# Simulation and Experimental Studies of Beam-beam Effects at the Tevatron

Bela Erdelyi
Fermilab

HALO '03
ICFA Advanced Beam Dynamics and
Beam-Beam Workshop
May 19 - 23, 2003

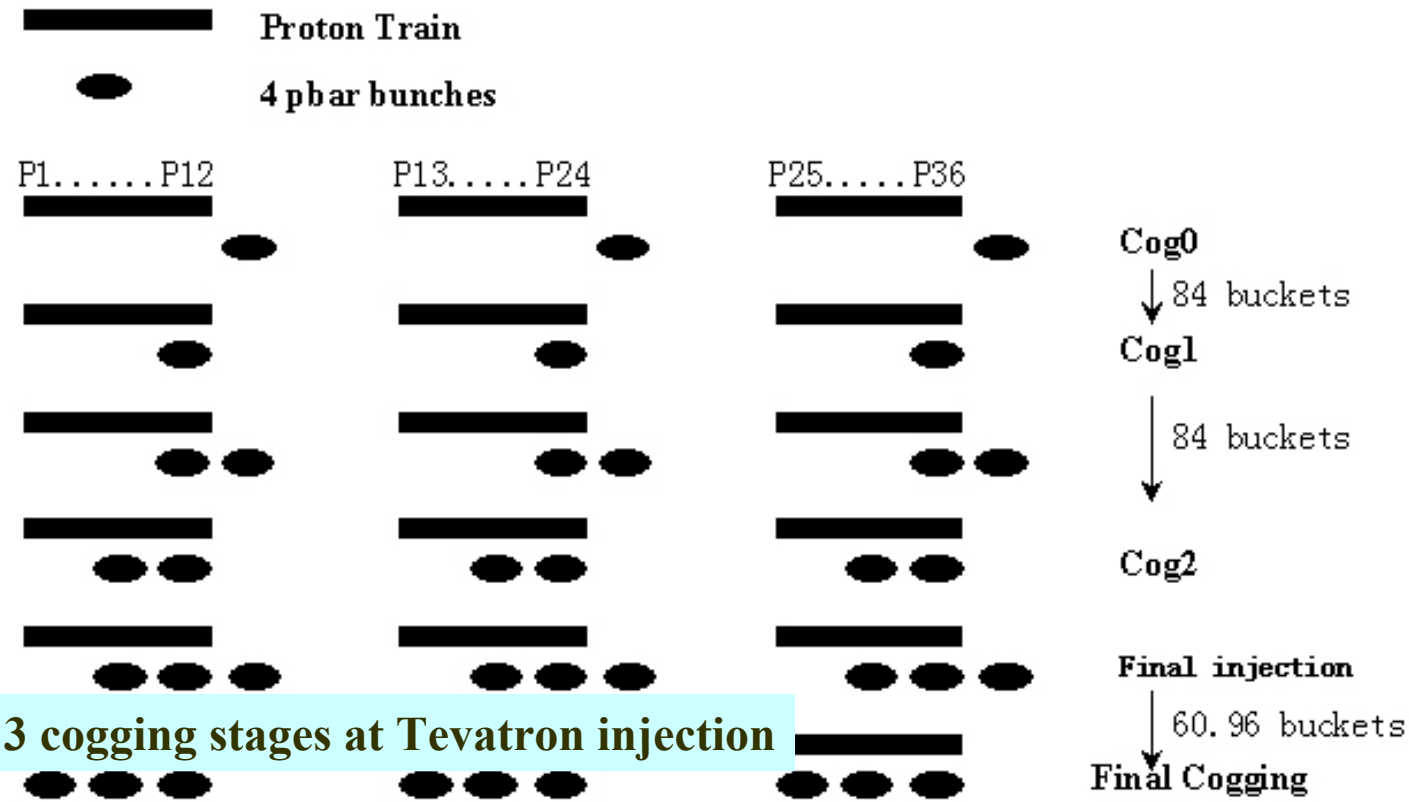
Joint work with: Tanaji Sen
Meiqin Xiao

# Introduction

- In Run IIa the Tevatron is operating with 36 proton and anti-proton (pbar) bunches, both are distributed in 3 trains of 12 bunches.
- Each pbar bunch experiences 72 long-range interactions during injection(after 2nd cogging) and ramping while at collision there are 70 long-range interactions and 2 head-on interactions at B0 and D0. Totally there are 138 interaction points in the ring.
- Beam-beam effects are different for each pbar bunch in a train since the sequence of long-range interactions is different for each of them.
- The main beam parameters at present machine conditions are used

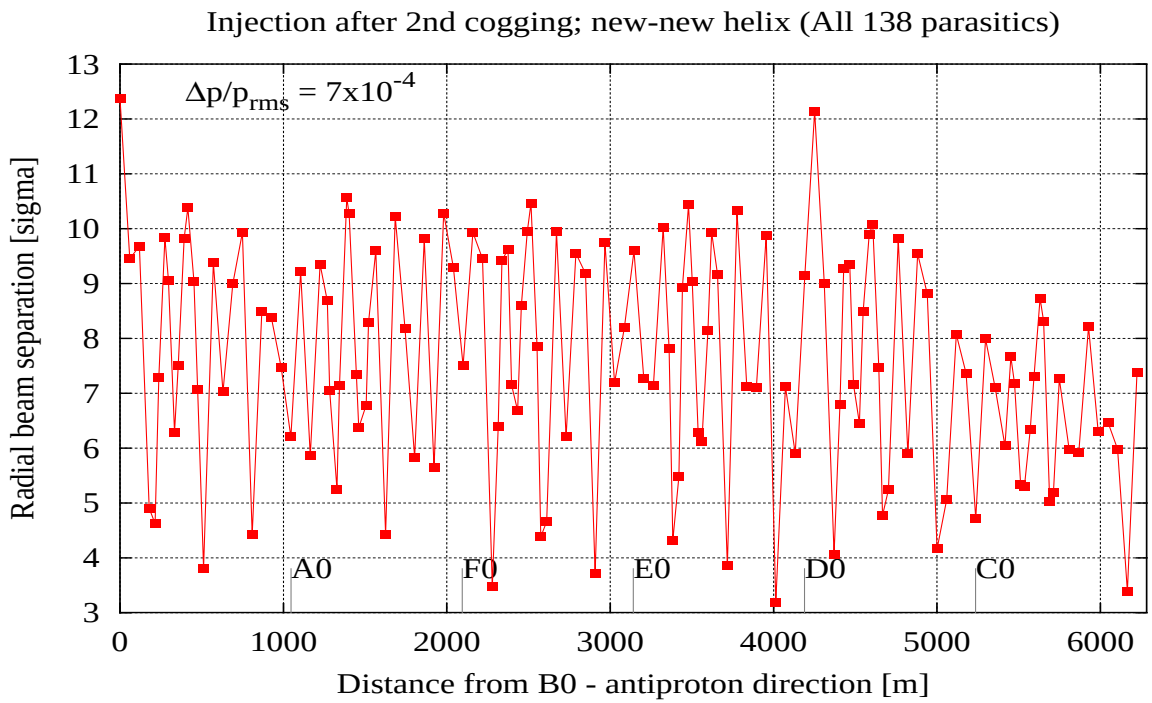
| parameters | Injection(p/pbar) | | Collision(p/pbar) | |
|---|---|---|---|---|
| | present | design | present | design |
| Bunch intensities $X10^{11}$ | 1.70/0.13 | 2.7/0.3 | 1.7/0.13 | 2.7/0.3 |
| Emittance95%[$\pi$mm.mrad] | 25/20 | 20/15 | 25/20 | 20/15 |
| Momentum deviation (r.m.s.,$1\delta_p$) | $7x10^{-4}$ /$4.5x10^{-4}$ | $4.3 x10^{-4}$ /$4.3x10^{-4}$ | $1.7x10^{-4}$ /$1.2x10^{-4}$ | $0.87x10^{-4}$ /$0.87x10^{-4}$ |

