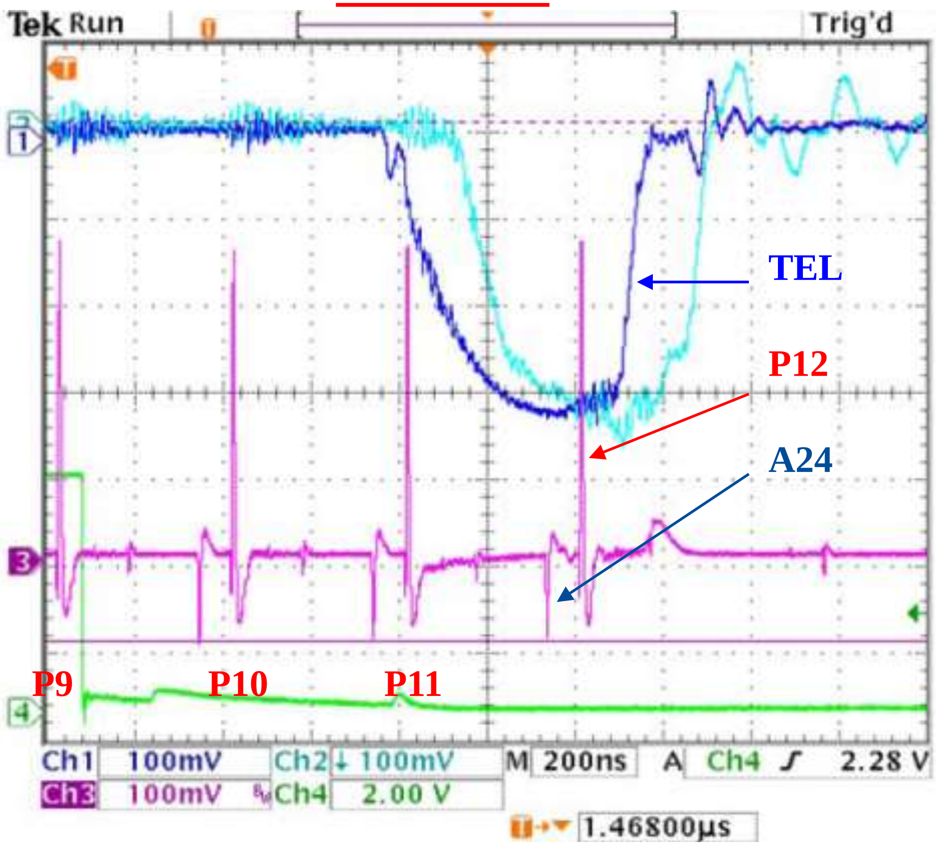


G. *Stancari*, et al., (2011)
Phys. Rev. Lett. 107, 084802

TEL e-beam aligned and timed on protons

in space / *in time*

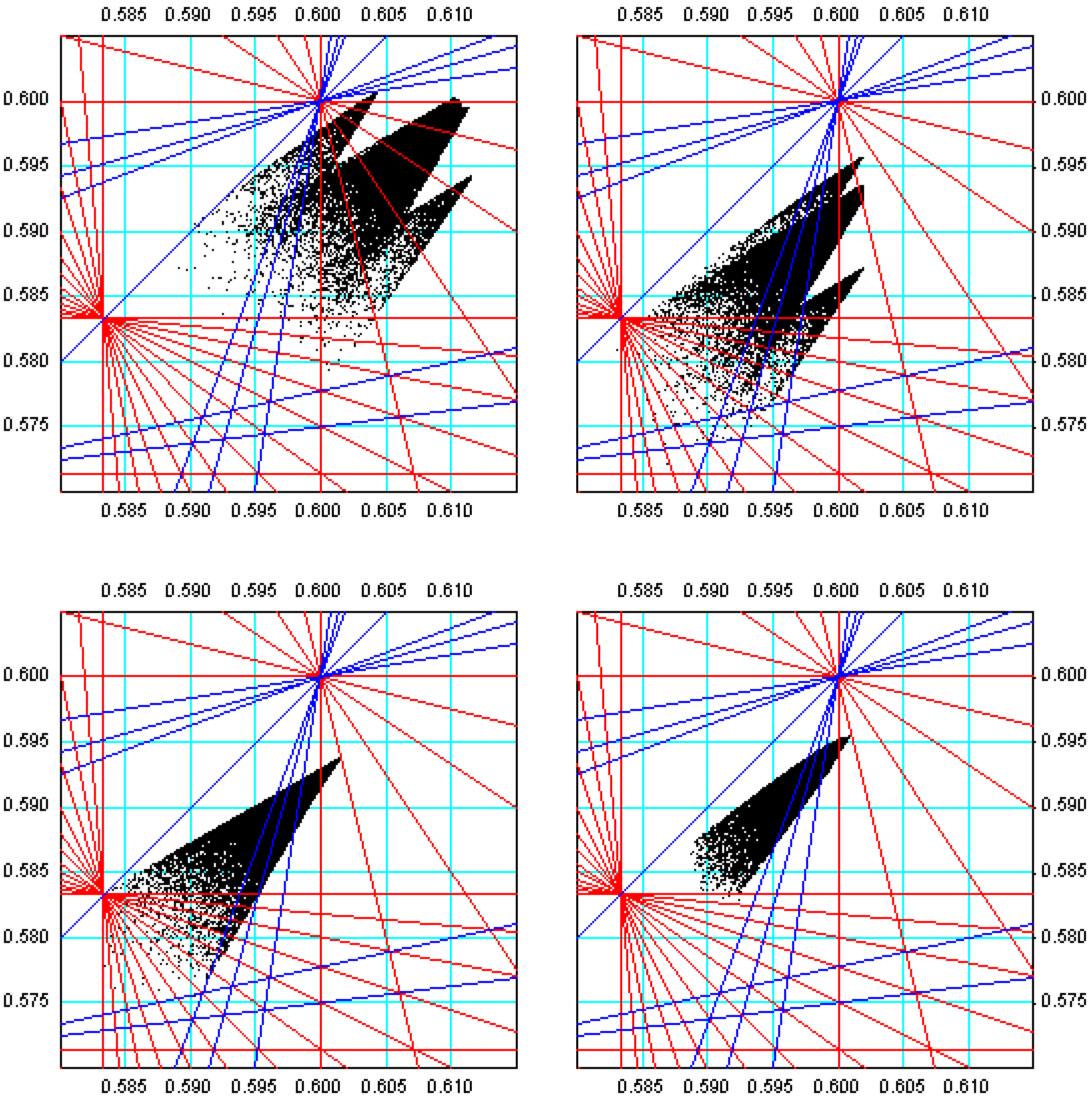


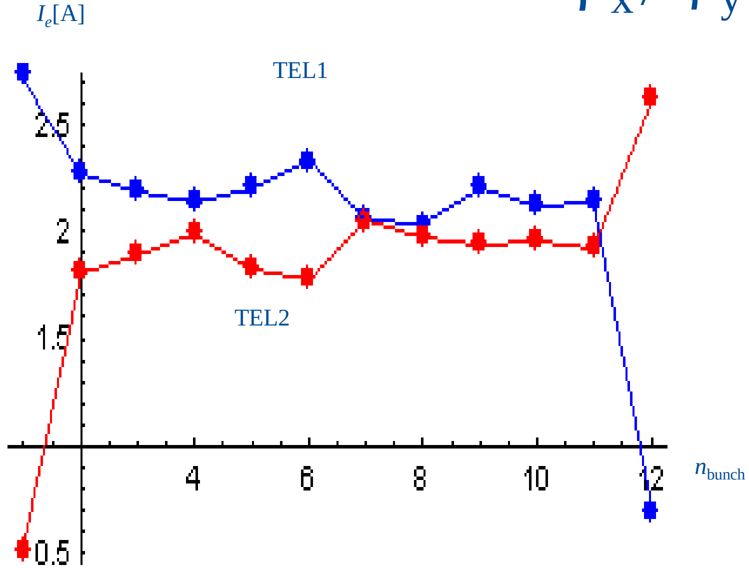


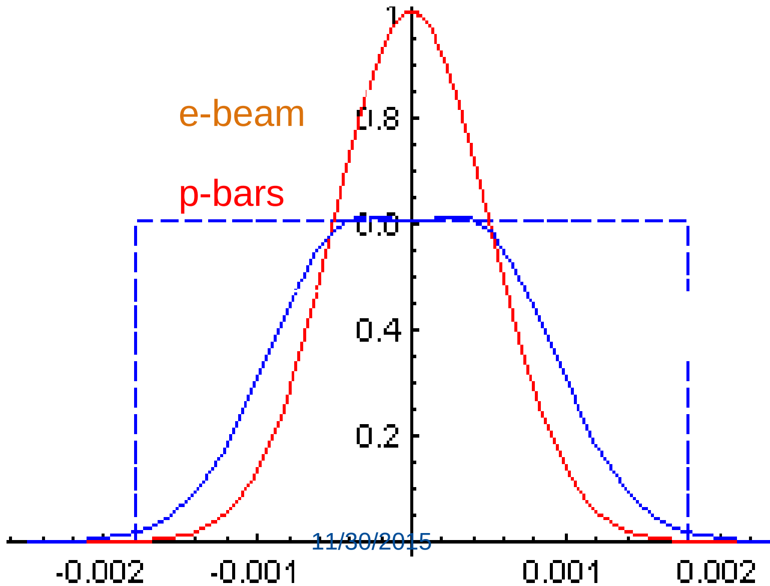
Transverse e-p alignment **is very important for minimization of noise effects and optimization of positive effects due to e-beam. *Timing* is important to keep protons on flat top of e-pulse – to minimize noise and maximize tune shift.**

