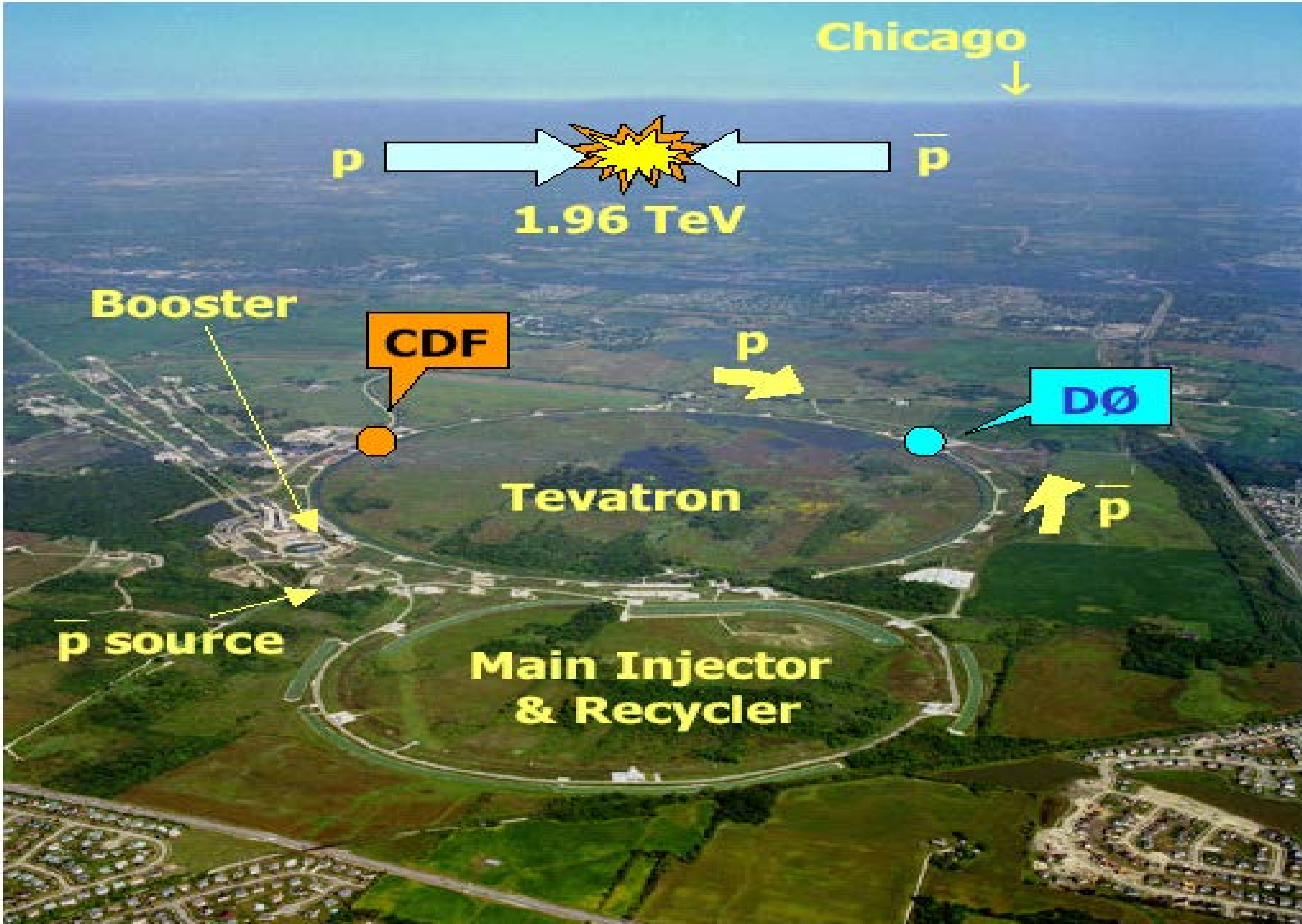
Tevatron Collider at Fermilab



Beam-Beam Effects in the Tevatron Collider : An Overview

Vladimir Shiltsev

Fermilab

Tevatron Timeline

Jul 1983	Tevatron SC synchrotron commissioned, reached world record 512 GeV (protons)
1982-1985	Antiproton source construction & commissioning, installation of the B0 low beta insertion magnets
Oct 1985	First 1.6 TeV c.o.m. p-pbar collisions in CDF
1987-1989	Collider Run at 1.8TeV c.o.m., magnet leads fix
1990 -1992	HV separators installed, new low beta insertions at D0 and B0 interaction regions
1992 -1993	Collider Run Ia at 1.8 TeV c.o.m.,both CDF & D0
1992 -1993	400 MeV Linac construction and commissioning
1994 -1996	Collider Run Ib, top quark discovery
1993 -1999	Main Injector construction and commissioning
2001 - 2011	Collider Run II, 1.96 TeV c.o.m.

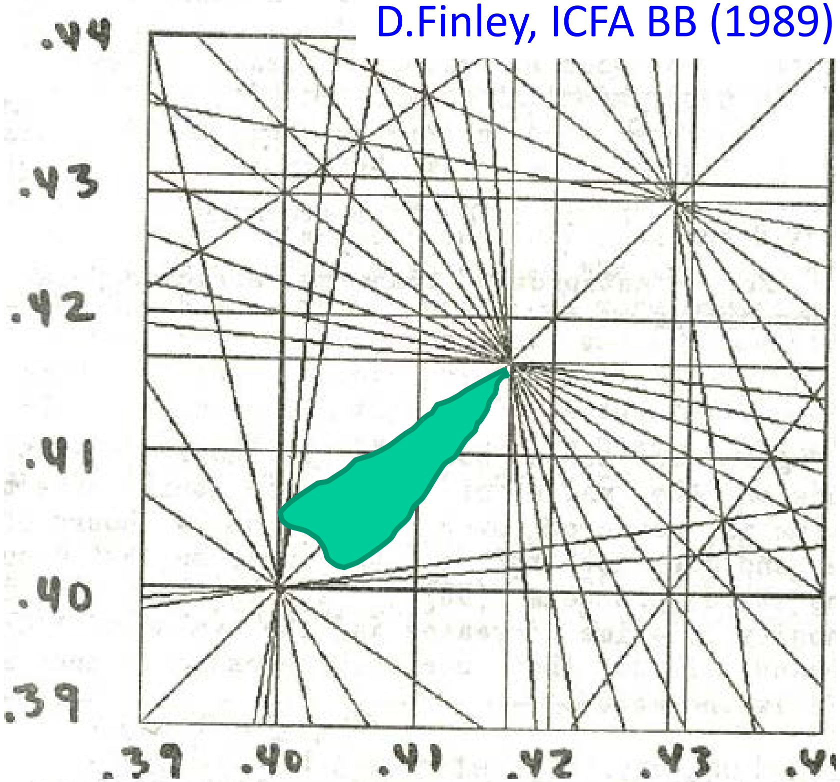
Content

- Beam-beam effects in Tevatron Collider Run I:
  - First observations
  - Helical orbits
  - Preparations for Run II
- Collider Run II beam-beam themes:
  - Surprises with 36 bunches
  - Fights for better separations and open apertures
  - Beam-beam phenomena
  - Theory and modeling
  - Better beam diagnostics and machine "stabilization"
- Beam-beam compensation:
  - The idea and modifications
  - Tevatron Electron Lenses and operation
  - Compensation results
  - By-product: collimation – longitudinal and transverse

Beam-beam observations and effects during Tevatron Collider Run I 1989-1996

First Effect – Importance of Resonances

D.Finley, ICFA BB (1989)

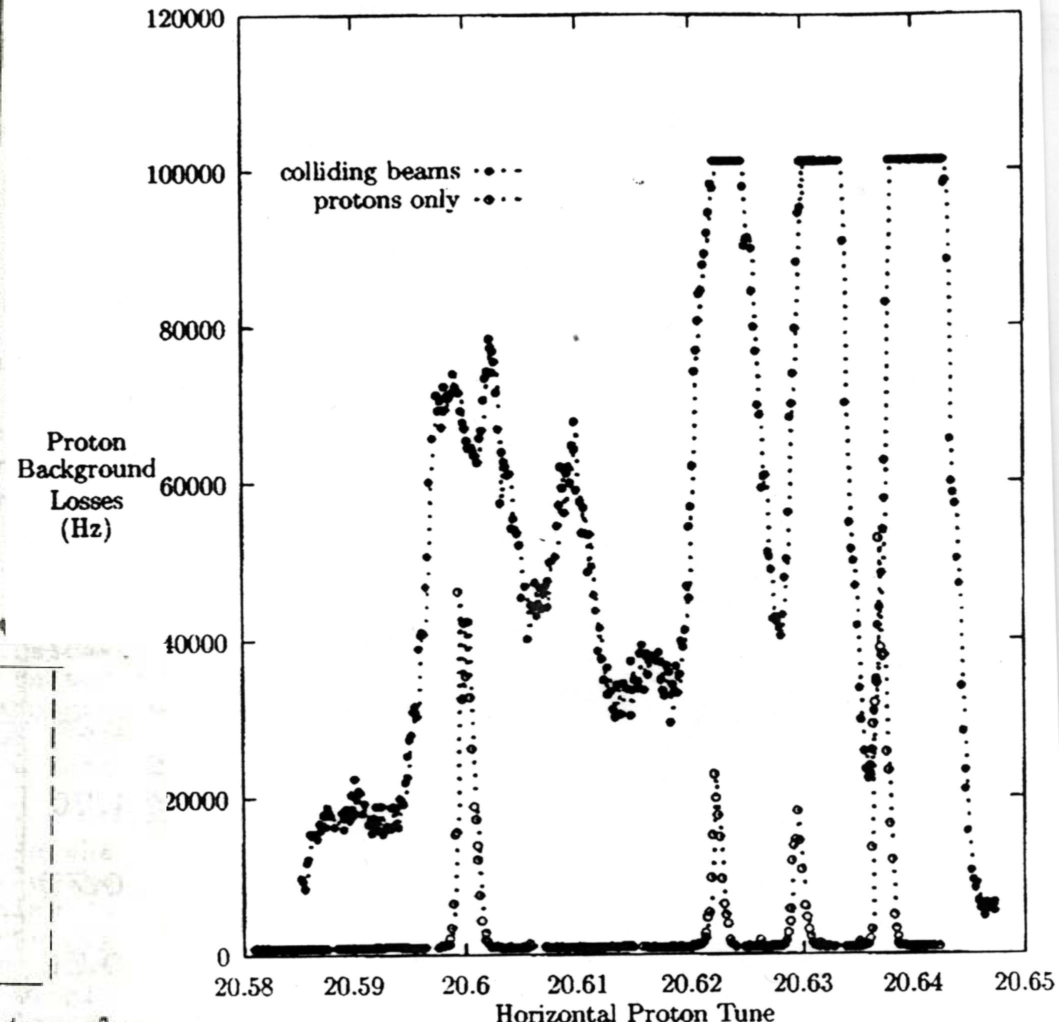


CERN	Fermilab	
3	12	Crossings per circumference
0.015	0.018	Total ξ_x of the protons
0.016	0.025	Total ξ_x of the antiprotons
0.011	0.018	Total ξ_y of the protons
0.011	0.025	Total ξ_y of the antiprotons

Table 2b. Comparison of beam beam parameters for proton antiproton colliders.

Tevatron p – pbar collider, ξ=0.005

D.Siergiej, PRE 55 (1997), 3521



Other effects and Countermeasures

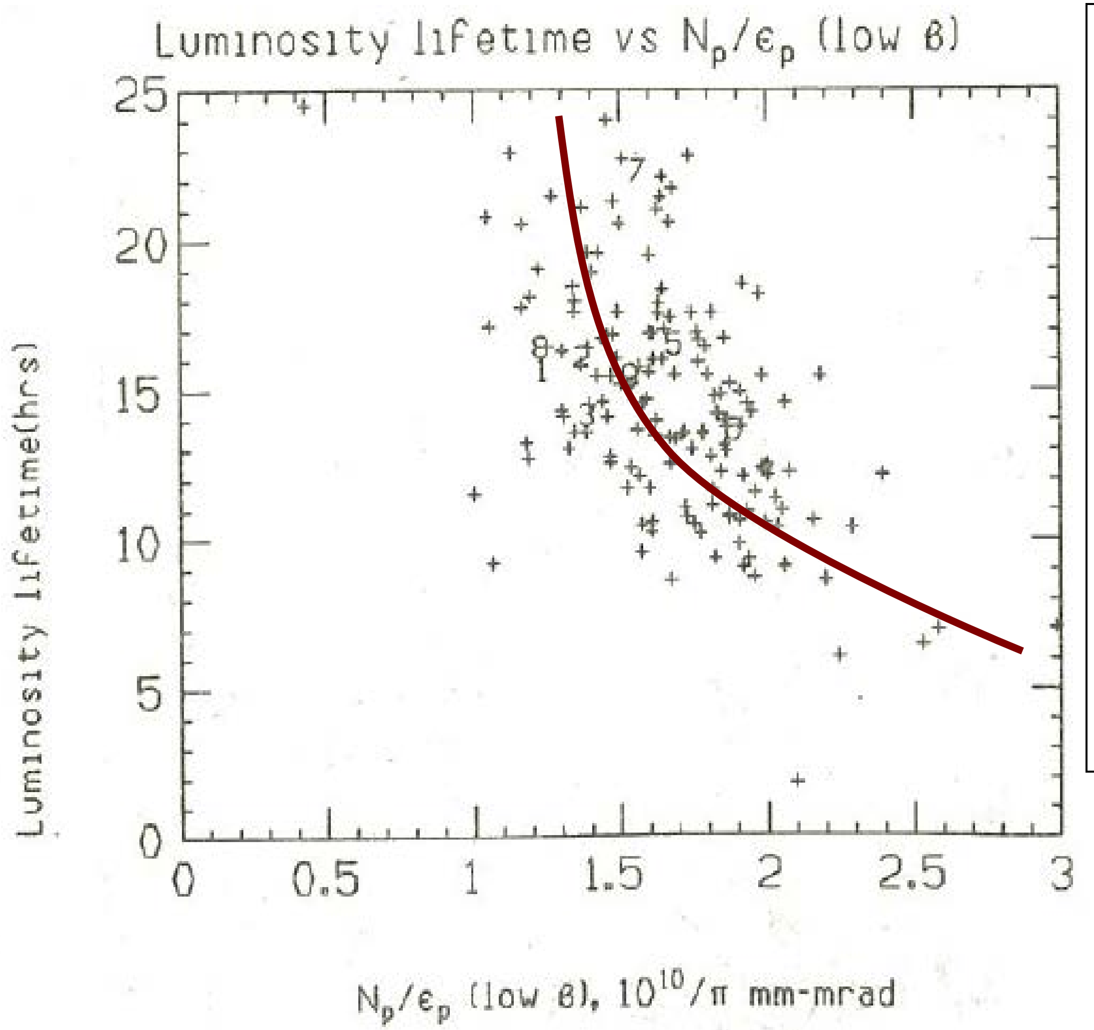


Figure 2c. Initial luminosity lifetime as a function of N/ε.

