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Quench Protection Studies of the 11 T Nb_3Sn Dipole for the LHC Upgrade

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***Abstract*—The planned upgrade of the LHC collimation system foresees additional collimators to be installed in the dispersion suppressor areas. Fermilab and CERN are developing an 11 T Nb_3Sn dipole to replace some 8.33 T-15-m-long Nb-Ti LHC main dipoles providing longitudinal space for the collimators. In case of a quench, the large stored energy and the low copper stabilizer fraction make the protection of the 11 T Nb_3Sn dipoles challenging. This paper presents the results of quench protection analysis, including quench protection heater design and efficiency, quench propagation and coil heating. The numerical results are compared with the experimental data from the 2-m-long Nb_3Sn dipole models. The validated model is used to predict the current decay and hot spot temperature under operating conditions in the LHC and the presently foreseen magnet protection scheme is discussed.**

***Index Terms*—Quench protection, High field accelerator magnets, LHC upgrade.**

I. Introduction

THE upgrade of the Large Hadron Collider (LHC) foresees the replacement of some 8.33 T 15-m-long Nb-Ti main bending dipoles (MB) with shorter 11 T Nb_3Sn magnets, delivering the same integrated strength of 119 Tm at the operating current of 11.85 kA [1]. To demonstrate the feasibility of Nb_3Sn technology for the dispersion suppression (DS) upgrade, Fermilab and CERN started a joint development program with the goal of building a 5.5-m-long twin-aperture Nb_3Sn dipole cold-mass. The first step of this program is the development of 2-m-long single aperture demonstrator magnets. In this paper we discuss the results in terms of quench protection studies for the first single aperture magnets built and tested at CERN, and we compare the results with previous studies performed by Fermilab [2].

Due to the relatively low fraction of copper stabilizer (required to achieve the desired margin) and the high stored energy density (almost a factor 2 times larger than in the MB, quench protection of the 11 T magnet is challenging. Table I compares the operating parameters relevant to quench protection of the MB and the 11 T dipoles at nominal current. The main concerns are the detection of the quench once the initial normal zone propagates along the conductor, the delay to induce a distributed quench using quench heaters or comparable mechanism and the time needed for the quench to propagate to the whole magnet cross section.

TABLE I
MB LHC dipole vs. DS-11 T magnet parameters at nominal current (I_{nom} = 11.85kA)

Parameter	Unit	MB	11T
Field in the aperture	T	8.3	11.2
Conductor peak field	T	8.6	11.6
Differential inductance	mH/m	6.9	11.7
Stored energy density in conductor volume	MJ/m^3	65	130
Magnetic length	m	14.3	2x5.3
Non-insulated conductor current density	A/mm^2	500	790
Temperature margin	K	1.8-6.5	4.5-14.5

The large disparity of time and length scales and the highly non-linear nature of the process makes accurate quench modelling challenging. The basic idea we follow here is to breakdown the complex problem in simpler building blocks that are solved separately and then joined into a consistent solution. The model of heat transfer within the coil is based on the 1D solution of quench initiation and propagation along the conductor (the winding direction). The heat equation is solved implicitly in space (finite elements) and time (multi-step finite differences) using an adaptive mesh algorithm to cope with the large disparity of length scales. Coil turns are thermally coupled across the winding using a second order thermal network. Details of the model are described in [3]. Quench heater delay is solved separately using a 2D finite element model and the results are used in the global solution. Heater delays are modelled using the approach described in [4], implemented in the commercial software COMSOL. Numerical results are compared here to experimental data from the first single coil assembly model (MBHSM101) [5] and the three single apertures MBHSP101, P102 and P103 [6]. The validated model is used to predict the hot spot temperature under operation conditions and to study the impact of different parameters on the maximum conductor temperature.

