Long-range Beam-Beam Interactions in the Tevatron Collider

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(with input from A. Valishev)

Fermilab
Content

• Tevatron Helical Orbits:
  – Separators and their limitations
  – Apertures and their limitations

• Patterns of beam-beam interactions:
  – Scaling laws for separated beams
  – Orbit variations for different bunches
  – Tunes for different bunches
  – Coupling for different bunches
  – Chromaticity for different bunches

• Beam-beam effects vary from bunch to bunch:
  – Emittance growth – “scallops”
  – Beam lifetime variation along the train
Tevatron Helical Orbits
36 proton x 36 antiproton

Same magnetic fields $\rightarrow$ same orbits $\rightarrow$ 72 IPs

396 ns bunch separation $\rightarrow$ 59 m btw IPs

Need only 2 $\rightarrow$ separate at 70 $\rightarrow$ Electric field
Tevatron High Voltage Electrostatic Separators

300 kV over 50 mm gap; 3 m ; 24 of them (H/V)
Tevatron Helix

size 12-15 mm
at 150 GeV

6-8 mm
at LB
Many Optimizations of Helix

\[ S = \sqrt{\left( \frac{\Delta x}{\sigma_{x\beta}} \right)^2 + \left( \frac{\Delta y}{\sigma_{y\beta}} \right)^2} \]

sequence 13
Sometimes - Drastic

16 mm aperture magnets at C0 were taken out and replaced with 40 mm aperture dipoles in 2003.
Patterns of Beam-beam Interactions
Collider Fill Cycle for Store 2511 in 2003

Store 2511 $L_0 = 0.4 \times 10^{32}$
Collider Fill Cycle for Store 7747 (2011)

- Total intensity
- Proton intensity
- Pbar intensity
- Pbar bunch no.13

Record Store 7747 \( L_0 = 4 \times 10^{32} \)

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LR Effects during Injection Process

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Losses Driven by Opposite Beam

Proton Loss Rate at 150 GeV1/τp [%/hr] vs Total Number of Antiprotons Na [10^9]

store #3972
Longitudinal Shaving of Antiprotons

![Graph showing RMS bunch length and 95% normalized vertical emittance over time.]

- **σ_s**: RMS bunch length [ns]
- **ε_v**: 95% normalized vertical emittance [π mm mrad]

Time after injection [min]

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Poor Pbar Lifetime on 150 GeV Helix

- Poor P/Pbar lifetime at 150
  - 1-4 hours, 15-20% loss
  - $\sqrt{\text{time}}$ dependence
  - Worse with larger Np, Q'
  - Longitudinal shaving

- Possibilities to fix it:
  - Open aperture (C0, align)
  - Reduce emittances (reshimming)
  - Reduce impedance (F0 liner)
  - Reduce chromaticities
    - Found experimentally (plot)
    - Confirmed in simulations →
    - Weak HT Instability →
      liner, dampers, octupoles
  - $dN=15-20\% \rightarrow 2-4\%$

Simulations by A.Kabel (SLAC)

Measurements 2002

- dN vs. time
- $Q'=8$
- $Q'=4$
- $Q'=2$
- $Q'=0$

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Proton Loss in Squeeze vs. Antiproton Brightness

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What we found empirically

• Losses were dependent on:

\[
\frac{\Delta N_{a,p}}{N_{a,p}} = 1 - \frac{N(t)}{N(t = 0)} \propto \sqrt{t} \cdot \varepsilon_{a,p}^2 \frac{N_{p,a}}{\varepsilon_{p,a}} Q_{a,p}^2 F(\varepsilon_L, Q_{x,y}, S_{a-p})
\]

• The can be described by the model of “Diffusion + DA set by Beam-Beam”

[Diagram showing physical aperture and dynamic aperture set by parasitic beam-beam interactions]
All beam indicators become bunch dependent due to long-range beam-beam effects

- Orbits
- Tunes and couplings
- Chromaticities
- In both – protons and pbars
- Have 3-fold symmetry (trains of 12)
Long-range B-B Seen at Low-Beta (980 GeV)

