Tevatron Status

UTev Seminar
June 6, 2003

Mike Martens

Talk Outline

Introduction to luminosity and the Tevatron.

Recent performance of the Tevatron.

Tevatron physics issues.

Plans for the near future.
Luminosity

Rate = $\mathcal{L} \sigma_{\text{int}}$

$P_{\text{int}} = N_{\text{prot}} \sigma_{\text{int}} / A$

$\mathcal{L} = f_{\text{rev}} N_{\text{pbar}} N_{\text{prot}} / A$
Low Beta Lattice
Hourglass shape

\[ \beta_x = \beta_x^* + (s-s_0)^2/ \beta_x^* \]

\[ \sigma_x^2 = \varepsilon_x \cdot \beta_x(s) \]

For 20 \( \pi \) mm-mrad emittance, \( \sigma_x = 31 \mu\text{m} \, \text{(rms)}. \)
Luminosity Integral

\[ \mathcal{L} = 2 \int_{\text{rev}} \int \int \int \rho_1 \rho_2 \ dx \ dy \ dz \ d(\text{ct}) \]

\[ \rho(x,y,z,ct) = \frac{N_1}{\sqrt{2\pi} \sigma_x} \exp\left[- \frac{(x+\Delta x/2)^2}{2 \sigma_x^2}\right] \]

\[ \frac{1}{\sqrt{2\pi} \sigma_y} \exp\left[- \frac{(y+\Delta y/2)^2}{2 \sigma_y^2}\right] \]

\[ \frac{1}{\sqrt{2\pi} \sigma_z} \exp\left[- \frac{(z+ct-ct_0)^2}{2 \sigma_z^2}\right] \]

Hourglass shape: Cogging offset: Separated Orbits:
\[ \sigma_x^2 = \varepsilon_x * \beta_x(z) \] center of beams \[ \Delta x = z \tan(\theta_x) + \Delta x_0 \]
\[ \sigma_y^2 = \varepsilon_y * \beta_y(z) \] collide at \( z = ct_0/2 \) \[ \Delta y = z \tan(\theta_y) + \Delta y_0 \]
Luminosity Formula

\[ L = \frac{f_{\text{rev}} BN_p N_p}{2\pi \beta^* (\epsilon_1 + \epsilon_2)} \cdot F(\sigma_z / \beta^*, \theta_x, \theta_y) \]

Major limitations:
- \( N_p / \epsilon_1 \) = Protons beam brightness
  (Beam-beam tune shift.)
- \( BN_p \) = Total number of antiprotons
  (Stacking rate.)

\( \beta^* = 35 \text{ cm is fixed by lattice.} \)
\( \epsilon \approx 20\pi \text{ mm-mrad (95\%, normalized).} \)
\( \sigma_z = \text{Bunch length.} \)
\( B = \text{Number of bunches.} \)
\( \theta_x, \theta_y = \text{Crossing angles (during 132 nsec operations.)} \)

\( F = \text{Form factor} \leq 1 \text{ for } 36 \times 36 \)
\( = \sim 0.5 \text{ for } 132 \text{ nsec.} \)
Factors in the luminosity integral:

- **Beam Intensities**
  \[ N_{\text{prot}}, N_{\text{pbar}} \]

- **Beam Emittances**
  \[ \varepsilon_x, \varepsilon_y, \sigma_z, \sigma_{\Delta p/\rho} \text{ (Proton)} \]
  \[ \varepsilon_x, \varepsilon_y, \sigma_z, \sigma_{\Delta p/\rho} \text{ (Pbar)} \]

- **Lattice Functions**
  \[ \beta^*_x, \alpha^*_x, \eta^*_x, \eta'_x \]
  \[ \beta^*_y, \alpha^*_y, \eta^*_y, \eta'_y \]

- **Separated orbits**
  \[ \Delta_x, \theta_x, \Delta_y, \theta_y \]

- **Cogging offset, revolution frequency**
  \[ ct_0, \text{frev} \]

24 factors in the luminosity integral!
Run II Bunch Configuration

36 x 36 configuration
396 nsec bunch spacing
3 x 12 proton bunches
3 x 12 pbar bunches
Beam-beam tune shifts

Tune shift becomes too large with more than 2 head-on collisions.

