Suitability of Different Quench Protection Methods for a 16 T Block-Type Nb_3Sn Accelerator Dipole Magnet

T. Salmi[1], M. Prioli[2], A. Stenvall[1], J. Ruuskanen[1], A. P. Verweij[2], B. Auchmann[2,3], V. Marinozzi[4]

Abstract— **Within the Future Circular Collider study a 100 km long circular hadron collider is being designed for 100 TeV center-of-mass collision energies. The design of the 16 T Nb_3Sn bending dipole magnets is carried out within the EuroCirCol collaboration. Three different type of dipole designs have been developed, each aiming to be as compact as possible, accounting for the design criteria. Quench protection a critical aspect of the magnet design and potentially limits the magnet compactness. The EuroCirCol magnets were designed assuming a protection system with significantly improved efficiency compared to the present LHC dipole protection. In this paper we consider present state-of-the-art quench protection technologies, such as quench heaters and CLIQ, and apply them into the designed 16 T Block-type dipole. Two different simulation models are used to estimate the magnet hotspot temperature and voltages after a quench and consequently estimate the suitability of the different methods.**

Index Terms—**Superconducting magnets, quench simulation, quench protection heaters, CLIQ, hotspot temperature.**

I. Introduction

The European Circular Energy-Frontier Collider Study project (EuroCirCol) aims to design a 16 T Nb_3Sn dipole magnet. This is part of the Future Circular Collider (FCC) conceptual design study for a 100 km long, 100 TeV post-LHC particle accelerator [1]-[3]. Three different types of dipole magnets are considered in the first design phase: Block [4], Cosθ [5], and, Common-Coil [6]. They will be evaluated based on common target criteria, a central criterion being the amount of used conductor [2]. The most promising option will be selected for the following design phases.

The aim for obtaining compact magnets leads to large stored energy densities, making quench protection a critical aspect. Solely relying on external energy extraction is not an option due to the large voltages associated with it. Therefore, after a quench is detected, and the magnet disconnected from the power supply, the windings must absorb all the energy that is stored in the magnetic field.

[1]T. Salmi, A. Stenvall and J. Ruuskanen are with Tampere University of Technology, P.O. Box 527, FI-33101 Tampere, Finland (e-mail: tiina.salmi@tut.fi), [2]M. Prioli and A. P. Verweij are with CERN, 1211 Geneva, Switzerland, [3]B. Auchmann is with CERN and PSI, Switzerland, [4]V. Marinozzi is with INFN, 20133 Milano, Italy.

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Quench heaters (QH) and/or the Coupling Loss Induced Quench (CLIQ) are potential protection methods for such accelerator magnets [7]-[11]. Both methods are based on rapidly transferring a large fraction of the windings to resistive state, thus providing the resistance to drive the magnet current discharge and allowing for uniform energy dissipation in the windings. One measure for the protection efficiency, and an indication of the resulting peak temperature, is the delay time between the activation of the protection system and the subsequent transition of the coil to the normal state. Various protection analyses have been carried out throughout the magnet design phase in order to ensure that the magnets will not require unrealistic protection efficiency.

The requirement for magnet protectability was set as a magnet design criterion. According to it, the magnet hotspot temperature must remain below 350 K with 40 ms protection delay [7],[12]. The 40 ms protection delay was based on assuming 20 ms for quench detection related delays and 20 ms for the protection system to bring the entire coil to resistive state. The 20 ms was based on an optimistic estimation of the average obtainable quench heaters delays.

In this paper we aim to demonstrate the feasibility of the 20 ms average delay using realistic quench heaters or CLIQ, and evaluate the advantage of using both of them simultaneously. The different methods will be compared in terms of resulting temperatures and voltages after a quench, the provided safety margin, and the energy that is needed from the protection system. To evaluate the influence of the simulation method, we compared the computation results using two different software, TALES [13],[14] and Coodi [7], which was interfaced with CoHDA [15] for heater simulation. Coodi is the tool that has been used to the most in the preliminiary quench analysis for the EuroCirCol magnets.

