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Instrumentation and Quench Protection for LARP Nb_3Sn Magnets

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***Abstract*—The US LHC Accelerator Research Program (LARP) is developing Nb_3Sn prototype quadrupoles for the LHC interaction region upgrades. Several magnets have been tested within this program and understanding of their behavior and performance is a primary goal. The instrumentation is consequently a key consideration, as is protection of the magnet during quenches. In all LARP magnets, the flexible circuits traces combine the instrumentation and the protection heaters. Their fabrication relies on printed circuit technology based on a laminate made of a 45-micron thick kapton sheet and a 25-micron thick foil of stainless steel. This paper reviews the protection heaters designs used in the TQ (Technology Quadrupole) and LR (Long Racetrack) series as well as the one used in LBNL HD2a high field dipole and presents the design of the traces for the Long Quadrupole (LQ), addressing challenges associated with the stored energy and the length of the magnet.**

***Index Terms*— Superconducting magnets, Nb_3Sn, protection heaters, quench protection, instrumentation, LARP**

I. INTRODUCTION

THE US LHC Accelerator Research Program (LARP) is developing Nb_3Sn quadrupole magnets in order to prepare the luminosity upgrade of the LHC Interaction Regions (IR). The ultimate goal of LARP is to demonstrate the feasibility of the Nb_3Sn technology by reaching at least 200 T/m in LQ: a 4-meter long 90 mm aperture quadrupole magnet. To meet this goal, several Nb_3Sn magnet series have been developed in the past years: the SQ series (Subscale Quadrupole) [1], [2], the 1-meter long TQ series (Technology Quadrupole) [3], [4] and the LR series (Long Racetrack in a common coil arrangement) [5]. The LQ series (Long Quadrupole), presently in construction, is a 3.7-meter scale up of the TQ [6]. Due to its length, the protection of LQ is challenging. Nevertheless, a better understanding and knowledge of the Nb_3Sn coils have been gained over the years and the LQ protection heater design relies on the analysis of the performances of the previous magnet protection heaters. In part II, some protection heaters design and performance are presented based on the analysis of some LR, TQ and HD2a tests data. The design of the LQ protection heaters (PH) is detailed in part III and finally the instrumentation of the LQ coils will be summarized.

II. PROTECTION HEATERS

A. *The concept of traces*

All LARP magnets adopted the instrumentation technique based on a flexible circuit called the trace [7], [8]. The fabrication of the trace relies on printed circuit technology based on a kapton sheet and a 25.4 micrometers thick foil of stainless steel. The effective thickness of the kapton is ~ 45 micrometers. A trace includes the circuits of the voltage taps, of the strain gages and possibly the spot heaters as well as the PH. Since the traces are obtained by an etching process (using a full scale negative called the "artwork"), the thickness of the stainless steel is the same for the circuits and the PH. The thickness is an important parameter since the resistance of the circuits/PH is inversely proportional to its thickness. From a PH viewpoint, the heat deposition is a critical parameter for the protection. Therefore, the thickness of the PH has to be judiciously chosen to reach the requirements. From a wiring standpoint, the thickness has to be sufficient to ensure a good mechanical strength along the circuits and a low voltage drop between the voltage taps and the data acquisition system. The 25.4 micrometers thickness of the stainless steel laminate meets these requirements.

B. *Key parameters*

Two key parameters drive the efficiency of the PH: the power deposition at the surface of the coil P_W (estimated in W/cm^2) and the time constant of the heater pulse τ given by the electrical circuit to which the PH are connected. The powering of the PH is usually provided by a capacitor bank leading to a time constant $\tau = RC$ where R is the equivalent resistance of the electrical circuit. P_w depends on the shape of the heaters (through their resistance R_{heater}), the current $I_{heater}(t) = I_{heater0}\, e^{-t/\tau}$ flowing through them squared, and the area $A_{heating}$ of contact between the PH and the coil. The power is then:

$$P_W(t) = \frac{R_{heater} I(t)^2_{heater}}{A_{heater}} \qquad (1)$$

The value of P_W (t=0) = P_{W0} = 50 W/cm^2 has been used as the reference value for all the LARP PH designs. In addition,

