Thermal performance analysis and measurements for the accelerator prototype modules of European XFEL

TESLA Technology Collaboration Meeting
IHEP, Beijing, China, 5-8 December 2011

X.L. Wang, W. Maschmann, J. Eschke, O. Sawlanski, R. Klos, K. Jensch, B. Petersen

Many other involved colleagues
Overview

- Introduction.
- Thermal analysis.
- Heat load measurements.
- Results and discussion.
- Conclusions.
- Sources and references.
Introduction

- Based on The TESLA/TTF-Type III design.
- 10 Hz pulsed operation.
- One Cryomodule consists of: 8 1.3 GHz 9-cell Nb cavities (2 K), 1 magnet package (2 K), two thermal shields (5/8 K and 40/80K), 8 main RF couplers, 3 support posts.
- 12 m length and 7.8 t total weight.
Thermal analysis

Heat transfers by

- Current leads.
- Power couplers.
- Support posts.
- Multilayer insulation (MLI).
Heat transfer by current leads

- Conduction cooled current leads with two heat sinks and developed by CERN.
- Heat transfer mechanisms:
  - Conduction through brass and copper; heat generated by current and material properties changes with temperature.
  - Negligible axial conduction through SS, Kapton tube and the helium gas and contact thermal resistances.
- A numerical model is developed by using Matlab.
- A analytical model is used to validate numerical results in appropriate limits.
Thermal performance analysis and measurements for the accelerator prototype modules of European XFEL

**Heat transfer by current leads**

**Design parameter of the current leads**

<table>
<thead>
<tr>
<th>Level</th>
<th>$T_{H}$, K</th>
<th>$T_{C}$, K</th>
<th>$L$, m</th>
<th>$D_{b}$, mm</th>
<th>$t_{cu}$, mm</th>
<th>Copper RRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>40/80 K</td>
<td>300</td>
<td>70</td>
<td>0.50</td>
<td>3</td>
<td>0.60</td>
<td>120</td>
</tr>
<tr>
<td>5/8 K</td>
<td>70</td>
<td>5</td>
<td>0.38</td>
<td>3</td>
<td>0.13</td>
<td>120</td>
</tr>
<tr>
<td>2 K</td>
<td>5</td>
<td>2</td>
<td>0.48</td>
<td>3</td>
<td>0.60</td>
<td>120</td>
</tr>
</tbody>
</table>

$D_{b}$: Diameter of the brass, $t_{cu}$: Thickness of copper plating.

**Comparisons from analytical and numerical models**

(One lead, constant thermal conductivity and electrical resistivity)

<table>
<thead>
<tr>
<th>Model</th>
<th>$q$, W (300-70 K)</th>
<th>$q$, W (70-5 K)</th>
<th>$q$, W (5-2 K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 A</td>
<td>60 A</td>
<td>0 A</td>
</tr>
<tr>
<td>CERN A</td>
<td>1.35</td>
<td>2.50</td>
<td>0.38</td>
</tr>
<tr>
<td>DESY A1</td>
<td>1.33</td>
<td>2.34</td>
<td>0.35</td>
</tr>
<tr>
<td>DESY N1</td>
<td>1.33</td>
<td>2.33</td>
<td>0.35</td>
</tr>
<tr>
<td>DESY A2</td>
<td>1.75</td>
<td>2.76</td>
<td>0.42</td>
</tr>
<tr>
<td>DESY N2</td>
<td>1.75</td>
<td>2.75</td>
<td>0.42</td>
</tr>
</tbody>
</table>

- **A**: Analytical solutions
- **N**: Numerical solutions
- ‘1’ and ‘2’ denotes respectively the solutions with neglecting and considering heat conduction of the brass

- CERN A and DESY A1 fit very well.
- Heat conduction through the brass had been neglected in CERN design.
- The analytical and numerical results have a good agreement.
### Heat transfer by current leads

#### Heat loads by current leads

<table>
<thead>
<tr>
<th>Ts, K</th>
<th>Ti, K</th>
<th>Q (Six leads), 0A/50A, W</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2K</td>
</tr>
<tr>
<td>40</td>
<td>2-10-50-300</td>
<td>0.77/0.84</td>
</tr>
<tr>
<td>50</td>
<td>2-10-60-300</td>
<td>0.77/0.84</td>
</tr>
<tr>
<td>60</td>
<td>2-10-70-300</td>
<td>0.77/0.84</td>
</tr>
<tr>
<td>70</td>
<td>2-10-80-300</td>
<td>0.77/0.84</td>
</tr>
<tr>
<td>80</td>
<td>2-10-90-300</td>
<td>0.77/0.84</td>
</tr>
</tbody>
</table>

