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FABRICATION AND TEST OF 4M LONG Nb_3SN QUADRUPOLE COIL MADE OF RRP-114/127 STRAND

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ABSTRACT

Fermilab is collaborating with LBNL and BNL (US-LARP collaboration) to develop a large-aperture Nb_3Sn superconducting quadrupole for the Large Hadron Collider (LHC) luminosity upgrade. Several two-layer quadrupole models of the 1-meter and 3.4-meter length with 90mm apertures have been fabricated and tested by the US-LARP collaboration. High-Jc RRP-54/61 strand was used for nearly all models. Large flux jumps typical for this strand due to the large sub-element diameter limited magnet quench performance at temperatures below 2.5-3K. This paper summarizes the fabrication and test by Fermilab of LQM01, a long quadrupole coil test structure (quadrupole mirror) with the first 3.4m quadrupole coil made of more stable RRP-114/127 strand. The coil and structure are fully instrumented with voltage taps, full bridge strain gauges and strip heaters to monitor preload, thermal properties and quench behavior. Measurements during fabrication are reported, including preload during the yoke welding process. Testing is done at 4.5K, 1.9K and a range of intermediate temperatures. The test results include magnet strain and quench performance during training, as well as quench studies of current ramp rate and temperature dependence from 1.9K to 4.5K.

KEYWORDS: Quadrupole coil, magnetic mirror, magnet test.

INTRODUCTION

A new generation of accelerator magnets is being developed based on Nb_3Sn conductor. One application of this technology is a planned upgrade of the interaction regions of the Large Hadron Collider (LHC), and is being pursued by the US-LHC

Accelerator Research program (LARP) [1]. Current developments of the cable and strand fabrication is a primary component of the research [2-3]. A series of short and long model quadrupoles have been built and tested containing various types of Nb3Sn conductor [4-7].

An efficient way to optimize coils is to test them individually in a magnetic mirror structure. This approach allows individual coils of various materials and features to be tested under conditions similar to those of real magnets. Since only one coil is tested at a time, fabrication costs and turnaround time is significantly decreased. This is particularly valuable for quadrupoles, where four coils are needed for a magnet. Several short (1 meter) coils have been previously tested in mirrors [8-9]. This paper describes the construction and testing of LQM01, a mirror containing the first long (3.4 meter) coil made of RRP-114/127 strand, a smaller filament strand having greater stability than the previous standard of RRP-54/61 and therefore expected to reach higher currents at 1.9K.

STRUCTURE

The traditional mirror structure used for 1-meter models is shown on the left in FIGURE 1. It consists of a coil, two solid steel upper and lower mirror blocks, a laminated iron yoke, and a bolt-on stainless steel skin. The magnetic flux distribution is similar to that of regular quadrupoles and is described in [8]. Preload is applied by a series of shims applied radially and azimuthally to the coil, and to the upper surface of the side "ears" on the lower mirror block.

The structure used for LQM01 is shown on the right side of FIGURE 1. It is identical to that used for short models, except that the skin is welded rather than bolted. The welded skin is the traditional method used for production cold masses, but is usually replaced by the bolted skin for test models because the bolted skin is reusable and easier to fabricate, and because a welded pressure vessel is not necessary for test models which do not need cryostats. However, the welded skin was used on LQM01 because tooling constraints limit the bolted skin to a maximum length of 2 meters.

