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A SCALING LAW FOR PREDICTING SNAP-BACK IN SUPERCONDUCTING ACCELERATOR MAGNETS

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Abstract

The decay and snap-back of sextupole in the bending dipoles are issues of common concern, albeit at different levels of criticality, for all superconducting colliders built (Tevatron, HERA, RHIC) or in construction (LHC) to date. The main difficulty is the correction of the relatively large and fast sextupole change during snap-back. Motivated by the above considerations, we have pursued an extended study of sextupole snap-back on two different magnet families, the Tevatron and the LHC bending dipoles, using the same measurement method. We show here that it is possible to generalise the results obtained by using a simple, exponential scaling law. Furthermore, we show that for magnets of the same family the parameters of the scaling law correlate linearly. This finding could be exploited during accelerator operation to produce accurate forecast of the snap-back correction based solely on beam-based measurements.

INTRODUCTION

In most large scale colliders the particle injection is performed at a constant magnetic field in the main arc magnets. In the Large Hadron Collider (LHC) the particle beams are injected at 0.54 T. In the Tevatron the injection field is 0.66 T. During this constant current porch the field inside the superconducting magnet bore changes with time. All multipoles of the magnetic field show a decay that depends on the powering history. When the current ramp starts again, all the multipoles suddenly go back to their value at injection before the decay, i.e. they snap-back [1]. This sudden variation at the beginning of the current ramp, and in particular the sextupole and decapole snap-back, can cause particle loss and are of concern for the operation of the LHC and the Tevatron at nominal beam intensity. For this reason we have pursued in the past two years a collaborative study between FNAL and CERN, devoted at improving the understanding of the sextupole snap-back in superconducting dipoles.

Measurements were carried out independently at CERN and FNAL, on the superconducting dipoles of the LHC and of Tevatron respectively, and were evaluated jointly. The main result of the measurements performed is that once all other known effects are removed (in particular the geometric and persistent current contributions) the sextupole and the decapole variation during the snap-back phase follow a simple exponential law, which applies to all magnets [2]. Moreover the fitting parameters of the exponential function, the snap-back amplitude at the beginning of the current ramp and the current necessary to resolve it, are strongly correlated for all magnets of a given design. The correlation found could provide an invariant property of a magnet design family, independent on the specificities of each magnet instance. We report in this paper the main results of the study of a general snap-back scaling law, which, if proven right, would make possible a novel, on-line correction of sextupole and decapole snap-back in superconducting colliders, based only on beam measurements.

EXPERIMENTAL

In an accelerator dipole magnet the 2-dimensional magnetic field is expanded in complex harmonics:

$$\mathbf{B}(x,y) = B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1} \qquad (1)$$

where b_n and a_n are the normal and skew multipole coefficients, respectively, and R_{ref} is the reference radius (17 mm for the LHC and 25.4 mm for the Tevatron). Multipoles are expressed in units of 10^{-4} with respect to the main dipolar component B_1. Because of the relevance for accelerator performance, we focus on the first two allowed multipoles of the dipole, namely the sextupole b_3 and the decapole b_5.

The snap-back is a relatively fast phenomenon [1], for which we have developed at CERN two Hall plate based probes. The measurement principle is to sample the radial component of the magnetic field at points with constant radius and equally spaced in angle [3]. The number of Hall plates depends on the multipole to be measured: 3 Hall plates spaced by 120 degrees on a circle for b_3 and 5 Hall plates spaced by 72 degrees for b_5. Each set of Hall plates in this arrangement is mounted on a support ring. Several rings are finally assembled on a single mechanical mount to measure the spatial dependence of the selected multipoles. The probe delivered and used at FNAL, included only two sextupole rings, spaced by half the twist-pitch of the superconducting cable to allow for a compensation of the periodic pattern induced by current distribution in the magnet bore [2, 4]. The probe in use at CERN contains six sextupole rings and two decapole rings that allow in addition a fast scanning of the sextupole dependence on position. Both sensors have an acquisition frequency in the range of 3 to 10 Hz and resolution well below 0.1 units.

The measurements quoted here focus on the snap-back at the end of a simulated injection porch followed by the acceleration ramp. In all cases the magnet was quenched before the measurement, then cycled to a current that is relevant to the operating conditions of the two accelerators. The cycle parameters were varied parametrically for each magnet to simulate typical run-to-run variations in the accelerator operating cycle.

