PERFORMANCE OF THE 1-M MODEL OF THE 6 kA SUPERCONDUCTING QUADRUPOLE FOR THE LHC INSERTIONS

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Abstract

The LHC dispersion suppressors and matching sections will be equipped with individually powered superconducting quadrupoles with an aperture of 56 mm. In order to minimise the cost of the powering circuits, the quadrupole has been designed on the basis of an 8 mm wide NbTi Rutherford-type cable for a nominal current of 5300 A, corresponding to a gradient of 200 T/m at 1.9 K. In order to validate the design options a model magnet program has been launched. In this report we describe the construction features of the first 1-m long magnet, and present its training performance and the results of protection studies.

1 INTRODUCTION

In order to increase the flexibility and performance of the collider and to decrease the cost of the powering infrastructure, the LHC dispersion suppressors and matching sections will be equipped with individually powered 6 kA superconducting quadrupoles. The 56 mm aperture quadrupole was designed using a previously developed 8.2 mm wide Rutherford-type cable, and has a nominal gradient of 200 T/m at 1.9 K and 160 T/m at 4.5 K [1]. In order to validate the magnet design a model program comprising two 1 m long single aperture magnets and a twin aperture magnet was recently launched. In this report, we describe the construction of the first single aperture magnet, and present its training performance, as well as the results of magnet protection studies.

2 MAGNET CONSTRUCTION

The 1 m long single aperture quadrupole consists of a stand alone collared coil, assembled in a vertically split iron yoke, Fig. 1. The coils were wound using an 8.2 mm Rutherford-type cable with 34 strands (strand diameter 0.48 mm, filament diameter 10 μm), a mid thickness of 0.84 mm and a keystone angle of 1.05 degree. The cable has a copper-to-superconductor ratio of 1.3, and a critical current density of 3100 A/mm^2 at 4.2 K and 5 T. The main parameters of the magnet are given in Table 1.

One trial and four production coils were wound in two layers from a single cable with the layer jump in the lead side. In each layer there are two conductor blocks separated by a copper wedge. The coils were moulded at 185^{o}C and high pressure. After moulding the coils were measured under a pressure of 50 MPa, and their size compared to the nominal coil size. In Fig. 2, the size difference of all five coils is shown in eight different positions along the coil. The coils are on the average oversized by 17 μm, with a dispersion of 31 μm. The winding and curing procedures are therefore repetitive and well under control.

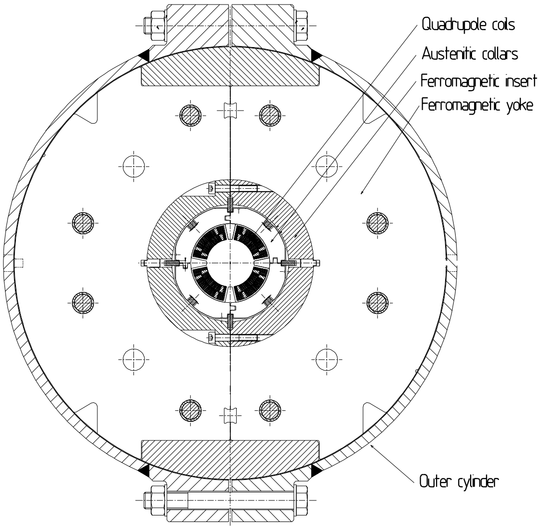

Figure 1: Cross section of the magnet.

Table 1: Properties of the magnet at 1.9 K and nominal current

Nominal gradient	200 T/m
Nominal current	5165 A
Peak field in coil	6.31 T
Current density in copper	1455 A/mm^2
Current density in superconductor	1891 A/mm^2
Number of turns in inner/outer layer	15/21
Inductance	4.55 mH/m
F_y per octant	-427 kN/m
F_x per octant	306 kN/m

The magnet is protected by two sets of strip heaters. The inner heaters are placed in between the two layers and induce a quench in 28 turns of a coil at a time. The outer heaters are placed on top of the coil and cover 17 turns. Although there was considerable concern about the integrity of the inner heaters during winding and curing of the coils, all inner heaters showed a high level of dielectric insulation in all phases of coil production. Two of the four production coils were instrumented with two spot heaters, located in the high and low field regions, and voltage taps for determining the hot spot temperatures. Additional voltage taps were added to the instrumented coils to localise the origin of the quenches.

