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METHODS FOR THE EVALUATION OF QUENCH TEMPERATURE PROFILES AND THEIR APPLICATION FOR LHC SUPERCONDUCTING SHORT DIPOLE MAGNETS

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Abstract

This paper presents a study of the thermal effects on quench performance for several Large Hadron Collider single aperture short dipole models. The analysis is based on the temperature profile in a superconducting magnet evaluated after a quench. Peak temperatures and temperature gradients in the magnet coil are estimated for different thicknesses of insulation layer between the quench heaters and the coil and different powering and protection parameters. The results show clear correlation between the thermo-mechanical response of the magnet and quench performance. They also display that the optimisation of the position of quench heaters can reduce the decrease of training performance caused by the coexistence of a mechanical weak region and of a local temperature rise.

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1. INTRODUCTION

The Large Hadron Collider (LHC) main superconducting dipole magnets will store a large amount of electromagnetic energy [1]. In 15 m long dipoles, 7 MJ is deposited in the magnet at 8.3 T. For this magnetic field the quench propagation velocity is in the range of 20-30 m/s and is not sufficient for the magnet protection against local overheating. The quench protection system is therefore active and consists of quench detectors and quench heaters [2, 3] to ensure that local temperature peaks are kept within the design limits. The quench heaters are fired after the quench detection in order to drive large fractions of the magnet coils normal and consequently to distribute the dissipated energy over the whole magnet length. However, even if the temperature rise is kept below the critical values, large hot spot temperatures and temperature gradients can influence significantly the magnet quench performance thereafter and can even cause performance degradation [4]. As a result, the knowledge of the temperature development in the different parts of the coil during a quench and of the maximum temperature is essential in order to localise the critical points in the magnet design and to assess the performance of the magnet protection system. The temperature can be calculated from the measured quench load (adiabatic method). It can also be obtained by the evaluation of the resistivity or from the energy balance equation (non adiabatic methods). In the two last cases the voltage which should be taken into account must be corrected because of the inductive component. A method based on the determination of the inductive voltage distribution on the magnet, the “partial inductance method”, was implemented [5] with this aim. Tests of different quench heater configurations were performed on various one meter long dipole magnets with six block design (see *figure 1*). During each test the temperature profiles in the coil were evaluated. In particular, the average temperature occurring in the warmest turn and the temperature gradient across the warmest block were systematically considered.

This paper is organised as follows: the first part consists of a brief description of the “partial inductance” method. In the second part, the peak temperatures obtained using the energy balance equation and the " partial inductance " values are compared with the values from two other experimental techniques, i.e. the temperatures extracted from the value of the quench load and from the determination of the copper resistance in the turn. The results are also compared with the peak temperatures computed with a numerical simulation including helium cooling. The last part of the paper presents the results obtained in the performed experiments. The correlation between quench performance and the thermo-mechanical response of the magnet is studied by the analysis of the temperature profiles. Finally the efficiency of the protection of selected LHC short dipole magnets by various insulation layer thicknesses and position of quench heaters are compared.

2. DESCRIPTION OF THE "PARTIAL INDUCTANCE" METHOD

Principle of the method

The electrical circuit of the magnet during a quench can be represented as an equivalent serial connection of a non-linear inductance L_E (I) and a time dependent resistance R(t). The temperature of a portion of cable bounded by two voltage taps, (in particular the temperature for a single turn) can be calculated from the heat energy released in this length of conductor. Following this idea, the procedure can be divided into three steps [5].

Energy equation for a single turn. The Joule heat Q(t) released in the magnet during the quench is obtained using the energy equation:

$$
\begin{aligned}
Q(t) &= \int_{t_o}^{t} \left(V(t') - V_{inductive}\right) I(t') dt' = \int_{t_o}^{t} \left(V(t') - \left[L_E(I) \frac{dI}{dt} \right] \right) I(t') dt' \\
&= \int_{t_o}^{t} V(t') I(t') dt' + \frac{1}{2} \left(L_E\left[I(t_0)\right] I(t_0)^2 - L_E\left[I(t)\right] I(t)^2 \right)
\end{aligned}
\qquad (1)
$$

In (1), V and $V_{inductive}$ mean the total voltage and the inductive voltage across the magnet, $L_E(I)$ the inductance of the magnet dependent on the excitation current I and t_0 a time before the quench when the magnet was still in the superconducting state. At the first order the inductance of the magnet is taken independent of time. The same energy balance is applicable for a single turn (in practice for a portion of cable between two voltage taps), provided that the ratio of the inductive voltage at any turn to the whole inductive voltage does not change with the current value. A "partial inductance" called L_n is attributed to the turn "n" and defined in (2) by:

$$L_n = \frac{V_{inductive}^{taps}}{V_{inductive}^{magnet}} L_E (I = 0) \qquad (2)$$

Simulations of the magnetic flux distribution show that the condition described above is fulfilled since the maximum change of the ratio (magnetic flux through a single turn/flux through the whole magnet coil) does not exceed 1% for any turn [5].

Inductive voltage distribution on the magnet. The second step consists in the determination of the inductive voltage distribution. For a 15-m magnet, it can be obtained with high precision from a 2 dimensional computer simulation (numerical programs MERMAID, ROXIE [6, 7]). For short dipole models, the ratio between the length and the transversal coil size is too small to validate the 2-dimensional calculation. Moreover for short dipole models, the contribution of a test station cabling to the partial inductance values can not be neglected. The inductance between two voltage taps, i.e. the "partial inductance", can be measured directly in the following way. 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. Assuming that in most of the voltage taps the resistive contribution is zero, L_n is extracted from the power integral $Q^{taps}=\int V^{taps} I dt$ for every recorded voltage V^{taps}. This calculation is repeated for several heater provoked quenches (because the quench location is well known in that case) in order to find the maximum value of L_n. This maximum represents the partial inductance of the turn defined in (2) which will be used in the next paragraph (see equation 3) to estimate the Joule heat released in a portion of cable between two voltage taps.

