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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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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.

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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.

1 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 [1, 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 aluminum 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 of 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 3180 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 diagnostic testing without removal of the magnet 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 the LHC operating point and measurements have been made of the quench velocities and peak temperatures.

2 DISASSEMBLY AND REBUILD

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. After the disassembly of the magnet, the location of the short was determined by 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. About half the strands of one piece of cable were damaged. In hindsight, this region was probably first damaged during energisation to 4112 A in March 1995.

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 all the other coils to prevent similar damage. Due to availability of material, the rewound coil incorporated a modified insulation system which was 9 μm thicker per turn than in the other coils. 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.

3 MAGNET TESTS

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 mΩ 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.

3.1 Training History

The training history is displayed in Fig. 1. 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 utilize a single aperture quadrupole (MQX), operated at G_{op} = 225 T/m and 1.9 K.

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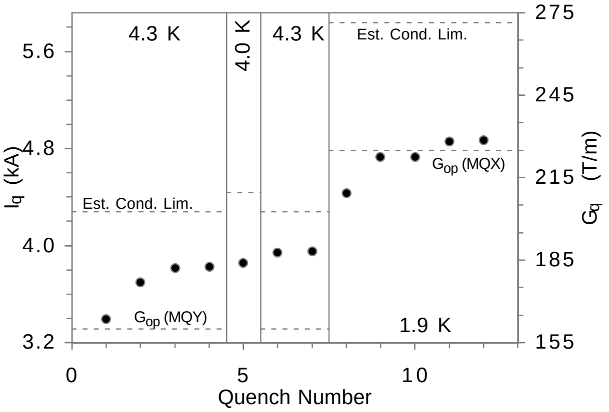

Figure 1: Quench training history.

In the dump insertion, a two-in-one version (MQY) operating at 4.5 K with G_{op} = 160 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 3712 A, 3828 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.

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 plateaus are achieved 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 these quenches occur at the high field point. The coil pressure is measured to be 74 MPa at zero field and decreases by only 13.3 MPa up to a current of 3750 A, suggesting that the coil remains adequately preloaded to well above the highest quench current achieved. Further testing will be required to verify if the magnet is mechanically limited or if the actual conductor limit is lower than that computed.

3.2 Quench Protection Studies

An important objective of this test was to measure the dependence of the peak conductor temperature $T_{\mathtt{peak}}$ 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 125 mm long cable segment which contains HA2, $T_{\mathtt{peak}}$ can be determined. Similarly, by measuring the time necessary for the quench front to propagate to another tap 585 mm away v_q can be determined. The quench velocity can be independently measured from the initial resistance growth dR/dt and the measured resistance per unit length of the cable (including magneto-resistance). The measured $\int I^2 \mathtt{dt}$ can be converted to peak temperature using the known conductor properties and the magnetic field at the point of the quench.

Figure 2 shows the v_q measured by time of flight (Δt) versus I_q. For spontaneous quenches which do not originate in quadrant A, the quench at HA2 is still triggered by that heater and v_q can be determined. Spontaneous and heater-induced quenches are displayed independently in Fig. 2; they clearly display the same trend. The v_q grows from about 5 m/s at low current to 65 m/s for the highest current 4.3 K quench. At 1.9 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 can also be measured from the initial dR/dt. Comparison is made between the velocities determined by the two methods in Fig. 3. For $v_q \leq 20$ m/s the two methods agree well; however for larger v_q the dR/dt method gives a systematically lower value. Since dR/dt also has a component due to resistivity growth with temperature, the velocity measurements are based only on the first 6-8 ms after the quench enters the cable segment adjacent to HA2. The Δt method, on the other hand, the velocity averaged over the time the quench front propagates between the two taps at the end of the 585 mm segment adjacent to HA2. For two quenches, with Δt velocities of 20 and 45 m/s, v_q ob-

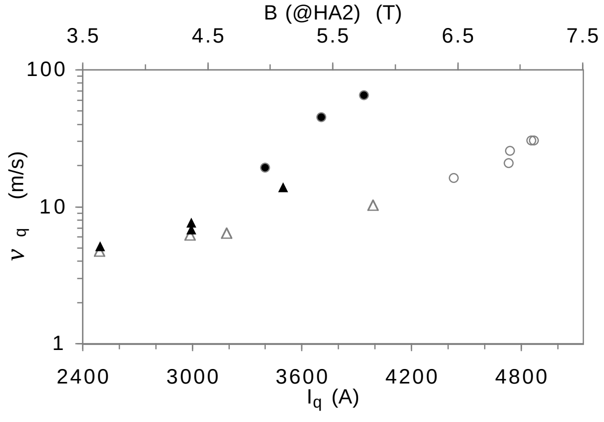

Figure 2: v_q vs. I_q for heater HA2 induced (triangles) and spontaneous (circles) quenches. Quenches at 4.3 (1.9) K are shown as filled (open) symbols.

