External Coil Coupled Loss Induced Quench (E-CLIQ) System for the Protection of LTS Magnets

Tim Mulder, Bernardo Bordini, Emmanuele Ravaioli, Erik Schnaubelt, Mariusz Wozniak, and Arjan Verweij

***Abstract*—The next generation of Nb_3Sn accelerator magnets are pushed to higher magnetic fields, higher stored energy and higher energy density. This brings additional challenges when it comes to quench protection. At CERN, a fast quench protection system is under development that introduces normal zones directly in the coil's conductor by inductive heating. This system is called External coil Coupled Loss Induced Quench (E-CLIQ). The E-CLIQ device comprises many small copper coils that are strategically placed near the main coils. Once a quench is detected, a capacitor is discharged in to the E-CLIQ coils, resulting in the characteristic damped oscillating current of an RLC circuit. This results in a large, but local applied dB/dt on the conductor of the main magnet system, which locally heats it by induced interfilament and interstrand coupling loss. Such a system has the advantage of being fast by introducing normal zones in potentially less than 10 ms, it doesn't rely on heat flow through the insulation layers of the coil, as is the case with traditional quench heaters, and it is not electrically connected to the main circuit. In this paper, the E-CLIQ system is introduced, several first demonstrator coils are presented and the results of a first proof-of-concept test are shown.**

***Index Terms*—E-CLIQ, coupled loss, quench protection, inductive heating, LTS magnets.**

I. Introduction

QUENCH protection of low temperature superconducting (LTS) magnet systems becomes more challenging as their magnetic field, stored energy and energy density increases. Protection with quench heaters has been an effective, well-developed and proven method for many LTS magnets. The normal zone induced by quench heaters is typically delayed by a few tens of ms after powering, as the generated heat must pass through several layers of insulation to reach the coil's conductor. Faster propagation of heat could be achieved with thinner insulation layers; however, this negatively impacts long-term insulation integrity and quench protection system reliability. A Coupling Loss Induced Quench (CLIQ) system [1] is another effective protection method that generates coupling loss in the magnet coils by a current oscillation created by discharging the energy stored in an external capacitor bank into the magnet. However, such a direct connection to the magnet's electrical circuit is often considered a disadvantage, the required capacitance is typically large and it imposes an additional large voltage to the coil's circuit.

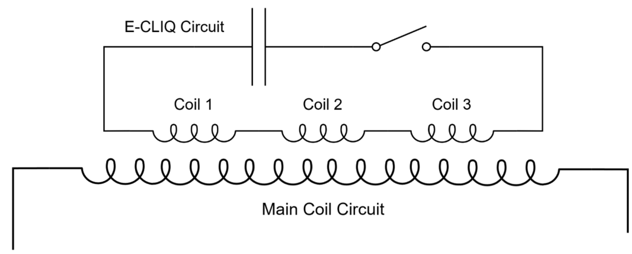

Fig. 1. Highly simplified electrical schematic of the E-CLIQ system together with the main electrical circuit of the magnetto be protected. The E-CLIQ system comprises a set of copper coils placed near the main magnet and is powered by a capacitor bank. Once a quench is detected, the circuit is closed and an RLC damped current oscillation will induce a high dB/dt locally on the main magnet.

As the latest generation of Nb_3Sn accelerator magnets is pushed further towards their limits [2], [3], [4], fast response of the protection system is key in order to limit the hot-spot temperature during a quench. An improved quench protection system is studied, which is potentially faster acting and more reliable than quench heaters, less costly than high-capacitance CLIQ systems, while at the same time electrically insulated from the coil. This contribution describes an External coil Coupled Loss Induced Quench (E-CLIQ) system that consists of several compact copper coils that inductively heat the coil by AC loss.

The coils of the E-CLIQ system are strategically positioned in the vicinity of the magnet coils and, when powered, generate high dB/dt locally on the conductor to induce a normal zone by AC loss. A simplified electrical schematic is presented in Fig. 1. The current through these coils follows a characteristic damped oscillation discharge of an RLC circuit, similar to the CLIQ discharge current. But compared to a CLIQ system, it is not electrically connected to the coil circuit and it can be used for high inductance magnets without the need for a large, costly capacitor bank. In principle, this system of multiple inductive heating stations operates very similar to quench heaters, it offers similar protection redundancy by having many small coils, but it has the potential of being faster, as the heat is generated directly in the conductor. Additionally, such a system can be better electrically insulated from the coil, which reduces the chance

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of shorts between the two circuits. Still, this protection method requires many wire connections to the cold mass, it relies on longitudinal quench propagation within the magnet, and it may not be as effective at low magnet current or in coils with small AC loss. Therefore, in some cases, it may be beneficial to use the E-CLIQ system not as a stand-alone system, but in combination with more established quench heaters and/or a CLIQ system for redundancy and to take full advantage of the strong points of each of the protection methods.

