CRYO-LOSSES MEASUREMENTS OF THE XFEL PROTOTYPE AND PRE-SERIES CRYOMODULES

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Abstract

Heat loads measurements (cryo-losses) of the 3 XFEL prototype and 1 pre-series cryomodules are here presented and compared with the XFEL requirements. Heat loads at the 5/8 K, 40/80 K and 2 K temperatures are calculated during the test period at CMTB (CryoModule Test Bench) at DESY to qualify the cryomodules before installation. This paper summarizes the test procedure for the different circuits (2 K, 5/8 K, 40/80 K) and in different load conditions: static loads, loads due to the magnet and dynamic loads due to the RF power sent to the cavities.

INTRODUCTION

The European XFEL Free Electron Laser is under construction at Hamburg, Germany [1]. The XFEL will deliver X-ray flashes with wavelength between 0.05 and 6 nm. The required electron beam energy of 17.5 GeV will be obtained using a superconducting (SC) accelerator operating at 2 K. The linac will consist of about 800 SC niobium cavities. Eight cavities and one SC magnet package will be assembled in one cryomodule about 12 m long. The design of the accelerator module is based on the third generation for the TESLA cryomodules [2].

From the cryogenic point of view, the thermal performances of the modules are crucial to qualify the modules in series productions, determine the heat load budget, capacity and cost of the European XFEL refrigerator and guarantee efficient operation of the system. The thermal performances can be separated in two main contributions: the static heat loads, which arise from the overall module design and are present during cold operation of the accelerator, and the dynamic heat loads, which originate during the RF and beam operations from specific components: the cold magnet and its current leads, and the cavities and power couplers.

This paper presents the measurement methodology applied to determine the static and dynamic heat loads for the 3 prototype modules (PXFEL1, 2 and 3) and the first (pre-) series module (XM-3) and compares the results with previous measurements and analytical calculations [3].

CALCULATIONS AND XFEL BUDGET

Extended analytical and numerical calculations of the heat loads have been performed for single elements of the cryomodule as well as for the whole assembly. An extended paper summarizing all these studies is under preparation and will be published soon.

The required XFEL Refrigerator Capacity (XRC) is based on the XFEL Refrigerator Budget (XRB), which is an updated version of the TDR heat load table [4], taking into account the latest analysis and measurements of the TESLA modules. The safety factor of 1.5 is taken into account to design the XFEL refrigerator, XRC=1.5*XRB.

MEASUREMENT METHODOLOGY

The test of the cryomodule take place in a dedicated cryogenic facility at DESY: the CryoModule Test Bench (CMTB, Figure 1).

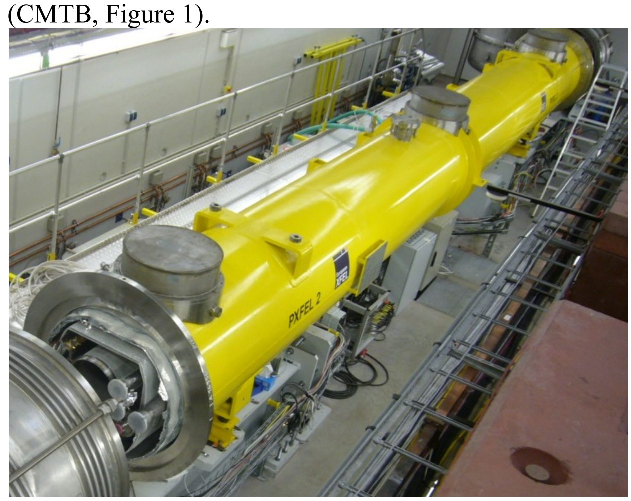

Figure 1: Overview of a cryomodule in the CMTB.

Two different measurement methods are applied for the evaluation of the heat loads at 2 K or at 5/8 K and 40/80 K.

Heat Loads at 5/8 K and 40/80 K

The heat loads at 5/8 K and 40/80 K can be measured using the “specific enthalpy” method, since the flow meters for these circuits are sufficiently precise and reliable.

If we consider the steady-state working mode of a cryomodule, without fluctuations of the latent energy, and no generated thermal energy, we can calculate the total power supplied to the helium flow as:

$$\dot{Q}_{lost} = \dot{m}\left(h_{out}(p_{out}, T_{out}) - h_{in}(p_{in}, T_{in})\right) - \dot{Q}_c$$

where $\dot{m}$ is helium mass flow, Δh is the difference of the specific He enthalpy at the inlet and outlet of the module at a certain temperature and pressure, $\dot{Q}_c$ is the power lost throw the feed-cap and the end-cap of the module (since the flow meters are positioned after the end and feed caps).

