

Serial testing of XFEL cryomodules: results of the cryogenic heat load measurements

T Böckmann¹, Y Bozhko¹, W Gay², P Halczynski², B Petersen¹, S Putselyk³,
T Schnautz¹, M Sienkiewicz² and J Swierblewski²

¹Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, 22607 Hamburg, Germany

²Instytut Fizyki Jadrowej (IFJ), Polskiej Akademii Nauk (PAN), 31-342 Krakow, Poland

³Ferchau Engineering GmbH, Butzweilerhof-Allee 4, 50829, Köln, Germany

E-mail: bernd.petersen@desy.de

Abstract. The European X-ray Free Electron Laser (XFEL) is in operation at DESY. The superconducting XFEL linac will produce pulsed electron beam at an energy of 17.5 GeV. The linac consists of 768 superconducting niobium 1.3 GHz nine cell cavities and 96 superconducting magnet packages assembled in 96 cryomodules. Each cryomodule is 12 m long and includes a 2 K helium II bath circuit for the cavities, and 5/8 and 40/80 K thermal radiation shields. Before being installed in the XFEL linac tunnel all cryomodules were tested in the Accelerator Module Test Facility (AMTF.)

In this paper methods and results of static and dynamic heat load measurements of all XFEL cryomodules are reported. A comparison with first integral heat load measurements in the XFEL linac is given.

1. Introduction

The European X-ray Free Electron Laser (XFEL) is in operation at DESY. The superconducting XFEL linac will provide a pulsed electron beam energy of 17.5 GeV. Currently the energy of 14 GeV has been reached. Before installation in the XFEL accelerator tunnel all 96 cryomodules were tested and qualified in the Accelerator Module Test Facility (AMTF.) Overall 103 XFEL cryomodules were produced and tested. Each cryomodule is 12 m long and includes a 2 K helium II bath circuit for the cavities, and 5/8 and 40/80 K thermal radiation shields. The tests were conducted by a team from Instytut Fizyki Jadrowej, Polskiej Akademii Nauk, Krakow, Poland (IFJ-PAN) as part of the in-kind contribution of Poland to the European XFEL Project. The IFJ-PAN team was supported by DESY. The cryomodules have undergone a complete system test, except beam operation. This included general acceptance tests after assembly (mechanics, alignment, cabling) and performance tests of vacuum (insulation-, beam-, RF coupler vacuum), RF (main RF-coupler, low level RF, cavities) and cryogenic components. In general, the test procedures were already reported in [1-3]. This paper is dedicated to the cryogenic heat load measurements.

All XFEL cryomodules were tested in a period of about two years. Three complete test benches were available in AMTF. A test rate of 1-1.5 cryomodules per week had to be established in order to be in schedule with the production rate and the tunnel installation progress. The measurement

procedures had to be optimized in order to validate the cryomodule performance related to acceptance criteria not only with the required precision but also on schedule.

2. Measurement, methodology, test procedure and test bench

Figure 1 shows the simplified PID diagram of the 2, 5/8 and 40/80 K circuits of one AMTF cryomodule test bench (XATB.) The AMTF test procedures were based on experience gained from prototype and pre-series measurements on the Cryomodule Test Bench (CMTB) at DESY [4].

