FERMILAB-CONF-09-328-TD

TESTING OF NB_3SN QUADRUPOLE COILS USING MAGNETIC MIRROR STRUCTURE

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ABSTRACT

This paper describes the design and parameters of a quadrupole mirror structure for testing the mechanical, thermal and quench performance of single shell-type superconducting quadrupole coils at field, current and force levels similar to that of real magnet. The concept was experimentally verified by testing two quadrupole coils, previously used in quadrupole models, in the developed mirror structure in the temperature range from 4.5 to 1.9 K. The coils were instrumented with voltage taps, heaters, and strain gauges to monitor their mechanical and thermal properties and quench performance. A new quadrupole coil made of improved Nb_3Sn RRP-108/127 strand and cable insulation based on E-glass tape was also tested using this structure. The fabrication and test results of the quadrupole mirror models are reported and discussed.

KEYWORDS: Quadrupole coil, magnetic mirror, magnet test.

INTRODUCTION

Fermilab is involved in the development of a new generation of accelerator magnets based on Nb_3Sn superconductor. The Nb_3Sn magnets will allow expanding the operation fields in accelerators above 10 T and increasing their operation margins. The development and implementation of this new technology involves fabrication and test of series of model magnets, coils and other components with various design and processing features, and structural materials. To provide an efficient way to test and optimize Nb_3Sn quadrupole coils for the US-LHC Accelerator Research Program (LARP) [1] a quadrupole magnetic mirror was developed at Fermilab based on the positive experience gained during Nb_3Sn dipole coil testing with a dipole mirror structure [2, 3]. This approach allowed testing individual coils at the operation conditions similar to that of real magnet, thus reducing the turnaround time of coil fabrication and evaluation, as well as material and labor costs. Long dipole mirror configurations were also successfully used for the Nb_3Sn coil technology scale-up [4, 5]. Implementation of the mirror configuration for a quadrupole magnet offers even greater benefits because of larger number of coils in quadrupoles with respect to dipole magnets.

This paper describes the magnetic and mechanical design of a quadrupole mirror structure for testing single shell-type superconducting quadrupole coils. The concept was experimentally verified by testing 90-mm Nb_3Sn quadrupole coils in the developed mirror structure in the temperature range of 1.9-4.5 K. The fabrication experience and test results of the quadrupole mirror models are reported and discussed.

MAGNETIC AND MECHANICAL DESIGN AND ANALYSIS

The proposed quadrupole mirror design is based on the mechanical structure of LARP technology quadrupole of TQC series [6] shown in Figure 1. Three coils, stainless steel collar blocks and preload control spacers were replaced by the magnetic mirror blocks and spacers (see Figure 2). This sub-assembly is installed in the standard TQC iron yoke and pre-compressed by a bolted stainless steel skin.

Several magnetic mirror configurations with various iron shape and distance to the coil were analyzed [7]. To provide better matching of magnet transfer functions and Lorentz force distribution in quadrupole mirror and complete quadrupole models the space between the iron mirror and the coil inner surface was reduced to 5 mm and the spacers were made of iron.

The inductance and stored energy of the quadrupole mirror magnet are ~1/4 of the full magnet values due to the proportionally smaller number of coils.

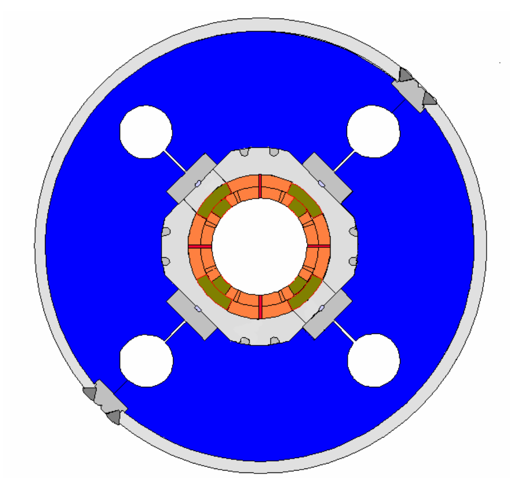

FIGURE 1. TQC quadrupole cross-section with 4 collared coils inside the iron yoke and SS skin.

