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First Implementation of the CLIQ Quench Protection System on a Full-Scale Accelerator Quadrupole Magnet

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Abstract—CLIQ, the Coupling-Loss Induced Quench system, is an innovative method for the protection of high-field superconducting magnets. With respect to conventional method based on quench heaters, it offers significant advantages in terms of electrical robustness and energy-deposition velocity. Its effective intra-wire heating mechanism targets a fast and homogeneous transition to the normal state of the winding pack, hence assuring a quick magnet discharge and avoiding overheating of the coil's hot-spot. Furthermore, it is possible to implement CLIQ as a time- and cost-effective repair solution for the protection of existing magnets with broken quench heaters. After being successfully tested on model magnets of different geometries and made of different types of superconductor, CLIQ is now applied for the first time for the protection of a full-scale quadrupole magnet at the CERN magnet test facility. One aperture of a 3.4 meter long LHC matching quadrupole magnet is equipped with dedicated terminals to allow the connection of a CLIQ system. Experimental results convincingly show that CLIQ can protect this coil over the entire range of operating conditions. The complex electro-thermal transient during a CLIQ discharge are successfully reproduced by means of a 2D model. The test is part of the R&D program of CLIQ quench protection systems, which has convincingly demonstrated the maturity of this technology and its effectiveness also for large-scale magnet systems. The proposed CLIQ-based solution for the quench protection of the LHC matching quadrupole magnet is now ready to be implemented in the LHC machine if needed.

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

I. INTRODUCTION

WHEN a sudden transition to the normal state occurs in a superconducting coil, a protection system is needed to quickly discharge the magnet current and avoid overheating of the coil's hot-spot. CLIQ (Coupling-Loss Induced Quench) is a new method for the protection of high-field superconducting magnets [1]–[8]. It relies on a capacitive discharge system that introduces fast current changes in the coil sections. The resulting fast changes of the local magnetic field introduce high inter-filament and inter-strand coupling losses, 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 method based on quench heaters, CLIQ offers a twofold advantage. Firstly, the power deposition is achieved with an external system, not interfering with the coil winding technology, and easy to install and to replace in the case of damage. On the contrary, quench heaters are fragile, prone to electrical breakdown, and cumbersome when to cover a large fraction of the coil surface. Secondly, CLIQ's heating mechanism, based on coupling loss deposited directly in the matrix of the superconducting strands, is by principle more effective than relatively slow thermal diffusion across insulation layers, upon which quench heaters rely.

The CLIQ technology already achieved a high level of maturity. In the last years it was successfully applied to various existing magnets of different geometry (quadrupole, dipole, solenoid), type of superconductor (Nb-Ti, Nb₃Sn), and size (small laboratory test magnets, model magnets) [2]–[7]. Although none of these magnets was specifically optimized for CLIQ, the performance in terms of quench initiation and resulting hot-spot temperature was always very good. For the first time, CLIQ is now tested on a full-scale accelerator magnet, namely the 3.4 meter long, Nb-Ti, LHC matching quadrupole magnet [9], at the CERN magnet test facility. Experimental results obtained under different operating conditions are presented 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 fault-cases studies [1], [10]–[12].

II. CLIQ CONFIGURATION

A schematic representation of the implementation of a CLIQ protection system on one aperture of the magnet is shown in Fig. 1. Note that the two-apertures magnet system can be effectively protected by a CLIQ system composed of two units, each connected to the mid point of one aperture (see Fig. 1, dashed lines). Given the weak magnetic coupling between the two apertures, the advantage of combining coil sections located in different apertures is negligible and does not justify the overcomplication of the circuit. Two additional by-pass diodes (D1 and D2), connected with reverse polarity across each aperture, provide the return paths for the currents

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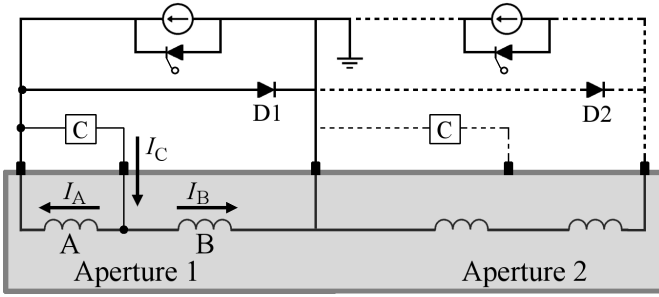


Fig. 1. Schematic of the magnet circuit including the CLIQ system. One-aperture test configuration (Continuous lines). Two-aperture final configuration (Continuous and dashed lines).

introduced by the CLIQ units. Thus, the currents flowing in the two apertures are independent, and the system can be analyzed as two separate 1-CLIQ systems with nearly identical performances. All tests are performed by powering only one aperture to reduce helium consumption.