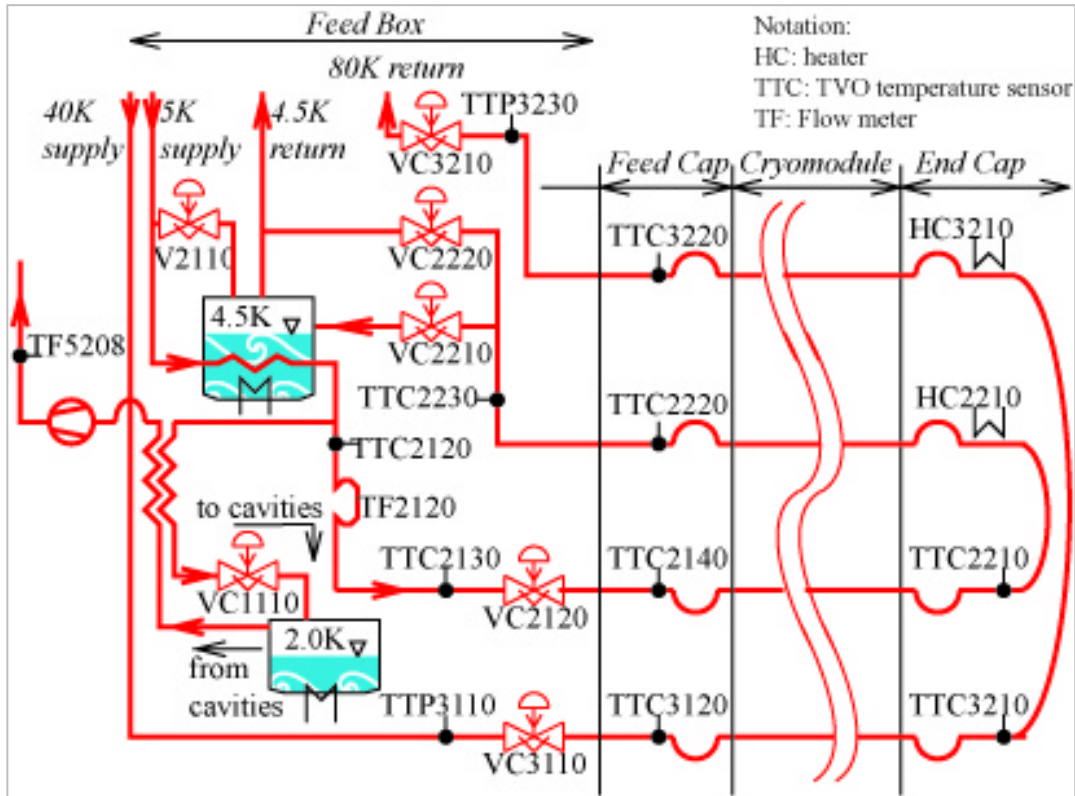


Figure 1. Simplified PID diagram of one test bench (Feed Box, Feed Cap, Cryomodule and End Cap).

The mass flow rate of evaporated helium was measured by means of the flowmeter TF5208 at the outlet of the warm compressors to monitor the heat loads of the 2 K circuit. The heat load is obtained by multiplication of the helium latent heat by the measured flow rate. The test procedure was conducted in steps: switching off electrical heaters, filling the 2-phase pipe with liquid helium (LHe) up to 60% level, closing the JT valve VC1110 and performing the measurements. Typically the measurements were completed in 4-6 hours, while the whole measurement procedure including re-filling the 2-phase pipe took about 7-8 hours.

The heat loads of the 5/8 K circuit were obtained from measurements of the temperature difference at the inlet and outlet of the circuit (temperature sensors TTC2140 and TTC2220), the pressure of the process fluid (the transducer is not shown in figure 1) and the mass flow (flowmeter TF2120). The test procedure comprised 12 hours of static heat load measurements (“first zero”) followed by 12 hours of heat load measurements with applied dynamic heat loads (RF, magnet or both) and was concluded by 12 hours of static heat load measurements (“second zero”).

The heat load of the 40/80 K circuit was measured in the way similar to that for the 5/8 K circuit by means of the temperature sensors TTC3120 and TTC3220 at the inlet and outlet of the circuit respectively, a pressure transducer (not shown in figure 1) and a dedicated flowmeter located in the

supply box XAVB. Measurements were performed during the same time period as those for the 5/8 K circuit. As the serial measurements progressed, the dedicated measurements for the 40/80 K circuit were replaced by measurements in the shadow of other activities, deriving heat load data from stable operation periods of the concerned test bench. Dynamic heat load measurements were much too time consuming. Since severe non-conformities of the main RF couplers, being the only source of the dynamic heat load, could be detected by RF measurements, this resulted in complete skipping of dynamic heat load measurements of the 40/80 K circuit.

In comparison to CMTB, the instrumentation for flow and temperature measurements was changed in AMTF. The orifices used in CMTB were replaced by Coriolis cold flowmeters in AMTF. As observed in CMTB, orifices operating at temperatures below 4.5 K are prone to thermal acoustical oscillations appearing in the capillaries for the related pressure measurements. In comparison to orifices, Coriolis flowmeters have a significantly larger range and better accuracy and stability. One Coriolis flowmeter installed in the 2 K circuit (not shown in figure 1) was cross-checked in-situ by the TF5208 warm flowmeter. A standard deviation of 2.5% was measured. The measurement was dominated by statistical errors. The long-term stability was investigated during several years of operation with multiple cool-down/warm-up cycles (>100) at another Coriolis flowmeter, which was permanently installed at the XFEL Magnet Test Stand (XMTS) [5]. No performance degradation was observed. Also the indications of the Coriolis flowmeters installed in the 5/8 and 40/80 K circuits could be cross-checked by means of the warm flowmeter TF5208. These additional measurements were quite time consuming and were performed only rarely during the cool-down of only a few cryomodules.