Similar protection techniques have been suggested in the past for both LTS and high temperature superconducting (HTS) magnets where normal zones are induced by local AC-loss or by locally increasing the magnetic field using an external coil [1], [5], [6], [7]. Such system shows as well similarities with a method of switching conductors from their superconducting state to a resistive state for superconducting switches in HTS flux pumps as described in [8], [9].

The E-CLIQ system is primarily being designed and optimized as a quench protection system for the next generation of Nb_3Sn accelerator magnets. This paper provides an introduction to the E-CLIQ system that is in development at CERN.

II. Target Operating Parameters

The time to induce a quench in a coil with the E-CLIQ system is potentially less than a few ms at nominal current of an accelerator magnet. A practical quench time (t_{target}) that is aimed for with the E-CLIQ system is around 5 ms at nominal current, a time that is in the same order of magnitude as the typical time constant of interfilament coupling currents and, depending on the cable, similar to the time constant of interstrand coupling currents. The two main components of the generated induced loss by the E-CLIQ coils are interfilament and interstrand coupling loss (IFCL and ISCL). Within time t_{target}, the integrated loss should increase the temperature of the cable above T_{cs}:

$$\int_0^{t_{target}} (P_{if} + P_{is})\, dt > \int_{T_{op}}^{T_{cs}} C_p\, dT, \tag{1}$$

where P_{if} and P_{is} are the IFCL and ISCP respectively. The maximum loss can be achieved by a constant or a very low frequency high applied dB/dt that is generated by the E-CLIQ coils within the target time. However, such a signal is difficult to achieve without a large, costly capacitor bank or bulky E-CLIQ coils. Therefore, at lower frequencies the dB/dt is limited by the peak current the E-CLIQ coils can accept, the properties of the capacitor bank and also of the electrical connections that go into the cryostat. At higher frequencies, the E-CLIQ coils become less efficient, as less current is induced due to the time constants of the strands and filaments, which therefore has to be compensated by going to much higher values of dB/dt and thus higher voltage and/or current of the E-CLIQ device. A good rule of thumb is to use a frequency that is $f < 1/(4 * t_{target})$ to generate less than a quarter of a period of the dB/dt signal within time-span t_{target} and $f < 1/(2 * \tau_{if})$ to ensure sufficient current is induced. Therefore, a practical target operating frequency of the E-CLIQ system is in the order of 20 to 500 Hz. A practical range for the total E-CLIQ inductance is around 0.1 to 2 mH to keep its coils relatively small, and the practical range for its capacitor bank is around 0.02 to 5 mF to have sufficient stored energy while keeping the voltage below 2 kV.

TABLE I
Properties of the Cable and Strand That Were Used for the Exemplary Loss Calculations. The Actual Loss is Cable and Strand Specific and Has to Be Calculated on a Case-to-Case Basis

Property	Value	Unit
Superconductor	Nb_3Sn	-
Type	Rutherford	-
Number of strands	20	-
Strand diameter	0.85	mm
Cable twist-pitch	50	mm
Cable width	9	mm
τ_{if}	10	ms
τ_{is}	100	ms
Cu/SC ratio	1.2	-

TABLE II
Parameters of the Demonstrator E-CLIQ Coils, the Nb_3Sn Wire (With a Defect) and Their Operating Range During the Test

E-CLIQ coil parameters	Value	Unit
Number of E-CLIQ coils	2	-
Number of sub-coils per E-CLIQ coil	4	-
Sub-coil type	Charging coil	-
E-CLIQ coil inductance	114	μH
Produced magnetic field	2.9	mT/A
Peak current / voltage used	6.0 / 20.0	A / V
dB/dt range	25-120	T/s
Frequency range	250-2000	Hz
Wire sample and test parameters		
Wire type	Nb_3Sn RRP [16]	-
Diameter	0.85	mm
Background field	0.0	T
Operating current	80-150	A
Margin to T_{cs}	up to 14	K

