Protecting a Full-Scale Nb$_3$Sn Magnet with CLIQ, the New Coupling-Loss Induced Quench System

E. Ravaioli, H. Bajas, V. I. Datskov, V. Desbiolles, J. Feuvrier, G. Kirby, M. Maciejewski, G. Sabbi, H. H. J. ten Kate, A. P. Verweij

Abstract — A new protection system for superconducting magnets called CLIQ (Coupling-Loss Induced Quench system) was recently developed at CERN. Recent tests on Nb-Ti coils showed that CLIQ is a valid, efficient, and promising method for the protection of high magnetic-field superconducting magnets. However, the protection of new-generation Nb$_3$Sn accelerator magnets is even more challenging due to the much higher stored energy per unit volume and to the significantly larger enthalpy needed to initiate and propagate a normal zone in such coils. Now the CLIQ system is tested for the first time on a Nb$_3$Sn magnet in the CERN magnet test facility in order to investigate its performance in practice thereby validating the method for this type of superconducting magnets as well. Furthermore, we successfully reproduced the electro-thermal transients during a CLIQ discharge. Finally, the implementation of various CLIQ-based protection schemes for the full-scale Nb$_3$Sn quadrupole magnet for the LHC high luminosity upgrade is discussed. The impact of key system parameters on CLIQ performance and the advantages and drawbacks of using multiple CLIQ units on a single magnet are discussed.

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

I. INTRODUCTION

The newly-developed CLIQ (Coupling-Loss Induced Quench system) is a promising method for the protection of high-field accelerator superconducting magnets. Its robust and simple electrical design, its expected lower failure rate, and its efficient energy deposition make it often superior to conventional quench heaters (QH).

After being successfully tested on Nb-Ti coils, CLIQ is now implemented and characterized for the first time on a Nb$_3$Sn quadrupole magnet. The performance of CLIQ is compared to conventional quench heaters in various operating conditions. Furthermore, a dedicated electro-thermal model of the magnet is developed to reproduce the transients measured after a CLIQ discharge. Once validated, the model can be used to simulate the performance of new CLIQ configurations and other magnets and assess the impact of key system parameters.

Finally, various CLIQ-based solutions for the protection of the full-scale Nb$_3$Sn quadrupole magnet for the LHC high luminosity upgrade (MQXF) are presented and analyzed.

II. CLIQ TESTS ON A QUADRUPOLE MODEL MAGNET

CLIQ can provoke a quick transition to the normal state of extensive regions of a coil winding pack by generating inter-filament and inter-strand coupling loss, hence heat, in the copper matrix of the superconductor. This is achieved by introducing a local magnetic-field change by means of fast oscillations of the magnet transport current. The current oscillation is obtained by discharging a capacitor $C$ charged to a voltage $U_0$ and connected to the middle of the magnet (see Fig. 4a). A complete description of the CLIQ system and the main equations ruling its behavior can be found in [1-4].

A 28.2 mF, 500 V CLIQ unit is tested on a 120 mm aperture, Nb$_3$Sn quadrupole model magnet (called HQ02b) developed by the US-LARP collaboration for the LHC high luminosity upgrade [5-10]. The main magnet and cable parameters are summarized in Table I.

A. Coupling-Loss Induced Quench

Figure 1 shows the results of a typical CLIQ test at a nominal current of 14.6 kA. At $t=0$ an oscillating 2 kA, 26 Hz current $I_C$ is introduced by the CLIQ unit. The resulting oscillations of the transport current in the two sides of the magnet, $I_1$ and $I_2$, are sufficient to start a transition to the normal state of the entire coil winding pack in less than 10 ms.

![Fig. 1. Magnet discharged by CLIQ. Measured currents $I_1$ and $I_2$, calculated current $I_C$ versus time after triggering CLIQ at 14.6 kA. Experimental effective coil resistance $R_Q$ versus time. Simulated $I_1$, $I_2$, $I_C$, and $R_Q$.](image-url)
Thus, a large quench resistance is developed in the coil winding pack resulting in a quick discharge of the magnet.

At $t=3$ ms a 10 mΩ energy-extraction system (EE) is triggered as well in order to study the superposition between CLIQ and EE transients. However, the value of the extraction resistor is significantly lower than the coil resistance. This can be observed in Fig. 1 where the effective coil resistance $R_{eq}$, calculated by subtracting the inductive component from the measured voltage across the magnet, is shown.

