16 T DIPOLE QUENCH PROTECTION

Tiina Salmi\textsuperscript{1} and Marco Prioli\textsuperscript{2}

Tampere University of Technology\textsuperscript{1}, CERN\textsuperscript{2}

\textit{Acknowledgement:} E. Ravaioli\textsuperscript{2}, A. Stenvall\textsuperscript{1}, A. Verweij\textsuperscript{2}, and EuroCirCol WP5 magnet designers and the team

\textit{FCC-week, Amsterdam, 11th April 2018}
Considered EuroCirCol 16 T dipole designs

<table>
<thead>
<tr>
<th>Magnet, version</th>
<th>Cosθ, 22b_38_v1</th>
<th>Block, V2ari194</th>
<th>Common coil, vh12_2ac6 (#11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inom (A)</td>
<td>11390</td>
<td>10000</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>LF-cable</td>
<td>HF-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, $\alpha = 0.96$, $C_0 = 267845 \text{ A/mm}^2\text{T}$

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Outline

Introduction: Why is quench protection so critical?

1. The steps in the quench protection design

2. Protection with CLIQ (baseline)
   • Cosθ, Block, Common-coil

3. Protection with quench heaters (back-up option)
   • Cosθ, Block, Common-coil

4. Summary

Appendix: Description of the computational tools and assumptions

See also the talks by M. Prioli “Mechanical analysis during quench” and “Circuit layout and protection”
Introduction: Why is quench protection so critical?

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Appendix: Description of the computational tools and assumptions
Introduction: Why quench protection is so critical?

- High magnetic field + compact size $\rightarrow$ High stored energy density
  - 16 T CosT, Block, C-c: $\sim$40 MJ, $\sim$130 MJ/m$^3$

- Quench $\rightarrow$ Energy needs to be absorbed
  - Joule heating in the quenched cables

![Graph showing stored energy density in dipoles vs. peak field. Plot by courtesy of L. Bottura and D. Schoerling.]

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Introduction: Why quench protection is so critical?

- High magnetic field + compact size \( \rightarrow \) High stored energy density
  - 16 T CosT, Block, C-c: \(~40\ \text{MJ}, \sim130\ \text{MJ/m}^3\)

- Quench \( \rightarrow \) Energy needs to be absorbed
  - Joule heating in the quenched cables

- Magnet resistance drives the energy discharge

- Need to quench the entire magnet fast
  - Detection (~20 ms)
  - Heaters/CLIQ (~10-30 ms)

\[ 
\text{Magnet powering circuit in accelerator} 
\]
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1. The steps in the quench protection design

STEP 1: Design criteria
Max temperature 350 K and voltage 1200 V
1. The steps in the quench protection design

STEP 1: Design criteria
Max temperature 350 K and voltage 1200 V

STEP 2: Simplified analysis
- Protection efficiency: 20 ms det. + 20 ms heaters
- Tools for quick feedback
1. The steps in the quench protection design

**STEP 1: Design criteria**
Max temperature 350 K and voltage 1200 V

**STEP 2: Simplified analysis**
- Protection efficiency: 20 ms det. + 20 ms heater
- Tools for quick feedback

![Schematic of magnet current decay after 20+20 ms protection delays](image)
1. The steps in the quench protection design

**STEP 1: Design criteria**
Max temperature 350 K and voltage 1200 V

**STEP 2: Simplified analysis**
- Protection efficiency: 20 ms det. + 20 ms heaters
- Tools for quick feedback

**STEP 3: Detailed protection schemes**
- CLIQ, quench heaters, circuit
  - Detection time 20 ms
  - Developed tools

Magnets can be protected: CLIQ chosen as baseline, heaters a back-up solution
Outline

Introduction: Why is quench protection so critical?

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2. Protection with CLIQ: The principle

CLIQ – Coupling Loss Induced Quench
• Discharge capacitor bank across part of the winding
  ➞ Oscillations of transport current
  ➞ Coupling losses ➞ Quench

Advantages:
• Heat deposition directly to the strand
• Connection can be made external to the magnet ➞ Accessible for repair etc.

