QUENCH PROTECTION ANALYSIS OF A SINGLE-APERTURE 11T NB_3SN DEMONSTRATOR DIPOLE FOR LHC UPGRADES*

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Abstract

FNAL and CERN are developing a 5.5-m long twin-aperture Nb_3Sn dipole suitable for installation in the LHC. The program started with the construction of a 2-m long single-aperture demonstrator dipole with 60 mm bore, a nominal field of 11 T at the LHC nominal current of 11.85 kA and 20% margin. This paper presents the results of quench protection analysis of the Nb_3Sn demonstrator dipole.

INTRODUCTION

The planned LHC collimation system upgrade foresees additional collimators in the dispersion suppressor (DS) areas around points 2, 3 and 7, and high luminosity interaction regions 1 and 5 [1]. The required space for the collimators could be provided by replacing some 8.33 T 15 m long NbTi LHC main dipoles with shorter 11 T Nb_3Sn dipoles compatible with the LHC lattice and main systems. These twin-aperture dipoles operating at 1.9 K and powered in series with the main dipoles will deliver the same integrated strength at the nominal LHC current.

To demonstrate feasibility of this approach, CERN and FNAL have begun a joint program with the goal to develop a 5.5-m long twin-aperture Nb_3Sn dipole for the LHC upgrades [2]. The program started with the design and construction of a 2-m long single-aperture demonstrator magnet. This paper presents the first results of quench analysis of the demonstrator dipole focusing on coil heating during a quench and heat transfer in the coil.

MAGNET DESIGN AND PARAMETERS

Details of the 11 T demonstrator dipole design are reported in [3]. Fig. 1 (left) shows the cold mass cross-section. The coil consists of 56 turns, 22 in the inner layer and 34 in the outer layer. Each coil is wound using a 40 strand Rutherford cable [4] insulated with two layers of E-glass tape 0.075 mm thick and 12.7 mm wide. The cable is made of RRP-108/127 strands 0.7 mm in diameter with a nominal J_c(12T,4.2K) of 2750 A/mm^2, a nominal Cu fraction of 0.53, and RRR>60.

The coils are surrounded by ground insulation made of 5 layers of 0.125 mm thick Kapton, stainless steel protection shells and laminated collars. The collared coil assembly is placed inside two half-yokes locked with Al clamps. The stainless steel skin is pre-tensioned and welded to obtain a coil pre-stress sufficient to keep it under compression up to the full design field of 12 T.

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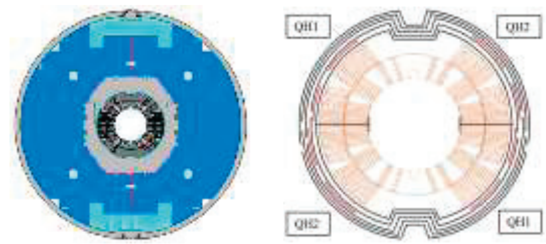

Figure 1: Cold-mass cross-sections (left) and quench heater position (right).

Two thick stainless steel end plates welded to the skin restrict the axial coil motion from the Lorentz forces.

Magnet quench protection is provided by four heaters composed of 0.025 mm thick stainless steel strips. They are inserted between the ground insulation layers and placed on the outer surface of the coil blocks (Fig.1, right). Each coil has two heaters, marked QH1 and QH2. Each heater covers 31 (15+16) turns per quadrant. The corresponding heaters on each coil are connected in series forming two parallel heater circuits. Each quench heater covers ~28% of the total coil volume.

The quench protection parameters of the 11 T demonstrator dipole at the nominal LHC current I_{nom}=11.85 kA are summarized in Table 1.