An adaptation is made to the equations from [10], [11], [12], [13], [14], [15] that describe ISCL and ISCL to include the time constants of the currents where needed and to get a rough estimate of the amount of loss that can be generated within a time-span t_{target} with an E-CLIQ device. Fig. 2 shows a typical damped current and voltage oscillation of a capacitor discharge in an E-CLIQ circuit using an arbitrarily chosen circuit time constant of 100 ms. With the resulting dB/dt, the loss in the cable is calculated and integrated to get the total loss within the desired time t_{target}. It shows that for the cable that is described in Table I, about 20 T/s is required at a frequency of 50 Hz to raise the cable temperature sufficiently within a few ms to initiate a normal zone when operated near its nominal current. Using higher values of dB/dt increases the loss significantly, thereby causing a larger temperature rise in the same period of time. This opens the possibility of protecting the coils during their ramp up and down, when the margin to T_{cs} may be large.

To account for cooling and the influence of copper and iron in proximity of the E-CLIQ coils, a target applied dB/dt of at least 50 T/s is envisioned at this frequency for a single cable. In practice, a larger applied dB/dt may be needed when a single E-CLIQ coil is expected to initiate normal zones in a stack of cables. The exact loss is frequency, applied dB/dt and cable specific and has to be calculated on a case-to-case basis. A further

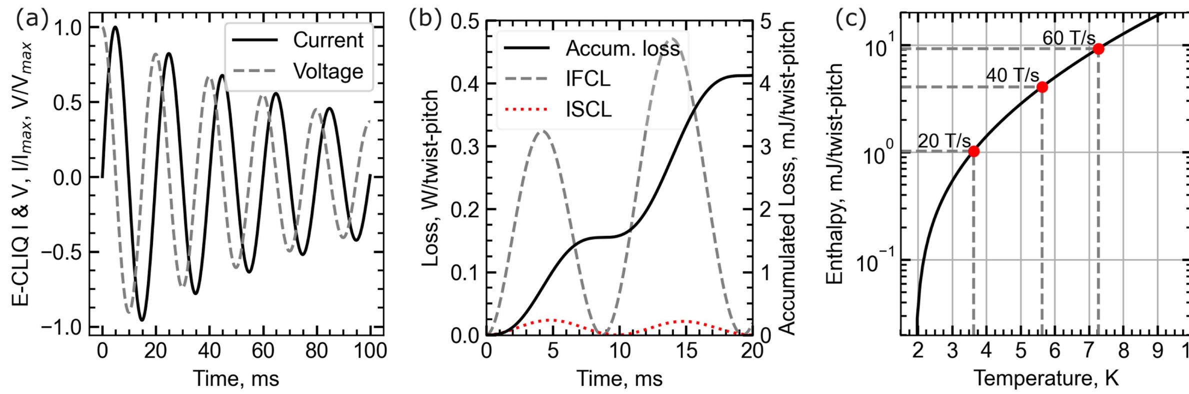

Fig. 2. (a) The damped oscillation of the current through and the voltage over an E-CLIQ coil normalized to its peak value for a frequency of 50 Hz, (b) the responding interfilament and interstrand loss using a initial peak dB/dt of 20 T/s for the Nb_3Sn cable that is described in Table I and (c) the enthalpy per twist-pitch of the cable and the temperature change that can be reached within time window $t_{target} = 5$ ms for a dB/dt of 20, 40 and 60 T/s. It shows that a dB/dt of at some 20 T/s at a frequency of 50 Hz is desired to adiabatically raise the temperature of the cable sufficiently to initiate a quench within a few ms when the cable is operating at its nominal operating current.

