25th International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25–ICMC 2014

Towards an optimized Coupling-Loss Induced Quench protection system (CLIQ) for quadrupole magnets

Emmanuele Ravaioli[a,b]*, Vladimir I. Datskov[a], Vincent Desbiolles[a], Jerome Feuvrier[a], Glyn Kirby[a], Michal Maciejewski[a,c], Kevin A. Sperin[a,d], Herman H. J. ten Kate[a,b], Arjan P. Verweij[a], Gerard Willering[a]

[a] CERN, Geneva, Switzerland
[b] University of Twente, Enschede, The Netherlands
[c] Lodz University of Technology, Lodz, Poland
[d] University of Birmingham, Edgbaston, Birmingham, United Kingdom

Abstract

The recently developed Coupling-Loss-Induced Quench (CLIQ) protection system is a new method for initiating a fast and voluminous transition to the normal state for protecting high energy density superconducting magnets. Its simple and robust electrical design, its lower failure rate, and its more efficient energy deposition mechanism make CLIQ often preferable to other conventional quench protection methods. The system is now implemented for the protection of a two meter long superconducting quadrupole model magnet and as such fully characterized in the CERN magnet test facility. Test results convincingly show that CLIQ allows for a more global quench initiation and thus a faster discharge of the magnet energy than conventional quench heaters. Nevertheless, the CLIQ performance is strongly affected by the length of the magnet to protect, hence an optimization is required for effective application to full-size magnets. A series of measures for the optimization of a quench protection system for a quadrupole magnet based on CLIQ is outlined here. The impact of various key parameters on CLIQ's performance, the most efficient CLIQ configuration, and the advantage of installing multiple CLIQ units are assessed.

---

* Corresponding author. Tel.: +41-22-76-78281.
   E-mail address:Emmanuele.Ravaioli@cern.ch

1. Introduction

CLIQ (Coupling-Loss Induced Quench system, see Fig. 2a) is an innovative and efficient method for protecting superconducting magnets (Ravaioli 2014a, 2014b, 2014c; EP13174323.9). It can rapidly transfer large portions of superconductors in coil windings to the normal state by introducing a high coupling loss, and hence heat, in the superconductor's copper matrix. This is accomplished by introducing a series of fast oscillations in the transport current of the coils, which in turn provoke high local magnetic-field changes. CLIQ offers a more robust electrical design, easier implementation and repair, a faster and more global quench initiation, resulting in a substantially lower hot-spot temperature after a quench. The results of a series of CLIQ tests performed on a 2 meter long quadrupole magnet are presented. The CLIQ performance is analyzed and compared to the quench performance using conventional quench heaters. Furthermore, a general strategy for optimizing the CLIQ performance is defined. The highest performing CLIQ configuration is presented, the advantage of installing more than one CLIQ unit assessed, as well as the influence of various key parameters analyzed.

Nomenclature

I_C	Current introduced by CLIQ [A]
U_0	CLIQ capacitor charging voltage [V]
C	Capacitance of the CLIQ capacitor bank [F]
L_{eq}	Equivalent inductance of the CLIQ discharge circuit [H]
L_A	Self-inductance of branch A [H]
L_B	Self-inductance of branch B [H]
M_{AB}	Mutual inductance between branches A and B [H]

---

2. CLIQ performance test on a 2 meter long quadrupole magnet

CLIQ is tested on the 2 meter long, 8.4 mH, Nb-Ti quadrupole model magnet for the LHC upgrade (MQXC, Kirby 2014), in order to assess its performance across a wide range of operating parameters.

In Fig. 1a the results of a typical CLIQ test are shown (U_0=500 V, C=28.2 mF). At t=0 a 3.2 kA, 42 Hz, oscillating current I_C is introduced by CLIQ. The resulting oscillation of the currents in the two branches I_A and I_B generates enough coupling loss in the conductor to start a quick transition to the normal state of large portions of the coil. It is estimated that the entire coil winding pack is quenched in less than 10 ms.

Two CLIQ units are tested separately, one with U_0=500 V and C=28.2 mF (unit C1), and another with U_0=700 V and C=8.8 mF (unit C2). Furthermore, conventional quench heaters are tested on the same magnet in order to compare the performance of the two systems. A good figure for comparing the performance of different protection methods is the quench load, defined as the time-integral of the square of the magnet current during the discharge and it also is a measure for the energy deposited in the magnet's conductor hot-spot after a quench.

