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First Implementation of the CLIQ Quench Protection System on a 14 m Long Full-scale LHC Dipole Magnet

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***Abstract*—The Coupling-Loss-Induced Quench (CLIQ) is an innovative system for the protection of superconducting magnets. Its energy-deposition mechanism, based on coupling loss generated directly in the superconductor, is by principle faster than heat diffusion, upon which conventional quench-heater based systems rely. Its electrical design relies on simple and robust components, easy to install and to replace in the case of damage. After being successfully tested on model magnets of different geometries and types of superconductor, CLIQ is now applied for the first time for the protection of a full-scale dipole magnet. For this purpose, a 14 meter long LHC twin-aperture dipole magnet is equipped with CLIQ terminals and two 80 mF, 500 V CLIQ unit are connected to its coil. Experimental results obtained under various operating conditions convincingly show that a CLIQ-based quench protection can effectively protect large-scale magnets by quickly and homogeneously transferring to the normal state voluminous regions of the winding packs. A developed dedicated simulation code correctly reproduces the complex electro-thermal transient occurring during a CLIQ discharge. The successful test completes the development program of CLIQ quench protection systems, which has convincingly demonstrated the maturity and readiness of the system for application in large-scale magnet systems.**

***Index Terms*—accelerator magnet, circuit modeling, CLIQ, quench protection, superconducting coil.**

I. Introduction

FAST and effective protection systems are needed in order to protect a high-field superconducting coil against the effects of a sudden transition to the normal state in a spot. One method consists in transferring large parts of the winding pack to the normal state, hence more homogeneously distributing the magnet's stored energy and quickly discharging the magnet current. This is usually achieved with quench heaters, which rely on thermal diffusion.

A new method for quickly transferring a superconducting coil to the normal state, CLIQ (Coupling-Loss Induced Quench), was recently developed at CERN [1]–[3]. It is based on a capacitor bank with capacitance C [F], charged to a voltage U_0 [V] and connected to the coil to protect by means of dedicated terminals. Upon quench detection, the capacitor bank is discharged, hence introducing oscillating currents in the coil sections. The resulting fast changes of the local magnetic fields introduce high inter-filament and inter-strand coupling losses [4], which, in turn, cause the heating of the conductor and a transition to the normal state of voluminous parts of the coil.

With respect to conventional quench heaters, CLIQ offers a twofold advantage. Firstly, its heating mechanism, based on coupling loss deposited directly in the matrix of the superconducting strands, is in principle more effective than thermal diffusion across insulation layers, upon which quench heaters rely. Secondly, CLIQ features a robust electrical design, is hardly interfering with the coil winding technology, and is easy to install and to replace in the case of malfunctions. On the contrary, it is impractical to cover a large fraction of the coil surface with quench heaters. Besides, they may cause electrical shorts, may get damaged by overheating, and may suffer from repetitive variation of Lorentz forces during operation and to stress and strain during thermal cycles [5], [6]. Quench-heater failure is one of the main causes of rejection of high-field accelerator magnets at CERN [5], [7], [8].

CLIQ technology already achieved a very good level of maturity. In the last years it was successfully applied to various existing magnets of different geometry (solenoid, dipole, quadrupole), type of superconductor (Nb-Ti, Nb_3Sn), self-inductance (from a few mH to a few H), and size [2], [9]–[13]. For the first time, CLIQ is now tested on a full-scale accelerator dipole magnet, namely the 14 meter long, Nb-Ti, LHC twin-aperture dipole magnet [14], [15], at the CERN magnet test facility. Experimental results obtained under different operating conditions are presented in this paper and compared with similar discharges obtained with conventional quench heaters. The transients during a CLIQ discharge are simulated with TALES (Transient Analysis with Lumped-Elements of Superconductors), a new software dedicated to quench-protection and failure-cases studies [1], [16]–[18].

II. Test Set-up

The LHC main dipole magnet is composed of two identical 14 meter long, two-layer, cos-θ dipole apertures, assembled in a common iron yoke structure and electrically connected in series [14], [15]. The magnet and conductor parameters based on design and measurements are summarized in Table I [15].

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TABLE I
MAIN MAGNET AND CONDUCTOR PARAMETERS [15].

