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Quench Performance and Field Quality Measurements of the First LHC Low-β Quadrupole Model

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Abstract

As part of the LHC magnet development program, CERN in collaboration with Oxford Instruments has designed, built and tested a one metre model of a 70 mm aperture low-β quadrupole. The magnet features a four layer coil, and is designed for 250 T/m at 1.9 K. We review the results of the magnet training and quench propagation studies performed at 4.3 K and 1.9 K, and report on the magnetic field measurements.

1 INTRODUCTION

As part of the LHC magnet development program, CERN in collaboration with Oxford Instruments, England, has designed built and tested a one metre model of a 70 mm aperture quadrupole for the LHC low-β triplets. The magnet [1] has a four layer coil wound from two 8.2 mm wide NbTi cables. Two layers are wound and cured at a time, with the transition between the two cable types in the middle of the second layer. The magnet is assembled using 10 mm wide stainless steel collars and a four-piece yoke, which transmits the compression from a set of aluminium force rings with stainless stell collets.

During the first test in March 1995 [2], the magnet reached a maximum current of 3780 A at 4.3 K, after which the performance became erratic and it was not possible to train further. All quenches occurred in layers 3 and 4 of one quadrant, but the instrumentation was insufficient to locate the quenches more precisely. After the disassembly of the magnet a multi-turn short was found, caused by scissoring in the ramp between layers. The size and location of the short precluded repair and a replacement coil was wound with a modified layer ramp. This modification was also made to all the other coils to prevent similar damage. Due to availability of material, the rewound coil incorporated an insulation system which was 9 μm thicker per turn than in the other coils. To compensate for the increased thickness the size of the copper wedges at the pole was reduced. The magnet was rebuilt with a modified set of voltage taps and all the ground plane insulation replaced. In all other ways the magnet was identical to the first build.

After the rebuild the magnet was tested on two occasions, in January and October 1996, when it was trained to 4920 A at 1.8 K, and a field gradient of 238 T/m measured. In this paper we summarise the results of the magnet training and quench propagation studies, and report on the transfer function and field multipole measurements.

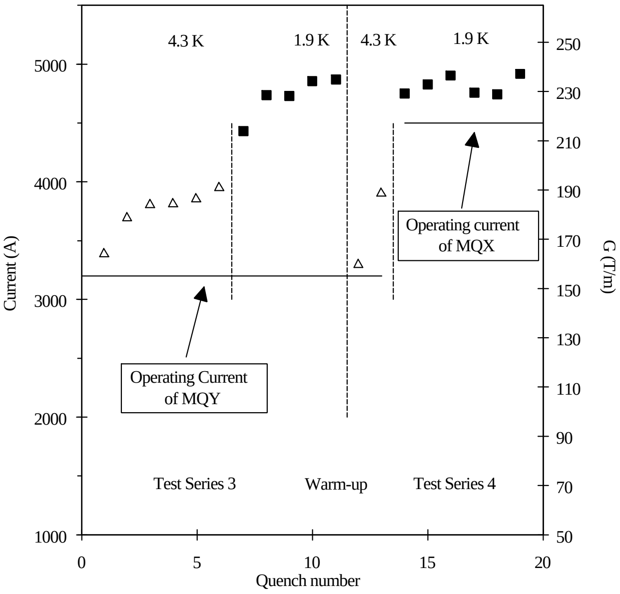

Figure 1: Training history of the model magnet.

2 TRAINING HISTORY

The training history is displayed in Figure 1. The maximum operating gradient of the low-β quadrupole (MQX) of 215 T/m at 1.9 K is also shown, as well as the required gradient of 160 T/m at 4.3 K of the two-in-one quadrupole (MQY), which uses the same coil and is installed in the injection and dump insertions.

