MEASUREMENT AND SCALING LAWS OF THE SEXTUPOLE COMPONENT IN THE LHC DIPOLE MAGNETS*

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Abstract

One of the main requirements for the magnet operation of the Large Hadron Collider at CERN is the correction of the dynamic multipole errors produced. In particular, integrated sextupole errors in the main dipoles must be kept well below 0.1 units to ensure acceptable chromaticity. The feed-forward control of the LHC magnets is based on the Field Description for the LHC (FiDeL), a semi-empirical mathematical model capable of forecasting the magnet's behaviours in order to suitably power the corrector scheme. Measurement campaign were recently undertaken to validate the model making use of a novel Fast rotating-coil Magnetic Measurement Equipment (FAME), able to detect superconductor decay and snapback transient with unprecedented accuracy and temporal resolution. We discuss in this paper the test setup and some measurement results confirming the FiDeL model.

INTRODUCTION

The Large Hadron Collider (LHC), the most complex accelerator ever built, started its operation in November 2009. The stringent beam optics requirements demand very precise control of the field generated by the about 10000 magnetic elements, most of which are superconducting. Such control is based on a feed-forward mathematical model called Field Description of the LHC (FiDeL), which provides the tools for effective forecasting of both main field and multipole field errors [1]. One of the main aims of the model is to enable the compensation of dynamic field errors in superconducting dipole magnets, i.e. decay and snapback of the undesired harmonics (mainly the sextupole) during injection and acceleration [2]. These effects, if uncontrolled, would greatly increase chromaticity and could lead to unacceptable beam losses [3].

The detailed mathematical formulation of the field dynamics in FiDeL, including scaling laws and current cycle effects, is reported in [4][5]. These results are based on the data gathered during series magnetic measurements and subsequent campaigns carried out on spares, mainly by means of a rotating coil system able to perform a measurement approximately every 30 s [6]. Since the time scale of some effects is well below one second, however, the slow sampling leads to apparent discrepancies that should be corrected. A fast Hall probe detector with acquisition frequency up to 10 Hz was developed and used to this end, although the system was limited to measurements over short length (20 cm) [7].

A novel fast rotating-coil magnetic measurement system (FAME), able to measure the integral field of main cryomagnets with a bandwidth approaching 10 Hz, has been recently developed to overcome these issues. This paper deals with the results of a measurement campaign carried out with this system on the LHC main dipole MB2524, aiming at refining and validating the algorithm for sextupole cancellation and building upon the result of an earlier test carried out in 2008 [8].

MEASUREMENT SETUP

A basic requirement for the recently commissioned Fast Measurement Equipment (FAME) is to measure the decay, snapback and ramp rate effects of the LHC superconducting dipole magnets with time resolution better than one second. Figure 1 demonstrates the measurement quality described in detail in [9]. using This measurement technique achieves an unprecedented level of resolution.

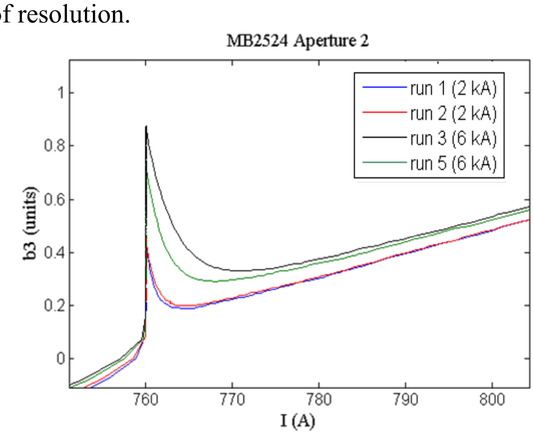

Figure 1 Measured normal sextupole b_3 during decay and snapback in the selected measurements from Table 1, as a function of the current. The curves are vertically shifted so that $b_3 = 0$ at injection (760 A).

