Temperature Profiles During Quenches in LHC Superconducting Dipole Magnets Protected by Quench Heaters.

V. Maroussov, S. Sanfilippo, A. Siemko
CERN, LHC Division, 1211 Geneva 23, Switzerland

Abstract–The efficiency of the magnet protection by quench heaters was studied using a novel method which derives the temperature profile in a superconducting magnet during a quench from measured voltage signals. In several Large Hadron Collider single aperture dipole models, temperature profiles and temperature gradients in the magnet coil have been evaluated in the case of protection by different sets of quench heaters and different powering and protection parameters. The influence of the insulation thickness between the quench heaters and the coil has also been considered. The results show clear correlation between the positions of quench heaters, magnet protection parameters and temperature profiles. This study allowed a better understanding of the quench process mechanisms and the efficiency assessment of the different protection schemes.

I. INTRODUCTION

The Large Hadron Collider (LHC) main superconducting dipole magnets will store a substantial amount of electromagnetic energy [1]. In 15 m long dipoles 7 MJ is stored at 8.3 T. For this magnetic field the quench propagation velocity is equal to 20-30 m/s and is not sufficient to make the magnet self protecting. A fast and reliable magnet protection system is therefore essential to avoid an over-voltage and/or an overheating of the magnet component in case of quench [2]. Quench heaters are therefore included to spread rapidly the normal zone across the coil. In order to better understand the efficiency of the magnet protection, several one-meter long dipole models have been built and tested with various design parameters. Concerning the quench heaters the main qualitative variants were the following:

a) the positions of quench heaters were in the outer layer of the coil either at the outer radius referred to as outer radius quench heater (ORQH) or between the inner and the outer layer referred to as inter radius quench heaters (IRQH).

b) Two insulation foils 75 and 200 μm thick placed between the heater strip and the magnet coil were tested.

During each test, voltage signals were measured to derive temperature profiles and to localise the critical points in the superconducting magnet during the quench [3]. In particular this method determined the average temperature occurring in the hottest turn and the temperature gradient across the hottest block. These parameters were of crucial importance as it was observed that high hot spot temperatures and large temperature gradients could cause a significant performance degradation [4]. The magnet protection by several sets of quench heaters is compared here for selected short dipole magnets with 6-blocks coil design.

II. EXPERIMENTAL

The magnet electrical circuit during a quench can be represented as an equivalent serial connection of nonlinear inductance L_E (I) and a time dependent resistance R(t). At the beginning of the quench, a pure inductive voltage is measured by most of the voltage taps. The reason is that the major part of the coil remains superconducting because the quench occurs in a limited cable length of the magnet. The first step of the method aimed to calculate the inductive voltage distribution of the coil parts from the quench recording. For the cable length between two voltage taps, the partial inductance L_n defined in (1) was calculated using heater provoked quenches (for details see [3]).

$$L_n = \frac{V_{\text{inductive}}^{\text{taps}}}{V_{\text{inductive}}^{\text{magnet}}} L_E(I=0) \tag{1}$$

By choosing for each signal between two voltage taps the maximum value of each L_n, the minimum Joule heat released during the quenches could be obtained using (2).

$$\begin{aligned} Q(t) = {} & \int_{t_0}^{t} V(t')\, I(t')\, dt' \\ & + \frac{L_n}{L_E(0)} \frac{1}{2} \left(L_E[I(t_0)]\, I(t_0)^2 - L_E[I(t)]\, I(t)^2 \right) \end{aligned} \tag{2}$$

In (2) V represents the total voltage across the magnet and t_0 a time before the quench where the magnet was still in the superconducting state.

Knowing the masses of the copper and of the superconductor and knowing the dependencies of the specific heat versus temperature, the average temperature of the part of the cable between the two voltage taps could be obtained. The advantage of this method is that one does not need to calculate the resistance of the turn which depends on the local ratio between the electron mean free path with respect to the interfilament and the inter bunch spacing. The peak temperature obtained by this method is by definition lower than the hot spot temperature extracted from the commonly used MIITS method because temperatures are averaged along the cable length bounded by two voltage taps. Fig. 1 presents examples of the temperature profiles in the coil for a natural

Manuscript received September 27, 1999.