One CLIQ unit is connected between one side of the magnet and its middle point by means of two dedicated terminals designed for short current pulses. Upon quench detection, the unit is triggered and a current I_C [A] is introduced through the leads. As a result, the currents in the two coil sections A and B, I_A and I_B [A], oscillate with opposite rates of change.

The electrical order of the coil sections and the positioning of the CLIQ terminals are crucial ingredients for an effective CLIQ system. In fact, the choice of the current changes to introduce in the various coil sections allows an effective magnetic-field superposition and an optimized distribution of the coupling loss generated in the strands [1], [5], [6]. In future magnets, the order of the poles or layers can be optimized, but in the case of existing magnets the available configurations are limited to those obtained by connecting additional terminals in coil positions which are easily reachable.

The LHC matching quadrupole was designed with an unusual order of the various coil sections, which allows implementing an effective CLIQ configuration with minimal mechanical intervention. The cross-section of each aperture of the magnet, shown in Fig. 2, is composed of four layers of cables. Each group of two outer or inner layers is connected in series, but some layers are connected in series to layers belonging to the opposite pole. Let us refer to P1-P4 as the four poles, ordered counter-clockwise, -O as groups of two outer layers, and -I as groups of two inner layers. Following this convention, the electrical order of the coil sections is P2-O, P4-I, P3-I, P1-O, P4-O, P2-I, P1-I, P3-O. The polarities of the current changes introduced in the various coil sections after triggering a CLIQ unit connected to the middle of one aperture are shown in Fig. 2. Note the presence of multiple regions where opposite current changes are introduced in physically adjacent sections. This feature improves the CLIQ performance due to the tighter magnetic coupling between the two CLIQ branches A and B, which highly reduces the impedance of the CLIQ discharge circuit and allows an effective superposition of the magnetic-field changes introduced by A and B [1], [5], [6].

The peak power density deposited by CLIQ in a wire is

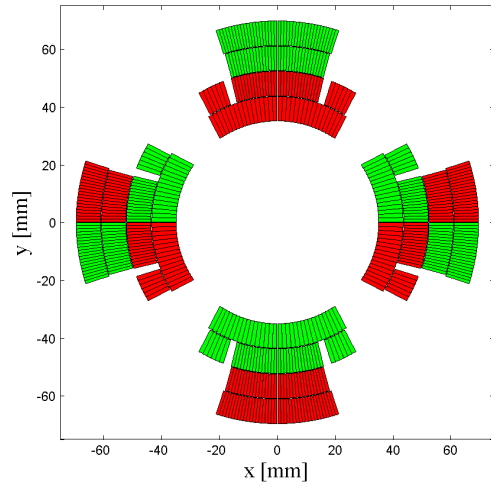


Fig. 2. Polarities of the current changes introduced in the coil sections of the LHC matching quadrupole magnet just after triggering CLIQ.

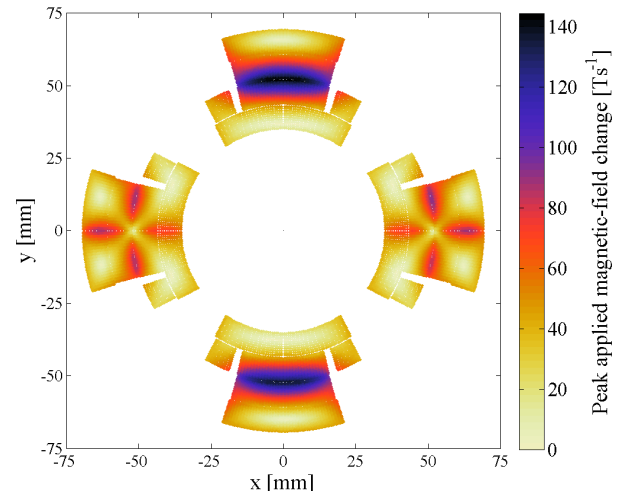


Fig. 3. Calculated peak applied magnetic-field change in the strands of the LHC matching quadrupole magnet, after triggering a 500 V CLIQ system.

proportional to the square of the introduced magnetic-field change [1]–[3], [13]. The calculated peak magnetic-field change in the strands, after triggering a CLIQ system charged at 500 V, is shown in Fig. 3.

