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***Abstract* — A series of 1-m long, 56 mm aperture dipole models has been built and tested at CERN within the scope of the R&D program for LHC. Here we report a summary of results of warm and cold steady state field measurements in these models, concentrating on the contribution of the coil geometry. The first allowed harmonics are clearly correlated to the coil azimuthal size, and the slope of the correlation can be predicted accurately.**

I. Introduction

Within the R&D program for the Large Hadron Collider [1] (LHC) main bending dipole magnets, several short (1 m) dipole models have been built [2]. The main purpose of these models is to explore parametrically the influence of manufacturing parameters on the quench level and training. The manufacturing changes were implemented in the course of the program depending on the results of the tests. In particular, shimming of the coils was chosen to achieve a pre-stress objective, rather than a nominal geometry. As an additional diagnostic, and to gain experience for the future series measurements, the magnetic field was measured in warm and cold conditions. We report here a summary of these measurements, concentrating in particular on the influence of the coil geometry and its variations throughout this small *series* production. The results reported refer to 14 dipole models. All magnets have the same nominal winding geometry, with 5 blocks and 2 layers per pole, and a 56 mm cold bore[2]. The four coils forming the winding (one inner and one outer layer coil for both upper and lower pole) are wound with a 15 mm wide Rutherford cable and cured independently. The coils are then assembled in a support structure, formed by laminated *collars*, that provides azimuthal pre-compression against the electromagnetic loads. The cold mass is completed by the iron yoke and an enclosing steel shell, the shrinking cylinder. Most of the short models, the so called MBSMSx series, have a single collared coil assembly inside the iron yoke. Two short models, the MBSMT1 and MBSMT2, have two collared coil assemblies in a single iron yoke that closes the magnetic circuit of both magnetic bores, or *apertures*. More details about the dipole design and the R&D program can be found in [2,3].

II. Experimental

A. Field quality definitions

As customary for accelerator magnets we consider the magnetic field **B** as two dimensional, and we express it in the magnet cross section *x*-*y* using the complex power series:

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

where 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. For all results presented here, multipoles have been corrected for higher order feed-down and rotated in a reference frame where the dipole is purely normal. Finally, for later use, we define the dipole *transfer function T* as the ratio of the dipole B_1 and the excitation current.

B. Magnetic measurement set-up and procedure

All dipole models were tested in vertical cryostats at superfluid helium temperature (ranging typically from 1.7 K to 1.9 K). Most of them were also measured in *warm* conditions (200 K to 300 K) in the same test set-up. The measurement of the magnetic field was done using radial rotating coils mounted on a glass-fiber shaft. Five adjacent coils sections are installed on the shaft to measure the field dependence along the magnet bore. The three coil sections in the center cover the straight part (200 mm length each section, covering approximately 600 mm) while the top and bottom coil sections (240 mm length each section) cover the magnet ends. The signals from the five coil sections are read-out simultaneously using a chain of VME integrators. In this paper we will refer to the measurements from the centermost coil section for the main dipole component of the magnetic field and its transfer function, while the higher order harmonics will be given as dipole-weighted averages over the straight part (on the three central coil sections).

The measurements reported here have been taken in steady state conditions at a total of approximately 20 current values along the magnet loadline. The measurements were taken on both ramp-up and ramp-down powering branches to evidence hysteresis effects. For all magnets the testing procedure started with a standard pre-cycle (ramp-up to 11.75 kA and down to 50 A) to achieve a known and reproducible initial state.

C. Coil size measurements

The coils used for the assembly of the model dipoles were systematically tested in a press to determine the relation between applied force and azimuthal coil size. The coil is

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measured taking as reference a steel master, precisely machined to the nominal coil dimensions. The result of this measurement is therefore the difference δ of the azimuthal coil length with respect to the nominal value as a function of the applied force. Both limbs (right and left) of a coil are measured. The convention choosen is that a positive δ indicates a coil larger than nominal. The collared coil stress is monitored during assembly and testing, and this allows, using the force-displacement relation established in the press, to estimate the eight azimuthal sizes δ_i of all four coils in a collared coil assembly after assembly (the index i runs on the right and left limb, inner and outer layer, upper and lower pole).

III. Results

A. Field quality as a function of excitation current

Figs. 1 and 2 show typical results for the dipole transfer function T, normal quadrupole b_2 and sextupole b_3 in the two apertures of a twin aperture model (magnet MBSMT2). At moderate current (in the range of 5 kA to 7 kA, corresponding to 3.5 T to 5 T) the curves are flat, and we assume that in this region the field quality is dominated by the coil geometry and the linear contribution from iron. We define as *geometric* field errors the average of the values measured in the ramp-up and ramp-down branches in this field range. At higher current the contribution of iron saturation becomes appreciable. At low field, on the other hand, the cable magnetization (persistent currents) causes a substantial hysteresis in the ramp-up and ramp-down branches of both T and b_3.

