FIRST TEST RESULTS OF THE 150 MM APERTURE IR QUADRUPOLE MODELS FOR THE HIGH LUMINOSITY LHC*

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Abstract

The High Luminosity upgrade of the LHC at CERN will use large aperture (150 mm) quadrupole magnets to focus the beams at the interaction points. The high field in the coils requires Nb_3Sn superconductor technology, which has been brought to maturity by the LHC Accelerator Research Program (LARP) over the last 10 years. The key design targets for the new IR quadrupoles were established in 2012, and fabrication of model magnets started in 2014. This paper discusses the results from the first single short coil test and from the first short quadrupole model test. Remaining challenges and plans to address them are also presented and discussed.

INTRODUCTION

With two successful tests the US LARP (LHC Accelerator Research Program) and CERN have closed the design phase for the High Luminosity LHC (HL-LHC) [1] IT quadrupoles and started the demonstration phase. The HL-LHC requires Inner Triplet quadrupoles with 150 mm aperture and 133 T/m gradient (MQXF) [2]. In developing these quadrupoles, LARP and CERN are basing design and technology on the successful demonstration of 90-mm and 120-mm aperture quadrupoles by LARP.

The successful tests of a single short coil (MQXFSM1) and of the first short quadrupole (MQXFS1) have demonstrated the validity of several MQXF magnet design and technology choices. In this paper we present and discuss these test results. Subsequently we discuss the main challenges in front of MQXF development, and the plans to address them.

MQXF MAIN DESIGN PARAMETERS

MQXF is a cos2θ quadrupole comprised of four double-layer coils assembled in a shell-based mechanical support structure. The design concept and main features are described in [3-4]. The conductor and performance parameters specific to the MQXFS1 assembly are summarized in Table 1.

The superconducting cable, which incorporates a stainless steel core to control the dynamic effects, was fabricated using 0.85 mm diameter Nb_3Sn strands of the OST-RRP design. Of the four coils used in MQXFS1, two were fabricated by LARP using the 108/127 wire layout and two by CERN using the 132/169 wire layout.

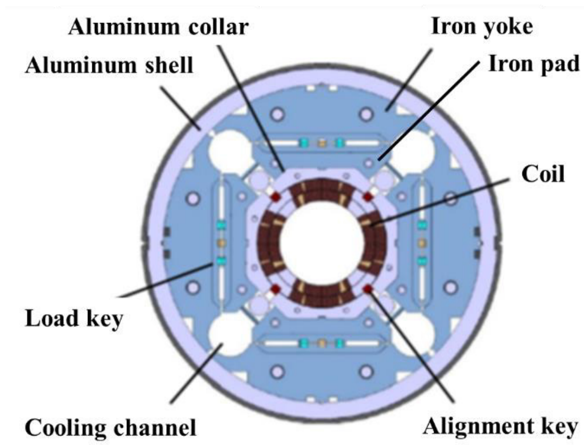

Figure 1: MQXF cross-section.

As shown in Fig. 1, the four quadrants are assembled using bolted aluminum collars, then aligned using keys inserted into each pole piece. The resulting coil pack is surrounded by bolted iron pads, inserted in a yoke-shell subassembly, and loaded using water-pressurized bladders and interference keys. Four tensioned aluminum rods are connected to stainless steel end plates to provide axial pre-load to the coils. Further details about MQXF magnet design and fabrication are provided in [5-6].

Table 1: MQXFS1 Cable and Magnet Parameters

Parameter	Unit	Value
Strand diameter	mm	0.85
Number of strands		40
Cable width	mm	18.094
Cable mid-thickness	mm	1.529
Core width/thickness	mm	12/0.025
Turn insulat. thickness	mm	0.15
Coil aperture	mm	150
No. turns in layer 1/2		22/28
Operational gradient	T/m	132.6
Operational current (I_{op})	kA	16.48
Peak coil field at I_{op}	T	11.4
Stored energy at I_{op}	MJ/m	1.17
Short sample current	kA	21.5

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SINGLE SHORT COIL TEST RESULTS

A single short coil was tested in a mirror structure at Fermilab's Vertical Magnet Test Facility [7]. Magnetic mirror structures for quadrupole and dipole coils were developed and successfully used at Fermilab [8-9]. These structures allow individual coils to be tested under conditions similar to those of an actual magnet, reducing cost and turnaround time.