# Injection



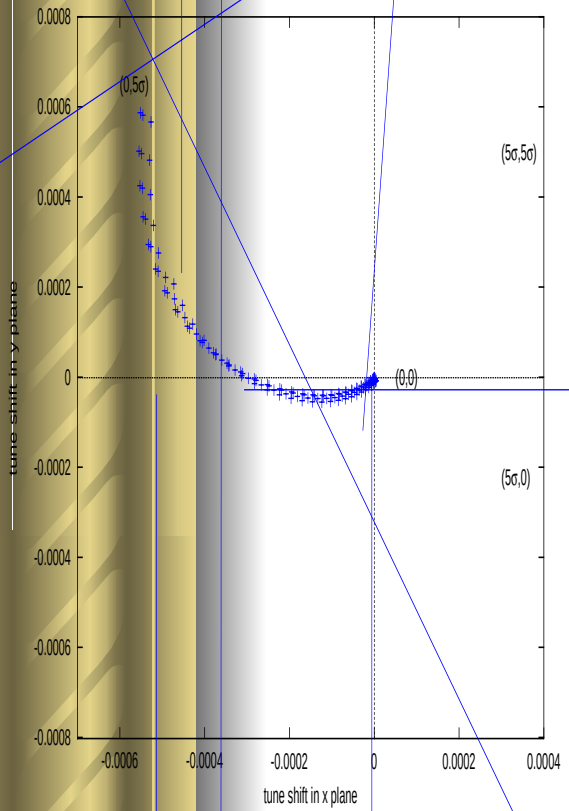

**3 cogging stages at Tevatron injection**

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



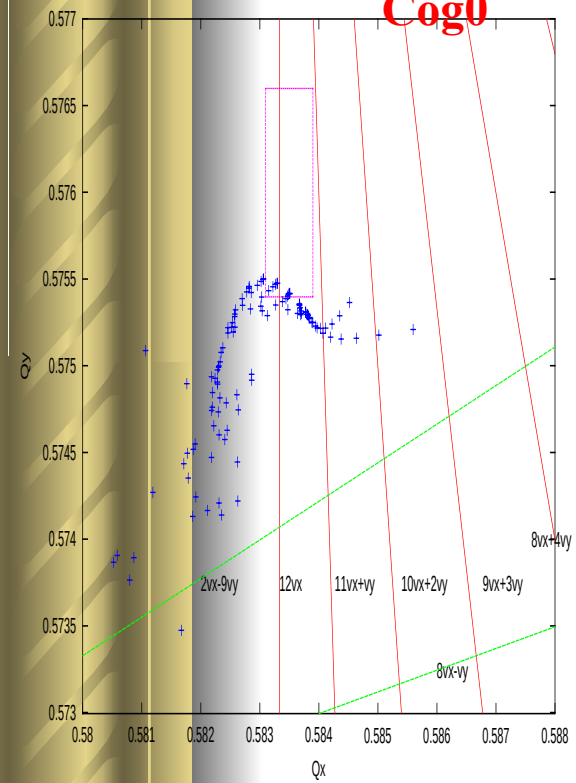

**The minimum separation is ~3σ, the separation follows dispersion pattern when the momentum spread of the beam is large.**

