

Measurements of Magnetic Field Pattern in a Short LHC Dipole Model

Luca Bottura, Marco Breschi, and Michael Schneider

Abstract—The magnetic field in superconducting accelerator magnets has a fine structure with longitudinal periodicity. This *periodic pattern*, with period identical to the cable twist pitch, is originated by uneven current distribution within the cable. Here we present results of measurements of the periodic pattern performed in an LHC dipole model. We report in particular the results obtained powering the magnet with simple current steps and typical operation cycles as will be used during accelerator operation. The main result of the analysis is the time variation of the amplitude of the periodic pattern, from which we infer the evolution of the current distribution in the cable. We discuss the dependence of the pattern amplitude on ramp and pre-cycle parameters.

Index Terms—Superconducting cables, current distribution.

I. INTRODUCTION

THE magnetic field in accelerator magnets wound with Rutherford-type cables exhibits a fine structure with longitudinal periodicity [1], [2]. This *periodic pattern* has a period identical to the cable twist pitch, and is due to an uneven current distribution among strands [3]-[5]. The main motivation for the experimental and analytical work on the periodic pattern is twofold. One reason is that a non-uniform current distribution is known to generate excess AC loss and affect the stability and quench performance of a magnet. The knowledge of the dependence of the current distribution on the cable characteristics and the magnet powering can thus help to understand performance limitations such as premature quenches. Furthermore we believe that the average strand magnetization is affected by the field changes internal to the cable that are necessarily associated with a redistribution of the current [6], [7]. This phenomenon is observed in accelerator magnets as a drift of the field when the transport current is held constant (e.g. during particle injection). The field drift must be known and corrected precisely for accurate accelerator operation. Thus a well established correlation and better understanding of the current distribution as a function of the operating conditions will lead to improved correction and control algorithms. The periodic pattern has already been observed on long and short models of the Large Hadron Collider (LHC) dipoles [8], [9]. In this paper we will focus on the time dependence of the pattern amplitude and its correlation with the magnet powering history.

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II. EXPERIMENTAL SET-UP AND CONDITIONS

A. Field Measurement

All measurements reported were performed on the 1-m long LHC dipole model MBSMT1. Details on the magnet construction and characteristics can be found in [10]. The tests were done at 1.9 K in a vertical cryostat that allows operation at atmospheric pressure, subcooled, superfluid helium conditions. The field was measured using arrays of short radial coils mounted on a glass-fibre shaft rotating in the bore of the magnet, in the superfluid helium bath. The coils in the shaft are clustered in three groups consisting of five adjacent coils sections (see Fig. 1). Each coil is 25 mm long, so that a coil group covers approximately 125 mm, to be compared to the nominal inner cable twist pitch of 105 mm. The *top* group was placed with the topmost coil at the beginning of the straight region of the coil winding, at the layer jump (connection end). The *center* group was placed with its topmost coil in the center of the magnet. The *bottom* group was placed with the bottom coil at the end of the straight part of the coil winding, in the non-connection end. The acquisition system allowed simultaneous read-out of five coils, i.e. a complete group. The shaft rotation frequency was typically in the range of 1 Hz. Because of additional dead times between rotations, the time interval between two measurements was 20 s. Further details on the test facility and acquisition system are given elsewhere [11].

B. Data Analysis

In the presentation of the test results we refer to the normal sextupole, i.e. the real part of the third harmonic component of the following complex expansion of the magnetic field \mathbf{B} in the magnet bore:

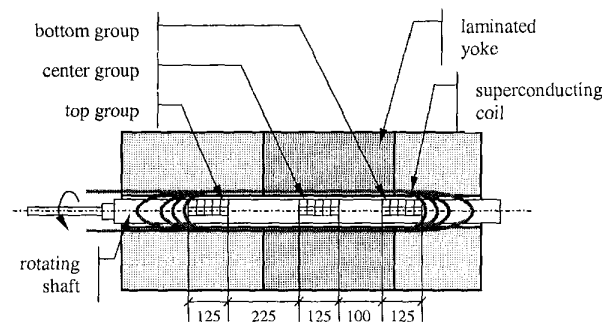


Fig. 1. Schematic position of the three rotating coil groups in the magnet bore. The total length of the magnet is 1 m, the three coil groups are placed so that they completely cover the straight length (approximately 0.6 m).

