QUENCH PROTECTION OF HIGH FIELD NB3SN MAGNETS FOR VLHC*

L. Imbasciati†, P. Bauer, G. Ambrosio, V. Kashikin, M. Lamm, A.V. Zlobin
FNAL, Batavia, IL 60510, USA

Abstract

Fermilab is developing high field magnets for a possible future VLHC. The high levels of stored energy in these magnets present significant challenges to the magnet quench protection. Simulation programs have been developed and used to analyze temperature and voltage distributions during a quench and to performed parametric studies on conductor and quench-heater requirements. This paper concludes with a proposal for a set of quench protection parameters for the VLHC magnets.

1 INTRODUCTION

Fermilab has recently completed a feasibility study for a post-LHC hadron collider, the Very Large Hadron Collider (VLHC) [1]. In its second stage the VLHC would collide protons at up to 175 TeV center of mass energy. Strong bending magnets are required to steer the beams. Fermilab is engaged in an R&D program to develop 10-12 T Nb3Sn dipole magnets using several design approaches. In the case of quench, the high stored energy in the magnet and the high current densities in the Nb3Sn superconductor can cause a high temperature rise in the region where the quench originally started, as well as high voltages in the coil and between the coil and ground. The thermo-mechanical stress generated in the winding during the fast temperature rise can result in cracks to the epoxy impregnation of the coils or even permanent damage of the brittle Nb3Sn. Simulation programs have been developed and used to analyze temperature and voltage distributions during a quench. Parametric studies have been performed to find the conductor and quench-heater requirements to limit the peak temperature and the voltages in the coil during a quench. We aim at limiting the temperatures and voltages to ~400 K/1 kV, as for LHC dipole magnets.

2 MAGNET PARAMETERS

The dipole models being developed in the frame of Fermilab's VLHC magnet R&D are a 2-layer shell type (cosθ) [2] and a one-layer block type in a common coil (CC) arrangement [3]. The cosθ magnet uses 1 mm-strand, 14 mm-cable for the Wind & React technique, while the CC magnet uses 0.7 mm-strand in a 22 mm large cable for the React & Wind technique. This article will refer to their full-scale version in view of a VLHC, and to the 2-in-1 configuration for the cosθ. The aperture diameter is 40 mm for CC and 43 mm for cosθ magnet. The operating temperature is 4.5 K.

Table 1: Characteristics of FNAL VLHC Magnets

	CC	**cosθ**
Bore Field/Peak Field (T)	10/11.3	10/10.5
Operating Current - I_o (kA)	23.5	21.3
Inductance (mH/m)	3	2.14
Stored Energy (kJ/m)	828	485
Length (m)	16	16
Cable Cross Section (mm^2)	23.1	22.5

Table 1 contains a list of the major magnet parameters, which are relevant for quench protection. The working assumption for the current carrying capacity of the conductor is a non-copper critical current density (J_c) of ~3 kA/mm^2 (at 12T 4.2K), which is the goal of a conductor development program [4]. VLHC magnets are demanding from quench protection viewpoint: they use cables with approximately the same cross-section as LHC main dipoles, but operate at double the current, taking advantage of the higher critical current density of Nb3Sn and using less copper.

The protection system of the VLHC magnets is based on quench heaters consisting of stainless steel strips, connected to a capacitor bank. As soon as a resistive voltage is detected in the magnet, the capacitors are discharged into the heater strips to trigger the transition in all the coils under them. The stored energy is thus distributed over the coils during the quench, in order to avoid voltage imbalances and high peak temperature.

3 PARAMETRIC STUDIES

Quench simulation programs have been used to perform parametric studies, varying the heater coverage (HC), the total heater delay time (τ_H), the copper to non-copper ratio (Cu/NCu), and the RRR. The studies performed on the CC model are described in detail in [5].

3.1 Quench simulation programs

For the study of the quench process, QLASA [6], [7] and Quenchpro [8] programs were used. The programs have in common that they calculate the temperature from the adiabatic heat balance equation, thus neglecting cooling and heat conduction. The adiabatic assumption is known to overestimate the temperature of the coils during the quench process, but the lack of Nb3Sn-based experimental evidence today, does not allow to predict the level of the overestimation. The temperatures in these studies were calculated with both programs (which agree to within ±10%) and the voltages with Quenchpro.

*Work supported by the U.S. Department of Energy.
†ilinda@fnal.gov

3.2 Heater Coverage and Heater Delay Time

Fig. 1 shows how a decrease in heater coverage raises the peak temperature. To respect the temperature limitation, the CC magnet requires 100% heater coverage and the cosθ magnet requires a minimum of 50% heater coverage.

