TESTING OF THE LARGE BORE SINGLE APERTURE 1-METRE SUPERCONDUCTING DIPOLES MADE WITH PHENOLIC INSERTS

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Abstract

Two identical single aperture 1-metre superconducting dipoles have been built in collaboration with HMA Power Systems and tested at CERN. The 87.8 mm aperture magnets feature a single layer coil wound using LHC main dipole outer layer cable, phenolic spacer type collars, and a keyed two part structural iron yoke. The magnets are designed as models of the D1 separation dipole in the LHC experimental insertions, whose nominal field is 4.5 T at 4.5 K. In this report we present the test results of the two magnet at 4.3 K and 1.9 K.

1 INTRODUCTION

In the present layout of the LHC low-β insertions [1], a pair of superconducting dipoles D1 and D2 brings the beams onto colliding orbits in the ALICE and LHC-B interaction points. One of the options that has been considered for the single aperture D1 is a magnet with an aperture of 87.8 mm featuring only the outer layer winding of the LHC main dipole. This type of single layer coil can provide a field of 4.5 T at 4.5 K. An identical coil could be used in the twin aperture D2, to give a symmetric separation-recombination dipole pair.

As part of the magnet development program for the LHC insertions, two identical 1-meter long 87.8 mm aperture single layer dipoles have been constructed in collaboration with HMA Power Systems (formerly HOLEC). The first magnet (H1) was completed in August 1997 and cold tested in the beginning of October 1997, while the second one (H2) was assembled and tested beginning of 1998. In this report we present the results of H1 and H2 training and magnetic field measurements, and review the performance of phenolic spacers.

2 MAGNET DESIGN

The cross section of the MBXSM magnet is shown in Fig.1. It consists of a single layer three-block coil wound using the outer cable of the LHC main dipole. The cable is insulated with an all polyimide tape. The coils are mounted into injection moulded RX613 phenolic spacers which hold them in position and serve as ground plain insulation, similarly as in RHIC magnets [2]. The magnet is protected with two strip quench heaters, placed between the coil and the spacers. Gaps are left between successive 100 mm long spacers to allow radial venting of helium.

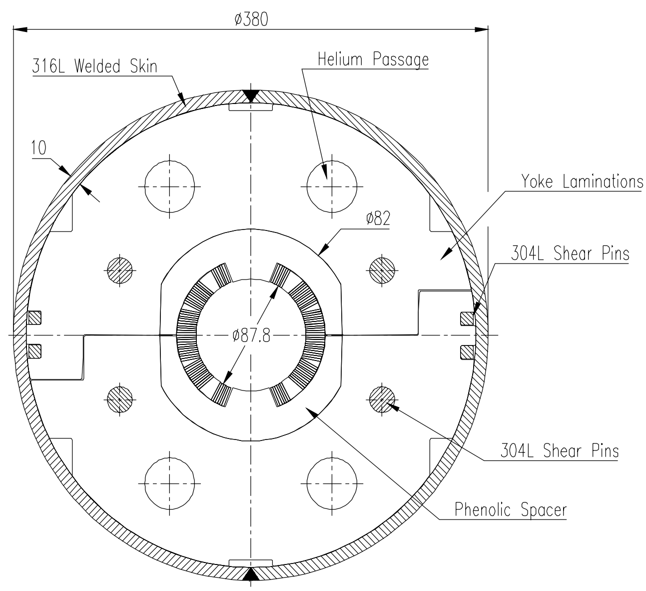

Fig. 1: Cross section of MBXSM type model.

The yoke has two functions: it provides coil pre-stress by compressing the phenolic spacers, and serves as the magnetic flux return path. It is assembled from a single lamination. Two such laminations are placed together, one being reversed then fixed with stainless steel shear pins. After the top and bottom yoke halves have been forced together under a press, four keys are inserted to maintain the stress in the coil. The construction and assembly procedures and the mechanical behaviour of the magnet during assembly and cooldown have been reported in [3].

The phenolic spacers can be fabricated with good reproducibility and make the assembly of the magnet easy and straightforward. However, due to the elastic properties of the phenolic material, the coil blocks may not be sufficiently well defined. Furthermore, the coil position may change at different stages of magnet operation, which could lead to geometric field errors that vary with field. This aspect of phenolic inserts requires careful study in LHe conditions. Finally, long-term creep effects need to be checked.