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

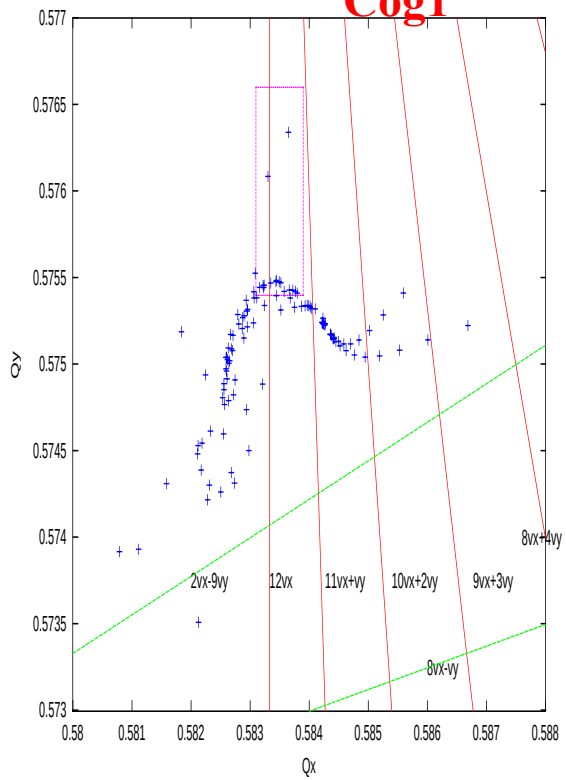


**Footprint with beam-beam and magnet field errors at injection**

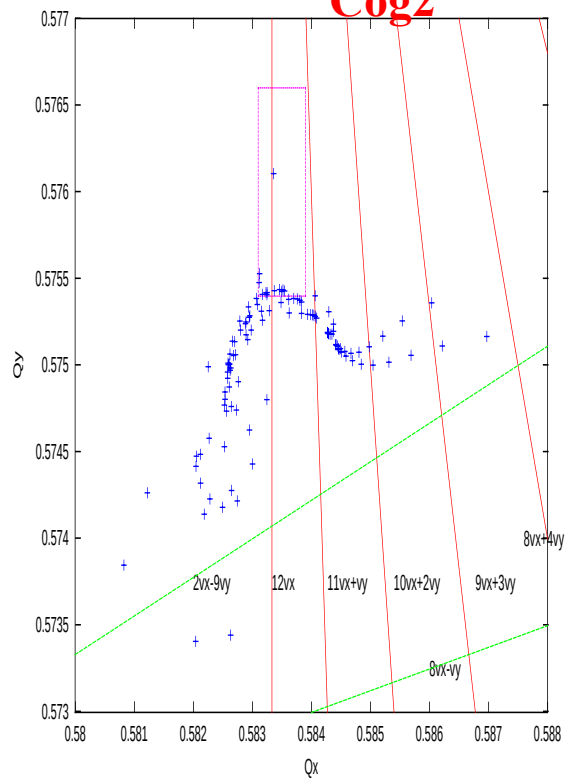
Cog0




Cog1

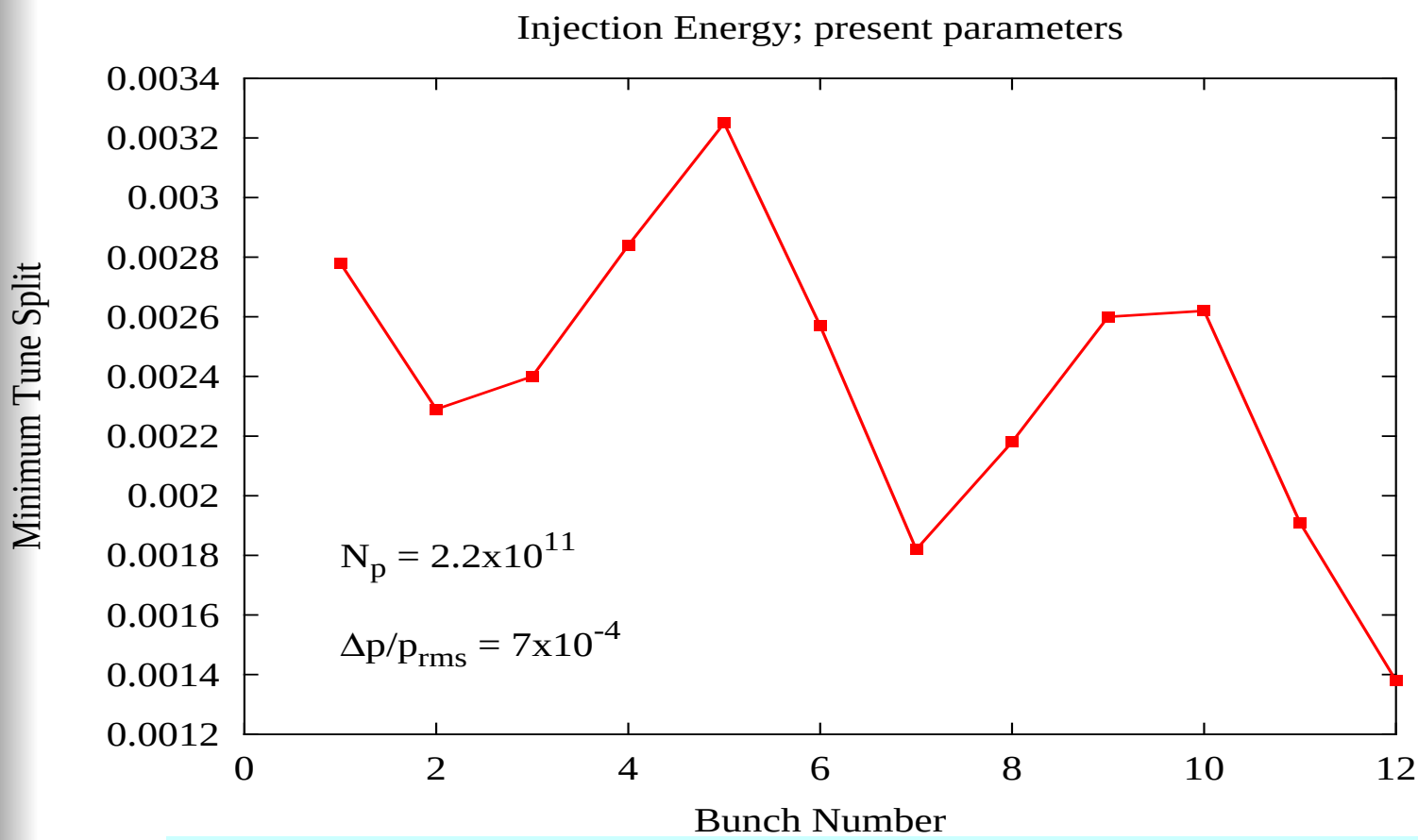



Cog2



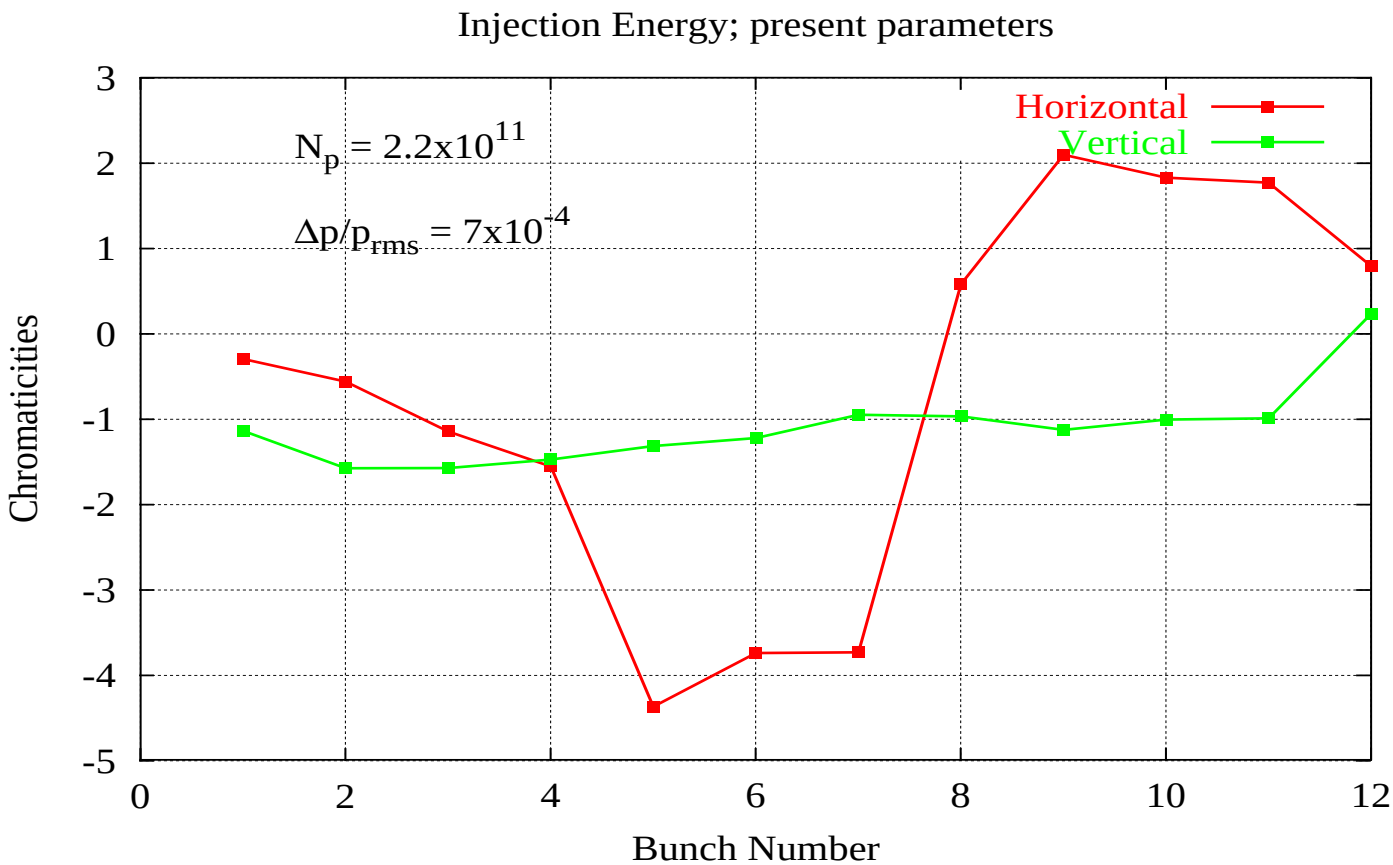

**Footprints are dominated by field errors, similar in three cogging stages.**

## Small amplitude beam-beam coupling at injection

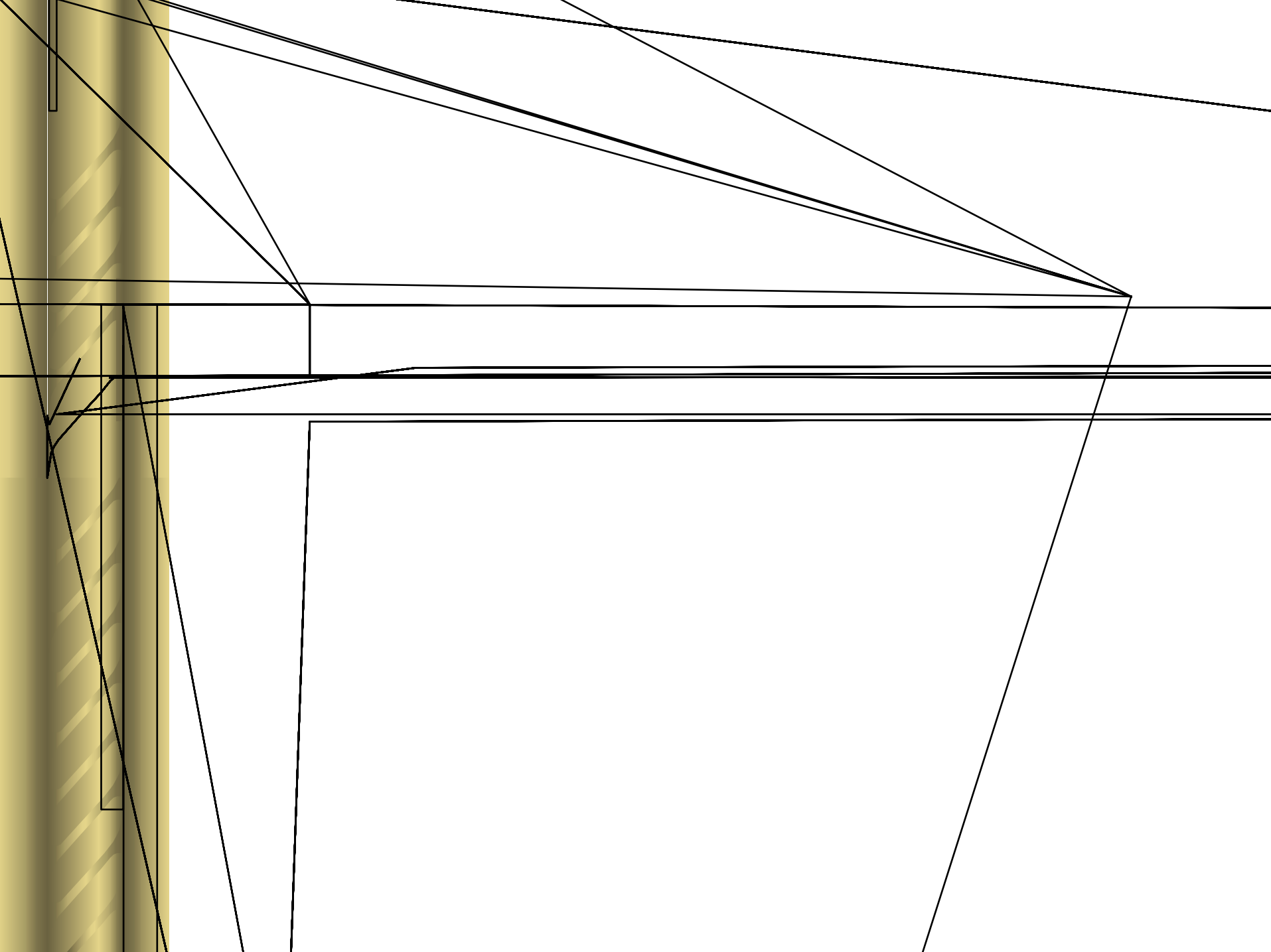



**Coupling due to beam-beam force calculated analytically for 12 pbar bunches in a train. Bunch to bunch difference in coupling can be indentified.**

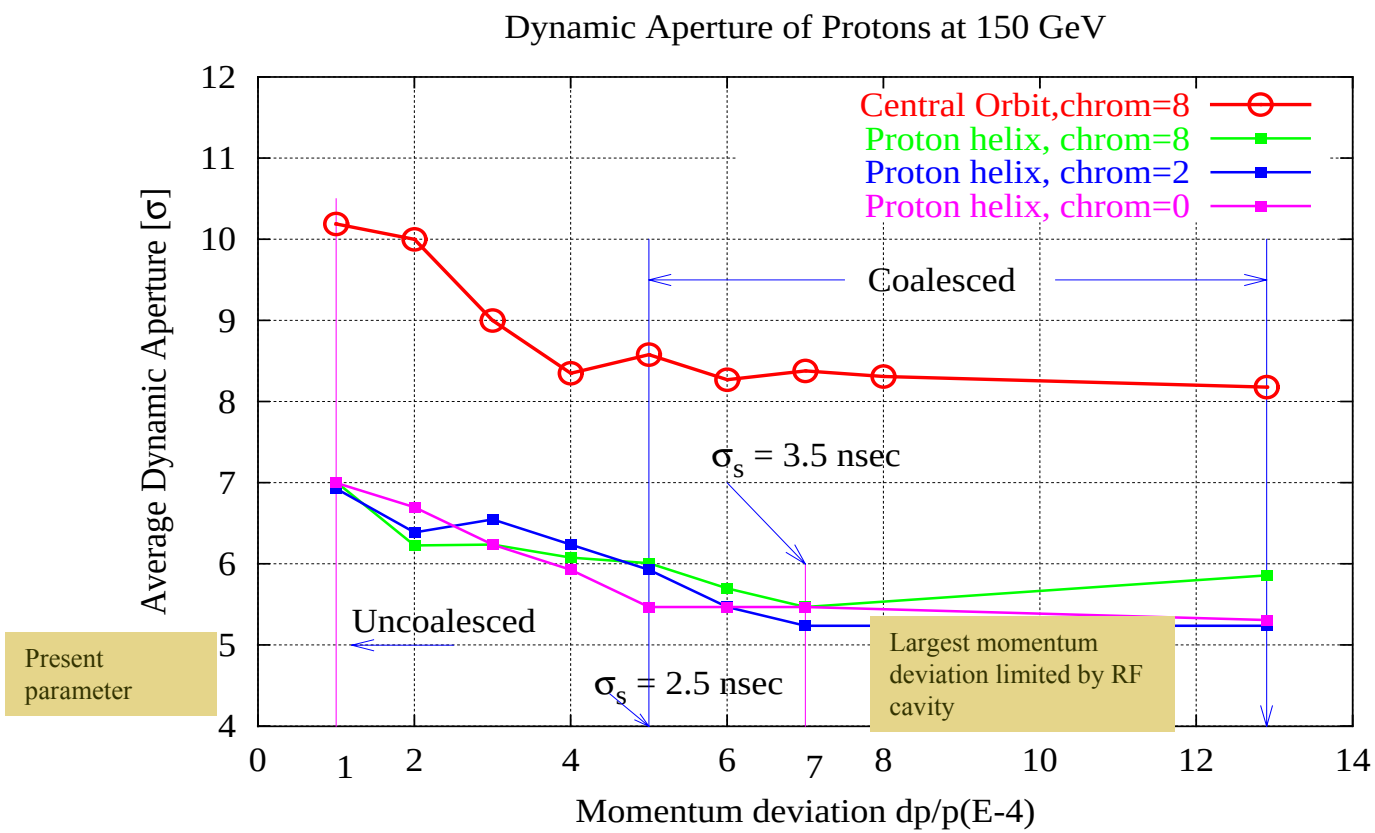
## Small amplitude beam-beam chromaticities at injection




**Chromaticities due to beam-beam force calculated analytically for 12 pbar bunches in a train. This additional chromaticity will enhance the synchro-betatron resonances. Bunch to bunch difference can be identified.