Parameter	Unit	Inner layers	Outer layers
Nominal current, I_{nom}	A	11850	
Operating temperature	K	1.9	
Differential inductance at I_{nom}	mH	2×49	
Stored energy at I_{nom}	MJ	2×3.44	
Magnetic length	m	14.3	
Number of turns per pole	-	15	25
Number of strands	-	28	36
Strand diameter	mm	1.065	0.825
Bare cable width	mm	15.10	15.10
Bare cable thickness	mm	1.90	1.48
Insulation thickness	mm	0.15	0.15
Copper/Nb-Ti ratio	-	1.65	1.95
Filament twist pitch	mm	18	15
RRR of the copper matrix	-	190	190

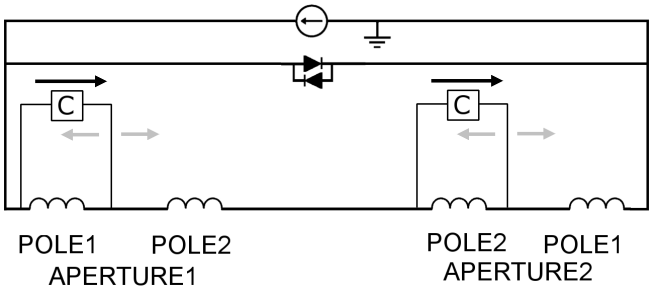

Fig. 1. Schematic of the test circuit including the 2-CLIQ system connected to the LHC twin-aperture dipole magnet.

Simulations showed that a CLIQ system composed of two units could effectively protect this coil, if connected as shown in Fig. 1 [1]. This configuration exploits the magnetic coupling between tightly-coupled coil sections, which improves CLIQ performance [1], [11]. Three CLIQ leads were attached to the coil conductor between the poles and apertures, thus subdividing the coil into four sections. If the two units are identical and the strand/cable properties of the four poles are the same, simultaneously triggering both units results in symmetric current changes introduced in the four poles. In the present set-up, each unit features a bank of film capacitors with capacitance of 80 mF rated for 500 V. Hence, this 2-CLIQ system has a stored energy of 20 kJ.

The test magnet is also equipped with the standard quench-heater system (QH) protecting main dipole magnets in the LHC machine [19]–[22]. It includes eight strips covering the coil's outer layer, each connected to a 7.05 mF, 900 V capacitor bank. Similarly to the protection during LHC operation, only four QH circuits out of eight are triggered. The total energy stored in the 4-QH system is therefore 11.4 kJ.

III. EXPERIMENTAL RESULTS

The 2-CLIQ system is tested under various operating conditions. During each test, the two QH circuits covering one aperture (Aperture 2) are triggered as well in order to provide redundancy in the case of failure of one of the two CLIQ units.

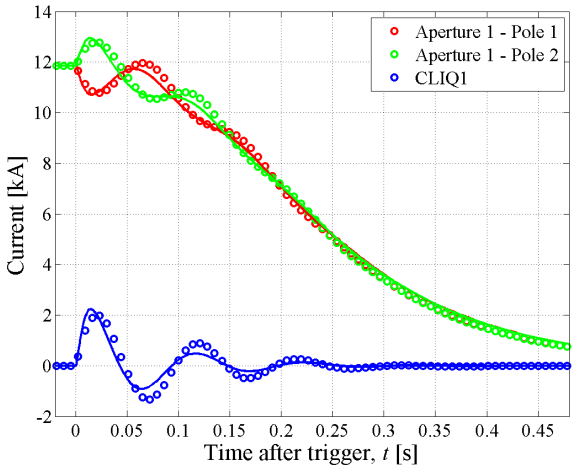

Fig. 2. LHC dipole magnet discharged by a 2×80 mF, 500 V CLIQ system and QH covering Aperture 2. Currents in the coil sections and introduced by CLIQ, versus time. Comparison between measurement (circles) and simulation (lines).

A. CLIQ Discharge

The measured currents flowing in the magnet coil sections and introduced by CLIQ during a discharge from nominal current (I_0=11.85 kA) are shown in Fig. 2. The introduced 2 kA, 10 Hz oscillating current is sufficient to quickly transfer large parts of the winding pack to the normal state. The resulting electrical resistance developed in the coil causes a fast discharge of the magnet transport current. Note that the currents flowing in the poles of Aperture 2, not shown in the figure, are almost identical to those flowing in Aperture 1 due to the symmetry in the discharge circuit. Similarly, the currents discharged by the two CLIQ units are the same.

