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FIELD QUALITY IN THE ENDS OF THE LARGE HADRON COLLIDER MAIN DIPOLE: MEASUREMENTS AND CORRELATION TO INDUSTRIAL ASSEMBLY PROCEDURES

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Magnetic field measurements are an important tool to monitor the LHC main dipole production. In this paper we analyse the data relative to a few tens of collared coils produced for the pre-series dipoles. Strong systematic differences between field at the magnet extremities are observed. Moreover, three different families of coil ends corresponding to the different coil manufacturers can be singled out. A 3D model of the coil ends is used to understand these differences in terms of the assembly parameters and the industrial procedures. We analyse the production trends in order to characterize the geometric parameters and the critical components for the field quality. The field components in the dipole ends are finally compared to the beam dynamics budget allowed for the whole dipole.

1 INTRODUCTION

Measurements at room temperature of the field quality are a powerful tool to have a first indication of the magnet behaviour under operational conditions [1,2,3]. In the case of the main dipoles of the Large Hadron Collider (LHC), under construction at CERN, all the magnets will be tested at the manufacturers in two phases of the production: after the assembly of the collared coil, i.e. the two coils in the common stainless steel structure (collars), and when the cold mass is completed. These measurements are used to steer the production within the beam dynamics targets [4] through the evaluation of the correlations to measurements at 1.9 K carried out at CERN [5]. Indeed, the measurement of the magnetic field also provides a powerful tool to check the assembly procedure and the geometry of the components.

In this paper we present results related to the analysis of the magnetic field in the coil ends carried out in Ref. [6]. Measurements based on the rotating coil technique provide separate values for the connection and for the non-connection side. Since the length of the rotating coil is much larger than the head length, the standard harmonic expansion can be used. In the collared coil, the main systematic components are the odd normal multipoles, due to the symmetry of the coil layout. Moreover, one has other small systematic components in the connection side, due to the layer jump and to the energizing cables. In the case of the LHC two-in-one dipoles, additional systematic components (even multipoles) arise from the non-symmetric iron yoke, and can be measured only in the assembled cold mass. We

restrict our analysis to the main field and to the odd normal multipoles, using data of a few tens of manufactured collared coils.

2 FIELD QUALITY MODEL

An electromagnetic tridimensional model of dipole heads has been created using the numerical code ROXIE [6]. With respect to previous works carried out on the LHC dipole heads, where the non-connection side only was considered, we implemented a model of the coil heads also in the connection side, taking into account of the nominal geometry of cables given by end spacers and of the layer jump that connects the inner to the outer layer. The geometry of conductors going to power supply used to energize the coil is also taken into account. We will show in the next sections that the impact on field quality of the different geometries of the connection and non-connection side is not negligible. This has already been observed in the HERA magnets [2].

The model contains three nominal layouts of coil heads, corresponding to the three different generations of end spacers that have been implemented in the pre-series dipoles. The possibility of different shims in the midplane of coil ends is also implemented. This option is used by the manufacturers to obtain the nominal pre-stress in coil heads.

3 ANALYSIS OF MAGNETIC MEASUREMENTS AT 300 K

3.1 Available data

31 collared coils belonging to the LHC pre-series dipoles have been produced by three different manufacturers here indicated as FIRM1, FIRM2 and FIRM3. The sample consists of 29 collared coils having a *first version* of the six blocks two-dimensional cross-section. Two collared coils feature a *second version* of the two-dimensional cross-section, where the copper wedges of the inner layer have been changed in order to recover an optimal value for the systematic b_3 and b_5 [5].

Collared coils of the first version are divided in three groups characterized by a different generation of end-spacers. In the *first generation* (4 collared coils) the outer layer is divided into two blocks as in the straight part, made by 16 and 9 cables respectively. In the *second generation* (2 collared coils), an extra-spacer is added in the outer layer to divide the first block into two blocks of 2 and 14 cables. Moreover, the longitudinal thickness of the outer layer spacer of the first generation has been increased of 5 mm. In the *third generation* (23 magnets),

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the extra-spacer is present, but the thickness of the above quoted spacer has been reduced to the original value. Collared coils with the second cross-section have third generation end spacers.