D.Finley, ICFA BB (1989)

In 6x6 bunch operation
There were 12 head-on collisions
Observed effects:

- Emittance blowup for pbars
- Transverse halo growth
- Losses in both beams
- Significant reduction in luminosity lifetime

Countermeasure:

Installation HV separators

Eventually 24 (+- 150 kV over 5cm)

Vertical and Horizontal

Thinking of 36x36 → 121x121 bunches

Expected (1997):

(a lot of antiprotons)

(very high luminosity x10)

(high pile up)

Helical separated orbits

Long-range effects:

Orbit variation in trains

Tune variation in the trains

> Compensation by e-lenses

P.Bagley, EPAC (1996)

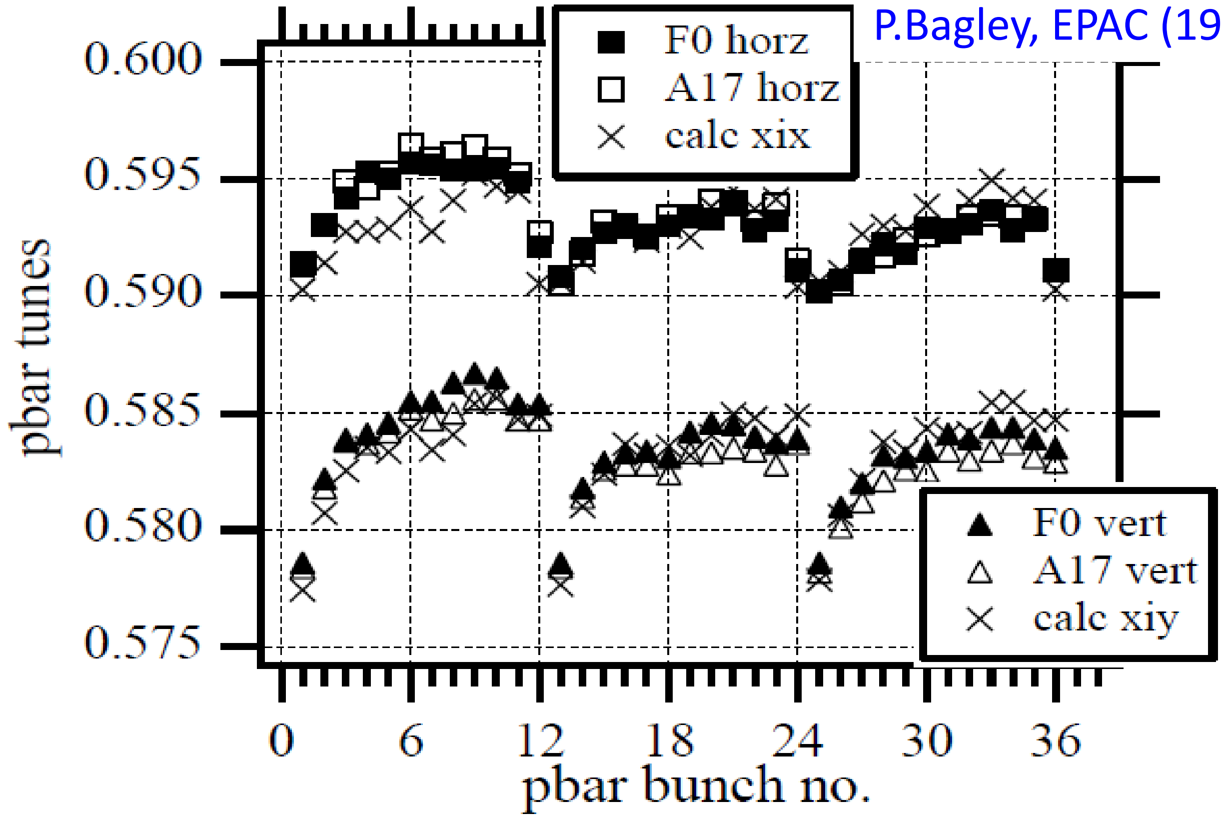


Figure 2 : Measured and Calculated Pbar Tunes for Colliding Beam Conditions. We assume base pbar horizontal and vertical tunes of 0.5855 and 0.5755, horizontal proton emittances equal to the vertical proton emittances, and we use a scale factor of 0.648 for the tune shifts from the head on beam beam interaction.

Beam-beam effects during Tevatron Collider Run II

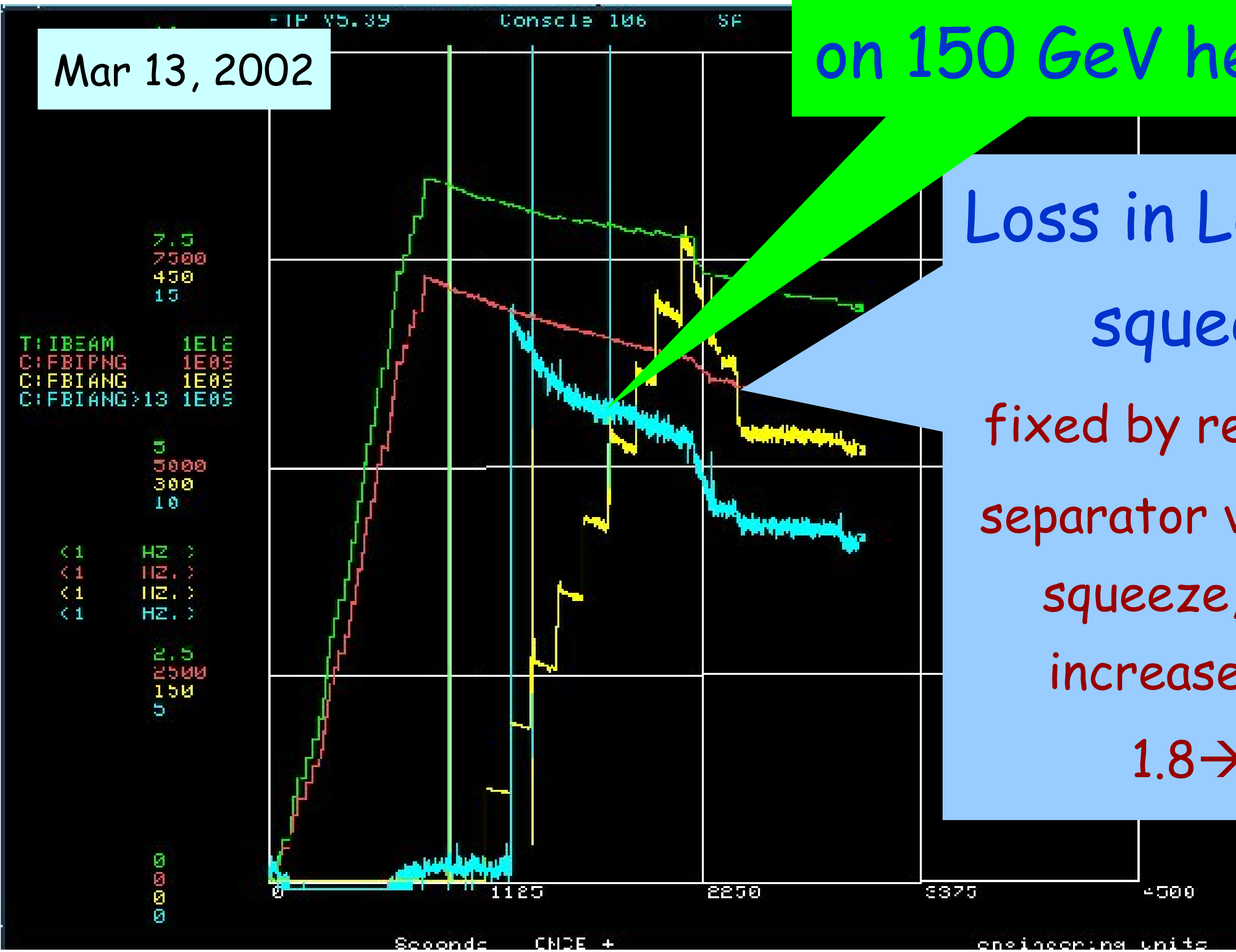
2001-2011

(more pbars)

(more bunches 6→36)

(brighter pbars)

Beam-Beam Effects in Tevatron

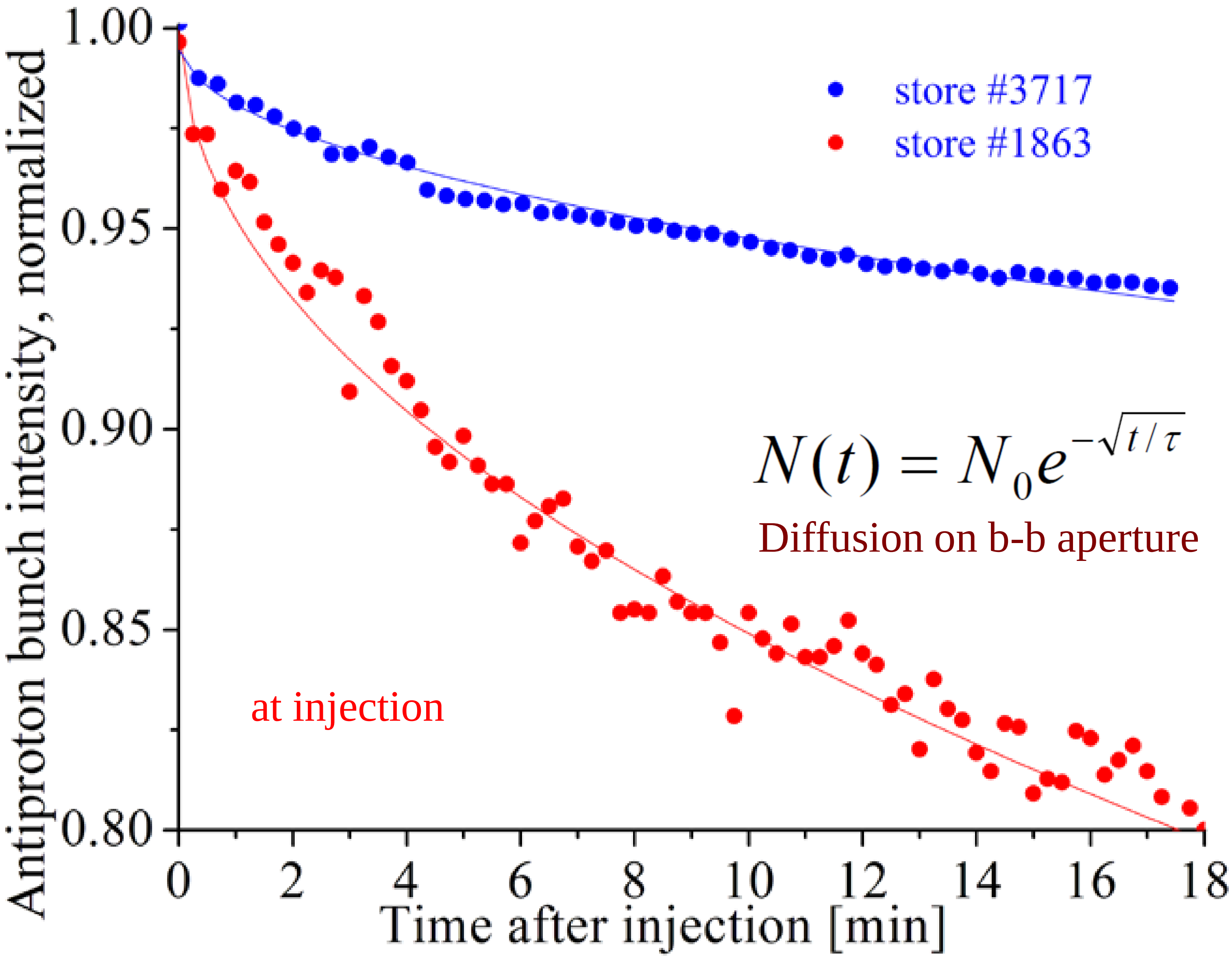


on 150 GeV helix

Loss in Low-Beta squeeze:

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

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

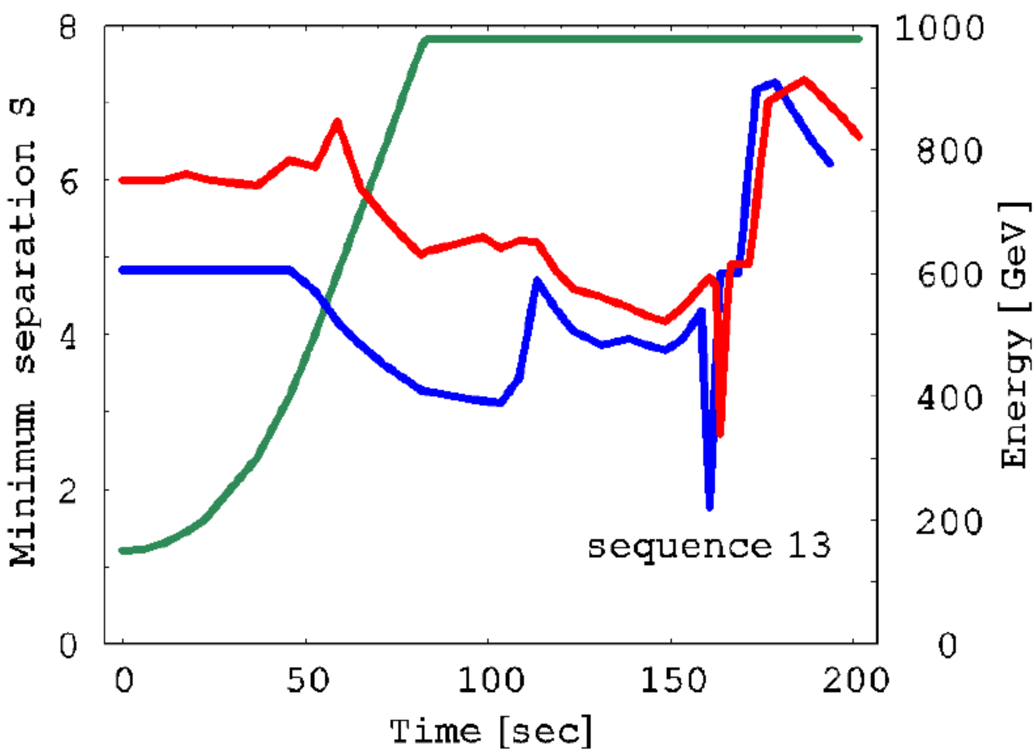


What we found empirically

- Losses were dependent on :

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

- Therefore: focus on Separation, emittances, tunes:



