INVESTIGATION OF THE PERIODIC MAGNETIC FIELD MODULATION INSIDE APERTURES OF LHC SUPERCONDUCTING DIPOLE MODELS

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Abstract

The windings of high-field accelerator magnets are usually made of Rutherford-type superconducting cables. The magnetic field distribution along the axis of such magnets exhibits a pronounced periodic modulation with a wavelength equal to the twist pitch length of the cable used in the winding. Such an effect, resulting from quasi-persistent currents, was investigated with a Hall probe array inserted inside the aperture of 1-metre long LHC superconducting dipole models. The amplitude and the time dependence of this periodic field oscillation have been studied as a function of the transport current history. The impact on the magnet stability of the non-uniform current redistribution producing such a field modulation is discussed.

1 INTRODUCTION

When an accelerator magnet made of multistrand superconducting cable is energized, an axial periodic modulation of the magnetic field is established with a wavelength equal to the cable transposition pitch length. This Periodic Field Pattern (PFP) was first discovered in HERA dipoles in 1991 and was found to be present in all normal and skew harmonic components [1]. The study of this phenomenon and its time decay is of importance for the field quality request for the LHC [2] as well as for magnet stability with respect to quench performance especially in real operating conditions of the machine. The PFP originates from non-uniform interstrand current distribution [3] which can lower the current margin of the cable significantly. This report mainly focuses on the latter aspect.

2 EXPERIMENTAL

2.1 General layout of the test station

The measurements have been performed at the cryogenic test station dedicated to the study of the LHC short magnet models and protection diodes. Two vertical set ups can be used to suspend and immerse magnets in superfluid helium. Inside cryostats, the so-called λ-plate separates the pool of boiling helium bath from the superfluid one, both maintained at atmospheric pressure (Claudet bath). The subcooled superfluid helium in the lower portion of the cryostat is achieved with a heat exchanger where saturated superfluid conditions are obtained from the Joule-Thomson expansion of the liquid helium. The λ-plate has a number of leak-tight feedthroughs for superconducting busbars, instrumentation wires and sliding bearing for the rotating shaft used for measurements of the field quality. A special shaft was equipped with stainless steel boxes containing Hall plates as described in 2.3.

2.2 Hall probe measurement system

Hall probes are ideal devices to measure the PFP inside apertures of accelerator superconducting magnets because of the small size of their sensitive area and their relative high sensitivity. Up to twelve AREPOC cryogenic Hall probes of three different types were used in this study. Their main characteristics are given in Table 1. The behaviour of each Hall probe type at 1.9 K was investigated [4]. In particular the so-called de-Haas-Van-Alphen oscillations were characterised. For the measurements of the PFP, Hall probes were connected in series to a KNICK DC-Strom-Calibrator J152 which delivers stable current with an error below ± 40 ppm. In the normal operation mode, the input current value for Hall probes was fixed to 5 mA.

Table 1: Characteristics of Hall probes used.

Hall Probes	Sensitivity in V/T A	Sensitive area (mm^2)	Number of units
HHP-NP	2.308	1.25 x 0.5	1
LHP-MP	0.275 - 0.44	0.1 x 0.1	2
HHP-MU	4.66 - 5.11	0.1 x 0.1	9

Two KEITHLEY 2001 digital multimeters, were used with scanner cards (Model 2000-Scan) to measure the voltage of 20 channels. The assignment of channels can be summarized as follows. Twelve channels were used for Hall voltages, three for the magnet temperature and two for the magnet current. The latter was measured with a Direct Current Current Transformer (DCCT) mounted on a 20 kA power supply. In addition, the drift of the KNICK DC-current calibrator as well as the offset of both KEITHLEY digital multimeters were measured precisely with the three remaining channels. Dedicated LabVIEW® software running on a SUN workstation, was used to interface with the digital multimeters via a GPIB bus for control, data acquisition and storage.

