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PROGRESS IN THE DEVELOPMENT OF THE 1-m MODEL OF THE 70 mm APERTURE QUADRUPOLE FOR THE LHC LOW-β; INSERTIONS

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Abstract

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Progress in the Development of the l-m Model of the 70 mm Aperture Quadrupole for the LHC Low-β Insertions

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Abstract—Within the LHC magnet development program Oxford Instruments has built a one metre model of the 70 mm aperture low-β quadrupole. The magnet features a four layer coil wound from two 8.2 mm wide graded NbTi cables, and is designed for 250 T/m at 1.9 K. The magnet has previously been tested between 4.5 K and 2.3 K. In this paper we review the magnet rebuild and the subsequent tests. Results on magnet training at 4.3 K and 1.9 K are presented along with the results related to quench protection studies. We also present the first results of magnetic field measurements done at room and liquid nitrogen temperatures.

I. INTRODUCTION

As part of the LHC magnet development program Oxford Instruments has built and tested a one metre model of the 70 mm aperture quadrupole for the low-β insertions. The design and construction of this magnet has been reported previously along with the results of the first tests [l, 2]. The magnet [3] has a graded 4-layer coil with the transition between the two cable types in the middle of the 2nd layer. Thin collars 10 mm wide ensure accurate coil location during assembly. Final preload is applied using a set of aluminium collet force rings, whose load is transmitted to the collared coil through the 4-piece iron yoke.

During the first tests in March 1995, the magnet reached a maximum current of 3780 A at 4.5 K and 4112 A at 2.5 K. After this point the performance became erratic and it was not possible to train further. It was thought that the quenches were caused by conductor motion. The magnet was warmed to room temperature and the coil preload increased by tightening the force rings. The magnet was tested again in August 1995, but repeatedly quenched at currents between 3045 and 3l80 A. The quench current was independent of temperature. The quenches were all in layers 3 and 4 of quadrant D, but the instrumentation was insufficient to locate the quenches within this coil pair. The magnet had protection resistors fitted across each pole which prevented further testing without removal from the test dewar.

In this paper we describe the rebuild of the magnet and present the results of the subsequent tests. The magnet has been energised to a gradient above that required for operation in the LHC. We report on the measurements of the quench velocities and peak temperatures, and on the first series of measurements of the magnetic field done at room and liquid nitrogen temperatures.

II. DISASSEMBLY AND REBUILD

A. *Disassembly*

With the magnet at room temperature and the support structure disconnected, the protection resistors across each pole were removed and the external joints broken. Measurements of resistance and inductance for each coil indicated the presence of a multi-turn short in quadrant D. Further investigations of this coil required the disassembly of the magnet. After modification of the tooling, the removal of the force rings and iron yoke was straightforward and removal of the collar packs was completed easily. With the coils separated it was a simple task to locate the short through applying a current to the coil and measuring the voltage to each turn. A multi-turn short caused by scissoring was found in the ramp between layers 3 and 4. On closer examination about half the strands of one piece of cable had been damaged. In hindsight this region was first damaged during energisation to 4112 A in March l995 and the coil has never performed as well since.

B. *Rebuild*

The size and location of the short precluded any attempts at repair and a replacement coil was wound with modified geometry in the layer ramp region. This modification was also made to ail the other coils to prevent similar damage.

Due to availability of material, the rewound coil incorporated a modified insulation system which featured double sided uncured polyimide as the outer layer, which increased the insulation thickness by 18 µm per turn. The new coil wound extremely well and no noticeable effects of the thicker insulation were seen at the end spacers. After curing this coil looked to have a better finish than the original coils and was mechanically considerably more stable and easier to handle.

To compensate for the increased thickness the sizes of the copper wedges at the pole were reduced. The magnet was rebuilt with a modified set of voltage taps on all coils and all the ground plane insulation replaced. The coil prestress at room temperature was reset to the same value as previously. In all other ways the magnet was identical to the first build.

III. MAGNET TESTS

Following the magnet rebuild a third test was performed in January and February l996. The objective of this test was to train the magnet to in excess of the LHC operating current and to record data for the calculation of quench velocities and peak temperatures. Initially a series of tests were performed to prove the instrumentation set up. This was necessary because several improvements had been made and these tests demonstrated that good agreement could be obtained between the quench detector and the voltage tap signals for the identification of quench initiation locations.