**



## Dynamic Aperture of protons at injection




The DA of uncoalesced protons(dp/p<1.E-4) on central orbit and on helix is larger than 6 σ, while the DA of coalesced beam is ~ 8σ on central orbit and ~5 σ on the helix. The physical aperture is (4~6 σ), limited at C0. We observed proton lifetime on the central orbit is 4-6 hrs, but 1.5-2 hrs on the helix. Beam loss of proton are due to 1) bunches are out of the RF buckets, 2) machine non-linearities.

## Chaotic border of protons at injection

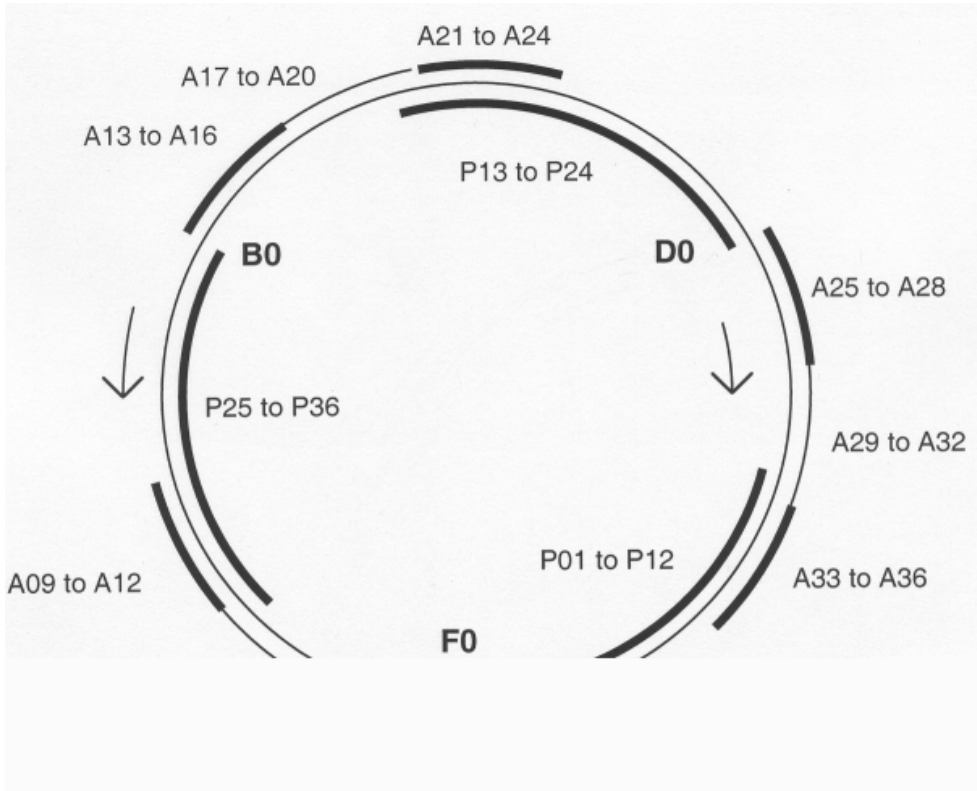
| Chromaticities ($\xi_x$, $\xi_y$) | (8,8) | (2,8) | (2,2) | (0,0) |
|---|---|---|---|---|
| Chaotic border (σ) | 4.8 | 5.0 | 5.2 | 5.4 |
| DA(σ) | 6.4 | 6.9 | 6.8 | 6.9 |

