Performance of HQ02, an optimized version of the 120 mm Nb_3Sn LARP quadrupole

G. Chlachidze, G. Ambrosio, M. Anerella, F. Borgnolutti, R. Bossert, S. Caspi, D.W. Cheng, D. Dietderich, H. Felice, P. Ferracin, A. Ghosh, A. Godeke, A. R. Hafalia, M. Marchevsky, D. Orris, P.K. Roy, G.L. Sabbi, T. Salmi, J. Schmalzle, C. Sylvester, M. Tartaglia, J. Tompkins, P. Wanderer, X.R. Wang, and A.V. Zlobin

***Abstract*—In preparation for the high luminosity upgrade of the Large Hadron Collider (LHC), the LHC Accelerator Research Program (LARP) is developing a new generation of large aperture high-field quadrupoles based on Nb_3Sn technology. One meter long and 120 mm diameter HQ quadrupoles are currently produced as a step toward the eventual aperture of 150 mm. Tests of the first series of HQ coils revealed the necessity for further optimization of the coil design and fabrication process. A new model (HQ02) has been fabricated with several design modifications, including a reduction of the cable size and an improved insulation scheme. Coils in this magnet are made of a cored cable using 0.778 mm diameter Nb_3Sn strands of RRP 108/127 sub-element design. The HQ02 magnet has been fabricated at LBNL and BNL, and then tested at Fermilab. This paper summarizes the performance of HQ02 at 4.5 K and 1.9 K temperatures.**

***Index Terms*—High-luminosity upgrade of Large Hadron Collider (HiLumi-LHC), LHC accelerator research program (LARP), Nb3Sn quadrupole magnet, quench performance.**

I. Introduction

THE US LHC accelerator research program (LARP) is developing a new generation of Nb_3Sn accelerator magnets for the high luminosity upgrade of the Large Hadron Collider (LHC) at CERN. High gradient quadrupole (HQ) coils with a 120 mm diameter bore are currently fabricated and investigated as a final step toward the eventual aperture of 150 mm recently approved for the LHC high luminosity upgrade.

Nine first generation HQ coils were tested in the HQ01 series. The first 5 tests (HQ01a-e) were performed at LBNL in boiling liquid helium at 4.4 K [1] and then HQ01e was re-tested at CERN in superfluid helium at 1.9 K [2]. The magnet reached 85-86% of its short sample limit both at 4.4 K and 1.9 K producing a field gradient up to 170 T/m. Despite the accomplished performance, these tests revealed the necessity for further optimization of coil design and fabrication process [3]. Main issues were related to insufficient space for coil expansion in the reaction and impregnation tooling, as well as insulation weakness, particularly in the coil ends and across coil layers. Modifications in coil design were gradually implemented in two HQ coils 12 and 13, both tested at Fermilab using a magnetic mirror structure (HQM01 and HQM02 respectively) [4]. These coils had the space increased for coil expansion during reaction by directly increasing the azimuthal space in the reaction mold (coil 12) or by eliminating one mid-plane turn in each layer (coil 13). This was done to reduce the azimuthal pressure on the coil during reaction.

The final design changes were introduced in coil 15 made of a cored cable, implementing smaller diameter strands than in previous coils. The new cable allows for increased room for azimuthal expansion during reaction. Coil 15 also included an increased axial gap and additional improvements to the end parts and the overall insulation system. This coil was tested in a mirror structure at Fermilab (HQM04) and demonstrated excellent quench performance reaching 97% of its short sample limit at 4.5 K and 94% - at 2.2 K [5].

HQ02 magnet consists of coil 15 and three new coils (16, 17 and 20) of the latest design with a stainless steel core in the cable. Details on the fabrication of the second-generation coils can be found in [6]. This paper describes the magnet design parameters and presents the test results at 4.5 K and 1.9 K.

II. HQ02 Magnet Design

A. Magnet design and parameters

HQ02 is a 1-meter long $\cos 2\theta$ magnet composed of 4 double layer coils assembled in a shell-type mechanical structure. All coils are made of a cored cable using 0.778 mm diameter Nb_3Sn strands of RRP 108/127 sub-element design.

The coils wound around a Titanium alloy pole are assembled into a coil pack made of 4 Aluminum alloy collars which are bolted against alignment keys inserted in each pole piece (Fig. 1). The collared coils are surrounded by 4 bolted iron pads. This sub-assembly is inserted into a yoke shell sub-assembly and partially loaded by the use of bladders and key.