All the analyses are done at 105% of nominal operation current, where the highest protection efficiency is required. We limit the study in the Block-type dipole design. A quench protection study for the Cosθ can be found in [16]. The study considers only a single magnet, decoupled from the rest of the circuit. This is the case when each magnet is by-passed by a cold-diode limiting its voltage and allowing the flowing of the circuit current.

II. The Block-Type Dipole Designs

The version of the EuroCirCol Block-type dipole magnet that is considered here is based on the so-called conservative design parameter space. The design parameter space was later updated because the limitations for maximum strand diameter of 1.1 mm and minimum copper-to-superconductor ratio of 1.0 led to magnets with high inductance and consequently high voltages during a quench as well as cables with large amounts of copper in the coil high field areas leading to large temperature gradients. Details can be found in [2] and [4]. These restrictions were relaxed for the updated design parameter space, even if it meant that the wire manufacturing will need additional R&D. In addition, the operation temperature was changed from 4.5 K to 1.9 K, and required load line margin at 1.9 K was reduced from 18% to 14%.

A. *Magnet parameters*

The Block-type magnet features four-layer coils with intralayer grading, where the 2, 3, or 9 innermost turns of the layers are wound using the large high-field (HF) cable, and the other turns are wound with smaller low-field (LF) cable. The parameters relevant for quench protection are summarized in Table I. In this analysis we consider a magnet in a single aperture mechanical structure.

TABLE I
MAGNET SIMULATION PARAMETERS.

Parameter (unit)	Value
Design version reference	V26cmag
Nominal current, I_{nom} (A)	8950
Magnet length (m)	14.3
Operation temperature (K)	4.5
Peak field at conductor at Inom (T)	16.4
Differential inductance at I_{nom} (mH/m/ap.)	39
Number of turns / coil	153
Width of cable, bare (mm)	13.85
Thickness of cable (HF / LF) (mm)	2.0 / 1.2
Number of strands (HF / LF)	24 / 37
Strand diameter (HF / LF) (mm)	1.1 / 0.7
Strand Cu /Nb_3Sn ratio	1.0 / 1.05
Voids fraction of bare cable	0.15
Cable insulation thickness (mm)	0.15
RRR	100
Inter-layer insulation (G10)	0.5 mm
Inulation btw outer layer heater and collar	0.5 mm
Insulation btw inner layer heater and cold bore	0.5 mm

B. *Enthalpy to quench*

The energy margin, i.e., the enthalpy to quench, was computed by integrating the heat capacity of the insulated cable from operation temperature to current sharing temperature, T_{cs}. Material properties were based on NIST [17] data.

The energy margin in coil turns varied from 0.1 J/m of cable in the high-field area to about 5 J/m of cable in the low-field area, the average being 1.7 J/m of cable. The total enthalpy of 14.3 m long magnet was about 15 kJ (one aperture).

III. Quench Heater Design

The concept of the quench heater technology is similar to what is used in the LHC-dipoles and foreseen for the High Luminosity LHC (HL-LHC) inner triplet quadrupoles [18][19]. It consists of 25 µm thick stainless steel heater strips glued on a 75 µm thick layer of polyimide. The insulation thickness is the same as in the present LHC dipoles and increased by 50% from the HL-LHC quadrupole. The heater strips have uniform width, and copper plating is used on top of the stainless steel to create rectangular stainless steel heating stations. The heating stations are needed to reduce the strip total resistance and focus the heating into the heating stations.

The heater power supply unit is assumed to be the same that is used in testing the HL-LHC magnets at Lawrence Berkeley National Laboratory (LBNL) and Fermi National Accelerator Laboratory (FNAL): A capacitor bank with 450 V charging voltage and 19.2 mF capacitance. The impact of the values chosen for the capacitance and heater insulation thickness will be further evaluated at a later stage of the study.

A. *Heater locations*

It is assumed that the heaters are placed on coil surfaces after the coil reaction and then impregnated together with the coil. We assume that the two double-pancakes forming the four-layer coil are reacted separately, and heaters can be positioned on the surface of each coil layer. The coils' cross-section with magnetic field distribution and the locations of the heater strips are shown in Fig. 1.