Fig. 1b shows the calculated quench load obtained after triggering the CLIQ units C1 and C2 and quench heaters between 3.0 and the nominal 12.8 kA. Interestingly, the maximum quench load is obtained at a current of 6 to 7 kA, corresponding to about 50% of the magnet nominal current. In fact, at higher currents the margin to quench is less and the magnet can be discharged more quickly by CLIQ due to a much faster quench initiation and propagation.

The performances of C1 and C2 are very similar even though the energy stored in C2 is about 60% of C1. It shows that it is possible to effectively protect this 2 meter long magnet with a CLIQ charged with even less energy. Furthermore, after studying the graphs it is evident that the CLIQ performance is significantly better as compared to using the present conventional quench heaters. At nominal current the quench load obtained using CLIQ is about 20% lower, corresponding to a reduction of the hot-spot temperature of more than 60 K. Nevertheless, as will be addressed in the following chapter, the CLIQ performance is decreasing with increasing magnet inductance.

Thus, an optimization and eventually parallel operation of a few CLIQ units are needed in order to enable the protection of full-size, say 10 to 20 m long magnets using CLIQ.
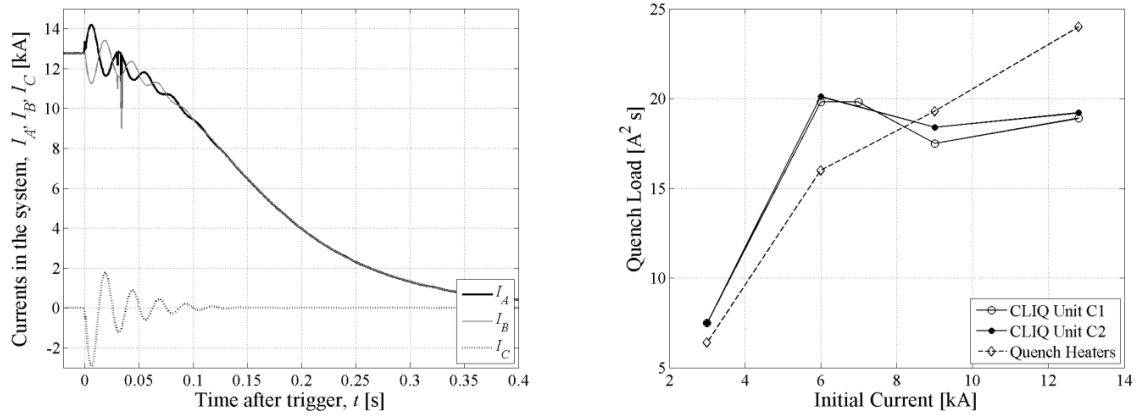
Fig. 1. (a) Magnet discharged by CLIQ. Measured introduced oscillating currents I_C and I_B, calculated current $I_A = I_B - I_C$, versus time after triggering CLIQ at an initial current of 12.8 kA. (b) Calculated quench load obtained with CLIQ and quench heaters versus initial current. Note: The energy extraction system is triggered with a delay of 950, 950, and 285 ms in the 3, 6, and 9 kA tests, respectively.

3. Strategy for optimizing a CLIQ protection system

The robust electrical design, the more efficient energy deposition mechanism, and being an external system not interfering with the coil winding technology, make CLIQ often preferable to conventional quench heaters. This section shows various ways to optimize its performance. The parameters of superconducting cables used for accelerator magnets are typically in a range where the CLIQ main energy-deposition mechanism is the inter-filament coupling loss. In fact, inter-strand coupling loss is usually characterized by a larger time constant not allowing an efficient energy deposition during the fast current oscillations provoked by CLIQ (Verweij 1995).

In first approximation, inter-filament coupling loss is proportional to the square of the filament twist-pitch, to the inverse of the transverse copper resistivity, and to the square of the magnetic-field change introduced by the magnet transport current. For a given strand type only the latter can be optimized by modifying various CLIQ parameters and connections. Although the arguments are based on protecting a quadrupole magnet as presented here, most considerations are generally valid for any type of superconducting magnet.