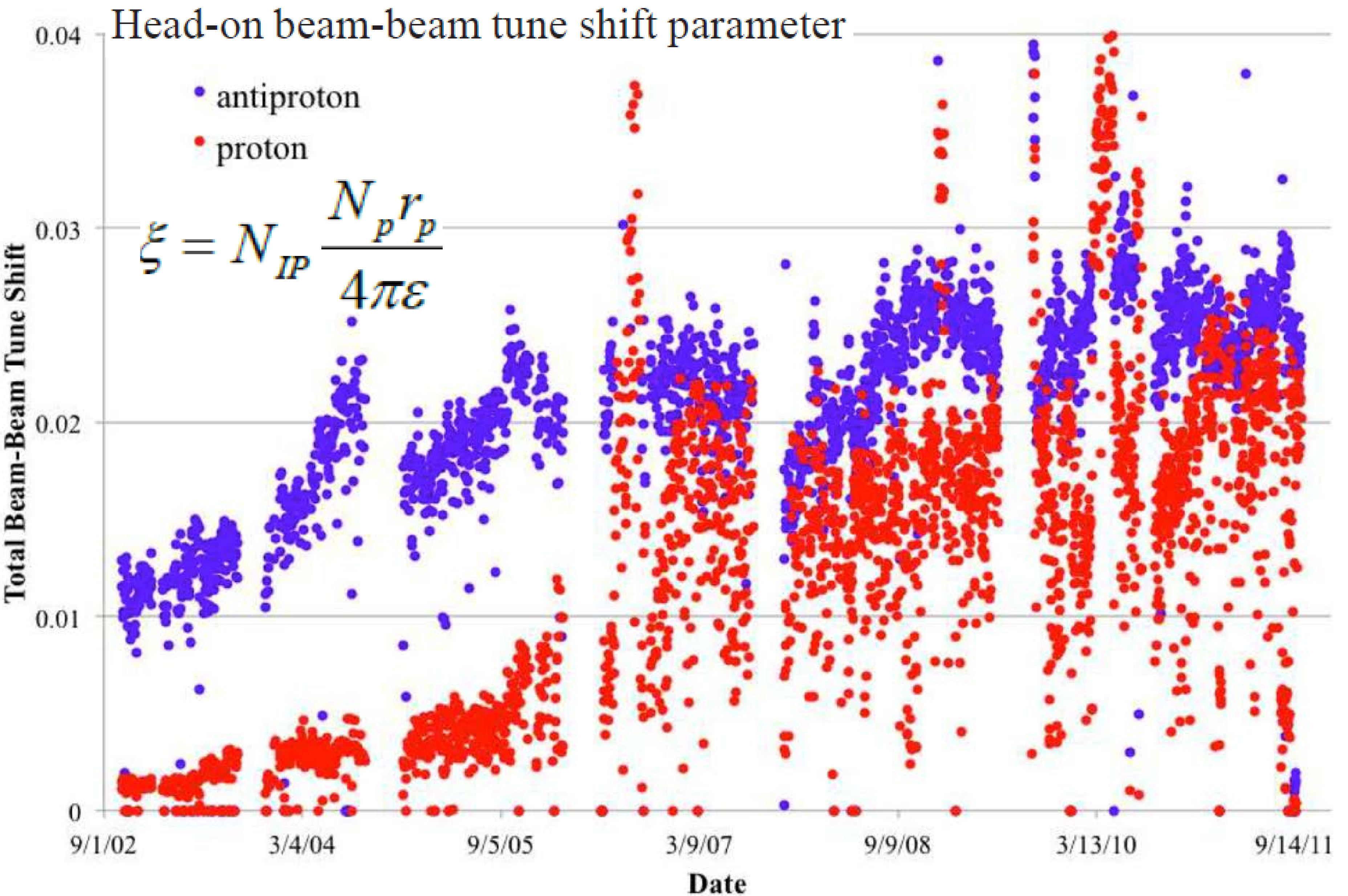
$$S = \sqrt{(\Delta x/\sigma_{x\beta})^2 + (\Delta y/\sigma_{y\beta})^2}$$

less than 5-6σ separation causes unsatisfactory losses

$$Q_x/Q_y = 20.584/20.576$$

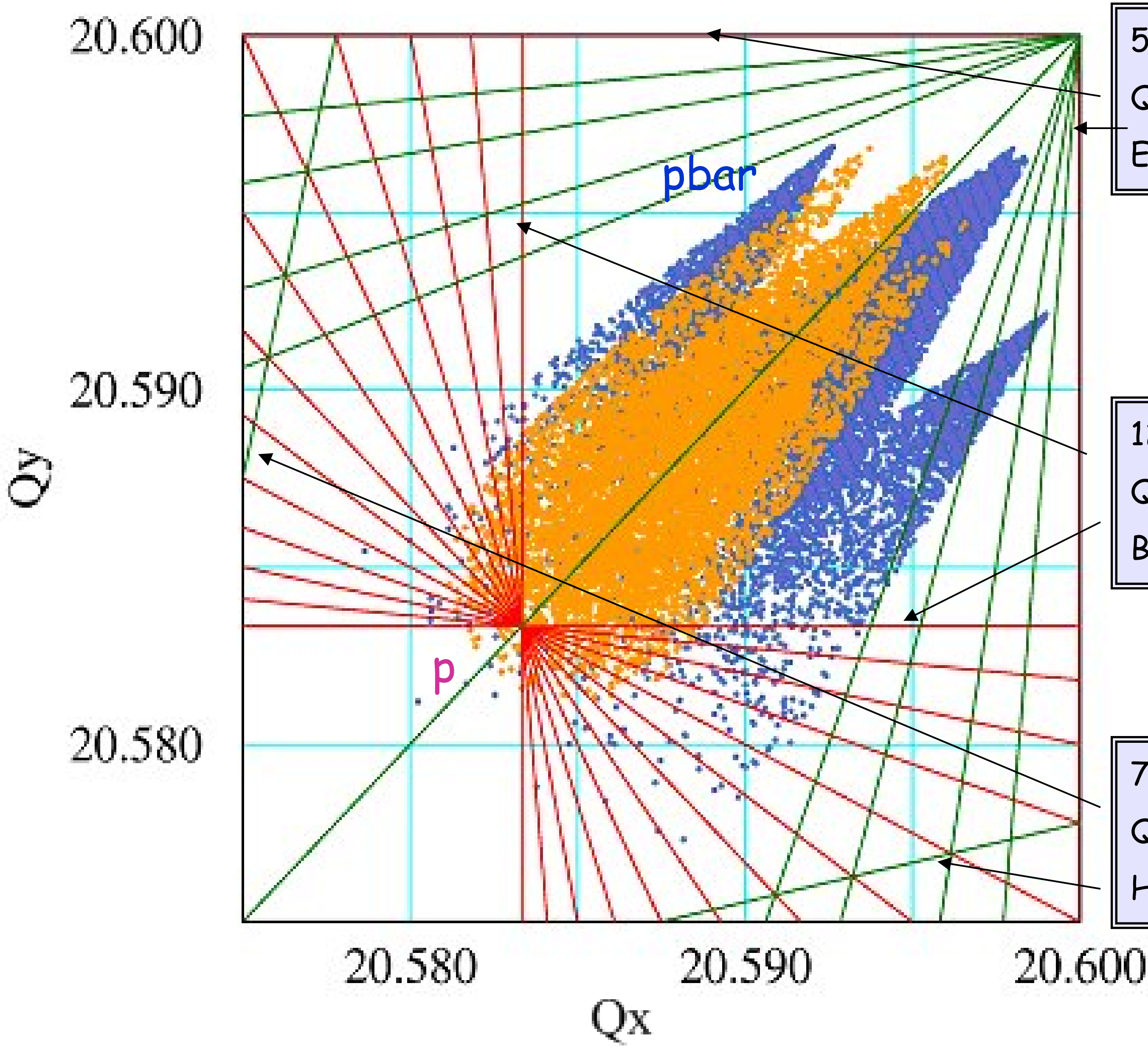
Decreased Q' to ~3 and then to ~0 (new octupole circuits

