Update on RCBRD protection studies

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27th of August, 2019
MCBRD magnet in RCBRD circuit: Protected with energy extraction

- Protection of individually powered MCBRD magnet apertures:
  - Quench detected → Discharge over energy extractor → Eddy currents in the formers with resulting heat development → Quench back in the magnet → Internal resistance development in magnet → Faster discharge → Even more Eddy currents → Etcetera
  - Voltage-to-ground and quench integral are dominated by energy extractor system
- For discharge over 1.43 Ω resistor at 435 A (= ultimate current), 1.9 K:
  - Quench-back after 33 ms, $R_{\text{Magnet}}$ reaches 4.6 Ω after 0.4 s, $QI_{\text{Discharge}} = 20.9$ kA²s
  - Energy dissipation: 37 % to EE + crowbar, 36 % to strands, 27 % to formers + outer cylinder
  - Without conductive formers: 4.4 Ω EE needed for identical quench integral
Comparison of simulation results versus experimental observations

- Experimental observation: Quench integral of training quenches ≈ manually triggered discharges → Quench origin may be neglected for QI
- STEAM-ProteCCT: Simulations of manually triggered discharges

Worst-case hotspot temperature and voltages:
- Larger energy extraction voltage gives lower hotspot temperature
- But also: Higher voltage-to-ground → More challenging for electrical integrity

What is minimal energy extraction for $T_{\text{Hotspot}} < 200$ K at ultimate current?
Simulation with STEAM-BBQ: 1+1D quench propagation simulation

- Single Nb-Ti/Cu strand with insulation
- Transverse quench propagation to neighboring strands not considered
- Distinguishes between high-field (HFQ) and low-field quench (LFQ) origin within periodically repeating turn

Measurement: Faster $dV/dt$ in case of significant pre-cursor, slower in case of only thermal quench propagation

Comparison: Good consistency between simulation and measurement
Detection + validation of quench

Quench detection (100 mV threshold) + validation (10 ms validation time)

- Quench propagation simulated with STEAM-BBQ, validated against MCBRDp1 training quenches
- Chinese variant of MCBRD (less copper + higher critical current in conductor), same quench integral for detection + validation expected: $3.9 \, \text{kA}^2\text{s at 435 A}$
Nb-Ti/Cu conductor properties and MLI Ts curves

- WST strand versus CERN strand: Lower copper fraction (Cu:non-Cu = 1.3 versus 1.95), higher critical current (~ +50%), higher hotspot temperature for given $Q_I$
- Most critical in terms of hotspot temperature (see slide 8): **WST strand, $RRR = 230$**
  - 24.9 kA$^2$s combined quench integral gives 200 K
  - 3.9 kA$^2$s for quench detection + validation
- **Target:** 21.0 kA$^2$s discharge quench integral for $T_{Hotspot} = 200$ K at 435 A
Considered circuit + energy extractors

- RCBRD circuit is discharged over crowbar (Crowbar + passive circuit resistance = 55 mΩ) and energy extractor
- Grounding point is located between crowbar and energy extractor
- Experimentally investigated energy extractors (along with other options):
  - Regular linear resistor: 1.29 Ω
  - Non-linear varistor 2 (Equivalent resistance higher at lower currents, lower at higher currents)
Discharge quench integral for $T_{\text{Adiabatic}} = 200$ K at 435 A: 24.5 kA²s for CERN MCBRD variant, 21.0 kA²s for Chinese variant

Chinese MCBRD variant is assumed identical to CERN variant except for conductor, and final EE HL-LHC switch with 2 ms delay instead of 10 ms delay

Varistor 2 and 1.29 Ω give $T_{\text{Adiabatic}} < 200$ K at 435 A

Varistor 2 vs hypothetical 1.18 Ω (identical $T_{\text{Adiabatic,435A}}$) → Varistor gives 14% less voltage to ground and guarantees quench back at $I_{\text{Op}} \geq 200$ A
Magnet property variations

<table>
<thead>
<tr>
<th>MCBRD material property variation, Implications at ultimate current (435 A)</th>
<th>Detection/Validation + discharge quench integral [kA²s]</th>
<th>Adiabatic hotspot temperature at fixed field [K]</th>
</tr>
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<tbody>
<tr>
<td>CERN variant, strand $RRR = 230$, Former $RRR = 8$, $t_{EE\text{Delay}} = 10 \text{ ms}$</td>
<td>$3.7 + 22.4$</td>
<td>$167$</td>
</tr>
<tr>
<td>CERN variant, strand $RRR = 230$, Former $RRR = 8$, $t_{EE\text{Delay}} = 2 \text{ ms}$</td>
<td>$3.7 + 20.8$</td>
<td>$146$</td>
</tr>
<tr>
<td>Chinese variant, strand $RRR = 230$, Former $RRR = 8$, $t_{EE\text{Delay}} = 2 \text{ ms}$</td>
<td>$3.9 + 20.6$</td>
<td>$193$</td>
</tr>
<tr>
<td>Chinese variant, strand $RRR = 100$, Former $RRR = 8$, $t_{EE\text{Delay}} = 2 \text{ ms}$</td>
<td>$3.0 + 16.4$</td>
<td>$170$</td>
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<tr>
<td>Chinese variant, strand $RRR = 230$, Former $RRR = 6$, $t_{EE\text{Delay}} = 2 \text{ ms}$</td>
<td>$3.9 + 23.5$</td>
<td>$255$</td>
</tr>
</tbody>
</table>

