TUNE AND COUPLING DRIFT COMPENSATION DURING THE TEVATRON INJECTION PORCH *

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Abstract

During Collider Run II operations drifts in the betatron tunes and coupling are observed over a several hour period while the Tevatron is on its injection front porch. Associated with these drifts is a so-called snapback of the tune and coupling at the beginning of the Tevatron energy ramp from the injection porch. The magnitude of the drifts and snapback has added to the efforts to keep the Tevatron tuned for optimal beam conditions and has made it more difficult to understand beam behaviour. Therefore a feed-forward system was implemented to compensate for the tune and coupling drifts and snapback. The cause of the drifts has not been conclusively identified but the leading hypothesis is persistent current effects in the Tevatron superconducting magnets. We have begun experimental investigations to verify this hypothesis and some of the results are presented in this paper.

MEASURED TUNE DRIFT

In Collider Run II drifts of the betatron tunes and the transverse coupling are observed while the Tevatron is at its injection front porch energy of 150 GeV. Fig. 1 shows plots of the measured horizontal and vertical tunes as a function of time at 150 GeV. Because a significant change in the coupling was also observed, each of these tune measurements was made after the Tevatron was decoupled using the trim skew quadrupole magnets.

Similarly, Fig. 2 shows plots of the measured coupling as a function of time at 150 GeV. The amount of coupling was determined by measuring the minimum tune split as the trim tune quadrupole circuits were used to push the horizontal and vertical tunes as close together as possible. We also measured the strength of two families of skew quad circuits that were required to decouple the Tevatron to a minimum tune split of 0.002 or better.

If these tune drifts are related to persistent current effects in the Tevatron magnets then the history of the previous energy ramp is an important factor determining the amount of drift. This factor was not examined in detail. Instead we focussed on the behaviour of the tunes and coupling after a standard Tevatron ramp pre-cycle. Presently the standard pre-cycle is essentially a ramp of the Tevatron magnets in the same sequence used during a collider store but without beam and with only a 20-minute duration at the flattop energy of 980 GeV (as compared to the ~12-24 hour flattop duration during a collider store.) Figs. 1 and 2 include measurements taken on several occasions over a one-year period. In each case the standard ramp pre-cycle was performed and the results demonstrate the repeatability of the drifts.

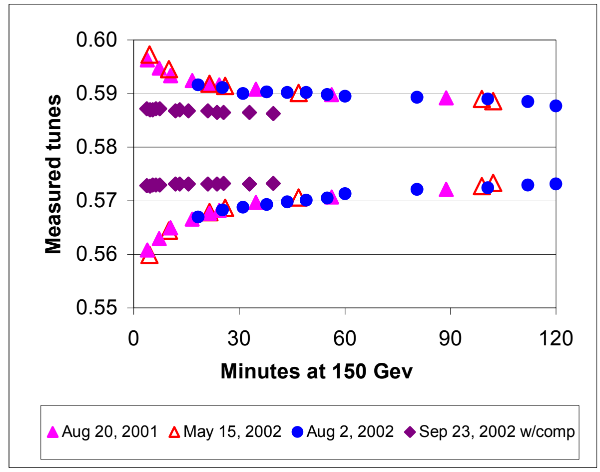

Figure 1: Measured horizontal (upper) and vertical (lower) tunes as a function of time at 150 GeV on three different days. Included is a plot of the measured tunes after the compensation was implemented in Sept. 2002.

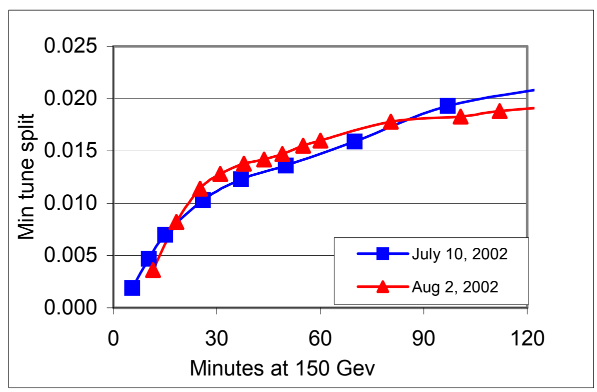

Figure 2: Measured minimum tune split as a function of time at 150 GeV on two different days.

