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Modeling Quench Protection Heater Delays in an HTS Coil

Tiina Salmi and Antti Stenvall

Abstract—The purpose of this research was to investigate the efficiency of the state-of-the-art quench protection heater technology applied to a High-Temperature Superconductor (HTS)-based accelerator type magnet. The heater delays, i.e., the time delay between the heater activation and consequent normal zone initiation in the winding, were simulated using the 2-D thermal modelling tool CoHDA, which has been successfully used for Low-Temperature Superconductor (LTS) coils. In addition to the quench onset criterion used for LTS, requiring the cable maximum temperature to reach the current sharing temperature (T_{cs}), a criterion accounting for the current redistribution within a cable was introduced in the model. The heater delays were analysed as a function of various heater parameters, their value ranges were based on the heaters in the recent LTS magnets: heater powers ($P_{PH}(t=0) = 20\text{--}200 \text{ W/cm}^2$), heating station lengths (down to 10 mm) and insulation thickness's (up to 150 μm Kapton). The simulated delays in the reference YBCO-cable ($T_{op} = 4.5 \text{ K}$, $I = 5 \text{ kA}$, $B = 20 \text{ T}$ (parallel to cable's wide surface), $T_{cs} = 16.5 \text{ K}$) were mainly between 20 and 100 ms. The heater efficiency seriously decreased for T_{cs} above 20 K when the cable energy margin approached the energy provided by the protection heater. Although experiments are needed to confirm these results, it seems clear that heater based quench protection for HTS-based accelerator magnets requires significant technology developments.

Index Terms—Protection heaters, thermal modelling, Quench protection, High Temperature Superconductors.

I. INTRODUCTION

RECENTLY, large international projects such as EuCARD [1] and EuCARD-2 [2] have demonstrated considerable interest in developing large High Temperature Superconductor (HTS)-based magnets for particle accelerators. Of particular interest is the high-energy upgrade of the CERN Large Hadron Collider (HE-LHC) [3] because HTS-based magnets would enable to surpass the practical limitation of 10-16 T magnetic flux density (B) related even with the most advanced Low Temperature Superconductors (LTS).

One of the several technical challenges in the HTS application is their quench protection [4]. It can be assumed that due to voltage considerations only a small fraction of the magnet stored energy can be extracted after a quench, so most of it must be absorbed in the quenched coil segments. A standard solution in the LTS-based accelerator magnets has been to activate protection heaters (PH) on the coil surfaces upon quench detection to accelerate the normal zone propagation

thus allowing for a more uniform temperature distribution and lower peak temperature. The use of active quench protection heaters is also foreseen for the HTS based 32 T user magnet at NHMFL [5]. A critical parameter characterizing the heater efficiency is the delay time to initiate a normal zone in the winding after its activation, i.e. the heater delay. Studies for the 11-15 T Nb₃Sn and NbTi magnets, which are being developed for the LHC luminosity upgrade by the U.S. LHC Accelerator Research Program (LARP) [6] [7] and CERN [8] [9], have shown that the delays obtained with the present stainless steel-polyimide heaters are at the borderline of protecting the novel LTS magnets [10] [11]. Compared with the LTS, the larger temperature margin in the HTS coils is assumed to lead to even longer delay times and the heaters suitability becomes increasingly unreliable. Therefore, a dedicated heater design study is required as part of the development of HTS coils.

The aim of the present study was to elucidate how the state-of-the-art heater technology developed for the LTS magnets would perform when applied to an YBCO tape based coil. Since experimental set-ups are not yet available, we used similar computation method than in the heater delay analysis for the Nb₃Sn magnets. The model and the reference coil are described in Section II. The heater delays are then simulated and their dependence of the most important heater design parameters (heater power, insulation, and geometry) as well as on the cable operational point are analysed. The results are presented in Section III. We conclude by summarizing the simulated heaters performance and with the first guidelines for the heater design for HTS.

II. SIMULATION MODEL

A. CoHDA thermal model

The computer program CoHDA (Code for Heater Delay Analysis), described in [12], was developed for the analysis of heater delays in impregnated Nb₃Sn magnets. It is based on 2-D thermal network model which computes the cable temperature (T) as a function of time based on the heat diffusion from the protection heaters to the cable. The model takes into account the different insulation layers, heater power and cable properties, see Fig. 1 and 2. In this work we apply the same model to an YBCO coil, by introducing the needed new material properties and adjusting the quench onset criteria.

