Commissioning and first cooldown of XFEL linac

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Abstract. Beam commissioning of the European X-ray Free Electron Laser (European XFEL project) is ongoing. Commissioning the XFEL cryogenic system has started by cooling down the XFEL injector section in December 2015. The stationary operation was continued until August 2016. After intermediate warming up of the complete XFEL cryogenic system, the commissioning of remaining components including the 1.5 km long superconducting XFEL linear accelerator (linac) has commenced and was completed in beginning of December 2016. After conclusive pressure and leak tests, and flushing the cooldown started on 11 December 2016. Stable 4.5 K operation both for the linac and injector was established on 28 December.

In this paper the XFEL cryogenic system is introduced and the first cooldown of the XFEL linac is reported. The cooldown sequences are described and the measured cooldown evolution is presented. Thermal losses of single circuits are given. Preliminary conclusions with the review of critical points are drawn.

1. System overview

A conceptual design of the XFEL cryogenic system was presented in 2006 [1]. The final XFEL cryogenic system is subdivided into three groups of components - linac, injector and refrigerator (see figure 1.)

1.1 XFEL refrigerator

Two former HERA refrigerators each consisting of a line of screw compressors (3LP, 1HP) and one cold box were overhauled and modified by Linde Kryotechnik AG (LKT, Switzerland) to supply the XFEL with the required cooling power. Several new components were added: low temperature purifier XLTP, distribution box DB54, transfer line XRTL, cold compressor (CC) box CB44 and XFEL distribution box XLVB.

The cold boxes CB41 and CB43 were upgraded to integrate the 2 K circuit and meet the design specification for a future 20 GeV beam operation of the linac or an equivalent load including additional margins (see table 1.) The actual goal is to operate the XFEL linac at 17.5 GeV. In June 2017 the linac is running at 14 GeV. The cold boxes are identical and can be operated in parallel or stand alone. Calculated and specified values (including margins) are compared with the measured capacities both for single and parallel operation (see table 1.) Each of the boxes can be operated either in 80 K or in 4.5 K mode. In the 80 K mode the last 4.5 K turbine of the cold box (Turbine 7) is not in operation and bypassed. The mode allows using the maximal output pressure of the screw compressors up to 1.9 MPa. The lowest achievable temperature in this mode is around 40 K. In the 4.5 K mode Turbine 7 is in operation resulting in a supplied pressure of about 0.45 MPa and temperature of 5.5 K.

The low temperature purifier XLTP (LKT) is intended for continuous purification of raw helium exiting the XFEL compressor units by absorption of air impurities with adsorbents cooled to LN_2 temperature. The XLTP is designed for purification of 1 kg/s (at 1.6 MPa and 300 K) of helium contaminated by 100 ppm (weight) of air to an impurity level less than 1 ppm. Charging and regeneration time for each of the two adsorber units amount to respectively 24 and 16 hours.

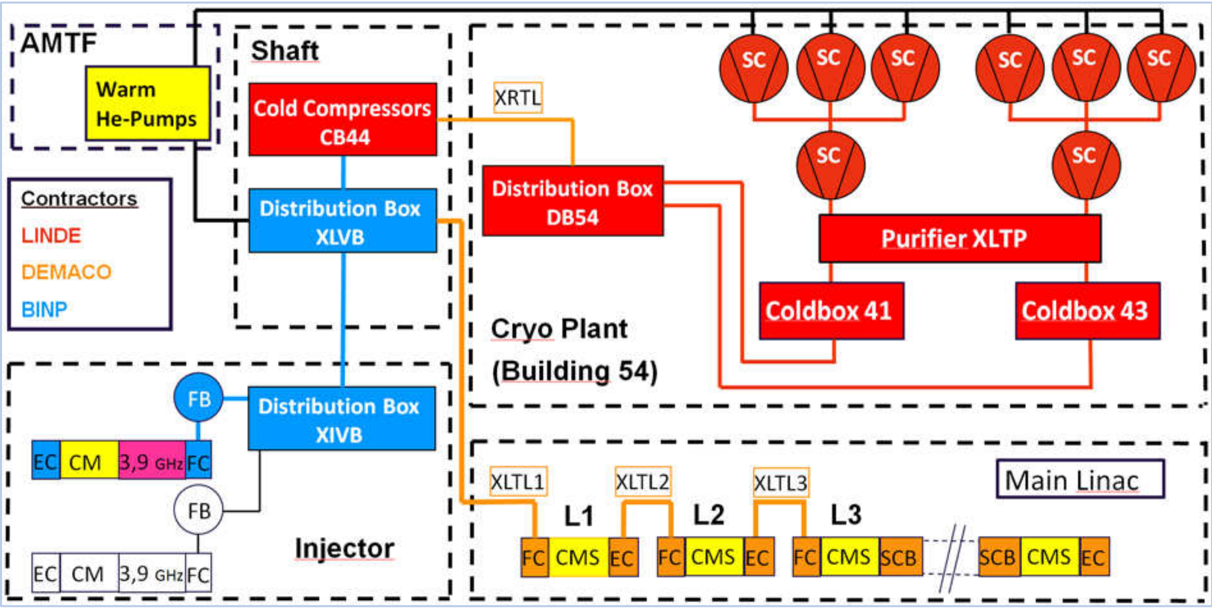


Figure 1. Layout of XFEL cryogenic components.