III. EXPERIMENTAL RESULTS

The parameters of the tested magnet and its conductor are summarized in Table I [9]. Two CLIQ systems are studied, each obtained by connecting one of the two units to the middle of one aperture of the magnet. The two units (Unit-1, Unit-2) are characterized by different capacitances C [F] and charging voltages U_0 [V] of their capacitor banks, as summarized in Table II. The standard quench-heater system (QH), including four strips attached between the magnet layers [14], [15], is also tested separately to provide a relevant performance comparison. This system stores about 6.1 and 1.6 times more energy than systems Unit-1 and Unit-2, respectively.

TABLE I
MAIN MAGNET AND CONDUCTOR PARAMETERS [9].

Parameter	Unit	Inner layers	Outer layers
Nominal current, I_{nom}	A		3610
Operating temperature	K		1.9
Differential inductance at I_{nom}	mH		2×74
Stored energy at I_{nom}	kJ		2×482
Magnetic length	m		3.4
Number of turns per pole	-	37	37
Number of strands	-	22	34
Strand diameter	mm	0.735	0.480
Bare cable width	mm	8.300	8.300
Bare cable thickness	mm	1.275	0.845
Insulation thickness	mm	0.080	0.080
Copper/Nb-Ti ratio	-	1.25	1.75
Filament twist pitch	mm	15	15
RRR of the copper matrix	-	80	80

TABLE II
MAIN PARAMETERS OF THE TESTED PROTECTION SYSTEMS.

Name	Number of units	C [mF]	U_0 [V]	E_0 [kJ]
Unit-1	1	8.80	650	1.86
Unit-2	1	56.40	500	7.05
QH	4	7.05	900	11.42

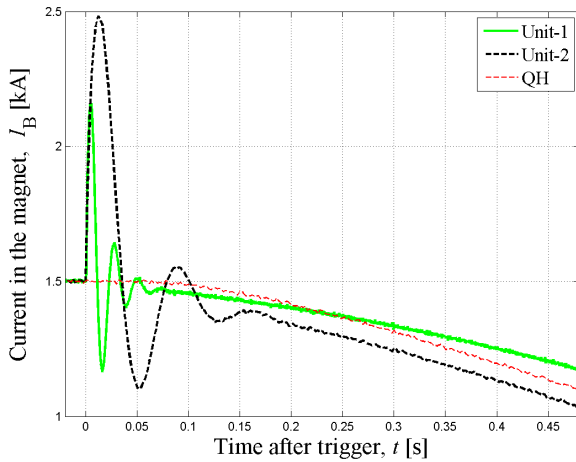


Fig. 4. Comparison between discharges obtained by triggering CLIQ Unit-1, Unit-2, or standard quench heaters (see Table II). Measured magnet current I_B versus time.

A. Effect of CLIQ Charging Voltage and Capacitance

The currents measured during two CLIQ discharges obtained by triggering Unit-1 and Unit-2, at an initial current of $I_0=1.5$ kA and a temperature of 1.9 K, are shown in Fig. 4. The peak introduced current is proportional to $U_0\sqrt{C}$, and the period of the introduced oscillations is proportional to \sqrt{C} , since the frequency is $f=1/(2\pi\sqrt{L_{eq}C})$ [Hz], with L_{eq} [H] the equivalent inductance of the CLIQ discharge circuit [1]–[3].

B. Comparison with Conventional Quench Heaters

The performances of the two CLIQ systems are benchmarked against the standard quench-heater system of this magnet in the LHC machine, whose performance is adequate to effectively protect this magnet [14], [15]. The current measured during a QH-induced discharge is shown in Fig. 4.

