Cooling performance of the HL-LHC cells affected by the TCLD and 11T-dipole including thermal assessment of 11T coil

Rob van Weelderen,
Mário David Grosso Xavier,
Serge Claudet,
Kirtana Puthran

+ multiple inputs from the Fluka & Collimation teams

HL-LHC Collaboration Meeting 2018
Overview

- Intro
- 11 T dipole steady-state cooling limits
  - Coil + beam-pipe
  - Cold-mass
- 11 T dipole thermal quench limit
- Nb$_3$Sn stack measurements
- DS – cryogenic hardware steady-state cooling limits
- Implications for proposed Beam-Lifetime scenarios
- Summary of implications for proposed Beam-Lifetime scenarios
Intro
Assessment on various scales of the thermal load withstand-levels of the 11T-dipole and the DS-cells
11 T dipole steady state as function of power: 
1) « static coil + beam-pipe cooling limits »

Coil-heat must go first from coil to annular space around beam-pipe and then towards the magnet ends.
Without radial cooling channels the total continuous extraction capacity limit from the coil area ranges from $\approx [50 \text{ W @1.95 K} - 15 \text{ W @2.10 K}]$ (both apertures combined)
Steady state as function of power: 2) « cold-mass cooling limits »

If we consider that the DS-bayonet heat exchanger is operated at its fullest capacity then the 11T cold-mass part will take \( \approx 8-10 \text{ W} \) under the corresponding \( \Delta P \) and wetting conditions. The remainder is conducted away.

Neighbouring magnets can then take \( \approx 50 \text{ W} \) max, hardware limited by the cold-mass interconnects’ free conduction area within limited \( \Delta T \).

\[ \rightarrow \text{total} \geq \approx 60 \text{ W} \text{ for the full 11T cold –mass (i.e. coil + collars + yoke + beam pipe +…)} \]

Precise profile to be evaluated with detailed model.
Implications for proposed Beam-Lifetime scenarios

Detailed data for cryogenics analysis

All the following plots and provided data are for:

- TCLD and 11T replacing **MBB.B8** (IR7)
- The **most exposed 11T** out of the two modules: downstream from TCLD

Beam LifeTime (BLT) of 1 h is just a rescaling of the 0.2h BLT results (0.2h results divided by 5).

**BLT of 0.2 hours, considers:** Ions: 1248 bunches 2.1e8 ions/bunch. **Protons:** 2760b 2.3e11 p / bunch

Previous benchmarks showed a **factor 3** underestimation in DS with respect to BLM measurements: **this factor is already accounted for in the data.**
Implications for proposed Beam-Lifetime scenarios

Protons: 11 mW/cm³ keeps > 3.6 K temperature margin according to CFD-model

Plot for BLT 0.2h
(For BLT 1h, values would be % of these)
Implications for proposed Beam-Lifetime scenarios

Radially averaged peak power inner coils: most exposed 11T in cell 8 (ions)

Plot for BLT 0.2h
(For BLT 1h, values would be ½ of these)

Ions: 21 mW/cm³ keeps > 3.6 K temperature margin according to CFD-model

Courtesy Cristina Bahamonde Castro
Implications for proposed Beam-Lifetime scenarios

Heat load to the cold mass part by part

<table>
<thead>
<tr>
<th>Heat load to the cold mass for HL-LHC most exposed 11T of cell 8 (W)</th>
<th>PROTONS</th>
<th>IONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BLT (12 min)</td>
<td>BLT (1 h)</td>
</tr>
<tr>
<td>Coils (return coils included)</td>
<td>54</td>
<td>11</td>
</tr>
<tr>
<td>Yoke</td>
<td>44</td>
<td>9</td>
</tr>
<tr>
<td>Collars</td>
<td>32</td>
<td>6</td>
</tr>
<tr>
<td>Spacers (between coils)</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Vacuum vessel</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Beam pipe</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Shrinking cylinder</td>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>Other parts</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>170</td>
<td><strong>34</strong></td>
</tr>
</tbody>
</table>

