Title

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Performance of the first short model 150 mm aperture Nb$_3$Sn quadrupole MQXFS for the High-Luminosity LHC upgrade

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***Abstract*—The US LHC Accelerator Research Program (LARP) and CERN combined their efforts in developing Nb3Sn magnets for the High-Luminosity LHC upgrade. The ultimate goal of this collaboration is to fabricate large aperture Nb3Sn quadrupoles for the LHC interaction regions (IR). These magnets will replace the present 70 mm aperture NbTi quadrupole triplets for expected increase of the LHC peak luminosity by a factor of 5. Over the past decade LARP successfully fabricated and tested short and long models of 90 mm and 120 mm aperture Nb$_3$Sn quadrupoles. Recently the first short model of 150 mm diameter quadrupole MQXFS was built with coils fabricated both by the LARP and CERN. The magnet performance was tested at Fermilab's vertical magnet test facility. This paper reports the test results, including the quench training at 1.9 K, ramp rate and temperature dependence studies.**

***Index Terms*—Accelerator magnets, large hadron collider, Nb$_3$Sn coils, superconducting magnets**

I. INTRODUCTION

THE MQXFS1 magnet is the first short model of a 150 mm aperture Nb$_3$Sn quadrupole developed by the US LHC Accelerator Research Program (LARP) and CERN in preparation for the High-Luminosity LHC upgrade [1]. The LHC peak luminosity will be increased by a factor of 5 and the integrated luminosity - by a factor of 10 within this upgrade. Among other components to be upgraded are the inner triplet (low-β) quadrupoles in the LHC interaction regions. Large aperture Nb$_3$Sn quadrupoles (MQXF) will replace the present 70 mm aperture NbTi magnets [2].

Previously LARP successfully fabricated and tested series of 90 mm and 120 mm aperture Nb$_3$Sn magnets [3, 4]. Based on this experience, LARP and CERN recently joined their efforts to fabricate and test a series of short and long, 1.5 m and 4.2 m long respectively, 150 mm diameter Nb$_3$Sn magnets. The very first short coil was successfully tested in a mirror structure MQXFSM1 at Fermilab [5]. MQXFSM1 demonstrated stable performance and reached 91.3% of SSL at 1.9 K.

Main magnet design and assembly parameters, as well as test results of the first short quadrupole MQXFS1 are presented in this paper. Results of field quality measurements are reported elsewhere [6].

II. MQXFS1 DESIGN AND PARAMETERS

Design concept of MQXFS1 was successfully tested in previous large aperture Nb$_3$Sn magnets (LQ and HQ) developed by LARP [3, 4]. The magnet components include two-layer *cos2Q* coils, collars, pads, yokes and aluminum outer shell. The cross section of the MQXFS1 quadrupole is shown in Fig. 1.

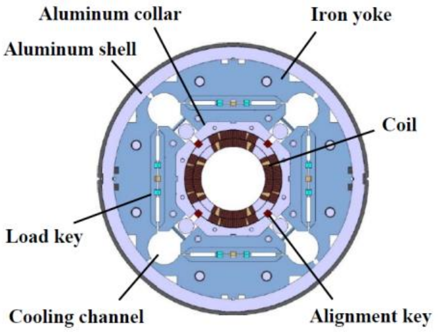

Fig. 1. MQXFS1 cross-section

Each of the two layers of the coil is wound around a titanium alloy pole. The outer layer pole includes a longitudinal slot where a G11 pole alignment key is inserted to provide coil-to-structure alignment. There are total of 22 turns in the inner coil

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layer and 28 - in the outer coil layer.

Two coils in MQXFS1 quadrupole were fabricated by LARP (coils 3 and 5), while other two coils were made at CERN (coils 103 and 104). 40-strand Rutherford cables in these coils are made of 0.85 mm diameter Nb_3Sn strand based on the “Restack Rod Process” (RRP). Two different strand architectures were implemented in MQXFS1: RRP 108/127 in LARP coils and RRP 132/169 - in CERN coils, both manufactured by Oxford Instruments Superconducting Technology [8]. The cable is insulated with braided S2-glass. 25 µm thick stainless steel (SS) core was placed between the layers of the superconductor. According to the specifications, the strand will have a critical current in the superconductor equal or greater than 2450 A/mm^2 at 12 T and 1280 A/mm^2 at 15 T of applied magnetic field and at 4.2 K. Some parameters of MQXFS1 are shown in Table 1. More details on magnet design and fabrication can be found in [9].

