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Cold Test Results of the LARP HQ Nb_3Sn Quadrupole Magnet at 1.9 K

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***Index Terms*— LARP, HQ, Nb_3Sn quadrupole, magnet protection.**

I. Introduction

For the luminosity upgrade of the Large Hadron Collider at CERN, the LHC Accelerator Research Program (LARP) collaboration is currently developing prototypes of large-aperture and high-gradient quadrupole magnets based on Nb_3Sn technology [1], [2], [3]. In this framework, the High gradient Quadrupole (HQ) is a one-meter-long prototype with a 120 mm aperture, designed to operate at a gradient of 170 T/m which corresponds to a current of 15 kA at 1.9 K with 20% of margin with respect to the load line [4-7].

The HQ test campaign performed at LBNL at 4.4 K has allowed several coils to be tested using the same collar and shell structure. The latest assembly called HQ01-e reached 86% of its short sample limit at 4.4 K [8]. Its four coils are referred to as C5, C7, C8 and C9 and are made of 35 strand cables with 50 μm Nb_3Sn filaments for C5 and C7 (OST RRP 108/127) and 70 μm for C8 and C9 (OST RRP 54/61) [9], [10]. After the test of HQ01-e at LBNL, the magnet has been shipped to CERN in March 2012 in order to study for the first time its behavior at 1.9 K and to perform additional magnetic measurements with dedicated equipment.

In this paper, we introduce the test setup at CERN and we discuss the results of the standard test in terms of (i) training quench performance, (ii) ramp rate dependence and (iii) quench location. Measurements of the splice resistances, RRR of the coils, inductance and AC losses are also given. The test was also dedicated to the protection of the magnet with the investigations on the Quench Heaters (QHs) efficiency and the occurrence of quench back during fast discharge. Moreover, the inner layer protection heaters and the dump resistor were removed for high energy quenches. At last, the mechanical behavior of the magnet during the cold powering test is analyzed using the records of the various strain gauge signals.

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II. Test Setup at CERN

At the CERN test facility, the HQ01-e magnet has been tested in the vertical cryostat (600 mm inner diameter, 3.8 m depth, filled with liquid He) using a 20 kA power supply. The cryostat is designed to sustain 3 bars absolute pressure before the safety valve opens evacuating the He gas evaporated during a quench. The pressure rise is of great concern because of the high deposited energy (0.86 MJ at short sample limit) and the limited space between the cryostat inner wall and the magnet outer edge (15 mm space). Therefore the pressure is monitored during all tests and data is carefully analyzed after each quench to avoid damage of the test station. The cryostat is instrumented with level gauges and temperature sensors to monitor the liquid level and the gas temperature.

A. *Energy extraction*

An external dump resistor is electrically connected in series with the magnet to extract the stored energy when a quench is detected. The value of its resistance was chosen to be 40 mΩ to limit the voltages across the magnet at high current to a maximum of 760 V (I_{ss} = 19 kA @ 1.9 K), having a safety margin of 240 V w.r.t. preliminary insulation test performed at cold condition (1 kV). The dump resistor was increased to 120 mΩ for the first few provoked quenches at low current.

B. *Quench detection*

To detect and locate transitions during a quench, voltage-taps independently monitor voltage rises across segments of cable (20 taps per coil), the splices (13 taps) and the two current leads of the test cryostat. Each consecutive segment is connected to an operational amplifier in a differential direct signal mode (as opposed to the derivative mode used at LBNL). The signals are acquired using fast DAQ system based on PXI NI cards with a record rate of 400 kHz. Regarding the positions of the taps on the coils with their referenced name one should refer to [8].

C. Magnet protection

To protect the magnet, 16 quench heaters (QH, four per coil, two per layer) are connected by pair in four parallel circuits powered by eight capacitors charged with negative voltage. According to the QHs resistance (5±0.15 Ω at 1.9 K), a voltage of -250 V is used to charge the 14 mF capacitances so that a current discharge of 50 A per strip provides a peak power of 50 ± 5 W/cm^2. Two QHs (C5B02, C7B02) had to be disconnected because of weak insulation, per results of the high potential test.

