STUDIES OF THE CHROMATICITY, TUNE, AND COUPLING DRIFT IN THE TEVATRON*

Michael A. Martens, Jerry Annala, Pierre Bauer, Vladimir Shiltsev, Gueorgui Velev
Fermilab, Batavia, IL 60510, USA

Abstract

Chromaticity drift is a well-known and more or less well-understood phenomenon in superconducting colliders such as the Tevatron. Less known is the effect of tune and coupling drift, also observed in the Tevatron during injection. These effects are caused by field drifts in the superconducting magnets. Controlling the behavior of the tune, coupling, and chromaticity is an important part of reducing beam loss at injection and at the start of the Tevatron ramp. In this context we conducted several beam-studies during the period of April to August 2004 in which we measured the drift in the Tevatron chromaticity, tunes, and coupling during the injection porch. In some cases we also measured the snapback at the start of the ramp. We will present the results of these studies data and put them into context of the results of off-line magnetic measurements conducted in spare Tevatron dipoles.

INTRODUCTION

It is well known [1] that the sextupole (b_2) component of the Tevatron superconducting dipole magnets decays during the injection plateau by approximately 1-2 units (defined as 10^{-4} of the main dipole field in the bore and measured at the reference radius of 25.4 mm.) During the first few seconds of the ramp from the injection plateau the b_2 quickly snaps back to the initial level before the decay while at the same time evolving along the hysteretic loop. These effects were first discovered in the Tevatron and are referred to as dynamic effects. If left uncompensated the b_2 drift in Tevatron results in a chromaticity drift of approximately 50 units during the ~2 hour injection plateau and a correspondingly large snapback of the chromaticity during the first few seconds of the energy ramp.

In addition to the well known chromaticity drift, a tune drift of approximately 0.015 units and a coupling drift of approximately 0.02 units of minimum tune split are also observed in the Tevatron during the injection plateau with correspondingly large snapbacks during the first few seconds of the energy ramp. The tune and coupling drifts have been measured but are not (yet) completely understood in terms of dynamic effects.

Efficient operation of the Tevatron during the injection plateau and energy ramp requires control of the chromaticity to within about 2 units, the tunes to within about 0.002 units, and the coupling to less than 0.003 units of minimum tune split. Variations in these machine parameters can lead to either slow beam loss or to transverse instability resulting in emittance blowup and fast beam loss.

To keep these machine parameters within tolerance the chromaticity sextupole and the tune and skew quadrupole corrector magnets are used to compensate for the dynamic effects during the injection plateau and at the start of the energy ramp. The compensation algorithms are determined from both the offline magnetic measurements reported elsewhere [2,3,4] and the beam based measurements reported in this paper. Implementation details of the compensation are given in [5].

The dynamic effects depend on the history of previous ramp cycles and depend, for instance, on the time spent at the flattop energy and on the back porch. A complete exploration of the ramp history effects would require a vast amount of Tevatron study time to the detriment of integrated luminosity. On the other hand, making measurements on only a handful of magnets (compared to the 774 dipoles used in the Tevatron) is not representative enough to precisely determine the correction algorithm needed for collider operations. The adopted approach was therefore to use the offline magnet measurements for understanding the ramp history dependencies and to use beam based measurements for fine tuning of the correction algorithms [6].

This approach led to an improved set of correction algorithms for the drifts and snapbacks and to a change in the operating scenario of the Tevatron which resulted in faster turn around time between stores by eliminating the need for a beam-less pre-cycle. This is explained in the next section.

Operating Scenarios

The energy ramp cycle of the Tevatron always follows the sequence: an injection porch; an acceleration ramp; a flattop; a deceleration ramp; a back porch; and a reset cycle from the back porch to 90 GeV and back to the front porch. In collider operations the injection and flattop energies are set at 150 and 980 GeV and the acceleration and deceleration portions of the ramp are 85 seconds long. The amount of time spent at flattop, on the back porch, and on the injection porch do vary from cycle to cycle.