TELs: Long-Range Beam-Beam Compensation

vary the currents bunch-by-bunch in two e-lenses installed at $\beta_x \neq \beta_y$







Effects of Long-Range Beam-Beam @ Collisions

All beam indicators become bunch dependent due to LR-BB:

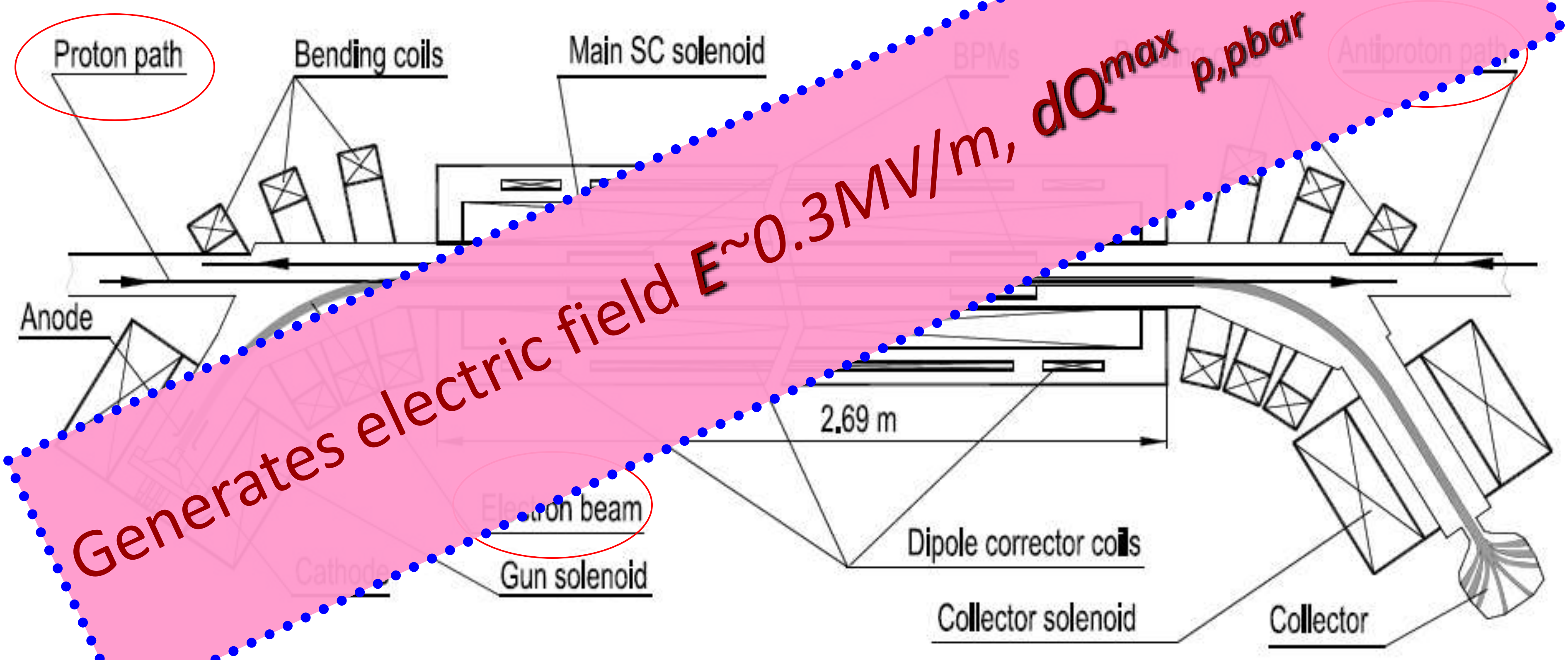
- Orbits vary by ~50μm
- Tunes and couplings by ~0.005
- Chromaticities by ~5 units
- Bunch losses by ×(2-3)
- Emittance growth (under certain conditions)
- In both – proton and pbar beams
- Have 3-fold symmetry trains of 12