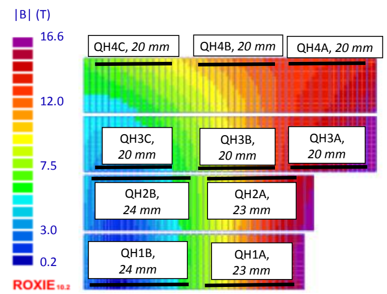

Fig. 1. Heater strip locations and their widths. The magnetic field map is from ROXIE [20], and computed at nominal current.

The heaters cover 80% of the turns. The heating stations cover 17-20% of each turn, as detailed in Table II.

B. *Heater strip geometries*

The heaters have either 6 cm long heating stations, placed at 35 cm period, or 8 cm long heating stations placed at 40 cm period. The longer heating stations and larger periods are used in the coil low-field region to ensure sufficient heater energy in the areas with larger energy margins. Quenching the low-field area rapidly is also essential for reducing the coil internal voltages because in this region the contribution of the inductive voltage is the largest [7].

All strips are 14.3 m long, except QH1B and QH2B, which each consists of two 7-m-long-strips. The powering of these strips potentially needs technology development if their current lead connections are in the middle of the magnet. A potential solution to this are special layered copper routes as presented in [21]. The strips could be also powered in series with the LHC-style 900 V capacitor bank.

C. *Heater powering*

The heater strips were combined in 20 Heater Firing Unit (HFU) circuits, each consisting of a capacitor bank and 2-3 strips connected in parallel, see Table II. For comparison, in the present LHC-dipoles, two 900 V HFU units per aperture are used, and two are kept as spares. This highlights the increased complexity of the protection system compared with the LHC.

The heater powers were computed considering only the stainless steel part, and its resistivity at 4.5 K (0.5 µΩm). A series resistance of 0.5 Ω was added to all circuits to account for the resistive wires and connectors [21]. The resulting heater peak powers (*P(0)*) vary from 66 to 150 W/cm^2. The RC-time constant (τ_{RC}) of the heater circuits is between 21 and 30 ms. The currents in individual strips are between 120 and 210 A, and the circuit total currents between 300 and 420 A.

TABLE II
HEATER POWERING IN PARAMETERS. EACH HFU CONSISTS OF A 19.2 MF CAPACITOR CHARGED TO 450 V AND 2 OR 3 HEATER STRIPS IN PARALLEL.

Circuit	QH Strips	Strip width (cm)	HS/ period (cm)	$P_{QH}(0)$ (W/cm^2)	τ_{RC} (ms)
HFU#1	4A ‖ 4B ‖ 4C	2.0	6/35	66	25
HFU#2	3A ‖ 3B ‖ 3C	2.0	6/35	66	25
HFU#3	1A ‖ 2A	2.3	6/35	78	30
HFU#4	1B ‖ 2B (7 m)	2.4	8/40	150	21
HFU#5	1B ‖ 2B (7 m)	2.4	8/40	150	21

D. Simulated heater delays with CoHDA

The heater delays were simulated using the 2-D heat diffusion model CoHDA [15], assuming a quench onset when the cable maximum temperature reaches T_{cs}. The simulated delays at 105% of nominal current in different magnetic field regions are shown in Fig. 2. The delays in coil high-field region are about 5 ms, and increase several tens of milliseconds when moving towards high-field region. The figures also show the advantage of higher heater power in low-field region, while in high-field region a smaller power is sufficient.

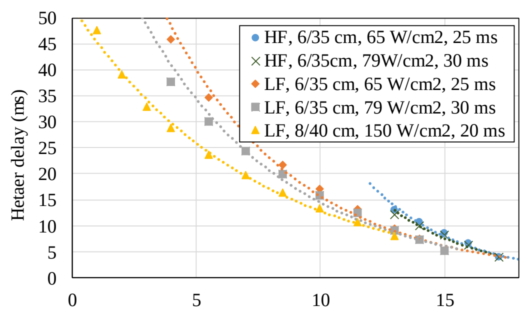

Fig. 2. Simulated heater delays in HF and LF cables with the different heater powers, and RC time constants.

