

Tevatron Accelerator: Methods and Techniques Applicable for Future Accelerators

Valeri Lebedev Fermilab

APS meeting August 2011 Providence, Rhode Island

Short History of the Tevatron

- 1967 Fermilab was founded as NAL (National Acc.Lab); FNAL since 1974
- Pre-Tevatron era of Fermilab
 - 1971 Booster achieves 8 GeV
 - 1972 Main Ring achieves 200 GeV & 500 GeV in 1975
 - 1977 b-quark discovery
 - Tevatron
 - 1972 Study of SC magnets
 - 1974 official start of 1000 GeV accelerator study (Energy Saver/Doubler)
 - 1983 500 GeV achieved
 - 1983-2000 eight fixed target Runs (400 -> 800 GeV)
 - Tevatron collider
 - Collisions were anticipated from the very beginning
 - 1977 publication by Wilson in Physics Today
 - 1982 Tevatron collider scheme is established
 - ♦ 1982-1985 Antiproton source construction
 - 1985 Installation low β quads and first collisions in CDF col. point

Short History of the Tevatron (continue)

- Tevatron collider Runs
 - ◆ First data taking: Jun. 1988-Jun.1989, JLdt=0.005 fb⁻¹ to CDF, 0.9 TeV
 - ♦ Run I: Aug.1992-Feb.1996, JLdt=0.18 fb⁻¹ to CDF & D0, 0.9 TeV
 - ♦ Run II: Mar.2001-Oct.2011, JLdt=11.5+0.5 = 12 fb⁻¹(67×Run I), 0.98 TeV



Luminosity Progress in the Course of Run II

- Tevatron was comparatively mature machine at the Run II beginning
 - 10% of design luminosity (35.10³⁰) achieved in 1.5 years
 - LHC, new machine 10% of design L_{peak} achieved in ~1.5+1 years
 Luminosity integral grows slower due to reliability
 - Exponential luminosity growth during 8 years of commissioning
 - Doubling time 17 months
 - 2007-2009 same L_{peak} but higher $dN_{\overline{p}} / dt$ and better reliability



<u>Tevatron - P – P Collider Operating at 980 GeV</u>



"Tevatron Accelerator Methods and Techniques Applic

Major Developments in Accelerator Physics/Technology

- SC magnets
 - Tevatron -> LHC IP quads -> IP quads for the LHC upgrade
- Linear optics
 - High accuracy optics with accounting of strong coupling in Tevatron
 - Optics redesign based on real elements and optimal ring use
- Stochastic cooling
 - Quantitative description of cooling
 - Correction of transfer function with equalizers
- Electron cooling
 - High voltage cooler, 4.3 MeV an order of magnitude higher than other
 - First weakly magnetized cooling + Strongly coupled beam transport
- Beam instabilities
 - Impedances of thin wall chambers and laminated chambers
 - Beam instabilities with space charger
- Intrabeam scattering
 - Coupling; Common description of single and multiple scattering
- Luminosity evolution model and Beam-beam effects
 - Tracking, effect of second order chromaticity

Coupling between two or more Degrees of Freedom

Extension of Mais-Ripken representation is used

$$\mathbf{x} = \operatorname{Re}\left(\sqrt{2I_1}\,\mathbf{v}_1 e^{-i\mu_1} + \sqrt{2I_2}\,\mathbf{v}_2 e^{-i\mu_2}\right)$$

- Amplitudes are $A_{kx,ky} = \sqrt{2I_k \beta_{kx,ky}}$
- v_{1,2} characterize the phase
 shift between x & y
- *u* is the coupling parameter
 - u=0.5 100% coupling
- The mode emittances, $\varepsilon_{1,2} = 2\langle I_{1,2} \rangle$, are invariants of motion
- Same as for uncoupled motion
 - Shape of 4D phase space ellipsoid uniquely determines the eigenvectors and Twiss parameters
- There are 4 parameters which characterize the coupling
 - ◆ Tune split is frequently used but zero tune split ≠ zero coupling



