Title

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ASSEMBLY AND TEST OF A 120 MM BORE 15 T NB$_3$SN QUADRUPOLE FOR THE LHC UPGRADE*

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Abstract

In support of the Large Hadron Collider (LHC) luminosity upgrade, the US LHC Accelerator Research Program (LARP) has been developing a 1-meter long, 120 mm bore Nb$_3$Sn IR quadrupole magnet (HQ). With a design short sample gradient of 219 T/m at 1.9 K and a peak field approaching 15 T, one of the main challenges of this magnet is to provide appropriate mechanical support to the coils. Compared to the previous LARP Technology Quadrupole and Long Quadrupole magnets, the purpose of HQ is also to demonstrate accelerator quality features such as alignment and cooling. So far, 8 HQ coils have been fabricated and 4 of them have been assembled and tested in HQ01a. This paper presents the mechanical assembly and test results of HQ01a.

INTRODUCTION

One of the goals of the LHC Accelerator Research Program (LARP) is to demonstrate the feasibility of the Nb$_3$Sn technology for the Large Hadron Collider (LHC) luminosity upgrade foreseen to take place in the 2018-2020 time frame. Among the requirements for this upgrade, large aperture and high gradient quadrupole magnets are critical components. Since the start of the program, several different series of Nb$_3$Sn quadrupoles have been fabricated and tested. The recent major achievement of the program is the completion of the first Long Quadrupole (LQ) [1], a 3.6 meter scale-up of the TQ magnet [2]. LQ has been tested at the end of 2009 at FNAL and reached the LARP 2009 milestone of 200 T/m. In parallel, the implementation of accelerator quality features has to be performed in order to comply with the LHC requirements in terms of alignment, field quality and cooling.

Table 1: HQ01a Conductor Parameters

Coils	Unit	Nom	1 / 2	3 / 4
Cable #			992R	991R/1000R
Bare cable width	mm	15.15	15.11	15.11/15.07
Bare cable mid-thick	mm	1.44	1.44	1.44
Keystone angle	Deg	0.75	0.79	0.70/0.77
Insulation thickness	mm	0.100	0.088	NA

The High gradient Quadrupole (HQ) series aims at fulfilling this goal. HQ is a 1-meter long 120 mm aperture cos2θ quadrupole. The fist magnet of this series is called HQ01a and consists of four HQ coils fabricated in 2009 and 2010 within the LARP collaboration (BNL, FNAL and LBNL). After summarizing the magnet parameters, this paper presents HQ01a assembly and test results.

MAGNET DESIGN

Magnetic Parameters

HQ01a is made of four virgin coils (1 to 4) wound and cured at LBNL using stainless steel end parts and Titanium alloy poles (Ti6Al4V) designed and fabricated by FNAL. The reaction, impregnation and instrumentation tasks are equally split between LBNL and BNL. The tooling was designed to maintain alignment at each step of the fabrication. The full process is described in detail in [3]. The experience in coil fabrication gained by the three labs during the TQ and LQ series as well as the winding tests performed beforehand [3] allowed using the first four fabricated coils in the magnet without any practice coil.

Table 2: HQ01a Magnet Parameters

Parameters	Units	4.2 K	1.9 K
I_{ss}	kA	17.3	19
B_{max} at I_{ss}	T	13.5	14.8
Gradient at I_{ss}	T/m	195	214
Stored Energy	MJ	0.9	1.1
F_x / F_y at I_{ss}	MN/m	2.7/-3.9	3.2/-4.7

As shown in Table 1, coil #1/#2 are made of 0.8 mm diameter OST 54/61 RRP strand while coil #3/#4 use a OST 108/127 RRP strand [4]. Due to the slightly lower critical current (I_c) of the 108/127 strand, the magnet is expected to be limited by coil 3 or 4 and the short sample current I_{ss} has been calculated based on the critical current measurements performed at BNL on witness samples from coil 3 and 4. Table 2 summarizes HQ01a magnetic parameters and a cross-section of the magnet is shown in Fig. 1.

Instrumentation and Quench Protection

The coil instrumentation belongs to a stainless steel / Kapton printed circuit called trace [5]. Each coil is instrumented with 20 voltage taps. Protection heaters are

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present on both layers. In order to monitor the mechanical structure during each step, the coil poles, shell and rods are instrumented with strain gauges.