The mirror assembly includes the coil, an iron "mirror" which replaces the three missing quadrupole coils, an iron yoke, and a stainless steel shell bolted together. Iron was placed in the aperture in order to increase iron volume and compensate for its saturation. The resulting MQXF mirror load line is within ±2% off the MQXF quadrupole load line.

Double-layer cos2θ coil was made of 0.85 mm diameter Nb_3Sn strand based on the "Restack Rod Process" (RRP) of 108/127 sub-element design by Oxford Superconducting Technology [10].

The mirror 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. Magnet protection is based on protection heaters installed both on the outer and inner coil surfaces.

The magnet test started with quench training at 1.9 K (Fig. 2) with a regular ramp rate of 20 A/s. The first training quench was at 14.8 kA, corresponding to 70.3% of SSL. In three quenches the magnet reached the nominal cur-rent of 16.47 kA. Later on the magnet continued training slowly, approaching the limit at around 19 kA or 90% of SSL. Most training quenches originated from the high field area – the pole block of the inner coil layer.

Quenches at different temperatures demonstrated that the magnet reached its quench limit at 90% of SSL. Ramp rate dependence is consistent with the performance of magnets with stainless steel core in the conductor. Average measured RRR was 150.

The test program also included quench protection studies. The magnetic mirror design does not allow field quality measurements.

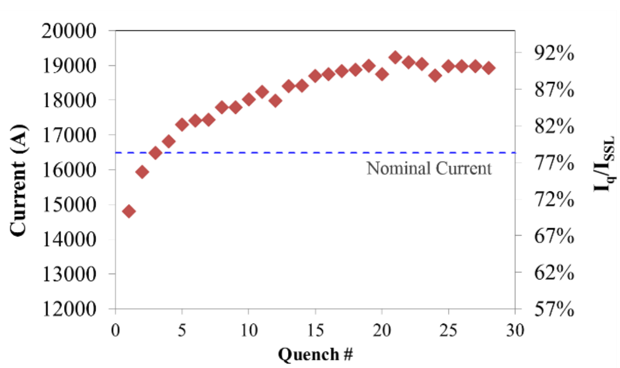

Figure 2: Quench history of single coil test at 1.9 K.

SHORT QUADRUPOLE TEST RESULTS

MQXFS1 was tested at Fermilab in two thermal cycles performed in March and April 2016. The test program included quench performance, mechanical and protection studies, and magnetic measurements.

A new top plate was developed specifically for MQXF in order to achieve the required current at 1.9K, and to maximize the warm bore diameter available for magnetic measurements. The magnet was instrumented with strain gauges for monitoring mechanical strain on the outer shell, the axial rods, and the coil pole pieces. Quench locations were determined by voltage taps covering both the inner and outer layers of the coil. An inductive antenna was installed in the magnet bore during quench training, to characterize its performance in view of a possible future use in full-scale prototypes. Magnetic measurements were performed using rotating coils manufactured with the Printed Circuit Board (PCB) technique [11].

Mechanical Assembly and Cool-Down

The target pre-load for MQXFS1 was selected to maintain compression at the pole up to nominal gradient [12]. After cool-down, shell and rod strain were close to design targets, while the coil pre-load based on SG measurement at the pole was significantly lower than the target. Since good results had been achieved in previous mechanical model tests using dummy aluminum coils, this discrepancy was attributed to the coil mechanical properties, and in particular the coil modulus. The analysis showed that it is possible to reproduce the measured strain if the coil modulus is reduced from 44 GPa to 20 GPa [12]. Measurements performed on coil samples are consistent with this result. Two sets of gauges and corresponding strain measuring systems were used: a LARP system powered in DC and a CERN powered in AC. Comparisons performed at assembly and cool-down showed consistent readings in a range of 10 MPa.