C. Bahamonde - WP 11 Technical machine interfaces working group

Protons: coil + beam-pipe 12 W (BLT 1h), total 34 W
Ions......: coil + beam-pipe 21 W (BLT 1h), total 66 W
11T dipole specific summary for proposed beam-Lifetime scenarios (MBB.B8)

<table>
<thead>
<tr>
<th></th>
<th>Peak power (mW/cm³)</th>
<th>11T: coil + beam-pipe (W)</th>
<th>11T total (W)</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>2</td>
<td>12</td>
<td>34</td>
<td>&amp; (&lt; 50 mW/cm³ and &lt; 41 W, total &lt; 60 W)</td>
</tr>
<tr>
<td>Ions</td>
<td>4</td>
<td>21</td>
<td>66</td>
<td>&amp; (&lt; 50 mW/cm³ and &lt; 41 W total close to 60 W)</td>
</tr>
</tbody>
</table>

For the 1h Blt the 11T dipole thermal design is sufficient
## 11T dipole specific summary for proposed beam-Lifetime scenarios (MBB.B8)

### Transient cooling $\leftrightarrow$ Blt 12min

<table>
<thead>
<tr>
<th></th>
<th>Peak power (mW/cm³)</th>
<th>11T: coil + beam-pipe (W)</th>
<th>11T total (W)</th>
<th>10 s Energy (kJ)/(kJ/m)</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>11</td>
<td>58</td>
<td>170</td>
<td>1.7/0.3</td>
<td>&lt; 50 mW/cm³ coil &gt; 40 W, total &gt; 60 W</td>
</tr>
<tr>
<td>Ions</td>
<td>21</td>
<td>105</td>
<td>330</td>
<td>3.3/0.6</td>
<td>&lt; 50 mW/cm³ coil &gt; 40 W, total &gt; 60 W</td>
</tr>
</tbody>
</table>

For the 12min Blt the 11T dipole thermal design is ok for peak power on coil - but overall temperature will drift during transient (slide 31)
The thermal quench limits as function of locally deposited power are assessed via:

1) **Computational Fluid Dynamics** of coil-section using inputs from (2) + material data
2) Thermal characterization of cut-out coil *stack-sample* in cryolab-test stand
11 T dipole thermal quench limit
Steady state modelisation results
(by former fellow Fouad Aabid)

11-Tesla Dipole

Mesh Quality:
Numerical Mesh: 375196 cells (hexahedral)
Min. cell volume: 6.2e-12 m³ – Max. cell volume: 8.8e-9 m³
99% of Mesh Cells < 0.5 in Equisize Skewness, worst element at 0.83

Boundary Conditions:
Constant Temperature T=1.9K at the Cold Source
Adiabatic Walls (No heat exchange) on the walls of the External Shell
Uniform heat flux from the Coldbore (where peak power density is): 3.31 W.m⁻³
Steady state modelisation results 11T-dipole
(by former fellow Fouad Aabid)

11-Tesla Dipole

Max. Temperature ≈ 3.1 K

Lowest Temperature Margin ≈ 3.58 K

The temperature margin is largely above the limit of quenching.
11 T dipole thermal quench limit
Steady state modelisation results 11T-dipole
(by former fellow Fouad Aabid)

Recap:

At 32 mW/cm$^3$ → Tmargin ~ 3.6 K
At 50 mW/cm$^3$ → Tmargin ~ 3.0 K
At 100 mW/cm$^3$ → Tmargin ~1.9 K

Locally the 11T dipole coil is can take high heating loads.

However these values apply only to the worst cold-mass coil-section!

Whether the loads can be sustained over large cold-mass volumes and multiple magnets and as function of time depends on the previous DS cooling capacity assessment for Proton and Ion runs respectively

Complementary validation is ongoing with Cryolab stack-measurements analysis

(Note: strong indications of some He presence in coil pack, to be confirmed)
Nb$_3$Sn stack measurements

Experimental setup

Exploiting different AC loss mechanisms the sample is heated and the temperature evolution in sample and bath is measured.