In the AMTF TVO temperature sensors were installed instead of Cernox sensors in CMTB. All temperature sensors were mounted on the external surface of the corresponding pipes with a minimal amount of grease and glue in order to improve the heat transfer between the sensor and pipe. Thermal anchoring of wires and mounting methods were very similar to those presented in [6]. The largest contribution to measurement uncertainties results from the temperature difference across the boundary layer of fluid and from improper swirling of helium inside the pipe. To exclude these effects, the free cross-sectional area was reduced locally by a factor of 20. The TVO temperature sensors were installed inside this reduced cross-section area. Reynolds numbers in the order of $2.3 \cdot 10^5$ were reached by means of these reduced cross sections. These cross-sections were integrated into the 80 K return, and 5 and 40 K supply lines. The measurements revealed systematic temperature shifts of approximately ≤ 0.15 K (very likely about 30 mK) for the 5 K supply line, and 0.2-1.2 K for the 40 K supply and 80 K return pipes. These systematic errors do not significantly contribute to the heat load measurement uncertainties because only temperature differences across the cryomodule are counted and a dependence of helium enthalpy from absolute temperatures could be neglected. Therefore only statistical uncertainties are considered in the final presentation of the data.

The static heat load measurement of the 2 K circuit could be verified by another independent method. The related 2 K volume was filled with liquid at 2 K and isolated. Then the time was measured, which was required to warm up the 2 K system to λ -point temperature. The integral heat capacities of stainless steel and helium vapor can be neglected. The remaining measurement uncertainties result from the precision of the determination of the liquid helium volume. Since almost all liquid helium in the 2 K circuit is contained inside the cavity vessels with exact known geometry these uncertainties were estimated to be about $\pm 0.5\%$ (1σ). This method was not used for serial measurements because it causes cavity detuning and is time consuming.

The heat load measurements of 5/8 and 40/80 K circuits were cross-checked by means of electrical heaters. The heating power was increased in small steps (2 and 5 W respectively for the 5/8 and 40/80 K circuits.) The system response was monitored by temperature sensors and the corresponding heat loads were re-calculated. The cross-check resulted in uncertainties of about $\pm 15\%$ for the 5/8 and $\pm 20\%$ (3σ) for the 40/80 K circuit. Statistical errors dominated the total measurement uncertainties. During serial tests such cross-checks were conducted for every third cryomodule in the beginning and for every 10-15th one after testing of about 10% of all cryomodules. During these cross-checks a

heating power up to 5 and 50 W was applied for the 5/8 and 40/80 K circuits respectively. The heat load measurements of the 5/8 K circuits became insensitive to dynamic heat loads above approximately 12 W (such an effect was not observed for the 40/80 K circuit for heat loads up to 55 W.) Since the 8 K return pipe has relatively large diameter, this effect could be attributed to improper swirling of helium inside the pipe.

3. Results

Table 1 summarizes the cryomodule acceptance criteria for the three cryogenic circuits. These values are based on the XFEL Refrigerator Budget (XRB) for the linac, which were theoretically calculated and experimentally verified on prototype cryomodules [7] and the refrigerator capacity design values (XRC), including 50% margin.

Table 1. XFEL Refrigerator Budget (XRB), XFEL Refrigerator Capacity (XRC=1.5·XRB) and acceptance criteria for cryomodules.

Circuit	Static heat loads (absolute values), [W]		Dynamic heat loads, (relative values), [W]		Total heat loads (absolute values), [W]		Acceptance criteria, [W]
	XRB	XRC	XRB	XRC	XRB	XRC	
40/80 K	83	124.5	40	60	123	184.5	125
5/8 K	13	19.5	2.3	3.5	15.3	23	16
2 K	4.8	7.2	8.6	12.9	13.4	20.1	14

The results of heat load measurements for all tested cryomodules are shown in figures 2, 3 and 4. Cryomodules XM-2 and XM-1 are also included in figures 2, 3 and 4 since these cryomodules were installed in XFEL tunnel. Cryomodule XM8 was not tested due to a leak from the 2 K circuit into insulation vacuum.

