Measurements of temperature on LHC thermal models

Christine Darve¹, Juan Casas², Moyses Kuchnir¹

¹: Fermi National Accelerator Laboratory, Batavia, IL, USA
²: CERN, European Laboratory for Particle Physics, Geneva, CH
Measurements of temperature on LHC thermal models

- Thermal measurements on models
  - Presentation of both projects
  - Sensors implementation
  - Results

- Use of cryogenic thermometers at Fermilab and at CERN

- Uncertainty evaluations
Introduction to LHC thermal models

Inner Triplet heat exchanger test unit (US-IT-HXTU)

- Validation of the Inner Triplet cooling scheme
  - Heat transfer based on the exchange between the two-phase saturated He II used to extract heat loads generated in the stagnant pressurized He II bath.
  - Extreme heat loads due to the detector proximity: nominal Q’=7 W/m.

- Investigation in a linear model-based predictive control
  - Reduce requirements on temperature sensor, cryogenic sys. performance
  - Self-regulating process

- Related project: Small scale heat exchanger test
  - Material property measurements: Kapitza resistance.
  - Results used to estimate the wetted area of the full-scale model.
From the LHC Inner Triplet to the Inner Triplet heat exchanger test unit

- Four modules
- Magnet simulators
- Full helium capacity

IT to Thermal model
Inner triplet heat exchanger test unit
Modules

Heat exchanger pipe

Safety valve

Instrumentation port flange

8 cryogenic thermometers
2 heaters
Inner triplet heat exchanger test unit
Piping system

Heat exchanger tube
Pressurized He circuit
Shield cooling pipes
Sat He II supply
Magnet simulator
Inner triplet heat exchanger test unit

Instrumentation port flange

Feed-box---

---Turnaround
Inner triplet heat exchanger test unit
Thermal measurements on the US-IT-HXTU

Why do we perform thermal measurements?

- To measure the temperature rise along the He II heat load path, for different LHC heat load scenarios -> maximum: heat load, Tsat.
- To understand the behavior of He II (co-current two-phase flow, wetted area).
- To calibrate and measure the performance of the HX tube.
- To validate the theoretical model -> ultimate LHC condition (472W).

Function of temperature measurements

- Display the transport of the heat load from pressurized to saturated He II.
- Indicator to check the evolution towards steady-state conditions.
- Variable parameter, Tsat, for various measurements of the HX tube performance.
Thermal measurements on the US-IT-HXTU

How are they implemented?

- Glued to printed circuit board (PCB) card.
  - Thermometers immersed in pressurized He II bath along the HX tube (pressurized side) and magnet simulator pipes.
  - Thermometer wires routed through a 3 m long feedthrough from the pressurized He II bath to the room temperature.

- Measurement of the saturated temperature provided from the pressure measurement.
  - To reduce air leaks through the instrumentation feedthrough (subatmospheric circuit).
Thermal measurements on the US-IT-HXTU

Saturated He II

Pressurized He II

Outer shell of the HX

Connector @ Room temperature

Cernox mounted on the card

Gold plated contacts
Thermal measurements on the US-IT-HXTU

DT1: from the Module thermal center, to the module end within the pressurized He II

DT2: within the connecting pipe

DT3: between connecting pipe and He II HX

DT4: within the pressurized He II side of He II HX

DT5: across the He II heat exchanger wall

DT6: due to the vapor pressure drop.

Vapor \( V = 448 \text{ cm/sec} \)
Thermal measurements on the US-IT-HXTU

Heat transfer into and through pressurized He II (DT 1 - 4)

One-dimension model
In steady-state, heat flux $Q'$ is given by:

$$Q' = S \left( \frac{X(T_c) - X(T_w)}{l} \right)^{0.29}$$

$$X(T) = 520 \cdot \left( 1 - e^{-\left(3 \cdot 2.16 - T\right)^{2.5}} \right)$$

![Diagram of heat transfer through pressurized He II](image)
US-IT-HXTU- Small scale HX

Kapitza Resistance and DT 5

\[ R_{th} = \frac{(T_{\text{pres}} - T_{\text{sat}})}{Q_{\text{elec}}} \]

\[ R_{th} = 2 \cdot R_{\text{Kapitza}} + R_{\text{Cu}} = \alpha(1/T_{\text{pres}}^3) + \beta \]

\[ \alpha = \frac{2}{C_{\text{Kapitza}} \cdot S} \]

\[ \beta = \frac{e}{S \cdot C_{\text{Cu}}} \]

Ch. D. 12/05/00  Measurements of temperature on LHC thermal models  14
Thermal measurements on the small-scale heat exchanger test unit - results