TABLE I

MQXFS1 PARAMETERS

Parameters	Units	
RRP strand diameter	mm	0.85
Sub-element diameter	µm	~55
Cu/SC		1.2
Number of strands		40
Cable width	mm	18.094
Cable mid-thickness	mm	1.529
Cable core width/thickness	mm	12/0.025
Keystone angle	degree	0.4
Cable twist pitch	mm	109
SSL at 4.3 K/1.9 K	kA	19.6/21.5
Peak field at 4.3 K/1.9 K	T	13.4/14.6

III. MQXFS1 TEST RESULTS

MQXFS1 magnet was tested at Fermilab’s Vertical Magnet Test Facility [7] in March-April 2016. The test program included quench performance study in two test cycles, as well as protection studies and field quality measurements.

The magnet was instrumented with strain gauges for monitoring mechanical strain and calculating coil stresses during the magnet construction and testing. Quench locations were determined by voltage taps covering both the inner and outer layers of the coil. Voltage taps in MQXFS1 coils are shown in Fig. 2.

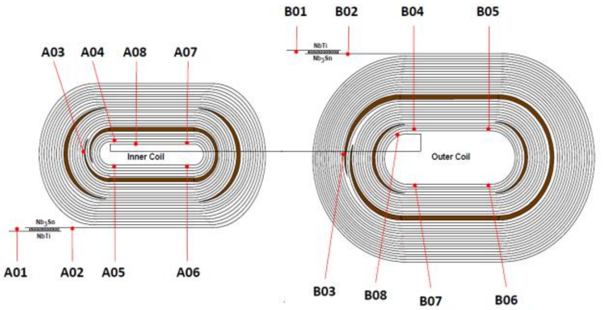

Fig. 2. Voltage tap locations in the inner (left) and outer (right) coil layers

A. Quench Training

The magnet test started with quench training at 1.9 K with a regular ramp rate of 20 A/s. The first training quench was at 14.25 kA, corresponding to 66.3% of SSL. In 7 quenches the magnet reached the operating current of 16.47 kA and in the following 7 quenches – the ultimate current of 17.8 kA. The ultimate current is defined as 108% of the operating current. The highest quench current in the first test cycle (TC1) was 18.1 kA or 84.2% of SSL.

Training memory of the magnet was verified after the thermal cycle, when the magnet was warmed up to room temperature and then cooled down to 1.9 K again. The only one ramp in the second test cycle (TC2) demonstrated excellent training memory. The magnet quenched at 18.2 kA or 84.7% of SSL.

The quench training history with location of the quench origin is presented in Fig. 3. Most quenches originated from the high-field area – the pole block of the inner coil layer.

From the very beginning of the quench training the magnet exhibited flattening of the coil azimuthal strain during the excitation, which usually is considered as an indication of the coil-to-pole detachment under strong electro-magnetic (Lorentz) forces at high currents. In order to minimize the coil damage risk due to possibly low magnet pre-load, it was decided to stop further magnet training and minimize the high current quenches. Frequent change of quench location in Fig. 3 could be another indication of insufficient magnet preload. 14 different coil segments participated in 19 training quenches.

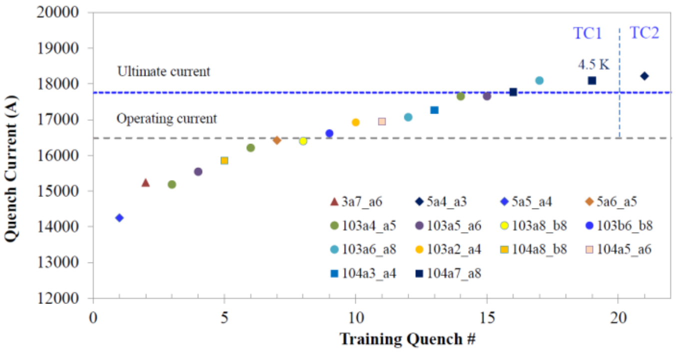

Fig. 3. MQXFS1 quench training history

B. Ramp rate and temperature dependence

No comprehensive ramp rate study was done in MQXFS1 since the magnet training was not completed. In order to avoid high quench currents, only few quenches were done at high ramp rates of 200-400 A/s. Ramp rate dependence in MQXFS1 and MQXFSM1 magnets are compared in Fig. 4.

