Fermi National Accelerator Laboratory

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LOW TEMPERATURE QUENCH PERFORMANCE OF FERMILAB LOW-β INSERTION QUADRUPOLES

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Abstract

The recently revived superconducting magnet program at Fermilab is currently focused on the development of high gradient quadrupoles for possible use in the Large Hadron Collider (LHC) interaction regions at CERN. In order to provide input for the new quadrupole design which will operate in superfluid helium, we have tested a Fermilab Tevatron low-β quadrupole cold mass and compared its low temperature performance to a newly assembled heavily instrumented version which was mechanically modified to take advantage of the gain in critical current.

1 INTRODUCTION

Fermilab has successfully operated low-β quadrupoles for the Tevatron D0/B0 interaction regions at an operating gradient of 141 T/m at 4.5 K. Future low-β insertions, in particular, the one proposed for the LHC[1], require a 50% higher operating field gradient. Fermilab in cooperation with Brookhaven National Laboratory (BNL) and Lawrence Berkeley National Laboratory (LBNL), is designing a higher gradient quadrupole suitable for the LHC low-β insertions which uses NbTi conductor in superfluid helium[2]. A first step in this program has been to evaluate the feasibility of using a mechanically modified version of the existing Fermilab low-β quadrupole for superfluid operation. We report on results from tests of two Fermilab-style superconducting high gradient quadrupoles.

2 MAGNET DESCRIPTION

The magnets for this study are 1.4 m long Tevatron low-β quadrupoles. Details of the design have been described elsewhere[3,4]. This cold iron superconducting quadrupole has a 2-shell, cos 2θ coil with a 76 mm aperture and an outer cold mass diameter of 276 mm. The inner and outer coils are made from 36 strand Rutherford cable. The strands are 0.528 mm in diameter and contain 13 μm filaments. There is a copper wedge in the inner coil whose primary purpose is to minimize the geometric 12- and 20-pole harmonics. Four inner to outer coil splices are located in the magnet lead end radially beyond the outer coil and are made through preformed solder-filled cable originating from the lead end pole turn. The coils are supported in the body by aluminum collars. The splice and the coil lead and return ends are clamped with a 4 piece G-10 collet assembly enclosed in a tapered cylindrical can. Iron yoke laminations surround the coil in the body region, and stainless steel laminations surround the end region cylindrical can. A welded stainless steel skin surrounds the yoke.

The two magnets differ in mechanical support and in instrumentation. One magnet (LBQ5425) was built as a spare for the Tevatron and as such has the nominal construction features and instrumentation for a production magnet. There are voltage taps across each quadrant (inner-outer coil pair). The aforementioned cylindrical end cans are made of stainless steel.

A finite element analysis mechanical model of the nominal production magnet at 1.8 K and full current excitation predicted inadequate coil support for both the body and the end regions[5]. Thus a second magnet (R54001) was built with the same tooling but with enhanced mechanical support. To increase the magnet end prestress at low temperature, the stainless steel end cans were replaced with aluminum cans. Kapton pole shims were inserted to increase the coil azimuthal prestress. These shims also increase the effective collar diameter to assure that there was an interference fit between the iron and collared coil. R54001 had several voltage taps in the inner coil concentrated near the pole turn and the copper wedge. Strain gauge transducers in the collars monitored changes in coil stress during manufacturing, cool down and excitation.

3 MAGNET TESTS

LBQ5425 was tested at the Lawrence Berkeley National Laboratory Magnet Test Facility in a horizontally oriented liquid helium dewar. The facility is designed to support superfluid helium at 1.8 K and at 1 atmosphere. R54001 was tested at the Fermilab Technical Support Section horizontal magnet test facility[6]. The test stand was originally designed to test SSC dipole cryostated cold masses at 4 atmospheres and temperatures from 4.6 K to 1.8 K. The outer diameter of our low-β quadrupole is roughly the same as an SSC dipole, thus we were able to build a special shorter length SSC-style cryostat to accommodate this magnet.