The protection scheme is as follows: (i) current cut off, (ii) dump of the energy into the external resistor and (iii) QHs firing is triggered when a voltage imbalance between the two magnet halves or in the absolute voltage across the coils exceeds a given threshold during a given validation time. For regular quench, the three steps are launched simultaneously. To limit the Joule heating during a quench, the threshold is fixed at 100 mV for a validation time of 10 ms.

Due to flux jumps occurring at low current, a second set of thresholds had to be set up to avoid triggering the protection with unnecessary dump of the current. To define this second set of thresholds (1 V for 10 ms), a dedicated study was conducted on the voltage signals to map the flux jumps activity: the maximum amplitude and the duration of the jumps have been identified. In general, the amplitudes are lower at 1.9 K than at 4.2 K with respectively a maximum of 750 mV versus 2 V. Their frequency of occurrence is higher at the lowest temperature (every hundred millisecond vs. every second). No jump was detected above 10 kA, therefore the threshold was manually reduced after 10 kA at their definitive values. These features are represented in Fig. 1, where the voltage peaks are shown as function of the current for both temperatures.

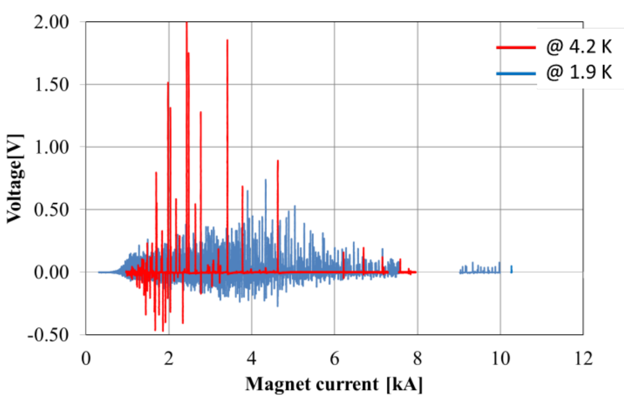

Fig. 1. Example of voltage peaks due to the flux jump as function of the current for temperature of 4.2 K and 1.9 K.

III. Quench Performance

A. Training quenches overview

In total, HQ01-e has undergone three thermal cycles and 68 training quenches. The history of the quench currents is reported in Fig. 2. At LBNL, the quench current (I_q) reached 14.8 kA at 4.2 K; at CERN, for the same temperature, it was initially 6% lower with I_q = 13.9 kA. At 1.9 K, the first two quenches were at I_q = 14.5 kA and 15.1 kA. After 20 training quenches, the highest current has been reached with I_q = 16.216 kA (q#42) corresponding to 85% of I_{ss} at 1.9 K. When later re-tested at 4.2 K, a stable plateau was recorded with consecutive quenches at around 14.7 kA (85% I_{ss} at 4.2 K). After the third thermal cycle, I_q at 1.9 K dropped to 14.1 kA but quickly got back to the highest current in eight training quenches.

The first 10 quenches (CERN & LBNL) were all occurring in coil 7 with exactly the same quench signal pattern. Hence it was decided to modify the powering method by changing the ramp rate from 50 to 20 at 10 kA, and to 5 A/s at 14 kA. However, it turned out that coil 7 was still limiting the training process at similar values. It was then decided to add 10 minutes long plateaus at 10 and 14 kA. With this method, a training process was observed. Each modification of the powering scenario that we have tried during the test implied a detraining of C7. The need of pauses at intermediate currents (2 minutes seem enough) points at heating transient phenomena, such as for example, eddy currents, that occur during the ramp and then subsequently decay during the pause.