-0.5

0

0.5

Х

 $i(1-u)+\alpha_{1x}$

 $iu + \alpha_{1y} e^{iv_1}$

"Tevatron Accelerator Methods and Techniques Applicable for Future Accelerators", Valeri Lebedev, APS meeting, August 2011

 $iu + \alpha_{2x} a^{iv_2}$

 $i(1-u)+\alpha_{2y}$

 $v_2 =$

X-Y coupling in Tevatron

- At the Run II beginning Tevatron had very large coupling
 - uncompensated tune split ~0.4
- The reason was a displacement of SC coils in dipoles relative to the steel core due to compression of thermo-isolating coil supports by ~150 µm



Tevatron dipole cross section

• It makes the skew-quad field in dipoles of $G_{sa}/B_{0}\sim1.4\cdot10^{-4}$ for a=2.54 cm



$$\frac{j_s(\phi)}{j_{s0}} \approx \frac{\Delta y}{2r_{coil}} \sin(2\phi)$$
Coil near steel \Rightarrow

 $G_{s} \approx B_{0} \frac{\Delta y}{2r_{coil}^{2}}$



X-Y coupling in Tevatron (continue)

- The problem was exacerbated by a partial removal of main family skew-quads in vicinity of the IPs which made long sections without coupling (112 dipoles without nearby skew-quad)
- The coupling was corrected by shimming dipoles which did not have nearby skew-quads in the summer 2003 shutdown
 - It reduced the emittance growth at transfers

$$\mathcal{E}_{1} = \mathcal{E}_{1}A_{11} + \mathcal{E}_{2}A_{12} \qquad A_{11} = \frac{1}{2} \left(\frac{\beta_{x}}{\beta_{1x}} \left[(1-u)^{2} + \alpha_{1x}^{2} \right] + \frac{\beta_{1x}}{\beta_{x}} \left[1 + \alpha_{x}^{2} \right] - 2\alpha_{1x}\alpha_{x} \right), \quad A_{12} = \frac{1}{2} \left(\frac{\beta_{y}}{\beta_{1y}} \left[u^{2} + \alpha_{1y}^{2} \right] + \frac{\beta_{1y}}{\beta_{y}} \left[1 + \alpha_{y}^{2} \right] - 2\alpha_{1y}\alpha_{y} \right)$$

$$\mathcal{E}_{2} = \mathcal{E}_{1}A_{21} + \mathcal{E}_{2}A_{22} \qquad A_{21} = \frac{1}{2} \left(\frac{\beta_{x}}{\beta_{2x}} \left[u^{2} + \alpha_{2x}^{2} \right] + \frac{\beta_{2x}}{\beta_{x}} \left[1 + \alpha_{x}^{2} \right] - 2\alpha_{2x}\alpha_{x} \right), \quad A_{22} = \frac{1}{2} \left(\frac{\beta_{y}}{\beta_{2y}} \left[(1-u)^{2} + \alpha_{2y}^{2} \right] + \frac{\beta_{2y}}{\beta_{y}} \left[1 + \alpha_{y}^{2} \right] - 2\alpha_{2y}\alpha_{y} \right)$$

- Later all dipoles were shimmed.
 - It reduced current of main skew-quad bus but did not reduce coupling coming from scatter of skew-quad components in dipoles
- It looks like that the coupling has not been making negative impact on the machine optics with one exception - the emittance growth at transfers
 - Before and after coupling correction we operated Tevatron at small tune split ($\Delta Q < 5.10^{-3}$)

Optics measurements

- Methods
 - Orbit response (also called differential orbits)
 - It is the only method for transfer lines
 - Two incarnations
 - \Rightarrow Minimal data acquisition transfer lines "manual" analysis
 - \Rightarrow Large data redundancy available in rings makes possible automatic data analysis yielding much better accuracy
 - One measurement normally takes 0.5 2 hours
 - Turn-by-turn
 - Much faster data acquisition (can be used during acceleration)
 - Significant advance but did not achieve the same sophistication
 - Measurements of sextupole component distribution around the ring were attempted but did not achieve required accuracy
 - Development of the optics measurements techniques
 - Only orbit response with manual data analysis was available at the Run II beginning
 - Automatic data analysis with SVD appeared in 2004 as result of collaboration with ANL

Orbit Response with "Manual" Data Analysis (continue)

- Build a model means finding the fudge factors for quad strengths so that 4 differential orbits and dispersion(s) would match the measurements
- If coupling is important quad rotations have to be also introduced
- Adjustments are done by a person
 - There is a considerable freedom =>the problem cannot be performed by software with "reasonable" intellect



- Errors of differential BPM response complicate analysis (up to 10%)
- Any "good" solution makes good representation of the optics!!!