New 15 m long measuring shafts were assembled based on the well-established design used for the LHC series tests, but with fewer turns on the coils to allow faster rotation. The specific developments for FAME concerned three fields:

- Micro Rotating Units (MRU) provide a vibration-free rotation rate up to 8 Hz [10],
- a PXI based Fast Digital Integrator provides the required acquisition bandwidth with a ~100× improved S/N ratio [11],

- a Flexible Framework for Magnetic Measurements (FFMM) provides the synchronisation with the magnet current supply. It acquires and validates the full set of data (40000 samples per second) over the whole current cycle lasting more than one hour [12].

MEASUREMENTS PERFORMED TO VALIDATE THE FIDEL MODEL

The FiDeL Model for the Snapback

The largest multipole affecting the field quality of a LHC dipole is b_3. The data presented in this paper refer to the behaviour of the sextupole term with respect to FiDel's forecasts. A description of the model is reported, limited to the mathematical formulation required to analyze the snapback phenomenon. The sextupole b_3 of the main dipoles during the snapback (sb) can be written as:

$$b_{3,sb}(I, I_{past}) = b_{3,d}(t_{ramp}, I_{past})e^{-\frac{I(t)-I_{inj}}{\Delta I_3}} \quad (1)$$

The snapback is modelled by an exponential function of the difference between instantaneous and injection current I_{inj}, with ΔI_3 as fitting parameter [1]. The term $b_{3,d}$ at the end of the decay depends on the duration of the injection plateau, t_{ramp}, and of the previous powering history I_{past} of the magnet [4]-[5].

Measurements Performed with FAME

We concentrated our effort on the measurement influence of the following precycle parameters: the maximum current of the precycle I_{FT}, the following minimum current I_{prep} and the duration at this preparation current t_{prep}.

Table 1: Measurements done on the LHC dipole MB2524.

meas run	I_{FT} (A)	I_{prep} (A)	t_{prep} (s)	$I_{collision}$ (A)
1	2000	350	0	2000
2	2000	500	1000	2000
3	6000	350	0	6000
4	6000	500	100	6000
5	6000	500	1000	6000
6	6000	500	3000	6000

The conditions correspond to the beam energies currently used in the LHC : 1.2 and 3.5 TeV respectively corresponding to excitation currents of 2 kA and 6 kA in the main dipoles, although most of the FiDeL model was based on 7 TeV current cycles, i.e. 11.8 kA. Current ramp rates are limited to 10 A/s. The duration at maximum current I_{FT} corresponding to the previous beam run and the duration corresponding to the injection plateau t_{ramp}, i.e. when the decay takes place, are both kept constant at 1000 s.

The experimental plan of measurement, so far performed on only one spare dipole (MB 2524), was defined varying the parameters according to Table 1.

CONFIRMATION OF THE FIDEL MODEL

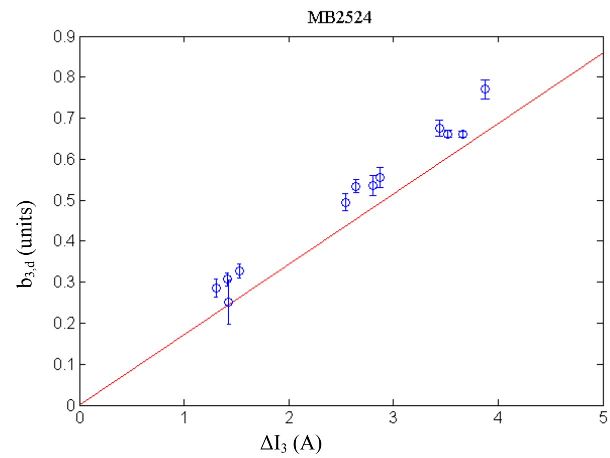

Figure 2: Scatter plot of the fit parameters and for the measurements of Tab. 1. The measurement series correlation line in red is also shown.

The correlation between the snapback amplitude and its decay constant must be verified in order to fully validate the model. FiDeL is based on the following relationship:

$$\Delta I_3 = \frac{b_{3,d}}{g_{3,sb}} \quad (2)$$

where $g_{3,sb}$ = 0.1782 (units/A) is the correlation coefficient used to predict the value of ΔI_3, established on the basis of the series measurement database. Figure 2 shows the correlation between the measured values and the linear model. Error bars refer to the maximum error of the fitting.

