Tevatron Accelerator Physics and Operation Highlights

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Acknowledgments

- This report presents the results of work of many people at Fermilab’s Accelerator Division and Accelerator Physics Center.
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Outline

- Run II performance and improvements
- Highlights from the last two years of running
  - Operational improvements
  - Reliability and quench statistics
- Accelerator physics studies
  - Dancing bunches
  - Ghost modes
  - Beam-beam compensation
  - Crystal collimation
  - Hollow electron beam collimator
Aerial View of the Tevatron

- Linac
- Booster
- Debuncher/Accumulator
- Main Injector/Recycler
- CDF
- D0
- Protons
- Antiprotons

## Tevatron Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>0.98 TeV</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>36</td>
</tr>
<tr>
<td>Protons per bunch</td>
<td>$2.9 \times 10^{11}$</td>
</tr>
<tr>
<td>Antiproton per bunch</td>
<td>$0.9 \times 10^{11}$</td>
</tr>
<tr>
<td>Initial proton emittance (95% norm)</td>
<td>18 $\mu$m</td>
</tr>
<tr>
<td>Initial antiproton emittance (95% norm)</td>
<td>8 $\mu$m</td>
</tr>
<tr>
<td>Initial proton bunch length</td>
<td>0.55 m</td>
</tr>
<tr>
<td>Initial antiproton bunch length</td>
<td>0.45 m</td>
</tr>
<tr>
<td>$\beta$-function at IP</td>
<td>0.28 m</td>
</tr>
<tr>
<td>Betatron tunes ($Q_x, Q_y$)</td>
<td>20.583, 20.585</td>
</tr>
<tr>
<td>Initial luminosity</td>
<td>$4.03 \times 10^{32}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Luminosity lifetime</td>
<td>5 h</td>
</tr>
</tbody>
</table>
Tevatron Run II Integrated Luminosity

Integrated Luminosity 10512.46 (1/pb)

- 2007: 1.3 fb^{-1}
- 2008: 1.8 fb^{-1}
- 2009: 1.9 fb^{-1}
- 2010: 2.47 fb^{-1}
- 2011: 1.2 fb^{-1}

best week: 73 pb^{-1}, Apr 2009
best month: 273 pb^{-1}, Mar 2010
Initial Luminosity and pbar Accumulation Rate

**Peak Luminosity (1/microbarn/sec)**
- Max: 402.4
- Most Recent: 389.5

**Average Pbar Accumulation Rate**

Collider Fill Cycle for Store 2511 in 2003

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

Store 2511 $L_0 = 0.4 \times 10^{32}$
Collider Fill Cycle for the Record Store

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

Record Store 7747 $L_0=4 \times 10^{32}$
## Contributions to Luminosity Loss and (Some) Fixes

<table>
<thead>
<tr>
<th>Issue</th>
<th>Fix</th>
</tr>
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<tbody>
<tr>
<td>Proton lifetime at 150GeV: currently lose 5% protons and 1% antiprotons</td>
<td>Optimization of sextupoles</td>
</tr>
<tr>
<td></td>
<td>Machine impedance (Lambertsons)</td>
</tr>
<tr>
<td></td>
<td>Improved injection helix</td>
</tr>
<tr>
<td>Beam losses on ramp:</td>
<td>Better helix</td>
</tr>
<tr>
<td>now ~2%</td>
<td>Improved coupling (repaired all 800 dipoles)</td>
</tr>
<tr>
<td></td>
<td>Improved instrumentation</td>
</tr>
<tr>
<td>Beam losses in squeeze:</td>
<td>Better helix</td>
</tr>
<tr>
<td>now 2% protons and &lt;1% pbars</td>
<td>Collimation (2010)</td>
</tr>
<tr>
<td></td>
<td>Improved aperture</td>
</tr>
<tr>
<td>$\beta^*$ and beam separation</td>
<td>Better lattice modeling</td>
</tr>
<tr>
<td>Luminosity lifetime: dominated by luminous losses, IBS. Beam-beam ~5%</td>
<td>Better helix</td>
</tr>
<tr>
<td></td>
<td>New proton working point</td>
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<tr>
<td></td>
<td>Second order chromaticity</td>
</tr>
<tr>
<td>Reliability: in FY2010 averaged 120 store hours/week (71%)</td>
<td>cryo, controls, TEL, orbit stabilization, collimation, etc.</td>
</tr>
</tbody>
</table>
Highlights of the Last Two Years

- Recycler storage efficiency
- Proton scraping in Main Injector
- Quench statistics and Collimation in the squeeze
- Operations strategy
Recycler Ring (RR)

- 8 GeV antiproton storage ring located in the Main Injector (MI) tunnel

  - Accumulates antiprotons coming from the Accumulator and prepares the beam to be sent to the MI/Tevatron
    - Increases 6D phase density of antiprotons by a factor of 50
    - Permanent magnet-based
  - Every 40-50 min, $(15 - 25) \cdot 10^{10}$ antiprotons are transferred from Accumulator through MI in three parcels
    - Became possible with improved electron cooling and streamlined procedures
      - Initially: $(40-50) \cdot 10^{10}$ antiprotons every 75-90 min

Typical Recycler accumulation cycle

At $N_p \sim (350 - 500) \cdot 10^{10}$, antiprotons are transferred to MI for acceleration and injection into Tevatron

**Circumference**: 3310.4 m
**Momentum**: 8.889 GeV/c
**Vacuum**: $< 5 \cdot 10^{-10}$ Torr
**Life time**: up to 1000 hour
**Max. number of stored antiprotons**: $608 \times 10^{10}$
**Tunes (H/V)**: 25.464/24.468
Equipped with stochastic and electron cooling
Recycler Ring operation in 2009-2011

- The average life time improved to 200 - 400 h for \( N_p = (300-525) \times 10^{10} \)
  - Procedures, improved RF manipulations, improved vacuum
  - The average life time is determined primarily by losses right after injections
    - In steady state, >500 h at \( 500 \times 10^{10} \)
  - Typical 'storage efficiency' is ~ 93% (up 3-5%)
    - Includes losses due to transfers and the finite RR life time

- Brightness of the antiproton beam is limited by a transverse instability
  - The threshold depends on the longitudinal tails (See WEP114)

- Additional flexibility
  - Capability to extract only a portion of the beam into the same 36 bunches

Also see WEP113, WEP228

Average life time in RR vs the number of antiprotons in Aug 2010 – Feb 2011

Typical oscillogram of an instability in RR.