Cautions:
• New technology, HL-LHC will provide first experience in real accelerator

CLIQ leads in the 15 m long LHC main dipole (Aug 2015), Photo by courtesy of E. Ravaioli

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2. Protection with CLIQ: Design considerations

- Important CLIQ design parameters:
  - Location of the CLIQ leads
  - Location of losses, voltage accumulation
  - Number of CLIQ units
  - Charging voltage and capacitance of the units

![Division of the magnet to electrical parts (8)](image)

![CLIQ connection scheme](image)

![Resulting current oscillations](image)

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2. Protection with CLIQ: Cosθ

**Location of the peak heat deposition in CLIQ-protected 2-aperture magnet**

**CLIQ configuration**

\[ V_0 = 1.25 \text{ kV}, \ C = 50 \text{ mF} \]

**Voltage distribution 120 ms after CLIQ activation**

Max. voltage to ground 800 V

**Final temperature distribution after CLIQ activation**

Hot-spot temperature 286 K

Simulation with -COMSOL (at \( I_{\text{nom}} \)) – M. Prioli

T. Salmi and M. Prioli, FCC week 2018
2. Protection with CLIQ: Cosθ
- Sensitivity analysis and redundancy

Simulated temperature and voltage for varying cable parameters

<table>
<thead>
<tr>
<th>Fil. Twist (mm)</th>
<th>RRR HF/LF</th>
<th>$f_{p,\text{eff}}$</th>
<th>$T_{\text{max}}$ (K)</th>
<th>$V_{\text{max}}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>100/100</td>
<td>1</td>
<td>304</td>
<td>950</td>
</tr>
<tr>
<td>10</td>
<td>100/100</td>
<td>1</td>
<td>305</td>
<td>940</td>
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<td>20</td>
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<td>1</td>
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<td>950</td>
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<td>1000</td>
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<td>1</td>
<td>306</td>
<td>1150</td>
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<td>200/50</td>
<td>1</td>
<td>298</td>
<td>1170</td>
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$F_{p,\text{eff}}$ = Scaling factor for matrix transverse resistivity for interfil. coupling loss.

Impact of filament twist, RRR and $f_{p,\text{eff}}$ is < 20 K, 250 V.

This analysis is done at 105% of $I_{\text{nom}}$ (1-AP.).

Simulation with LEDET

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### 2. Protection with CLIQ: Cosθ

**- Sensitivity analysis and redundancy**

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\(f_{p,\text{eff}}\) = Scaling factor for matrix transverse resistivity for interfil. coupling loss.

This analysis is done at 105% of Inom (1-ap.).

**Impact of filament twist, RRR and \(f_{p,\text{eff}}\) is < 20 K, 250 V.**

Based on a CLIQ reliability study by A. Fernandez:

Redundancy can be obtained within the CLIQ unit:

- Components related to triggering fully redundant
- Configuration of several capacitors: Short circuit in one leads only to reduction of energy.

Simulation with LEDET

Simulation with CLIQ

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17
2. Protection with CLIQ: Block

- **Location of the peak heat deposition in CLIQ-protected 2-aperture magnet**

- **CLIQ configuration**

  - CLIQ1: $V_0=0.6$ kV, $C=50$ mF
  - CLIQ2: $V_0=1.2$ kV, $C=50$ mF

- **Voltage distribution 70 ms after CLIQ activation**

  - Max. voltage to ground 0.7 kV

- **Final temperature distribution after CLIQ activation**

  - Hot-spot temperature 286 K

-Simulation with COMSOL (at $I_{nom}$) – M. Prioli

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2. Protection with CLIQ: Common-coil

Location of the peak heat deposition in CLIQ-protected 2-aperture magnet

CLIQ configuration

CLIQ1: $V_0=0.9$ kV, $C=80$ mF, CLIQ2: $V_0=0.9$ kV, $C=80$ mF

Current oscillations

Strong di/dt requires experimental validation

Temperature and voltage distribution

Hot-spot temperature 280 K

Max. voltage to ground 1.35 kV

Simulation with STEAM-LEDET, 2 apertures (at $I_{nom}$)

