Simulation of Beam-Beam Effects and Tevatron Experience

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Outline

- Overview of Beam-Beam Effects
  - Injection
  - Ramp
  - Squeeze
  - Collisions

- Analysis tools
  - Luminosity Evolution Model
  - Beam-Beam Simulations

- Countermeasures
  - New Collision Helix
  - Second Order Chromaticity Correction
  - (New Tune Working Point)

- Results and Summary
Collider Fill Cycle

Record Store 5989 \( L_0 = 3.15 \times 10^{32} \)
Long-Range Effects at Injection
Importance of Losses in Squeeze

- Total quenches this year 140
- Percentage
  - Ramp: 3
  - Squeeze: 22
  - Collisions: 13 = 38
  - No beam: 102
- Most quenches in squeeze are caused by a combination of beam-beam and orbit issues
Proton Loss in Squeeze vs. Antiproton Brightness

![Graph showing the relationship between proton inefficiency and antiproton brightness.](image)
Luminosity and Luminosity Integral

\[ L = \frac{3\gamma \int_0^B \frac{N_p}{N_{\bar{p}}} N_{\bar{p}}}{\pi \beta^* (\varepsilon_p + \varepsilon_{\bar{p}})} H\left(\frac{\sigma_l}{\beta^*}\right) \quad L = L_0/\left(1 + t / \tau_L\right) \]

\[ I = \int L\,dt \cong N_{\text{stores}} \tau_L L_0 \ln\left(1 + T / \tau_L\right) \]

- **Luminosity Integral**: primary factors
  - Beta* at IP and bunchlength: \( H(x)/\beta^* \)
  - Emittances: \( \varepsilon_p, \varepsilon_{\bar{p}} \)
  - Number of protons: \( N_p \)
  - Number of antiprotons: \( B N_{\bar{p}} \)
  - Lumi-lifetime: \( \tau_L \)
Effects at Collisions

- Emittance blowup
- Lifetime deterioration

- Long-Range
- Head-on
Luminosity Evolution Model

- Beam-Beam is not the single strongest effect
- A model was built to describe evolution of the beam emittances and intensities taking into account the following factors:
  - Scattering at IP (luminosity)
  - Intra Beam Scattering
  - Scattering on residual gas
  - RF noise
- Initial parameters (bunch by bunch intensity, transverse and longitudinal emittances) are provided by measurements
- Main free model parameters are:
  - Gas pressure
  - RF noise power
- Fast computations
Store 6200. $L_0=2.95 \times 10^{32}$
Beam-Beam Code LIFETRAC

- Weak-strong, Gaussian strong bunch
- Macro-particle weak bunch, typically 10000 particles
- Full details of the machine optics, beam separation, and collision pattern with all 72 IPs
- Effects of random noise
- Parallel, up to $10^8$ turns
- Deliverables – emittances and beam life time

- D. Shatilov et al., TPAT084, PAC05
- A. Valishev et al., TPAT083, PAC05
"Scallops": Simulation and Measurement

![Graph showing comparison between measured and simulated vertical antenna emittance as a function of bunch number.](image)
Antiproton Bunch-to-bunch Orbit

Vertical Orbit (mm)

Bunch Number

Meas.
Calc.
Store 5052 $L_0=0.92 \times 10^{32}$
$\beta^*$ Reduction (8/2005)
Effect of the Helix Size on Lifetime

Average Antiproton Non-Luminous Loss Rate vs Helix Size

Helix size [% of nominal]

Antiproton NL Loss Rate [% / hr]

Stores #4021 - #4109

Helix size (%)

Antiproton loss rate

<table>
<thead>
<tr>
<th></th>
<th>CDF upstream</th>
<th>CDF downstream</th>
<th>DO upstream</th>
<th>DO downstream</th>
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<td>5.4</td>
<td>5.6</td>
<td>5.0</td>
<td>5.2</td>
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<tr>
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<td>6.4</td>
<td>5.8</td>
<td>6.2</td>
<td>5.6</td>
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</tbody>
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Store 4581, $L_0 = 1.72 \times 10^{32}$ Old Helix

**Bunch 7**

**Number of Particles**

**Luminosity ($cm^{-2} s^{-1}$)**

**Luminosity Integral ($cm^{-2} s^{-1}$)**

**Bunch Length (cm)**

**Horizontal Emittance (in mm mrad)**

**Vertical Emittance (in mm mrad)**

**Time (h)**
Store 4859, $L_0=1.70 \times 10^{32}$ New Helix
Head-on Beam-Beam Tune Shifts.

**Antiprotons Vertical**

- Total
- CDF

**Protons Vertical**

- Total
- CDF

- 4581
- 4859

Bunch
Contributions to Luminosity Loss

![Graph showing contributions to luminosity loss over time. The graph displays data points for different dates and categories such as HEP, Protons Squeeze, Protons Ramp, Antiprotons Squeeze, and Antiprotons Ramp. The x-axis represents dates from 4/17/05 to 3/17/08, while the y-axis shows luminosity loss in percentage.]

