QUENCH HEATER EXPERIMENTS ON THE LHC MAIN SUPERCONDUCTING MAGNETS

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Abstract

In case of a quench in one of the main dipoles and quadrupoles of CERN's Large Hadron Collider (LHC), the magnet has to be protected against excessive temperatures and high voltages. In order to uniformly distribute the stored magnetic energy in the coils, heater strips installed in the magnet are fired after quench detection. Tests of different quench heater configurations were performed on various 1 m long model and 15 m long prototype dipole magnets, as well as on a 3 m long prototype quadrupole magnet. The experiments aimed at optimising the layout of the quench heater strips, minimising the complexity of the protection system and determining its redundancy.

In this paper we discuss the results of the performed experiments and describe the optimised quench heater design for the LHC main magnets.

1 PROTECTION SCHEME

In the Large Hadron Collider at CERN 1232, 15 m long dipole magnets and 392, 3 m long quadrupole magnets will be powered with a current of up to 13 kA. Each of the eight sectors of the machine is powered independently to limit the amount of the stored energy in the main electrical circuits, with 154 magnets for the dipoles, and 47 or 51 magnets for the quadrupole circuits.

In case of a resistive transition (quench), heaters are fired to initiate enough resistive volume that the energy can be safely dissipated in the coils, keeping maximum temperatures and voltages within safe limits. Every magnet is "de-coupled" from the rest of the circuit using a cold by-pass diode, and the resistive voltage across the magnet provokes a fast commutation of the current from a quenching magnet to its parallel diode.

The magnet chain is de-excited by opening switches across a dump resistor, in which the energy stored in the remaining superconducting magnets will be dissipated. Because of the large values of the inductance, de-excitation is slow (time constants of about 100 seconds for dipole circuits, and of about 50 seconds for quadrupole circuits) [1].

2 PROTECTION ELEMENTS

Quench detectors: Resistive transitions are detected with floating bridge detectors for each magnet. After the validation of the signal, the energy from dedicated power supplies is discharged into the quench heater strips of the quenching magnet.

Quench heaters: The heaters for the dipole magnets consist of pairs of (0.025 ± 0.002) mm thick and (15.0 ± 0.1) mm wide austenitic stainless steel strips bonded in between two layers of polyimide electrical insulation foil. The latter acts as support and insulates the strips against the coils and the collar structure that is at ground potential. The thickness of each insulation foil is 0.075 mm ± 5 %. A layer of 0.025 mm of epoxy glue will be clad on the internal face of the polyimide foils for proper bonding to the strips during a warm rolling process. The quench heaters are subsequently creased to match the geometry of the outer coils of the magnet. They are then equipped with powering leads through soldered connector elements. Once installed in a magnet, the heater strips are strongly compressed between superconducting coil and collars (pressures around 50 MPa for the LHC dipoles). Therefore, the austenitic stainless steel strips must have smooth burr-free edges to avoid punching through the electrical insulation foil.

The heater strips have a length of about 15 m each, and cover the entire length of each outer coil. For redundancy there are two strips per coil quadrant, roughly 9 mm apart, and placed to cover about 13 cable turns.

It is sufficient to heat some sections of the superconducting cable as the quench propagates longitudinally into the non-heated sections with typical velocities in the range of 15 m/s to 20 m/s at nominal current. As an example, a 400 mm long section would be quenched in less than 10 ms. Therefore, the austenitic steel strips are partially plated with copper, either on one or on both sides. The total plating pattern is 520 mm long, alternating 400 mm plated and 120 mm unplated periods. The copper thickness is 0.004 ± 0.001 mm and its "Residual Resistivity Ratio" (RRR) exceeds 30. The electrical resistance of the strips drops from 1.5 Ω/m at room temperature to about 0.35 Ω/m at 1.9 K.

The design of the quench heaters for the quadrupole magnets is similar: their length will be about 2x3 m, and each strip covers two poles. The copper plating pattern will alternate 120 mm of unplated steel with 320 mm of copper plated parts.

Heater power supplies: After detection of a quench, a capacitor power supply applies a voltage of 900 V across the heater strips connected in series, providing a peak current of about 85 A. The time constant of the heater circuit is about 75 milliseconds. The supply is based on the thyristor-triggered discharge of aluminium electrolytic capacitors. Each power supply contains a bank with 6 capacitors (4.7 mF/500 V), where two sets of 3 parallel capacitors are connected in series, resulting in a total capacitance of 7.05 mF. The nominal operating voltage of the capacitors will be $U_{nom} = \pm 450$ V with a mid connection to ground, giving a maximum stored energy of 2.86 kJ.