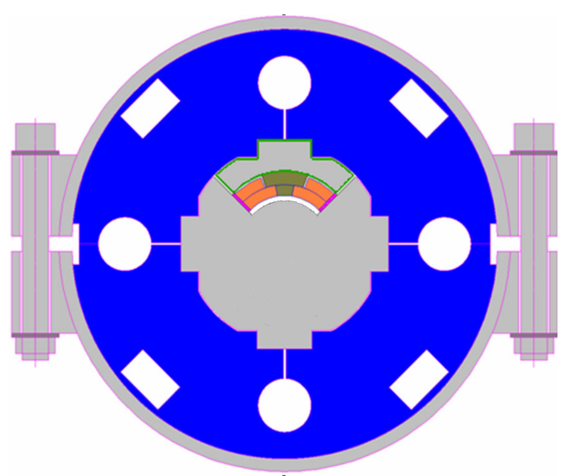

FIGURE 2. TQM quadrupole mirror cross-section with single 90-mm TQ coil inside the TQC iron yoke and bolted skin.

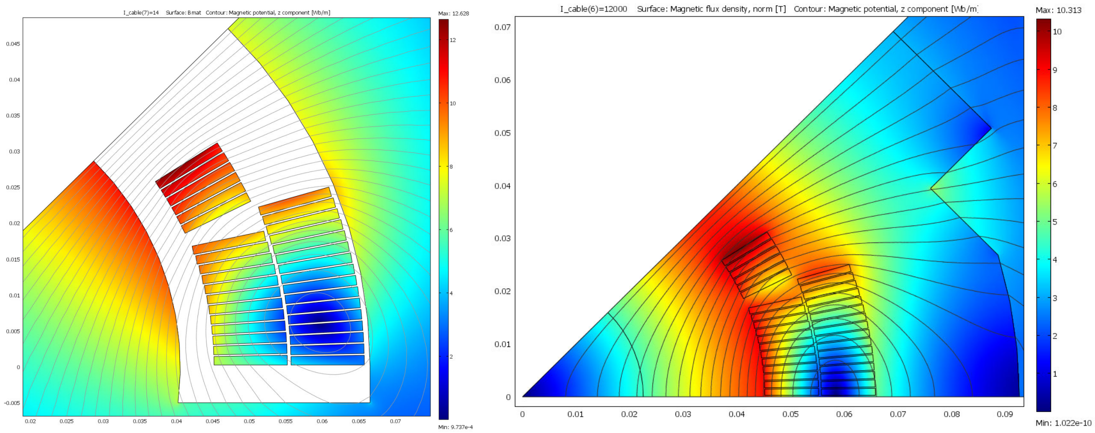

FIGURE 3. TQM (left) and TQC (right) cross-sections with flux distribution at 14 and 12 kA respectively.

Magnetic flux distribution at high current level in the coil inside the quadrupole mirror (left) and a TQC quadrupole model (right) is shown in Figure 3. In both configurations the maximum field in cross-section is reached in the inner-layer pole turns. While in general both distributions look quite similar, some small differences can be noticed in the coil midplane turns. As can be seen later on, these differences reduce the azimuthal component of Lorentz force and eddy current losses in the midplane turns in the mirror configuration.

The iron yoke in quadrupole mirror was extended over the coil ends, similar to TQC models and the magnetic mirror and upper spacer were of the same length as the iron yoke. For these reasons, the peak field point in the coil ends in the quadrupole mirror is reached in the pole turn of the outer layer. Figure 4 shows the ratio between the peak field in the end and in the straight section as function of the magnet current. This ratio is not constant because of the large iron saturation varying from 0.98 at 4 kA to 1.06 at 16 kA.