Associated with the drifts at 150 GeV is a so-called snapback of the tune and coupling that occurs at the beginning of the Tevatron energy ramp from the injection porch. The magnitude of the tune and coupling snapback has not been measured as accurately as the tune drift at 150 GeV. However, from observations of the tunes near the start of the Tevatron ramp it is clear that tune variations of ~0.01 are present.

For Tevatron operations we prefer to maintain the tunes within a tolerance of about ~0.002 and to keep the transverse coupling below ~0.003 units. Thus these large drifts were a problem and a feed-forward system was implemented to counter act these drifts.

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DRIFT COMPENSATION

The drift compensation system applies a correction to the tune and coupling circuits on the 150 GeV front porch in the form a logarithm function. The change in the tune circuits follows the equations

$$\Delta\nu_x(t) = -0.00778 + 0.0019 * \ln(t) \quad (1)$$

$$\Delta\nu_y(t) = +0.0127 - 0.0031 * \ln(t) \quad (2)$$

$$\Delta\kappa_{SQ}(t) = +0.0250 - 0.0061 * \ln(t) \quad (3)$$

where t is the time in seconds since the start of the injection porch and the coefficients were determined from fits to the measured data shown in Figs. 1 and 2.

After implementing the correction algorithm the tunes and coupling were measured again as a function of time on the front porch and these are plotted in Fig. 1. We also measured the coupling as a function of time and found that the minimum tune split remained below 0.002 during this time.

In addition to the drifts at 150 GeV, there is also a snapback effect that causes large coupling and tune changes at the start of the energy ramp. It is time consuming to measure the tunes and coupling at the start of the Tevatron ramp so the snapback has not been investigated as thoroughly as the drift on the front porch. Instead we chose to implement the snapback correction the same manner as the chromaticity snapback correction. The correction that is applied at the start of the Tevatron energy ramp has a polynomial form

$$< x^2 > = x_{2,start}\,[1-(t/T)^2]^2$$

where $<x_2>$ represents one of the tune or coupling variables $<\Delta\nu_x>$, $<\Delta\nu_y>$, or $<\Delta\kappa_{SQ0}>$. The value of $x_{2,start}$ is the value of $<x_2>$ at the time of the start of the Tevatron energy ramp. The values of $x_{2,start}$ are determined just before commencing the energy ramp and the corresponding corrections are loaded into hardware. The time constant for the snapback correction, T, is presently set to 6 seconds. This choice was based on the hypothesis that the source of both the chromaticity and the tune/coupling coupling drifts are related to persistent currents and would therefore have similar time variations.

Without the snapback compensation we observed tune changes of about 0.01 at the start of the Tevatron ramp. With the snapback compensation in place the tunes at the start of the ramp deviate by less than ~0.003 tune units.

SOURCE OF THE TUNE DRIFT

It has been known for some time that persistent current effects in the Tevatron dipoles create time-varying sextupole fields that cause drifts in the chromaticity on the injection front porch and a snapback at the start of the energy ramp [1,2,3]. Furthermore the magnitude of the time-varying sextupole fields depends on the previous Tevatron energy ramp cycle and parameters such as: the energy of the previous flattop, the time spent on the previous flattop, and the time spent on the previous front porch. In order to compensate for the drifting sextupole fields a correction algorithm is used to control the trim sextupole correctors while the Tevatron is at 150 GeV and during the snapback at the start of the ramp [2,3].