Courtesy L.Prost
Proton Scraping in MI

Momentum scraping of proton beam at injection in MI
3–4% increase of initial luminosity, better losses

Courtesy C. Gattuso
Quench Statistics

- Percentage
  - Ramp: 16
  - Squeeze: 41
  - Collisions: 68
- 32 quenches in squeeze were caused by beam dynamics related losses

- Total number of stores 1200 - one in 40 lost in squeeze, between Apr. 09-Mar.11 14 of 372 lost in squeeze - one in 30
- A quench during squeeze accounts for ~8pb⁻¹ - lost ~3% integral
  - Integrated doses lead to equipment failures at detectors
A single proton collimator + orbit control reduced losses. Since implementation in Dec. 2010 114 stores - no quenches in squeeze
Operations Strategy

- Model of collider operation
  - Antiproton transmission efficiencies
  - Stacking rate in Accumulator as function of stack size
  - Pbar lifetime in Recycler
  - Tevatron initial luminosity and luminosity decay
  - Shot setup time
Optimization of Store Duration

- The model was used to determine the optimal operating parameters to maximize luminosity integral
  - Emphasis on repeatability of stores
  - Model allows to work around exceptions: schedule accesses, studies to minimize impact
Accelerator Physics Studies

- Stable machine allows time for studies of accelerator physics
- There is strong interest from Fermilab, CERN, LARP, BNL to use Tevatron for beam physics studies
  - A workshop was held in 2010 to collect the list of topics
  - Currently a program is being generated
- Some experiments are in progress (were done) parasitically or using end-of-store dedicated time:
  - Dancing bunches
  - Ghost modes
  - Beam-beam compensation
  - Crystal collimation
  - Hollow electron beam collimator
Dancing Bunches

LLD threshold tune shifts

\[ F(I) \propto \sqrt{I_{\text{lim}} - I} \]

\[ F(I) \propto (I_{\text{lim}} - I)^2 \]

\[ F(I) \propto (I_{\text{lim}} - I)^2 \left[ 1 + \cos \left( \frac{8\pi I}{I_{\text{lim}}} \right) \right] \]

A. Burov talk MOODS4
experimental confirmation WEP116
“Ghost” Modes

- Ghost lines were present in the Shottky spectra since the early days of Run II
  - They are not stable in time, oscillating with period 15 min to hours
  - Move by as much as 0.02
  - Estimated effect on emittance growth is $0.06 \pi$ mm mrad/h
**Tevatron Electron Lenses**

- **e- beam energy**: < 10 kV
- **Peak e- current**: < 3 A
- **Solenoid B-field**: 30 kG
- **Gun B-field**: 3 kG
- **e- beam radius (SEFT)**: 2.3 mm
- **Interaction length**: 2 m
- **TEL-1 $\beta_x/\beta_y$**: 95/32 m
- **TEL-2 $\beta_x/\beta_y$**: 66/160 m

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Electron Lens for Beam-Beam Compensation

- With Gaussian profile electron beam overlapping with antiprotons, a number of studies were performed
  - Tune shift and tune spread measurements
  - Effect of misalignments
  - Tune scans to determine the effect of TEL on resonances
Collimation with Hollow Electron Lens

- Use hollow profile electron beam as slow diffuser to clean halo particles.

G. Stancari et al., MOP147

Kick $0.2 \, \mu\text{rad}$
Collimation with Hollow Electron Lens

- Hollow e- gun was designed, built and tested
- Installed in TEL-2 in 2010
- First experiments on collimation are successful: demonstrate scraping beam intensity without negative effect on luminosity!

Particle removal is detectable and smooth

- 2.5% /h
- 0.32% /h

-<i>4.5σ hole</i>
-<i>5σ hole</i>

-<i>-0.57% luminosity vs. -1.4% intensity</i>
-<i>&lt;0.05% luminosity vs. -0.39% intensity</i>

Halo scraping, small or no effect on core!
Collimation with Bent Crystals

- Deflect halo particles by a large angle using bent crystals
  - Repeated Volume Reflections in an array of parallel crystals results in larger deflection, e.g. at $E=1$ TeV:

One crystal $\theta_{VR} = 8 \mu$rad; $\theta_{bend} = 200 \mu$rad

8 crystals $\theta_{VR} = 8 \times 8 = 64 \mu$rad

Crystal produced by: IHEP

8 Crystal “Strips” separated by “groves”
Summary

- Numerous improvements in the Tevatron collider complex allowed stable operation at initial luminosities of $3.5\times10^{32}\text{ cm}^{-2}\text{s}^{-1}$
- The weekly integrated luminosity exceeded 70 pb$^{-1}$, average ~50 pb$^{-1}$
- For a 25 year-old machine, the Tevatron is exceptionally reliable averaging 110-120 hours of HEP time per week
- Recent operational improvements targeted mostly reliability and efficiency of operations and account for approx. 10-13% of luminosity
- Tevatron is a test bed for many accelerator physics experiments
  - Beam collimation
  - Beam-beam effects and their compensation
  - Beam dynamics
  - Instrumentation and optics