The complex electro-magnetic and thermal transient is modeled with TALES [1], [16]–[18]. The simulated currents, also shown in Fig. 2, are in good agreement with the experimental data.

The measured and simulated voltages developed across each pole are shown in Fig. 3. Just after triggering CLIQ, the voltages are purely inductive and reach $\pm U_0$=±500 V. Due to the slightly different transition to the normal state in the four poles, unbalanced voltages of a few hundred volt develop during the magnet discharge. This is partly due to the triggering of QH's covering Aperture 2, whose poles are therefore quenched and heated up faster, and partly due to the asymmetric transport currents flowing in Poles 1 and 2 of each aperture. In fact, Poles 2 of both apertures receive an initial positive increase of the transport current, which lowers the margin to quench and generates higher ohmic loss in their normal-zone.

B. Comparison with Standard Quench Heaters

Similar discharges are performed at current levels in the range 3 to 11.85 kA and compared with discharges obtained by triggering the standard QH-based system, including two independent QH-strip circuits per aperture. The measured currents are shown in Fig. 4. At medium to high current

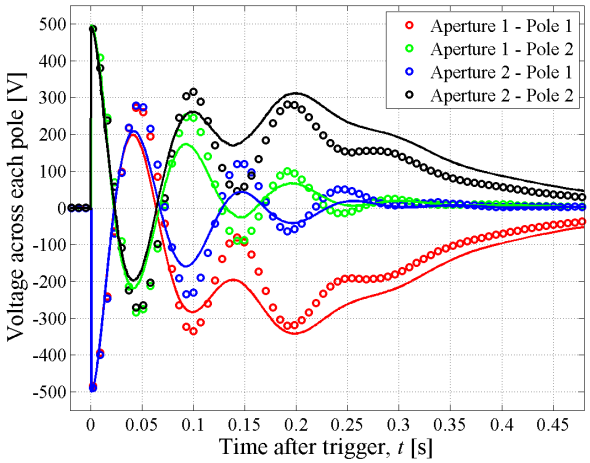

Fig. 3. LHC dipole magnet discharged by a 2×80 mF, 500 V CLIQ system and QH covering Aperture 2. Voltage across the four poles, versus time. Comparison between measurement (circles) and simulation (lines).

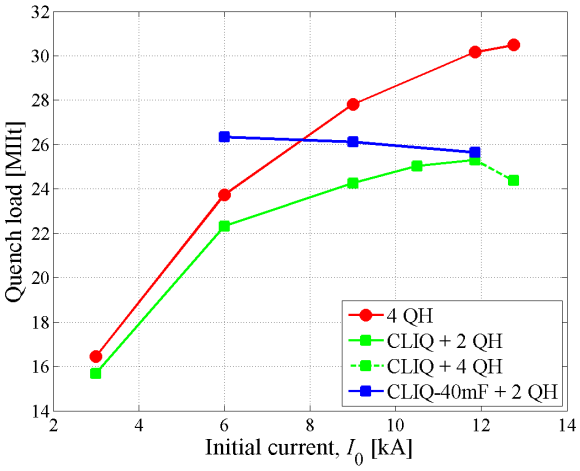

Fig. 5. Comparison between various protection systems. Quench load calculated using the measured current, versus initial current.

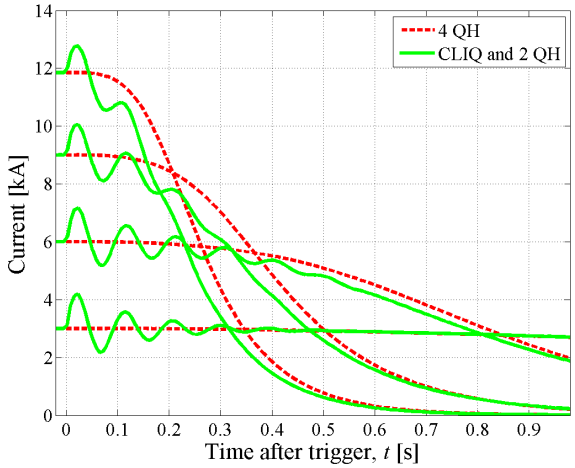

Fig. 4. LHC dipole magnet discharged with the standard QH-based system or with CLIQ. Measured magnet current versus time. Note: During CLIQ tests, QH covering one aperture are triggered as well in order to provide redundancy in the case of failure in a CLIQ unit.