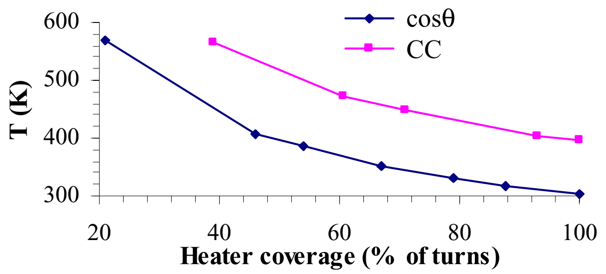

Figure 1: Peak temperature vs. heater coverage. (τ_H=40 ms, RRR=50, Cu/NCu=1.2/1.0 (cosθ /CC))

The voltages depend not only on the percentage of heater coverage, but also on the position of the heater strips. The voltages reported in Table 2 were calculated for heaters distributed symmetrically over both apertures. However, in case of a non-symmetric heater distribution, as in the case of heater failure, larger voltages arise [9]. To limit the peak voltage to 1 kV, the cosθ/CC magnets requires a minimum of 50/70% heater coverage.

Table 2: Peak voltage to ground vs. heater coverage. (τ_H=40 ms, RRR=50, Cu/NCu=1.2/1.0 (cosθ /CC))

	V (kV)	Heater position	turn %
cosθ	0.30	all 48 turns	100
	0.91	outer layer only	54
	1.36	inner layer only	46
CC	0.24	all 52 turns	100
	0.98	36 mid-plane turns	71
	1.87	18 mid-plane turns	35

The effect of the delay time (τ_H=quench detection time + heater delay time) on peak temperature is shown in Fig. 2. With $\tau_H \leq 40$ ms the peak temperature remains within the 400 K limitation

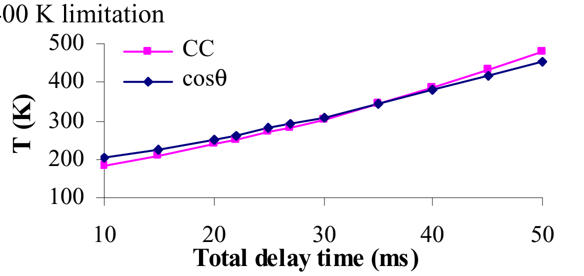

Figure 2: Peak temperature vs. total delay time. (HC=50/100%, RRR=50, Cu/NCu=1.2/1.0 (cosθ /CC))

3.3 Cu/non-Cu Ratio and RRR

Fig. 3 (dashed lines) shows that the hot spot temperature decreases almost linearly with the copper content (at fixed wire diameter and fixed current).

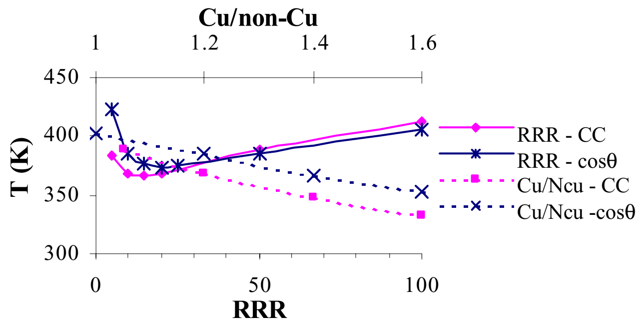

Figure 3: Peak temperature vs. RRR (Cu/NCu=1.2/1.0) and copper content (RRR=50). (τ_H=40 ms, HC=50/100% (cosθ /CC))

The slopes of the curves are small, thus a large increase in copper content is required to decrease significantly the peak temperature. The resistance affects the quench process in antagonistic ways: on one hand, the lower the resistance the lower the heat generation at the hot spot; on the other hand, the lower the resistance the longer the decay time, which ultimately raises the peak temperature. Simulations of the quench process for different RRR of the conductor (at constant Cu/NCu) reveals that the peak temperature increases with growing RRR, because of the slowed current decay, due to the lowered matrix resistance. The peak temperature has a minimum near RRR~15-20 (continuous lines). It has to be noted that the peak voltages increase with lower RRR.

To limit the peak temperature to 400K, the Cu/NCu has to be larger than 1.0 for both magnets type. The RRR has to be in the range of 10-70.

4 FINITE ELEMENT HEATER STUDIES

As shown in Fig. 2, the total heater delay time has to be ≤40 ms, to remain within the temperature limit. Reserving 10 ms for quench detection, the heater delay time has to be restricted to ≤30 ms. An additional problem stems from the fact that the critical temperature of Nb3Sn is high (relative to NbTi used in the LHC magnets) and requires therefore a bigger amount of heat to start the transition. The quench heater performance has been studied with a finite element (FE) model [10]. The model represents a cross section of the magnet (2D model), including the cable, the insulation, the heater strip, and the collar. Fig. 4 shows the central parts of the meshed 2D model and the materials.