We note firstly that a normal quadrupole can be present in the twin aperture concept because of the right/left asymmetry built in the magnet. This is demonstrated in Fig. 2 by the presence of a *geometric* b_2 in both apertures of MBSMT2, with the same magnitude and opposite sign, caused by the return field of one aperture on the adjacent one. The symmetric changes of b_2 in both apertures at high field are caused by the iron saturation that changes the magnetic link between the two apertures. Remark that the low field hysteresis on b_2 is due to a residual feed-down from b_3, caused by centering imperfections in the measurement system that can be corrected only partially by analysis.

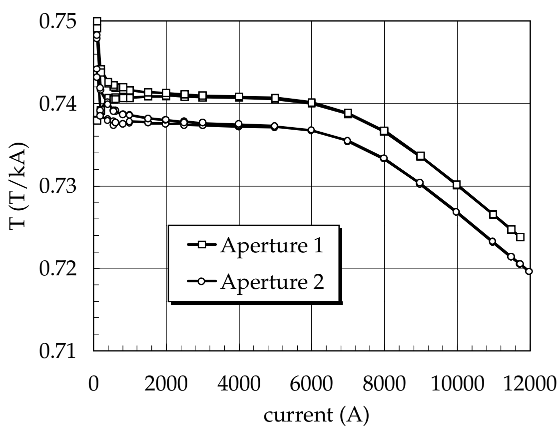

Fig. 1. Transfer function of the double aperture model MBSMT2 as a function of the excitation current.

A second interesting feature of Figs. 1 and 2 is that the geometric values of T and b_3 are evidently different between apertures of the same magnet. As we will discuss later, we can attribute most of this difference to the different coil sizes.

As a final remark, care should be taken in the direct extrapolation of the results of the short models to the 15 m long dipoles foreseen in the LHC. Because of the short length the iron contribution in the model dipoles is strongly affected by end effects. Compared to the long dipoles, the end effects result in earlier saturation and strong stray fields between apertures, as demonstrated by exceedingly high geometric b_2.

B. Cold vs. warm measurements

Warm measurements are foreseen for the LHC series production to control manufacturing and as a reception screening for all magnets. An obvious question is whether warm measurements represent well the field quality of the magnet at cold conditions. We claim that this is the case for

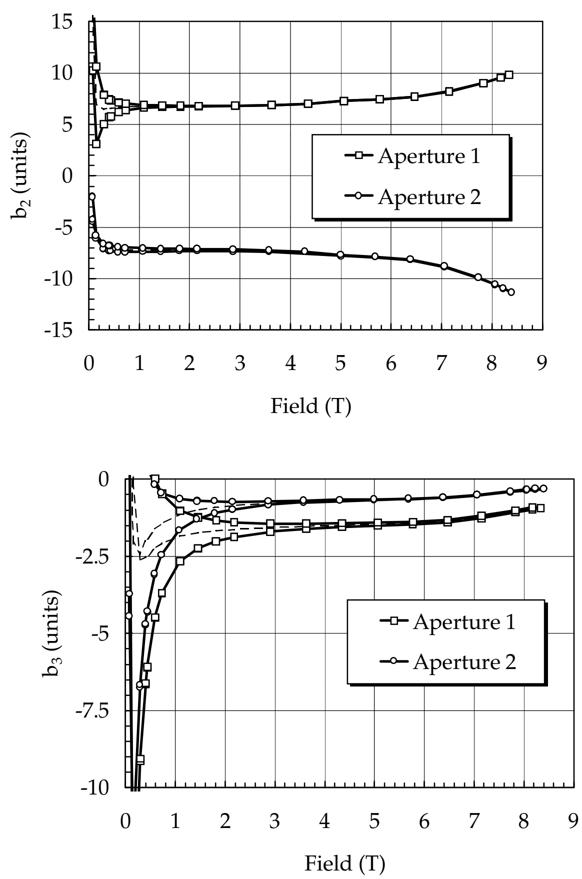

Fig. 2. Normal quadrupole b_2 (top) and normal sextupole b_3 (bottom) as a function of the excitation field, for the two apertures model MBSMT2.