The magnet was equipped with a set of spot heaters located between turns, one in each of the inner three layers of each quadrant. The heaters could be energised individually to trigger a quench, and all were energised once a quench was detected. Bypass resistors of $R = 2.3\ \text{m}\Omega$ were connected across each quadrant of the coil in an effort to provide additional protection. Although complicating analysis, these resistors were refitted, since the previous tests had not produced sufficient data to allow confidence in their removal.

A. Training History

The training history is displayed in Figure l. This figure also shows the estimated conductor limits (2-4% uncertainty), the calculated gradients (including iron saturation) and the operating gradients G_{op} of two versions of this magnet. The high luminosity low-β insertions utilise a single aperture quadrupole (MQX), operated at a G_{op} = 225 T/m and l.9 K In the dump insertion, a two-in-one version (MQY) operating at 4.5 K with G_{op} = l60 T/m is envisaged.

The magnet was initially trained at 4.3 K and the first quench occurred at 3408 A. This was about 150 A lower than the first quench of the first test. The next three quenches were at 37l2 A, 3838 A and 3833 A, slightly above the plateau of the first test. In view of possible conductor limitation at 4.3 K, the magnet was pumped to 4.0 K and energised with a quench at 3860 A. The increase of 30 A was less than the expected gain by cooling and further training was continued at 4.3 K. The following quenches at 3953 A and 3958 A were deemed to represent a relatively stable plateau, and the magnet was cooled to superfluid helium temperature. Throughout this stage quenches occurred in all the coils except in the rebuilt coil D, although coil C (layers 2 and 4) showed a propensity for quenching.

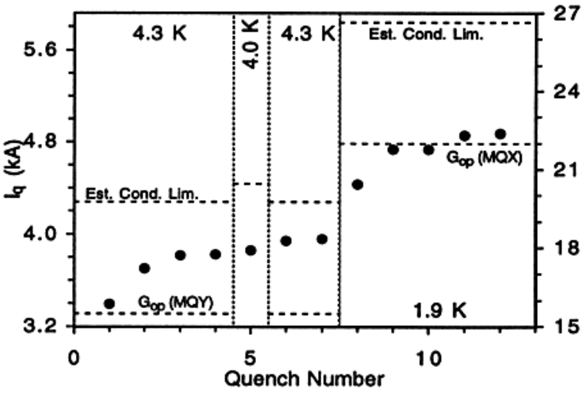


Figure 1: Training Quench History.

The first quench in superfluid helium occurred at 4441 A. the next two quenches were recorded at 4746 A and 4743 A, with a change in quench location. On the next two runs the current increased to 4862 A and 4879 A. Further training was discontinued due to test equipment failure.

At both test temperatures, the magnet has achieved a plateau above the operating gradients required for the LHC. However, the plateaux are somewhat below the computed conductor limits. The last quench at each temperature was in layer 2, where conductor limited quenches are expected to occur, but the instrumentation is insufficient to determine if the quenches occur at the high field point. Further testing will be required to verify if the magnet is mechanically limited or if the actual conductor limit is lower than that computod.

B. Quench Protection Studies

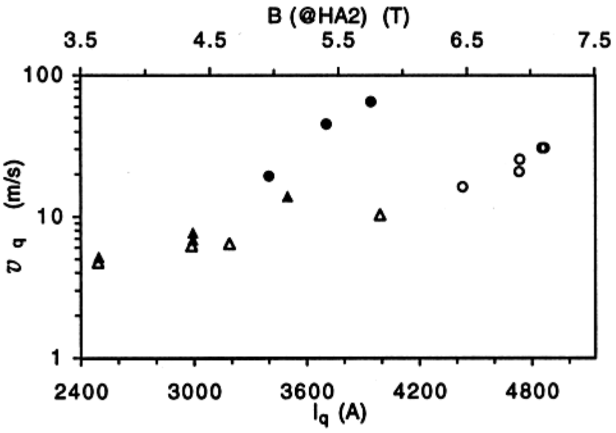
An important objective of this test was to measure the dependence of the peak conductor temperature T_{peak} and the initial quench velocity v_q on the magnet current I_q, in order to help in the design of a quench protection system for a full length magnet. For these studies, special voltage taps were used. They are placed adjacent to the spot heater (HA2), which is located near the lead end of the second layer of quadrant A between turns of the small cross-section cable. By measuring the final resistance of the cable segment which contains HA2, T_{peak} was determined. Independently, $\int I^2 dt$ was converted to peak temperature using the known conductor properties and the magnetic field at the point of the quench. By measuring the time for the quench front to propagate between sucessive voltage taps v_q was determined. The quench velocity was also independently determined from the initial resistance growth dR/dt and the measured resistance per unit length of the cable (including magnetoresistance).

