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Test Results of the First Pre-Series Quadrupole Magnets for the LHC Hi-Lumi Upgrade

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Abstract— **The future high luminosity (Hi-Lumi) upgrade of the Large Hadron Collider (LHC) at CERN will include eight (plus two spares) 10.2 m-long Cryo-assemblies which will be components of the triplets for two LHC insertion regions. Each cold mass in the Cryo-assemblies will consist of two 4.2 m-long Nb_3Sn high gradient quadrupole magnets, designated MQXFA, with aperture 150 mm and operating gradient 132.2 T/m, for a total of twenty magnets. Before assembling and testing the final cold masses at Fermilab, the component quadrupoles are being tested first at the vertical superconducting magnet test facility of the Superconducting Magnet Division (SMD) at Brookhaven National Laboratory (BNL), in superfluid He at 1.9 K and up to 18.0 kA, in accordance with operational requirements of the LHC. The tests of the first two full-length prototype quadrupole magnets MQXFAP1 and MQXFAP2 at BNL have been reported previously. The first two pre-series magnets, the first two that will be used in the LHC, have also now been tested. This paper reports on the quench test and training results of these two magnets. The test results of these magnets will be important for validating the final MQXFA design for operational magnets.**

Index Terms—**AUP, Hi-Lumi, LHC, Nb_3Sn, superconducting magnets**

I. INTRODUCTION

The future high luminosity (Hi-Lumi) upgrade of the Large Hadron Collider (LHC) at CERN will include eight 8.4 m-long cryostatted cold masses (plus two spares) which will be components of the Q1 and Q3 elements of the triplets at two LHC insertion regions. Each cold mass will consist of two 4.2 m long (magnetic length) high gradient quadrupole magnets, with coils wound with Nb_3Sn cable and designated MQXFAxx, and with aperture 150 mm and nominal operating gradient 132.2 T/m. The fabrication and testing of these magnets are the combined effort of three US DOE laboratories: Brookhaven National Laboratory (BNL), Fermilab, and Lawrence Berkeley National Laboratory (LBNL), which together comprise the Accelerator Upgrade Project (AUP). Before assembling and testing the final cold masses at Fermilab, the component quadrupoles will be tested individually at the vertical superconducting magnet test facility of the Superconducting Magnet Division at BNL [1], in superfluid He at 1.9 K and 1 bar pressure, and up to 17.5 kA, in accordance with LHC operational requirements [2]-[3]. Lessons learned from extensive cold testing of two full-length prototypes [4] have resulted in the final magnet design for the twenty magnets to be sent to Fermilab for assembly into cold masses and cryo-assemblies. Testing of these magnets has begun at BNL to verify quench training to specified operating current, and training memory over thermal cycles, when the magnet is warmed up and then cooled down again. The first two pre-series models MQXFA03 and MQXFA04, destined for the first cryo-assembly to be fabricated at Fermilab and sent to CERN, have been tested at BNL, and the results of the quench training for these two tests are discussed here.

II. MAGNET DESCRIPTION

Fig. 1 shows the cross-section of the MQXFA design, with four 2-layer coils in the preloading structure. It should be noted that the stainless steel He containment vessel shown in the cross-section of Fig. 1 was not present during vertical testing; it will be installed at Fermilab when assembling the cold mass containing two quadrupoles. For MQXFA03, starting with the upper right quadrant in Fig. 1 and moving counterclockwise, the four coils are designated 204, 110, 202, and 111. For MQXFA04, the coils are 203, 113, 206, and 112. Unlike the prototypes, all coils are of final design and length, with the option of shimming for correction of the b6 harmonic.

