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ABSTRACT

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INTRODUCTION

The Large Hadron Collider¹ (LHC) will accelerate proton beams from an injection energy around 450 GeV to the nominal coast value of 7 TeV. The superconducting magnets, operated in superfluid helium and forming the main part of the LHC ring, will need to be cycled in accordance to maintain the bending and focussing strength required. In particular, the main arc dipole magnets will receive the beam at the injection field of 0.54 T, and will follow its acceleration up to the nominal operating field of 8.36 T. From the experience on other superconducting accelerator magnets (Tevatron², HERA³, RHIC⁴ and SSC⁵), and from measurements of the field quality of LHC dipole prototypes, we expect that the field quality in the ring at the low field levels needed at injection will be dominated by the contribution of the magnetization of the superconducting filaments⁶. The LHC performance will be determined by field quality at injection, hence much attention has been paid till now to the prediction and measurement of magnetization effects^{7,8}.

The results reported here refer to several short (1 m) and one long (10 m) dipole models built and tested in the past 2 years within the scope of the on-going R&D programme for LHC. All magnets have the same coil geometry, with a 56 mm cold bore¹. The coil is wound in 5 blocks and 2 layers with a 15 mm wide Rutherford cable. Most of the short models, the so called MBSSx series, have a single collared coil inside an iron yoke. A single short model, the MBST1, has two collared coils in a single vertically split iron yoke that closes the magnetic circuit of both magnetic bores, or *apertures*. The MBL1N1 is a twin aperture 10 m model, the first long dipole with 56 mm aperture. The Rutherford cables used for these magnets have the same geometry, but the NbTi strand has evolved from magnet to magnet. In particular the magnetization (related to the critical current I_c and filament diameter D_{fil}) is different for the various magnets. Typical filament diameter for the cables used range between 4.6 μm to 7 μm . The features of these magnets that are of interest here are summarised in Tab. 1, where we have reported in particular the average

Table 1. Main features of the LHC short and long, 56 mm aperture dipole models tested

Magnet	Length (m)	type ^(*)	I _c @ 4.2 K		D _{fil}		Cu:NbTi	
			inner layer (kA@7T)	outer layer (kA@6T)	inner layer (μm)	outer layer (μm)	inner layer (–)	outer layer (–)
MBSS1	1	S	14.898	14.622	4.6	6	>1.60	>1.80
MBSS2	1	S	14.917	14.700	4.6	6	>1.60	>1.80
MBSS3	1	S	14.937	14.700	4.6	6	>1.60	>1.80
MBSS4	1	S	14.465	15.555	4.6	6	>1.60	>1.80
MBSS5	1	S	14.397	15.555	4.6	6	>1.60	>1.80
MBSS6	1	S	14.829	15.555	7	6	>1.60	>1.80
MBSS7	1	S	14.329	14.700	4.6	6	1.62	>1.80
MBSS8	1	S	14.829	15.528	7	6	>1.60	1.96
MBSS9	1	S	14.660	-	7	6	1.63	>1.80
MBSS10	1	S	-	-	7	6	-	>1.80
MBSS11	1	S	-	-	7	6	-	>1.80
MBST1	1	T	14.829 ^(†)	15.351 ^(†)	7 ^(†)	6 ^(†)	>1.60 ^(†)	1.96 ^(‡)
			14.829 ^(‡)	15.351 ^(‡)	7 ^(‡)	6 ^(‡)	>1.60 ^(†)	1.96 ^(‡)
MBL1N1	10	T	14.494 ^(†)	14.844 ^(†)	4.6 ^(†)	6 ^(†)	1.64 ^(†)	1.83 ^(†)
			14.638 ^(‡)	16.392 ^(‡)	4.6 ^(‡)	6 ^(‡)	1.63 ^(‡)	1.75 ^(‡)

(*) S = single aperture, T = twin aperture

(†) first aperture

(‡) second aperture

cable critical current (measured at 4.2 K at 6 or 7 T depending on the layer) and the filament diameter data for the inner and outer layer of each aperture.