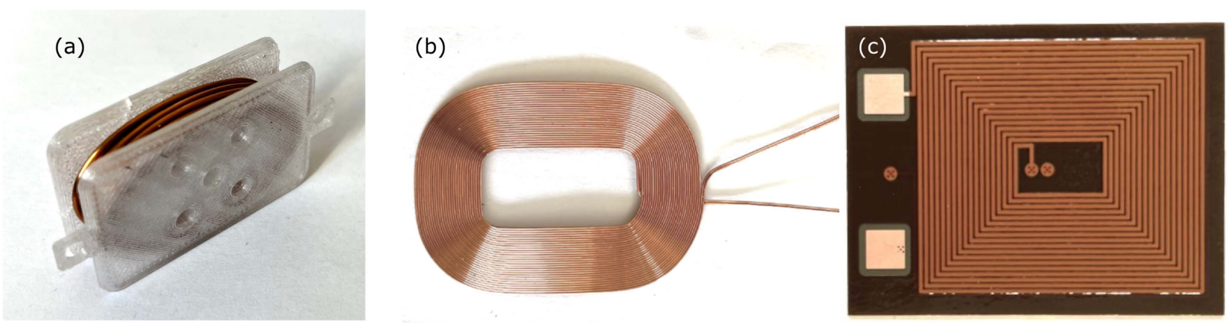

Fig. 3. Photos of the demonstrator coils that are pursued for the E-CLIQ device with (a) a copper wound coil on a 3-D printed former, (b) a commercially available inductive charging coil and (c) a PCB coil on Kapton designed for high-voltage, high-current capacitor bank discharges. All of the demonstrator coils have outer dimensions (width x length) in the range of 25 by 35 mm.

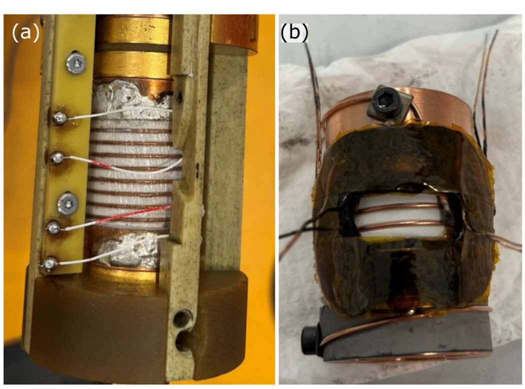

Fig. 4. Pictures of (a) the Nb_3Sn wire sample in its sample holder and (b) of one of the E-CLIQ coils mounted around a wire sample.

development effort is underway to establish modeling tools that in detail describe geometry and frequency specific AC loss in Nb_3Sn strands and cables.

III. Demonstrator E-CLIQ Coils

The development of three different types of E-CLIQ coils is pursued. Each of the types has their individual advantages and disadvantages. Pictures of the three E-CLIQ coil types are presented in Fig. 3.

1) The first coil type is based on coils wound from a thin copper wire. These are robust and its former enables practical mounting in proximity of magnet coils (if space allows it). Its wire-size and its shape can be tailored to the magnet and the capacitor or power-supply that powers it.
2) The second coil type uses commercially available inductive charging coils. The inductive charging coils are components that are typically found in modern electronics, like smartphones. These coils are not optimized for cryogenic use, nor to cope with high-voltage. However, their shape and inductance are in the desired range of the E-CLIQ system, which makes them an inexpensive and easily obtainable solution for prototyping. The coils on their own are flexible and can be bent around test samples and coil packs.
3) The third is based on a PCB track on Kapton film. The PCB based coils are designed specifically for high-voltage and high-current capacitor bank discharges. They comprise two to four layers of tracks, which allow the envelope to remain thin and relatively flexible. The dimensions of the track-size are chosen such that they can accept the very short, but high-current discharge (of up to some hundreds