3.1. Effect of the size of capacitor and charging voltage

Most of the energy deposited by CLIQ is transferred to heat in the coil windings during the first oscillation of the current. As a result, the peak power deposition just after triggering CLIQ significantly affects the overall performance. The peak loss per unit volume deposited by CLIQ is proportional to the square of the ratio U_0/L_{eq}; thus, longer magnets with a higher inductance can be protected without performance degradation by increasing the charging voltage U_0. However, for safety and risk reduction reasons the maximum voltage to ground allowed in the coil circuit is generally limited to some 1000 to 1500 V level in the case of internally protected magnets.

Increasing the capacitance of a CLIQ protection system has small impact on the system safety and is relatively cheap, but it has no direct impact on the peak power deposited by CLIQ. On the other hand, the total deposited energy depends linearly on C. Besides, the CLIQ oscillation period is proportional to $C^{0.5}$, hence, for larger C the peak power deposition is maintained for a longer time (Ravaioli 2014b).

3.2. Optimum configuration for the CLIQ discharge circuit

A key ingredient for optimizing the CLIQ performance is the correct design of its discharge circuit, in particular the polarity of the current introduced in adjacent electrical elements. As shown in Ravaioli (2014b), the energy per unit volume deposited by CLIQ in any point of the coil is proportional to the square of the local magnetic
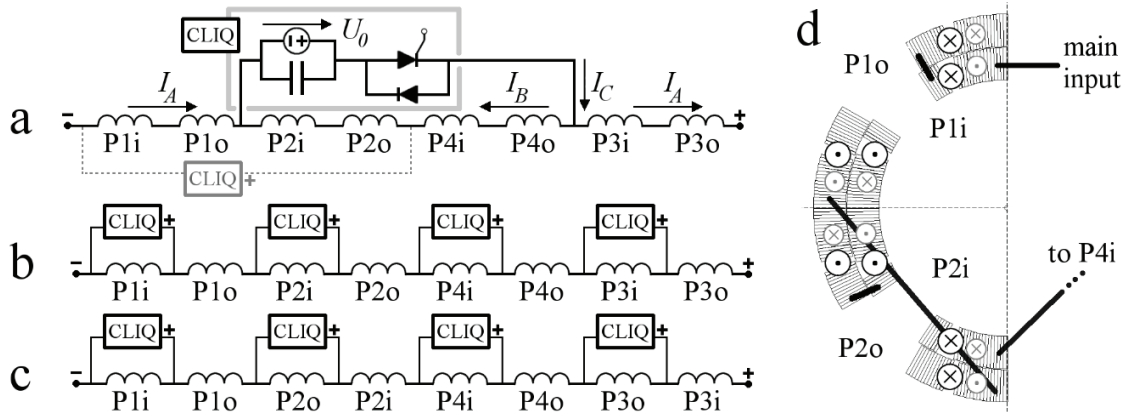
Fig. 2. (a) 1-CLIQ, optimized (continuous line) and not optimized (dotted line) configuration; (b) 4-CLIQ ("P1i-P2i-P3i-P4i P1o-P2o-P3o-P4o");
(c) 4-CLIQ ("P1i-P2o-P3i-P4o P1o-P2i-P3o-P4i"); (d) Connection scheme of poles 1 and 2 ("P1i-P2o-P3i-P4o P1o-P2i-P3o-P4i").
Larger dark circles show the current direction in stationary condition; smaller gray circles show the current change introduced by CLIQ.

field change, which in turn depends linearly on the current change introduced in the coil branches L_A and L_B. Thus, symmetric CLIQ configurations ($L_A=L_B$) are preferable in order to introduce the same current change in L_A and L_B and hence for obtaining a homogeneous energy deposition within the coil windings.

Furthermore, the current change can be maximized by reducing the equivalent inductance of the CLIQ discharge circuit which can be calculated as the inductance of two coupled parallel inductors:

$$L_{eq} = \left(L_A \cdot L_B - M_{AB}^2\right)/\left(L_A + L_B + 2M_{AB}\right). \tag{1}$$

In the case of a quadrupole magnet, the order in which its four poles are electrically connected has a large impact on L_{eq} although it does not change the stationary inductance of the magnet. This result can be explained by considering the self- and mutual inductances of the four poles. Let us define P1-P4 as the four poles of the magnet, ordered counter clockwise; L_s as the self-inductance of one pole; $M_a>0$ as the mutual inductance between adjacent poles; and $M_o<0$ as the mutual inductance between opposite poles. Depending on the pole electrical order, each of the two branches A and B of the CLIQ discharge circuit can be composed of two opposite poles (for example P1-P3 and P2-P4, see Fig. 2a, continuous line), or of two adjacent poles (P1-P2 and P3-P4, see Fig. 2a, dotted line).