The main parameters important for testing of the MQXFA quadrupoles are listed in Table I. Some of these parameters have changed since the tests of the prototypes [3]. As shown in the table, the nominal operating current was 16.470 A, and the ultimate current was 17.890 A, for a future upgrade of the HL-LHC. For the two tests reported here, maximum test current was I_{nom} + 200 A = 16.670 kA. But it should be noted that, by the end of the MQXFA04 test, the nominal and ultimate currents had been re-calculated to be lower, with the values as shown in

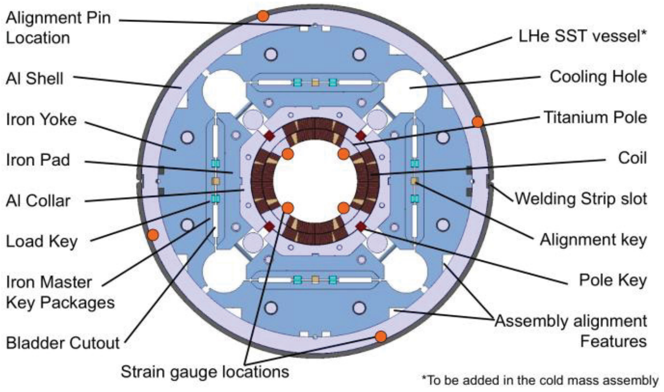

Fig. 1. MQXFA high gradient quadrupole cross-section.

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TABLE I
MQXFA DESIGN AND TEST PARAMETERS

Parameter	Value
Coil inner aperture:	150 mm
Coil magnetic length:	4.2 m
Coil length overall (RT):	4.532 m
Yoke length (RT):	4.565 m
Total assembly length w/end plates (RT):	5 m (nom)
Total assembly OD with Al shells (RT):	614 mm
Total assembly mass:	6850 kg (nom)
Operational temperature and pressure:	1.9 K and 1 bar
LHC nominal operating current (1.9 K):	16.470 kA (16.230 kA)
LHC ultimate operating current (1.9 K):	17.890 kA (17.500 kA)
Maximum test current I_{max}	16.670 kA
Maximum current at 300 K	15 A
Conductor (short sample) limit at 1.9 K:	21.24 kA
Conductor (short sample) limit at 4.5 K:	~20 kA
Nominal gradient (straight section):	132.6 T/m (132.2 T/m)
Nominal ramp rate:	20 A/s
Magnet resistance at 300 K	2.37 Ω
Magnet inductance (1.9 K, 1 kA):	43.0 mH
Magnet inductance (1.9 K, 16.470 kA):	34.4 mH
Maximum test stored energy (at I_{max})	4.78 MJ
Maximum allowed temperature at quench:	250 K ≈ 32 MIIts
Maximum allowed voltage across magnet:	625 V (313 V to ground)
Dump resistor (energy extraction) options:	30, 37.5, 50, 75, 150 mΩ
Data sampling rate:	10 – 100 MHz

parentheses in Table I. The initial values were estimates from earlier modeling calculations, using conservative assumptions. The new values are re-calculations using magnetic field measurements in short models and MQXFA03 [5]. Also, as seen, the maximum allowed hot spot temperature for training quenches is 250 K, and, for the conductor used in the final design coils, the corresponding quench integral ($\int I^2 dt$) value is about 32 MIIts.

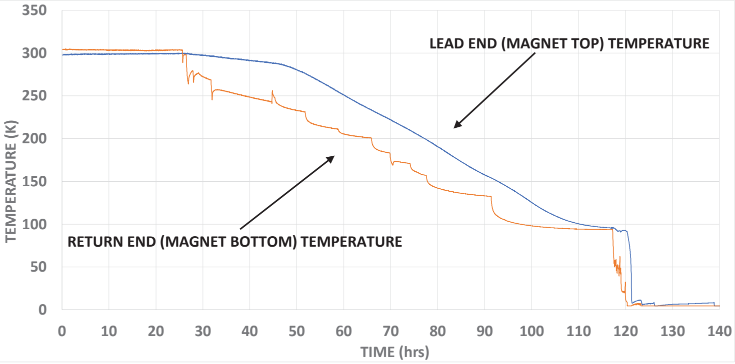

Fig. 2. Temperature plot of MQXFA04 second cooldown.

III. EXPERIMENTAL PARAMETERS, PROCEDURES, AND INSTRUMENTATION

Test parameters, test procedures, and magnet and test facility instrumentation for the pre-series and series models are mostly the same as for the testing of the prototypes, and details of these are described in [4]. Testing was done in a 6 m deep vertical test cryostat in 1.9 K superfluid He at 1 bar vapor pressure. Ramp rate for quench training was 20 A/s, and, for special tests such as ramp rate studies, was 14 – 100 A/s.