The generic short sample limits of the quadrupole mirror magnet was estimated based on the parameterization of critical current for Nb_3Sn superconductor [8] with the upper critical field of Bc20=26 T, Tc0=18 K and the reference critical current density Jc(12T,4.2K)=3000 A/mm^2. No stress/strain correction was applied. Figure 5 shows the TQ cable critical currents at 4.5 K and 1.9 K vs. magnetic field together with load lines of the TQM quadrupole mirror and a TQC quadrupole model related to the peak field in the straight section and the coil end. The estimated maximum currents of quadrupole mirror models with TQ coils are 13 kA and 14.5 kA at 4.5 and 1.9 K respectively.

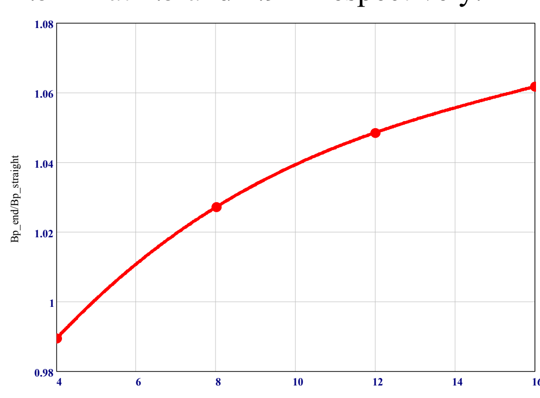

FIGURE 4. The ratio of the peak fields in the end and the straight section vs. the magnet current.

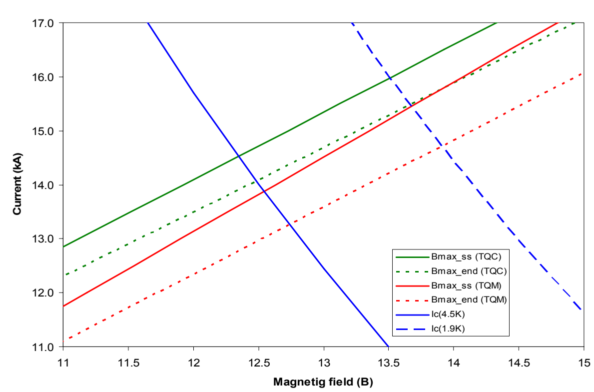

FIGURE 5. Cable critical current and magnet load lines for TQC and TQM models at 4.5 and 1.9K.

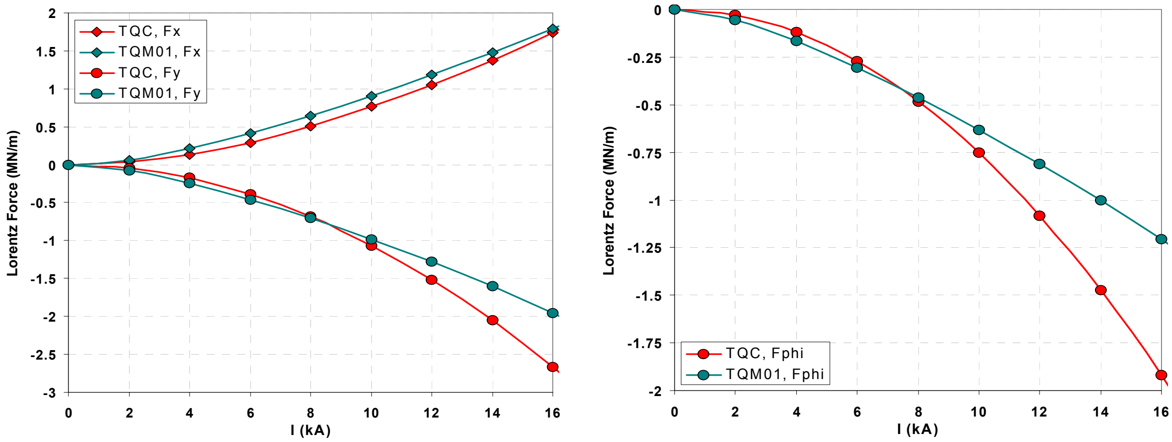

FIGURE 6. Horizontal and vertical Lorentz force components (left) and azimuthal Lorentz force component (right) in TQM and TQC as functions of magnet current.