Mechanical Structure

The HQ mechanical structure shown in Fig. 1 is a shell-based structure similar to the one used in previous LARP magnets [6] but goes one step further by providing full alignment between all components. To do so, the coils, wound around a Titanium-alloy pole, are surrounded by four Aluminum collars (6061) bolted against an Aluminum key pinned in the outer layer pole of the coil.

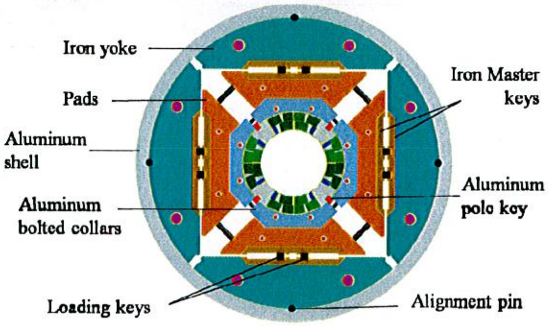

Figure 1: HQ cross-section.

Each collar section is 50 mm long. Four pads (1018 steel in the center and 304L stainless steel in the end) are bolted around the collar-coil sub-assembly. The coil-pack is inserted into a second sub-assembly made of the iron yoke quadrants (1018) and the 25 mm thick, 570 mm outer diameter Aluminum (7075-T6) shell. Yokes and shell are aligned at each mid-plane via a pin. The pads as well as the yoke include alignment slots for the insertion of iron master keys. The master keys provide alignment between pads and yokes and include grooves for the bladders and the loading keys. At room temperature, the bladders made of two thin stainless steel sheets welded together are pressurized to pre-tension the shell and compress the coils. The preload is locked by the shimming of the two loading keys and is followed by the bladders removal. During cool-down, the differential thermal contraction between the outside Aluminum shell and the iron yoke completes the full pre-loading of the coil. The coil ends are supported by two Nitronic 40 end plates connected with Aluminum (7075-T6) rods.

The behaviour of the structure has been studied using ANSYS. The models defined the preload target at room temperature so that the coils remain in contact with the Ti-alloy poles after cold-down and during excitation. According to the model, the alignment is preserved during each step: the contact between the pole keys and the collar established during the room temperature assembly remains during all magnet operations. The case where the alignment key is not part of the system has also been simulated and is referred to as the "no key" case in this paper. As shown in Fig. 2, the shell behaviour is very similar in both cases. The main difference between the two cases is the strain on the Ti-alloy pole which undergoes higher compression in the "no key" case due to a stronger bending of the coil.

MAGNET MECHANICAL BEHAVIOR

Assembly of HQ01a

Prior to HQ01a assembly, a "dummy" assembly with nominal size Aluminum dummy coils has been performed in order to validate the behaviour of the structure at room temperature. In particular, this exercise showed that with nominal coil dimensions, the azimuthal gap between the pole keys and the collars is closed and remains closed during assembly. In comparison, the assembly of HQ01a with the real coils showed an oversized coil pack at the magnet center with a gap between key and collar of 200 microns per side in average. This was imputed to the oversized virgin coils which were expected to conform into shape during the bladder operation allowing the closure of the key/collar gaps.

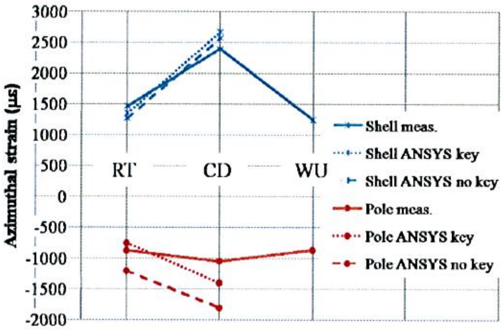

Figure 2: Average azimuthal strain comparison in the shell and in the pole after assembly (RT), cool-down (CD) and after warm-up (WU)

The "key" case and the "no key" case have been compared to measurements during loading. The results showed that the rate of loading of the structure corresponded to the case without alignment key at the pole, confirming that the gaps between the collar and the key were not closed. Fig. 2 shows the strain target used during the assembly and their comparison with the strain gauges measurements. The computed average stress on the coil pole turn is expected to be around -90 MPa.

