MAGNETIC PERFORMANCE OF FIRST LOW-B DIPOLE CORRECTOR PROTOTYPE, MCBX

Z. Ang, L. Bottura, A. Ijspeert, M. Karppinen, L. Walckiers, CERN, Geneva, Switzerland
N. Hauge, B. R. Nielsen, Danfysik A/S, Jyllinge, Denmark

Abstract

The LHC low-β triplets require a short and strong dipole corrector. The MCBX is a superconducting single aperture magnet, which features a horizontal dipole nested inside a vertical dipole. The cold tests of the first prototype, which was designed by CERN and built by Danfysik A/S, have been carried out at CERN.

This paper presents the results of the magnet training and quench propagation studies at 4.3 K and 1.9 K. The magnetic measurements carried out at constant field and in ramped conditions are compared to the expected figures from the calculations.

1 INTRODUCTION

In total 16 strong dipole correctors are needed in the LHC inner triplets to correct for the misalignment of the low-β quadrupoles. The first MCBX prototype magnet features a horizontal dipole nested inside a vertical dipole. The magnetic and mechanical design was made by CERN [1] and Danfysik A/S did the manufacturing design and built the magnet [2]. The two magnets are individually powered to provide an integrated dipole field of 1Tm in any angular direction.

The coils were wound with a monolithic, PVA-enamelled superconducting wire, pre-assembled as a flat cable. The wire terminals were connected in series on the end plate. The main parameters are given in Table 1. Each coil and the subsequent inner and outer coil assemblies were vacuum impregnated with epoxy. The compressive pre-stress in the coils was obtained with shrink-fitted aluminium rings. The magnets were centred and backed up for the electromagnetic forces with an iron yoke, which was made with so-called scissor-laminations [3] surrounded by a stainless steel outer shell.

2 MEASURING EQUIPMENT & INSTRUMENTATION

The cold tests at 4.3K and 1.9K including magnet training and magnetic measurements were carried out at CERN [4]. The horizontal and vertical dipole magnets were connected to a bipolar 2kA and a unipolar 20kA power supply. Based on the quench simulations [5] using estimated quench propagation velocities an external resistor of 0.45Ω was connected to the circuit to absorb part of quench energy and to ensure a safe operation. Overall 28 voltage taps were soldered to the series connections on the end plate across each radial coil layer, and another three pairs were soldered in the lead end to locate the block in which the quench was initiated.

Table 1: Main parameters of MCBX-magnet

		Inner/Outer Coil
Operating dipole field	[T]	3.3 / 3.3
Integrated dipole field	[Tm]	1.21 / 1.13
Peak field in the cond.	[T]	4.43 / 4.75
Margin on the load line		52.2% / 47.2%
Operating current	[A]	511 / 599
Magnetic length	[m]	0.37 / 0.34
Overall length	[m]	0.6
Wire dimension (ins.)	[mm]	1.65 x 0.97
Wire dimension (metal)	[mm]	1.53 x 0.85
Cu/Sc-ratio		1.6
Operating temperature	[K]	1.9
No. of turns per coil		414 / 406
Stored energy	[kJ]	17.9 / 25.2
Self inductance	[mH]	137 / 140

The field measurement was carried out by means of three 200mm long coils assembled on a rotating shaft, approximately centred along the magnet. All the measurements were corrected for feed-down based on cancelling of non-allowed harmonics of order 10 and 12.

3 POWER TESTS

The RRR-value of the conductor had increased significantly during the manufacturing process. The measured value was 140-160 instead of 68 quoted by the wire supplier, probably due to annealing of the copper during curing at about 150ºC. The series connections were made by soldering the connecting pairs into U-shaped copper channels. The measured contact resistances of the inner and outer dipoles ranged from about 14 to 67nΩ per 100m long joint to be compared to 10-12nΩ measured on three 60mm long samples. Apparently some of the joints were not cleaned properly.

The clamping system was designed to provide sufficient rigidity for the coils at nominal conditions and is therefore not rigid enough to sustain the electromagnetic forces at critical current when the forces are four times higher. For this first test campaign the vector sum of the currents was limited to 800A to avoid damaging the coils.

Both magnets were first individually trained at 4.3K. The inner dipole reached 96% of its short-sample current after 5 training quenches and it took 7 quenches to train the outer dipole to 98% of its I_{ss} as shown in Figure 1. The delay of switching the energy extraction was gradually increased monitoring the induced voltages and hot-spot

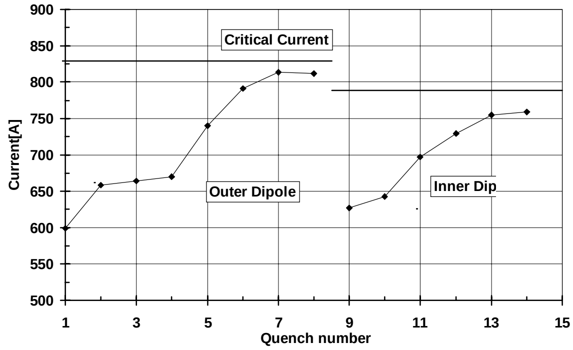

Figure 1: Inner and outer dipole training at 4.3K

temperatures in the coils, and finally the magnets absorbed their full energies. The estimated hot spot temperature reached 150K, corresponding to 110kA^{2}s. The internal voltages in the coils were always smaller than measured across the coils' terminals once the energy extraction was triggered. The quench propagation times will require some further analysis on the measured voltage signals.

