Quench protection performance measurements in the first MQXF magnet models

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MQXF powering and protection strategy

- High Luminosity LHC inner triplets
- 132.6 T/m gradient, 4.2/7.1 m long
- 16.5 kA, ~12 T in the conductor
- Nb$_3$Sn superconductor
- Quench protection is challenging

Quench protection system includes heaters and CLIQ to improve redundancy and effectiveness
Heaters

Strip heating

Heat transfer to coil

Temperature increase

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CLIQ (Coupling-Loss Induced Quench)
MQXF quench protection studies

<table>
<thead>
<tr>
<th>Studies</th>
<th>MQXFS1a-b-c (1.2 m short model)</th>
<th>MQXFS3a-b (1.2 m short model)</th>
<th>MQXFPFM1 (4.0 m mirror)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quench integral – oQH</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Quench integral – oQH+iQH</td>
<td>~</td>
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<tr>
<td>Quench integral – oQH+CLIQ</td>
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<tr>
<td>QH delays</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>QH min energy to quench</td>
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<tr>
<td>CLIQ studies</td>
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<td></td>
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<tr>
<td>EE discharge (quench-back)</td>
<td>✓</td>
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</tbody>
</table>

**Goal:** Verify that the baseline quench protection system parameters are suitable for quench protection performance
Outer layer heater delays

- High-field OL heaters: 9-11 ms at $I_{\text{nom}}$
- Low-field OL heaters: 14-19 ms at $I_{\text{nom}}$

Graph showing the heater delay in ms against the initial current in kA for different OL heaters.
Inner layer heater delays

Long-term reliability not yet demonstrated

IL heaters 8-20 ms at \( I_{\text{nom}} \)

![Graph showing heater delays vs. initial current](image)

- IL-H MQXFS1b
- IL-H MQXFS3ab
- IL-H MQXFPM1

- J. Muratore, P. Joshi (BNL)
- H. Bajas, S. Izquierdo Bermudez (CERN)
- G. Chlachidze, S. Stoynev (FNAL)
Heater minimum energy density to quench

OL heaters deposit enough energy to quench at current \( \geq 1.5 \, \text{kA} \)

IL heaters deposit enough energy to quench at current \( >3-5 \, \text{kA} \)

**Graph:**

- LF-OL-H MQXFS1
- LF-OL-H MQXFPM1
- HF-OL-H MQXFS1
- HF-OL-H MQXFPM1
- IL-H MQXFS1
- IL-H MQXFPM1
- MQXFA OL-H
- MQXFA IL-H
- MQXFB OL-H
- MQXFB IL-H

**Contributors:**

- G. Chlachidze, S. Stoynev (FNAL)
- J. Muratore, P. Joshi (BNL)

**Title:**

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### CLIQ studies – Energy to quench

#### Initial current

<table>
<thead>
<tr>
<th>Initial current</th>
<th>CLIQ capacitance [mF]</th>
<th>CLIQ charging voltage [V]</th>
<th>CLIQ stored energy [kJ]</th>
<th>CLIQ stored energy per unit length wrt 7m baseline</th>
<th>Quench</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3 kA</td>
<td>40</td>
<td>300</td>
<td>1.8</td>
<td>54%</td>
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<tr>
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<td>40</td>
<td>400</td>
<td>3.2</td>
<td>96%</td>
<td>X</td>
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<td>80</td>
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<td>300</td>
<td>3.6</td>
<td>108%</td>
<td>X</td>
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<tr>
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<td>80</td>
<td>400</td>
<td>6.4</td>
<td>192%</td>
<td>X</td>
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<td>40</td>
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<td>80</td>
<td>300</td>
<td>3.6</td>
<td>108%</td>
<td>X</td>
</tr>
</tbody>
</table>

G. Chlachidze, S. Stoynev (FNAL)
MQXFS1b – Two discharges at nominal current

![Graph showing magnet current vs. time after trigger](image-url)
Quench protection performance

**Calculated from triggering of quench protection system**

**Note!**
Heater performance are poorer than baseline
- Unavailability of some I-QH strips (4008)
- Hardware limitations
  limited power density

Quench load due to detection + validation time to be added
At nominal current ~4 MIIIt

**RRR**
MQXFS1ab: 250, 105, 255, 135
MQXFS3ab: 140, 140, 140, 170

H. Bajas, S. Izquierdo Bermudez (CERN)
G. Chlachidze, S. Stoynev (FNAL)
Comparison to LEDET simulation results

Possible causes for the faster experimental discharges

- strain-dependency of the Nb$_3$Sn critical current
- effect of the strand twist-pitch on the ohmic loss per unit length
- superconductor hysteretic loss (magnetization)
- temperature gradient within the conductor’s metal, epoxy, and insulation

H. Bajas, S. Izquierdo Bermudez (CERN)
G. Chlachidze, S. Stoynev (FNAL)
Conclusion & next steps

**Latest MQXF quench protection studies**

Two 1.2 m short model and one 4.0 m mirror magnets tested at FNAL, CERN, BNL.

With baseline quench protection parameters:

- **HF O-QH**: 9-11 ms delays at nominal current. Energy density sufficient to quench at 1.6 kA
- **LF O-QH**: 14-19 ms delays at nominal current. Energy density sufficient to quench at 1.6 kA
- **I-QH**: 8-20 ms delays at nominal current. Energy density sufficient to quench at ≥3-5 kA
- **CLIQ**: quench in <5 ms. Energy density sufficient to quench at ≥3 kA

→ Quench protection up to ultimate current successfully demonstrated
→ Baseline parameters offer satisfactory quench protection performance (fast quench initiation, redundancy, scalability, reproducibility)
→ Long-term reliability of inner QH not yet demonstrated (failures, detachment)

**Next MQXF quench protection studies**

New 1.2 m short models and 4.0 m prototype magnet to be tested at BNL, CERN, FNAL.

**Goal**: Define the baseline for the quench protection system after quench protection studies on the first 4 m prototype magnet

**Electro-magnetic and thermal modeling**

→ LEDET model needs to be refined to reproduce faster than expected CLIQ discharge

**Goal**: Implement the identified potential sources of inaccuracy and validate the new model
QUESTIONS?

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MQXF powering and protection circuit
LEDET (Lumped-Element Dynamic Electro-Thermal)

Validated on dipole (MB) and quadrupole (MQY, MQXC, HQ, MQXF) magnets
The interaction between the superconducting magnet and the local coupling currents is modeled with an array of RL dissipative loops mutually coupled with the magnet self-inductance.

All simulations presented today are performed with the **LEDET 2D model** (Lumped-Element Dynamic Electro-Thermal).

**Example:** HL-LHC 12 T Nb$_3$Sn quadrupole magnet (MQXF)
- 2x 16000 IFCL loops
- 400 ISCL loops