LOCO (Linear Orbit from Closed Orbit = Orbit Response)

- Data analysis is based on SVD inversion of response matrix
 - We extended the algorithm developed by V. Sajaev of ANL
 - The extension included
 - Fully coupled x-y treatment of betatron motion
 - Addition of dispersion measurements to the fit
 - Software also includes a correction to dif. orbit due to energy change related to the orbit length change
 - Good initial approximation (made manually) was important for convergence
 - Design model did not converge
 - Data analysis is not completely automatic - a good physicist is still required
 - SVD cut-off, choice & number of quads & skew-quads for correction, etc.



The spectrum for Tevatron SVD cut-off was typically chosen at 1, which corresponds to 600-650 singular values.

Orbit Response Measurements in Tevatron

New Tevatron BPMs significantly improved accuracy (50 \rightarrow 15 μ m)



RMS difference (mm) between the measured and modeled orbit vs. BPM name. Top - horizontal orbit, bottom - vertical orbit. Amplitude of dif. orbit is ~5 mm.

Second order chromaticity correction

Beta-beating excited by a single quadrupole for an off-momentum particle can be described by the formula

$$\frac{\delta\beta_k}{\beta_k}(s) = (-1)^k \frac{\left(\delta p / p\right)}{2\sin\left(2\pi Q_k\right)} \frac{\left(QL\right)}{\left(B\rho\right)} \beta_{0k} \cos\left(2\left|\psi_{0k} - \psi_k\left(s\right)\right| - 2\pi Q_k\right), \quad k = 1, 2 \equiv x, y.$$

The contribution to second-order chromaticity of the horizontal tune derived from the perturbation theory is given by the following expression



Chromatic beta-function vs. azimuth: left - entire machine starting at FO, right - in vicinity of CDF. Blue line - measured, red - model, black - proposed correction.

Splitting chromaticity quads into families resulted in a suppression of beta-function chromaticity and, consequently, the second order chromaticity





Dependence of the vertical betatron tune on particle momentum in the collider mode

"Tevatron Accelerator Methods and Techniques Applicable for Future Accelerators", Valeri Lebedev, APS meeting, August 2011

Optics Corrections in Antiproton source

- Optics corrections both in Debuncher and Accumulator were aimed to maximize their acceptances for given aperture limitations set by the stochastic cooling pickups and kickers
 - Balancing beta-functions in nearby aperture limitations was used
 - It also improved performance of transverse stochastic cooling
 - Optics redesign in Debuncher required shuffling quad shunts
- The slip-factor was adjusted in Accumulator to optimize the stacktail
 - The "dual-optics" operation was introduced and used before
 Recycler commissioning (two optics modes were optimized for stacking and IBS)

Beam envelopes in the pickup straight of the Debuncher

Electron Cooling

- Fermilab made next step in electron cooling technology
 - Main Parameters
 - ♦ 4.34 MeV pelletron
 - up to 0.5 A DC electron beam with radius ~4 mm
 - Magnetic field in the cooling section ~100 G
 - Interaction length 20 m (out of 3319 m of Recycler length)

The cathode is immersed in the longitudinal magnetic field

- Two mode
 emittances are
 different in
 ~10³ times
- Optics is build from rotationally invariant blocks





bottom – the phase advances ($\mu_1 \& \mu_2$) and the eigen-vector phases ($\nu_1 \& \nu_2$) divided by 2π ; $\nu_1 \& \nu_2 = \pm (2\pi) \times 0.25$ (± 90 deg.) correspond to circular modes

