Plans for the 11T Dipole Quench Protection Heaters

67th Meeting of the HL-LHC Technical Coordination Committee


CERN – Room 30/7-010 – 2019-02-14 – https://indico.cern.ch/event/762917/
Outlook

- Introduction
- Chronology of events
- Findings, investigations, and current design of the QH
- New design, and how to do it
- Other ongoing tests
- Concluding remarks
Introduction

- Following
  - The technical meeting on the Quench Protection Heaters and Electrical Tests of the 11T Dipole held on 11 January 2019 at CERN, see Indico https://indico.cern.ch/event/778100/
  - The close out meeting held on 21 January 2019
  - The TETM meeting held on 21 January 2019, see Indico https://indico.cern.ch/event/762917/
  - Further technical discussions within the MSC Group
- It has been decided
  - To change the location of the quench heaters that will be installed on the impregnated coil (and not anymore on the reacted coil, then impregnated with the coil), as the first item prior to installation of the 5 layers of ground insulation
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Chronology of events

- In June 2018, the 11T dipole prototype LMBHB001 reached 1.9 K in SM18
- The cold tests were carried out in July 2018
- The tests results were not satisfactory, one coil, CR07, was limiting the performance well belows nominal
- It was then decided to disconnect Aperture 2 in order pursue the cold tests with only Aperture 1 powered
- Upon completion of the cold mass reconstruction, the electrical tests were repeated, as usually done on any sc magnet after consolidation in the large magnet facility
- **A systematic breakdown voltage was observed at circa 2.1 KV between the QH circuits and the coils, resulting in reduced electrical insulation, below 1GΩ**
Installation layout of the coils

**MBHP-AP1**

- **Upper pole**
  - External layer
  - YT111+ → YT121+
  - YT112- → YT122-
  - Internal layer
  - QH1 → YT121-
  - YT211+ → YT221+
  - YT212- → YT222-
  - QH5 → YT221+
  - QH7 → YT222-
  - CR05

- **Lower pole**
  - External Layer
  - YT111+ → YT112+
  - YT112- → YT122-
  - Internal layer
  - QH3 → YT112+
  - YT211+ → YT212+
  - YT212- → YT222-
  - QH4 → YT211+
  - CR04

**MBHP-AP2**

- **Upper pole**
  - External layer
  - YT211+ → YT221+
  - YT212- → YT222-
  - Internal layer
  - QH2 → YT221+
  - YT311+ → YT321+
  - YT312- → YT322-
  - QH6 → YT321+
  - QH8 → YT322-
  - CR07

- **Lower pole**
  - External Layer
  - YT211+ → YT212+
  - YT212- → YT222-
  - Internal layer
  - QH2 → YT211+
  - YT311+ → YT312+
  - YT312- → YT322-
  - QH4 → YT311+
  - CR06

Plans for the 11T Dipole Quench Protection Heaters - F. Savary @ TCC
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Hi-pot tests overview

<table>
<thead>
<tr>
<th>Coil name *</th>
<th>State of Hi-pot tested coils</th>
<th>History of coils</th>
<th>Hi –pot test sequence</th>
<th>Initial Breakdown voltage value</th>
<th>location</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR06, CR07 (MBH001)</td>
<td>collared</td>
<td>✓ (1) ✓</td>
<td>All QHs-coils, Hi pot dielectric test then individual C bank discharges</td>
<td>Brkd @ 2.1 kV</td>
<td>LF-strips</td>
</tr>
<tr>
<td>CR06, CR07 (MBH001)</td>
<td>bare</td>
<td>✓ ✓</td>
<td>Hi pot dielectric test + C bank discharges</td>
<td>Brkd slightly above 2 kV</td>
<td>LF-strips</td>
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<tr>
<td>CR 01</td>
<td>bare</td>
<td>✓ (3) x</td>
<td>Each QH, Hi pot dielectric test + insulation test</td>
<td>Brkd @ 8.5 kV</td>
<td>LF-strips</td>
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<tr>
<td>CR 02</td>
<td>bare</td>
<td>✓ (3) x</td>
<td>Each QH, Hi pot dielectric test + insulation test</td>
<td>Tested @ 4kV OK, i.e. no brkd</td>
<td>N/A</td>
</tr>
<tr>
<td>SP106</td>
<td>collared</td>
<td>✓ (1) ✓</td>
<td>Each QH, Hi pot dielectric test + insulation test, then C bank discharges</td>
<td>Brkd @ 2 kV</td>
<td>N/A</td>
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<tr>
<td>#114, #115</td>
<td>bare</td>
<td>✓ ✓</td>
<td>Each QH, Hi pot dielectric test + insulation test, then C bank discharges</td>
<td>Brkd @ 2.1 kV</td>
<td>LF-strips</td>
</tr>
<tr>
<td># 110</td>
<td>bare</td>
<td>x x</td>
<td>Each QH, Hi pot dielectric test + insulation test, then C bank discharges</td>
<td>Brkd @ 6 kV</td>
<td>LF-strips</td>
</tr>
<tr>
<td># 201</td>
<td>bare</td>
<td>x x</td>
<td>Each QH, Hi pot dielectric test + insulation test, then C bank discharges</td>
<td>Brkd @ 4kV surface to trace</td>
<td>LF-strips</td>
</tr>
<tr>
<td>SP107</td>
<td>collared</td>
<td>✓ ✓</td>
<td>Left QH, Hi pot dielectric test + ramp test</td>
<td>Brkd @ 2.8kV</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* Note: All coils but SP107 were made with turn insulation design before the Nov. 2017 change

