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Test Results of the LARP HQ02b Magnet at 1.9 K

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Keywords: Niobium-tin, Superconducting coils, quadrupole magnet.

Abstract

The HQ magnet is a 120 mm aperture, 1-meter-long Nb3Sn quadrupole developed by the LARP collaboration in the framework of the High-Luminosity LHC project. A first series of coils was assembled and tested in 5 assemblies of the HQ01 series. The HQ01e model achieved a maximum gradient of 170 T/m at 4.5 K at LBNL in 2010-2011 and reached 184 T/m at 1.9 K at CERN in 2012. A new series of coils incorporating major design changes was fabricated for the HQ02 series. The first model, HQ02a, was tested at Fermilab where it reached 98% of the short sample limit at 4.5 K with a gradient of 182 T/m in 2013. However, the full training of the coils at 1.9 K could not be performed due to a current limit of 15 kA. Following this test, the azimuthal coil pre-load was increased by about 30 MPa and an additional current lead was installed at the electrical center of the magnet for quench protection studies. The test name of this magnet changed to HQ02b. In 2014, HQ02b was then shipped to CERN as the first opportunity for full training at 1.9 K. In this paper, we present a comprehensive summary of the HQ02 test results including: magnet training at 1.9 K with increased pre-load, quench origin and propagation, and ramp rate dependence. A series of powering tests was also performed to assess changes in magnet performance with a gradual increase of the MIITs. We also present the results of quench protection studies using different setting for detection, heater coverage, energy extraction and the Coupling-Loss Induced Quench (CLIQ) system.

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***Abstract*— The HQ magnet is a 120 mm aperture, 1-meter-long Nb_3Sn quadrupole developed by the LARP collaboration in the framework of the High-Luminosity LHC project. A first series of coils was assembled and tested in 5 assemblies of the HQ01 series. The HQ01e model achieved a maximum gradient of 170 T/m at 4.5 K at LBNL in 2010-2011 and reached 184 T/m at 1.9 K at CERN in 2012. A new series of coils incorporating major design changes was fabricated for the HQ02 series. The first model, HQ02a, was tested at Fermilab where it reached 98% of the short sample limit at 4.5 K with a gradient of 182 T/m in 2013. However, the full training of the coils at 1.9 K could not be performed due to a current limit of 15 kA. Following this test, the azimuthal coil pre-load was increased by about 30 MPa and an additional current lead was installed at the electrical center of the magnet for quench protection studies. The test name of this magnet changed to HQ02b. In 2014, HQ02b was then shipped to CERN as the first opportunity for full training at 1.9 K. In this paper, we present a comprehensive summary of the HQ02 test results including: magnet training at 1.9 K with increased pre-load, quench origin and propagation, and ramp rate dependence. A series of powering tests was also performed to assess changes in magnet performance with a gradual increase of the MIITs. We also present the results of quench protection studies using different setting for detection, heater coverage, energy extraction and the Coupling-Loss Induced Quench (CLIQ) system.**

***Index Terms*— Niobium-tin, Superconducting coils, quadrupole magnet.**

I. Introduction

THE High Gradient Quadrupole (HQ) magnet is developed within the LARP collaboration for the High Luminosity upgrade of the CERN Large Hadron Collider.

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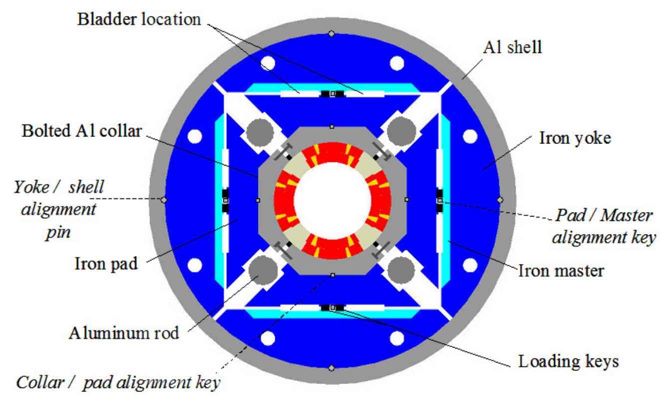

Fig. 1. High Gradient Quadrupole (HQ) transverse cross-section.