In our case, $\dot{Q}_{c,5K} = 3.9\ W$, $\dot{Q}_{c,40K} = 54\ W$ at the outer shield temperature of around 40 K.

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Heat Loads at 2 K

The 2 K heat loads measurement is performed using the "latent heat" method, due to the inaccuracy of the cold helium flow measurement in the 2 K temperature region. For this method, we stop supplying liquid helium to the module and measure the total mass flow of the evaporated gas just after the warm pump station (this flow meter at the ambient temperature is much more precise and reliable than the one on the 2 K circuit). This measurement includes also the feed and end caps, since these are located between the module and the compressor.

We have to guarantee during this measurement that enough liquid helium is always available (for example, the cavities are always completely immersed in LHe) so that we can consider this measurement isothermal. Then, the amount of LHe evaporated is directly proportional to the power flowing into the system. We consider 3 main sources of power:

- $\dot{Q}_{lost}$, thermal energy coming from the environment through the cryomodule
- $\dot{Q}_{d}$: thermal energy generated by the module magnet or by the RF to the cavities and couplers
- $\dot{Q}_{c,2K}$: thermal energy coming from the end and feed boxes to the module.

We can then calculate the heat load at 2K as:

$$\dot{Q}_c = L\dot{m} - \dot{Q}_{b,2K} - \dot{Q}_d$$

where $\dot{m}$ is the mass flow of the evaporated helium after the compressor, L the latent heat of the helium and $\dot{Q}_{b,2K} = 1.4\,W$.

TEST SET-UP

The following conditions have to be reached before we can perform the measurement:

- The pump station is in use only for the CMTB system;
- Stable cryogenic conditions are reached since more than 72 hours;
- The isolation vacuum inside the cryomodule is $< 1\text{x}10^{-5}$ mbar
- The leak rate of the cryomodule is $< 1\text{x}10^{-5}$ mbar-l/s
- The flow in the 40/80K circuit is circa 5 g/s and 40 K

The measurement is then repeated, for each circuit (2 K, 5/8 K, 40/80 K) in the following conditions:

- Static loads: no RF to the cavities, no current to the magnet ($\dot{Q}_d = 0$)
- Dynamic RF loads: RF to the cavities, no power to the magnet ($\dot{Q}_d$ = power to the cavities)
- Dynamic magnet loads: no RF to the cavities, 3*50 A to the magnet ($\dot{Q}_d$ = power to the magnet)

The standard test is performed with the outer shield temperature around 40 K. Additional tests have been performed to evaluate the influence of the outer shield temperature on the static heat loads at 5/8 K and 40/80 K. A warm helium flow has been added to the outer shield cooling circuit to reach the 80 K temperature and the heat loads have been measured.

RESULTS

The following tables summarize the results of the measurements performed on the prototype modules (PXFEL) and on the first 2 pre-series modules (XM).

For the prototype modules, we consider the measurement performed on PXFEL2_1 and 3_1: each module has been disassembled and reassembled for training purposes and a new MLI material and blanket design has been installed.

Heat Loads at 2 K

Table 1: Heat Loads at 2 K, W

Module	Static loads W	Dynamic loads	
		Magnet (3*50A), W	RF loads W (MV/m)
PXFEL 1	9.9	-	4.9 (25)
PXFEL 2_1	5.9	1.4	4.9 (25*)
PXFEL 3_1	6.4	0.5	3.1 (24.4#)
XM-3	6.4[1]	2.2	3.0 (23.5)
Calculated	2	0.1	8.5
XRC	7.2	12.9	

[1] value to be confirmed
* Two detuned cavities, #three detuned cavities

The measured values show a good agreement between each other but they are much higher than the value calculated with numerical simulations. This can be attributed to the difficulty and complexity of accurately estimate the heat load through the cables and the fact that the thermal intercept performance of current leads is strongly affected by the real installation skills

Among the measured values, the higher heat load of 9.9 W from PXFEL1 can be explained by a different current lead layout, which has a shorter heat transfer length between the 2 K and the 5/8 K thermal intercept.