3.2 Measuring apparatus

Magnetic field in the collared coils is measured at room temperature in 20 consecutive positions along the magnet axis using 750 mm long rotating coils. The first and the last measurements include the contributions of coil heads in the connection side (CS) and in the non-connection side (NCS) respectively. Since the length of the straight part of the collared coil is around 14210 mm, measurements in the first and in the last position include 355 mm of straight part, 180 mm of coil heads, and 215 mm outside the dipole. This ensures that the ends of the measuring coil are in a region where the main field is uniform, and therefore the standard harmonic expansion of the magnetic field can be used. Two different ways of moving the rotating coil along the magnet axis have been used, the first one for 4 collared coils, and the second one for the remaining ones. In the first case the collared coil current has been set to 15 A, whilst in the second one it has been set to 8.5 A.

3.3 Main Field

In Fig. 1 we plot the main field per units current, averaged in the first and last measuring position for all the available collared coils. Measurements with the first apparatus give a value of around 365 mT/kA, whilst the remaining ones give around 380 mT/kA. This systematic difference is due to the different procedures and tools used to position the measuring coil along the axis. In both cases the spread is of 3 mT/kA (one sigma), which reflects the natural spread of the magnetic length in the collared coil.
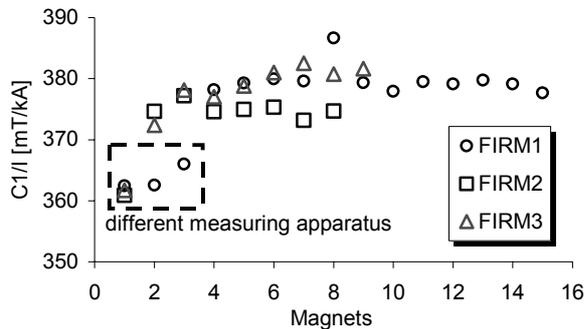
Figure 1: Main field divided by current: average between first and last measuring position versus collared coil.

Measurements of transfer function in each of the heads show a much larger variation (around 12 mT/kA, one sigma). This variation is traced back to a precision of 25 mm (one sigma) in the positioning of the measuring coil with respect to the longitudinal centre of the magnet. One can prove that this has a negligible impact on the estimates of the field harmonics in the heads.

3.4 Odd Multipoles

Strong systematic differences are observed in the measured low-order odd multipoles in the CS and in the NCS. From measurements we see that b_3 has an average value of 35 units in the CS, and −5 units in the NCS. This difference is due to the different geometry of the end spacers in coil heads, to the presence of the layer jump and the powering cables in the CS. In Fig. 2 we plot b_3 versus b_5 measured in the heads. b_5 shows no systematic differences between CS and NCS, but the spread in the CS is much larger. Systematic differences between the manufacturers can also be observed. Finally, in the CS there is a rather good correlation between b_3 and b_5: this means that main part of the spread in b_3 and b_5 is caused by the same effect. Comparison with the models developed for the CS and for the NCS is also shown in Fig. 2. For the CS one finds a rather good agreement both in b_3 and b_5, whilst for NCS the agreement is found for b_5 only, the sextupolar component being overestimated by the model.
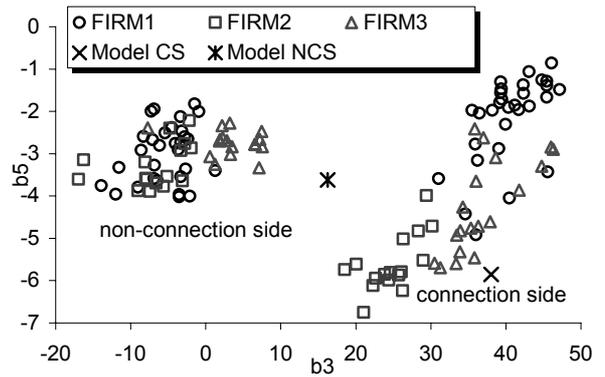
Figure 2: b_3 versus b_5 measured in coil ends.

