High Luminosity Operation, Beam-Beam Effects and Their Compensation in Tevatron

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(Thanks to C. Gattuso, K. Gollwitzer, V. Kamerdzhiev, R. Moore, V. Papadimitriou, W. Pellico, A. Valishev)

Fermi National Accelerator Laboratory
Accelerator Physics Center
Tevatron complex: 10 accelerators

**120 GeV Main Injector:**
- rapid cycling
- high intensity
- proton synchrotron
- 2 sec period

**8 GeV Booster**
- proton synchrotron
- 15 Hz

**400 MeV Linac**

**8 GeV Recycler Ring:**
- high quality
- storage ring
- stochastic cooling
- electron cooling
- 12-24 hours cycle

**8 GeV Accumulator:**
- high quality
- storage ring
- stochastic cooling
- ~4 hours cycle

**8 GeV Debuncher:**
- large aperture
- synchrotron
- 2 seconds cycle

**Li Lens**

**Target**

**Tevatron Collider**
- CM energy of 1.96 TeV
- 36x36 bunches
- Collision rate ~ 2 MHz

**In operation since:**
- Tevatron: 1983
- Pbar Source: 1985
- Main Injector: 1999
- Electron lenses: 2001
- Recycler: 2004
- Electron cooler: 2005

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Global View

- FNAL Accelerator Complex works in parallel for:
  - Tevatron Collider Run II (CDF and D0 experiments)
  - Neutrino program (8 GeV and 120 GeV protons on target)

- Collider Run II will definitely run thru FY09 (09/30/09)
  - FY2010 Run is very probable but not approved yet

- After the end of the Tevatron Collider Run II:
  - Tevatron to be decommiss’ed and conserved (kept at LN temp)
  - Neutrino experiments will continue (350kW → 700kW @ 120 GeV)
  - New experiments to start (e.g., NoVA, μ2e, etc)

- Fermilab’s next big thing - “Project X”
  - High Intensity 1.3 GHz SC RF 8 GeV proton linac
  - The linac, Recycler and Main Injector to be employed for
    8 GeV and 120 GeV fixed target experiments (ν’s, K’s, μ’s)
  - Construction to start in ~2012
Tevatron Luminosity

Maximum Initial Luminosity Achieved:

\[ \pi \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} \]

- This is record high luminosity for hadron colliders
- This is above Run II Upgrade goal of 2.9e32
- This allows us to integrate luminosity fast
Tevatron Peak Luminosity

- Luminosity Record
- Weekly Integral

Run II Upgrade Goal

Run IIa Goal
Tevatron Peak Luminosity

Record Initial Luminosity ($10^{31}$ cm$^{-2}$s$^{-1}$)

Record month May 2008 = 221 pb$^{-1}$
Record weekly delivered luminosity = 56.1 pb$^{-1}$

Weekly Luminosity Integral (pb$^{-1}$)

Run II Upgrade Goal

Run IIa Goal
Very Good Progress Since 2007

- No big upgrades, progress is due to operational tune-ups
- Still, we've got (compared to Summer 2007)
  - +8% in max peak luminosity (2.92e32 → 3.15e32)
  - +24% in max weekly luminosity (45 pb-1 → 56 pb-1)
  - +25% in avg weekly lumi (32pb-1 → 40 pb-1 in 2008)
  - +17% in peak pbar production rate (23e10/hr → 27e10/hr)
  - +14% in average pbar production (19.3e10/hr → 22.1e10/hr)

- Why:
  - Optimization of pbar stoch.cooling systems in Debuncher & AA
  - Faster pbar transfers from Accum to Recycler (30 → 2 min)
  - New RR WP → lifetime and mining efficiency
  - New MI collimators and faster Booster m-pole correctors
  - Shot set up time 2 hr 45 min → 1 hr 45 min
  - Tevatron optics tune up ($\beta^*$, $D^*$) and orbit stabilization
  - A lot of attention to (preventive) maintenance and uptime
Collider Natural Predators: *Dreissena polymorpha*

**Zebra mussels**

January 2000

[Zebra Mussel Distribution](http://has.er.usgs.gov/images/currzm00.gif)
Collider Natural Predators: *Dreissena polymorpha*

**Zebra mussels**

Main injector heat exchanger pipe clogged by mussels

[Zebra Mussel Distribution Map](http://has.energos.gov/images/czrzm00.gif)
Collider Natural Predators: Weather