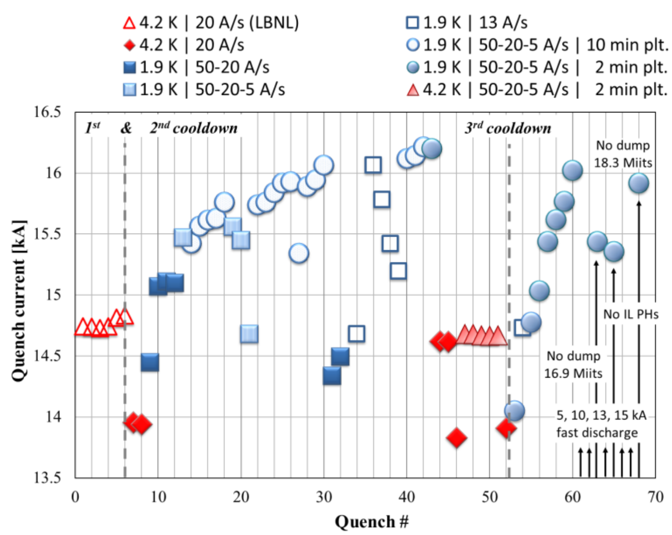

Fig. 2. Training quench history at 4.2 K and 1.9 K of the three runs of HQ01e for different current ramp up scenario. Maximum current of 16,216 A.

The fast current discharges without firing the QHs, with the goal to observe quench-back effect, are the quenches q#61, #62, #64, #66 and #67. The final part of the test included quenches without dump resistor (q#63), without firing of the inner layer QHs firing (q#65) and without dump and inner layer QHs (q#68), which are also shown in Fig. 2. This protection study was done to assess protection for a long magnet integrated in the LHC upgrade.

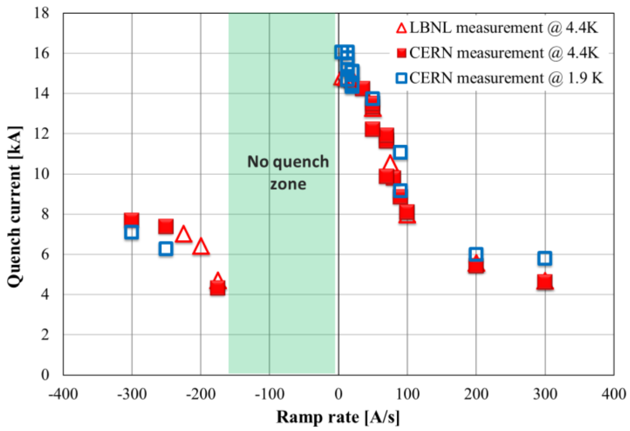

Fig. 3. Quench current as function of the ramp rate obtained at 4.4 and 1.9 K. No quench are measured in the green zone.

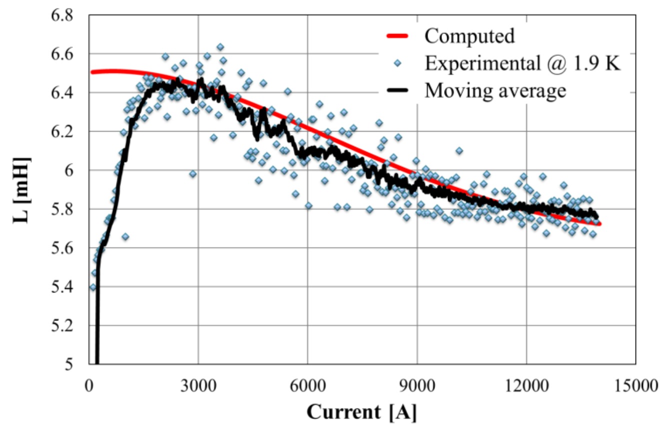

Fig. 4. Inductance measurement of the HQ01-e at 1.9 K ramping at 13 A/s, and comparison to numerical model.