Some Facts on Electron Lenses

~4 mm dia 2 m long very straight beam of ~10kV

~1A electrons (~10^{12}) immersed in 3T solenoid

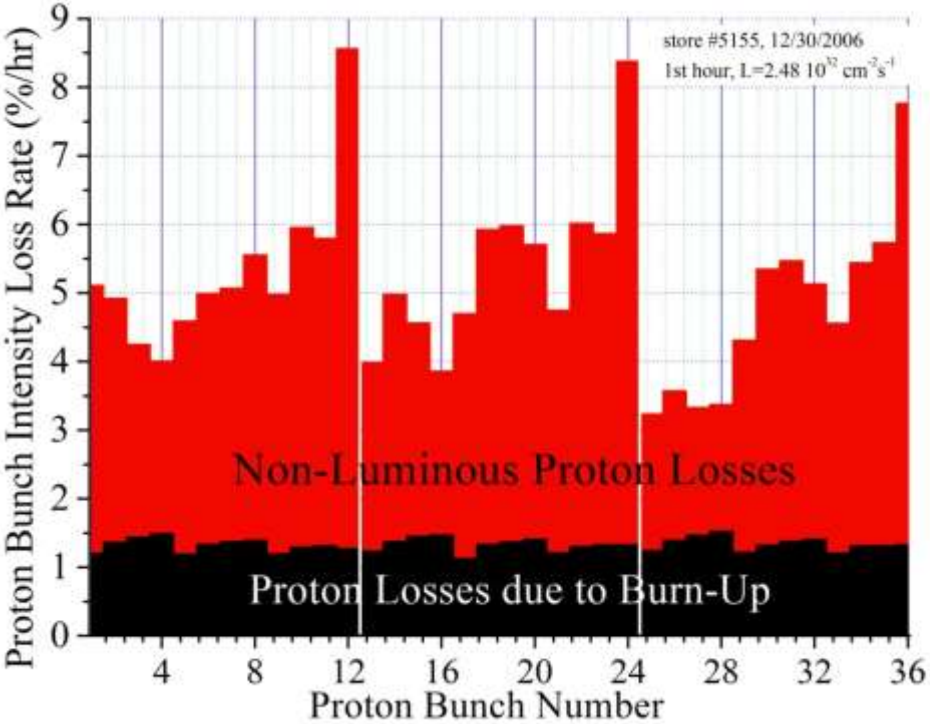
Generates electric field E~0.3MV/m, $dQ^{max}_{p,pbar}$ ~ 0.010

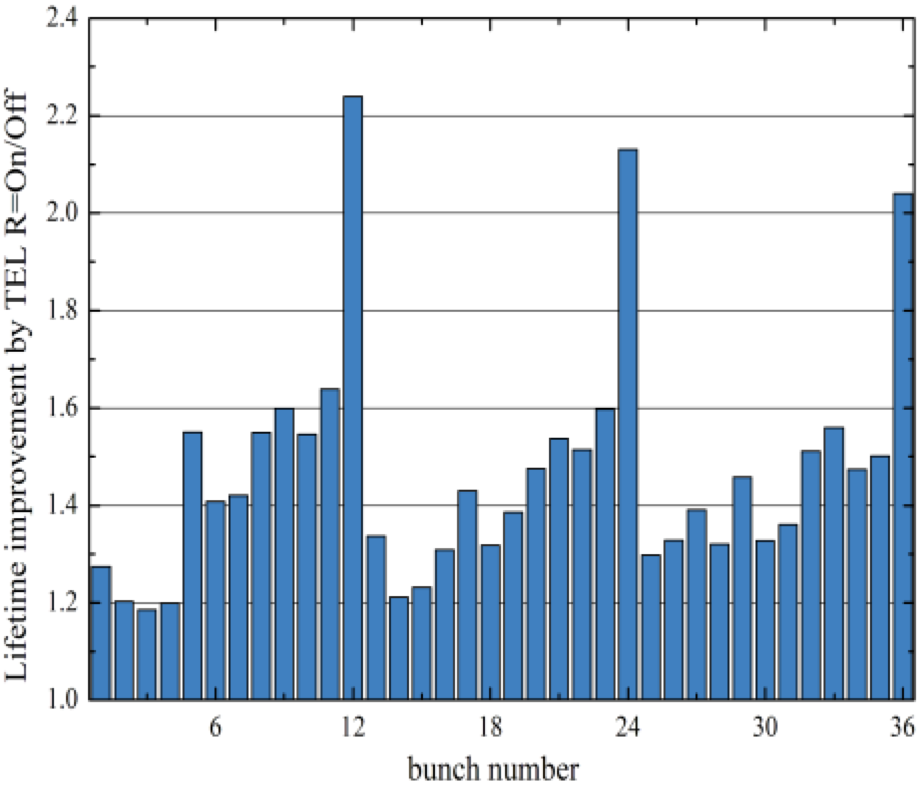


Electron Lens Doubles Beam Lifetime

Protons @ collisions 980 GeV :
ξ_{max}=+(0.016-0.024)