The HQ magnet structure has been used in two different assemblies, HQ01 and HQ02 with two generations of Nb_3Sn coils [1]-[3]. The HQ cross-section is shown in Fig. 1. In 2011-12, nine coils, C1-C9 were tested in the HQ01 magnet as reported in [4]-[6]. In 2013, four coils C15, 16, 17, 20 were tested in the HQ02 model [7]. The conductor is made of 35-strand (RRP108/127) cable with a short sample current of 18.2 kA at 1.9 K (16.6 kA at 4.3 K) [8]. The HQ02 cable incorporated a 25-mm-thick, 8-mm-wide stainless steel core between the two layers of strands that significantly reduced the AC loss from inter-strand coupling currents [9].

A first configuration of HQ02 was tested twice at Fermilab at temperatures ranging from 1.9 K to 4.5 K. These two tests refer to as HQ02a [7] and HQ02a2. The magnet trained rapidly to its operational current, defined as 80% of the short sample limit (I_{ss}). However, slower training was observed above that level. It was attributed to insufficient coil preload, consistently with the conservative targets selected for the first assembly.

In 2014, a second configuration, named HQ02b with a 15 MPa increase of azimuthal coil pre-load [2] has then been tested at CERN at the vertical test station of SM18 at 1.9 K and 4.3 K. For this test, a third current lead was installed at the middle of the magnet in order to be able to test the new protection system developed at CERN, called the Coupling-Loss Induced Quench (CLIQ) system [10]. It aims at discharging a current at the quench detection trigger. This extra current oscillates at a given frequency and creates enough AC loss within the conductor to provoke the quench of the whole coil [11]-[14]. In the next section of this paper, the organization and the main parameters of the 3-week test offered by the facility for HQ02b are presented. The HQ02b experiment had four main goals that are dealt along this paper. The first one was to check the effect of the increased pre-stress on the coil performances during the magnet training as compared to HQ02a. In section III, the measurement of HQ02b performances are presented. The second goal was to acquire more data on the relative efficiency (delay) of the Inner and Outer Layer (IL & OL) Protection Heaters (PH) protection system. The measurements of the PH delay between their firing and the detection of the quench initiation are presented in section IV. The third goal was to assess for the first time the ability of CLIQ to protect a high field Nb_3Sn quadrupole magnet as discussed in section V. As discussed in the section VI, the 1.9 K limiting quenches were located, in a reproducible way, at one of the coil pole straight sections (highest field area) providing the proper condition to study how the Joule energy deposited during the quench affects the magnet performance. In section VI, the attempts to reach enough deposited energy to cause degradation, both in a reversible (de-training) and irreversible (degradation) ways are presented in detail. The assessments of the Hot Spot Temperature (HST), the maximum value reached during the quench, computed from the voltage and the current are compared with theoretical adiabatic expectation within a range from 100 to around 450 K.

II. Test Main Features

A. *Test instrumentation and electrical Quality Assurance*

The magnet instrumentation includes voltage taps, quench antenna (QA) and acoustic sensors for quench characterization. Strain gauges are integrated for mechanical behavior measurements [15]-[17]. The azimuthal and axial strains are measured on the instrumented Aluminum shell and on the coil Titanium pole pieces. Unfortunately, during the first test of HQ02a, the coil gauges started to produce erroneous signals, attributed to defective temperature compensation. From HQ02a to HQ02, the magnet was not disassembled preventing the replacement of the coil strain gauges. Given these circumstances, the coil gauges data were disregarded during the test and preload level were monitored via shell strain gauges.

The high potential test was performed with the following protocol:

- Coils to ground: 500 V for 1 min
- PH to ground: 1 kV for 1 min
- Coil to PH: 1 kV for 1 min
- Spot Heater to Coil 500 V for 1 min

All magnet tests passed at room temperature (leakage of the order of ten nano-ampere), confirming the effectiveness of the design changes implemented in the second generation of coils. A coil to ground failure at cold after 700 V was discovered attributed to one of the current lead of the test facility based on impulse test results. In consequence, the dump resistor had to be lowered from expected 60 mΩ to 40 mΩ for regular training quenches to lower the voltage across the magnet down below 700 V during the current extraction. In addition, during a CLIQ discharge, the voltage at the coil raises up to typically 500 V. This voltage adds up to the voltage from the extraction resistance when the switch opens of about 700 V. To avoid summing up both voltages, two options are possible: delay the extraction with respect to CLIQ firing (enough to get opposite voltage after half a period) or use a smaller dump keeping the HST below 150 K in case of CLIQ misfires. The second option was chosen because it comes out that CLIQ was able to quench the magnet already at low current insuring low energy with a 10 mΩ dump. Regarding the protection heaters, their firing units were configured to reproduce the powering characteristics of HQ02a test of 50-55 W/cm^2 power with a time constant of 40-45 ms. It is recalled that Spot Heater (SH) are also integrated at the coil poles. For the quench detection regular setting, the delay between initiation (400 mV on differential signals) and protection trigger was 10 ms.

