Fermilab

Simulations and Observations of Beam - Beam Effects at the Tevatron in Fermilab

Meiqin Xiao
Beam Physics Department
Fermilab

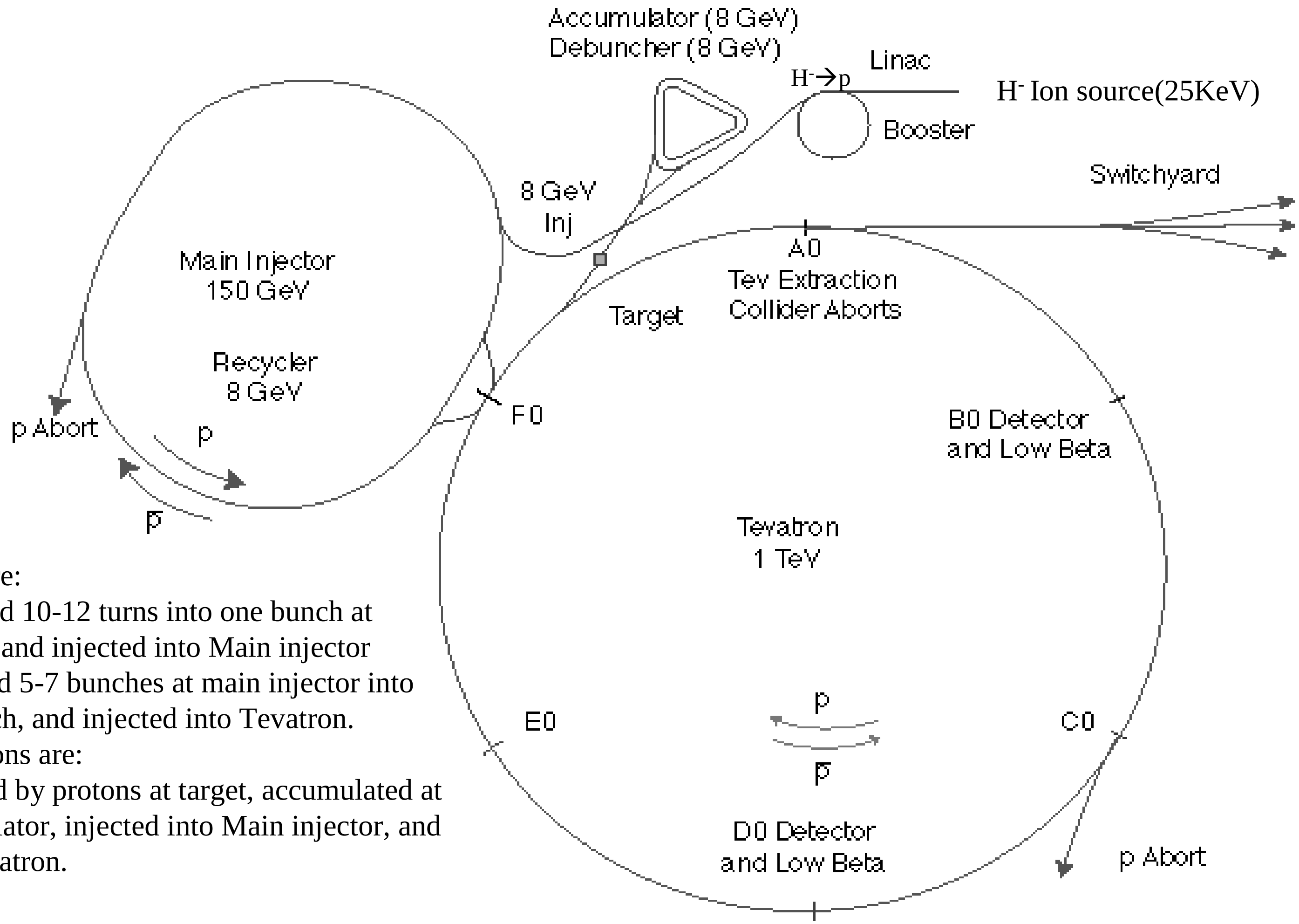
I will talk about…

Fermilab

- Fermilab accelerator complex, Tevatron Scenario, and general information
- Beam-beam effects , together with machine non-linearities, at injection at present machine conditions
- Beam-beam effects at collision at design machine conditons
- Conclusions

Fermilab accelerator complex

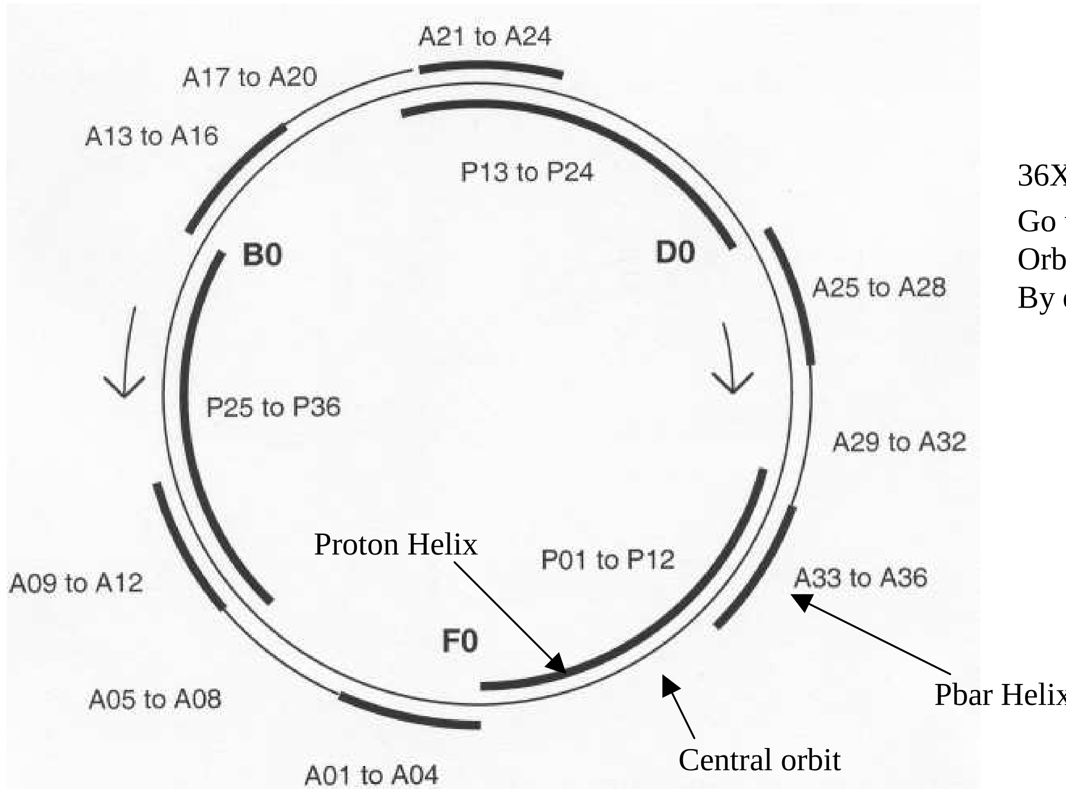
Fermilab



Protons are:
- combined 10-12 turns into one bunch at Booster, and injected into Main injector
- Coalesced 5-7 bunches at main injector into one bunch, and injected into Tevatron.

Anti-protons are:
- produced by protons at target, accumulated at Accumulator, injected into Main injector, and then Tevatron.

The scenario at Tevatron collision

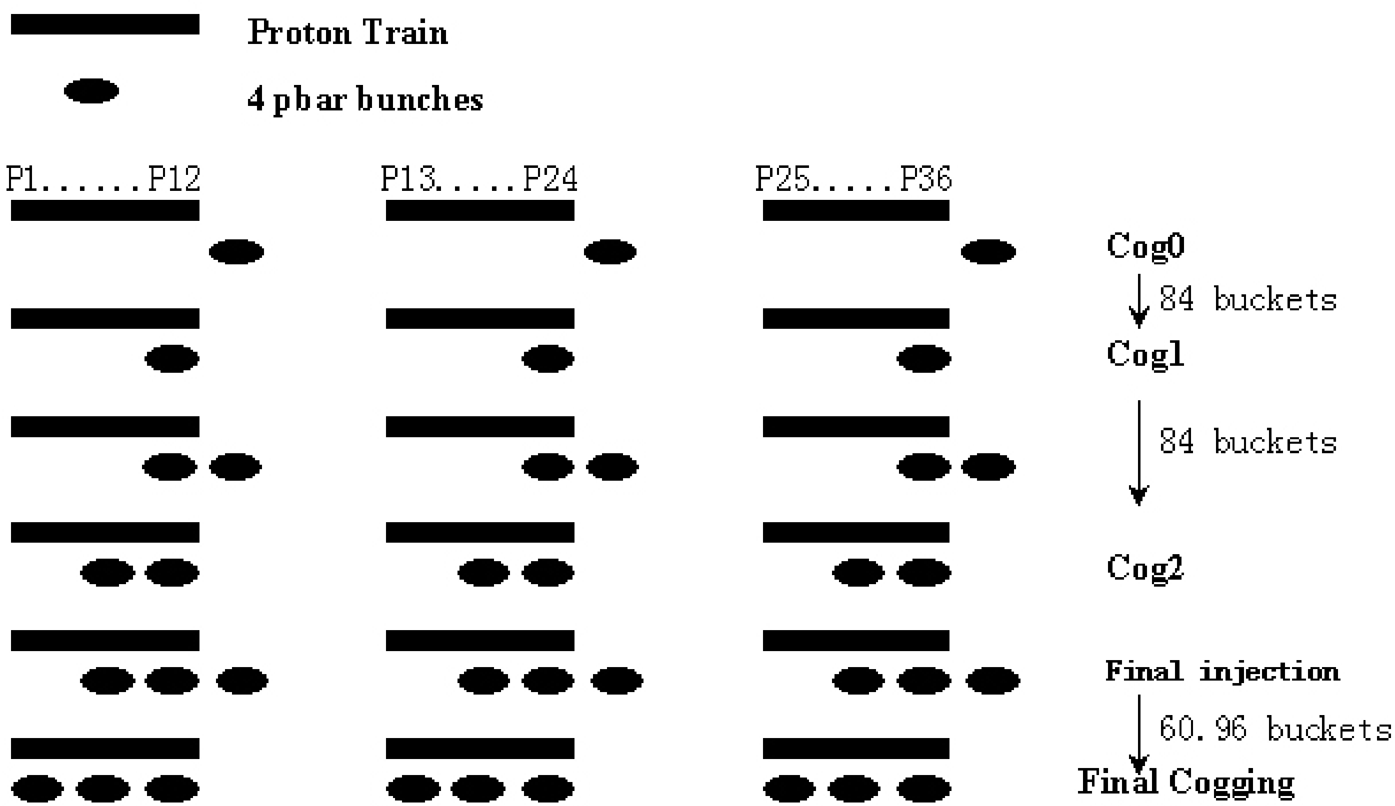


36X36 *p* and *pbar*

Go through different closed Orbit(called Helix), separated By electrostatic sepatators.

For each pbar bunch:
Two Head-on interactions: beams collide at B0 and D0
70 long-range interactions
A01 and P01 meet at F0

3 cogging stages at Tevatron injection



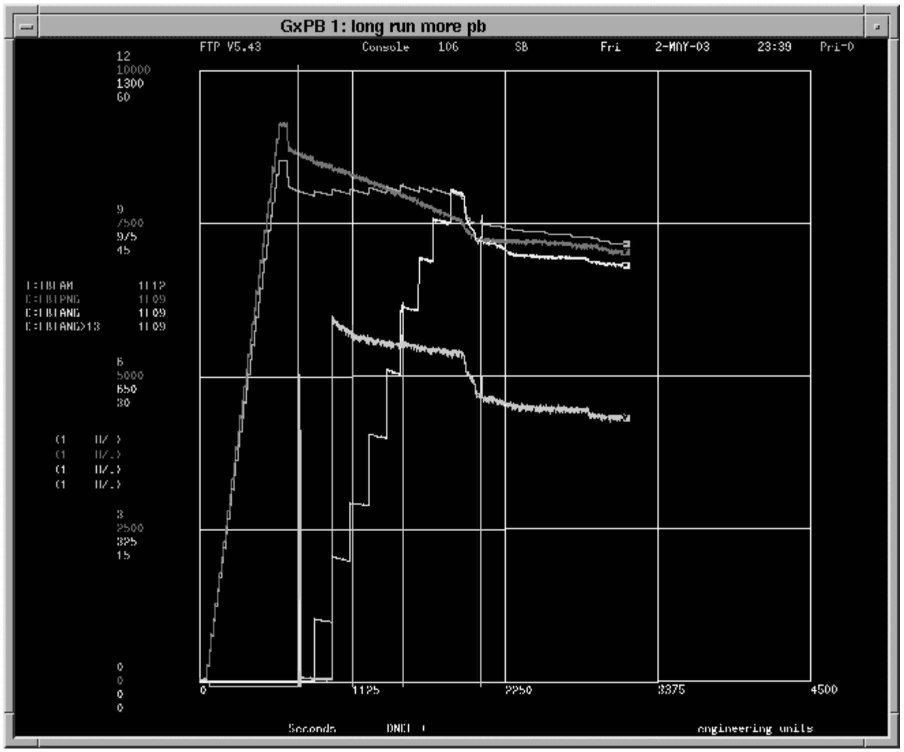
Each pbar bunch experiences 72 long-rang interactions, and beam-beam effects are different for each pbar bunch in a train since the sequence of the long-range interations is different for each of them.

Main parameters

Fermilab

parameters	Injection(p/pbar)		Collision(p/pbar)	
	present	design	present	design
Bunch intensities $X10^{11}$	2.20/0.13	2.7/0.3	1.7/0.13	2.7/0.3
Emittance95%[πmm.mrad]	25/20	20/15	25/20	20/15
Momentum deviation (r.m.s.,1δ_p)	$7x10^{-4}$ /$4.5x10^{-4}$	$4.3\ x10^{-4}$ /$4.3x10^{-4}$	$1.7x10^{-4}$ /$1.2x10^{-4}$	$0.87x10^{-4}$ /$0.87x10^{-4}$
Chromaticities	(8,8)	(8,8)	(20,20)	(5,5)
Working point	(0.583,0.575)	(0.585,0.575)	(0.585,0.575)	(0.585,0.575)

Comfort plot and beam lost in the Tevatron



Date

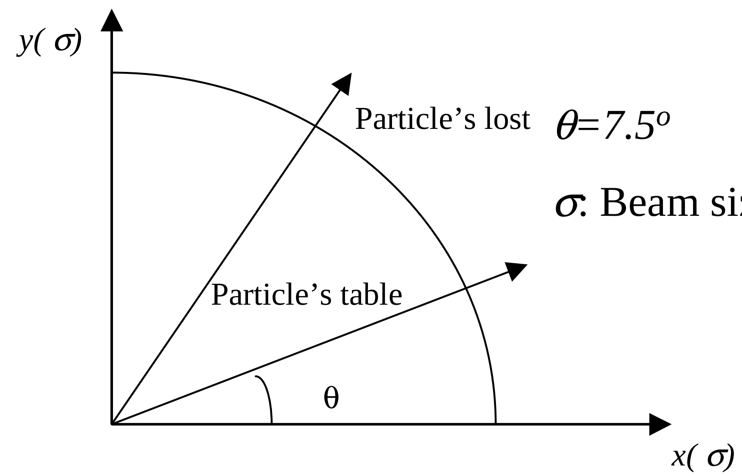
Stage	03/02	10/02	01/03	03/03
P-loss at injection(%)	23	14	16	10
Pbar-loss at injection(%)	20	9	4	4
P-loss on ramp(%)	7	6	9	5
Pbar-loss on ramp(%)	14	8	12	11
Pbar-loss in squeeze(%)	25	5	3	2
P/bunch at low beta(E9)	140	170	180	205
pbar/bunch at low beta(E9)	7.5	22	20	23

General information

Fermilab

- **Machine non-linearities:**
  - **(1) Magnet field errors (ARC+IR) +**
  - **(2) Chromaticity Sextupoles +**
  - **(3) Feeddown sextupoles**
- **Three concepts:**
  - **(1) Tune shift: experienced by zero amplitude particles**
    one way to parameterize the strength of a kick with separated beams.
  - **(2) Footprint: a good measure of the strength of the nonlinearity**
  - **(3) Dynamic Aperture(DA)**
- **Tracking codes**
  - **(1) MAD: 1-2 days(10^5 turns)**
  - **(2) SIXTRACK: 10 hours(10^5 turns)**

10^5 turns → 2 second in the Tevatron



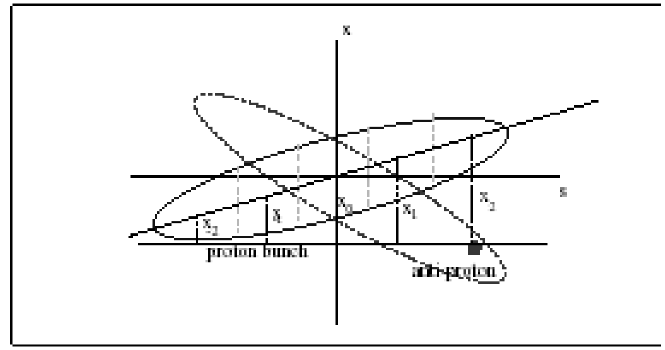
$\theta = 7.5^o$

σ: Beam size

Fermilab

Simulation model for headons interactions

- Bunch length effects:
  - Houglass Effects: the transverse size of each disk is different
  - Longitudinal desity variation: a Gaussian distribution
  - Phase variation: Propagation between slices
  - Beam-beam kick



The strong proton bunch is divided into 9 slices

At the Tevatron where $\sigma_s \simeq 37$cm, $\beta^* = 35$cm

- Complete beam-beam map:

$$\mathcal{M} = \mathcal{M}_{BB}(N_S)M_d(N_S-1 \rightarrow N_S)\mathcal{M}_{BB}(N_S-1)M_d(2 \rightarrow 3)\ldots\mathcal{M}_{BB}(2)M_d(1 \rightarrow 2)\mathcal{M}_{BB}(1)$$