Beam-beam effects in Collisions



$$\xi = N_{IP}\frac{N_p r_p}{4\pi\varepsilon}$$

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

Head-On Beam-Beam Collisions

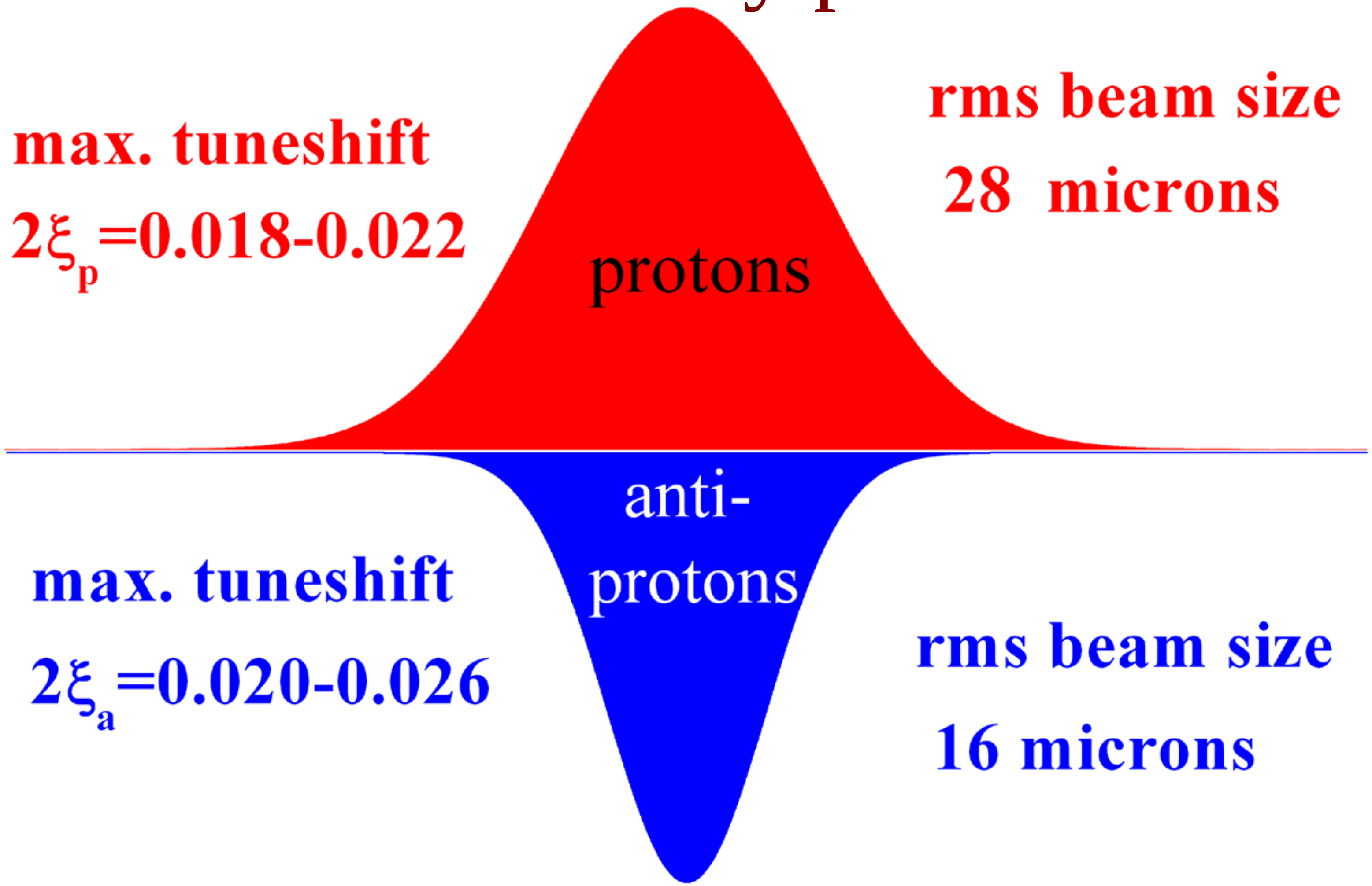
- affected mostly protons

max. tuneshift

$2\xi_p$=0.018-0.022

rms beam size

28 microns



max. tuneshift

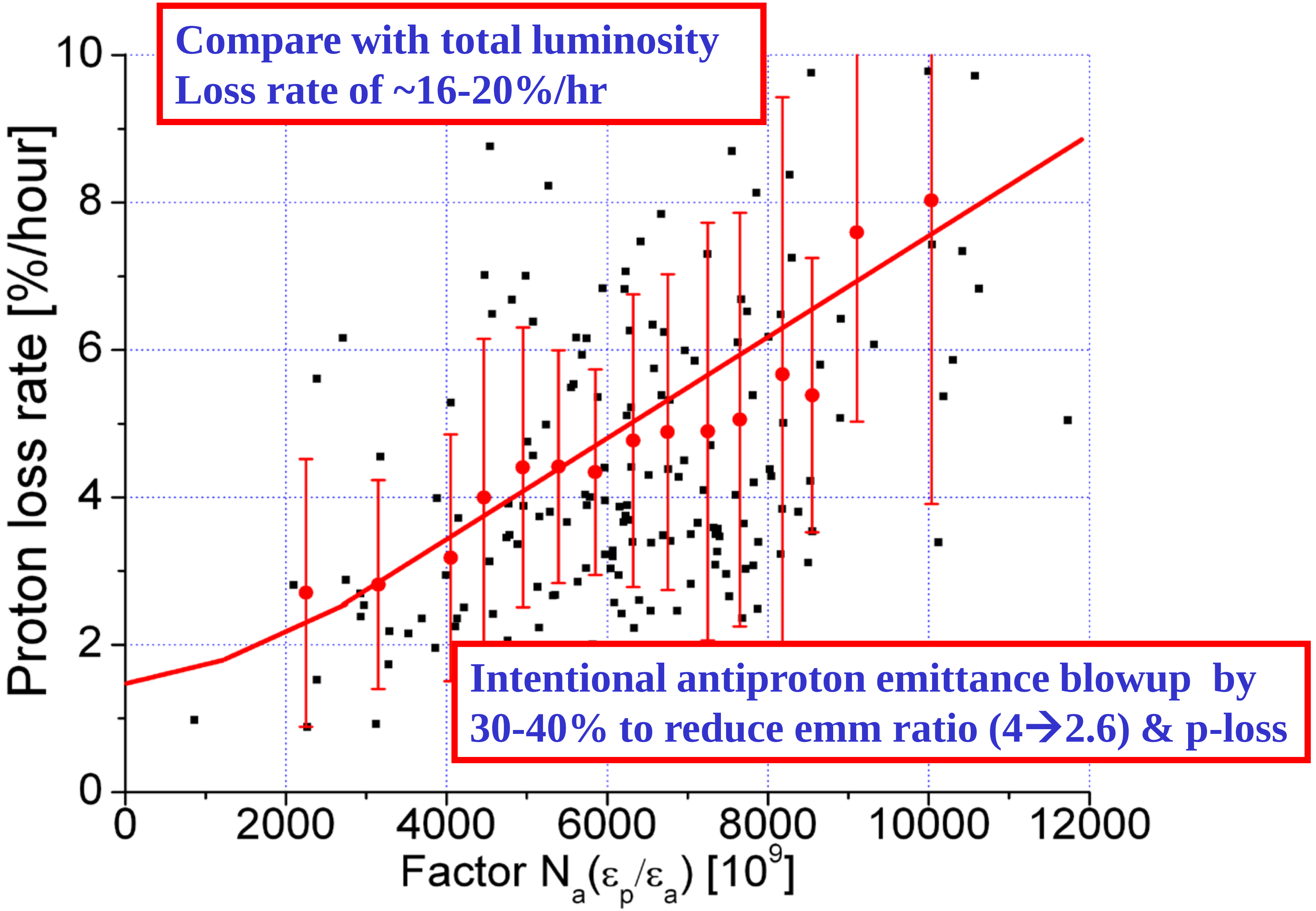
$2\xi_a$=0.020-0.026

rms beam size

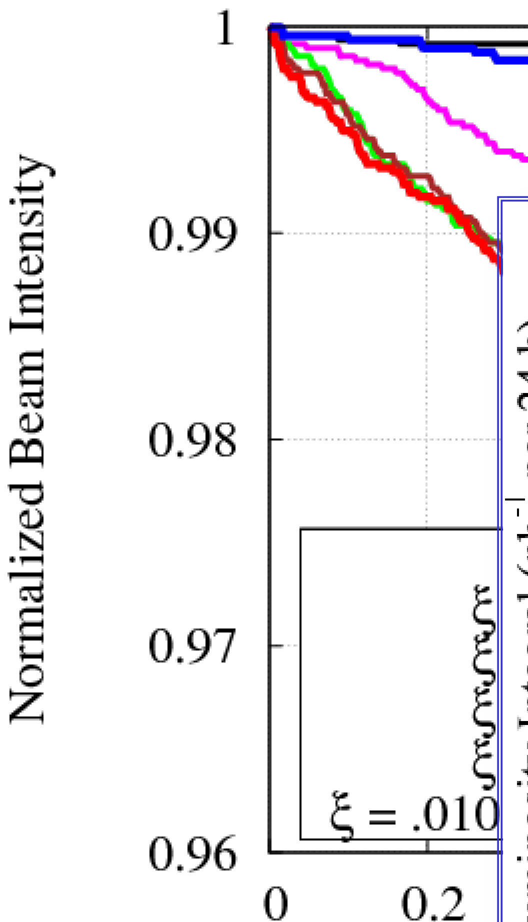
16 microns

emittance ratio (ε_p/ε_a) ~3

Very High Proton Losses Early in Stores

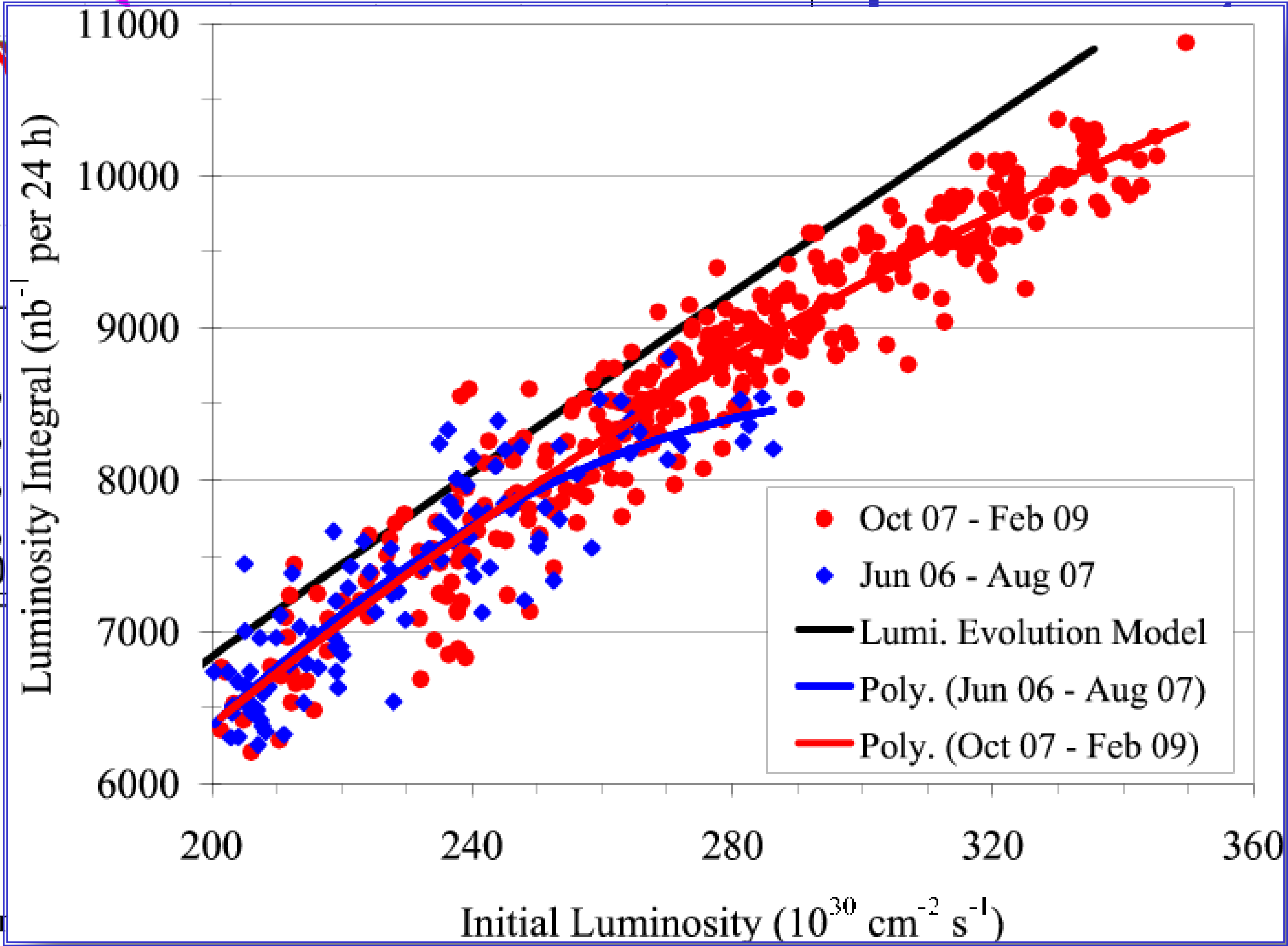


Effect of β* Chromaticity: Simulation → Practical Implementation



C2=-16000

→ C2=500



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% LR Beam-Beam
- Proton lifetime = >50% Beam-Beam + <50 % burnup
- Hougrlass lifetime = >90% IBS + <10% Beam-Beam

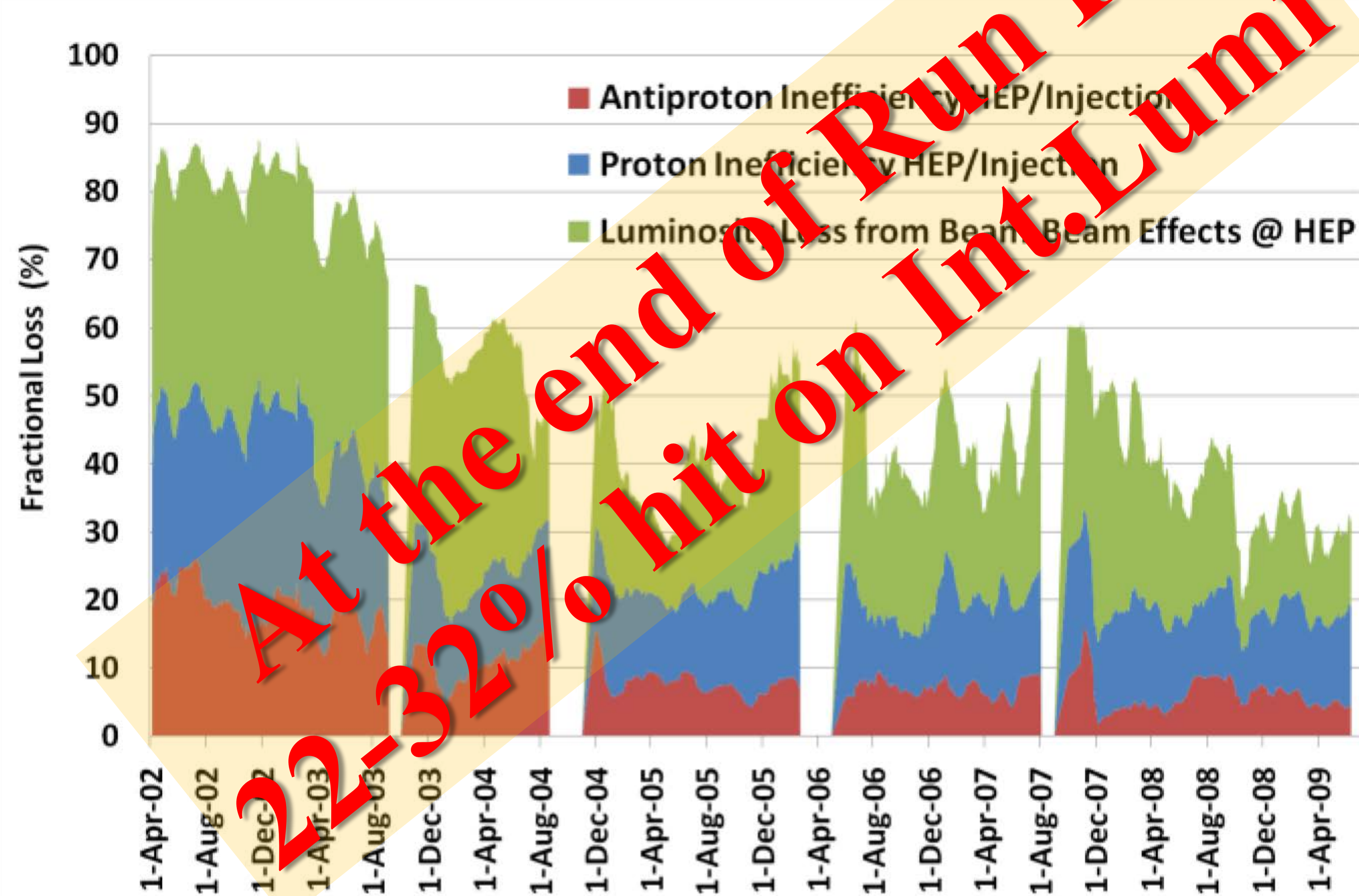
$$\left(\frac{1}{\tau_a}\right)_{BB} = \left(\frac{dN_a}{N_a dt}\right)_{BB} \propto N_p \frac{\varepsilon_a^2}{S^3}$$

IBS determined ~50-55% of lifetime

Burnup due to luminosity – another 30-35%

Beam-Beam Interaction reduces lumi- lifetime by 12-17 %

Total Beam-Beam Luminosity Loss



At the end of Run II

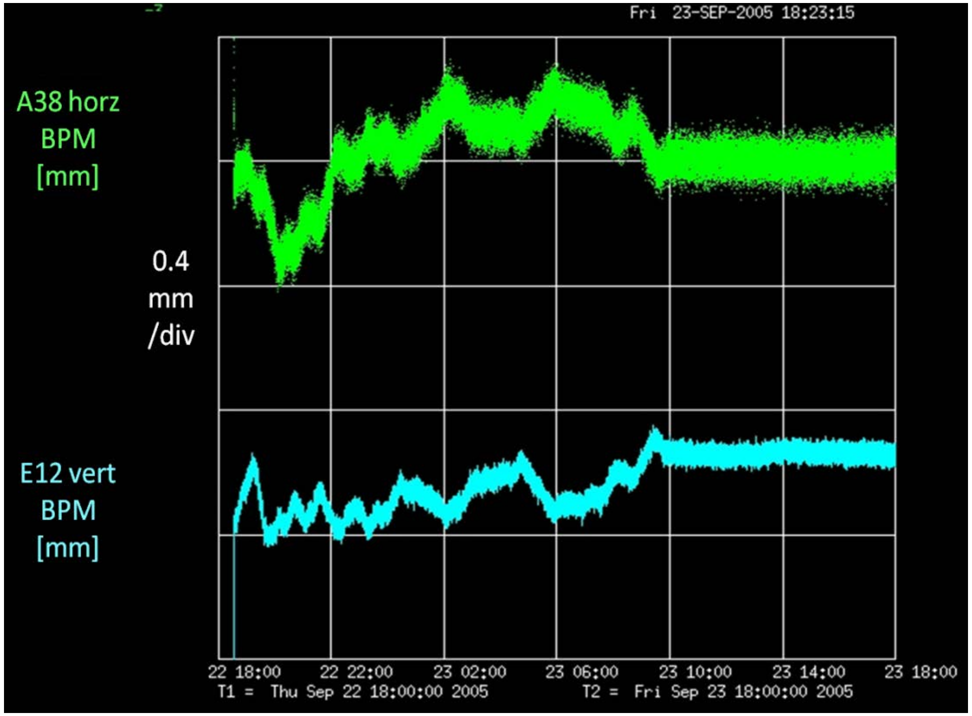
22-32% hit on Int.Lumi

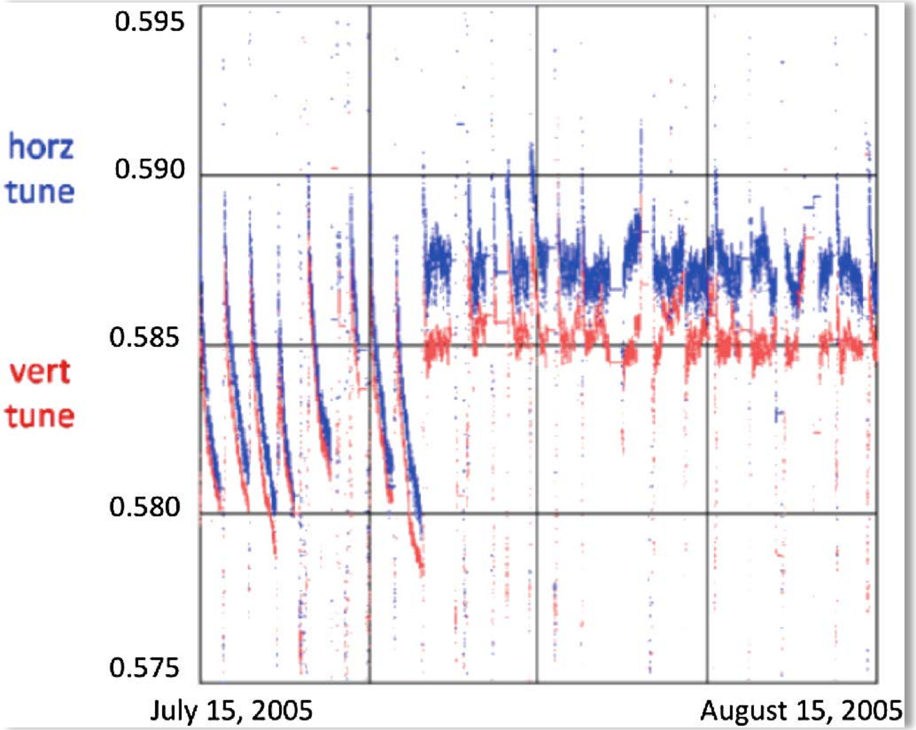
What helped us to improve *BB-situation*

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

Just Couple Examples

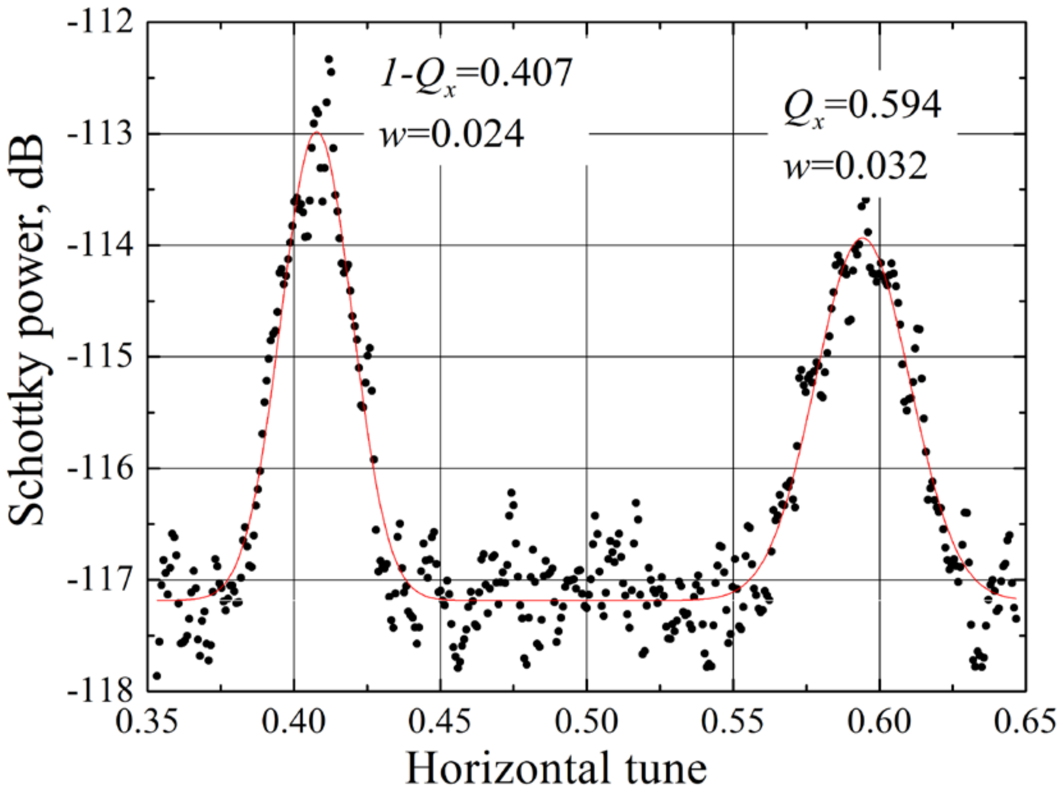
- Orbit stabilization
- Tune stabilization