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.

# Conclusions at Injection

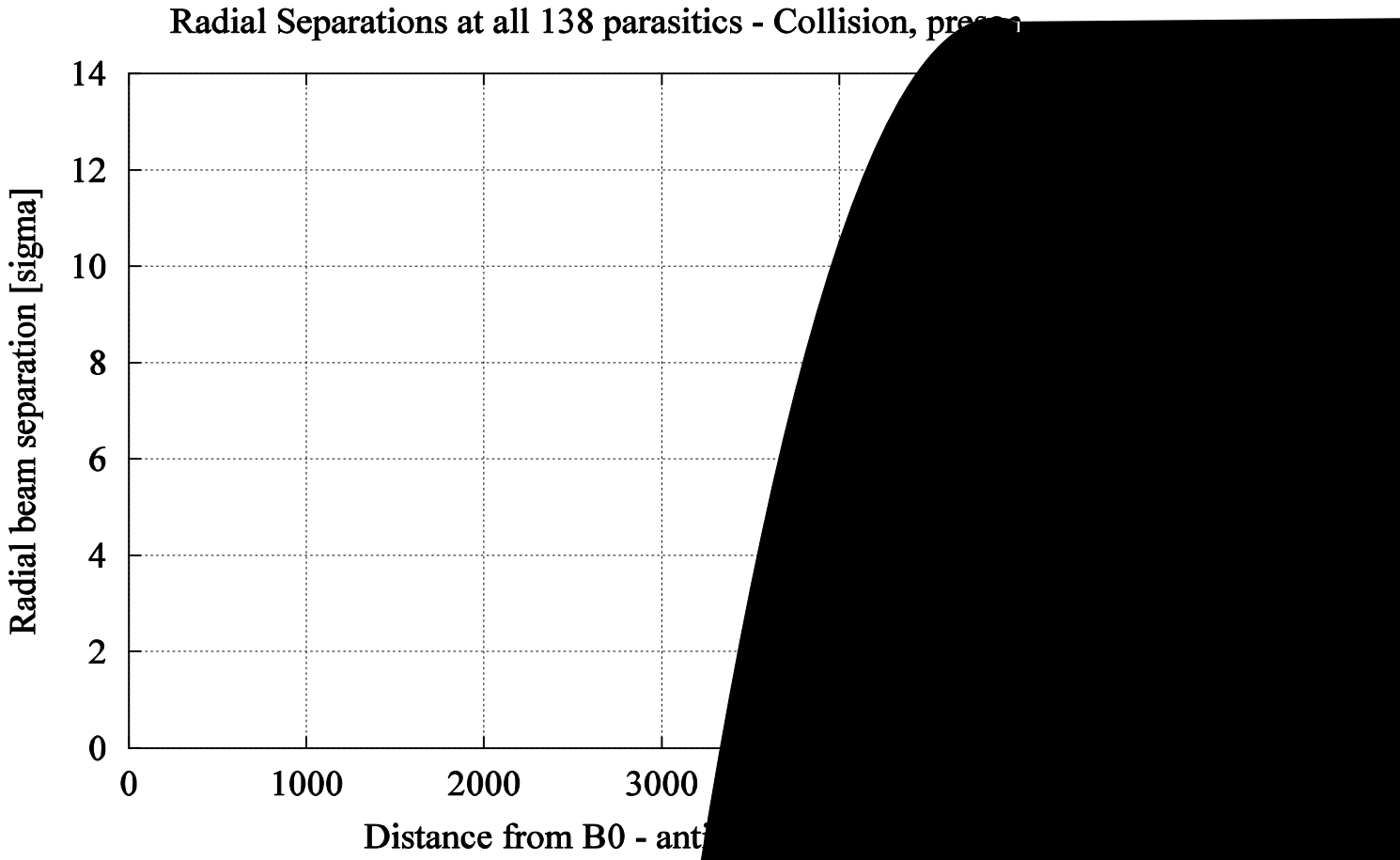
- At injection, for uncoalesced beam, the DA of protons on the central orbit and proton helix is much larger than physical aperture at C0. For coalesced beam, the DA of protons on the helix is ~6$\sigma$ ($\varepsilon_x = \varepsilon_y$ = 25$\pi$mm.mrad). Decreasing proton bunch length to the design value would increase the lifetime significantly.
- The DA of pbars at injection is ~4$\sigma$, 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