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Appendix: Description of the computational tools and assumptions
3. Protection with heaters: Heater technology

- Similar technology than in LHC\(^1\) and HL-LHC\(^{2,3}\):
  - 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): **1200 V and 10 mF** (LHC: 900 V and 7 mF)
  - 1 Ω for wires etc. / circuit

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\(^3\) P. Ferracin et al, “Development of MQXF, the Nb3Sn Low-β Quadrupole for the HiLumi LHC”, *IEEE TAS*, 26(4), 2016.
3. Protection with heaters: $\cos \theta$

- Heaters cover 62% of turns
- 14 HFU’s / 2-ap. magnet
- **At 100% $I_{nom}$**: Heater delays: 8-21 ms

**Hotspot temperature 322 K**
- **Peak voltage to ground 980 V**
- Between turns 80 V
- Between layers 980 V

**Locations of heater strips**
(No inner layer heaters!)

**Heater strip geometries and powering**

<table>
<thead>
<tr>
<th>HFU</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>#1</td>
<td>2A$_c$</td>
<td></td>
<td>2B$_c$</td>
<td></td>
<td>2A$_e$</td>
</tr>
<tr>
<td>#2</td>
<td>3C$_e$</td>
<td></td>
<td>3A$_c$</td>
<td></td>
<td>3B$_c$</td>
</tr>
<tr>
<td>#3</td>
<td>4A$_c$</td>
<td></td>
<td>4B$_c$</td>
<td>1.3</td>
<td>6/30</td>
</tr>
<tr>
<td>#4</td>
<td>4C$_c$</td>
<td></td>
<td>4D$_c$</td>
<td>1.3</td>
<td>6/30</td>
</tr>
<tr>
<td>#5</td>
<td>2C$_d$</td>
<td></td>
<td>3A$_d$</td>
<td></td>
<td>3B$_d$</td>
</tr>
<tr>
<td>#6</td>
<td>4A$_d$</td>
<td></td>
<td>4B$_d$</td>
<td>1.3</td>
<td>6/30</td>
</tr>
<tr>
<td>#7</td>
<td>4C$_d$</td>
<td></td>
<td>4D$_d$</td>
<td>1.3</td>
<td>6/30</td>
</tr>
</tbody>
</table>

**Simulation with CoHDA+Coodi**

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3. Protection with heaters: \( \cos \theta \)

-Failure analysis

- 1 strip fails on both sides of the coil, for both apertures
- \( \rightarrow \) Temperature and voltage increases only 5 K & 100 V

\[ \text{Simulation of temperature and voltage after strip failure*,**} \]

<table>
<thead>
<tr>
<th>Failed strip</th>
<th>( \text{Tmax (K)} )</th>
<th>Vmax, gnd (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QH2A</td>
<td>325</td>
<td>930</td>
</tr>
<tr>
<td>QH2B</td>
<td>324</td>
<td>930</td>
</tr>
<tr>
<td>QH2C</td>
<td>324</td>
<td>930</td>
</tr>
<tr>
<td>QH3A</td>
<td>327</td>
<td>900</td>
</tr>
<tr>
<td>QH3B</td>
<td>325</td>
<td>910</td>
</tr>
<tr>
<td>QH3C</td>
<td>324</td>
<td>930</td>
</tr>
<tr>
<td>QH4A</td>
<td>330</td>
<td>870</td>
</tr>
<tr>
<td>QH4B</td>
<td>326</td>
<td>1130</td>
</tr>
<tr>
<td>QH4C</td>
<td>325</td>
<td>1100</td>
</tr>
<tr>
<td>Qh4D</td>
<td>324</td>
<td>1070</td>
</tr>
</tbody>
</table>

*Turns under failed strip quench 40 ms after heater activation (layers 2-3) and 50 ms later (layer 4)

**Failures on layer 2 do not affect the quenching time of layer 1

No failures: 322 K, 960 V

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3. Protection with heaters: Block