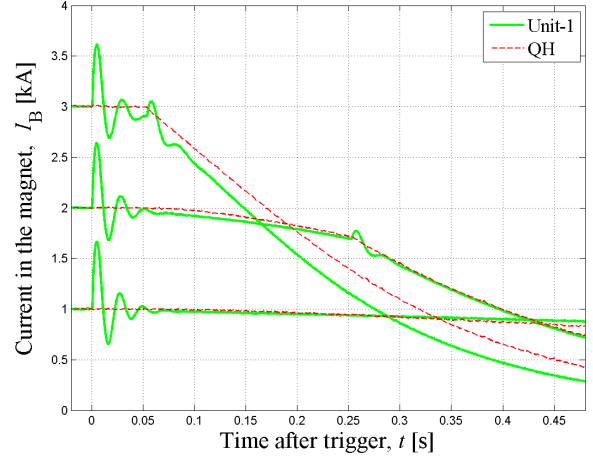


Fig. 5. Comparison between discharges obtained by triggering CLIQ Unit-1, Unit-2, or standard quench heaters (see Table II). Measured magnet current I_B versus time. Note that the energy-extraction system is triggered at $t=50$, 250, and 500 ms during the 3, 2, and 1 kA tests, respectively.

Unit-1 initiates a transition to the normal state earlier than QH due to the more effective heating mechanism, which deposits energy directly inside the conductor. As observed in Fig. 3, given the selected configuration, CLIQ achieves a highly concentrated power generation in two zones roughly corresponding to 25% of the windings volume. However, the limited energy stored in Unit-1 makes it more difficult to transfer a large fraction of the coil at this relatively low current level, when the margin to quench is large.

Quench heaters are slower to start the transition, but when they become effective they transfer a larger part of the coil since they have a higher stored energy and are glued between the two inner and two outer layers. Unit-2 achieves the best performance since it features both the effective CLIQ heating mechanism and a sufficient stored energy.

The currents measured during similar discharges obtained by triggering Unit-1 or QH, for various initial currents in the range 1 to 3 kA, are plotted in Fig. 5. In order to provide redundancy in the case of system malfunctioning, a 160 m Ω energy-extraction system is triggered with a delay of 50, 250, and 500 ms during the 3, 2, and 1 kA tests, respectively.

Over the entire range of operating currents, Unit-1 quickly transfers to the normal state a significant part of the winding pack and effectively discharges the magnet due to the fast development of the electrical resistance of the normal zone. The discharges obtained by triggering CLIQ are as fast as those obtained by triggering QH at low to intermediate current (1 and 1.5 kA), and even faster than QH at intermediate and high current (2 and 3 kA).

This result is confirmed by estimating the coil resistances R_C [Ω] during the tests, shown in Fig. 6. The coil resistance is calculated by subtracting the inductive component from the measured voltage across the magnet,

$$R_C = \frac{U_{tot} - L_{mag}dI_{mag}/dt}{I_{mag}}, \quad [\Omega] \quad (1)$$

where U_{tot} [V] is the voltage measured across the magnet,

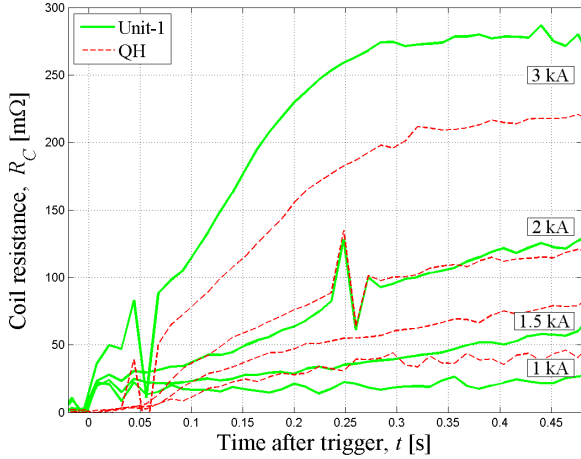


Fig. 6. Comparison between discharges obtained by triggering CLIQ units with different parameters or quench heaters (see Table II). Calculated coil resistance R_C versus time. Note that the energy-extraction system is triggered at $t=50, 250, 500,$ and 500 ms during the 3, 2, 1.5, and 1 kA tests, respectively.

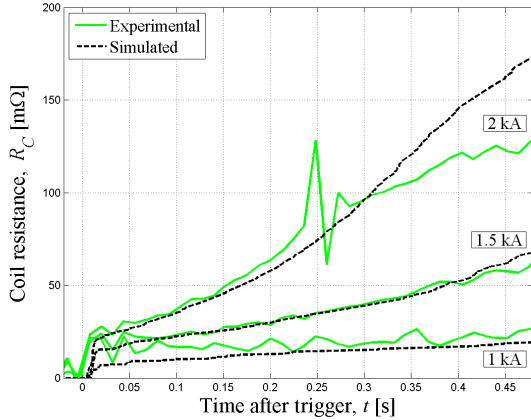


Fig. 7. Comparison between measured and simulated coil resistance R_C versus time, after triggering a 650 V, 8.8 mF CLIQ unit at an initial current of 1, 1.5, and 2 kA.