# Collision

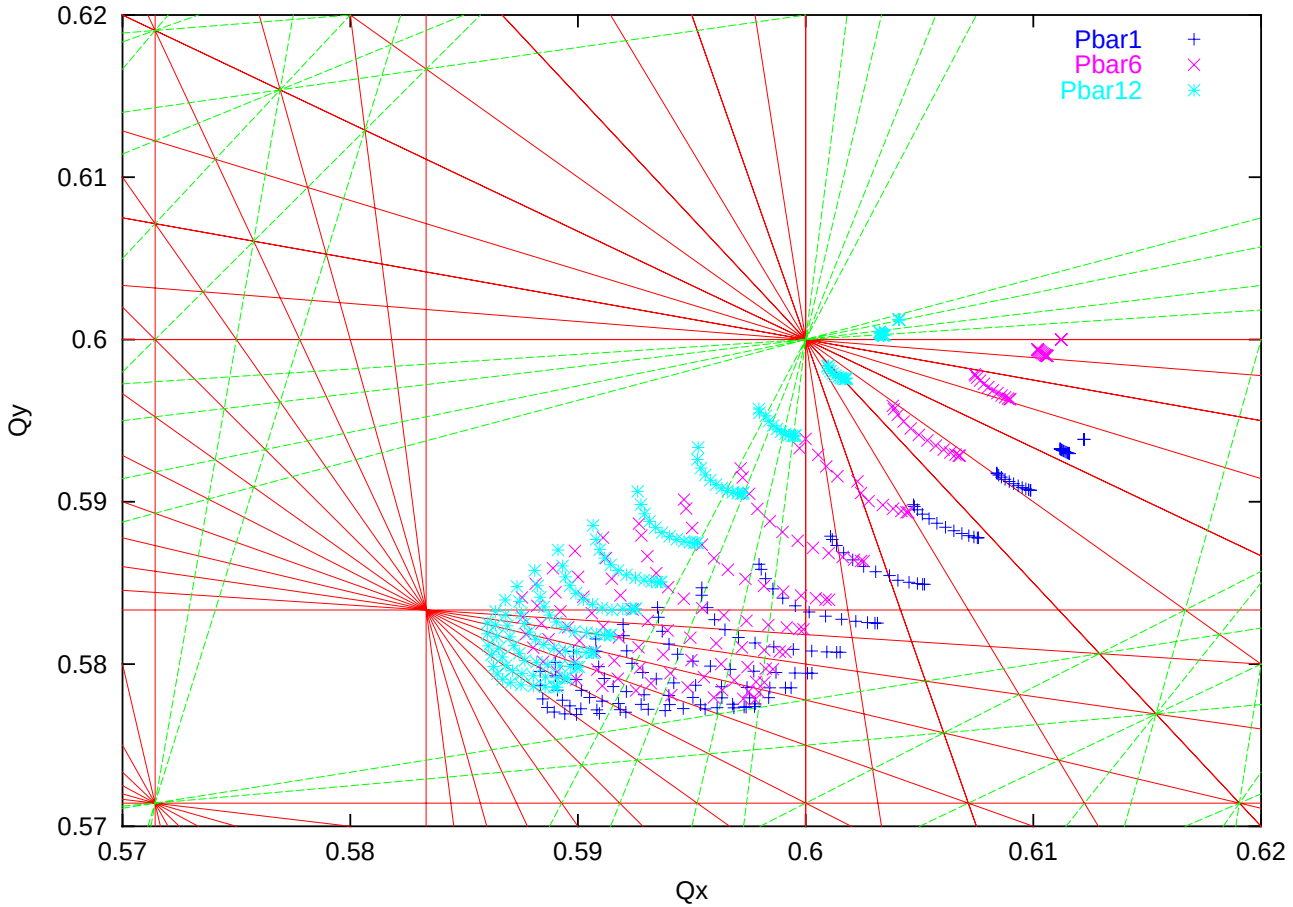



The scenario at Tevatron collision. The proton and pbar bunches are labeled P01,P02,… and A01,A02,.. Starting from the upstream end of the bunch train so that A01 and P01 meet at F0, beams collide at B0 and D0