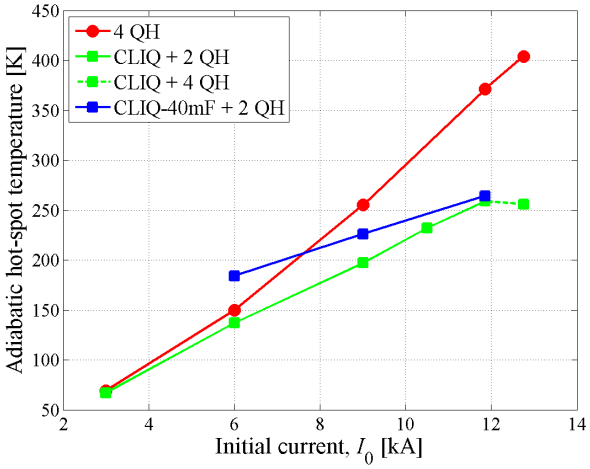

Fig. 6. Comparison between various protection systems. Adiabatic hot-spot temperature calculated using the measured current, versus initial current. A 15 ms delay is assumed between the quench start and the triggering of the protection system.

levels, triggering CLIQ achieves a significantly faster magnet discharge, since a transition to the normal state is induced 30 to 50 ms sooner than QH.

A useful parameter to assess the effectiveness of a protection system is the quench load, defined as $\int I^2 dt$ [A^2s] and proportional to the energy deposited in the coil's hot-spot. The quench loads calculated from the triggering of the protection system (t=0) are shown in Fig. 5. The quench load is reduced by about 15% at 9 and 11.85 kA by triggering CLIQ. Note that at 11.85 kA an almost identical performance is achieved with a 2×40 mF CLIQ system featuring only half stored energy.

On the other hand, at lower current levels the CLIQ performance is not much improved with respect to QH's. During "CLIQ and 2 QH" tests at 3 and 6 kA, a larger part of the winding pack is transferred to the normal state by the QH's covering Aperture 2 rather than by CLIQ, even though the energy stored in each CLIQ capacitor bank is roughly twice that of two QH circuits. This result can be explained by considering that CLIQ deposits its energy much more homogeneously in the winding pack with respect to QH. Thus, at lower current, when the margin to quench is higher, QH's can perform better as they concentrate the deposited energy into a limited number of turns.

CLIQ performance at low current could be easily improved by increasing the size of its capacitor banks. However, this is not deemed necessary for an effective protection of this coil. In fact, the temperature T_{hot} [K] reached in the coil's hot-spot at the end of a low-current discharge is much lower than after a high-current discharge. Consider for instance the results shown in Fig. 6, where the estimated hot-spot temperatures are reported. The calculation is performed assuming adiabatic conditions, a 15 ms delay for quench detection and validation, and a quench occurring in the high magnetic-field region of

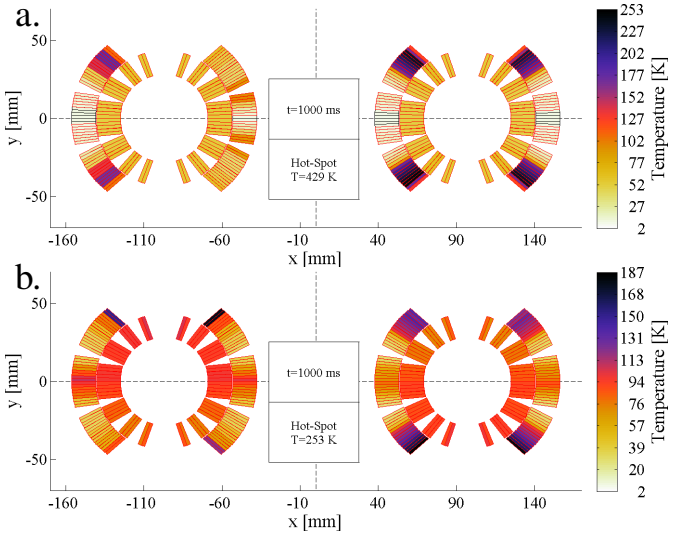

Fig. 7. Simulated magnet temperature over the cross-section of the coil windings of Apertures 1 and 2 (right and left, respectively), at 1 s after detection of a quench at nominal current. a. Triggering 4 QH. b. Triggering CLIQ and 2 QH. Note the difference in the two temperature scales.