MQXFS1 quenches at 200 A/s and 300 A/s ramp rates are consistent with the performance of magnet with a stainless steel core in the conductor. At 400 A/s, MQXFS1 quench current dropped down to 14.8 kA, which is lower than the quench current at the same ramp rate in the mirror magnet. Magnetic flux distribution in the mid-plane turns of the quadrupole and mirror magnets are different, which could explain the observed difference of ramp rate dependence in these two magnets.

In the very first ramp to quench at 4.5 K the magnet reached 18.1 kA, corresponding to more than 92.5% of SSL at 4.5 K. No more training quenches were done at 4.5 K or at intermediate temperatures in order to avoid high current quenches. MQXFS1 quench currents at 1.9 K and 4.5 K, as well as temperature dependence of MQXFSM1 are shown in Fig. 5.

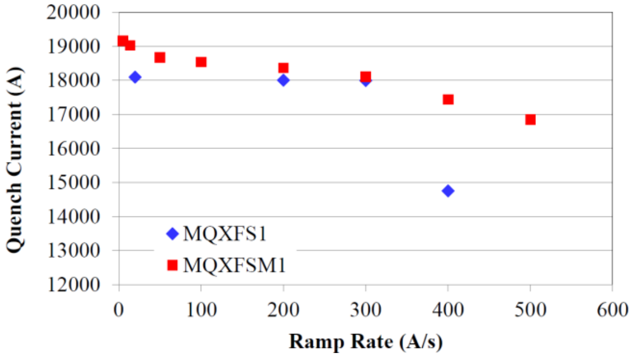

Fig. 4. MQXFS1 and MQXFSM1 ramp rate dependence

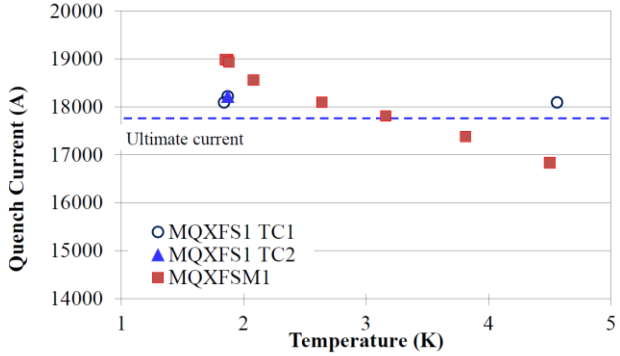

Fig. 5. MQXFS1 and MQXFSM1 temperature dependence. Horizontal line indicates the ultimate current of 17.8 kA

C. Quench protection study

Quench protection studies were significantly reduced to minimize the coil damage risk in MQXFS1 due to insufficient magnet preload. Protection heaters (PH) in CERN made coils 103 and 104 were tested at currents not exceeding the operating current of 16.5 kA.

Protection heaters in coils 103 and 104 are installed on the inner and outer coil surfaces. Heaters are composed by 25 µm thick copper cladded SS strips with 50 µm polyimide layer. There are 2 heater strips on the inner coil layer, and 4 strips on the outer coil layer (see Fig. 6). PH design in CERN coils are shown in Fig. 7. Colored areas in Fig. 7 represent the copper cladded sections of the heater. It is assumed that most of the heating power is deposited in the stainless steel, or so called heating stations.

One of the goals of quench protection study was to reproduce the machine related conditions of the magnet protection. The heater test parameters were selected according to the expected values in a full-length magnet MQXFA, which will operate at the High-Luminosity LHC.