Ts: Shield temperature, Ti: Thermal intercept temperature

- 2 K static one: $\sim 1$ W
- 2 K dynamic one: $\sim 0.1$ W
- 5/8 K static one: $\sim 2-3$ W
- 5/8 K dynamic one: $\sim 0.4-0.9$ W
- 40/80 K static one: $\sim 10-12$ W
- 40/80 K dynamic one: $\sim 3-4$ W
Heat transfer by power couplers

- Eight power couplers in one module.
- Conductors made up of SS tubes coated by the copper.
- Two thermal sinks at 5/8 K and 40/80 K levels.
- Heat transfer mechanisms:
  - Conduction through the inner and outer conductors.
  - Heat generation by the RF power coupler.
  - Radiation heat from the antenna to 2 K and 5/8 K levels.
- The numerical model is similar with that of current leads.
Thermal performance analysis and measurements for the accelerator prototype modules of European XFEL

Heat transfer by power couplers

Basic parameters of the power coupler

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Segment</th>
<th>D, mm</th>
<th>L, mm</th>
<th>tss, mm</th>
<th>tcu, µm</th>
<th>Copper RRR</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer conductor 40/80 K</td>
<td>1</td>
<td>71</td>
<td>203</td>
<td>0.25</td>
<td>10</td>
<td>10</td>
<td>SS bellow</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>62</td>
<td>79</td>
<td>1.5</td>
<td>10</td>
<td>10</td>
<td>SS tube</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>92</td>
<td>65</td>
<td>1.5</td>
<td>10</td>
<td>10</td>
<td>SS tube</td>
</tr>
<tr>
<td>Inner conductor 40/80 K</td>
<td>1</td>
<td>23</td>
<td>209</td>
<td>2</td>
<td>30</td>
<td>10</td>
<td>SS tube</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>26</td>
<td>155</td>
<td>0.15</td>
<td>30</td>
<td>10</td>
<td>SS bellow</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>23</td>
<td>100.6</td>
<td>2</td>
<td>30</td>
<td>10</td>
<td>SS tube</td>
</tr>
<tr>
<td>Outer conductor 5/8 K</td>
<td>1</td>
<td>40</td>
<td>66</td>
<td>1.5</td>
<td>10</td>
<td>10</td>
<td>SS tube</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>46.5</td>
<td>186</td>
<td>0.2</td>
<td>10</td>
<td>10</td>
<td>SS bellow</td>
</tr>
<tr>
<td>Outer conductor 2 K</td>
<td>1</td>
<td>46.5</td>
<td>9.5</td>
<td>1.25</td>
<td>10</td>
<td>10</td>
<td>SS tube</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>40</td>
<td>17.1</td>
<td>1.5</td>
<td>10</td>
<td>10</td>
<td>SS tube</td>
</tr>
</tbody>
</table>

Comparisons with DESY previous model (M. Dohlus, Proc. LINAC 2004)
(One coupler, static, q<sub>cp1</sub>: Present, q<sub>cp2</sub>: Previous)

<table>
<thead>
<tr>
<th>Level</th>
<th>T&lt;sub&gt;C&lt;/sub&gt;,K</th>
<th>T&lt;sub&gt;H&lt;/sub&gt;,K</th>
<th>q&lt;sub&gt;cp1&lt;/sub&gt;, W</th>
<th>q&lt;sub&gt;cp2&lt;/sub&gt;, W</th>
<th>Conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 K</td>
<td>2</td>
<td>4</td>
<td>0.01</td>
<td>0.02</td>
<td>Outer conductor</td>
</tr>
<tr>
<td>5/8 K</td>
<td>4</td>
<td>70</td>
<td>0.2</td>
<td>0.2</td>
<td>Outer conductor</td>
</tr>
<tr>
<td>40/80 K</td>
<td>70</td>
<td>300</td>
<td>1.4</td>
<td>1.1</td>
<td>Outer conductor</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>300</td>
<td>0.9</td>
<td>0.8</td>
<td>Inner conductor</td>
</tr>
</tbody>
</table>

The other comparison with Fermi model (T. Peterson, TESLA report, 1993)