In addition, the electro-thermal transients are simulated with a model developed using Matlab/Simulink. The simulated currents $I_1$, $I_2$, and $I_C$ and coil resistance $R_{eq}$, reported in Fig. 1, are in very good agreement with the measured curves.

B. Comparison to Conventional Quench Heaters

Similar tests are performed at different initial currents $I_0$ ranging from 3 to 14.6 kA triggering CLIQ at $t=0$ and the energy-extraction system at $t=3$ ms. Figure 2 shows the current $I_1$ measured during such tests, compared to discharges obtained by triggering conventional quench heaters attached to the outer layer of the coil (OL QH) [8] or both to its inner and outer layers (IL+OL QH). One can conclude that this 0.8 m long magnet can be discharged significantly faster by CLIQ.

However, for given settings, capacity and voltage of a CLIQ unit, its efficiency reduces with the magnet length. In fact, the power per unit volume deposited by CLIQ is roughly proportional to the square of the magnetic-field change generated in the superconducting strands [11], which in first approximation is proportional to the current change introduced by CLIQ. It can be shown that the peak introduced current-change is proportional to $U_0/L_{eq}$, i.e. the ratio between the CLIQ charging voltage and the equivalent inductance of the discharge circuit [1-2]. The latter can be expressed as the product between two components, the magnetic length $l_m$ and the equivalent inductance per unit meter $L_{eq}$ which depends only on the coil geometry, the position of the CLIQ connections, and the electrical order of the magnet poles [12].

We therefore tested CLIQ with reduced charging voltage in order to assess its performance when the ratio $U_0/L_{eq}$ is closer to the case of the protection of a full-length magnet. A comparison between the quench load $\int I_1^2 dt$ obtained after triggering quench heaters, a 500 V CLIQ unit, or a 250 V CLIQ unit is shown in Fig. 3. In the current range of 3 to 7.5 kA the quench load obtained after triggering a CLIQ unit charged with $U_0=250$ V is larger than with quench heaters. On the contrary, for initial currents higher than 9 kA the performance of a CLIQ unit charged at half voltage is similar to a full-voltage CLIQ. This result can be explained by considering that CLIQ deposits roughly the same power along the magnet length, hence homogeneously distributing the energy delivered in the coil windings. At low current where the margin to quench is higher, the energy stored in the CLIQ capacitor bank may not be sufficient to start a voluminous transition to the normal state in the coil. On the other hand, at high current where the energy required to quench is lower, CLIQ’s fast and efficient energy-transfer mechanism allows a quick and homogeneous transfer to the normal state of almost the entire magnet volume.

III. OUTLOOK ON CLIQ PROTECTION OF FULL-LENGTH QUADRUPOLE MAGNETS

After successfully testing CLIQ on the short model magnet, various options for a CLIQ-based protection of the full-length version of the magnet (called MQXF) are analyzed. Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>HQ02b</th>
<th>MQXF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal current, $I_{nom}$</td>
<td>kA</td>
<td>14.6</td>
<td>17.3</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>K</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Differential inductance at $I_{nom}$</td>
<td>mH/m</td>
<td>7.0</td>
<td>8.2</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>m</td>
<td>0.8</td>
<td>4.0/6.8</td>
</tr>
<tr>
<td>Short-sample current at $T=1.9$ K</td>
<td>kA</td>
<td>18.2</td>
<td>21.3</td>
</tr>
<tr>
<td>Number of turns per pole</td>
<td>-</td>
<td>46</td>
<td>50</td>
</tr>
<tr>
<td>Number of strands</td>
<td>-</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Strain diameter</td>
<td>mm</td>
<td>0.778</td>
<td>0.850</td>
</tr>
<tr>
<td>Bare cable width</td>
<td>mm</td>
<td>15.15</td>
<td>18.1</td>
</tr>
<tr>
<td>Bare cable thickness</td>
<td>mm</td>
<td>1.437</td>
<td>1.50</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>mm</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>Copper/Nb/Sn ratio</td>
<td>-</td>
<td>1.23</td>
<td>1.13</td>
</tr>
<tr>
<td>Filament twist pitch</td>
<td>-</td>
<td>13.5</td>
<td>19</td>
</tr>
<tr>
<td>RRR of the copper matrix</td>
<td>-</td>
<td>75-140</td>
<td>140</td>
</tr>
</tbody>
</table>

Fig. 2. Comparison between the measured magnet current after triggering quench heaters or CLIQ at current levels ranging from 3 to $I_{nom}$=14.6 kA.