B. *Organization of the test*

Due to electrical and cryogenics constrains, only three quenches per day could be performed instead of 4-5 as originally expected. The test plan was adapted accordingly as it is now detailed. The different goals of the experiment have been addressed along the 3-week experiment combining the PH and CLIQ tests at low current first. The training was divided in two phases, with PH and CLIQ studies carried out in between, to provide the most critical data for their specific studies. Their systems have been fired at various currents (ranging from 0 to 14.5 kA) independently or together (hybrid test). After the training was resumed, the higher energy quenches were performed with verification quenches in between. Fig. 2 displays all the quenches performed on HQ02b at different currents in a chronological order. All quenches were done at 1.9 K except two quenches at 4.3 K (red cross: quench 32 and last). Three hours were needed to go back to 1.9 K after regular training quenches (60% of the stored energy dissipated in the Helium bath, 40 % in the dump) but up to seven hours after the highest energy quenches. At maximum current, the deposited energy was sufficient to transit the whole HeII bath to supercritical He and boil off up to 70 m^3 of gas over 0.8 m^3 of liquid in the cryostat. The quenches at 4.3 K were also the longest to recover because they do not profit for the superfluid transition to absorb energy and thus larger amount of evaporated liquid.

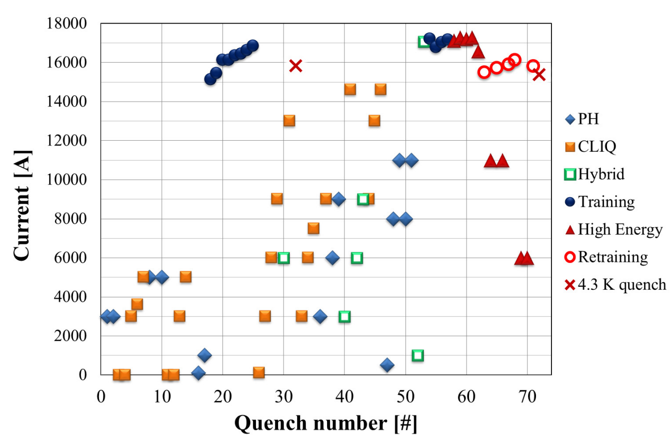

Fig. 2. Organization of the quenches performed on HQ02b. PH and CLIQ systems tested at various current. Training at 1.9 K divided in two parts. More protection tests in between. Higher energy quenches with verification quenches done at last. Two quenches at 4.3 K performed during the test.

III. MAGNET PERFORMANCES

A. *Mechanical performance*

During cool-down, the differential thermal contraction between the Aluminum shell and the yoke provides additional compression to the coils. Between HQ02a and HQ02b, the measured shell azimuthal average stress after cool-down was increased from 164 MPa to 203 MPa. This increase of azimuthal stress tension produces an increase of coil compression. Based on FEM analysis, the equivalent gain of coil preload is of the order of 15 MPa. Despite the lack of coil strain gauge data, shell strain gauge data along with improved training performance confirmed the successful increase in coil preload.

B. *Quench currents during training*

As shown in Fig .2, during the first training, eight quenches have been performed. The first quench is at 83% of I_{ss}. After 8 quenches, the magnet reaches 93% with a training rate of 200-240 A per quench. The first quench at 4.3 K, done after those, was at 95% of I_{ss} comparable to HQ02a (270 A decrease). This quench confirmed that former CLIQ tests did not damage the coils. For the second training, a plateau at 95 % of I_{ss} was obtained with the highest current at 17271 A. The second quench at 4.3 K and the last of the whole test was 93% of I_{ss}.

C. *Training curves*

Fig. 3 shows the first part of the training curves of HQ02a and HQ02b for different temperatures. From the comparison, the beneficial effect of the increase of the azimuthal pre-stresses is clearly visible with HQ02b in term of better training rate (150 - 250 A per quench) and a higher maximum current.