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G. Chlachidze, G. Ambrosio, R. Bossert, D. Orris, C. Sylvester, M. Tartaglia, J. Tompkins and A.V. Zlobin are with Fermi National Accelerator Laboratory, Batavia, IL 60510 USA (e-mail: guram@fnal.gov, phone: 630-840-4622).

M. Anerella, A. Ghosh, J. Schmalzle, and P. Wanderer are with Brookhaven National Laboratory, Upton, NY 11973 USA.

F. Borgnolutti, S. Caspi, D.W. Cheng, D. Dietderich, H. Felice, A. Godeke, A. R. Hafalia, M. Marchevsky, P.K. Roy, G.L. Sabbi, T. Salmi and X.R. Wang are with Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA.

P. Ferracin is with the European Organization for Nuclear Research, CERN CH-1211, Geneve 23, Switzerland.

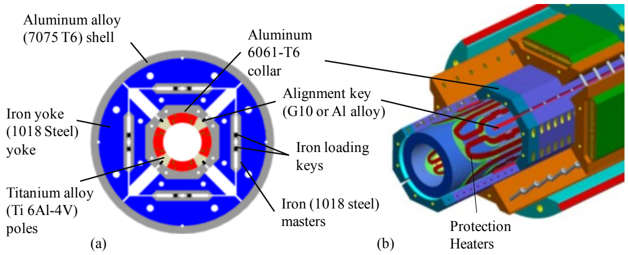

Fig. 1. (a)-HQ cross-section. (b)- Exploded view of the HQ02 magnet

The rest of the preload is reached during cool-down by the differential thermal contraction between the iron yoke and an external Aluminum shell. Axial preload is provided by 4 Aluminum rods connected to endplates. Detailed description of HQ magnet design can be found in [7-8]. HQ02 has been assembled at LBNL before being shipped for testing at FNAL. The assembly target was set so that the preload after cool-down insures compression of the coil up to 200 T/m. The magnet did not exhibit signs of mechanical limitations during the test. Strain gauge signals analysis remains in progress.

Intra-layer insulation in the new HQ coils was increased from 250 µm to 500 µm. Modifications to the coil ends (both LE and RE) included an axial shift in the outer layer end-shoes and spacers with respect to the inner layer. The radial dimension size of the end-parts and pole pieces remained unchanged. Some HQ02 magnet parameters are summarized in Table I.

TABLE I HQ02 PARAMETERS

Parameters	Units	
Restacked Rod Process (RRP) strand diameter	mm	0.778
Number of strands in the cable		35
Nominal reacted bare cable dimension	mm	15.002
Nominal reacted bare cable mid-thickness	mm	1.44
Nominal S2-glass sleeve insulation thickness	µm	100
S2-glass sleeve insulation thickness @ 7 MPa	µm	86
Nominal keystone angle	deg	0.75
Short sample current I_{ss} at 4.5 K / 1.9 K	kA	16.5 / 18.3
Short sample gradient at 4.5 K / 1.9 K	T/m	186 / 205

III. TEST RESULTS

HQ02 was tested at Fermilab's Vertical Magnet Test Facility (VMTF) [9] in May-June 2013. The main goal of this test was to study quench performance and field quality of the magnet at the LHC operation temperature of 1.9 K. Therefore the header assembly rated for currents only up to 15 kA, but equipped with a lambda plate for testing magnets at superfluid helium temperatures, was used in this test.

Quench positions were determined by voltage taps covering both the inner and outer coil layers. Locations of the voltage taps in the inner and outer coil layers are shown in Fig. 2.

A. *Quench history*

The HQ02 cold test started with training at 4.5 K. Regular ramp rate of 20 A/s was used during the training. History of the training quenches with location of the quench origin is shown in Fig. 3.

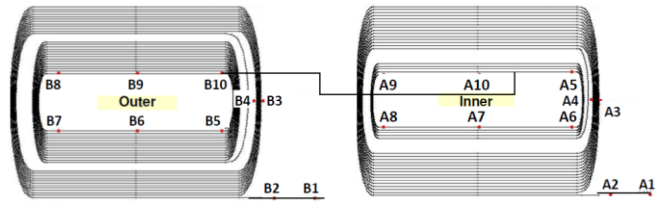

Fig. 2. Voltage tap location for the inner and outer coil layers.

The magnet reached 80% of its short sample limit (SSL) in the second quench corresponding to a field gradient of 150 T/m. The following quenches showed slow training. The highest quench current of 14.3 kA was reached during the initial training at 4.5 K, corresponding to 87% of SSL. All training quenches initiated in the pole-turn segments (the high field area) of the inner or outer coil layers. Cooling-down to 1.9 K was decided to accelerate training at 1.9 K.

