PERFORMANCE OF THE 1-METRE MODELS OF THE 70 mm APERTURE QUADRUPOLE FOR THE LHC LOW-β INSERTIONS

L. Bottura, Ch. Giloux, G.A. Kirby, M.J. Lamm[1], <u>R.Ostojic</u>, F. Rival, F. Rodriguez-Mateos,

S. Schloss, A. Siemko, T.M. Taylor

CERN, Geneva, Switzerland,

S.R. Milward, K.D. Smith, M.C. Townsend, J.R. Treadgold, J.M. Wiatrzyk,

Oxford Instruments Ltd, UK

Abstract

Following the successful testing of the first 1-metre model of the 70 mm aperture quadrupole for the LHC low-β insertions, two further 1-metre magnets have been built. All magnets feature a four-layer coil wound from two 8.2 mm wide graded NbTi cables and a four-way split yoke supporting structure. In this paper we review the training history of the three magnets performed at 4.3 K and 1.9 K in several tests. All magnets surpassed the operating gradient required for the LHC, with the third magnet reaching 260 T/m, its short-sample gradient at 1.9 K. The peak temperatures in the superconductor at various operating conditions are reported and a summary of magnetic field measurements is given.

1 INTRODUCTION

The design of the LHC low-β triplets is based on a 70 mm aperture high gradient quadrupole operating at 1.9 K with a design gradient of 240 T/m [1]. Besides accommodating fully separated beams at injection, the quadrupoles must provide a high field gradient and low multipole errors required for the 7 TeV colliding beams, and sustain high heat load from the secondary particles. During the past 5 years, CERN in collaboration with Oxford Instruments, has designed, built and tested three 1-metre long single aperture quadrupoles fulfilling these requirements. The quadrupole coils were also designed to function in a twin aperture configuration, with a nominal operating gradient of 160 T/m at 4.5 K [2]. A number of such magnets will be required in the LHC insertions, in all cases where the 56 mm nominal aperture of the insertion quadrupoles may be a limiting factor.

In this paper we summarise the performance of the three quadrupoles and present the training history, the main results of the quench protection studies and of the magnetic field measurements.

2 MAGNET DESIGN

The design and construction of the first low-β quadrupole model (Q1) for the LHC has been described

in [3]. To summarise, the magnet has a four layer coil wound with two 8.2 mm wide graded NbTi cables, with the transition between the cables in the middle of the second innermost layer. The coil pre-stress is accomplished with aluminium force rings, which are placed around the four-way split yoke structure, which in turn presses against 7 mm wide stainless steel collars.

As a result of the tests of Q1 [4], in which the magnet was found to have a peak temperature close to 450 K, the copper-to-superconductor ratio for the next two magnets (Q2 and Q3) was modified from 1.3 to 1.2 for the inner, and from 1.3 to 1.7 for the outer cable. The other parameters of the cables are identical. As a consequence of these modifications the peak field in the coil is shifted from the inner cable (second layer) to the outer cable (third layer), with a slight reduction of the short sample gradient, from 265 to 260 T/m. On the other hand, the peak temperature in the coil is expected to decrease to around 300 K. In all other respects, Q2 and Q3 are identical to Q1, with some minor modifications in the assembly procedure.

The major difference between Q2 and Q3 is in the scope of instrumentation. While Q2 is instrumented with the basic set of spot heaters for magnet protection (located on the pole turns of layers 1 and 3 and in the middle of the outer conductor in layer 2), Q3 has also a full set of accompanying voltage taps for quench propagation studies. In addition, it is equipped with strip heaters located in two radial positions: one set is located between layers 2 and 3, and the other on the outside of layer 4. In both positions, there are a total of four strip heaters, each one covering approximately 1/2 of each of the two adjacent coil octants. This system is proposed for the protection of the full length quadrupoles.

3 TRAINING HISTORY

The training of the magnets was performed at Oxford Instruments. Q1 was tested on two occasions in 1996 [4], while Q2 and Q3 were tested in June and November 1997. Finally, an extensive program of power tests and magnetic measurements was performed on Q3 in CERN in May and June 1998.