1.7GHz Schottky Tune Monitor

R.Pasquinelli P.Lebrun A.Jansson



- *Q* and *1-Q* lines are seen
- Fit gives:
  - Betatron frequencies
  - dP/P ∝ sum of two widths
  - C_vh ∝ difference of two widths
  - Emittance ∝ area under the peaks
- Did that for each bunch !
- Very helpful software and controls, fully incorported in the ACNET

Beam-beam compensation:

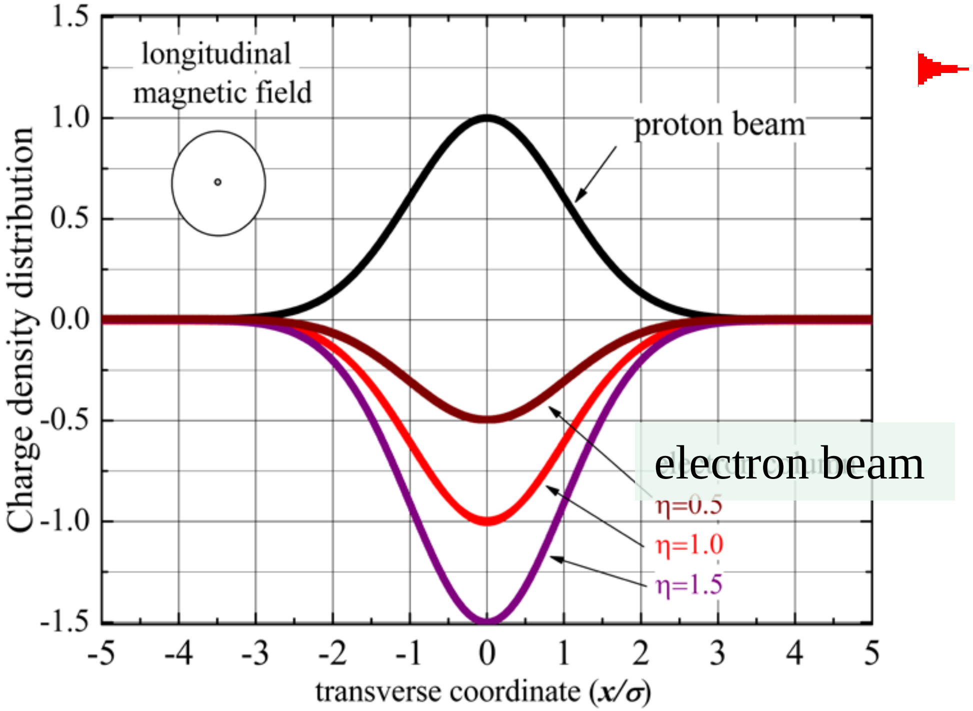
Idea

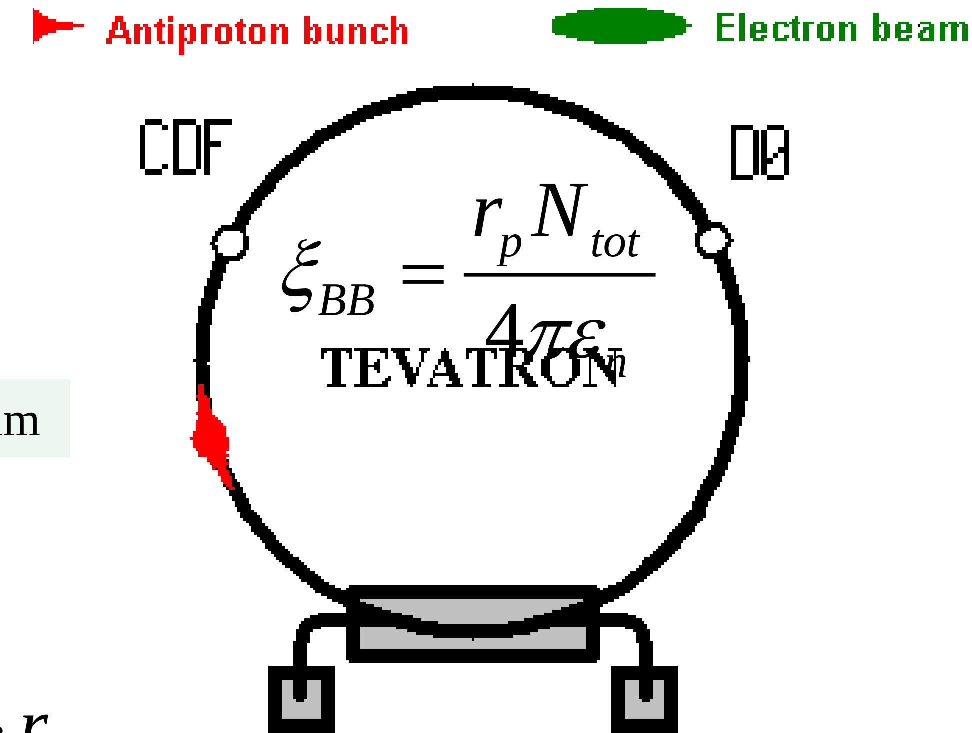
Realization (TELs)

Results

By-products (collimation longitudinal and transverse)

Beam-Beam Compensation Idea





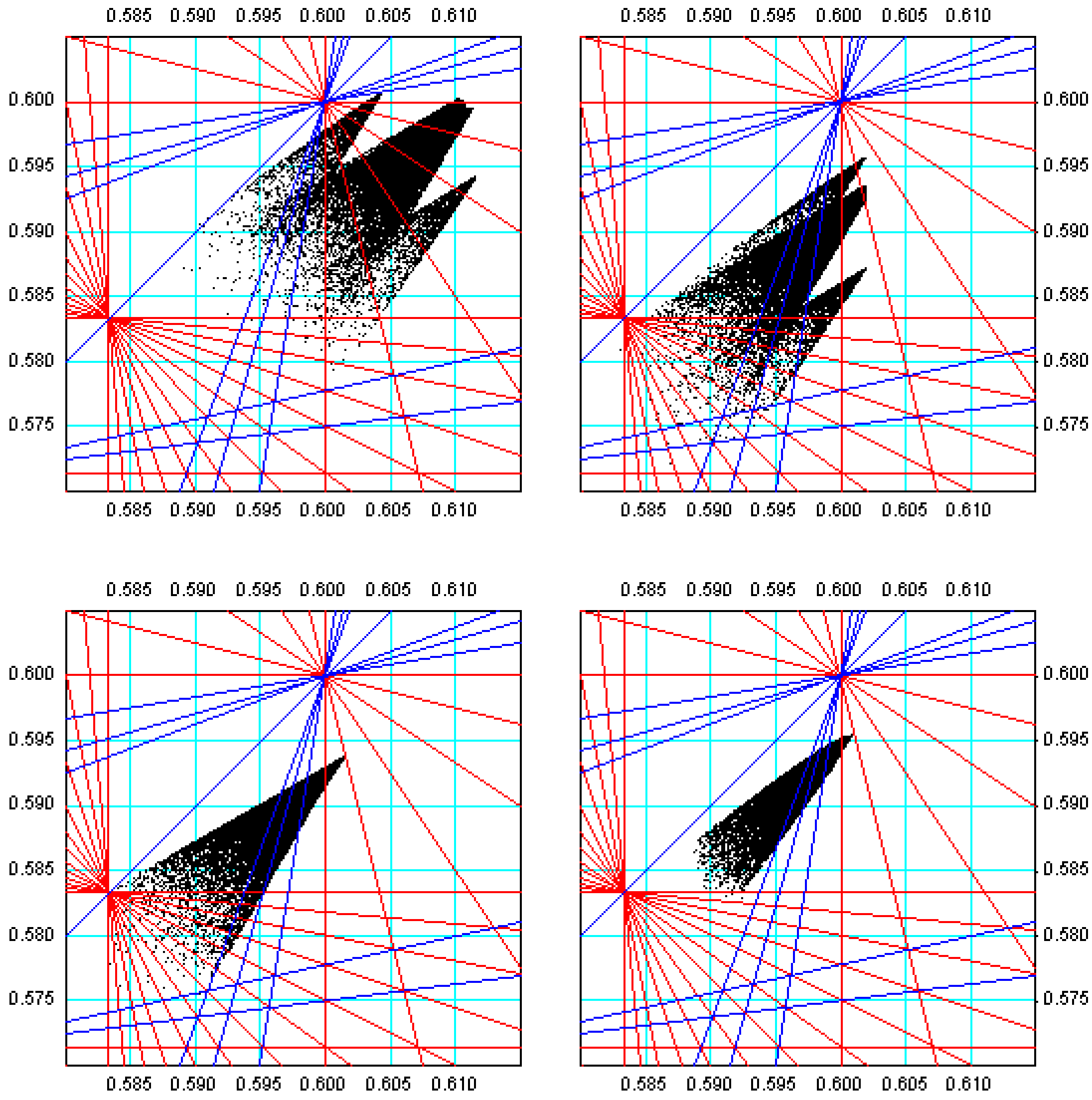
$$\xi_{BB} = \frac{r_p N_{tot}}{4\pi\varepsilon_n}$$

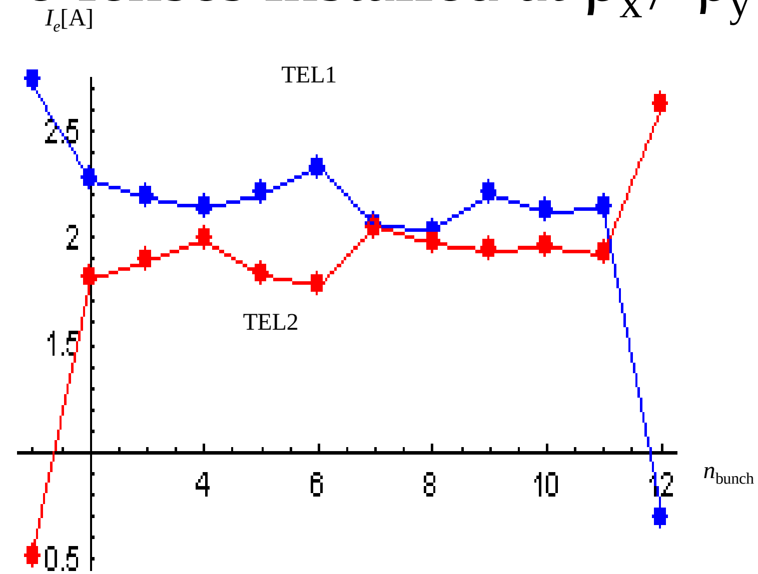
$$dQ_{x,y} = \mp \frac{\beta_{x,y}}{2\pi} \cdot \frac{1 \pm \beta_e}{\beta_e} \cdot \frac{J_e \cdot L_e \cdot r_p}{e \cdot c \cdot a_e^2 \cdot \gamma_p}$$

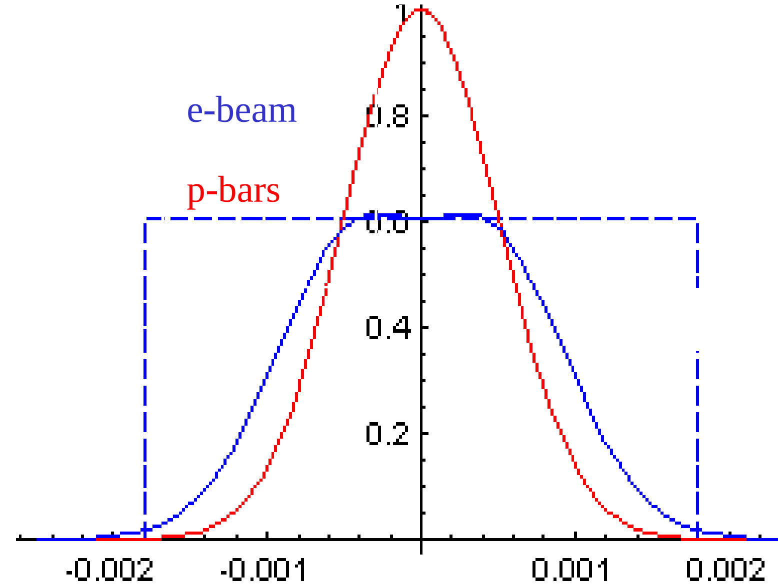
"…to compensate (in average) space charge forces of positively charged protons acting on antiprotons in the Tevatron by interaction with a negative charge of a low energy high-current electron beam " (1997)