$$\mathbf{B} = B_y + iB_x = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{s}{R_0} \right)^{n-1} \quad (1)$$

where $s = x + iy$ is the complex co-ordinate in the (x,y) coil cross sectional plane, R_0 is the reference radius (17 mm) and B_n and A_n are the normal and skew multipole coefficients. The multipoles at any given time t are computed from the integrated voltage signal read-out from each of the 5 coils in a group. As stated above, all coils in a group are measured simultaneously, therefore the result of a measurement is a map of multipoles at time t as a function of the coil position z_i along the magnet bore axis (with $i=1\dots5$). The characteristic quantities describing the periodic pattern on any (normal or skew) multipole C_n are the amplitude Δ_n and the phase ϕ_n . To obtain them we fit the following model for a generic multipole $C_{n,i}$ to the experimental data measured at location i :

$$C_{n,i} = F_0 + F_1 z + \Delta_n \sin\left(\frac{2\pi z_i}{L_p} + \phi_n\right) \quad (2)$$

where L_p is the twist pitch of the cable and F_0 , F_1 , Δ_n , ϕ_n are the fitting parameters of the model. In particular F_0 is a constant offset and F_1 is the slope of a linear term taking into account field gradients along the magnet axis.

C. Current Cycles

We have performed two types of measurement cycles in order to obtain detailed information on the parameters influencing the generation and the development of the periodic pattern. The magnet was quenched before every cycle in order to erase the *memory* of all induced currents. In a first series of tests the magnet was ramped up in a single step from a small current (30 A) to a flat top current I_{FT} , at constant ramp-rate RR (see Fig. 2a). In this series of tests we have taken I_{FT} in the set 2 kA, 5kA and 8 kA, and RR in the set 50 A/s, 200 A/s and 450 A/s.

The second type of cycle reproduces the typical operating current cycle for LHC dipole magnets (see Fig. 2b). The magnet was pre-cycled ramping at 50 A/s to a maximum current I_{FT} , remaining at flat-top for a time t_{FT} , and finally ramping down at -50 A/s to a minimum current of 50 A. The measurement phase consisted then of a linear increase of the current up to 810 A with a ramp rate of 1 A/s, a 1000 s constant current period, corresponding to the injection phase in the LHC, and a final current ramp up to about 1500 A. For this series of tests we have varied parametrically the flat top

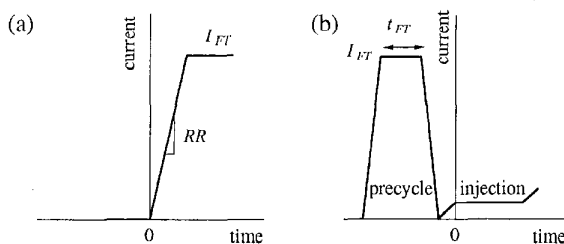


Fig. 2. Current cycles tested: (a) step response and (b) LHC operating cycle.

current I_{FT} in the set 4 kA, 8 kA and 11.75 kA and the flat top time t_{FT} in the set 60 s, 300 s, 900 s, 1800 s and 5400 s.

III. MEASUREMENT RESULTS

A longitudinal variation of the multipoles was found in every measurement that we performed. In the following discussion we concentrate on the results obtained on the normal sextupole component B_3 . The normal sextupole is the first allowed harmonic in the geometric configuration of the dipole and can be measured very accurately using the rotating coil technique. We found that the behaviour of B_3 is representative of most other harmonics and hence, without loss of generality, of the field in the bore of the magnet.

The longitudinal variation of B_3 has different features in the three positions along the magnet. In the *top* part of the magnet we observe a strong longitudinal gradient of the field harmonics, so that it is not possible to recognize a precise and repeatable pattern. This could be due to the end field deformation at the connection end. For this reason we have discarded the measurements from this coil group.

In the *center* and *bottom* locations of the magnet the field harmonics exhibit a strong oscillation with period equal to the inner cable twist pitch, i.e. the periodic pattern. An example of the measured values of the normal sextupole is shown for the *bottom* location in Fig. 3. The measurements have been taken at 100 s after reaching the flat top of a step excitation with $I_{FT}=2$ kA and $RR=450$ A/s. Note how the fitting model of Eq. (2) adapts very well to the measurements. The amplitude of the periodic pattern Δ_3 is about 0.8 mT @ 17 mm.

A. Step Response

In the case of a step in current the sextupole pattern amplitude Δ_3 is zero before the current ramp, then quickly increases during the ramp-up, and finally decays when the flat top is reached. An example of the results obtained is shown in Fig. 4 for two steps with the same ramp-rate $RR = 450$ A/s, but different flat-top current $I_{FT} = 2$ kA and $I_{FT} = 8$ kA.