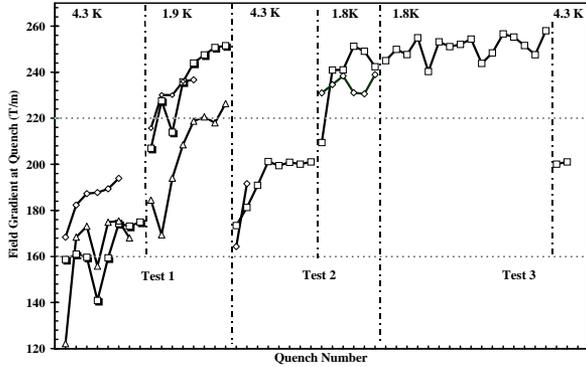[1] Permanent address: FNAL, Batavia, USA

Figure 1: Training history of the three 70 mm single aperture quadrupoles: Q1 (diamonds), Q2 (triangles), Q3 (squares). Quenches were performed at the nominal ramp rate of 5 A/s. Starting from quench no. 4 of test 3, the fraction of energy dissipated in Q3 was increased to 100%. Horizontal dashed lines represent nominal operating gradients in the LHC: 160 T/m at 4.5 K and 220 T/m at 1.9 K. The short sample gradients are 200 T/m at 4.3 K and 260 T/m at 1.9 K.

The training history of the three magnets is summarised in Figure 1. On the first 4.3 K training test, Q1 reached a plateau of 193 T/m (3980 A), which corresponds to 98% of the short sample limit. The magnet was subsequently tested at 1.9 K, where it reached 238 T/m (4850 A). After a long thermal cycle, the magnet was retested and the previous quench levels were reached after one quench both at 4.3 K and 1.9 K.

Q2 and Q3 were first trained to 3750 A, required for the 4.3 K magnetic measurements. In both cases this was achieved in 7-8 quenches. The somewhat erratic training of Q2 both at 4.3 K and 1.9 K was traced to inadequate shimming of the coil, which was later corrected in Q3. At 1.9 K, Q3 trained well, with a monotonic increase in the quench current, reaching 251 T/m, 95% of the short sample gradient.

In the second test performed at CERN, Q3 was first trained at 4.3 K reaching the short sample gradient of 200 T/m in four training quenches, a significant improvement over the previous test. At 1.9 K, the magnet started training at the same level as in the preceding thermal cycle, but reached the previously achieved gradient of 250 T/m in only three quenches. In the subsequent quenches it went up to 260 T/m, the short sample gradient at 1.9 K. After a thermal cycle, where the magnet was removed from the cryostat to repair faulty instrumentation wires, it was cooled to 1.9 K and continued training at the same level, retaining its trained state. In the following quenches, the fraction of energy dissipated into the magnet was increased from about 50% to the full energy deposition. As the fraction of energy dissipation increased, fluctuations in the quench field of 2-3% were observed, with subsequent regaining

of the short sample gradient. This behaviour may be related to the fact that apart from the few initial training quenches, which occurred in layers one and three, all quenches close to short sample were traced to the transition region between the inner and outer cables in layer two of pole C. Finally, at the end of the training sequence, the magnet was quenched twice at 4.3 K to confirm its quench plateau.

4 QUENCH PROTECTION STUDIES

One of the important tests for Q3 was to determine the efficiency of the strip heater protection scheme at 4.3 K and 1.9 K, and to establish experimentally the effect of the modification of the copper-to-superconductor ratio of the cables.

A summary of peak temperatures achieved in Q1 and Q3 at 1.9 K and 4.3 K is shown in Fig. 2. In all cases, the quenches were induced by firing spot heaters (in layer 2 for Q1, and in layer 1 or layer 3 for Q3). In case of Q1, the power supply was turned off upon quench detection, the terminals effectively shorted and the remaining spot heaters fired. For Q3, the same power supply sequence was followed, but instead of the spot heaters, the strip heaters were fired. In both cases over 99% of the energy was dissipated into the magnet.

The voltage across the cable segment adjacent to the heater was monitored throughout the current decay. After accounting for magneto-resistance and conductor geometry, the copper resistivity was determined. The peak temperature then followed from its peak value.
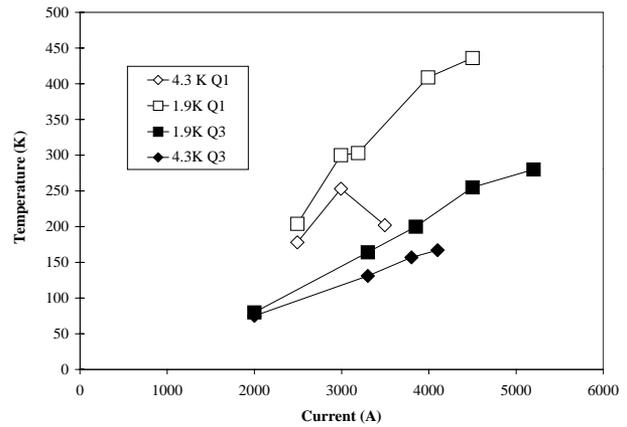

Figure 2: Peak temperatures in Q1 and Q3 at 4.3 K and 1.9 K. The overall error in peak temperature is ± 15 K.