1051-8223/00$10.00

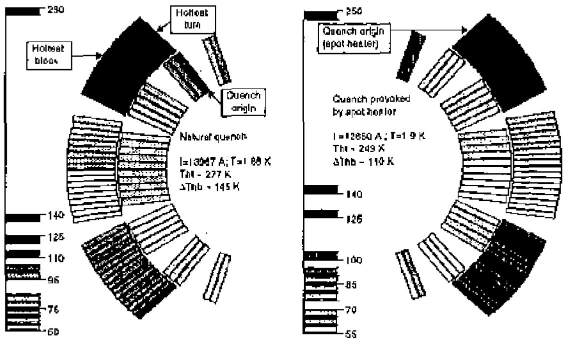

Fig. 1. Temperature profile for training quench without energy extraction at 13967A (left) and for a spot heater provoked quench at 12850A (right).

quench and a quench provoked by the firing of a spot heater. Both quenches were performed without energy extraction.

As one can see in Fig. 1 for quenches without energy extraction the highest temperature was reached in the pole turn of the outer layer independent of the quench origin [5]. This particular turn of the outer layer (in the pole where the quench started), and the whole block were developing the highest temperatures. This was caused by the higher current density of the outer layer as compared to the inner layer, coupled with the existence of a higher magnetic field in this region with respect to the rest of the outer layer. For spot heater induced quenches the similar temperature profiles were recorded. In the following the variation of the temperature of this turn T_{ht} i.e. the peak temperature and the temperature difference between the pole turn and the average temperature of the related block (block 2) ΔT_{hb} will be considered.

$$\Delta T_{hb} = T_{ht} - T_{block2(average)}$$

where ΔT_{hb} is a measure of the temperature gradient across the sixteen turns of the block 2.

III. RESULTS

A. Effect of the Quench Heater Position

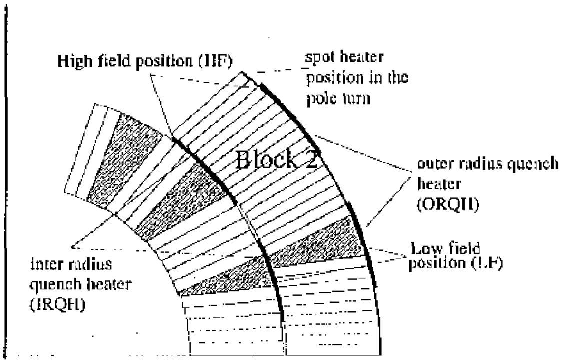

Fig 2. Layout for a model equipped with ORQH and IRQH.

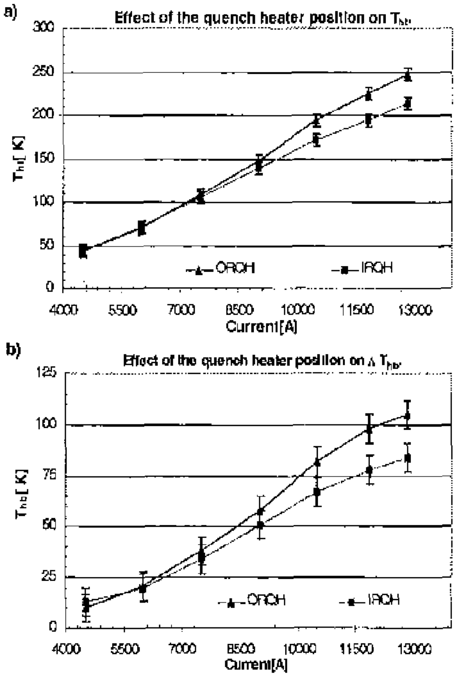

Fig. 3. Hottest temperature (a) and temperature gradient (b) vs current when magnet protection was performed by IRQH or ORQH.