The Lorentz forces in the TQM mirror and TQC quadrupole models vs. the magnet current are shown in Figure 6. The horizontal Lorentz force in the mirror is nearly the same as in the quadrupole magnet, while the vertical force at high currents is lower. The average azimuthal Lorentz forces in TQM and TQC are practically the same at currents below 8 kA. At maximum quench current the azimuthal Lorentz force in the mirror is ~30% lower than in the quadrupole model due to the different field distribution in the midplane turns in the mirror.

Stress distribution diagrams in the TQ coil in a mirror configuration calculated using ANSYS model at room temperature, after cooling down to 4.5 K and at the magnet current of 14 kA are shown in Figure 7. The maximum coil stress after assembly ~130 MPa allows keeping the coil under compression up to its ultimate short sample limit of ~14 kA. Due to the larger azimuthal length the coil inner layer is unloaded earlier than the outer layer. The maximum stress in the coil of ~160 MPa is reached after cooling down in the inner layer next to wedges and then moves towards the midplane turns at high currents.

TQM MIRROR MODEL ASSEMBLY AND INSTRUMENTATION

The assembly of mirror magnet starts with installation of iron mirror blocks into the lower yoke and thick stainless steel skin. The coil, wrapped with multilayer ground insulation, is then placed onto the mirror and the iron spacers, upper yoke blocks, and the upper skin installed. The coil ground insulation consists of 4 layers of 75-125 µm Kapton. Thick G10 spacers are added in the coil midplanes to accommodate coil size variations as well as special gauges and instrumentation (strip heaters, strain and temperature gauges, etc.).

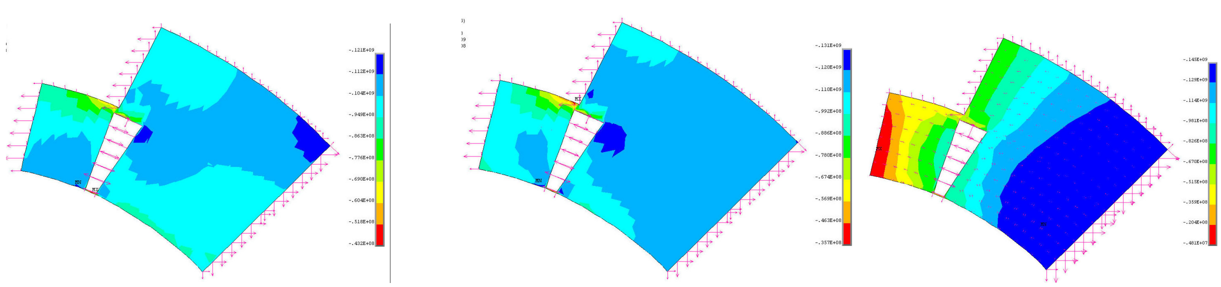

FIGURE 7. Coil stress in TQM at 300K after assembly, and after cooling down to 4.5K at current 0 and 14 kA.

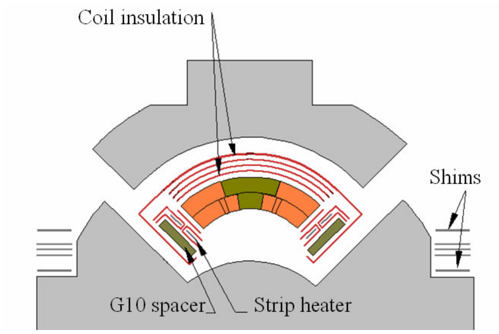

FIGURE 8. Coil assembly inside the mirror.

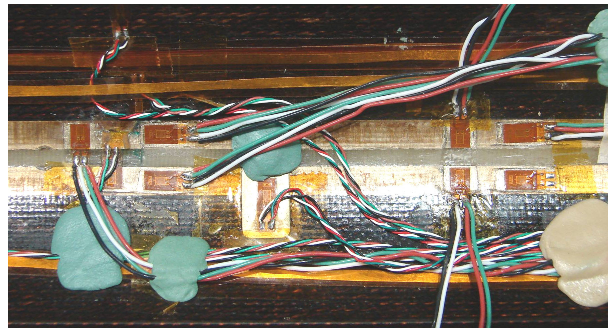
FIGURE 9. Coil instrumentation.

