Consequences of warming-up
a sector above 80 K

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A warm thank you to those who contributed to this presentation, in particular D. Bozzini, N. Catalan, D. Duarte, B. Jenninger, S. Russenschuck, A. Siemko, J.-P. Tock, R. Veness, U. Wagner and L. Williams
Outline

• Introduction

• Expected thermally induced movements

• Strategy on a fully warmed-up sector
  – For the PIMs
  – For the electrical quality controls

• Strategy on a partially warmed-up sector
  – Observed temperature profiles
  – Consequences for the PIMs
  – Consequences on the electrical quality controls
Introduction

• **First buckled PIMs found in Summer 2007**
  - Found by chance by inspecting around the dipole which had to be exchanged
  - Reason traced back to a wrongly documented non-conformity
Thermally induced movements (1)

- Thermal contraction not proportional to $T$
Thermally induced movements (2)

- Only about 6% of contraction between 80 K and 1.9 K
  - Safety no longer considered as an issue
  - PIMs should not be permanently deformed

Δl ≈ 2.2 mm for a QQBI type

- Can there be damages on electrical circuits?
Arc completely warmed-up: PIMs

• Most, if not all, PIMs in the arc are non conform
  – “Ball” or “Sputnik” test
    • Today from Q7 to Q7, endoscopic inspection between Q7 and DFB
    • Later from RT side of continuous cryostat
  – Repair both PIMs (line V1 and V2) if a faulty one is discovered

We may be safe at the next warm-up, but so far we have only the experience of the extremities of sector 4-5 (2 warm-up)

– Exchange the PIMs at the extremity of the arcs
  • Between Q7 and MBA
– Exchange PIMs between Q11 and interconnection cryostat

We will be safe during partial warm-up during 4 – 5 weeks
Arc completely warmed-up: EIQA

- Re-qualify the circuits (minimum HV test at cold)
  - There have been faults observed during cool-down
    - Interconnection cryostat
    - Q11L8: short during cool-down, disappeared after warm-up

Electrical quality control is similar to leak detection on a vacuum system: **must be done after any intervention on the circuits**
Evolution of temperature in arc 4-5 right of IP4

Slope 2 to 3 K a day

- LCNAA_07R4_TT821 [K]
- LBALE_08R4_TT821 [K]
- LBBLF_08R4_TT821 [K]
- LCNCD_08R4_TT821 [K]
- ARC45_MAGS_TTAVG [K]
Evolution of temperature in arc 4-5

Left of IP5

Interconnecting cryostats

4 February 2009

Chamonix 2009
Consequence on the PIMs (1)

- The most vulnerable PIM is compressed by 7.2 mm
  - If both Q7 and downstream dipole are at 125 K

**Calculations by D. Duarte**

Reference (non constrained finger)

Compressed by 8 mm

Back to nominal at cold

$\Delta l \approx 7.2$ mm for a QQBI type

Minimum as per specification

Residual force after cool-down of a partially buckled finger

4 February 2009

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Consequence on the PIMs (2)

- **Buckling tests**

  Compressed by 10 mm

  Residual deformation after \( x = 10 \) mm

  - At room temperature, in air
  - Using real LHC components (recovered from 7-8)
  - Block the fingers extremities in position to simulate ‘cold welding’ during a partial warm-up
  - Measure initial finger diameter \((d1)\)
  - Compress PIM by \( x \) mm, simulating a partial warm-up
  - Return to installed position and measure finger diameter \((d2)\) – ‘residual plastic deformation is \((d1-d2)\)’
Consequence on the PIMs (3)

- Results of buckling tests

<table>
<thead>
<tr>
<th>Compression from cold position</th>
<th>Residual plastic deformation (test1)</th>
<th>Residual plastic deformation (test2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 mm</td>
<td>-</td>
<td>0 mm</td>
</tr>
<tr>
<td>5 mm</td>
<td>0.5 to 2.5 mm</td>
<td>0.1 to 0.7 mm</td>
</tr>
<tr>
<td>7 mm</td>
<td>1.2 to 3.5 mm</td>
<td>1.2 to 2.6 mm</td>
</tr>
<tr>
<td>10 mm</td>
<td>2.5 to 6.7 mm</td>
<td>2.2 to 6.3 mm</td>
</tr>
</tbody>
</table>

- Application to observed temperatures in arc 4-5

<table>
<thead>
<tr>
<th>Magnet 1 (temperature)</th>
<th>Magnet 2 (temperature)</th>
<th>Calculated compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q7R4 (121 K)</td>
<td>MBB (95 K)</td>
<td>3.6 mm</td>
</tr>
<tr>
<td>MBB (95 K)</td>
<td>MBA (70 K)</td>
<td>2.3 mm</td>
</tr>
<tr>
<td>MBA (70 K)</td>
<td>Q8R4 (67 K)</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Q8L5 (75 K)</td>
<td>MBA (75 K)</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>MBA (75 K)</td>
<td>MBB (75 K)</td>
<td>1.1 mm</td>
</tr>
<tr>
<td>MBB (75 K)</td>
<td>Q7L5 (95 K)</td>
<td>1.5 mm</td>
</tr>
</tbody>
</table>
Evolution of temperature in LSS left of IP5
Consequence on the PIMs (4)

• So far, no buckled PIM found in LSS
  – Also non-conform, but seem less vulnerable
    • Shorter span
  – Not in all standalone cryostats
    • Triplet, D2Q4 and (only in IP4) Q5/D4 and D3/LU

• Proposal
  – Repair all PIMs in LSS during this shutdown
    • Priority on triplets (first activated -> ALARA)
  – If not possible (resources or time)
    • Inspect with endoscope and repair if required
      – Needs to be at room temperature
      – May need to vent neighbouring vacuum sector
    • Later in the year, use X-ray tomography
X-Ray Tomography

- Tests on a mock-up very convincing

Order to be placed this week after
- market survey
- invitation to tender
- “fast track” procedure at FC
Delivery expected early September 2009
What about EIQA?

• **Displacement during 4 – 5 weeks maintenance**
  – Below 20% of full expansion (to room temperature) on any part of magnets and bus-bars
  – Should no be a problem if everything is built as designed
  – But there is always a movement, even if it is only 6% at 80 K

• **Consider**
  – There can be (as yet not identified) unwanted contacts between insulation and other pieces
    • Was the case of the interconnecting cryostat
  – More than one cycle possible during a shutdown
    • E.g. longer than foreseen maintenance or tunnel repairs
  – Longer periods than 4 – 5 weeks -> higher temperatures
    • Minimise cryogenics operation during shutdown
      – To be considered once the PIMs at extremities of the arcs and the LSS are consolidated
Proposal for EIQA

• After a full warm-up
  – With modification of electrical circuits
    • (e.g. exchange of a magnet)
    
    Full qualification at room temperature and at cold (ELQA-TP4 and ELQA-DOC)
  – Without modification of electrical circuits
    
    High voltage qualification at cold (ELQA-TP4)

• After a partial warm-up
  
    High voltage qualification at cold (ELQA-TP4)
  – At cold means magnets not warmer than 2.1 K
  – Foresee 2 weeks per sector
    • Some parallelism is possible
Conclusions

• Strategy to consolidate the PIMs now clear
  – Repair systematically the most vulnerable ones
    • Extremities of the arcs and LSS
  – Continue to use the “ball” or “sputnik” test when warm
  – Use X-ray tomography when in doubt
    • Available in August / September 2009

• Recommendation to perform EIQA
  – Full procedure after full warm-up and modifications
  – At least HV test after full warm-up without modifications or partial warm-up