Protection of FCC 16 T dipoles

Tiina Salmi (TUT), Marco Prioli (CERN), Emmanuele Ravaioli (LBNL), Antti Stenvall (TUT), Bernhard Auchmann (CERN), Arjan Verweij (CERN), Janne Ruuskanen (TUT), together with all the EuroCirCol WP5 members

FCC week 2017, Berlin
Outline

• 16 T dipole design options in EuroCirCol WP5

• Integration of quench protection into the magnet design

• Protection with quench heaters

• Protection with CLIQ (Block)

• Protection with and CLIQ+heaters (Block)

• Conclusions
Magnet designs

All 14.3 long
Cosθ and Block 1-ap. versions

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Block, V20ar</th>
<th>Cosθ, 22b-37-optd7f8</th>
<th>CommonCoil, vh12_2ac6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inom / 105% Inom (A)</td>
<td>11470 / 12040</td>
<td>11240 / 11800</td>
<td>16400 / 17220</td>
</tr>
<tr>
<td>Ld,nom (mH/m)</td>
<td>17.57</td>
<td>18.4</td>
<td>21.1 (2-ap.)</td>
</tr>
<tr>
<td>Cable</td>
<td>HF-cable</td>
<td>LF-cable</td>
<td>HF-cable</td>
</tr>
<tr>
<td>Cable w x t (bare) (mm)</td>
<td>13.05 x 2.1</td>
<td>13.05 x 1.25</td>
<td>13.2 x 1.950</td>
</tr>
<tr>
<td>Number of strands</td>
<td>21</td>
<td>35</td>
<td>22</td>
</tr>
<tr>
<td>Strand diam. (mm)</td>
<td>1.155</td>
<td>0.705</td>
<td>1.1</td>
</tr>
<tr>
<td>Cu/SC</td>
<td>0.8</td>
<td>2.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Cable ins. (mm)</td>
<td></td>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td>RRR</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fil. twist (mm)</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jc-fit</td>
<td>From B. Bordini with Tc0 = 16 K, Bc20 = 29.38 T, α = 0.96, C0 = 267845 A/mm²T</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Quench protection integrated in magnet design

• After a quench, the magnet must absorb its stored energy
  1. Quench detection
  2. Switch off magnet current and activate quench protection (QP) system
     • Quenching magnet by-passed with a diode
→ The QP system (heaters or CLIQ) quench the entire magnet → Rapid current discharge

• EuroCirCol WP5: Requirement for quench protection set as a design criterion
  • If quench at 105% of $I_{\text{nom}}$, temperatures must be < 350 K and voltages < 1200 V
     • Assuming 20 ms detection time, and QP system quenching the entire coil in 20 ms
  • Fast-feedback quench simulation tools for magnet design adjustments

• Significant impact on conductor quantity and technology:
  • $\text{Prot. delay and } T_{\text{max}}$ → Minimum copper in cable → Coil size
  • $V_{\text{max}}$ → Maximum inductance / minimum current → Cable size / number of turns
Temperature and voltage after the 20+20=40 ms delay

- Assuming that every coil-turn quenches 40 ms after initial quench
- Adiabatic computation with Coodi (Computation of current decay based on known protection delays)

Cos\(\theta\): 22b-37-optd7f8

Block: V20ar

Common-coil: Vh12_2ac6
Temperature and voltage after a 20 + 0 ms delay

- Lower limit to temperatures that can be obtained with real protection system

$\text{Cos}\theta: 22b-37-optd7f8$

Block: V20ar

Common-coil: Vh12_2ac6
Design of quench heaters

- Heater technology similar than in LHC and HL-LHC:
  - Cu-plated stainless steel strips:
    - SS thickness 25 µm, Cu thickness 10 µm
    - Insulation to coil: 75 µm polyimide

- Powering with capacitor bank discharge:
  - 1000 V and 10 mF (LHC: 900 V and 7 mF)

- Analysis at 105% of $I_{nom}$
- The heaters must protect also at low current (1000 A)
Simulation software and assumptions

**CoHDA**

- Calculation of heater delay
- 2-D model for one coil turn, longitudinally
- Heat generation in heater and diffusion to cable