2 K level, identical parameters, error of about 10%.
Thermal performance analysis and measurements for the accelerator prototype modules of European XFEL

Heat transfer by power couplers

Static Heat loads by power couplers

<table>
<thead>
<tr>
<th>Ts, K</th>
<th>Ti, K</th>
<th>Q (Eight couplers), W</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 K</td>
<td>5/8 K</td>
</tr>
<tr>
<td>40</td>
<td>2-10-60-300</td>
<td>0.48 1.20</td>
</tr>
<tr>
<td>50</td>
<td>2-10-70-300</td>
<td>0.48 1.52</td>
</tr>
<tr>
<td>60</td>
<td>2-10-80-300</td>
<td>0.48 1.84</td>
</tr>
<tr>
<td>70</td>
<td>2-10-90-300</td>
<td>0.48 2.16</td>
</tr>
<tr>
<td>80</td>
<td>2-10-100-300</td>
<td>0.48 2.96</td>
</tr>
</tbody>
</table>

- 2 K static one: ~0.5 W
- 5/8 K static one: ~1-3 W
- 40/80 K static one: ~16-18 W
Heat transfer by support posts

- Three support posts in one module.
- Two thermal sinks at 5/8 K and 40/80 K levels.
- Heat transfer mechanisms:
  - Conduction through G-10 tube.
  - Radiation heat from the MLI (Negligible)
- The numerical model is similar with that of the current leads.
- The analysis model is used to validate the numerical results.
- Cryocomp properties version 3.0 provides three kinds of G-10 with various conductivities depending on the angles between the thermal gradient and the fiber direction.
- The maximum conductivity G10 is taken.
Thermal performance analysis and measurements for the accelerator prototype modules of European XFEL

**Heat transfer by support posts**

**Comparisons with INFN previous model** (S. Barbanotti, INFN/TC-08-01)
(One support post, $q_A$: DESY analytical, $q_N$: DESY numerical)

<table>
<thead>
<tr>
<th>Level</th>
<th>$T_{C}, K$</th>
<th>$T_{H}, K$</th>
<th>$q_{INFN}, W$</th>
<th>$q_{A}, W$</th>
<th>$q_{N}, W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 K</td>
<td>2</td>
<td>5</td>
<td>0.041</td>
<td>0.035</td>
<td>0.035</td>
</tr>
<tr>
<td>5/8 K</td>
<td>5</td>
<td>70</td>
<td>0.865</td>
<td>0.93</td>
<td>0.94</td>
</tr>
<tr>
<td>40/80 K</td>
<td>70</td>
<td>300</td>
<td>9.906</td>
<td>11.51</td>
<td>11.52</td>
</tr>
</tbody>
</table>

**Heat loads by support posts**

<table>
<thead>
<tr>
<th>$T_s, K$</th>
<th>$T_i, K$</th>
<th>$Q$ (three posts), W</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 K</td>
<td>5/8 K</td>
</tr>
<tr>
<td>40</td>
<td>2-10-40-300</td>
<td>0.42</td>
</tr>
<tr>
<td>50</td>
<td>2-10-50-300</td>
<td>0.42</td>
</tr>
<tr>
<td>60</td>
<td>2-10-60-300</td>
<td>0.42</td>
</tr>
<tr>
<td>70</td>
<td>2-10-70-300</td>
<td>0.42</td>
</tr>
<tr>
<td>80</td>
<td>2-10-80-300</td>
<td>0.42</td>
</tr>
</tbody>
</table>

- 2 K: ~0.5 W
- 5/8 K: ~1-3.5 W
- 40/80 K: ~34-37 W
Heat transfer by the MLI

- 30 layers at 40/80 K and 10 layers at 5/8 K.
- Surface areas: 30.9 m² at 40/80 K and 26.4 m² at 5/8 K.
- Heat transfer mechanisms:
  - Conduction through the solid.
  - Radiation heat.
  - Conduction through residual gas (Negligible P<10⁻³ Pa).
- Difficulty to calculate accurately.
- Reviewed empirical results from CERN and NASA.
Heat transfer by the MLI

Empirical results of heat fluxes
2 K: Negligible, 5/8 K: 0.05 W/m², 40/80 K: 1.5 W/m² (many openings).

