OBSERVATIONS OF STRONG TRANSVERSE COUPLING IN THE TEVATRON*

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Abstract

During the beginning of Run II of the Tevatron Collider it became apparent that a large skew quadrupole source, or sources, had developed in the superconducting synchrotron. Efforts to locate the current source of coupling were undertaken, with the eventual discovery that the main magnets had developed a systematic skew quadrupole moment over their lifetime. Over the past year, the magnets have been altered in place in an attempt to restore the systematic skew quadrupole moment to zero. Beam observations and their interpretations are presented, and remedial measures are discussed.

INTRODUCTION

When slow extraction was attempted from the Fermilab Main Ring in the summer of 1970 horizontal-vertical coupling prevented adequate transverse oscillation growth for efficient slow spill. This situation was corrected by an 8 mrad roll of each of twelve equi-spaced quadrupoles[1]. In order to avoid a repetition of this problem in the Tevatron, an extremely strong skew quadrupole circuit was built in at the outset. When the Tevatron was commissioned only 4% of the capability of this circuit was required. In 2003, 20 years later, the excitation of this skew quadrupole circuit was running at approximately 60%.

In the normal Tevatron tuning process the skew quad circuits are adjusted to minimize the difference between the horizontal and vertical betatron tunes to the level of $\Delta\nu_{min} \approx 0.003$. It was realized in late 2002 that if the main skew quadrupole circuit were to be turned off, the resulting minimum tune difference would be 0.3 units!

After further deliberations, it was recognized that strong coupling could also account for a distinct pattern of vertical dispersion in the Tevatron, which also could lead to emittance growth upon transfer of coalesced (large momentum spread) bunches from the Main Injector. Additionally, cross-talk between the horizontal and vertical motion hindered the early commissioning of the transverse damper systems early in the run.

THE EXPERIMENTS OF EARLY 2003

With a correction corresponding to 0.3 units of tune difference, coupled orbital motion should be easily observable with the skew quad magnets turned off. In February 2003 a search was conducted for the sources of transverse coupling by turning off the skew quadrupole correctors and injecting with a transverse offset in one degree of freedom and looking for growth in the other degree of freedom making use of orbit difference measurements. For Figure 1 a steering magnet was adjusted to inject beam with a large horizontal betatron oscillation, and the progressive growth of the vertical amplitude is recorded. This was the first data to suggest a systematic skew quadrupole term in the ring. Corresponding data using a steering element one cell downstream (60°) was consistent. Attempts to find a significant localized disturbance by using a variety of steering dipole locations were not successful.

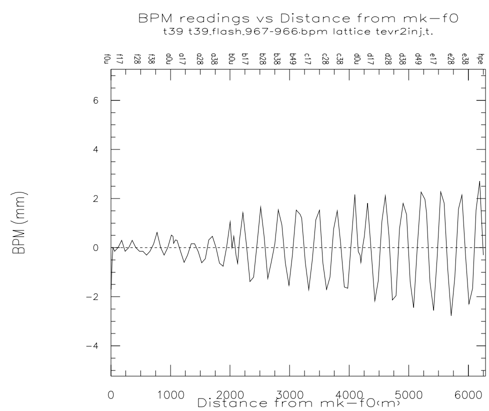

Figure 1: Vertical orbit data displaying growth of amplitude along the Tevatron circumference.

The measurements of a follow-on study are elegantly characterized by Figure 2 which shows the progress through several turns. This figure shows a difference orbit with an initial oscillation in the horizontal degree of freedom generated by a mistuned steering dipole in the injection transfer line. In textbook fashion within about 1.5 turns the motion couples fully into the vertical and in another 1.5 turns returns fully to the horizontal.

ANALYSIS

Several attempts in 2002 were made by T. Sen, B. Erdelyi, M. Martens, and others to determine strong local sources of coupling in the Tevatron without success. The roll angles of almost all quadrupole and dipole magnets in the Tevatron were measured in 2003[2], and the resulting data can account only for a tune difference an order of magnitude lower than what is observed.