Quench Performance

Quench training was performed entirely at 1.9 K. The standard ramp rate at quench is 20 A/s, but a faster rate of 50 A/s is used in the first part of the ramp to reduce the turnaround time.

Figure 3 shows the training history for both thermal cycles [13]. Training started at 14.25 kA, corresponding to 66.3% of the Short Sample Limit (SSL). The nominal current was reached in 7 quenches, and the ultimate current was reached in 7 additional quenches. The highest quench current in the first test cycle was 18.1 kA or 84.2% of SSL. Most quenches originated from the high field region of the coil (pole turn). A large number of coils and segments participated in the quench training. In addition, the pole azimuthal strain as a function of current squared shows a non-linear response at high current indicating that coils are unloading. These results confirm that insufficient pre-load is the cause of the slow rate of progress observed during training.

No degradation of the quench current was observed after increasing the temperature to 4.5K, corresponding to 93%

SSL. Similarly, no degradation of the quench current was observed after performing a full thermal cycle, demonstrating excellent training memory. Finally in order to demonstrate stable performance at high current, the magnet was ramped to nominal and ultimate current, and maintained at each level for eight hours without quench.

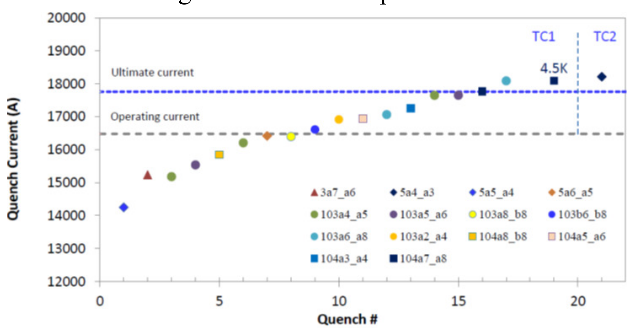

Figure 3: MQXFS1 Quench History [13].

Ramp Rate Dependence

The ramp rate study was limited in scope since training was not completed. However, MQXFS1 quenches at 200 A/s and 300 A/s ramp rates showed no degradation of the quench current, consistent with previous results using a stainless steel core. Down-ramps from nominal and ultimate current at a rate of 300 A/s were also successfully performed without quench.

Field Quality

The analysis of MQXFS1 magnetic measurements [14] has shown good agreement between computed and measured allowed harmonics, which were all lower than one unit. Longitudinal variations of ±1 unit and averages of - 4.4/3.1 units were measured for b_3/a_3. With 0.1/-6.9 units, b_4/a_4 were very close to expectations (0.3/-6.8 units) because of systematic differences between LARP and CERN coils, and of the assembly layout (alternating LARP and CERN coils). The decapole had a normal component of 2.8 units, and a skew component slightly lower than one unit. All other harmonics had magnitude lower than 0.7 units. There was a good correlation between cold magnetic measurements and warm measurements even before loading.

CHALLENGES AND PLANS

Coil Length Scale-Up

Coil length scale-up poses some challenges because of Nb_3Sn brittleness requiring heat-treatment after coil winding, epoxy potting, and careful coil handling. LARP has addressed these challenges by fabricating and testing ~3.5 m long coils [15-16], and the FNAL HFM program fabricated a few 2-4 m coils tested singularly in iron-mirror structures [17]. These developments successfully demonstrated the present Nb_3Sn coil fabrication technology [18] for coils up to 4 m. CERN is developing 5 m long coils for 11 T dipoles [19], although at the time this paper was written no long 11 T coil had yet been tested. Given this status of long Nb_3Sn coil development, the US LHC Accelerator Upgrade Project decided to make the Q1 and Q3 elements, with a magnetic length of 8.4 m, by using two magnets (each magnet is made of coils and structure up to the Al-shell) in every cold mass. By doing so the Nb_3Sn coils in Q1 and Q3 have a 4.2 m magnetic length, which is a low-risk scale-up from the currently proven technology. In contrast CERN has decided to use a single magnet in the Q2a and Q2b elements, which have a 7.15 m magnetic length. CERN is counting on the 11T project for the development of infrastructure (for instance for coil potting) and for risk reduction.