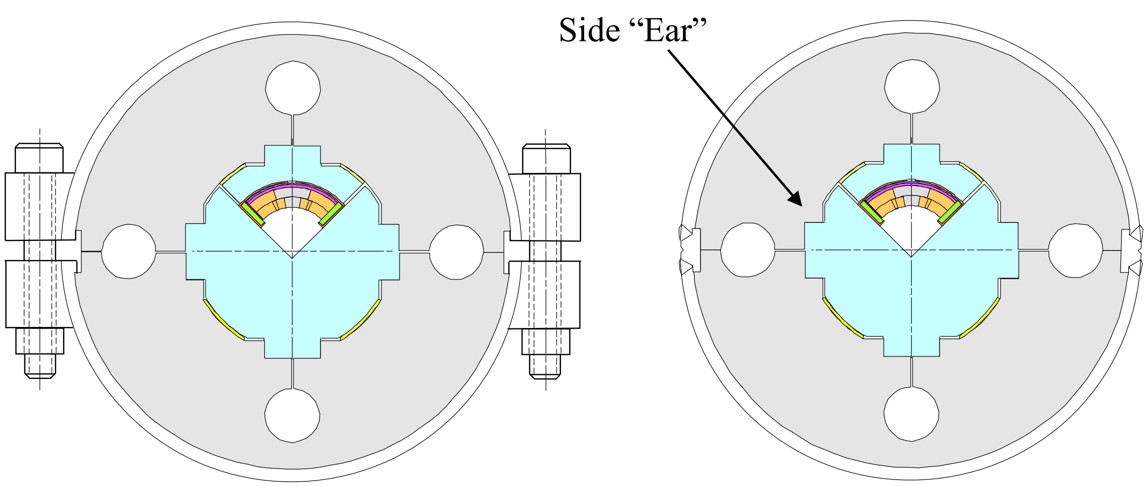


FIGURE 1. Traditional mirror structure with bolt-on skin (left) and LQM01 structure with welded skin (right).

CONSTRUCTION

Cable Insulation

The cable in LQM01 was insulated with two layers of 75um e-glass tape, as shown in FIGURE 2. This is the first long Nb3Sn coil that has been insulated exclusively with e-glass. One previous 1-m long mirror has been insulated with this system. The coil fabrication process is discussed in [10].

Instrumentation

Quench positions were determined by voltage taps and a quench antennae. The inner layer of LQM01 was instrumented with nine taps on the pole turn and 2 in the multiturn area, with the outer layer including 4 taps on the pole turn and 1 mulititurn tap. Taps were also placed at each end of both lead splices.

Strain gauges were placed on the inner surface of the inner layer to measure preload. An array of gauges as shown in FIGURE 3 was placed at two different positions. Gauges included both azimuthal and longitudinal full bridges and azimuthal quarter bridges on the titanium pole. Single gauges were also bonded to the inner surface near the pole and midplane to verify azimuthal preload during construction. Gauges bonded directly to the coil surface are not used after cooldown due to uncertainty with regard to cold calibration of these gauges. Quench protection heaters were placed on the outer surface of the outer coil.

Shim System

During assembly, the coil is surrounded by kapton® sheets to prevent shorts to ground. The amount and thickness of kapton is adjusted to achieve the desired preload at room temperature. Before magnet assembly, the coil cross section size is measured in the free state on a coordinate measuring machine. The measured size is used to determine the amount of midplane shim, based on previous experience and finite element analysis.
Shims are also placed on the horizontal surface of the side "ears" (called side shims) as shown in FIGURE 4. These shims have two purposes. They are easy to adjust during assembly, so can be used to make preload adjustments during the pressing operation. Also, they are used to control the preload change during cooldown. Traditionally, the hydraulic pressure is increased until the shims are contacted and the desired preload is verified by the strain gauges placed on the inner surface of the coil. Contact is assumed when the coil azimuthal stress ceases to increase with increased press pressure. Then the press is released, a specified amount of shim is removed, and the final pressing is done. During the final pressing, the pressure is stopped when the strain gauges reach the same level that they had when contact was previously made with the shims. This leaves an open area (where the shims were removed) into which the structure contracts during cooldown, increasing

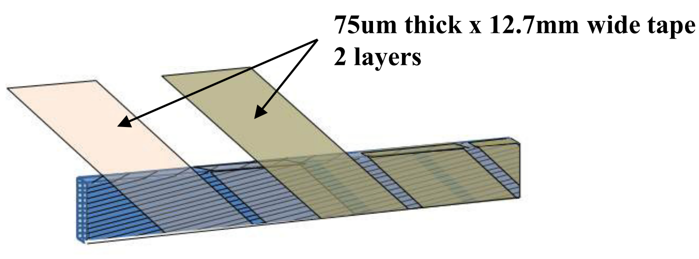
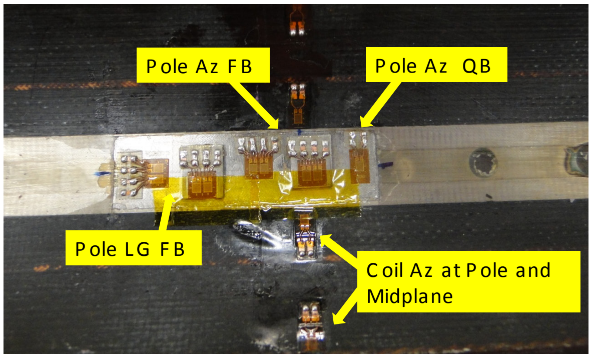


FIGURE 2. Cable insulation system used for LQM01.