B. Heater delay definition

In the LTS magnets the heater delay was estimated as the time to increase the maximum temperature of the cable from the operation temperature to the current sharing temperature T_{cs} , i.e., the temperature at which the critical current (I_c)

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Fig. 1. Schematic view of one cable and heater (not in scale).

Fig. 2. 2-D model with periodically placed heater elements (shown with black) on top of the cable (not in scale). Due to symmetry, only half of the heater period needs to be modelled (shown with dashed lines). In y -direction the boundaries are fixed at bath temperature and in z -direction adiabatic boundary conditions are assumed.

equals the magnet operation current (I_{mag}). This criterion is optimistic since it neglects the current redistribution between the strands in the non-uniformly heated cable cross-section. A more conservative criterion based on average critical current density (J_c) was presented in [13]. It succeeded in giving upper bound to simulation encompassing over 95% of the measured delays for the coil outer surface heaters. In this paper we aim at improving the second criterion by calculating the current redistribution within the YBCO tape. We consider two criteria for quench onset:

1) *Delay to current redistribution (cr)*: The cable maximum temperature reaches T_{cs} .

2) *Delay to current sharing (cs)*: A fraction of the current redistributes to the cooler parts of the conductor cross-section as the warmer parts (closer to the heater) reach T_{cs} . The current continues to flow in the conductor but its density at each point is at maximum the local J_c . The excess current is divided to the region still below J_c . The heater delay is computed to the time instant when the temperature and current distribution is such that J_c is reached at all points. It is assumed that after this the current diffuses into the copper stabilizer and resistive voltage is observed. Both the current redistribution and the current flow in the YBCO layer are assumed lossless.

C. Reference cable

The considered YBCO tape and operation range are loosely based on the EuCARD-2 WP 10 "Future magnets" develop-

Fig. 3. Parallel field critical current and current density versus temperature in the YBCO cable. The cable consists of four 12 mm wide tapes, each having 1 μm thick YBCO layer.

ment goals [2]. The cable consists of four 12 mm wide YBCO tapes stacked together and insulated with 30 μm thick Kapton layer. Each tape has 1 μm thick YBCO layer, see Fig. 1. The reference operation point is at 4.5 K, $B = 20$ T, and $I_{mag} = 5$ kA. The cable dimensions and the insulation scheme are summarized in Table I.

D. YBCO critical surface

The I_c is based on the measured data of SuperPower SC4050 YBCO tape and parameterization at parallel field as presented in [14]:

$$I_c(T, B) = I_c(T, 0) \frac{1}{\left(1 + \frac{B}{B_{peak}(T)}\right)^{1.43}}, \quad (1)$$

where $I_c(T, 0)$ and $B_{peak}(T)$ are based on polynomial fit of experimental data [15]:

$$I_c(T, 0) = 0.2213T^2 - 35.99T + 1485.51 \quad (2)$$

$$B_{peak}(T) = -1.37 \times 10^{-6}T^4 + 1.47 \times 10^{-4}T^3 + 8.87 \times 10^{-3}T^2 - 1.52T + 47.74. \quad (3)$$

The measured data is for 4.04 mm wide and 0.094 mm thick tape. Therefore, we scaled the current carrying capacity to four 12 mm wide tapes, see Fig. 3. The angular dependency to I_c is not considered in this study, but the parametric studies will examine the impact of temperature margin to the heater delay. In principle, this can be achieved for YBCO tapes by either varying I_{mag} or the magnitude or direction of B .

E. Cable material properties

The thermal properties of the uninsulated cable are based on weighted volumetric average of Hastelloy [16] and Cu [17] properties. The thin layers of YBCO, Ag, and the buffer stack are assumed negligible since they together occupy less than 5% of the cable volume. The temperature dependence is taken into account. The Cu thermal conductivity depends also on B , although data is available only up to 30 T [17]. In the simulation above 30 T, the thermal conductivity is computed using 30 T.

The cable insulation on the wide sides is not included in the material properties. The correct way to its inclusion will be investigated in future studies.

TABLE I
CABLE PARAMETERS THAT ARE NOT CHANGED IN THE SIMULATION.