At 1.9 K, the magnet reached the current limit of 15 kA or 82% of SSL in two training quenches. Due to limitations set by the header assembly further training was not possible.

The next steps in the test plan included the ramp rate dependence and quench protection studies. The latter involved high MIITs quenches to investigate the magnet performance in conditions expected in the accelerator. After these tests the magnet demonstrated a minor detraining, but in two quenches it reached again the current limit of 15 kA.

After testing at 1.9 K was completed, the quench performance at 4.5 K was verified. The magnet reached the current limit of 15 kA, corresponding to 92% of SSL at this temperature, without any training.

HQ02 training quenches both at 4.5 K and 1.9 K developed in the high field area (Fig. 3). The Residual Resistivity Ratio (RRR) of HQ02 coils was measured during magnet warm up, with values varying from 80 to 90 in coils 15 and 16, and from 130 to 140 in coils 17 and 20.

B. *Ramp rate and temperature dependence*

The ramp rate dependence of the quench current of HQ02 at 4.5 K and 1.9 K is presented in Fig. 4. Since the magnet was trained only up to the current limit of 15 kA, the maximum current for the ramp rate study was set at 14605 A, corresponding to 80% of SSL at 1.9 K and 89% of SSL at 4.5 K. No quenches were observed up to the maximum current for ramp rates below 200 A/s at 1.9 K and 150 A/s at 4.5 K.

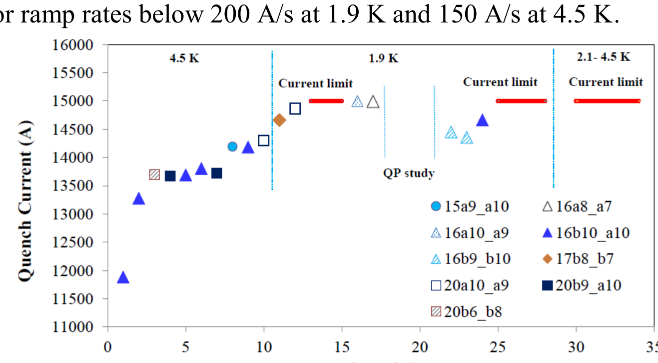

Fig. 3. HQ02 quench training at 4.5 K and 1.9 K. Voltage tap segments of the quench origin are also shown.

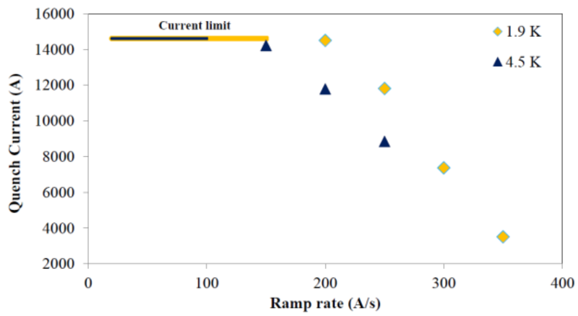

Fig. 4. HQ02 ramp rate dependence. Horizontal lines indicate the area of ramp rates without quenching up to the maximum quench current.

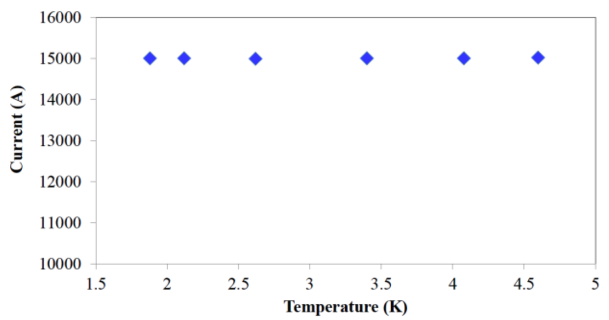

Fig. 5. Temperature dependence of the maximum current reached at a regular ramp rate of 20 A/s.

The expected temperature dependence is observed for the ramp rate quenches. All quenches at ramp rates of 150 A/s and above occurred in the mid-plane blocks of the inner and outer layers of coil 17.

Ramp rate dependence was studied also for ramping down from a maximum current of 14605 A. No quenches were observed for ramp rates 13-300 A/s both at 4.5 K and 1.9 K.

The results of the temperature dependence study are presented in Fig. 5. The maximum current limit of 15 kA was reached without quenching at all temperatures. Temperature dependence study was performed at a regular ramp rate of 20 A/s.

C. Protection heater study

HQ02 protection heaters (PH) are installed both on the inner and outer coil surfaces. 11-mm wide and 0.025-mm thick stainless steel strips cover the whole coil length. Heater shape is designed for the optimal coverage of all turns.

