Summary of the Persistent Current Effect Measurements in Nb_3Sn and NbTi Accelerator Magnets at Fermilab

G. V. Velev, G. Chlachidze, J. DiMarco, S. E. Stoynev

***Abstract*—In the past 10 years, Fermilab has been executing an intensive R&D program on accelerator magnets based on Nb_3Sn superconductor technology. This R&D effort includes dipole and quadrupole models for different programs, such as LARP and 11 T dipoles for the LHC high-luminosity upgrade. Before the Nb_3Sn R&D program, Fermilab was involved in the production of the low-beta quadrupole magnets for LHC based on the NbTi superconductor. Additionally, during the 2003-2005 campaign to optimize the operation of the Tevatron, a large number of Tevatron magnets were re-measured. As a result of this field analysis, a systematic study of the persistent current decay and snapback effect in these magnets was performed. This paper summarizes the result of this study and presents a comparison between Nb_3Sn and NbTi dipoles and quadrupoles.**

***Index Terms*—Accelerator magnets, Superconducting magnets.**

I. Introduction

Persistent current effects in superconducting magnets were observed for the first time during early Tevatron runs in 1987 [1]. These effects found to be responsible for a large chromaticity growth (up to 70 units over the course of several hours) and, consequently, beam loss in the Tevatron collider. Since then, persistent current effects have been an important consideration in the operation of any accelerator based on superconducting magnets [2], [3]. For example, for LHC operation a set of semi-empirical equations were developed to provide complete modeling of the normal sextupole (b3) and decapole (b5) dynamic behavior in the main dipole magnets, and dodecapole (b6) in the quadrupoles (see discussion in [4]). The dynamic-behavior induced changes in the magnetic field can be of relatively long or short durations (from several hours to several seconds). Typical examples are the slow decay of the allowed field harmonics during the dwell at the beam injection (injection "porch") followed by fast field change in these harmonics, called snapback, when the current is increased at the beginning of an acceleration ramp.

Over the last decade, we performed a consistent set of measurements at the Fermilab Magnet Test Facility to investigate the decay and snapback effects in samples of the production and R&D superconducting accelerator magnets. Magnets measured during this program included those with NbTi superconducting cable, e.g. a set of the Tevatron dipoles and quadrupoles [5]-[6] and the Fermilab built LHC interaction region (IR) quadrupoles [7], as well as, Nb_3Sn superconductor based magnets represented by dipole models for the Very Large Hadron Collider (VLHC) [8], dipole models for the 11 T high luminosity LHC upgrade program, and LHC IR quadrupole models and prototypes, which are part of the US-LHC accelerator research program (LARP).

This paper presents the comparison of the decay and snapback behavior between magnets based on NbTi and Nb_3Sn superconductor cables. Some of the older results are summarized in detail in [2], [7] and [9].

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II. Definition of Field Expansion

The results in this paper are expressed in a standard form of harmonic coefficients defined in a series expansion

$$B_y + iB_x = B_{1,2} 10^{-4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{r_0} \right)^{n-1} \quad (1)$$

where B_x and B_y in (1) are the field components in Cartesian coordinates, b_n and a_n are the $2n$-pole normal and skew coefficients at the reference radius r_0 (B_1 or B_2 corresponds to the main dipole or quadrupole fields). Different measurements utilize different r_0, which varies between 17 mm, 30 mm and 40 mm for the LHC magnets to 25.4 mm for the Tevatron dipoles.

III. Summary of Decay and Snapback in NbTi Magnets

NbTi cable continues to be the workhorse for production of superconducting accelerator magnets. Since the Tevatron, all superconducting colliders are based on this cable (HERA at DESY, RHIC at BNL and LHC at CERN).