Table 1: Magnet Quench Protection Parameters

Parameter	Value
Magnet inductance at I_{nom}	6.04 mH/m
Stored energy at I_{nom}	424 kJ/m
Energy density at I_{nom}	85.9 MJ/m^3
Effective coil length	1.7 m
Maximum current/field at 1.9 K	15.0 kA/13.4 T
Maximum stored energy	680 kJ/m

QUENCH PROTECTION ANALYSIS

The analysis was performed for two cases: a) magnet training up to the estimated conductor limit of 15 kA at 1.9 K [5], and b) quench heater study at currents up to the LHC nominal operation current of 11.85 kA.

The maximum coil temperature T_{max} after a quench in adiabatic conditions is determined by the equation:

$$\int_0^\infty I(t)^2 dt = S^2 \cdot \int_{T_q}^{T_{max}} C(T)/\rho(T)\, dT \,, \qquad (1)$$

where $I(t)$ is the current decay after a quench (A); T_q is the conductor quench temperature (K); S is the cross-section of the insulated cable (m^2); $C(T)$ is the average specific heat of the insulated cable (J/(K·m^3); $\rho(T)$ is the cable resistivity (Ω·m).

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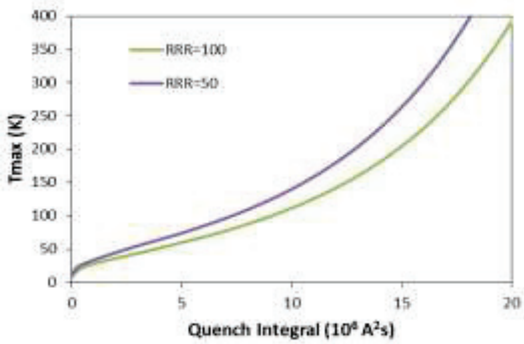

Figure 2: Cable maximum temperature T_{max} vs. Quench Integral for the insulated demonstrator dipole cable.

The dependence of T_{max} on the value of quench integral (*QI*) for the insulated demonstrator dipole cable for two values of cable RRR is shown in Fig. 2. To keep the cable temperature during a quench below 400 K (this criterion was used for the Nb-Ti LHC main dipoles and is considered also to represent a safe limit for Nb_3Sn accelerator magnets [6]), the quench integral has to be less than (18-20)·10^6 A^2s or 18-20 MIITs.

Model Test with Dump Resistor

An external dump resistor R_d is used to extract the magnet stored energy during magnet tests. Magnet current decay calculated for I_o values of 15 kA and 8 kA with R_d=60 mΩ including and excluding the coil resistance is shown in Fig. 3. This plot demonstrates the contribution of the coil resistance, determined by the normal zone size and temperature, cable heating and quench propagation, to the current decay at low and high quench currents.

The maximum value of the quench integral in the turn where the quench starts depends on the magnet current, I_o, quench detection and dump delay time, τ_D, and current decay, *I(t)*, as follows:

$$\int_0^\infty I(t)^2 dt = I_0^2\cdot\tau_D + \int_{\tau_D}^\infty I^2(t)dt \quad , \qquad (2)$$

The *QI* vs. the magnet quench current calculated for R_d=60 mΩ, coil RRR=50, a 10 mm long quench origin section, a longitudinal quench velocity proportional to I^2, and τ_D=5 ms, is shown in Fig.4.

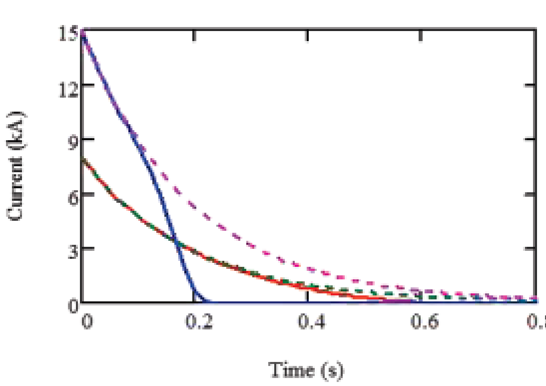

Figure 3: Current decay with R_d=60 mΩ including (solid lines) and excluding the coil resistance (dashed lines).