The standard deviations for the total heat loads were in the ranges of 0.78÷1.78 W, 0.45÷2.56 W and 3.28÷7.71 W for the 2, 5/8 and 40/80 K circuits respectively.

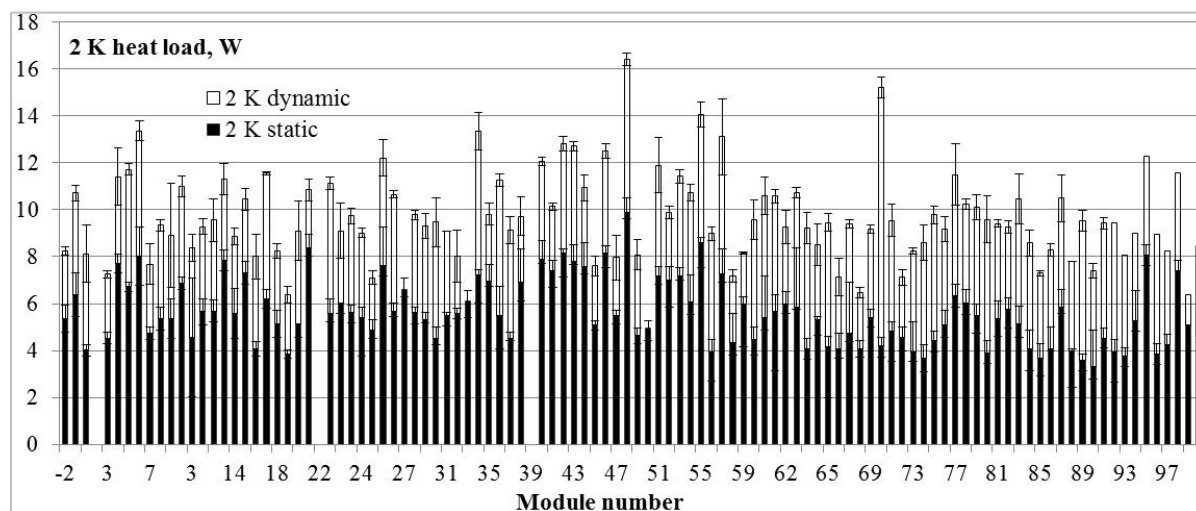


Figure 2. Static and dynamic heat loads of the 2 K circuit. The standard deviations ($\pm 1\sigma$) for each cryomodule are also shown. The averaged static heat load over all cryomodules is 5.60 W with standard deviation (1σ) of the mean value ± 1.39 W.