Cool-down of HQ01a

As mentioned earlier, the differential thermal contraction of the structure components provide additional preload to the coil during cool-down. As shown in Fig. 2, the shell tension and the pole compression increased respectively by 70% and 30 % of the expected gain. A mismatch between the coils outer diameter and the collar inner diameter is a possible reason. Nevertheless, with -150 MPa, the preload on the coil winding itself was estimated to be sufficient to test the magnet safely. In terms of axial loading, the gain of preload expecting during cool-down has been reached with an axial stress in the rods of 190 MPa corresponding to a total axial force of ~ 600 kN.

TESTS RESULTS

Training

HQ01a was tested in April 2010 at LBNL. The 4.3 K training curve is shown in Fig. 3. The first quench reached 12183 A or 141 T/m (71% of I_{ss}) which is significantly higher than the design operating gradient of LHC Phase I upgrade (120 T/m) [7]. However, the subsequent 4 quenches at 20 A/s showed only modest improvements. An attempt to accelerate the training was made by reducing the ramp-rate from 20 to 10, 5 and 2 A/s. The magnet responded with a significant gain of current. The maximum quench current reached was 13680 A (157 T/m and 79 % of I_{ss}).

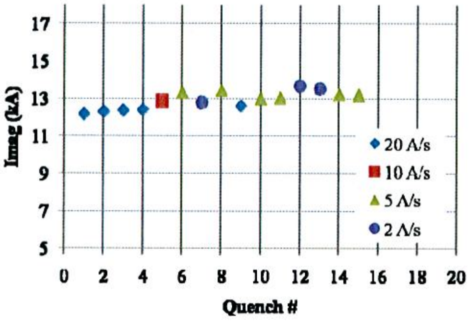

Figure 3: HQ01a training curve.

All training quenches were located in coil 3. Only the first quench showed a motion prior to quench in a segment of the pole turn in the lead end side. A quench velocity of 10 m/s was computed for this quench. All the following quenches were very similar to each other starting in the mid-plane turn of coil #3 and did not have any mechanical signature.

Ramp Rate

A ramp-rate study was performed as shown in Fig. 4.

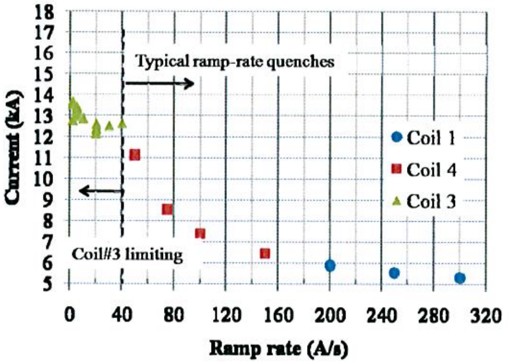

Figure 4: HQ01a limited ramp rate curve.

From 300 A/s down to 50 A/s the quenches were typical ramp rate quenches located in the mid-plane block of coil 1 and 4 inner layer. For lower ramp-rate, the signature of the quenches changed to the limited coil #3 type quenches described in the previous part.

Magnetic Measurements

Magnetic measurements were performed on HQ01a with a 100mm long, 12.4 mm radius probe and a 820 mm long, 21.9 mm radius probe. Most of the results are still being analyzed but an example of cycle measurement performed during the test with the shortest probe is plotted in Fig. 5.

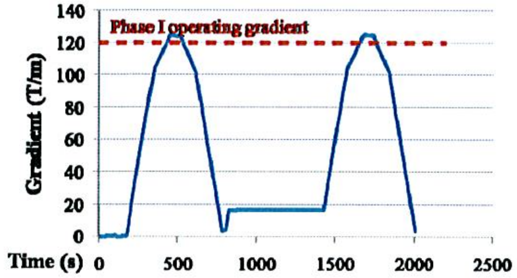

Figure 5: Current cycle to 11 kA surpassing the LHC Phase I Upgrade design value of 120 T/m [7].

NEXT STEPS

The first model of the HQ series was tested at LBNL where it reached 79 % of its 4.3 K estimated short sample current but was limited by coil #3 mid-plane turn. The magnet is now being reassembled as HQ01b by replacing the limiting coil. Meanwhile, the mechanical analysis continues trying to address assembly and coil size issues observed during HQ01a assembly. The test of HQ01b is expected in June 2010 at LBNL.

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