A. Tevatron Magnets

The Tevatron dipoles are the first mass production superconducting accelerator magnets. A typical current profile for the excitation of the Tevatron magnets is shown in Fig.1. First, a long pre-cycle with nominal operating current and duration of 60 min is executed. It is required to clear the

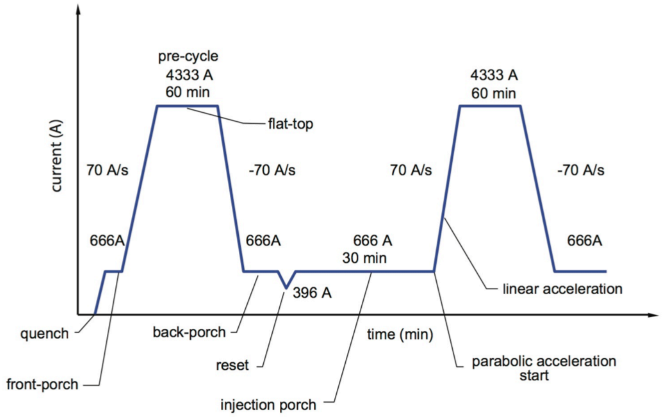

Fig. 1. An example of the Tevatron excitation profile.

magnet "memory" from the previous excitation, returning it to a reproducible state of magnetization. The pre-cycle emulates the real operating condition similar to Tevatron operation at the proton-antiproton collision state. Next, the current is ramped down to the injection level of 666 A, "back-porch" in Fig. 1, for a short period of time between one and five minutes. Later, the magnets are reset to approximately 400 A and ramped again to a relatively long injection "porch" of 30 min.

Figure 2 shows a typical sextupole (b_3) hysteresis loop in a Tevatron dipole. The b_3 behavior can be explained by a decrease in the persistent currents at a constant excitation of the magnet during the injection porch, during which time the sextupole field component starts to drift to its geometrical value. At the moment when the excitation current is changed, (i.e. a ramp to the flat-top is initiated), the coil magnetization promptly recovers to its initial value on the hysteresis curve. For the Tevatron dipoles, average decay-snapback amplitude of 1.45 units and average snapback duration of 4.5 s are observed for 30 min at injection porch [5].

Similar dynamic effects, but with smaller amplitudes, are seen in the higher order allowed multipoles, b_5 and b_7, as discussed in [5]. The decay amplitude of b_5 (b_7) is found to be 19% (7%) of the b_3 value.

Current understanding of the dynamic effects in NbTi

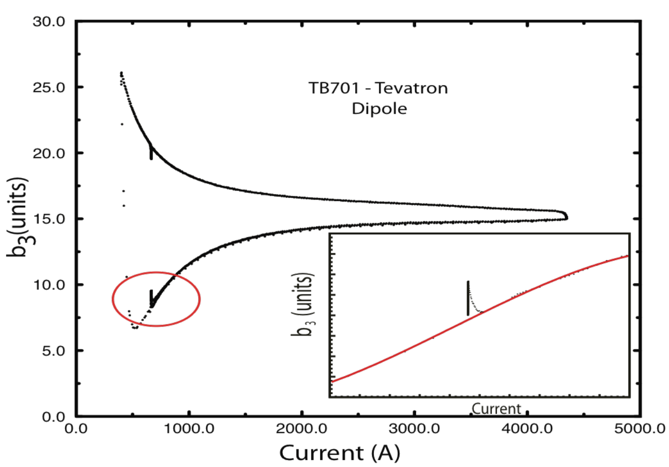

Fig. 2. Sextupole hysteresis loop measured in the TB701 Tevatron dipole. The inset shows the decay and snapback characteristics after 30 min at the injection porch. The second order polynomial is used to parameterize the region under the snapback.

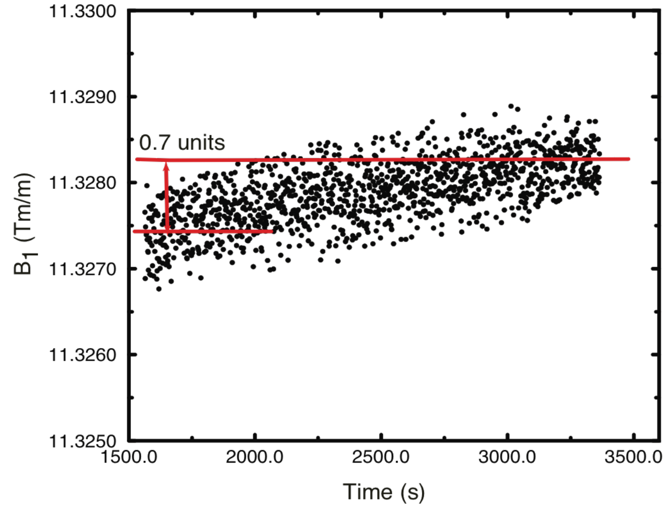

Fig. 3. Main field variation for a typical Tevatron quadrupole after 30 min dwell at injection porch from [6]. An increase of 0.75 units is observed.