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>#1 - OFHC</th>
<th>#2 – OFHC + HCl</th>
<th>#3 - Bronze</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD/ ID (mm)</td>
<td>97/86</td>
<td>97/86</td>
<td>123/101</td>
</tr>
<tr>
<td>Wall thickness (mm)</td>
<td>0.7</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Corrugation depth (mm)</td>
<td>5</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Corrugation pitch (mm)</td>
<td>12.4</td>
<td>12.4</td>
<td>11.7</td>
</tr>
<tr>
<td>Surface (cm²) for one side</td>
<td>416</td>
<td>416</td>
<td>978</td>
</tr>
<tr>
<td>Shape of the corrugated pipe</td>
<td>Helical</td>
<td>Helical</td>
<td>Bellows</td>
</tr>
<tr>
<td>Surface treatment</td>
<td>None</td>
<td>Hydrochloric acid</td>
<td>None</td>
</tr>
<tr>
<td>Results</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CKapitza (W·K⁻⁴·m⁻²)</td>
<td>893</td>
<td>1138</td>
<td>565</td>
</tr>
<tr>
<td>Kapitza conductance @ 1.85 K (W·K⁻¹·cm⁻²)</td>
<td>0.565</td>
<td>0.72</td>
<td>0.357</td>
</tr>
<tr>
<td>Thermal conductivity @ 1.85 K (W·K⁻¹·m⁻¹)</td>
<td>88</td>
<td>88</td>
<td>2.4</td>
</tr>
<tr>
<td>Relative performance</td>
<td>Ref.</td>
<td>27%</td>
<td>-37%</td>
</tr>
</tbody>
</table>

Bronze (95%Cu-5% Sn)
OFHC-US-IT-HXTU
OFHC+ HCl
US-IT-HXTU - Nominal Condition: 248 W

Ch. D. 12/05/00 Measurements of temperature on LHC thermal models
US-IT-HXTU - Ultimate Condition: 315 W
C/C: The difference of temperature on the heat exchanger interface < 50 mK.
The thermal gradient within the heat exchanger pipe is still to be measured in december at CERN.
Thermal measurements on the US-IT-HXTU

Heat loads on the US-IT-HXTU extrapolated from the heat load in the Inner Triplet at IP5 or IP1, by Tom Peterson.

Example for Tsat= 1.915 K, Q’tot= 315 W

Equations:

\[ \frac{dT}{dx} = -f(T) q^m \]

\[ \Rightarrow \Delta T = \frac{q^3L}{1200} \]
Introduction to LHC thermal models

Cryostat thermal model (CTM)

- Measurements of the LHC cryostat dipole performance
  - + Heat loads to the actively cooled shield and to the dummy cold mass.
  - + Components performance:
    - ➔ Multi-Layer Insulation,
    - ➔ support posts,
    - ➔ beam screen,
    - ➔ cryogenic thermometers.

- Conditions under investigation
  - ➔ Steady-state and transient modes for the LHC conditions
  - ➔ Insulation vacuum degradation

- Adoption of an actively cooled screen @ 5-10 K (CTM3)?
Thermal measurements on the CTM
Thermal measurements on the CTM

View of the radiation screen

View of the dummy cold mass
Thermal measurements on the CTM

LHC accelerator cross-section

CTM3 cross section
Thermal measurements on the CTM

Cryostat Thermal Model 3

Legend
- TPl: Platinum sensor
- TC: Carbon sensor
- Pe: Pressure sensor
- HeL: Level sensor
- Q: Heater
- F: Flowmeter
- V: Flow valve
- Safety valve

Ch. D. 12/05/00
Measurements of temperature on LHC thermal models
Thermal measurements on the CTM

Performance of the thermal shield (50-75K) and radiation screen (5-10K)

The temperature is measured at each extremity of the helium pipes

\[
Q' = m' \cdot \Delta H
\]

\(\Delta H = \text{enthalpy difference}\)

Heat load to the dummy cold mass

Heat load to the dummy cold mass is measured with the boil-off method

\[
Q_{1.9K}' = m' \cdot L
\]

\(m' = \text{mass-flow,}\)

\(L = \text{latent heat of vaporization}\)
Implementation of sensors on the CTM

On a pipe

On the shield
Implementation of sensors on the CTM

In the MLI

Thermalization of the instrumentation wires
Some results - CTM2

Total heat load measured:

<table>
<thead>
<tr>
<th>Heat inleak [W/m]</th>
<th>@ 50-75 K / Line E+F</th>
<th>@ 5-10K / Line C+D</th>
<th>@ 1.9 K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>measured</td>
<td>calculated</td>
<td>measured</td>
</tr>
<tr>
<td>CTM1</td>
<td>4.78</td>
<td>4.58</td>
<td>0.23</td>
</tr>
<tr>
<td>CTM2</td>
<td>4.32</td>
<td>4.12</td>
<td>0.48</td>
</tr>
</tbody>
</table>

The contribution of the feed box on the measured He in-leak at 1.9 K is estimated to 390 mW.