Figure 2 shows v_q measured by time of flight versus I_q For spontaneous quenches which do not originate in quadrant A, the quench at HA2 is still triggered by that heater and vq can be determined. Spontaneous and heaterinduced quenches are displayed independently in Fig. 2; they clearly display the same trend. At l.9 K, v_q grows more slowly with current, but quenches at a similar fraction of the conductor limit at the two temperatures have similar velocities. The quench velocity was also measured from the initial dR/dt. As discussed in detail in [4] comparison of the two methods strongly suggests an acceleration of the quench front.

Figure 3 displays T_{peak} vs. I_q for heater induced quenches at two operating temperatures- At 4.3 K, T_{peak} has a maximum of about 250 K which occurs between 3000 and 3500 A, 70-80 % of the conductor limit. At 1.9 K a similar distance to the conductor limit occurs near 4000 A when a maximum temperature of 410 K is measured. This agrees well with 465±40 K calculated on the basis of $\int I^2 dt$, where the error includes uncertainties in the start time of the integration and in the value of B at the quench location. For these conditions the magnet absorbs its own energy safely as only 0.l % of the stored energy was deposited in the bypass resistors.

C. Magnetic Field Measurements

The third series of tests was ended with measurements of the magnetic field at room temperature and cold. The measurement system employed is based on the harmonic coil method and is identical to the system used at CERN for LHC prototype dipole measurements [5]. The power supply used had a rating of ± 4 V and stability of l000 ppm, supplying a current of ± 4 A and ± l0 A at room and liquid nitrogen temperatures.



Fgure 2: v_q vs. I_q for heater HA2 induced (triangles) and spontaneous (circles) quenches. Quenches at 4.3 (1.9) K are shown as filled (open) symbols.

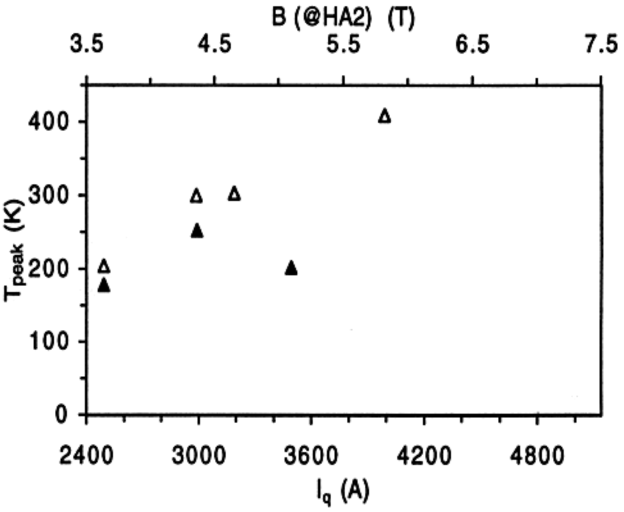


Figure3: T_{peak} vs. I_q for quenches induced by HA2. Quenches at 4.3 (1.9) K are shown in filled (open) symbols.

The relative field errors measured at 77 K are shown in Figures 4 and 5. As remarked above, the rebuild of coil D included a slightly thicker insulation system than in the previously built coils; as a consequence the magnet does not have a perfect quadrupole symmetry. This type of asymmetry affects the multipoles up to the dodecapole. Higher order multipoles are relatively insensitive to positioning of the coil blocks and iron. The relative b_{10} multipole of 0.006 units at l0 mm reference radius is in very good agreement with the design values, and confirms that the coil structure is behaving predictably during cool down.