3.1 Magnet Training

Both magnets were first trained at 4.3 K prior to superfluid testing. This allows one to compare the training of these magnets with previous low-β quadrupoles[7] and to observe the change in magnet training between normal and superfluid helium. The training histories for LBQ5425 and R54001 are presented in Figures 1 and 2.

At 4.3 K LBQ5425 achieved 4700A on the first quench and required 4 quenches to reach its plateau of 5150 A. The magnet was warmed to room temperature and then cooled to 1.8 K. The first quench was above 6000 A, significantly higher than the 4.3 K plateau quenches. After two more training quenches, the quench current fell to near 5000 A and did not increase in the next 3 quenches. Two quenches (not shown) at 3.8 K yielded similar results. The magnet was then warmed to 4.3 K and quenched again at just above 5000 A. Finally, it was again cooled to 1.8 K and came within 100 amps of reaching its previous quench current maximum. The 5000 A quenches at 1.8 K, as well as the low quench at 4.3 K (#6 in Fig. 1), are likely due to insufficient coil support.

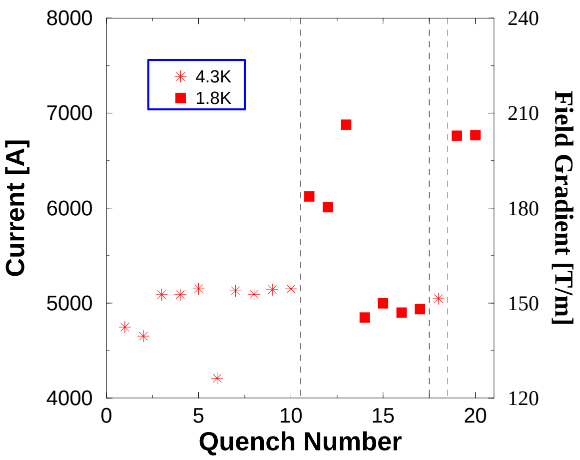

Figure 1: Quench training history for LBQ5425.

R54001, with enhanced mechanical structure, exhibited improved quench performance relative to LBQ5425, as seen in Fig. 2. At 4.3 K it came within 200 amps of its quench plateau in three quenches. The training quenches largely occurred within the pole turn return end. After 9 quenches, but before it reached its plateau, the magnet was cooled to 1.8 K. Here it exhibited significant training, but with monotonically increasing quench current. The training quenches occurred predominantly in the coil ends. After the 1.8 K testing

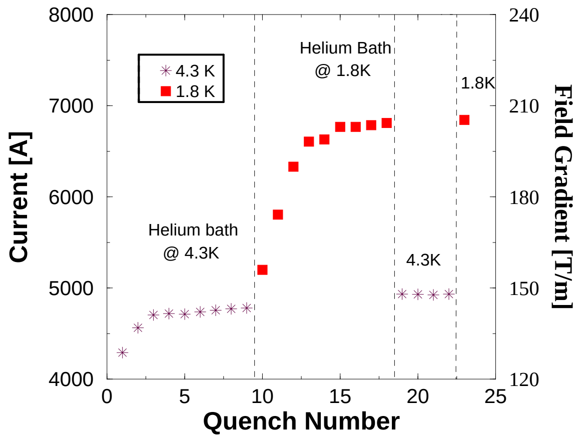

Figure 2: Quench training history for R54001.

the 4.3 K quench plateau was achieved. The plateau quenches occurred near the inner-outer coil splice.

3.2 Temperature Dependence of Quench Current

After 9 quenches at 1.8 K, R54001 was quenched at several temperatures between 1.8 K and 4.3 K as shown in Fig. 3. There was a monotonic decrease in quench current with increasing temperature as expected for a magnet which is not limited by mechanical instabilities. However, the shape of the quench current vs. temperature, particularly near the λ–point, is not as predicted by temperature dependence of the conductor critical current. The deviation of the observed temperature dependence from the theoretical prediction can be explained by resistive heating in the coil, which increases as the current rises. The change in the curve shape at temperatures less than 2.17 K is likely due to the improvement of the coil cooling condition in superfluid helium.