Simulation model for Long-range interactions - δ function

The kicks are given by the Bassetti-Erskine expressions for Gaussian beams(assuming $\sigma_x > \sigma_y$)

$$\Delta x' = \frac{N_b r_p}{\gamma_p}\sqrt{\frac{2\pi}{\sigma_x^2-\sigma_y^2}}\text{Im } F(x,y)$$

$$\Delta y' = \frac{N_b r_p}{\gamma_p}\sqrt{\frac{2\pi}{\sigma_x^2-\sigma_y^2}}\text{Re } F(x,y)$$

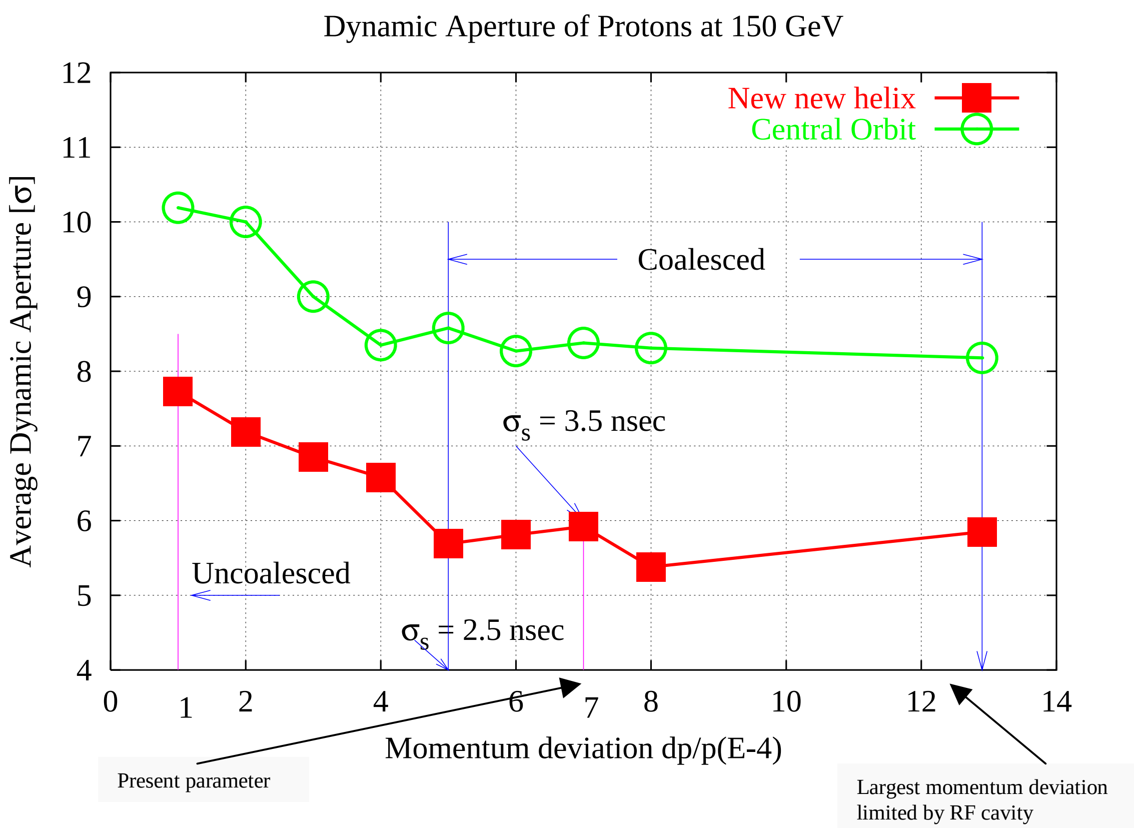
$$F(x,y) = W\left[\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right] - \exp[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}]W\left[\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right]$$

where W is the complex error function.

$$\sigma_{x,eff} = \sqrt{\beta_x\epsilon_x + (D_x\delta_p)^2}.$$

Dynamic Aperture of protons at injection

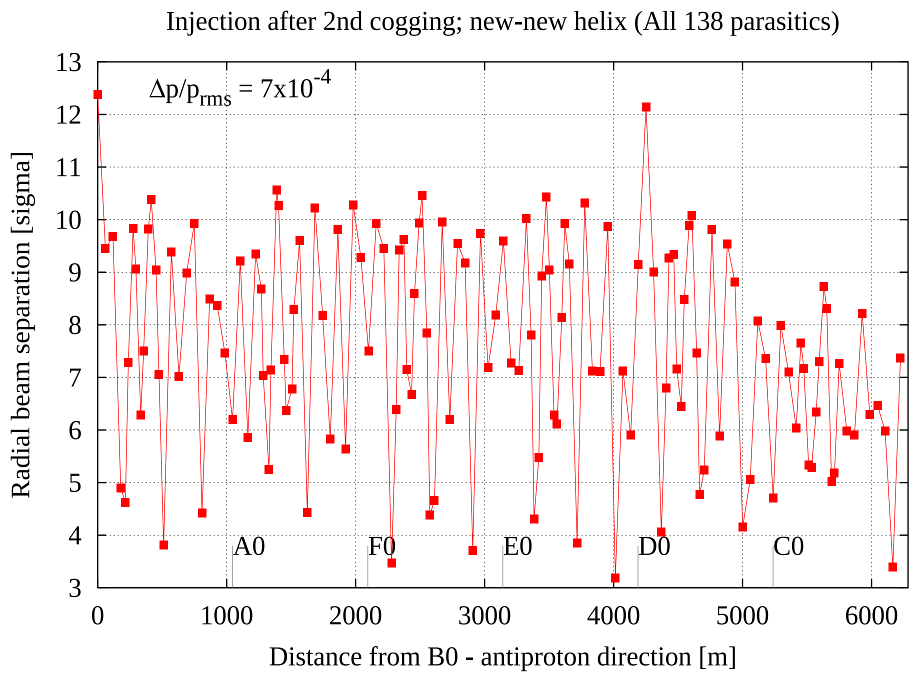
Fermilab

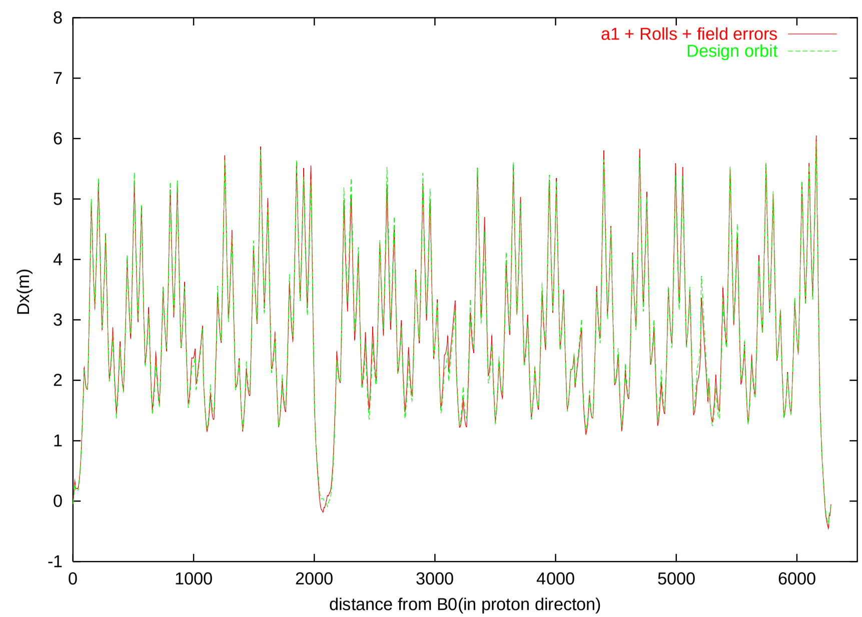


	DA on central orbit	on helix	physical aperture
uncoalesced protons(dp/p<1.E-4)	**~ 10σ**	**~ 8 σ**	**(4~6) σ at C0**
coalesced beam	**~ 8 σ**	**~ 5 σ**	**(4~6) σ at C0**
Proton lifetime(observed)	**4-6 hrs**	**1.5-2 hrs**	

Proton beam loss due to: 1) bunches are out of the RF buckets, 2) machine non-linearities.

Beam-beam separations at injection (after 2nd cogging)

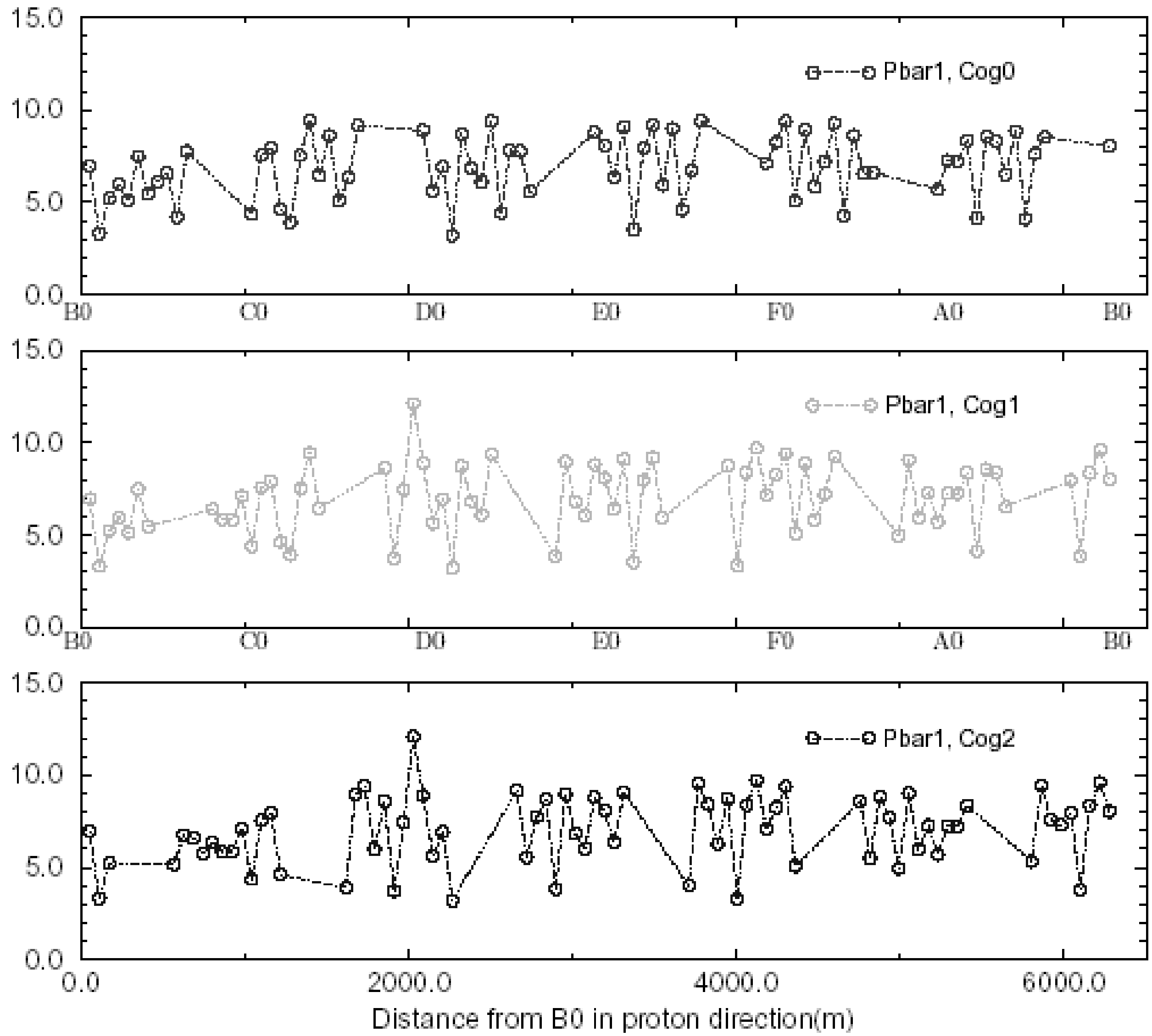




The minimum separation: ~3σ. The separation follows dispersion pattern when the momentum spread of the beam is large.

Beam-beam separation of pbar bunch 1

Fermilab



Analytical formulae

Fermilab

Beam-beam tune shift :

$$\Delta\nu_x = \frac{4\pi C}{\varepsilon_x}\int_0^1 \frac{e^{-(p_x+p_y)}}{v\left[v\left(r^2-1\right)+1\right]^{1/2}}\sum\nolimits_x \sum\nolimits_y dv, \quad (1)$$

where

$$\sum\nolimits_x = \sum_{k=0}^{\infty}\frac{\left(\frac{a_x}{d_x}\right)^k}{k!}\Gamma\left(k+\frac{1}{2}\right) \times \left[I_k\left(s_x\right)\left(\frac{2k}{a_x^2}-v\right)+I_{k+1}\left(s_x\right)\frac{s_x}{a_x^2}\right], (2)$$

$$\sum\nolimits_y = \sum_{l=0}^{\infty}\frac{\left(\frac{a_y}{d_y}\right)^l}{l!}\Gamma\left(l+\frac{1}{2}\right)I_l\left(s_y\right). \quad (3)$$

As shorthand notations we introduced the ratio of rms beam sizes $r = \sigma_y/\sigma_x$, and dimensionless variables for the amplitudes and separations according to $a_x = \sqrt{2\beta_x J_x}/\sigma_x$, $d_x = D_x/\sigma_x$ and similarly defined a_y and d_y. Using these notations, the following relationships have been used in (1): $p_x = v\left(a_x^2+d_x^2\right)/2$, $r_x = va_x^2/2$, $s_x = va_xd_x$, $p_y = fv\left(a_y^2+d_y^2\right)/2$, $r_y = fva_y^2/2$, $s_y = fva_yd_y$, where $f = \frac{r^2}{v(r^2-1)+1}$. The vertical amplitude dependent tune shift is derived analogously, due to symmetry in x and y.

Beam-beam chromaticity:

ments in (1): $d_x \mapsto d_x + \eta_x\delta$, $d_y \mapsto d_y + \eta_y\delta$, where δ is the relative momentum or energy deviation. The horizontal zero amplitude chromaticity is given by

$$\xi\frac{4}{d^6}\left(d_x^3\eta_x + 3d_x^2d_y\eta_y - 3d_xd_y^2\eta_x - d_y^3\eta_y\right). \quad (4)$$

The vertical chromaticity can be calculated similarly.

Beam-beam coupling:

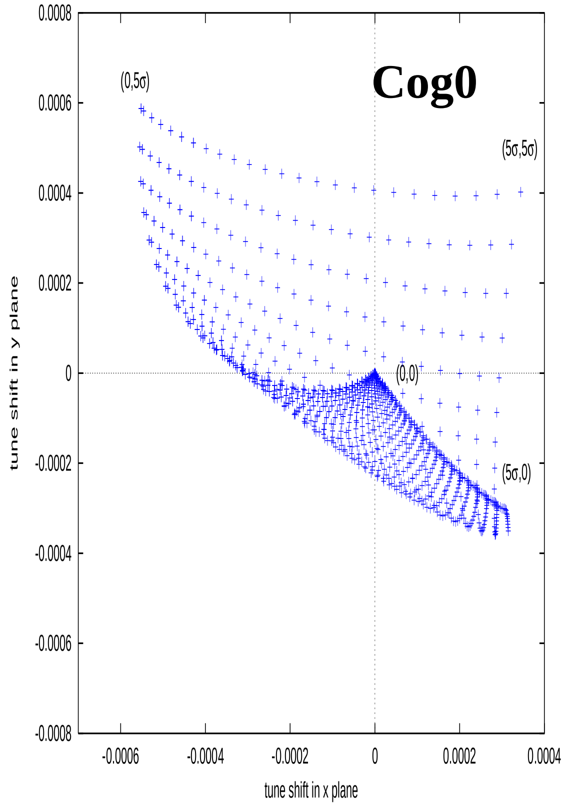
Given by the amplitude of the complex term driving the difference resonances(ν_x-ν_y)=p:

$$\begin{aligned}&F_{1,-1,p}(a_x,a_y)\\ =\ &-\frac{1}{2\pi}\frac{N_pr_p}{\gamma_p}\sqrt{\beta_x\beta_y}\frac{r}{\sigma_x^2}(a_x+d_x)(a_y+d_y)\\ &\times\exp\left\{i(\psi_x-\psi_y-(\nu_x-\nu_y-p)\frac{s}{R})\right\}\times\\ &\int_0^1 dv\frac{v}{[v(r^2-1)+1]^{3/2}}\exp\left\{-\frac{v}{2}[(a_x^2+d_x^2)+f(a_y^2+d_y^2)]\right\}\end{aligned} \quad (8)$$

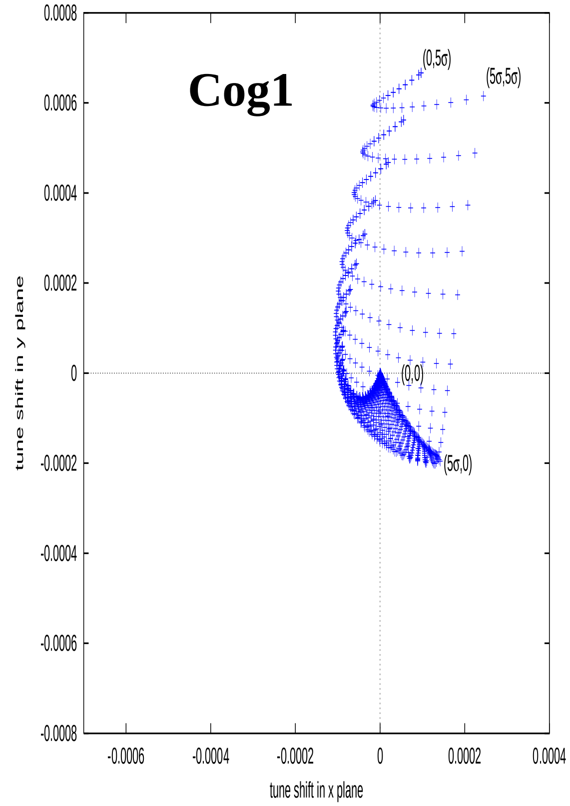
For zero amplitude($a_x = a_y = 0$) particle:

$$\begin{aligned}&F_{1,-1,p}(0,0) = -\frac{1}{2\pi}\frac{N_pr_p}{\gamma_p}\sqrt{\beta_x\beta_y}\frac{r}{\sigma_x^2}d_xd_y\\ &\exp[i(\psi_x-\psi_y-(\nu_x-\nu_y-p)\frac{s}{R})]\\ &\times\int_0^1 dv\frac{v}{[v(r^2-1)+1]^{3/2}}\exp[-\frac{v}{2}(d_x^2+fd_y^2)]\end{aligned} \quad (9)$$