IV. SIMULATED TEMPERATURES AND VOLTAGES WITH COODI

The magnet temperatures and voltages were simulated with the adiabatic model Coodi [7]. The heater delays computed with CoHDA were input to Coodi using an exponential fit, which is shown with the dashed lines in Fig. 3. Conservatively, the average field of each turn was used to obtain the delay from the fit.

The quench propagation velocity between the heating stations was an input and set to 20 m/s. The quench propagation time between turns was set to 10 ms. These values are consistent with the QLASA [22] simulations for the EuroCirCol Cosθ magnet [16]. Quench propagation between layers was not considered. AC-losses and other dynamic effects were neglected as well. In all cases we considered 20 ms detection time. The hotspot location is always the worst-case for the hotspot temperature, i.e., the low-field cable with the highest field.

The maximum temperature in the Coodi-simulations was 350 K. The maximum voltage to ground was about 1500 V. The voltage between laterally adjacent turns reached 140 V and the maximum voltage between adjacent layers was nearly 2000 V. Note, that the potential to ground does not include the voltage from the circuit with energy extraction, which can be 1-2 kV in a long chain of magnets. The high voltages are one of the reasons why the design parameter space was updated as discussed in Section II.

V. SIMULATED TEMPERATURES AND VOLTAGES WITH TALES

The TALES simulation model features a 2-D thermal model of the coil cross-section, including a state-of-the-art model of the interfilament coupling effects during the current decay [11], [14]. It can include heaters on coil surface, and the CLIQ protection circuit. The voltage computation assumes that the inductive voltage across each layer is uniformly distributed in the coil turns.

We simulated three cases with TALES: A) Quench heaters only, considering the design presented here, B) CLIQ only, considering the design presented in [7],[9],[10], and C) Quench heaters + CLIQ hybrid solution. It has to be noted, that RRR in TALES simulations was set to 150.

A. TALES simulation with heaters only

In the 2-D TALES model the heaters cannot have heating stations, but it is assumed that the entire coil turn is covered with the heaters. The fraction of the coil covered by heating stations scales the QH strip resistance and QH-coil thermal contact area. Fig. 3 shows the time instants of quench initiation in different turns in the CoHDA+Coodi and TALES simulations. The delays from TALES refer to the time instant when the entire turn quenches, and from Coodi the delays refer to the time instant when quench initiates under the heating stations.

At coil high field region, the quench delays from the two simulation methods agree reasonably. However, at the low field regions the delays are significantly longer in TALES than in Coodi. Possible reasons are the different simulation of the heaters, different definition of the shown quench delay, and that the magnetic field distribution considered in TALES is slightly different than in Coodi.

The resulting peak temperatures however were quite similar, probably the longer quench delays were compensated with the dynamic effects during the current decay. In TALES the simulated peak temperature was 355 K, 5 K higher than in Coodi. The voltage to ground was 1.2 kV, 300 V lower than the value simulated with CoHDA. This stresses the effect of the dynamical phenomena (interfilament coupling losses) in voltage simulation.

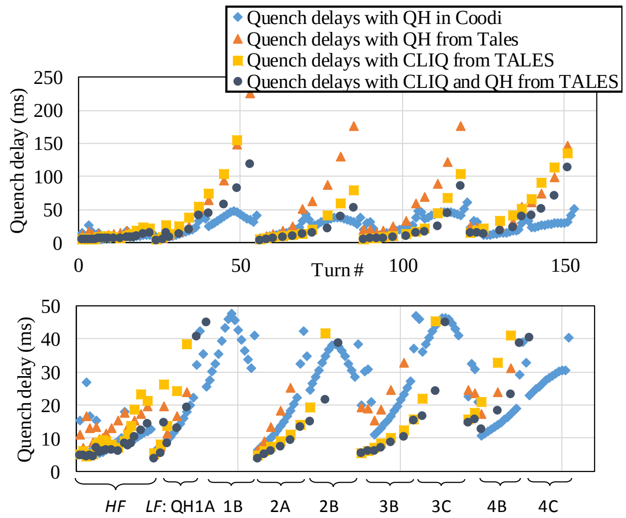

Fig. 3. Simulated quench delays in different coil turns in all considered cases: Heater delays with CoHDA+Coodi, heater delays with TALES, CLIQ delays with TALES and heater+CLIQ delays with TALES. At the bottom is a zoom for the delay times under 50 ms and the relation of the turn numbers to the heater ID's and coil cross-section (see Fig. 1).