- Boundary conditions: Ultimate current (435 A), varistor 2 used for energy extraction, magnet operating at 1.9 K
- Voltage-to-ground is dominated by energy extractor (Varistor 2: $V_{\text{GndMax}} = 439 \text{ V}$)
- MCBRDp1 former $RRR$ measurement: 8.0 (Courtesy: F. Pincot)
- Lower hotspot temperature given by: Faster EE switch opening, lower critical current and more copper in the conductor, lower strand $RRR$, and higher former $RRR$
Summary

• RCBRD circuits with MCBRD magnets
  • Quench detection → Discharge over energy extractor → Quench back in the magnet → Much faster discharge than $t_{\text{Discharge}} = \frac{L}{R_{\text{External}}}$
  • Extensive experimental protection studies in SM18 on MCBRDp1 apertures
  • Simulation tools for detection + discharge: STEAM-BBQ & ProteCCT, consistent results with experimental observations (MCBRDp1, MCBRDs1, and MCBRDs1b)

• How much energy extraction is needed?
  • Chinese MCBRD variant is more critical than CERN variant due to lower Cu:non-Cu in Nb-Ti / Cu conductor, with all else expected to be identical
  • Detection + validation (100 mV + 10 ms) gives $3.9 \text{kA}^2\text{s} \rightarrow$ Leaves $21.0 \text{kA}^2\text{s}$ for discharge quench integral in Chinese MCBRD variant to have $T_{\text{Hotspot,435A}} < 200 \text{ K}$
  • Experimentally investigated energy extractor options: Both $1.29 \Omega$ and Varistor 2 give $T_{\text{Hotspot,435A}} < 200 \text{ K}$ for both CERN and Chinese MCBRD variant, with $V_{\text{Gnd,Max}} = 562 \text{ V}$ (1.29 $\Omega$) and $439 \text{ V}$ (Varistor 2)
ProteCCT, thermal aspects

Turn-to-turn periodic boundary condition

Three-dimensional thermal propagation in simplified geometry [2]

- Longitudinal heat propagation along length of strands, insulation, and formers
- Transverse heat propagation
  - Individual thermal elements for strands, insulation, formers, former insulation
  - Heat flow to the bath: 1.9 K: Kapitza + film boiling cooling, 4.5 K: Nucleate + film boiling
- Periodic boundary condition: Simulation of single turn per former to simulate entire magnet
  - Non-linear magnetic-field- and temperature-dependent properties taken from STEAM library and LEDET material database

ProteCCT, internal circuits

Circuit types:

- Internal circuit: inductance of CCT coils, internal resistance, crowbar, dump resistor + switch
- External circuit: ProteCCT takes external current waveform (co-simulation)
- Both cases: Main circuit (CCT coils) inductively coupled to formers and outer cylinder

Adaptive time-stepping (constraints on maximum $dT/dt$, maximum $dl/dt$ in formers, user-specified $dt$)
ProteCCT, User interface

- ProteCCT user manual [3]
- All user input is taken from a single Excel file (inspired by LEDET user interface)
- Co-simulation: Tool exchanges information through text-files
- For the most part, easy-to-understand parameters (Conductor RRR, Operating current, etc.)

Model input: Excel file

Complexity & correction factor #1: \( f_{\text{LoopFactor}} \)

- **Coupling matrix calculated in Comsol, assuming simplified 2D geometry with \( \cos\theta \) current distribution**

- Assumption: Eddy current flows axially through formers
- Reality: Eddy current model is oversimplified, so global correction factor \( f_{\text{LoopFactor}} \) needed that augments the effective path lengths of the eddy currents
- Global parameter \( f_{\text{LoopFactor}} \) determined by matching discharge to experimental result at low current without quench-back

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Complexity & correction factor #2: addedHeCpFrac

- Sliding and deformation of formers during powering (Courtesy Martin Novak)

- In addition to helium to bath cooling: Additional liquid helium present between non-bonded formers and outer cylinder \(\rightarrow\) Slows down quench-back onset

- Extra helium heat capacity: 0.13 MPa liquid + gas, with inclusion helium gas enthalpy

- Added as global correction factor \(\text{addedHeCpFrac}\) \(\rightarrow\) Additional heat capacity in formers (~0.6%)

- Determination of global correction factor by matching quench back onset \(t_{QB}\) at \(I_0 = 400\) A, 1.9 K, 1.43 Ω
Simulation vs. Experimental observation

Comparison between simulation and experimental (MCBRD prototype apertures and short models):

- High degree of consistency between simulations and experimental observations
- Checked for: Different magnetic lengths, former material types, operating temperatures, varying dump resistors + Metrosil varistors, operating currents
- Two fixed global correction parameters \( f_{\text{LoopFactor}} \) and \( \text{addedHeCpFrac} \) for all cases
- Measurement data: Courtesy F. Mangiarotti