Precooling in Debuncher and Stacking & Cooling in Accumulator

Debuncher

- Each of 3 systems (H + V + L) has 4-8 GHz band split into 4 sub-bands
- Accumulator
 - Core cooling
 - H & V 4-8 GHz
 - Longitudinal: 2-4 GHz and 4-8 GHz
 - Stacktail 2-4 GHz
 - moves injected antiprotons to the core
- Accurate quantitative description was essential for determining the upgrade path
- Core 2-4 GHz and Core 4-8 GHz Stacktail and Core 2-4 GHz betatron pickups momentum pickups 5 AP10 Core 4-8 GHz Ì momentum pickups Core 2-4 GHz Core and Core 4-8 GHz AP50 4-8 GHz betatron kickers AP30 moméntum kickers Stacktail and Core 2-4 GHz momentum GR kickers
- It was important to understand an effect of band overlap on the performance of different systems and beam heating mechanisms

Effective bandwidth of stochastic cooling system

Evolution of Long. distribution is described by Fokker-Planck eq.

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial x} \left(F(x)f \right) = \frac{1}{2} \frac{\partial}{\partial x} \left(D(x) \frac{\partial f}{\partial x} \right)$$

$$F(x) = f_0 \sum_{n=-\infty}^{\infty} \frac{G(x,\omega_n)}{\varepsilon(\omega_n)} e^{i\omega_n T_2 \eta_2 x}, \quad D(x) = N\psi(x) f_0 \sum_{n=-\infty}^{\infty} \frac{1}{|n\eta|} \left| \frac{G(x,\omega_n)}{\varepsilon(\omega_n)} \right|^2, \quad \omega_n = n\omega_0 (1 - \eta x)$$

where $x = \frac{\Delta p}{p}$ and we neglected noise of electronics G(f) $\frac{t_{max}}{max} =$ $F(x) \propto \operatorname{Re}(G), \quad D(x) \propto |G|^2 \implies$ Effective bandwidth $W_{eff}(x) = \int_{\Omega}^{\infty} \operatorname{Re}(G(x, 2\pi f)) df / \sqrt{\int_{\Omega}^{\infty} |G(x, 2\pi f)|^2} \frac{df}{f}$ 0.5 2 3 1 f/f_{min} $G_{\omega}(2\pi f) = \begin{cases} G_0, f \in [f_{\min}, f_{\max}] \\ 0, \text{ otherwise} \end{cases} \qquad W_R = \frac{f_{\max} - f_{\min}}{\sqrt{\ln(f_{\max} / f_{\min})}} \qquad \frac{W_L}{W_R} \frac{1.1}{1.08} \end{bmatrix}$ Linear gain function (G~f) 1.04 $G_{\omega}(2\pi f) = \begin{cases} af , f \in [f_{\min}, f_{\max}] \\ 0, \quad otherwise \end{cases} \implies W_{L} = \sqrt{\frac{f_{\max}^{2} - f_{\min}^{2}}{2}}$ 1.02 2 3 4 f_{max}/f_{min}

Stacktail system

Very complicated system - its improvement was one of most challenging beam physics problem in Run II



System has 3 pickups which signals are added with right gains and delays and come through 3 notch filters. It makes the exponential gain profile in the stacktail area (Van der Meer solution) $G(x, \omega) \approx G_{\omega}(\omega) \exp(-x/x_d)$

The maximum flux

$$J_{\max} = T_0 \left| \eta \right| x_d W_{eff}^2$$



Test Equalizer specifications

- Phase part corrects phase
- Amplitude part corrects amplitude so that to get the desired total amplitude

$$K_{i}(\omega) = \frac{A_{i}}{1 + iQ_{i}} \frac{\omega^{2} - \omega_{i}^{2}}{\omega\omega_{i}}, \quad i = 1, 2, 3$$
$$K_{A}(\omega) = 1 + 0.91\cos(\omega\tau), \quad \tau = 195 \ ps$$

 $K_{tot}(\omega) = K_A(\omega) (K_1(\omega) + K_2(\omega) + K_3(\omega))$ Final equalizer has 5 resonators and

one-stage amplitude correction

<image>

frequency [GHz]