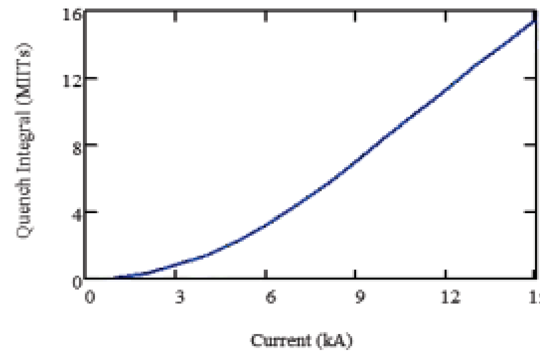

Figure 4: Quench Integral vs. magnet quench current.

The transverse quench propagation is not included in these calculations. Based on Fig. 4 the quench integral at I_o=15 kA is ~15 MIITs which according to Fig. 2 corresponds to T_{max}~250 K. Thus, with R_d=60 mΩ the magnet will be safely protected during test up to its short sample limit of 15 kA.

Quench Heater Study

The demonstrator dipole has two quench protection heater circuits which will be tested separately. During heater test, the dump resistor is not used (R_d=0) or significantly delayed and thus all the stored energy after heater induced quenches is dissipated in the magnet coil. Each heater circuit quenches ~28% of the magnet coil volume.

The average maximum coil temperature under the heaters can be estimated from the equation:

$$W(I_o)/l \cong N_{qt} f\cdot S\cdot \int_{T_q}^{T_{max}} C(T)dT \; , \qquad (3)$$

where $W(I_o)/l$ is the stored energy per magnet unit length (J/m), N_{qt} is the number of turns quenched by the quench heater and *f* is the number of quench heaters used.

The average maximum coil temperature under the heaters vs. magnet current is shown in Fig. 5. The longitudinal and transverse quench propagation is not considered in these calculations. As it follows from the plot, at the nominal operation current 11.85 kA the coil maximum temperature under the heaters even with one operation heater circuit is less than 250 K.

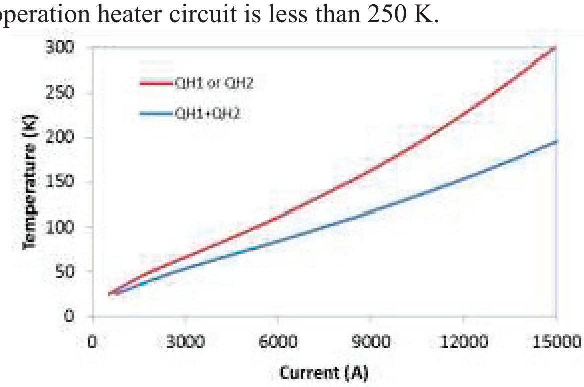

Figure 5: The average maximum coil temperature under the heater vs. magnet current for one and two heater circuits.

Transverse Heat Propagation

The effect of transverse heat propagation was analyzed using a 2D quench simulation code based on ANSYS [7] for the two cases discussed above. Fig. 6 shows the temperature profile in the demonstrator magnet after 38 ms from a quench at 11.85 kA in the inner-layer pole turn. The coil pole blocks and wedges are involved in the quench process absorbing a part of the dissipated heat. The turn-turn propagation time is very low, only 10 ms.

Fig. 7 shows the temperature profile in the demonstrator magnet after 48, 96 and 552 ms from the heater induced quench at the coil initial current of 11.85 kA. After ~50 ms from igniting a heater the quench starts in the outer-layer pole block. Then in less than 100 ms the quench propagates to the inner layer through the interlayer insulation. The coil reaches its maximum temperature of 213 K (compare with the average value of 150 K for QH1+QH2 in Fig. 5) after 550 ms from the heater ignition. As in the previous case, efficient heat transfer from the heater to the coil outer layer, from the outer-layer to inner-layer turns and other coil components helps to spread and absorb the magnet stored energy. These observations will be further studied and experimentally verified during testing of the quench heaters in the demonstrator dipole.