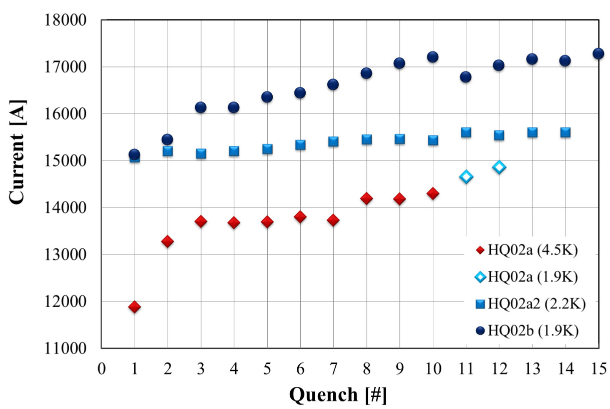

Fig. 3. HQ02a and b first training comparison at different temperatures. The benefit of the increased pre-stress between both assemblies is visible.

D. *Quench location and propagation velocity*

Fig. 4 shows the scheme of the voltage taps location along the turns of the coil outer (B) and inner (A) layers and an example of voltages signals acquired during a quench. It shows the quench propagation from an initiation in coil 20 at pole turn segment 20A06-07. Coil 15 outer and inner layer quench 5 ms later. During the training, the first five quenches were located either in coil 20 and 15 or in coil 17 and 16 at outer layer, followed by the inner layer mid plane. The next three quenches were located at coil 20 inner layer last turn (A5-A4) presumably at the coil head due to the observed fast propagation to segment A4-A3. For the second training part, the first three quenches were at coil 20 segment A4-A3 with propagation to segments A3-A2 and A5-A4. The pole turn A8-A7 started quenching as well. Next quenches were located at the pole turn A8-A7 of coil 20 with axial propagation to adjacent segments. Coil 15 was quenching 5 ms later at segment A3-A4 and A9-A10. Coil 16 and 17 were not quenching. Based on time of flight, the quench propagation velocity is measured at 30±2 m/s for plateau quenches.

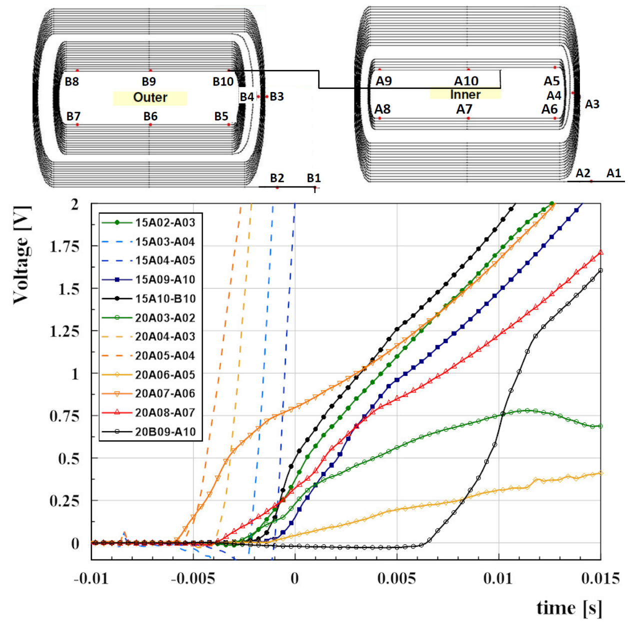

Fig. 4. HQ02b voltage tapes scheme and typical voltage pattern for a plateau quench. Coil 20 and coil 15 are quenching almost simultaneously but quenches initiates at pole turn.

E. *Ramp rate dependence*

Fig. 5 shows the dependence of the quench current with the ramp rate at different temperatures. In the plot, the limited range of HQ02b ramp rate data is combined with more extensive studies performed on HQ02a. The effect of the core cable is visible as the current does not significantly decrease up to 150 A/s. Compared to HQ01e results in [6], the ramp rate dependence is much less pronounced.