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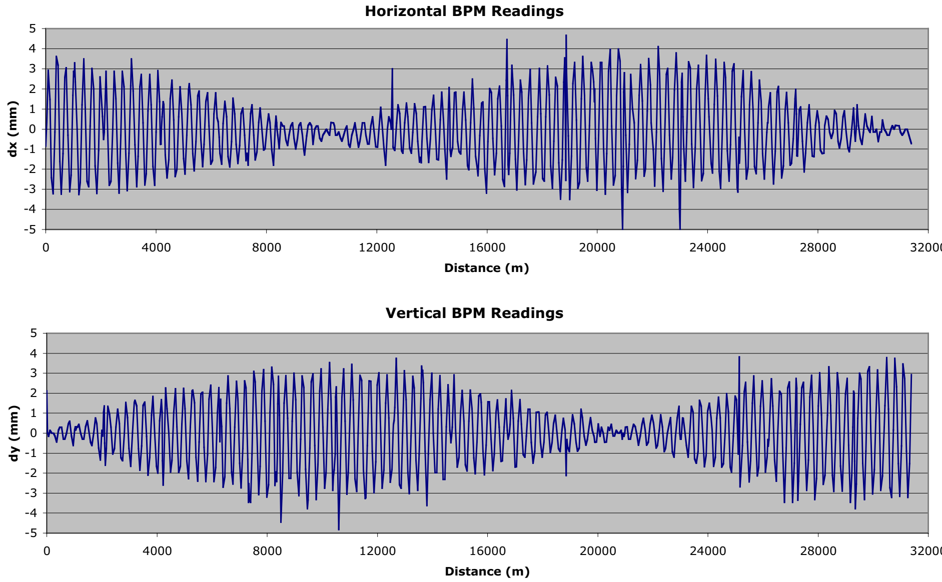

Figure 2: Orbit difference data, taken on February 22, 2003, for 5 consecutive turns. The circumference of the Tevatron is 6283 m. The incoming horizontal oscillation (top) completely couples to the vertical plane (bottom) in ∼1.5 revolutions.

The data of February 2003 suggest that a systematic skew quadrupole component existed in the Tevatron distributed along the circumference. A systematic rotation of the 200 quadrupoles seemed unfeasible, since each focusing quad would need to be rolled inward and each defocusing quad rolled outward, for example. However, if all the dipole magnets had systematically developed a skew quadrupole component to their magnetic field, this could account for the observations. The skew quadrupole multipole coefficient, a_1, is defined by $a_1 = (\partial B_x/\partial x)/B_0$ where B_0 is the main dipole field strength. The minimum tune split due to a systematic a_1 in the Tevatron dipoles would be $\Delta\nu_{min} = (1/2\pi)(B_0 a_1 \ell/B\rho)\sqrt{\beta_x\beta_y} \;\; N_{dip} \approx 2Fa_1$, where F is the focal length of the FODO lattice quadrupoles. A tune split of 0.3 would imply a value of $a_1 \approx$ 0.006/m = 1.5×10^{-4}/in (1.5 "units" of a_1, in the standard Fermilab Tevatron magnet system of units). Suspicion of a systematic a_1 in Tevatron dipoles had already been raised by measurements performed in the tunnel during the January 2003 shutdown period as reported by Harding, *et al.* Physical magnet measurements performed in the Tevatron tunnel also suggested an a_1 at the level of one unit.[3] [4]

Reprise of 1970 Estimate

This is just a repeat of the 1970 calculation, with suspicion resting on the dipoles on this occasion. Localize the four dipoles between each pair of quadrupoles at the midpoint of the inter-quadrupole space. These four dipoles will represent a skew lens of focal length f given by $1/f = 4\theta a_1$ where θ is the 8 mrad bend of each dipole. Suppose a horizontal oscillation exists such that at the nth inter-quadrupole position the displacement is $x_n = x_0 \cos(n\mu)$, where μ is the half-cell phase advance. At this location, a vertical oscillation will be initiated with deflection angle x_n/f. Downstream after N half-cells, the total vertical displacement may be approximated by $y_N \approx x_0 4\theta a_1 \beta \sum \cos(n\mu)\sin[(N-n)\mu]$, where β is the amplitude function midway between the quadrupoles. Ignoring the oscillatory terms in the sum, its amplitude is $N/2$. The condition that the horizontal oscillation fully couple into the vertical plane is $x_0 4\theta a_1 \beta N/2 = x_0$, from which $a_1 \approx 1.6 \times 10^{-4}$ per inch, where we have taken $N = 200$ to represent one turn and $\beta = 50$m.

Other Early Analyses

Following the initial measurements described above, several methods of analysis were pursued, including an analytical difference resonance calculation and a linear coupled matrix calculation. These gave results consistent with the data. Unfortunately, for such a claim of understanding to be accepted by the most skeptical of critics one must perform computer simulations using sophisticated models of the Tevatron lattice. This was performed through two independent approaches using the codes MAD and TEVLAT, each of which again supported the hypothesis. Further details of all of these calculations can be found in [5].