B. *Quench location*

During magnet training, quench location is expected to change from one coil to another and to gradually approach the location of highest magnetic field or highest strain. For the following, one can refer to [7] for the location of the coils and the voltage-taps. The initial quenches with no ramp rate adaptation were located in C7 with a very reproducible pattern: first, a voltage rise was detected at the mid-plane turn of the inner layer (A3-A2), 2 ms later at the outer multi-turn (A4-A3), 8 ms later at the inner multi-turn (A5-A4), and finally, 10 ms later at the pole turn (A6-A5). With the ramp rate adaptation earlier described, all the four coils participated in the training.

In Table I, the location of the first quench initiation is reported. All but two quenches are located in the inner layer of the coils. When no ramp rate adaptation is done, C7 is clearly the limiting coil. Otherwise it is either C8 or C9 with quenches occurring at the straight part of the cable around the pole (A7-6 and A8-7). When C5 is quenching, C9 is quenching also. In the same way, after quench initiation in C7, C8 also transitions a few milliseconds after.

TABLE I QUENCH LOCATION IN HQ01-E

Coils	number of quench	Location		Layer	
		Pole	Mid-plane	A	B
5	**5**	**1** (A6-8)	**4** (A3-2)	6	0
7	**27**	**0**	**27** (A3-2)	27	0
8	**19**	**14** (A7-6 & A8-7)	**5** (A3-2)	17	2
9	**8**	**8** (A7-6 & A8-7)	**0**	8	0

The quench propagation velocity based on the *dv/dt* measured between the V-taps A5-6, A7-6 or A8-7 and using a copper resistivity of 7×10^{-10} Ω.m gives values ranging from 10 to 20 m/s depending on the quench current. The time of flight method could not be used in any of the recorded quenches due to the quasi-simultaneous quenches near the pole turn and lack of clear quench propagation around the pole.

A. *Ramp rate dependence*

A ramp rate study was carried out. In Fig. 3, the results are shown, both at 4.4 K and 1.9 K. For this test, the magnet is powered with current ramp rates ranging from 5 to 300 A/s until quench. The negative rates correspond to current discharges starting at 14 kA. Results are similar to those obtained at LBNL at 4.4 K [8], with no quench at negative ramp rate between -150 A/s and zero. At 1.9 K, the quench current slightly lowers by about 15%. The test showed a limited erratic behavior at the lowest ramp rates: 20 and 13 A/s (see Fig. 3 or results of earlier tests [8]) where the quench current is varying pointing again at the transient thermal effect earlier mentioned.

IV. RRR, SPLICES, INDUCTANCE AND AC LOSSES

The average RRR of the coils has been measured during the cool-down and the warm-up, giving 190 for C8 & 9 and 100 for C5 & 7. The measurement of the resistances of the thirteen splices indicated values below 2 nΩ for all of them proving very good quality of joints also between Nb-Ti and Nb_3Sn.

The inductance of the magnet measured during the ramps is shown in Fig. 4. The expected non-linear behavior due to the iron saturation is in good agreement with numerical models [11]. The inductance is 5.8 mH at nominal current. At low current a drop of about 10% is observed, due to persistent currents (not included in the model shown in Fig. 4).

The AC losses of the magnet have also been measured. For this test, the current is ramped at different rates and is kept constant for 10 minutes (to avoid transient effect during the first two minutes) before ramping down. The energy expressed in joules during one cycle is computed as the integration of the product of the current by the voltage across each coil. The loss is then the difference of energy before and after the cycle. The linear evolution of the loss with the ramp rate is presented in Fig. 5. The four coils present the same behavior despite their different cables. The measured losses are quite high which might explain the need of the pause during the ramp up as earlier mentioned.

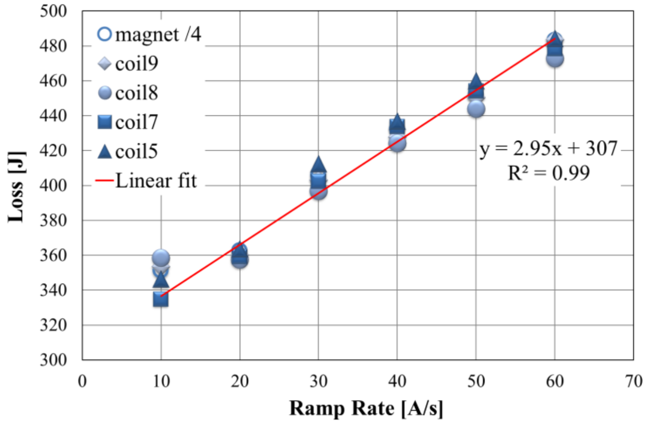

Fig. 5. Linear evolution of the AC losses with the ramp rates. The four coils present similar values.

