NEW MEASUREMENTS OF SEXTUPOLE FIELD DECAY AND SNAPBACK EFFECT ON TEVATRON DIPOLE MAGNETS *

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Abstract

To perform detailed studies of the dynamic effects in superconducting accelerator magnets, a fast continuous harmonics measurement system based on the application of a digital signal processor (DSP) has been built at Fermilab. Using this new system, the dynamic effects in the sextupole field, such as the field decay during the dwell at injection and the rapid subsequent "snapback" during the first few seconds of the energy ramp, are evaluated for more than ten Tevatron dipoles from the spare pool. The results confirm the previously observed fast drift in the first several seconds of the sextupole decay and provide additional information on a scaling law for predicting snapback duration. The information presented here can be used for an optimization of the Tevatron and for future LHC operations.

INTRODUCTION

In recent years, an extensive program to measure persistent current effects in the Tevatron dipoles was executed. Initially, the program was started to optimize the Tevatron correction algorithm for the sextupole field decay during the dwell at injection and for the subsequent "snapback", which occurs in the first few seconds of the energy ramp. As a result of the program, a new improved set of feed-forward correction algorithms for the decay and snapback was proposed [1].

In 2005, the new algorithms were first tested and later implemented in the Tevatron operation [2-3]. Beam tests, however, suggested a difference in b_3 of ~0.21 units (1 unit is 0.01% of the main dipole field) between the accelerator and stand-alone magnet measurements. The discrepancy was later explained with a fast sextupole decay in the first 6-20 s of the injection plateau. This fast decay, reported for the first time in [4], added an additional challenge to our understanding of the dynamic processes in superconducting magnets.

The combined result from measurements of the snapback amplitude and snapback duration on LHC and Tevatron dipoles indicated a simple linear dependence between them. This dependence, or “scaling law” [5], states that the field decay amplitude and the current necessary to resolve it (the snapback duration is thus a function of this current) are strongly correlated for magnets of similar design. To quantify this statement more accurately, especially in the case of very short injection plateaus where the decay amplitudes are expected to be close to zero, additional measurements were needed.

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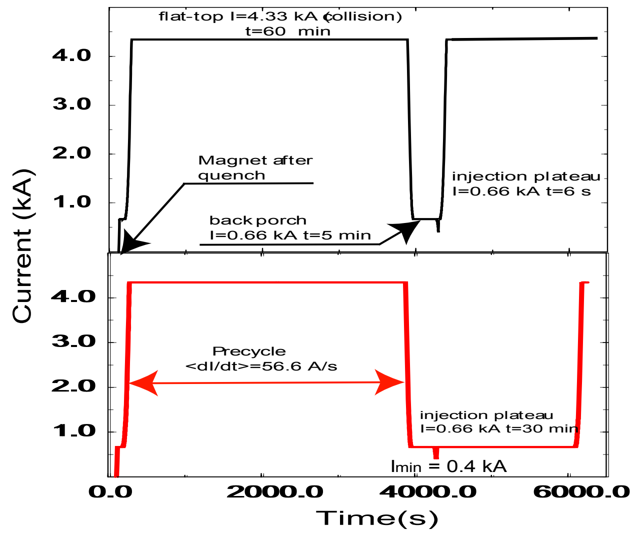

Figure 1: Two typical current cycles used in the decay and snap-back measurements. The upper (lower) plot represents a cycle with the shortest (longest) IP duration of 6 s (30 min).

A new fast continuous measurement system, based on DSP boards, was recently developed for the Fermilab magnet measurement program. This system was initially deployed in the summer of 2005 and the results from three dipoles (TB0834, TC0710 and TC1077) were presented in [6]. Since then, ten additional Tevatron dipoles from the spare pool (TB0295, TB0491, TB0701, TB1063, TB1067, TC0861, TB1130, TC1047, TC1061, TC1206) were measured in the Fermilab Magnet Test Facility.

In preparation for the measurements, each magnet was quenched and then powered with the same pre-cycle (60 min flat-top (FT) at 980 GeV, followed by 5 min back-porch (BP) at 150 GeV, fast reset at 90 GeV and a ramp to 150 GeV injection plateau) which are as close as possible to the operational Tevatron cycle. After the pre-cycle, we executed measurements with different durations of the injection plateau (IP): 6, 12, 20, 30, 60 s and 1, 5, 10, 15, 20, 25, 30 min. Figure 1 shows two typical examples for the executed current profiles with the minimal (6 s) and maximal (30 min) duration of IP.