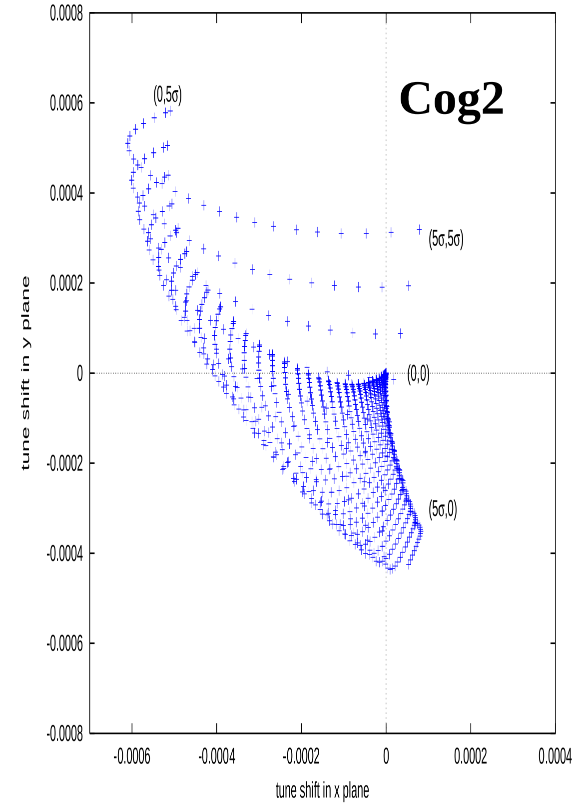
Tune footprint of pbar bunch 1 with only beam-beam at injection



fold at 3 σ in *x*-plane



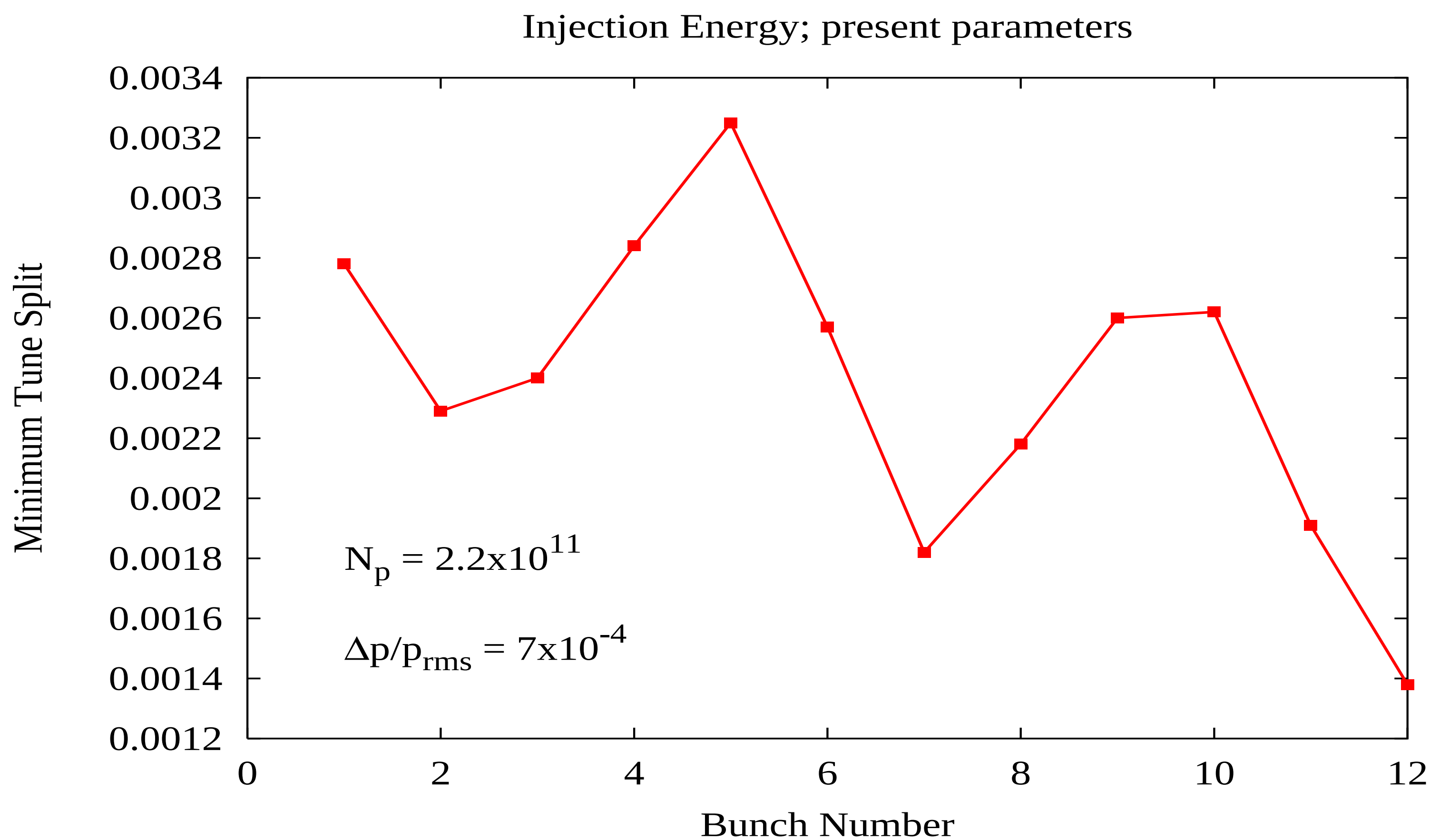
fold at 3 σ in *x*-plane and *y*-plane



fold at 3 σ in *x*-plane and 2 σ in *y*-plane

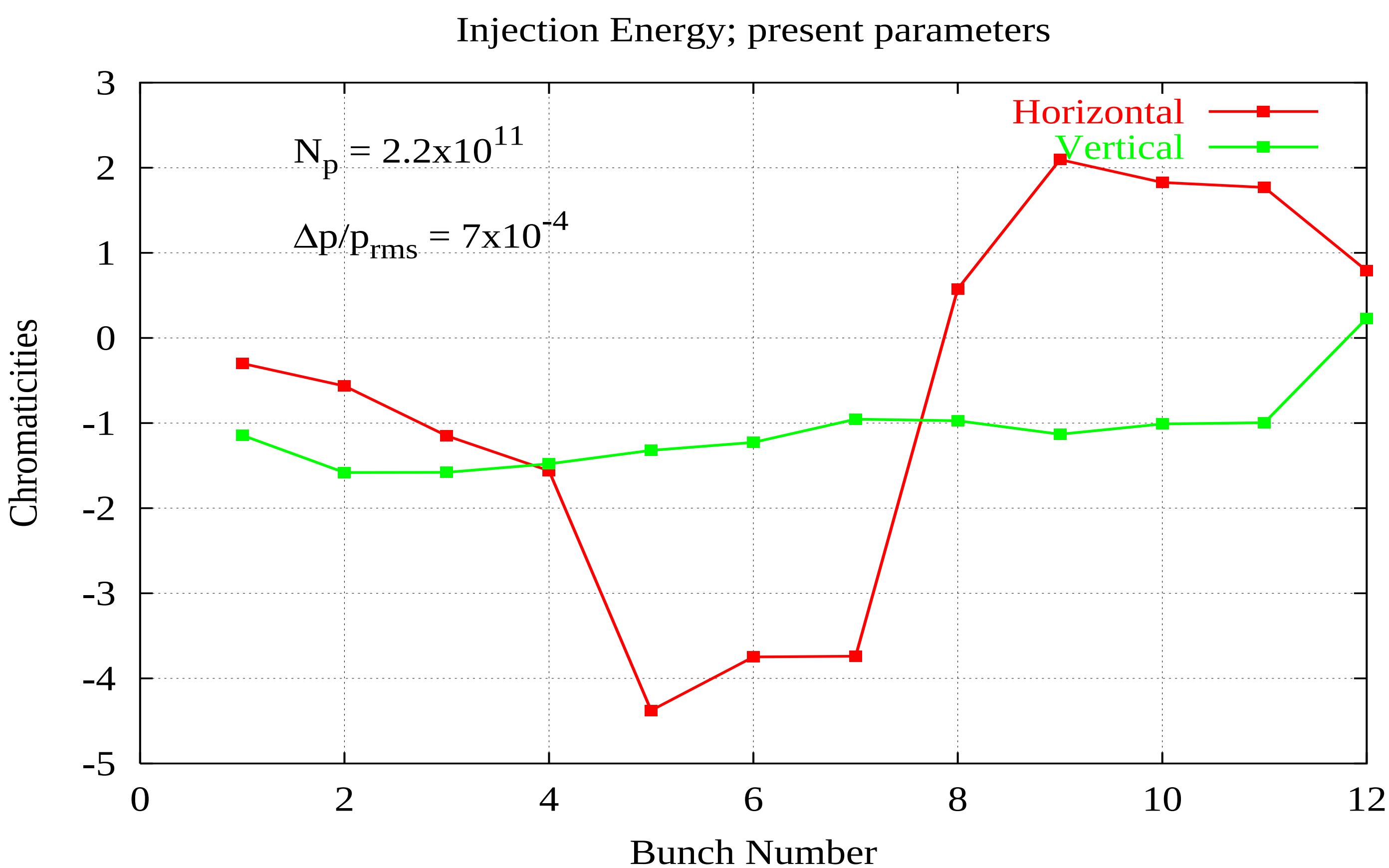
Folds can be identified, at the folds resonance widths are large. When tune shift crosses zero, the beam-beam force has a maximum.

Small amplitude beam-beam coupling at injection



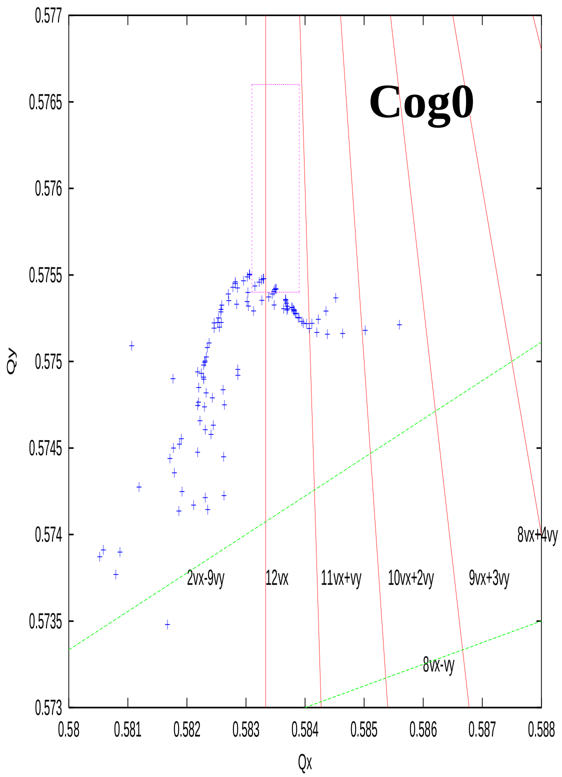
Coupling due to beam-beam force calculated analytically for 12 pbar bunches in a train. Bunch to bunch difference in coupling can be identified.

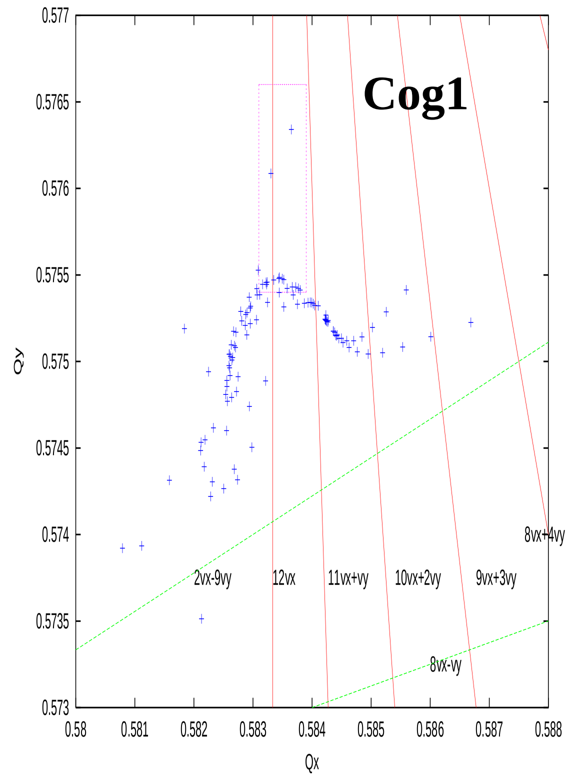
Small amplitude beam-beam chromaticities at injection

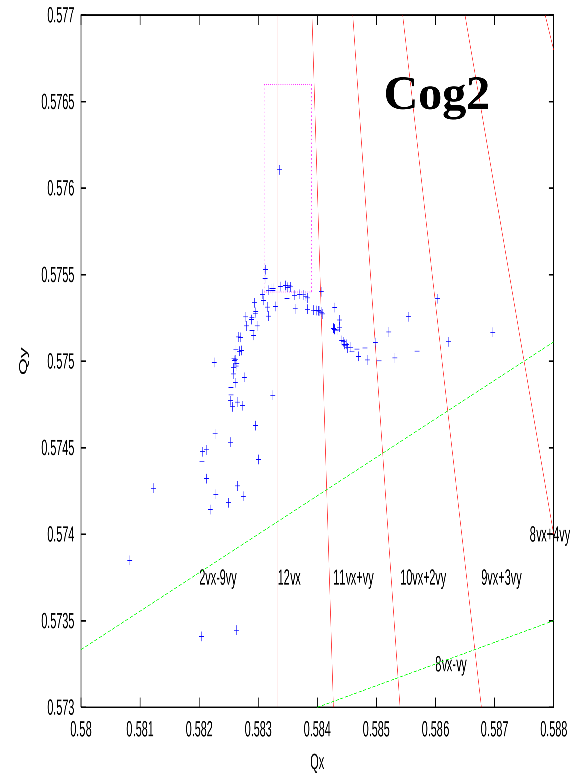


This additional chromaticity will enhance the synchro-betatron resonances. Some bunches are more susceptible to synchro-betatron resonances, instabilities.

Footprint with beam-beam and magnet field errors at injection

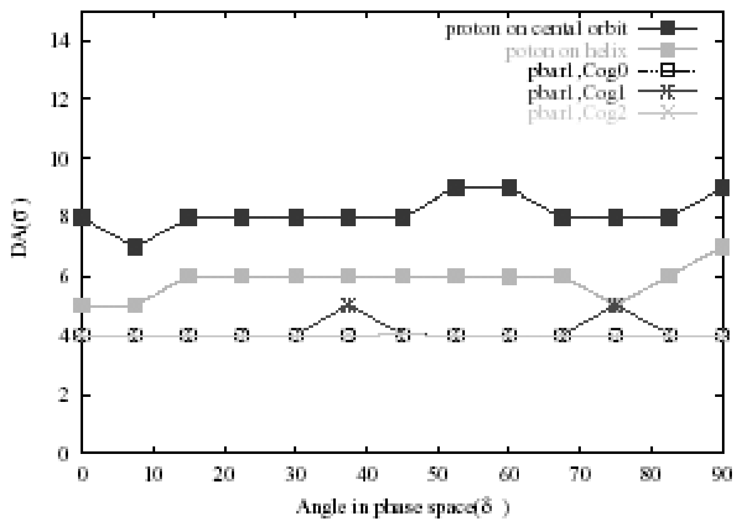




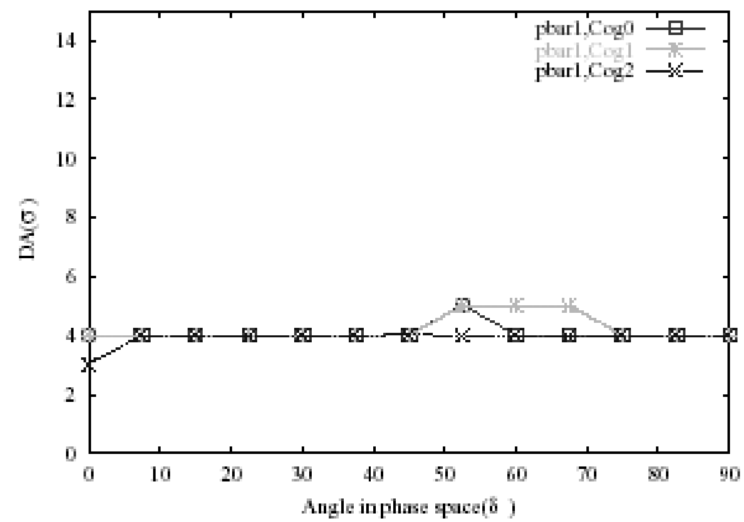


Footprints are dominated by field errors, similar in three cogging stages.

Dynamic Aperture at three Cog stages at injection



Proton bunch length σ_s=2 nsec, dp/p=4.3e-4



Proton bunch length σ_s=3.5 nsec, dp/p=7.e-4

Average DA for proton and Pbar.

