PROPOSALS FOR IMPROVEMENTS OF THE CORRECTION OF SEXTUPOLE DYNAMIC EFFECTS IN TEVATRON DIPOLE MAGNETS*

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Abstract

It is well known that the sextupole (b_2) component in superconducting dipole magnets decays during the injection plateau and snaps back rapidly at the start of the ramp. These so-called dynamic effects, which also appear in other magnetic multipoles, were originally discovered in the Tevatron. The chromaticity correctors, distributed around the ring, correct for this effect. Imperfect compensation of the dynamic b_2 in the magnets, in particular during injection and snapback, can contribute to beam loss and emittance growth. In the context of recent efforts to improve the Tevatron luminosity, a thorough investigation of the b_2 correction in the Tevatron was conducted, including beam chromaticity measurements and extensive offline magnetic measurements on Tevatron dipoles. This study has yielded new information about the effect of the powering history on the dynamic b_2 effects. Study findings have also resulted in new proposals for improvement of the sextupole snapback correction in the Tevatron, including a revised functional form for the snapback algorithm and the possibility of eliminating the beam-less pre-cycle. This paper introduces the proposals for an improved b_2 correction in the Tevatron and reports on the results of beam studies performed recently to test them. A companion paper describes in detail the results of the magnet measurements [1].

INTRODUCTION

Dynamic effects were discovered in the Tevatron, too late for systematic study of the magnets prior to installation in the ring. They are therefore known only from dedicated measurements conducted on a small number of magnets, dominantly from the spare-pool. The latest measurement campaign is being conducted now in the context of the Tevatron collider run-II. Thus far, we have magnetic measurement data for ~10 magnets. This is too little to derive a statistically significant average of the entire machine. Combined with beam-studies, however, in which the all-Tevatron average b_2 is explored (albeit with less accuracy), the magnetic measurements guided us in the task of improving the accuracy of the Tevatron b_2 feed-forward correction algorithm. Also helpful in this regard were recent improvements in the general understanding of dynamic effects in superconducting magnets, provided to us by the LHC magnet R&D.

This paper is a follow-up to a previous publication, [2], which discussed the status of this work one year ago, when first evidence from magnetic measurements and beam-studies pointed to possible improvements of the Tevatron b_2 correction. Also, a technical note, [3], can be consulted for further details. Dynamic effects in superconducting magnets are described in detail in [4]. The currently used dynamic b_2 compensation is derived from fits of the b_2 decay and snapback characteristics measured in 1996 on one Tevatron dipole. These fits are functions of different pre-cycle parameters, such as the flat-top time, t_{FT}, and back-porch time, t_{BP}, and given below (Eq. 1&2), where $m \sim 0.3$ and $b_{2,ini} \sim -1$ units of 10^{-4} of the dipole field (at 25.4 mm). The pre-cycle, which precedes beam injection in the Tevatron, serves to homogenize the magnet ensemble with respect to the dynamic effects.

$$b_2^{drift}(t) = b_{2,ini}(t_{FT}, t_{BP}) + m(t_{FT}, t_{BP})\ln(t) \quad (1)$$

$$b_2^{SB}(t) = b_2^{drift}(t_{IP}, t_{FT}, t_{BP})\left(1-\left(\frac{t}{t_0}\right)^2\right)^2 \quad (2)$$

MAGNET MEASUREMENTS

Fig. 1 shows the drift and snapback in these magnets measured with rotating coils (see [1] for details on the magnetic measurements), following a standard Tevatron pre-cycle. Such a pre-cycle consists of a 20 min flat-top at 980 GeV, a 1 min back-porch at 150 GeV, followed by a brief reset at 90 GeV before returning to the 150 GeV injection porch. Note that for this plot the geometric and hysteretic b_2 were removed from the measurement results to reveal the dynamic effects only. We believe that the variations of the starting point of the drift seen in Fig. 1 are an artifact of the measurement*. Fig. 1 clearly reveals magnet-to-magnet variations of the drift amplitudes for a given pre-cycle by up to a factor two. Fig. 1 also shows that the snapback function now used in the Tevatron dynamic b_2 compensation under-estimates the duration of the snapback. Note that these measurements were performed after a 30 min injection porch. The discrepancy becomes larger for snapbacks following 1-2 hours at injection, as is typical for the Tevatron shot setup. This, because the snapback duration increases with the drift amplitude, since it takes a larger field change (in the bore

