TUNE DRIFTS ON THE TEVATRON FRONT PORCH*

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Abstract

It has long been known that the tunes of the Tevatron drift on the 150GeV front porch. The drift is observed to have the same time dependence as the drift in the chromaticity. The variation in the chromaticity is due to the change in the b_2 of the superconducting dipoles, which represents the integrated sextupole moment of the magnet. It is reasonable to assume that the tune drift is due to the feed down from the changing b_2. Calculations based on this assumption, both here and in earlier attempts to explain the tune drift, show, absent unreasonable assumptions about the closed orbit, that the simple models of the variation of the sextupole moment will not explain the tune drift. An explanation, for both the tune drift, and the tune split observed when the Tevatron was first operated, is proposed. The suggestion is based on the longitudinal variation of the time varying sextupole component of the dipoles and the fact that the dipoles are not perfect sector magnets.

INTRODUCTION

The time drift of the Tevatron tunes on the front porch at 150GeV is a well known, and well documented phenomena. In 2004 an extensive series of measurements were made of the tunes and chromaticities in the Tevatron at 150GeV [1],[2]. These data show a variation of the tune (Fig. 1), coupling and chromaticity during the time on the front porch. The tune data can be fit with the following expressions:

$$\Delta Q_h(t) = +0.003543 \ln((t(s) + 170)/170) \quad (1)$$

$$\Delta Q_v(t) = -0.004196 \ln((t(s) + 170)/170) \quad (2)$$

The explanation of the change in the chromaticity was ascribed to the well known change in the sextupole (b_2) strength of the dipoles. The time dependence of the tune drift is the same as the dependence of the change in b_2. It is natural to look for the tune drift as in the change in the sextupole moments in the dipole. The tune shift due to the sextupole moments in the dipoles depends on the displacement of the beam in the dipoles relative to the magnet center. The expected tune drifts, due to the observed drift in the value of b_2, have been calculated the using the measured closed orbit and the measured values of the a_1 and b_2 multipoles (also shown on Fig. 1). This calculation, as well as earlier, similar, attempts [3] to explain the tune drift, show that, absent unreasonable assumptions about the closed orbit, the variation of the sextupole moment assigned to the

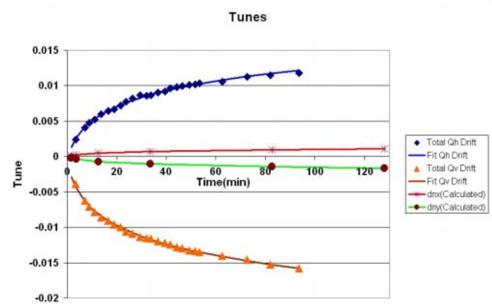

Figure 1: Tune Drift as a Function of Time on the 150GeV Front Porch, Measured and Calculated Values.

dipoles, the value of b_2 needed to explain the chromaticity, will not explain the measured tune drifts. The calculated tune drifts are much smaller than the observed drifts. To understand the difference between the measured and calculated tune drifts we need to understand the characteristics of the Tevatron dipoles.

CHARACTERISITCS OF TEVATRON DIPOLES

An extensive discussion of the Tevatron dipoles can be found in reference [4]. The magnets are of a two layer. wedgeless cos-theta design inside a cryostat. The cryostat is inserted into a warm iron yoke. The dipole field is designated as B_0. The high order harmonics of the magnetic field are described in terms of the multipole coefficients, b_n for the normal moments and a_n for the skew moments. These multipole coefficients are defined relative to the dipole field so that at the reference radius of 1 a multipole strength of 1 unit will contribute to the magnetic field an amount equal to 10^{-4} of the dipole field. At the ends of the magnet the super-conducting strands are bent to form the coils. The shape of the coils produces a large sextupole component of the magnetic field, a large negative b_2, localized at the ends of the magnet. This was recognized during the design of the magnets and an additional sextupole component was introduced into the body of the dipole to compensate for the end sextupole. This design yielded a value of b_2 at a current of 4kA of ≈1unit, well with the correction capability of the chromaticity sextupoles in the Tevatron. The problem with this solution is that if the beam does not go through the center of the magnet there will be feed down from the sextupole and and as a result,the dipoles will have a significant quadrupole component in the field. The solution to the feed down problem was to bend