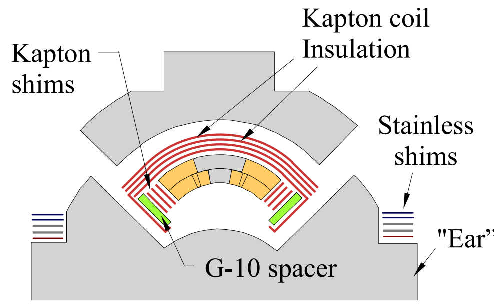


FIGURE 3. Strain gauge placement on inside surface of coil

FIGURE 4 LQM01 Shim System

the preload. Analysis shows that if no open area is left, preload will decrease during cooldown by about 50 MPa. Depending on the amount of open space, the structure can be configured to achieve any warm-cold change between a decrease of 50 MPa and an increase of 50 MPa. 1-meter mirrors have been constructed to achieve anywhere from no change to an increase of 50 MPa.

For the bolt-on assembly, the vertical force is controlled by the hydraulic press. Since LQM01 was the first mirror to be made by welded construction, the ability to control the vertical force during the weld process was not as certain. The press was therefore closed on the side shim, which allowed for a positive stop to close upon, eliminating the uncertainty, but left no space for contraction during cooldown. This meant that a preload decrease of 50 MPa was expected, so the warm preload needed to be 150 MPa, to achieve the desired cold preload of 100 MPa.

Application of Preload

Preload to LQM01 was applied in a full-length hydraulic press, while reading strain gauges on the coil surface and outer skin. Horizontal welds were then made with press pressure applied. FIGURE 5 shows the preloads read by the strain gauges mounted to the coil inner pole during pressing. Two individual pressings took place, first with 400 um (16 mil) “side” shims to verify the expected pressure/shim ratio, then the final pressing with 225 um (9 mil) side shims. Finally the yoke was welded in the press while closed on the 225 um shim.

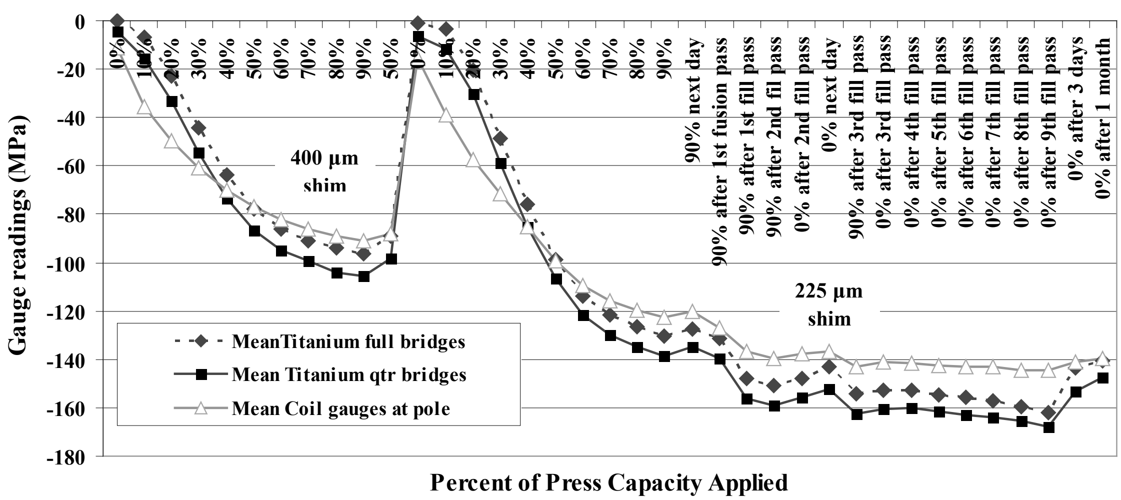


FIGURE 5. LQM01azimuthal preloads during pressing. Horizontal axis denotes % of press capacity, where full press capacity is 3500 KN per linear meter.