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Store 5245, $L_0=2.92 \times 10^{32}$ New Helix
Head-on Beam-Beam Tune Shifts. Store 5245
Effect of $\beta^*$ Chromaticity. Simulation
Effect of $\beta^*$ Chromaticity. Simulation
Correction of $\beta$-function Chromaticity

- Reconnection of sextupoles into new families

![Graphs showing correction of chromaticity and connection of sextupoles into new families.](image)
Second Order Chromaticity

Sextupoles OFF
$C_2 = -16500$

Sextupoles ON
$C_2 = -2700$
Contributions to Luminosity Loss

![Graph showing contributions to luminosity loss over time]

- HEP
- Protons Squeeze
- Protons Ramp
- Antiprotons Squeeze
- Antiprotons Ramp

Date:
- 4/17/05
- 9/17/05
- 2/17/06
- 7/17/06
- 12/17/06
- 5/17/07
- 10/17/07
- 3/17/08

Luminosity Loss (%)
Store 5802. $L_0=2.09 \times 10^{32}$
$\varepsilon_p = 20 \pi \text{ mm mrad}$

$\varepsilon_d = 5 \pi \text{ mm mrad}$
Effect of $\varepsilon a$ on Proton Losses. Simulation

![Graph showing the effect of antiproton emittance on proton loss rate. The x-axis represents antiproton emittance in mm mrad, with values 7, 5, and 4. The y-axis shows the proton loss rate in %/h. The graph indicates a higher loss rate at 4 mm mrad compared to 7 and 5 mm mrad.](image-url)
Store 6200. $L_0 = 2.95 \times 10^{32}$  PBJ Implemented
Head-on Beam-Beam Parameter

![Graph showing beam-beam tune shift over time with dates 12/1/04 to 3/15/08.

- Protons represented by blue squares.
- Antiprotons represented by red squares.

Date:
- 12/1/04
- 6/19/05
- 1/5/06
- 7/24/06
- 2/9/07
- 8/28/07
- 3/15/08]
Contributions to Luminosity Loss

- HEP
- Protons Squeeze
- Protons Ramp
- Antiprotons Squeeze
- Antiprotons Ramp

Date:
- 4/17/05
- 9/17/05
- 2/17/06
- 7/17/06
- 12/17/06
- 3/17/08
- 5/17/07
- 10/17/07

Luminosity Loss (%)
Integrated Luminosity Performance

- Luminosity Integral (nb^-1 per 24 hr)
- Initial Luminosity (10^{30} cm^{-2} s^{-1})

Legend:
- Jun 06 - Aug 07
- Oct 07 -
- Poly. (Jun 06 - Aug 07)
- Poly. (Oct 07 -)
New Tune Working Point

- Currently operating between 4/7 and 3/5 with beam-beam $\xi = 0.02$
- To increase number of particles need more tune space - WP near $\frac{1}{2}$ should allow 30% more!
- Requires lengthy commissioning - hence will not be implemented in RunII
Coherent Instability in HEP Store

A. Valishev et al., THPC074

R. Ryne, Advanced Computing Tools and Models for Accelerator Physics
Summary

- Beam-beam effects and orbit stability issues in squeeze impact collider reliability

- At collisions, the decrease of antiproton intensity lifetime and emittance blowup prior to 6/06 was caused by long-range effects
  - Implementation of the new collision helix with increased separations at particular LR collision points gave improvement of the luminosity lifetime

- Currently, beam-beam effects at collisions are dominated by proton losses due to head-on interactions
  - Correction of $\beta^*$ chromaticity allowed high-luminosity operation without deterioration of lumi life time (10% at present luminosities)
  - Control of proton/antiproton emittance ratio was commissioned
  - Tune near half integer would allow 30% more luminosity but will not be implemented

- Beam-beam simulations correctly describe various effects and are used to support operational changes and improvements.
Acknowledgments