We then tried to use simulations to trace back the origin of the variations in the multipolar content of coil heads. Longitudinal position of coil turns cannot explain the observed variations, even in the hypothesis of dimensional variations much larger than the geometrical tolerances. On the other hand, we find a strong dependence on the thickness of the shims that separate the upper and the lower poles in the middle plane. This thickness is not fixed by design but is decided by each manufacturer on the basis of the measurements of the coil dimensions to reach the nominal pre-stress in coil heads. In the above results of the model, with nominal geometry, no mid-plane shims are implemented. Indeed, large thickness has been used (up to 1.5 mm). If the average thickness used in each firm is implemented in the model, we obtain the estimates shown in Fig. 3, for the case of the CS. The comparison between model (filled markers) and measurements (empty markers) shows good agreement for the b_3, whilst for the b_5 the model results are always smaller than the measurements. In Fig. 3 we also plot the simulated effect of a shim variation in the inner and in the outer layer where a maximum thickness

of 0.5 mm and 0.8 mm respectively was applied (dashed lines). The slopes of the lines are close to the trend observed in experimental measurements.
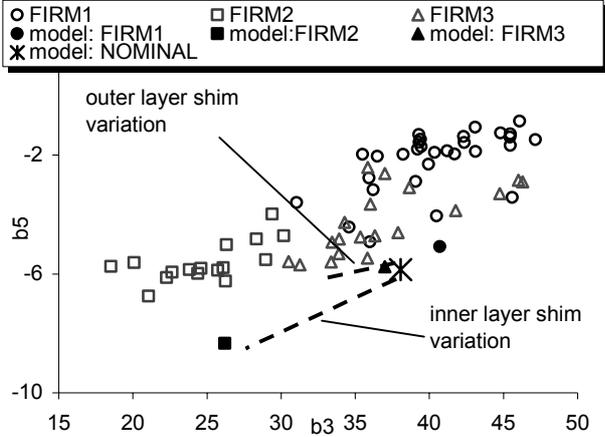

Figure 3: b_3 versus b_5 in connection side head, comparison between measured and calculated values.

In the non-connection side the effect of shims variation is less important (see Fig. 2). Even though in this case FIRM3 shows a systematic difference in b_3 with respect to the other manufacturers, it was not possible to find any correlation between assembly procedures and magnetic field.

The analysis of the available data shows no correlation between the field harmonics in the heads and the different end-spacers generations. The same observation can be made for the change of the cross-section, even though more collared coil are needed before obtaining a significant result. In both cases this is in agreement with simulations, showing that the impact of these changes is negligible with respect to the measured variation of field harmonics.

4 COMPARISON WITH BEAM DYNAMIC TARGETS

In this section we compare the measured field harmonics in the dipole heads to the budget allocated by beam dynamics. We first consider the contribution of the collared coil heads to the systematic components of b_3, b_5 and b_7 (see Table 1, first row). This is given by the average of the heads contribution rescaled to the magnetic field in the heads and to the length of the magnet. Data are compared to the width of the allowed ranges for the systematic components, based on beam dynamics considerations. One observes that the head contribution is much smaller than the allowed ranges for the b_3 and b_7. On the other hand, the head effect on b_5 is not negligible.

In the lowest part of the table we analyse the case of the random components. In the first row we give the sigma of the low-order odd multipoles measured in the heads, and scaled to the whole magnet. Data are compared to the random components in the straight part of the dipole, and to the budget allocated by beam dynamics. The random component due to the heads is negligible with respect to the random in the straight part, and is small compared to the budget. This means that from the point of view of field quality, the production of the collared coils has a sufficiently good reproducibility.

Table 1: Contribution of coil heads to systematics and randoms, and comparison to beam dynamics ranges and targets.

SYSTEMATICS			
	b_3 [units]	b_5 [units]	b_7 [units]
Heads	0.9	-0.2	-0.08
Range width	6.0	0.6	0.4
RANDOMS			
	b_3 [units]	b_5 [units]	b_7 [units]
Heads	0.2	0.03	0.01
Straight	2.0	0.5	0.15
Total	2.0	0.5	0.15
Target	1.5	0.5	0.2

5 CONCLUSIONS

We presented the analysis of the magnetic measurements at 300 K of 31 manufactured collared coils and a comparison with a tri-dimensional electromagnetic model. Relevant differences of the b_3 between connection and non-connection side have been traced back to the different geometry of the two sides of the coil heads. Three different generations of end spacers that have been implemented show a negligible impact on field quality, in agreement with simulations. The main source of variability in b_3 and b_5 is the dimension of the thickness of the shims used in the coil mid-plane to give the nominal pre-stress to coil heads. The observed systematic differences between manufacturers in the connection side are traced back to this geometrical parameter. Systematic components in the coil heads are found to be small compared to the allowed budget for the beam dynamics, but not negligible for b_3 and b_7 and considerable for b_5. Randoms components in the coil heads are found to be negligible compared to the straight part and to the beam dynamics targets.

6 REFERENCES

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