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

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Protecting a Full-Scale Nb₃Sn Magnet with CLIQ

CLIQ
Coupling-Loss Induced Quench

First CLIQ tests on a Nb₃Sn magnet
Validation of the simulation tools
Optimization strategy

CLIQ-based solution for the protection of full-scale quadrupole magnets

Analyzed case: Quadrupole magnet for the LHC high luminosity upgrade (US-LARP collaboration)
Quench Protection in a Superconducting Magnet

High Current Density
\( J \approx kA/cm^2 \)

High Magnetic Field
\( B = 5-10 \, T \)

High Energy Density
\( e = B^2/(2 \, \mu_0) \approx 10-40 \, MJ/m^3 \)

Quench
If a portion of the cable suddenly becomes non-superconducting, it starts heating up.

The energy stored in the magnet is usually sufficient to melt kilos of Copper and destroy the magnet!

Quick propagation of the quench needed

Homogeneous distribution of the quench energy

Discharge of the magnet current with coil resistance

Conventional Quench Heaters may be too slow (relying on thermal diffusion across insulation layers) and are prone to electrical breakdown (thin insulation).
CLIQ – Coupling-Loss Induced Quench

Current Change

Magnetic Field Change

Coupling Losses (Heat)

Temperature Rise

QUENCH
CLIQ – Main Advantages

- More **efficient** energy deposition
- **Faster** and more **homogeneous** quench initiation
- **More robust** design
- **Easier** to implement and repair
- Lower expected **failure rate**
- **External** system not interfering with the coil winding technology
- Possible to use CLIQ as a **back-up solution** for protecting magnets with failing quench heaters

All you need is available **connection(s) to the middle of the magnet** (a few mm² of copper) and a good understanding of **how CLIQ works**
CLIQ tests on the model magnet for the LHC high luminosity upgrade

First CLIQ tests on a Nb$_3$Sn magnet!

Excellent agreement between simulations and measurements

Currents in the system, $I_1$, $I_2$, $I_C$ [kA]

Time after trigger, $t$ [s]

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

Magnetic Length 0.8 m
Self-inductance 6.4 mH
Nominal current 14.6 kA

(US-LARP collaboration)
see G. Sabbi, 1LOr2B-02
see H. Bajas, 4LPo2E

1 CLIQ Unit
$U_0=500$ V $C=28.2$ mF
Comparison with Quench Heaters performance

CLIQ protects the magnet at any current level

On this short magnet CLIQ discharges the magnet significantly faster than QH
Summary of CLIQ and QH performance on the model magnet

At nominal current quench load reduced by ~30% using CLIQ

However, CLIQ performance strongly depends on the magnet length

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Quench Load [$A^2 \text{s}$]

Initial Current [kA]
Protecting full-scale magnets with CLIQ – The strategy

**Power per unit volume** deposited by CLIQ depends on inter-filament loss (IFCL)

- **Charging voltage** (limited for safety reasons)
- **Number of CLIQ units** (for quadrupoles up to 2 units)
- **Magnet length** (defined by design)
- **Capacitance of CLIQ unit** (no effect on power, but \( \propto \) to discharged energy)

\[
\frac{P_{IF}}{vol} \propto \left( \frac{dI}{dt} \right)^2 \propto \left( \frac{U_0}{l_m} \cdot \frac{N_C}{L_{1-CLIQ}} \right)^2
\]

- **For a given quadrupole magnet**
- **Choose optimum CLIQ configuration**
- **Increase voltage** \( U_0 \)
- **Increase capacitance** of CLIQ unit(s)

Equivalent **inductance** of the discharge circuit
- **Coil geometry**
- **Position** of CLIQ connections
- **Electrical order** of the poles (always an advantage, typically possible with minor changes)
Optimum CLIQ discharge configuration

Golden rule for optimizing any CLIQ discharge circuit
Introduce opposite current change in coils which are physically adjacent

Significant reduction of $L_{eq} (2.5-3 \text{ times})$
→ Increase of deposited loss (6-9 times!)

$$\frac{P_{IF}}{vol} \propto \left( \frac{dI}{dt} \right)^2 \propto \left( \frac{U_0}{l_m} \cdot \frac{N_C}{L_{1-CLIQ}} \right)^2$$
Optimum CLIQ discharge configuration

**Efficient** distribution of magnetic-field change

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**Golden rule for optimizing any CLIQ discharge circuit**

Introduce opposite current change in coils which are physically adjacent
Further decreasing the impedance of the circuit can be reduced by subdividing the electrical circuit into $2 \times N_C$ elements, effectively in parallel when CLIQ is triggered.