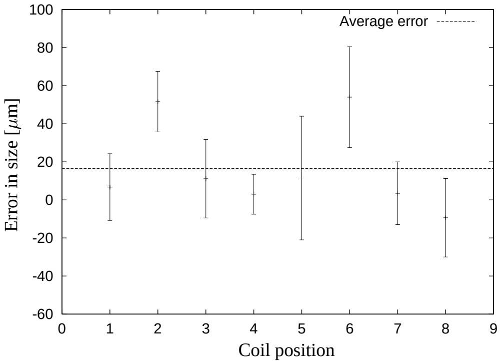

Figure 2: Coil size difference along the coil. Positions 1-4 and 5-8 correspond to two opposite sides of the coil with 1 and 5 at the lead end. Error bars correspond to min-max values for all measurements.

The coils were assembled in a self supporting collared structure. The austenitic steel collars are held together with full length keys welded to both end-plates in order to partially react the longitudinal magnetic forces. The keying was performed in several passes using a collaring press with four collaring rams and four keying rams displaced by 45 degrees. As shown in Fig.3, the collar assembly was compressed at the four poles over 200 mm to allow key bending during their gradual insertion. In trial collaring tests no damage of the keys or the collar slots was observed.

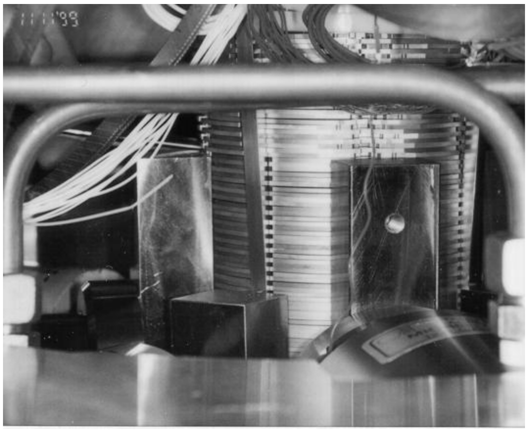

Figure 3: Collaring of the magnet. Full length keys are pushed in over 100 mm with four 20 tonne rams while the four 60 tonne collaring rams compress the assembly at each pole over 200 mm.

The coils were instrumented with capacitive gauges for measurement of the azimuthal pre-stress. The measurements were done at collaring and at cold, and showed good uniformity between the four poles. After collaring, the average value of the pre-stress in the inner and outer layers was 110 MPa and 80 MPa and dropped due to creep after one week to 104 MPa and 75 MPa, respectively. These values are compatible with the average oversize of the coils (Fig. 2).

After completion of the pole connections, the self-supporting collared coil was finally assembled in the vertical split iron yoke (Fig. 1). This arrangement is an adaptation of the structure normally used for testing the 1 m long single aperture models of the LHC main dipole [2]. In order to mount the collared coil, a ferromagnetic insert was provided which centred the coil within the outer yoke and its clamped shell.

3 TEST RESULTS

3.1 Magnet training

The magnet was tested twice with a thermal cycle in between. The tests started by magnet training at 1.9 K and 4.4 K, Fig. 4. The first quench occurred at 5285 A (203 T/m), slightly above the nominal current in the LHC. After the second quench the current went above 6 kA, and reached the conductor limit of 6900 A (270 T/m) in 10 quenches. At 4.4 K no training was observed, the quench current being stable above 5300 A (205 T/m). After a thermal cycle, the first quench at 1.9 K occurred at 5466 A (210 T/m), showing a weak memory effect. However the training proceeded much faster and the magnet reached its conductor limit after only four quenches. The seven initial training quenches in the second test were performed with a full energy dump in the magnet. Small detraining was observed near the conductor limit related to the peak temperature above 240 K. A number of quenches were performed with the bath temperature slightly above 4.4 K in order to confirm the conductor limit.

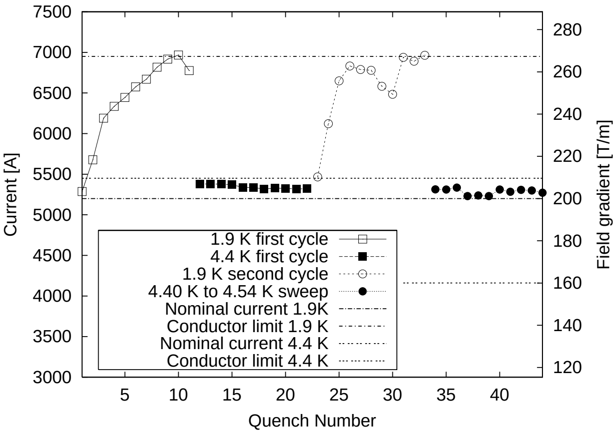

Figure 4: Training of the magnet at 1.9 K and 4.4 K.