3 TRAINING HISTORY

The H1 and H2 magnets were extensively tested at CERN. The training history of the magnets is shown in Fig. 2. For H1, the first quench occurred at 5.15 T, 87 % of short sample limit, and after 5 training quenches the magnet reached the short sample current at 4.3 K. For quench number 13, the energy deposited in the magnet was increased from 20 % to 65 %, which resulted in a reduction in quench field for quench 14. After 16 quenches the magnet was cooled to 1.9 K, and the first quench was at 6 T, 84 % of the estimated short sample. After 7 quenches the magnet trained to above 7 T, very close to its short sample limit at 1.9 K. The capacitance gauges showed that the coil poles were unloaded at about 5.2 T, which did not seem to harm the performance of the magnet. All quenches were determined to occur in the transition region between the straight section and coil ends, in the peak field area. After training at 1.9 K, another 11 quenches were performed at 4.3 K, some with over 90% of the energy deposited in the magnet. In all cases, the magnet quenched at its short sample limit.

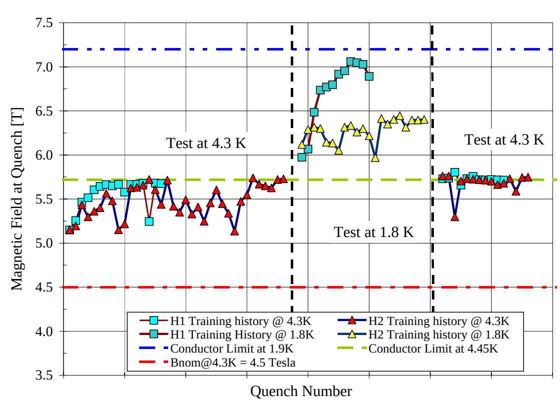

Figure 2. Training history of H1 (squares) and H2 (triangles) at 4.3 K and 1.8 K.

At 4.3 K, H2 started training at the same field as H1, but reached the short sample limit after 14 quenches. At a number of intermediate quenches the quench field frequently decreased to the level of the first quench. The fluctuations of the quench field were even more pronounced as the energy deposited in the magnet was increased; with 90% energy deposited, the quench field decreased to 6 % below the short sample. However, the quench field never dropped below the initial quench field of 5.15 T.

The first quench at 1.8 K was observed at 6 T, slightly above that of H1. However, further quenching was erratic, with fluctuations of close to 4 % and with a slow increase of the moving average. The majority of quenches (18 out of 21) occurred in one of the poles, either in the pole turn, or in the transition region between the ends and the magnet straight section. This behaviour was traced to a mechanical weak spot in the transition region between the straight section and the coil heads, which was already noticed during magnet assembly. Contrary to H1, the poles were not unloaded at even the highest quenches. Subsequent test at 4.3 K showed a stabilising effect of superfluid training, as almost all quenches occurred at the short sample limit.

4 MAGNETIC FIELD MEASUREMENTS

The magnetic field was measured in the two dipoles in the vertical cryostat using radial rotating coils. Five adjacent coil sections measured the field dependence along the magnet bore. Here, the results from the centremost coil have been used to compute the transfer function. Higher order harmonics are given as dipole-weighted averages over the straight part (on the three central coils). They are quoted in units of 10^{-4} of the main field at the LHC reference radius of 17 mm.

Table 2 gives a summary of the field quality as measured in the two dipoles at an intermediate field (5 kA, approximately 2.5 T) and 1.8 K after training. We report the magnitude of the harmonics up to order 11, compared to the expected values for the allowed harmonics. The transfer function for the dipole field compares well at intermediate fields with the results of simulations. Furthermore, the difference in the geometric transfer function between the two magnets is small, approximately 4 units.

The measured sextupole is significantly higher than expected, and in addition there is a large difference between the two dipoles (2.3 units). The higher order allowed harmonics (decapole and above) are similar in both magnets, and close to the expected values.

Table 2. Magnitude of the field harmonics measured at 5 kA (2.45 T) in the H1 and H2, compared to the expected allowed harmonics for the nominal coil design.

order	H1	H2	expected
1	0.4888	0.4890	0.487
2	1.651	0.712	
3	10.199	7.707	5.497
4	0.200	0.130	
5	0.734	0.799	0.808
6	0.020	0.051	
7	0.118	0.110	0.017
8	0.013	0.012	
9	0.062	0.063	0.049
10	0.004	0.008	
11	0.044	0.036	0.040

The variations of low order harmonics between the two magnets, and the difference with respect to the expected values, can be explained in terms of minor changes in coil size between magnets. A symmetric change of the azimuthal pole dimension by 0.1 mm gives approximately 4 units of dipole and 1.5 units of sextupole field. Therefore, the sextupole and dipole variations between the two magnets could be ascribed to differences in coil sizes of the order of 0.1 to 0.15 mm. This is comparable to coil size variations observed in the LHC main dipoles.