Joule heat released and temperature profile. The Joule heat released in the cable length between two voltage taps can be computed by:

$$Q^{taps}(t) = \int_{t_o}^{t} V^{taps}(t')I(t')dt' + \frac{L_n}{L_E(0)}\frac{1}{2}\left(L_E[I(t_0)]I(t_0)^2 - L_E[I(t)]I(t)^2\right) \qquad (3)$$

From Q^{taps} (t), the development of the temperature of any turn of the coil can be figured out as shown in *figure 2,* provided that the masses of the copper and of the superconductor and the dependencies of the specific heat versus temperature are known. *Figure 2* displays the growth of the temperatures after a quench, evaluated between selected voltage taps distributed in the magnet coil. This instrumentation is commonly used in the tests of the LHC dipole magnets for the location of the quench origin. The name used to identify the voltage tap is as follows: "U2T1" means the voltage measured in the first turn (pole turn) of the block 2 (external block of the outer layer) in the upper pole.

The main advantages of the "partial inductance" technique are the following:

- The procedure is based on the Joule heat equation (1). 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.
- In addition, it allows the evaluation of the warmest point of the coil and also the temperature distribution across the coil sections.

Figure 3 shows examples of the temperature profiles in the coil for a natural quench and for a quench provoked by the firing of a spot heater. Both quenches were performed without energy extraction. The quench heaters, covering the outer layer, were fired 10 ms later after the quench detection. As one can see in *figure 3*, the pole turn of the outer layer (in the pole where the quench started) and the related whole block developed the highest temperatures, independent of the quench origin [8]. This is quite surprising because one would expect that the stronger heating would happen at the origin of the quench. In fact the pole turn of the outer layer is the location of the highest temperature because it is the most resistive turn. This can be explained by two facts:

- the outer layer is more resistive as compared to the inner layer, since the cross section of the copper in the cable is smaller [1] (12.46 mm^2 instead of 13.53 mm^2);
- with respect to the rest of the outer layer, the pole turn and its related block (named block 2) are submitted to the highest magnetic field [7].

In the following analysis, the variation of the temperature of the warmest 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. ΔT_{hb} is a measurement of the temperature gradient established between the first turn and the sixteen turns of block 2.

$$\Delta T_{hb} = T_{ht} - T_{block2(average)} \qquad (4)$$

3. COMPARISON WITH THE PEAK TEMPERATURES OBTAINED USING OTHER METHODS

In order to check our results, the peak temperature was evaluated using three other techniques in the case of several natural quenches without energy extraction:

- the peak temperature was derived from the determination of the quench load [9]

- the peak temperature was extracted from the growth of the resistance during a quench, measured in the pole turn of the outer layer (i.e. in the warmest turn). To evaluate the importance of the inductive part of the voltage after the beginning of the quench, the resistance was calculated by taking into account successively the resistive voltage and then the total voltage

- the peak temperature was computed using a numerical program, Simulation Program for Quench Research (SPQR), which takes the cooling by helium into account [10].

The values of the peak temperature obtained by these experimental techniques and calculated with SPQR are presented in *figure 4* for eight natural quenches without energy extraction.

Comparison with the temperature extracted from the quench load. Good agreement was found between the values obtained from the measured quench load and those calculated from the "partial inductance" method for which the starting point is the energy balance equation. It is rather surprising because the peak temperature evaluated by the later is expected to be lower since the temperature is averaged along the cable length bounded by the two voltage taps. The comparable values obtained could be explained by the relatively small length of the short dipole models. The two voltage taps which bound the pole turn of the outer layer are separated by 1.5 m and with a quench propagation of 30 m/s, the whole turn is quenched within 23 ms. Taking into account a typical quench load close to 29 MA^2s, this results in lowering by 0.66 MA^2s of the quench load value of the whole turn, i.e. a difference of 15 K in terms of temperature. This disparity stays within the accuracy of the two methods.

Peak temperature calculated from the resistance growth. The measured resistance growth in the warmest turn was deduced from the resistive part of the voltage, $V_{resistive}$. This was evaluated by subtracting from the total voltage across the turn V^{turn} (the pole turn of the outer layer), the inductive voltage L_{ht} dI/dt. L_{ht} represents the partial inductance associated to the pole turn of the outer layer calculated using the method described in §2. The variation of R_{ht} in time was therefore determined by the following equation:

$$R_{ht}(t) = \frac{V^{turn}(t) - L_{ht}\, {}^{dI}\!/_{dt}(t)}{I(t)} \qquad (5)$$

The calculated "partial inductance" for the pole turn of the outer layer L_{ht}, was for this magnet equal to 26.8 μH. The temperature T_{ht} was extracted from R_{ht} ,taken at the time at which T stabilises i.e. in a time interval between 350 and 400 ms after the beginning of the quench. As shown in *figure 4*, the values of peak temperature were similar to those calculated by the "partial inductance method", considering the energy balance equation for a single turn as starting point. This demonstrates without ambiguity the equivalence between a determination based on the energy equation and based on the calculation of the copper resistance. *Figure 4* displays also the temperature obtained by considering at the same time only the value of the total voltage V^{turn}, neglecting therefore $V_{inductive}$. The peak temperatures were lower by an average of 33 K (15 % in average), showing clearly that the inductive part of the voltage provoked by the decrease of the current could not be neglected until 400 ms after the quench.