Solution is electrostatic separators.

Tune Shift of a pbar bunch from 2 head on collisions
Electrostatic separators are used to separate the proton and pbar orbits transversely except at the IPs where the protons and pbars collide head-on.
Tevatron Efficiencies

- **Open helix**
- **ramp**
- **proton injections**
- **poor lifetimes**
- $\approx 10\%$ bunched beam loss in ramp and squeeze
- **pbar injections**
Luminosity Since June 2002

- 225 HEP stores
- 212 pb\(^{-1}\) to each detector
- Increase in luminosity from 15e30 to 40.5e30
- Run I record of 25.0e30 broken on 7/26/2002
- Run II record of 44.8e30 set on 5/17/2003
Beam Intensities

**Number of protons**
Mostly steady
in the 200e9 range ⇒ 250e9 max

**Number of antiprotons**
Increase factor of 2.5 Oct ⇒ March
from 9e9 ⇒ 25e9 per bunch
Tevatron Emittance

General comments on emittance blow-up from Flying Wire measurement**
(95%, normalized emittances):

• $< 1\pi - 2\pi$ at proton injection
• $\sim 5\pi - 6\pi$ at pbar injection
• $< \text{(negative) } 2\pi - 3\pi$ protons at 150 (scraping)
• $\sim \text{(negative) } 0\pi - 3\pi$ pbars at 150 (scraping)
• $4\pi - 7\pi$ blowup on ramp (prots and pbars)
• occasional instability, $5\pi - 50\pi$, at 980 Gev

** There remains uncertainty of FW emittance measurements. (See later slides)
Reasons for $L$-progress Since Jun’02

- “Shot lattice” $\times 1.40$
- $P$-bar emittance at injection $\times 1.20$
- $P$-bar coalescing improvement $\times 1.15$
- Shoot from larger stacks $\times 1.10$
- Improved Tev $P$-bar efficiency $\times 1.10$
- More Protons at Low Beta $\times 1.10$

\[ \text{total } \times 3.3 \]

...plus additional improvements in the Tevatron:

- Tunes/coupling/chromaticities at 150/ramp/LB
- Orbit smoothing
- Longitudinal dampers to stop $\sigma_s$ blowup
- Transverse dampers improves 150 Gev lifetime
- F11 vacuum
# Goals and Current Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current Status</th>
<th>Record Store</th>
<th>FY03 Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Luminosity</td>
<td>3.5e31</td>
<td>4.5e31</td>
<td>6.6e31 cm⁻²sec⁻¹</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td>6.0</td>
<td>12.0</td>
<td>pb⁻¹/week</td>
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<tr>
<td>Protons/bunch</td>
<td>200e9</td>
<td>240e9</td>
<td>240e9</td>
</tr>
<tr>
<td>Antiprotons/bunch</td>
<td>22e9</td>
<td>25e9</td>
<td>31e9</td>
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Higher intensity ⇒ Fundamental physics limitations
- Beam-Beam Effects
- Instabilities
- Beam Halo and Lifetimes

Understanding/Solving these issues requires ...
- Stable Tevatron Lattice
- Diagnostics
- Study Time
Integrated Luminosity FY 2003

150 pb$^{-1}$ to each detector

Record integrated luminosity 9.1pb$^{-1}$/week
Beam-beam Interaction As Major Factor

• *P*bar transfer efficiency strongly depends on *N*_p, helix separation, orbits, tunes, coupling, chromaticity and beam emittances at injection

• Summary of progress with beam-beam since March 2002:

<table>
<thead>
<tr>
<th></th>
<th>Mar’02 *</th>
<th>Oct’02 **</th>
<th>Jan’03 ***</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Protons/bunch</strong></td>
<td>140e9</td>
<td>170e9</td>
<td>180e9</td>
</tr>
<tr>
<td><strong>Pbar loss at 150 GeV</strong></td>
<td>20%</td>
<td>9%</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Pbar loss on ramp</strong></td>
<td>14%</td>
<td>8%</td>
<td>12%</td>
</tr>
<tr>
<td><strong>Pbar loss in squeeze</strong></td>
<td>22%</td>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td><strong>Tev efficiency Inj → low beta</strong></td>
<td>54%</td>
<td>75%</td>
<td>75%</td>
</tr>
<tr>
<td><strong>Efficiency AA → low beta</strong></td>
<td>32%</td>
<td>60%</td>
<td>62%</td>
</tr>
</tbody>
</table>

* average in stores #1120-1128
** average in stores #1832-1845
*** average in stores #2114-2153 (9 stores)
Beam-beam Effects: Pbar Only

Antiproton Only Store: 1% loss on ramp, \( \tau_{150} = 20 \) hrs, \( \tau_{980} = 160 \) hrs

8% loss on ramp – DC beam (depends on MI tuneup)
Attacking the Beam-beam Effects

- Smaller emittances from AA ("AA shot lattice")
- Reduced injection errors
  - Beam Line Tuner
- Better control of orbits / tunes / coupling
  - Tunes up the ramp
  - Tune and coupling drift at 150 Gev
  - Orbit smoothing
- Larger injection helix
  - CO Lambertson replacement
  - New Separator settings
Lifetime of 12 pbar bunches: A1-A4 are injected first with emittances of 32 \( \pi \text{ mm mrad} \) – lifetime is 0.95 hr \( \rightarrow \) 2.4 hrs; the second set of bunches A13-16 with emittance of 12\( \pi \) had 4 hours lifetime; and the 3\(^{rd}\) train A25-28 with emittances of about 18 \( \pi \text{ mm mrad} \) had some 3.2 hr lifetime.
Antiproton Lifetime at 150 Gev

Pbar losses depend strongly on pbar emittances and N_p

Proton Beam as “Soft Donut Collimator”

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Injection Oscillations in Tevatron

- Turn-by-turn position monitor, (and bunch-by-bunch for pbar)
- Use to tune up injection closure
- 1 mm corresponds to roughly $3-4\pi$ emittance blowup
- Improved Pbar emittance blowup by $\sim3-5\pi$
Tune/coupling/chromaticity/orbits

• Tune up is essential for consistent operations ...
  - Much effort during “Studies Periods” is actually maintenance (orbit smoothing and tune/coupling/chromaticity adjustments)

• ... and for understanding more complicated physics
  - Beam-beam effects, instabilities and dampers, beam lifetimes, beam halo rates, etc. are more difficult to understand when machine parameters drifting.

• Some troubles:
  - Tune/coupling drifts at 150 Gev. (Now compensated.)
  - Tune/coupling snapback on the ramp. (Now compensated.)
  - Chromaticity snapback? (Was measured. Is OK.)
  - Orbit drifts. (Started BPM and smoothing improvements)
Tune Drift @ 150 Gev

- Horizontal without compensation.
- Vertical without compensation.
- Horizontal with compensation.
- Vertical with compensation.
Coupling Drift @ 150 Gev

Measured min tune split
7/10/02 (after dry squeeze)

\[ y = 0.0061 \ln(x) - 0.0094 \]

Minutes at 150 Gev
Tune Variations on Ramp/squeeze

- Near start of ramp (150 → 153 Gev): large tune/coupling excursions
- Tune/coupling changes of (0.02 tune units, 0.02 minimum tune split)
- Variations fixed with additional breakpoint at 153 Gev and tune/coupling snapback correction at start of ramp.
Chromaticity Snapback Measurements

Measured $b_2$ in the Tevatron dipoles at start of the ramp after 20 minute front porch

