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.

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 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).](image-url)
The second type of cycle reproduces the operating current cycle for LHC dipole magnets (see Fig. 2b). The magnet was pre-cycled ramping at 50 A/s to a maximum current \( I_{\text{RT}} \), remaining at flat-top for a time \( t_{\text{RT}} \), and finally ramping down to -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 current \( I_{\text{RT}} \) in the set 4 kA, 8 kA and 11.75 kA and the flat top time \( t_{\text{RT}} \) 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 \( I_{\text{RT}}=2 \text{ kA} \) and \( RR=450 \text{ A/s} \). Note how the fitting model of Eq. (2) adapts very well to the measurements. The amplitude of the periodic pattern \( \Delta_3 \) is about 0.8 mT @ 17 mm.

#### A. Step Response

In the case of a step in current the sextupole pattern amplitude \( \Delta_3 \) 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 \( RR = 450 \text{ A/s} \), but different flat-top current \( I_{\text{RT}} = 2 \text{ kA} \) and \( I_{\text{RT}} = 8 \text{ kA} \).

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...
constant leads to a range of 3000 to 4500 s.

The evolution of the phase of the sextupole pattern $\phi_i$ 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 $I_{\text{FT}}$ and $RR$, 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 $I_{\text{FT}} = 8$ 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 $\delta A_i$ that takes place during the 1000 s of the simulated injection flat-bottom. In Figs. 8 and 9 we plot $\delta A_i$ as a function of the flat-top current $I_{\text{FT}}$ and of the flat-top duration $t_{\text{FT}}$ during the pre-cycle. The results show that there is a clear correlation between $\delta A_i$ and both $I_{\text{FT}}$ and $t_{\text{FT}}$. The change of sextupole pattern $\delta A_i$ 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 $I_{\text{FT}}$ and $t_{\text{FT}}$. 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.
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 spatial 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 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 $t_F$. 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 $I_F$. Both scalings with $t_F$ and $I_F$ 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