DATA REDUCTION

To compare measurements for different cycles and magnets, we first compute the change of the sextupole and decapole subtracting the *baseline hysteresis curve*, i.e. the value that would be measured with no injection porch. This last was estimated directly from the measurements of each cycle, fitting the data after the end of the snap-back with a parabola and extrapolating the fit down to the injection field. The result is the multipole change during snap-back:

$$b_n^{snap-back} = b_n^{measured} - b_n^{baseline} \tag{2}$$

In Fig. 1 we report an example of the measured sextupole and the fitted baseline hysteresis curve, extrapolated to injection field. Clearly the fit deviates only slightly from linearity and the extrapolation of the baseline curve should introduce only small errors. Once the baseline hysteresis curve is removed, the multipole change during snap-back is approximately linear in a semi-log plot, as shown in Fig. 2 that collects all measurements taken in the LHC dipoles. This suggests that a suitable modelling can be obtained using the fit:

$$b_n^{snap-back}(t) = \Delta b_n e^{-\frac{I(t)-I_{injection}}{\Delta I}} \tag{3}$$

where $I(t)$ is the instantaneous value of the current, initially at the injection value $I_{injection}$. The snap-back amplitude Δb_n and the current change ΔI are the two fitting constants. The quality of the fit is generally better than 0.01 units on the r.m.s. error on the sextupole and decapole respectively. The fitted exponentials are reported in Fig. 2 for comparison with the reduced data.

THE SNAP-BACK INVARIANT

Examining in detail the reduced data reported in Fig. 2 we see that the fit parameters Δb_3 and ΔI change from magnet to magnet for the same powering cycle and from powering cycle to powering cycle for the same magnet. This reflects the well-known fact that the snap-back is a strong function of the magnet powering history, and exhibits large variations among magnets. We observed however that the fit parameters Δb_3 and ΔI obtained in the analysis are strongly correlated, and once represented in a scatter plot they cluster on a straight line, as shown in Figs. 3 and 4 for the sextupole measurement performed in the CERN and in the FNAL dipoles, respectively.

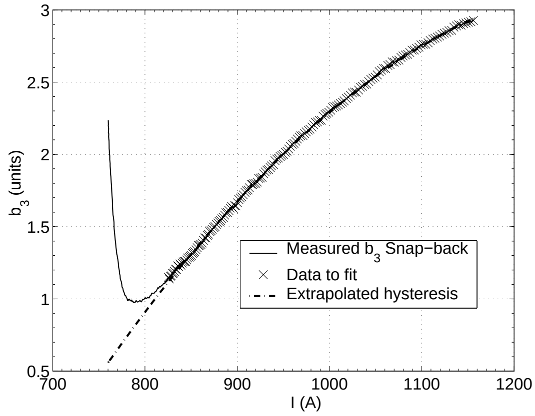

Figure 1: Example of measured sextupole (LHC dipole 1009) and fitting as used for data reduction.

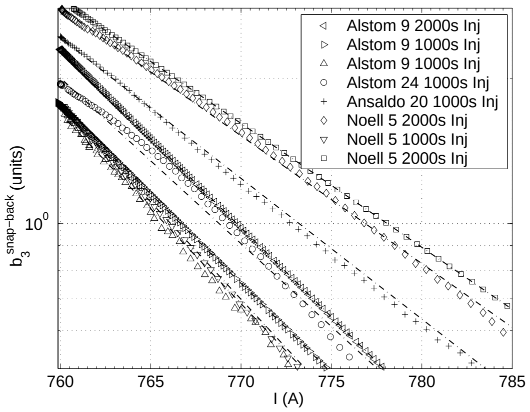

Figure 2: Summary of the sextupole change during the snap-back for all measurements on LHC dipoles.

This fact suggests that the scatter plot representation adopted and the correlation found could provide an *invariant* property of a *magnet design family*, independent on the specificities of each magnet instance. This postulate is substantiated by the fact that the magnets tested were not specially selected (e.g. in respect to cable properties) and that comparable results are found for two dipole designs that have large differences in cable, coil and iron. Finally, we have noted that the same invariance appears to hold also for the correlation of the fitting parameters for the decapole snap-back. The data collected to date on the LHC dipoles are plotted in Fig. 5, and although scarce, are consistent with the picture obtained for the sextupole [5].

These finding have two implications. Firstly, only one of the two fit parameters, Δb_n or ΔI, is strictly necessary to predict the multipole change during snap-back. Furthermore, the correlation plot established over few magnets can be expected to represent the behaviour of the dipoles in the whole accelerator. These properties could provide a very effective and precise mean to forecast fast sextupole and decapole changes during snap-back based on chromaticity measurements during injection, as we elaborate in the following section.