II. Initial Quench Propagation And Detection

A good characterization of the initial quench propagation is important to determine the time needed to detect the quench and validate its detection. Figure 1 compares the measured and computed longitudinal propagation velocity in the FNAL mirror assembly MBHSM01. The agreement is very good, in particular for the quenches initiated with a spot heater in the

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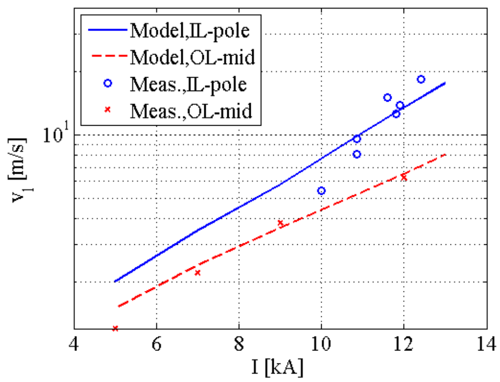

Fig. 1. Longitudinal Quench Propagation Velocity in FNAL mirror magnet MBHSM01.

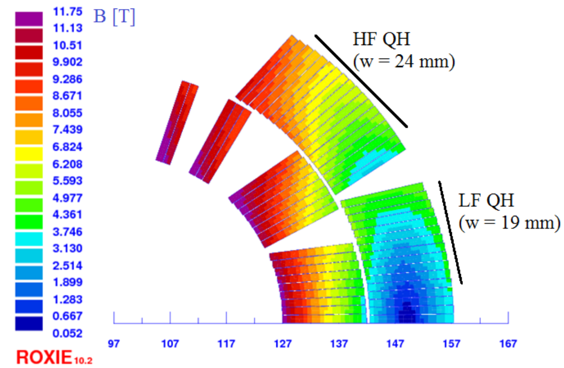

Fig. 2. Field in the coil at nominal current (11.85 kA) and quench heaters position.

low field area (outer layer mid plane turn, OL-mid). For the natural quenches starting in the high field area (inner layer pole turn, IL-pole), the data have larger spread but are still in agreement with the model. The same effect is observed in the experimental data from the Short Model Racetrack Coil (SMC) built and tested at CERN using the same cable (without keystone angle) [3].

III. Quench Heater Design and Performance

Quench protection on the 11 T magnet is relying on quench heaters on the outer layer. Heater strips are made of 25 μm stainless steel strips and are embedded in a layered polyimide (Kapton©) foil that is glued on the outer radius of the coil after impregnation. Insulation thickness from heater to coil has a significant effect on the delay to quench. A thickness of 50 μm of Kapton has been selected as the minimum required for electrical integrity based on LARP experience [7]. In the baseline design for the first short models, a 0.2 mm S2 glass protection is installed between the heaters and the insulated conductor prior to impregnation. The plan is to remove this additional insulation layer by impregnating the heaters with the coil during manufacturing.

The physical limits on the heaters are the temperature and the maximum voltage from heater to coil. Typically, the maximum allowable temperature on the heaters under adiabatic conditions is 350 K, and the peak voltage from heater to coil $\pm$ 450 V. In order to reduce the overall strip resistance and limit the heater voltage for long magnets, the stainless steel heaters are plated with 5 μm of copper for part of the length so as to create pure stainless steel heating stations. The length of the heating stations is 50 mm and the distance in between stations is 90 mm in the low field block and 130 mm in the high field block. Heater stations are placed closer in the low field region to compensate for the slower quench propagation. The width of the heaters have been defined to maximize the coil area covered by the heaters. In order to quench the coil cross section in a uniform way, power dissipated in the low field block is about 1.6 times larger than in the high field. Figure 2 shows the field in the coil and the quench heaters position.

The baseline design considers the use of a standard LHC heater power supply [8], with a capacitance of 7.05 mF and total stored energy of 3.5 kJ. At low magnet current, the heater delay is dominated by the integral of the power dissipated on the heaters and it is important to have a heater current decay long enough ($RC \approx 50$ ms). At high magnet currents, where the protection of the 11 T magnet is critical, the heater delay dominated by the initial peak heater power density, defined as:

$$P_d(t) = \frac{I(t)^2 R_{QH}}{wl} = \frac{I(t)^2 \rho_{ss}}{w^2 th} = \frac{I_0^2 \rho_{ss} e^{(-2t/RC)}}{w^2 th} [W/m^2] \quad (1)$$