Inter-layer QH
Current design of the HL-LHC Quench Heaters

- The quench heaters (QH) are large flexible circuits produced in a photolithographic process.
- In order to reduce the overall heater resistance the steel circuits are partially Cu coated.
- The series production of the QH is complete (32 were ordered), all QH are delivered.

- The base material of the heaters is a commercially available laminate (GTS laminate L960461), consisting of a **50-µm thick polyimide film** (Kaneka Apical AV) and a **25-µm thick austenitic stainless steel** EN 1.4307 (304L) hard temper foil.
- The steel foil is glued onto the film with a **15 µm-thick epoxy adhesive** (GTS AS1084). The steel surface of the laminate is electrolytically coated with an approximately **10 µm-thick Cu layer**.
- Overall, the thickness of the QH is comprised between 95 and 100 µm.
Destructive tests on LMBHB001 prototype (CR06-07)

- The initial QH to coil insulation resistance is in range of 2-3 GΩ after manufacture (virgin coils)
- Direct shorts provoked in collared coils were found in the same cross section on paired coils, with a residual resistance of few Ω
- The uncollared state requires higher test voltage to provoke degradation

Direct short created during severe Hi-pot tests on coil CR07: hole of 2 mm diameter, dumped $E_{TOT} > 1kJ$
3D rendering of the wires below defect CR06-2.20 m “microtomography”

Encircled wire region might show signs of Cu melting
μ-CT cross section of cable and cable insulation

- Cable insulation can be distinguished from background by a slight absorption contrast
- There are signs of insulation damage in the encircled region
μ-CT cross section of quench heater, cable and cable insulation in undamaged coil region

- No signs of insulation damage
- Distance between heater circuit and cable is about 180 µm
Plans for the 11T Dipole Quench Protection Heaters

Courtesy M.D. Crouvizier EN-MME
Insulation System Imperfections

C005-010005
• Delamination along the edge of a new long coil

Cross-section pictures of CR06 courtesy of M. Crouvizier EN/MME/MM

C005-010003
• Wrinkles in QH, probably linked to assembly procedure (mould opened several times – not regular procedure)

Coil #106 – cracks in resin

Plans for the 11T Dipole Quench Protection Heaters - F. Savary @ 2018
About thickness

Courtesy M.D. Crouvizier EN-MME

Plans for the 11T Dipole Quench Protection Heaters - F. Savary @ TCC
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Alternative to Impregnated Heaters

- Key parameters to be looked at
  - Quench heater delay, and the resulting hot spot temperature in the coil
  - The electrical insulation between the coil and the quench heater
    - Needs to meet the specification requirements in terms of dielectric
    - Needs not to impact the QH delay (thicker insulation means longer delay, which means higher hot spot T)

- Non impregnated heaters is retained
  - The QH is installed on the coil after impregnation
Overview on short model magnets tested