magnets suggests that any allowed component of the field drifts during constant current dwell time, with no exception for the main fields in dipole and quadrupole magnets. As a rule, measurements of the main field variation during the injection porch are difficult to perform: one should be certain that it does not correspond to a variation of the excitation current. In the Tevatron dipoles, we observed an increase of the main field by an average of 0.75 units [5]. A similar result of 0.67 units [6] is obtained for the measured quadrupole gradient change, an example of which is shown in Fig. 3.

B. LHC Interaction Region Quadrupoles

During the Fermilab production measurements of the LHC IR quadrupoles (MQXB cold masses [7]), a current profile with a structure similar to the Tevatron profile (Fig. 1) was used. The distinctive features of the LHC profile are the absence of the back and front porches, lower ramp rate, and higher collision flat-top of 12 kA. The duration of the injection porch is set to 15 min.

A typical example of the decay and snapback of the dodecapole field component (b_6) in MQXB production quadrupoles is shown in Fig. 4 (see [7]). In this analysis, the

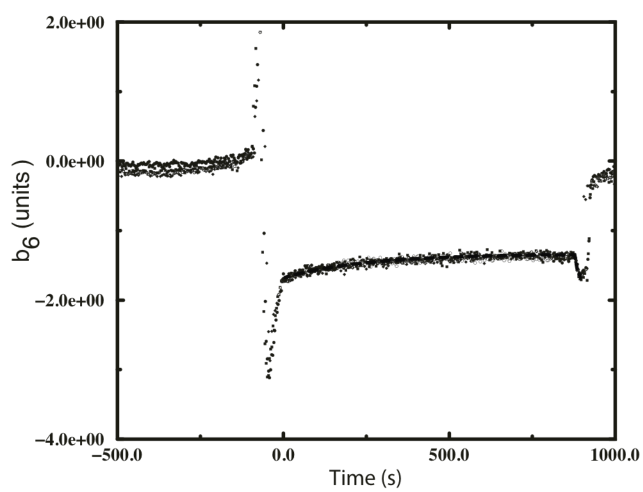

Fig. 4. Decay and snapback in the dodecapole (b_6) of the LHC IR quadrupoles from [7].

decay and the snapback are parametrized with the same logarithmic and gaussian functional forms used for characterization of these effects in the Tevatron magnets [5]. After 900 s at injection dwell, the average decay amplitude is approximately 0.4 units, followed by a snapback of approximately 11 s.

IV. Decay and Snapback in Nb_3Sn Magnets

More recently, over the past 10 years, Fermilab has been executing an intensive R&D program to develop and evaluate accelerator magnets based on Nb_3Sn superconductor technology.

A. VLHC Model Dipoles

The Nb_3Sn magnet development (HFDA magnets [10]) started as a R&D program for the second stage of VLHC [8] proposed on the basis of 10-11 T dipole magnets. For this program, six 1 m long dipole models HFDA02-HFDA07 were assembled and five of them were tested. The first three models HFDA02-04 were made with a strand produced using the Modified Jelly Roll (MJR) process. The strand for the HFDA05-07 models was made using the Power-in-Tube (PIT) process. The MJR strand had a larger filament size of approximately 100-110 µm while the PIT strand had a larger number of filaments with smaller size of approximately 70 µm. We expected that magnets built with such a large filament-sized cable would show substantial dynamic effect, but this proved not to be the case [10].

An updated analysis of the sextupole field measurements at the injection porch at 2.4 kA and 3 kA is shown in Fig. 5. The HFDA02-04 and HFDA06 dipoles were measured with a 250 mm long tangential probe optimized for the cable twist pitch (one probe length corresponding to two cable twist pitches). Using this probe, we performed an accurate integration over the spatially periodic field pattern typical for the Rutherford cables [11], [12]. We did not observe any decay of the sextupole field component in the HFDA02-04 and HFDA06 models.