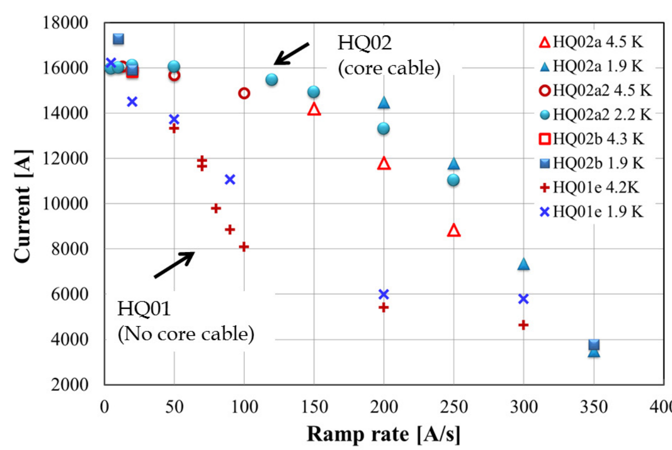

Fig. 5. HQ02a and b (core cable) quench current ramp rate dependence at different temperature. HQ01e (no core cable) data is displayed as well.

IV. Quench Protection

A. Protection Heater efficiency

The test consists in activating one heater strip either on OL or IL coil at different magnet current and to measure the quench initiation delay. The test was repeated for the OL at several temperatures and for different coils to check the reproducibility of the measurement. The measured heater resistances at 1.9 K were about 5.2 Ω (IL) and 4.6 Ω (OL) in agreement with expectation. The heaters are powered with a capacitor discharge with peak voltages of 270 or 275 V and decay time constant of 50 ms (IL) or 45 ms (OL) to obtained a peak currents and powers of 53 A and 54 W/cm^2 for IL and 58 A and 54 W/cm^2 for OL. The heater delay as a function of the normalized magnet current is shown in Fig. 6.

The delays at operational current (80% of I_{ss}) are about 18 ms on OL and 11 ms at IL. At lower currents the delays increase faster than linearly, at 40% of I_{ss} both layers having delays of about 40 ms. This test confirms the previous measurement from FermiLab, where the IL heater is more efficient than the OL heater, at least at high current. This is in contrary to what was observed in HQ01e [6]. On one hand, the shorter delay on IL is expected due to lower temperature margin and larger heater coverage. But on the other hand, both magnets manifest non-uniformly degraded heater contact on coil inner surface due to detachment of various insulation layers. Investigation of extend of this damage in HQ02 coils is ongoing.

The variation of OL heater delay in different coils is about 10-20%, so this should be taken as the minimum uncertainty for the protection design. The variation at low current is larger because of the slower transition to resistive state and the associated greater sensitivity to the quench onset definition from the voltage tap signals or to the heater powering [18]. In the plot is also shown the prediction by a heat diffusion simulation code CoHDA [18]. The delays are close to the expectation, apart from the lowest current in the coil inner layer. Further analysis of the HQ02 heater delays and uncertainties, as well as comparison with HQ01e can be found in [19] and [20].

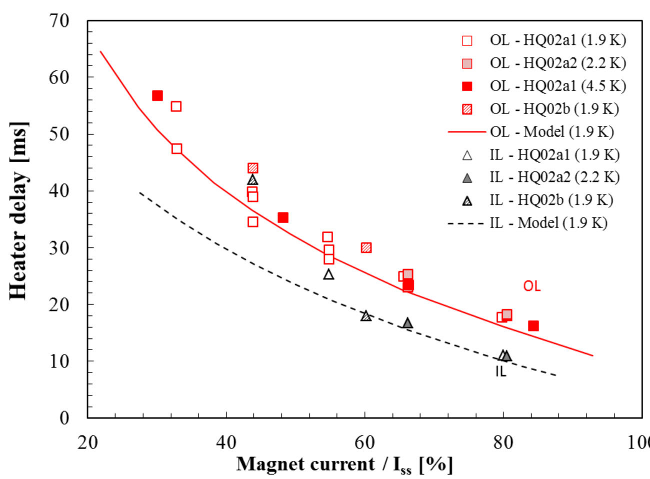

Fig. 6. Protection heater delay measured at various magnet operation currents and temperatures (markers). Delays predicted by simulation are shown (lines).

B. Coupling-Loss Induced Quench tests

CLIQ is composed of a capacitor bank C that is charged to an initial voltage U_0. Upon quench detection, the capacitors are discharged and an AC current is introduced. Two CLIQ units with different capacitance value (28.2 and 8.8 mF) and charging voltage (between 50 and 500 V) were successfully tested as protection system.