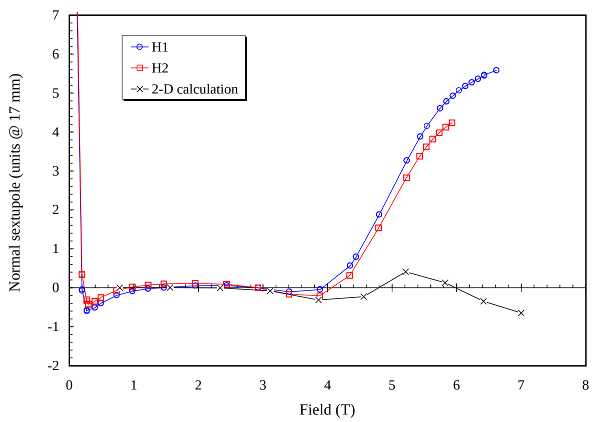

Figure 3. Measured and computed sextupole for H1 and H2 dipoles. Measured values have been shifted by the amount reported in Table 2 to remove the geometric sextupole and ease the comparison.

In Fig. 3 we show the high field behaviour of the normal sextupole for H1 and H2. For ease of comparison, the measured curves were shifted by the value of the geometric sextupole (Table 2). Both magnets behave similarly, but the sextupole increases at high fields considerably more than expected. We believe that this is due to an elastic displacement of the coils. The order of magnitude of the azimuthal displacement can be estimated to be around 0.3 mm. The small but systematic difference between the two magnets would correspond to approximately 30 μm variation in coil displacement.

Both magnets were measured at several stages during training at 4.3 and 1.8 K. The main purpose was to detect any change in the coil geometry under the action of Lorentz force and temperature gradients during quench. This is a critical issue as phenolic collars, mechanically weaker than metallic collars, could potentially lead to variations of the field quality in time. Fig. 4 shows the maximum range (max-min) of variations of the field harmonics as observed throughout testing. The changes are relatively large for the sextupole (in the range of 0.5 units), and become less significant as the harmonic order increases (0.01 units or less for orders higher than octupole). These variations correspond to small block displacements, in the range of 35 μm. Furthermore, they are broadly comparable to the behaviour of the main dipole magnets under similar testing conditions, and therefore it does not seem that reproducibility of the field quality imposes limits on the use of phenolic inserts.

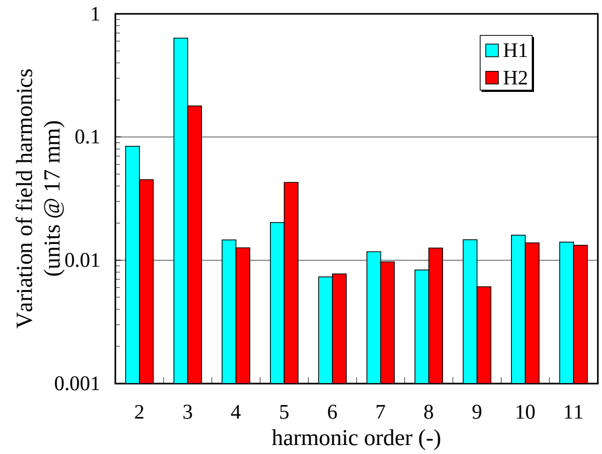

Figure 4. Maximum range of variation in the harmonics throughout the testing period for the H1 and H2 dipoles.

5 CONCLUSIONS

Two identical 1-m superconducting dipoles, featuring a single layer 87.8 mm aperture coil and phenolic inserts, have been manufactured and cold tested. The magnets trained to their short sample field of 5.6 T at 4.3 K and to 7 T at 1.8 K (90 % of the conductor limit). The quenches occurred predominantly in the coil ends and in the transition region to the straight section. Magnetic field measurements indicated that although there is evidence of elastic movement of the coils at high fields, the long term reproducibility is comparable to that of dipoles with metallic collars.

REFERENCES

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