DISPERSION MEASUREMENTS

Soon after the magnitude of the coupling was realized, it was suggested to look at the vertical dispersion in the Tevatron as this should be easily predicted from the systematic coupling and its localized correction. Dispersion can be measured operationally by varying the radial position feedback loop of the RF system and recording orbit differences. An example of such a measurement is shown in Figure 3. The horizontal positions vary roughly in accordance to the design dispersion in the ring, which has peak values of about $D_x = \Delta x/(\Delta p/p)$ = 5 m. However,

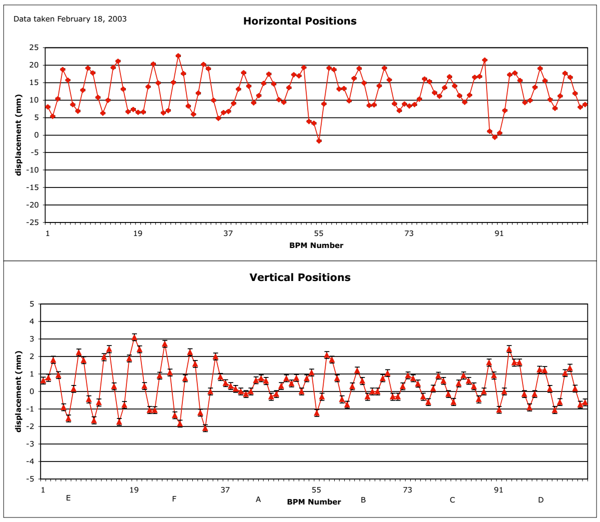

Figure 3: Beam position data from the Tevatron showing difference between two orbits with different average momenta. Horizontal positions above, vertical below.

the vertical dispersion, zero by design, takes on values with peaks of $D_y \approx$ 0.6-0.8 m. A common feature of these vertical measurements has been the coherent oscillatory pattern with frequency near the betatron tune, and with smaller vertical dispersion seen through B- and C-sectors, and much smaller dispersion through A-sector.

With the newly understood strong coupling in the Tevatron, it is straightforward to predict the effects on vertical dispersion given the sources of coupling, including the correction elements.

Skew Quadrupole Circuits

To make improvements to the Low-Beta optics for collider operations, certain superconducting skew quadrupole correctors near the CDF and D0 experiment interaction regions were removed during Run I in order to include stronger corrector quadrupoles, reducing the main skew circuit from 48 magnets down to 42. Also, other skew quadrupoles were commissioned in the neighborhood of four of the long straight sections. The seemingly relatively minor changes in configuration solely could not account for the increased corrector strengths, but nonetheless produced other noticeable effects on the Tevatron

Vertical Dispersion due to Coupling

A horizontal orbit offset through a skew quadrupole due to a change in momentum will generate a vertical orbit distortion. For random quadrupole roll angles in the Tevatron, the expected rms vertical dispersion would be of order $\Delta D_y^{rms} \approx$ 8 cm for a typical rms roll angle error of $\sim$1 mrad and the pattern should appear random. However, with the "missing correctors" near the Interaction Regions, and additional skew quadrupole circuits being used to tune the coupling, the observed vertical dispersion can be understood.

A simple calculation, using the design lattice parameters and the operational corrector circuit settings, gives a rough prediction for the vertical dispersion and is shown in Figure 4. As can be seen, this gives a very fair resemblance to the vertical position data shown in Figure 3. Further notes on this subject can be found in [6].

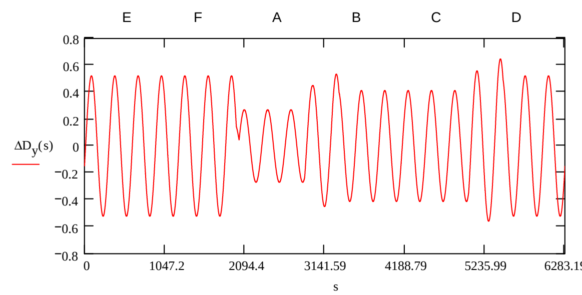

Figure 4: Estimated dispersion pattern generated by skew quad corrector settings and "missing" SQ components.

CONCLUDING REMARKS

Since its discovery and interpretation, the coupling in the Tevatron has been reduced by *in situ* correction of dipole magnets in the tunnel. Further details may be found in [3]. The magnets have to be fixed during planned shutdown periods, and in a pattern consistent with the skew corrector pattern. So far, 68% of the magnets have been repaired, the vertical dispersion has been reduced by more than 70%, injection emittance growth is better under control, and Tevatron performance improved, helping pave the way to record luminosities for the collider program.

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