FIELD QUALITY DEFINITION AND THE EFFECT OF MAGNETIZATION

For accelerator magnets it is customary to consider the magnetic field as two dimensional, ignoring the length z , and to express the magnetic flux density $\mathbf{B}$ in the x - y plane normal to the beam using the following complex power series:

$$\mathbf{B}(x, y) = B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x + iy}{R_{ref}} \right)^{n-1} \quad (1)$$

where the B_1 is the dipole strength, R_{ref} is the reference radius (10 mm for LHC), while b_n and a_n are the normal and skew $2n$ -pole coefficients. As given in Eq. (1), the multipole coefficients are expressed in so-called *units*, i.e. normalised and scaled by a factor 10,000.

One of the main source of field errors in a superconducting magnet is the magnetization M of the superconducting filaments. Screening currents, of persistent nature, are induced by any field change during operation of the magnet. These currents appear in first approximation as a trapped magnetization dipole $m = A_{fil} M$ with hysteretic behaviour, where A_{fil} is the filamentary cross section in a strand. The multipoles generated by the plane magnetic moment $m = m_y + i m_x$ located at the position $R = x + i y$, including the effect of the cylindrical iron yoke with inner radius R_{iron} , can be calculated as follows:

$$(b_n + ia_n) = -10^4 \frac{n}{B_1} \frac{\mu_0}{2\pi R_{ref}^2} \left[m^* \left(\frac{R_{ref}}{R} \right)^{n+1} + m' \left(\frac{R_{ref}}{R'} \right)^{n+1} \right] \quad (2)$$

where m^* is the complex conjugate of m and the mirror moment m' and radius R' are:

$$m' = -\frac{R'^2}{R_{iron}^2} \frac{\mu - 1}{\mu + 1} m^* \quad R' = \frac{R_{iron}^2}{R^*} .$$

Equation (2) shows that in principle all harmonic orders are generated. Symmetry conditions in a perfect dipole are such that only *allowed* harmonics are generated⁶. For a normal dipole magnet these are the multipoles b_n , with $n=2k+1$ and $k=[0...\infty]$. The model for the filament magnetization $M(B)$ is based on a fit⁷ of measured magnetization data⁹. The fit consists of two formulae, one for the fully penetrated state and one for the penetration phase. The envelope of upper and lower magnetization branches in fully penetrated state is fitted as:

$$|M(B)| = \frac{\mu}{B^n} \quad (3)$$

where B is the module of the magnetic field, while μ and n are fit constants. The sign of $M(B)$ depends on the direction of the field change. The penetration phase, after a field reversal starting at B_{rev} (corresponding to a magnetic moment $|M_{rev}| = \mu / B_{rev}^n$) is fitted as:

$$M(B) = M_{rev} + (h^2 - 2h) \Delta M(B_{rev}) \quad (4)$$

where h is the normalised variable:

$$h = \frac{B - B_{rev}}{B_p(B_{rev})} \quad (5)$$

and $\Delta M(B_{rev})$ is the width of the hysteresis loop from the field reversal point B_{rev} to full penetration at $B = B_{rev} + B_p(B_{rev})$. The value of $B_p(B_{rev})$, the penetration field starting from the field reversal point B_{rev} , is computed scaling the experimental value of the penetration field $B_p(0)$ and the width of the magnetization loop $\Delta M(0)$ measured at zero field:

$$B_p(B_{rev}) = B_p(0) \frac{\Delta M(B_{rev})}{\Delta M(0)} \quad (6).$$

Note that Eq. (6) is non linear because $\Delta M(B_{rev})$ can be calculated (using Eq. (3)) only when B_p is known. To give orders of magnitude, the values of the parameters used to fit the magnetization of a LHC strand with 7 μm filament diameter are $\mu \approx 0.027 \text{ (T}^{1+n}\text{)}$, $n \approx 0.5$, $B_p(0) \approx 0.15 \text{ (T)}$, and $\Delta M(0) = 0.105 \text{ (T)}$. As we are interested in the magnetization at low field, where the critical current is much larger than the transport current, we do not make any transport current correction. Finally, all strands are assumed to be in a fully penetrated state at the end of a field sweep. This assumption limits the use of this model to major magnetization loops. We checked *a posteriori* that this causes a negligible error.