*Supported by the Universities Research Association, Inc., under contract DE-AC02-76CH03000 with the U.S. Department of Energy
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*The length of the rotating coils is not an integer multiple of the period of the periodic pattern (~2.5”) such that the integration over the longitudinal b_2 pattern is not complete, with some residual b_2 pattern coupling into the measurement. The effect seen in Fig. 1 is the change of pattern amplitude during the 30 min injection porch. The pattern, of course, is not relevant to the beam.

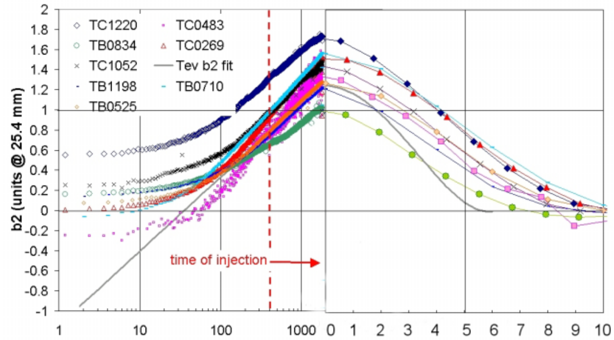

Figure 1: b_2 drift and snapback (vs time in sec) measured in Tevatron dipoles after a standard pre-cycle. Also shown is the prediction from the Tevatron b_2 correction algorithm.

and in the coils) on the ramp to resolve the snapback. Therefore, one of the proposals for the improvement of the Tevatron b_2 correction discussed below is to change the snapback function. Another paper submitted to this conference discusses the correlation between the snapback field (i.e. the bore-field needed to completely resolve the snapback) and the drift amplitude for Tevatron and LHC dipoles [5].

As discussed in [1], the most important pre-cycle plateaus for the dynamic effects are the back-porch and flat-top. The drift is more pronounced the shorter the back-porch and the longer the flat-top. Fig. 2 shows the drift amplitudes in five Tevatron dipoles after 30 min at injection for different pre-cycle flat-top and back-porch durations. Also shown is the prediction of the current Tevatron b_2 fit, which, in the case of the flat-top duration effect, clearly departs from the experimental results†.

The saturation of the drift slope after ~40 min on the flat-top is also an important experimental finding. It indicates a characteristic time for the memory in the magnets for dynamic effects. In order to have all magnets in a similar state (with the same "memory") it is necessary to ramp the machine through a ≥~40 min beam-less pre-cycle. This will be another proposal for improvement of the Tevatron b_2 correction, as discussed next.

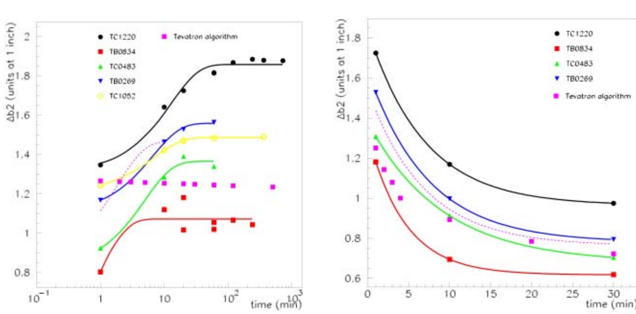

Figure 2: b_2 drift amplitude after 30 min at injection for different pre-cycle flat-top (left) and back-porch (right) durations in five Tevatron dipole magnets at 4.0 K.

† *The discrepancy is, in part, the result of the change of some of the parameters of the original fit during fine-tuning in the Tevatron, during which the correct dependence from the original magnet data was lost.*

PROPOSALS FOR IMPROVEMENTS

As a conclusion to the experimental data discussed above and in [1], the following three modifications of the current Tevatron b_2 correction scheme are proposed:

- Fix (and extend) the back-porch in the pre-cycle.
- Eliminate the beamless pre-cycle in most cases; change its parameters in the remaining cases.
- Improve the functional shape of the drift and snapback algorithm.