3 QUENCH HEATER OPTIMISATION

The optimisation aims at finding a heater strip layout such that the heaters are effective at every current level from injection to ultimate current. The copper plating cycle for quench heaters is an important parameter that determines the resistance of the strips. In order to limit the number of heater power supplies, the resistance of the strips should allow for powering several strips in series. The initial power density and the time constant of the heater pulse depend on the resistance and have an impact on the heater delay.

Simulation studies were performed with SPQR [2] and QUABER [3] to predict the influence of the copper plating cycle and of the insulation layer thickness on the quench heater delays. The outcome of simulations has been used to prepare and perform an experimental test programme on several short dipole magnets with different parameters for the quench heaters, such as insulation layer thickness, plating cycles and powering configurations.

Table 1: Heater powering parameters and heater delays measured and predicted at nominal magnet current.

Pattern	P_0/A	τ	U_{min}	Heater delay [ms]		
[mm]	W/cm^2	ms	V	F	LF	Sim
250-250	*50*	*85*	*750*	*30*	*50*	*34*
120-240	35	112	900	35	60	38
120-360	60	85	750	28	40	30
120-400	**70**	**77**	**700**	**25**	**35**	**28**
120-480	94	68	700	-	-	24
100-400	94	68	750	-	-	26
40-240	112	48	>900	25	30	30

The test results for the heater delays performed on short dipole magnets are summarised and compared with simulations in Table 1. The test set-up was equivalent to a power supply voltage of 900 V feeding two 15 m long heater strips connected in series. For the strip with a plating cycle of 250-250 mm a single heater strip was powered with 800 V. HF are heater strips in high field region, LF are heater strips in low field region. The simulations were performed for HF heaters. U_{min} gives the minimum heater voltage required to provoke a quench at injection current. The heater delays in the table are averaged values with a spread of about 5 ms.

The optimised heater strip computed with SPQR has a cycle of 100 to 120 mm of heated part, and 300 to 400 mm copper plated length. The lower limit of 100 mm heated length is due to the transposition pitch of the superconducting cable. Heater strips with plating cycles (unplated-plated lengths in mm) of 250-250, 120-240, 40-240, 120-360 and 120-400, have been tested in various short dipole magnets. A heated part of 40 mm proved to be too short to provoke quenches at operating currents lower than 4.5 kA. The predicted minimum propagation zone at this current level is in the order of 100 mm. The shortest heater delays for HF strips were obtained with 120-400 heater strips. This length gives also a maximum yield (due to geometrical aspects) during the continuous production of quench heaters for the LHC dipoles by industry. Using a minimum voltage of 700 V, the quench heaters are effective at every current within the magnet operating range.

Further simulations and tests were carried out to investigate the maximum temperature of a heater strip during the current pulse. This temperature, if calculated adiabatically, would reach about 400 K with an operating voltage of 900 V. Considering the heat transfer from the heater strip through the insulation layer into the cable, the simulation predicts a maximum temperature of about 280 K (with nominal insulation thickness).

The heater current and voltage were measured after the firing of the heater at different magnet operating currents to evaluate the heater strip resistance and the temperature of the heated parts. Although the error of this temperature measurement is rather large due to electromagnetic noise, the maximum temperature was determined to remain below 300 K.

The simulation studies show an exponential increase of the heater delays as a function of the insulation layer. The trend has been confirmed experimentally with tests on a short dipole magnet. A doubled insulation layer thickness increased the quench heater delays such that the magnet could not be protected using only half of the high field heaters.

From these studies the optimum plating cycle was found to be 120-400 for the main dipole magnets with a polyimide insulation thickness of 0.075 mm and 0.025 mm of epoxy glue.

4 QUENCH LOAD EXPERIMENTS

For the LHC main dipoles it is foreseen to connect two, 15 m long strips in series to one power supply, and to install four power supplies per magnet. Four, 2x3 m long strips will be connected in series in the case of the LHC quadrupoles, requiring only two power supplies per magnet.