where w is the heater strip width, l the total length of the heater stations and th the thickness. ρ_{ss} is the resistivity of stainless steel. The time constant for the heater current is a function of the heater circuit resistance (R, which is the sum of the quench heater strip resistance (R_{QH}) and the wiring resistance (R_w)) and the capacitance (C) of the heater power supply. The not-effective parts of the quench heater strips are neglected in this equation. Figure 3 shows the expected and measured heater delays as a function of the percentage on the load line for different heater currents. Based on these studies, the nominal heater initial current will be 150 A which corresponds to heater power density of 90 W/cm^2 in the high field region and 145 W/cm^2 in the low field. Further increase of the heater power will have a marginal impact on the heater delays in magnet operation conditions. The maximum temperature on the heaters is lower than 250 K.

The amount of electrical insulation between heater and coil plays a key role on the quench heater delay. Figure 4 shows the computed and measured delays for the five coils tested in MBHSP101, MBHSP102 and MBHSP103. In coil 106 and 109, the S2-glass protection layer in the outer diameter was not present. In coils 107, 108 and 111, the thickness of the S2-glass layer is 0.1 mm. The impact on the heater delay is about 10 ms at nominal operation conditions. Following these experimental results, in agreement with the expectations, it is planned for the next coils to impregnate the heaters with the coils, removing the layer of impregnated fiber glass between coil and heaters.

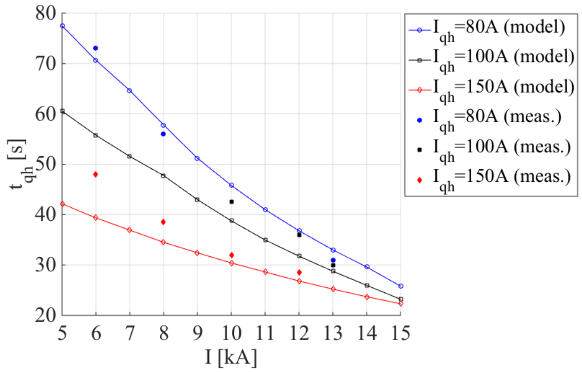

Fig. 3. Effect of the power dissipated in the heater on the quench heater delay, as a function of the normalized magnet current. Measurements from the CERN single aperture assembly MBHSM101.

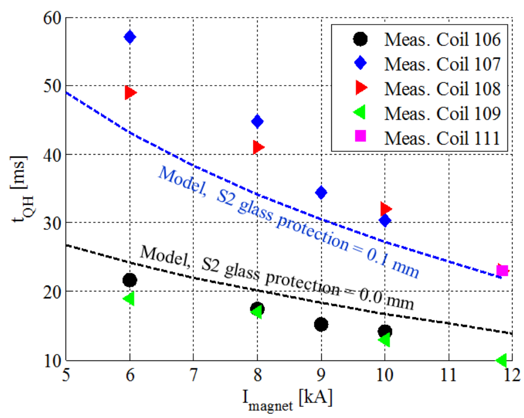

Fig. 4. Quench heater delay as a function of the magnet current on the coils tested at CERN in single aperture configuration.

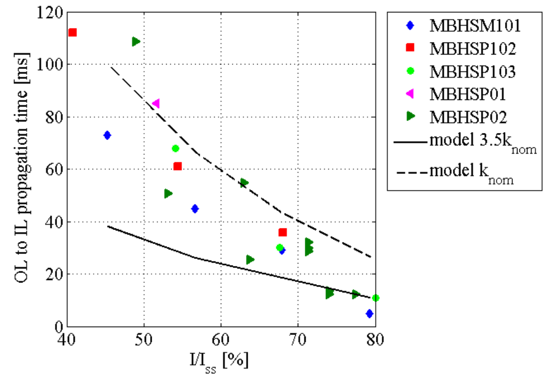

Fig. 5. Layer to layer quench propagation for CERN and Fermilab tested models as a function of the operation point on the magnet load line.

