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Thermo-hydraulic Quench Propagation at the LHC Superconducting Magnet String

F.Rodriguez-Mateos, R.Schmidt, L.Serio

Abstract

The superconducting magnets of the LHC are protected by heaters and cold by-pass diodes. If a magnet quenches, the heaters on this magnet are fired and the magnet chain is de-excited in about two minutes by opening dump switches in parallel to a resistor. During the time required for the discharge, adjacent magnets might quench due to thermo-hydraulic propagation in the helium bath and/or heat conduction via the bus bar. The number of quenching magnets depends on the mechanisms for the propagation. In this paper we report on quench propagation experiments from a dipole magnet to an adjacent magnet. The mechanism for the propagation is hot helium gas expelled from the first quenching magnet. The propagation changes with the pressure opening settings of the quench relief valves.

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Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

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F.Rodriguez-Mateos, R.Schmidt, L.Serio

LHC Division, CERN, Geneva (Switzerland)

The superconducting magnets of the LHC are protected by heaters and cold by-pass diodes. If a magnet quenches, the heaters on this magnet are fired and the magnet chain is de-excited in about two minutes by opening dump switches in parallel to a resistor. During the time required for the discharge, adjacent magnets might quench due to thermo-hydraulic propagation in the helium bath and/or heat conduction via the bus bar. The number of quenching magnets depends on the mechanisms for the propagation. In this paper we report on quench propagation experiments from a dipole magnet to an adjacent magnet. The mechanism for the propagation is hot helium gas expelled from the first quenching magnet. The propagation changes with the pressure opening settings of the quench relief valves.

1 INTRODUCTION

The protection of the LHC superconducting main dipole and quadrupole magnets in case of a quench is based on quench heaters [1] and cold by-pass diodes [2]. Once a quench is detected, the quench heaters are fired to warm-up a large fraction of the outer coils, provoking a large electric resistance growth. The current commutates from the quenching magnet over to the cold by-pass diodes connected in parallel. The magnets that do not quench are de-excited by switching off the power converter and opening switches, with resistances in parallel. The time constant for the de-excitation is about 100 s for the dipole magnet circuit and about 45 s for each of the quadrupole magnet circuits.

The energy released by the magnet into the 1.9 K helium bath leads to an increase of helium temperature and pressure. Pressure relief valves protect against over-pressure. In the LHC machine, the number of quenching magnets should be limited to a minimum. A quench of a large number of dipole magnets may become a dangerous hazard for some elements of the magnet protection system (namely, high reverse voltages might appear across a number of cold diodes). The cryogenic recovery time as well as the helium inventory and exergy recovery after a quench depends on the number of quenched magnets [3]. Typically, multiple quenching can be provoked by thermo-hydraulic quench propagation, quench propagation along the connecting bus bars, by excessive negative dI/dt, by beam losses, or by a global quench detection or control system error.

Within the R&D program for the Large Hadron Collider (LHC), a String of three 10-m long dipole magnets and one 3-m long quadrupole magnet has been assembled at CERN [4]. Experiments on quench propagation have been performed since 1996. The first series of experiments were limited to measure quench propagation from a quadrupole magnet [5], since only the cold by-pass diodes of the quadrupole magnet allow for a 100 s long discharge through a resistive load after a quench (for the electrical scheme, see [2]). The energy stored in a quadrupole magnet is with about 0.5 MJ one order of magnitude less than in a dipole magnet (5 MJ). The installation of a quench protection diode in 1997 [6] parallel to the third dipole magnet permitted to extend the experiments. The propagation of a heater induced quench in the third dipole magnet to the second dipole magnet was studied.

2 INSTRUMENTATION

The voltage across magnets and bus bars, the temperatures and pressures are recorded from the start of the quench until the current has decayed to zero. Pressure sensors and temperature probes (Allen-Bradley carbon resistors, platinum 100, and piezo-resistive cold pressure sensors) in the end volume of each superconducting magnet are glued to the end plates at the extremities of the coil assemblies. The present configuration of the String includes one quench relief valve at each end (see Fig.1). Prior to the quench propagation experiments the transient pressure peaks after a quench were studied [7]. For the experiments presented here both relief valve position and pressure opening settings were varied.