A careful fitting of the DC magnetization and geometric components of the sextupole term is mandatory to isolate the decay and snapback components $b_{3,d}$ and ΔI_3. This fitting procedure is still subject to fine tuning. It is performed for each measurement of each magnet aperture prior to the analysis of the behaviour of the factor $b_{3,d}$ as a function of the powering history parameters. Figure 3 illustrates the behaviour of the computed $b_{3,d}$ from the measurements, as a function of I_{FT} and t_{prep}. The model well describes the dependency of the sextupole field error as a function of the powering history. The plots also show that the maximum error amounts to 0.28 units. This discrepancy could come from:

- the limited bandwidth of the equipment used for series test (1 measurement every 30 s at most);
- different behaviour between dipole 2524 and the average of those measured during series tests;
- different precycle current I_{FT}, mainly 11.8 kA during series tests and 2kA or 6 kA forMB 2524.

In order to verify the need for a further tuning of the model parameters, the collected data must be compared with the whole statistics available from the series tests.

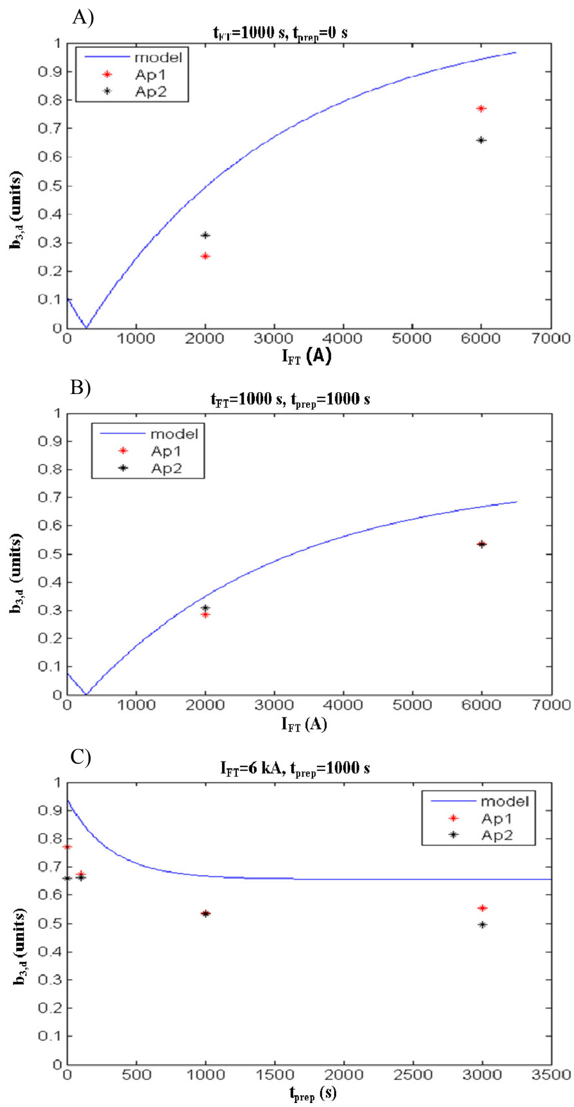

Figure 3: Measurements and model of the amplitude of $b_{3,d}$ vs. I_{FT} with t_{prep}=0 (A) and t_{prep}=1000 s (B). In (C) vs. t_{prep} with I_{FT}= 6 kA.

CONCLUSION

The results of a measurement campaign for the validation of the Field Description model for the LHC (FiDel), carried out with the new Fast Acquisition Measurement Equipment (FAME), are illustrated. The novel rotating coil magnetic measurement system has shown the capability to detect superconductor magnet decay and snapback transient with unprecedented accuracy and temporal resolution.

The comparison of the collected data with the model shows i) the suitability of the system to perform fast harmonic measurements, and ii) the soundness of the FiDel model. The parameters however could need further tuning possibly when more statistics will be available on other magnets.

Therefore further measurements campaigns are foreseen over other LHC dipoles and higher order magnets for establishing a new set of reference data for the LHC operation with beams.

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