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the circuit must be designed to yield a τ so as to insure a fast quench initiation and to avoid a large increase of temperature of the PH, which could cause a degradation of the kapton / stainless steel laminate and impact the behavior of the PH. The adiabatic increase of temperature can be estimated by:

$$\int_{4.2K}^{T_{final}} d_{ss} C_{p,ss}(T) dT = \int_0^{\infty} \rho_{ss} \frac{I_{heater0}^2}{S_{heater}^2} e^{-2t/\tau} dt \qquad (2)$$

the objective being to keep T_{final} below room temperature. $C_{p,ss}$, d_{ss} and ρ_{ss} are respectively the specific heat in $J.K^{-1}.kg^{-1}$, the density in kg/m^3 and the resistivity in Ω.m of the stainless steel. The choice of P_{W0} and τ aim at generating a quench in the coil as fast as possible without degrading the PH. The performance of the PH is characterized by the quench delay time t_{delay} between the firing of the PH and the quench onset. In order to justify the choice made for the LQ design, some PH designs used in previous Nb_3Sn magnets are presented in the next parts.

III. APPLICATION TO RECENT NB_3SN MAGNETS

A. *Long Racetrack LR*

The Long Racetrack (LR) magnet was made of two 2-layer 3.6-meter Nb_3Sn racetrack coils assembled in a common-coil configuration in a shell-based structure [5]. The design of the LR PH is detailed in [9]. As shown in Fig. 1, the PH heater can be split into an active part (heating stations (a) and (b)) where the stainless strip is narrow providing a large heat deposition P_{W0} and an inactive part where the stainless steel strip is wider leading to a smaller resistance, a larger contact area with the coil and therefore a smaller heat deposition on the coil. The design decreases the overall resistance of the PH and relies on quench propagation velocity between two heating stations to propagate the normal zone.

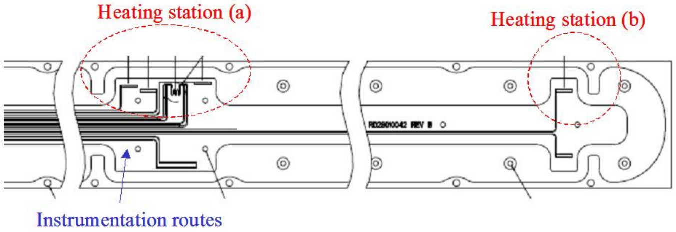

Fig. 1. Zoom on a section of the LR trace.

The response of the PH has been studied in the LRS01 test [9] by provoking magnet quenches using different powering parameters of the PH. The voltage across the capacitance ranged between 42 to 220 V. For a fixed capacitance (therefore a constant τ), this leads to a variable P_{W0} in the PH. Some parameters of the tests performed on LR PH are summarized in Table I and the variation of t_{delay} with respect to P_{W0} is shown in Fig. 4.

B. *Technology Quadrupoles TQ*

The TQ magnets are 1-meter long, 90 mm aperture cosine two theta quadrupole magnets [3], [4] (all of the TQ series magnets use the same 2-layer coils, but two distinct mechanical structures are tested: a shell-based structure (TQS) and a collar-based structure (TQC)). For all the magnets the heater coverage and shape was identical with 2 strip heaters covering the outer layer of the coils (see Fig. 2). Nevertheless, depending on the coils, two types of PH have been used: with and without copper cladding.

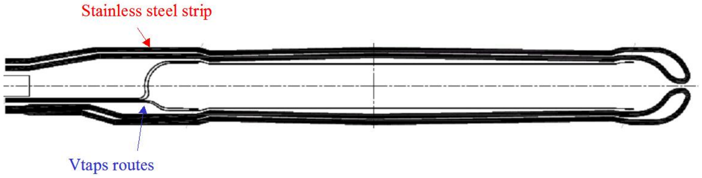

Fig. 2. TQ trace. The PH of each coil are made of 2 stainless steel strips providing two independent circuits, one on each side of the coil central pole.