In the January 1996 test (Test 3) the magnet was initially trained at 4.3 K. The first quench occurred at 3400 A, and in the next three quenches it passed the plateau of the March 1995 test. In view of possible conductor limitation, the magnet was pumped to 4.0 K and energised with a quench at 3860 A, less than the expected gain by cooling. In the next two quenches it reached 3960 A, corresponding to 98% of the short sample limit. Throughout this stage quenches occurred in all the coils except in the rebuilt coil.

The first quench at 1.9 K occurred at 4440 A, and the next two recorded at 4745 A, with a change in quench

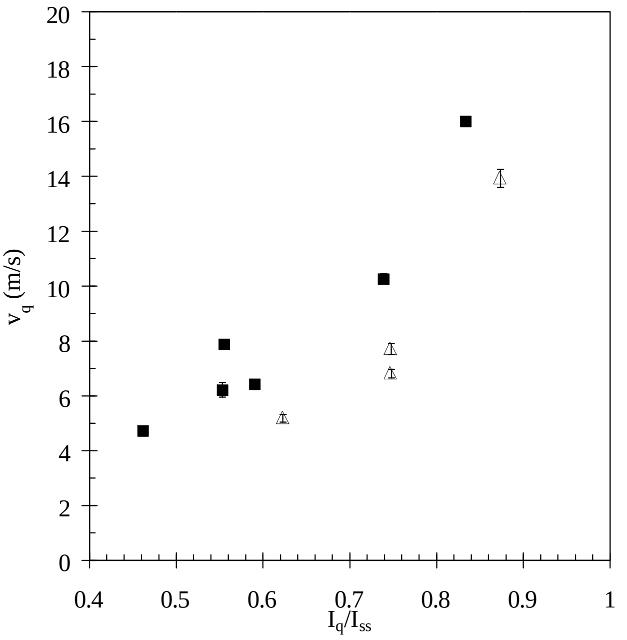

Figure 2: Quench velocity for spot heater induced quenches at 4.3 K (open symbols) and 1.9 K (full symbols). The estimated conductor limits are 4000 A at 4.3 K and 5400 A at 1.9K.

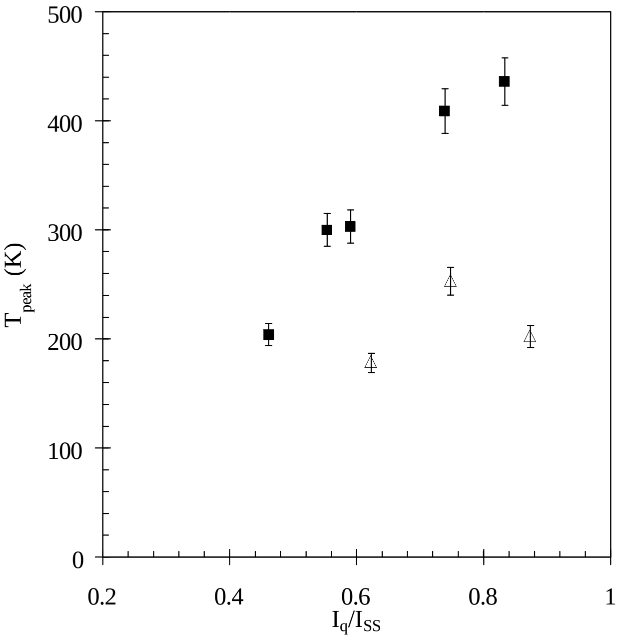

Figure 3: Peak conductor temperature for induced quenches at 4.3 K (open symbols) and 1.9 K (full symbols).

location. Subsequently, the quench current increased to over 4850 A, indicating that the magnet has not reached a plateau. The test was discontinued in order to install the field measurement coils, and the training of the magnet resumed in October 1996 (Test 4).

A total of six training quenches were performed at 1.9 K during Test 4. The first quench current was close to that of the last quench of Test 3. All others showed a gradual increase of the current, the final quench recorded at 4920 A, corresponding to 91% of the short sample limit. In the middle of the quench series the magnet had to be warmed up to about 90 K, to unblock a faulty needle valve. A slight decrease in quench current followed, confirming the tendency of the magnet to detrain on warm up, a feature that was also noted after a long period at room temperature between January and October 1996.