As shown, Q3 exhibited a much improved behaviour over Q1, as the peak temperature decreased from 450 K to 250 K at 4400 A (220 T/m). At 4.3 K, the peak temperatures in Q3 in the case of firing layer four strip heaters only, shown in Fig.2, were only slightly higher than those when all strip heaters were used. For both 4.3 K and 1.9 K the Q3 peak temperature did not depend whether the quench was initiated in the inner or outer

cable. Furthermore, it increased monotonically with current, indicating that the magnet protection was dominated by the strip heater-induced resistance and not from quench propagation. The effectiveness of the heaters is due to their wide area of coverage and short time delay between firing and onset of resistive voltage growth (20 ms at 4400 amps). A complete study of the quench velocities and heater delay times will be presented in a forthcoming report.

5 MAGNETIC FIELD MEASUREMENTS

Magnetic field measurements were performed using cold radial measurement coils designed at CERN. For Q3, the measurements were performed using coils sensitive to both the body and end fields, while for Q1 they were done with a coil set sensitive to the body field only. For Q2, the measurement coils did not function properly and the field was not measured.

The multipole errors in the body of Q1 and Q3 at 220 T/m are summarised in Table 2. In Q1, a 10% thicker insulation system was used in one of the poles [4], and the quadrupole symmetry of the magnet was partially lost, as seen by the expected non-zero multipoles of order n<6. In general, the difference between the measured and expected multipoles may be attributed to the errors in positioning of the coil blocks. For Q1, it was found that the displacements that reproduce the residual errors obey a Gaussian distribution with rms of 0.02 mm and 0.04 mm for the radial and azimuthal directions. When compared to the random multipole errors based on these rms displacements, the measured non-allowed multipoles, except for b_5, are within 2σ.

Table 2 Relative multipole errors of Q1 and Q3 at 220 T/m, at reference radius of 17 mm (in units of 10^{-4}). The expected random errors from coil construction are given in the last column.

	Q1 measured	Q1 expected	Q3 measured	2σ
b_3	-0.472	0.214	-3.334	2.90
a_3	0.836	0.214	-1.589	2.90
b_4	-1.136	0.	0.439	1.04
a_4	1.728	0.569	0.326	1.04
b_5	3.179	-0.200	-0.290	0.74
a_5	0.349	0.200	-2.447	0.74
b_6	-3.867	-3.458	-4.543	
a_6	-0.234	0.	0.384	
b_{10}	-0.418	-0.418	-0.349	
a_{10}	-0.070	0.	0.007	

In Q3, only the allowed b_6 and b_{10} multipoles are expected. The measured values of -4.54 and -0.35 units are in excellent agreement with the predictions of -4.30 and -0.35 units. Except for the sextupole, the non-allowed multipoles are in general smaller than for Q1. Similarly to b_5 in Q1, the a_5 multipole in Q3 is outside the 2σ interval. Further investigation is needed to determine whether this is related to a systematic feature in coil construction.

The multipoles show weak dependence on current: the saturation contributes 0.12 units to b_6 and 0.035 units to b_{10}. The width of the b_6 hysteresis curve due to persistent currents at 4.4 K is 4.68 units at 250 A.

The measurements were repeated before and after the training and thermal cycles. None of these changes of state seems to have an influence on the field quality of the magnet. For example, the b_6 multipole is reproduced at the level of 10^{-3} units, while the repeatability of the measurements, including the bath temperature and power supply control, were at the level of $2\ 10^{-4}$ units.

3 CONCLUSIONS

As part of the LHC magnet development program, three 1-metre long 70 mm single aperture quadrupoles were built and extensively tested. All magnets surpassed the operating gradient required for the LHC of 220 T/m, with the third magnet reaching 260 T/m, its short-sample gradient at 1.9 K. Peak conductor temperatures have been measured, confirming that the magnets safely absorb their own energy. The measured field harmonics are in good correspondence with the design values, confirming the coil construction technique.

Following the tests in single aperture configuration, Q2 and Q3 quadrupoles will be disassembled and the coils used for building a two-in-one wide aperture quadrupole, to be tested by the end of 1998.

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