TABLE II
THERMAL ANALYSIS FOR THE ANALYZED CONFIGURATIONS.

Configuration	$T_{\rm hot}$ [K]	$T_{\rm ave}$ [K]	σ_T [K]	Δ_T [K]
4 QH	429	67	61	245
CLIQ and 2 QH	253	77	33	160

the outer layer. At low current there is no significant difference between the $T_{\rm hot}$ obtained with CLIQ or QH, whereas at high current triggering CLIQ achieves a decrease of $T_{\rm hot}$ from 400 to 250 K.

C. Thermal Analysis

After successful validation over a wide range of operating conditions, the model can be used to further analyze the transients occurring in the coil during and after a CLIQ discharge. The simulated temperature profiles in the coil cross-section at the end of discharges from nominal current, in the cases "4 QH" and "CLIQ and 2 QH", are shown in Fig. 7a and Fig. 7b, respectively. Furthermore, the average value $T_{\rm ave}$ [K] and standard deviation σ_T [K] of the temperature at the end of the discharges are reported in Table II, as well as the difference between the maximum and minimum local temperature in the coil Δ_T [K].

If only QH's are triggered, the temperature profile is highly inhomogeneous since only the turns covered by QH strips are transferred to the normal state in the first 50 ms after quench detection. The coil's inner layer quenches more than 100 ms after QH triggering due to quench-back and heat diffusion from the outer layer. The mid-plane region quenches very late or not quenched at all during the discharge, resulting in a very large Δ_T=245 K. In the analyzed case, a further source of non-uniformity is constituted by the asymmetric triggering of the QH circuits. In fact, one of the QH circuits covering the high-field region of Aperture 2 was broken and a circuit covering its low-field region was triggered instead.

Triggering CLIQ results in a more uniform transition to the normal state of the winding pack and therefore in a more homogeneous temperature distribution. With respect to the QH case, σ_T is decreased from about 60 to 30 K, and Δ_T reduced to 160 K. Thus, it is expected that the thermal stresses within the magnet are significantly reduced.

A detailed analysis of the mechanical stresses introduced by the CLIQ oscillating currents was not performed. However, after a few tens of CLIQ discharges at various current levels no sign of magnet detraining was observed, and therefore this does not seem

IV. CONCLUSION

For the first time, the CLIQ method is successfully tested on a full-scale accelerator dipole magnet at the CERN magnet test facility. A system composed of two 80 mF, 500 V units is connected to the two apertures of this coil through three dedicated terminals situated at the joints between magnet poles and apertures.

Experimental results convincingly show that such a method is effective in protecting this 14 m long coil. CLIQ initiates a transition to the normal state in the winding pack as soon as or faster than conventional quench heaters. At nominal current, triggering CLIQ transfers the coil about 35 ms faster than using quench heaters, resulting in a 15% reduction of the quench load. The estimated adiabatic hot-spot temperature consequently reduces from about 400 to 250 K.

This remarkable performance is achieved with a system featuring a more robust electrical design and not interfering with the coil winding.

The experimental magnet current and voltage evolutions are found to match closely the predictions of the electro-thermal model developed in the past few years. After validation, the model is used to further investigate the transients occurring during the magnet discharge, providing useful information regarding the thermal gradients in the winding pack and the voltage distribution across the various coil sections. In the future, the model can be used to assess the performance of the magnet and its protection system in a wide range of operating conditions, and analyze the impact of failures in the system.

This measurement campaign, together with the similar tests performed on the full-size LHC matching quadrupole magnet [13], conclude the full characterization of the CLIQ system applied to low-temperature superconducting magnets. Although none of the tested magnets was specifically optimized for CLIQ, the performance in terms of effective heat deposition and resulting hot-spot temperature was always very good. The CLIQ R&D program showed that this technology has reached full maturity and is now ready for implementation on existing and future magnets.

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