The electrical insulation between the PH and coil was 76 µm of Kapton layers in HQ02 instead of 25 µm Kapton in HQ01. One of the most important parameters to study the PH efficiency is heater delay – the time between the heater ignition and the start of quench development in the coil.

The outer layer (OL) heater delays in HQ coil 20 are shown in Fig. 6. The heater delays are consistent at 4.5 K and 1.9 K. At 80-85% of SSL heater delays are between 18 ms and 16 ms. The average PH peak power density in these tests was about 55 W/cm^2 with a time constant (RC) of the heater circuit ~45 ms. Additional heater tests showed, that variations in the heater delays for different HQ coils are 2-5 ms for currents up to 10 kA. The inner layer (IL) heater delays are shorter for 6-7 ms at currents up to 80% of SSL.

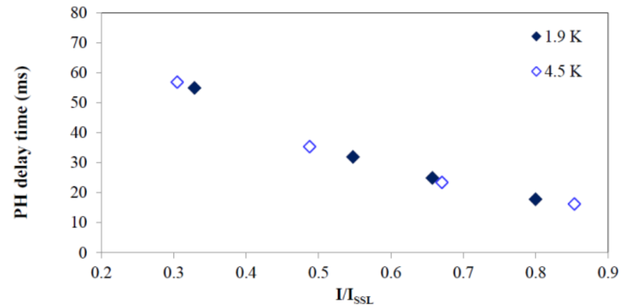

Fig. 6. Outer layer PH delays in coil 20 at 4.5 K and 1.9 K.

Heater delays could be further reduced by increasing the PH peak power density. The heater delay as a function of the peak dissipated power density at 65% of SSL (1.9 K) is shown in Fig. 7. The time constant of the heater circuit was ~45 ms.

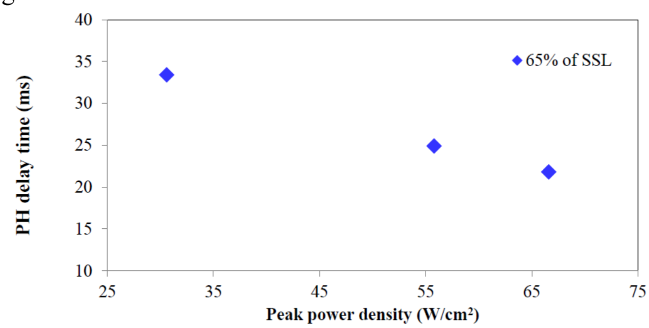

Fig. 7. Outer layer PH delay as a function of the peak power density measured at 1.9 K.

D. Quenches with high MIITs

Cable maximum temperature during the quench, or so-called hot-spot temperature, is correlated with the accumulated quench integral (QI). In order to avoid overheating and related risk of damage to the conductor it was decided to limit the maximum quench integral for this test at ~15 MIITs, corresponding to a conservative hot-spot temperature of about 200 K.

The magnet quench detection system was manually tripped with the extraction dump delayed for 1000 ms and the outer layer heaters only in the magnet protection system. The dump delay of 1000 ms is essentially equivalent to the operation without the extraction dump. Magnet current was gradually increased to experimentally verify the QI dependence on the magnet current and safely approach the 15 MIITs limit.

QI as a function of the magnet current is shown in Fig. 8. The hotspot MIITs, calculated for the magnet current decay only after the quench development, and the decay MIITs, calculated for the whole current decay, were estimated at each current. High MIITs test was stopped at 13 kA (72% of SSL at 1.9 K) in order to avoid accumulated QI above the limit of 15 MIITs.

Extrapolation of the QI dependence on the magnet current in Fig. 8 shows that without any extraction dump and with the outer layer heaters only in protection, the expected quench integral at 80% of SSL is less than 15 MIITs.

The accumulated QI without the extraction dump and with the 10 mΩ extraction dump are compared in Fig. 9. Even the small dump resistor helps to reduce the accumulated quench integral almost for 2 MIITs for currents up to 60% of SSL.

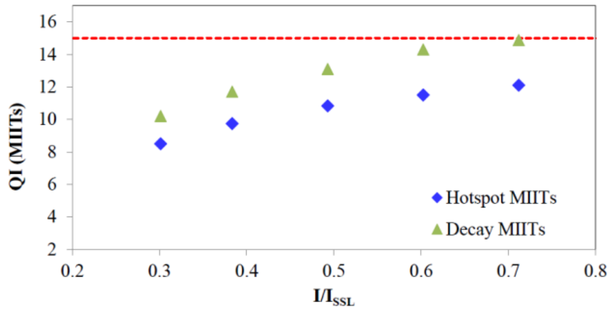

Fig. 8. QI as a function of the quench current ratio to the SSL at 1.9 K.

