11T Dipole short model coil metrology at cold and measurement of thermal contraction

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11T Dipole measurement demand

- Demand from the HL-LHC Work Package 11
  - Second task force on 11 T dipole magnet following a CERN Machine Advisory Committee review

- Deformation measurement of 11 T short model dipole to define the coefficient of thermal contraction (CTE)
  - warm measurement at room temperature
  - cold in nitrogen gas just above liquid (> 77 K)

- Measurement precision < 100 micron

- Preparation time 6 weeks
Test set-up of Cryolab

- Installation with dummy load
- Test occasion for survey team:
  - Isostatic support
  - Target type and target size
  - Influence of vapour cloud
  - Cool down and warm-up time and achievable temperature difference
  - Sensible to air humidity
- Validation of procedure, equipment, precision and useable time slot
Photogrammetric set-up

Setup prepared by TE-CRG-CI

- 11 T model coil on isostatic supports
- Cool-down with liquid nitrogen bath
- Covered during cool-down/warm-up
- Temporarily opened for the photogrammetric measurement
- Scale bars and photogrammetric coded targets outside the cold bath
Temperature data

- Detailed data for cold measurement
- Inhomogeneous temperature distribution for cold measurement

<table>
<thead>
<tr>
<th>Series</th>
<th>Max – Min (K)</th>
<th>Average (K)</th>
<th>( \Delta T ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1-Warm</td>
<td>1.3</td>
<td>291.81 ± 0.17</td>
<td>M2 - M1 = - 177.68</td>
</tr>
<tr>
<td>M2-Cold</td>
<td>14.8</td>
<td>114.13 ± 3.81</td>
<td>M3 - M2 = - 177.54</td>
</tr>
<tr>
<td>M3-Warm</td>
<td>1.6</td>
<td>291.67 ± 0.29</td>
<td>M3 - M1 = - 0.14</td>
</tr>
<tr>
<td>M4-Warm</td>
<td>0.8</td>
<td>288.62 ± 0.16</td>
<td>M4 - M1 = - 3.19</td>
</tr>
</tbody>
</table>

Temperature during photogrammetry data acquisition
11 T short model coil (02.02.2020)
Photogrammetric equipment

AICON DPA-Pro (Hexagon) for analysis

2 cameras
• 1x Canon 5DS, 28 mm lens
• 1x Nikon D3X, 28 mm lens

10-12 reference scales (carbon fibre)

Non-coded targets
• Self-adhesive foil stickers on loading plates, thickness 70 µm, Ø 3 mm
• Self-adhesive paper stickers on coil, thickness 100 µm, Ø 2 mm
# Measurement constraints

## Constraints

- Thin vapour cloud on top of “swimming pool”
- After few minutes a small ice layer forms on the targets and coil
- High temperature gradient for measurements rays
- Points distributed on multiple surfaces

## Consequences

- Reduced visibility for target measurement
- Limited time for data acquisition
- Small number of missing points in individual measurements
- Decreased precision of measurement in cold
- Increase of measurement time
Coordinate system definition

Origin: intersection of the cylinder axis and the mean plane of targets on the connection side end.

X-axis: perpendicular to the two others in a right handed Cartesian Coordinate System.

Y-axis: in direction of the loading plates.
- The average angle of the calculated mean planes for the two loading plates is defined as 0°.

Z-axis: calculated best-fit cylinder axis

Only for the 1st warm measurement!
Point distribution on 11T model coil (I)

List of measured surface

- 2 layers of 10 targets per end face
- 12 targets per section and 4 additional in loading plate area
- 4x sections on connection end
- 3x sections on short end
- 21x sections (every 75 mm) in the area of the loading plates
- If possible, targets on the key surface
Point distribution on 11 model coil (II)

End surface of the coil
(View side from connection end)

End surface of the coil
(View side from non-connection end)
At least ~400 photos

~600 measured points

> 70000 observations

~4100 unknowns

Average RMS of 3D coordinates ~5-15 µm

RMS of scale residuals ~5-15 µm
Preparation Deformation Analysis

Analysis based on 7-parameter least-square transformation

(3 translations, 3 rotations, 1 scale factor)

Reference measurement
01.02.2021 (warm)
• 7-DOF transformation for cold 02.02.2021
• 7-DOF transformation for warm 03.02.2021
• 7-DOF transformation for warm 11.02.2021

Outputs:
• Residual deformations after application of global scaling factor (slides 14-18)
Deformation Analysis X-direction (I)

Cold To Reference

The loading plates open by +0.40 mm

Warm After To Reference

The loading plates open by +0.25 mm

Analysis of residuals after application of global scale factor!
Deformation Analysis Y-direction (II)

Cold To Reference

The coil is bended by +2.9/-1.9 mm

Warm After To Reference

The coil is bended by +1.8/-1.2 mm

Analysis of residuals after application of global scale factor!
Deformation Analysis Z-direction (III)

Cold To Reference

The coil is twisted by +0.26 mm

Warm After To Reference

The coil is twisted by +0.15 mm

Analysis of residuals after application of scale factor!
Estimation of thermal contraction

Procedure to get best estimated scale factor of “bended” coil

Bending of nearly 5 mm could influence the global scale factor in the least square 7-parameter transformation

The following procedure has been used instead:

• Transformation 6 DOF (3 translations, 3 rotations, scale fixed to 1.0) to get in the coordinate system of the reference measurement.
• Transformation 4 DOF to get the scale factor (translation XZ, rotation Y, scale factor in XZ plane)
• Correction for bending (difference of arc to straight line)
Estimation of thermal contraction

Reference to Cold

Result using XZ coordinates of all points on coil surfaces:

- Cold to reference (no correction)
  - 2.285 mm/m (1σ = 13 µm)
  - 12.86 µm/m/K
- Final contraction after bending correction:
  - 2.269 mm/m
  - 12.77 µm/m/K

Reference to Warm (after test)

Even after warm-up the 11 T model coil stays bended/twisted

The form is significantly different from the zero measurement before the test

Warm (2nd) to reference measurement

- -0.099 mm/m
- The coil is longer than before
Conclusion (deformation and CTE)

- The 11T model coil contracts but also bends (4.85 mm), twists (0.26 mm) and the pole opens during the cold test (±0.4 mm)

- The form of the 11T dipole short model coil changes significantly after cooling cycle. The residual bend after the cold test is permanent and significant.

- The best estimate of a global CTE is 12.8 ± 0.3 μm/m/K for the difference from room temperature and a ΔT ≈ 177.68 K but probably more than a single coefficient needs to be taken into account to characterize the coil as a composite structure.
Conclusion (photogrammetry)

• The photogrammetric measurements in cryogenic condition has been successfully completed despite the harsh environmental conditions and the 3D measurement precision has been close one of the room temperature measurement.

• Statistical data for image measurement precision and scale bar residuals have been at the same level for warm and cold measurements.

• The homogeneous temperature of the coil and the corresponding measurement is crucial for the setup. Modification of setup for MQXF with immersed coil.