MEASUREMENTS OF FIELD QUALITY AT INJECTION

To perform measurements of field quality we have used a radial rotating coil system. The short (1m) models were measured in a vertical cryostat, with a cold measurement coil covering 60 cm (the central part) of the dipole length. The 10 m-long dipole model was tested on a horizontal bench. In this case the rotating coil was in a warm bore, measuring a length of 75 cm at the center of the straight part of the magnet. To identify the contribution of the magnetization of the superconducting filaments, we have defined a dedicated measurement procedure. The procedure starts precycling the magnet to a maximum current of 11.75 kA (about 8.4 T), to simulate a collision run, followed by a ramp-down to a minimum current of 50 A (corresponding to a field of 35 mT). This cycle brings the magnet into a well defined magnetization state, on the upper magnetization branch, where most of

the superconducting filaments in the cables are fully penetrated. We then ramp slowly, with a ramp rate of 2 A/s (1.5 mT/s), up to 2 kA (about 1.5 T), well above the nominal injection level (at approximately 800 A). During this slow ramp measurements are taken continuously (*on-the-fly*). The magnet is then ramped up to maximum current and down to 2 kA. From here a downward ramp at 2 A/s is started, where measurements are again taken continuously.

The purpose of the two slow ramps is to have a measurement of both upper and lower magnetization branches. The ramps are sufficiently slow that ramp-rate effects (due to coupling currents in the Rutherford cables) are negligible for most of the magnets tested. The reason for taking measurements *on-the-fly*, rather than stopping at several currents, is that we wish to avoid the decay of magnetization observed during current plateaus. We have shown elsewhere that a continuous magnetic field change can indeed prevent decay⁸. In the measurements reported here the minimum current has been taken as a parameter in the range of 50 to 650 A, with the aim to investigate the influence of the precycle procedure on the field quality at injection. All measurements were taken in superfluid helium, at stable bath temperatures ranging from magnet to magnet from 1.65 K to 1.85 K.

Figure 1. Normal sextupole (b_3) measured in the MBL1N1 long dipole model (thick continuous line). The arrows mark the ramping directions. The magnet has been cycled taking the minimum current as a parameter to investigate precycling influence at injection. The computed value (broken line) is reported for comparison.

Figure 2. Normal decapole (b_5) measured in the MBL1N1 dipole (solid line) and computed (broken line).

Figure 3. Higher order multipoles (b_7 and b_9) measured in the MBL1N1 dipole.

Discussion of measurement results

Figures 1, 2 and 3 show an example of the detailed result of the measurements performed on the MBL1N1 dipole, the first 10-m long, 56 mm aperture model. We have plotted there the low field behaviour of the first allowed harmonics (b_3 to b_9), as measured with the procedure described above. The geometric component of the field error has been removed, shifting the measured curves so that they have zero average at middle field. The upward and downward ramps are marked by the arrow direction. Magnetization effects are clearly visible on these allowed multipoles. The steep portion of the curves, at low field in the upward branches, corresponds to the penetration phase for the majority of the filaments. After penetration the filament magnetization starts decreasing according to the $J_c(B)$ dependence. We see this effect as an extremum in the upward branch followed by a decrease as the field is increased. The upward branches with the more pronounced extrema correspond to a minimum current of 50 A. The subsequent cycles with minimum currents of 250, 450 and 650 A can be identified by the shift of the penetration phase towards higher field and the less pronounced extrema. As expected, for all allowed multipoles the penetration phase is significantly affected by the minimum current (i.e. minimum field) reached in the previous cycle. An interesting feature is that in all cases the upward branches with higher minimum current tend to overshoot slightly those with smaller minimum current. This small effect, common to all multipoles, can be most clearly seen on the decapole (b_5) curves of Figure 2. We attribute this effect to the difference in magnetization status of the different coil blocks, as discussed later. The downward branch is not affected by the minimum current, which is consistent with the fact that we cycle the magnet up to high field values, so that most of the filaments are in a fully penetrated state.