Fig. 7 shows the current decays for two quenches with the magnet protected either by 20 mΩ EE and PH discharge or by CLIQ and 10 mΩ EE. For both training quenches, the current were about 17.1 kA. The current discharged from CLIQ is also displayed. Fig. 7 shows on the right axis, the MIITs representative of the energy deposited on the cable during the quench and the current discharge, as defined in section V. A.

Although the value of the dump resistor during the CLIQ test was halved, the magnet was discharged more quickly by CLIQ. The MIITs is then lowered due to faster and homogeneous transition to the normal state for CLIQ with respect to PH. It should be noted that while this is a very promising result, it is not directly applicable to the case of a longer magnet. A detailed analysis of the CLIQ results and their scaling to full-scale magnets operating in the accelerator can be found in [21].

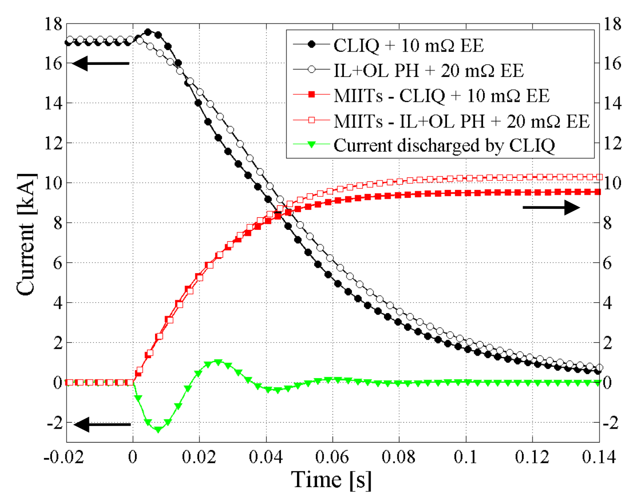

Fig. 7. Magnet current and MIITs during two training quenches protected either by PH (54 W/cm^2) or by CLIQ (C=28.2 mF, U_0=500 V).

V. High Energy Quenches

A. Test description

For this test, the energy deposited on the conductor during the quenches was gradually increased controlling the delay between quench detection and protection trigger with the goal of raising the conductor's temperature. To quantify this energy, the MIITs [MA^{2}s] will be used. It is defined as the integral of the square of the current I, t_q the quench detection and t_f the end of the current extraction that is written:

$$MIITs = \int_{t_q}^{t_f=+\infty} I^2\,dt. \quad (1)$$

For successive natural quenches (standard protection), the delays that were used are 15, 25 and 66 ms getting the following MIITs: 13, 13.5 and 15.8 MA^2s. It yields to HST of 200 K and 250 K. As shown in Fig. 8, a dramatic drop of the supplied current (from 16.6 to 8.4 kA after 66 ms) was observed during the quench due to the fast resistance growth of the coil (from quench propagation and quench back). In these conditions, further increases in the delays would not have resulted in an increase of the hot spot.

It should also be noted that the detraining effect associated with these quenches was much less pronounced with respect to the case of HQ02a. We attribute the improvement to the increased pre-load. However, a detraining of about 7% was observed following these quenches.

We therefore attempted to provoke a quench at lower current (11 kA) where a lower propagation speed is expected. These quenches were triggered firing one strip of coil 16 IL PH with 110 and 300 ms extraction delay getting 14.7 and 19 MA^2s. At this point the current drop was again too large (1.3 kA left after 300 ms delay) to get temperature higher than 250 K. Despite the increase in MIITs with respect to the high current natural quenches, no significant increase of the hot spot temperatures was obtained due to the lower field. It was then decided to further decrease the current to 6 kA with a delay of 650 ms which resulted in 21 MIITs. However, the pole turn were not quenching during this low current quenches, only A2-A4 and A4-A5. Finally to further limit the quenched zone, the Spot Heater (SH) of Coil 17 was used and triggered (6 A, 1 s pulse) at 6 kA with 650 ms extraction delay. This solution enables to get to 24 MIITs or and maximum temperature of 420±20 K.

For each of the three phases of the high MIITs study (natural quenches, 11kA and 6 kA provoked quenches) a different coil was used (coil 20, 16 and 17, respectively). In this way, the effect of progressively higher quench integrals could be assessed on a fully performing coil. The quenches performed after 19 MIITs with coil 16 PH was still situated in coil 20 pole turn showing no effect of it. The last quench at 1.9 K and 4.3 K after 24 MIITs occurred at the inner layer of coil 17 showing 2% de-training due to SH firing on that coil.