Although the goal was 150 MPa, average preloads during the welding process reached 165 MPa in the inner pole, with some individual gauges exceeding 170 MPa.. After some stress relaxation, the magnet was delivered for testing with an average of about 145 MPa at the inner pole.

TEST RESULTS AND DISCUSSION

Cooldown

Strain gauge readings are shown in TABLE 1. During cooldown, strain gauges mounted to titanium showed an apparent large preload loss, far in excess of the expected 50 MPa, even extending into tension. Nevertheless, these gauges showed continued decrease in preload with excitation, indicating that preload did exist after cooldown. Although the reasons are not yet completely understood, this effect may be due to bending, and does not appear to affect coil performance. Similar strain gauge effects have been seen in 1-meter mirrors with bolt-on skin. This phenomena is currently being studied.

Gauges mounted to the outside shell (skin) show the expected strain increase during cooldown.

Quench Training

The training quenches of LQM01 in two test cycles are shown in Fig. 6. At 4.6 K, LQM01 reached 13.1 kA which is 100% of its short sample limit (SSL) based on witness sample data. LQ coil made of RRP 108/127 Nb3Sn strand showed good stability and an expected increase of quench current at 1.9 K. At the end of 1.9 K training LQM01 reached a current of 14.5 kA or 99% of its SSL at this temperature.

LQM01 showed good training memory and without any training reached 100% of its SSL at 4.6 K in the 2nd thermal cycle. A small amount of training was observed at 1.9 K. Note that the coil performed well despite high preload during assembly, suggesting that large warm preloads can be accepted during construction.

A thorough discussion of the test results of LQM01 is given in [11].

TABLE 1. Strain gauge readings of gauges on titanium pole at room temperature and after cooldown.

Gauge	At Room Temperature	At 4.6K
Azimuthal Full Bridge Average	-143 MPa	Not Available
Longitudinal Full Bridge Average	-13 MPa	-80 MPa
Azimuthal Quarter Bridge Average	-152 MPa	Not Available
Azimuthal Pole Coil Gauge Average	-141 MPa	Not Available
Shell (skin) azimuthal Average (at 60 degrees from horizontal)	396 MPa	575 MPa

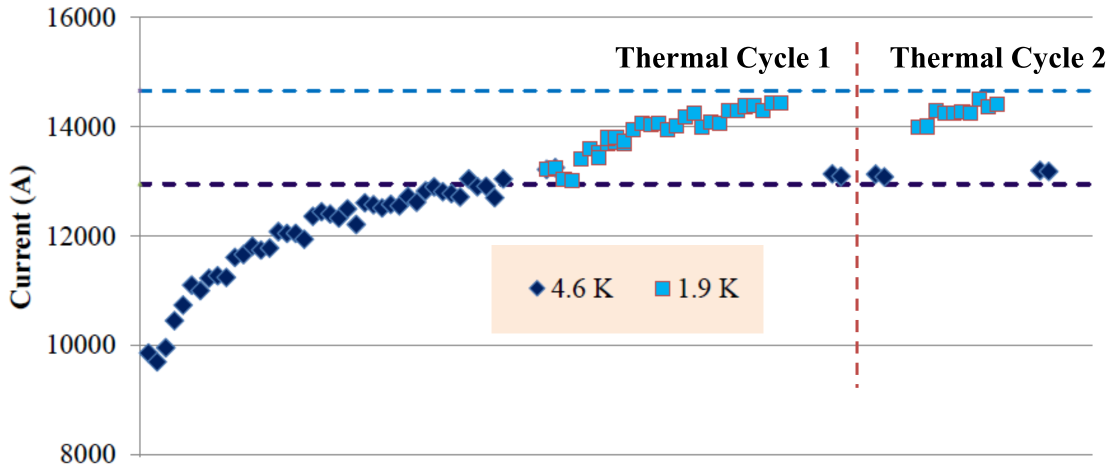


FIGURE 6. LQM01 Training quenches in 2 test cycles. SSL at 4.6 K and 1.9 K also are shown.