For the first several years of Collider Run II all Tevatron ramp cycles intended for beam were preceded by a beamless pre-cycle to return the Tevatron to the same hysteretic loop. This pre-cycle, with a ~20 minute flattop time and a 90 second back porch time, was performed after the Tevatron was turned off for any reason (i.e. tunnel access or quench) or after the completion of a collider store. Based on the work reported here the pre-cycle has been eliminated as part of operations in

*Fermilab is operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy.

situations that do not require turning off the Tevatron such as after an intentionally ended store.

It was determined from offline magnet measurements that the amount of b_2 drift as a function of flattop time saturates after 60 minutes on the flattop and that longer back porch times result in less b_2 drift on the front porch. With this knowledge it was decided to develop correction algorithms for Tevatron operations preceded by a ramp with flattop time greater than 1 hour and with a back porch time of 5 minutes. The beam based measurements to develop this algorithm are the focus of the next sections.

CHROMATICITY MEASUREMENTS

Chromaticity Drift

During four separate Tevatron study periods in 2004 the chromaticity as a function of time on the front porch was measured with flattop time greater than 1 hour and back porch time of 5 minutes. The measurements were then used to calculate the amount of b_2 in the Tevatron dipoles. The total chromaticity,

$$\xi_{\text{total}} = \xi_{\text{measured}} = \xi_{\text{b2,dipoles}} + \xi_{\text{b2,correctors}} + \xi_{\text{natural}}$$

is the sum of three components. The natural chromaticity, ξ_{natural}, is determined from calculations of the design Tevatron optics, the chromaticity from the sextupole correctors $\xi_{\text{b2,correctors}}$ is determined from their excitation currents, and the total chromaticity is measured using the standard technique of varying the RF frequency and measuring the tunes. Using these values in the above equation gives the amount of chromaticity contributed by the Tevatron dipoles, $\xi_{\text{b2,dipoles}}$. This is then used to calculate the b_2 in the dipoles by using calculated ratios of chromaticity to b_2 in dipoles. For the design Tevatron lattice one unit of b_2 in the Tevatron dipoles gives +26.4 units (-24.1 units) of horizontal (vertical) chromaticity. A separate determination of the b_2 component is made from the horizontal and vertical chromaticity. These two values differ by about 0.1 units, but we only report the average value in this paper.

Figure 1 shows the results of the b_2 drift measurements. In each case the Tevatron was returned to the injection porch after a long flattop time, beam was injected as soon as possible (after ~2 minutes), and the chromaticity was measured as a function of time on the front porch. The average amount of b_2 was extracted from these results and plotted in Figure 1. As can be seen from the plot the measured b_2 in the Tevatron dipoles is repeatable in the four experiments which cover a four month period and a range of flattop times from 2.7 to 39.5 hours.

Based on experience from the offline magnet measurements the total b_2 is fitted to a logarithmic function giving the result

$$b_{2,\text{total}}^{\text{fit}}(t) = -4.54 + 0.512 \times \ln\left(\frac{t + 170\text{ s}}{170\text{ s}}\right)$$

where t is the time on the front porch in seconds and b_2 is in units @ 1 inch. Since the total b_2 on the injection porch is a sum of the hysteretic and dynamic sextupole a method is needed to separate the two contributions.

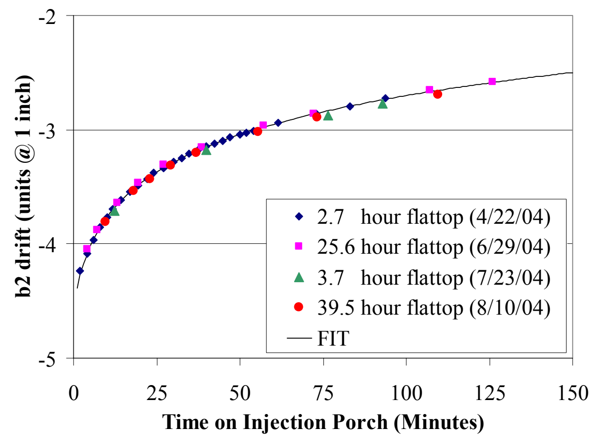

Figure 1. Measured b_2 as a function of time on the injection front porch for four different flattop times.