- SL reportsσ, mean, N, tilt bunch-by-bunch for both protons and pbars
- SL reports scallops (when they appear) in good agreement with FWs
- It also shows 40 micron b-by-bunch hor pbar orbit variation along the bunch train with 3-train symmetry (4 microns for protons)
Pbar Bunch Tunes @ LB

![Graph showing Antiproton Betatron Tune vs. Bunch Number]

- **Antiproton Betatron Tune**
- **Horizontal**
- **Vertical**

Bunch Number:
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
Pbar Bunch Chromaticity@ LB

![Graph showing chromaticity vs bunch number for horizontal and vertical components.](image-url)
Antiproton Bunch-to-bunch Orbit

In general – very good agreement btw simulations and measured Q, orbits, Q’s
Beam-beam interactions affecting performance:
Beam-Beam Tune Shifts

\[ \xi = 2 \frac{N_p r_p}{4 \pi \varepsilon_p} \]

head-on tune shift, two IPs, now with at the end of the Run II
total max head-on tuneshift was about 0.025 for pbars, 0.02-0.025 for protons
tune shift for separated beams is smaller:

\[ \Delta \nu = \sum_i \frac{\beta_i N_p r_p}{2 \pi \gamma d_i^2} = \sum_i \frac{2\xi}{(d_i / \sigma_i)^2} \]

but: a) always present, \( \Delta \nu = 0.002-0.005 \)
b) MANY near-misses \( i = 70 \)
c) different bunch-by-bunch
d) HV separator limited: \( \gamma d^2 \) scales as \( V^2 / \gamma \)
Situation at Low-beta: Confinement

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

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

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

protons antiprotons

p pbar
WP (Tunes) is not the Only Story - Effect of $\beta^*$ Chromaticity. Simulation
2nd Order Tune Chromaticity

Measured $C_2 = -16560$

Model $C_2 = -16480$

- Reduced to ~500 by reconnection of sextupoles into new families
Pbar Emittance Growth Near Qy=0.6

over 10 min: SQ → HEP

bunch #

dEmittance, vert, π mm mrad

0 1 2 3 4 5

1 2 3 4 5 6 7 8 9 10 11 12
"Scallops": Simulation and Measurement

Beam-Beam Code LIFETRAC
D. Shatilov, A. Valishev
Losses due to beam-beam interactions

Antiprotons 980 GeV:
\[ \xi_{\text{max}} = + (0.020 - 0.024) \]

![Graph showing antiproton losses due to burn-up and non-luminous losses.](image-url)
TEL2 acts on all bunches (DC)

Bunches are not equal!

Bunch P12 has systematically the lowest vertical tune that reduces its lifetime (too close to 7/12 resonance). TEL2 raises the tune up by $dQ=+1.5e-3$ at 0.6 A.
LIFETRAC Simulation of TEL

![Graph showing normalized beam intensity over time with different TEL statuses.]

- TEL = ON (solid red line)
- TEL = OFF (dotted blue line)

Normalized Beam Intensity vs. Time (h)

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Summary

• Long-range beam-beam effects occurred in the Tevatron at all stages (injection, ramp, squeeze, collisions) and in both beams

• They resulted in beam losses, and emittance blow-ups – with bunch-to-bunch dependent patterns

• Careful optimization of helical orbit separation and many operational tune-ups and upgrades have led to essentially putting the effects on the luminosity under control by the mid/end of Run II

• Trustable LIFETRAC simulations helped us a lot, beam-beam compensation by TELs demonstrated
Complexity of Beams in $\log$-Scale:

- Complexity 0
  - $e^-$
  - APS, LCLS

- Complexity 0.5
  - $p$
  - FNAL/MI

- Complexity 1
  - $e^-$
  - $e^+$
  - B-factories

- Complexity 1.5
  - $p$
  - $e^-$
  - eCool, HERA

- Complexity 2
  - $e^+$
  - $e^-$
  - DCI/Orsay, 80

- Complexity 2
  - $p$
  - pbar, p
  - Tevatron, LHC

- Complexity 2.5
  - $e^-$
  - $p$
  - pbar
  - BBComp/3BI

Vladimir Shiltsev - Beam-beam workshop, CERN - March 18, 2013