16 T dipole magnet quench protection

Tiina Salmi and Marco Prioli with the EuroCirCol WP5 members and support from the STEAM team at CERN TE-MPE-PE

FCC week 2019, Brussels, 27th June 2019
EuroCirCol 16 T dipole designs*

<table>
<thead>
<tr>
<th>Magnet, version</th>
<th>Cosθ, 22b_38_v1</th>
<th>Block, V2ari204</th>
<th>Common coil, vh12_2ac6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inom (A)</td>
<td>11390</td>
<td>10111</td>
<td>16400</td>
</tr>
<tr>
<td>Ld,nom (mH/m)</td>
<td>2 x 19.8</td>
<td>2 x 24.8</td>
<td>21.1</td>
</tr>
<tr>
<td>Cable</td>
<td>HF-cable</td>
<td>HF-cable</td>
<td>HF-cable</td>
</tr>
<tr>
<td></td>
<td>LF-cable</td>
<td>LF-cable</td>
<td>LF-cable</td>
</tr>
<tr>
<td>Cable w x t (bare) (mm)</td>
<td>13.2 x 1.95</td>
<td>14.0 x 1.265</td>
<td>12.6 x 2.0</td>
</tr>
<tr>
<td>Number of strands</td>
<td>22</td>
<td>38</td>
<td>21</td>
</tr>
<tr>
<td>Strand diam. (mm)</td>
<td>1.1</td>
<td>0.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Cu/SC</td>
<td>0.82</td>
<td>2.1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Cable ins. : 0.15 mm, RRR = 100, filament twist = 14 mm, strand twist= 15°

Jc with Bordini fit: $T_{c0} = 16$ K, $B_{c20} = 29.38$ T, $\alpha = 0.96$, $C_0 = 267845$ A/mm$^2$T
Outline

1. Ensuring magnet protectability

2. Simulation tools

3. Conceptual quench protection schemes:
   - CLIQ - Coupling Loss Induced Quench
   - QH - Quench heaters

4. Simulated temperatures and voltages after quench
   - Comparison of CLIQ and QH

5. Conclusions

*Stored energy density in dipoles vs. peak field, by courtesy of L. Bottura and D. Schoerling*
1. Ensuring magnet protectability

- Protetability with a real quench protection system (CLIQ or QH)
- Safe limit of temperature and voltages: **350 K, 2.5 kV** in circuit, **1.2 kV** in single magnet
- **A simplified quench analysis for fast-feedback – The EuroCirCol protectability criterion**
  - Assume a protection system quenches the entire magnet 40 ms after initial quench
  - **20 ms det + 20 ms QH/CLIQ**
  - At 105% of Inom

Related publications within this project


Relevant literature / previous works

E. Todesco, Proc. WAMSDO 2013
G. Amborsio, Proc. WAMSDO 2013
2. Simulation tools

What did we simulate?

• Initial quench and 20 ms detection time with constant current (incl. validation time etc.)
• Coil heating and evolution of normal zones after protection activation (IFCC of CLIQ, or heat from heaters)
• Coil temperature and resistance increase current decay
• Post-process for voltage distribution

Magnet powering circuit in accelerator

Analysis of MIITs separately before and after quench detection
How did we simulate?

• Initial analysis with 40 ms uniform quench delay:
  • 0 D thermal

• CLIQ design
  • Analytical equations for IFCC
  • Thermal diffusion between turns

• QH design
  • 2D heat transfer model for heater delay
  • Adiabatic thermal based on heater delays and given NZPVs

• Internal voltages with a circuit model

• Profit from tools already used in magnet design for magnetic field, inductance and mechanical modeling

More details and references in appendix!

STEAM: Website: https://espace.cern.ch/steam
Model validation

- LEDET and CoHDA previously validated with HL-LHC model magnets
- Coodi validated during the time of project
  - Helped to adjust cable simulation method
- Validations mainly are comparison of current decays

Three different cases on cable modeling assumptions.

Case A: Round strands & straight current path

Case B: Elliptical strands & straight current path

15 deg pitch angle

Case C: Current in round twisted strands, elliptical strands in for material fractions

15 deg pitch angle

Best match with experimental data

To be presented at MT26, 2019
3. Conceptual quench protection schemes

CLIQ – Coupling-Loss Induced Quench

- Discharge capacitor bank across part of the winding
  - Oscillations of transport current
  - Coupling losses in strands → Quench

New technology with advantages:
- Connections external to the magnet → Accessible

CLIQ leads in the 15 m long LHC main dipole (Aug 2015), Photo by courtesy of E. Ravaioli
Design of CLIQ-based protection: $\cos \theta$

Connection of CLIQ units and the charging voltage and capacitance

Resulting current oscillations

M. Prioli et al., "The CLIQ quench protection system applied to the 16 T FCC-hh dipole magnets", IEEE TAS (under review)

(Example case at 105% Inom)
Design of CLIQ-based protection: \( \text{Cos} \theta \)

Voltage distribution 120 ms after CLIQ activation

Max. voltage to ground 800 V

Final temperature distribution after CLIQ activation

Worst-case \( T_{\text{hotspot}} \) with 20 ms \( t_{\text{det}} \): 286 K

Mechanical stress after quench and protection in part of the circuit, see:

