Jiani Gao :: PhD Student :: Paul Scherrer Institut
B. Auchmann (CERN/PSI), L. Brouwer (LBNL), S. Caspi (LBNL), J. Mazet (CERN), G. Montenero (PSI), S. Sanfilippo (PSI)

Quench Protection of CCT-Type High-Field Magnets for Accelerators

Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI
Annual Meeting of the Swiss Physical Society, 28-31 August 2018, EPFL
• Problem Description
• Simulation Methods
• Detection & Protection Concepts
• Future Work
Quench Protection

- **Quench**: transition from superconducting to normal-conducting state
  - $R_{\text{quench}} \uparrow$ Joule heating in Cu, causing $T \uparrow$ in normal zone

\[
\begin{align*}
T < T_{cs} & \quad \text{Superconductivity} \\
& \quad \text{Current in SC} \\
& \quad \text{No heating} \\
T_{cs} < T < T_{c0} & \quad \text{Current-sharing regime} \\
& \quad \text{Partial current in SC} + \\
& \quad \text{Partial current in stabilizer} \\
& \quad \text{Joule heating + Quench} \\
T > T_{c0} & \quad \text{Normal conductivity} \\
& \quad \text{Current in stabilizer} \\
& \quad \text{Joule heating + Quench}
\end{align*}
\]
• Protection: dissipate magnetic energy as heat or quench entire coil to limit $T_{\text{peak}}$ and avoid damage in coil

• Different phases in a quench:
  – $I$ constant, heat propagation:
    1a. Detection $\Delta t_{\text{thres}}$
    1b. Validation $\Delta t_{\text{val}}$
  – $I$ decreases, energy dissipation by Joule heating:
    2a. Protection $\Delta t_{\text{prot}}$
    2b. Discharge $\Delta t_{\text{dec}}$

• Magnet design efficiency: less time – less Cu fraction – smaller coil

\[ I(t) = I_0 e^{-\frac{R(t)}{L(I)}} \]
Simulation Methods

• Study quench phenomenon in two-/four-layer CCT geometry
  – Use of ANSYS User-Defined Elements (UDEs) developed at LBNL
    – Thermal: multi-dependency material properties
    – Electromagnetic: effects of cable-eddy currents

• Coupled quench simulation in a hierarchical approach
  1. MIITs adiabatic calculation (Joule heat source) \( \rightarrow \) time budget
  2. MATLAB adiabatic integrator (update on \( R(t) \)) \( \rightarrow \) current decay
  3. Magnetostatic & Electrothermal model \( \rightarrow \) quench propagation
  4. Electrothermal & Electromagnetic model (UDEs) \( \rightarrow \) protection methods
  5. Electromagnetic-thermal full model of model magnets

Helical model
Periodic model
Full model
• Study different detection & protection concepts and design a fast and efficient protection system for CCT

1. Voltage detection using co-wound Cu wires: $V \uparrow (I \text{ cst})$
   – Low-risk but $\Delta t_{\text{val}}$ obligatory
2. Current detection using co-wound SC wires: $I \downarrow (V \text{ cst})$
   – Expect to eliminate $\Delta t_{\text{val}}$; can be studied in detail
3. Co-wound optical fibers: temperature and strain data from analysis of spectral shift (Rayleigh backscattering spectra)
   – High-risk but shorter delay time; collaboration with Penn State Univ.

1. Energy extraction: suitable for a single-magnet system; basic method for R&D magnets
2. Coupling-Loss Induced Quench (CLIQ): $I$ oscillations $\rightarrow$ coupling losses (heat) $\rightarrow$ quench; most promising method
3. Inductive protection using co-wound Cu tapes: quench process enhancement
Protection of Two-layer Model Magnet CD1 with Energy Extraction (+ Voltage Detection)

<table>
<thead>
<tr>
<th>$I$ [kA]</th>
<th>$B$ [T]</th>
<th>$\Delta t_{\text{thres}}^{\text{ref}}$ [ms]</th>
<th>$\Delta t_{\text{thres}}^{\text{ANSYS}}$ [ms]</th>
<th>MIITs [MA$^2$S]</th>
<th>$T_{\text{max}}$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>11</td>
<td>23.5</td>
<td>3.8</td>
<td>7.6</td>
<td>199</td>
</tr>
<tr>
<td>15.5</td>
<td>9.5</td>
<td>33.5</td>
<td>12</td>
<td>7.5</td>
<td>193</td>
</tr>
<tr>
<td>12</td>
<td>7.3</td>
<td>59</td>
<td>26.9</td>
<td>6.8</td>
<td>145</td>
</tr>
</tbody>
</table>

Temperature profiles along the coil at different times

→ Good time margin and temperature margin
→ CD1 protectable with energy extraction; test-bed for other detection & protection methods
Future Work

• Continue studying different protection concepts, especially CLIQ, via coupled simulations in two-/four-layer CCT magnets

• Implement, test and validate the detection & protection system in two-layer model magnet that will be built at PSI during the thesis
My thanks go to

- Bernhard Auchmann
- Lucas Brouwer
- Giuseppe Montenero
- Gabriella Rolando
- Stephane Sanfilippo
- Federico Scurti