Effect of minimum current

The effect of the minimum current during a precycle has been summarised in Figure 4, for the normal sextupole and decapole. We plot there the amplitude of the hysteresis cycles Δb_3 and Δb_5 at injection field (difference of the values on the upward and downward branches) as a function of the minimum cycle current. The effect is significant, and monotonous on Δb_3 , while on Δb_5 only a small effect can be seen, with a peaking at minimum current of 450 A. The peak is due to the overshoot feature discussed earlier. The curves are flat below 250 A. If we consider this minimum cycle current and ideally change it by ± 50 A the effect on the normal sextupole, the allowed multipole with the tightest relative tolerance for the machine optics, is less than 3 %. We consider this range of minimum current to be a safe compromise between the necessity to bring the magnets into a reproducible state and power supply design considerations.

Statistics on measurements

As we stated in the introduction we have measured up to now several (12) 56 mm aperture short models in addition to the MBL1N1 long model discussed in detail in the previous sections. The general features of the measurements are similar to the ones presented for the MBL1N1. To summarise the statistic of these results, we have reported in Figure 5 the measured amplitude of the hysteresis on the sextupole and decapole for a minimum cycle current of 50 A. We see that the points are grouped, with two exceptions, in two clusters (marked to aid the eye). These two clusters correspond in Tab. 1 to the magnets wound with inner cables with small (4.6 μm , filled symbols) and large (7 μm , open symbols) filament diameter. The two outliers are magnets MBSS4 (filled symbol with exceptionally small b_3) and MBSS10 (open symbol with exceptionally large b_3). The first magnet had an extremely low interstrand resistance (around 3 $\mu\Omega$), and therefore already at 2 A/s ramp-rate had significant cable eddy currents effects⁵ invalidating our hypothesis of quasi-steady state measurement. There is no apparent explanation for the second outlier point. The residual scatter of the points in the two clusters can be attributed to the scatter in the magnetization properties that can be deduced from the variations in the cable critical current of Tab. 1, and in different bath temperatures from magnet to magnet during the measurements.

CALCULATION OF MAGNETIZATION EFFECTS

The effect of magnetization can be calculated using Eqs. (2)-(6). A pre-computed map of the magnetic field is used to calculate the local field at each strand for the same current cycle used in the measurements. The contribution of the magnetic moment is then computed on a strand basis, using the local field value in the strand to determine $M(B)$, and summed over the complete coil cross section. The b_3 and b_5 computed with this procedure are plotted in Figures 1 and 2 (dashed lines), and they show an excellent agreement with the measurements. We attribute the accuracy of the calculation to the fact that we have calibrated $M(B)$ on a measured magnetization curve for a strand similar to those actually used in the coils of MBL1N1⁹. For b_3 both the penetration phase and the peaking as the filaments start reaching full penetration are matched very well. A small deviation is found on Δb_3 at injection, of the order of 20 %, that could be due to small residual differences between the fit $m(B)$ and the actual strand magnetization. In the case of b_5 the simulation correctly predicts the overshoot at increasing minimum cycle current, as observed

Figure 4. Amplitude of the sextupole and decapole hysteresis cycles at injection in the MBL1N1 dipole as a function of the minimum current during precycle as measured (squares) and simulated (circles).