**Coodi**

- Calculation of coil temperatures and voltages during quench
- Adiabatic
- Inputs:
  - Magnetic field (from ROXIE)
  - Turn mutual inductances
  - Heater delays (from Cohda)
  - Detection time (20 ms at 105% Inom)
  - Quench propagation (20 m/s longit., and 10 ms turn-to-turn at at 105%

  \( (\text{Quench propag. and det. time scaled } \propto I_{mag}^2) \)

**Benchmark**

- Simulation of MQXFS03 current decay: Conservative w.r.t. experiment

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**Figure:**

- Coodi, with all heaters
- Coodi, with 2 heaters failed
- Measurement (with 2 heaters failed)

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Thanks to S. Izquierdo Bermudez and H. Bajas for exp. data
Quench protection with heaters: Block

Location of heater strips:

Simulated delays in every turn:
(heater delay + 20 ms det. delay):

Heater geometry and powering circuits:

<table>
<thead>
<tr>
<th>Circuit</th>
<th>QH Strips</th>
<th>Strip width (cm)</th>
<th>HS / period (cm)</th>
<th>$P_{QH}(0)$ (W/cm²)</th>
<th>$\tau_{RC}$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFU#1</td>
<td>1A</td>
<td>1.6</td>
<td>5 / 25</td>
<td>120</td>
<td>80</td>
</tr>
<tr>
<td>HFU#2</td>
<td>2A</td>
<td>1.6</td>
<td>5 / 25</td>
<td>120</td>
<td>80</td>
</tr>
<tr>
<td>HFU#3</td>
<td>1B</td>
<td>1.6</td>
<td>7 / 40</td>
<td>150</td>
<td>72</td>
</tr>
<tr>
<td>HFU#4</td>
<td>2B</td>
<td>1.6</td>
<td>7 / 40</td>
<td>150</td>
<td>72</td>
</tr>
<tr>
<td>HFU#5</td>
<td>(3A)</td>
<td></td>
<td>(3B)</td>
<td>2.3</td>
<td>7 / 40</td>
</tr>
<tr>
<td>HFU#6</td>
<td>(4A)</td>
<td></td>
<td>(4B)</td>
<td>2.3</td>
<td>7 / 40</td>
</tr>
</tbody>
</table>

Result of quench simulation:

$T_{\text{max}} = 350$ K, $V_{\text{gnd}} = 960$ V

Each strip is 14.3 m and always connected in series with identical strip
In heater power is assumed strip resistance + 1 Ohm margin for wires, etc.
Quench protection with heaters: $\cos \theta$

**Location of heater strips:**

**Simulated delays in every turn:** (heater delay + 20 ms det. delay):

**Heater geometry and powering circuits:**

<table>
<thead>
<tr>
<th>Circuit</th>
<th>QH Strips</th>
<th>Strip width (cm)</th>
<th>HS / period (cm)</th>
<th>$P_{QH}(0)$ (W/cm$^2$)</th>
<th>$\tau_{RC}$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFU#1</td>
<td>1B</td>
<td></td>
<td>1A</td>
<td></td>
<td>2A</td>
</tr>
<tr>
<td>HFU#2</td>
<td>2C</td>
<td></td>
<td>3A</td>
<td></td>
<td>3B</td>
</tr>
<tr>
<td>HFU#3</td>
<td>4A</td>
<td></td>
<td>4B</td>
<td>1.4</td>
<td>7 / 40</td>
</tr>
<tr>
<td>HFU#4</td>
<td>4C</td>
<td></td>
<td>4D</td>
<td>1.4</td>
<td>7 / 40</td>
</tr>
</tbody>
</table>

Each strip is 14.3 m and always connected in series with identical strip.
In heater power is assumed strip resistance + 1 Ohm margin for wires, etc.

$T_{\text{max}} = 340$ K, $V_{\text{gnd}} = 1010$ V
Quench protection with heaters: Common coil

Location of heater strips:

Simulated delays in every turn:
(heater delay + 20 ms det. delay):

Heater geometry and powering circuits:

<table>
<thead>
<tr>
<th>Circuit</th>
<th>QH Strips</th>
<th>Strip width (cm)</th>
<th>HS / period (cm)</th>
<th>$P_{QH}(0)$ (W/cm$^2$)</th>
<th>$\tau_{RC}$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFU#1</td>
<td>4A</td>
<td></td>
<td>4B</td>
<td>1.75</td>
<td>6 / 40</td>
</tr>
<tr>
<td>HFU#2</td>
<td>4C</td>
<td></td>
<td>4D</td>
<td>1.75</td>
<td>6 / 40</td>
</tr>
<tr>
<td>HFU#3</td>
<td>3A</td>
<td></td>
<td>3B</td>
<td>1.75</td>
<td>6 / 40</td>
</tr>
<tr>
<td>HFU#4</td>
<td>3C</td>
<td></td>
<td>3D</td>
<td>1.75</td>
<td>6 / 40</td>
</tr>
<tr>
<td>HFU#5</td>
<td>2A</td>
<td></td>
<td>2B</td>
<td>1.75</td>
<td>6 / 40</td>
</tr>
<tr>
<td>HFU#6</td>
<td>2C</td>
<td></td>
<td>2D</td>
<td>1.75</td>
<td>6 / 40</td>
</tr>
<tr>
<td>HFU#7</td>
<td>1A</td>
<td></td>
<td>1B</td>
<td></td>
<td>1C</td>
</tr>
<tr>
<td>HFU#8</td>
<td>0A</td>
<td></td>
<td>0B</td>
<td></td>
<td>0A$C_2$</td>
</tr>
</tbody>
</table>

Result of quench simulation:

$T_{max} = 350$ K, $V_{gnd} = 1170$ V
Comparison of magnets with heater based protection

<table>
<thead>
<tr>
<th></th>
<th>Block</th>
<th>Cosθ</th>
<th>Common-coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hotspot temperature (K) (limit 350 K)</td>
<td>353</td>
<td>341</td>
<td>350</td>
</tr>
<tr>
<td>Voltage to ground (V) (limit 1200 V)</td>
<td>960</td>
<td>1010</td>
<td>1170</td>
</tr>
<tr>
<td>Energy of QH system (kJ) / 1 aperture</td>
<td>60</td>
<td>40</td>
<td>35</td>
</tr>
</tbody>
</table>

- All heaters quench also at 1000 A
- At $I_{\text{nom}}$ hotspot temperature and voltage are smaller by ~15-25 K, and ~100 V
- Work in progress: Further optimizations are possible
Some sensitivity analyses for the Cosθ heater design

Heater design:

• Increase heater polyimide insulation from 0.075 mm to 0.1 mm
  \[ T_{\text{max}} + 14 \text{ K}, \ V_{\text{max}} + 90 \text{ V} \]

• Remove inner layer heater (layer-to-layer propag. ~20 ms):
  \[ T_{\text{max}} + 8 \text{ K}, \ V_{\text{max}} - 110 \text{ V} \]

Material parameters and model assumptions:

• Heater delays uncertainty (cable average field instead of peak)
• Material properties (MATPRO instead of NIST)
• Propagation velocities (reduction of 50%)
  \[ T_{\text{max}} + < 20 \text{ K}, \ V_{\text{max}} + < 300 \text{ V} \]

→ The design is relatively stable

→ 20 K could be a reasonable margin in later analysis and failure scenarios

Reference at 105 % \( I_{\text{nom}} \):
\[ T_{\text{max}} = 340 \text{ K}, \ V_{\text{max}} = 1010 \text{ V} \]
Protection with CLIQ – Coupling-Loss Induced Quench

- CLIQ is a new technology for the protection of superconducting magnets. The core component is the capacitor bank that generates:

  - An alternated transport current in the magnet
  - A variable magnetic field in the coils
  - High inter-filament and inter-strand coupling losses
  - Heat on the superconductor
  - Quick spread of the normal zone after a quench
Protection of the Block with CLIQ

- Very promising results with a Multi-CLIQ system (2 x 1200 V/20 mF)

Details in the poster by M. Prioli

Quench simulation with LEDET¹+PSPICE²

\[ T_{\text{max}} = 300 \text{ K}, \quad V_{\text{gnd}} = 1100 \text{ V} \]

¹E. Ravaioli, Cryogenics, 2016.
²I. Cortes Garcia et al., submitted to IEEE JMMCT, 2017
Protection with heaters and CLIQ

- CLIQ for fast quenching at high current,
- QH for voltage control and protection at low current

**Advantages** when applied to Block:
1. Allows using a smaller CLIQ unit
2. No interlayer leads for CLIQ
3. Heaters only on outer surfaces
4. Less total energy in the QP-system