Empirical formulas adapted to empirical heat fluxes

\[ q = \frac{C_S(N)^{2.56} T_m}{N_s + 1} (T_H - T_C) + \frac{C_R \varepsilon_{RT}}{N_s} (T_H^{1.67} - T_C^{1.67}) \]  
(T. Nast, Multilayer insulation system)

<table>
<thead>
<tr>
<th>Level</th>
<th>q, W/m²</th>
<th>(N_s), layers</th>
<th>(\bar{N}), layers/cm</th>
<th>(T_H), K</th>
<th>(T_C), K</th>
<th>(\varepsilon_{RT})</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/8 K</td>
<td>0.05</td>
<td>10</td>
<td>19.0</td>
<td>80</td>
<td>10</td>
<td>0.03</td>
</tr>
<tr>
<td>40/80 K</td>
<td>1.5</td>
<td>30</td>
<td>37.4</td>
<td>300</td>
<td>80</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Heat loads by the MLI

<table>
<thead>
<tr>
<th>Ts, K</th>
<th>Ti, K</th>
<th>Heat load Q, W</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2 K</td>
</tr>
<tr>
<td>40</td>
<td>2-10-40-300</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>2-10-50-300</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>2-10-60-300</td>
<td>-</td>
</tr>
<tr>
<td>70</td>
<td>2-10-70-300</td>
<td>-</td>
</tr>
<tr>
<td>80</td>
<td>2-10-80-300</td>
<td>-</td>
</tr>
</tbody>
</table>

- 2 K: -
- 5/8 K: ~0.3-1.3 W
- 40/80 K: ~46-49 W
Thermal analysis summary

- 2 K: 2.1 W.
- 5/8 K: 6-12 W strongly depending on the 40/80 K shield temperatures.
- 40/80 K: 110-120 W slight effected by the 40/80 K shield temperatures.

Others including heat loads from HOM absorbers, cabling, etc. is extra cted from refrigerator budget, where 2 K: 0.4 W, 5/8 K: 1.7 W, 40/80 K: 5.4 W.
Heat load measurements

<table>
<thead>
<tr>
<th>Test</th>
<th>Cold mass vendor</th>
<th>Assembly</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>PXFEL2_1</td>
<td>Felguera, Spain</td>
<td>CEA, Saclay</td>
<td>Jun. 2011</td>
</tr>
<tr>
<td>Dummy test</td>
<td>DESY</td>
<td>DESY</td>
<td>Feb. 2011</td>
</tr>
<tr>
<td>PXFEL3 (B)</td>
<td>Thales, France</td>
<td>DESY</td>
<td>Nov. 2010</td>
</tr>
<tr>
<td>PXFEL3 (A)</td>
<td>Thales, France</td>
<td>DESY</td>
<td>Sep. 2010</td>
</tr>
<tr>
<td>PXFEL2 (B)</td>
<td>Felguera, Spain</td>
<td>CEA, Saclay</td>
<td>Jun. 2010</td>
</tr>
<tr>
<td>PXFEL2 (A)</td>
<td>Felguera, Spain</td>
<td>CEA, Saclay</td>
<td>May 2010</td>
</tr>
<tr>
<td>PXFEL1</td>
<td>IHEP, China</td>
<td>DESY</td>
<td>Jul. 2009</td>
</tr>
</tbody>
</table>

- Tested at Cryomodule test bench (CMTB).
- Four modules and seven measurements plus dummy test.
- PXFEL2_1: New MLI at 40/80 K shield.
- PXFEL3 (B): Disconnected the 40/80 K thermal intercept of current leads.
- PXFEL2 (B): T sensors at sliding muff range calibrations.
- Dummy test: pure heat load of CMTB without the module.
Methodologies and instrumentation

2 K:
- Measure the mass flow rate of the evaporated helium in an enclosed space.
- Calorimetric flow meter at room temperature (0-1 g/s).
- Heater calibrations.
- Accuracy of less than 10 %.
5/8 K and 40/80 K: Enthalpy balance

For Helium
\[ \dot{Q} = \dot{m}_{He} C_{pHe} \Delta T_{He} \]

For Cold mass
\[ \dot{Q} = m_c C_{pc} \Delta T_c / \Delta t \] for cross check

Cold mass: AL of 388 kg and helium of 0.5 kg.
Averaged T increase: 58.9 K to 66.3 K within 2 hours.
Heat load of 94 W

Pure heat load of 99 W
At 40/80 K
Methodologies and instrumentation

- **40/80 K**: Pt1000 (on tube installation), Venturi flow meters.
- Warm flow input to change outer shield T from 40-80 K.
- **5/8 K**: Cernox™ (in tube installation), Venturi flow meter.
- Heater calibrations for all circuits.
- Accuracy of less than 10%.
Thermal performance analysis and measurements for the accelerator prototype modules of European XFEL