01:20 CDT 05/26/08
06:20 UTC 05/26/08

Max reflectivity 60 dBZ
Vol. cov. pattern 21

5 dBZ
10
15
20
25
30
35
40
45
50
55
60
65
70
75

La Crosse
Madison
Milwaukee
Quad Cities

wunderground.com
Collider Natural Predators: Weather

01:20 CDT 05/26/08
05/26/08

06:20 UTC
05/26/08

Max reflectivity 60 dBZ
Vol. cov. pattern 21

5 dBZ

LIGHT
10
15
20
25

MODERATE
30
35
40
45

HEAVY
50
55
60
65

EXTREME
70
75

La Crosse

Wausau

Green Bay

Manistee

48 mi
64 km
Collider Natural Predators: Complexity

Pbar collection 10 mm Li lens stripline failure early March
Collider Natural Predators: Complexity

Pbar collection 10 mm stripline failure early M

Tevatron D33 dipole magnet lost insulating vacuum & frosted
Collision Time → 100 Hours a Week

FY Average Store Hours per week 97.88

- FY Average Store Hours per week
- 10X Average Store Hours per week
Planning Ahead: get to 60-70 pb-1/wk

- Commission of individual band equalizers in the pbar stochastic cooling systems of the Debuncher and the Accumulator rings
- Increase of the proton beam brightness by scraping 8 GeV protons in the Main Injector by recently installed collimators
- Complete installation of fast corrector magnets in the Booster together with commissioning of transverse and longitudinal dampers to keep beam stable while crossing transition energy
- Optimize further the operation strategy - e.g. Recycler antiproton stash size for the Tevatron shots, the store length, etc
- Better proton optics matching during injection in the Tevatron
- Faster loading of protons into the Tevatron by injecting them in batches (of 2)
- Make the beam-beam compensation (BBC) by the Tevatron Electron Lenses (TEL) operational
Beam-beam interactions affect beams at all stages resulting in 20-30% reduction of luminosity integral:
  - Pbar loss of ~2% at 150 GeV and 2% ramp and low-beta squeeze
  - Proton loss of ~5% at 150 and ~5% in ramp and squeeze
  - Luminosity decays 5-15% faster (mostly due to p-loss)

The effect in collisions is a mix of long-range and head-on
  - Record high beam-beam parameter $\xi(2 \text{ IPs}) \sim 0.024$
  - $\xi$ is about the same for protons and antiprotons
  - Extreme sensitivity to many things:
    - Tunes, optics, chromaticities, coupling
    - Bunch intensities, emittances, ratio of p/a emittances, (dp/p)

Very good understanding of the effects
  - Sophisticated Data Analysis
  - Trusted Numerical Tracking tools
  - Please come to Sasha Valishev's talk Thur. morning THYM01
Synopsis: Beam-Beam Tune Footprint

protons

antiprotons
Head-On Beam-Beam Collisions

max. tuneshift
$2\xi_p = 0.018 - 0.022$

protons

rms beam size
28 microns

max. tuneshift
$2\xi_a = 0.020 - 0.026$

anti-protons

rms beam size
16 microns

emittance ratio $(\varepsilon_p/\varepsilon_a) \sim 3$
Tune Distributions are Very Different

- Equal emittances $\epsilon_p = \epsilon_a$
- Antiprotons $\epsilon_p = 3 \times \epsilon_a$
- Protons $\epsilon_p = 3 \times \epsilon_a$

$dN/d(\Delta v/\xi)$ vs Tune shift ($\Delta v/\xi$)
Very High Proton Losses Early in Stores

Compare with total luminosity
Loss rate of ~16-20%/hr

Proton loss rate [%/hour]

Factor $N_a (e_p/e_a) [10^9]$
Very High Proton Losses Early in Stores

Compare with total luminosity
Loss rate of ~16-20%/hr

Intentional antiproton emittance blowup by 30-40% to reduce emm ratio (4→2.6) & p-loss
Losses due to beam-beam interactions

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

**Protons 980 GeV:**
\[ \xi_{\text{max}} = + (0.016 - 0.024) \]
Beam-Beam Compensation with Tevatron Electron Lenses
What is Electron Lens?

~4 mm dia 2 m long very straight beam of ~10kV
~1A electrons (~10^{12}) immersed in 3T solenoid
What is Electron Lens?