The purpose of the copper cladding is to reduce the overall resistance of the PH by adding copper plates on the PH strip. The effect is to focus the heat deposition in a few locations and shunt the stainless strip in between these locations. The quality of the bonding between the copper and the stainless steel is essential for the good performances of the heaters. In Table I, the PH parameters are detailed for the TQ magnets considered in this study. The variation of t_{delay} versus the P_{W0} is plotted in Fig. 4. The results of the TQC02 and TQS02b,c series are under investigation and are not reported here.

C. *High field Dipole HD2a*

HD2a is a high field 36 mm bore block-type dipole designed and tested at LBNL [10]. HD2a is made of two 2-layer coils. Each layer is equipped with 2 stainless strips: one strip on each side of the central pole. In coil #1, the PH have copper cladding on the inner layer whereas the outer layer and both layers of coil # 2 do not. The values of the resistance of the strip heaters are summarized in Table I.

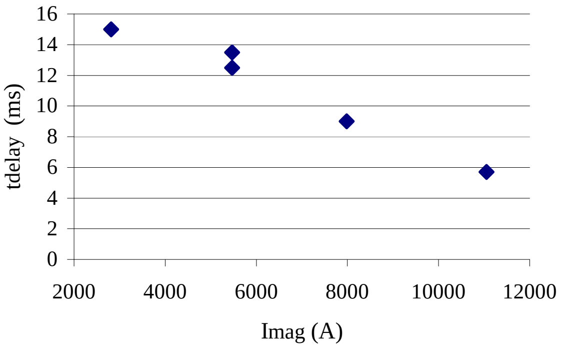

Fig. 3. Summary of HD2a PH test: delay time in ms versus the current in HD2a.

The PH tests of HD2a consisted in provoking quenches for a magnet current ranging from 2 and 11.05 kA. For all these quenches, the configuration of the PH powering units was identical (same P_{W0} and same τ) and is described in Table I. Fig. 3 represents the variation of the delay time with respect to the current in the magnet. As expected, this delay time is decreasing when the temperature margin of the magnet decreases. The characteristics of this variation have to be investigated and the data have to be correlated with the actual temperature margin in the magnet.

HD2a PH pointed out the difficulty to ensure a high quality copper cladding. Indeed, as indicated in Table I, the copper cladding of the PH did not improve the resistance of the PH as expected. A likely explanation is an insufficient bonding between the copper plates and the stainless steel strip, but this is still under investigation.

D. Data Analysis

The performances of the PH described previously are summarized in Fig. 4. It shows the variation of t_{delay}, corresponding to the delay between the firing of the PH and the quench onset, as a function of power density. Several PH performances are represented at different values of the fraction of the magnet short sample current I/I_{ss}. The first conclusion that can be made is that there is a saturation of t_{delay} reduction for a P_{W0} starting around 50 W/cm^2. The minimum delay time that can be reached ranges from 4 and 6 ms.

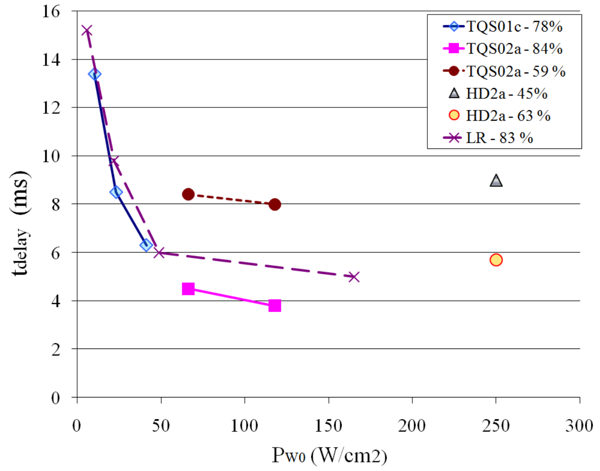

Fig. 4. Delay time in ms versus Heat deposition in W/cm^2 for several Nb3Sn magnets. The percentage corresponds to the short sample current fraction at which the data are given.

As expected, when the temperature margin of the magnet increases, the delay time increases. Indeed, the TQS02a data show that t_{delay} improves when the magnet current is closer to the short sample. This is consistent with the HD2a data presented in Fig. 3.