Heat Loads at 5/8 K

Table 2: Heat Loads at 5/8 K

Module	Static loads W	Dynamic loads	
		Magnet (3*50A), W	RF loads W (MV/m)
PXFEL 1	5.7	0.7	1.8
PXFEL 2_1	6.8	4.8	2.3
PXFEL 3_1	5.0	4.7	1.6
XM-3	4.5	6.0	n.a.
Calculated	6.1	0.4	2.4
XRC	19.5	3.5	

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The measured static heat loads at 5/8 K are consistent with the calculated value at the shield temperature of 40 K. The measured dynamic RF heat loads at 5/8 K are within the calculated value. The measured dynamic heat loads of the magnet are significantly higher than the calculated one due to the not-optimal thermal intercept performance of the current leads.

Heat Loads at 40/80 K

Table 3: Heat Loads at 40/80 K

Module	Static loads W	Dynamic loads	
		Magnet (3*50A), W	RF loads W (MV/m)
PXFEL 1	116	1.8	27.6
PXFEL 2_1	99	7.8	41.1
PXFEL 3_1	96	4.9	37
XM-3	105	7.0	n.a.
Calculated	120	3.0	37
XRC	124.5	60	

The measured heat load for PXFEL1 is in good agreement with the calculated value of 120 W. The lower heat load from PXFEL2_1, PXFEL3_1 and XM-3 can be explained with better performances of the new MLI material and blanket design.

Effect of the 80 K Shield Temperature on the Heat Loads

The outer shield of the European XFEL linac will be operated in real conditions at a temperature between 40 and 80 K. It is therefore necessary to investigate the outer shield temperature effects on the heat loads at various circuits. The results are shown in the figure below together with the calculated values.

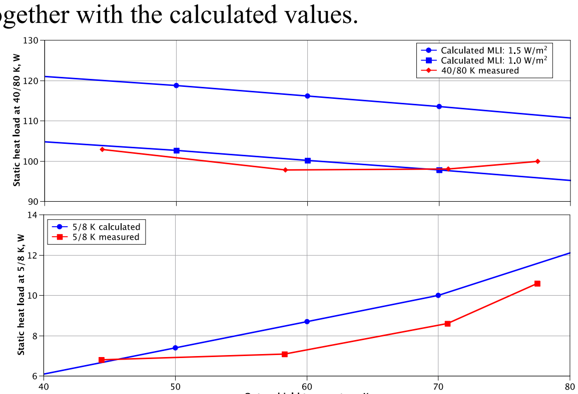

Figure 2: Effect of the 80 K shield temperature on the 5/8 K and 40/80 K heat loads.

It can be clearly observed that the outer shield temperature has a minor effect on the 40/80 K and 2 K heat load; while it strongly affects the 5/8 K heat loads.

We can explain this behaviour noticing that the static heat load at the 5/8 K shield is dominated by the heat conduction through various materials, such as the aluminium foil of the MLI, the copper and brass in the current leads, the copper and stainless steel in the power couplers and the G-10 in the posts. The physical laws of conduction determine therefore that the heat load is strongly dependent on the temperature difference and thermal conductivity. This dependence determines the remarkable increase of the heat load at 5/8 K with the outer shield temperature. At the same time, the static heat load at the 40/80 K shield is dominated by the heat conduction and the thermal radiation. The outer shield temperature change from 40 K to 80 K has a limited effect on the heat conduction and the thermal radiation in a range of 40/80-300 K so the heat load at 40/80 K only slightly decreases with the outer shield temperature.

CONCLUSIONS

Thermal performance measurements have been performed for the 3 prototype and a pre-series module of the European XFEL under real operation conditions.

At 40/80 K level, the static heat loads of 100-120 W show a very good agreement between the calculated and measured results. The total measured dynamic heat loads are within the calculation range.

At 5/8 K level, the static heat load of 6-11 W is measured, a value well predicted by the thermal analysis. The XRB of 13 W corresponds to the calculated value of 12 W at the outer shield temperature of 80 K.

At 2 K level, the measured static heat load of 3.4-6.4 W is considerably higher than the calculated one of 2 W. Possible reasons of this big deviation are the underestimation of 2 K cabling contributions and the not-optimal performance of the thermal intercept for the current leads. The total measured dynamic heat loads are all well within the calculated ones.

The specified refrigerator capacity for one module covers the total heat loads at various temperature levels and has enough margins for safe operation, even considering the maximum measured heat load values.

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