The foreseen protection scheme for the main dipole magnets has been tested for its redundancy on the first long prototype dipole magnet (15 m long, 6 block coil geometry). Redundancy of the protection scheme is an important issue, since about 6000 heater power supplies will be installed in the LHC tunnel. Such supplies will have a certain failure rate, and protection should not be compromised if some fraction will not be available. It was concluded that the high field heaters are fully redundant since powering only half of the high field heaters safely protects the magnet (see Fig. 1). The tests demonstrated that using only two high field heater strips (one power supply) leads to values of the quench load $\int I^2 dt$ of about 30 MA^{2}s, which is considered to be too large and which might cause a degradation of the magnet.

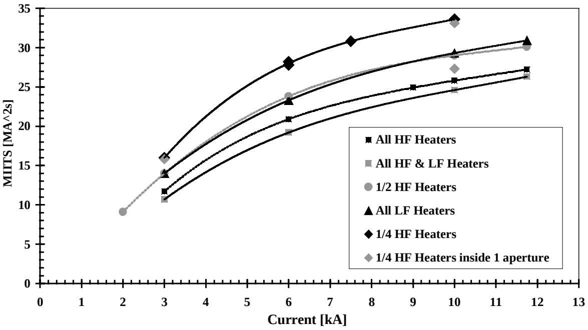

Figure 1: Quench load versus current for different heater protection schemes of the prototype MBP2N1-V2. Note that quenches were provoked by spot heaters.

The maximum operating current at which the heaters are not required to protect the magnet under machine conditions (series connection of magnets with cold diodes across them) has been calculated with QUABER to be about 2 kA. In this case, the turn-on voltage of the protection diode will still be reached due to natural quench propagation after some time, and a quench load of about 30 MA^{2}s would not be exceeded.

For a provoked quench at 2 kA, a quench load of 22.4 MA^{2}s was measured for the dipole prototype MBP2N1-V2 (without a diode mounted parallel to the magnet) after the switch off of all protection systems. The simulated value of the quench load is higher since the turn-on voltage of the diode (about 8 V) has to be reached before the current decay starts.

The scattering in heater delays of about 10 ms does not lead to unacceptable high voltages in between coil layers or to ground. The performed simulation study reveals a negligible effect of the copper plating cycle on the quench load due to the quench propagation velocities of about 15 to 20 m/s at nominal current [4].

Due to the firing of the quench heaters the resistance growth in the magnet is fast enough to cause a large dI/dt up to 60 kA/s that induces eddy currents in between the filaments, the strands and in the copper wedges. Experiments have shown that these eddy currents contribute to the heating of the cable and produce a resistive transition in areas that are not in direct contact with the quench origin nor with the heater strips. Without firing the quench heaters, the current decay is slower and the quench back process is not fast enough for adequate protection.

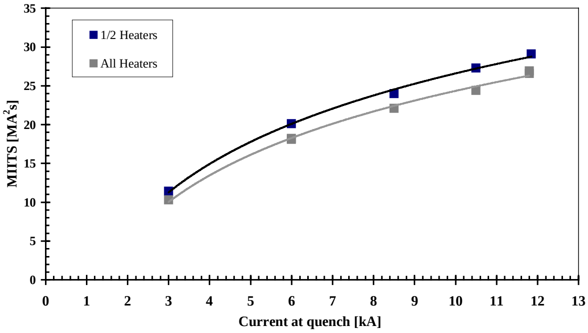

Figure 2: Quench load versus current for different heater protection schemes of the SSS3 prototype. Note that all quenches were provoked by firing a quench heater strip.

Quench load experiments were also performed on the first full-scale prototype Short Straight Section (SSS3) in slightly different conditions (see Fig. 2). With a protection scheme containing “½ Heaters”, the quench load at nominal current reached 29.1 MA^{2}s. It can be concluded that the heaters are fully redundant as half of the heaters can safely protect the quadrupole magnet.

CONCLUSIONS

It has been proved that the protection in case of a quench of the main magnets has the required level of redundancy in view of their operation in the LHC machine conditions.

Definitions of the parameters pertaining to the design of quench heaters for the LHC main magnets have been completed. Pre-series production of these elements has been launched for the dipoles, and will very soon start up for the quadrupoles.

The test programme on different models and prototypes has also allowed for the confirmation of the design parameters of the heater power supplies. In this case, production of pre-series units is under way.

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