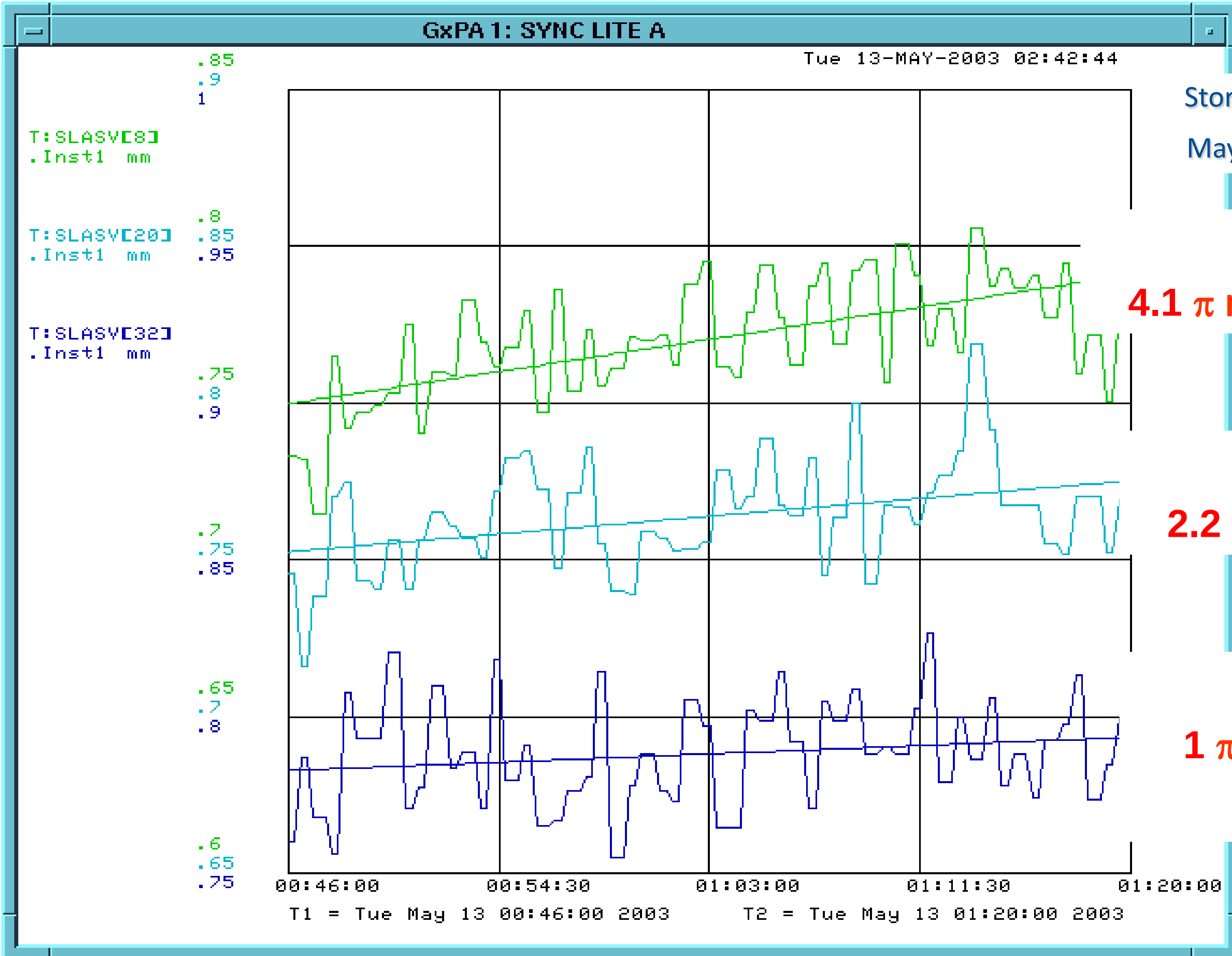
TEL2 moves Q_v up 0.002





Bunches P12, 24, 36 have systematically the lowest vertical tune that reduces beam lifetime (too close to 7/12 resonance). TEL2 raises the tune up by dQ~+1.5e-3 at 0.6 A

Emittance Growth of A33 Suppressed by TEL-1



Store #2540

May 12, '03

A9

4.1 π mm mrad/hr

A21

2.2 π mm mrad/hr

A33

1 π mm mrad/hr

-TEL on it

Long-Range Beam-Beam @ Collisions

All beam indicators become bunch dependent due to LR-BB:

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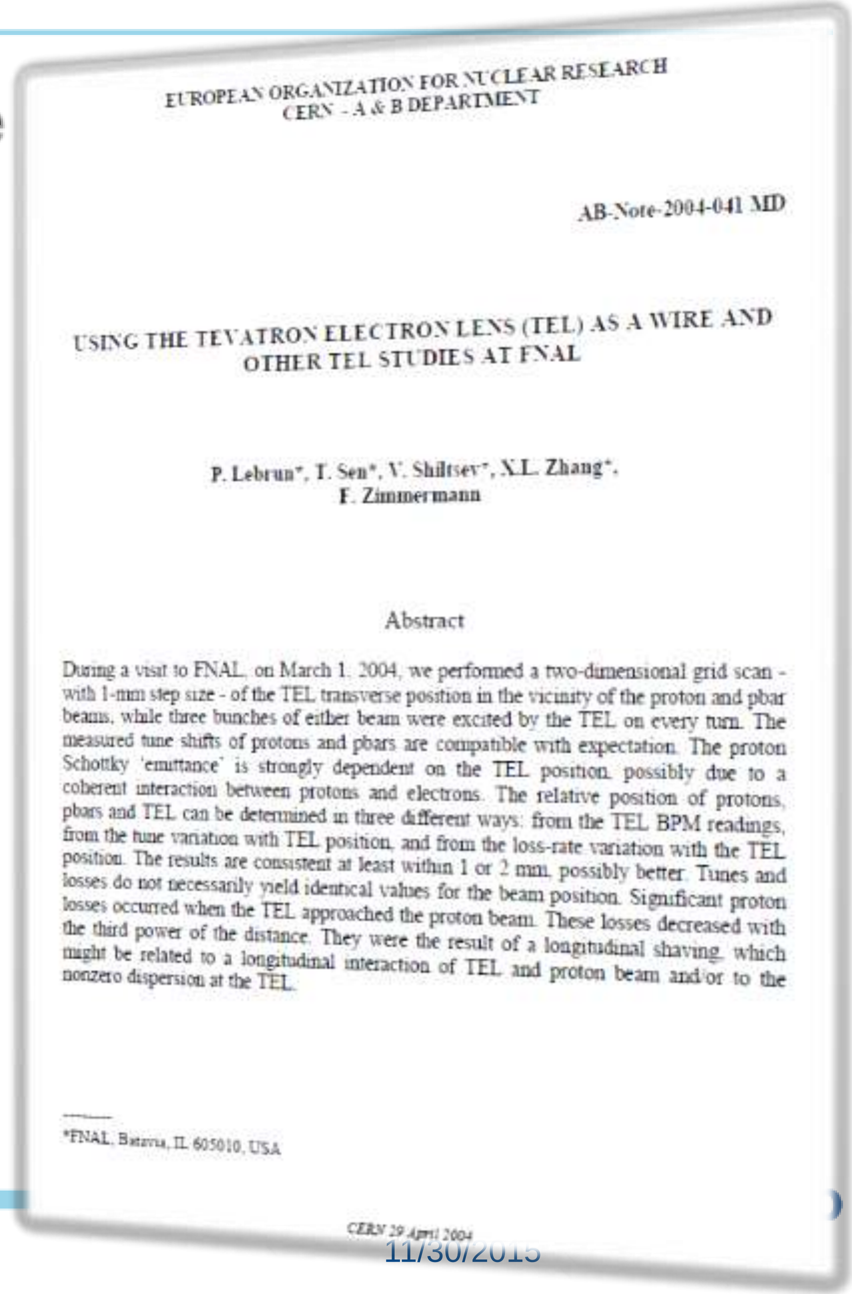
- Tunes and couplings by ~0.005
- Chromaticities by ~5 units
- Bunch losses by ×(2-3)
- Emittance growth (under certain conditions)
- In both – proton and pbar beams
- Have 3-fold symmetry trains of 12

Electron Lens as a Wire – 1st time @Tevatron

- 2004 Tevatron Collider Run II, one MD to test operational use of electron lenses as “wires”:
  - P.Lebrun, T.Sen, V.Shiltsev, X.L.Zhang, F.Zimmermann
- Successful “Proof of Principle”
- Electron wire is fully consistent with operation of a hadron super collider
- Many important beam physics insights with 0.6A e- beam: Gaussian, 0.6 mm → dQ=0.007 timed on triples of p/pbar bunches