Parameter	Value
"Ground insulation" (Kapton) (mm)	0.10
Cable insulation (Kapton)(mm)	0.03
Interlayer insulation (Kapton)(mm)	0.04
Bare cable width (mm)	12.0
Bare cable thickness (mm)	0.376
Bare cable Cu-%	50.0
Bare cable Hastelloy-%	50.0

TABLE II
PARAMETERS REFERENCE VALUES AND THE RANGE OF VARIATION IN THE PARAMETRIC ANALYSIS OF HEATER DELAYS.

Parameter	Reference	Variation range
Magnetic field (T)	20	6.5 - 50
Current sharing temperature (K)	16.5	4.9 - 26.6
Heater power (W/cm ²)	50	20 - 200
Heater insulation (mm)	0.050	0.001 - 0.15
Heater coverage (mm)	100%	10-100 (period 120)
Heater thickness (mm)	0.025	0.025 or 0.050

F. Heater properties

The heater is a stainless steel strip on the coil's outer surface facing the thin side of the cable. Generally, the heater consists of periodically placed "heating stations". However, in the reference case the cable longitudinal coverage is assumed so long, that the impact of longitudinal heat diffusion in the cable can be neglected. This allows also performing the simulations in a 1-D domain.

The reference heater peak power density, $P_{PH}(0)$, is 50 W/cm², which has been the reference value for the LARP Nb₃Sn magnets [18]. This parameter represents the volumetric power density scaled for the 25 μ m thick stainless steel. The heater is assumed to be powered with a capacitor bank discharge with RC time constant (τ_{RC}) of 50 ms.

III. SIMULATED HEATER DELAYS

In the parametric analysis all other parameters are kept at their reference values, and the delay dependence on one parameter at time is investigated. The parameters reference values and variation ranges are summarized in Table II.

A. Delay time vs Current sharing temperature

In this study B was varied between 6.5 and 50 T. Consequently, T_{cs} varied between 4.9 and 26.6 K. In each simulation B was constant in the cable cross-section and the plotted T_{cs} is computed for the initial uniform current density.

As shown in Fig. 4, the delays increased approximately linearly up to $T_{cs} = 15$ K but for higher T_{cs} the increase was exponential. After about 100 ms simulation time, when the cable temperature was about 21.5 K, the cable started to cool down. Simulations for T_{cs} higher than 21.5 K therefore never led to a quench. This limit corresponds to $B = 12$ T. In our reference case ($B = 20$ T, $T_{cs} = 16.5$ K) the delay was 25 ms to current redistribution and 34 ms to the current sharing.

Fig. 4. Simulated heater delay vs. current sharing temperature. The magnet operates at 4.5 K and 5 kA and the magnetic field is varied from 50 T ($T_{cs} = 4.9$ K) to 6.5 T ($T_{cs} = 26.6$ K).

The calculated current redistribution phase took between 5 and 20 ms (15-65%) when T_{cs} was above 10 K.

An interesting analysis of the heater performance boundaries is obtained by comparing locally the energy provided by the protection heater with the cable's energy margin from operational temperature to T_{cs} . The energy margin per coil's surface area, as shown in Fig. 4, is computed using

$$E_{margin} = w_{tape} \int_{T_{op}}^{T_{cs}} \gamma c_p dT, \quad (4)$$

where c_p is the specific heat capacity of the non-insulated cable, γ is the mass density, and w_{tape} is the non-insulated tape width. The energy of the protection heater per area is computed using:

$$E_{PH} = \int_0^\infty P_{PH}(t) dt = P_{PH}(0) \times \frac{\tau_{RC}}{2}. \quad (5)$$

In this case E_{PH} is 12500 J/m², and it equals E_{margin} when T_{cs} is about 25.9 K. The delay simulation with adiabatic boundary conditions also in y -direction confirmed that the cable quenches for $T_{cs} = 25$ K, but not for $T_{cs} = 26$ K (delay to cs). At $T_{cs} = 16.5$ K, or lower, the difference between adiabatic and non-adiabatic simulations was less than 2 ms.

B. Delay time vs Heater power

The heater delay dependence on heater peak power is shown in Fig. 5. The heater delays increased strongly when the heater power was reduced below 50 W/cm². This is consistent with the experiments and simulations in LTS magnets [18] [19]. Increasing the power from 50 to 200 W/cm² reduced the delays almost linearly by approximately 50%, down to 12 or 18 ms depending on the simulation criteria.