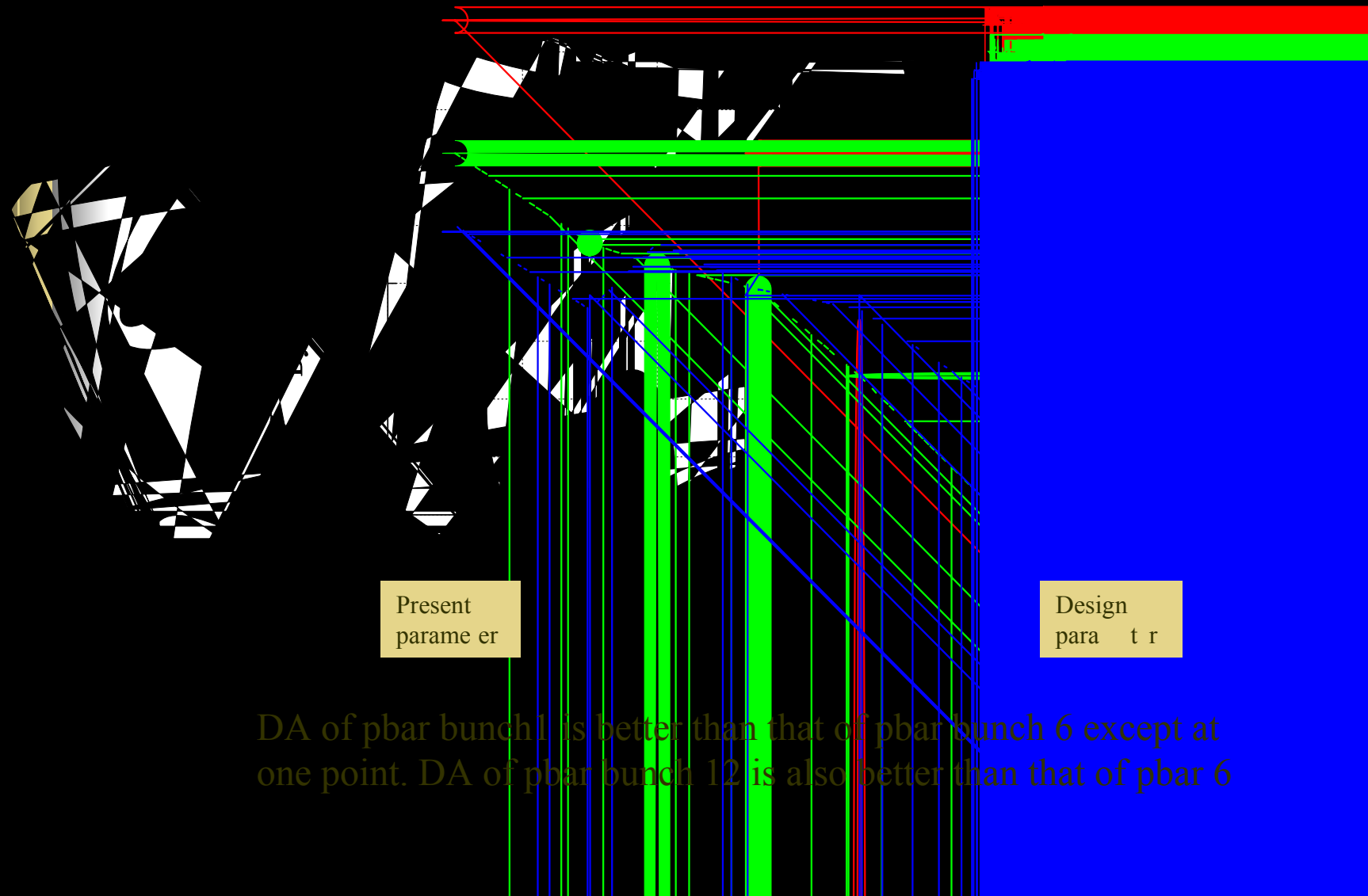
## Beam-beam separations at collision



## Footprint of pbar bunch 1, 6 and 12 at collision

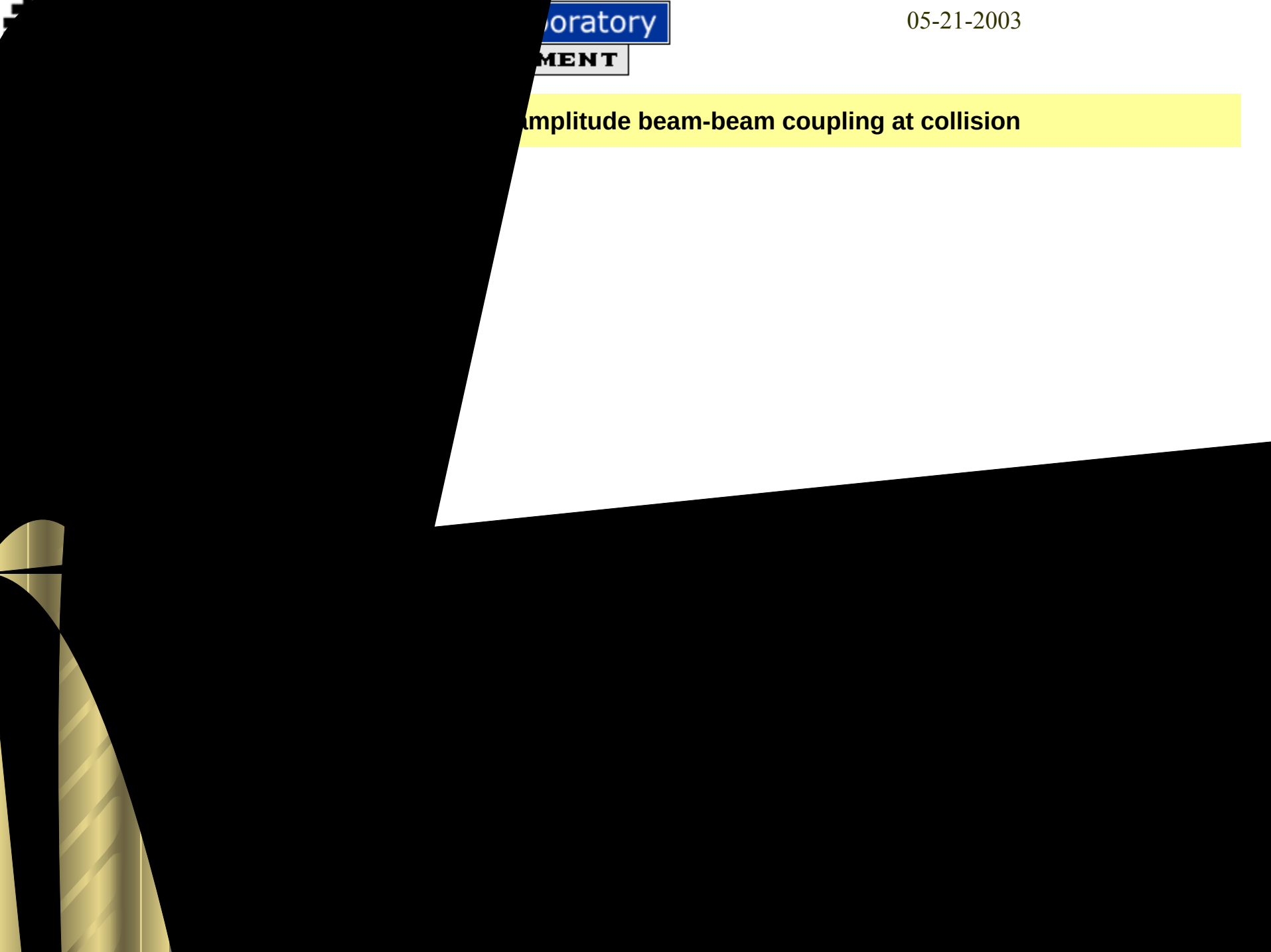



Difference is due to the missing parasitic collisions downstream for pbar bunch 1 and upstream for pbar bunch 12. Beam-beam effects and IR errors are included



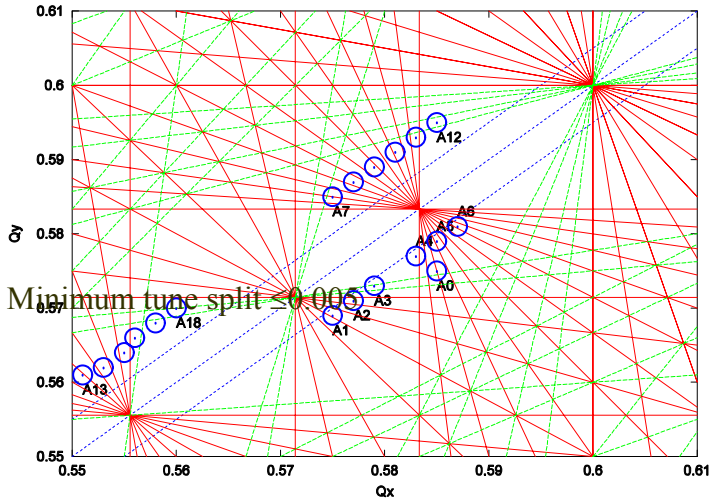

DA of pbar bunch1 is better than that of pbar bunch 6 except at one point. DA of pbar bunch 12 is also better than that of pbar 6

**mplitude beam-beam coupling at collision**



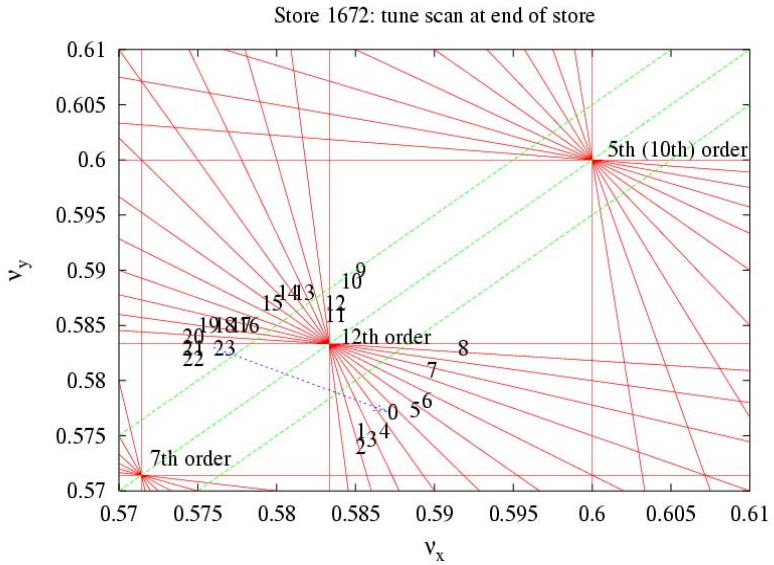
# Tune scan by tracking

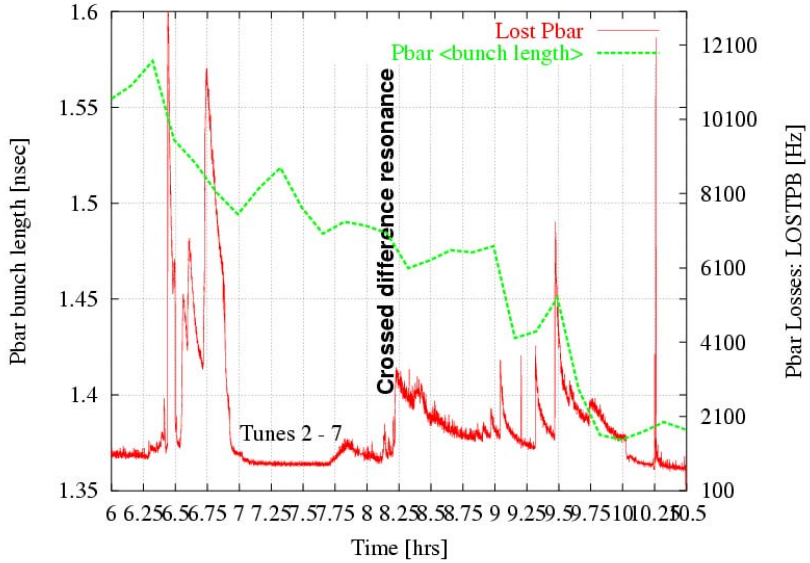
| | Bare tunes | 4D DA (<DA>,$Da_{min}$) | 6D DA($\delta_p$=3X10$^{-4}$) (<DA>,$DA_{min}$) |
|---|---|---|---|
| A0 | 0.585,0.575 | (10.0,9.0) | (7.8,6.0) |
| A1 | 0.575,0.569 | (9.2,7.0) | (5.1,4.0) |
| A2 | 0.577,0.571 | (9.3,8.0) | (7.5,6.0) |
| A3 | 0.579,0.573 | (9.4,9.0) | (8.1,7.0) |
| A4 | 0.583,0.577 | (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) |



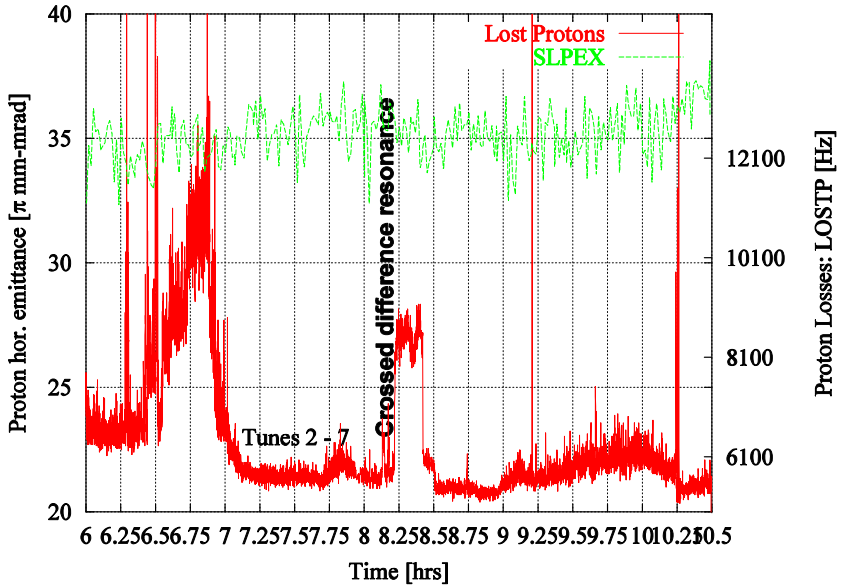

- A0: design working point
- A1,A2,A17,A18: close to 7th order resonances
- A11,A12:close to 5th order resonances
- All Beam-beam interactions are included,$10^5$ turns

# Store 1672: tune scan experiment at the end of store




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.