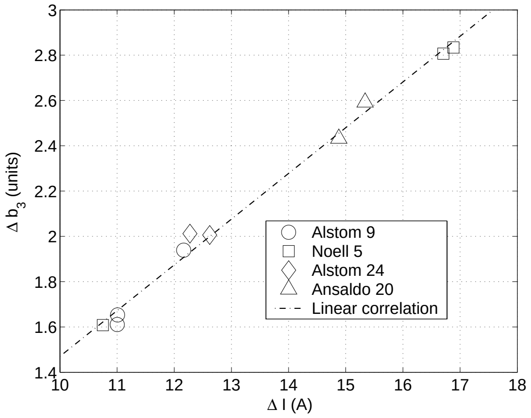

Figure 3: Scatter plot of the fit parameters for the sextupole Δb_3 and ΔI in the LHC dipoles.

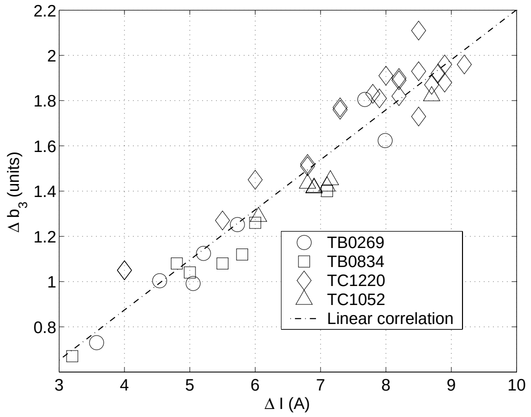

Figure 4: Scatter plot of the fit parameters for the sextupole Δb_3 and ΔI in the Tevatron dipoles.

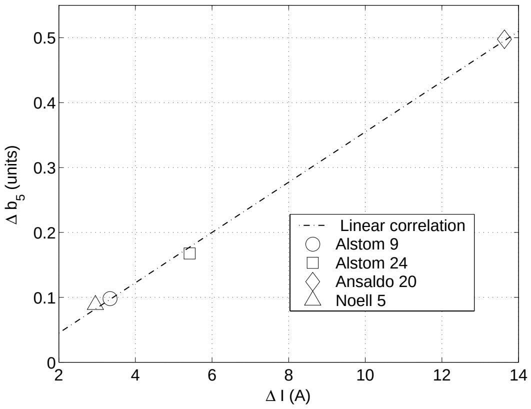

Figure 5: Scatter plot of the fit parameters for the decapole Δb_5 and ΔI in the LHC dipoles.

BEAM-BASED COMPENSATION

The idea is to perform a few beam chromaticity measurements during the long injection porch (few hundreds of s) to forecast sextupole and decapole snap-back. The chromaticity measurements can be converted to sextupole change in the dipoles and used to predict the expected sextupole change at snap-back, Δb_3, at an arbitrary ramp-time. A $b_3(t)$ fit formula established during magnetic measurements of the dipoles, or during machine development time, would be used for this extrapolation. At present, based on magnetic measurement of LHC series dipoles, a double exponential dependence on time appears to be appropriate. As an alternative, a logarithmic function has been found to describe well the behaviour of the Tevatron dipoles. The expected Δb_3 would then be used to compute the corresponding ΔI through the linear correlation in the Δb_3 vs. ΔI scatter plot of Fig. 3. Finally, the Δb_3 and ΔI parameters would be used to forecast the sextupole correction during snap-back using the exponential fit of Eq. (3).

For the decapole, we make use of the correlation found in [1] between sextupole and decapole changes during decay. Once the sextupole change Δb_3 is known (as described above), the decapole change Δb_5 can be inferred from the correlation established using magnetic measurements over a sample of the magnet population. As for the sextupole, we would then derive the current change necessary to resolve the snap-back ΔI using the scatter plot of Fig. 5. The correction waveforms would be given inserting the Δb_5 and ΔI parameters in the exponential fit of Eq. (3). Note that given the mutual correlation, the values of ΔI for sextupole and decapole are very close, and could indeed be taken as identical to simplify the algorithm.

CONCLUSIONS

We have proposed an on-line compensation of the b_3 and b_5 snap-back based on beam chromaticity measurements at injection. The method is flexible, and can be applied to any machine state, with or without conditioning pre-cycle before injection, and arbitrary ramp to injection or injection time. As these findings apply to both the LHC and the Tevatron dipoles, we believe that the proposal discussed here for the LHC can be seen in fact as a more general method that could be applied to any superconducting synchrotron where sextupole and decapole snap-back are of concern.

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