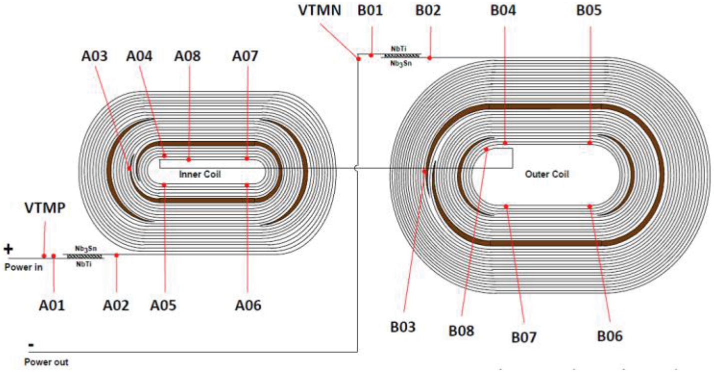

Fig. 3. MQXFA voltage tap configuration.

The cooldown procedure is described in [4], but for these tests, and all following tests in the AUP test program, there is an added requirement of a maximum allowed end-to-end temperature gradient of 50 K [3]. Test facility hardware and software upgrades were successfully implemented to achieve the required gradient or less during cooldown to 90 K and during warmup. With the requirement of 50 K maximum gradient, cooldown to 90 K using 80 K He gas takes about 115 hours. Further cooldown with liquid He to 4.5 K takes another 3 hours. Fig. 2 shows a plot of temperature data during the second cooldown (during the thermal cycle) of MQXFA04. Since the cold He gas is introduced at the bottom of the vertical test dewar, the magnet return end cools down at a higher rate than the lead end at top. Also, the return end temperature plot indicates the times when the program-controlled valves are operated to maintain the 50 K gradient and is therefore not smooth like the lead end plot.

Both magnets were instrumented with voltage taps, quench antennas, and strain gauges, among other devices [4]. Since this report is concerned with quench results only, the instrumentation most relevant to the present discussion are the voltage taps and quench antennas. Other testing operations and results are reported elsewhere [6] – [9]. The voltage tap configuration, which is the same as that used in the prototypes, is shown by a schematic in Fig. 3, which is important in understanding the quench test results to be shown here.

The quench antennas used in these tests are different than those used in the prototype tests [4]. For MQXFA03, the previous antenna was upgraded from 16 elements to 27 elements to increase axial resolution [8]. For MQXFA04, a new antenna, using a very different design with 123 elements, was designed to provide better axial and azimuthal data [9]. With this antenna, axial detection resolution was 50 mm over the central 3800 mm of the 4800 mm quench antenna active length, and 25 mm over 500 mm at each end. Upgrades to the data acquisition system had to be made to accommodate the addition of the many new data signals from the new antenna. Details of the data acquisition and quench detection systems can be found in [4] and [10].

Quench protection during testing was provided by the following systems and settings:

1) Energy Extraction using 37.5 mΩ dump resistance, and delayed by 10 ms, to decrease internal voltage during a quench;
2) Quench Protection Heaters (strip heaters) set at 465 V, 190 A, and 12.4 mF to achieve similar power density to that to be used in the HL-LHC, to quench all coils;
3) Coupling Loss Induced Quench (CLIQ) system [11], set to 500 V and 40 mF.

IV. QUENCH TRAINING RESULTS

A. MQXFA03 Results

For MQXFA03, the training history is plotted in Fig. 4, and it shows that the magnet reached the target maximum test current of 16.670 kA after 9 quenches. As can be seen in the plot, all quenches except the first were in Coil 111 and all were in the inner layer pole turn, as is expected for a nominally training magnet. As shown by voltage tap data (Fig. 4) and quench antenna data [8], the quench locations in Coil 111 were not at the same place and varied axially from end to end and azimuthally from side to side, as can be seen in the plot legend.