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the dipoles so that the trajectory of the particles inside the dipole coincided with the center line of the magnet. This effort was only partially successful and it was found, when the Tevatron began operations, that, contrary to expectation the tunes, rather than being equal, in the vertical and horizontal planes differed by 0.4 with $\nu_x > \nu_y$ [5]. (The coupling was minimized before measuring the tunes.) The effect was modeled by incorporating a zero length pseudo-quadrupole at each end of the dipoles in the lattice.This pseudo element, (referred to as *kbendq* in the lattice descriptions), is due to the feed down of the sextupole in the dipole. Since the strength of the sextupole, and in particular the relative strengths of the end field and the body field change with time, (due to the change in the persistent currents) the strength of the feed down quadrupole will also change. This change in the feed down quadrupole accounts for the tune drift.

EXTRACTION OF THE STRENGTHS OF THE BODY AND END FIELDS OF THE DIPOLES

We can extract the body and end fields of the dipoles from the magnetnic measurements because in addition to the full length dipoles (TB and TC magents of length$\approx 6.2m$) there are two half length dipoles (TD magnets with length, $\approx 2.4m$) in the Tevatron. same design geometry as the full length dipoles. The b_2 at the ends of these magnets is the same as the b_2 at the ends of the normal magnets, the length of the body is shorter. The cancellation of the end field and the body field that worked for the full length magnets does not work here, because of the smaller contribution from the body, and these magnets have a large negative b_2. (The width of the distribution for the measured b_2 is given for the full length dipoles in the tunnel.There are not enough shorter magnets to compute a meaning width.) We can use the measured b_2 moments (Table I) of the full

Table 1: Measured Values of b_2

Magnet Type	Current(A)	b_2	Width
TB/TC	660	-4.32	$\approx$3
TD	660	-21.56	-
TB/TC	4000	0.83	≈ 3
TD	4000	-16.20	-

length and half length magnets to extract the contributions of the body field and the end field to the b_2 and the length of the end field. The strength of the feed down quadrupole was also used in the fitting to obtain the sagitta of the magnet. The results are shown in Table II. These values are consistent with the measurements made at the Fermilab Magnet Test Facility.

A SIMPLIFIED MODEL

The quantity *kbendq* depends on the values of the b_2 at the ends and in the body of the dipole and the trajectory of

Table 2: Solutions for the End and Body Fields at 660A and 4000A.

Parameter	Current A	Value	Units
Len. of end		$0.157 \pm \approx 0.005$	m
b_2 end	660	$-597.95 \pm \approx 5$	
b_2 body	660	$11.41 \pm \approx 0.4$	
b_2 end	4000	$-583.12 \pm \approx 5$	
b_2 body	4000	$16.38 \pm \approx 0.4$	
sagitta[6]		$234.18 \pm \approx 0.11$	mills
sagitta		5.9481	mm

the beam relative to the center line of the magnet. These quantitlies vary over time and hence the value of *kbendq* also varies. The time variation in the strength of *kbendq* is the cause of the tune drift. While this quantity has not been measured it can be calculated, as a function of time, from measured tune drifts. It is impossible to reconstruct the actual conditions in the Tevatron when the tune was measured. If the tune drift is due to the variation in the sextupole in the dipoles then the tune drifts $\delta\nu_x$ and $\delta\nu_y$ should be equal and opposite. Figure 1 shows a significant difference between the drifts. This is most likely due to coupling. To eliminate this effect the average of the magnitude of the drift coefficients shown in equations(1) and (2) is calculated. The tunes as a function of time are then calculated. With these tune valuesthe model of the Tevatron lattice is used to calculate the value of *kbendq* which will yield these tunes. The result is the computed value of *kbendq* as a function of time. The result is plotted in Fig. 2. From these computed values of *kbendq*, and the measured

