Parameter range for protection analysis

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on behalf of the MQXF collaboration

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14-16 October 2019
Fermilab, Batavia, USA
Motivation

<table>
<thead>
<tr>
<th>Nominal current (I_{nom}=16.5 \text{ kA})</th>
<th>Reference parameters</th>
<th>Realistic* parameters uniformly distributed</th>
<th>Realistic* parameters not uniformly distributed</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEAM-LEDET sims MQXFB, 7.15 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No failures</td>
<td>≤615</td>
<td>≤636</td>
<td>≤927</td>
</tr>
<tr>
<td>2 QH failures</td>
<td>≤641</td>
<td>≤657</td>
<td>≤920</td>
</tr>
<tr>
<td>1 CLIQ and 1 QH failures</td>
<td>≤578</td>
<td>≤604</td>
<td>≤820</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ultimate current (I_{ult}=17.8 \text{ kA})</th>
<th>Reference parameters</th>
<th>Realistic* parameters uniformly distributed</th>
<th>Realistic* parameters not uniformly distributed</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEAM-LEDET sims MQXFB, 7.15 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 QH failures</td>
<td>≤816</td>
<td>≤846</td>
<td>≤1167</td>
</tr>
</tbody>
</table>

*Realistic conductor parameters by B. Bordini: Cu/noCu = 1.10-1.25; RRR = 150-250

Initial hot-spot resistance neglected. All simulations run with STEAM-LEDET. Simulations cross-checked by V. Marinozzi (FNAL).

For realistic* parameters, with up to two failures, and coil ordering

→ **Worst-case**: \( U_g < 670 \text{ V at } I_{nom}, U_g < 850 \text{ V at } I_{ult} \)

Ordering coils within a magnet is needed to keep peak voltages to ground within electrical design criteria

Note: MQXFA values are ~1.7 lower (ordering may not be needed)
Objectives

• Asses our capability to predict the RRR of a coil prior to magnet assembly based on conductor and cable qualification samples (we relay on coil-ordering to keep voltage to ground within electrical design criteria).

• Compare parameter range considered for protection simulations with the available data up to now. Current assumption for simulations:
  • Cu/noCu = 1.10-1.25;
  • RRR = 150-250
# CERN – Available data

<table>
<thead>
<tr>
<th></th>
<th>CERN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round samples</td>
<td>For a fraction of the production: ≥ 1/spool Supplier For the rest 3/billet Supplier 1/spool CERN</td>
</tr>
<tr>
<td>15 % rolled samples</td>
<td>1/billet CERN 1/billet Supplier</td>
</tr>
<tr>
<td>Cable* (qualification samples)</td>
<td>2/billet (1 virgin and 1 extracted) in the cable (4-5 per UL)</td>
</tr>
<tr>
<td>Coil** (witness samples)</td>
<td>6/coil (3 virgin and 3 extracted), coming from 3 different billets</td>
</tr>
</tbody>
</table>

* Extracted form the cable, reacted by CERN cable team  
** Extracted form the cable, reacted with the coil
CERN – RRP wire

- CERN measures about 20 % larger RRR in round wire
  - For quench simulations, the range is more important than the absolute value, so a systematic offset is not critical.
- The less aggressive heat treatment (50 hours at 665ºC instead of 72 hours) increased the RRR by ~ 70
- Rolled samples have ~ 100 lower RRR than round samples
CERN – cables

- Consistent increase of the RRR by $\sim 70$ due to the less aggressive heat treatment (50 hours at 665°C instead of 72 hours)
- Around 20% cabling degradation when comparing virgin to extracted strands.

Cable qualification strands (Extracted)
CERN – Estimate coil RRR

• Both qualification and witness samples are considered to compute the RRR, to maximize the amount of information.

Estimated coil RRR = $\bar{R} \bar{Q}$

$\bar{R}$ = weighted average of W/R ratio
$\bar{Q}$ = weighted average of Qualification Extracted Samples

• In average, W/R = 0.8 for the coils produced so far

Table:

<table>
<thead>
<tr>
<th>Billet</th>
<th>Number of wires</th>
<th>Qualification Extracted Samples</th>
<th>Witness Extracted Samples</th>
<th>Ratio W/R</th>
</tr>
</thead>
<tbody>
<tr>
<td>89</td>
<td>3</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>108</td>
<td>7</td>
<td>192</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>112</td>
<td>10</td>
<td>209</td>
<td>203</td>
<td>0.971</td>
</tr>
<tr>
<td>121</td>
<td>10</td>
<td>197</td>
<td>154</td>
<td>0.782</td>
</tr>
<tr>
<td>122</td>
<td>10</td>
<td>266</td>
<td>206</td>
<td>0.774</td>
</tr>
</tbody>
</table>

Example:

Extracted from the cable, reacted by CERN cable team
Extracted from the cable, reacted with the coil

In average, W/R = 0.8 for the coils produced so far
Can we predict coil RRR?