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - A & B DEPARTMENT

AB-Note-2004-041 MD

USING THE TEVATRON ELECTRON LENS (TEL) AS A WIRE AND OTHER TEL STUDIES AT FNAL

P. Lebrun*, T. Sen*, V. Shiltsev*, X.L. Zhang*, F. Zimmermann

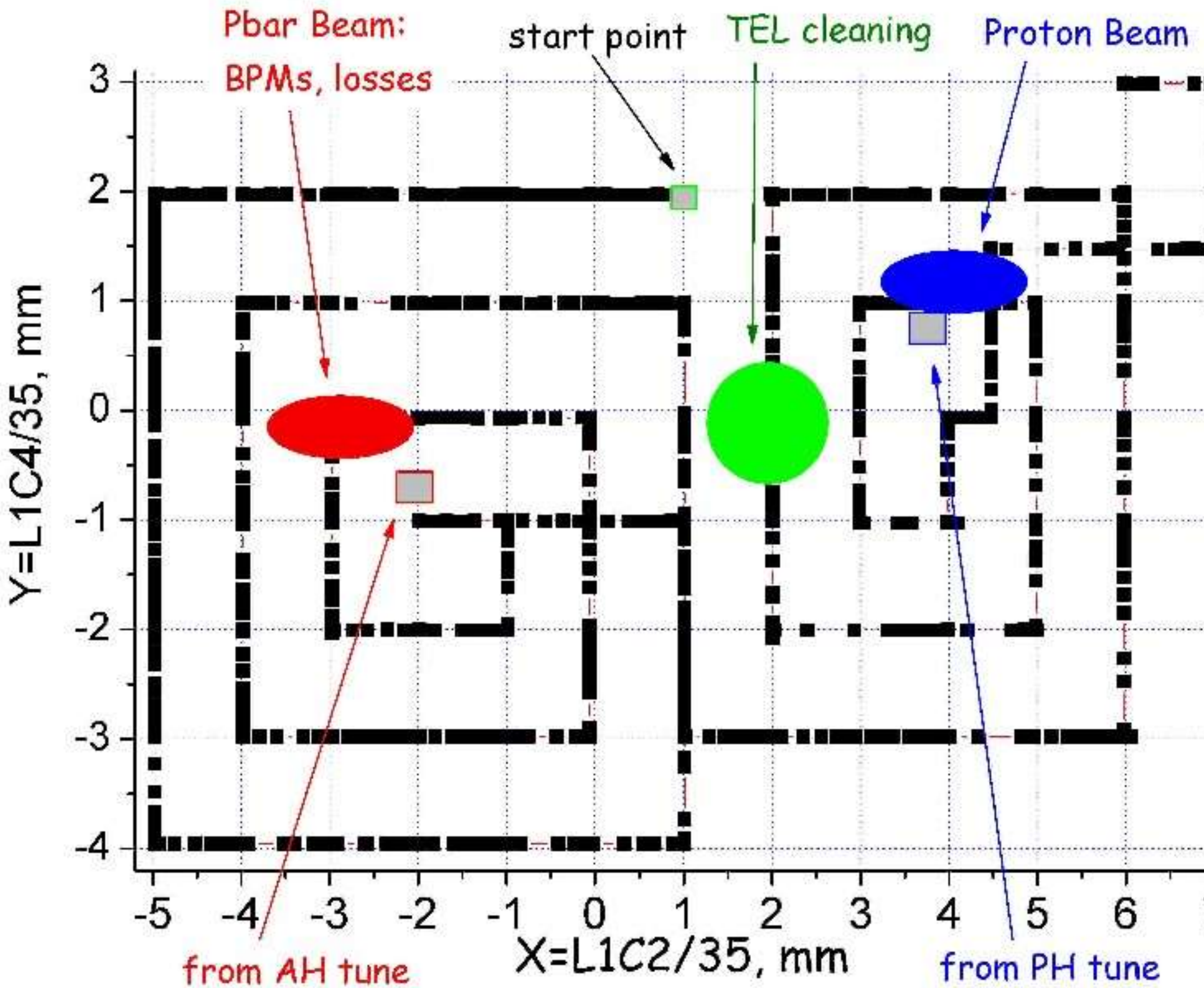
Abstract

During a visit to FNAL, on March 1, 2004, we performed a two-dimensional grid scan - with 1-mm step size - of the TEL transverse position in the vicinity of the proton and pbar beams, while three bunches of either beam were excited by the TEL on every turn. The measured tune shifts of protons and pbars are compatible with expectation. The proton Schottky 'emittance' is strongly dependent on the TEL position, possibly due to a coherent interaction between protons and electrons. The relative position of protons, pbars and TEL can be determined in three different ways: from the TEL BPM readings, from the tune variation with TEL position, and from the loss-rate variation with the TEL position. The results are consistent at least within 1 or 2 mm, possibly better. Tunes and losses do not necessarily yield identical values for the beam position. Significant proton losses occurred when the TEL approached the proton beam. These losses decreased with the third power of the distance. They were the result of a longitudinal shaving, which might be related to a longitudinal interaction of TEL and proton beam and/or to the nonzero dispersion at the TEL.