<table>
<thead>
<tr>
<th>Circuit</th>
<th>QH Strips</th>
<th>Strip width (cm)</th>
<th>HS/period (cm)</th>
<th>$P_{QH}(0)$ (W/cm²)</th>
<th>$\tau_{RC}$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFU#1</td>
<td>(1A+4A)</td>
<td></td>
<td>(1A+4A)</td>
<td>1A: 1.6, 4A: 2.3</td>
<td>1A: 5/25, 4A: 7/40</td>
</tr>
<tr>
<td>HFU#2</td>
<td>(1B+4B)</td>
<td></td>
<td>(1B+4B)</td>
<td>1B: 1.6, 4B: 2.3</td>
<td>7/40</td>
</tr>
</tbody>
</table>

$1 kV, 10 mF$
Protection with heaters and CLIQ

Simulation with CoHDA and LEDET

\[ T_{\text{max}} = 340 \, \text{K}, \quad V_{\text{gnd}} = 1190 \, \text{V} \]

A check: Assume that CLIQ decreases the heater delays by 20% and increases longitudinal propagation velocity by 20%:
\[ T_{\text{max}} = 340 \, \text{K} \text{ and } V_{\text{gnd}} = 1160 \, \text{V} \]

<table>
<thead>
<tr>
<th>Circuit</th>
<th>QH Strips</th>
<th>Strip width (cm)</th>
<th>HS/ period (cm)</th>
<th>( P_{\text{QH}(0)} ) (W/cm²)</th>
<th>( \tau_{RC} ) (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFU#1</td>
<td>(1A+4A) \parallel (1A+4A)</td>
<td>1A: 1.6, 4A: 2.3</td>
<td>1A: 5/25, 4A: 7/40</td>
<td>1A: 130, 4A: 63</td>
<td>38</td>
</tr>
<tr>
<td>HFU#2</td>
<td>(1B+4B) \parallel (1B+4B)</td>
<td>1B: 1.6, 4B: 2.3</td>
<td>7/40</td>
<td>1B: 150, 4B: 71</td>
<td>36</td>
</tr>
</tbody>
</table>
Comparison of different methods applied to Block

<table>
<thead>
<tr>
<th></th>
<th>QH only</th>
<th>CLIQ only</th>
<th>CLIQ + QH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hotspot temperature (K) (limit 350 K)</td>
<td>353</td>
<td>300</td>
<td>343</td>
</tr>
<tr>
<td>Voltage to ground (V) (limit 1200 V)</td>
<td>960</td>
<td>1100</td>
<td>1200</td>
</tr>
<tr>
<td>Energy of QH system (kJ) / 1 aperture</td>
<td>60 (HFU)</td>
<td>29 (CLIQ)</td>
<td>5 (CLIQ) + 20 (HFU)</td>
</tr>
</tbody>
</table>

- **Work in progress**: Further optimization obtainable for all methods
- Highly efficient CLIQ:
  - Increases the safety margin in protection,
  - OR can be used to reduce the requirement for copper in the magnet design
Conclusions

• **Quench protection integrated in the 16 T dipole magnets design from beginning**
  • At 105% of $I_{\text{nom}}$ assumed protection efficiency 40 ms, and required $T_{\text{max}} < 350 \text{ K}$, $V_{\text{max}} < 1200 \text{ V}$

• **Two protection systems available:**
  • Quench heaters: $T_{\text{max}}$ 340 – 350 K and $V_{\text{max}}$ 1000 – 1200 V
  • CLIQ: $T_{\text{max}}$ 300 K (demonstrated for Block)
  • Quench heaters + CLIQ: Reduction of QP system energy (demonstrated for Block)

• **Road map to further optimization of quench protection and magnet design:**
  1. Analyze CLIQ and CLIQ+QH for all magnets (incl. sensitivity analysis)
  2. Update the protection efficiency vs. type of magnet and protection
  3. Software calibration with experimental data → Quantify the needed margin
  4. Iterate magnet design based on the updated protection efficiency and margin on $T_{\text{max}}$
     → Possible reduction in magnet size

• In parallel: Analyze thermal stresses and protection integration with the circuit design
Posters about quench protection in EuroCirCol WP5

M. Prioli et al.: Voltage reduction, analysis of circuits

J. Zhao et al.: Mechanical analysis during a quench