Peak temperature obtained with the numerical program SPQR. The temperature values are computed using the numerical program, Simulation Program for Quench Research (SPQR)[10]. The numerical program simulates the quench process by solving the heat balance equation with the finite difference method and evaluates the temperature profile after a quench as a function of time and space. In this model, parameters like quench propagation along the superconducting cable, quench heaters effect, impact of the eddy currents and transverse helium cooling are output results. As shown in *figure 4*, the computed peak temperatures are similar to those calculated from the quench load. This suggests that in the dipoles, helium cooling contributes to the lowering of the peak temperature by only a few percent. This is due to the fact that the cable is not permanently cooled: the helium fraction surrounding the conductor is vaporised in the region where the hot spot appears and helium can not return immediately after a quench.

4. APPLICATIONS OF THE "PARTIAL INDUCTANCE" METHOD

Study of the "de-training effect " in the LHC short dipole models

The *figure 5* shows the training curve at 1.9 K for one short dipole model with a six block design. The curve representing the percentage of energy deposited in the magnet structure is also shown. After a few quenches with all the stored energy dissipated in the magnet, a significant "de-training" (drop of quench level) appeared. When the energy was extracted again, the quenching field was observed to recover after a few training quenches. The quench location analysis revealed that all normal training occurred in the inner layer whereas all the "de-training" quenches were found in the pole turn of the outer layer, the region most sensitive to thermal effects [11]. *Figure 6* demonstrates the correlation between the evolution of the quenching field and the temperature of the warmest turn. The de-training began when T_{ht} was higher than 210 K and the magnetic field at quench dropped continuously from 10 T to 8.7 T after few quenches with a peak temperature close to 280-290 K. This "de-training effect", already observed for several six-block coil models [8] was provoked by the coexistence of a mechanical weak region and the wrong positioning of the cable caused by the thermal deformation occurring when the temperature rises for all the energy dissipated in the magnet.

The correlation between the de-training effect and the temperature profile was studied for several single aperture short dipole models. *Figures 7a and 7b* display the results of tests performed for six models with six block design and with similar mechanical features. Only the natural quenches without energy extraction and occurring in the specific location of the de-training were taken into account. In the case of one magnet, S15.V5, the tests were also carried out with an increased delay to fire the quench heaters. As shown in the *figures 7a* and *7b*, the average amplitude of de-training was found to be proportional to the rising of T_{ht} and ΔT_{hb}. This important result suggests that:

- the peak temperatures (and also the temperature gradients) should be kept below 300 K (140 K for gradients) in order to avoid a strong drop of the training performance for the present LHC dipole design
- for magnets with the same mechanical features, the de-training effect could be reduced by the lowering of T_{ht} and ΔT_{hb}.

Tests of several quench heater variants for the protection of short dipole magnets

Quench heaters variants. In superconducting magnets with large energy, the quench heaters are vital elements in case of quench. If the full energy of the magnet is dissipated in a too small volume, the magnet may suffer irreparable damage. Quench heaters are therefore used to heat the surface of the coil. They allow better dissipation of the stored energy over a large volume and limit excessive temperatures after a quench. For high efficiency, the heater strip must be in close thermal contact with the coil. Studies performed for similar coil design showed that the optimum position is between the coil layers [12, 13, 14]. To test this, a one meter long dipole model was equipped with heater strips in two different positions. Heater strips were placed between the inner and the outer layers in addition to heaters placed in the standard position i.e. covering the outer radius of the outer layer. For redundancy, there were two circuits for each type in coil quadrant. Heaters covering the high field and the low field regions were respectively called HF and LF (see *figure 1* for the position in the cross section). The heaters were made of pairs of 25 μm thick and 15 mm wide stainless steel strips, sandwiched between, and bonded to both layers of the electric insulation foil [15]. The length of the steel and of the copper plated part was the same for all the strips. The heaters in both positions are powered with a capacitor bank discharge producing a peak current of 50 A at a voltage of 400 V. The main qualitative variants for the quench heaters 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 different thicknesses of the insulation foil between the heater strip and the coil, 75 and 200 μm, were tested for ORQH.

Study of the efficiency of the two heater positions. To study the efficiency of each set of quench heaters, quenches were provoked at different currents by firing a spot heater located in the outer layer (see *figure 1*). The heaters were activated 10 ms after the detection of the quench and the magnet power supply was switched off 50 ms after, in order to avoid artificial quench back effect. *Figures 8a and 8b* display the variation of T_{ht} and ΔT_{hb} vs magnet current when the magnet was protected alternatively by the ORQH and the IRQH. The two types of heaters protected the magnet with an equivalent efficiency at low currents ($I < 10$ kA). However quenches provoked at higher currents show clearly the influence of the heater position. In particular, 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 14% in terms of maximum temperature and of 20% for the temperature gradient evaluated in the warmest block. The higher efficiency of the IRQH is the consequence of two facts:

- due to a keystone angle of the cable, the IRQH covered four turns more than the ORQH
- the IRQH were located in high magnetic field regions and therefore the effective temperature margin was lower. Less energy was needed to raise the temperature of the coil to the critical one. Indeed close to the ultimate current, the delay needed to trigger a quench was shortened by a factor of two for the IRQH, i.e. 20 ms instead of 40 ms for the ORQH.

