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Measurements of the LHC Corrector Magnets at Room and Cryogenic Temperatures

Z. Ang, A. Arn, L. Bottura, C. Giloux, P. Sievers, N. Smirnov, S. Vincent, L. Walckiers

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MEASUREMENTS OF THE LHC CORRECTOR MAGNETS AT ROOM AND CRYOGENIC TEMPERATURES

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The superconducting twin aperture main dipole magnets of the LHC accelerator are equipped with pairs of sextupole and decapole correctors at their ends. Similarly, octupole correctors are aligned at the end of the main quadrupole magnets. Dedicated stations have been built for tests of these correctors at room temperature as well as superfluid helium temperature. Measurements of the training behaviour and of the magnetic field quality are routinely performed. The search for the magnetic axis and the transfer of its position to fiducials are performed at room temperature. A description and the performances obtained with these two benches are also presented.

1 INTRODUCTION

This paper focuses on the description of the equipment to evaluate the performances and the field quality of three types of correctors [1]. Pairs of MCS's sextupole and MCD's decapole magnets are mounted at each end of the MB's, main LHC dipole bending magnets, to correct the sextupole and decapole harmonics due mainly to persistent currents in their superconducting cables. The MO octupole's are foreseen for Landau damping and are mounted in the short straight sections with the main LHC quadrupoles.

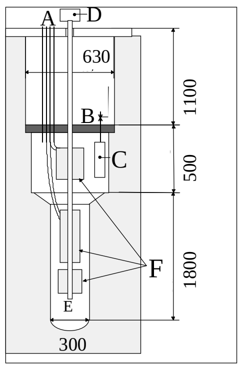
The reference radius to express the field quality of all LHC magnets has recently been increased to 17 mm which reflects better the larger good field region needed, particularly in the interaction region magnets. The field characteristics of the correctors analysed below will be compared with the integrated field errors of the MB's. Therefore the units used in this paper for the field harmonics are in T·m at the reference radius of 17 mm :

- the MCS with a nominal strength of 0.055 T·m,
- the MCD " " " 0.01 T·m,
- the MO " " " T0.092 ·m.

2 THE CRYOGENIC TESTS STATION

The measurement and power test equipment follows the successful design of the stands used for the tests of the main LHC dipole short models.

The cryostat (Fig. 1) is designed to test magnets as long as 2.1 m and has a useful aperture of 0.3 m. The enlarged part holds the heat exchanger below the lambda plate, and four 2 kA current leads to feed the three magnets either separately or in series. All types of LHC correctors that are slimmer than the inter-aperture distance of 0.194 m can be tested in that cryostat. Dedicated suspension pieces allow to test three short magnets mounted on top of each other : 0.16 m long MCS or 0.11 m long MCD's. Eight hours are needed to reach liquid helium temperature, another four hours to cool down the 250 litres of helium to superfluid temperature. Electrical heaters at the bottom of the cryostat warm up the assembly to room temperature in about 20 hours.



A : 2kA gas cooled current leads
B : Joule - Thomson valve
C : Heat exchanger
D : Encoder & motor for the magnetic measurement
E : Magnetic measurement shaft
F : Corrector magnets

Fig.1 The Cryostat to test up to 3 corrector magnets.

3 THE MAGNETIC MEASUREMENT'S EQUIPMENT

The measuring coils assemblies are made with 5 identical coils (C_1 to C_5) adjacent to each other, the central one , C_3, being centred on the rotating axis. This allows to reject the main harmonic for both quadrupole and sextupole magnets :

Quadrupole term rejection : $V_1 - (V_2+V_3) + V_4$,
Sextupole rejection : $V_1 - 3\cdot V_2 + 3\cdot V_3 - V_4$,

with V_1 = voltage across C_1, etc ...

Easy checks of the accuracy of the mounting for the strengths measurements or of the quality of the rotation of the shaft are performed due to its symmetrical feature : comparing values measured by C1 to those by C5. A detailed comparison between measurements of the harmonic orders higher than the sextupole in the MCS shows that bucking the main harmonic is not necessary for the warm measuring bench but clearly improves the measurements with the cold bench where the the quality of the shaft rotation is much more difficult to ensure.