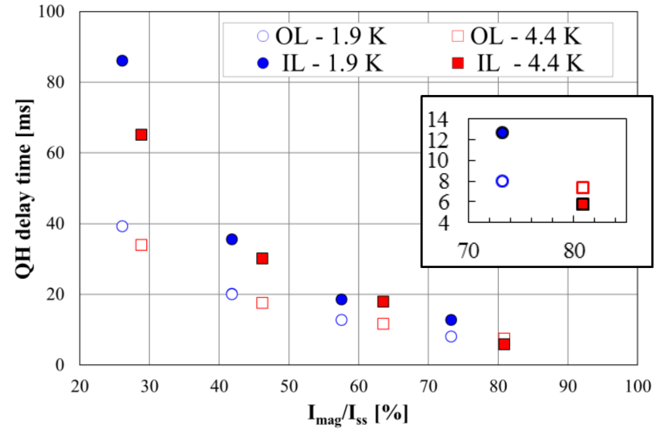

Fig. 6. Delay to normal zone initiation after provoking a quench using a QH on the inner, or outer layer.

V. Protection Study

A. Protection heater efficiency

The protection heaters are 25 µm thick stainless steel strips glued on a 25 µm thick Kapton foil, and impregnated on the surface of the coils [12]. The impact of operating temperature, magnet current and heater location on the quench delay time has been investigated. For these tests, the magnet is powered up to a constant current I from 5 kA to 14 kA and quench is induced by powering a single heater, which can be either on the inner layer (IL) or the outer layer (OL) of coil 9. The QH voltage is set to 230 ± 10 V, with a decay time constant of 40 ± 2 ms. The QH delay time is then defined as the difference between the time at which the QH is fired and the time of the first resistive voltage rise monitored by the voltage taps.

Fig. 6 shows the delay times as function of the normalized current with respect to I_{ss} at 4.4 K and at 1.9 K. The uncertainty in the quench onset estimate is 1 ms. As expected, the delay time decreases as I approaches I_{ss}, due to the reduced margin, see [13]. Lowering the operational temperature from 4.4 K to 1.9 K does not seem to affect the delay time. The quench at OL at 46% of I_{ss}, was repeated twice, demonstrating that the delay time is reproducible within 1 ms. At the lowest currents, inducing a quench at the OL results in a smaller delay time compared to the IL. This difference decreases at higher current with difference in the delay times within the margin of error at 80% of I_{ss}, at 4.4 K (6 ms for IL vs. 7 ms for OL). Smaller delay time for OL may be explained by better thermal contact between QH and coil and less efficient cooling (for both coil and QH) than for IL. In conclusion, at nominal current (80% of short sample) the quench is induced in less than 10 ms.

B. Quench back occurrence

The question of eddy currents inducing quenches when the current is rapidly discharged has been addressed. For this experiment, the magnet current is discharged from different values (I_d = 5, 10, 13, 15 kA) in the external dump resistor by opening the switch of the circuit without firing the QHs.

To detect if quench-back occurs, the evolution of the total electrical resistance R_T (t) of the magnet (sum of the four coils R_n) during the discharge is computed through a local fitting of $I(t)$ by a RL circuit with variable resistance:

$$R_T = \sum_n R_n(t) = -L\frac{d}{dt}\left(\ln\left[\frac{I(t)}{I_d}\right]\right) - R_d \qquad (1)$$

where R_d is the dump resistance. Data are shown in Fig. 7, the increase of the magnet resistance indicates that the magnet partially quenches for I_d = 5 kA but then recovers. With increasing current, a larger part of the magnet seems to quench resulting in a total magnet resistance of R_T = 48 mΩ at 15 kA.