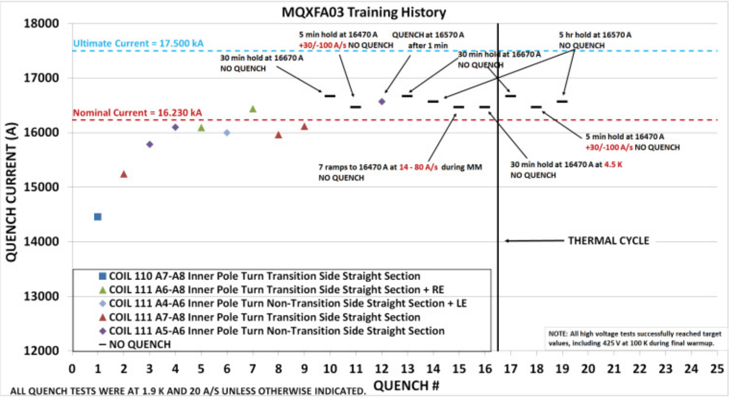

Fig. 4. MQXFA03 quench performance plot.

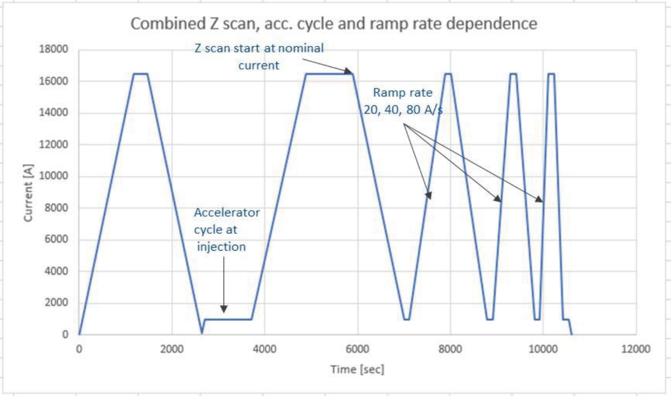

Fig. 5. Ramp rate study done during magnetic field measurements.

Ramp rates to the nominal current of 16.470 kA were varied from 14 – 100 A/s with no effect on quench performance. Fig. 5 shows a ramp rate study performed during magnetic measurement ramps. Also, during quench testing, the following acceptance specification ramp rate test was done before and after the thermal cycle: 30 A/s to 16.470 kA, 5 min hold, 100 A/s to 0. No quenches occurred during any of these ramps.

Also, to test temperature margin, a ramp at 4.5 K to the nominal current was reached without quench. After a thermal cycle, all ramps up to 16.670 kA were reached with no quenches. For all quenches, the quench integral in MIIts was ~26 (~175 K), which is well within the maximum allowed value of 32 (250 K). It should be noted that 12 voltage taps were lost during quench tests, with all but 2 in the inner layers of different coils, not just the quenching Coil 111 [7]. This behavior emphasizes the need for quench antennas for quench location during testing of the MQXFA magnets.

All room temperature and cold high voltage withstand target voltages [2] were met, with < 1.0 µA leakage currents. After final warmup, final electrical checkout of MQXFA03 showed no issues, and it has been accepted for installation in the first cold mass and cryo-assembly at Fermilab.

B. MQXFA04 Results

Fig. 6 shows the test results for MQXFA04. As can be seen, the magnet reached the maximum target current of 16.670 kA after only six quenches. All quenches except the fifth and seventh were in Coil 113, and all were in the inner layer. Since 15 inner layer voltage taps (in all coils, not just the quenching Coil 113) were lost during the first 3 quenches (10 during the first quench), it was not possible to positively locate most of the quenches to be in the pole turn (as was the case for all quenches in MQXFA03). The new quench antenna [9] was used for the first time in MQXFA04 and was able to show that, as in MQXFA03, the axial locations varied from end to end. Azimuthal location data from the quench antenna was being analyzed to determine which turns quenched but this was not yet finished as of this writing.