Long-Range Beam-Beam Compensation

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



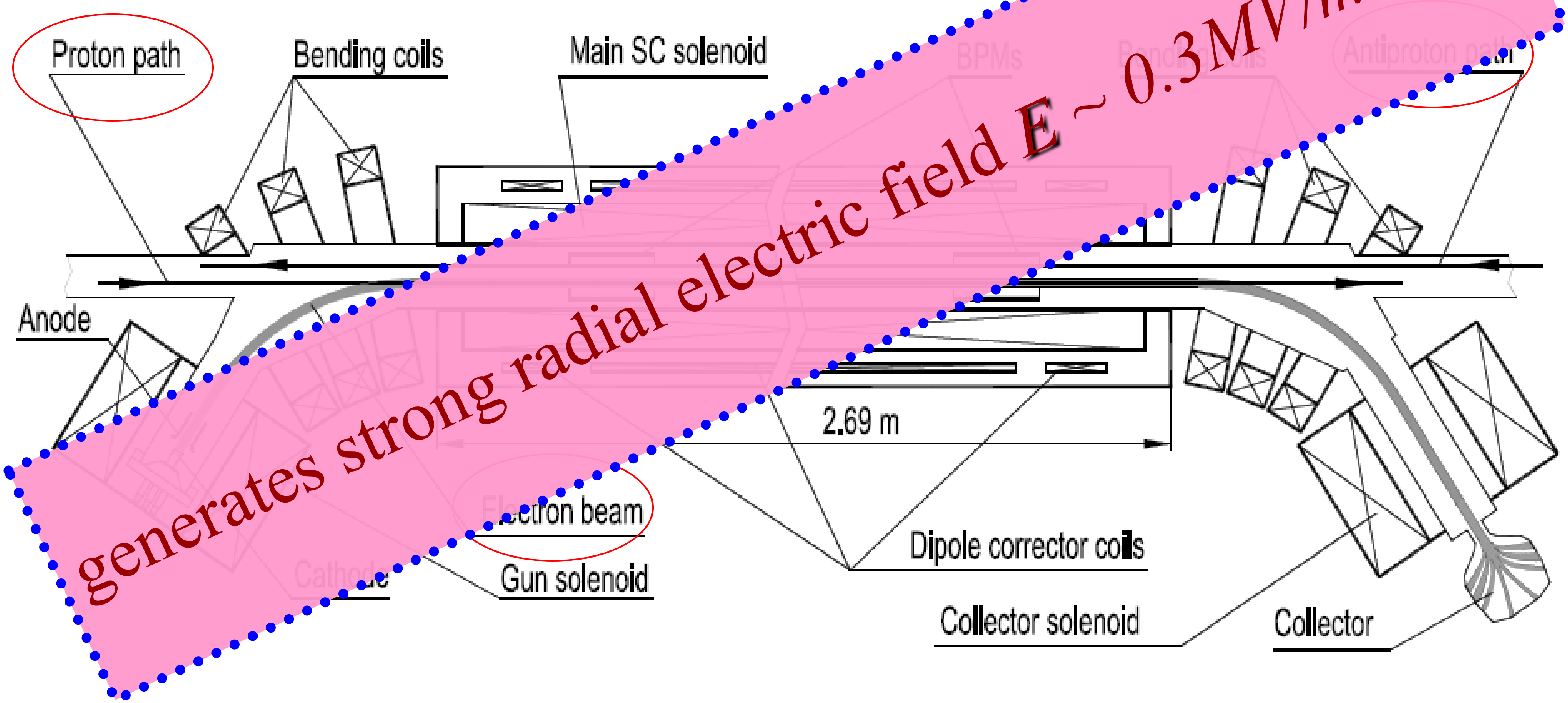




Some Facts on Electron Lenses

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

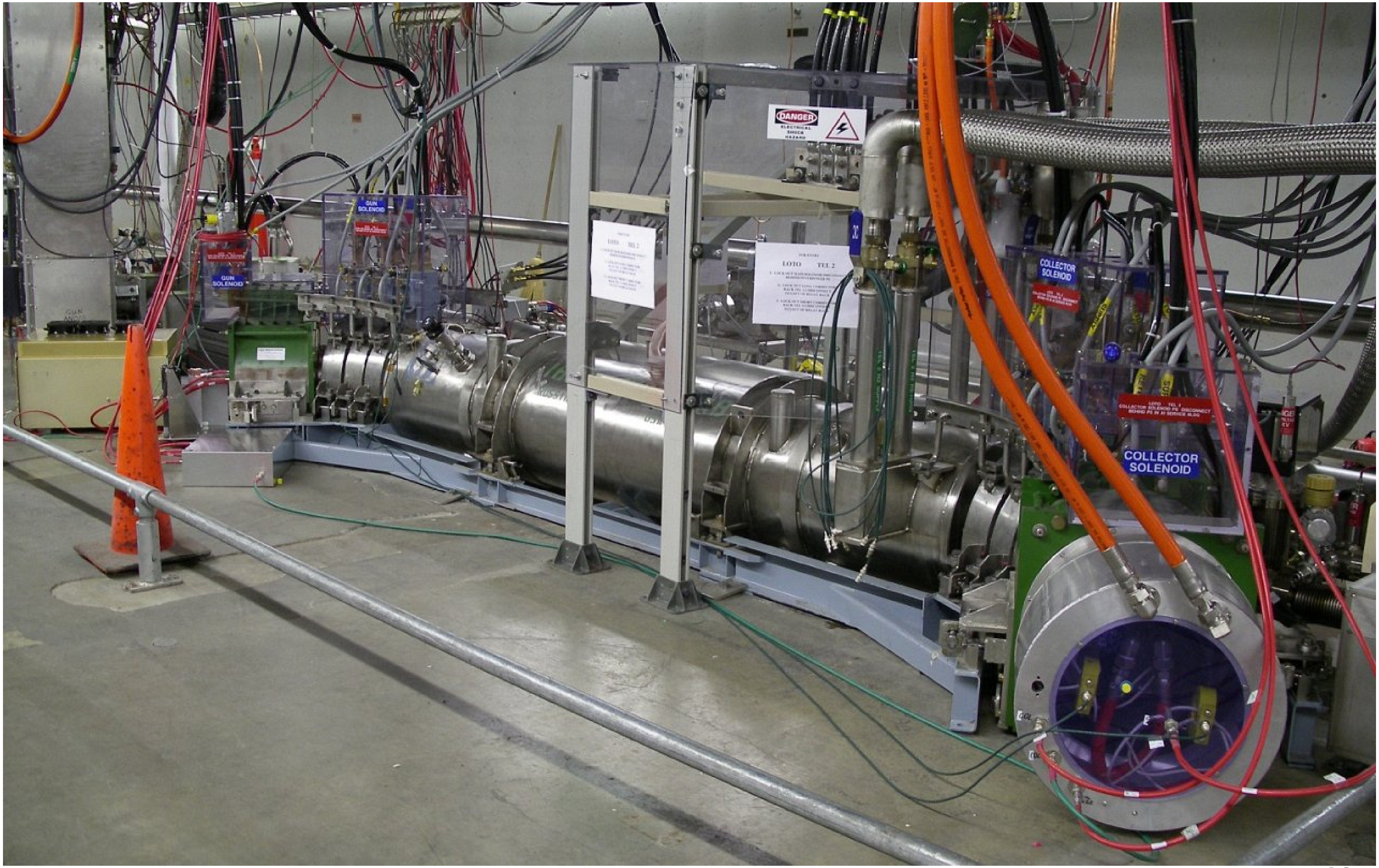
~1A electrons (~10^{12}) immersed in 3T solenoid



generates strong radial electric field $E \sim 0.3MV/m$

Tevatron Electron Lens #1 (F48)

TEL2 in the Tevatron Tunnel (A11)



Electron Charge Distribution

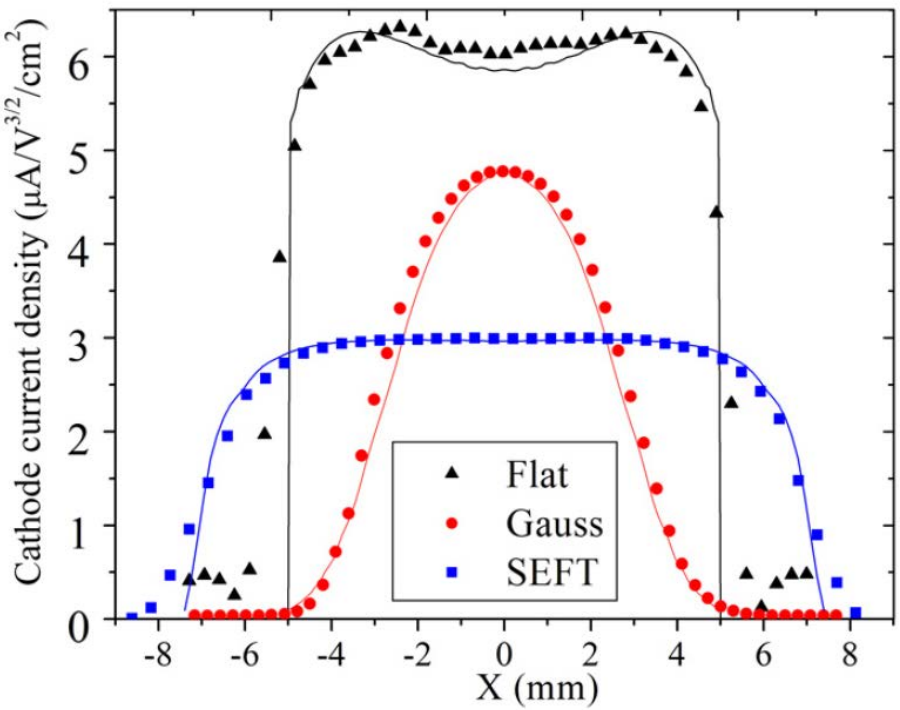


Figure 2. Three profiles of the electron current density at the electron gun cathode: black, flattop profile; red, Gaussian profile; blue, SEFT profile. Symbols represent the measured data and the solid lines are simulation results. All data refer to an anode–cathode voltage of 10 kV.

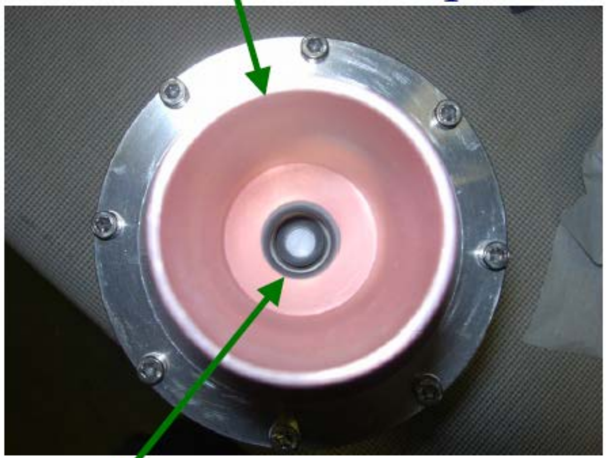
Shiltsev et al., *PRL* 99, 244801 (2007).
Shiltsev et al., NJP 10, 043042 (2008).

Electron gun

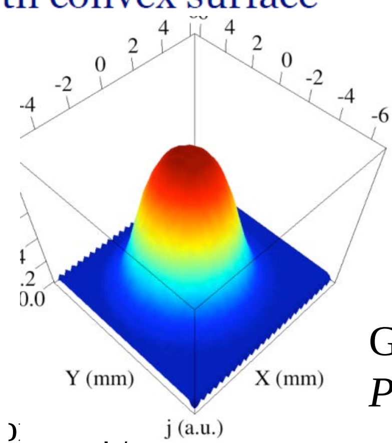
Copper anode

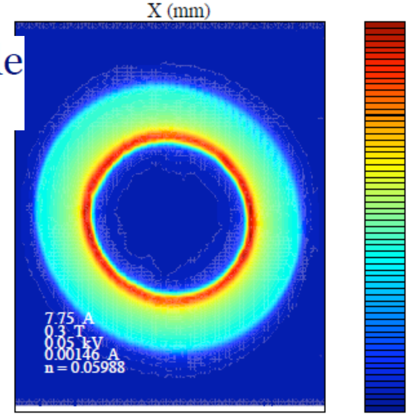
side view

top view



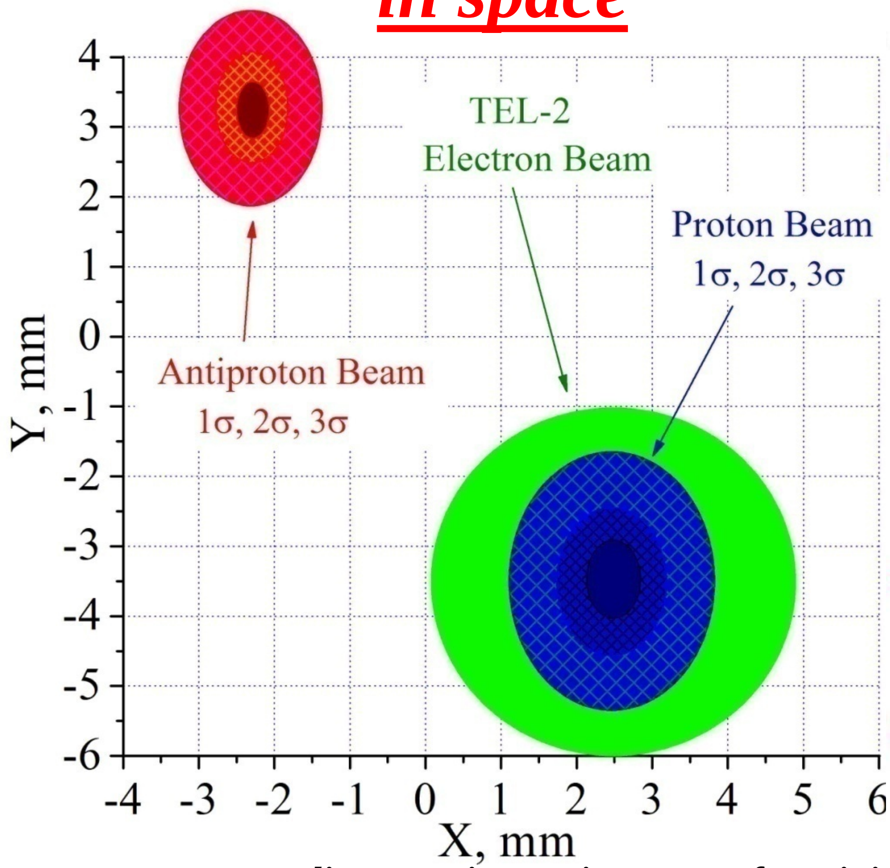
Tungsten dispenser cathode with convex surface