Fig. 6. Inner layer (top) and outer layer (bottom) protection heaters in CERN coils

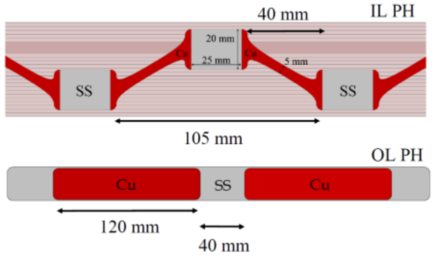

Fig. 7. Inner layer (top) and outer layer (bottom) protection heaters parameters in CERN coils

The minimum peak power density P_{PH} required to quench the magnet at different currents is shown in Fig. 8. Dashed lines in this plot represent the corresponding heater power densities expected in a full-length magnet MQXFA. Corresponding minimum energy density, calculated as $P_{PH}*(\tau/2)$, where τ=RC is a time constant of voltage discharge in the heater circuit, is shown in Fig. 9. Expected energy density deposition in a full-length magnet MQXFA is also shown.

According to Figs. 8 and 9 the outer layer heaters are well protecting MQXFA magnet at a wide range of currents, while the inner layer heaters need more power density at low currents. Efficiency of the inner layer heaters at low currents could be improved by increasing the number of the heater power units. For example, if one heater power unit is used for a single heater strip, instead of two heater strips of the inner layer MQXFA. In this scenario the peak power density and the energy density in MQXFA become 217 W/cm^2 and 3.3 J/cm^2 respectively, and the magnet can be quenched at low currents as well (see Figs. 8 and 9).

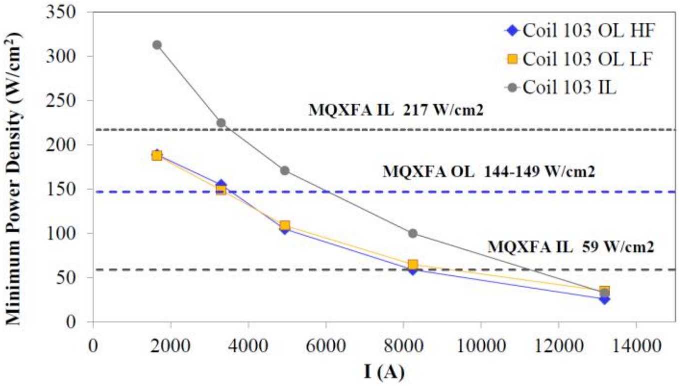

Fig. 8. Minimum peak power density required to quench the magnet at different currents. MQXFA IL 217 W/cm^2 is expected with one power unit for a single heater strip

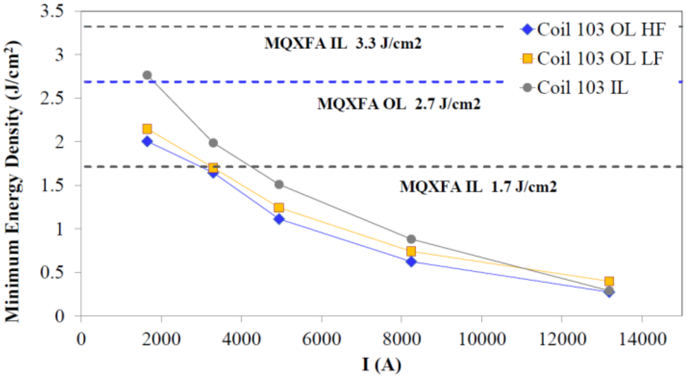

Fig. 9. Minimum energy density deposition in heaters required to quench the magnet at different currents. MQXFA IL 3.3 J/cm^2 is expected with one power unit for a single heater strip

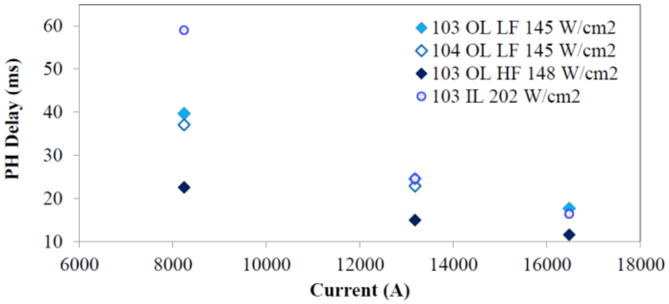

Fig. 10. Protection heater delays in CERN coils at different currents

Protection heater delay time is defined as the time between the heater ignition and the start of quench development in the magnet. Shorter heater delays are necessary to maintain conductor temperature under a safe limit when magnet is quenching. Some characteristic heater delays measured in CERN coils are shown in Fig. 10.