For the 200 W/cm² peak power, E_{PH} corresponds to E_{margin} for T_{cs} about 37 K. With such large heater energies, attention must be paid in order to avoid overheating the heater itself as well as too high powering voltages. The heater voltage will depend on the heater geometry (resistance), but the temperature can be estimated based on the stainless steel heat capacity. The traditional limit is obtained by adiabatic calculation. Then, for τ_{RC} of 50 ms, the peak power in 25 μ m thick stainless steel should not exceed 90-100 W/cm² in order to stay below 350 K. However, this limit may be overly conservative for thin heaters because the simulated heater temperature was below 300 K even with 200 W/cm².

Fig. 5. Simulated heater delay vs. heater peak power. The heater is powered with a voltage pulse which decays exponentially with $\tau_{RC} = 50$ ms. Cable operation point at 4.5 K, 20 T and 5 kA.

Fig. 6. Simulated heater delay vs. heater insulation. In all cases present is also the cable insulation 30.0 µm. Cable operation at 4.5 K, 20 T and 5 kA.

C. Impact of heater thickness

To investigate how the stainless steel thickness affects the heater temperature, a simulation with power density of 100 W/cm² was repeated with two times thicker stainless steel heater (50.8 µm). This leads to the same volumetric heater power density than in the reference case (19.7 W/mm³). This allows doubling the heater energy without increasing the heater voltage - although twice larger heater current must be supported, and a twice larger capacitance needed for the heater powering unit.

The simulated delays with thicker heater were about 20% shorter than in the reference case (20 ms to current redistribution and 28 ms to current sharing). The maximum heater temperature was 30% larger (130 K). Similar result was obtained using an adiabatic boundary condition on top of the heater and discarding the "ground insulation". This suggests that the insulation around the heater as well as the heater thickness should be part of the heater design study.

D. Delay time vs Heater insulation thickness

Fig. 6 presents the heater delay versus the heater Kapton insulation thickness. Consistently with the studies of Nb₃Sn magnets [20], the delay increased faster than linearly when increasing the insulation thickness. In this case each additional 25.0 µm Kapton layer to the nominal 50.0 µm increased the delay by about 10 to 15 ms (20-40%). The increase is larger with larger total insulation thickness.

Fig. 7. Simulated heater delay vs. heater coverage. The period is 120 mm. Cable operation at 4.5 K, 20 T and 5 kA.

E. Delay time vs Heater geometry

The simulated delay as a function of heater's longitudinal coverage is shown in Fig. 7. The delay strongly increased when the heater coverage was shorter than about 40 mm. For coverages longer than 40 or 50 mm the delays levelled off, and did not deviate more than 10% from the reference 1-D cases. The optimal coverage in the HTS magnets seems to be in the same range as for Nb₃Sn magnets [20].

IV. DISCUSSION AND CONCLUSION

The 2-D heat diffusion model CoHDA was applied to study protection heater delays in a four-tape YBCO cable (effectively 50% Hastelloy and 50% Cu) operating at 4.5 K. Two criteria for quench onset were used: A) The delay time to reach T_{cs} in the cable and B) computing the current redistribution within the tape and the time delay to current diffusion into Cu.

The simulated delay in the chosen reference conditions (T_{cs} 16.5 K, heater insulation 50 µm, heater peak power 50 W/cm² with τ_{RC} of 50 ms) was 24 ms for criteria A, and 34 ms for criteria B. These are only by a moderate amount higher than in the state-of-the-art high-field Nb₃Sn magnets. It seems that 50 W/cm² is the minimum heater power to consider, because for lower power the heater delays increased exponentially. For higher power the delays decreased linearly, down to 12 and 18 ms at 200 W/cm², although such high heater power may lead to overheating of the heater itself. The heater coverage should be at least 40-50 mm to avoid longer delays. Increasing the heater insulation thickness by 25.0 µm from the reference 50 µm led to increase of the delay by 30-40%.

Serious difficulties to quench the investigated cable started when T_{cs} was above 20 K, presumably because then the cable energy margin approached the heater energy (per coil surface). Based on the calculations, one option for improving the heater delays could be to increase the heater energy by using a thicker stainless steel and larger capacitance in its powering. Although experimental data is needed to confirm these results, it is likely that new heater technologies are needed for the future HTS accelerator magnets in order to provoke quenches also in the coil's lower field regions and at lower magnet currents.

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