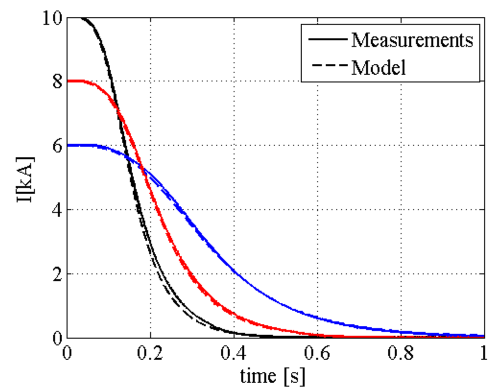

Fig. 6. Current decay for quench heater provoked quench. Computed and measured decay on MBHSP102

IV. Radial Heat Propagation

Once the heaters provoke a quench in the outer layer, an appropriate model of the transverse heat flux in the composite formed by the cable and its insulation is important to determine the time needed to discharge the magnet. We use a second order thermal network to describe the coupling between the turns in the magnet cross section [3]. Figure 5 compares the measured time needed for the quench to propagate from the outer layer to the inner layer with the one predicted by the model. The upper boundary corresponds to the computed delay for the nominal insulation thickness and thermal material properties of the insulation. The lower boundary is the computed delay for thermal conductivity 3.5 times higher. The discrepancy in between measurements and model can be linked to the un-knows in terms of actual geometry and thermal properties of the insulation. In addition to that, quench back is not included in the model and it has a beneficial effect in the layer to layer propagation, in particular at high current.

Quench integral studies were performed in MBHSP102. For these tests, a quench is provoked with the quench heater strips and the dump resistor is delayed by 1000 ms such that it is possible to study the current decay and resistance growth. The average heater power density is 118 W/cm^2, with a current of 150 A going through the heaters. Figure 6 shows the computed and measured current decays. The difference on the quench integral between measurements and model is lower than 5% at all magnet currents.

V. Hot Spot Temperature Under Accelerator Conditions

The design target is to have a hot spot temperature lower than 350 K, currently assumed a safe limit with respect to permanent degradation [9]. The validated model is used to predict the hot spot temperature under operation conditions for a quench starting in the high field region at nominal current (11.85 kA). If the quench starts in the low field region the hot spot temperature is about 50 K lower. The threshold voltage is 100 mV and the validation delay 10 ms. A delay of 5 ms is assumed in between the moment the quench is validated and the moment the current is actually going through the heaters. This is a conservative assumption as it is expected to reduce this delay to less than 1 ms with an improvement of the heater power supply. Quench heater delay is about 20 ms, assuming a 0.1 mm layer of impregnated fiber glass between coil and heaters.

As the degree of thermal coupling in between conductors is not a well known parameter, we present the results for two extreme values. If the conductor and insulation are in good

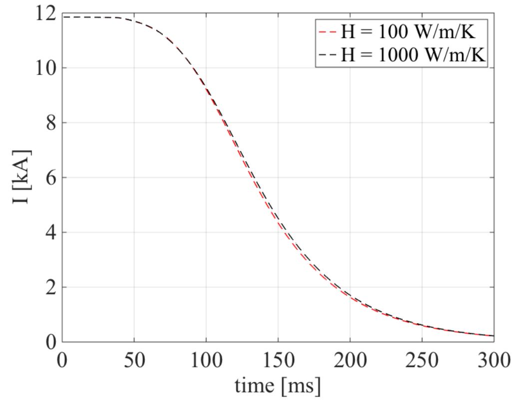

Fig. 7. Current decay in nominal operation conditions for two different levels of coupling among coil turns.

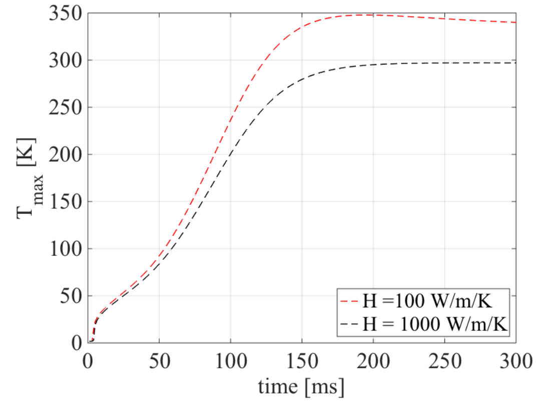

Fig. 9. Hot spot temperature at nominal operation conditions for two different levels of coupling among coil turns.