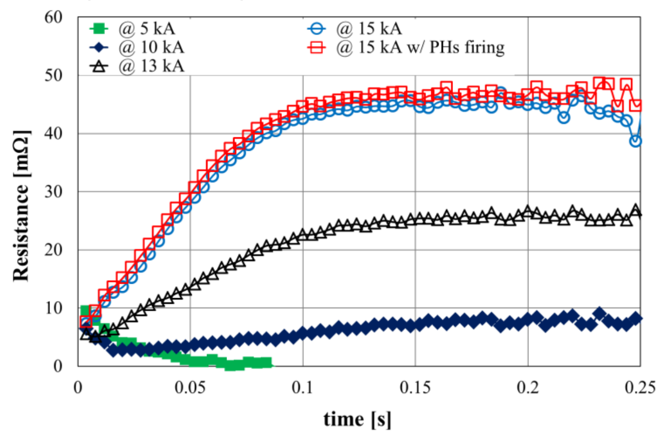

Fig. 7. Magnet resistance increases during the fast current discharge showing strong evidence of quench-back and negligible effect of the QHs firing

C. Protection without external dump resistor

The goal of the final part of the test was to study the protection of the magnet with no external dump resistor and without the QHs for the inner layer (the OL QHs were each time fired). In both cases, all the energy has been dumped in the helium bath. In Fig. 8 we present the current decays of quenches #60 (I_q = 16.0 kA with dump resistor), # 63 (I_q = 15.4 kA without dump resistor) and #68 (I_q = 15.9 kA without dump resistor and without firing IL QHs). In absence of dump resistor, the magnet energy is all dumped on the resistance of the magnet itself; the Miits for the quench#60 are 16.8, corresponding to a temperature below 140 K in the adiabatic approximation. We remind here that the Miits is the integral of the square of the current over the time from the quench detection, useful to characterize the energy dissipated during a quench.. The evolution of the magnet resistance during the current decay is also plotted. In the case without dump resistor and without inner layer heaters, the Miits increase to 18.3, i.e. to the limit of 300 K hotspot in a adiabatic approximation. This shows that having also the inner layer QH reduces the Miits by 1.5 at a current of ~16.5 kA, i.e. it has a marginal impact on the protection. More statistics would be welcome to confirm or invalidate this important statement.

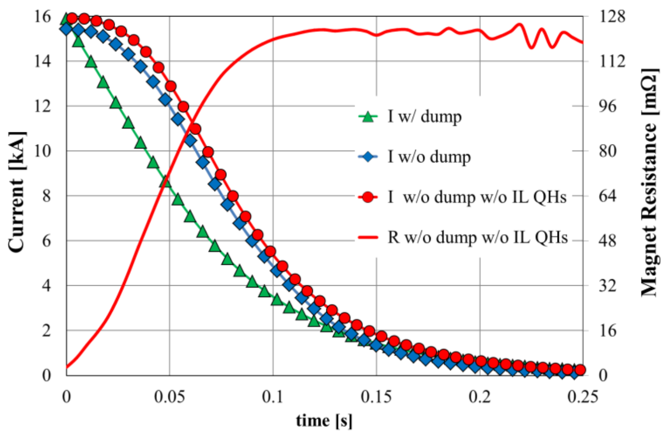

Fig. 8. Current decay for quenches #60 (13.2 Miits), #63 (16.8 Miits) without dump resistor and #68 (18.3 Miits) without dump resistor and without inner layer PHs. For #68, the increase of the resistances with time is also shown.

VI. Mechanical Behaviour

The mechanical behavior of the HQ is monitored with strain gauges: eight mounted on the aluminum shell (axial and azimuthal directions), four on the rods (axial) and eight on the coil titanium poles (axial and azimuthal direction).