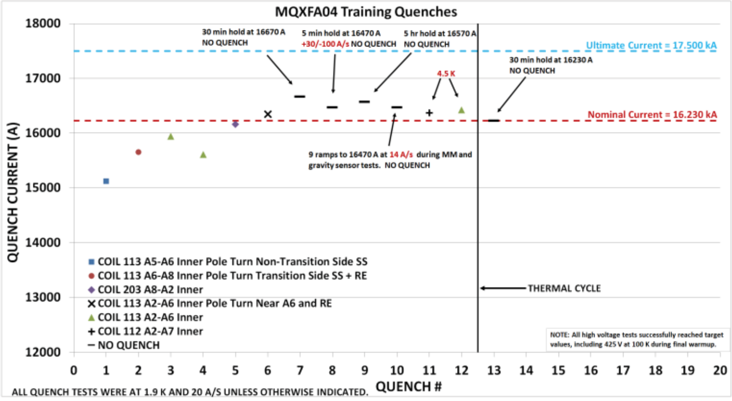

Fig. 6. MQXFA04 quench performance plot.

Ramp rates were varied from 14 – 100 A/s with no effect on quench performance. Ramps to the nominal current of

16.470 kA at 4.5 K resulted in quenches but these were above the new lower nominal current of 16.230 kA, as can be seen in the plot, so it was decided to proceed to the thermal cycle to verify training memory at 1.9 K. After the thermal cycle, a ramp to the lower target of 16.230 kA, with a 30-minute hold, was done without quench, and this was considered acceptable with regard to quench performance.

For all quenches, the quench integral in MIIts was ~25 (~165 K), which again is comfortably below the maximum allowed hot spot temperature. All room temperature and cold high voltage withstand target voltages [2] were met, with <1.0 µA leakage currents. MQXFA04 was given final electrical tests when fully at room temperature with no non-conformities exhibited, and it has been accepted, along with MQXFA03, for installation in the first cold mass and cryo-assembly at Fermilab.

V. SUMMARY AND CONCLUSIONS

The first two pre-series magnets MQXFA03 and MQXFA04, which are destined for the first cryo-assembly to be shipped to CERN for the HL-LHC, have been successfully tested at BNL in superfluid He at 1.9 K in a vertical Test Dewar. Both magnets satisfied all the key requirements [2] for acceptance. Both magnets trained successfully to their target currents in fewer than 10 quenches, and both “remembered” training after a thermal cycle. For both magnets, training was almost exclusively in one coil, with locations in the inner layer pole turn (MQXFA03 for sure, MQXFA04 not yet determined but likely), but varying axially from end to end. MQXFA04 azimuthal locations are still to be determined. There was no effect due to higher ramp rates up to 100 A/s. There have not been determined any reasons that almost all the training in each magnet was in a single coil.

The use of quench protection heaters, energy extraction, and the CLIQ system kept the quench hot spot temperatures significantly below the maximum allowed value of 250 K. There was a high loss of voltage taps during quench tests for both magnets, in all coils, and not just the quenching coils. This loss of voltage taps indicates the need for the use of quench antennas during testing of all MQXFA magnets. Both magnets reached target maximum high voltage withstand values with little or no leakage current, showing that ground insulation and insulation between coil and quench protection heaters were uncompromised.

The successful results of these first two MQXFA pre-series quadrupoles represent an important milestone for the US-AUP contribution to the HL-LHC upgrade since the magnet design, which is a challenging one due to the use of potted Nb_3Sn coils, has now been approved by the recent DOE CD-3 Review (November 2020) for production of the remaining magnets and cryo-assemblies; and both magnets have been accepted for the fabrication and test of the first cryo-assembly for future use in the high luminosity LHC inner triplets.

Significant milestones have also been reached by the BNL vertical test facility as a result of testing of the AUP MQXFA quadrupoles:

1.The BNL vertical test facility has been successfully upgraded to eliminate leakage to ground due to the test fixture during MQXFA high voltage withstand testing.
2.The test facility has successfully implemented hardware and software upgrades to keep the temperature gradient during cooldown and warmup to the required 50 K or less.
3.Test facility DAQ upgrades have been successfully completed to handle the increased number of signal channels needed for the new quench antenna and other added instrumentation not discussed here.

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