<u>Stacktail equalizer (continue)</u>



frequency [Hz]

frequency [Hz]





Effective bandwidth before and after installation of the equalizer

Transverse core heating

Stacktail is a longitudinal system

• However its kickers also produce transverse quadrupole kicks

$$U(x, y) = U_0 \left(1 \pm \frac{x^2 - y^2}{2a_{eff}^2} \right), a_{eff} \approx 1.87 \text{ cm}$$
Panofsky-Wenzel theorem $\Rightarrow E_x \propto \frac{dU(x, y)}{dx} = U_0 \frac{x}{a_{eff}^2}$

$$The problem is mitigated by 90^{\circ} \text{ rolls of nearby kickers}$$

$$V = V = V = 100 \text{ means} \text{ mitigated by 90}^{\circ} \text{ rolls of nearby kickers}$$
Core transverse cooling tanks $H = H + H + V = V = 100 \text{ means} \text{ means}$

- Large betatron phase advance along kicker straight results in insufficient compensation and transverse emittance growth due to
 - Not perfectly zeroed dispersion in the kicker straight
 - Offset of kicker electrical center relative to the beam center
 - kicker electrical center varies with frequency
 - Parametric heating (kickers at ends heat more)
 - It is addressed by swapping core cooling and stack-tail kickers and switching of 3 of 31 kickers

Luminosity Evolution Model

- Luminosity evolution is driven by
 - Single and multiple intrabeam scattering (IBS)
 - Elastic and non-elastic scattering on counter-rotating beam
 - RF noise
 - Elastic and non-elastic scattering on the residual gas
 - LHC \perp Emittance growth due to e.-m. noises and \perp damper
 - Beam-beam effects
- The model is based on ODEs ($N_{1,2}, \varepsilon_{x,y(1,2)}, \sigma_{s(1,2)}$)
 - Details of evolution for longitudinal distribution came from parameterization of solution of integro-differential equation describing single and multiple IBS
 - Was build for Tevatron and was recently updated for the LHC
- The model
 - was the base for the Tevatron luminosity evolution scenario (2003)
 - helps in understanding of the machine and beam-beam effects
 - Recently was used to look the LHC luminosity optimization





"Tevatron Accelerator Methods and Techniques Applicable for Future Accelerators", Valeri Lebedev, APS meeting, August 2011

27

Model Predictions for the LHC (fill 1852, June 2011)



<u>Beam-beam effects</u>

- Very different from electron-positron colliders
 - No damping
 - Emittance growth is driven by IBS and other heating mechanisms
 - Beam-beam effects are a small perturbation for real collider param.
- No analytical solution -Tracking is only a way to achieve sufficient accuracy (predictive power); LifeTrack, D. Shatilov, Novosibirsk
 - Diffusion (IBS, etc.) is a major driver for luminosity evolution
 - For Tevatron parameters coherence for 12-th order resonance disappears after ~50,000 turns
 - Weak-strong simulations, >10⁶ turns
 - Chromaticity of tunes and beta-functions is important
 - Non-linearity of beam-beam force is much stronger than the lattice non-linearities inside aperture available to a beam
 - Normally we use a smooth lattice approximation between IPs
- Accurate strong-strong simulations cannot be done for ~10⁶ turns
 - They are used for coherent stability check only
 - Impedance contribution has to be taken into account
 - Simulations were important to support the upgrade choices made

<u>Conclusions</u>

- Accelerator physics developments in the course of Run II have been absolutely essential for its success
 - ♦ Same as operation, engineering, etc.
- Diverse contributions were required
 - they will certainly affect many future developments
- Good team to run Tevatron at the edge of its ultimate performance was also essential
 - Collaboration of many devoted individuals
 - Communications at parallel levels
- Most of work had to be done with minimum effect on collider operation (minimize interruptions, recabling, new PS, etc.)
 - Careful analysis of each upgrade/improvement helped to avoid unnecessary work
- This presentation covers comparatively small part of the entire work required to achieve presentTevatron performance