Quench Locations

Quench locations during training occurred primarily in the central region of the pole turn of the inner layer until plateau was reached. After that, quenches were located in the end region of the pole-turn segments of the inner layer (the high field region). To determine the locality of the quenches, the magnet was instrumented with a quench antenna (see FIGURE 7). 12 circuit-boards used in this antenna covered the straight section of the magnet pole.

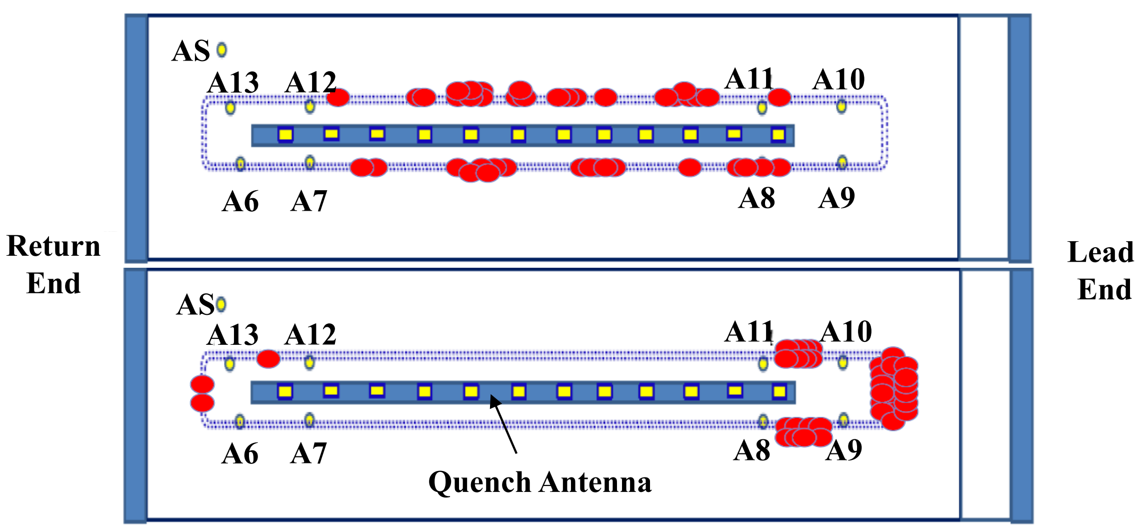


FIGURE 7. Solid (red) dots represent quench positions during training (at top) and after plateau has been reached (bottom). Open (yellow) dots show the position of voltage taps and open (yellow) squares the position of quench antennae circuit boards.

Magnet Ramp Rate and Temperature Dependence

The ramp rate dependence in LQM01 was similar to that in previous mirrors with coils made of RRP 108/127 cable. Ramp rate dependence for LQM01 and TQM03 (a previous one-meter mirror containing 108/127 cable) is compared in Fig. 8.

The quench current dependence on magnet temperature was measured throughout the range of 1.9 - 4.6 K and at two different ramp rates, 20 A/s and 100 A/s. The results are presented in FIGURE 9. For comparison, temperature dependence is also shown for long quadrupole magnet (LQS01b) [7] with coils made of RRP 54/61 Nb3Sn strand.