The characteristic time of the decay is long, as expected for a current diffusion phenomenon. Analysing the data in detail we have found that we can interpret the decay during the flat-top as a superposition of exponentials with several time constants. The relatively short measurement time (1000 s at flat-top) does not allow a precise evaluation of the longest time constant in the system. An underestimate of this time

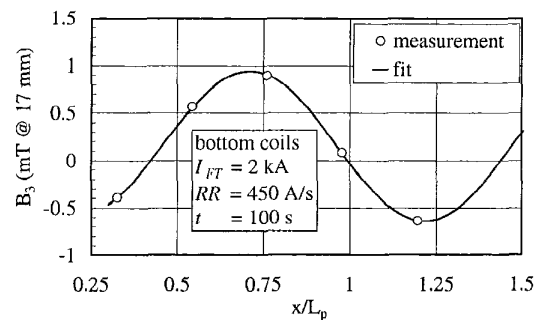


Fig. 3. Measured (symbols) and fitted (solid line) normal sextupole.

constant leads to a range of 3000 to 4500 s.

The evolution of the phase of the sextupole pattern ϕ_3 is essentially the same for all current steps, independently on the flat-top current and ramp-rate. We have observed a phase change of about 0.1 radians during the 1000 s spent at flat-top. The phase shift of the sinusoidal pattern can be interpreted as a translation of the current distribution along the magnet. The average velocity corresponding to the phase change observed is 6.6 mm/h. This velocity should not be confused with the time required for the pattern to establish or decay. As can be seen in Fig. 4 the evolution of the pattern in the center and bottom locations (200 mm apart) is in practice simultaneous within our time resolution.

Comparing the two step excitations reported in Fig. 4 we see that the amplitude of the pattern increases at increasing flat-top current. To verify the exact scaling with I_{FT} and RR ,

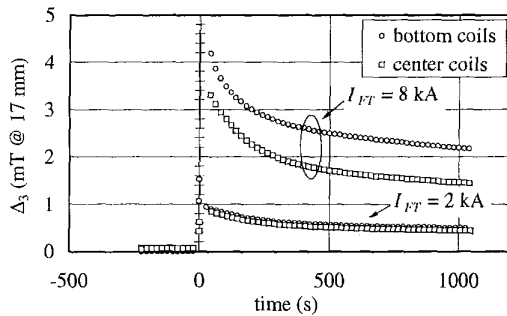


Fig. 4. Evolution of the periodic pattern amplitude of the normal sextupole following a step in current with $RR=50$ A/s and $I_{FT}=2$ kA and 8 kA.

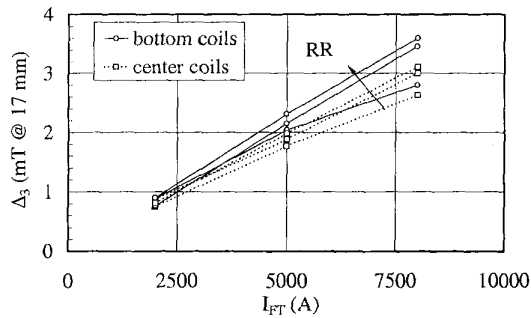


Fig. 5. Amplitude of the periodic pattern in the center and bottom coil groups at the end of a current step, plotted as a function of the flat-top current. Different ramp-rates values $RR=50$ A/s, $RR=200$ A/s and $RR=450$ A/s are shown together (direction of increasing ramp-rate as marked).

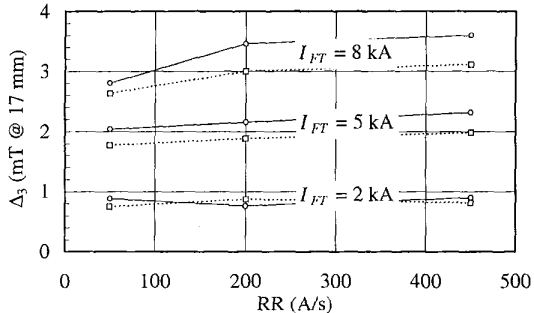


Fig. 6. Amplitude of the periodic pattern at the end of a current step, as a function of the ramp-rate. Different flat-top currents $I_{FT}=2$ kA, $I_{FT}=5$ kA and $I_{FT}=8$ kA are reported as indicated. Legend for lines and symbol as in Fig. 5

we have plotted in Figs. 5 and 6 the amplitude of the sextupole pattern as evaluated at the end of the ramp. The pattern amplitude scales linearly with the flat-top current, and it does not depend on the ramp-rate. A small deviation from linearity is visible for the steps to high flat-top current $I_{FT} = 8$ kA with low ramp-rate $RR = 50$ A/s, for which the time spent during the ramp becomes significant (160 s).

