Quench protection
of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets

Emmanuele Ravaioli (CERN)

S. Izquierdo Bermudez, J.C. Perez, D. Tommasini, A. Verweij (CERN)

26 September 2019
The eRMC and RMM program at CERN

**eRMC**
Enhanced Racetrack Model Coil
16 T mid-plane field
- Demonstrate field on the conductor
- Coil technology development

**RMM**
Racetrack Model Magnet
16 T in a 50 mm cavity
- Demonstrate field on the aperture
- Mechanics (including inner coil support)

Base for the development of the technology needed for the 16 T dipole program

*Slide courtesy of S. Izquierdo Bermudez*

Quench protection of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019

### 2-D Magnet Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>ERMC</th>
<th>RMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed aperture diameter</td>
<td>mm</td>
<td>8</td>
<td>50</td>
</tr>
<tr>
<td>Aluminum shell thickness</td>
<td>mm</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Magnet outer diameter</td>
<td>mm</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Number of turns per quadrant</td>
<td>–</td>
<td>90</td>
<td>132</td>
</tr>
<tr>
<td>Nominal current $I_{nom}$</td>
<td>kA</td>
<td>13.13</td>
<td>11.40</td>
</tr>
<tr>
<td>Insulated cond. current density at $I_{nom}$</td>
<td>A/mm$^2$</td>
<td>282</td>
<td>245</td>
</tr>
</tbody>
</table>

- **Nominal bore field $B_{nom}$**: T 15.7 16.0
- **Coil peak field at $I_{nom}$**: T 16.00 16.15
- **Short sample current $I_{ss}$ at 4.2 K**: kA 14.38 12.66
- **Coil peak field at 4.2 K $I_{ss}$**: T 17.28 17.72
- **Short sample current $I_{ss}$ at 1.9 K**: kA 15.91 14.05
- **Coil peak field at 1.9 K $I_{ss}$**: T 18.90 19.39

- **Stored energy per unit length at $I_{nom}$**: MJ/m 1.5 2.1
- **Inductance per unit length at $I_{nom}$**: mH/m 16.6 31.1
- **$F_x$ per quadrant at $I_{nom}$**: MN/m 5.86 8.03
- **$F_y$ per quadrant at $I_{nom}$**: MN/m $-3.34$ $-4.05$
Focus of today’s presentation

Design of the quench protection systems for full-scale [14.3 m] eRMC and RMM magnets

Main features:
→ CLIQ technology
→ Multi-physics analysis with STEAM-LEDET
→ Analysis of transients at all current levels
Quench protection of the 16 T Nb₃Sn ERMC and RMM dipole magnets

Quench protection based on CLIQ

Modelling with STEAM-LEDET

eRMC magnet quench protection

RMM magnet quench protection
CLIQ (Coupling-Loss Induced Quench) technology

Main CLIQ ingredients
- **Connection** scheme
- Capacitance $C$
- Charging voltage $U_0$

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Quench protection of the 16 T $\text{Nb}_3\text{Sn}$ ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019

Inter-filament coupling loss

"Fast" loss:
Characteristic time constant in the order of \( ms \) or tens of \( ms \)

Deposited power density roughly proportional to \( (dB/dt)^2 \)
**CLIQ advantages & disadvantages with respect to conventional technology**

<table>
<thead>
<tr>
<th><strong>Advantages</strong></th>
<th><strong>Disadvantages</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>More <strong>effective</strong> energy deposition</td>
<td><strong>Integration</strong> in the magnet circuit to be studied</td>
</tr>
<tr>
<td><strong>Faster</strong> and more <strong>homogeneous</strong> quench initiation</td>
<td><strong>Internal voltage distribution</strong> to be carefully analyzed</td>
</tr>
<tr>
<td><strong>More robust</strong> electrical design</td>
<td><strong>Redundancy</strong> of the system</td>
</tr>
<tr>
<td><strong>Easier</strong> to implement and repair</td>
<td><strong>Lower expected failure rate</strong></td>
</tr>
<tr>
<td>Lower expected <strong>failure rate</strong></td>
<td><strong>Integration</strong> in the magnet circuit to be studied</td>
</tr>
</tbody>
</table>

Quench protection of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019
## CLIQ technology tests