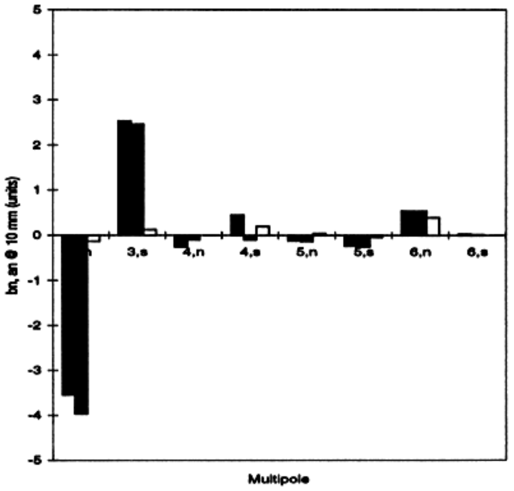


Figure 4: Measured relative normal and skew sextupole to dodecapole multipoles at 77 K; coil currents of -10 A (horizontal batch) and 10 A (cross hatch). Open symbols are calculated multipoles of the magnet with the asymmetric coil D.

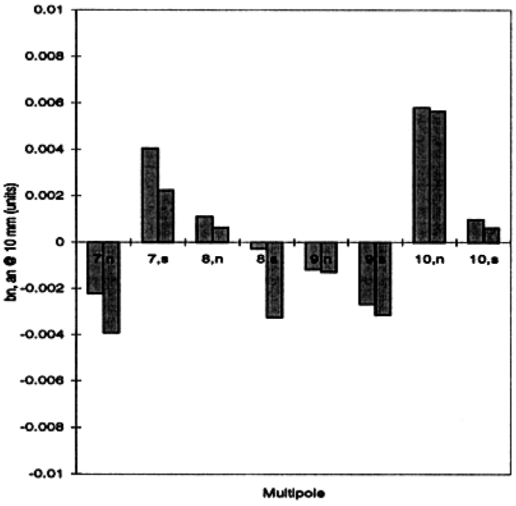


Figure 5: Measured relative normal and skew higher order multipoles at 77 K.

In an attempt to understand the possible sources of movement inside the coil that may have produced the measured field multipoles, we have analysed the measurements with the inverse field technique. Beforehand, the systematic errors due to asymmetric coil geometry were calculated and subtracted from the measured values. In the analysis, two degrees of freedom were considered for each of the 40 coil blocks - radial and azimuthal displacements - giving a total of 80 variables for 11 measured values (normal and skew multipoles of order n= l, 3, 4, 5 and 6, and quadrupole transfer function). Constraint conditions were introduced to limit the allowed displacements, and to eliminate the over-determination of the problem. On the basis of a sensitivity matrix for the coil, the block parameters were determined so as to reproduce the measured multipoles in the weighted least square sense.

The distribution of resulting radial displacements in the total number of blocks is shown in Figures 6, with a similar distribution for azimuthal displacements. When analysed for statistical significance, these results show that the measured multipoles can be explained on the basis of random positioning of the coil blocks, with rms errors of 0.02 mm and 0.03 mm for the radial and azimuthal directions respectively. These values confirm the validity of the winding and curing techniques employed.

IV. CONCLUSIONS AND FUTURE PLANS

The one metre model of the 70 mm aperture quadrupole for the LHC low-β insertions built by Oxford Instruments has achieved the operating current of 4790 A (225 T/m) with only three training quenches in superfluid helium. In comparison with other quadrupoles tested for the LHC, the highest gradient times aperture has been achieved. The mechanical structure of the magnet was shown to be appropriate, and the construction was achieved without the use of expensive tooling. The magnetic field has been measured at room and liquid nitrogen temperatures, and good correspondence with design values has been found. A further test of the magnet is planned in order to measure the magnetic field transfer function and field multipoles up to top fields, and to examine the training behaviour following a thermal cycle.

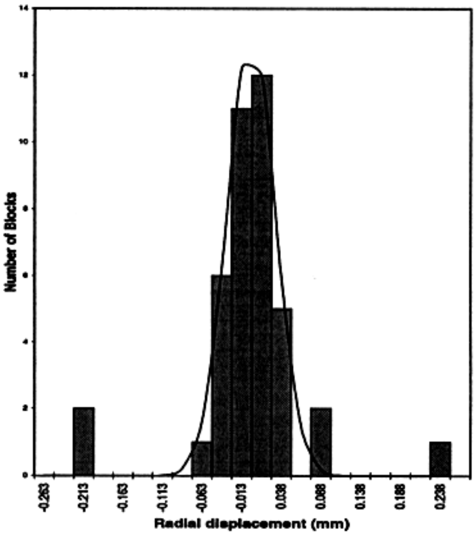


Figure 6: Distribution of radial displacements of the coil blocks resulting from the inverse field analysis of the measured multipoles. The distribution is fined with a Gaussian fit with an rms of 0.02 mm.

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