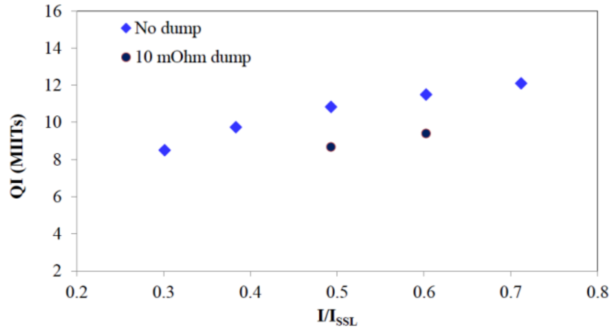

Fig. 9. QI without and with the extraction dump at 1.9 K.

E. Radial (OL to IL) quench propagation

Quenches with the delayed extraction described in the previous subsection were used for study of the quench propagation from the outer to the inner coil layer at 1.9 K. The quench propagation time between the coil layers at different currents is shown in Fig. 10. These results are in agreement with the measurements in other Nb_3Sn magnets [10].

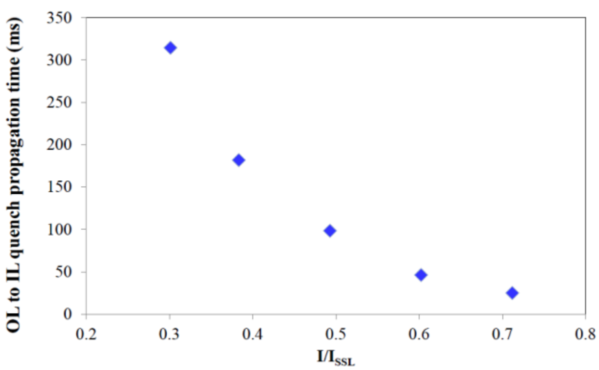

Fig. 10. Quench propagation time between the outer and the inner coil layers at 1.9 K

IV. Discussion of Test Results

HQ02 magnet with the new generation of coils demonstrated improved performance both at 4.5 K and 1.9 K. The magnet reached the maximum current limit of 15 kA at all temperatures. Magnet exhibited a stable performance at 1.9 K, no signs of conductor instabilities were observed during the whole test. The magnet current was held many hours at 14.6 kA during the magnetic measurements both at 4.5 K and 1.9 K [11].

The ramp rate dependence in HQ01a and HQ02 at 4.5 K is compared in Fig. 11.

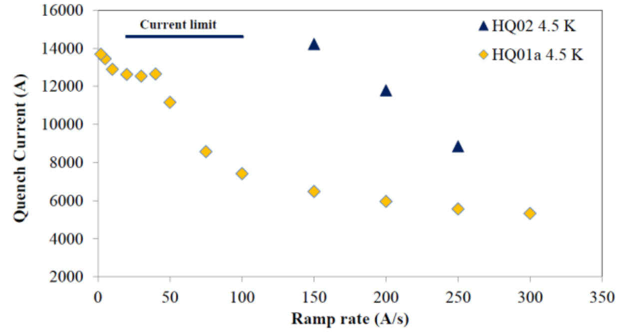

Fig. 11. Ramp rate dependence of the quench current in HQ01a and HQ02.

HQ02 test results confirm that the stainless steel (SS) core in the cable did not introduce any degradation in the magnet performance at currents up to the limit of 15 kA. Field quality measurements also confirmed that the SS core in the cable helps to control eddy current related losses [11].

Test at higher currents is required to complete the study of HQ02 quench performance.

V. Conclusion

HQ02 magnet with Nb_3Sn coils of the improved design has been built at LBNL and then successfully tested at Fermilab. All coils were made with additional space for the azimuthal expansion and with improved electrical insulation. The maximum magnet current in this test was limited by the 15 kA header assembly, equipped with a lambda plate for testing at superfluid temperatures. The magnet reached the maximum current limit of 15 kA at 4.5 K, 1.9 K and at intermediate temperatures, corresponding to a maximum of 92% of SSL. All training quenches developed in the high field area.

No quenches were observed up to the maximum current for ramp rates below 200 A/s (1.9 K) and 150 A/s (4.5 K), as well as in down ramps from 14.6 kA and for ramp rates up to 300 A/s both at 4.5 K and 1.9 K.

HQ02 results demonstrate that a stainless steel core can be introduced in the Nb_3Sn coils without causing performance degradation. The magnet quench performance at higher currents will be investigated in the following test.

Acknowledgment

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