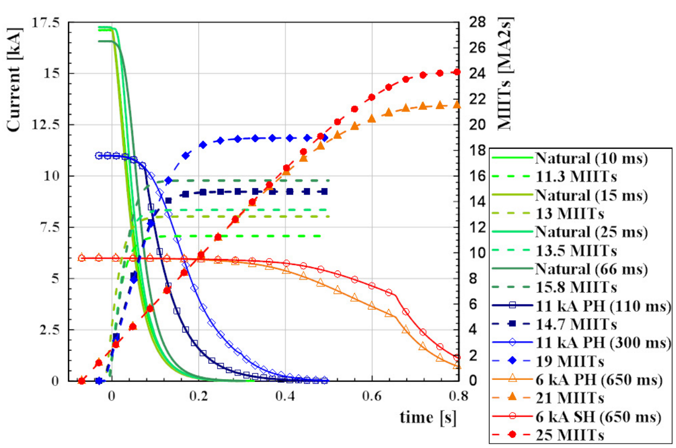

Fig. 8. Plot of the current (solid) and the MIITs (dashed) vs. time for the highest energy quenches. In green, blue and red, respectively, the natural, the 11 kA and 6 kA provoked quenches. 24 MIITs was obtained with SH firing.

Due to time constrain, it was not possible to perform a full re-training and performance verification following each phase. This limits the constraints on the degradation level that might have been caused by these quenches. Nevertheless, in the last ramp at 1.9 K the magnet reached 88% of its short sample performance based on extracted strand measurements, and 93% in the last verification quench at 4.3 K, indicating that no major damage occurred during the test campaign. The effect of multiple quenches in the same area was not investigated.

B. Hot Spot Temperature assessment methods

For the high energy quenches, the HST is assessed from the experimental current and voltage measurement using three different methods that are exposed in [22]. The first method uses the copper resistivity as thermometer, the second and the third are based on an adiabatic model taking as input either the experimental current square or the product of the voltage by the current. Pure theoretical adiabatic 0-D model is also used to compute the HST as function of the MIITs for two different fields and RRR. For the different quenches, Fig. 9 shows the calculated hot spot temperatures as function of the MIITs along with the theoretical curves. The measurements are coherent although the three proposed methods may vary up to 50 K at the highest temperature. A maximum temperature of 400-450 K is computed for the highest MIITs.

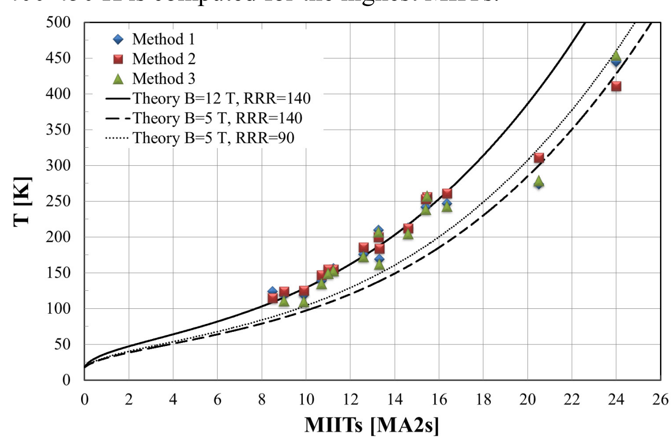

Fig. 9. Hot spot temperature for experimental (markers) and theoretical (lines) estimates function of the MIITs for the quenched straight segments.

VI. Conclusion

The HQ02b magnet has been successfully tested at CERN for three weeks. The experiment has shown the beneficial effect of increased of azimuthal coil pre-stress on the magnet performances, in terms of higher current and faster training rate. The Protection Heater efficiency has been measured completing data from HQ02a. For the first time CLIQ system has been tested on Nb_3Sn quadrupole. The test has proved the feasibility of the system to protect such short length magnet. At last, the deposited energy during a quench on the conductor has been gradually increased in order to study the limit in MIITs before which the magnet performance starts to decrease. No significant effect has been observed after 25 MIITs. However, more tests are needed in order to fully characterize the effect of the MIITs on possible degradation.

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