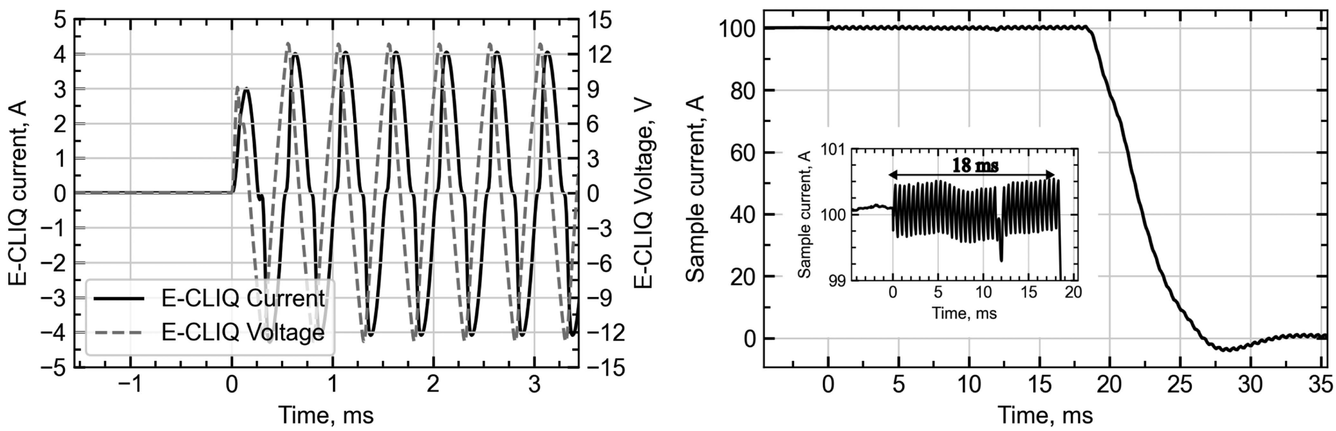

Fig. 5. An exemplary measurement result of the tests that were performed. The E-CLIQ coils were powered using 12 V (6 V per coil) resulting in a coil current of 4 A at a frequency of 2000 Hz. A measurable current ripple was observed on top of the sample current and the sample current was discharged approximately 18 ms after powering the E-CLIQ coils.

of amperes) from a capacitor bank without its temperature to rise such that its resistance changes significantly, as that would affect the parameters of the RLC circuit.

IV. First E-CLIQ Demonstration

A first proof-of-concept test was set up to demonstrate that a normal zone can be created in an MQXF Nb_3Sn wire sample [16] using an E-CLIQ device due to IFCL and to gain operational knowledge for further improvement of it.

The test sample was a Nb_3Sn wire that is spiralled around a 30 mm diameter cylindrical sample holder. Since it is a single wire, the dominant loss is the IFCL and there is no ISCL. The E-CLIQ device comprised two coils, each made of four of the inductive charging coils connected in series, as shown in Fig. 4. The coils are bent around the sample and made to fit the envelope in between the sample and the sample holder. Each of the coils has an inductance of 114 μH and they produce a magnetic field of 2.9 mT/A on the wire sample. The test was performed in liquid helium. The E-CLIQ coils were powered using a 70 V/6 A amplifier, whose output followed the input signal that was created using a function generator. This specific combination of coils and power supply limited the operating frequency range to mainly frequencies above 250 Hz and a peak dB/dt of over 25 T/s to generate sufficient loss. In this setup, due to a defect in the wire sample, all tests were performed in zero background magnetic field, therefore the temperature margin to T_{cs} that had to be overcome is much larger than what would be needed in an accelerator magnet at nominal current. The exact temperature margin was unknown, due to the unknown origin of the defect. In addition, the Nb_3Sn wire was directly exposed to the helium bath, thus cooling was significant. In total 32 tests were performed with an E-CLIQ frequency range of 250 to 3000 Hz and an average applied dB/dt of up 120 T/s, that lead to 30 positive quench-detection events and 2 no-quench events.

Activating the E-CLIQ coils resulted in a measured current ripple on top of the sample transport current, followed by a discharge of the current some ms later. An example of a typical measurement run is presented in Fig. 5. In this measurement a current with an amplitude of 4 A and a frequency of 2000 Hz was supplied to the E-CLIQ coils, which lead to an average applied dB/dt of 120 T/s on the sample. A summary of the main parameters of the used E-CLIQ coils and their operating range during the test campaign are provided in Table II.

The current discharge was started typically between ten and twenty ms after the triggering the E-CLIQ system. The test results demonstrate the potential of such a device to initiate normal zones in Nb_3Sn wires that operate far below I_c or in magnets during the entire ramp up or down, an operating current range in which a CLIQ system, for example, is less effective [1]. It is expected that with a more insulated wire in a high background field, the quench time would be notably shorter. More measurements on single wires, cables and small demonstrator coils are foreseen in the near future to further demonstrate the capabilities and explore the limits of the E-CLIQ coils.

V. Conclusion

At CERN, the development of a quench protection technique based on local inductively coupled loss initiated by a set of strategically placed small copper coils is pursued for the next generation of LTS accelerator magnets. This system is called External coil Coupled Loss Induced Quench (E-CLIQ). Three coil types are investigated for use in an E-CLIQ system, with the main focus on the development of a flat PCB-track based coil. Preliminary tests have provided promising results that indicate that such E-CLIQ system may be a feasible replacement of or an addition to existing quench protecting system for future high-field LTS accelerator magnets.

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