2.3 Magnets tested and Hall probe location

The PFP was measured inside the aperture of several short superconducting dipole models (Table 2) built mainly to improve the mechanical structure and the field quality of the LHC main dipoles [5]. The Hall probes were mounted inside a stainless steel case and fixed on a special rotating shaft dedicated to such measurements. The probes were located at a radius of 17 mm and covered the central part of short dipole model over a length of 20 cm. They allow measurement of the radial component of the total magnetic field as a function of azimuthal angle for different positions along z-axis.

Table 2: LHC short dipole models where the PFP was measured. The first 3 magnets are single aperture models whereas the others are twin dipole models.

Name	Main characteristics
MBSMS17.V3	Single aperture, 6-block variant design, aluminium collar
MBSMS23.V3	Single aperture, 6-block baseline design, stainless steel collar
MBSMS23.V4	Like .V3 but higher pre-stress
MBSMT4.V2	Twin apertures, 6-block baseline design, stainless steel collar
MBSMT5.V2	Twin apertures, 6-block baseline design, plastic & stainless steel collar
MBSMT4.V5	Twin apertures, 6-block baseline design, stainless steel collar, ferromagnetic yoke centred.

3 MEASUREMENTS, RESULTS AND ANALYSIS

3.1 Measurements

The superconducting magnets were submitted to current cycles of the type shown in Fig. 1, with different values of the maximum current (I_{max}) and times t_1, t_2 and t_3.

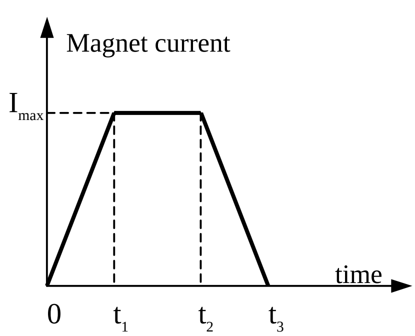

Figure 1: Example of current cycle performed.

The local magnetic field inside the magnet aperture was measured with the Hall probes as a function of time during the flat-top and at the end of the current cycle. Only results obtained for orientation of the sensitive area of the Hall probes perpendicular to the main dipole field direction are discussed in this article.

3.2 Results and analysis

The PFP was observed at the end of the current cycles for all magnets which were investigated when the flat-top duration $t_2 - t_1$ was larger than 3000 s. It was not measured for all magnets on the plateau (i.e. between time t_1 and t_2) mainly because the contribution of other sources of field inhomogeneity (like ferromagnetic yoke laminations) can be larger. When measured, the PFP has a very long decay time observed up to 56 hours after the end of the current cycle.

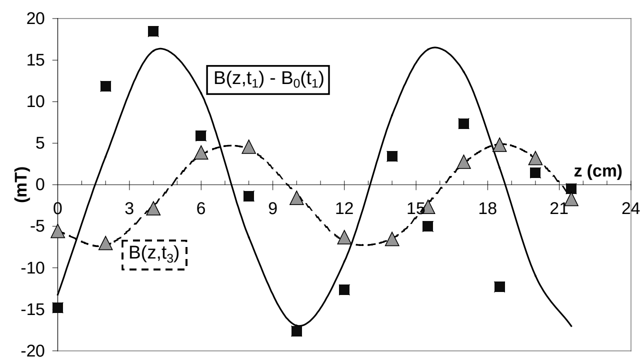

Figure 2: PFP measured at time t_1 and t_3 of the current cycle shown in Fig. 1.

Two examples of PFP measured on MBSMS17.V3 at times t_1 and t_3 are given in Fig. 2. They correspond to a current cycle with a ramp-up to 9 kA at 40 A/s followed by a ramp-down at –40 A/s after a plateau duration of 3000 s. Typical PFPs can be well approximated by the relation:

$$B(z,t) = B_0(t) + B_1(t) \sin (2\pi z/\lambda + \phi) \qquad (1)$$

where λ is found to be equal to the twist pitch length of the cable used for the inner layer of the coil. This result suggests a non-uniform interstrand current distribution inside the superconducting cable of the coil [3]. In order to understand the origin of such non-uniformity, previous studies have identified two main mechanisms. The first one concerns the spatial variation of the time derivative of the magnetic field along the cable [6], [7]. The second one is related to the variation of the contact resistance between strands of the cable [7].