The off-line magnetic measurements have shown that the back-porch time is the pre-cycle parameter with the strongest impact on the b_2 drift and snapback behavior in Tevatron magnets. In the current Tevatron shot set-up procedure the time on the back-porch is variable since it requires some manual machine adjustments by the operators. We propose that the Tevatron back-porch time be fixed to reduce the shot-to-shot variability in dynamic effects. This will be beneficial to the Tevatron because it will simplify the b_2 correction algorithm by eliminating the back-porch time parameter. Our proposal is to set the back-porch duration to a constant, >5 min, to reduce the drift amplitude, especially if this can be done without a net increase of the total shot setup time.

The current collider pre-cycle, consists of a 20 min "dry-squeeze" at flat-top and takes approximately 45 min. In the case of a quench, for instance, there are differences in ramp and temperature history within the magnet population and the pre-cycle is needed. Following an intentional beam abort, however, the powering history is the same for all magnets and it is possible to eliminate the pre-cycle and reduce the shot set-up time. The estimated gain in integrated luminosity is ~3% (and this includes the fact that ~1/3 of the beam aborts are not intentional). The elimination of the beam-less pre-cycle will result in a condition in which the preceding shot becomes the pre-cycle of the following shot. This implies that the flat-top duration of the pre-cycle can be very long (~20 hrs) and that the pre-cycle front-porch becomes a variable parameter (since the injection for the previous shot is performed there). Regarding the former we now know that the dynamic b_2 drift slope saturates for a pre-cycle flat-top duration >40 minutes. Long flat-top times therefore are another reason for better shot-to-shot reproducibility in dynamic effects. The increase of the drift slope that the long "pre-cycle" flat-top entails is not desired. However, it can be compensated with the decrease in slope due to the extension of the back-porch. The effect of the front-porch parameter was investigated in a series of measurements in one Tevatron dipole. Since no noticeable effect was found, we concluded that the variable front-porch does not need to be addressed in the b_2 correction. Obviously, the pre-cycle cannot be eliminated when a magnet quench occurred. One or more pre-cycles have to be applied in order to erase differences between the quenched and non-quenched magnets. At present, the Tevatron is ramped through six fast pre-cycles in this case. Instead, we propose to use only one pre-cycle with a 40 min flat-top. We have shown in dedicated measurements, reported in [1], that the sequence of six fast pre-cycles results in a drift slope below the saturated value found after a single pre-cycle with a >30 min flat-top. This indicates that the condition obtained after the multiple pre-cycles is one where residual memory persists. This and the fact that a single pre-cycle reduces the thermal load on the Tevatron cryo-system led us to propose the 40 min flat-top pre-cycle for this case.

As clearly shown in Fig.1 and discussed in [2], our magnet- and beam-based measurements show that the Tevatron b_2 correction algorithm underestimates the drift amplitude and snapback duration. The snapback time, t_0, for the case in Fig. 1 should be ~10 sec rather than the current 6 seconds. Furthermore, we find that the functional form that fits the snapback best is a Gaussian function rather than the polynomial function (Eq.2). Eq.2's most significant weakness is that it does not reflect the correlation between snapback field and drift amplitude‡, discussed in detail in [5]. Our proposed snapback fit is given in Eq. 3, where $b_{2,drift}$ is the drift amplitude at the start of the snapback and t is the time from the start of the snapback. The time constant, $t_{0,sb}$, depends on the drift amplitude (and thus indirectly on ramping history parameters). This ensures that a longer snapback interval, accompanies a greater drift.