3.1 The equipment for cryogenic measurement

The measuring shaft used for the cold measurements [2] comprises four coil assemblies each with an effective lengths of 0.2 m and measure individually the magnets.

Since it is impossible to precisely center the measuring shaft onto the magnet's axis, the measurements are systematically corrected for this offset, based on the suppression of the skew term of the main harmonic and the lower harmonic order measured at the nominal strength.

3.2 The bench for room temperature measurement

The bench measuring the magnet at room temperature (Fig. 2) is transportable and set up for measurements in a short time. Moreover it has proven to be a very useful tool for training staff in magnetic measurement and as a test bed for the software and hardware needed for all magnetic measurement systems to be developed for the LHC project. The equipment and procedure for axis measurement are described in 5.2.

The voltage signal across the 400 turns measuring coil [3] amounts to 16 mV for a MCS corrector powered with 1 A. The measurements must be taken with both polarities to correctly subtract the effect of the earth magnetic field and of the magnetisation of the iron yoke after cold tests.

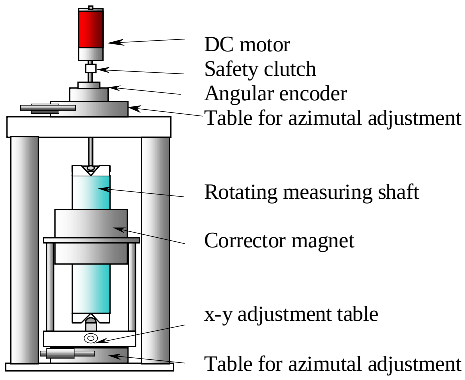


Figure 2: Bench for the magnetic measurement and axis positioning of the different types of correctors at room temperature.

4 POWER TESTS PERFORMED

The power tests at cryogenic temperature follow the program applied to the 1 m long LHC model dipoles [4].

Ramp rates as high as 1 kAs^{-1} induce quenches much above the nominal field strength (nominal rate =10 As^{-1}).

The measured resistance due to the inter-pole connections range between 15 and 300 nΩ. The measurements resolution is 3 nΩ. These resistance will have to be reduced since the allowed loss is 10 mW at 600 A.

The hot spot temperature never exceeds 80 K if magnets are quenched alone. A dedicated test was performed to analyse whether a quenching sextupole magnet can absorb the stored energy of several other magnets in series with the power supply intentionally kept running during the duration of the quench. Although the quenching magnet has dissipated 900 J, 6 times the stored energy at nominal current, a maximum of 18 kA^2*s was reached in the conductor, corresponding to 80 K and the voltage across the magnet stayed below 50 V.

5 MEASUREMENT AND TOLERANCES OF THE MAGNETIC FIELD QUALITY

5.1 Main field component

Figure 3 shows, as a function of current, the difference between the measured strength of a MCS sextupole magnet and a straight line to enlighten the hysteresis due to the persistent currents in the superconducting cable. The width of this hysteresis ($1.7*10^{-4}$ Tm @ 17 mm of radius) corresponds to 0.2 unit of sextupolar error in a MB (main LHC 15 m long dipole) at the injection field of 0.54 T. The MCS's will correct the sextupole component of the MB's including the time dependent effects. The slope of the current has therefore to change sign to first compensate the decay during injection then the snap-back at the start of acceleration. The hysteresis loop will be crossed and fine tuning of the current will control the resulting effect of 5 units of chromaticity.

Similarly the MO octupole correctors have a width of the hysteresis equal to 1.5*10-4 Tm : 3 times the tolerance requested for the control of the footprint in the tune diagram at LHC injection. The hysteresis width of the MCD's is expected to have a small but noticeable effect on the dynamic aperture if not taken into account.

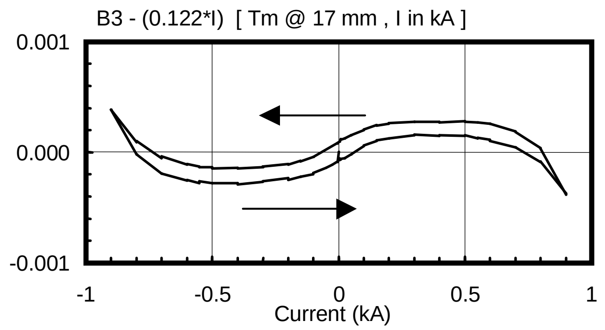


Figure 3 : Field strength of a MCD corrector : difference between the strength and straight line giving the average to enlighten the hysteresis due to persistent currents.