B. Operating Cycles

In the case of simulated operating cycles the evolution of the pattern amplitude is more complex. A typical example of the amplitude measured at times around the injection flat-bottom, following a pre-cycle with different flat-top duration, is shown in Fig. 7. As found for current steps, the pattern amplitude behaves essentially in the same way in the two locations in the bottom and center of the magnet, and is strongly dependent on the current cycle.

The pattern amplitude is proportional to the pre-cycle flat-top duration. In addition longer flat-top times correspond to larger variations of the pattern during the constant current phase (from $t=0$ to $t=1000$). We finally note that, apart for an offset, the behaviour of the pattern amplitude during the slow (1 A/s) ramps to and from injection does not depend on the pre-cycle.

As anticipated in the introduction, we seek a correlation between change in current distribution and the drift of cable magnetization during constant current phases. Therefore we have concentrated on the change of sextupole periodic pattern $\delta\Delta_3$ that takes place during the 1000 s of the simulated injection flat-bottom. In Figs. 8 and 9 we plot $\delta\Delta_3$ as a function of the flat-top current I_{FT} and of the flat-top duration t_{FT} during the pre-cycle. The results show that there is a clear correlation between $\delta\Delta_3$ and both I_{FT} and t_{FT} . The change of sextupole pattern $\delta\Delta_3$ scales approximately linearly with the flat-top current reached in the pre-cycle. The scaling with the flat-top time in the pre-cycle can be well approximated by an exponential function. As reported in [12], the decay of the average multipoles during injection follows the same scaling with I_{FT} and t_{FT} . The match between the scaling of the periodic pattern and the multipoles decay reinforces thus the hypothesis of an interaction between current distribution and superconductor magnetization.

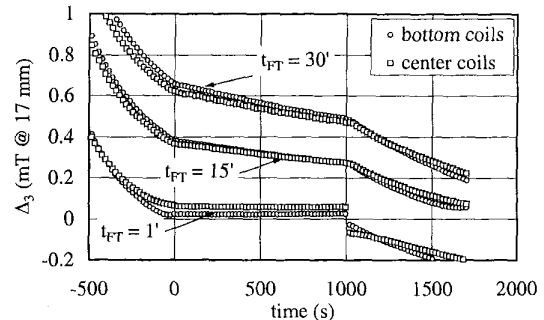


Fig. 7. Amplitude of the periodic pattern in the center and bottom coil groups during the injection flat-bottom as measured for operating cycles with different flat-top time, as indicated.

C. Discussion

It is possible to interpret our experimental results under the assumption that the measured sextupole pattern is proportional to the current distribution in the Rutherford cable. The current distribution, excited by the flux changes associated with transposition errors or spacial variations of the field, diffuses along the cable with a characteristic time that can be exceedingly long [5]. If the excitation of the current distribution takes place over a time much shorter than the characteristic current diffusion time, the magnitude of the induced currents only depends on the flux change and not on the flux change rate. This is indeed the measured response of the sextupole pattern to current steps, where the pattern amplitude only depends on the current change (i.e. the total field change on the cable) and not on the ramp-rate (see Figs. 5 and 6).

By virtue of the long time constants involved in the current diffusion process, the pattern amplitude *remembers* the powering history. This is the case for the pre-cycle that models the typical operating mode of an accelerator magnet. If the currents in the strands are far from critical conditions, which is the case in our experiment, we can make the additional hypothesis that subsequent ramps produce current distribution effects that are linearly additive. Hence the current distributions generated by the two identical ramps with opposite direction in the pre-cycle would tend to mutually cancel. In reality the current distribution diffuses and decays exponentially during the ramp- and flat-top time, so that the cancellation at the end of the pre-cycle is not perfect. As a result the residual current distribution should

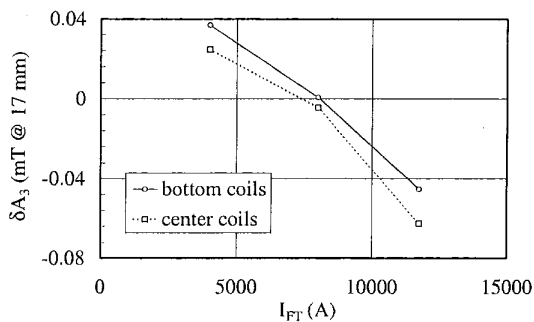


Fig. 8. Change of the sextupole pattern amplitude in the center and bottom coil groups during the injection flat-bottom as a function of the flat-top current reached during cycles with 300 s flat-top time.