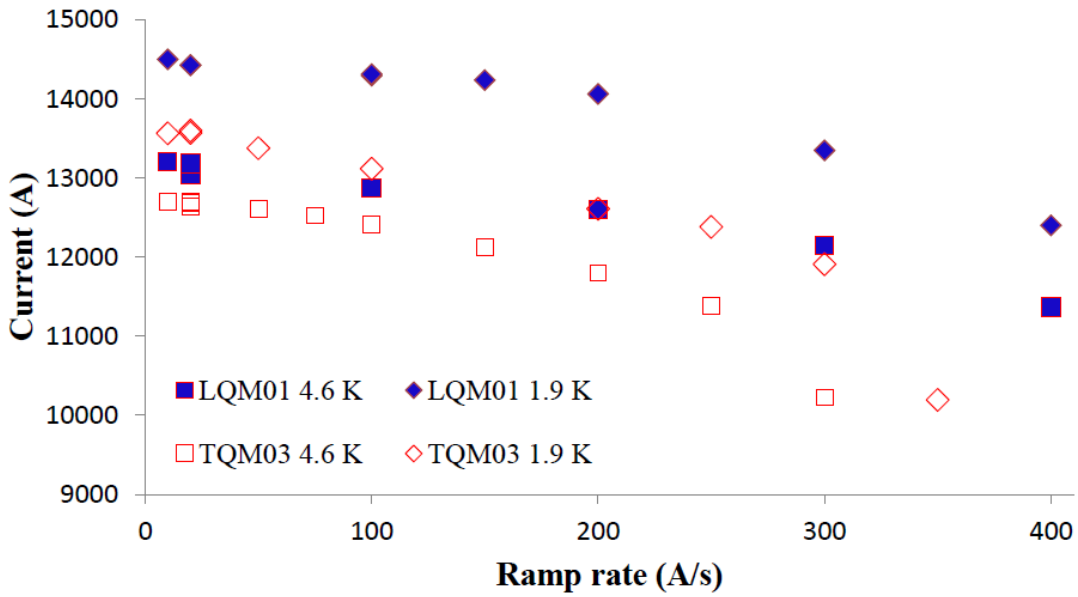


FIGURE 8. Ramp Rate dependence of LQM01

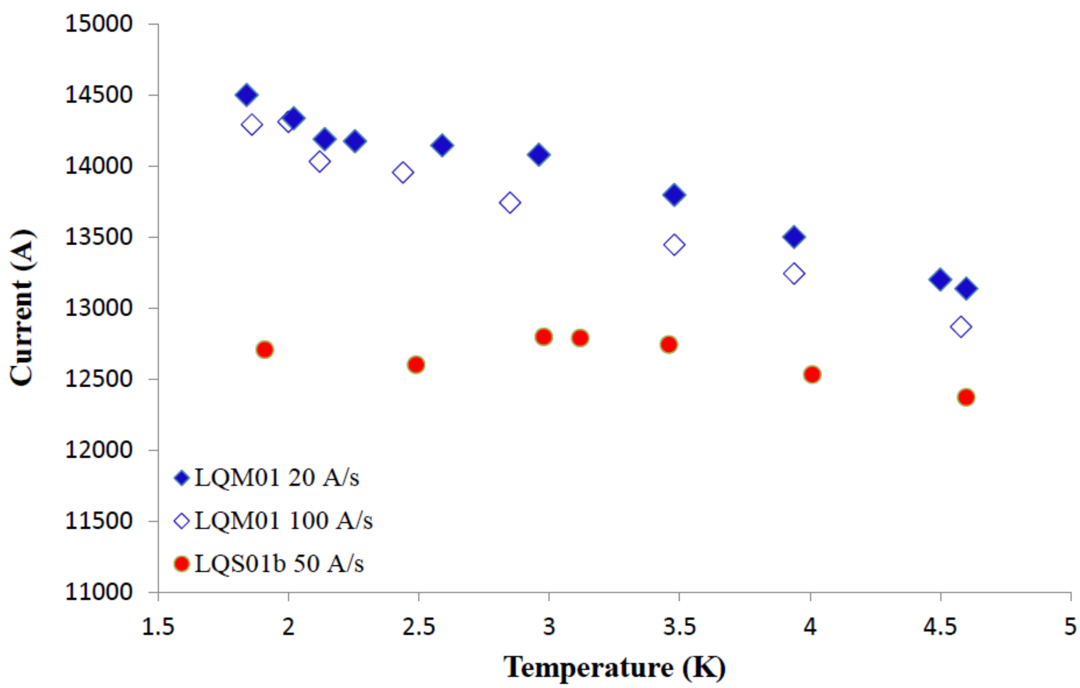


FIGURE 9. Temperature dependence of LQM01

CONCLUSIONS

The first quadrupole coil made of smaller-filament RRP-114/127 strand has been successfully tested in a mirror structure. This test demonstrates that the smaller filament strand can achieve higher currents and increased stability in long coils. It also demonstrates the viability of the mirror structure to test individual long coils efficiently.

ACKNOWLEDGEMENTS

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