For the latter configuration $L_A=L_B=2L_s+2M_a$ and $M_{AB}=2M_a+2M_o$ and by substituting in equation (1) one obtains $L_{eq}=L_s-M_o>L_s$. On the contrary, for "P1-P3 P2-P4" we find $L_A=L_B=2L_s+2M_o$, $M_{AB}=4M_a$, and $L_{eq}=L_s-2M_a+M_o<L_s$. In conclusion, selecting the correct electrical order does not change the magnet stationary performance but typically allows reducing L_{eq} by a factor 2.5 to 3, due to the increased coupling between the two branches M_{AB}.

In addition, a configuration like "P1-P3 P2-P4" generates a more efficient distribution of magnetic-field change in the magnet cross-section. This is evident when considering that each pole generates a magnetic field with opposite direction in its coil and in the coil of the adjacent poles. Thus, when an opposite change is introduced in the transport current of two adjacent poles, the magnetic field generated by the two poles superimposes in the region at their edge. Thus, after triggering CLIQ connected in a configuration like "P1-P3 P2-P4" four separate regions are created where the local magnetic-field change is large and a high coupling loss is deposited in all four areas. On the contrary, a configuration like "P1-P2 P3-P4" only creates two such regions. This result is shown in Fig. 3a-b where the peak magnetic-field change calculated for the two above-mentioned CLIQ configurations is compared.

A further improvement can be obtained if terminals are available at the joint between inner and outer layers of the magnet, thus subdividing the circuit in eight distinct inductors but magnetically and electrically coupled. Let us define P1i, P2i, P3i, and P4i as the inner layers of the four poles, and P1o, P2o, P3o, and P4o as their outer layers. These eight inductors and a CLIQ unit can be arranged so as to introduce in the four inner layers a current change opposed to the outer layers (Configuration "P1i-P2i-P3i-P4i P1o-P2o-P3o-P4o", see Figs. 2b and 3c).
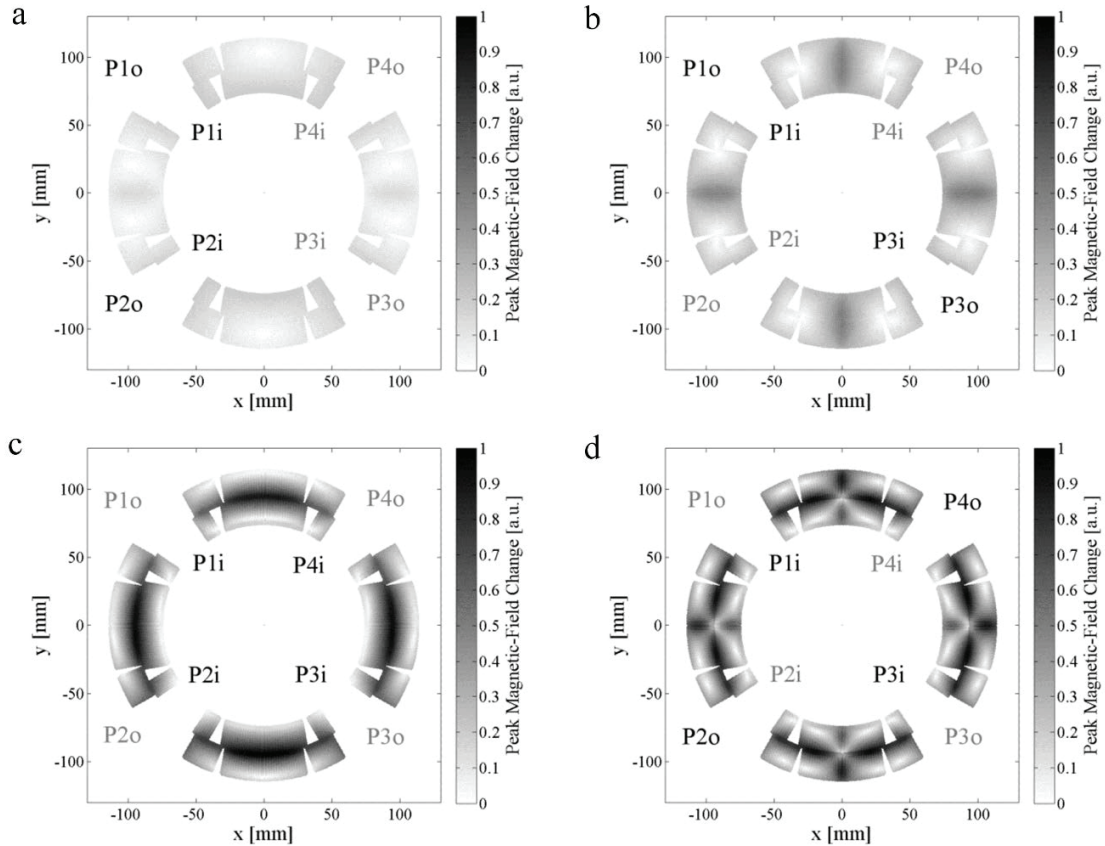
Fig. 3. Comparison between the calculated peak magnetic-field change after triggering CLIQ arranged in different configurations: (a) "P1-P2 P3-P4"; (b) "P1-P3 P2-P4"; (c) "P1i-P2i-P3i-P4i P1o-P2o-P3o-P4o"; (d) "P1i-P2o-P3i-P4o P1o-P2i-P3o-P4i". The layers whose name is colored the same (black or gray) are subjected to the same current change.