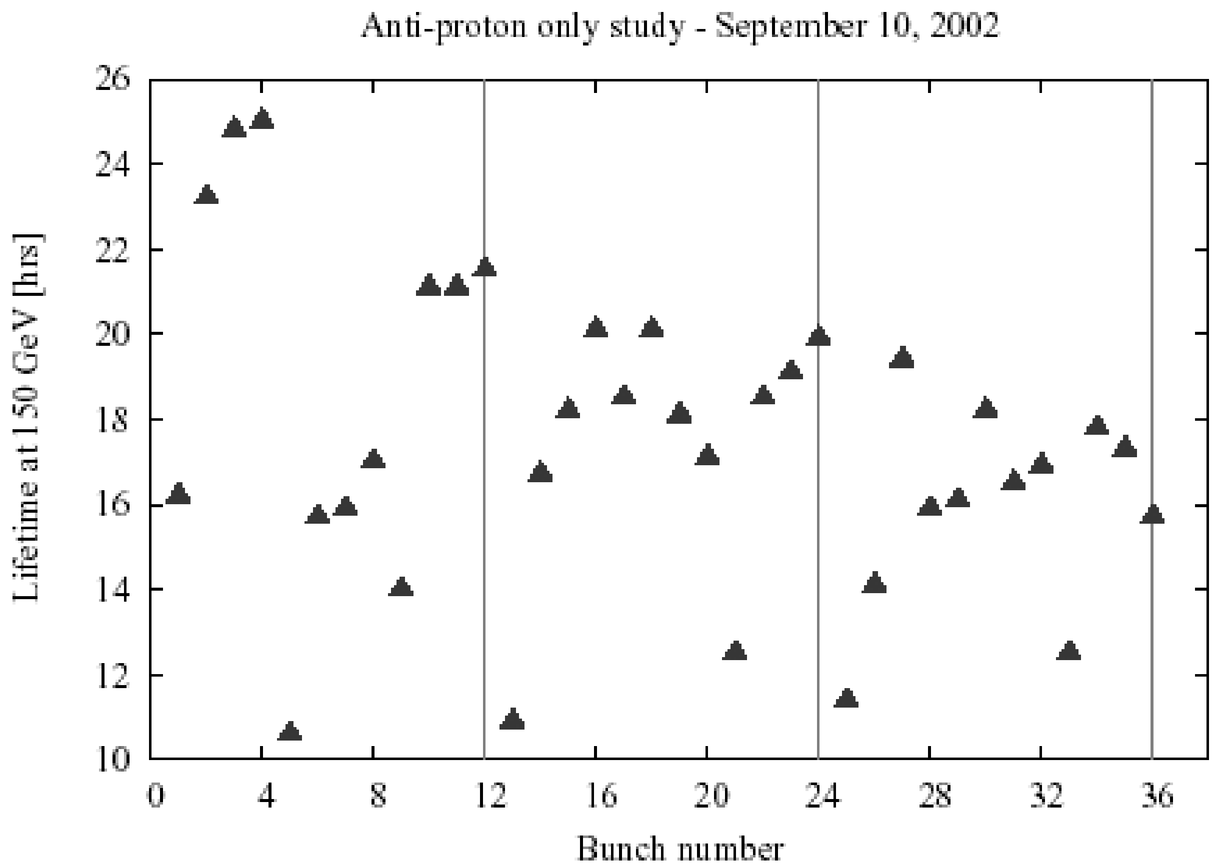
Proton: σ_p=7.E-4

	On central orbit	On helix
$dp/p=7.\times10^{-4}$	8.3	6
$dp/p=1.3\times10^{-3}$	8.2	5.9

Pbar: σ_p=4.5E-4

	Cog0	Cog1	Cog2
$dp/p=\sigma_p=4.5\times10^{-4}$	4.4	4.5	4.4
$dp/p=3\sigma_p=1.35\times10^{-3}$	4	4.2	4.

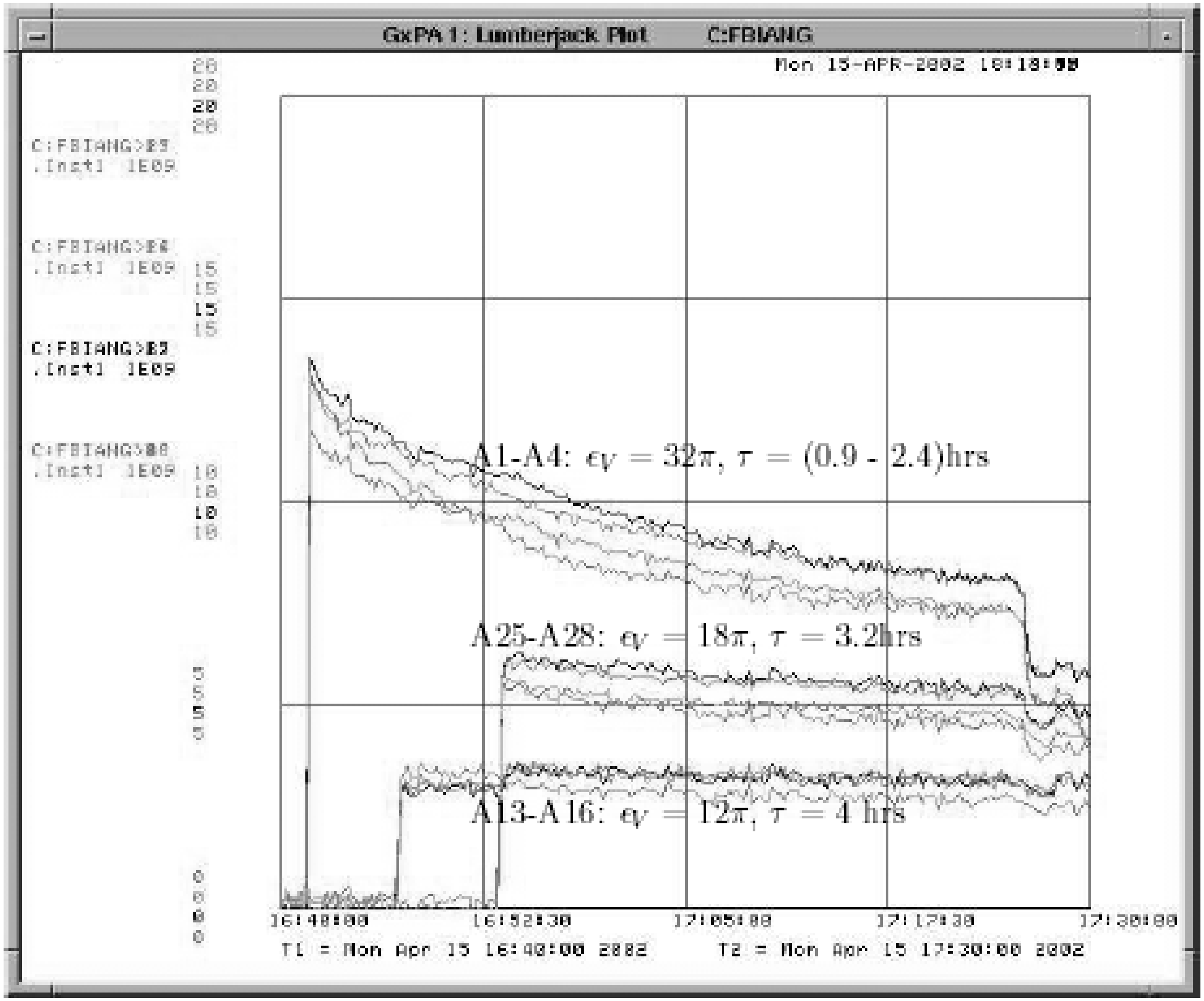
Anti-protons only – beam study



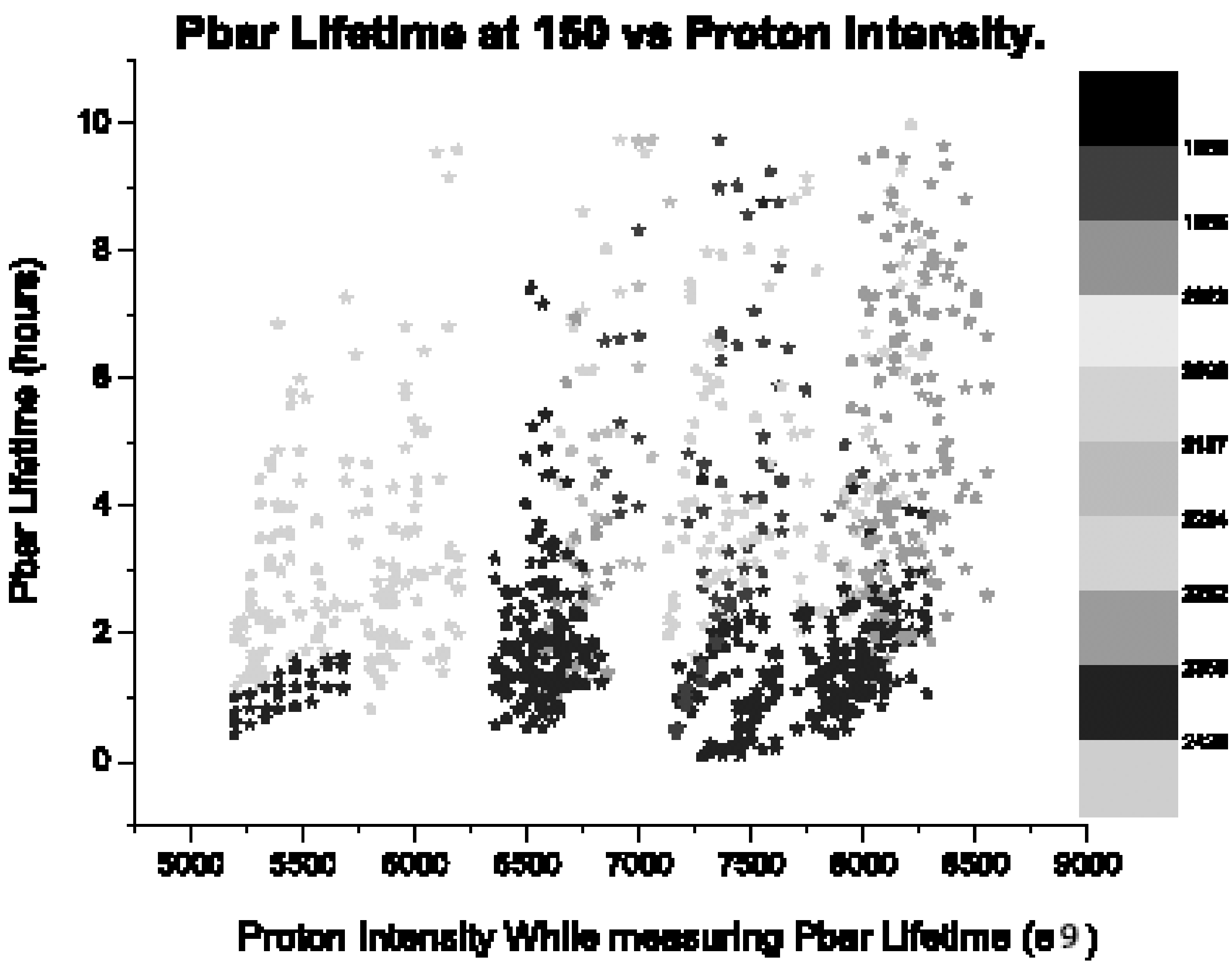
In this study, τ was well anti-correlated with the vertical emittance.

In typical stores, $1 \le \tau(\bar{p}) \le 10$ hours.

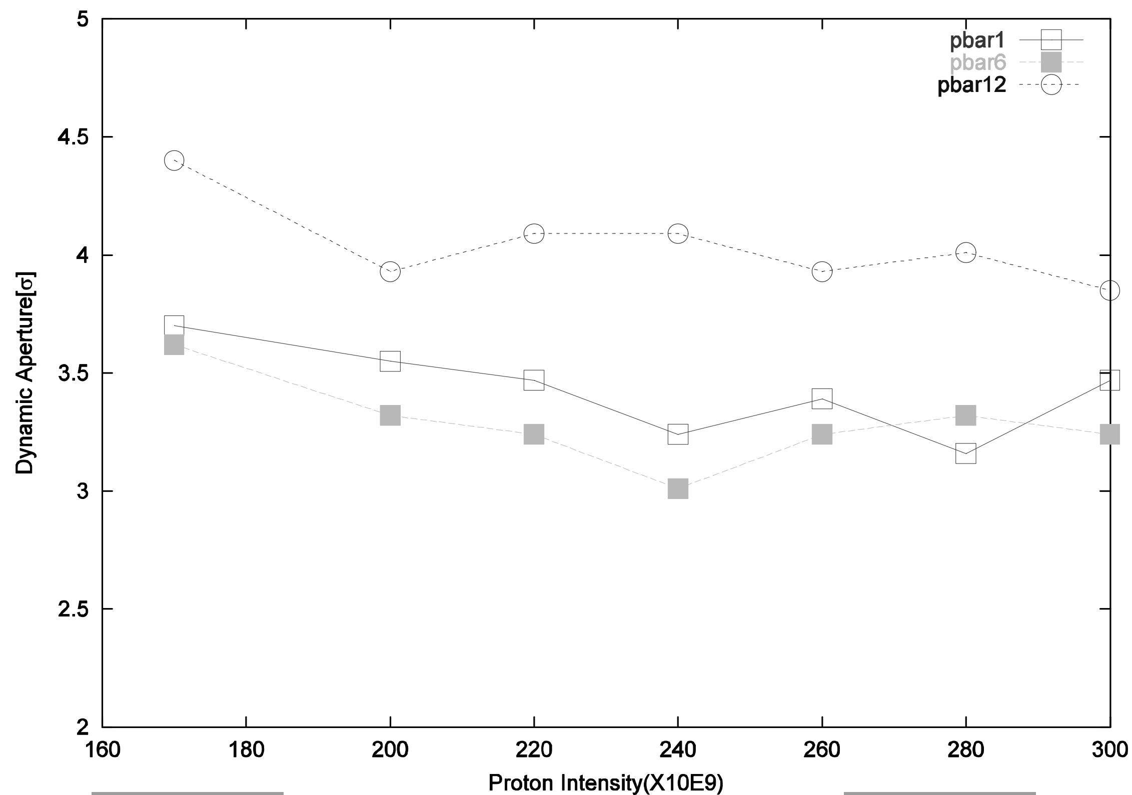
Anti-proton lifetime at injection - Beam study



Anti-proton lifetime at injection - observation



Dynamic Aperture of pbar *vs*. proton intensities after 2nd cogging, with beam-beam and magnet field errors



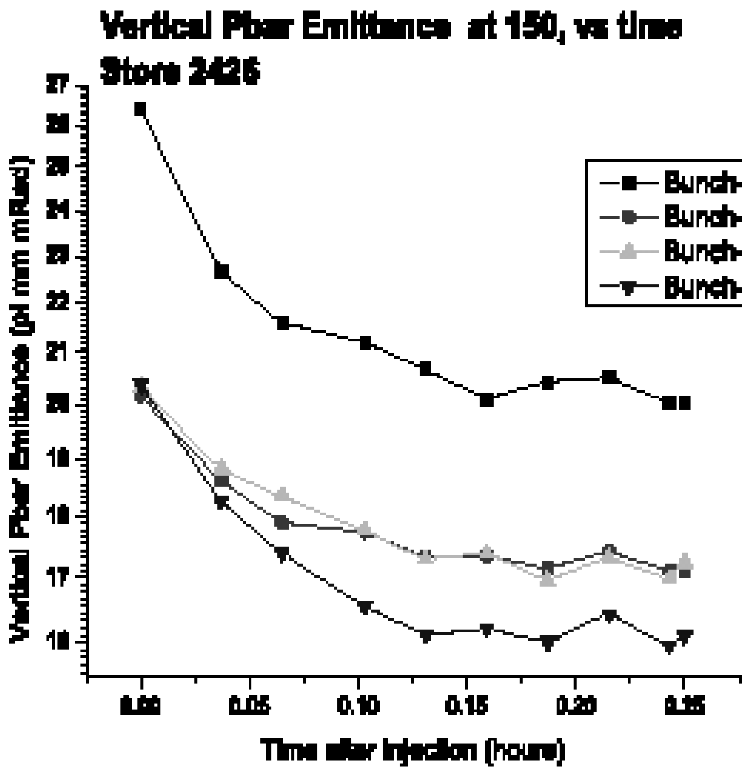
Present parameter

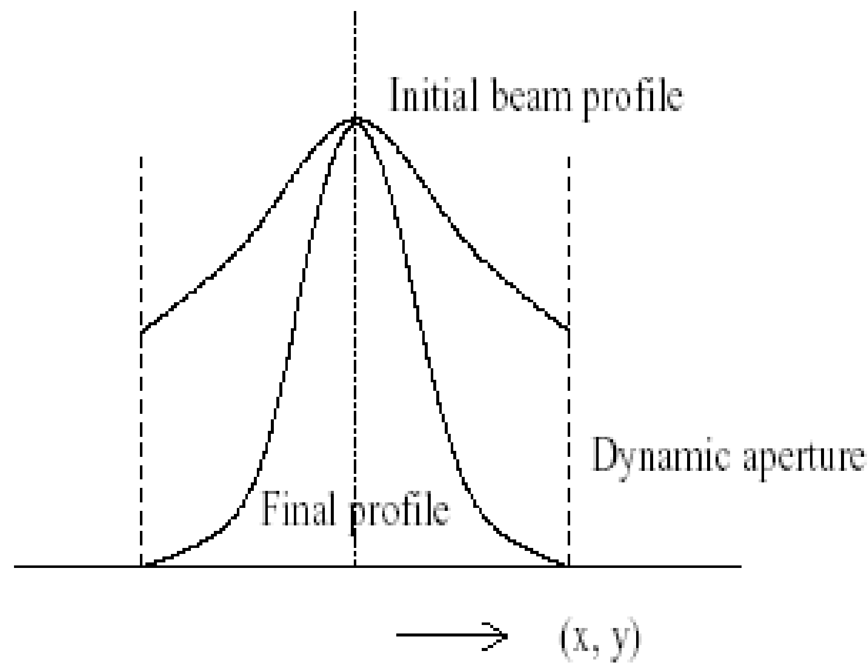
Design parameter

DAs of pbar1 and pbar12 ➔ better than those of middle bunches

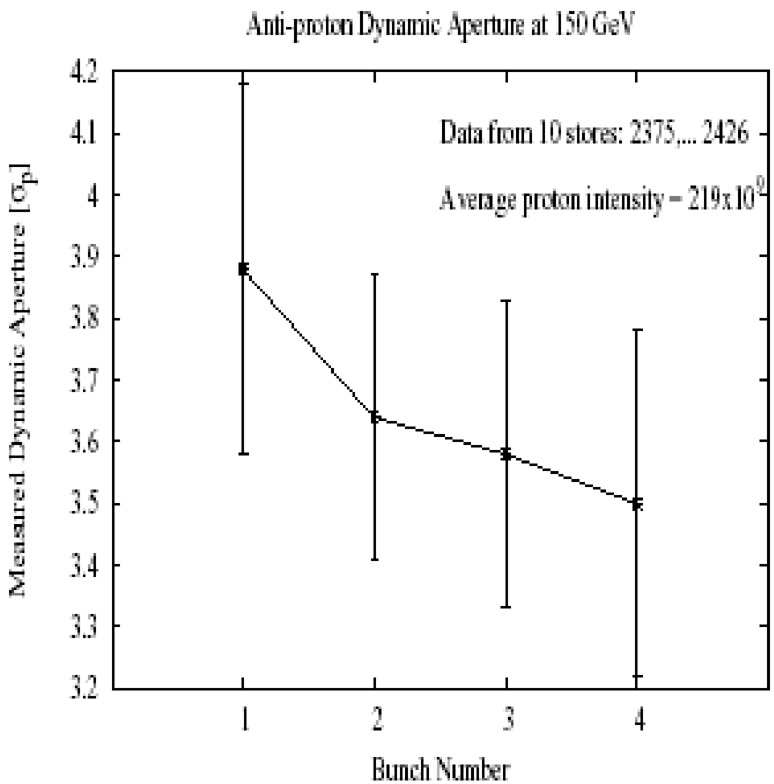
(pbar 6 as a representative)