TABLE I PROTECTION HEATERS PARAMETERS

	Unit	LR	TQS01c	TQS02a	HD2a
I_{mag}	kA	9	9.5	11.5	11.05
C	mF	31	4.8	4.8	20.8
$R_{str\ av}$[1]	Ω	3.1[a]	9.2[a]	5.25[b]	5[a,b]
Cover[2]		I / O	O	O	I / O
V_{av}	V	70 / 136 / 220	200/300/400	300/400	333
τ	ms	39.9	44.1	25.1	22
I_{heater}	A	27.8 /41.7/ 76.8	10.8/16.2/21.6	28.9/38.5	105
P_{W0}	W/cm^2	22 / 49 /165	10 / 23 / 41	66 / 118	250
t_{delay}	ms	9.8 / 6 / 5	13.4 / 8.5 / 6.3	4.5 / 3.8	5.7

[a/b] without / with copper cladding
[1] average resistance of one strip
[2] indicates which layer are covered: Inner Layer IL / outer layer OL

For the same fraction I/I_{ss} (~60 %), we can see that the performances of HD2a PH are slightly better than TQS02a. This could be explained by the fact that these two magnets have a different conductor (different strand diameter, different copper non-copper ratio) and mostly a different cable insulation thickness (95 microns for HD2a and 125 microns for TQ), which probably makes the diffusion process easier in the case of HD2a. The difference of response between the LR and the TQS02a PH will be investigated with additional tests.

IV. LQ QUENCH PROTECTION

A. Quench Protection Analysis

The Long Quadrupole, under construction, is a 3.7-meter long scale-up of the TQ series. At short sample current, its stored energy reaches ~1.8 MJ. The quench analysis of the LQ magnet is detailed in [11] and [13] and shows that essentially 100 % heater coverage is required to keep the hot spot temperature below 380 K, without including any quench back effect. This means that the whole coil has to be covered with PH. Furthermore, the quench protection requires a very short detection time (5 ms) and a heater delay time smaller than 12 ms. Based on measurements performed on the TQ01 and SQ series [2], [12], such a detection time is considered achievable.

B. LQ Protection Heater Design

The 100 % coverage requirement leads to PH on the inner and on the outer layer of the coils. Due to the length of the coil, multiple heaters are needed to maintain a low resistance: one strip heater will cover half the length of a layer leading to 4 strip heaters per coil. The artwork of the LQ traces are presented in Fig. 5.

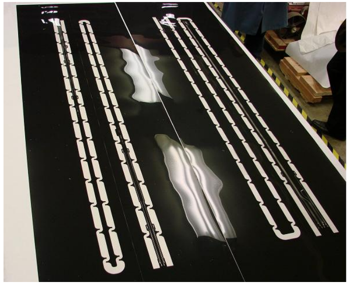

Fig. 5. Artwork of LQ layer 1 and layer 2 traces

Due to the length of the LQ coils, the width and the length of the TQ PH could not be maintained. Furthermore, due to concerns over the quality of the copper cladding in HD2a, it has been decided to use the same design principle as in LR by implementing heating stations (HS) by narrowing the strip at specified locations along the length of the coil. Based on the results presented in Fig. 4, we can anticipate a t_{delay} of 6 ms if a power density of at least 50 W/cm^2 is generated in the PH. Under these conditions, the quench has to propagate in the coil in 12 ms - t_{delay} = 6ms to provide a 100 % coverage. The quench propagation velocity study presented in [2] shows a quench velocity ranging between 7 and 45 m/s between 60 and 95 % of the short sample current. Assuming a quench propagation velocity of 10 m/s is a conservative approach and leads to a maximum distance between two heating stations of 12 cm. In order to lower the resistance of each strip, the width of the strip between the HS has been chosen as large as possible (23 mm). The HS shape and size must satisfy competing criteria: it is preferable to cover a large number of strands (i.e. large heater area), but sufficient power density must be provided to yield fast response t_{delay}. The final dimensions of the LQ heaters are presented in Fig. 6. A width of 9 mm was a compromise in order to cover a sufficient number of strands (4) and to provide at least 50 W/cm^2. The resistance of each HS is estimated to be equal to 0.06 Ω with an area of ~ 1.8 cm^2.