<table>
<thead>
<tr>
<th>MAGNET</th>
<th>COLLARED COIL</th>
<th>COIL</th>
<th>CONDUCTOR</th>
<th>cl/sc</th>
<th>COIL R AT 300 K</th>
<th>RRR</th>
<th>HEATER TYPE</th>
<th>GLASS HEATER-COIL</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>RRP 108/127</td>
<td>1.22</td>
<td>423</td>
<td>66</td>
<td>GLUED</td>
<td>0.00</td>
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<td>SP101</td>
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<td>CC102</td>
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<td>400</td>
<td>131</td>
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<td>0.08 (E-Glass)</td>
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<td>403</td>
<td>125</td>
<td>GLUED</td>
<td>0.08 (E-Glass)</td>
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<tr>
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<td>0.00</td>
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<td></td>
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<td>112 SP109</td>
<td>RRP 132/169</td>
<td>1.27</td>
<td>403</td>
<td>125</td>
<td>GLUED</td>
<td>0.08 (E-Glass)</td>
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<tr>
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<td>RRP 132/169</td>
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<td>125</td>
<td>GLUED</td>
<td>0.08 (E-Glass)</td>
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<td>CC104b</td>
<td>CC105b</td>
<td>RRP 150/169</td>
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<td>432</td>
<td>115</td>
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<td>0.00</td>
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<td></td>
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<td>CC106b</td>
<td>RRP 150/169</td>
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<td>436</td>
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<td>0.00</td>
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<td>190</td>
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<td>RRP 108/127</td>
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<td>CC109</td>
<td>SP109</td>
<td>RRP 108/127</td>
<td>1.19</td>
<td>409</td>
<td>*296K/20K</td>
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</table>

Final conductor
### Alternatives for the 11T Dipole Quench Protection Heaters

<table>
<thead>
<tr>
<th></th>
<th>Impregnated QH Baseline</th>
<th>Impregnated QH Enhanced</th>
<th>External QH 1</th>
<th>External QH 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable insulation thickness, @ 5 MPa [μm]</td>
<td>105</td>
<td>105</td>
<td>105</td>
<td>105</td>
</tr>
<tr>
<td>Cable insulation Dielectric Strength, Mica + resin [kV]</td>
<td>0.8 + 0.25</td>
<td>0.8 + 0.25</td>
<td>0.8 + 0.25</td>
<td>0.8 + 0.25</td>
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<tr>
<td>Coil to QH impregnated fiber glass wrap thick. [μm]</td>
<td>-</td>
<td>60</td>
<td>60</td>
<td>90</td>
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<tr>
<td>Coil to QH impregnated fiber glass wrap DS [kV]</td>
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<td>0.60</td>
<td>0.60</td>
<td>0.90</td>
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<tr>
<td>QH substrate thickness [μm]</td>
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<td>50</td>
<td>50</td>
<td>50</td>
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<tr>
<td>QH to coil insulation thickness, total [μm]</td>
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<td>215</td>
<td>215</td>
<td>245</td>
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<tr>
<td>QH to coil insulation Dielectric Strength [kV]</td>
<td>10.90</td>
<td>11.50</td>
<td>11.50</td>
<td>11.80</td>
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<tr>
<td>QH delay, @ $I_{\text{Nom}}$, and 150 A in QH [ms]</td>
<td>12.5</td>
<td>18.5</td>
<td>18.5</td>
<td>22</td>
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<tr>
<td>Expected hot spot T [K], @ $I_{\text{Nom}}$</td>
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<td>350</td>
<td>350</td>
<td>370</td>
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<tr>
<td>Expected hot spot T [K], @ $I_{\text{Ult}}$</td>
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<td>372</td>
<td>372</td>
<td>392</td>
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<tr>
<td>Expected hot spot T [K], @ $I_{\text{Nom}}$ - 1 QH circuit</td>
<td>327</td>
<td>357</td>
<td>357</td>
<td>377</td>
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<tr>
<td>Expected hot spot T [K], @ $I_{\text{Ult}}$ - 1 QH circuit</td>
<td>349</td>
<td>379</td>
<td>379</td>
<td>399</td>
</tr>
<tr>
<td>Expected hot spot T [K], @ $I_{\text{Nom}}$ - 2 QH circuit</td>
<td>333</td>
<td>363</td>
<td>363</td>
<td>383</td>
</tr>
<tr>
<td>Expected hot spot T [K], @ $I_{\text{Ult}}$ - 2 QH circuit</td>
<td>356</td>
<td>386</td>
<td>386</td>
<td>406</td>
</tr>
</tbody>
</table>
Impregnation mould / cavity