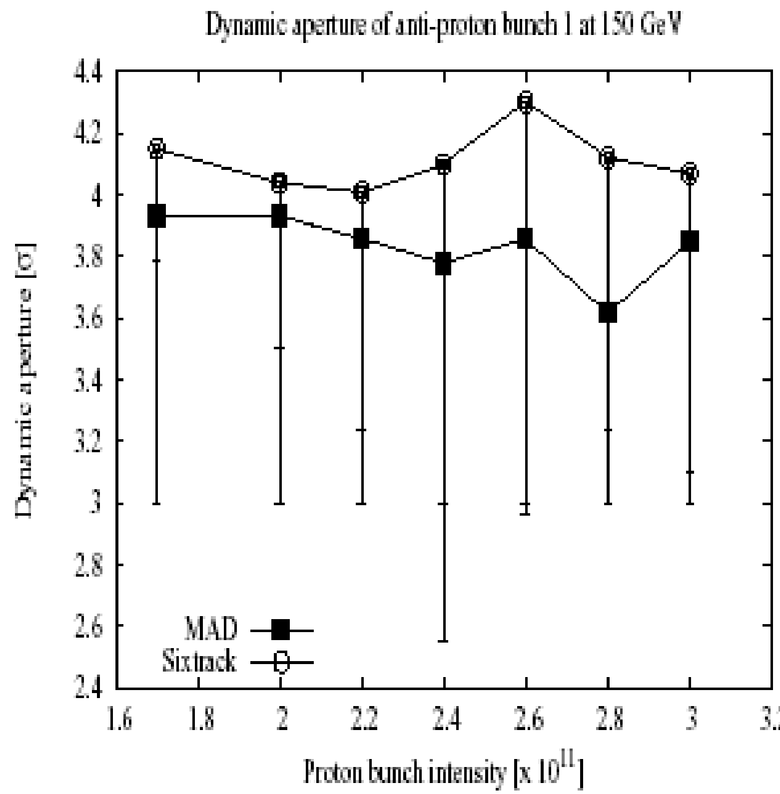
Anti-proton dynamic aperture at Injection- Observation



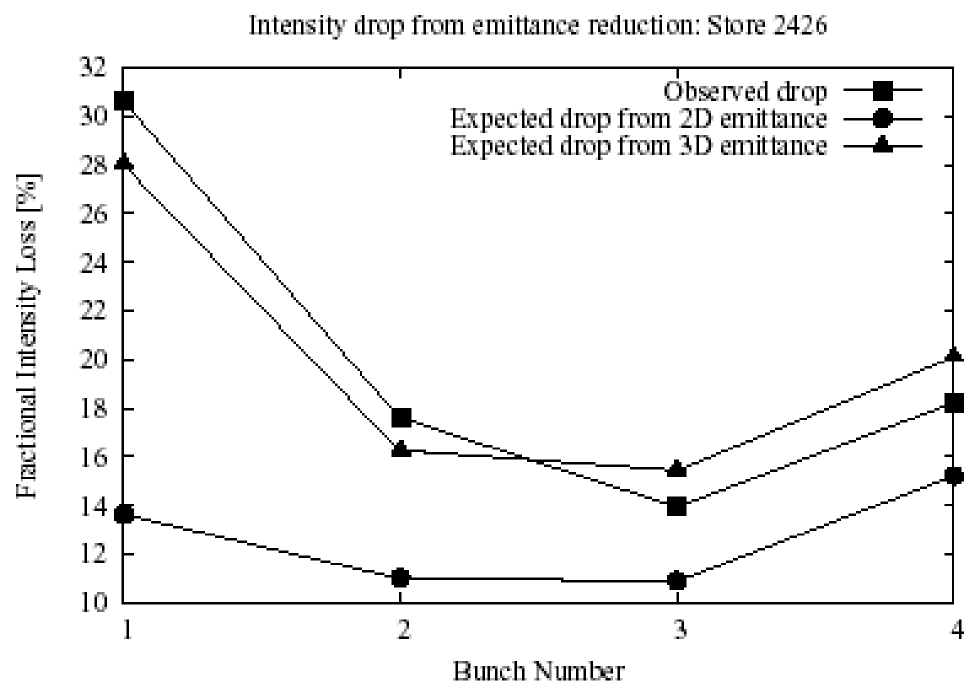


Anti-proton dynamic aperture at 150GeV- calculated from observations and simulations



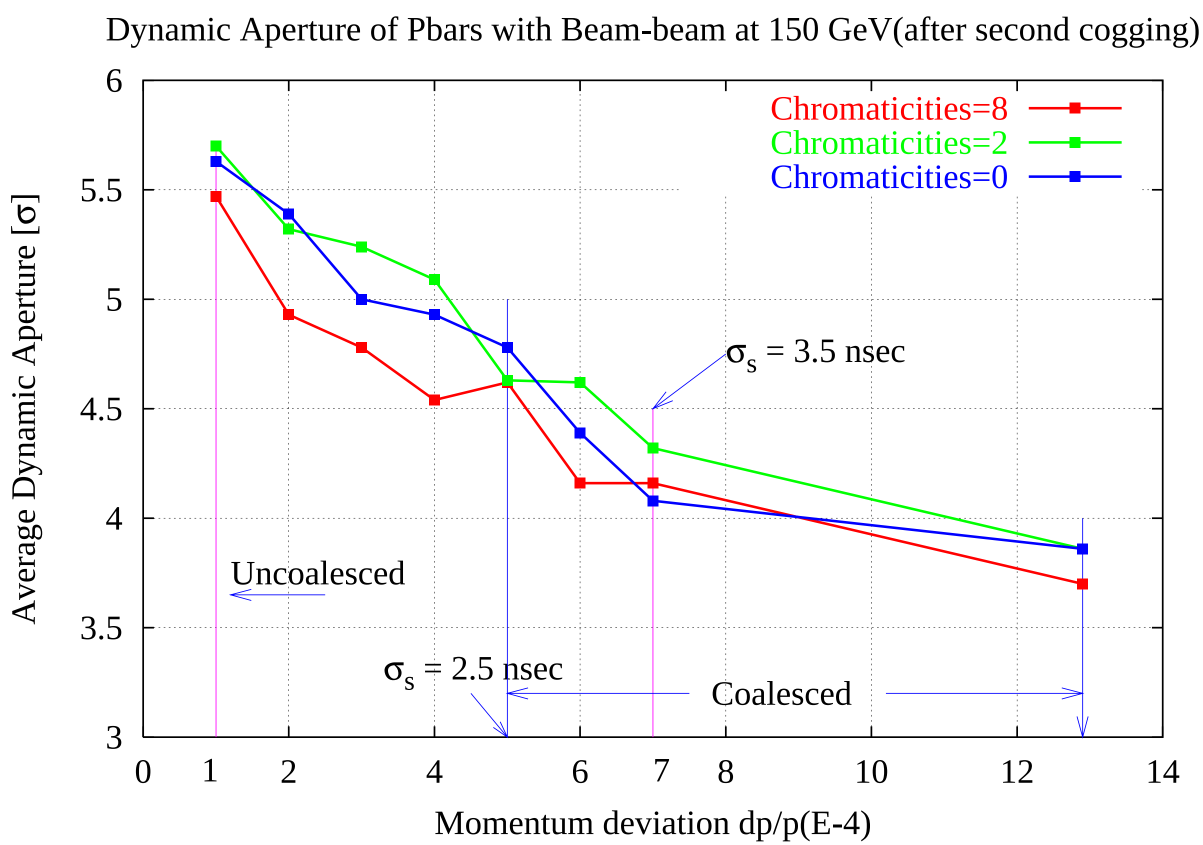


Expected and Measured Intensity Drop: Store 2426



- The expected drop in intensity was calculated from the final bunch area (2D and 3D). The bunches are assumed to completely fill their dynamic aperture. The expected 3D loss and measured loss agree to within 2%.
- The largest difference in 2D and 3D areas was for bunch 1. This bunch had the greatest reduction in longitudinal emittance.
- This store occurred before the vertical dampers were restored. Since then, we have not seen this significant emittance shaving at injection.

Dynamic Aperture of pbar bunch 1 *vs.* Momentum deviation at different chromaticities



DA is getting larger as chromaticities decrease. Better pbar lifetime was also observed in the machine when the chromaticities are reduced from 8 to 2 units.

Chaotic border of protons at injection

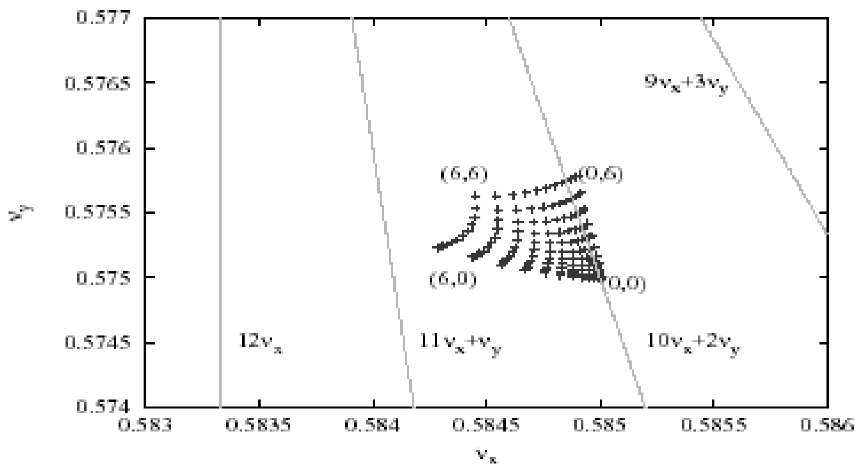
Chromaticities (ξ_x, ξ_y)	(8,8)	(2,8)	(2,2)	(0,0)
Chaotic border (σ)	4.8	5.0	5.2	5.4
DA(σ)	6.4	6.9	6.8	6.9

Chaotic border is defined as the border between regular and chaotic motion, it allows to predict the long term Dynamic Aperture. The momentum deviation in this calculation is dp/p=4.3e-4. Small chromaticities help to improve long term dynamic aperture. Better lifetime of protons in the machine was observed when we reduce the chromaticities from 8 units to 2 units.

Collision – simulations(1)

Fermilab

Tune fooprint of a single beam with IR errors and chromaticity sextupoles.



Due to the nonlinearities

tune spread: 0.0006

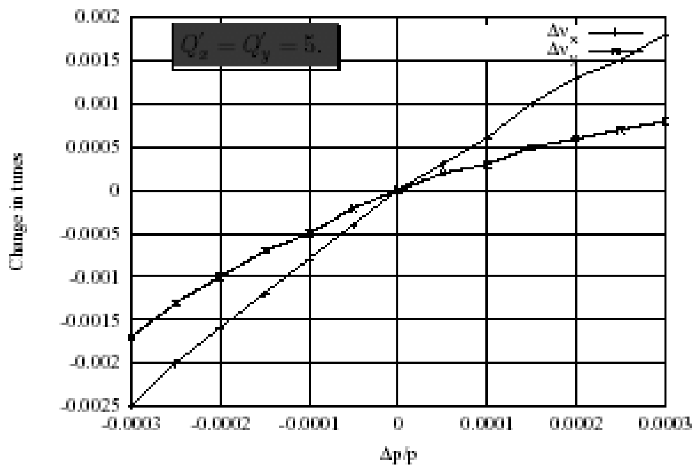
Beta beating: ignore

Due to the chromaticities

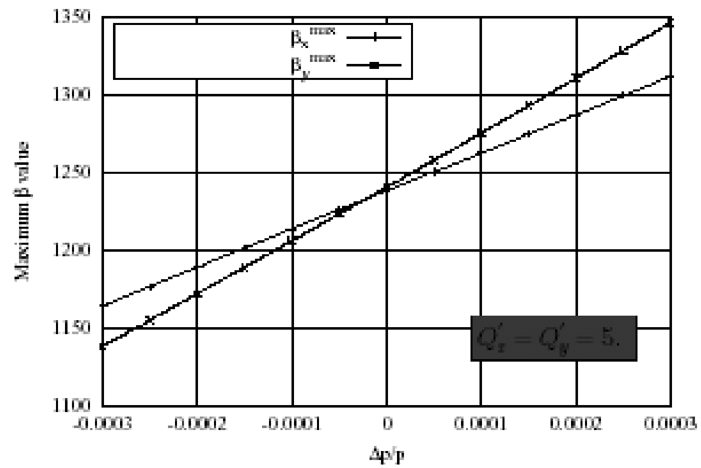
tune spread: 0.004

Beta beating: 8%

Change in tunes with $\Delta p/p$



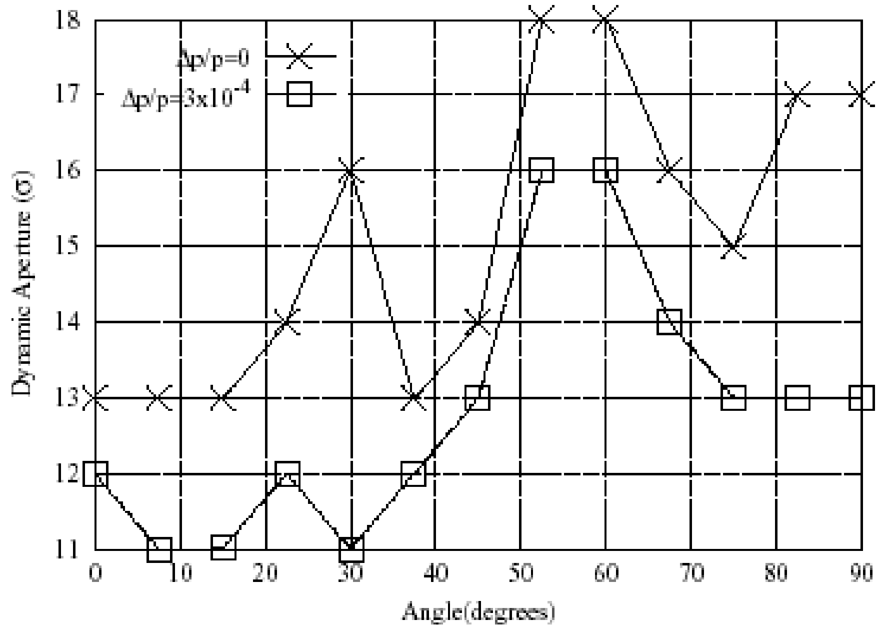
Maximum beta values vs $\Delta p/p$



Collision – Simulations (2)

Fermilab

Dynamic aperture of a single beam on helix



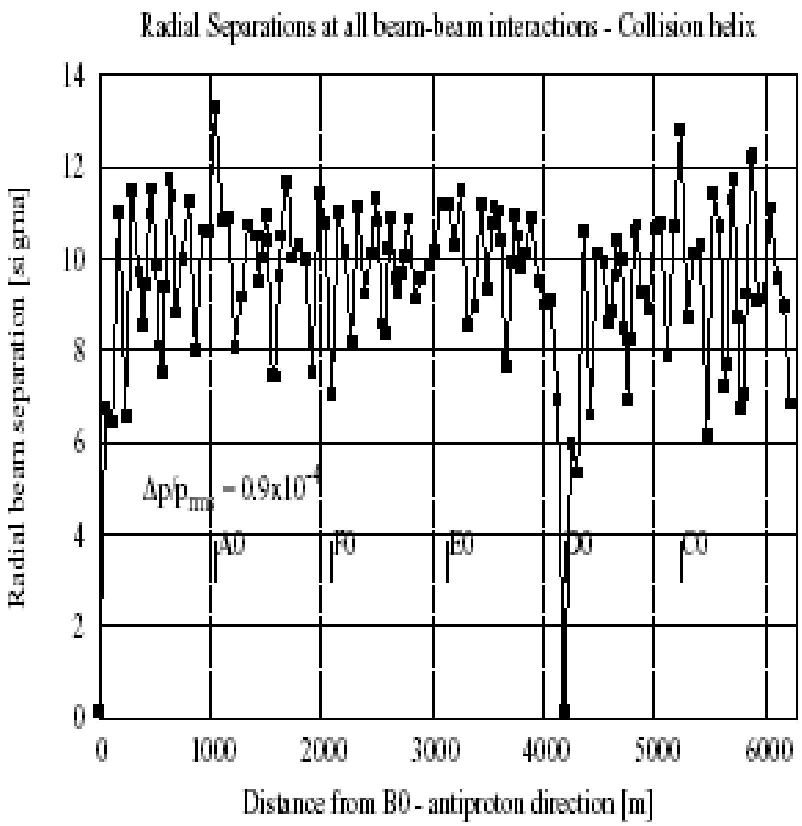
6D dynamic aperture of a single beam at three values of the momentum deviation after 10^5 turns.