MEASUREMENTS OF THE SNAPBACK AND FAST FIELD DECAY

At the Tevatron, the snapback compensation is done according to a Gaussian form, shown in Eqn. 1,

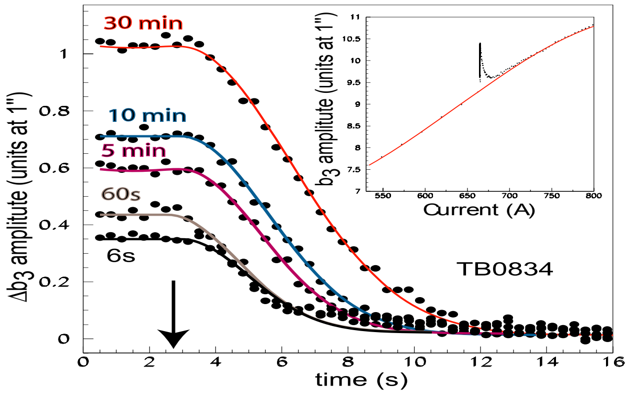

Figure 2: Typical sextupole decay amplitudes Δb_3 versus the snapback time for magnet TB0834. The different fits with corresponding points are the measured snapbacks for different IP durations. The arrow points at the beginning of the snapbacks. The inset shows the correction to the b_3 hysteresis loop, which was done by a second order polynomial.

$$\Delta b_3^s(t) = \Delta b_3^{dec}(t_{inj})\exp(-t^2/t_{sb}^2) \quad (1)$$

where Δb_3^{dec} is the amount of decay as a function of injection time, t_{sb} characterizes the duration of the snapback starting at the beginning of the current ramp (Fig. 1).

Typical sextupole snapbacks for different IP durations are shown in Fig.2. To decouple the snapback from the underlying hysteresis loop, we parametrized the b_3 loop with a second order polynomial in the regions 0.56-0.65 kA and 0.72-0.80 kA, outside of the decay and snapback regions. We interpolated the b_3 hysteresis value to the injection plateau current at 0.66 kA and subtracted it from the sextupole field (see the inset in Fig. 2) to derive the snapback component.

From Fig.2, one can observe that the decay after 6 s IP is on the order of 0.35 units and increases relatively slowly with the IP duration. This phenomenon suggests relatively fast decay (order of 0.05 units/s) in the first several seconds after the current has reached the nominal IP value. The decay amplitudes after the 6 s IPs for the measured Tevatron dipoles are summarized in Fig. 3 (left). The dashed line shows the average decay amplitude (0.35 units), which is comparable to 0.21 units found in the Tevatron beam studies [2], at the beginning of the IP. This decay amplitude is unexpectedly large compared to the predictions of the existing models and empirical parametrizations [7].

As was reported in [4], one of the magnets (TC1130) showed a large deviation from the pattern. Its decay amplitude is much larger (Fig. 3, right), approximately one unit. We extensively compared this magnet to the 12 other measured dipoles. One hypothesis was that this magnet was produced from a different cable batch than the other dipoles. We found another spare dipole (TB1136) produced close in time to TC1130, and it was examined: it performed like the other magnets, with decay amplitude of 0.25 units after 6 seconds of IP.

The only observed difference in the comparison between TC1130 and the other batch of magnets was its strong dependence of the hysteresis loop on the ramp rate, which points towards a large eddy current effect in the magnet.

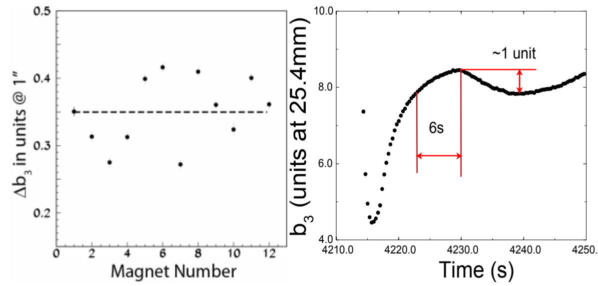

Figure 3: The sextupole decay amplitudes after 6 s IP for the set of 12 measured Tevatron dipoles (left). The dashed line represents the average decay amplitude (note TC1130 is not included in the average). The relatively large decay and snapback observed in TC1130 (right).

CHECKS OF THE SCALING LAW

The recent tests of the LHC and Tevatron dipoles have shown a strong correlation between the decay amplitude Δb_3^{dec} and snapback duration t_{sb} [5]. The second variable is directly connected to the current change ΔI in the beginning of the energy ramp. In the case of the Tevatron current profile, the beginning of the ramp has parabolic dependence on time: $\Delta I = a\, t_{sb}^2$ where a is a current ramp constant (it is the same for all of the performed measurements) and as a consequence

$$\Delta b_3^{dec} \sim \Delta I \quad (2)$$

The first main assumption of the recently proposed scaling law [5] is that the functional form (2) has a linear dependence without an intercept term. The second one has a more general form and states that all the magnets of similar design, for example the Tevatron dipoles, have the same linear dependence.

Having at hand a statistically relevant sample of twelve magnets measured with our fast signal processing system, we are able to perform an additional check of the above assumptions.