*FNAL, Batavia, IL 605010, USA

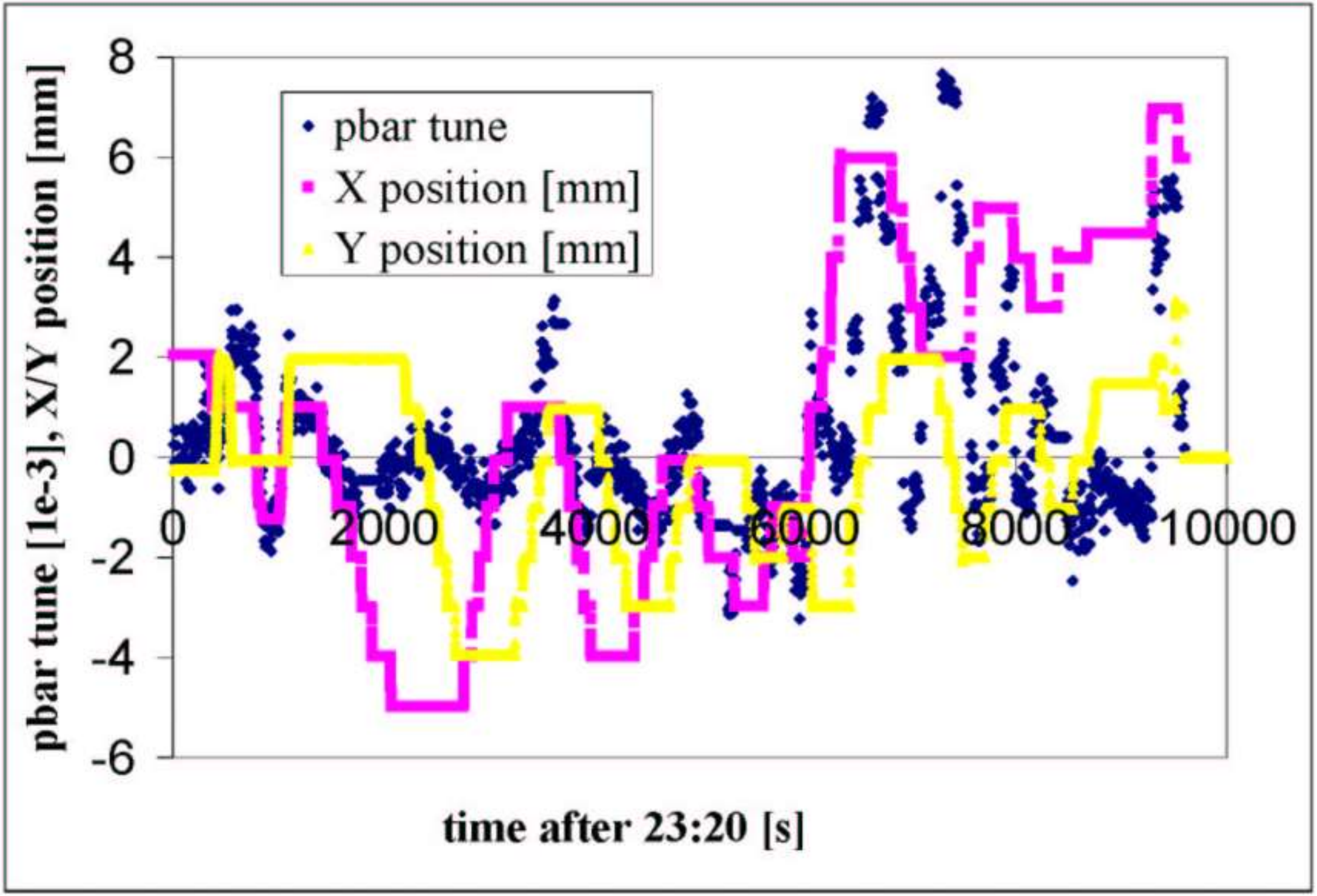
CERN 29 April 2004

MD results: moving e- beam around p/pbars

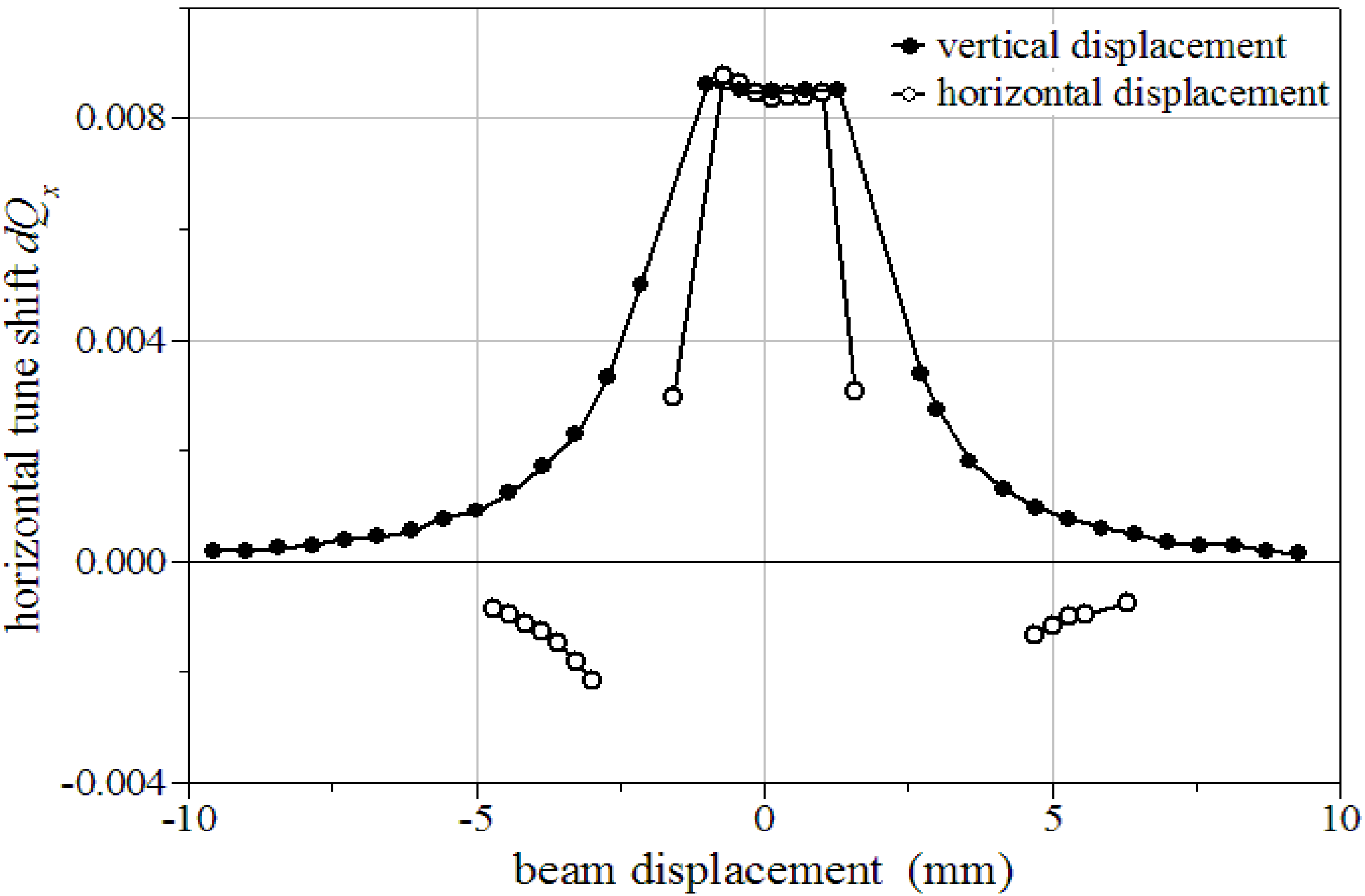


ermilab

Tuneshift vs e- beam position: 0.007



Proton Hor tuneshift dQ_x vs d_x, d_y



(**another MD, TEL-1,** J_e =1A, U_c =6.0 kV, flat-top electron gun)

Summary

- Long-range beam-beam effects occurred in the Tevatron at all stages (injection, ramp, squeeze, collisions) and in both beams
- They resulted in significant beam losses, and, sometimes, in emittance blow-ups – with bunch-to-bunch dependent patterns
- Even after careful optimization of helices and many operational tune-ups and upgrades – at the end of the Tev Run II beam-beam claimed *~25% of Integr. Lumi but at ~40x higher peak L*
- LR beam-beam compensation by TELs demonstrated
- Electron lenses operated for 17 years combined
- In MDs, TEL was used as a “wire”
- Trustable LIFETRAC simulations helped us a lot
- Tevatron/TEL experience can help HL-LHC

Tevatron Parameters

Table 2. Design and achieved performance parameters for Collider Runs I and II (typical values at the beginning of a store).

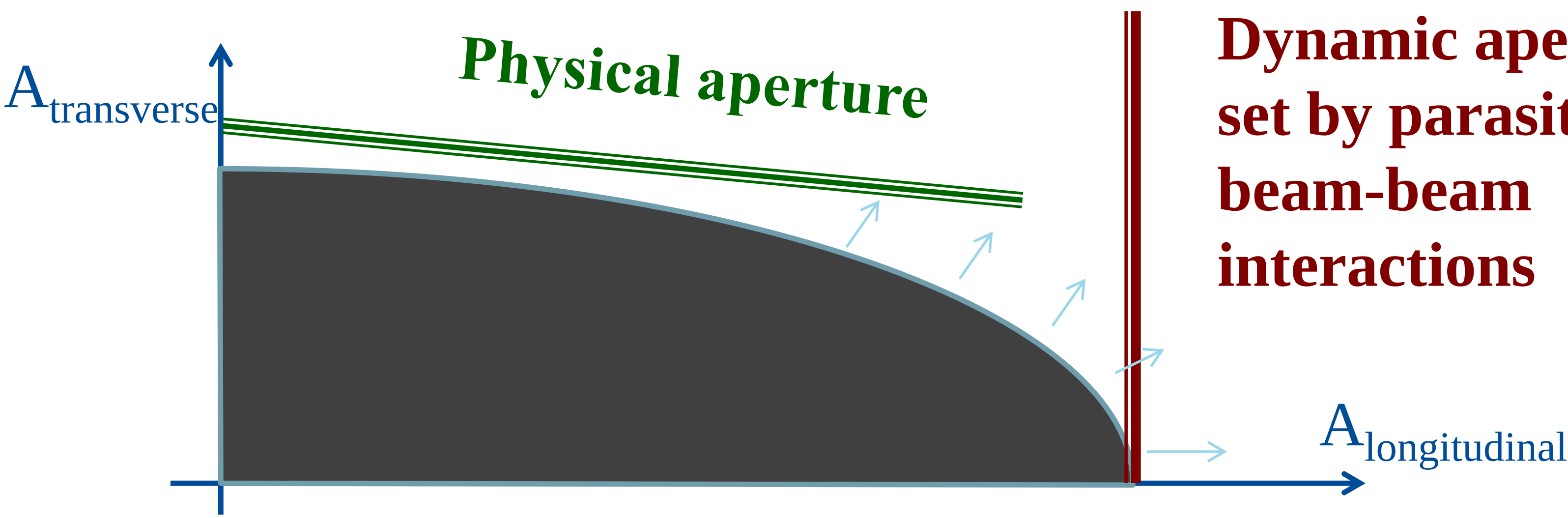
	Run Ia	Run Ib	Run II	
Energy (center-of-mass)	1800	1800	1960	GeV
Protons/bunch	1.2	2.3	2.9	$\times 10^{11}$
Antiprotons/bunch	3.1	5.5	8.1	$\times 10^{10}$
Bunches/beam	6	6	36	
Total Antiprotons	19	33	290	$\times 10^{10}$
Proton emittance (rms, normalized)	3.3	3.8	3.0	π mm-mrad
Antiproton emittance (rms, normalized)	2	2.1	1.5	π mm-mrad
β^*	35	35	28	cm
Luminosity (Typical Peak)	5.4	16	340	$\times 10^{30}$ cm^{-2}sec^{-1}
Luminosity (Design Goal)	5	10	200	$\times 10^{30}$ cm^{-2}sec^{-1}