The HFDA05 model showed an increase of b_6, an effect similar to that is observed in the NbTi magnets without any snapback. This dipole was measured with a 43 mm-long tangential-type probe that was not designed to perform optimal integration over the cable twist pitch. The magnet was built with a low inter-strand resistance cable and due to the large eddy currents, showed even reverse behavior of the hysteresis loops [10]. The combination of the large local eddy currents, circulating within one twist pitch distance, and usage of the short probe might generate an observed change similar to decay in the NbTi magnets.

B. LHC 11 T Dipoles

The planned LHC upgrades include additional collimator areas in different service points [13]. The development of the 11 T Nb_3Sn dipole for this LHC upgrade started in 2011 and currently continues at CERN.

The Fermilab program built one 2 m and two 1 m long single aperture magnets, MBHSP01-03. For the last two of these model dipoles, in order to resolve problems with significant local eddy currents due to low inter-strand resistance, we used a cable with stainless steel core between the layers.

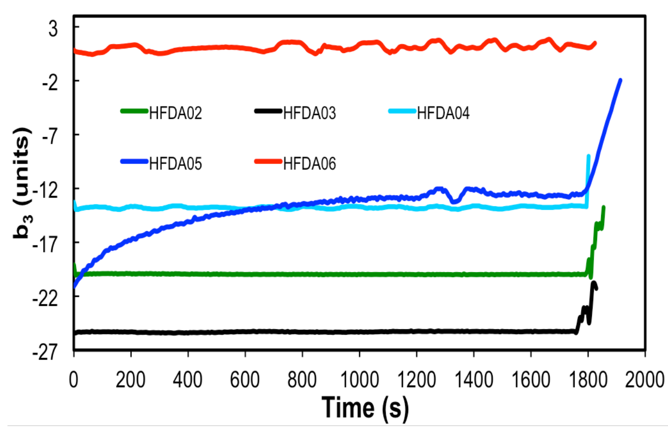

Fig. 5. Decay and snapback in the sextupole field component in the VLHC dipole models, based on the Nb_3Sn cable. HFDA02-04 were tested at 3kA while HFDA05-06 at 2.4 kA.

For MBHSP02-03, a full set of magnetic measurements was executed. The measured snapback amplitudes after subtracting the underlying hysteresis loop are shown in Fig. 6. The decay amplitudes, after 15 min at injection (840 A), were of the order of 4 to 6 units, which is somewhat larger than observed in the NbTi Tevatron dipoles. An unexpected rapid increase of the decay in the first 10-20 seconds of the current ramp was observed for the first time, which apparently stemmed from fast dynamic effects (ISCC, see chapter Discussion of the Results). The large snapback time is an effect of the slow acceleration in the current ramp.

C. LHC Model Quadrupoles for IR

In the next phase of the Nb_3Sn program, Fermilab, as part of LARP collaboration, tested the technological model of a new generation of large-aperture IR quadrupoles for LHC. Initially, this phase included tests of six 1 m-long TQC and TQS quadrupoles, and two 3.7 m-long models from LQS series with a 90 mm diameter bore. The dynamic effect measurements in a subset of magnets (TQS01-02 and LQS01-

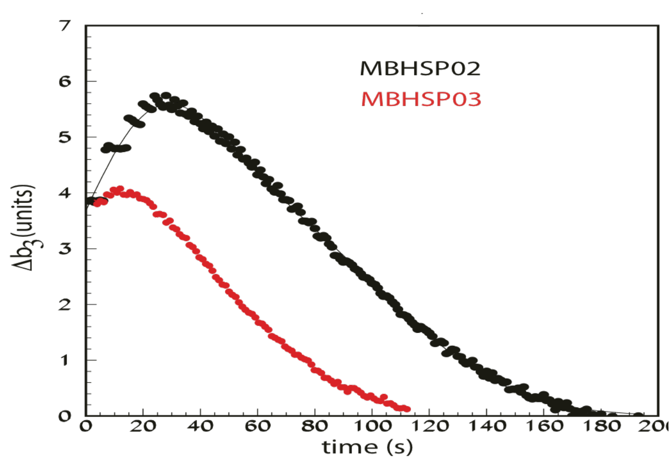

Fig. 6. Snapbacks of the sextupole field component in the MBHSP dipoles.