For high efficiency the heater strip must be in close thermal contact with the coil. Studies showed that the optimum place was between the coil layers [6]-[7]-[8]. A dipole model was equipped with two heating circuits between the inner and the outer layers in addition to the "classical" heaters covering the outer radius of the outer layer. For redundancy there were two circuits for each type and coil quadrant. Heaters which covered the high field and the low field regions were respectively called HF and LF. The insulation thickness between the coil and the quench heater (inter and outer radius) was 75 μm for this test. Fig. 2 shows the position of the ORQH and the IRQH in the cross section of this dipole.

A.1 Comparison of the Peak Temperature and of the Temperature Gradient

The variation of T_{ht} and ΔT_{hb} vs magnet current is shown in figs. 3a and 3b when the magnet was protected by the ORQH and the IRQH. Quenches were provoked at different currents by firing a spot heater located in the outer layer.

At low currents (I < 10 kA) the protection by the two types of heaters was in practice equivalent. The influence of the heater position occurred at higher currents. For an ultimate current I = 12850 A, a reduction of 35 K and 20 K was measured for T_{ht} and ΔT_{hb} respectively when the magnet was protected by the IRQH. This means a lowering of about 13% in terms of maximum temperature and of 20% for the temperature gradient evaluated in the hottest block. The improved efficiency of the IRQH had at least two origins. First, due to a keystone angle of the cable IRQH covers four turns more than ORQH. Second, the IRQH were located in high magnetic field regions and therefore the effective temperature margin was lower and less enthalpy was needed to raise the temperature of the coil to the critical one. The protection of the magnet using the IRQH was more efficient because the delay needed to trigger a quench was shortened.

A.2 Influence on the Training Performance

During the training, quenches without energy extraction were protected by firing successively the four outer radius and the four inter radius quench heaters. As one can see in Fig. 4, the magnetic field level at quench dropped after several quenches without energy extraction to two different levels (D_{inter}, D_{outer}) depending on the type of the protection. Protection by the IRQH limited the drop of the magnetic field to an average value of 8.7 T (D_{inter}), and to 8.4 T (D_{outer}) in case of protection by the ORQH. This de-training effect already observed for several six-block coil models had a thermo-mechanical origin induced by the coexistence of a mechanical weak region in the coil and a temperature rise occurring when all the stored energy is dissipated in the magnet.

In order to evaluate the importance of the thermal effect in the instability of the training, the T_{ht} and ΔT_{hb} were calculated for quenches without energy extraction. As one can see in Figs. 5a and 5b a clear correlation existed between T_{ht} and ΔT_{hb} determined by the position of the quench heaters and the quench level. The drop of the magnetic field to D_{outer} (or the increase to D_{inter}) was preceded by a quench during which the magnet was protected by the ORQH (or by the IRQH) i.e. by the quench number 33 (the quench number 38).

The drop to a lower magnetic field at quench appeared after an increase of T_{ht} and ΔT_{hb} (increase of 35 K and 26 K respectively) calculated for the case when the magnet was protected by the outer radius quench heaters.

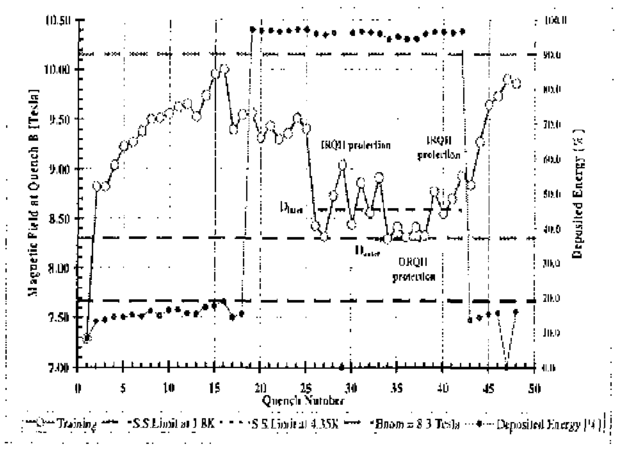

Fig. 4. Training curve at 1.8 K. For quenches without energy extraction the magnet de-trains to two different levels of magnetic fields D_{inter} and D_{outer} depending on the type of protection.