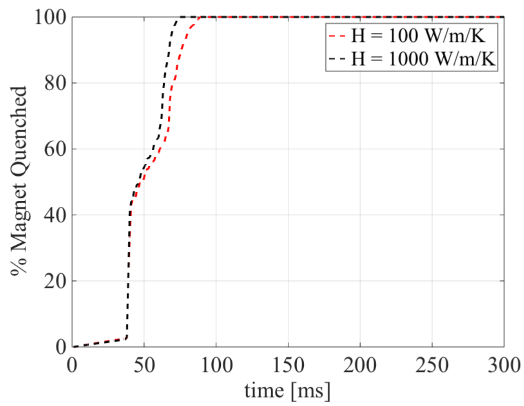

Fig. 8. Percentage of magnet quenched at nominal operation conditions for two different levels of coupling among coil turns.

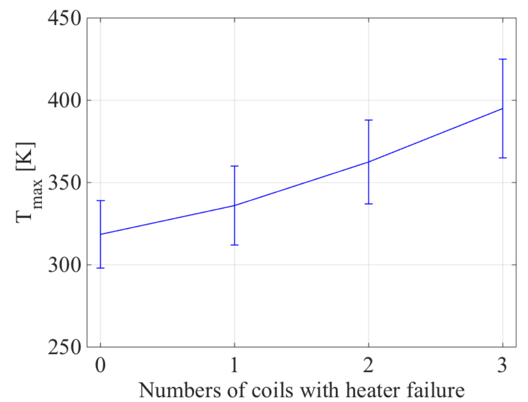

Fig. 10. Hot spot temperature as a function of the number of coils with heater failure.

contact (thermal conductance H = 1000 W/m/K, more details can be found in [3]), the quench propagates faster and the hot spot temperature is lower. In the case of H = 100 W/m/K the quench propagation is slower and the maximum temperature higher. Figures 7, 8, and 9 present the current decay, percentage of magnet quenched and hot spot temperature for the two different values of thermal conductance. Even if the current decay is very close for the two cases (difference on the quench integral lower than 1%), there is a significant impact in the hot spot temperature.

VI. Protection Redundancy

In the baseline configuration, each 11 T cryo-assembly is made out of 2 x 5.5 m magnets connected in series and protected by one standard LHC cold diode [10]. Each aperture is protected with 4 quench heater circuits, i.e., two heater circuits per coil. For the nominal scenario, where all the heaters are effective, the maximum temperature expected during a quench is below the 350 K limit. Here we study the increase on the hot spot temperature as a function of the number of heater failures. In order to be conservative, it is assumed that the two heater circuits of the coil are failing.

Figure 10 shows that if the heaters of 3 coils out of 8 are failing, the hot spot temperature increases to ≈ 400 K. The upper and lower boundaries of the temperature correspond to the two degrees of thermal coupling discussed before. In order to introduce further redundancy to the system, several solutions are being investigated in parallel. The simplest solution is to introduce a secondary circuit in the outer layer. Other solutions such as the introduction of inter-layer heaters or the use of the Coupling-Loss-Induced Quench System (CLIQ) [11] are preferable, as they will provide additional margin in terms of protection.

VII. Conclusion

Quench protection on the 11 T magnet is challenging. A fast detection of the quench and triggering of the quench protection system are a must. Detection of symmetric quenches shall be carefully studied and improved with respect to the current situation on the LHC-RB circuits [12]. Effective heat transfer from heater to coil is important to ensure magnet protection, leading to efforts to optimize quench heater geometry and performance. Experimental tests on the first single aperture magnets built and tested at CERN have been used to validate the model. The expected hot spot temperature in case of quench is below the 350 K limit with the baseline protection scheme, relaying only on outer layer quench heaters. Solutions to provide additional redundancy and margin to the system in terms of protection are under study.

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