First we checked the linearity separately for each of the measured Tevatron dipoles by fitting with a 3rd order polynomial Δb_3^{dec} versus ΔI distributions. To account for the possibility of underestimating the uncertainties from the initial snapback distribution fits, we conservatively increased them by 80%. This number covers additional systematic effects that we estimated from the point-to-point fluctuation in the initial distributions. Fig. 4 (left) shows the parabolic term coefficient returned by the fit. The average value of 0.0002±0.0003 units/A^2 is consistent with zero. In the next step, we refitted the Δb_3^{dec} versus ΔI distributions with a linear form. The intercept values returned from these fits are shown in Fig.4 (right). The average value, 0.056±0.002, is inconsistent with zero. This observation is indirect confirmation that some fast non-linear process occurs in the first several seconds of

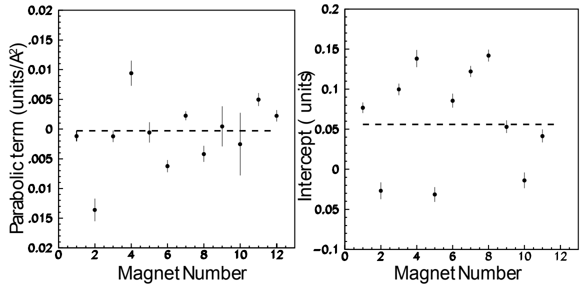

Figure 4: The parabolic term returned by the fit of Δb_3^{dec} versus ΔI distributions for the set of 12 Tevatron dipoles (right). The same plot but for the intercept in case of the linear fit is shown on the right. The dashed lines represent the average values.

the decay at IP. For example, if the same linear dependence is valid for the first several seconds of the IP, one might expect that the intercept should be consistent with zero.

In addition, the performed measurements gave us the ability to check the more general statement of the scaling law: the magnets of the same family should have the same linear dependence Δb_3^{dec} vs ΔI. Fig. 5 shows the linear fits for the examined dipoles. The twelve magnets have slope values with large variation, spreading in the range from 0.150 to 0.231 units/A with an average statistical and systematical uncertainty of 0.002 units/A. The obtained result contradicts the second statement of the scaling law.

Irrespective of the above result, the scaling law was implemented successfully in the Tevatron operation. The dashed line in Fig. 5 corresponds to the linear dependence used to predict the snapback duration knowing the Δb_3^{dec} amplitude from the decay parametrization (for details see ref. [2]). For every measured magnet, we showed that the linear approximation describes very well the Δb_3^{dec} versus ΔI evolution of the snapback, if the duration of the IP is larger than several seconds. In the case of the Tevatron, the operational IP durations may vary from several minutes up to hours where, for individual magnets, the Δb_3^{dec} vs ΔI is in the linear region. In the Tevatron, where the beam sees a superposition of every magnet's characteristics, any linear effect in the dipoles will manifest itself as linear dependence on the same effect in the beam based measurement.

CONCLUSION

Using our fast DSP-based DAQ system [6], a detailed program of magnetic measurements was performed on a dozen Tevatron dipoles. The existence of the relatively large decay in the dipoles after very short IPs (6 s) [4] was confirmed. The Δb_3^{dec} vs ΔI dependence for IP durations greater than 6s is clearly linear; we found that the average parabolic term in the third order polynomial fit is consistent with zero. The linear fits, however, improved when using a non-zero value for the intercepts.

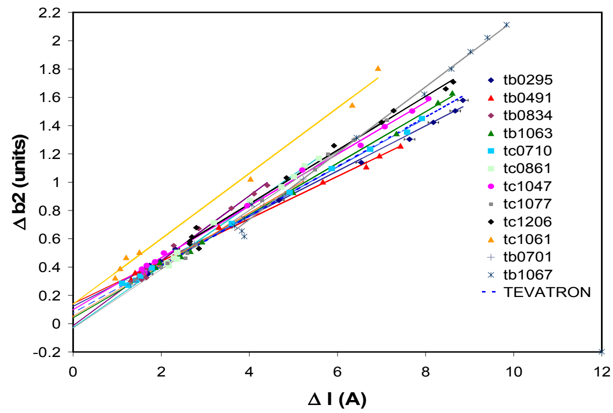

Figure 5: The sextupole decay amplitude Δb_3 versus the snapback current ΔI for twelve Tevatron dipoles. The linear parametrizations are also shown. The dashed line represents the average Tevatron line obtained from the beam measurements.

In addition, an accurate check of the scaling law was performed. The Tevatron dipoles show close but distinguishably different slopes, varying in the range 0.150-0.231 units/A, in the Δb_3^{dec} vs ΔI evolution of the snapback.

The results from these measurements will be useful at the beginning of the future LHC operation, where the injection plateau is expected to be relatively short and accurate dynamic corrections are critical to the initial beam stability.

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