Fig. 3. Calculated quench load obtained by triggering CLIQ or quench heaters at current levels ranging from 3 to $I_{nom}$=14.6 kA.
summarizes the main full-length magnet and cable parameters [13]. Two versions of the magnet will be built with a magnetic length of 4 and 6.8 m; however, only the more challenging case, \( l_{\text{m}} = 6.8 \text{ m} \), is addressed here.

### A. Proposed CLIQ Protection Designs

Recent studies indicated that it is possible to improve the performance of a CLIQ-based protection system by optimizing its discharge circuit or by installing multiple CLIQ units protecting a single long magnet [12]. Most of the energy deposited by CLIQ is transferred to heat in the coil windings during the first oscillation of the current. Thus, the peak power deposition just after triggering CLIQ significantly affects the overall performance. The peak power density deposited by a CLIQ protection system is proportional to

\[
P_{\text{peak}} \propto \left( \frac{1}{N_C} \frac{dI_{C,\text{peak}}}{dt} \right)^2 = \left( \frac{1}{N_C} \frac{U_0}{l_{\text{m}}} \sqrt{\frac{N_C}{L'_{\text{eq,1-CLIQ}}}} \right)^2,
\]

where \( L'_{\text{eq,1-CLIQ}} \) is the equivalent inductance per unit length of a system composed of one single CLIQ unit and \( N_C \) is the number of installed CLIQ units. The magnetic length \( l_{\text{m}} \) is defined by magnet design and the CLIQ charging voltage \( U_0 \) is usually limited for safety reasons; however, it is possible to optimize \( L'_{\text{eq,1-CLIQ}} \) and \( N_C \).

In fact, the equivalent inductance \( L'_{\text{eq,1-CLIQ}} \) can be significantly reduced by introducing opposite current-change in poles which are physically adjacent [12]. The remarkable performance shown in Section II is achieved with a non-optimized CLIQ configuration (see Fig. 4a, dashed line). However, an optimized configuration can be easily implemented with no effect on the stationary performance of the magnet by changing the position of the CLIQ connections (see Fig. 4a, continuous line).

Furthermore, the installation of multiple CLIQ units (Multi-CLIQ) can offer significant advantages. In the case of a single-aperture quadrupole magnet, connecting two CLIQ units across non-adjacent poles (see Fig. 4b) allows a reduction of the equivalent inductance of the circuit \( L'_{\text{eq}} \) by a factor 4, resulting in a peak power deposition 4 times higher.

The same electro-thermal model successfully reproducing the measured transients following a CLIQ discharge is used to simulate the protection of the 6.8 m long magnet. Both 1-CLIQ and 2-CLIQ configurations are analyzed in order to assess their performance. In addition, for each configuration two values of charging voltage are considered, 500 and 1000 V, corresponding to the limits for safe and reliable operation of electrolytic and film capacitors, respectively. Note that film capacitors are more suited for operation with alternating voltage but are less compact and more expensive.

### B. CLIQ Protection of the Full-Length MQXF Magnet

The protection of the 6.8 m, Nb₃Sn MQXF magnet with the four CLIQ-based protection systems under study is simulated. Figure 5 shows the calculated temperature reached in the magnet hot-spot after a quench at an initial current of \( I_0 = I_{\text{nom}} = 17.3 \text{ kA} \), for values of capacitance \( C \) of each CLIQ unit varying between 2.5 and 150 mF, assuming a delay of 10 ms for detection of the quench and triggering of the protection system. Due to the high energy density in the magnet coil, only systems capable to transfer most of the coil winding pack to the normal state in a few tens of milliseconds can maintain the hot-spot temperature \( T_{\text{hot}} \) below the design target of 350 K, currently assumed to be a safe limit with respect to permanent degradation.

As expected, the performance of the four systems is primarily depending on the peak power deposition achieved during the CLIQ discharge. From (1) one can easily see that a 2-CLIQ system charged with 1 kV deposits about 4 times more power than a 1-CLIQ-1 kV system or a 2-CLIQ-500 V system; and about 16 times more power than a 1-CLIQ-500 V system.