At both test temperatures, the magnet has achieved a gradient above the the nominal values required for the LHC. The last quench at each temperature was in layer 2, where conductor limited quenches are expected to occur, but the instrumentation was insufficient to determine if these quenches occurred at the high field point.

3 QUENCH PROPAGATION STUDIES

An important objective of the tests was to measure the dependence of the quench velocity v_q and of the peak conductor temperature $\mathrm{T_{peak}}$ on the magnet current $\mathrm{I_q}$, in order to help design a quench protection system for the full-length magnet. For these studies a special spot heater was used, located in the second layer near the high field point. A set of voltage taps defined two measurement sections. The first one, 125 mm long with the spot heater in the centre, was used for resistance measurements. The other, 585 mm away from the spot heater, was used for time of flight measurements.

The quench velocity v_q for induced quenches measured by time of flight is shown in Figure 2 as function of quench current normalised to the conductor short sample limit. For both 4.3 K and 1.9 K, v_q grows from about 5 m/s at low currents to 15 m/s at 85% of the conductor limit. For spontaneous quenches, the quench heater used for these measurements was still triggered as part of the protection system. The quench velocities obtained from these quenches display the same trend as in Figure 2, with the quench velocity approaching 65 m/s for highest currents. For both temperatures the relative increase of the quench velocity is well explained by the adiabatic theory. However, the measured quench velocities are systematically a factor of three smaller than predicted. A possible explanation may be in the fact that the all-polyimide insulation used in the coil construction is highly permeable, and that the assumption of adiabatic quench propagation is not fulfilled.

Quench velocities were also independently measured on the basis of the initial resistance growth dR/dt in the 125 mm section. These measurements relate to quench development over the first 10 ms, while those based on the time of flight give an average velocity over the time needed for the quench to propagate over 585 mm, typically 30-40 ms. The two methods agree well for low velocities. However, systematic differences were observed at higher fields, suggesting possible acceleration of the quench front at 4.3 K and deceleration at 1.9 K. These indications will be further investigated on the next quadrupole model, presently under construction.

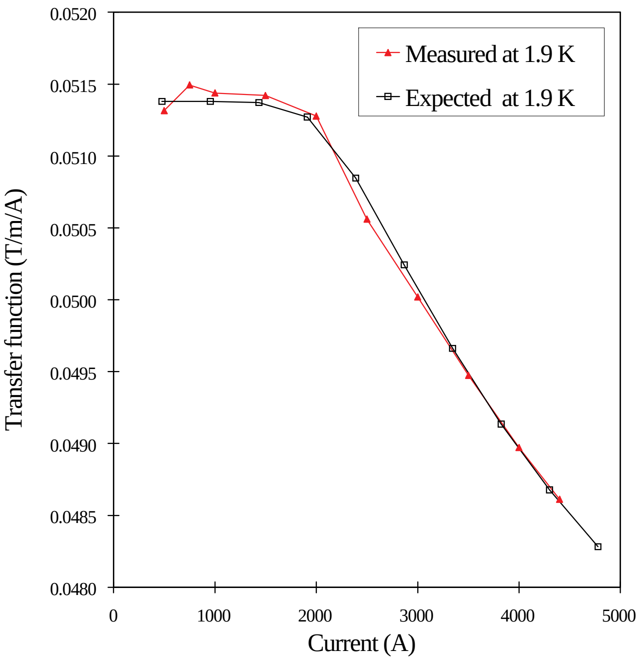

Figure 4: Measured and calculated transfer function in the body of the quadrupole at 1.9 K.