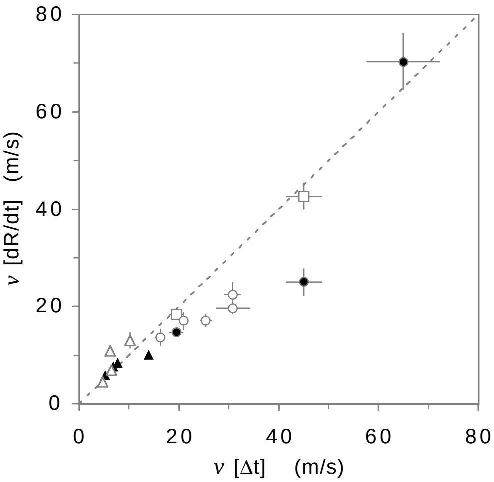

Figure 3: v_{q} measured by initial dR/dt vs that by $\Delta\mathrm{t}$ for heater HA2 induced (triangles) and natural(circles) quenches. Quenches at 4.3 (1.9) K are shown as filled (open) symbols. The open squares give the v_{q} measured by average dR/dt for the same quenches plotted directly below them.

tained on the basis of the average dR/dt were calculated, and are shown in Fig. 3. For the highest v_{q} point $\Delta\mathrm{t}$ is too short to measure initial and average dR/dt independently and the two calculations coincide. The velocities obtained from the average dR/dt agree at both low and high v_{q} with those from the $\Delta\mathrm{t}$ method. This strongly suggests there is an acceleration of the quench front, at least during the time interval covered by these data.

Figure 4 displays $\mathrm{T}_{\mathtt{peak}}$ vs. I_{q} for heater induced quenches at two operating temperatures. At 4.3 K, $\mathrm{T}_{\mathtt{peak}}$ has a maximum of about 250 K which occurs between 3000 and 3500 A, 70-80% of the estimated conductor limit. $\mathrm{T}_{\mathtt{peak}}$ is substantially higher at 1.9 K and no maximum is evident up to 4000 A. However, if the highest temperature occurs at 70-80% of the conductor limit, the 4000 A point is close to the maximum. Based on this consideration, it was deemed safe to train the magnet at 1.9 K.

To estimate $\mathrm{T}_{\mathtt{peak}}$ for spontaneous quenches, $\int \mathrm{I}^2\mathrm{dt}$ is computed and displayed in Fig. 5 for the heater induced and the spontaneous quenches. For the heater quenches, the pattern of $\int \mathrm{I}^2\mathrm{dt}$ and $\mathrm{T}_{\mathtt{peak}}$ vs I_{q} are similar, as expected. The induced and natural quenches follow similar trend in $\int \mathrm{I}^2\mathrm{dt}$ vs I_{q}. At 1.9 K, $\int \mathrm{I}^2\mathrm{dt}$ achieves a maximum near 4400 A, about 75% of the conductor limit, and decreases substantially at higher current. The $\mathrm{T}_{\mathtt{peak}}$ for the highest point is computed to be 465±40 K, where the error includes uncertainties in the start time of the integration and in the value of B at the quench location.

The coil resistance R(t) as a function of time and the energy deposited in the coil $\int \mathrm{I}^2\mathrm{Rdt}$ were computed. It was found that only about 0.1% of the stored energy was deposited in the bypass resistors, the rest being absorbed by the coil. Since the magnet absorbs its own energy safely, the protection resistors can be removed for subsequent tests.

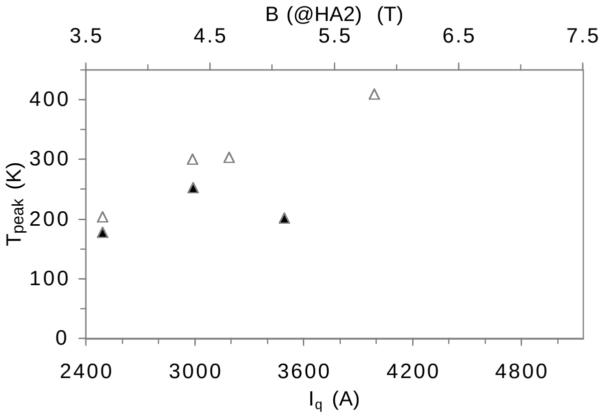

Figure 4: $\mathrm{T}_{\mathtt{peak}}$ vs. I_{q} for quenches induced by HA2. Quenches at 4.3 (1.9) K are shown as filled (open) symbols.

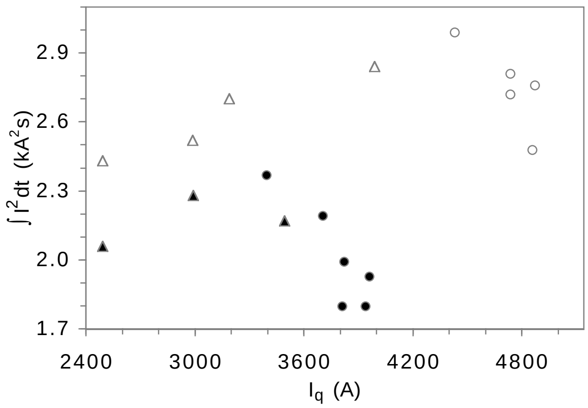

Figure 5: $\int \mathrm{I}^2\mathrm{dt}$ vs. I_{q} for spontaneous (circles) and heater HA2 induced (triangles) quenches. Quenches at 4.3 (1.9) K are shown as filled (open) symbols.

4 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. A further test of the magnet is planned in order to measure the field quality, examine the training behaviour following a thermal cycle, and collect additional data relevant for quench protection.

5 REFERENCES

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[2] G. A. Kirby et al., Proc. 4th European Particle Accelerator Conference, London, England, June 1994, pp 2271-2273

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