Ch. D. 12/05/00
Measurements of temperature on LHC thermal models
CTM3 - Some results

Influence of the insulation vacuum degradation

Averaged heat loads (Watts): Insulation vacuum $7.5 \times 10^5$ Pa

<table>
<thead>
<tr>
<th>Component</th>
<th>Average Temperatures K</th>
<th>50-75 K</th>
<th>5-10 K</th>
<th>1.9 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply and return boxes</td>
<td></td>
<td></td>
<td></td>
<td>0.300</td>
</tr>
<tr>
<td>Thermal shield</td>
<td>68</td>
<td>8.7</td>
<td>43.2</td>
<td>3.1</td>
</tr>
<tr>
<td>Radiation screen</td>
<td></td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold-mass</td>
<td>14.9</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support System</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total CTM Cryostat</td>
<td>28.3</td>
<td>2.0</td>
<td></td>
<td>0.012</td>
</tr>
</tbody>
</table>

- CTM3, dummy cold mass experienced He leaks
  - results difficult to interpret.
- MLI qualification on an horizontal cryostat was performed.
- Choice of the shield assembly: welded to the extruded pipe

C/C: Since the cost of a radiation screen material is dominant and even if a better performance with a 5K cryostat was measured, the LHC cryostat will only consider to wrap 10 layers of MLI around the cold mass. No rigid radiation screen (5-10 K) will be used in the LHC accelerator.
Some cryogenic thermometers used at Fermilab - US-IT-HXTU

- Thermometer immersed into He II bath
  - Commercial sensors
  - Printed circuit board
  - Calibration facility
  - Chebychev polynom

🌟 Pro and cons
  + Cryogen true value
  - Implementation
  - Feedthrough&Connector
Some cryogenic thermometers used at Fermilab

Allen-Bradley

Cernox on cards

Cernox+copper
Calibration of the thermometer

- Fermilab facility
Some cryogenic thermometers used at CERN - CTM

- Under vacuum: Industrial-type cryogenic thermometers with built-in heat intercept
  - Sensor implementation
  - Thermometric bloc
  - Accessories
    - Copper blocs
    - Radiation protection
    - Thermalization foil

🌟 Pro and cons
  + Easy-to-use
  - Thermal anchoring
Some cryogenic thermometers used at CERN

- Layout of the cryogenic thermometer
Some cryogenic thermometers used at CERN

Cryogenic thermometer

Radiation protection

Thermalization board

Epoxy support for Platinum sensor

// foil
Uncertainty evaluations

**Measurement string**
- Cryogenic thermometer
- wire, conditioner
- control system and acquisition
- calibration fit

**Environmental factor**
- Thermo-cycling
- Moisture
- Magnetic field
- Irradiation

**Systematic error**
- Calibration: fit
- Effect of the liquid level gauge

**Statistical error**
- Stability of the bath temperature
- Stability of (T\text{pres}-T\text{sat})

Error± 5 mK at 1.8 K
Overheating

Check US-IT-HXTU thermal measurements:

- Thermometers calibrated with a 0.2 µA current but used with a 1 µA.
- Implementation on the PCB

- High resistance at low temperature (40 kΩ at 1.8 K)
- Large dispersion of resistance (40-12 kΩ at 1.8K)
Overheating - Resistance influence

To = Temperature out of the calibration fit relative to a current of 0.2 μA used for the calibration data.

If:

- \( R = 32 \text{ KΩ} @ 1.8 \text{ K} \)
- \( I = 1 \text{ μA} \)

then 
Error = 0.1%

If:

- \( R = 12 \text{ KΩ} @ 1.8 \text{ K} \)
- \( I = 1 \text{ μA} \)

then 
Error = 0.02%
Overheating - fitting expression

\[ Z = \log(R) \]
\[ X = ((Z-Z_l)-(Z_u-Z))/(Z_u-Z_l) \]
\[ T = \sum A_i \cdot \cos(i \cdot \arccos(X)) \]
Overheating - Current influence

Temperature drift vs. current

Calibration fit:
w/ R@ 0.2 microAmp
T=Cherb(R0.2)

To: R w/ 0.2 microAmp
T: R w/ 0.5- 20 microAmp
Overheating

Drift of temperature vs. current

Drift = 1.3 mK
for T₀=1.8 K
I=1 microAmp
Conclusion

- Measurement of thermal model performances
  - Temperatures rise in He II => US-IT-HXTU
  - Heat loads => CTM

- Improvement of techniques for measurements of temperature

- Better reliability