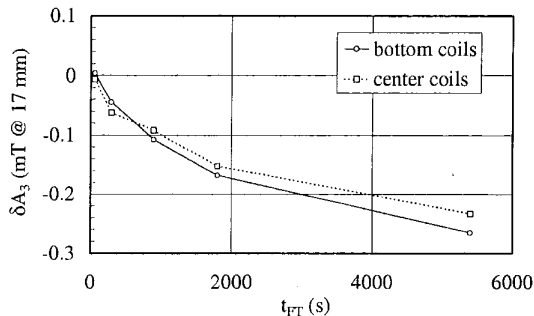


Fig. 9. Change of the sextupole pattern amplitude in the center and bottom coil groups during the injection flat-bottom as a function of the flat-top time during cycles with 11750 A flat-top current.

scale exponentially with the total ramping and waiting time in the pre-cycle, which in our case can be simply approximated by the flat-top time t_{FT} . In addition we should expect a proportional scaling with the magnitude of the current distribution induced by each ramp. As we observed for the current steps, the current distribution excited by a sufficiently fast ramp is proportional to the flat-top current I_{FT} . Both scalings with t_{FT} and I_{FT} have been verified on the variation of sextupole pattern amplitude following the pre-cycle (see Figs. 8 and 9).

IV. CONCLUSIONS

We have obtained data on the current distribution in a model accelerator magnet through measurement of field periodicity in the magnet bore. The features found are in very good agreement with experimental results obtained by Krempasky and Schmidt on a 2-strand cable [5]. Our results therefore give confidence in the extrapolation of the simplified theory of [5] to the much more complex situation found in magnets.

The long characteristic time associated with current diffusion in the cable is responsible for the fact that the magnet *remembers* the powering history. The scaling of current distribution with powering history is essentially the same as the decay observed on average harmonics [12]. This reinforces the present understanding of the origin of the field decay in accelerator magnets.

REFERENCES

- [1] H. Brueck et al., "Observation of a Periodic Pattern in the Persistent Current Fields of the Superconducting HERA Dipole Magnets", *Proc. of 1991 Part. Acc. Conf.*, San Francisco, pp. 2149-2151, 1991.
- [2] A. K. Ghosh, K. E. Robins, W. B. Sampson, "The Ramp Rate Dependence of the Sextupole Field in Superconducting Dipoles", *IEEE Trans. Mag.*, vol. 30 (4), pp. 1718-1721, 1994.
- [3] A. A. Akhmetov, A. Devred, T. Ogitsu, "Periodicity of Cross-over Currents in a Rutherford-type Cable Subjected to a Time Dependent Magnetic Field", *Jour. Appl. Phys.*, vol. 75 (6), pp. 3176-3183, 1994.
- [4] A.P.Verweij, H.H.J. ten Kate, "Super Coupling Currents in Rutherford Type of Cables due to Longitudinal Non-homogeneities of dB/dt", *IEEE Trans. Appl. Sup.*, vol. 5 (2), pp. 404-407, 1995.
- [5] L. Krempasky, C. Schmidt, "Experimental verification of 'supercurrents' in superconducting cables exposed to AC fields", *Cryogenics*, 39, pp. 23-33, 1999.
- [6] R. Stiening, "A Possible Mechanism for Enhanced Persistent Current Sextupole Decay in SSC Dipoles", *SSCL-359*, 1991, unpublished.
- [7] R. Wolf, "The Decay of the Field Integral in Superconducting Accelerator Magnets Wound with Rutherford Cables", *Proc. of 15th Int. Mag. Tech. Conf.*, Beijing, pp. 238-241, Science Press, 1998.
- [8] L. Bottura, L. Walckiers and Z. Ang, "Experimental Evidence of Boundary Induced Coupling Currents in LHC Prototypes", *IEEE Trans. Appl. Sup.*, vol. 7 (2), pp. 801-804, 1997.
- [9] P. Pugnât, T. Schreiner, A. Siemko, "Investigation of the Periodic Magnetic Field Modulation inside Apertures of LHC Superconducting Model Dipoles", Presented at 7th EPAC, Vienna, June 23-26, 2000.
- [10] N. Andreev, et al., "Present State of the Single and Twin Aperture Short Dipole Model Program for the LHC", *Proc. of 15th Int. Mag. Tech. Conf.*, Beijing, pp. 115-118, Science Press, 1998.
- [11] Z. Ang, et al., "Measurement of AC Loss and Magnetic Field during Ramps in the LHC Model Dipoles", *IEEE Trans. Appl. Sup.*, vol. 9 (2), pp. 742-745, 1999.
- [12] M. Haverkamp, L. Bottura, M. Schneider, "Studies of Decay and Snapback Effects on LHC Dipole Magnets", *Int. Phys. Conf. Ser.*, 167, 1183-1186, 2000.