The coil assembly inside the mirror is shown in FIGURE 8. Skin halves are compressed in the press and bolted together. The compression is done in several steps, while stress in the coil is monitored by the gauges. Finally, the 50 mm thick end plates are bolted to the skin ends. Transverse coil preload and support is provided by stainless steel skin. Axial preload and support is provided through end bolts in the end plates. To control the coil azimuthal stress during assembly and operation, resistive strain gauges are used. In the body, resistive strain gauges are glued to the inside surface of the impregnated coil near the pole and next to the midplane. Resistive gauges are also mounted on the inner surface of inner pole blocks. The general position of the gauges is shown in FIGURE 9. The axial coil preload and longitudinal Lorentz forces are controlled through the resistive gauges installed on the end bolts.

Quench origin and development in the coil is monitored by voltage taps soldered to coil turns in the inner and outer layer, and coil leads. A special quench antenna placed in the gap between the coil inner surface and iron mirror blocks independently registers quenches in the coil in the axial direction.

Three quadrupole mirror models, TQM, have been fabricated and tested in January-June 2009. The first two models, TQM01 and TQM02, used TQ coils previously tested in TQC quadrupole models [9]. The primary goal of these tests was to verify the quadrupole mirror design concept and assembly procedure, and compare coil quench performance in the quadrupole mirror with TQ models. TQM02 was also equipped with midplane strip heaters to study Nb_3Sn coil thermal performance. The results of these studies are reported elsewhere [10]. The third mirror model TQM03 was assembled with a new TQ coil made of improved Nb_3Sn RRP strand of 108/127 design [11]. The cable was fabricated using Fermilab's cabling machine [12] and insulated with E-glass tape using standard cable insulating technique. The acceptable performance of this insulation for Nb_3Sn coils was confirmed previously by ten-stack sample tests [13]. The baseline TQ coil design is described in [14], the specific features of the coils used in TQM01-03 are summarized in Table 1. All three mirror models were assembled with the same coil target prestress of ~120 MPa at room temperature and the final cold peak prestress of ~100 MPa after cooling down. This was provided by the specific size of vertical shims based on measured coil sizes.

TABLE 1. Coil specific design features.

Mirror	Coil #	Strand	Cable	Cable insulation	Coil poles	Coil test history
TQM01	#19	RRP-54/61	LBNL	S2-glass sleeve	Bronze	TQC02a, TQC02b
TQM02	#17	RRP-54/61	LBNL	S2-glass sleeve	Bronze	TQC02a, TQC02b
TQM03	#34	RRP-108/127	Fermilab	E-glass tape	Titanium	None

TEST RESULTS AND DISCUSSION

Quadrupole mirror models TQM01, TQM02 and TQM03 were tested in liquid helium in the Vertical Magnet Test Facility at Fermilab. The standard test plan for all the magnets included training and ramp rate dependence measurement at 4.5K and 1.9K, temperature dependence studies, and coil RRR evaluation.

The primary goal of TQM01 was to test the mirror design and compare the TQ coil quench performance in the mirror and quadrupole models. FIGURE 10 shows the training (left) and ramp rate (right) curves at 4.5K for mirror TQM01 and quadrupoles TQC02E and TQS02a. All the models used regular TQ coils made of RRP-54/61 Nb_3Sn strand with the only difference that the poles in coil #19 tested in TQM01 were bronze whereas the coils used in TQC02E and TQS02a had Ti poles. One can see an excellent consistency of coil training in the mirror and in the quadrupole models. Notice that the coil with bronze poles demonstrated the same quench performance as the coils with Ti poles.

The ramp rate sensitivity of coil quench current after training in the mirror and quadrupole models is similar only at low current ramp rates (dI/dt<100 A/s) when in both models quenches started in the pole turns. At higher ramp rates, the quench origin in quadrupole models moves to the midplane turns whereas in the mirror model it stays in the pole turns due to the lower AC losses and better cooling of coil midplane turns in the mirror structure.