There was only a slight improvement in the training after the magnet had been cooled down to 1.9K suggesting that the energy release from mechanical origins is high enough to overcome the energy margin in both operating conditions. After each dipole had been trained independently, training with different field combinations were performed setting one dipole at a fixed current and ramping up the other one. Figure 2 shows the summary of the training quenches. The magnet operates within the so-called working envelope (the inner circle), whose edge represents the nominal 1 Tm dipole field. All quenches were outside of this area. Some (re-) training can be observed as the electromagnetic forces act in different directions and the position of the peak field in the conductor blocks changes.

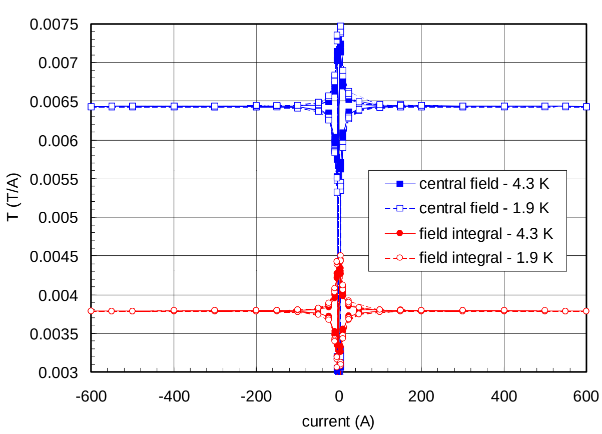

Figure 3: Transfer functions of the inner dipole. Both central field and field integrals at 4.3K and 1.9 K are shown.

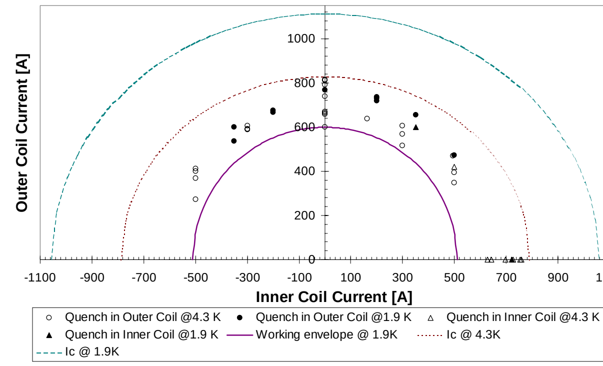

Figure 2: Summary of training quenches at 4.3K and at 1.9K

4 MAGNETIC MEASUREMENTS

The magnetic measurements were performed powering the two dipoles independently and with different combinations of horizontal and vertical dipole fields. A normalisation pre-cycle was done before all the measurements. The standard pre-cycle was:

- 0➔600A at 10A/s
- flat top at 600A for 10 seconds
- 600➔-600A at 10A/s
- flat top at -600A for 10 seconds
- -600 ➔ 0A at 10A/s

4.1 Independent powering

The field harmonics were measured separately for the coil ends and the straight part of the magnet. Measurements were performed along the loadline separately for inner and outer dipoles from zero current to the 600 A. The measured transfer functions along the loadline for both the straight section and integrated over 0.6m at 4.3K and 1.8K for the inner dipole are shown in Figure 3. The straight section of the outer coils was shorter than the measuring coil and the measured field quality of this part was influenced by the ends.

No differences can be seen at the two different temperatures for currents higher than 150A. The transfer functions for the central field produced by the inner and outer dipoles at nominal current were 6.43 T/kA and 5.32 T/kA, respectively. The iron saturation decreases the central field transfer function at nominal current by about 0.3% as compared to that at 300A. There was a significant hysteresis in the transfer function at low current. The larger hysteresis at 1.9K is consistent with the expectation of larger magnetisation. At low current (50A) and 1.9K the magnetisation hysteresis between the ramp-up and ramp-down branches has an amplitude of $\Delta A1$=0.046T, $\Delta a3$=17.14 units, $\Delta a5$=1.00 units in the inner dipole and $\Delta B1$=0.041T, $\Delta b3$=18.61 units, $\Delta b5$=0.41 units in the outer dipole, measured at a reference radius of 17mm.