L_{mag} [H] the magnet self-inductance, and I_{mag} [A] the measured current in the magnet. In the case of CLIQ tests, I_{mag} is approximately $(I_A + I_B)/2$. Although this equation is not correct during the first tens of millisecond after triggering a CLIQ unit or the energy-extraction system, it provides a reasonable approximation, which is useful to assess the performances of different protection systems.

C. Simulations

The electro-magnetic and thermal transients during and after a CLIQ discharge are successfully reproduced with TALES [1], [10]–[12]. As an example, the simulated coil resistances developing during the discharges obtained by triggering the unit Unit-1, for various current levels, are shown in Fig. 7. The transition to the normal state is initiated 5 to 20 ms after triggering CLIQ. This performance is remarkable when compared to the 40 to 60 ms required to initiate a transition with the quench-heater based system.

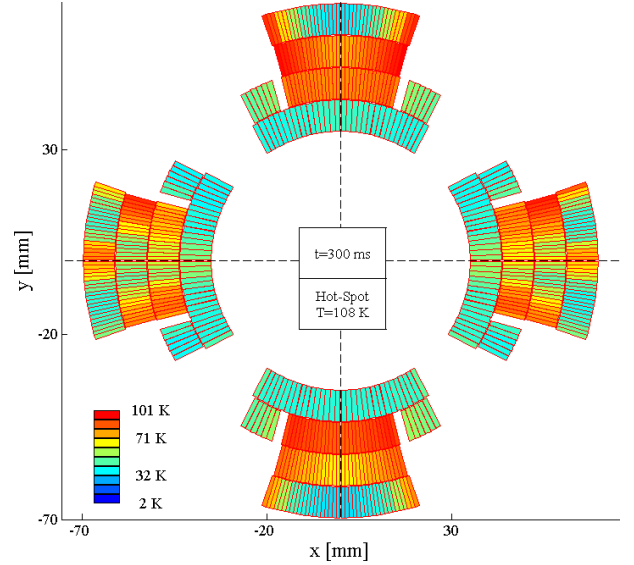


Fig. 8. Simulated magnet temperature over the cross-section of the quadrupole coil windings featuring four blocks of windings in four coil layers, at 300 ms after triggering Unit-2 ($C=56.4$ mF, $U_0=500$ V, $I_0=3.61$ kA).

In all cases the simulated resistance is in good agreement with the experimental results until the moment when the energy-extraction is triggered. No energy-extraction is included in the simulations to model a configuration similar to that implemented in the LHC machine.

The simulated temperature profile in the aperture cross-section, 300 ms after triggering Unit-2 at nominal current, is shown in Fig. 8. The asymmetric temperature distribution is due to the non-uniform heat deposition in the winding pack, which is a direct result of the distribution of CLIQ effectiveness in the various strands, shown in Fig. 3. The coil's hot-spot temperature is maintained below 110 K.

IV. CONCLUSION

The CLIQ method is successfully tested for the first time on a full-scale accelerator magnet. Two CLIQ units with different capacitances and charging voltages of their capacitor banks are connected to one aperture of the LHC matching quadrupole magnet and tested separately. Experimental results show that such a method can initiate a transition to the normal state in the winding pack as soon as or even faster than conventional protection systems based on quench heaters, over the entire range of operating currents. The transition is initiated 5 to 20 ms after triggering CLIQ.

A simulation software is available, which correctly reproduces the complex electro-magnetic and thermal transients occurring during a CLIQ discharge. The simulation results provide useful insights on the profile of the energy deposition and of the temperature in the winding pack.

This measurement campaign, together with the analogous tests recently performed on the full-size LHC main dipole magnet [7], complete the R&D program of the CLIQ system, which has proven very effective and reliable for protecting high magnetic-field magnets. CLIQ technology is mature and ready to be implemented in LHC magnets and other magnets.

The application range is very wide and advantages numerous. On present LHC magnets it can be a cost-effective backup solution for the protection of existing magnets, should their quench heaters fail in the future.

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