Table 2. Layers contributions to Δb_3 and Δb_5 , as computed for MBL1N1 at injection field. ⁸

	Δb_3 (units)	Δb_5 (units)
outer layer	-4.92	-0.090
inner layer	-1.62	0.261

experimentally. The width of the peaks of b_5 is slightly different, narrower in the simulation than in the measurement.

We have compared the simulations to the measurements on the effect of minimum cycle current in Figure 4. The Δb_3 curves, measured and simulated, are parallel. The shift is possibly due, as we said above, to residual inaccuracy in the fit of the strand magnetizations at injection. In the case of Δb_5 the initial behaviour, up to 450 A, is similar (apart again for a rigid shift). Because the simulated b_5 peak is slightly sharper than the one measured (compare to the details at injection in Fig. 2), we miss the maximum at 450 A minimum cycle current. We judge this inaccuracy to be a detail, rather inessential as compared to the overall good agreement found.

The simulation gives additional insight in the measurements, and in particular on the reason why the b_5 overshoot takes place. As already shown in Ref. 7, the different blocks in the coil have different weight on the overall contribution to the multipoles, depending on the complex interplay of their geometric location and magnetization strength. We show this fact in Table 2, where we report the partial contributions of the inner and outer coil layers to the Δb_3 and Δb_5 at injection, after a cycle at minimum current of 50 A. We see there that while for b_3 both contributions have the same sign, in the case of b_5 the inner layer has a strong positive contribution, as opposed to the weak negative contribution of the outer layer. These contributions change in magnitude, and for b_5 also in sign, depending on the operating field. In particular the outer layer gives a positive contribution to b_5 for small field changes $\Delta B \leq 0.25$ T after field reversal, and becomes negative for larger field changes. The peak in b_5 is found within the first range of field, where the two contributions add to each other. An increase of the minimum cycle current shifts the region where both inner and outer layer give positive contribution to b_5 towards higher field. This explains the presence of the overshooting peaks at increasing minimum cycle currents.

We have finally used the computed weights of inner and outer layer as given in Table 2

Figure 5. Summary of measured amplitudes of the hysteresis on b_3 and b_5 , for 12 short models and one long model. The filament diameter D_{fil} of the inner layer cables is reported in legend. All magnets have the same outer layer $D_{fil} = 6 \mu m$ (see Table 1). Also reported the calculated point for MBL1N1 (square) and the scaling with the magnetization of the inner layer (see text).

to examine the scaling of the clusters of measurements of Figure 5. As seen from Table 1, all magnets tested had the same filament diameter for the outer layer cables, and different filament diameters for the inner layer cables. Therefore, if we neglect the contribution of the changes in critical current, we can expect that these two groups should differ just by the contribution of the magnetization of the inner layer. We have taken the computed point for MBL1N1, the square in Figure 5, and scaled the inner layer contribution according to the weights in Table 2. The result is the dashed line in Figure 5. Apart for a rigid shift, the magnets seem to broadly follow the scaling line, including the apparently anomalous MBSS4 and MBSS10. Hence we can interpret these two apparent outliers as having either an anomalously low (MBSS4) or high (MBSS10) inner layer magnetization.

CONCLUSIONS

We have reported details and statistics on low field magnetic measurements on 12 short (1 m) and one long (10 m) LHC dipole models. We have shown how a relatively simple computer model is capable to reproduce the experimental results presented here with a very satisfactory agreement. The key to this good agreement is the use of directly measured magnetization data to produce an empirical fit used by the computer model. In addition the model gives information which is not available from the measurements, such as the weight of different coil layers to the total multipoles observed, used here to give a possible interpretation to the anomalous behaviour of two dipoles.

From a practical standpoint we could determine experimentally a safe value for the minimum precycle current to be used to bring the LHC dipoles into a known and stable magnetization state, in the range of 250 A. Relatively large variations in this range (± 50 A) produce small effects at injection field (below 3 % on the sextupole). A value in the range 250 to 300 A is thus a safe compromise between reproducibility and power supply design considerations, and can be taken as a standard for series measurements of the LHC dipoles.

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