- Inside radius of form block: 61.5 mm
- Series coils:
  - Seal foil (paint on ID, and adhesive Teflon film on OD: 0.655 mm
  - Radius of the cavity: 60.845 mm
  - Radius of the mandrel: $29.77^2 + 0.115^3 = 29.885$ mm

1. As per following drawings:
   - Form block: LHCMBH_T0267
   - Mandrel: LHCMBH_T0259

2. Measured

3. Thickness of the adhesive Teflon film
Coil vs impregnation cavity – Impregnated QH

Outside radius of the coil = 60.899 mm / 60.787 mm (target of 60.800 mm on drawing)

Radius of the impregnation cavity (form block) = 60.845 mm / 60.945 mm

Radius of the impregnation mandrel = 29.885 mm / 29.823 mm

Radial compression of 0.054 mm / looseness of -0.158 mm

“Long coils vs short coils”

Coil as per drawing LHCMBH_C00005 (long)

<table>
<thead>
<tr>
<th>Long / Short</th>
<th>I. Radius [mm]</th>
<th>I. Wrap Glass fiber tissue [mm]</th>
<th>Cable insul. @ 5 MPa [mm]</th>
<th>Reacted cable height [mm]</th>
<th>Cable insul. @ 5 MPa [mm]</th>
<th>Interlayer [mm]</th>
<th>Cable insul. @ 5 MPa [mm]</th>
<th>Reacted cable height [mm]</th>
<th>Cable insul. @ 5 MPa [mm]</th>
<th>Quench heater [mm]</th>
<th>O. Wrap Glass fiber tissue [mm]</th>
<th>O. Radius [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long</td>
<td>29.885</td>
<td>0.150</td>
<td>0.105</td>
<td>14.847</td>
<td>0.105</td>
<td>0.500</td>
<td>0.105</td>
<td>14.847</td>
<td>0.105</td>
<td>0.100</td>
<td>0.150</td>
<td>60.899</td>
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<tr>
<td>Short</td>
<td>29.823</td>
<td>0.150</td>
<td>0.105</td>
<td>14.847</td>
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<td>0.500</td>
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<td>0.105</td>
<td>0.100</td>
<td>0.100</td>
<td>60.787</td>
</tr>
</tbody>
</table>
Plans for the 11T Dipole Quench Protection Heaters

Quench Heater

Copper
Steel
Glue

Kapton

Fiber Glass Wrap

9.0
6.0
10.0
25.0
15.0
16.0
150.0
Coil vs impregnation cavity – External QH

Outside radius of the coil = 60.709 mm / 60.647 mm

Radius of the **impregnation cavity** = 60.845 mm / 60.945 mm

Radius of the **impregnation mandrel** = 29.885 mm / 28.823 mm

The above implies a **radial looseness of** -0.136 mm / -0.298 mm

We can reduce the radial size of the cavity. This can be done by adding a thin metallic strip of 0.150 mm thickness (**0.150 to 0.300 mm for the short coils to be discussed**) between the seal foil and the form blocks >>> 60.695 mm (**60.795 mm if 0.150 mm is used**)
Design of the external Quench Heater

- Use the existing QH on which a 50 $\mu$m thick layer of polyimide, a coverlay, can be glued on the top in order to protect the circuit, i.e. the metallic part
  - Gluing implies 25 $\mu$m extra thickness
  - The coverlay gives robustness to the heater

- The overall thickness of the QH becomes 175 $\mu$m
- This can be done at the CERN PCB laboratory. Two prototypes were made successfully
- The QH can be flipped vertically such that the coverlay is on the side of the coil (this fresh, well inspected layer, will improve further the robustness of the electrical insulation between the coil and the QH)
New scheme

Ground insulation

Plans for the 11T Dipole Quench Protection Heaters - F. Savary @ TCC
Ground insulation

Plans for the 11T Dipole Quench Protection Heaters

Top of the pole

Bottom of the pole

Mid plane
On Radii and ground insulation layers [mm]