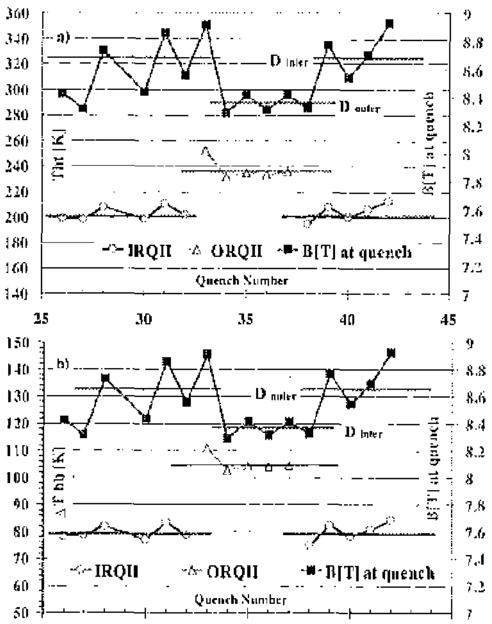

Fig. 5. Variation of T_{ht} and ΔT_{hb} during the training for protection by : a) the IRQH b) the ORQH.

A.3 Protection by Different Sets of IRQH

The efficiency of different sets high field (HF) and low field (LF) quench heaters was separately tested in the case of inter radius quench heaters (see Fig. 2 for the position of these strips). This study aimed at optimisation of the protection scheme by assessing its redundancy. For quenches

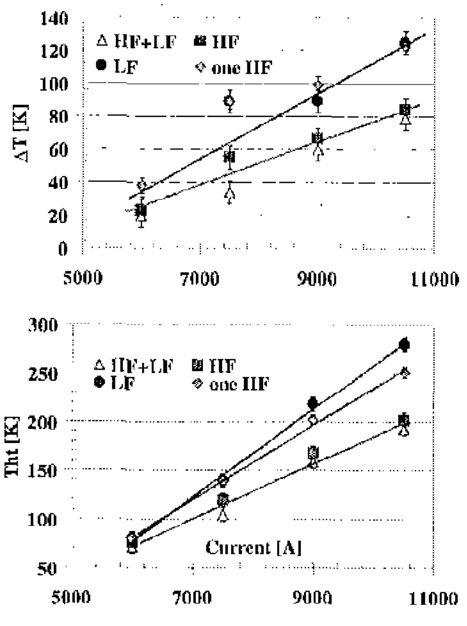

Fig. 6. Effect of protection by several sets of IRQH on a) T_{ht} and b) ΔT_{hb}.

provoked by firing a spot heater, the magnet was successively protected by all the four IRQH (HF+LF), by only the two high field strips IRQH (HF), by only one high field strip IRQH (one HF) and finally by only the two low field strips IRQH (LF). For each case the temperature profile of the magnet was determined. Figs. 6a and 6b present the calculated values of T_{ht} and ΔT_{hb} for four currents i.e. for I = 6000 A, I = 7500 A, I = 9000 A, I = 10500 A. It was found that protection by all the heaters or only by HF is equivalent. This suggests that the delays till the beginning of the quenches were higher when the magnet was protected only by LF. This assumption was confirmed by the high peak temperatures and the high gradients obtained in the case of protection by only this set of heaters (Fig. 6). In the case of protection only by half high field IRQH produced temperatures which stayed well within the design specification. Thus for adequate redundancy protection by one set of HF IRQH is fully sufficient.

B. Effect of the Insulation Thickness

Two different Kapton® insulation layers between the coils and the outer radius strips, 75 μm thick and 200 μm thick, were tested. This test aimed at investigating how the thermal conductivity between the heaters and the coil affected T_{ht} and ΔT_{hb}. Quenches were provoked by firing the spot heater and the magnet was protected by all the ORQH. Figs. 7a and 7b show the variation of T_{ht} and of ΔT_{hb} for currents up to 13 kA. Obviously T_{ht} and ΔT_{hb} increased with the insulation thickness. At high currents the increase was important and equal to about 80 K and 54 K respectively. Heat transfer was significantly slowed down by the addition of one 125 μm thick sheet of Kapton® and led for the nominal current (11850 A) to temperatures close to 300 K. The measured heater delays for 200 μm thick ORQH increased as expected by a factor of two.