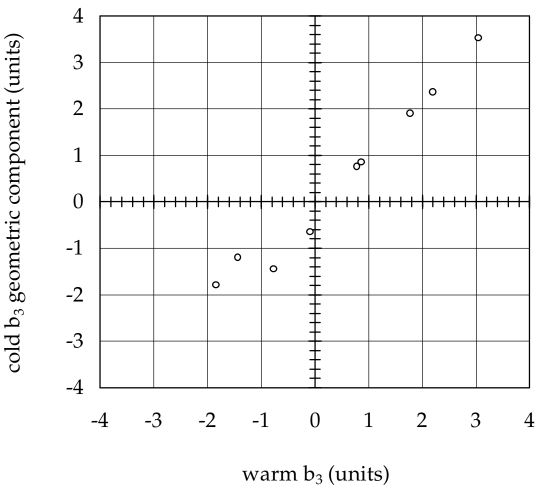

Fig. 3. Summary of cold geometric (evaluated at 5 T) vs. warm sextupole measured in the series of short models.

the geometric contribution, as it is demonstrated for the normal sextupole, shown in Fig. 3. There we compare the results of warm measurements to the geometric contribution deduced from the measurement in cold conditions (computed at 5 T), showing a very good correlation (correlation coefficient 0.99). Similar results are obtained for other harmonics. Table I reports the typical standard deviations σ_{cw} of the cold-warm correlation for low order harmonics, defined for an arbitrary harmonic c_n as:

$$\sigma_{cw} = \sqrt{\frac{\sum_{i=1}^{N}\left(c_n^{cold} - c_n^{warm}\right)^2}{N-1}} \qquad (2)$$

Equation (2) gives a measure of the confidence in warm measurements with respect to the behaviour during operation in cold conditions.

C. Geometric component and coil size

As discussed in the previous section, there is a good correlation between warm and cold coil geometry. Here we wish to strengthen this statement demonstrating that the harmonics are also well correlated to the actual coil size obtained from mechanical measurements performed during construction.

From basic considerations on electromagnetic design, we know that any change in the coil geometry with respect to the reference dimension causes necessarily a variation of the magnetic field and field quality[4,5]. To ease the analysis of the effect of a geometry variation on the harmonics, it is useful to define deformation *modes*. Because we have information only on the azimuthal coil size we will limit ourselves to the modes involving the displacement δ_i of coil poles. The mode of the lowest order of this class is the one involving a symmetric, uniform deformation of all coils, that can be described by a base vector v_i = 1 (unit increase or decrease of all eight coil dimensions). This mode maintains the symmetry of the magnet (right/left, top/bottom and rotation) and therefore only normal allowed harmonics are generated. The amplitude of the mode can be readily calculated from the estimated δ_i, and it corresponds simply to the average of the pole sizes δ.

TABLE I
STANDARD DEVIATION OF THE CORRELATION BETWEEN WARM AND COLD (GEOMETRIC) HARMONICS

Order	σ_{cw} (units)	Order	σ_{cw} (units)
b_2	0.72	a_2	1.36
b_3	0.37	a_3	0.36
b_4	0.15		
b_5	0.05		

We have verified the correlation of normal harmonics with the mode amplitude in Figs. 4 and 5, where the geometric dipole and sextupole (the first two allowed harmonics in a dipole) have been plotted as a function of the average azimuthal coil size. Note that in Fig. 4 we have defined the geometric dipole error b_1 as the variation of the transfer function T at 5 kA around the average value computed for the series of models, normalised to the dipole and scaled by the factor 10,000 in accordance with Eq. (1). The correlation found is indeed satisfactory, with typical correlation coefficients around 0.6 (for b_1) to 0.7(for b_3).

To confirm further these results, a simulation program has been used to calculate the effect of a change of the coil geometry on the field harmonics. Within the assumption of elastic behaviour, the lowest order mode was simulated by a displacement of the coil cables increasing linearly as a function of the azimuth, from zero on the coil midplane to the maximum δ at the coil pole turn. The changes of dipole and sextupole Δb_1 and Δb_3 were computed and normalised to the displacement applied, obtaining the slopes $\beta_1=\Delta b_1/\delta$ and $\beta_3=\Delta b_3/\delta$. The lines in Figs. 4 and 5 correspond to the calculated slopes, where the intercept has been arbitrarily shifted to obtain a best fit to the data clusters. We see from there that the calculated slopes describe properly the dependence observed experimentally.

Finally, we have reported in Table II the computed slopes for the first three allowed harmonics and the standard deviation σ_{cm} of the data set around the best fits, where σ_{cm} is defined in analogy to Eq. (2) using the difference of the measured and calculated harmonics. Again σ_{cm} is a measure of the level of confidence in the mechanical measurement for the prediction of cold geometric harmonics. The scatter is significant, and we attribute it mostly to the fact that we have examined here a correlation to a single deformation mode. We have ignored in particular radial modes that could have been *excited* by changes in the manufacturing procedures undertaken in the course of the production of the models.