<table>
<thead>
<tr>
<th>Item</th>
<th>Impregnated QH Coil like on drawing</th>
<th>Impregnated QH Size based on impregnation cavity</th>
<th>External QH Size based on impregnation cavity</th>
<th>Model Impregnated heater</th>
<th>Model External heater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal coil radius (dwg)</td>
<td>60.800</td>
<td>60.800</td>
<td>60.700</td>
<td>60.800</td>
<td>60.700</td>
</tr>
<tr>
<td>Coil radius = Addition of the different elements</td>
<td>-</td>
<td>60.899</td>
<td>60.709</td>
<td>60.787</td>
<td>60.647</td>
</tr>
<tr>
<td>Coil radius = Cavity radius</td>
<td>-</td>
<td>60.845</td>
<td>60.695</td>
<td>60.860* (60.945)</td>
<td>60.710* (60.795)</td>
</tr>
<tr>
<td>Radial compression / looseness at impregnation</td>
<td>-</td>
<td>0.054</td>
<td>0.014</td>
<td>-0.158</td>
<td>-0.148</td>
</tr>
<tr>
<td>QH Thickness</td>
<td>-</td>
<td>-</td>
<td>0.175</td>
<td>-</td>
<td>0.175</td>
</tr>
<tr>
<td>GI-1 [R_{\text{Inside} + Thick}]</td>
<td>60.800 + 0.125</td>
<td>60.845 + 0.125</td>
<td>60.870 + 0.125</td>
<td>60.860 +0.125</td>
<td>60.885 +0.125</td>
</tr>
<tr>
<td>GI-2 [R_{\text{Inside} + Thick}]</td>
<td>60.925 + 0.125</td>
<td>60.970 + 0.125</td>
<td>60.995 + 0.125</td>
<td>61.070 +0.125</td>
<td>60.945 +0.125</td>
</tr>
<tr>
<td>GI-3 [R_{\text{Inside} + Thick}]</td>
<td>61.050 + 0.125</td>
<td>61.095 + 0.125</td>
<td>61.120 + 0.125</td>
<td>61.195 +0.125</td>
<td>61.070 +0.125</td>
</tr>
<tr>
<td>GI-4 [R_{\text{Inside} + Thick}]</td>
<td>61.175 + 0.125</td>
<td>61.220 + 0.125</td>
<td>61.245 + 0.125</td>
<td>61.320 +0.125</td>
<td>61.195 +0.125</td>
</tr>
<tr>
<td>GI-5 [R_{\text{Inside} + Thick}]</td>
<td>61.300 + 0.125</td>
<td>61.345 + 0.125</td>
<td>61.370 + 0.075</td>
<td>61.570 +0.125</td>
<td>61.320 +0.125</td>
</tr>
<tr>
<td>Outer radius, with GI and QH</td>
<td>61.425</td>
<td>61.470</td>
<td>61.445</td>
<td>61.485</td>
<td>61.510</td>
</tr>
</tbody>
</table>

*average of metrology on coils of SP107/SP109 (models)©
Outlook

- Introduction
- Chronology of events
- Findings, investigations, and current design of the QH
- New design, and how to do it
- Other ongoing tests
- Concluding remarks
Other ongoing tests

- Characterize the effect of compression on the dielectric strength of polyimide films
- Characterize the effect of compression on the dielectric strength of QH insulation system (type 10-stacks)
- Characterize the effect of flexure on the dielectric strength of QH insulation system, and on its mechanical behavior (determine failure mode, and understand crack propagation from resin to polyimide for a fully impregnated system)
- Characterize the behavior of the QH to coil insulation system in Paschen conditions (with contribution from TE-VSC, thank you!)
- Characterize the possible degradation of the QH to coil insulation system due to thermal cycling (ongoing for short CC assembly with contribution from TE-CRG, thank you! Will be done on the hybrid prototype)
- Carry out endurance tests at cold, characterize the effect of current cycling (170 beyond 10 kA on SP106, now 1075 on SP109), and of QH firing (130 on SP106, now 125 on SP109). These tests are being done on SP109, currently on the test bench in SM18. Impact of QH failure will be tested at cold.
- Carry out partial discharge tests
  - Very sensitive measurement, OK to detect miniature failures in insulation, e.g. bubbles and voids
  - Standardized test, used in industry, non-destructive
  - Good for benchmarking
Outlook

- Introduction
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- Findings, investigations, and current design of the QH
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Concluding remarks