CONCLUSIONS

Quench protection analysis of the single-aperture Nb_3Sn demonstrator dipole shows that the 60 mΩ dump resistor provides an adequate protection of the magnet during test up to 15 kA. Heater induced quenches are also safe in the current range up to 12 kA. In both cases, the maximum coil temperature is within the safe limit for Nb_3Sn magnets. Experimental studies and optimization of the 11 T dipole quench protection is an important part of the demonstrator magnet R&D program.

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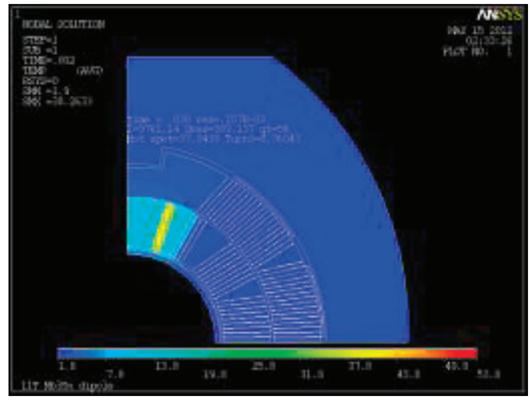

Figure 6: Temperature profile in the demonstrator magnet after 38 ms from the inner-layer pole turn quench.

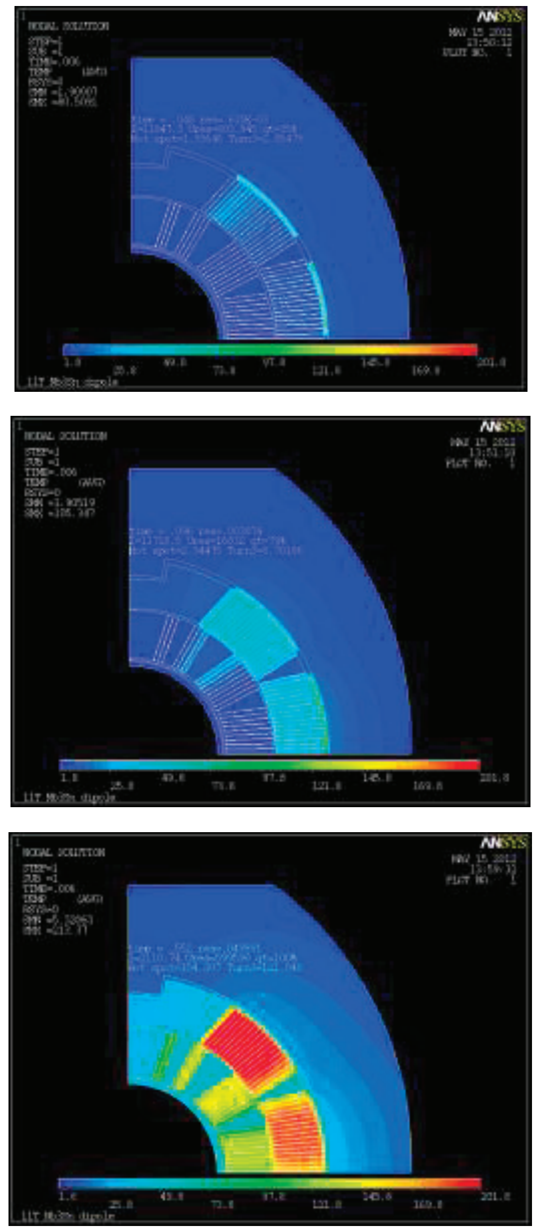

Figure 7: Temperature profile in the demonstrator magnet after 48 (top), 96 (middle) and 552 (bottom) ms from the heater induced quench.

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