- Estimated RRR based on Qualification and Witness samples correlate with the measured coil RRR during cold powering test.
  - Measured coil RRR in the magnet is typically lower

\[ y = x - 32 \]
\[ R^2 = 0.8746 \]
# AUP – Available data

<table>
<thead>
<tr>
<th></th>
<th>AUP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round samples</td>
<td>2/3 billet Supplier</td>
</tr>
<tr>
<td></td>
<td>1/ billet AUP</td>
</tr>
<tr>
<td>15 % rolled samples</td>
<td>1/billet supplier</td>
</tr>
<tr>
<td>Qualification samples (extracted)</td>
<td>5/cable (major minor edges + 2 straight sections)</td>
</tr>
<tr>
<td>Coi** (witness samples)</td>
<td>6/coil (2 virgin and 4 extracted), Tested (1 virgin/ 2 extracted)</td>
</tr>
</tbody>
</table>

## From cable P43OL1134

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<th>AUP</th>
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<tr>
<td>Round samples</td>
<td>2/3 billet Supplier</td>
</tr>
<tr>
<td></td>
<td>1/ billet AUP</td>
</tr>
<tr>
<td>15 % rolled samples</td>
<td>1/billet supplier</td>
</tr>
<tr>
<td>Qualification samples* (extracted)</td>
<td>5/cable (major minor edges + 2 straight sections) by LBNL + 2/cable HT at FNAL</td>
</tr>
<tr>
<td>Coi** (witness samples)</td>
<td>6/coil (2 virgin and 4 extracted), Tested (minimum 1 virgin)</td>
</tr>
</tbody>
</table>

*Extracted form the cable, reacted by AUP
** Extracted form the cable, reacted with the coil
## MQXFA magnet: history

<table>
<thead>
<tr>
<th>Magnets</th>
<th>MQXFAP1</th>
<th>MQXFAP2</th>
<th>MQXFAP1b</th>
<th>MQXFA03</th>
</tr>
</thead>
<tbody>
<tr>
<td>coils</td>
<td>P2, P3, P4, P5</td>
<td>102, 104 105, 106</td>
<td>P2, P3, P4, P6</td>
<td>202, 204, 110, 111</td>
</tr>
<tr>
<td>cables</td>
<td>P35OL1060, P47OL1064, P45OL1069, P43OL1070A</td>
<td>P43OL1073, P43OL1081, P43OL1082, P43OL1084</td>
<td>P35OL1060, P47OL1064, P45OL1069, P43OL1095</td>
<td>P43OL1092, P43OL1099, P43OL1091, P43OL1098</td>
</tr>
</tbody>
</table>

- Coil P2 P3 and P4: OST 132-169 and OST 144-169 conductor
- Rest of the coils conductor is OST 108-127
- Extracted strands major and minor edges + 2 straight sections RRR’s started from cable P43OL1095
- 15 % rolled started from cable P43OL1070A
- No RRR data from Magnet testing (only coil pairs in MQXFAP1)
- First experimental data from MQXFA03
AUP – Estimate coil RRR

Strand data from vendor up to billet #463

- Rolled samples have around 100 smaller RRR than round wires
- 15% rolled samples RRR are good candidates for coil RRR predictions

\[
\left( \sum_i \frac{RRR_{ri} \times f_i}{N} \right) \times x
\]

Weighted mean of rolled samples RRR

Scaling factor to be determined by experimental data

L. Cooley, V. Lombardo, I. Pong, D. Turrioni
AUP – Estimate coil RRR: extracted samples

5 wires per cable from the representative spools of a cable

MQXFA03

4 set of data: major and minor edges and 2 straight sections.

Assuming $R_{300K}$ to be the same of each section, the RRR of the wire:

$$RRR_{tot} = \frac{4}{\frac{1}{RRR_{min}} + \frac{1}{RRR_{maj}} + \frac{1}{RRR_{s1}} \frac{1}{RRR_{s2}}}$$

Coil RRR prediction: $RRR_{tot} \times x$

Scaling factor to be determined by experimental data

Coil RRR data from MQXFA03 will be used to identify the best method

L. Cooley, V. Lombardo, I. Pong, D. Turrioni
Where we are with respect to initial estimates?

**CERN:**
- Initial range based on prototype experience 150-250
- Cable from series has a systematic offset of +70 due to the less aggressive heat treatment.
- The spread among cables seems a factor 2 smaller, but it is early to update numbers.

**AUP:**
- Initial range based on prototype experience 150-250
- Rolled and extracted samples are good candidates for RRR predictions
- Rolled samples are consisted with parameters used in simulations
Conclusions

• Based on CERN experience in MQXF and 11 T coils, the RRR of the coil can be predicted prior magnet assembly with the RRR measurements currently included in the QA plan.
  • From virgin to rolled $\rightarrow$ 100 reduction
  • Rolled are a good representation of the cable qualification strand (might be a bit conservative)
  • From cable qualification strand to average estimated in the coil $\rightarrow$ - 20 % reduction
  • From average estimate to measured average in the coil $\rightarrow$ offset of about 30

• Based on AUP experience:
  • From virgin to rolled $\rightarrow$ 100 reduction
  • Rolled or extracted strands could be a good representation of the cable

• Comparing parameter range with the current assumptions in simulations:
  • At CERN, there is a systematic shift of 70 due to the less aggressive heat treatment, and the spread among cables in series production is smaller. But it is early for an update on the reference parameters.
  • At AUP, verification of predictions will start with MQXFA03
Additional slides
AUP- RRP spool vs billet

Assumption: Spool RRR values are representative of billet RRR values
\[ y = x - 32 \]
\[ R^2 = 0.8746 \]