Figure 3 shows the $T_{\rm peak}$ for induced quenches measured without energy extraction, obtained by measuring the final resistance of the 125 mm cable section. At 4.3 K, $T_{\rm peak}$ has a maximum of about 250 K which occurs at 75% of the conductor limit. At 1.9 K, $T_{\rm peak}$ steadily rises and reaches 430 K at 85% of the conductor limit, with an indication that a point of inflexion has been reached. This agrees well with the 465±40 K calculated on the basis of $\int I^2 {\rm dt}$, where the error includes uncertainties in the start time and in the value of B at the quench location. For these conditions the magnet absorbs safely its own energy.

4 MAGNETIC FIELD MEASUREMENTS

The magnetic field of the quadrupole was measured using a harmonic coil system developed at CERN [3], consisting of four sets of compensated coils covering the straight section and the end regions of the magnet. The measurements were done at 4.3 K and 1.9 K, but runs were also performed at room temperature and 90 K. The measured transfer function in the body of the magnet is shown in Figure 4. The measurements performed at different temperatures agree well, and are well reproduced by the calculations which take into account coil deformation.

The measured relative field errors, given in Table I, are dominated by the low order multipoles. As remarked above, a 10% thicker insulation system was used for the replaced coil, and as a consequence, the perfect quadrupole symmetry of the magnet has been partially lost. The expected multipoles that take into account the larger size of the replaced coil are also given in Table I. They are important for all normal and skew terms up to the dodecapole and are comparable to the measurements. Higher order multipoles are relatively insensitive to individual coil size and block positioning. The relative b_{10} multipole of -0.006 units was consistently measured at all temperatures and currents, and is in very good agreement with the design value.

TABLE I
RELATIVE MULTIPOLE ERRORS AT 1.9 K AND 4600 A.
(REFERENCE RADIUS = 10 MM, IN UNITS OF 10^{-4})

Multipole	Measured		Expected	
	b_n	a_n	b_n	a_n
3	-0.278	0.492	0.126	0.126
4	-0.393	0.598	0.	0.197
5	0.647	0.071	-0.041	0.041
6	-0.463	-0.028	-0.414	0.
7	-0.009	-0.002	-0.001	-0.001
8	-0.002	-0.008	0.	0.
9	0.001	0.005	0.	0.
10	-0.006	-0.001	-0.006	0.

The difference between the measured and expected multipoles may be attributed to the errors in positioning of the coil blocks. As the coil sensitivity matrix is known, the radial and angular block displacements which reproduce the residual multipoles could be determined. It was found that the displacements follow a normal distribution, indicating that the residual multipoles are due to random errors in positioning of the coil blocks. The rms errors of coil positioning are 0.02 mm and 0.04 mm for the radial and azimuthal directions respectively, and confirm the validity of the winding and curing techniques employed in the construction of the magnet.

5 CONCLUSIONS

The first one metre model of the 70 mm aperture low-β quadrupole was trained to 193 T/m at 4.3 K and 238 T/m at 1.9 K, in excess of the operating current required for the LHC. Quench velocities and peak conductor temperatures have been measured, confirming that the magnet safely absorbs its energy. The measured transfer function and field harmonics are in very good correspondence with the design values, confirming the coil construction technique.

6 REFERENCES

[1] R. Ostojic T.M. Taylor and G.A. Kirby, "Design and Construction of a One-Metre Model of the 70 mm Aperture Quadrupole for the LHC Low-β Insertions", *IEEE Trans. Magn.* **30** pp 1750-1753, 1994.

[2] S.R. Milward et al., "Progress in the Development of the 1-m Model of the 70 mm Aperture Quadrupole for the LHC Low-β Insertions" Proc. 1996 Appl. Superconductivity Conf, August 1996, Pittsburgh, USA, LHC Project Report 68.

[3] J. Billan et al., "Design and Test of the Benches for the Magnetic Measurements of the LHC Prototype Dipoles", *IEEE Trans. Magn.* **30** pp 2658-2661, 1994.