5.2 Positioning of the magnet's axis

A MCD corrector misaligned with respect to the decapolar component of the MB will result in a proportional octupolar field applied to the beam, the average of it over octants of the LHC will degrade the dynamic aperture. A tolerance of 0.1 mm is needed for the magnetic axis survey of the correctors. The most demanding tolerance is to centre these correctors with respect to the measured MB's curved axis to better than 0.3 mm in average. On the other hand, the accuracy of positioning the poles in the MCS or MCD correctors hardly ascertains that mechanical and magnetic axes coincide within 0.1 mm [1]. The "warm" measuring bench is therefore equipped with all the facilities needed to mark the correctors with survey points.

The magnet is first oriented by the angle and positioning tables in order to cancel respectively the skew main term and the component one order lower than the main harmonic. A precise arm locks the lateral reference surface of the rotating measuring shaft into a reproducible angular position in order to first rotate the encoder case at the reference position, then the magnet.

The measuring shaft is then replaced by a reference jig having the same rotation axis and equipped with the same reference surfaces. This jig is equipped with fingers in hard metal able to punch survey marks in the magnet's case. Both the measurement sensitivity and the mechanics including the accuracy between these fingers and the rotation axis or the reference surfaces allow a positioning of the survey marks within 25 μm.

The MCS will correct a sextupolar component of 0.0087 T·m at 17 mm due to persistent current effects in the MB's at injection field, giving a change of chromaticity of about 550 units. The control of the chromatic coupling requests a skew sextupole term lower than $4*10^{-4}$ T·m at 17 mm. The systematic error allowed in the field direction adjustment is therefore 5 mrad. A verification of the parallelism between the reference surface of the measuring shaft and the coils effective surfaces is possible by swopping the shaft top to bottom. The actually measured error of 2.8 mrad can be taken into account in the alignment software.

5.3 Field quality

A dipole field component of $4*10^{-7}$ Tm measured on the "warm bench" was traced to be due to the current leads of the MCD correctors : it would induce a field equal to 5 ppm of the main dipole at injection. Time dependent effects have been measured in the MCS to be negligible : the 18-pole term is below $1*10^{-8}$ Tm for a width of the persistent current amounting to $6*10^{-6}$ Tm.

Figure 4 compares the quality of the measurements of the harmonic content of a MO octupole corrector made with both the warm and the cold benches to typical field components and specifications. All the values are referred to the nominal strength of the magnets. The ratio between measurement quality and values tolerated for the beam is similar for the other types of correctors.

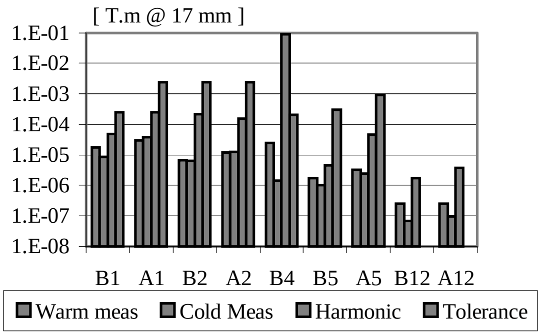


Figure 4 : Accuracy of the measurements for the "Warm measurement", for the "Cold measurement", Field error "Harmonic" measured on a MO corrector, "Tolerance" for the beam.

6 CONCLUSIONS FOR THE SERIES MEASUREMENTS

The measurements performed so far on the model corrector magnets allow to define the following strategy for the series measurements of the LHC correctors.

A simple bench measures at room temperature the field quality : a good correlation has been obtained with measurements at nominal strength in superfluid helium. The accuracy of positioning the magnetic axis is 25 μm.

It is planned that the magnet manufacturers will make quench tests at 4.3 K on the series since the three types of correctors analysed here reach their nominal strength in normal boiling helium.

The cold test station described here would have to verify statistically some of their characteristics : joint resistance, field strength and hysteresis due to persistent current.

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