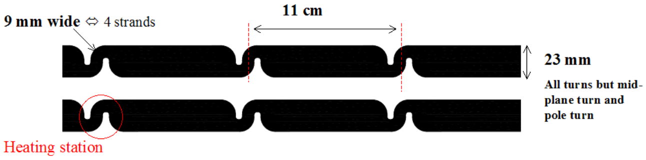

Fig. 6. Dimensions of LQ PH.

C. *LQ Protection Heater Powering*

Based on the design of the LQ PH, the resistance of one stainless strip is expected to be equal to 7 Ω. The measurement of the resistances of the first set of traces fabricated confirmed this values with 6.78, 6.79, 6.77 and 6.67 Ω measured for each strip. The results of the previous PH performance show that τ = 25 ms and P_{W0} above 50 W/cm^2 provide a small t_{delay}. The electrical network generating these parameters depends on the test facility where the magnet is tested. LQ is going to be tested at FNAL. Four HFUs (Heater Firing Unit) are available, each having a maximum capacitance of 19.2 mF. Connecting each HFU to four strips in parallel would give τ = 33.6 ms. Varying the voltage across the capacitance from 270 V to 450 V would give I_{heater} between 40 and 64 A and P_{W0} between 50 and 135 W/cm^2. In case of a power deposition of 135 W/cm^2, τ would need to be smaller (28 ms according to Eq. (2)) in order to keep the temperature of the PH below room temperature.

V. LQ INSTRUMENTATION

A. *Voltage taps*

In all the LARP magnets, the wiring of the voltage taps (VT) is part of the trace as shown in Fig. 7. The VTs are positioned during the winding and are connected to the trace before impregnation.

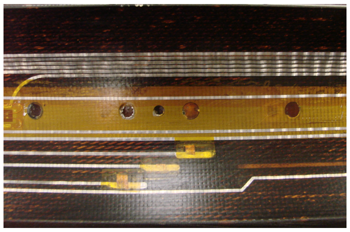

Fig. 7. TQ inner layer traces - connection of the traces to the voltage taps

LQ will follow the same procedure. Each LQ coil will be equipped with 20 VTs, 13 on the inner layer and 7 on the outer layer. On each layer, 2 VTs are used to monitor the coil leads. In layer 1, 8 VTs are used to monitor the pole turn, one is used to monitor the turn 2, which becomes the pole turn after the ramp area (layer 1 to layer 2 transition) and 2 VTs are used on the turns in contact with the wedge to monitor the multi-turn area and the wedge. In the outer layer, 4 VTs are located on the pole turn and one is used on turn 8 to monitor the multi-turn area of the coil outer layer.

B. *Strain gages and spot heater*

All the LARP magnets were instrumented with strain gages, mounted on the coil poles and on the structure. Each LQ coil Titanium pole will be instrumented with 5 strain gage stations: 4 on the inner layer pole, 1 on the outer layer pole. A station consists of 2 full bridges: one measuring the strain in the azimuthal direction and the other in the axial direction. Each full bridge is temperature compensated, since they are made of 1 half bridge (uni-axial steel SK09030PB350) directly mounted on the titanium pole and 1 half-bridge mounted on a free piece of Titanium. One spot heater will be mounted on each coil. Due to the importance of the PH, and to ensure the reliability of the VTs, the traces were dedicated to them in priority leaving no room for the strain gages and spot heater routes. Therefore, the wiring of all of the inner layer strain gages and the spot heater will be external. Where the PH shape allows it, the strain gages are directly wired to the trace as illustrated in Fig. 8.

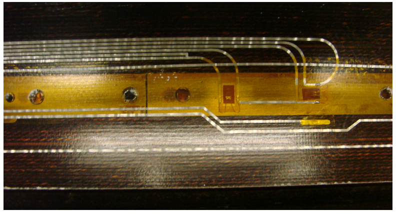

Fig. 8. TQ inner layer traces - connection of the traces to the strain gages

VI. CONCLUSION

The performances of different protection heaters mounted on Nb_3Sn magnets have been summarized and analyzed. The results have been used to design the protection heaters of the LARP Long Quadrupole. Furthermore, details of the LQ instrumentation and its implementation have been presented.

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