- Heaters cover 77% of turns

- 13 HFU’s / 2-ap. magnet

- **At 100% Inom**: Heater delays: 7-41 ms

**Hotspot temperature 321 K**
- Peak voltage to ground 870 V
- Between turns 90 V
- Between layers 1160 V

### Locations of heater strips

### Heater strip geometries and powering

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<thead>
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<th>Strip width (cm)</th>
<th>HS/ period (cm)</th>
<th>( P_{QH}(0) ) (W/cm²)</th>
<th>( T_{RC} ) (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1A₁c₁</td>
<td></td>
<td>2A₁c₁</td>
<td>1.9</td>
<td>5/22</td>
</tr>
<tr>
<td>#2</td>
<td>1B₁c₁</td>
<td></td>
<td>2A₁c₁</td>
<td>1.8</td>
<td>6/30</td>
</tr>
<tr>
<td>#3</td>
<td>(3A₁c₁ + 4A₁c₁ + 3A₂c₂ + 4A₂c₂)</td>
<td></td>
<td>(3A₁c₁ + 4A₁c₁ + 3A₂c₂ + 4A₂c₂)⁺</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>3B₁c₁</td>
<td></td>
<td>4B₁c₁</td>
<td>2.4</td>
<td>6/30</td>
</tr>
<tr>
<td>#5</td>
<td>1A₁c₁</td>
<td></td>
<td>2A₁c₁</td>
<td>1.9</td>
<td>5/22</td>
</tr>
<tr>
<td>#6</td>
<td>1B₁c₁</td>
<td></td>
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<td></td>
<td>4B₁c₁</td>
<td>2.4</td>
<td>6/30</td>
</tr>
</tbody>
</table>
3. Protection with heaters: Common-coil

- Heaters cover 70% of turns
- 15 HFU’s / 2-ap. magnet
- **At 100% Inom**: Heater delays: 6-20 ms

**Hotspot temperature 330 K**
- **Peak voltage to ground 1040 V**
- Between turns 80 V
- Between layers 1060 V

Heater strip geometries and powering

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<tr>
<td>#1</td>
<td>0A₂₁</td>
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<tr>
<td>#2</td>
<td>1A₂₁</td>
<td></td>
<td>1B₂₁</td>
<td></td>
<td>1C₂₁</td>
</tr>
<tr>
<td>#3</td>
<td>2A₂₁</td>
<td></td>
<td>2B₂₁</td>
<td>1.75</td>
<td>6/31</td>
</tr>
<tr>
<td>#4</td>
<td>2A₂₁</td>
<td></td>
<td>2B₂₁</td>
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Simulation with CoHDA+Coodi
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   • $\cos\theta$, Block, Common-coil

4. Summary

Appendix: Description of the computational tools and assumptions
# Comparison of the methods

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<tr>
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### CLIQ

- **Pros**: Homog., efficient, loss
- **Cons**: Low current prot.

### Heaters

- **Pros**: Focused heating
- **Cons**: Diffusion delay

### Efficiency

- **Pros**: Accessible connection
- **Cons**: Leads btw pancake layers, part of magnet circuit

### Technology

- **Pros**: External circuit
- **Cons**: Delicate technology

### Cost / complexity

- **Pros**: Few units needed
- **Cons**: Complex units

- **Pros**: Simple units
- **Cons**: Many units+heaters needed
## Comparison of the methods

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T. Salmi and M. Prioli, FCC week 2018
Summary

- Magnets were designed to comply with the “40 ms/350 K “ protectability design criteria
  - Continuous feedback loop between quench protection studies and magnet designs

- **Protection with CLIQ feasible for all magnet options**
  - Max temperatures below 300 K
  - Internal voltages below 1000 V (except C-c, but work in progress)

- Protection with heaters is considered a back-up option

→ **Used methodology for protection design seems successful and the developed tools useful**

- For CDR: Almost all the studies are ready, writing of a final report is underway
Outline

Introduction: Why is quench protection so critical?

1. The steps in the quench protection design

2. Protection with CLIQ (baseline)
   • \( \cos \theta \), Block, Common-coil

3. Protection with quench heaters (back-up option)
   • \( \cos \theta \), Block, Common-coil

4. Summary

Appendix: Description of the computational tools and assumptions
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

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