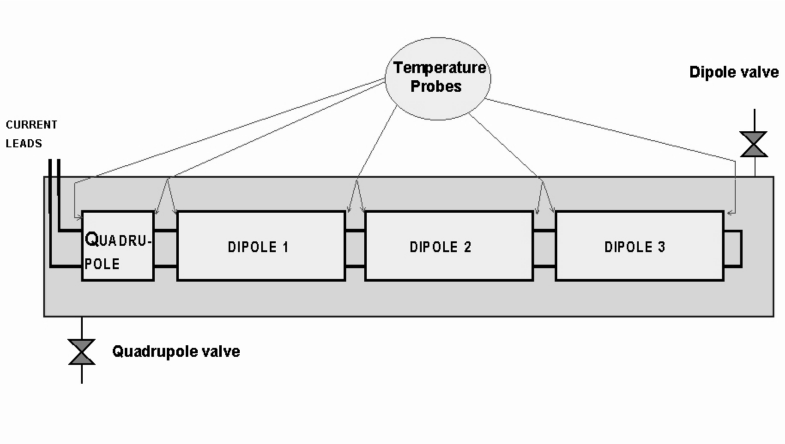

Figure 1: Simplified schematics of the String with temperature sensors and quench relief valves

3 EXPERIMENTAL PROCEDURE

The tests were performed at a helium bath temperature of 1.9 K. The String magnets are ramped to a given current value. A magnet, either a quadrupole or a dipole, is then quenched by firing the quench heaters. The power converter is switched off and a resistor is switched in series with the magnets to discharge the energy in about 100 s. The current in the quenched magnet decreases in some hundred milliseconds to about zero. If the quench propagates to any other magnet, the quench heaters on all magnets are fired and the current decreases rapidly to zero.

4 QUENCH PROPAGATION FROM QUADRUPOLE MAGNET

The delay between the induced quench in the quadrupole magnet and the start of the quench in the adjacent dipole magnet ranged between 45 s at a current of 13 kA, and 70 s at 6 kA [5]. Below 5 kA the quench did not propagate. For higher values of the current, a resistive voltage was observed across the bus bar between diode pack and dipole magnet. Some seconds later the dipole magnet quenched. The temperature at the end plate of the dipole magnet was below the critical temperature of the superconductor. The experiment was repeated with different pressure opening settings of the quench relief valves. Only a weak correlation between the time to the dipole quench and the pressure in the String was observed. It was concluded that the mechanism for quench propagation is thermal conduction through the bus bar.

5 QUENCH PROPAGATION FROM DIPOLE MAGNET

The third dipole magnet was quenched by firing the quench heaters at different values of the current. A summary of the experiments with the parameters for the quench relief valves is given in Table 1. For a current of 12.4 kA (nominal magnet current) and pressure opening settings for both valves of 10 bar the quench propagates to the adjacent dipole magnet after about 86 s (see Fig.2). In a first phase of about

300 ms after the initial quench, the temperature of the coil increases to about 100 K. Liquid helium in close contact with the coil is heated, quickly vaporised and expands compressing the remaining bulk helium. The pressure along the String is uniform. The temperature at both ends of the third magnet starts to increase. After some hundred milliseconds a second phase of slow pressure rise starts. The heat transfer from coils to the helium and to the mechanical frame of the magnet is much less efficient. After about 14 s the valves open and maintain the pressure at 10 bar. The hot helium gas forms a bubble which slowly expands. When this bubble reaches the end of the second dipole magnet, its temperature increases and this leads eventually to a quench. Before the quench propagates, the helium in the other magnets remains superfluid. In Figure 3 the temperature at the end of the second dipole magnet is shown for different experiments.

quench number	**Current [kA]**	**Remarks**	**Time for propagation [s]**
2167	12.4	Dipole valve opens on pressure of 10 bar	no
2169	13.1	Dipole valve opens on pressure of 10 bar	158
2267	12.4	Quadrupole valve opens on pressure of 10 bar	31
2311	9.0	Quadrupole valve opens on pressure of 10 bar	58
2314	12.4	Both valves open on pressure of 10 bar	86
2321	12.4	Quadrupole valve opens on pressure of 5 bar	27
2328	12.4	Quadrupole valve opens on pressure of 12 bar	34
2330	12.4	Quadrupole valve opens on pressure of 2 bar	40

Table 1: The time for the propagation of the quench to the second dipole magnet is measured, for different experimental parameters