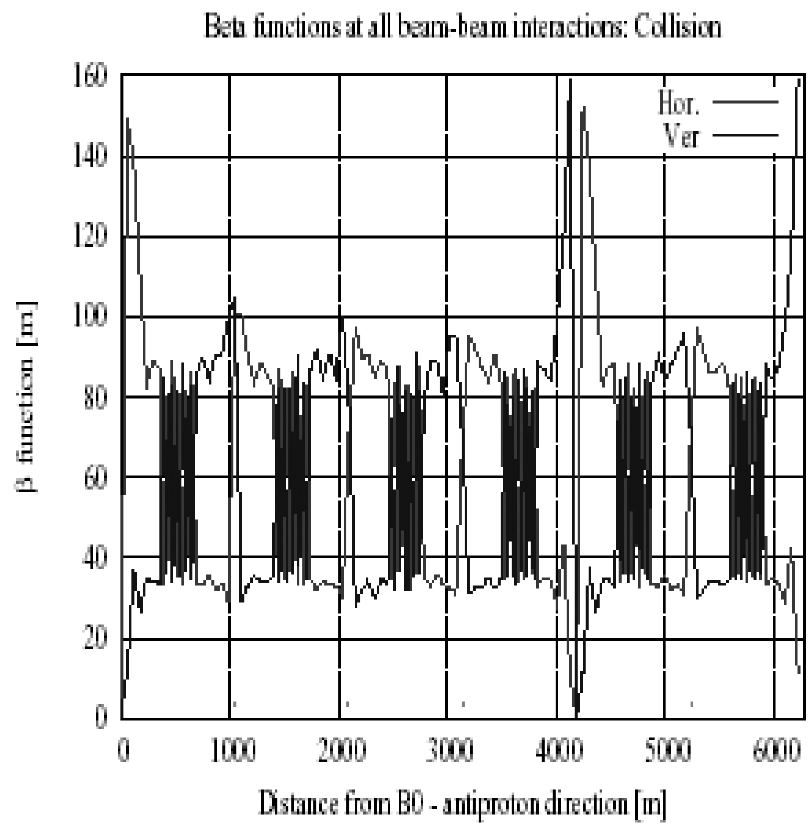
	Average DA (DA)	Minimum DA DA_{min}
$dp/p = 0$	15.2	13.0
$dp/p=\sigma_p=1\times10^{-4}$	14.3	12.0
$dp/p=3\sigma_p=3\times10^{-4}$	12.9	11.0

Physical Aperture: 18 σ

Collimator: 8 σ

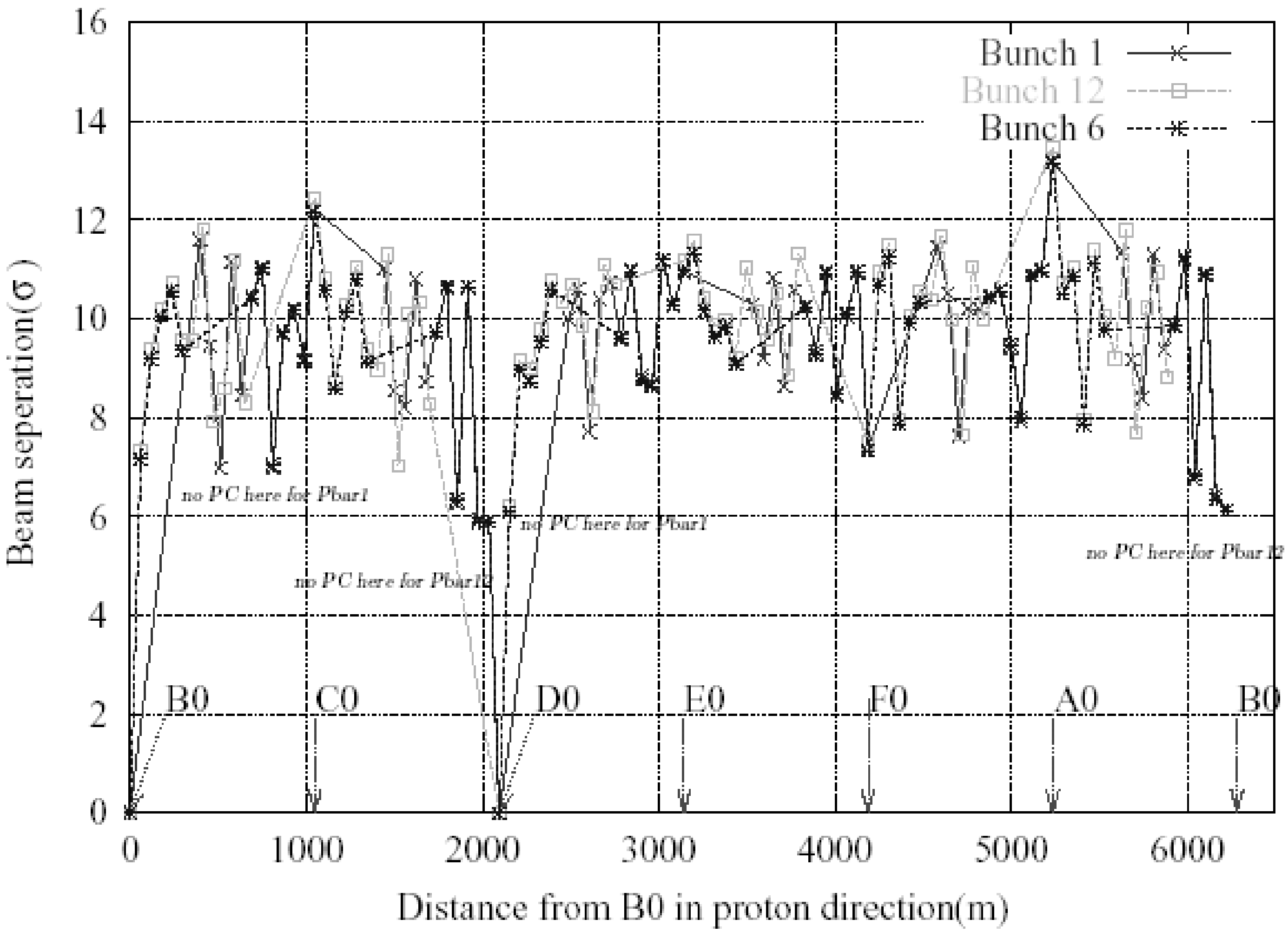
Beam-beam separations at collision



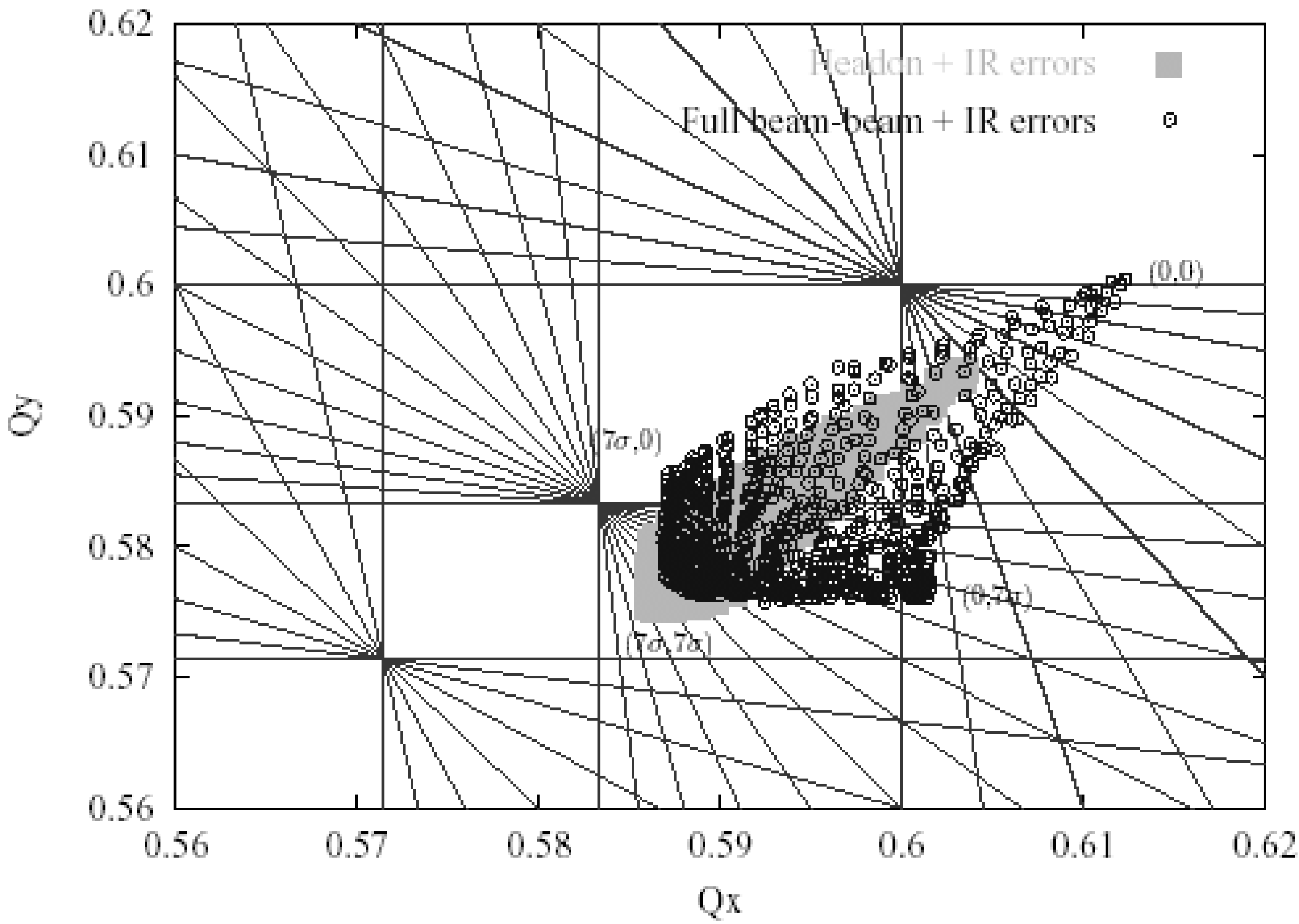


Average separation is about 10σ, minimum separation is ~6σ at nearest parasitic positions

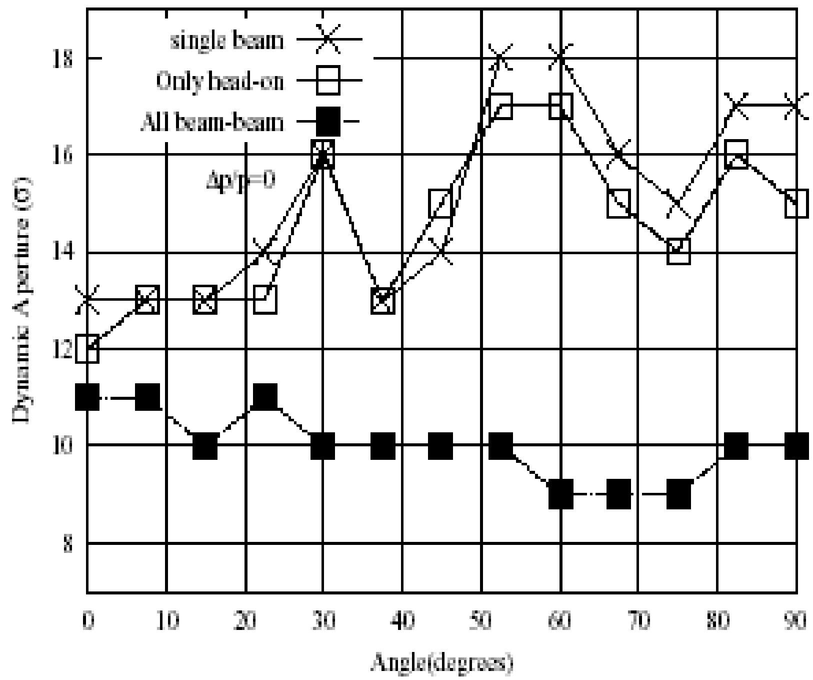
Separations at beam-beam encounters for Pbar Bunch 1,6 and 12



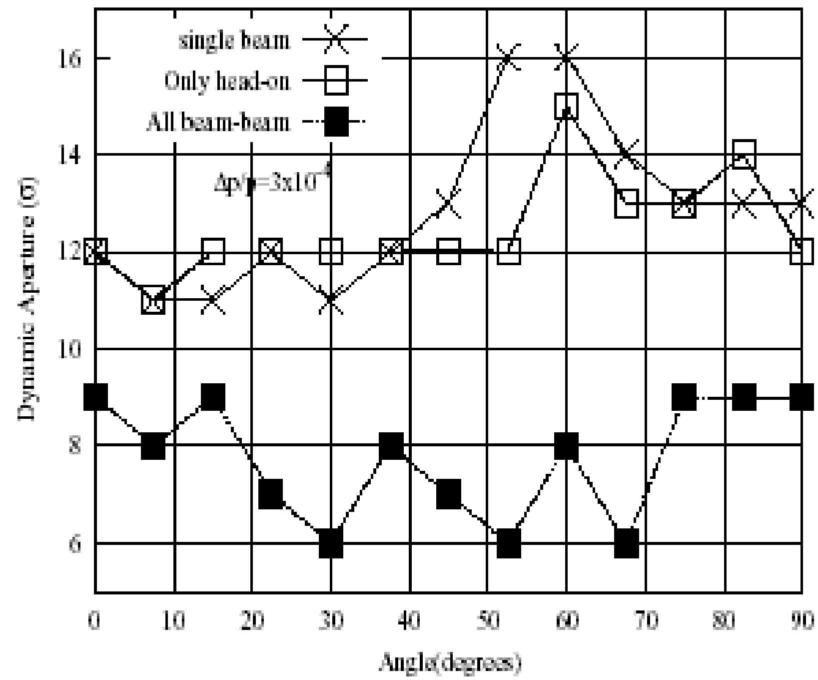
Tune fooprint of $\bar{p}$ bunch 6



4D dynamic aperture of pbar bunch 6



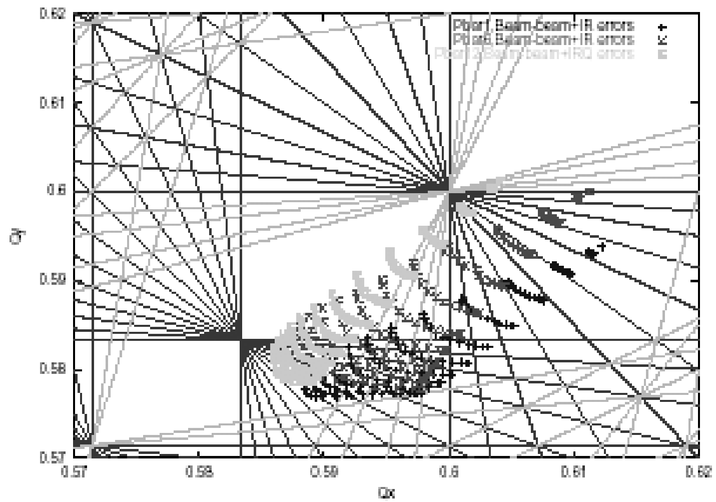
6D dynamic aperture of pbar bunch 6



6D DA with all Beam-beam at different values of $\Delta p/p$ after 10^5 turns and 10^6 turns

	Average DA $\langle DA \rangle$	Minimum DA DA_{min}
dp/p = 0	10.0	9.0
dp/p=$3\sigma_p$=3×10^{-4} (No RF)	8.6	8.0
dp/p=$3\sigma_p$=3×10^{-4}	7.7	6.0
10^6 turns		
dp/p=$3\sigma_p$=3×10^{-4}	5.4	4.0

Tune footprint for bunches 1, 6 and 12

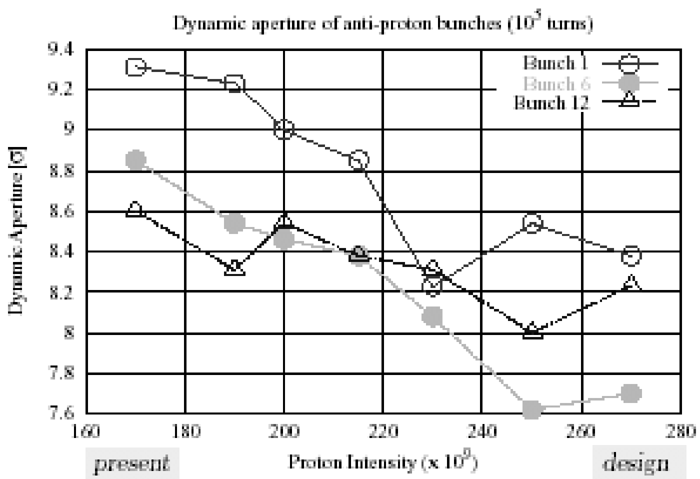


Diference due to:

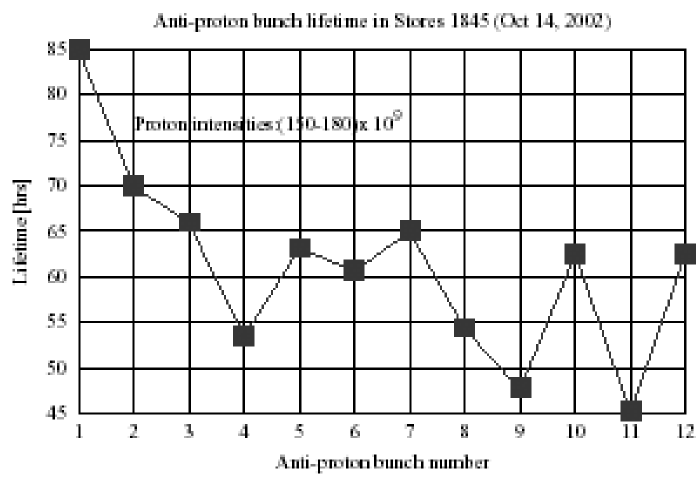
the missing PCs downstream for Pbar1

the missing PCs upperstream for Pbar12

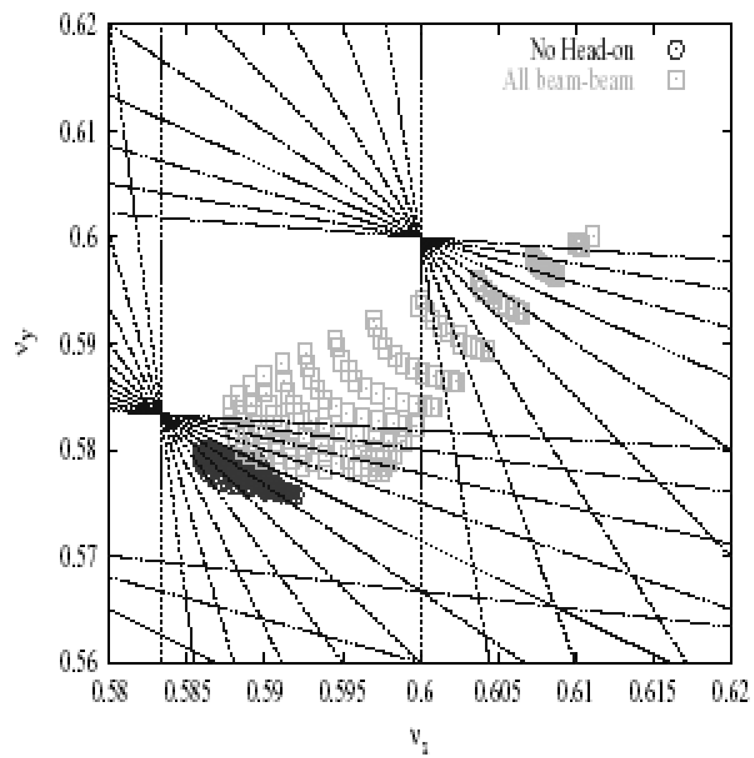
The DAs Vs. Proton Beam intensity



Pbar bunch lifetime in store 1845

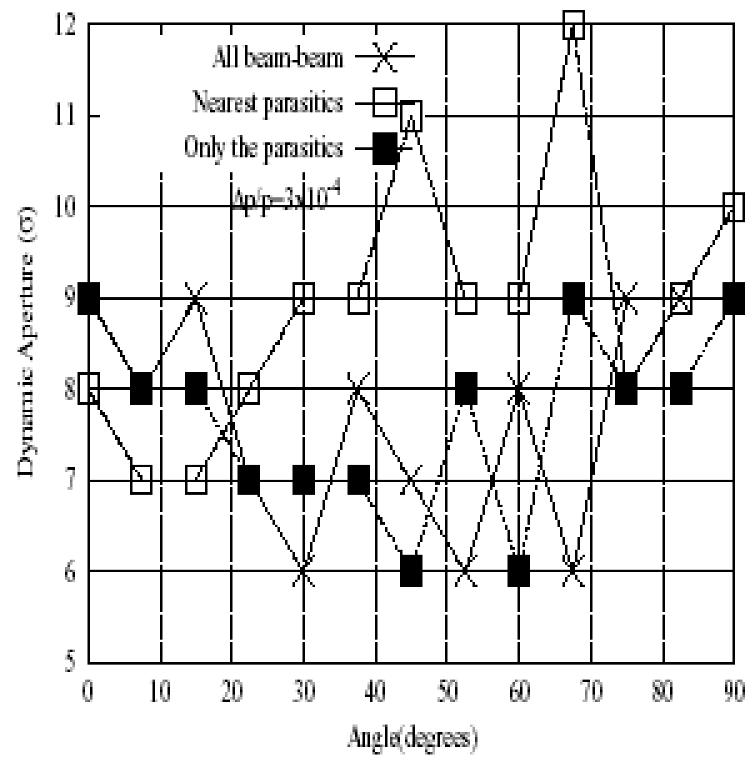


Footprint for bunch 6



Footprint is dominated by head-on interactions

Dynamic aperture of bunch 6



DA is dominated by parasitic interactions,

Especially by four nearest parasitics

Fermilab

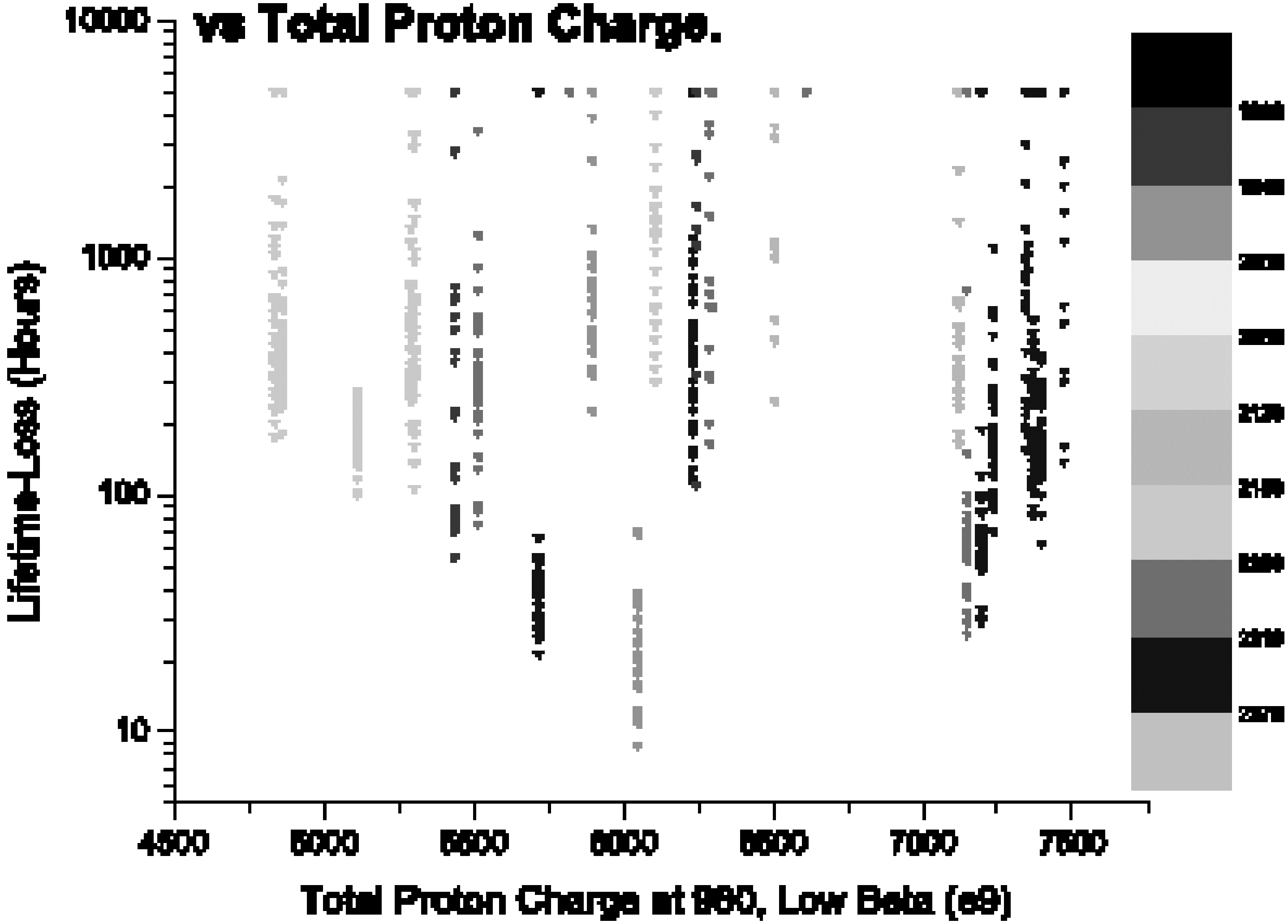
Summary of different cases

Bunch 6: $\nu_x = 0.585$, $\nu_y = 0.575$ DA after 10^5 turns	$(\langle DA \rangle, DA_{min})$ [4D] $\Delta p/p = 0$	$(\langle DA \rangle, DA_{min})$ [6D] $\Delta p/p = 3 \times 10^{-4}$
IR errors	(15.2, 13.0)	(12.9, 11.0)
Head-on and IR errors	(14.5, 12.0)	(12.5, 11.0)
Head-on, nearest PCs, IR errors	(10.5, 9.0)	(8.9, 7.0)
Only the parasitics, IR errors	(10.2, 9.0)	(7.7, 6.0)
All beam-beam, IR errors	(10.0, 9.0)	(7.7, 6.0)
$(\langle DA \rangle, DA_{min})$ for bunches 6, 1 and 12 [6D, $\Delta p/p = 3 \times 10^{-4}$]	10^5 turns	10^6 turns
Single beam	(12.9, 11.0)	(12.3, 11.0)
Bunch 6: all beam-beam	(7.7, 6.0)	(5.4, 4.0)
Bunch 1: all beam-beam	(8.4, 6.0)	(5.6, 3.0)
Bunch 12: all beam-beam	(8.2,7.0)	(5.8, 4.0)

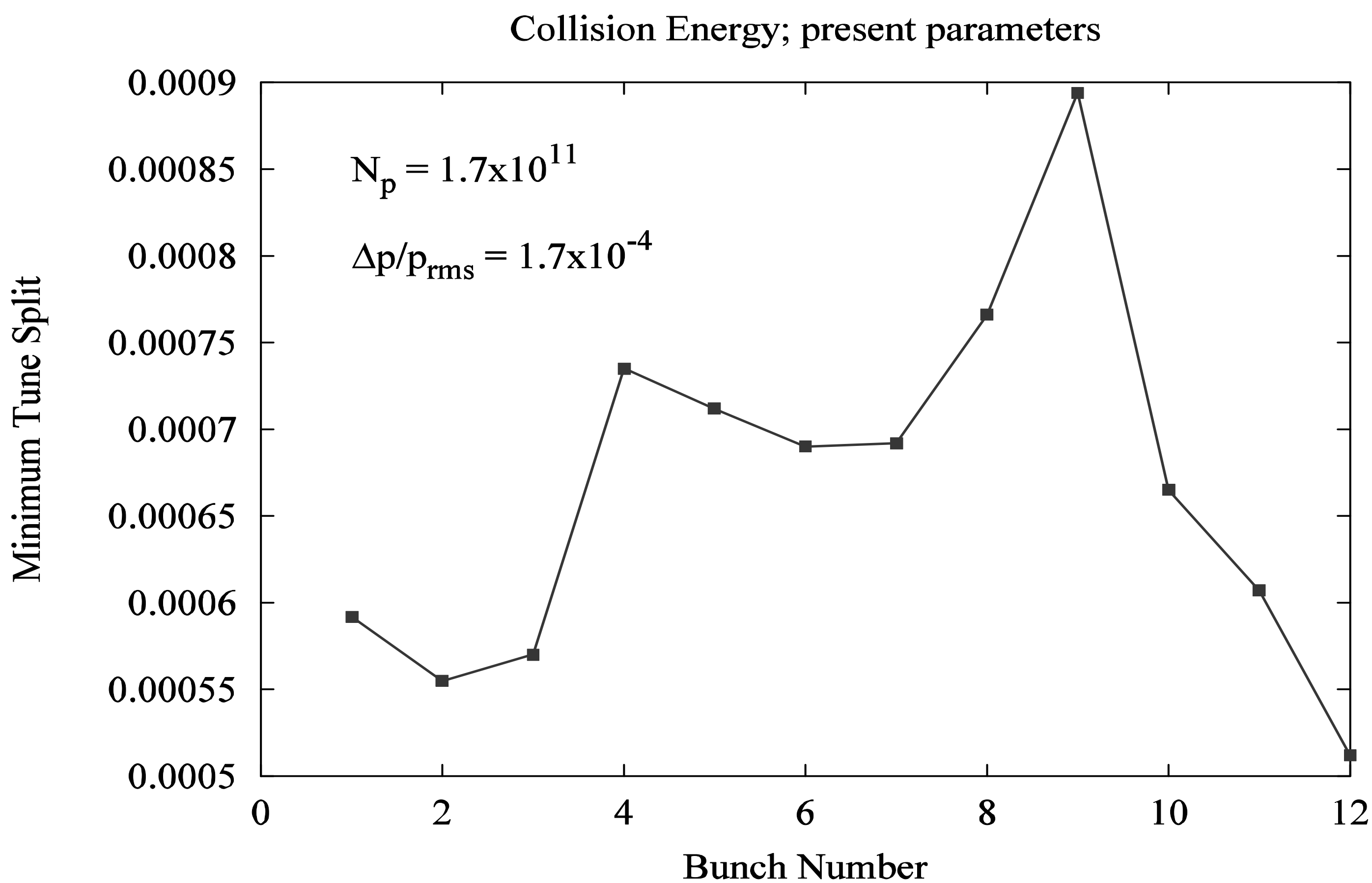
Main points:

- Single beam DA $\geq$ Physical aperture set by collimator 8σ
- Head-ons have little effect on DA
- All Beam-beam reduce DA about a fact of 2
- [redacted]
- bunch 1 and bunch 2 are better than bunch 6

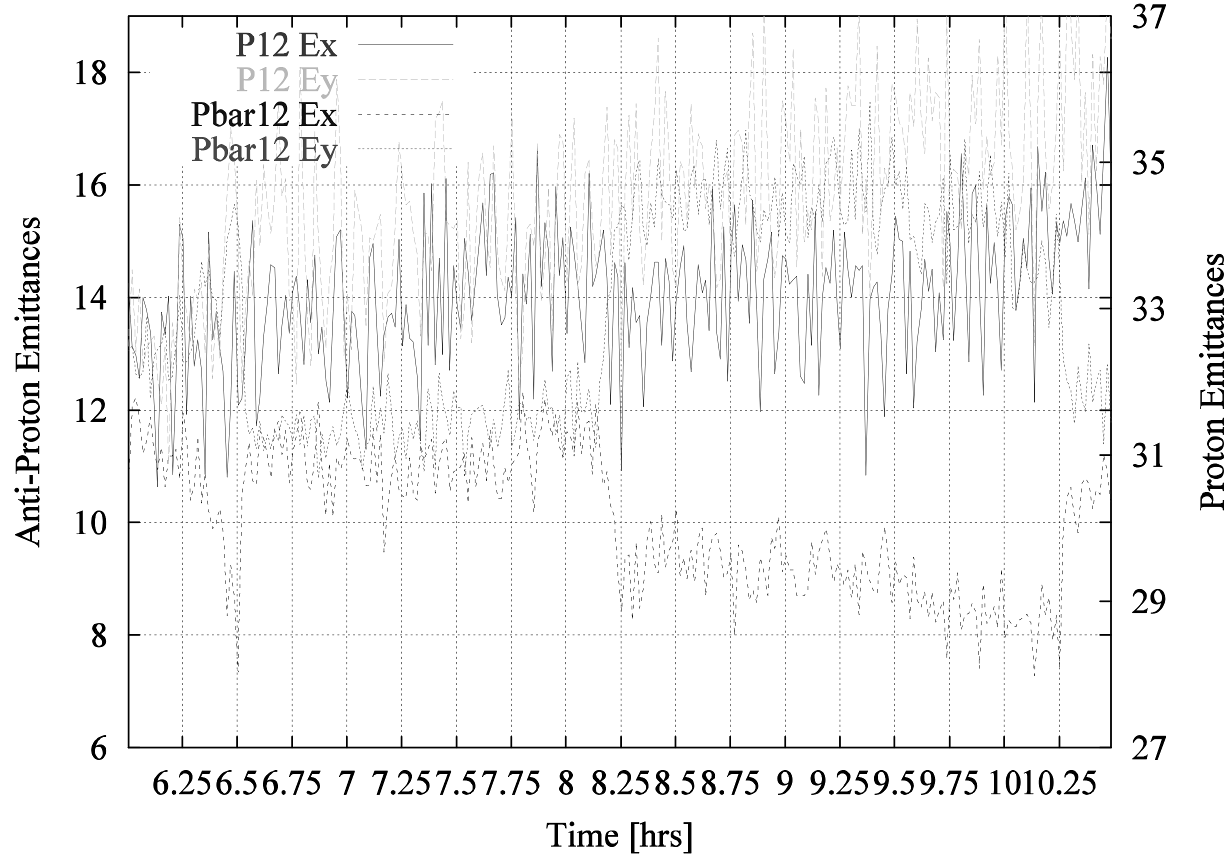
Pbar Lifetime due to losses at Collision, vs Total Proton Charge.



Small amplitude beam-beam coupling at collision



Observed coupling due to beam-beam force in the experiment

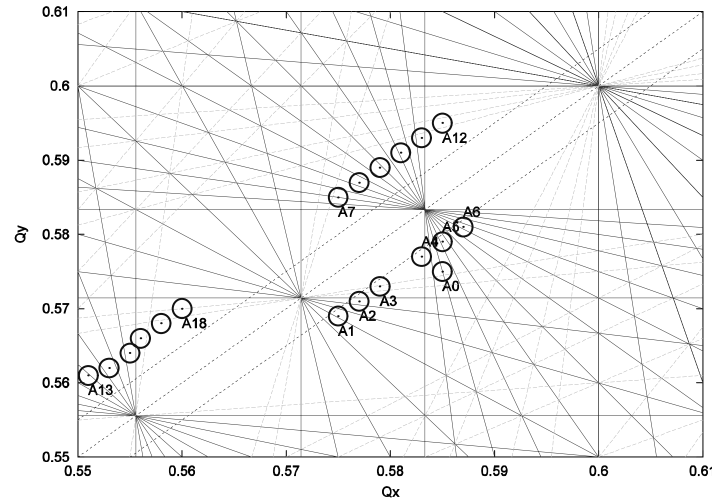


When the tunes cross the difference resonance in the tune scan experiment, we observed the emittances of pbar in x-y planes exchanged, while the proton emittances did not.