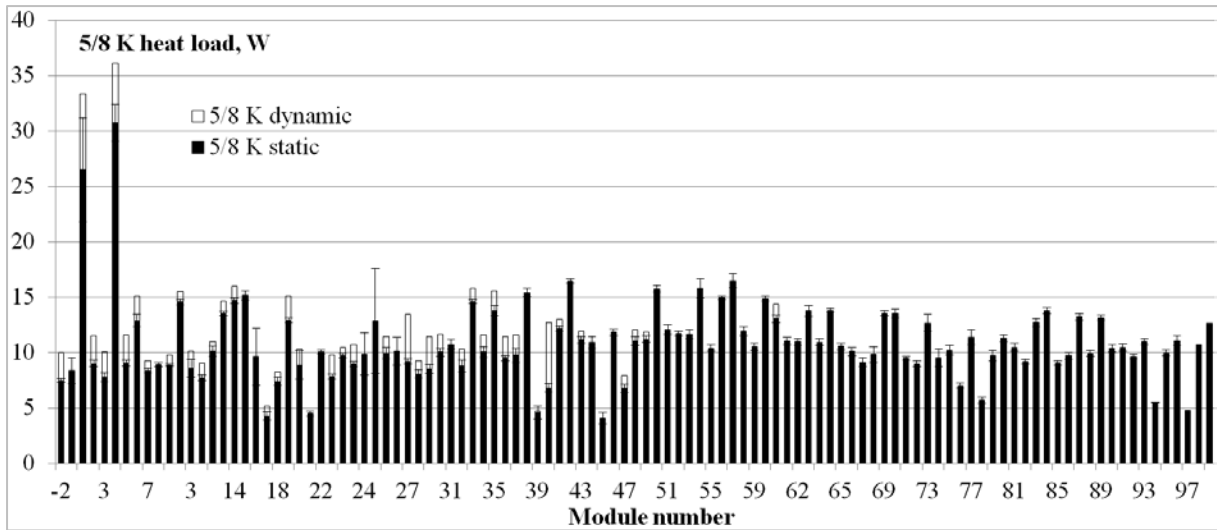


Figure 3. Static and dynamic heat loads of the 5/8 K circuit. The standard deviations ($\pm 1\sigma$) for each cryomodule for the static heat load (the standard deviations for the dynamic heat loads have comparable values) are also shown. The averaged static heat load over all cryomodules is 10.9 W with standard deviation (1σ) of the mean value ± 2.7 W.

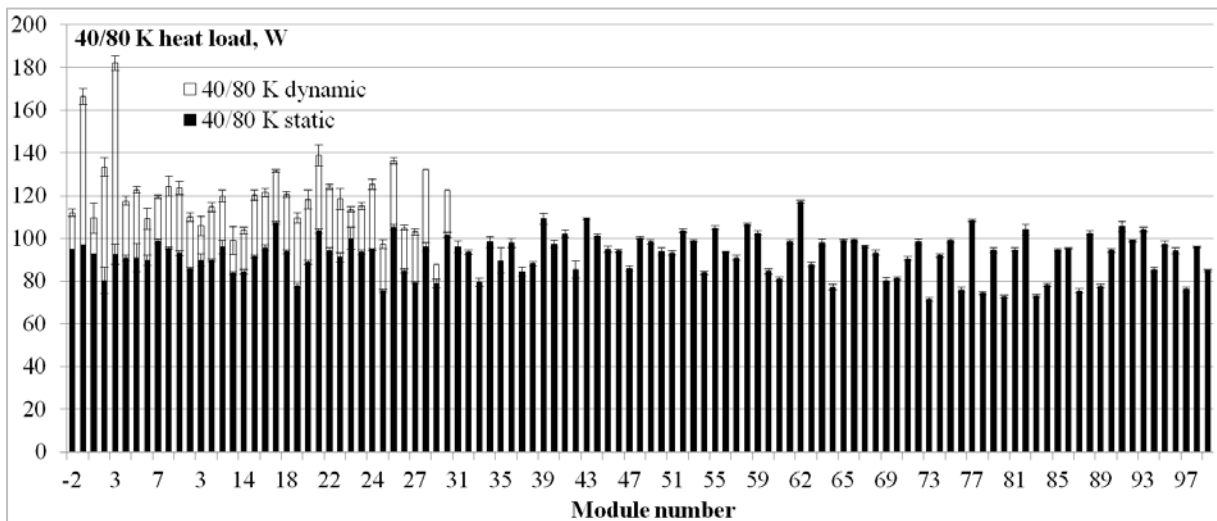


Figure 4. Static and dynamic heat loads of the 40/80 K circuit. The standard deviations ($\pm 1\sigma$) for each cryomodule are also shown. The averaged static heat load over all cryomodules is 92.3 W with standard deviation (1σ) of the mean value ± 9.4 W.

3. Discussion

Most XFEL cryomodules fulfilled the heat load acceptance criteria. However the static heat load of the 5/8 K circuit for the cryomodules 1, 4 and 19 was out of the expected range. The reason was not identified. Cryomodules 1, 3 and 4 exhibited significantly higher dynamic heat loads of both 5/8 and 40/80 K circuits. Very likely, this could be attributed to inaccurate mechanical and thermal intercepts of the main RF coupler at the 40/80 K circuit. This conclusion could be confirmed by temperature measurements direct at the RF couplers. After the reassembly/repair of the couplers at these cryomodules, one cryomodule (XM3) was re-measured and heat loads were within expected values.

Because the operation of the magnet current leads caused only small additional heat loads of the 5/8 and 40/80 K circuits ($0.2\div 1.5$ W and $1.2\div 5.8$ W respectively,) the decision was taken to combine

RF and magnet dynamic heat load measurements, after testing of the first about 15 cryomodules. This resulted in a “time-saving” of 1 day per cryomodule test. Also separate dynamic 2 K heat load measurements of the magnet were skipped.