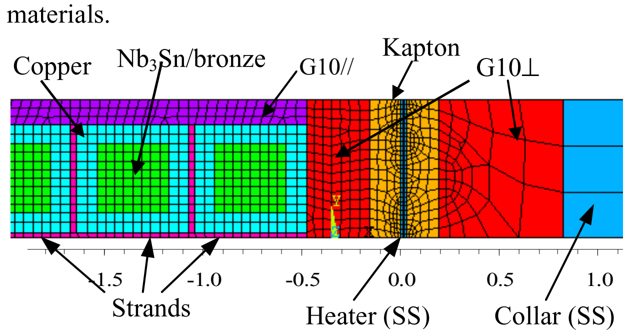

Figure 4: FE model for heater study (dimensions in mm).

At time zero, the heat generation starts in the heater strip region. The stainless steel strip heats quickly. The insulation slows down the heat transfer to the cable. Once through the insulation barrier, the heat propagates faster and the temperature profile becomes relatively flat inside the cable.

Fig. 5 shows the resulting temperature in the strand closest to the heater, 30 ms after the heaters are fired, for varying heater power and insulation thickness. At higher heater powers, the peak temperatures in the heater increases and, in turn, the thermal diffusivity of the insulation decreases, eventually counteracting the larger temperature gradients between heater and cable. The results clearly show that the most important parameter for the heater efficiency is the insulation layer thickness (dashed line in fig. 5).

The generation temperature at nominal current is ~11 K on the outside of the cosθ outer layer and on the outside surface of the CC (average field ~4 T). To reach this temperature within 30 ms, the power per coil area must be ≥130 W/cm^2 in both the cosθ and the CC magnet, at a total insulation thickness of 0.5 mm. Using 70 W/cm^2 heater power, the insulation thickness has to be less than 0.48 mm.

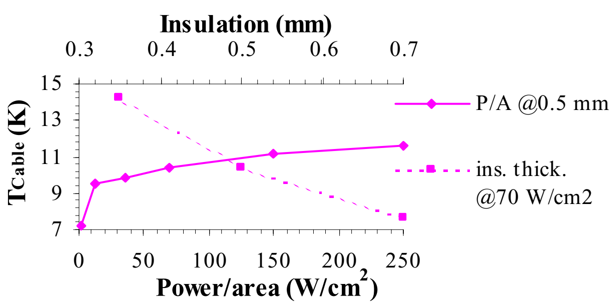

Figure 5: Cable temperature after 30 ms, vs. power per unit area and insulation thickness.

5 CONCLUSIONS

A possible set of quench protection system parameters for the VLHC dipole magnets was proposed (they are summarized in Table 3). A Cu/NCu=1 for the CC and a Cu/NCu=1.2 for the cosθ magnet were chosen, to satisfy not only quench-protection but also bore-field requirements. In the case of the CC magnet, assuming 20% total critical current degradation, Cu/NCu=1 gives a 0.85% bore field margin. A RRR value of 50 was chosen. It is not the optimum solution, but it corresponds to the average RRR of commercially available Nb3Sn conductor today. It is interesting to compare the resulting Quench Integrals (time integrated current) to those of the LHC dipoles. For the VLHC magnets, the QI at 40 ms is about half the value of the QI at 400 K, while the LHC dipoles at 40 ms are at only 8% of the 400 K value. Therefore VLHC magnets have a small margin for current ramp down. With a heater coverage of 100% for the CC, and ~50% for the cosθ (heaters on the outer layer), the total heater delay time has to restricted to 40 ms.

Table 3: Quench Parameters of FNAL VLHC Magnets

	VLHC cosθ	**VLHC CC**
Cu/Ncu	1.2	1.05
RRR	50	50
Heater Coverage (%)	>50	100
Total Heater Delay Time (ms)	<10+30	<10+30
QI @ 400 K (MA^{2}s)	43	42
QI @ 40 ms (I=I$_o$) (MA^{2}s)	22	18
Heater insulation (mm)	<0.5	<0.5
Heater Power (W/cm^2)	>130	>130
Peak Temperature (K)	380	390
Bulk Temperature (K)	140	120
Max Volt to Ground (V)	900	255
Current Decay Time (ms)	120	100

The magnet parameters were chosen such as to limit the peak temperatures to ~400 K and the peak voltages to ground to 1 kV. An R&D program is currently underway at Fermilab to determine these limits, based on experiments and on theoretical investigations of the thermo-mechanical stresses generated in the magnets during a quench.

6 REFERENCES

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