A function of the type given in Eq. 4 (with t_0~60 sec and m~0.3) provides a better fit of the magnet b_2 drift data, than Eq.1. Also note that the back-porch parameter has been eliminated. The use of a new b_2 drift function would also resolve the issue of the b_{2ini} parameter in Eq.1. We now believe that the history dependence of b_{2ini} is an artifact of a residual pattern effect, as discussed above for Fig. 1.

$$b_2^{snap}(t) = b_2^{drift} e^{-\frac{t^2}{\left(t_{0,sb}\left(b_2^{drift}\right)\right)^2}} \qquad t_{0,sb}\left(b_2^{drift}(t_{inj})\right) = \sqrt{\frac{\left(b_2^{drift}(t_{inj})\right) - a}{b}} \quad (3)$$

$$b_2^{drift}(t) = m(t_{FT})\ln\left(\frac{t-t_0}{t_0}\right) \quad (4)$$

BEAM STUDIES

Beam studies were conducted to test the proposed changes in the Tevatron b_2 correction. The following describes a chromaticity (ξ) measurement during the drift on injection porch following a 5 min back-porch, 2.7 hr flat-top pre-cycle, as proposed above for the Tevatron. The Tevatron was prepared with the prescribed pre-cycle and after fast injection of an un-coalesced, proton-only beam on the center orbit, fast ξ measurements were performed every two minutes. The average magnet b_2 was derived from the measured ξ with Eq.5, where ξ_{nat} is the natural chromaticity (~-29 units according to MAD) and ξ_{b2corr} is the chromaticity supplied by the sextupole correctors (extracted from the Tevatron corrector control program). Note that ~25 units of ξ in the Tevatron correspond to 1 unit of b_2 in the dipoles.

‡ *This correlation, however, is partly masked in the time-base by the fact that the magnetic field ramp from injection is parabolic.*

$$\xi_{tot,i} = \xi_{meas,i} = \xi_{nat,i} + \xi_{b2mag,i} + \xi_{b2corr,i} \quad i = x, y \quad (5)$$

Fig. 3 shows the chromaticity derived average b_2 in the Tevatron during the injection porch. More details on the beam study are given in [6]. Fig. 3 also shows the prediction with the present Tevatron b_2 drift algorithm. It over-estimates the drift at times <30 min and under-estimates it at times >30 min, causing ξ in the Tevatron to first increase by several units and then to decrease. The plot also contains a drift curve derived from a measurement on a particular Tevatron dipole for a 60 min flat-top and 5 min back-porch condition. This is the only magnet for which 5 min back-porch magnetic measurements were performed. –4.5 units of b_2 were added to the drift fit for this magnet to represent the average hysteretic and geometric b_2 of the Tevatron at injection (those are naturally included in the beam measurement). The details of this procedure are described in [3]. It is not surprising that this particular measurement does not agree with the beam-derived average Tevatron behavior. As can be seen in Fig. 1, this magnet has a smaller than average drift slope. A simple scaling factor of 1.45, however, generates very good agreement. This is very encouraging since it indicates that the average Tevatron behavior is proportional to that of any single magnet. The next beam study planned will put the new b_2 snapback function to the test.

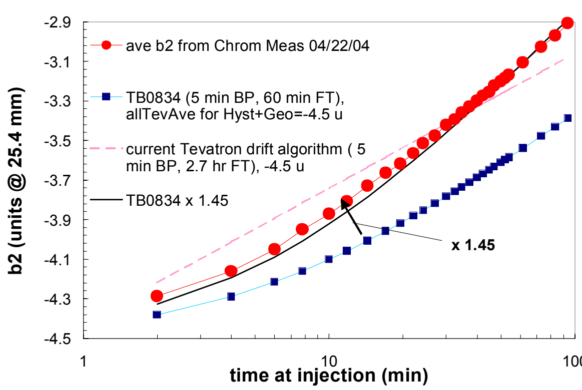

Figure 3: b_2 drift derived from chromaticity measurements after a 5 min back-porch / 2.7 hrs flat-top as compared to a measurement in Tevatron dipole 834.

ACKNOWLEDGMENTS

The continued encouragement and support of R. Kephart, head of Fermilab's Technical Division, and V. Shiltsev, head of the Tevatron department, is gratefully acknowledged. We would also like to thank L. Bottura from Cern for his very valuable advice and his interest.

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