The generated power can be varied by changing the combination of the resistor box.

**Important parameters:**

- $T_{eq}$: equilibrium temperature
- $\tau$: time constant (time to reach 63.2 % of peak temperature)
Nb$_3$Sn stack measurements

Typical measurement curve

![Graph showing a typical measurement curve for Nb$_3$Sn stack measurements. The graph displays the temperature over time, with key points labeled as $T_0$, $T_{eq}$, and $\tau$. The curve transitions from an initial state to a steady-state temperature.](image-url)
Nb$_3$Sn stack measurements

WARNING: Uniform power deposition results CANNOT be simply translated to 11 T Dipole loss profile.
Nb$_3$Sn stack measurements

Converted into a classical heat transfer coefficient by taking the inner layer surface area exposed to He II.

- Above $T_\lambda$, it relaxes to $\sim 200 \text{ W} / \text{m}^2 \text{ K}$.
- Below, heat transfer is enhanced by presence of He II: calculated to the order of some %

\begin{figure}
\centering
\includegraphics[width=\textwidth]{heat_transfer_chart.png}
\caption{Heat transfer coefficient vs. steady-state temperature.}
\end{figure}
Influence of helium in our measured heat capacity is calculated at some % on average.

In summary:

- \( \tau \) seems to have a lower boundary at \( \sim 1 \) second
- Very strong peak at the \( \lambda \) temperature
- \( \tau \) can be related to heat capacity by:
  \[
  \tau = RC = \frac{C}{\Lambda} = C_v \frac{\Delta T}{q}
  \]
- \( \tau \) is then proportional to volumetric heat capacity
- What volume fraction of helium is needed in the sample to have this heat capacity? (note: it is an approximation)
Nb₃Sn stack measurements

Conclusions and outlook

• Measurements of superconducting cable stacks directly from MSC production are possible
  • Absolute values shown cannot simply be translated to the 11 T collimation loss profile
  • Steady-state temperatures, as well as response times, are measured up to a UNIFORM power deposition of 5 mW per cm³, whereas collimation-induced power distribution is a narrow cone, within a limited area.

• Steady-state results are consistent with other assessments (see L. Bottura’s talk)

• Possible indication of small LHe presence in the cable

• Experiment currently being used to validate details of the 11 T Dipole magnet simulation model (Kirtana Puthran, ongoing work)
Generically LHC-cell (107 m) cooling-power provided by the collective performance of:

1. Bayonet heat exchanger, protruding through all cold masses: design limit 7 g/s ≡ 140 W (at 1.9 K, pumping)

2. Very low pressure counterflow heat exchanger installed in the QRL-service module: limit 5 g/s ≡ 100 W (at 1.9 K, pumping)

3. Every 2nd LHC-cell, cooling exchange between cells is blocked by hydraulic restrictions → 214 m collective cooling
Proton & Ion runs

<table>
<thead>
<tr>
<th>Static + Splices (0.25 W/m *)</th>
<th>23</th>
<th>23</th>
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</thead>
<tbody>
<tr>
<td>Beam-Gas (0.0 W/m *)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total (0.25 W/m)</td>
<td>23</td>
<td>23</td>
</tr>
</tbody>
</table>

Available for collimation: 77 W

Redundancy - ½ -Cells 10+11 (W)

- Loss data from CERN-ATS-2010-016
- Considering beam-gas based on present LHC vacuum (factor 200 lower than TDR)

→ Cells 8&9 have 77 W available for collimation loads, all magnets combined!
→ Some extra load ≤ 77 W could be taken via conduction through the neighbouring cell-10&11 cooling, if all loads would be < 200 W total (see later on).
LHC operating experience puts the DS-helium temperatures ≤ 1.95 K

→ We aim to keep the 11T helium at 1.95 K
→ This is only possible for total loads not exceeding the 2x100 W limit of neighbouring cooling-loops
→ The exceptions are high short – time losses when the helium temperature will drift as the heat gets absorbed.
Loss data (in red) Fluka team, 1h beam life time