As determined from measurements with the Tevatron in a ramping state (see the next section) and from magnet measurements, there is also a fast drift of ~0.2 units that occurs in the first few seconds of the injection porch. Using this information we estimate that the hysteretic b_2 on the injection porch is equal to -4.75 units and that the b_2 drift is equal to

$$b_{2,\text{drift}}^{\text{fit}}(t) = 0.21 + 0.512 \times \ln\left(\frac{t + 170\text{ s}}{170\text{ s}}\right)$$

where the fast drift is has been integrated over time into the factor of 0.21 units.

The fast drift in the b_2 was first hypothesized during beam based measurements of the hysteretic b_2 in the Tevatron and later verified with offline magnets. This will become clearer in the next section on snapback measurements

Chromaticity Snapback

Offline magnet measurements have uncovered two features of the snapback: 1) the snapback is well described by a Gaussian function of time since the start of ramp and 2) that the characteristic snapback decay time, t_{SB}, is longer the larger the magnitude of snapback. These results are summarized by the formula for describing the snapback

$$b_{2,SB}(t) = b_{2,\text{drift}}(t_{\text{inj}})e^{-\left(t/t_{SB}\right)^2}$$

$$t_{SB}(b_{2,\text{drift}}) = \sqrt{\frac{b_{2,\text{drift}}(t_{\text{inj}}) - 0.061}{0.0682}}$$

where $b_{2,SB}(t)$ is the amount of snapback as a function of time on the energy ramp.

These two features of the snapback were confirmed with beam measurements of the b_2 snapback in the Tevatron after two different front porch times. In the first case the Tevatron was in a state of continual ramping with a flattop time of about 30 seconds and a front porch length of only 6 seconds. The main purpose of this particular measurement was to determine the amount of b_2 as a function of energy under conditions with minimal b_2 drift. In the second case the snapback was measured after the Tevatron had been on front porch for one hour and the flattop time for the previous cycle was longer than 1 hour. The results of the measured b_2 as a function of time on the energy ramp are shown in Figure 2. Only the start of the energy ramp up to 190 GeV is plotted.

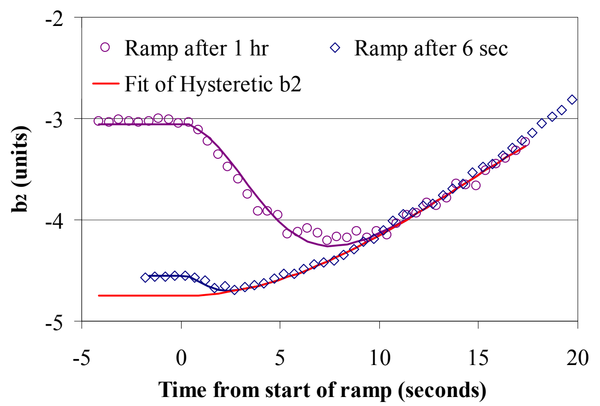

Figure 2. Plot of the measured b_2 as a function of time on the energy ramp for two different length front porches.

To separate the hysteretic and dynamic (snapback) components a quadratic fit was done of b_2 versus energy in the range of 160 to 180 GeV. Since the snapback has completely decayed by these energies only the hysteretic portion of the b_2 remains. An additional constraint of a value for -4.75 units of b_2 at the start of the ramp has also been imposed in the fit resulting in hysteretic value of the b_2 as a function of energy

$$b_{2,\text{hysteretic}}^{\text{fit}}(\Delta E) = -4.75 + 0.063 \times \Delta E - 0.00049 \times \Delta E^2$$

where ΔE is the energy difference from 150 GeV. By extrapolating the fit to lower energies the hysteretic and the dynamic b_2 can be separated. The solid red line in Figure 2 shows the fit to the hysteretic b_2. We note that the hysteretic value at injection of -4.75 was not a free parameter in the fit but vary by about +/- 0.1 units without significantly changing the quality of the fit. The value of -4.75 was chosen based on magnet measurements showing a fast drift of about 0.13 b_2 units [4] and on the results of snapback measurements presented in the next section.