LARP is planning to test a single long coil in a mirror structure of the same design used for MQXFSM1. This coil has a 4 m magnetic length because of an oven limitation. For the same reason the first LARP magnet prototype has 4 m long coils, which are presently under fabrication or being instrumented. The second and third LARP prototypes (MQXFA2/3) will have coils with the final length (4.2 m). The fabrication of MQXFA2 coils has started together with the oven upgrade. A vertical test facility at BNL has been successfully upgraded [20] for testing the MQXFA prototypes. It will be used to test the 4 m coil in a mirror structure in fall 2016.

CERN is planning to test a single 7.15 m long coil in the MQXF structure. Three practice coils will be used to complete the coil package, and only the test coil will be powered. A temporary cryostat may be used for this test to be performed in a horizontal test facility at CERN. Cryostats with the final design will be used for two MQXFB prototypes.

Assembly and Alignment of Long Structures

Up to this time there is limited experience with the assembly and alignment of long Al-shell based structures for Nb_3Sn magnets. The LARP program started this development with the Long Racetrack [15] and the Long Quadrupole [16] programs.

The Long Racetrack was a technology development magnet made of two double-layer flat racetrack coils 4 m long, supported by an Al-shell based structure. This program had two goals: develop and test long Nb_3Sn coils and long Al-shell based structures. Both goals were successfully achieved [15] and cold tests demonstrated that Al-shell based structures need to be segmented in order to avoid stick-slip behavior during cooldown and energization. The different longitudinal thermal contractions of the iron yoke and the Al shells causes strain build-up triggering slippage, which may cause training, detraining and possibly coil damage. Shell segmentation prevents the accumulation of excessive strain (since it is zero at shell cuts) avoiding the stick-slip behavior.

The Long Quadrupole program confirmed the effectiveness of shell segmentation on 90-mm aperture quadrupoles. It also showed that Al-shell based structures can be successfully used on long Nb_3Sn accelerator magnets providing adequate prestress and support. This program also demonstrated [21] that the shims between coils and pads can be adjusted in order to optimize the prestress distribution in the coils, compensating for differences between nominal and actual coil dimensions. The Long Quadrupole program made a very significant step toward the demonstration of Nb_3Sn readiness for use in accelerator magnets. Nonetheless it lacked an important feature: full alignment from coils to structure outer surface. Alignment features were in fact present in the mechanical structure, but missing between coils and structure.

This step was demonstrated in another very successful LARP program: the 120-mm aperture High field Quadrupole (HQ). In these magnets, with a nominal gradient of 160 T/m and a peak coil field of 12 T, bolted aluminium collars were introduced between coils and iron pads, together with a groove in the coil poles. A key inserted into the pole groove and locked by the collars provided coil-structure alignment (Fig. 1 shows this concept in MQXF). The excellent performance of HQ02 [22] and HQ03 [23] demonstrated that the introduction of these features did not have a negative impact on the structural design. Since only short HQ models were fabricated and tested there is still an open question about the quench performance (training and maximum current) of long Al-shell based structures and the achievable alignment tolerances.

The MQXF development is addressing these questions. An analysis of the impact of tolerance stack up on coil stress variations (the possible cause of degradation and long training) has shown that tight tolerances may keep the coil prestress longitudinal variations caused by tolerances within a range of ± 9 MPa (Root Sum Squares method) [3]. Another source of coil stress longitudinal variations are 3D effects caused by shell segmentation and magnet ends. A study based on 3D ANSYS simulations [3] has shown that these variations are reduced from ± 20 MPa to ± 8 MPa if the shell segments in the ends are shorter (1/2 length) than the segments over the straight section. This solution was implemented and tested on MQXFS1, which used a segmented shell made of a full-length central shell and two half-length shells at the ends. The excellent quench performance of MQXFS1 demonstrated the validity of this solution.