M. Martens, J. Annala, P. Bauer

- Measured $b_2$ without snapback
- Estimated $b_2$

Graph showing measured $b_2$ and estimated $b_2$ over time.
Chromaticity Snapback Compensation

Comparison of measured and applied snapback for 20 min and 120 min front porch

M. Martens, J. Annala, P. Bauer

$\mathbf{b_2}$ snapback is correctly compensated (for shot setup conditions.)
Orbit Drifts

“orbit – reference” at low beta after about 2 weeks in September’02

Orbit drifts vary with closed orbits distortions

“Rule of thumb” -- keep orbit drifts under 0.5 mm rms from “silver orbit”

Orbit drifts of that scale occur in 1-2 weeks (see picture)

Requires routine orbit smoothing at 150 Gev, ramp, flat-top, squeeze, and low-beta.
Motion of Tevatron Dipole

Newly added a tiltmeter to a Tevatron dipole.

Observed 10 urad roll after a quench.

Still watching!!

Larger rolls on other dipoles?

Long term drifts?

Roll of E35-1 dipole after a Tevatron quench.

1 day
**Helix Improvement**

Increasing proton/pbar helix separation

- Replace CO Lambertson with MI magnets
- Increase vertical aperture at CO from ~15mm -> 40 mm (but only ~30% larger helix due to other aperture limitations.)
- Modify helix to increase min separation, $S_{\text{min}}$, from 5.5 to 6.6

\[
S = \sqrt{\left(\frac{\Delta x}{\sigma_x}\right)^2 + \left(\frac{\Delta y}{\sigma_y}\right)^2}
\]
Pbar lifetime depends on emittances and helix size.

CO Lambertson is severest aperture restriction. (See picture)

Design injection helix modified and optimized to fit tight CO aperture ("new-new helix")

(Jan 2003)
Replace CO Lambertsons
Gain 25 mm vertically
Beam-beam Tune Shift Reduction

Proposed injection helix (with larger C0 aperture) will reduce small amplitude tune shift of pbars
Proton Lifetime Issues at 150 Gev

• Poor proton lifetime on helix ~ 2 hr
  - depends on chromaticity
  - Instability prevents lower chromaticity (now 8)
  - Orbits/size of helix affect lifetime
  - Tunes/coupling are a factor
• Lower chromaticity is better for lifetime

• Instabilities appear $\xi < 3-4$

• Run with $\xi_H = 8$, $\xi_V = 8$ to avoid instabilities

• Dampers allow us to lower chromaticity and improve lifetime
Unstable Head-tail Motion

Developing head-tail instability with monopole configuration
Beam is unstable for $\xi_x \approx 6, \xi_y \approx -3$
Longitudinal and transverse dampers OFF
$N_p = 260E9$

$N \approx 2.6 \cdot 10^{11}, \xi_x \approx 6, \xi_y \approx -3, [\nu_x] = 0.5857, [\nu_y] = 0.5725$
Transverse Instability

- Beam remnants point to coherent betatron mode with $l=2$

$$N_{ppb} = 2.6 \cdot 10^{11} \text{(init. beam)} \quad \Rightarrow \quad N_{ppb} = 1.03 \cdot 10^{11} \text{(remain. beam)}$$

P. Ivanov, A. Burov
Unstable Head-tail Motion

Observed transverse oscillation for stable conditions
Beam is stable for $\xi_x \approx 8, \xi_y \approx 8$
Longitudinal and transverse dampers OFF
$N_p = 260E9$

$$ N \approx 2.6 \cdot 10^{11}, \xi_x \approx 8, \xi_y \approx 2, \left[ \nu_x \right] = 0.5850, \left[ \nu_y \right] = 0.5736 $$
TeV Transverse Damper

To 5kW Injection Damper Power Amps

Auto Zero

$\Delta$

Notch Filter

VCO

Gain Control

1.9 MHz

1.9 MHz

From pbar damper signal

Gain Control
Longitudinal Impedance – “Dancing Bunches”