The influence of the capacitance on the CLIQ performance is twofold. First, the total energy stored in the CLIQ system and delivered to the coil, \( E_C = 0.5 \cdot N_C \cdot C \cdot U_0^2 \), is proportional to \( C \). Second, the oscillation period of the current discharged by CLIQ is \( t_C = 2\pi \sqrt{L_{\text{eq}} \cdot N_C \cdot C} \); thus, systems with larger capacitance maintain a high current-change for a longer time [1-2]. As a result, for each configuration a minimum value of \( C \) is required to protect the magnet assuring \( T_{\text{hot}} < 350 \text{ K} \).

Nevertheless, the minimum hot-spot temperature achievable with a certain CLIQ configuration is ultimately limited by the peak power deposition which is independent of \( C \). Thus, increasing the capacitance of the CLIQ capacitor bank above a
certain threshold only deposits more energy in the normal zone of the magnet and slightly increases $T_{hot}$.

In addition, the performance of the same four CLIQ systems is simulated at an intermediate current level ($I_0=9$ kA) where the enthalpy margin required to initiate a transition to the normal state is higher. As a consequence, the minimum capacitance required to protect the magnet increases.

However, if the energy discharged by CLIQ is sufficient to homogeneously transfer most of the winding pack to the normal state, the hot-spot temperature obtained at the end of the transient is lower than at nominal current due to the lower magnet energy-density.

It is important to remark that a 1-CLIQ-500 V system is not sufficient to protect the magnet at $I_0=9$ kA even with a capacitor bank as large as 300 mF.

On the contrary, both 1-CLIQ-1 kV and 2-CLIQ-500 V configurations with capacitance in the range 50 to 150 mF are valid protection systems for the full-scale quadrupole magnet. The better performance of the former can be explained considering that two CLIQ units store half the energy of a single CLIQ unit charged at double voltage.

The 1-CLIQ-1 kV configuration requires a lower number of connections to the magnet. On the other hand, a 2-CLIQ-500 V system allows halving the maximum voltage to ground in the circuit, hence reducing the risk of electrical breakdown. Naturally, the lowest hot-spot temperature can be achieved with the 2-CLIQ-1 kV configuration. However, the performance improvement is rather limited and for this application does not justify the additional complication of the system and higher voltage to ground.

If characterized by sufficient capacitance, the analyzed CLIQ protection systems keep the magnet hot-spot temperature at a level very similar to the theoretical limit constituted by the performance of an ideal protection system switching instantaneously the whole coil to the normal state (see Fig. 5-6). This result is an indication of the fast and efficient energy-deposition mechanism utilized by CLIQ.

C. Temperature Profile

Figure 7 shows the simulated temperature profile in the magnet cross-section after triggering a 2-CLIQ-500 V-120 mF protection system at $I_0=17.3$ kA. The entire inner layer of the magnet and part of its outer layer are transferred to the normal state in less than 10 ms (see Fig. 7a). After 20 ms about 80% of the entire winding pack is in normal state (see Fig. 7b). As a result of this fast and voluminous transfer to the normal state, the magnet energy is almost homogeneously distributed in its coil windings and the temperature distribution in its cross-section at the end of the discharge is highly uniform as well ($t=200$ ms, see Fig. 7c).

IV. CONCLUSION

The recently-developed CLIQ system is successfully tested for the first time on a Nb$_3$Sn magnet. The quench load obtained testing CLIQ on quadrupole model with 0.8 m magnetic length is up to 45% smaller than conventional quench heaters. Nevertheless, CLIQ performance is strongly affected by the magnet length, thus a thorough analysis is required to extend these results to full-scale systems.

To this end, a dedicated electro-thermal model is developed which can accurately reproduce the complex transients following a CLIQ discharge. After its validation, the model is used to study the performance of different CLIQ configurations under varying operating conditions.

Finally, a promising solution for the quench protection of a full-scale long quadrupole magnet is described based on CLIQ. Compared to conventional systems, this method offers a simpler, more robust electrical design and a faster, more homogeneous energy deposition in the coil winding pack.
REFERENCES


[4] “AC-Current Induced Quench Protection System,” application has been filed with the European Patent Office on June 28, 2013 under the application number EP13174323.9