All quenches near the current plateau in TQM01 were located in the coil outer layer where the field is highest for this configuration. This fact, as well as the ramp rate dependence, confirms that the magnet reached its conductor limit. The maximum quench current of coil #19 in TQM01 was above 95% of its short sample limit (SSL) calculated based on "reference" conductor parameters. Based on witness sample data TQM01 reached ~99% of its SSL.

During TQM01 training at 4.5K, a current leak developed between one quench protection heater and ground. During the first quench at 1.9K a dead short between coil and ground has occurred, resulting in coil damage and discontinuation of the test. Nevertheless, this first quadrupole mirror test confirmed the soundness of the mirror design and its high technical and economical efficiency for single quadrupole coil testing.

The global goals of this mirror series were to studies the quench performance of regular TQ coils at 4.5 and 1.9 K including "flux jump" instabilities observed previously during the TQ model test at 1.9 K [9], evaluation of the temperature margin of Nb_3Sn quadrupole coils with respect to the heat deposition in the coil midplane turns, and test of a new TQ coil made of the more stable RRP-108/127 strand and modified cable insulation based on E-glass tape.

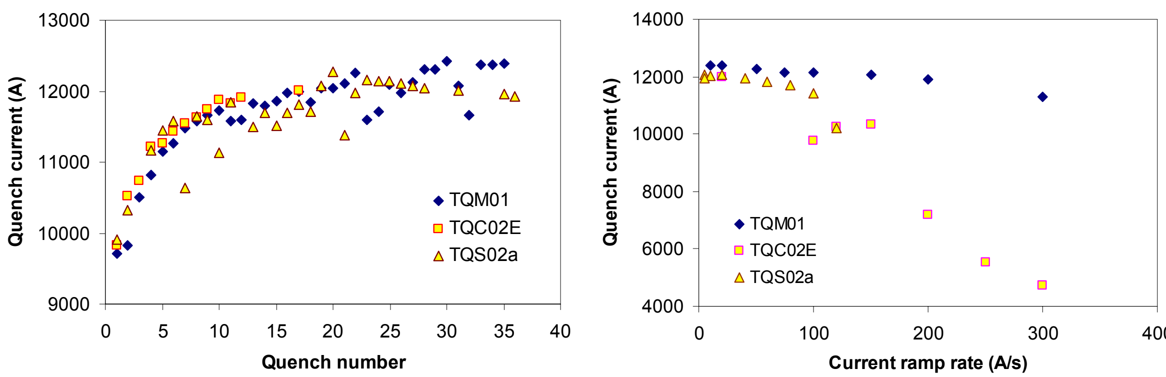

FIGURE 10. Comparison with TQ model training (right) TQM quench current vs. current ramp rate at various temperatures (left) and TQM and TQ ramp rate dependence comparison at 4.5 K.

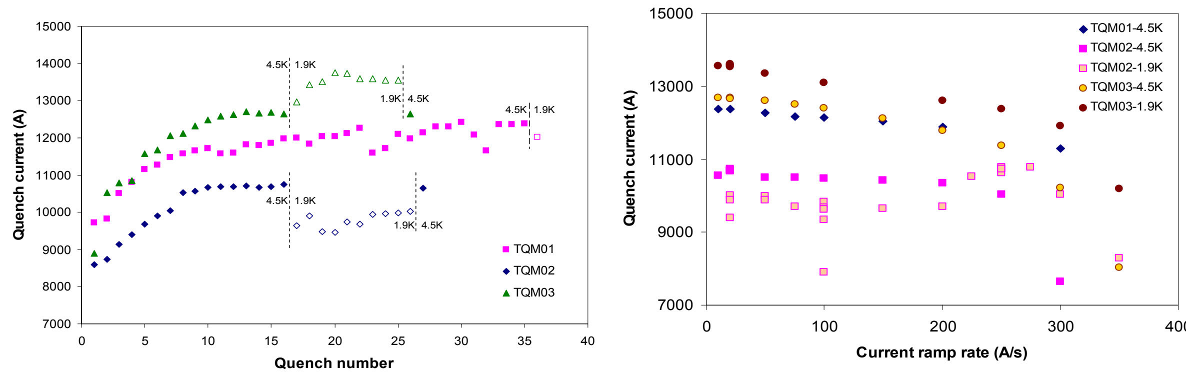

FIGURE 11. TQM01-03 magnet training (left) and the ramp rate sensitivity (right) at 4.5 and 1.9 K.