Effect on training performance and de-training effect. During the training, quenches without energy extraction, the magnet was protected by firing successively the four outer radius and the four inter radius quench heaters. As shown in *figures 9a and 9b*, 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. The amplitude of this de-training effect was limited to an average value of 8.7 T (D_{inter}) when the IRQH were fired, whereas the drop of magnetic field was more pronounced in case of protection by the ORQH with a field level of 8.35 T (D_{outer}). In order to confirm the role of the thermal effect in the instability of the training, T_{ht} and ΔT_{hb} were calculated for each quench without energy extraction. As one can see in *figures 9a and 9b*, a clear correlation existed between T_{ht} and ΔT_{hb} determined by the position of the quench heaters and the amplitude of the de-training effect. 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} (average increase of 35 K and 26 K respectively) calculated for the case when the magnet was protected by the outer radius quench heaters. It has been found that magnet protection using quench heaters placed between the inner and the outer layer coil can reduce the amplitude of the de-training effect. This solution has not yet been adopted for the 15 meter long dipole models because of the difficulty to preserve the integrity of the quench heater over a supplementary polymerisation cycle. The heaters have to be inserted between the layers after the polymerisation of the layers, after which a further polymerisation cycle is required [16].

Effect of the insulation thickness. In order to investigate how the thermal conductivity between the heaters and the coil affected T_{ht} and ΔT_{hb}, two different Kapton® insulation layers between the coils and the outer radius strips, 75 μm thick and 200 μm thick, were tested. Quenches were provoked by firing the spot heater and the magnet was protected by all the ORQH. *Figure 10* reflects the raise of T_{ht} with the insulation thickness. At high current (I = 10500 A), the increase was significant and equal to 80 K, resulting at the nominal current (11850 A) in peak temperatures close to 300 K. Note that temperatures close to 300 K could provoke a strong de-training effect (see *Figure 6 and 7).* The addition of one 125 μm thick sheet of Kapton® increased the heater delay by reducing the heat transfer from the heater into the cable. As expected the measured heater delays for 200 μm thick ORQH increased by a factor of two.

5. CONCLUSION

The evaluation of the temperature profile during quenches was found to be very helpful in the understanding of the critical points and in the interpretation of the quench behaviour of magnets. It also provided results for validation of simulation models of the quench process.

It was found that in the LHC short dipole models, the pole turn of the outer layer and the related block were developing the highest temperature, independent of the quench origin. Moreover, a strong correlation between the temperature profile and the de-training effect has been demonstrated for short dipole models with six block design with similar mechanical features. Using the temperature profiles, the protection of selected LHC short dipole magnets by several sets of heaters has been compared. Protection by heaters located on the inter layer radius was more efficient than by those located on the outer radius of the coil. Peak temperatures and temperature gradients were lowered resulting in a reduced de-training effect.

It was also found that an insulation thickness of 200 μm between the heater and the coils led to peak temperatures exceeding maximum design temperature.

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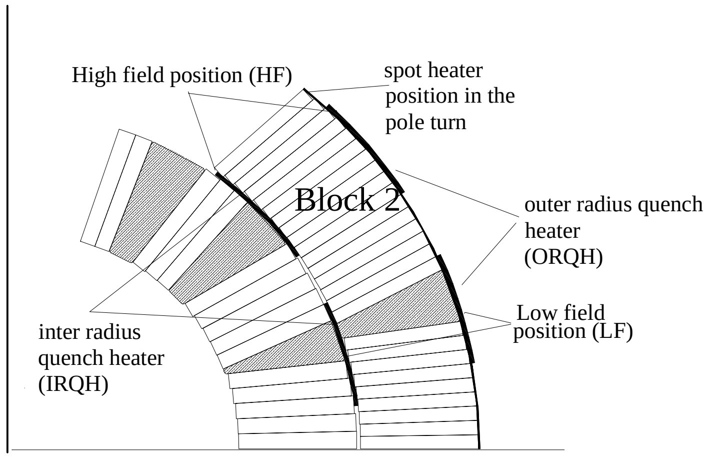

Fig. 1: Layout of a short dipole model with six block design equipped with quench heaters placed between the layers (IRQH) and covering the outer layer (ORQH).

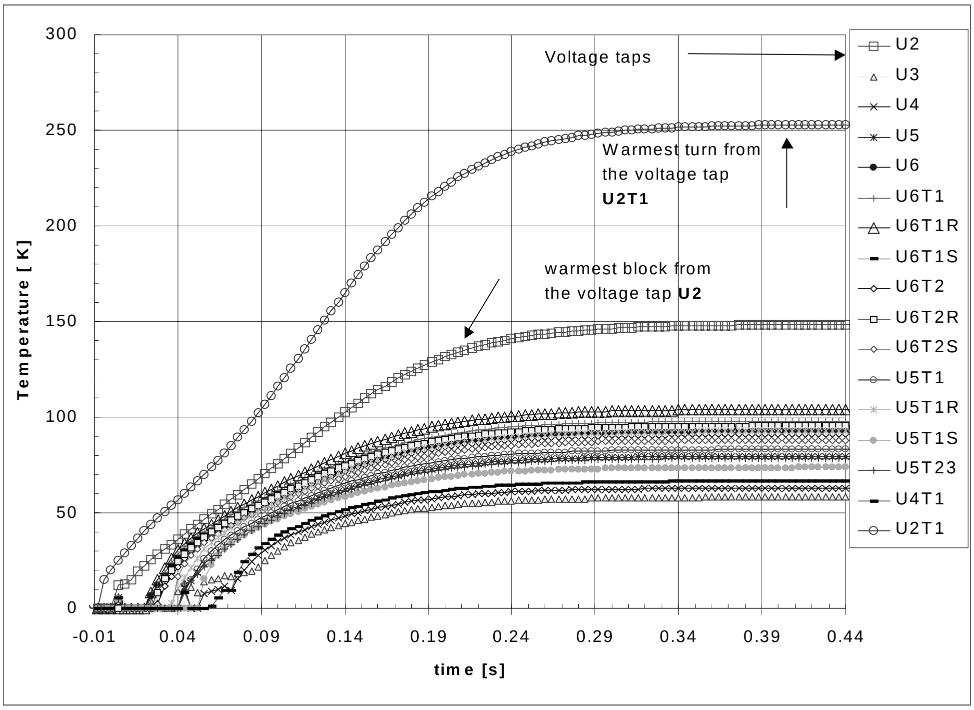

Fig. 2: Growth of the temperature versus time evaluated between selected voltage taps of the magnet listed in the right side. The name used to identify the tap is as follows: "U2T1" means the voltage measured across the first turn of the block 2 (outer layer) in the upper pole. U2 means the voltage appearing in the block 2. The quench began at the time -10 ms and the heaters are fired 10 ms after.