Coil stress variations may be caused also by coil dimensional variations. MQXF coils of 1.2 and 4 m magnetic length have been measured with Coordinate Measuring Machines (CMM). The results show arc-length variations along the coil length of 100 um, with a few peaks up to 200 um [6, 24]. CMM measurements of other LARP coils after cold powering tests have shown a small reduction (50-100 um) of the coil arc length due to plastic deformation. Analysis of the impact of these variations on coil stress variations is in progress.

MQXF stress analysis [5] has shown peak coil compression of 192 MPa at 1.9 K in the pole turn. Tolerances and 3D effects may increase the peak stress above the 200 MPa threshold, which was demonstrated to be safe territory by the TQ program [25], although coil plastic deformation should help to reduce local stress concentrations. MQXF short models and prototypes are being used for assessing safe prestress range.

The alignment requirements may be summarized by the following statements, here presented for Q1:

1) The two magnetic axes of Q1a and Q1b with respect to the common axis are ±0.5 mm from the center.
2) The local twist shall not exceed ±2 mrad (corresponding to ±0.5 mm on the outer surface of the cold mass).

Given the brittleness of Nb_3Sn coils it would be quite dangerous planning for a mechanical correction (for instance under a press) if magnets or cold masses do not meet alignment requirements after assembly. Therefore the plan is to perform survey and magnetic measurements during most steps of magnet and cold mass assembly. These measurements will show if the assembly can proceed or if the last step must be redone. This procedure will be followed during prototype assemblies in order to set the targets for each step.

Field Quality

Tests of short models and full length prototypes are planned to assess systematic and random errors. Nonetheless, some observations are already possible. For instance, the longitudinal variation of harmonics along the straight section can be used to estimate the turn waviness (variation of turn position around its average position). The MQXFS1 turn waviness based on field quality measurements (as described above) is about 50 um, which is consistent with the waviness measured by comparing several cross-sections of an MQXFS coil that was cut for this purpose [24]. The analysis of these MQXFS coil cross-sections also showed turn displacements in an amount that may explain b_5.

After the fabrication of MQXFS1 coils had started, LARP and CERN decided to do a small fine-tuning of cable dimensions (reducing the keystone angle) and of coil cross-section (aiming at reducing the integral harmonics) [26]. In the design of the new coils (“second generation coils”) it was decided to reduce the space for cable growth during heat treatment. This change should reduce turn displacements contributing to better and more uniform field quality. Nonetheless it is clear that at this time the field quality achievable in Nb_3Sn magnets is not at the same level as NbTi magnets. The coil fabrication technology, which requires heat treatment and epoxy impregnation, and the structure assembly, which requires several parts increasing overall tolerances, are among the causes of this difference. Therefore the MQXF strategy to meet field quality requirements is based on correction by shimming. Three options for shimming are planned:

Intra-coil shims Intra-coil shims were added to the design of second-generation coils on the coil midplane (125 um) and close to the pole (150 um) in order to allow for a possible fine-tuning of coil blocks position [26]. These shims are made of S2-glass and inserted during coil winding. They become G10-like during epoxy potting. These shims can be used to correct a systematic error of b_6 with negligible impact on other harmonics. The preferred correction involves removing up to 125 um on the midplane and adding the same amount at the pole, or vice versa. In this way the turns are shifted and the total space for conductor expansion during heat treatment does not change. This shifting of turns can correct up to -5.6/+5.3 units if performed on both inner and outer layers.

Coil-pad shims These shims are inserted during the coil-pads sub-assembly preparation. This is the first step of magnet assembly during which the coils are put together inside the pads. The shims, made of polyimide, can be inserted between coils and pads (radial correction), between coil midplanes (azimuthal correction), or both. Of course the radial and azimuthal corrections are not decoupled because the coils-and-shims package has to fit within the pads in a way that avoids excessive stress when preload is applied (for instance steps should be prevented at the coil-pads interface). Nonetheless the radial and azimuthal corrections are different methods to compensate for coil geometrical differences and each has a different impact on harmonics. Therefore, given a set of coils with their CMM data, it is possible to find different shim configurations, which provide acceptable coil prestress after loading. Among these configurations it will be possible to select the one that yields the best harmonic compensation. MQXFS1 has shown good warm-cold field quality correlation. If this correlation is confirmed it will be possible to fine tune the coil-pads shims through a series of warm magnetic measurements and shim adjustments. This process will be tested in the next short MQXF model.

