Thermal Qualification of the HL-LHC Beam Screens for the Inner Triplets

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Outline

- Introduction to the HL-LHC beam screen
- Overview of requirements
- Thermal validation test stand: emulating HL-LHC thermodynamic conditions
- Summary of measurement runs
- Results & discussion
  - Run #1
  - Run #2
- Conclusions and outlook
HL-LHC beam screens: overview (D1-type)

- **cold bore**
  - $T = 1.9$ K
  - cooled by He II
  - pressurised bath / saturated loop

- **inner beam screen**
  - intercepts synchrotron radiation

- **cooling tube**
  - $T = 60$ K to 80 K
  - circulates He at 20 bar

- **thermal link**
  - connects the absorber to the cooling tube

- **absorber radiation shield**

- **ball bearings / springs**
  - supporting system

- **≈120 mm**
HL-LHC beam screen mock-up (D1-type)

0.8 m full-scale prototype (cooling tubes connected in series for initial pressure tests)
Piping & Instrumentation Diagram

- **He II pressurised circuit**
- **He II saturated circuit**
- **Pre-cooling and expansion from 4.2 K**
- **4.2 K liquid He guard and supply**
- **Heatmeter / rupture disk**

**BS circuit:** supercritical He at 20 bar, 60 K - 80 K

**beam screen mock-up**

**annular He II pressurised space at 1.9 K, 1.1 bar**

**annular LHe guard**

**Heatmeter**

**He II saturated pot**

**to pump**

**JT valve**

**cold circulator**

**HEX to PTR**
HL-LHC beam screen test stand at the Cryolab
Requirements and first measurement run

- Operating $T$ of beam screen (inner surface): 60 K to 80 K
- Maximum allowed $\Delta T$ over 60 m: 15 K (5 K in radial direction)
- Operating $T$ of the helium flow: 55 K to 75 K

- Nominal heat load on the tungsten blocks: 15 W/m
- Working fluid: supercritical helium, 17 bar – 23 bar
- Mass flow rate of helium circuit: $\approx 11$ g/s
- Maximum heat load to 1.9 K bath: 0.5 W/m
Results: beam screen temperature profile

- Steady-state measurements
- Homogeneously distributed heat load on all 4 quadrants (0 to 20 W/m)
- Varied base (helium) temp. between 40 K and 80 K
- Pressurised He II bath (cold bore) actively controlled at 1.9 K ± 1 mK

![Graph showing temperature differences](image)

**Requirement** $\Delta T < 5$ K

Low $\Delta T$ on tungsten blocks
Measuring the heat load to the 1.9 K cold bore

- Heat load transmitted to the 1.9 K bath (cold bore) by radiation and conduction
- Requirement < 0.5 W/m
- Conduction through each of the 32 spring + sphere sets
- Radiation from the tungsten and beam screen surfaces
Results: heat load to the 1.9 K cold bore

Heat load from beam screen to cold bore in HL-LHC environment

200 mW/m if beam screen is at 60 K, 375 mW/m if beam screen is at 80 K → 17 W over the 60 m
Results: heat load to the 1.9 K cold bore

200 mW/m if beam screen is at 60 K, 375 mW/m if beam screen is at 80 K → 17 W tover the 60 m

For operational beam screen (and Inermet block) temperatures, most of the heat load to the 1.9 K cold bore is transferred via conduction through the springs (90% at 60 K and 70% at 80 K)
Results: thermal time constants “beam ON → beam OFF”

- Time constants of the tungsten blocks rise with rising base temperature

- Steady state in $\approx 5\tau$:
  - $\approx 43$ min at 60 K
  - $\approx 75$ min at 80 K (tungsten at 90 K)
Results: thermal time constants “beam ON → beam OFF”

- Time constants of the tungsten blocks rise with rising base temperature

- Steady state in \( \approx 5\tau \):
  - \( \approx 43 \text{ min at } 60 \text{ K} \)
  - \( \approx 75 \text{ min at } 80 \text{ K} \) (tungsten at 90 K)
Results: uneven heating on beam screen quadrants

- Nominal overall heat load on beam screen (15 W/m)
- Unevenly distributed heat load
- Base temperature kept constant
- Influence of heat load distribution on tungsten and beam screen temperatures
- Influence of heat load distribution on 1.9 K bath

![Graphs showing temperature changes with heat load distribution](image)
Results: uneven heating on beam screen quadrants

<table>
<thead>
<tr>
<th></th>
<th>Nominal heating</th>
<th>Uneven “South”</th>
<th>Uneven “Northeast”</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>60 K</td>
<td>70 K</td>
<td>80 K</td>
</tr>
<tr>
<td>Min. $\Delta T$ to base $T$</td>
<td>7.8 K (S)</td>
<td>7.8 K (S)</td>
<td>7.7 K (S)</td>
</tr>
<tr>
<td>Max. $\Delta T$ to base $T$</td>
<td>9.0 K (E)</td>
<td>8.9 K (E)</td>
<td>8.9 K (E)</td>
</tr>
<tr>
<td>Heat load to 1.9 K</td>
<td>189 mW</td>
<td>243 mW</td>
<td>282 mW</td>
</tr>
</tbody>
</table>

Even though heat load on BS is the same, heat load transferred to 1.9 K bath changes → south quadrant dominates heat transfer (2 rows of springs)
Conclusions for the first run

- Maximum temperature rise on inner BS: 0.5 K
  - Factor 10 lower than max. allowed (nominal conditions)

- Maximum temperature rise on tungsten blocks: 9 K (nominal conditions)
  - Independent of base temperature
  - Highly linear with increasing heat loads

- Heat load to 1.9 K cold bore: 200 mW to 375 mW per meter (nominal conditions, 60 K to 90 K tungsten blocks temp.)

- Thermal time constants tungsten blocks 0-15 W/m: 9 min to 15 min, temp.-dependent

- Uneven heat loads show no instabilities in the flow
Parameters for the second measurement run

- Identical run to assess \textit{reproducibility} of results
- Base temperature varied from \textbf{40 K to 90 K}
- Heat load on beam screen varied from \textbf{0 to 20 W/m} (fewer steps)
- \textbf{Beam screen circuit pressure} varied from 17 bar to 23 bar
Results: beam screen temperature profile (both runs)

Mean $\Delta T$ between tungsten blocks and base temperature

Max $\Delta T$ between inner surface of BS and base temperature
Results: heat load to the 1.9 K cold bore (both runs)

Tungsten block temperature
(base $T$ of cooling tubes + $\Delta T$
due to heat load of 15 W/m) drives heat load to 1.9 K

Fit curve:
Data from measured springs
Radiation with emissivity values
of 0.10 and 75% of total beam screen area
Conclusions & Outlook

New measurement run will focus on analysing what happens to the overall 1.9 K heat load if the beam screen touches the cold bore (motivated by the tolerances between beam screen and cold bore)

Experimental results validate the thermal design of the HL-LHC beam screens
Thank you for your attention!