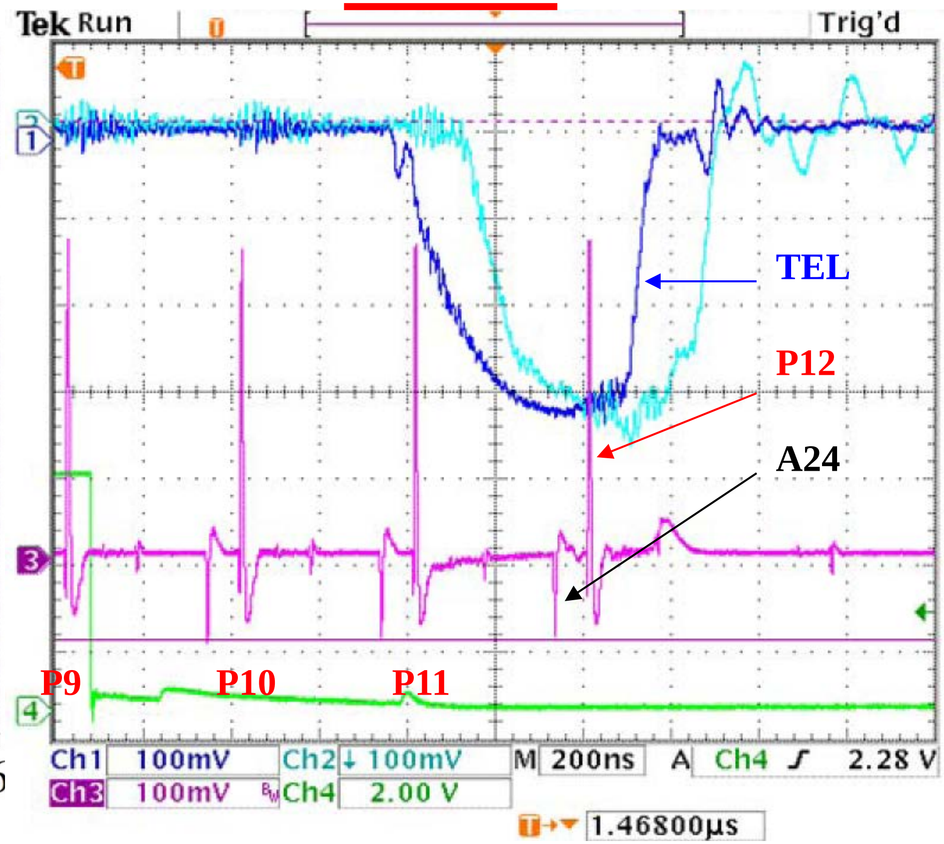




G. *Stancari*, et al., (2011)
Phys. Rev. Lett. 107, 084802
2013

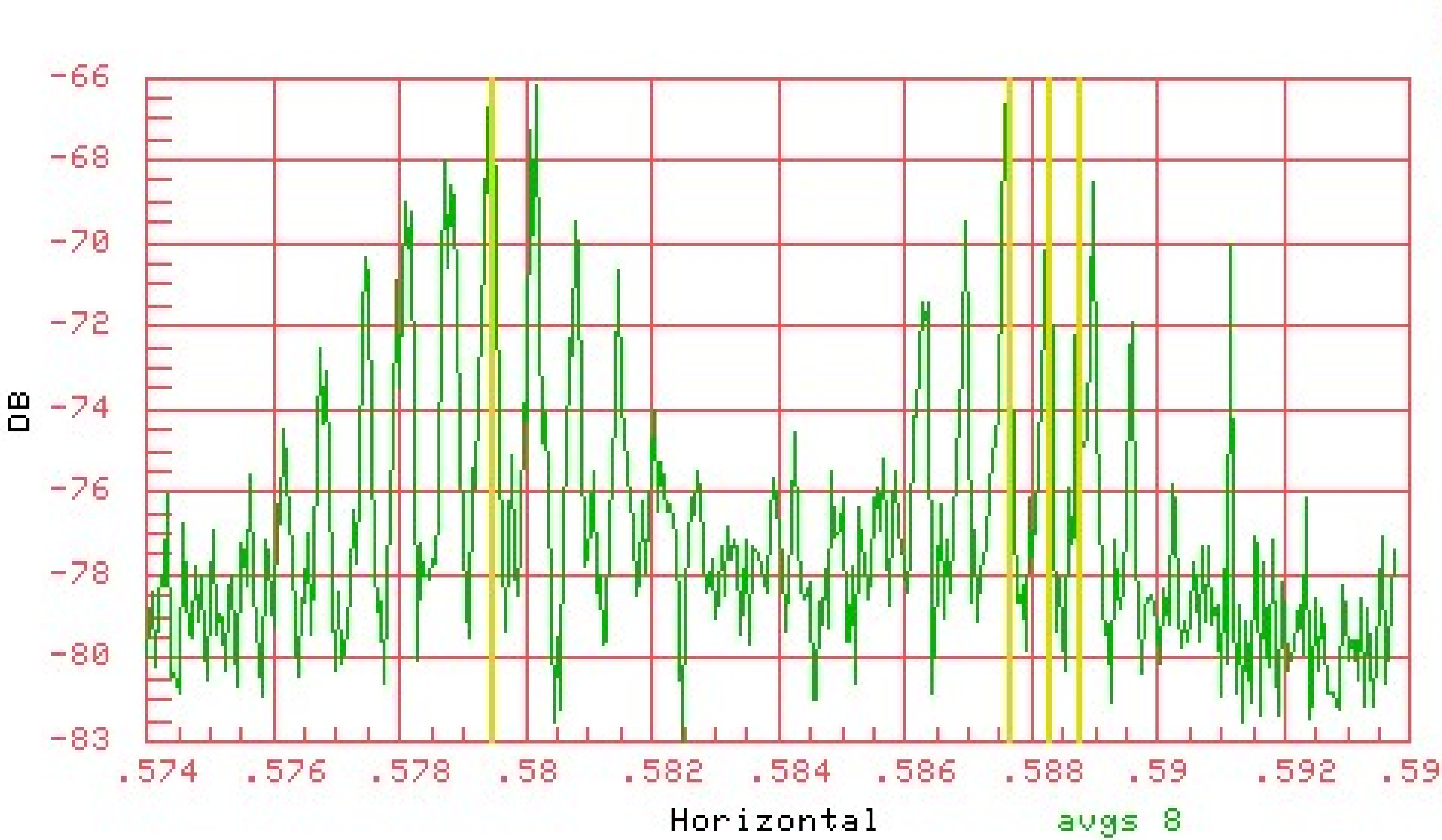
TEL e-beam aligned and timed on protons





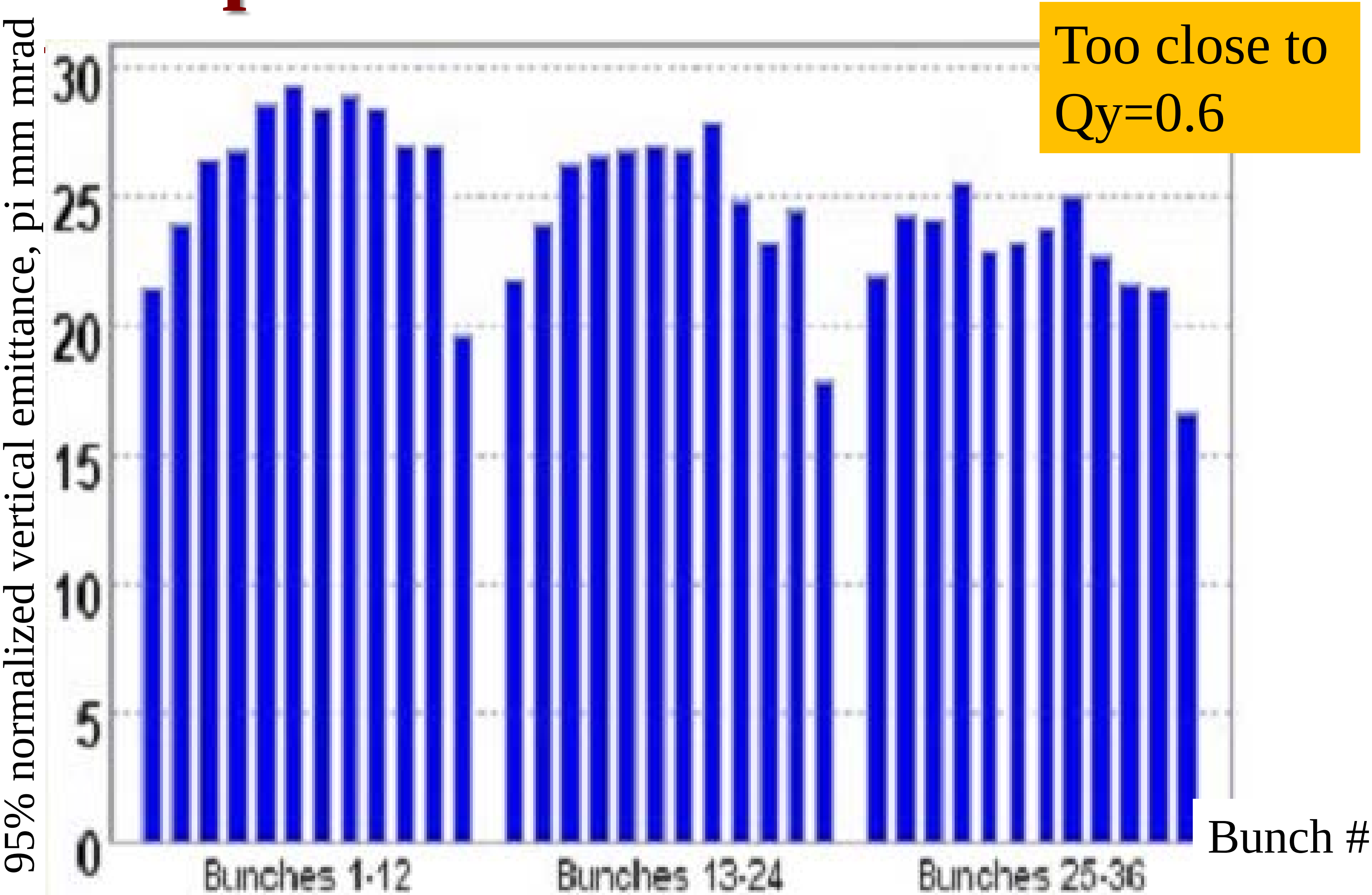
Transverse e-p alignment **is very important for minimization of noise effects and optimization of positive effects due to e-beam.** ***Timing*** **is important to keep protons on flat top of e-pulse – to minimize noise and maximize tune shift.**

