

# QUENCH PROTECTION ANALYSIS OF A SINGLE-APERTURE 11T Nb<sub>3</sub>SN DEMONSTRATOR DIPOLE FOR LHC UPGRADES\*

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## Abstract

FNAL and CERN are developing a 5.5-m long twin-aperture Nb<sub>3</sub>Sn dipole suitable for installation in the LHC. The program started with the construction of a 2-m long single-aperture demonstrator dipole with the nominal field of 11 T at the LHC nominal current of 11.85 kA in a 60 mm bore with 20% margin. This paper presents the results of quench protection analysis of the Nb<sub>3</sub>Sn demonstrator dipole.

## INTRODUCTION

The planned LHC collimation system upgrade expects 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<sub>3</sub>Sn 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 started a joint program with the goal to develop a 5.5-m long twin-aperture Nb<sub>3</sub>Sn 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 a cold mass cross-section. The coil consists of 56 turns, 22 turns in the inner layer and 34 turns in the outer layer. Each coil is wound using a 40 strand Rutherford cable [4] insulated with two layers of 0.075 mm thick and 12.7 mm wide E-glass tape. The cable is made of RRP-108/127 strands 0.7 mm in diameter with the nominal  $J_c(12T, 4.2K)$  of 2750 A/mm<sup>2</sup>, the nominal Cu fraction of 0.53, and RRR>60.

The coils are surrounded by the 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 in between 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.

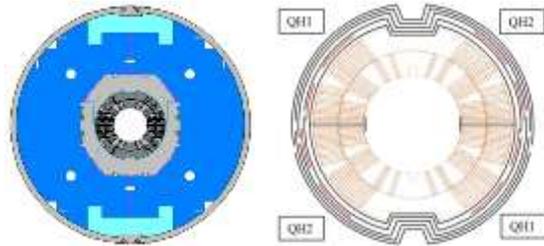


Figure 1: Cold-mass cross-sections (left) and quench heater position (right).

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 and placed on top of the coil outer layer blocks in between the ground insulation layers (Fig.1(right)). Each coil has two heaters, marked QH1 and QH2, which cover 31 (15+16) turns. The heater strips on each side of 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 $I_{nom}$ , mH/m	6.04
Stored energy at $I_{nom}$ , kJ/m	424
Energy density at $I_{nom}$ , MJ/m <sup>3</sup>	85.9
Maximum quench field, T	13.4
Maximum quench current, kA	15.0
Maximum stored energy, kJ/m	680

## 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

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

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 insulated cable (m<sup>2</sup>);  $C(T)$  is the average specific heat of insulated cable (J/(K·m<sup>3</sup>));  $\rho(T)$  is the cable resistivity (Ohm·m).

\* Work supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy

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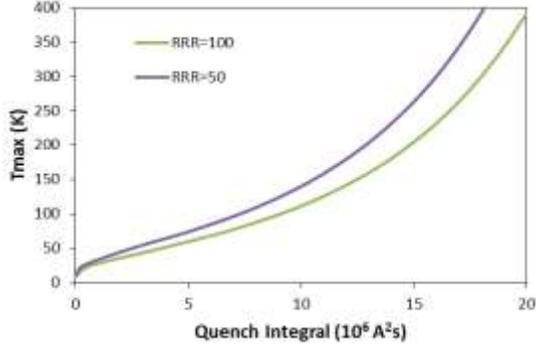


Figure 2: Cable maximum temperature  $T_{max}$  vs. Quench Integral for the insulated demonstrator dipole cable.

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 criteria was applied for the Nb-Ti LHC main dipoles and is also considered at the present time as a safe limit for Nb<sub>3</sub>Sn accelerator magnets [6]), the quench integral has to be less than  $(18-20) \cdot 10^6 A^2s$  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  $I_o$  15 and 8 kA with  $R_d = 60$  mOhm including and excluding coil resistance is shown in Fig. 3. This plot shows the effect of coil resistance determined by the normal zone size and temperature, cable heating and quench propagation at low and high quench currents.

The maximum value of the quench integral in the turn where quench started depends on the magnet current  $I_o$ , the quench detection and dump delay time,  $\tau_D$ , and the current decay,  $I(t)$ ,

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

Quench integral vs. magnet quench current calculated for  $R_d=60$  mOhm, coil RRR=50, 10 mm long quench origin section, longitudinal quench velocity proportional to  $\sim I^2$ , and  $\tau_D=5$  ms is shown in Fig.4.

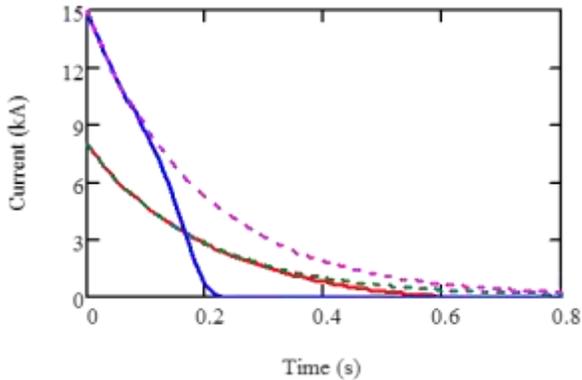


Figure 3: Magnet current decay with  $R_d$  including (solid lines) and excluding coil resistance (dashed lines).