3.3 Ramp Rate Dependence of Quench Current

Figure 4 shows the dependence of the magnet quench current vs. the ramp rate for LBQ5425 and R54001. For both magnets, the quench current does not decrease with increased ramp rate up to 150 A/s. At higher ramp rates, cable heating due to AC losses decreases quench current. As above, we observed erratic quench behavior with LBQ5425 during these ramp rate tests.

Figure 5 shows the quench current normalized to the 16 A/s value vs. ramp rate for R54001 measured at 4.3 K in normal helium and at 1.8 K in superfluid helium. An improvement in the quench current at high ramp rate in superfluid helium is evident due to improved coil cooling conditions.

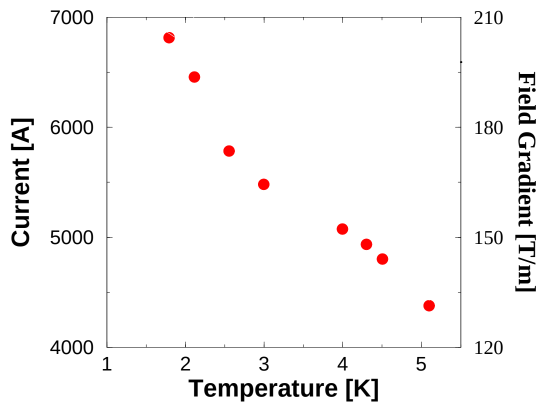

Figure 3: Quench current as a function of magnet temperature (nominal ramp rate of 16 A/s).

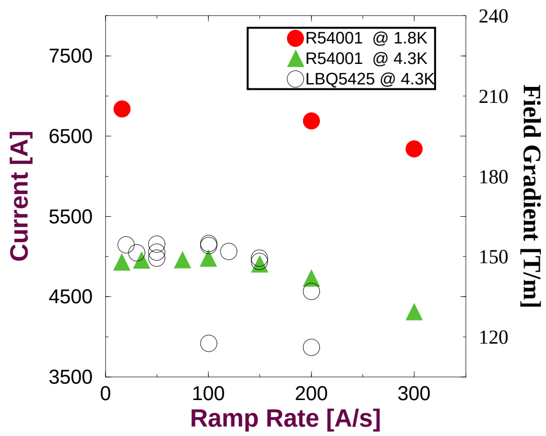

Figure 4: Quench current as a function of ramp rate. (Data were not taken at 1.8 K for LBQ5425.)

4 CONCLUSION

Two Fermilab low-β quadrupoles have been tested in superfluid helium. LBQ5425, a production spare for the Tevatron, reached 200 T/m gradient at 1.8 K but exhibited erratic quench behavior. R54001, a magnet from the same design but with improved coil mechanical support, also reached 200 T/m at 1.8 K and had significantly better quench behavior. Most quenches in R54001 above 1.9 K were generated by resistive coil heating. We also observed a significant improvement in the coil cooling condition and quench performance of this magnet in superfluid helium.

5 ACKNOWLEDGMENTS

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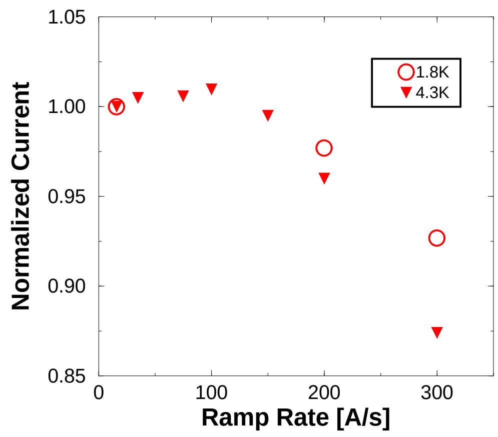

Figure 5: Magnet quench current normalized to the 16 A/s value vs. current ramp rate.

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