The computed average values of the stress for the various positions at warm, after cool-down, and after powering are shown in Fig. 9. The results are consistent with the numerical expectations from the finite element model and with the test performed at LBNL. After cool-down, the shell stress reached 189±11 MPa and 100±14 MPa for respectively azimuthal and axial directions, 159±4 MPa for the rods and the poles compressed up to -142±17 MPa and -60±7 MPa for respectively azimuthal and axial directions. After powering, the shell and rods stresses hardly changed by about 3%. With electromagnetic force, the pole azimuthal and axial stresses unload down to respectively 38 MPa and -11 MPa for the last quench. The strain gauges survey proved that the mechanics of HQ01-e is well controlled.

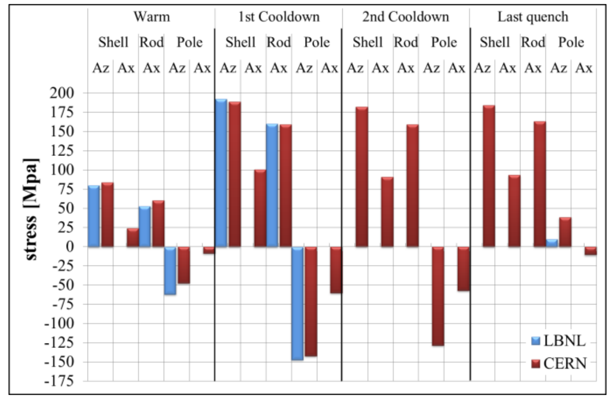

Fig. 9. HQ01-e stress evolutions for the three runs.

In Fig. 10, the expected linear variation of the poles azimuthal strain as function of the square of the current is shown for the four coils and for the 68 training quenches. The four coils behave coherently showing the symmetry of the magnet loading. As the current reaches the highest values (> 15 kA), the curves tend to flatten. This flattening becomes more evident as the number of quenches increases for coil 8 and 9 pointing at ratcheting effect occurring with the cycles (see the difference between blue and red curves). A progressive detachment of the cable off the poles may happen at approximately 80% of the I_{ss} @ 1.9K: the target value of the mechanical design for the HQ.

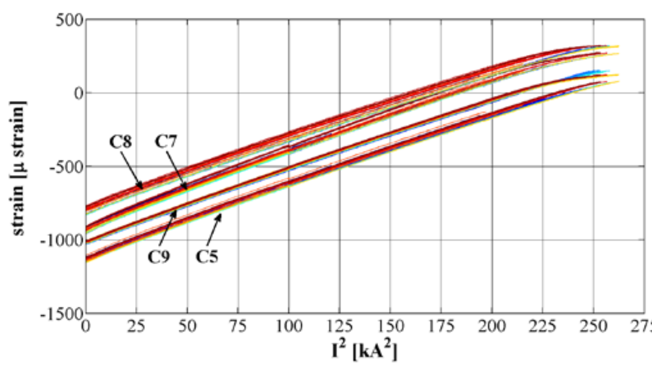

Fig. 10. Evolution of the pole azimuthal strain measured for the four coils.

VII. Conclusion

The Nb_3Sn HQ quadrupole has been tested at CERN at 1.9 K for the first time. Using a 20 A/s ramp rate (nominal is 13 A/s), a plateau at 15 kA has been observed on the quench current, corresponding to 80% short sample. With slower ramp rate and waiting periods at 10 and 15 kA, the magnet reached 16.2 kA, i.e. 87% of short sample. The ramp rate studies confirmed the behavior at 4.2 K observed in LBNL. The quench delay at 1.9 K has been measured, giving less than 10 ms at 15 kA, and shorter times for the outer layer heaters. A special series of ramp-down dumps on the resistor from 15 kA showed a clear evidence of quench-back in the magnet, in concert with the high eddy currents seen in magnetic measurements. The final part of the test demonstrated a promising possibility of having protection without dump resistor and inner layer quench heaters. However, additional supporting tests are needed.

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