Total loads are < 200 W →
Cryo-infrastructure can maintain this in steady state!
Loss data (in red) Fluka team, 12min life time

| Q7 | MB | 11T | TC | 11T | MB | Q8 | MB | MB | Q9 | MB | MB | Q10 | MB | MB | LE | Q11 | plug | MB | ...
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</tr>
</thead>
<tbody>
<tr>
<td>21W</td>
<td>7W</td>
<td>170W</td>
<td>5W</td>
<td>2.4W</td>
<td>&lt;---- 20W ----&gt;</td>
<td>&lt;------ 2W --------&gt;</td>
<td>12W</td>
<td>31W</td>
<td>17W</td>
<td>3-10W</td>
<td></td>
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Total loads are >> 200 W → Cryo-infrastructure cannot maintain this in steady state!

The heat capacity of the DS-helium content will be engaged!

23 W + 210 W + 100 W = 333 W

**DS - cryo hardware steady-state cooling limits**

heating of the DS – cells 8 to 11: helium starting at 1.95K

Protons (1hr Blt): The **12 W** which need to be extracted from the coil+beam-pipe area can be sustained continuously

Protons (12min Blt): The **58 W** which need to be extracted from the coil+beam-pipe area **cannot be taken by the helium at 1.95 K** → **Adiabatic T-rise of coil** (to be evaluated), The DS cooling would fail after ~ 33 min (power considered constant)
Loss data Fluka team, 1h life-time

Total loads are > 200 W → Cryo-infrastructure cannot maintain this in steady state!

The heat capacity of the DS-helium content will be engaged!
**DS - cryo hardware steady-state cooling limits**

**Loss data Fluka team, 12min life-time**

\[
23 \text{ W} + 350 \text{ W} + 135 \text{ W} = 508 \text{ W}
\]

\[
23 \text{ W} + 20 \text{ W} + (675-750) \text{ W} = 718 - 793 \text{ W}
\]

<table>
<thead>
<tr>
<th>Q7</th>
<th>MB</th>
<th>11T</th>
<th>TC</th>
<th>LD</th>
<th>Q7</th>
<th>MB</th>
<th>11T</th>
<th>MB</th>
<th>Q8</th>
<th>MB</th>
<th>MB</th>
<th>Q9</th>
<th>MB</th>
<th>MB</th>
<th>Q10</th>
<th>MB</th>
<th>MB</th>
<th>LE</th>
<th>Q11</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8W</td>
<td>2W</td>
<td>325W</td>
<td>8W</td>
<td>15W</td>
<td>&lt;----- 135W ----&gt;</td>
<td>&lt;------ 20W ------&gt;</td>
<td>160W</td>
<td>360W</td>
<td>115W</td>
<td>40-120W</td>
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</tbody>
</table>

**Total loads are >> 200 W →**

Cryo-infrastructure cannot maintain this in steady state!

The heat capacity of the DS-helium content will be engaged!
Ions (1hr Blt): The **21 W** which need to be extracted from the coil+beam-pipe area is reached after ~ **90 min** (power considered constant)

Ions (12min Blt): The **105 W** which need to be extracted from the coil+beam-pipe area **cannot be taken by the helium at 1.95 K** → **Adiabatic T-rise of coil** (to be evaluated), The DS cooling would fail after ~ **16 min** (power considered constant)
Summary of implications for proposed Beam-Lifetime scenarios

Cryogenic-limitations of DS cells cooling:

1hr Blt: **cooling of 11-T-dipole ok for Protons and for Ions**
1hr Blt: **cooling of cells 8, 9, 10 & 11 ok for Protons**

12min Blt: helium cooling not sufficient in the long term
→ **adiabatic T-rise of 11-T-dipole coil** (to be evaluated)

Thermal assessment of 11T-dipole T-margin:

**CFD assessment** indicates that **locally** the 11T dipole coil is **can take high heating loads**.

**Thermal measurements** of production-source Nb₃Sn coil-stacks are giving **consistent results** (see Luca Bottura’s talk), but reveal a **possible presence of helium inside the coil-stack**.