~4 mm dia 2 m long very straight beam of ~10 kV
~1A electrons (~10^{12}) immersed in...

generates strong radial electric field E ~ 0.3 MV/m
TEL Electron Beam

Thermionic gun
**TEL e-beam aligned and timed on protons**

**in space**

- TEL-2 Electron Beam
- Proton Beam $1\sigma, 2\sigma, 3\sigma$
- Antiproton Beam $1\sigma, 2\sigma, 3\sigma$

**in time**

- TEL
- P12
- A24
- P9, P10, P11

*Transverse e-p alignment* is very important for minimization of noise effects and optimization of positive effects due to e-beam. *Timing* is important to keep protons on flat top of e-pulse – to minimize noise and maximize tune shift.
TEL2 on one bunch P12

bunch 24
\[ \tau_{24} = 8.66 \pm 0.1 \text{ hr} \]

bunch 12
\[ \tau_{12} = 8.75 \pm 0.1 \text{ hr} \]
\[ \tau_{12} = 17.4 \pm 0.1 \text{ hr} \]

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TEL2 on one bunch P12

bunch 24
$\tau_{24} = 8.66 \pm 0.1$ hr

bunch 12
$\tau_{12} = 8.75 \pm 0.1$ hr

When TEL off: bunches #12 and #24 have same lifetime of 8.7 hrs = 11% hr loss

Proton bunch intensity ($10^9$)

Time in collisions (min)

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When TEL on:

bunch #12 lifetime is $\approx 2 \times$ #24 lifetime:
17.4 hrs vs 10.0 hr

When TEL off:
bunches #12 and #24 have same lifetime of 8.7 hrs/hr loss

$\tau_{12} = 10.0 \pm 0.1$ hr

$\tau_{24} = 8.66 \pm 0.1$ hr

Proton bunch intensity ($10^9$)
TEL2 acts on all bunches (DC)

Bunches are not equal!

TEL2 moves $Q_v$ up

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

Normalized Beam Intensity

TEL = ON
TEL = OFF

Time (h)
Electron Lenses: Tevatron and Beyond

- Tevatron Electron Lenses act on proton bunches and **DOUBLE** the beam intensity lifetime
  - TEL1 (hor) improvement is big, too ~40%
  - Improves luminosity lifetime, too, by ~(5-11)%
  - Most effective in the 1st ~10 hrs of store
  - Awaits introduction in operation
    (= development of multibunch pulser - see poster THPP058)

- Electron lens technique is capable of much more:
  - Head-on compensation, eg. in LHC and RHIC
  - EM collimation by hollow electron beams, also in the LHC
  - Compensation of space-charge forces in proton synchrotrons and linacs
2.4 A DC lens with Gaussian current profile shrinks LHC footprint (LHC Upgrade simulations – U.Dorda, V.Shiltsev, et al)

**TEL off, LRBBWire off** ➔ **TEL on, LRBBWire on**
Can Gaussian Distribution be generated?

Supported by US-LARP

Gaussian electron gun
0.4” cathode

Current density
distribution

\[ \begin{align*}
U_{\text{cath}} &= -5\text{kV} \\
U_{\text{ce}} &= -5\text{kV} \\
U_{\text{anode}} &= -5.4\text{kV}, \text{Gnd} \\
B_{\text{gun}} &= 1.5\text{KG} \\
B_{\text{main}} &= 2\text{KG} \\
B_{\text{col}} &= 1.5\text{KG} \\
F &= 200\text{Hz} \\
PW &= 4\mu\text{s}
\end{align*} \]

V. Kamerdzhiiev, et al

THPP 058
Effect of E-Lens at $\xi=0.0075$

A. Valishev

LIFETRAC eLens simulations for LHC $\xi=0.0075/IP$
Effect of E-Lens at $\xi=0.0075$

LIFETRAC eLens simulations for LHC $\xi=0.0075/IP$
Effect of E-Lens on Beam Lifetime

LIFETRAC eLens simulations for LHC (A. Valishev)
Hollow e-beam collimation (MOPC098)

10 A in hollow e-beam – driven at the betatron frequency
Hollow beam system - like TEL
Hollow beam system - like TEL
Good Efficiency in Tevatron Model

A. Drozhdin
Advantages of Hollow e-beam Colimator

LHC Collimation system:
(i) Does not work for ions (breaks them)
(ii) cannot handle large currents (power jaw)
(iii) needs sophisticated jaw damage diagnostics
(iv) transverse impedance of collimators is a big issue for upgrade
(v) intrinsically spiky losses (beam jitter, etc)
Advantages of Hollow e-beam Colimator

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Hollow e-beam collimators address ALL these issues!
Finally, e-Column for SCC

Very much like TEL - but no electron gun!
E Columns for SCC

Net force
$E - \beta B = E/\gamma^2$

adding $1/\gamma^2$ e-
E Columns for SCC

Yu. Alexahin
V. Kapin

\[
\frac{N}{N_0}
\]

\[
\varepsilon_x/\varepsilon_0, \varepsilon_y/\varepsilon_0
\]

\[f = 0\]

\[f = 0.5\]
Summary

Long way ahead from Tevatron to LHC:

\[ \pi \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \]

\[ \Pi = \pi \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]

... and experience and methods - like Electron Lenses - must be fully utilized!