- Beam in 30 buckets
- 100 Tevatron turns (~2 ms) between traces
- Synch freq ~ 85 Hz
- Oscillation amplitude depends on bunch, changes slowly with time (minutes at 150 GeV, seconds at 980 GeV)
- Model needs inductive impedance $Z/n \approx 2$ Ohm interplaying with cavity impedance
- Coalesced bunches have dancing bumps
TeV Longitudinal Damper Block

VCO

90° Delay

Beam In

100 MHz

Gain Control

Cavity Compensation

1.5 MHz

To Fanout

Phase Shifter

Q

I

30 MHz

Digital Delay

1 turn

53 turns

Digital Delay

1.5 MHz

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Bunch Length Blowup During Stores

- Intensity-dependent, leads to significant CDF background rise
- Usually only one or a few bunches would suffer
- Problem solved by bunch-by-bunch longitudinal damper
Diagnostics Progress: SyncLite Monitor

- Works >800 GeV
- Significant progress since March’02
- Reports rms, mean, N, tilt bunch-by-bunch for both protons and pbars
- Invaluable instrument

Values averaged over 10 mins from 18:33:51 10-4-2002

H.Cheung
Diagnostics: Flying Wires

• Proton channels tuned up in March
• Still some (15%?) calibration needed
• Pbar channels data are subject of correction
• “Jumping” emittances
• (improper dP/P?)
• Recalibration of both p and pbar channels is due
• Need raw data
Tev Scraping Studies

Vertical prot emittance measurement (95%, normalized)

Use scrapers to measure emittance. Then compare to FW and Sync. Lite

Scraping: 24-27 \( \pi \)
Flying Wire: 30 \( \pi \)
Sync. Lite: 34 \( \pi \)

Intensity versus collimator position assuming Gaussian beam (1D scraping):

\[
N = N_0 \left( 1 - e^{-\frac{(x-x_0)^2}{2\sigma^2}} \right)
\]

Need to know \( \beta \) function at monitors!
Tev Scraping Studies

Horizontal proton

Scraping: $31-33 \pi$
Flying Wire: $22-28 \pi$
Sync. Lite: $34 \pi$

Dispersion is an issue !!!

Vertical pbar

Scraping: $20-24 \pi$
Flying Wire: $42 \pi$
Sync. Lite: $44 \pi$
Progress on Tevatron Physics Issues

- Lattice Measurements
- FO Lambertson major impedance source
- Smart bolts and coupling
- 1st indication of Beam-beam comp. (TEL)
- Dancing bunches analyzed
- New 1.5 GHz Schottky tune detector
- SBD/FBI calibration
- Work on the new helix
- Octupole studies to improve beam stability
Beam-beam Effects at 980 Gev

- Pbar bunches near abort gaps have better emittances and live longer
- Emittances of other bunches are being blown up to 40% over the first 2 hours – see scallops over the bunch trains
- The effect is (and should be) tune dependent - see on the right
- Recently, serious effects of pbars on protons – completely unexpected
Beam-beam Tune Shift Measurement

- Measured and predicted pbar tune shift as function of bunch number at collisions.
- Used gated “tickler” to excite individual pbar bunches and measured tunes with schottky pickup
Working Point Tune Scans

Measured pbar halo loss rate during collisions as function of pbar tunes
Goals for near future

• Deliver 200 - 300 pb\(^{-1}\) to each detector by end October 2003

• Steadier running (less studies)

• Reach peak luminosities of 45-50e30 be end of summer.

• 5-10% more protons
  - From MI, better in Tev

• 5-10% more pbars
  - Larger stacks
  - New helix

• 5-10% smaller emittances
  - Scallops tuned
  - Injection matching
  - Dampers
Tevatron Beam Physics Issues

- New helix
- MI -> Tev injection mismatch
- Octupoles or dampers on the ramp
- Beam-beam studies and compensation
- Tevatron BPMs, orbit smoothing
- Tevatron alignment (smart bolts and rolls)
- Lattice measurements