Most training quenches at 1.9 K were located in the region of the layer jump. This is a mechanically weak point, which in addition corresponds to the location of the peak field in the magnet. In the initial test, the first training quenches occurred in coil number 2, while in the second one they moved to coil 3. Measurements of the pre-stress in the coils showed that the straight section is still compressed, pointing to a weakness of the layer jump of structural origin. The quenches at the conductor limit were located in the straight section and in the coil ends, indicating that the design of the end spacers was well optimised.

During the excitation, the coils lose pre-stress in both layers with identical rate of 0.95 MPa/kA^2. Nevertheless, at nominal current the compression of the coil poles is still more than 10 MPa in the inner and 25 MPa in the outer layer.

3.2 Protection studies

The efficiency of the magnet protection critically depends on the heater delay times, which were independently measured for the inner and outer heaters. The measurement results, Fig. 5, show that the heater delay decreases with current from about 80 ms at low currents to about 20 ms at the nominal current of 5100 A, similar to what was measured previously on this cable type [3]. Surprisingly, although the inner heaters act on turns in higher magnetic field, the heater delay times for the inner and outer heaters are almost identical. This could partly be related to the fact that the polyimide insulation of the inner heaters is 100 μm on each side of the stainless steel strip, while it is 75 μm for the outer heaters.

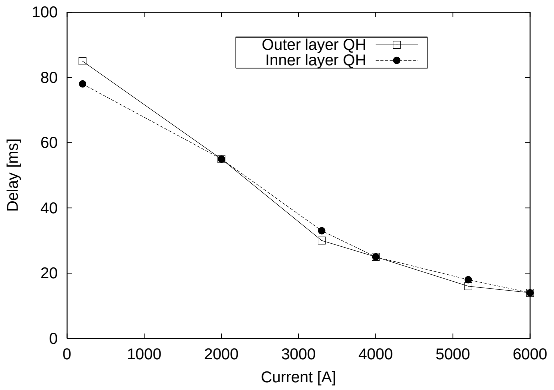

Figure 5: Heater delay as a function of current. The heaters were fired with an initial power of 21 W/cm^2 and a time constant of 112 ms.

The hot spot temperature in the magnet during a quench was derived on the basis of the MIITS measured after a spot heater provoked quench. The test was performed for cases when the magnet was protected by prompt firing of all inner or outer heaters, or of half of the inner or outer heaters. The hot spot temperature for these cases is shown in Fig.6 as a function of magnet current. As expected, the protection scheme with only half of the outer heaters results in the highest temperature, which nevertheless remains well below 300 K. The hot spot temperature is reduced from 234 K to 200 K if all outer heaters are used, and by an additional 20 K if the inner heaters are fired. The maximum voltage to ground measured in these cases was 27 V and 20 V for protection with outer and inner heaters, respectively. As the outer heaters protect the magnet sufficiently, the use of inner heaters seems unnecessary, especially since they create considerable difficulties in coil winding.

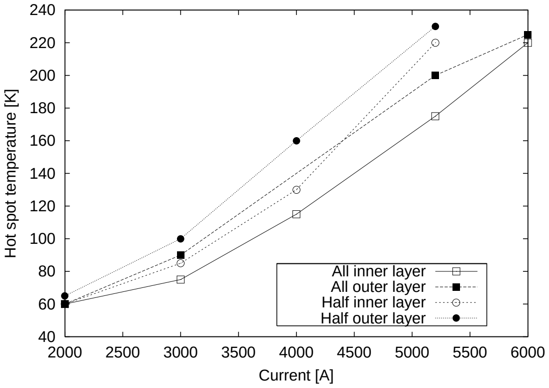

Figure 6: Hot spot temperature as a function of current.

In order to study the effect of the additional heater delay related to quench detection time for magnets installed in the LHC tunnel, the firing of the outer heaters was gradually delayed in steps of 5 ms. The hot spot temperature was found to be proportional to the delay, with the proportionality factor of 5 K/ms. A quench detection and filtering time of 20 ms would therefore imply an additional temperature increase in the hot spot of 93 K. A temperature of 293 K was measured in the worst case.

4 CONCLUSION

A 1 m long single aperture model of the 6 kA superconducting quadrupole for the LHC insertions was built and tested in CERN. The magnet features a two layer coil wound using an 8.2 mm wide Rutherford-type cable with 34 strands and a copper-to-superconductor ratio of 1.3. The two layers were wound with a single length of cable and cured at the same time with the inner heaters in between. The magnet was tested in two occasions separated by a thermal cycle, and performed very well. All initial training quenches at 1.9 K were above the nominal gradient of 200 T/m in the LHC, and the magnet reached its conductor limit of 270 T/m in 10 and 4 quenches in the first and second training tests, respectively. There were no training quenches at 4.3 K. Protection studies showed that the magnet is sufficiently well protected with the outer heaters only, so that coil winding can be significantly simplified.

REFERENCES

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