As an example, if we look in details to the correlation for the normal dipole in Fig. 4, we find that the magnets with the largest deviation from the correlation best fit are the

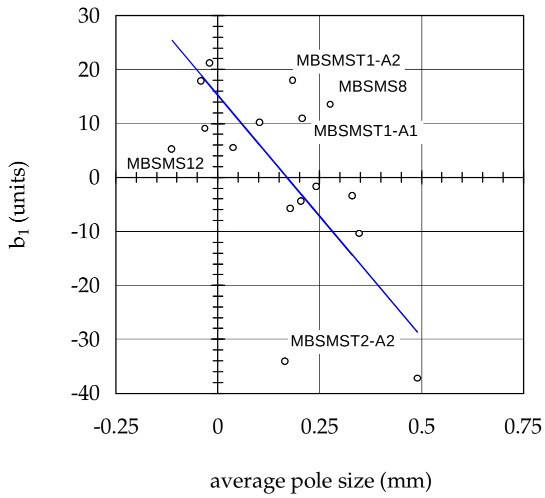

Fig. 4. Geometric normal dipole b_1 (evaluated at 5 kA) vs. average estimated pole size. The line represents the best fit to the correlation obtained from the calculated slope β_1 and an arbitrary shift. The magnets with largest deviation from the best fit have been evidenced.

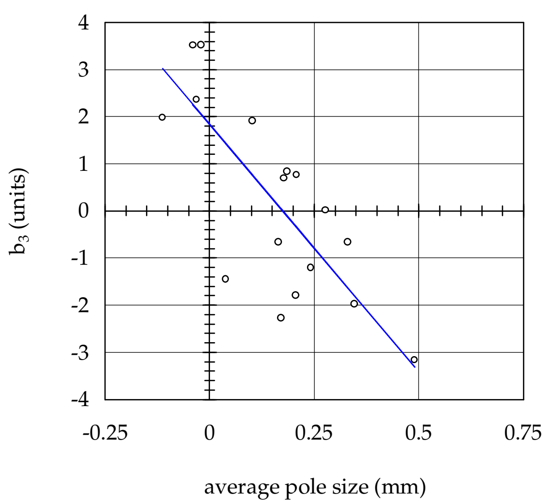

Fig. 5. Geometric normal sextupole b_3 (evaluated at 5 T) vs. average estimated pole size. The line represents the best fit to the correlation obtained from the calculated slope β_3 and an arbitrary shift.

single aperture models MBSMS8 and MBSMS12, and three apertures of the twin aperture models MBST1 and MBST2 (marked on the plot). In the case of the single aperture models we can attribute the deviation to changes in the radial dimensions made on purpose during manufacturing. In particular MBSMS8 was collared with radial shims larger than nominal, resulting in a smaller radial coil size, which is consistent with a larger dipole field than expected by the correlation fit. Similarly MBSMS12 had smaller radial shims, hence larger radial coil size after assembly, consistent with the observation of a smaller dipole field than expected from the correlation fit.

TABLE II

Slope and Standard Deviation for the Correlation between Cold Geometric Harmonics and Average Pole Size

Order	slope β (units/mm)	σ_{cm} (units)
b_1	-90	12.
b_3	-11	1.2
b_5	0.5	0.1

IV. Conclusions

We have shown in this paper that the field quality in warm and cold conditions can be clearly correlated to mechanical measurements of the geometry of the dipole coils being developed for LHC. In addition, the slopes of the correlations considered appear to be well predicted by computer models, confirming our understanding of the relation between azimuthal coil size and allowed field harmonics. Warm/cold correlation, as well as the correlation between coil size and magnetic field measurement are thus expected to play a major role in the control of the series production of the LHC dipoles. Graphs of the type of Figs. 4 and 5, based both on measurements and calculations, could be used in industry to project coil size corrections.

At the moment the spread around the correlations is large compared to the LHC field quality specifications[1]. On the other hand. as we mentioned earlier, the models tested cannot be considered fully representative of a series production, mainly because their purpose was to explore parametrically manufacturing solutions and thus were not manufactured on a strict coil geometry specification. For this reason we can expect the correlations between mechanical measurements and field harmonics to improve as soon as the reference geometry will be frozen and series production will start.

Acknowledgments

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References

[1] The LHC Study Group, “The Large Hadron Collider”, CERN Report CERN/AC/95-05, 1995.

[2] N. Siegel, “Status of the Large Hadron Collider and magnet program”, *IEEE Trans. Appl. Sup.*, **7**, 2, 252-257, 1997.

[3] N. Andreev, et al., “Present state of the single and twin aperture short dipole model program for the LHC”, this conference.

[4] K.-H. Mess, P. Schmueser, S. Wolff, *Superconducting Accelerator Magnets*, World Scientific, 1996

[5] T. Ogitsu, A. Devred, “Influence of Azimuthal Coil Size variations on Magnetic Field Harmonics of Superconducting Particle Accelerator Magnets”, *Rev. Sci. Inst.*, **65**, 6, 1998-2005, 1994.