IV. DISCUSSION OF TEST RESULTS

MQXFS1 magnet successfully exceeded the ultimate quench current of 17.8 kA, which was one of the main goals of this test. The ultimate current is defined as 108% of the expected operating current of 16.5 kA. In order to demonstrate stable operation of the magnet, so called holding current test was performed. This test demonstrates capability of the magnet to hold high currents, close to or exceeding the operating current, for an extended time period. The magnet was held without quenching for about 8 hours both at 16.5 kA and 17.8 kA.

Coil RRR values from the extracted witness samples, as well as from measurements in MQXFS1, are summarized in Table II. Even though the coil heat treatment was similar, RRR in LARP coils are consistently larger than in CERN coils.

Despite the successful quench performance, MQXFS1 testing was not completed due to possibly low mechanical preload. From the very first training quench, the magnet exhibited flattening of the coil azimuthal strain at currents above 14 kA, which usually is considered as an indication of the coil-to-pole separation. The reason of this effect could be insufficient coil preload provided during the magnet assembly. The azimuthal coil strain as a function of I^2 (A^2) for coils 5 and 103 in the first 10 quenches are shown in Fig. 11.

The shell strain should also behave linearly with I^2 (A^2), and the slope should stay constant as long as the poles are compressed by coil blocks. However, as seen in Fig. 12, at the point the coil strain starts to turn around in each training run, the shell strain also starts to show a corresponding change in slope.

In order to avoid coil damage due to possibly low magnet pre-load, it was decided to stop further training and minimize the high current quenches. The plan is to increase the preload and retest the magnet. Further quench training will be done in MQXFS1b magnet with increased preload. Quench protection studies, including detailed comparison of heater performance in CERN and LARP coils, also will be done in MQXFS1b.

V. SUMMARY

The first short model of a 150-mm diameter Nb_3Sn quadrupole MQXFS1 was successfully tested at Fermilab. The magnet exceeded the ultimate quench current of 17.8 kA which corresponds to 108% of the operating current expected at the High Luminosity LHC. The highest quench current in the 1st test cycle was 18.1 kA or 84.2% of SSL at 1.9 K.

The magnet demonstrated excellent training memory after the thermal cycle. In the first and only ramp to quench of the second test cycle the magnet reached 18.2 kA or 84.7% of SSL. Ramp rate dependence is consistent with the performance of magnets with a stainless steel core in the conductor. Overall, the magnet showed very stable operation.

Despite the good quench performance MQXFS1 test program was shortened. Analysis of the SG data indicates possibly low mechanical preload of the magnet and related coil-to-pole separation at high currents. In order to eliminate risk of coil damage, it was decided to increase the preload and retest the magnet. Remaining quench training and quench protection studies will be done in MQXFS1b magnet with increased preload in September 2016.

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TABLE II

RRR MEASURED IN THE WITNESS SAMPLES AND IN MQXFS1

Coil #	103	104	3	5
# of extracted samples	3	3	6	6
RRR in extracted samples	164-186	146-172	232-432	347-604
RRR in MQXFS1	134	105	251	256

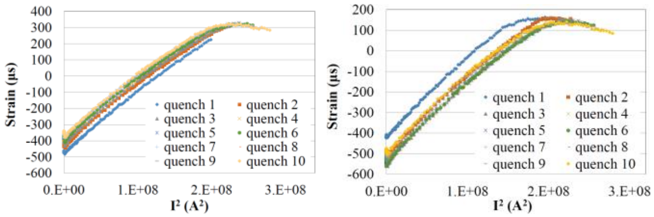

Fig. 11. Azimuthal coil strain as a function of current squared in coils 5 (left) and 103 (right)

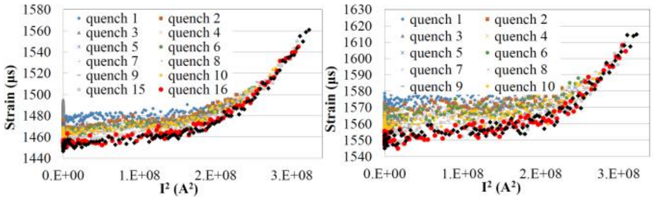

Fig. 12. Azimuthal shell strain as a function of current squared in the bottom (left) and top (right) shell sections

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