# 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-bea

# Current Wire Compensation of the Beam-Beam Effects

- **Principle:** the strong beam is regarded as a current, so its effect on the weak beam could be alleviated by an appropriately placed current flowing in the opposite direction
- **Advantage:** simple, deals with all multipole orders at once
- **In the Tevatron:** 72 interactions spread all over the ring's circumference and phase space

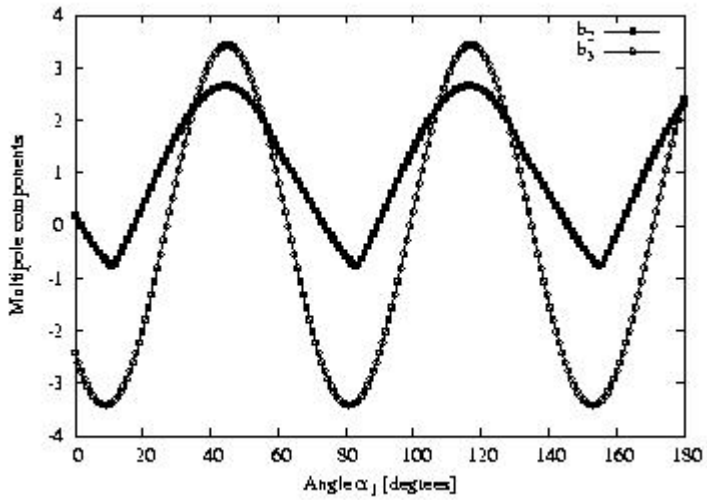
- **Implementation:** in Cosy Infinity, compute transfer map of the wire, include lattice nonlinearities, compute truncated one-turn map, optimize for resonance driving terms using normal form methods

# Wire Cages: Multiple Wires at a Single Location

- Increase robustness and flexibility by placing several wires around the surface of a cylindrical cage.
- Assume $N_w$ wires placed at angles $\alpha_j$ w.r.t. the horizontal axis at distances $r_j$ from the pbar beam. Then the multipoles are (with $r_w$ being the average distance)

$$b_n = -\sum_{j=1}^{N_w} \cos(n+1)\alpha_j \left[\frac{\langle r_w \rangle}{r_j}\right]^{n+1}$$

$$a_n = \sum_{j=1}^{N_w} \sin(n+1)\alpha_j \left[\frac{\langle r_w \rangle}{r_j}\right]^{n+1}$$



# Work in Progress: Application to the Tevatron

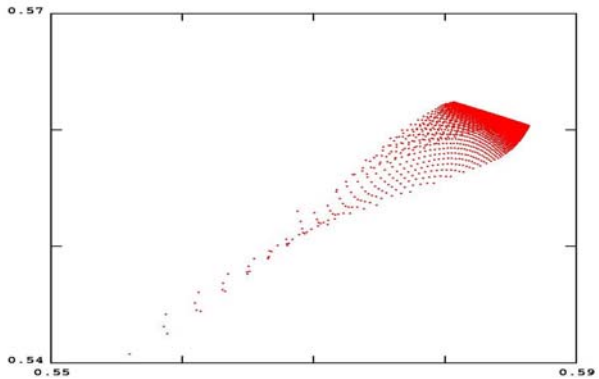
- **Number of wires:** 4
- **Longitudinal placement:** in available drifts where horizontal and vertical beta functions are not too different, and the proton and anti-proton beams are well separated
- **Transverse placement:** reasonable distance from both the beam pipe and pbar beams
- **Length:** fixed to 1 m
- **Current:** assuming round beams with design parameters ($N_b$=2.7x10$^{11}$), and kicks adding up linearly

$$I = 10^7 \left( \frac{r_p m_p c^2}{0.2998} \right) N_b \times \frac{72(\text{interactions})}{4(\text{wires})} = 232 \text{ A}$$

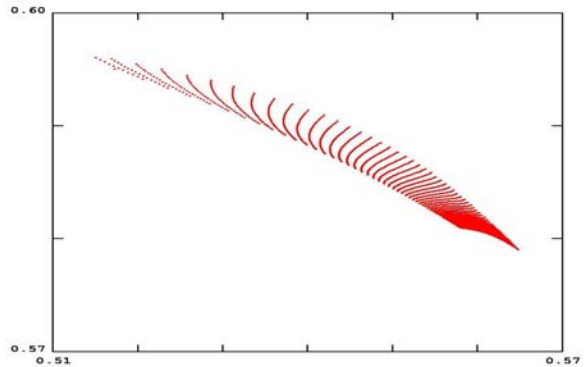
Wires placed in sectors: A17, F0, E0, C0

# Normal Form: Tune Footprints from the Map

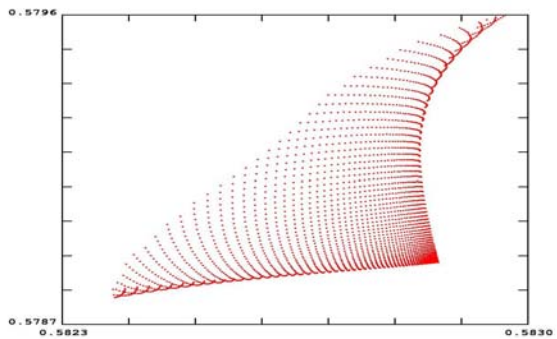
**Injection, lattice only**




**Injection, lattice and wires**



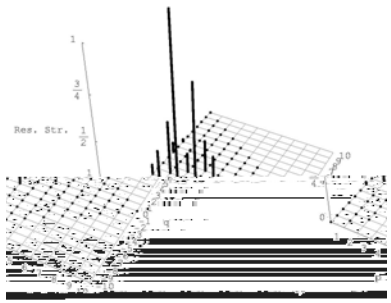

**Collision, lattice only**



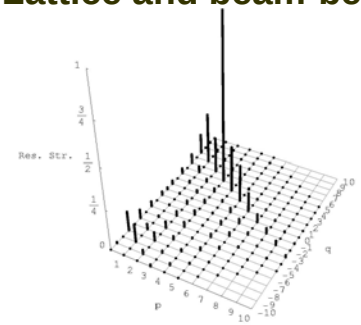
# Normal Form: Resonance Strengths from the Map

## Injection

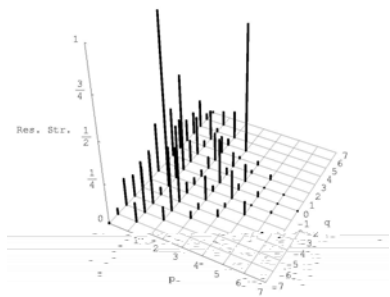
**Lattice only**



**Lattice and beam-beam**

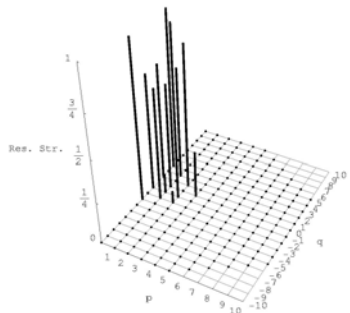
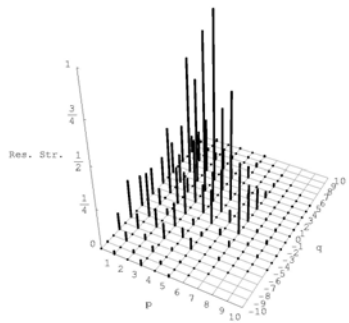


**Lattice and wires**



## Collision

**Lattice only**



**Lattice and beam-beam**