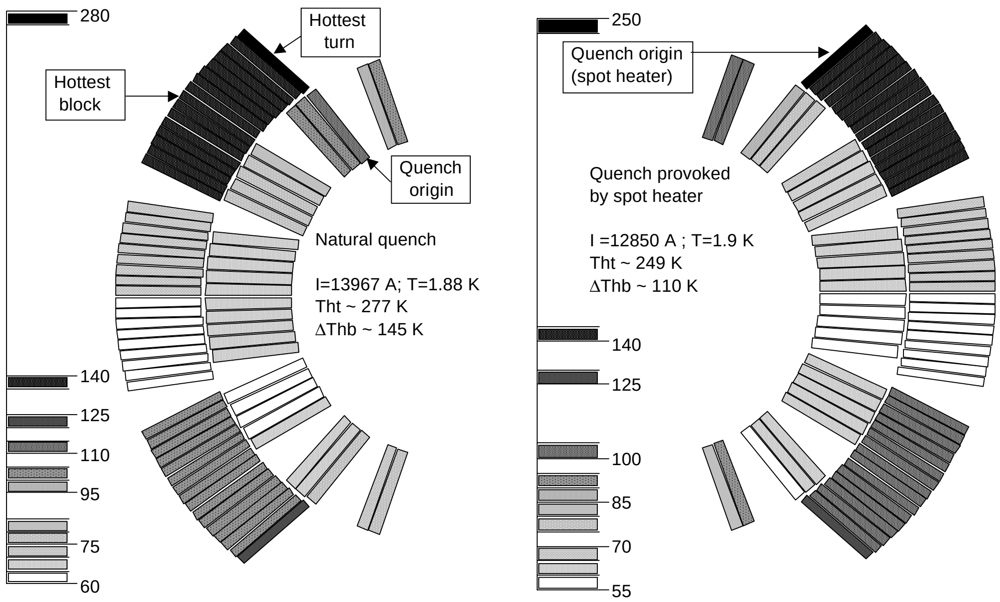

Fig. 3: Temperature profile determined in the case of two quenches, a training quench without energy extraction at 13967 A (left) and a spot heater provoked quench at 12850 A (right).

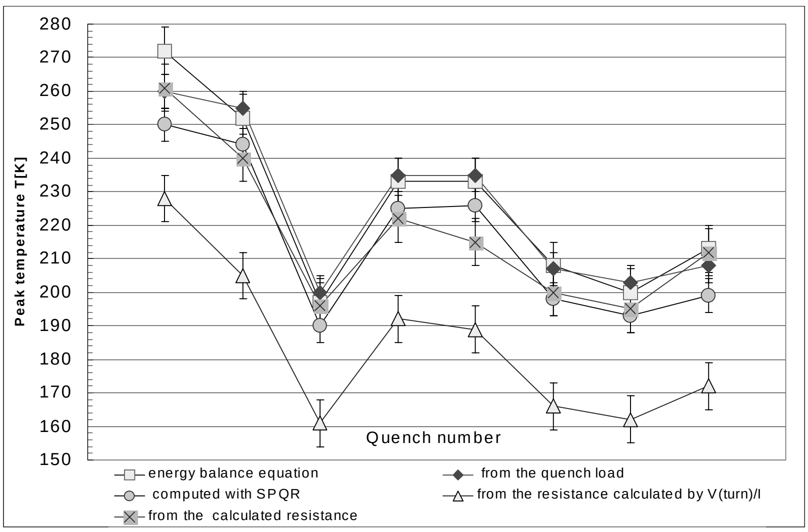

Fig. 4: Maximum temperature calculated in five different ways for eight natural quenches with full energy dump.