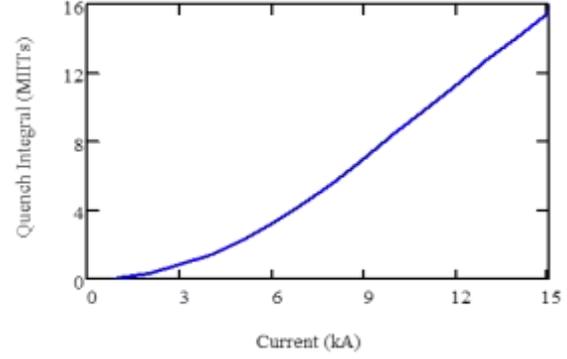


Figure 4: Quench Integral vs. magnet quench current.

The transverse quench propagation is not included in these calculations. Based on Fig. 4 the quench integral at  $I_o=15$  kA is  $\sim 15$  MIITs which according to Fig. 2 corresponds to  $T_{max} \sim 250$  K. Thus, with  $R_d=60$  mOhm 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 heaters 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 quenches  $\sim 28\%$  of the magnet coil volume. The average maximum coil temperature under heaters can be estimated from the equation

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

where  $W(I_o)/l$  is the stored energy per magnet length (J/m),  $N_{qt}$  is the number of turns quenched by the quench heater ( $N_{qt}=62$ ), and  $f$  is the number of quench heaters used ( $f=1,2$ ).

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

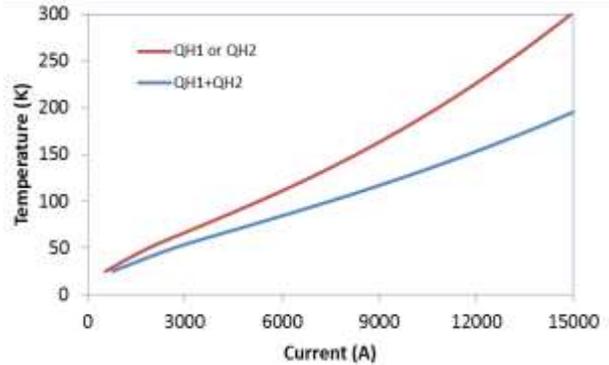


Figure 5: The average maximum coil temperature under heater vs. the magnet current for one and two heaters.

## Transverse Heat Propagation

The effect of transverse heat propagation was analyzed using 2D quench simulation code based on ANSYS [7] for 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 quench heaters in the demonstrator dipole.

## CONCLUSIONS

Quench protection analysis of the single-aperture Nb<sub>3</sub>Sn demonstrator dipole shows that the 60 mOhm dump resistor provides an adequate protection of the magnet during test up to 15 kA. Heater induces quenches are also safe in the current range up to 12 kA. In all the cases the maximum coil temperature is within the safe limit for Nb<sub>3</sub>Sn 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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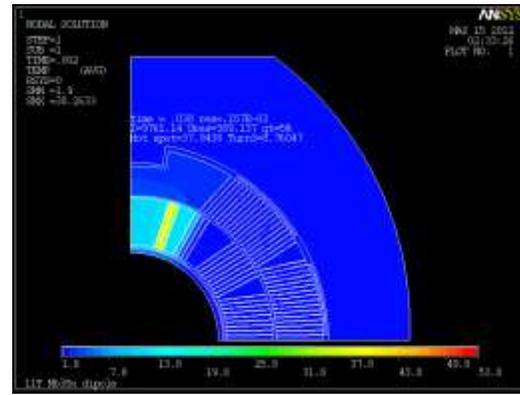


Figure 6: Temperature profile in the demonstrator magnet after 38 ms from the inner-layer pole turn quench.

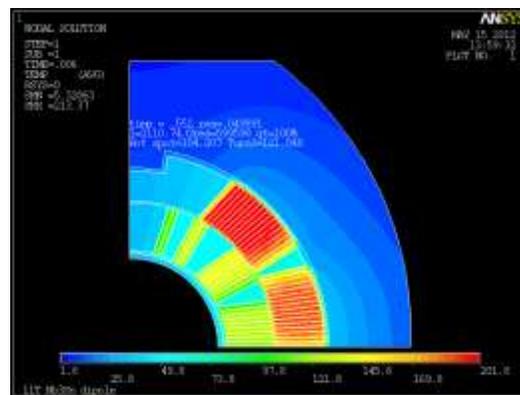
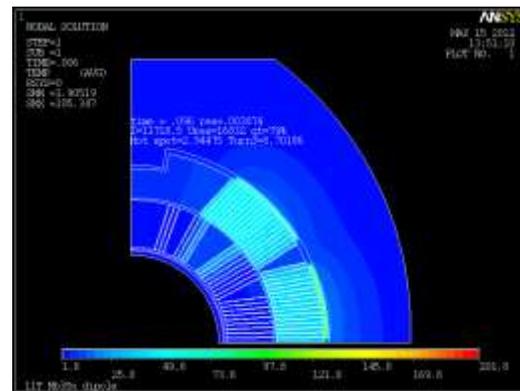
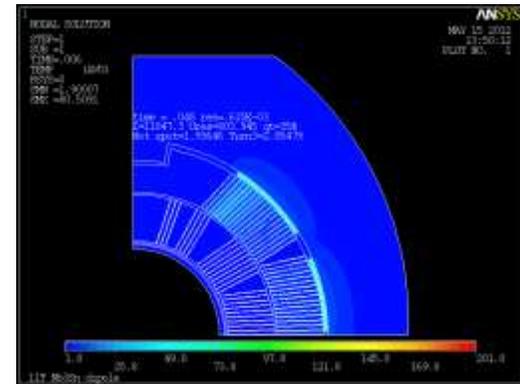


Figure 7: Temperature profile in the demonstrator magnet after 48 (top), 96 (middle) and 552 (bottom) ms from the heater induced quench.