Tune scan by tracking

Fermilab

	Bare tunes	4D DA (<DA>,Da_{min})	6D DA(δ_p=3X10^{-4}) (<DA>,DA_{min})
A0	0.585,0.575	(10.0,9.0)	(7.8,6.0)
A1	0.575,0.569	(9.2,7.0)	(5.1,4.0)
A2	0.577,0.571	(9.3,8.0)	(7.5,6.0)
A3	0.579,0.573	(9.4,9.0)	(8.1,7.0)
A4	0.583,0.577	(9.8,9.0)	(7.6,6.0)
A5	0.585,0.579	(9.6,8.0)	(7.5,7.0)
A6	0.587,0.581	(9.5,8.0)	(7.5,6.0)
A7	0.575,0.585	(11.0,9.0)	(8.6,7.0)
A8	0.577,0.587	(10.7,9.0)	(8.4,8.0)
A9	0.579,0.589	(10.5,9.0)	(7.6,5.0)
A10	0.581,0.591	(10.0,8.0)	(7.0,5.0)
A11	0.583,0.593	(9.5,6.0)	(4.8,3.0)
A12	0.585,0.595	(8.5,6.0)	(1.9,1.0)
A13	0.551,0.561	(10.9,9.0)	(7.2,5.0)
A14	0.553,0.562	(10.7,9.0)	(6.2,5.0)
A15	0.555,0.564	(10.2,9.0)	(7.2,6.0)
A16	0.556,0.566	(9.9,8.0)	(5.7,3.0)
A17	0.558,0.568	(11.0,9.0)	(5.4,3.0)
A18	0.560,0.570	(10.5,8.0)	(5.4,3.0)

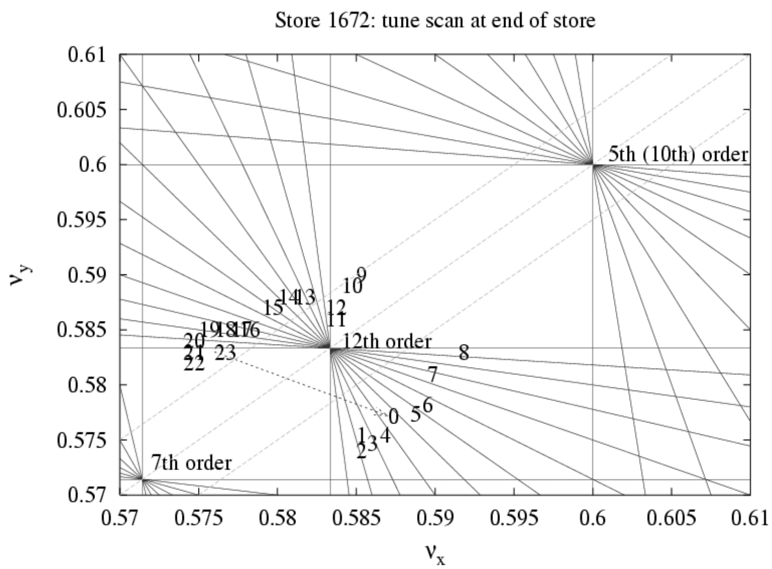


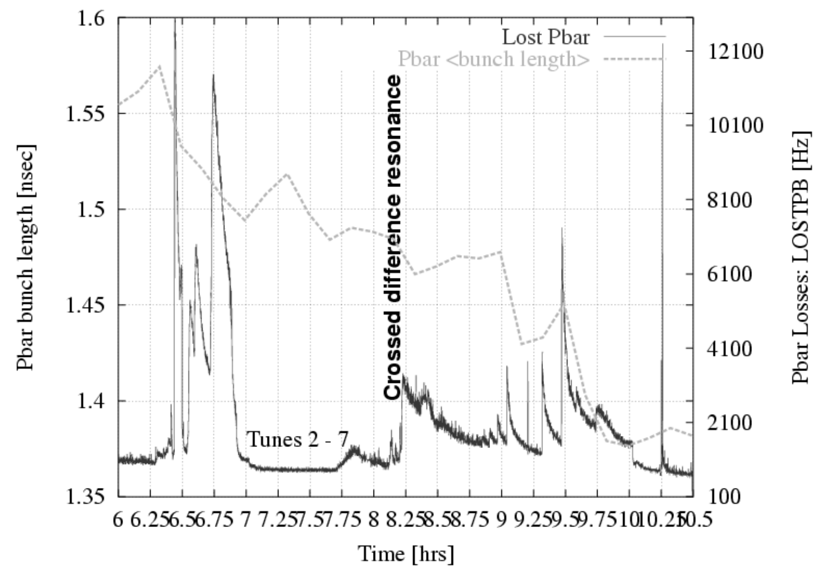
Minimum tune split ≤0.005

- A0: design working point
- A1,A2,A17,A18: close to 7th order resonances
- A11,A12:close to 5th order resonances
- All Beam-beam interactions are included,10^5 turns

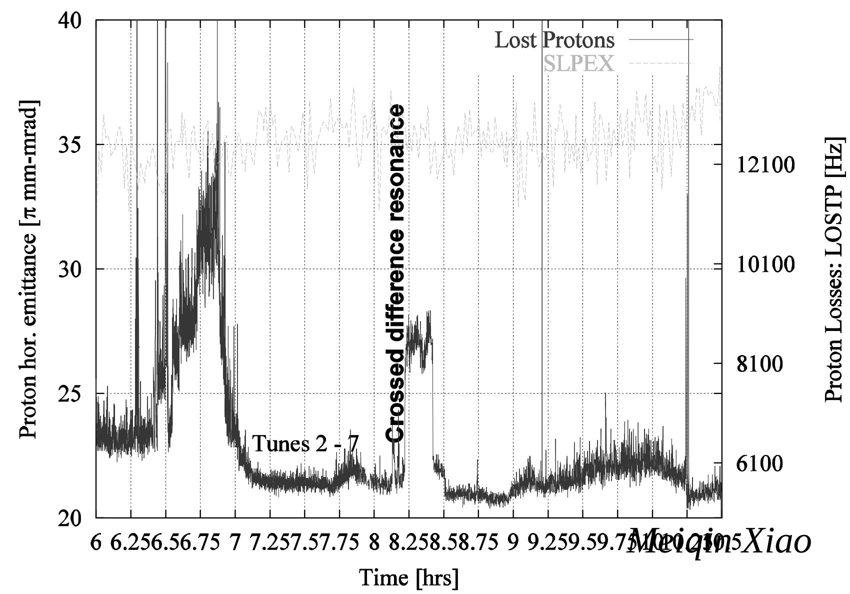
Store 1672: tune scan experiment at the end of store

Fermilab





We tried to scan on the tunes close to those we did by tracking, and monitored the beam lost for proton and pbar at the same time.

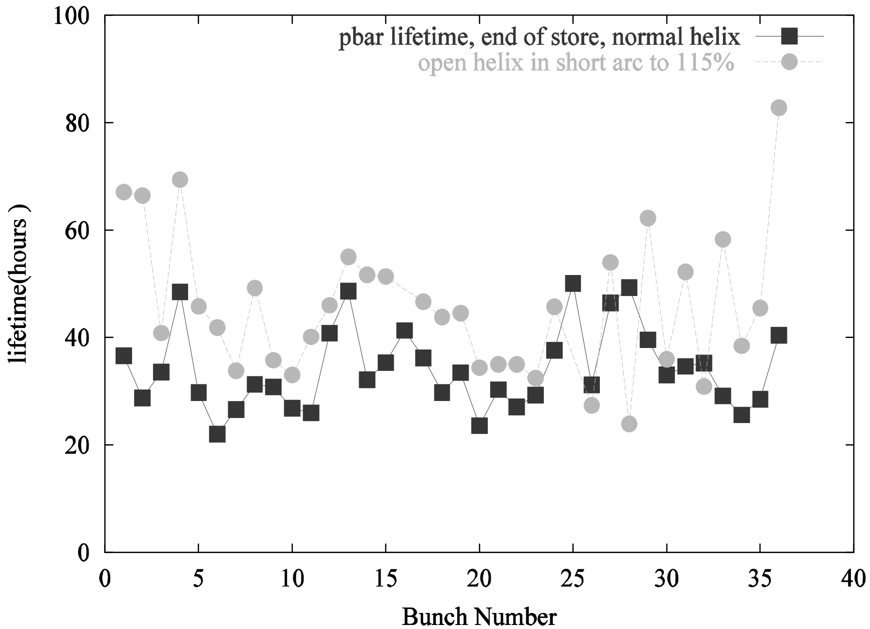


Jlab siminar, June 19, 2003

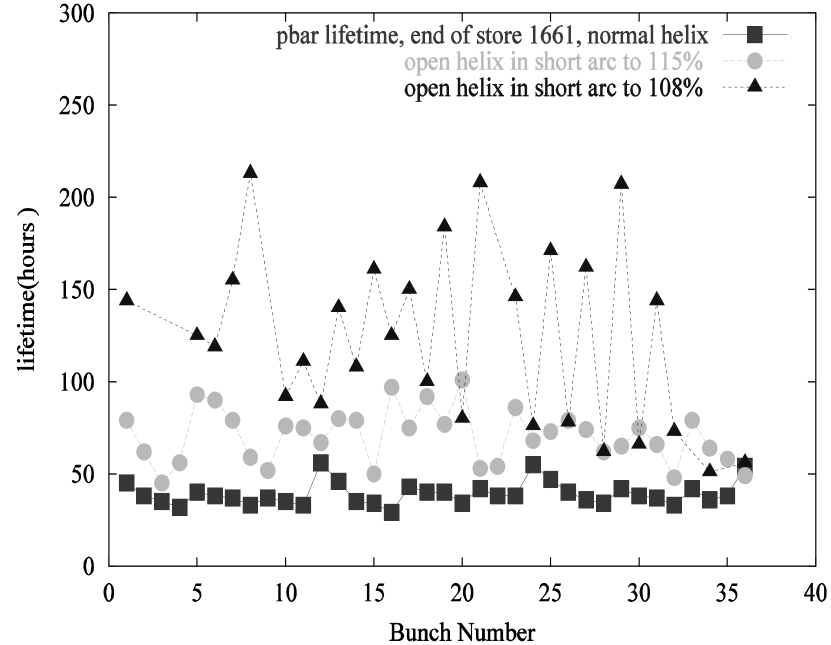
Meiqin Xiao

The experiment of pbar lifetime *vs.* helix(closed orbit)

Fermilab



at end of the store 1369



at end of the store 1661

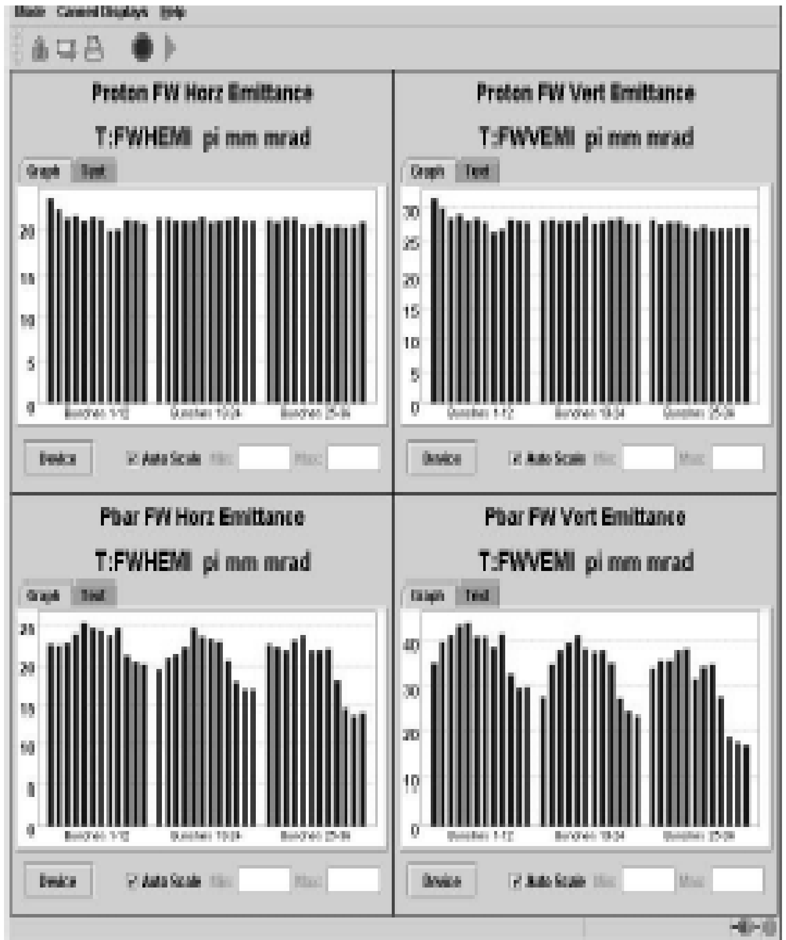
6D DA by tracking for 10^5 turns under the conditions of the experiment,store 1369

	Pbar1 <DA>	Pbar4 <DA>	Pbar6 <DA>	Pbar12 <DA>
Normal helix	6.4	7.2	7.1	7.2
Vertical short 115%	6.8	7.5	6.7	7.7

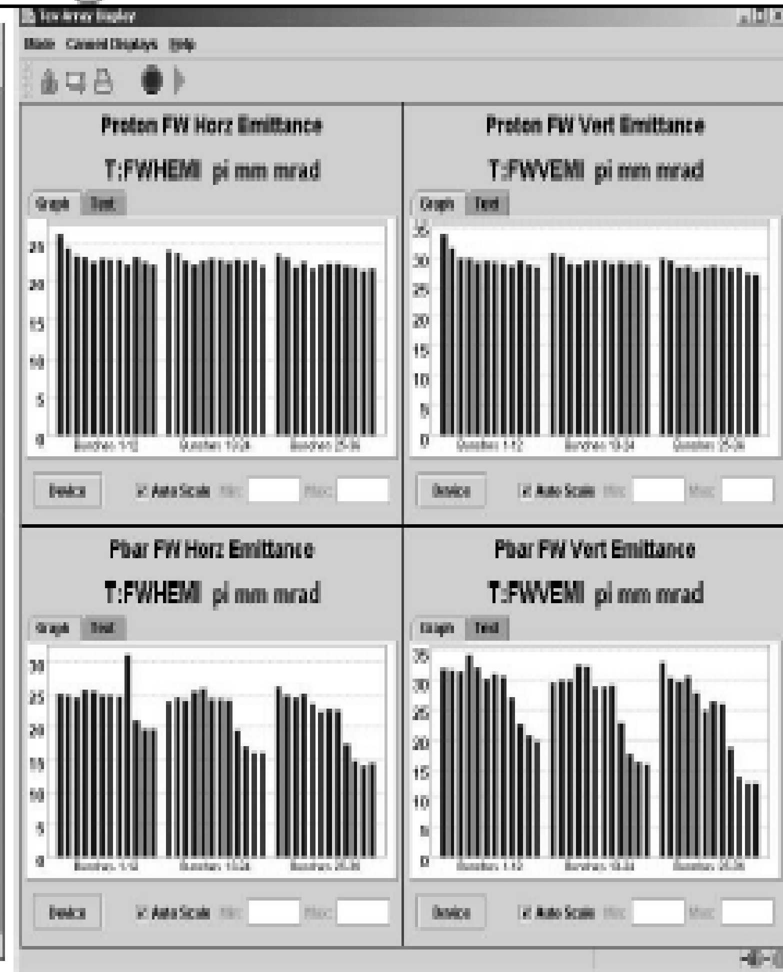
"Open helix in short arc to 108%" has been put into operation

Fermilab

Anti-proton emittance growth at Collision

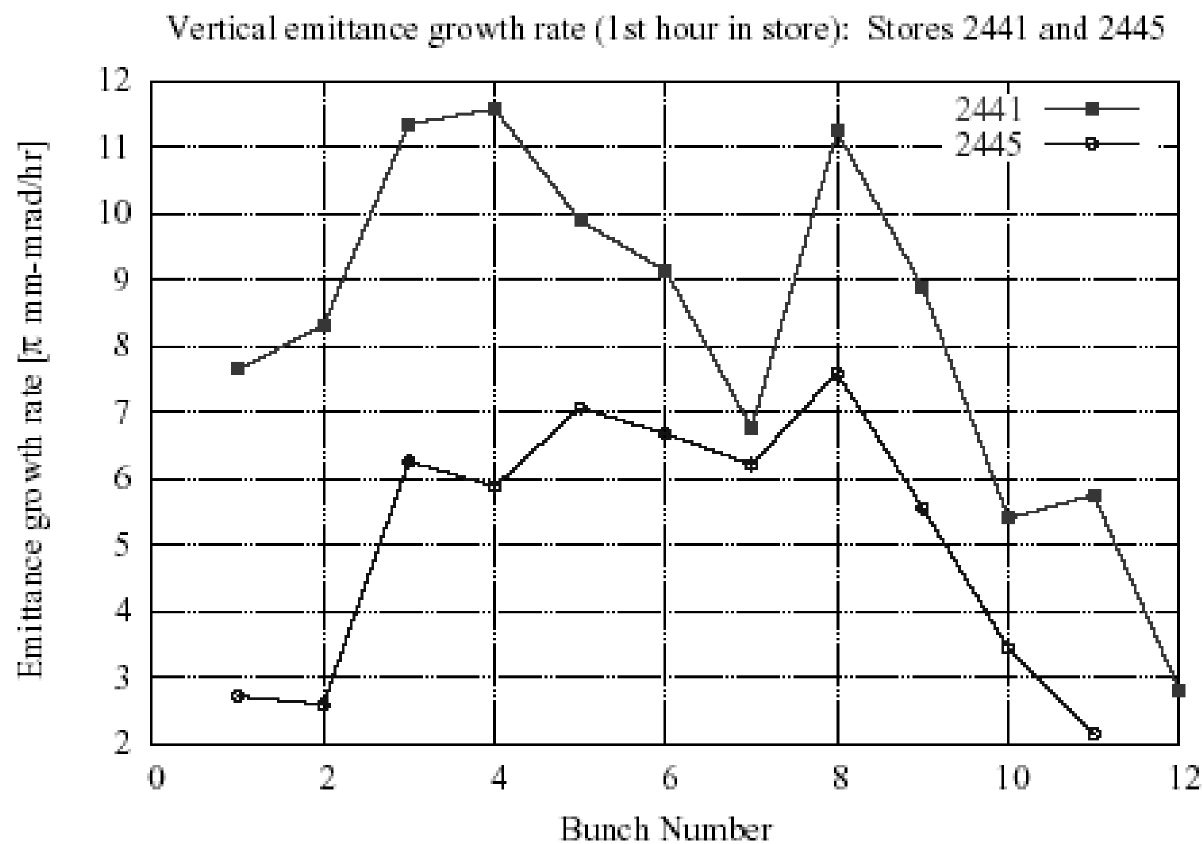


Start of Store 2441.



Start of Store 2445: $\Delta\nu_y =- 0.001$.

Anti-proton emittance growth at Collision



Vertical emittance growth rates in the two stores.

Conclusions at Injection

•At injection, for uncoalesced beam, the DA of protons on the central orbit and proton helix is much larger than physical aperture at C0. For coalesced beam, the DA of protons on the helix is ~6σ ($\varepsilon_x = \varepsilon_y$ = 25πmm.mrad). Decreasing proton bunch length to the design value would increase the lifetime significantly.

•The DA of pbars at injection is ~4σ, this value is the same at all 3 cogging stages.

•Pbar lifetime at injection needs significant improvement. Requires

- changes in the helical separations

- better control of machine nonlinearities (alignment)

- better working point

- smaller pbar emittance

- beam-beam compensation (under study)

- understanding of how lifetime scales with proton intensity

Conclusions at Collision

- **At collision, the DA is determined by the long-range interactions. The tune footprint is largely determined by the head-on collisions, but head-on collision have very little effect on the DA.**
- **At present proton intensities, pbar lifetime is determined by luminosity.**
- **At higher proton intensities, beam-beam effects may be important. Improvements will require similar steps as at injection.**