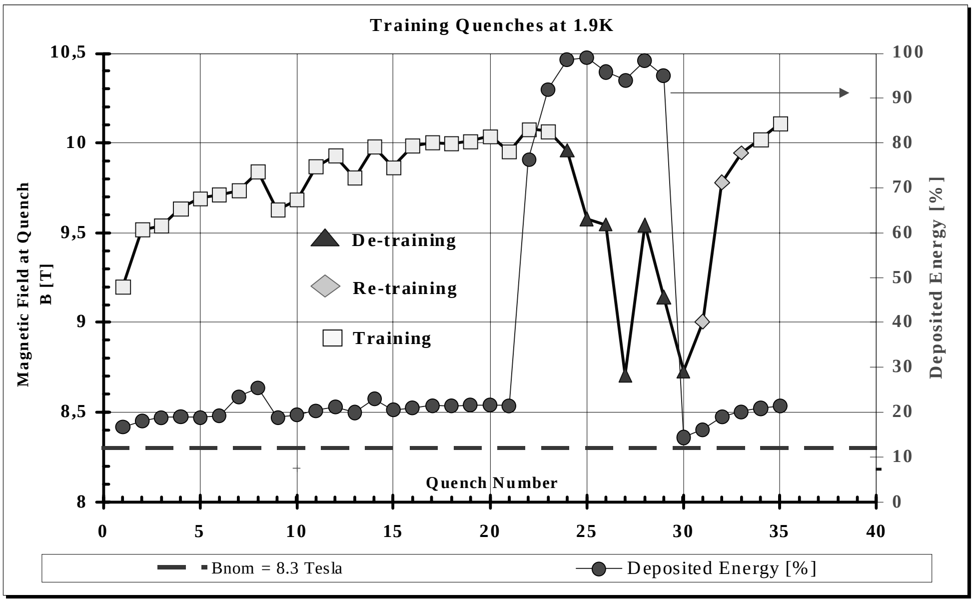

Fig. 5: Example of training behavior and effect of increasing the deposited energy on the training performance in a short dipole model with six block design. The training quenches where the quenching field recovers are called “re-training quenches”.

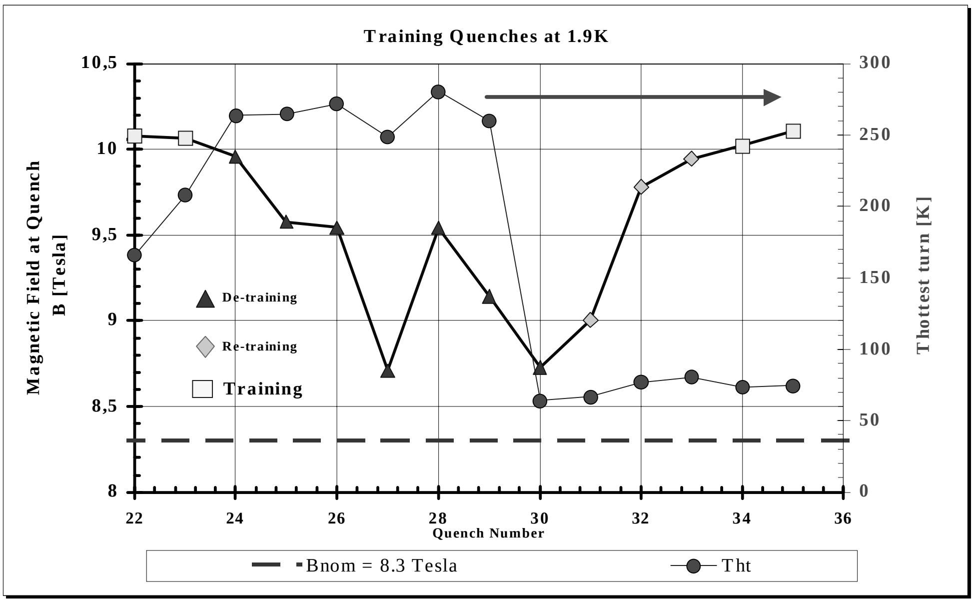

Fig. 6: Correlation between the increase of temperature in the warmest turn T_{ht} and the performance of the magnet.

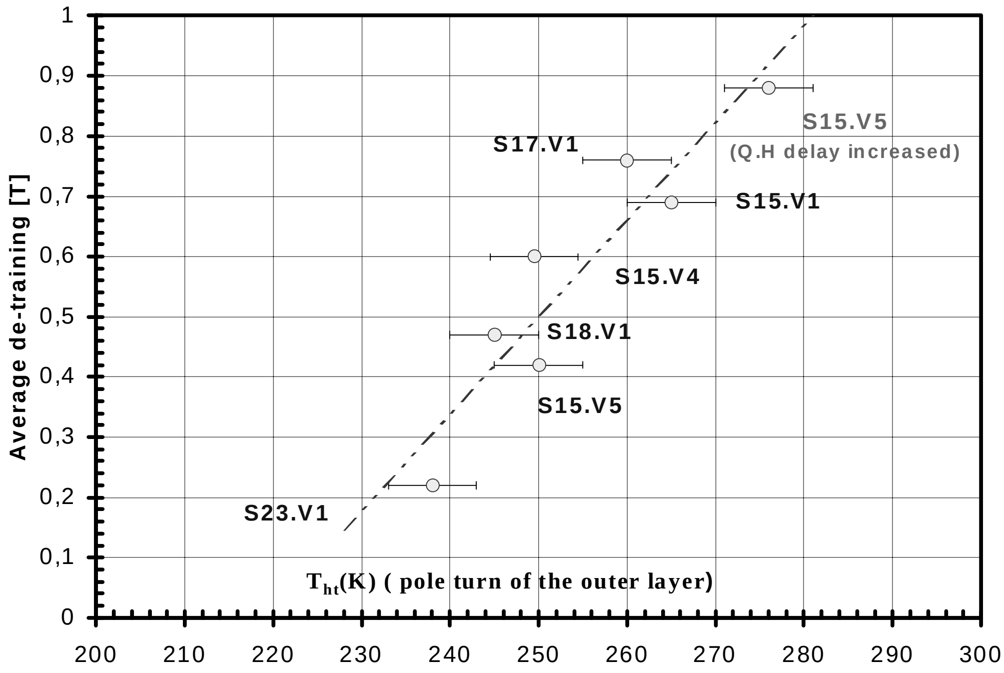

Fig. 7a)