Or to introduce an opposed current change in the inner-outer layers of each pole, and in the inner-inner and outer-outer pairs of adjacent poles ("P1i-P2o-P3i-P4o P1o-P2i-P3o-P4i", see Figs. 2c, 2d, and 3d). The equivalent inductance of such schemes is typically decreased by a factor 2.5 to 3.5 with respect to the "P1-P3 P2-P4" configuration. In addition, the efficient distribution of the peak magnetic-field change achievable with these two configurations, shown in Figs. 3c and 3d, creates wide and symmetric regions where the heat is deposited.

3.3. Multi-CLIQ

A protection system composed of multiple CLIQ units (Multi-CLIQ) can offer considerable advantages. In fact, the equivalent inductance of the discharge circuit can be effectively reduced by connecting N_C separate CLIQ units across $2 \cdot N_C$ different branches of the magnet, which are therefore connected in parallel. Moreover, the total capacitance of the system is increased by a factor N_C since the CLIQ units are also in parallel. Table 1 summarizes the main equations used to calculate the performance of Multi-CLIQ systems. In particular, note that an N_C-CLIQ system can achieve a peak power deposition N_C^2 times higher than a 1-CLIQ system.

However, this reduction of L_{eq} and related increase of power deposition is achieved only when the discharge circuit can be subdivided in a number of distinct branches N_B equal to or greater than $2 \cdot N_C$. The only net effect of installing more than $N_B/2$ units is an increase of the total capacitance of the system. The N_B inductors can be the elements of a magnet chain, the poles of a magnet, or the inner and outer layers of each pole.

Table 1. Main equations used to assess the performance of Multi-CLIQ protection systems (Ravaioli 2014b).

Parameter	1 CLIQ	1 CLIQ, $2 \cdot U_0$	2 CLIQ	4 CLIQ	N_C CLIQ
Number of parallel branches, N_B	2	2	4	8	$2 N_C$
Equivalent inductance [H]	$L_{eq}|_{ref}$	$L_{eq}|_{ref}$	$L_{eq}|_{ref}/4$	$L_{eq}|_{ref}/16$	$L_{eq}|_{ref}/N_C^2$
Total capacitance, C_{tot} [F]	C	C	$2C$	$4C$	$N_C C$
Charging voltage [V]	U_0	$2 U_0$	U_0	U_0	U_0
Peak current change [A/s]	$dI_A/dt|_{ref} = U_0/L_{eq}/N_B$	$2 dI_A/dt|_{ref}$	$2 dI_A/dt|_{ref}$	$4 dI_A/dt|_{ref}$	$N_C dI_A/dt|_{ref}$
Peak deposited loss [W/m³]	$P_{if}|_{ref} \propto (U_0/L_{eq}/N_B)^2$	$4 P_{if}|_{ref}$	$4 P_{if}|_{ref}$	$16 P_{if}|_{ref}$	$N_C^2 P_{if}|_{ref}$
Peak introduced current [A]	$I_{A,max}|_{ref} \propto U_0 \cdot \mathrm{sqrt}(C_{tot}/L_{eq})/N_B$	$2 I_{A,max}|_{ref}$	$2^{0.5} I_{A,max}|_{ref}$	$2 I_{A,max}|_{ref}$	$N_C^{0.5} I_{A,max}|_{ref}$