Tuneshift dQ_{hor}=+0.009 by TEL

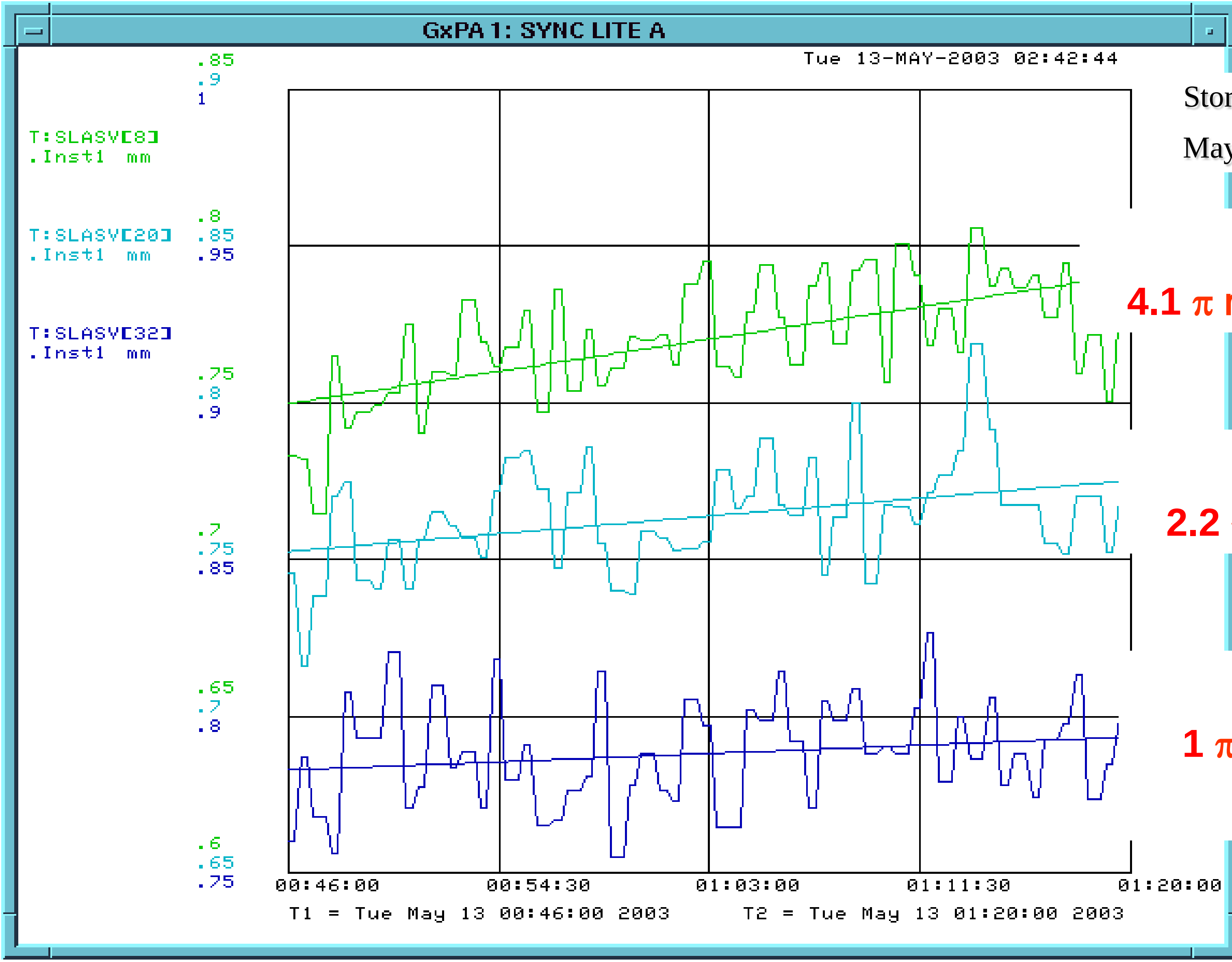


Three bunches in the Tevatron, the TEL acts on one of them

“Scallops” in Pbar Bunch Emittances



Emittance Growth of A33 Suppresed by TEL



Store #2540

May 12, ‘03

A9

4.1 π mm mrad/hr

A21

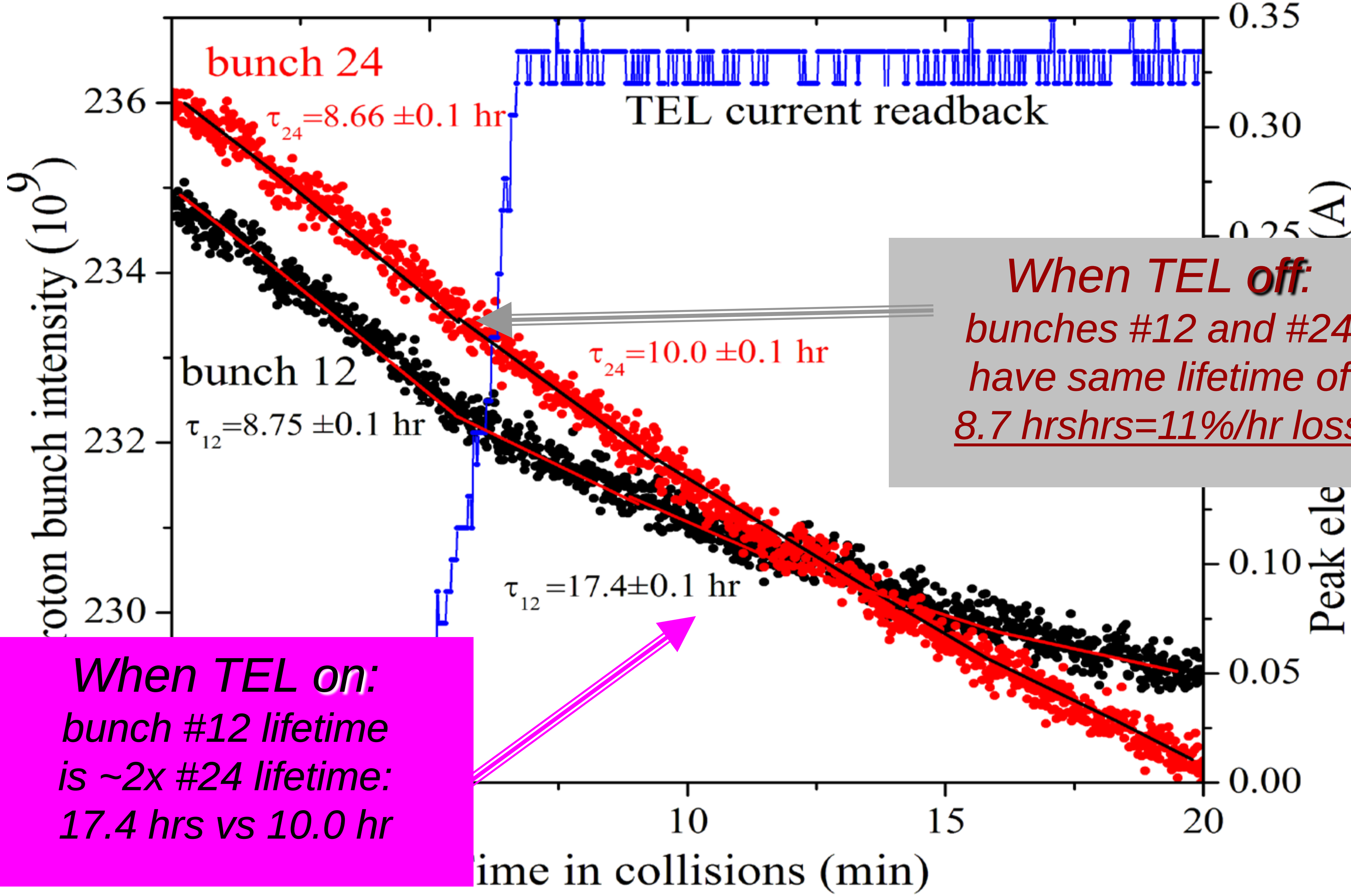
2.2 π mm mrad/hr

A33

1 π mm mrad/hr

-TEL on it

TEL2 on One Proton Bunch P12

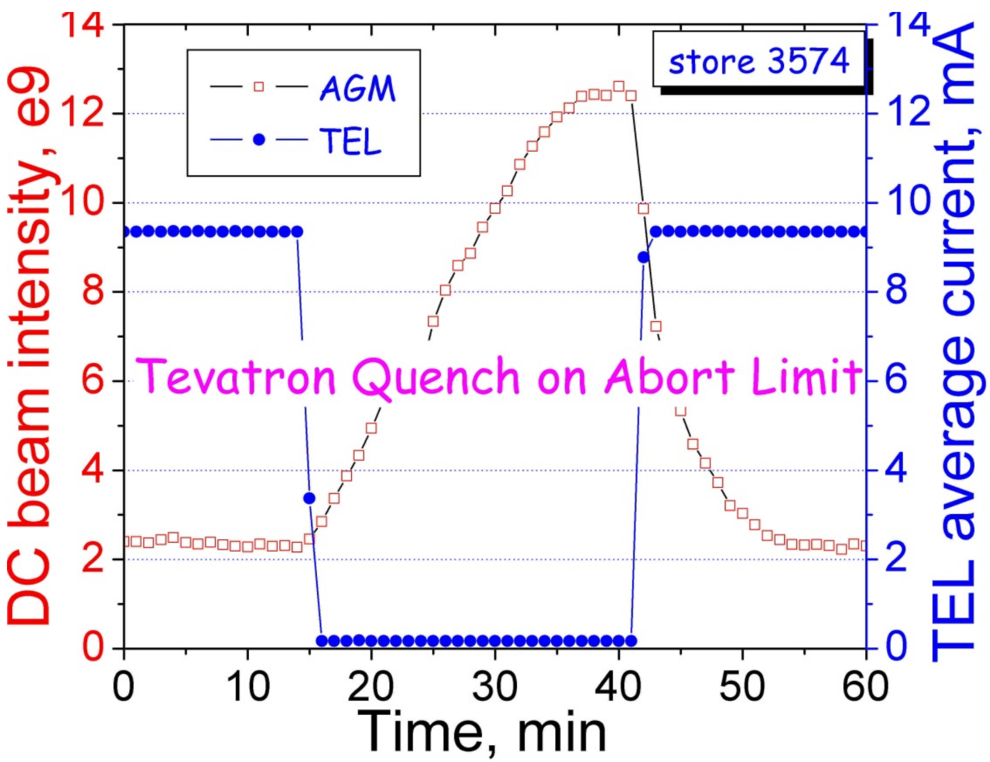


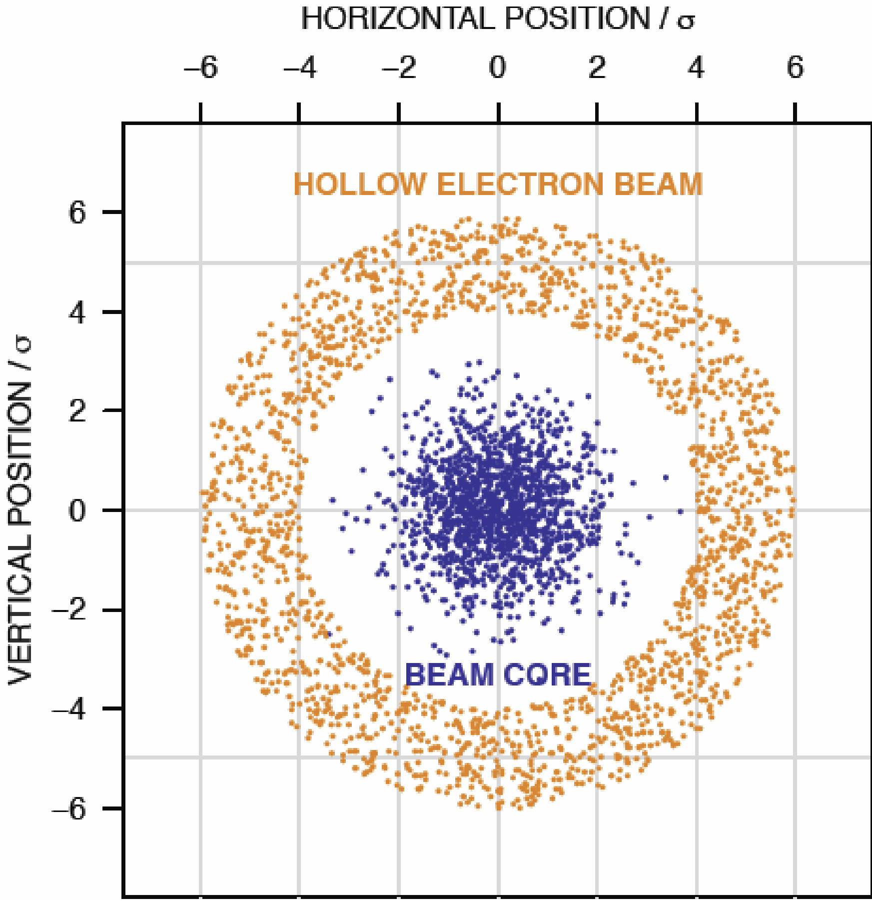
When TEL off:
bunches #12 and #24 have same lifetime of *8.7 hrshrs=11%/hr loss*

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

By-products: e-Beam Collimation

Pulsed e-current
in the abort gap
→ Drive out DC beam





Hollow-e-beam →
no EM field inside
Strong field outside

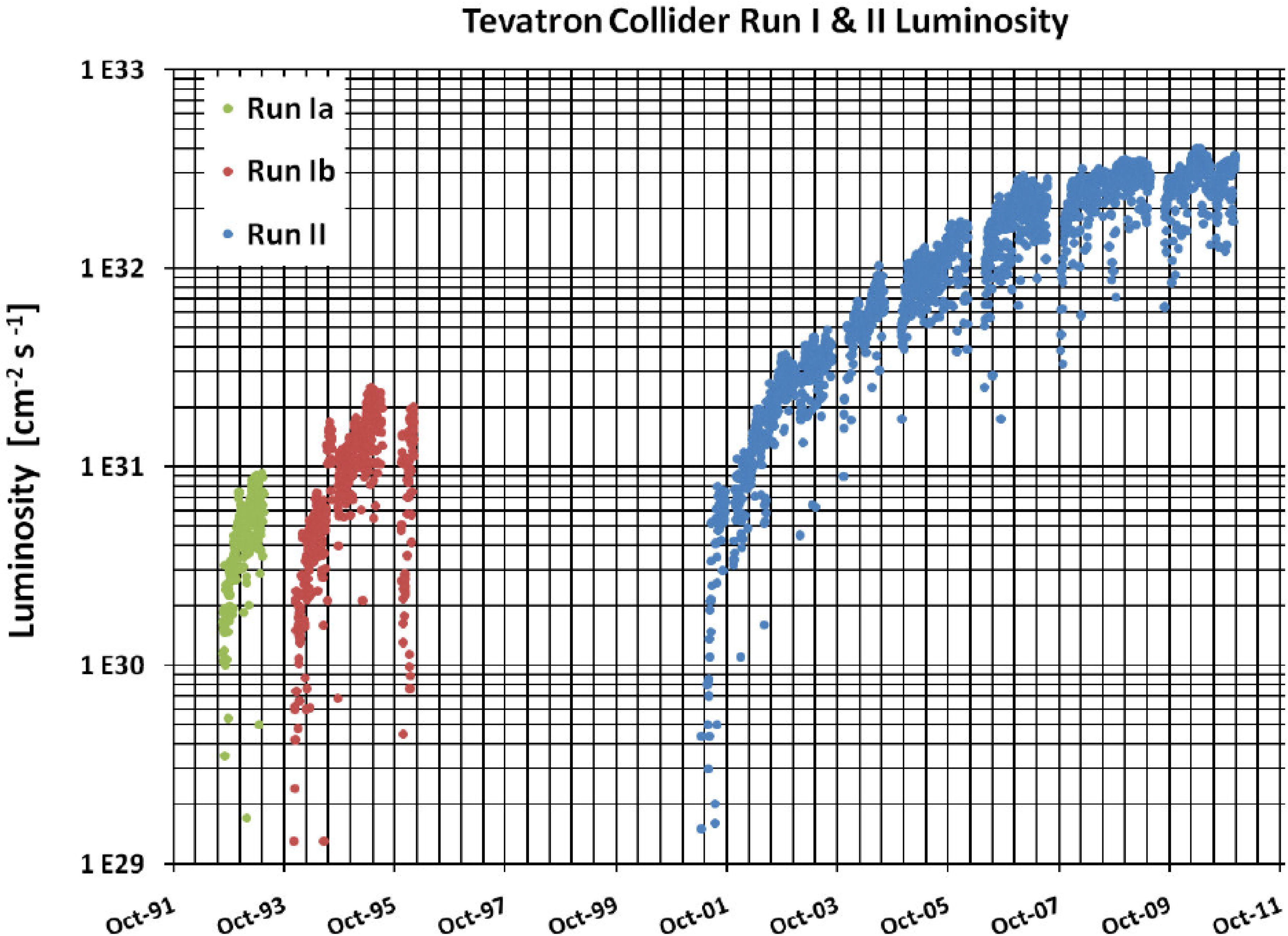
A word on complexity:

...BUT ALL ARE DOABLE!

colliders are very complex

The work of many:

- Beam-beam effects in the Tevatron Collider Run I:
  - J.Annala, S.Assadi, P.Bagley, D.Finley, G. Goderre, D.A.Herrup, R.Johnson, J.Johnstone, E.Malamud, M.Martens, L. Michelotti, S.Mishra, G.Jackson, S. Peggs, S.Saritepe, D.Siergiej, P.Zhang
- Beam-beam effects in the Collider Run II:
  - Yu.Alexahin, J.Annala, D.Bollinger, V.Boocha, J.Ellison, B.Erdelyi, N.Gelfand, B.Hanna, H.J.Kim, P.Ivanov, A.Jansson, A.Kabel, V.Lebedev, P.Lebrun, M.Martens, R.S.Moore, V.Nagaslaev, R.Pasquinelli, V.Sajaev, T.Sen, E.Stern, D.Shatilov, V.Shiltsev, D.Still, M.Syphers, A.Tollestrup, A.Valishev, M.Xiao
- Beam-beam compensation:
  - A.Aleksandrov, Y. Alexahin, L.Arapov, K. Bishofberger, A.Burov, C.Crawford, V.Danilov, B.Fellenz, D.Finley R.Hively, V.Kamerdzhiev, S.Kozub, M.Kufer, G. Kuznetsov, P.Logatchov, A.Martinez, F.Niell, M.Olson, V.Parkhomchuk, H.Pfeffer, V.Reva, G.Saewert, V.Scarpine, A.Seryi, A.Shemyakin, V.Shiltsev, N. Solyak, G.Stancari, B.Sukhina, V.Sytnik, M. Tiunov, L.Tkachnko, A.Valishev, D.Wildman, D.Wolff, X. Zhang, F.Zimmermann, A.Zinchenko



Tevatron Collider Run I & II Luminosity
Run Ia
Run Ib
Run II
Luminosity [cm-2 s-1]
1 E33
1 E32
1 E31
1 E30
1 E29
Oct-91
Oct-93
Oct-95
Oct-97
Oct-99
Oct-01
Oct-03
Oct-05
Oct-07
Oct-09
Oct-11

Table 3. Tevatron Collider Run II major luminosity improvements history.

Improvement		Luminosity gain
Optics correction in Accumulator (AA) to Main Injector (MI) beam line	12/2001	25 %
Tevatron quenches on abort stopped by electron lens	02/2002	0 %, reliability
Antiproton loss at the step #13 of Tevatron low-beta squeeze fixed	04/2002	40 %
New Tevatron injection helix implemented	05/2002	15 %
New AA lattice reduces IBS, emittances	07/2002	40 %
Beam Line Tuner to reduce emittance dilution at Tevatron injection	09/2002	10 %
Antiproton multi-bunch coalescing efficiency improved in MI	10/2002	5 %
Small aperture Lambertson magnets removed from Tevatron C0 sector	02/2003	15 %
Tevatron sextupoles tuned / SEMs taken out of antiproton beam lines	06/2003	10 %
New Tevatron helix implemented on ramp to reduce beam losses	08/2003	2 %
Tevatron magnet reshimming (to center coils inside iron yokes)	12/2003	10 %
MI dampers operations / HEP store length increased	02/2004	30 %
Improved efficiency of 2.5 MHz antiproton transfers from AA to MI	04/2004	8 %
Reduction of Tevatron β^* to 35 cm	05/2004	20 %
Antiproton injections from both Recycler and Accumulator	07/2004	8 %
Electron cooling system in Recycler operational	01–07/2005	$\sim$ 25 %
Longitudinal slip-stacking system in Main Injector operational	03/2005	$\sim$ 20 %
Tevatron octupoles optimized at injection energy of 150 GeV	04/2005	$\sim$ 5 %
Further reduction of the Tevatron beta-function at IPs β^* to 28 cm	09/2005	$\sim$ 10 %
Antiproton production optimization	02/2006	$\sim$ 10 %
Tevatron helical separation scheme at 150 GeV improved, more protons	06/2006	$\sim$ 10 %
Tevatron collision helical separation scheme improved, better lifetime	07/2006	$\sim$ 15 %
New Recycler working point results in smaller antiproton emittances	07/2006	$\sim$ 25 %
Faster antiproton beam transfers from AA to RR (1 hour $\longrightarrow$ 1 min)	12/2006	$\sim$ 15 %
New antiproton target with higher gradient Li lens operational	01/2007	$\sim$ 10 %
Tevatron sextupole magnet circuits set up for new working point	2007	$\sim$ 10 %
Compensation of 2nd order chromaticity in Tevatron beam optics	2008	$\sim$ 5 %
Shot-setup time reduced by multi-bunch proton injection	2008–09	$\sim$ 5 %
Better proton beam quality by scraping in Main Injector	2008	$\sim$ 5 %
Antiproton beam size dilution at collisions / B0 aperture opened up	2008	$\sim$ 5 %
Booster proton emittances reduced / tune up of P1 and A1 transfer lines	04/2010	$\sim$ 10 %
Tevatron collimators employed during low-beta squeeze, more protons	04/2011	$\sim$ 8 %

12 out 32 luminosity steps –

via beam-beam work

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Summary

- Beam-beam effects in the Tevatron turned from "tolerable" (Run I) to "nightmare" (early Run II)
- The variety of effects was unmatched:
  - In both beams, at all stages of the cycle, LR and head-on
- The Tevatron team has been able to address them and provide critical contribution to **more than 30-fold luminosity increase** by the end of Run II
- We also enriched beam physics by:
  - Experimental studies, theory & trustable modeling tools
  - development of the electron lenses and first demonstration of active beam-beam compensation

Please, don’t miss :

- Tue 9:30 Alex Valishev (Fermilab) Modeling beam-beam in the Tevatron
- Tue 10:30 Alexey Burov (Fermilab) Beam-beam, impedance and damper
- Tue 15:00 Giulio Stancari (Fermilab) Measurements of the effect of collisions on transverse beam halo diffusion in Tevatron and LHC
- Tue 17:30 Vladimir Shiltsev (Fermilab)Experience with long range beam-beam effects in the Tevatron
- Wed 09:00 Giulio Stancari (Fermilab) Beam-beam compensation studies in the Tevatron
- Thur 08:30 Giulio Stancari (Fermilab) Detection of coherent beam-beam modes with digitized BPM
- Thur 14:00 Alex Valishev (Fermilab) Beam-beam for the HL-LHC
- Thur 15:00 Alexey Burov (Fermilab) Circular Modes

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}

Complexity of Beams in *log*-Scale:

Complexity 0	APS, LCLS
Complexity 0.5	FNAL/MI
Complexity 1	B-factories
Complexity 1.5	eCool, HERA
Complexity 2	DCI/Orsay,80
Complexity 2	Tevatron,LHC
Complexity 2.5	B-B-Comps'n