M. Prioli et al., ”The CLIQ quench protection system applied to the 16 T FCC-hh dipole magnets”, IEEE TAS (under review)

M. Prioli et al., ”Conceptual design of the FCC-hh dipole circuits with integrated CLIQ protection system”, IEEE TAS (accepted for publication)
**CLIQ1:** $V_0=0.6 \, \text{kV}$, $C=50 \, \text{mF}$

**CLIQ2:** $V_0=1.2 \, \text{kV}$, $C=50 \, \text{mF}$

**CLIQ1,2:** $V_0=0.9 \, \text{kV}$, $C=80 \, \text{mF}$

**COMSOL simulation by M. Prioli:**

Hot-spot temperature 286 K
Max. voltage to ground 0.7 kV

Hot-spot temperature 284 K
Max. voltage to ground 1.1 kV
QH – Quench heaters

• Similar technology than in LHC and HL-LHC:
  • Cu-plated stainless steel strips:
    • SS thickn. 25 µm, Cu thickn. 10 µm
  • Insulation to coil: 75 µm polyimide

• Powering with capacitor bank discharge:
  • Heater Firing Unit (HFU): **1.2 kV and 10 mF**
    (LHC: 900 V and 7 mF)
  • 1 Ω for wires etc. / circuit

P. Ferracin et al, "Development of MQXF, the Nb3Sn Low-β Quadrupole for the HiLumi LHC ", *IEEE TAS*, 26(4), 2016.
Locations of heater strips

Strip geometry and powering

<table>
<thead>
<tr>
<th>Block</th>
<th>Common-coil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cosθ</td>
</tr>
<tr>
<td></td>
<td>QH2-3</td>
</tr>
<tr>
<td>w_{strips} (cm)</td>
<td>1</td>
</tr>
<tr>
<td>P_{QH,t=0} (W/cm^2)</td>
<td>100</td>
</tr>
<tr>
<td>\tau_{RC} (ms)</td>
<td>40</td>
</tr>
</tbody>
</table>

4. Simulated peak temperatures and voltages

**Operation at nominal current**

<table>
<thead>
<tr>
<th></th>
<th>$T_{\text{Hotspot}}$ (K) with 20 ms detection time</th>
<th>$V_{\text{gnd}}$ (V)</th>
<th>$N_{\text{Units/magnet}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CLIQ</td>
<td>QH</td>
<td>CLIQ</td>
</tr>
<tr>
<td>Cos(\theta)</td>
<td>286</td>
<td>322</td>
<td>800</td>
</tr>
<tr>
<td>Block</td>
<td>281</td>
<td>321</td>
<td>730</td>
</tr>
<tr>
<td>C-c</td>
<td>284</td>
<td>330</td>
<td>1100</td>
</tr>
</tbody>
</table>

Magnets can be protected with both systems

40±5 K lower temperature with CLIQ

Voltages quite similar

Simpler system with CLIQ

CLIQ was selected as a baseline, heaters a back-up option
Conclusion

• Quench protection integrated in the magnet em-design to ensure protectable magnets
  • 40 ms/350 K criteria

• Several simulation tools developed for the fast-feedback during initial design, and for the detailed protection designs

• Protection with CLIQ feasible for all magnet options
  • Max temperatures below 300 K at nominal current
  • Internal voltages below 1200 V
  • Protection with heaters is considered a back-up option

• Experiments with the demo magnets needed to validate the simulation results and adjust designs

• Success is thanks to successful collaboration and communication between the magnet design teams in INFN, CEA and CIEMAT and quench protection teams at TAU and CERN, and project coordination → A winning team!

Thank you!
Simulation tools and assumptions 1/2

Common assumptions in all simulations:
• Adiab. Hotspot temperature
• Current decay simulated in 2-D, discretized at turn level
• Material properties based on NIST libraries
• Material properties based on cable average magnetic field
• Tcs for quench computed based on the cable peak field
• Hotspot computed for the worst case cable
• 20 ms detection delay

• "40 ms delay":
  • Coodi: Adiabatic model for current decay, temperature, and voltage computation (no heat diffusion between turns)
    • Quench time and propagation for each turn is an input
    • No AC (interfilament coupling loss)
    • Current follows the strand path after quench

Simulation tools and assumptions 2/2

- **CLIQ studies:**
  - LEDET: Lumped element model for interfilament coupling loss after CLIQ activation
    - Current decay, temperature and voltage evolution
  - Co-simulation used to couple with PSPICE for asymmetric multi-CLIQ simulations
  - COMSOL: FEM for electrothermal behaviour after CLIQ discharge
  - Heat diffusion between turns accounted
  - E. Ravaioli, PhD Thesis

- **Heater based protection:**
  - CoHDA: 2-D heat diffusion model for heater delays
    - Accounts for the heater station length
    - Quench when cable maximum temperature reaches Tcs
  - Coodi: Current decay when heater delay and quench propagation velocity are input for each turn
    - Quench propagation: 18 m/s btw heating stations, 11 ms btw turns, 20 ms btw layers at nominal current