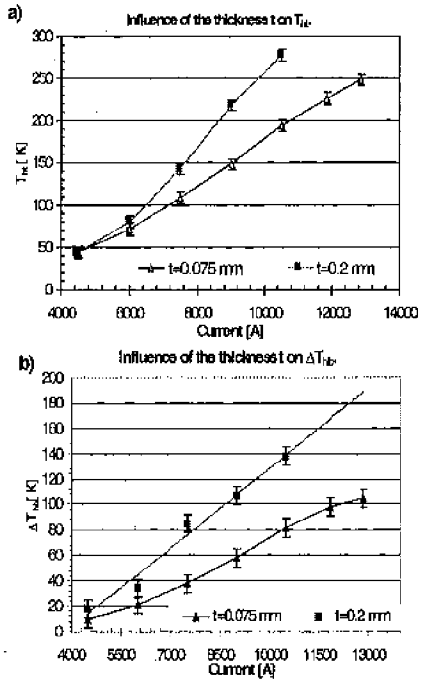

Fig. 7. Effect of the insulation thickness on a) T_{ht} and b) ΔT_{hb}

CONCLUSION

The efficiency of the protection of a selected LHC short dipole magnets by several sets of heaters has been compared. The highest temperature reached in the coil and the highest temperature gradient were considered. We find that an insulation thickness of 200 μm between the heater and the coils results in peak temperatures exceeding design maximum temperature. Protection by heaters located on the inter layer radius is much more efficient than by those located on the outer radius of the coil. In the first case protection by only high field heaters is sufficient. Evaluation of the temperature profiles during quenches was found to be very helpful in the interpretation of the quench behaviour of magnets. Strong correlation between temperature profile and the de-training effect has been demonstrated. This method is an efficient and independent crosscheck of the temperature values obtained from the MIITS method and provides results for validation of simulation models of the quench process.

ACKNOWLEDGEMENT

The authors would like to thank the MMS and the MTA teams for building and testing the LHC short models, F. Rodriguez-Mateos, R. Schmidt, F. Sonnemann for fruitful discussions. In particular, we wish to thank N. Siegel and D. Tommasini for their contribution.

REFERENCES

[1] The LHC Study Group, "The large hadron collider conceptual design, CERN," CERN/AC/95-05 (LHC), 1995, Yellow Book.

[2] L. Coull, D. Hagendorn, V. Remondino and F. Rodriguez-Mateos, "LHC quench protection system," *IEEE Trans. Magnet. 30*, pp. 1525-1529, 1994.

[3] V. Maroussov and A. Siemko,"A method to evaluate the temperature profile in a superconducting magnet during a quench," *IEEE Trans. Applied Superconductivity 9*, pp. 1153-1156, 1998.

[4] A. Siemko et al., "Power test results on the long models and full scale prototype of the second generation LHC arc dipoles," in *ICEC16/ICMC Proc.*, Kitakiushu, Japan, May 1996, T. Haruyama, T. Mitsui, K. Yamafuji, *Eds. Elsevier Science*, pp. 837-842, 1997.

[5] F. Rodriguez-Mateos, R. Schmidt, F. Sonneman and A. Siemko, "Quench process and protection of the LHC dipole magnets," CERN-LHC Project Note 184, 1999.

[6] G. Ganetis and A. Stevens, "Result of quench protection experiment on DM1-031," SSC Tech Note 12, BNL, 1984.

[7] L. Bottura et al., "Performance of the 1-meter model of the 70 mm aperture quadrupole for the LHC low-beta insertions," CERN-LHC Project Report-240, 1998.

[8] F. Chapuis,"Modélisation du comportement électrothermique des aimants supraconducteurs en cas de transition résistive," DEA report LHC, 1998.