The results of TQM01-03 training and ramp rate sensitivity measurements at 4.5 and 1.9 K are shown in FIGURE 11. At 4.5 K all three models show standard training behavior with some variations of the first quench current, the number of training quenches and the maximum quench current. The ramp rate dependences for all the three tested coils are also typical.

At 1.9 K the regular TQ coils made of RRP-54/61 strand show some reduction of quench current and an erratic quench behavior. The erratic quench behavior is also observed in the ramp rate measurements at the low current ramp rates. One can see also some unusual increase of the quench current at ramp rates within 200-275 A/s. Meanwhile, the new coil made of more stable RRP-108/127 strand shows the expected increase of quench current and regular ramp rate dependence at 1.9 K. After short training this coil reached 98-99% of its SSL based on the witness sample data.

The observed quench training and ramp rate behavior of TQM01 and TQM02 with the regular TQ coils made of RRP-54/61 strand is consistent with the effect of “flux jump” instabilities on magnet performance [15]. This is also confirmed by the temperature dependence measurements performed in the temperature range of 1.9-4.5 K for TQM02 and TQM03. The results are summarized in FIGURE 12. One can see that TQM02 shows an unstable quench behavior at temperatures below 2.5-3 K. The temperature of transition to the unstable range reduces with the increase of current ramp rate. On the contrary, TQM03 shows stable quench performance at all tested temperatures.

CONCLUSIONS

A quadrupole mirror structure to test single quadrupole coils has been developed and successfully tested. This structure allows testing shell-type quadrupole coils with inner radius

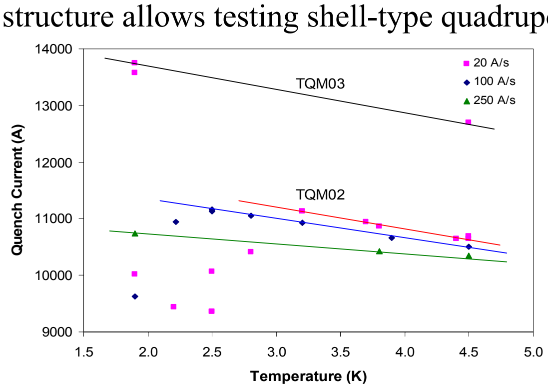

FIGURE 12. TQM02 and TQM03 quench current vs. helium bath temperatures.

larger than 45 mm and outer radius smaller than 90 mm, including LARP 90-mm and 120-mm coils. Two mirror models have been assembled and tested using regular LARP TQ coils previously tested in TQ quadrupole models. These tests demonstrated high efficiency and consistent technical parameters confirming the soundness of this approach. The coil quench performance in the mirror structure was similar to that of TQ quadrupole models.

The effect of flux jumps on the quench performance of TQ coils made of Nb_3Sn RRP-54/61 strand at low temperatures has been confirmed. A new TQ coil made of the optimized Nb_3Sn RRP-108/127 strand and new cable insulation was also tested demonstrating consistent quench performance and improved stability with respect to flux jumps at both 1.9 and 4.5 K. The next tests will include 90-mm TQ coils made of Nb_3Sn cable with SS core, advanced Nb_3Sn strands and coil impregnation materials. The 120-mm HQ coils and 4-m long LARP quadrupole coils will be also tested using the developed quadrupole mirror structure.

AKNOWLEDGMENTS

This work was supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy. The authors thank technical staff of Fermilab's Technical Division for their contributions to magnet fabrication and test.

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