Figs. 2c and 2d show examples of connection schemes of a 4-CLIQ protection system applied to the quadrupole geometry. In the case of a quadrupole magnet, if no connections are available at the joint between inner and outer layers N_B=4; thus, 2 CLIQ units are sufficient to obtain the minimum achievable equivalent inductance of the discharge circuit, $L_{eq}=(L_s-2M_a+M_o)/4$.

The results reported in Table 1 show that a 2-CLIQ protection system achieves the same peak power deposition of a single CLIQ unit charged with a voltage twice as large. This solution is very promising for protecting full-size accelerator magnets without the need to increase the charging voltage U_0 beyond acceptable limits (Ravaioli 2014d).

4. Conclusion

Experimental results show that the newly-developed Coupling-Loss Induced Quench (CLIQ) system is a very effective and efficient method for protecting new-generation, high-field superconducting magnets. With respect to alternative conventional quench protection systems, such as quench heaters, CLIQ offers a more robust electrical design, an easier implementation and repair, and a faster and more global quench initiation, resulting in a lower hot-spot temperature after a quench.

A general strategy for the optimization of a quench protection system for quadrupole magnets based on CLIQ is outlined here. The impact of various key parameters on the CLIQ performance, the most efficient CLIQ configuration, and the advantage of installing multiple CLIQ units are addressed.

The peak power per unit volume deposited by CLIQ is proportional to the square of the charging voltage which is generally for this type of internally protected magnets limited by the coil winding technology, safety constraints and risk reduction. Even so, the CLIQ performance can be applied very well and greatly improved with an optimum connection of the circuit electrical elements, namely the poles and their layers, which offers a reduction of the equivalent inductance of the discharge circuit and a more homogeneous energy deposition in the coil winding-pack. Furthermore, the peak power deposited by CLIQ is proportional to the square of the number of CLIQ units installed across distinct electrically elements; thus, the use of more CLIQ connections at the joint between inner and outer layers allows a further subdivision of the discharge circuit resulting in a major enhancement of the performance.

References

Ravaioli E. et al., "New, Coupling Loss Induced, Quench Protection System for Superconducting Accelerator Magnets," Applied Superconductivity, IEEE Transactions on, vol. 24, no. 3, June 2014, doi: 10.1109/TASC.2013.2281223

Ravaioli E. et al., "First Experience with the New Coupling-Loss Induced Quench System," Cryogenics, 2014, Vol. 60, pp. 33-43, http://dx.doi.org/10.1016/j.cryogenics.2014.01.008

Ravaioli E. et al., "A New Hybrid Protection System for High-Field Superconducting Magnets," Superconductor Science and Technology, 2014, Vol. 27 (4): 044023, DOI:10.1088/0953-2048/27/4/044023

"AC Current Induced Quench Protection System," application with the European Patent Office, June 28, 2013 under number EP13174323.9.

Kirby G. et al., "LHC IR Upgrade Nb-Ti, 120mm Aperture Model Quadrupole Test Results at 1.8K," Applied Superconductivity, IEEE Transactions on, vol. 24, no. 3, June 2014, doi: 10.1109/TASC.2013.2284962.

Verweij A., "Electrodynamics of Superconducting Cables in Accelerator Magnets," Ch 4, PhD thesis, Univ. of Twente, the Netherlands, 1995.

Ravaioli E. et al., "Protecting a Full-Scale Nb$_3$Sn Magnet with CLIQ, the New Coupling-Loss Induced Quench System," Applied Superconductivity, IEEE Transactions on, vol. 25, submitted for publication, 2014.