B. *TALES simulation with CLIQ*

The protection scheme with the CLIQ system consisted of one CLIQ unit, including a 20 mF capacitor charged to 2.0 kV. The terminals were connected between the 2nd and 3rd layer of the two coils. Based on the TALES simulation, the peak temperature was 330 K and voltage to ground 1.3 kV. [7]

C. *TALES simulation with heaters and CLIQ*

The hybrid solution including both heaters and CLIQ was simulated with TALES [23]. The heater design and CLIQ design were as presented earlier in this paper. The simulated quench delays in each turn are reported in Fig. 3. One notices, that the delays from CLIQ or CLIQ+QH are faster than delays with only QH in the high field regions. Based on this, the quench heaters do not impact the delay in high-field regions, but help in quenching the lower field areas. The heater design could be therefore further optimized for the hybrid solution by focusing the heaters on the low-field region.

The simulated peak temperature was 305 K, featuring a reduction of 50 K with respect to the case with heaters only, and 30 K with respect to the CLIQ only case. The maximum temperature gradient was about 130 K. The maximum voltage to ground was 1.2 kV. Fig. 4 shows the distribution of temperatures and voltages to ground (without the hotspot).

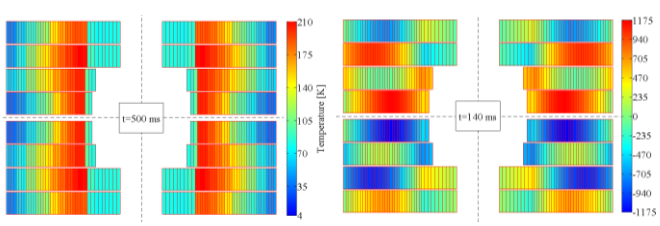

Fig. 4. Simulated maximum temperature and voltage distribution from TALES considering protection scheme with heaters and CLIQ.

VI. Comparison of the Methods

The main results for the different protection methods are summarized in Table III. Based on this analysis, the protection based on quench heaters only or CLIQ only can both protect the magnet, although the margins and tolerances become very small in the heaters only case.

The hybrid solution seems to provide a protection scheme with large margin in the peak temperature. It obviously provides full redundancy in case of a failure of CLIQ or some of the heaters. The price to pay is the high total energy of the protection system: 80 kJ per magnet aperture. The redundancy in the heaters only and CLIQ only scheme must be studied separately. The large energies and the complexity of the quench protection system suggests that its cost may become significant. The magnet cost model study [24], essential for the eventual decision whether to construct the FCC or not, should therefore analyze the cost of the protection and compare it with the savings in the cable (copper) that could be added to allow for longer protection times and less powerful protection.

TABLE III
COMPARISON OF THE PROTECTION SCHEMES OPTIONS.

Protect. method	QH		CLIQ	QH + CLIQ
Simulation tool	Coodi	TALES	TALES	TALES
T_{max} (K)	350	355	330	305
V_{max} to ground (V)	1500	1200	1300	1200
V_{max} between turns (V)	140	75	71	60
V_{max} between layers (V)	1950	-	-	-
QP system energy (kJ)	39	39	40	79

VII. Conclusions

We considered the 14.3-m-long EuroCirCol 16 T Block-type dipole magnet, and its protection with three different technologies: Quench heaters, CLIQ, and a hybrid including both systems. None of the methods was fully optimized, but the simulation results suggested that each of them was able to keep the magnet peak temperature around 350 K, or below. Two different simulation programs were compared for the heaters only case, and the resulting temperature differed less than 2%.

These results give confidence that the 40 ms time margin, which was chosen as a design criterion in EuroCirCol magnets, was reasonable considering that the aim was to be optimistic. The used analysis methods also seem appropriate. The future protection design should focus on optimizing the heaters and CLIQ for the hybrid-solution. In particular, the heater design should focus on positioning the heat in the areas of lower CLIQ heating power, taking into account the coil energy margin distribution. Protection at low field and analysis of failure cases will be considered in the next phase of this study.

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