Due to time limitations there was no a possibility to carry out a reproducibility test, i.e. to repeat heat load measurements for an already tested cryomodule at another test bench for comparison. However several cryomodules were re-tested at different test stands after repairs, for example, cryomodules XM3, XM23, XM24 and XM62 were tested at XATB1 and XATB3. The results for the static heat loads of the 2, 5/8 and 40/80 K circuits and in many cases also for the dynamic loads could be reproduced within the measurement uncertainties.

Table 2 shows the average values of static heat load measurements and the standard deviation of the mean values sorted according to the test benches. All three test benches exhibit roughly the same heat load of the 2 K circuit. However XATB2 shows higher heat loads of the 5/8 K circuit and smaller values of the 40/80 K circuit in comparison to the results obtained at XATB1&3. This could be attributed either to small temperature offsets of the temperature sensors located at the outlets of the 5/8 and 40/80 K circuits or to a thermal problem in the end cap of XATB2 (e.g. a short circuit between the 5/8 and 40/80 K thermal shields.)

Table 2. Average values of static heat load and standard deviation (1σ) of the mean value for measurements performed at different test benches.

	2 K circuit, [W]	5/8 K circuit, [W]	40/80 K circuit, [W]
XATB1, 35 cryomodules	5.67±1.35	9.73±1.72	96.7±5.2
XATB2, 37 cryomodules	5.88±2.11	12.7±3.19	82.8±6.4
XATB3, 33 cryomodules	5.20±1.30	9.30±1.79	98.6±6.8

After the first cooldown of the XFEL linac [8] the resulting static heat loads can be compared (see table 3) to the original theoretical calculations (up-date of 2009), the calculations with some offset, which resulted from prototype results at that date, and the AMTF measurements. Within the error margins AMTF and linac measurements are in close agreement for the 5/8 and 40/80 K circuits, and also close to the original calculations. Obviously the ‘offset’ to the calculation is no longer validated. It is assumed that current lead prototypes for the XFEL magnets may have caused increased heat loads in the prototype cryomodules. The offset for the 2 K level was validated by the AMTF measurements.

Table 3. Comparison of the calculated average static heat loads for one XFEL cryomodule with reference to the XFEL refrigerator specification (2009), the heat loads measured in the AMTF and the resulting measurements in the XFEL linac [8].

	2 K circuit, [W]	5/8 K circuit, [W]	40/80 K circuit, [W]
Calculations 2009	1.45	9.8	83
Calculations+’Offset’	4.8	13.0	83
AMTF	5.6±1.6	10.6±2.2	92.7±6.1
XFEL linac	6.4	7.9	86

4. Lessons learned

The use of Coriolis flowmeters have improved the measurements, despite of high investment costs and an increased pressure drop compared to orifices. In addition, simple and robust TVO temperature sensors, properly mounted on the outer surface of the process pipes, have also greatly contributed to the stability and reproducibility of measurements.

There were difficulties related to pressure fluctuations in the 40/80 K circuit. Operations at the refrigerator and activities at other AMTF test facilities were identified as sources of these disturbances. These pressure fluctuations in the order of 5-10 kPa at pressures of 1.1-1.3 MPa caused

also fluctuations of temperature and flow rate. The implementation of additional control loops for pressure or flow rate stabilizations has resulted in no significant success.

Some experience gained at CMTB could not be transferred to AMTF. In particular, the measurement of small heat loads could not be copied to AMTF (e.g. magnet.) Such measurements at CMTB were performed over weekends when the cryogenic system and refrigerator were at quite stable operation, and repeated then several times for better statistics. This approach had to be changed for AMTF in order not to delay serial tests.

The heat load measurements, which were conducted during the serial production of the XFEL cryomodules, contributed significantly to the quality controls. Hence, it is worth applying sufficient efforts to the design, construction and commissioning of the measurement system.

5. Summary

All XFEL cryomodules were tested in the AMTF. A test rate of 1–1.5 cryomodules per week could be established in line with the production rate and the XFEL tunnel installation progress. The heat load measurements contributed significantly to the production quality control. The final cryogenic operation of the superconducting XFEL linac could be prepared with reference to the heat load measurements. Beside some issues during the start-up of production no significant fluctuations of the cryogenic performance of the XFEL cryomodules were observed during the run of production. The excellent performance of the XFEL cryomodules could be verified.

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