Methodologies and instrumentation

STC: Cermax temperature sensor for 5/8K area
STP and STS: Pt1000 temperature sensor for 40/80K area
SF: Orifice or Venturi flow meter
SP: Pressure transmitter
SL: Level sensor
SM: Sliding muf
*: In tube installation
Results and discussion

- 2 K: PXFEL1 quite higher than others. Differences from others (due to installation skill of current leads)
- 5/8 K: PXFEL3 (B) higher than others.
- 40/80 K: $\Delta Q = 14$ W from PXFEL3. Calculated: 12 W, fit reasonably
- 40/80 K: PXFEL3 (A) higher than others.
- 40/80 K: PXFEL2_1 lower than others.

- 5/8 K: Reasonable agreements. Strongly effected by outer shield T.
- 40/80 K: Could fit well with assumption of 1 W/m$^2$ through the MLI for PXFEL2_1.
Results and discussion

Layout of current leads causes quite high 2 K heat load of PXFEL1 (Confirmed)

Tuner misalignment causes higher 40/80 K heat load of PXFEL3 (Guess)

New MLI at 40/80 K shield in PXFEL2_1 improves the thermal performance (TBC)
Conclusions

Static heat load summary of PXEFL modules

<table>
<thead>
<tr>
<th>Level</th>
<th>Measured</th>
<th>Calculated</th>
<th>XRB</th>
<th>Factor</th>
<th>XRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>40/80 K</td>
<td>100-120</td>
<td>100-120</td>
<td>83</td>
<td>1.5</td>
<td>125</td>
</tr>
<tr>
<td>5/8 K</td>
<td>6-11</td>
<td>6-12</td>
<td>13</td>
<td>1.5</td>
<td>20</td>
</tr>
<tr>
<td>2 K</td>
<td>6</td>
<td>2.1</td>
<td>4.8</td>
<td>1.3</td>
<td>6</td>
</tr>
</tbody>
</table>

XRB: XFEL refrigerator budget, XRC: XFEL refrigerator capacity

- 40/80 K: **100-120 W** depending on the performance of MLI.
- 5/8 K: **6-12 W** depending on the outer shield temperatures.
- 2 K: **3.5-6 W** depending on the installation skills of current leads.
- Measured and calculated values have a good agreements at 5/8 K and 40/80 K.
- Big deviation at 2 K caused by underestimation of cabling heat load and the installation skills of current leads.
- Specified refrigerator capacity still could cover the heat load at 2 K and 40/80 K (Even come to limit) and have enough margin at 5/8 K.
1. B. Petersen, Some fundamentals of cryogenic and module engineering with regard to SRF technology, SRF2007 Tutorial Program
2. T. Peterson, What's inside a TESLA Cryomodule, Proton driver meeting, 2005
3. C. Pagani, Cryomodule design, assembly and alignment, SRF 2005
4. N. Ohuchi, Fundamentals of cryomodule, SRF2009 Tutorial Program
5. T. Peterson, ILC cryogenic systems reference design, CEC 2007
9. L. Mazzone, Measurement of multi-layer insulation at high boundary temperature, ICEC19
10. L. Dufay, A large-scale test facility for heat load measurements down to 1.9K, CEC2002
11. J. Fesmire, Performance characterization of perforated multilayer insulation blankets, ICEC19, 2002
14. A. Ballarino, Current leads for the LHC Magnet System, MT17, Switzerland, 2001
15. M. J. White, Numerical model for conduction cooled current lead heat loads, Presented to CEC 2011
18. HEPAK, Cryodata, Inc., Version 3.40
20. M. Dohlus, TESLA RF power coupler thermal calculations, LINAC 2004, Germany
22. S. Barbanotti, Traction tests for the qualification of the TTF/ILC composite support posts, INFN, Italy, 2008
23. Y. Bozhko, XFEL Cryomodule Test Bench, ICEC21, 2006
24. N. Ohuchi, SCRF Cryomodule R&D in KEK-STF, 2nd Asia ILC R&D seminar, 2008
25. N. Ohuchi, Experimental study of thermal radiation shield for ILC Cryomodule, ICEC23
26. N. Ohuchi, Study of thermal radiation shields for the ILC Cryomodule, Presented to CEC 2011
Thank you for your attention!