Update on RCBRD protection studies

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Protection of the HL-LHC RCBRD circuits

- Protection of RCBRD circuits with individually powered MCBRD magnet apertures:
  - **Protected by energy extraction + quench-back**
  - Quench-back: $dl/dt$ from EE $\rightarrow$ Eddy currents in the formers, heat flows to strands $\rightarrow$ Nb-Ti/Cu strands transition to normal state
  - For discharge over 1.43 $\Omega$ resistor at 435 A (= ultimate current), 1.9 K:
    - Quench-back after 33 ms, $R_{\text{Magnet}}$ reaches 4.6 $\Omega$ after 0.4 s, $QI_{\text{Discharge}} = 20.9$ kA$^2$s
    - Energy dissipation: 37 % to EE + crowbar, 36 % to strands, 27 % to formers + outer cylinder
  - **Without conductive formers:** 4.4 $\Omega$ EE (3x higher) needed for identical $QI$
Motivation for this talk

- Simulations with ProteCCT to understand quench behaviour of the magnet
  - Experimental observations: Quench integral of training quenches ≈ manually triggered discharges → Quench origin may be neglected for quench integral
  - ProteCCT: Simulates manually triggered discharges (details in annex)
- Impact of energy extractor choice
  - Larger energy extraction voltage gives lower hotspot temperature
  - But also: Higher voltage-to-ground → More challenging for electrical integrity
- What is the minimum energy extraction for $T_{\text{Hotspot}} < 200$ K at ultimate current?

Typical discharge curves, sim vs. meas, Varistor #2

Quench integral, training quench versus manually triggered, sim versus measurement
Initial voltage development before quench detection

- Simulation with BBQ, a 1+1D quench propagation simulation tool
  - Single Nb-Ti/Cu strand with insulation, no transverse quench propagation
  - Distinguishes between high-field (HFQ) and low-field quench (LFQ) origin within periodically repeating turn
- Experimental observations: Consistent $dV/dt$ in absence of precursors, faster $dV/dt$ with precursors, transverse quench propagation starts to play a role at lower currents
- Comparison: Good consistency between simulation and measurement
Detection + validation of quench

- Expected quench detection integral derived from measurements + simulations
- Chinese variant of MCBRD (less copper + higher critical current in conductor), same quench integral for detection + validation expected: $\Rightarrow 3.9 \text{ kA}^2\text{s at } 435 \text{ A}$

Quench detection (**100 mV** threshold) + validation (**10 ms** validation time)
- Faster detection due to pre-cursor
- Slower detection due to absence of significant pre-cursor

*Detection QI, sim versus measurement*

*Detection QI, CERN vs WST conductor*
Nb-Ti/Cu conductor properties

- WST strand versus CERN strand: Lower copper fraction (Cu:non-Cu = 1.3 vs 1.95), higher critical current (~ +50%), higher hotspot temperature for given QI, slightly bigger diameter (0.83 mm vs. 0.825 mm)
- Most critical in terms of hotspot temperature (also 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
RCBRD circuit + energy extractor options

- RCBRD circuit is discharged over crowbar (Crowbar + passive circuit resistance = 55 mΩ) and energy extractor, with ground located between them
- Experimentally investigated energy extractors (along with other options):
  - Regular resistor: 1.29 Ω
  - Non-linear varistor 2 (Equivalent resistance higher at lower currents, lower at higher currents)
Resulting hotspot temperature

Simulation versus measurement: Generally good agreement, simulation is pessimistic for intermediate current quench back

- Varistor 2 and 1.29 Ω give $T_{Adiabatic} < 200 \text{ K} \text{ at } 435 \text{ A}$ for both CERN and Chinese variant
- Varistor 2 vs hypothetical 1.18 Ω (identical $T_{Adiabatic, 435A}$) → Varistor gives 14% less voltage to ground
Magnet parameter studies

<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>
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</thead>
<tbody>
<tr>
<td>CERN variant, strand $RRR = 230$, Former $RRR = 8$, $t_{EE\text{Delay}} = 10$ ms</td>
<td>$3.7 + 22.4$</td>
<td>167</td>
</tr>
<tr>
<td>CERN variant, strand $RRR = 230$, Former $RRR = 8$, $t_{EE\text{Delay}} = 2$ ms</td>
<td>$3.7 + 20.8$</td>
<td>146</td>
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<tr>
<td>Chinese variant, strand $RRR = 230$, Former $RRR = 8$, $t_{EE\text{Delay}} = 2$ ms</td>
<td>$3.9 + 20.6$</td>
<td>193</td>
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<tr>
<td>Chinese variant, strand $RRR = 100$, Former $RRR = 8$, $t_{EE\text{Delay}} = 2$ ms</td>
<td>$3.0 + 16.4$</td>
<td>170</td>
</tr>
<tr>
<td>Chinese variant, strand $RRR = 230$, Former $RRR = 6$, $t_{EE\text{Delay}} = 2$ ms</td>
<td>$3.9 + 23.5$</td>
<td>255</td>
</tr>
</tbody>
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**Effect of magnet parameter variations on quench integral and hotspot temperature**

- Boundary conditions: Ultimate current (435 A), Varistor 2 ($V_{\text{Gnd}}=439$ V), $T_{\text{Bath}} = 1.9$ K
- MCBRDp1 former and outer cylinder $RRR$ 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 $RRR$ for formers and outer cylinder
Summary

- RCBRD circuits with MCBRD individually powered apertures
  - Protection: Discharge over energy extractor + quench back → More than three times faster discharge than with just EE
  - Extensive experimental protection studies in SM18 on MCBRDp1 apertures
  - Simulation tools for detection + discharge: BBQ & ProteCCT
  - Simulation versus measurement: 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
  - Detection + validation (100 mV + 10 ms) gives 3.9 kA²s → Leaves 21.0 kA²s for discharge quench integral in Chinese MCBRD variant to have $T_{\text{Hotspot,435A}} < 200$ K
  - Experimentally investigated energy extractor options: Both 1.29 Ω and Varistor 2 give $T_{\text{Hotspot,435A}} < 200$ K for both CERN and Chinese MCBRD variant, with $V_{\text{Gnd,Max}} = 562$ V (1.29 Ω) and 439 V (Varistor 2)
  - Busbar (N-line type) quench protection verified: $T_{\text{Hotspot}} << 100$ K for $V_{\text{Threshold}} = 10$ mV, $t_{\text{Validation}} = 0.5$ s
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 $dt$)

Formers + outer cylinder: Inductively coupled to main circuit

Main circuit with CCT coils: Inductance, internal resistance, crowbar and dump resistor

Representation of internal circuit
ProteCCT, User interface

Model input: Excel file

- 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.)
- ProteCCT tool and user manual freely available on STEAM website (cern.ch/steam)
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**, determined by matching discharge to experimental result at low current without quench-back \( \rightarrow f_{\text{LoopFactor}} = 2 \)

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

- Extra helium heat capacity: 0.13 MPa liquid + gas, with inclusion helium gas enthalpy
- Added as global correction factor $\text{addedHeCpFrac}$ → Additional heat capacity in formers
- Determination of global correction factor by matching quench back onset $t_{QB}$ at $I_0 = 400$ A, 1.9 K, 1.43 Ω → $\text{addedHeCpFrac} = 0.6\%$
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 $f_{LoopFactor}$ and $addedHeCpFrac$ for all cases
- Measurement data: Courtesy F. Mangiarotti