- The four coils needed for the first magnet are finished, the four coils for the second magnet are well advanced, and will be equipped with impregnated heaters.
- Coil #10 will be the first equipped with external QH. It is now in preparation for impregnation.
- An ECR is in preparation to describe the change.
- It is proposed to buy components for the fabrication of up to 5 additional coils with external heaters, and 4 collared coils assemblies, in order to have the possibility to replace, if need be, those equipped with impregnated heaters.
  - The current service contract will provide up to 5 additional coils (30 as per contract, for 24 needed – 1 scrapped)
  - There is wire on stock for 5 additional cable unit lengths.
- The next model, made with PIT conductor, will be made with external QH.
Thank you for your attention
Design of the coil insulation system

The coil insulation system comprises:

1. Inter-turn insulation, or cable insulation
   - A layer of Mica in the form of a C-shaped tape of 80 μm thickness (FIROX™ 63P24A, 25 mm width, 700 m length, from the company http://www.cogebi.com, phlogopite mica paper reinforced by glass cloth impregnated with a specially selected high temperature resistant silicon resin)
   - A layer of braided S2-glass fiber of about 75 μm thickness
   - The total thickness of the cable insulation is therefore about 155 μm in free conditions and 100 μm under 30 MPa (actually comprised between 110 and 115 μm, or 130 μm under 5 MPa)

2. Ground insulation

*as from Nov. 2017

<table>
<thead>
<tr>
<th></th>
<th>Mica width “developed” [mm]</th>
<th>Total thick. @ 5 MPa [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Models till SP106</td>
<td>25</td>
<td>130</td>
</tr>
<tr>
<td>Prototype</td>
<td>25</td>
<td>130</td>
</tr>
<tr>
<td>Models from SP107*</td>
<td>31</td>
<td>105</td>
</tr>
<tr>
<td>Series*</td>
<td>31</td>
<td>105</td>
</tr>
</tbody>
</table>
Putting in place the QH
11T Dipole models / prototype made @ CERN to date

- Single Aperture OD 534 mm
  - MBHSP101
  - MBHSP102
  - MBHSP103
  - MBHSP104
  - MBHSP105
  - MBHSP106
  - MBHSP107
  - MBHSP108 to be built
  - MBHSP109

- Two-in-One OD 580 mm
  - MBHDP101

- Two-in-One OD 570 mm
  - MBHDP102
  - Prototype LMBHB001
  - Hybrid Proto LMBHP001 in construction

- 6 blocs
- 56 turns:
  - 22 in IL
  - 34 in OL
Slices from coil CR06 (prototype LMBHB001)

Courtesy M.D. Crouvizier EN-MME

Straight part

Transition with coil head
The defect CR06-2.20 m between quench heater circuit and Rutherford cables is visualised in the μ-CT images.

The μ-CT images indicate a direct short between heater circuit and cable through the polyimide foil, as was already speculated from the visual check after peeling off the stainless steel heater strip.

The origin of the dielectric weakness of the entire insulation system between Rutherford cable and quench heater circuit (i.e. the S2 glass and Mica cable insulation plus the CDT101K epoxy impregnation plus the 50 μm thick polyimide film) was not revealed by the μ-CT examination.
11 T prototype dipole quench heater defect CR06-4.80 m observed after provoking shorts to coil

- Defect CR06-4.80 m: Metal foil is partly melted and bare Cu cable is visible.
Impact of insulation on QH delay at nom. current

- Quench heater delay at nominal current, where the protection is critical, increases by:
  - 10 ms if we add 0.1 mm of S2 impregnated glass between heater and coil
  - 17 ms if we add 0.15 mm of S2 impregnated glass between heater and coil

![Graph showing the impact of insulation on quench heater delay.](image)

(Courtesy Susana Izquierdo Bermudez)
Impact of QH delay on hot spot temperature

**Courtesy Susana Izquierdo Bermudez**

- **320 K** @ $I_{\text{nom}}$, nominal protection parameters, no failure.
- **370 K** @ $I_{\text{nom}}$, additional 0.1 mm G10 between heaters and coil, no failure.
- **420 K** @ $I_{\text{nom}}$, additional 0.15 mm G10 between heaters and coil, no failure.

Experience from High MIITs studies in SP106

- No degradation
- 2% degradation on the load line

![Graph showing hot spot temperature vs. additional time required to quench](#)

**Adiabatic Cable Temperature,**

- $B = 12$ T, RRR = 100
- HT Block 3,
- Adiabatic estimate

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