What we've found empirically

- Losses were dependent on :

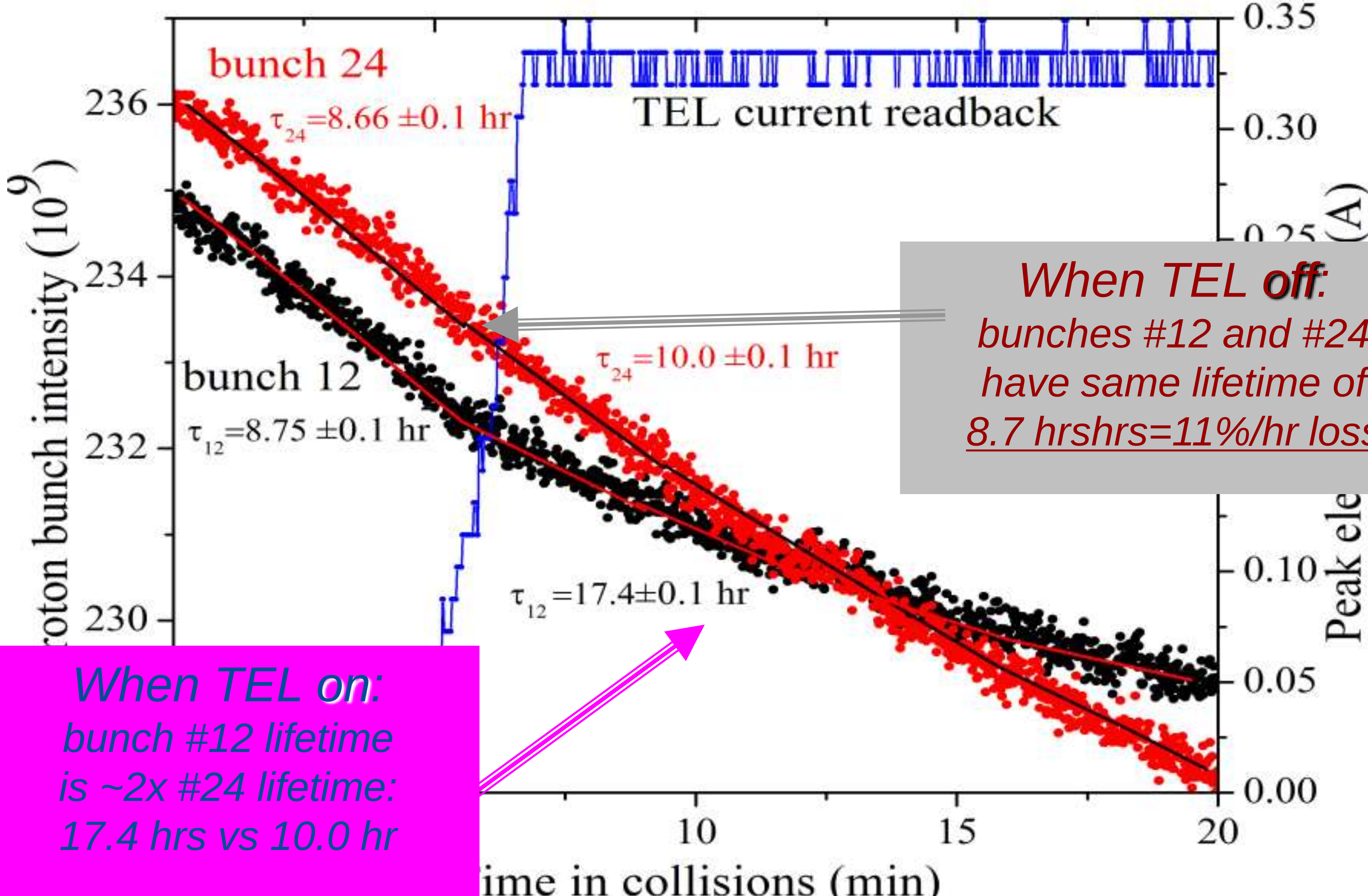
$$\frac{\Delta N_{a,p}}{N_{a,p}} = 1 - \frac{N(t)}{N(t=0)} \propto \sqrt{t} \cdot \varepsilon^2_{a,p} \frac{N_{p,a}}{\varepsilon_{p,a}} Q'^2_{a,p} \cdot F(\varepsilon_L, Q_{x,y}, S_{a-p})$$

Beam-Beam sets DA and drives diffusion → *sqrt* (t)



Dynamic aperture set by parasitic beam-beam interactions

TEL2 on One Proton Bunch P12



When TEL off:
bunches #12 and #24
have same lifetime of
8.7 hrshrs=11%/hr loss

When TEL on:
bunch #12 lifetime
is ~2x #24 lifetime:
17.4 hrs vs 10.0 hr

LIFETRAC Simulation of TEL