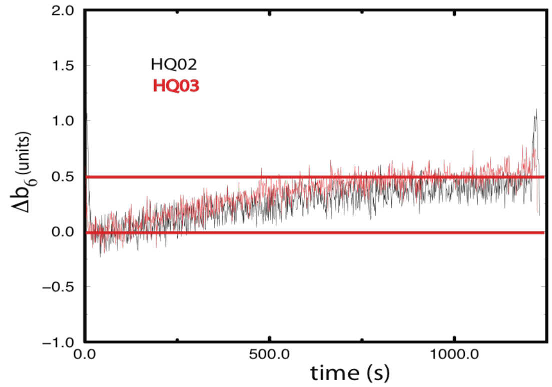

Fig. 7. Decay and snapback in the dodecapole field component in the HQ models for the LHC IR upgrade.

02) are discussed elsewhere [9]. These magnets were built without stainless steel core in the cable and they showed behavior similar to the HFDA models. We did not observe any decay in the dodecapole (b_6) during the injection porch, but rather wide b_6 hysteresis width associated with the large inter-strand eddy currents.

Later, a new HQ magnet series (HQ01-HQ03) with 120 mm bore was tested. Starting with the HQ02 model, a stainless steel core was introduced in the cable. The new core substantially increased the inter-strand resistance between the cable layers and reduced the effect of the localized eddy currents. As a result, the width of the b_6 hysteresis loop decreased and small decay and snapback were observed. A typical example of the b_6 decay for HQ02 and HQ03 magnets, after the subtraction of the underlying hysteresis loop, is shown in Fig. 7. Average decay amplitude of 0.5 units was observed, which is comparable to the results obtained for NbTi magnets.

V. Discussion of the Results

Recent models explain the dynamic effects observed in NbTi magnets by a current redistribution between strands in multi-strand Rutherford cables (see [14]-[17]). According to these models, the magnet ends are dominating sources of the current redistribution among the strands. This redistribution is affected by the strand resistances in current lead splices and the complex net of interstrand contact resistances within the cable. The current redistribution occurs at a relatively slow rate with time constants in the order of hundreds or thousands of seconds. These current imbalances have also been referred as Boundary Induced Coupling Currents (BICC). It is believed that they are dominantly responsible for the field decay seen in superconducting accelerator magnets [16], [17].

To understand the differences in the dynamic behavior of the NbTi and Nb_3Sn magnets, one should look at differences in cable manufacturing and coil winding. For the Nb_3Sn magnets, a commonly used practice is the "Wind&React" method for the coils due to the brittleness of the Nb_3Sn strand after the reaction. Before the heat treatment, the copper strands are compressed to each other. During the long heat treat phase, a strong bond between them is created. This effect reduces BICC and increases the Inter-Strand Coupling Currents (ISCC), which flow only in loops with a length equal to the cable twist pitch and have short time constant of 0.01-1.00 s. In this case, because the current redistribution can take place through the much faster ISCC, the drift and snapback should be expected to decrease.

When a stainless steel core is added to the cable, ISCC are highly suppressed, and BICC are restored. This explains observation of the dynamic effects in the later models built for LARP and 11 T dipole programs.

VI. Conclusion

This paper presents a summary of the dynamic effects, decay and snapback, in the NbTi and Nb_3Sn dipoles and quadrupoles measured at Fermilab. We find that the common decay of the allowed multipoles, firmly observed in the NbTi magnets, is not present in the early Nb_3Sn magnet models built without a stainless steel core in the cable. In current models built by LARP and 11 T programs, the decay and snapback is detected in amplitudes comparable with those observed in the NbTi magnets. A plausible explanation for this discrepancy is discussed and can be attributed to the difference in the production processes between the NbTi and Nb_3Sn coils.

VII. Acknowledgment

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