\[
\frac{P_{IF}}{vol} \propto \left( \frac{dI}{dt} \right)^2 \propto \left( \frac{U_0}{l_m} \cdot \frac{N_C}{L_{1-CLIQ}} \right)^2
\]
Protecting a Full-Scale Nb$_3$Sn Magnet with CLIQ

- CLIQ tests on the model magnet (HQ02b, 1 m)
- Validation of the simulation tools
- Optimization strategy

Simulations of the protection the full-scale magnet (MQXF, 7 m) using CLIQ

4 tested configurations: 1-CLIQ, 500 V, 1-CLIQ, 1 kV, 2-CLIQ, 500 V, 2-CLIQ, 1 kV
Simulated T profile  – \( I_0 = 17.3 \text{ kA (} I_{\text{nom}} \text{)} \) – 2-CLIQ, \( U_0 = 500 \text{ V, } C = 120 \text{ mF} \)

- Very fast quench initiation
- Entire inner layer quenched in \(<10 \text{ ms}\)
- 90% of the magnet quenched in \(<40 \text{ ms}\)
- Homogeneous temperature distribution

Assumptions: no QH; no EE; \( RRR = 140; \) 10 ms detection time
Simulation results \( I_0 = 17.3 \text{ kA} \) \((I_{\text{nom}})\)

**MQXF**

Magnetic Length 6.8 m  
Self-inductance 70 mH  
Nominal current 17.3 kA  

Quadrupole magnet for the **LHC high luminosity upgrade** (US-LARP collaboration)

For each studied configuration a minimum capacitance is needed to protect the magnet.

As expected performance of 2-CLIQ-500 V similar to 1-CLIQ-1 kV

Assumptions: no QH; no EE; RRR=140; 10 ms detection time

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Protecting a Full-Scale Nb3Sn Magnet with CLIQ, the New Coupling-Loss Induced Quench System  
11 August 2014
Simulation results – $I_0 = 9 \text{ kA} \ (\sim 50\% \ I_{\text{nom}})$

Protector a Full-Scale Nb3Sn Magnet with CLIQ, the New Coupling-Loss Induced Quench System

- 1-CLIQ-500 V is not sufficient to protect the full-length magnet
- Both 2-CLIQ-500 V and 1-CLIQ-1 kV are valid protection solutions for $C > 50 \text{ mF}$

Assumptions: no QH; no EE; RRR=140; 10 ms detection time
CLIQ is a very good solution for the protection of superconducting magnets: efficient, low hot-spot temperature, robust, easy to repair, less failures

First CLIQ tests on the Nb$_3$Sn model magnet for the LHC high luminosity upgrade very successful

Optimization strategy for full-scale magnets clearly outlined

1. Select optimum CLIQ discharge circuit
2a. Increase CLIQ charging voltage
2b. Multiple CLIQ units (Multi-CLIQ)
3. Increase CLIQ capacitance

Simulations show that CLIQ is a valid solution for the protection of the full-scale quadrupole magnet for the LHC high luminosity upgrade (MQXF)

Next CLIQ test campaigns: 15 m LHC Main Dipole, Nb$_3$Sn quadrupole for LHC High-Luminosity Upgrade, LHC spare quadrupoles, 11 T dipole, Nb$_3$Sn solenoids from Oxford Instruments, ...?
QUESTIONS?

Ask me the CLIQ Recipe!

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References


E. Ravaioli et al., MT23, 2013.

E. Ravaioli et al., EUCAS11, 2013.


E. Ravaioli et al., Cryogenics, 2014.


E. Ravaioli et al., ICEC/ICMC, 2014.

E. Ravaioli et al., ASC, 2014.
Development of a CLIQ-based protection system for the full-scale quadrupole magnet for the LHC high luminosity upgrade

Preliminary Analysis and Simulations

CLIQ tests on the model magnet (HQ02b)

Validation of the simulation tools and further CLIQ optimization

Simulation of CLIQ-based protection the full-scale magnet (MQXF)

CLIQ tests on the model magnet (HQ03) with improved CLIQ config

Design of a CLIQ-based protection for MQXF (possible integration with Quench Heaters or Energy Extraction)

**Model magnet** (HQ02b)
- Nb$_3$Sn Quadrupole Magnet
- Magnetic Length: 0.8 m
- Self-inductance: 6.4 mH
- Nominal current: 14.6 kA

**Full-length magnet** (MQXF)
- Nb$_3$Sn Quadrupole Magnet
- Magnetic Length: 6.8 m
- Self-inductance: 70 mH
- Nominal current: 17.3 kA

**TODAY**
CLIQ – Coupling-Loss Induced Quench

Current Change

\[ I_c(t) \approx -U_0 \sqrt{\frac{C}{L_{eq}}} \cdot \sin \left( \frac{t}{\sqrt{L_{eq}C}} \right) \]