<table>
<thead>
<tr>
<th>Name</th>
<th>Where</th>
<th>Year</th>
<th>Geometry</th>
<th>Superconductor</th>
<th>Stored energy [MJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small-scale solenoid</td>
<td>CERN</td>
<td>2013</td>
<td>Solenoid</td>
<td>Nb-Ti</td>
<td>0.04</td>
</tr>
<tr>
<td>Solenoid system</td>
<td>Private</td>
<td>2014</td>
<td>Solenoid</td>
<td>Nb$_3$Sn</td>
<td>-</td>
</tr>
<tr>
<td>MQXC2</td>
<td>CERN</td>
<td>2014</td>
<td>Quadrupole</td>
<td>Nb-Ti</td>
<td>1.10</td>
</tr>
<tr>
<td>HQ</td>
<td>CERN</td>
<td>2014</td>
<td>Quadrupole</td>
<td>Nb$_3$Sn</td>
<td>0.60</td>
</tr>
<tr>
<td>MQY</td>
<td>CERN</td>
<td>2015</td>
<td>Twin-aperture quadrupole</td>
<td>Nb-Ti</td>
<td>0.96</td>
</tr>
<tr>
<td>MB</td>
<td>CERN</td>
<td>2015</td>
<td>Twin-aperture dipole</td>
<td>Nb-Ti</td>
<td>6.88</td>
</tr>
<tr>
<td>MQXF</td>
<td>FNAL</td>
<td>2016-2019</td>
<td>Quadrupole</td>
<td>Nb$_3$Sn</td>
<td>1.46</td>
</tr>
<tr>
<td>→Baseline for HL-LHC inner triplet magnets</td>
<td>CERN</td>
<td>2017-2019</td>
<td>Quadrupole</td>
<td>Nb$_3$Sn</td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>BNL</td>
<td>2018-2019</td>
<td>Quadrupole</td>
<td>Nb$_3$Sn</td>
<td>4.91</td>
</tr>
<tr>
<td>11T dipole</td>
<td>CERN</td>
<td>2017</td>
<td>Twin-aperture dipole</td>
<td>Nb3Sn</td>
<td>1.94</td>
</tr>
<tr>
<td>PUP4</td>
<td>NHMFL</td>
<td>2017</td>
<td>Solenoid</td>
<td>Bi-2212</td>
<td>0.3E-3</td>
</tr>
</tbody>
</table>

...and more in the pipeline

CLIQ was tested in 7 different test facilities on **more than 15 magnets** with different superconductor types (Nb-Ti, Nb$_3$Sn, Bi-2212), geometries, and magnet sizes
Quench protection of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets

- Quench protection based on CLIQ
- Modelling with STEAM-LEDET
- eRMC magnet quench protection
- RMM magnet quench protection
LEDET in a nutshell

Tool to simulate electro-magnetic and thermal transients in superconducting magnets.

- 2D magnet model + simplified electrical circuit
- Magnetic field maps and inductance dependence on iron yoke saturation calculated externally (usually with ROXIE)
- **Inter-filament and inter-strand coupling currents included**
- Turn-to-turn heat exchange, simplified helium cooling included
- Energy-extraction, quench heaters, CLIQ transients simulated
- Comes as a .exe file. A typical simulation runs in ~2 minutes.

Key feature for CLIQ simulations

https://cern.ch/steam

Framework to simulate transient effects in superconducting magnets and circuits


Application and tutorial freely available!
→More info: https://cern.ch/steam/ledet
LEDET validation and current studies

<table>
<thead>
<tr>
<th>Project</th>
<th>Magnet</th>
<th>Notes</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>MQXA</td>
<td>Helium, Heaters</td>
<td>Partial</td>
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<tr>
<td>LHC</td>
<td>MQXB</td>
<td>Helium, Heaters</td>
<td>Partial</td>
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<tr>
<td>LHC</td>
<td>MQ</td>
<td>Helium, Heaters, initial hot-spot</td>
<td>Yes</td>
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<tr>
<td>LHC</td>
<td>MQY</td>
<td>Helium, Heaters, initial hot-spot</td>
<td>Started</td>
</tr>
<tr>
<td>LHC</td>
<td>MCBY</td>
<td>Helium, Self-protection</td>
<td>Started</td>
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<tr>
<td>HL-LHC</td>
<td>MQXF</td>
<td>Quench protection design</td>
<td>Yes</td>
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<tr>
<td>HL-LHC</td>
<td>11 T dipole</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>FCC</td>
<td>Cos-θ</td>
<td>Quench protection design</td>
<td>No data available</td>
</tr>
<tr>
<td>FCC</td>
<td>Block-coil</td>
<td>Quench protection design</td>
<td>No data available</td>
</tr>
<tr>
<td>FCC</td>
<td>Common-coil</td>
<td>Quench protection design</td>
<td>No data available</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Project</th>
<th>Magnet</th>
<th>Notes</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other</td>
<td>FECR sextupole</td>
<td>Sextupole</td>
<td>No data available</td>
</tr>
<tr>
<td>Other</td>
<td>FECR solenoids</td>
<td>Solenoids</td>
<td>No data available</td>
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<tr>
<td>Other</td>
<td>eRMC / RMM</td>
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<tr>
<td>Other</td>
<td>HEPdipo</td>
<td>Block-coil</td>
<td>No data available</td>
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<tr>
<td>Other</td>
<td>HD3</td>
<td>Block-coil</td>
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<tr>
<td>Other</td>
<td>16T common-coil</td>
<td>Insert/Outsert</td>
<td>No data available</td>
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<tr>
<td>Other</td>
<td>PYPUP magnets</td>
<td>Bi-2212, Solenoids</td>
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<tr>
<td>Other</td>
<td>RC series</td>
<td>Bi-2212, Current-sharing</td>
<td>Partial</td>
</tr>
<tr>
<td>Other</td>
<td>LBL common-coil</td>
<td>Bi-2212, Current-sharing</td>
<td>No data available</td>
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<tr>
<td>Other</td>
<td>15 T dipole</td>
<td></td>
<td>No data available</td>
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<tr>
<td>Other</td>
<td>***</td>
<td>New quench protection ideas</td>
<td>No data available</td>
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</table>