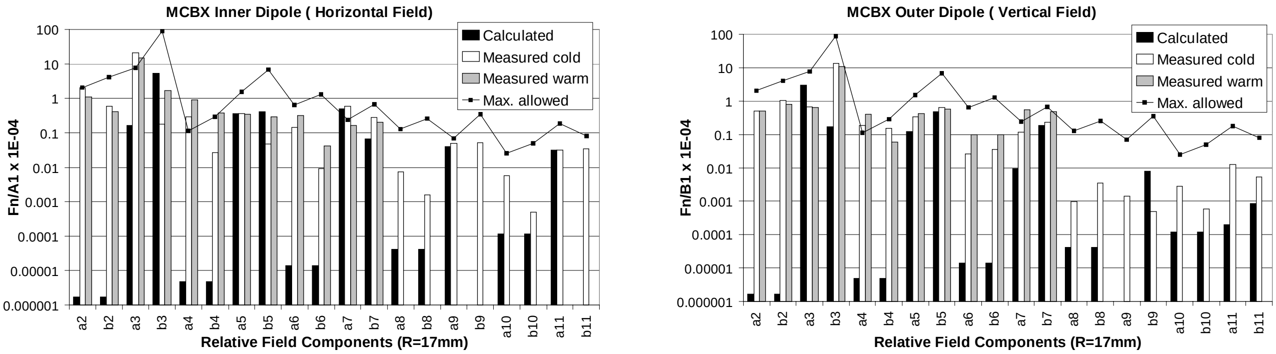

Figure 4: Relative field errors of MCBX inner and outer dipoles at nominal current.

DC-magnetisation effects were studied for both layers separately at low ramp rate (1A/s) in 1.9K superfluid helium. The measured normal sextupole and decapole components agreed very well with the calculations.

Warm measurements were performed at –4A and +4A, in both dipoles independently. Figure 4 compares the maximum allowed field errors [6] to the calculated field integrals and to the measured values at warm and cold at 17mm radius. The integrated field quality of the inner layer meets the requirements apart from a skew sextupole of 20.23 units (maximum allowed 7.71), skew octupole of 0.29 (0.11) units, and skew 14-pole of 0.60 (0.24) units. The integrated multipole content of the field of the outer dipole was practically within the specified range. There was a good agreement between the warm and cold measurements up to harmonics of order 7.

The relative angle between the horizontal and vertical dipole field was 1579 mrad i.e. there was 8.2 mrad misalignment between the inner and outer dipoles. The angle did not depend on the test temperature.

4.2 Series powering

The inner and outer layers were powered in series and the measurements along the loadline were repeated. The transfer function was within 0.003% of the vector composition of the two dipoles powered individually. The hysteresis was significantly smaller in this powering condition

4.3 Cross talk

The measurement of the cross-talk between the layers was performed by powering them independently. Three different phases were carried out. In the first phase the inner dipole was pre-cycled and ramped up, while the outer dipole produced a background field. In the second phase the roles of the layers were inverted and the third phase was made without the pre-cycle to check whether significant changes could be observed due to different initial state in the magnet. In all three phases the low field hysteresis was practically non-existent and there was only a slight difference when the pre-cycle was skipped.

5 CONCLUSIONS

The first low-β dipole corrector prototype, MCBX has successfully undergone the first test campaign. Both dipoles trained quickly to their critical currents at 4.3K and the first quenches occurred above the operating currents. Some retraining was observed when the two layers were powered together. Apart from the significant skew sextupole of the inner dipole the integrated multipole content meets the tight tolerances of the LHC inner triplets. There was significant hysteresis at low fields when the two dipoles were individually powered. With combined powering, however, these effects were dramatically decreased.

ACKNOWLEDGEMENTS

The authors want to express their gratitude for R. Schmidt (quench simulations), J. Mazet, A. Arn and the whole measuring team for preparing the test setup and for carrying out the tests.

REFERENCES

[1] M.Karppinen, S. Russenschuck, A. Ijspeert, “Automated Design of a Correction Dipole Magnet for LHC”, EPAC, Sitges, Spain, June1996.

[2] M. Karppinen, A. Ijspeert, N. Hauge, B. R. Nielsen, “The Development of the Inner Triplet Dipole Corrector (MCBX) for LHC”, MT-15, Beijing, China, September 1997.

[3] A. Ijspeert, J. Salminen, ”Superconducting Coil Compression by Scissor Laminations”, EPAC, Sitges, Spain, June 1996.

[4] Z.Ang, L. Bottura, “Magnetic Measurement Results of MCBX Combined Dipole”, MTA-IN-98-020, CERN, Geneva, Switzerland, February 1998.

[5] D. Hagedorn, F. Rodriguez-Mateos, R. Schmidt, “Protection of LHC Superconducting Magnets”, LHC Project Report 46, CERN, Geneva, Switzerland, September 1996..

[6] A. Verdier, “Tolerance on the Multipole Components in the Closed Orbit Correctors”, LHC Project Note 51, CERN, Geneva, Switzerland, August 1996.