Magnetic Field Change

\[ I_{c,peak} \propto U_0 \sqrt{\frac{C}{L_{eq}}} \]

\[ \frac{dI_c(t)}{dt} \approx U_0 \sqrt{\frac{C}{L_{eq}}} \cdot \cos \left( \frac{t}{\sqrt{L_{eq}C}} \right) \]

Coupling-Losses (Heat)

\[ dB(t) = f_m \frac{dI_c(t)}{dt} \left[ 1 - \exp \left( -\frac{t}{\tau_{IF}} \right) \right] \]

\[ P_{IF} = \beta_{IF} \left[ \frac{dB(t)}{dt} \right]^2 \propto \left( \frac{U_0}{L_{eq}} \right)^2 \]

Temperature Rise

\[ \tau_{IF} = \frac{\mu_0}{2} \left( \frac{l_p}{2\pi} \right)^2 \frac{1}{\rho_{eff}(B)} \]

\[ \beta_{IF} = \left( \frac{l_p}{2\pi} \right)^2 \frac{1}{\rho_{eff}(B)} \]

**Principle:** When subjected to a magnetic field change, **coupling losses** occur in superconducting wires and cables. These losses are **heat** generated directly in the superconductor to quench!
With CLIQ connections at the joint between inner/outer layers

Golden rule for optimizing any CLIQ discharge circuit
Introduce opposite current change in coils which are physically adjacent

Existing magnets
Configurations easy to implement on most existing magnets

Future magnets
With connections between in/out layers

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2014 (Preview 1).
ASC 2014 presentation and paper 1LOr2B-01; 1st Prize in Best Student Paper Contest, Large Scale.
Advantages

- Heat generated directly in the superconductor to quench (not relying on thermal diffusion)
- Robust electrical design, easier implementation and repair
- Faster quench initiation
  - More homogeneous temperature distribution
  - Lower hot-spot temperature
- Lower failure risk
- Easy repair solution for a magnet with damaged quench heaters
- For the same price and size of conventional quench heater systems
- Possible to avoid the installation of quench heaters

Drawbacks

- Additional current lead(s) connected to the magnet (pulse current for <100 ms)
- High voltage introduced in the circuit
  - If applied to a magnet which is part of a chain, additional studies have to be carried out (how to implement, transient waves, avoid resonances, etc)
  - Integration with an energy-extraction system is possible but it needs to be carefully studied
- Additional mechanical stresses due to the introduced current need to be analyzed
<table>
<thead>
<tr>
<th>Issues</th>
<th>Possible Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integration with an energy-extraction system:</td>
<td>Delaying the triggering of the energy-extraction system to wait the damping of the</td>
</tr>
<tr>
<td>Avoid too high voltage to ground due to voltage superposition</td>
<td>CLIQ oscillation (30-100 ms?)</td>
</tr>
<tr>
<td>If “1 CLIQ” solution is chosen, high voltage to ground (up to 1 kV?)</td>
<td>Increasing insulation thickness would not decrease the CLIQ performance</td>
</tr>
<tr>
<td>If “Multi-CLIQ” solution is chosen, three current leads connected to</td>
<td></td>
</tr>
<tr>
<td>the magnet (pulsed current for t&lt;100 ms)</td>
<td></td>
</tr>
<tr>
<td>Redundancy</td>
<td>More then one trigger thyristor in parallel (2?)</td>
</tr>
<tr>
<td></td>
<td>More than one CLIQ unit connected in parallel (2?)</td>
</tr>
<tr>
<td>Use of CLIQ to protect a magnet which is part of a chain or of a</td>
<td>Use by-pass elements (pair of diodes or parallel resistor) to allow introducing an AC</td>
</tr>
<tr>
<td>nested circuit</td>
<td>current on a single magnet of the chain</td>
</tr>
<tr>
<td>Integration with Quench Heaters</td>
<td>No problem</td>
</tr>
</tbody>
</table>
The current introduced in the magnet coil generates a change in the local magnetic field. When a superconductor is subjected to an applied magnetic-field change, an induced magnetic field is generated which opposes to the applied field. For fast transients, the actual magnetic field does not change much, because the applied and induced magnetic field almost cancel out. The presence of the induced field generates currents between superconducting filaments and between superconducting strands. These currents flow through the copper matrix of the conductor, thus they generate loss (=heat) inside the cable.