It is reasonable to hypothesize that tune and coupling drifts and snapback are also related to persistent currents. We have been investigating this possibility with both beam based measurements and magnetic field measurements in the Tevatron superconducting magnets. We have not reached a conclusion regarding the source of the drifts but we have begun analysis and we report some to the results in this section. The three main possibilities being considered are a feeddown effect from the drifting sextupole field in the Tevatron dipoles and an orbit offset, drifting quadrupole component in the Tevatron dipoles, and drifting quadrupole strength in the Tevatron quadrupoles.

Tune drift from sextupole feeddown effect

One possible explanation for the tune and coupling drifts is a feeddown effect from orbit offsets and the time-varying sextupole fields in the dipole magnets. The horizontal tune change from horizontal orbit offsets in sextupole magnetic fields is given by the formula

$$\Delta\nu_x = \frac{1}{4\pi}\sum\left((\beta_x\ L\Delta K_2)\left((\Delta p/p)D_x + x_0\right)\right) \quad (4)$$

where β_x is the horizontal beta function, L is the length of the magnet, ΔK_2 is the change in sextupole field gradient, and $((\Delta p/p)\ D_x + x_0)$ is the horizontal orbit position due to position and momentum errors. The sum is over all sextupole fields which, in the case of the Tevatron, includes the sextupole component, b_2, of the Tevatron dipoles and the two families of chromaticity correction sextupole magnets (which we refer to as T:SF and T:SD in the Fermilab nomenclature.)

We make use of Eq. 4 by assuming: 1) that we know the lattice functions β_x and D_x at the locations of the sextupole fields, 2) the sextupole gradient strength in the chromaticity sextupoles are known from the current in these circuits, and 3) that we can determine the average time varying sextupole component in the Tevatron magnets from chromaticity measurements. As for item 3) above, we know that the chromaticity does not change, $\Delta\xi = 0$, when the chromaticity compensation is active. Since the total variation in the chromaticity is the sum of the change from the b_2 in the dipoles and sextupole correctors, and the applied correction is known, we can estimate the average time-varying b_2 field in the Tevatron dipoles. With these assumptions the undetermined variables in Eq. 4 are the average horizontal orbit offsets in the dipoles and chromaticity sextupoles.

To determine the average offset in the sextupole correctors we measure the tune shift from a change in the strength of the sextupole field, ΔK_2, in the T:SF or T:SD magnets. If we make this measurement as a function of momentum offset Δp/p then we can determine the average value of the horizontal orbit offset in T:SF and T:SD circuit. Using the relationship between the RF frequency and the beam momentum, (Δf/f) = -η(Δp/p) where η is the slip factor, we can extract this tune change from Eq 4 as

$$\Delta \nu_x = (\Delta K_2 \mathrm{L}) \frac{N}{4\pi} \left(-\frac{1}{\eta} \langle \beta_x \mathrm{D}_x \rangle (\Delta f / f) + \langle \beta_x \mathrm{x}_0 \rangle \right)$$

where N is the number of magnets in the circuit and 〈〉 denotes the average value.

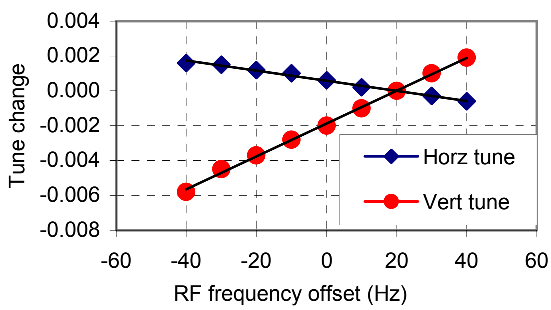

Figure 4: Measured tune change from a 0.5 amp change in the sextupole circuit T:SD versus the RF frequency offset.

An example measurement is shown in Fig. 4 for the T:SD sextupole family. In this case we see that a +20 Hz offset from the nominal RF frequency is needed in order to observe no tune shift from the T:SD circuit. This corresponds to an average horizontal orbit offset of +0.34 mm to the radial outside. A similar measurement for the T:SF circuit shows that an RF frequency offset of 0 Hz is needed corresponding to no average horizontal orbit offset in the T:SF magnets. The average orbit offset in T:SF and T:SD, along with the measured tune drift, can be used in Eq. 4, to determine the average orbit offset in the Tevatron dipoles that is required to explain the feedown hypothesis.