The amount of measured b_2 that is not hysteretic is then the amount of snapback and should follow a Gaussian form. In Figure 2 we plot in solid lines the total amount of b_2 as a sum of the fit hysteretic and a fit to a Gaussian snapback. This is done for both the ramping state with a 6 second front porch and for the ramp after a 1 hour injection porch. For the ramping state we get the fit

$$b_{2,\text{total}}(t) = b_{2,\text{hysteretic}}^{\text{fit}}(t) + 0.21 \times e^{-(t/1.45)^2}$$

and for the 1 hour ramp we get

$$b_{2,\text{total}}(t) = b_{2,\text{hysteretic}}^{\text{fit}}(t) + 1.69 \times e^{-(t/4.75)^2}.$$

In both cases the fits agree will with the measured data. Furthermore we find that the characteristic snapback decay time (1.45 seconds for the ramping state and 4.75 seconds for the ramp after 1 hour) is consistent with the values of 1.42 and 4.88 seconds predicted by the offline magnet measurements for snapbacks with magnitudes of 0.21 and 1.69.

TUNE AND COUPLING DRIFT AND SNAPBACK MEASUREMENTS

Also measured during the studies period were the tune and coupling drifts on the injection plateau. The source of the tune drift has not been conclusively determined but might be explained by feeddown effects from the drifting sextupoles and orbit offsets of ~ 1mm. (See [7] for more on the feedown hypothesis.)

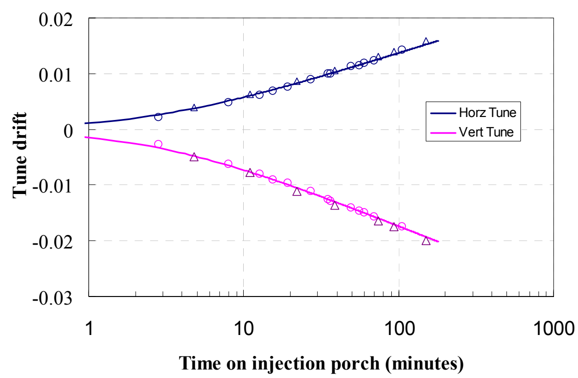

Figure 3. Horizontal and vertical tunes as a function of time on the injection porch.

The amount of tune drift was found to be

$$\nu_{x,\text{drift}}^{\text{fit}} = +0.003819 \times \ln\left(\frac{170\ \text{s} + \text{t}}{170\ \text{s}}\right)$$

$$\nu_{y,\text{drift}}^{\text{fit}} = -0.004840 \times \ln\left(\frac{170\ \text{s} + \text{t}}{170\ \text{s}}\right)$$

Also the coupling drift was measured as a function of time on the injection porch and found to be

$$\kappa_{SQ,\text{drift}}^{\text{Tev-algo}} = -0.00665 \times \ln\left(\frac{170\ \text{s} + \text{t}_{\text{inj}}}{170\ \text{s}}\right)$$

REFERENCES

[1] D.A. Finley, et al., *1987 Proc. of Part. Acc. Conf.* pp. 151-153.

[2] G. Velev, et al., Fermilab note TD-03-045, Dec 2004.

[3] P. Bauer, et al., Fermilab note TD-03-008 Rev 1, Jan 2005.

[4] G. Velev, et. al., TPAP029, these proceedings.

[5] M. Martens, et al., Fermilab note, Beams-doc 467, Nov. 2004.

[6] P. Bauer, et al., EPAC04, Lucerne, Switzerland, July 2004.

[7] P. Bauer, et al., Fermilab note TD-04-052, Dec. 2004.