Magnetic shims After magnet preload is applied and the bladders are removed, the gaps in the masters used to accommodate them are left empty. ROXIE analysis [26] has shown that these gaps are in the correct position for field quality adjustment using magnetic shims. Depending on which slots are filled it is possible to correct up to 5 units of b_3/a_3 and 3/1 units of b_4/a_4. This correction technique was successfully demonstrated on 90-mm aperture quadrupoles of the HQ series [22]. A test of magnetic shims is planned for MQXS1 after preload increase.

Quench Protection

The energy density of MQXF magnets at operating current is 50% higher than the energy density of the LHC main dipoles, showing the challenge of protecting these magnets. The present targets for MQXF magnet protection are: (i) hot spot temperature below 350 K [27]; (ii) peak voltage to ground below 1000 V; (iii) peak turn-turn voltage below 100 V.

Several studies [28-29] and tests have been performed in order to find a reliable quench protection strategy. The use of dump resistors was ruled out because the large inductance of these magnets allows extracting only a small fraction of energy even if two power convertors are used for each triplet. Therefore it was decided to have all magnets of each triplet on one power convertor, which reduces the impact of current ripple on the beams. The quench detection will be based on redundant voltage taps with low threshold (100 mV) and sufficient verification time (10 ms) in order to avoid spurious signals. Three quench protection tools are presently being developed and tested on short models and prototypes:

Outer layer (OL) heaters These heaters are made of 25 um thick, 20 mm wide stainless steel strips partially plated with 10 um copper, and photoetched on a 50 um polyimide foil. The polyimide foil is set in direct contact with the outer surface of the coil and is potted together with it. This solution provides short heater delay time (time difference between heater firing and heater-induced quench start) and sufficient coil-heater electrical insulation (150 um of G10 plus 50 um of polyimide). The LARP program has been using similar heaters (mostly without copper plating) on all its 90 and 120 mm aperture magnets. After a few issues were fixed (heater-lead connections and coil ends crossing) these heaters proved to be very reliable surviving hundreds quenches, thermal cycles and even high coil peak temperature studies [22]). MQXFS1 test confirmed the reliability of OL heaters.

Inner layer (IL) heaters These heaters are fabricated in the same way as the outer layer heaters, but their design has some additional features. There is a requirement to keep 40% of the coil inner surface polyimide free in order to ensure sufficient cooling from the helium in the coil aperture. Therefore the metal surface is minimized and perforations are distributed widely over the polyimide foil. This feature also helps to address an issue seen in LARP coils with IL heaters. After cold test the coils presented partial delamination (bubbles) of the heaters from the polyimide foil, and of the foil from the coil. These bubbles reduce heater efficiency and in a few cases IL heater breakage was related to bubble location. From this point of view MQXFS1 test gave mixed results. Two coils (fabricated at CERN and extensively tested) showed large bubbles, whereas the two other coils (fabricated by LARP and less tested) showed a few small bubbles. More tests are planned.

Coupling Loss Induced Quench (CLIQ) system This is a relatively new concept based on capacitor banks that are discharged in the windings causing ripple currents, eddy currents, and coil heating. Since the heat is generated within the conductor it is extremely fast, in particular at high current where protection with heaters can be marginal in some failure scenarios. Tests on a short Nb_3Sn quadrupole [23] and a long NbTi dipole [30] provided very promising results showing that the CLIQ system and magnets behaved as expected. Nonetheless this system has never been used in an accelerator, and since it is connected with the main powering circuit its integration poses questions and challenges. CLIQ will be tested on the next short models and prototypes. The planned string tests will offer opportunities to test its integration.

The present plan, endorsed by several reviews, is to keep developing all three protection systems, test them on short models and prototypes, and make a decision (possibly selecting two systems) when sufficient data is available.

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