An analysis along these lines would require a –0.68 mm average orbit offset in the Tevatron dipoles if the horizontal tune drift is used and would require a –0.95 mm horizontal orbit offset if the vertical tune drift measurement is used.. Thus the horizontal and vertical tune data are not consistent for this hypothesis. In addition to these measurements, we also have Beam Position Monitor data of the orbits. In particular the average horizontal BPM position at the location of the T:SF magnets is –0.71 mm. This is inconsistent with the value of 0 mm determined from the feeddown measurements. If we choose to use the BPM data as the position in the T:SF magnets then an even larger average horizontal orbit offset in the dipoles is needed to explain the observed tune drift.

In addition to the tune drift, there is a time varying coupling change that, if left uncorrected, results in a minimum tune split of about 0.02 tune units after about 2 hours. Explaining this drift with the feeddown hypothesis requires an average vertical orbit offset of about +0.94 mm in the Tevatron dipoles. Recent survey results have shown that there are systematic mechanical rolls of many Tevatron dipoles which result in vertical kicks of the beam. Although the orbits are corrected using trim dipole magnets the relatively large spacing between vertical correctors (8 dipoles between correctors) produces a scalloped orbit that results in a net vertical orbit offset in the dipoles even though the BPMs record no net vertical offset. An analysis of this effect has been done but the vertical orbit offset resulting from the rolled dipoles explains only about 1/3 of the coupling drift [4].

Drifting quadrupole fields in the Tev magnets

Another possible source of the tune drift is a time-varying quadrupole field in the Tevatron, for example a drift of the main field in the arc quadrupoles. In order to explain the tune drifts at 150 GeV we find that an integrated gradient of $\Delta K_1 L=0.0033$ is needed, which is equivalent to ~2 b_1 units (of 10^{-4} of the main quad gradient) per Tevatron arc quadrupole,This is of the same order as the main field decay observed in HERA and LHC dipole magnets. It can therefore not be excluded that main field decay in the Tevatron quadrupoles explains part of the tune drift. Experimental verification of this issue is in the planning stages. These drifts can presumably be explained by the same phenomena that cause the drift in the sextupole and other allowed harmonics. Although a significant b_1 component should not be present in the dipole magnets, there is also the possibility of a b_1 drift in Tevatron dipole magnets. A very small drift of ~0.1 units in b_1 would be required.

Similarly the coupling drift can be related to a drifting skew quadrupole, a_1. A derivation of the a_1 needed to produce the observed change of minimum tune split over a 2 hrs injection, indicates that ~70 units of a_1 distributed over all dipoles would be required, again a very small effect. Although a significant a_1 component should not be present in the dipole magnets, there is some experimental evidence of such a_1 drifts exist in Tevatron dipole magnets. Although hard experimental evidence is still missing, the possibility of explaining part of the tune and coupling drift by drifting b_1 and a_1 in the Tevatron main magnet should not be excluded.

REFERENCES

[1] G.V. Velev, et. al, "*Measurements of Field Decay and Snapback Effect on Tevatron Dipole Magnets*," WPAE016, this conference.

[2] M. Martens and J. Annala, "*Chromaticity, Tune, and Coupling Drift and Snapback Correction Algorithms in the Tevatron,*" Internal Fermilab Memo, Beams-doc-467, March 3, 2003, available on-line at http://beamdocs.fnal.gov/cgi-bin/public/DocDB/ShowDocument?docid=467.

[3] P. Bauer, et. al. "*Analysis of the b2 Correction in the Tevatron.*" TPPB055, this conference.

[4] M. J. Syphers, "*Effects of Systematic Rolls of Tevatron Magnets*," Internal Fermilab Memo, Beams-doc-429, February 11, 2003.