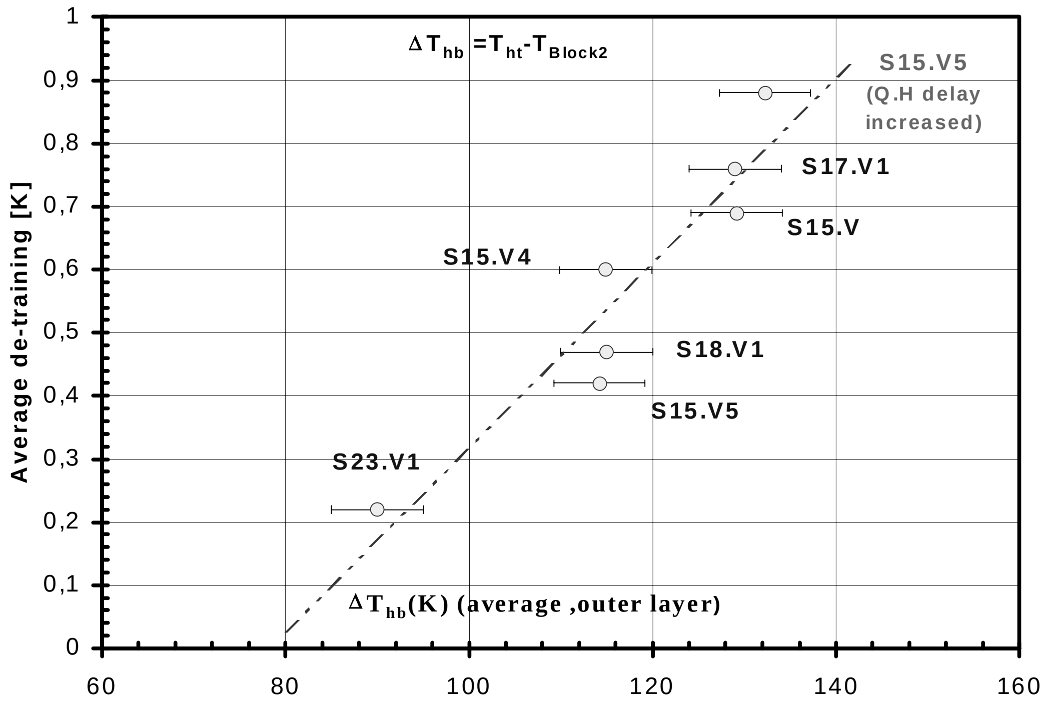

Fig. 7b)

Fig. 7a) and 7b): Correlation between the increase of temperature in the warmest turn T_{ht} and of the temperature gradient in the warmest block and the de-training effect of the magnet in the case of six short dipole models with similar mechanical features. In the two figures the dashed lines are for guiding the eyes.

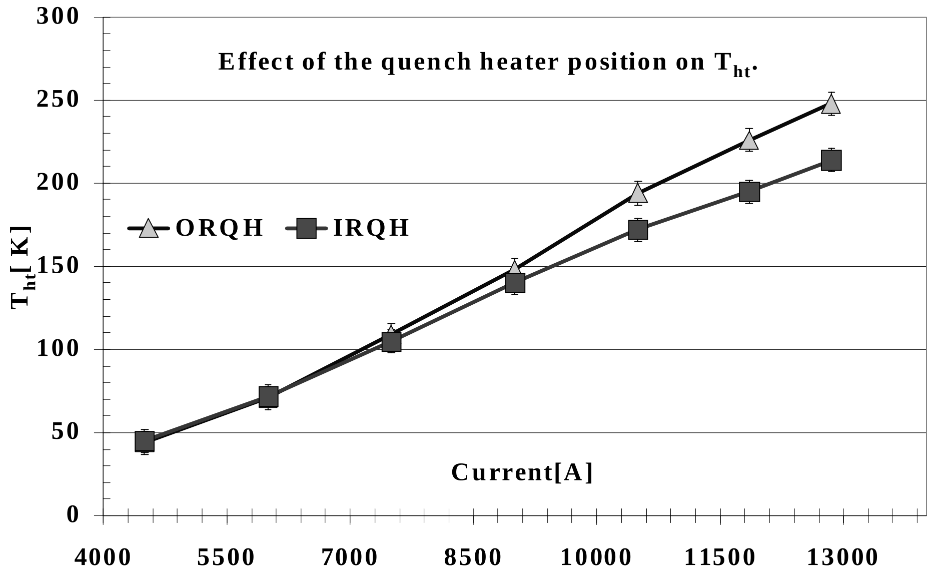

Fig. 8a)

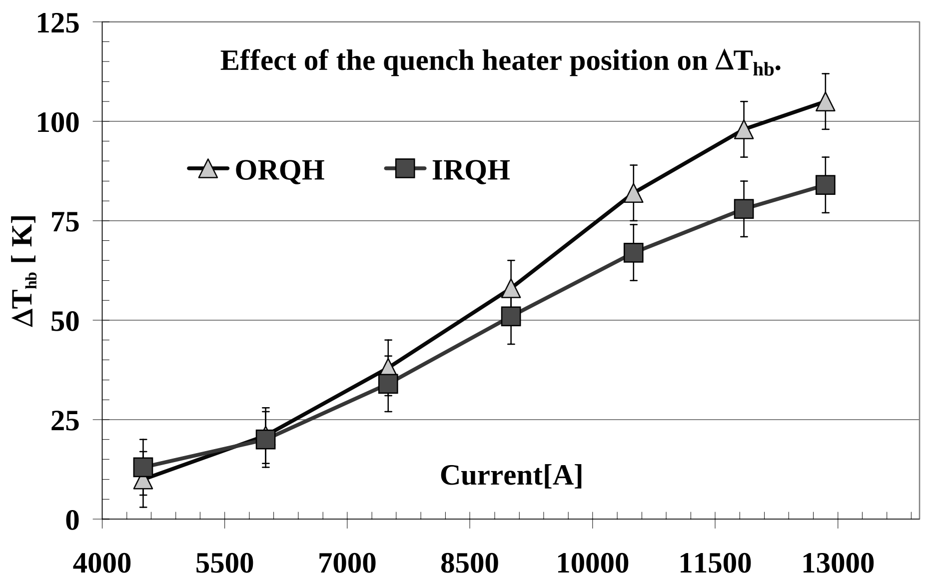

Fig. 8b)

Fig. 8a) and 8b): Variation of the warmest temperature and of the temperature gradient when magnet protection was performed by IRQH and ORQH.