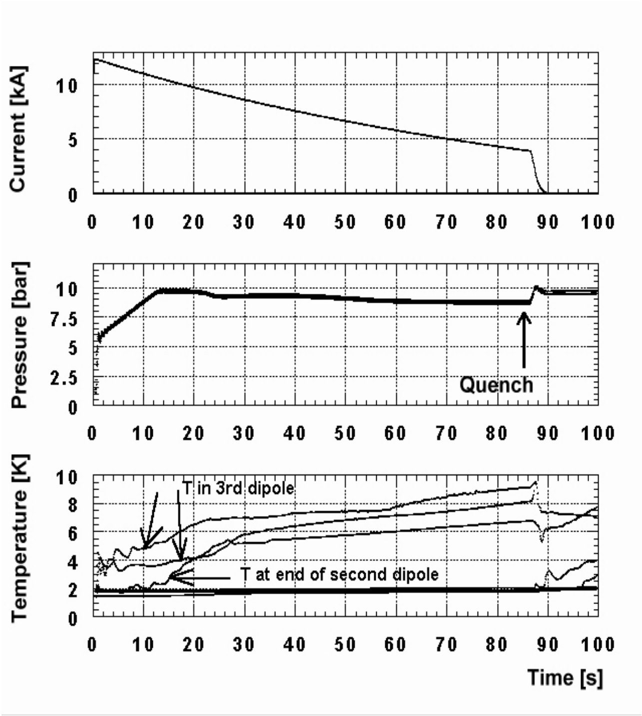

Figure 2: Current, pressure and temperature evolutions after a quench in the third dipole magnet (quench 2314). After 86 s the quench propagates to the second magnet.

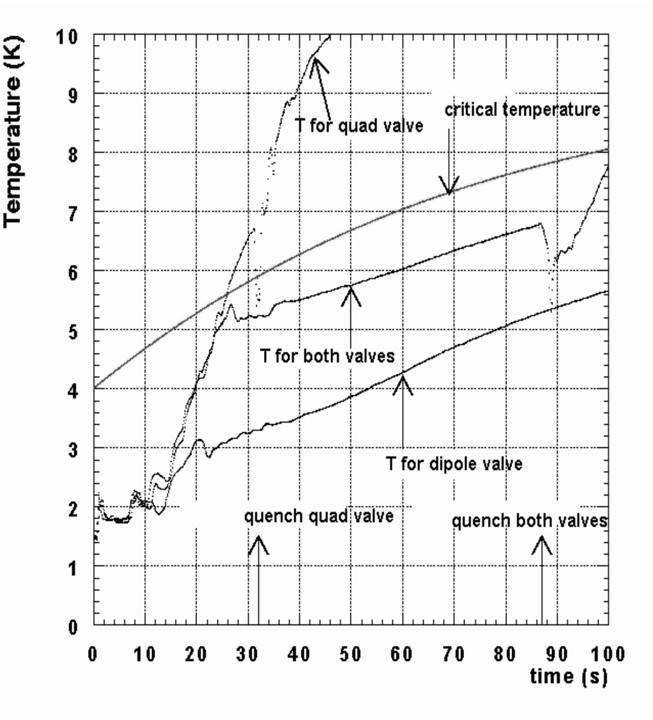

Figure 3: Temperature at the end of the second dipole magnet MB2 versus time after a quench of the third dipole magnet for different parameters of the quench relief valves (Quenches 2314,2267 and 2167)

The critical temperature of the magnets increases with time due the current decay. If only the dipole valve opens, the helium bubble moves towards the end of the magnet. The temperature at the end of the second dipole magnet increases much slower and the String can be discharged without quenching. If the quadrupole valve opens, the bubble moves towards the feed-box, thus in the direction of the second dipole magnet. The temperature increases much faster and the magnet quenches after only about 30 s. In a last series of experiments, the threshold pressure for the quadrupole valve was set to 2, 5 and 12 bar. The time for propagation varied between 27 s and 40 s. An increased value for the pressure opening setting leads to a somewhat slower expansion of the bubble, and therefore the quench in the adjacent magnet is delayed. The above is not valid at a pressure of 2 bar, because of the different helium thermodynamic state below the critical point.

6 CONCLUSIONS

Two mechanisms for quench propagation were observed. The quench in a dipole magnet propagates due to a formation of a hot helium gas bubble, which can reach the adjacent magnet. The delay for the propagation depends on position and pressure settings of the quench relief valves. It was surprising that an energy of 5 MJ could be released by quenching the third dipole magnet in some hundred ms without quenching the adjacent magnet. A quench in a quadrupole magnet leads to a temperature increase of the protection diodes. Heat generation in the diode increases the temperature of the bus bar between diode and dipole magnet. When the temperature at the entrance of the dipole magnets exceeds the critical temperature of the superconductor, the magnet quenches. The main delay is given by the length of fully stabilised bus bar which is 2 m.

The results have shown that in the final machine it should be possible to avoid excessive quench propagation after a quench in one magnet. The final configuration of magnet interconnections and quench relief valves will be installed in the next String and quench propagation experiments will be performed.

7 ACKNOWLEDGEMENTS

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