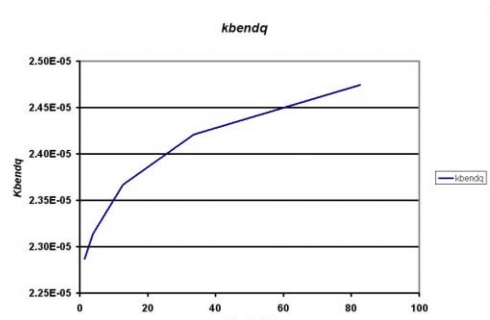

Figure 2: Calculated Value of /emkbendq from the Measured Tune Drifts.

(from the chromaticity) values of b_2 as a function of time, we can calculate the values of the body and end fields function of time. The results are found in table III and plotted in Fig. 3 and Fig. 4.

SUMMARY

The discussion presented here provides a plausible explanation of both the tune drift observed in the Tevatron on the 150GeV/c front porch, as well the reason for the large tune split observed in the early days of the Tevatron. Both effects are due to the feed down from the sextupole moments in the dipoles. While the variation of the b_2(body) ($\approx$ 40%) and b_2(end) ($\approx$ 17%) are large so are the tune shifts and the change in the b_2($\approx$ 45%) in the nearly two hours on the front porch. Since the calculations are done with an approximation to the tune drift (the coupling has been removed from the model) the changes should be regarded as approximations to the behavior of the sextupole fields in the ends and body of the Tevatron dipoles. The actual behavior should, however, resemble closely the calculations presented here.

Table 3: Calculated Values of $b_2(Body)$ and $b_2(End)$ as a Function of Time

Time (min)	b_2	***kbendq***	b_2 **(Body)**	b_2 **(End)**
0.00	-4.320	2.25987E-05	11.4	-598.
0.67	-4.212	2.27328E-05	11.6	-604.
1.50	-4.104	2.28668E-05	11.9	-610.
3.81	-3.888	2.31348E-05	12.5	-622.
12.72	-3.456	2.36710E-05	13.6	-646.
33.62	-3.024	2.42070E-05	14.6	-671.
82.60	-2.592	2.47432E-05	15.7	-695.
127.94	-2.376	2.50112E-05	16.3	-707.

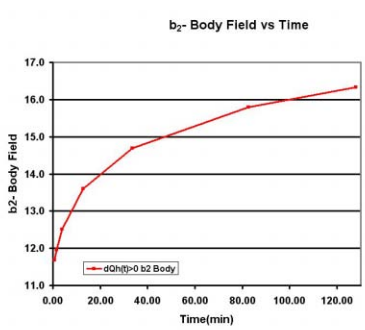

Figure 3: Calculated Value of $b_2(body)$ from the Measured Tune Drifts.

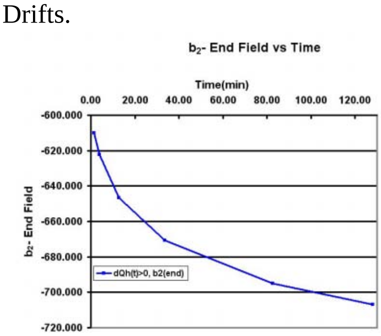

Figure 4: Calculated Value of $b_2(end)$ from the Measured Tune Drifts.

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[5] G. Michael A. Martens, "Tevatron Commissioning and Operating Experience",Beams-doc-1595-v1(Mar. 2,2005)

[6] "The design sagitta for the 235" long magnet core is 0.230". We tried to keep the sagitta within a 20 mil envelope, in practice we were happy with twice that.", John Carson(Fermilab), private comunication. The sagitta of the beam in the dipoles is ≈ 0.244". I do not know why the design sagitta and the beam sagitta are not equal.