For typical ranges of magnet inductance (5-100 mH) and CLIQ capacitance (5-50 mF), the range of the **CLIQ oscillation period is 10-100 ms** (frequency range 10-100 Hz)

### Inter-Filament Coupling Loss
For typical filament twist-pitch and Cu transverse resistivity, time constant in the order of tens of ms

- **High** energy deposition with CLIQ discharge

### Inter-Strand Coupling Loss
For typical strand twist-pitch and cross-contact resistance, time constant in the order of hundreds of ms / seconds

- **Limited** energy deposition with CLIQ discharge

### Magnetization Loss
Very limited change in the local magnetic field, hysteresis loops are small

- **Limited** energy deposition with CLIQ discharge
Optimum CLIQ discharge configuration – 1-CLIQ

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Ls</td>
<td>Mc</td>
<td>Mf</td>
<td>Mc</td>
</tr>
<tr>
<td>P2</td>
<td>Mc</td>
<td>Ls</td>
<td>Mc</td>
<td>Mf</td>
</tr>
<tr>
<td>P3</td>
<td>Mf</td>
<td>Mc</td>
<td>Ls</td>
<td>Mc</td>
</tr>
<tr>
<td>P4</td>
<td>Mc</td>
<td>Mf</td>
<td>Mc</td>
<td>Ls</td>
</tr>
</tbody>
</table>

Self and Mutual inductance of the 4 poles of a quadrupole magnet

\[ L_{mag} = 4L_s + 8M_c + 4M_f \]

8.4 mH

MQXC2

Ls > Mc

+1.6 mH

Mc > 0

+0.4 mH

Mf < 0

-0.2 mH

Ls Self inductance of one pole

Mc Mutual ind between close poles

Mf Mutual ind between front poles

Self and Mutual inductance of the 4 poles of a quadrupole magnet

\[ L_{eq} = L_s - M_f \]

1.8 mH

MQXC2

\[ L_{eq} = L_s - 2M_c + M_f \]

0.6 mH

MQXC2

3 times smaller
Multi-CLIQ – 2 CLIQ units, 4 CLIQ units, \(N_C\) CLIQ units...

\(L_{eq}\) can be reduced by further subdividing the electrical circuit into \(N_E\) elements, effectively in parallel when CLIQ is triggered. They can be **magnets** in a chain, **poles** of a magnet, or inner/outer **layers** of each pole.

Peak power deposition proportional to \(N_C^2\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1 CLIQ</th>
<th>1 CLIQ 2(U_0)</th>
<th>2 CLIQ</th>
<th>4 CLIQ</th>
<th>(N_C) CLIQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements, (N_E)</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>2 (N_C)</td>
</tr>
<tr>
<td>Equivalent inductance, (L_{eq})</td>
<td>(L_{eq})</td>
<td>(\div 4)</td>
<td>(\div 16)</td>
<td>(\div N_C^2)</td>
<td></td>
</tr>
<tr>
<td>Total capacitance, (C_{eq})</td>
<td>(C)</td>
<td>(\times 2)</td>
<td>(\times 4)</td>
<td>(\times N_C)</td>
<td></td>
</tr>
<tr>
<td>Charging voltage, (U_0)</td>
<td>(U_0)</td>
<td>(\times 2)</td>
<td>(\div)</td>
<td>(\div)</td>
<td>(\div)</td>
</tr>
<tr>
<td>Peak current change, (dI/dt)</td>
<td>(U_0/L_{eq}/N_E)</td>
<td>(\times 2)</td>
<td>(\times 2)</td>
<td>(\times 4)</td>
<td>(\times N_C)</td>
</tr>
<tr>
<td>Peak deposited loss</td>
<td>(\propto(U_0/L_{eq}/N_E)^2)</td>
<td>(\times 4)</td>
<td>(\times 4)</td>
<td>(\times 16)</td>
<td>(\times N_C^2)</td>
</tr>
<tr>
<td>Peak AC current, (I)</td>
<td>(\propto U_0 \sqrt{C_{eq}/L_{eq}}/N_E)</td>
<td>(\times 2)</td>
<td>(\times 2^{0.5})</td>
<td>(\times 2)</td>
<td>(\times N_C^{0.5})</td>
</tr>
<tr>
<td>Frequency, (f)</td>
<td>(1/2/\pi\sqrt{L_{eq} \times C_{eq}/N_E})</td>
<td>(\div)</td>
<td>(\times 2^{0.5})</td>
<td>(\times 2)</td>
<td>(\times N_C^{0.5})</td>
</tr>
</tbody>
</table>
Why do we need to delay the triggering of the extraction-system?

Avoid interference between CLIQ and EE system
- Avoid superposition of voltage across CLIQ and across EE resulting in voltage too high
- Avoid reducing CLIQ performance
Protecting a Full-Scale Nb3Sn Magnet with CLIQ, the New Coupling-Loss Induced Quench System

1 CLIQ Unit
$U_0=500 \text{ V}$
$C=28.2 \text{ mF}$

MQXC2

CLIQ protects the magnet at any current level