All the fitting parameters deduced from equation (1) for both PFPs of Fig. 2 are given in Table 3 and will now be compared and interpreted. Concerning the homogeneous term of (1) obtained from the fit of the PFP measured at t_1, $B_0(t_1)$, it is in good agreement with the value of 6430 mT deduced from the transfer function measured by means of the rotating coil technique. The corresponding term measured at t_3 after the suppression of the magnet current, $B_0(t_3)$, is negative because it comes mainly from the remanent magnetisation of superconducting filaments.

Table 3: Fitting parameters extracted from (1) for both PFPs shown in Fig. 2.

Parameters	PFP at t_1	PFP at t_3
B_0(mT)	6444	-1.33
B_1(mT)	16.8	6.23
λ(mm)	114	114
ϕ(rad)	-0.885	-2.4

Concerning the amplitudes of the PFP, the value $B_1(t_1)$ is clearly larger than $B_1(t_3)$. This result can be understood qualitatively within the framework of existing theoretical models [3], [6] and [7]. During the ramp-up of the current cycle (i.e. up to t_1), the Rutherford type superconducting cable charges itself with a non-uniformly distributed current wave. On the plateau of the cycle this wave diffuses slowly, in other words the current tends to be shared more uniformly between strands. The decay of the PFP amplitude shown in Fig. 2 was too low to be measured after 3000 s. During the ramp-down, the superconducting cable charges itself with a non uniformly distributed current wave of an opposite sign as compared to the current ramp-up (antiwave). As a consequence, the PFP measured at the time t_3 is the composition of two waves which can partially cancel.

The amplitudes $B_1(t_1)$ and $B_1(t_3)$ of the PFP are found to depend strongly on the current cycle performed. For the case of an asymmetric cycle with a ramp-down much faster than the ramp-up, the PFP exhibits a larger amplitude $B_1(t_3)$ as compared to a symmetric cycle. This effect can be explained by a lower compensation effect between the two waves. Another result obtained is that the amplitude of PFP at time t_3 increases exponentially with the duration of the current cycle like the voltage of a charging capacitor. The amplitude of $B_1(t_1)$ is also found to increase significantly with the maximum current of the cycle. As an example of combined effects, the amplitude of the periodic pattern measured on the flat-top inside the aperture of MBSMS17.V3 reached 32 mT at 13 kA after a cycle starting from 0 to 9 kA at 40 A/s followed by a ramp-up to 13 kA at 10 A/s.

4 IMPACT OF THE CURRENT REDISTRIBUTION ON THE QUENCH PERFORMANCE

An estimate of the current imbalance between strands required to produce the maximum of PFP amplitude measured up to now (32 mT) is around ± 350 A for the case of short dipole models investigated (i.e. with 6-block coil structure). This value is not negligible and should be compared to the current margin at the nominal field of half of the cable which is around 1000 A. Moreover for the real operation of the LHC machine such a margin will be drastically reduced due to the beam loss. As a consequence, non-uniform superimposed induced currents can certainly provoke premature quenches of the dipoles.

All the PFPs measured in magnet models listed in the Table 2 are different and the amplitudes of the field oscillation $B_1(t_1)$ and $B_1(t_3)$ seem not to depend directly on the main magnet characteristics. This lack of correlation highlights the dependence of non-uniform current distribution on local characteristics.

5 CONCLUSIONS

The PFP and its decay affect the field quality of LHC main dipoles as well as their stability with respect to quench performance. To reduce both these effects, a current cycling strategy should be developed and further studies in full scale LHC dipoles should be launched.

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