LEDET was used to simulate transients in more than 25 magnets with different superconductor types, geometries, quench protection systems

At MT26:
Mon-Mo-Po1.03-07
Mon-Af-Po1.16-04
Thu-Mo-Po4.02-03
Wed-Af-Or13-03
LEDET current studies – The “zoo”
LEDET simulations workflow

- Magnetic model (ROXIE)
- Semi-automatic model generation
- Input file is an excel file + .exe file
- Simulations are run in a batch
- Output as txt files, figures, animated GIFs, pdf report,...
Quench protection of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets

- Quench protection based on CLIQ
- Modelling with STEAM-LEDET
- eRMC magnet quench protection
- RMM magnet quench protection
Above ~20% of nominal current, active protection is needed

Magnet self-protected for currents ≤3 kA
Assumed $v_Q=2.5$ m/s
eRMC – CLIQ connection scheme (per aperture)

Normal operation DC current polarities and magnetic field

Upper pole

Lower pole

Simplified CLIQ circuit

CLIQ-induced oscillating current polarities and magnetic field
Quench protection of the 16 T Nb₃Sn ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019

eRMC – Generation of inter-filament coupling loss

Oscillating current polarities and magnetic field

Peak inter-filament coupling loss (heat)
In first approximation:

- Peak current $\propto U_0$
- Current rate $\propto U_0$
- Power $\propto U_0^2$
- Energy $\propto U_0^2$
- Frequency $\sim$
In first approximation:

- Peak current $\propto C^{0.5}$
- Current rate $\sim$
- Power $\sim$
- Energy $\propto C$
- Frequency $\propto 1/C^{0.5}$
Quench protection of the 16 T Nb₃Sn ERMC and RMM dipole magnets – E. Ravaïoli – 26 September 2019
At nominal current, hot-spot temperature maintained in a comfortable range of 250 to 300 K
Quench protection of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019

eRMC – Quench protection at $I=50\%\; I_{\text{nom}} = 6.56$ kA

At mid-range current, sufficient energy to quench large coil sections must be provided ($\text{C} \uparrow$)
At low current, even more energy must be provided ($C^\uparrow$)
eRMC – Quench protection summary

Selected configuration
C=60 mF  $U_0=1.5$ kV

Induces quench at all current levels
eRMC – Quench protection at $I_{\text{nom}}$ – Reference quench protection

**Currents in the system**

**Voltage to ground distribution and hot-spot temperature**
Quench protection of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019
Quench protection of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets

- Quench protection based on CLIQ
- Modelling with STEAM-LEDET
- eRMC magnet quench protection

RMM magnet quench protection
Above ~20% of nominal current, active protection is needed.
RMM – CLIQ connection scheme (per aperture)

Normal operation **DC** current polarities and magnetic field

Middle pancake

Simplified CLIQ circuit

CLIQ-induced **oscillating** current polarities and magnetic field

Quench protection of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019
RMM – Generation of inter-filament coupling loss

Oscillating current polarities and magnetic field

Peak inter-filament coupling loss (heat)

Quench protection of the 16 T Nb₃Sn ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019
RMM – Quench protection at $I_{\text{nom}}$ – Effect of CLIQ voltage $U_0$

In first approximation:

- Peak current $\propto U_0$
- Current rate $\propto U_0$
- Power $\propto U_0^2$
- Energy $\propto U_0^2$
- Frequency $\sim$
In first approximation:

- Peak current $\propto C^{0.5}$
- Current rate $\sim$
- Power $\sim$
- Energy $\propto C$
- Frequency $\propto 1/C^{0.5}$
RMM – Quench protection at $I_{\text{nom}}$ – Effect of $U_0$ and C

Selected configuration

$C=80 \text{ mF} \quad U_0=1.5 \text{ kV}$
At nominal current, hot-spot temperature maintained in a comfortable range of 250 to 300 K
At mid-range current, sufficient energy to quench large coil sections must be provided (C↑)
At low current, **even more energy** must be provided (C↑).
Selected configuration

\[ C = 80 \text{ mF} \quad U_0 = 1.5 \text{ kV} \]

Induces quench at all current levels
RMM – Quench protection at $I_{\text{nom}}$ – Reference

**Currents in the system**

**Voltage to ground distribution and hot-spot temperature**
RMM – Quench protection at $I_{\text{nom}}$ – Reference
Conclusion

Quench protection of two 16 T Nb$_3$Sn dipole magnets analyzed → All simulations performed with STEAM-LEDET

Proposed solution is based on CLIQ (Coupling-Loss Induced Quench) → CLIQ connection optimized for both magnets → CLIQ unit capacitance and charging voltage selected for both magnets → Solution will be tested in the coming month on a short magnet

With the proposed quench protection system → Hot-spot temperature <250 K at nominal current → Peak voltage to ground <1500 V at nominal current → Magnets protected at all current levels, with margin

Don’t forget to analyze the mid-current range!...
QUESTIONS?

Emmanuele Ravaioli (CERN)
S. Izquierdo Bermudez, J.C. Perez, D. Tommasini, A. Verweij (CERN)

Acknowledgments
N. Bourcey, A. Carlon Zurita, R. De Paz Ludena, C. Fernandes, P. Ferracin,
S. Ferradas Troitino, M. F. Garcia Perez, J. Massard, D. Martins Araujo,
Annex
Energy exchanges in multiphysics models

Electro-thermal models

LEDET

Quench protection of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019
In this analysis: $I_{\text{nom}}=13.13$ kA
In this analysis: \( I_{\text{nom}} = 12.10 \, \text{kA} \)
Quench protection of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019
eRMC – Quench protection at I=4 kA

![Graph showing quench protection for 16 T Nb$_3$Sn ERMC and RMM dipole magnets. The graph plots time, $t$ [s], against current, $I$ [kA], and hot-spot temperature, $T_{hot}$ [K]. Different curves represent various protection schemes, such as CLIQ - 40 mF, 1000 V, CLIQ - 60 mF, 1200 V, CLIQ - 40 mF, 1500 V, and CLIQ - 60 mF, 1500 V.](image)
eRMC – Quench protection at I=3 kA

![Graph showing quench protection at I=3 kA](image)

- No protection
- CLIQ - 40 mF, 1000 V
- CLIQ - 60 mF, 1200 V
- CLIQ - 40 mF, 1500 V
- CLIQ - 60 mF, 1500 V

Quench protection of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019
Quench protection of the 16 T $\text{Nb}_3\text{Sn}$ ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019

**eRMC – Reference quench protection system – $C=60 \text{ mF}, U_0=1.5 \text{ kV}$**

- $C=60 \text{ mF}$, $U_0=1.5 \text{ kV}$

![Graph showing the quench protection system with time, temperature, and current for different currents.](

The graph illustrates the behavior of currents and hot-spot temperatures over time for various currents, demonstrating the quench protection system's effectiveness in managing thermal stresses and preventing damages under the given conditions.
Quench protection of the 16 T Nb$_3$Sn ERMC and RMM dipole magnets – E. Ravaioli – 26 September 2019

C=60 mF, $U_0=1.5$ kV
RMM – Quench protection at $I=75\% \ I_{\text{nom}} = 8.66$ kA
RMM – Quench protection at I=4 kA
RMM – Ref quench protection system – C=80 mF, $U_0=1.5$ kV
RMM – Reference quench protection system – Zoom out

C=80 mF, $U_0=1.5$ kV
RMM – Quench protection at $I_{\text{nom}}$ – Reference
RMM – Self-protectability – I=2 kA
RMM – Effect of quench propagation velocity – I=2 kA

![Graph showing quench propagation velocity vs. hot-spot temperature for different conditions.](image-url)

- **I_0=2.0 kA - No protection**
- **I_0=2.0 kA - CLIQ - 60 mF, 1500 V**
- **I_0=2.0 kA - CLIQ - 80 mF, 1500 V**
- **I_0=2.0 kA - CLIQ - 100 mF, 1500 V**