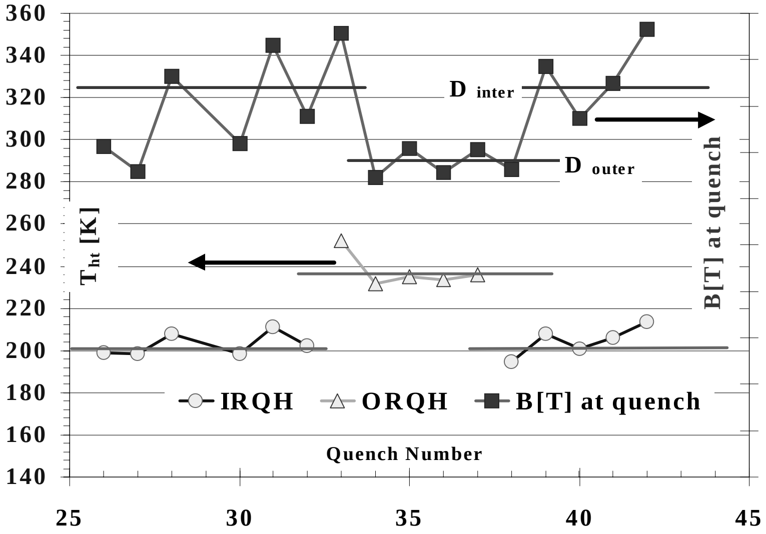

Fig. 9a)

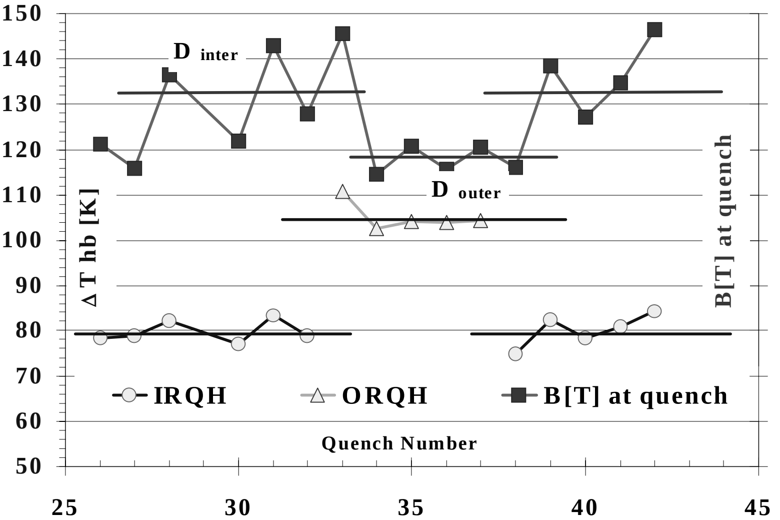

Fig. 9b)

Fig. 9a) and 9b): Correlation between the evolution of the quench performance (magnetic field at quench) and the values of T_{ht} and ΔT_{hb} during the training. The different plateaus of temperature are the consequence of the efficiency of the two type of magnet protection i.e. the protection by the inter and the outer layer quench heaters. An increase of the T_{ht} and ΔT_{hb} induces a drop of the quench level from D_{inter} to the level called D_{outer}.

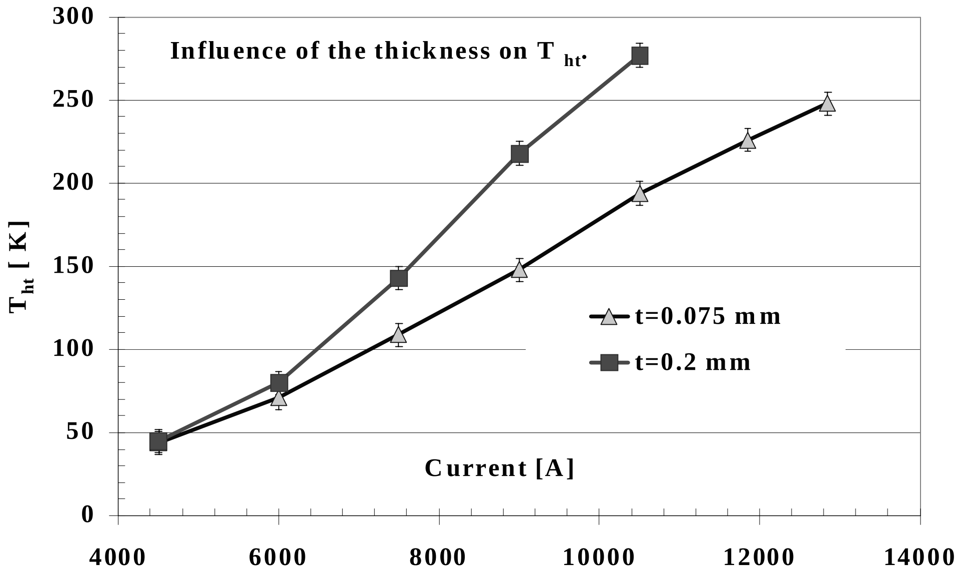

Fig. 10: Variation of the temperature in the warmest turn versus the current for two insulation thicknesses.