Table 1. XFEL Refrigerator capacities. The table shows the specified and measured capacities of the XFEL refrigerator. In some cases the test equipment limited the measurements. These cases are marked with (*). The real values should exceed the numbers in the table.

Circuit	17.5 GeV operation calculated [kW]	17.5 GeV design [kW]	Single CB operation measured [kW]	Parallel CB operation measured [kW]
2 K	1.46	1.896	>2.0 (*)	>2.56 (*)
5/8 K	2.4	3.593	2.78	>4 (*)
40/80 K	16	24	18	>26.7 (*)

The distribution box DB54 (LKT) is intended to combine/distribute flows from/to the cold boxes CB41 and CB43.

The transfer line XRTL (DeMaCo, Netherlands) connects DB54 with CB44 and carries 7 process pipes: forward and return pipes for the 5/8 and 40/80 K circuits (respectively 5KF, 8KR, 40KF and 80KR), forward pipe for the 2 K circuit 2KF, helium vapour return pipe 4KR and return pipe 20KR from the cold compressors outlet. The process pipes are surrounded by the 40/80 K thermal shield.

The cold compressors box CB44 (LKT) contains a chain of 4 cold compressors intended to compress ~110 g/s of helium at 3.5 K from a pressure of about 2.7 to 60-120 kPa. The compressed helium at a temperature of about 23 K is then returned to the thermodynamic cycle of the cold boxes. CB44 has available a CC bypass circuit intended to keep the constant mass flow of 110g/s across the CCs. Furthermore CB44 contains an 860 l phase separator to supply saturated liquid helium at 120 kPa for the 2KF circuit.

The XFEL distribution box XLVB (BINP, Russia) is connected to CB44 by a slightly inclined short transfer line. XLVB collects all cryogenic circuits to the XFEL linac and injector and contains a JT heat exchanger for cooling the 2KF flow with the 2KR vapour. The 2KR vapour can then be processed either by the cold compressors or by the AMTF warm pumps. This option helps to keep the

XFEL linac still at 2 K during maintenance periods of the cold compressors. The 2KR pipe is additionally connected to the 4KR pipe to keep superconducting components of XFEL linac also at 4.5 K. XLVB is equipped with control valves to mix warm and cold helium flows for controllable cooldown or warmup of all XFEL linac circuits. XLVB houses two DN250 valves in the 2KR circuit.

1.2 XFEL injector

The XFEL injector (BINP) [2] cryogenic system is designed to supply two parallel injectors. For the time being only one injector is installed and in operation. The injector consists of transfer line XITL, injector box XIVB, feed box XI1FB, transfer line XI1TL, feed cap XI1FC and end cap XI1EC.

The transfer line XITL connects the XLVB with the XIVB and houses the 2KR, 5KF, 4KR, 40KF and 80KR process pipes surrounded by a 40/80 K thermal shield.

The XIVB box collects all cryogenic circuits to both injectors and houses a 300 l sub-cooler with two integrated heat exchangers. XIVB has available provisions for mixing warm and cold helium flows to carry out controllable cooldown or warmup of both injectors independently from each other.

The installed injector consists of a standard 1.3 GHz XFEL and a 3.9 GHz cryomodule. Close to the cryomodules the 2 K liquid supply is expanded from the 5 K supply via a JT valve in the appendix of the feed cap XI1FC.

Figure 2. Cryomodules inside XFEL tunnel.

1.3 XFEL linac

The XFEL linac includes three transfer lines XLTL1-3, 96 1.3 GHz XFEL cryomodules (see figure 2) arranged into 9 strings and 12 linac connection boxes.

The transfer lines XLTL1-3 (DeMaCo) have identical design regarding cross-section but differ in shape and length. Each transfer line carries the forward and return process pipes for the 2, 5/8 and 40/80 K circuits. The process pipes are surrounded by 5/8 and 40/80 K thermal shields and by a DN750 vacuum shell. The transfer line XLTL1 connects XLVB with the first string of cryomodules L1 while the transfer lines XLTL2-3 are required to bypass two bunch compressors BC1 and BC2.

The linac connection boxes (DeMaCo) include 3 Feed Caps (FC1-3), 2 Bunch Compressor End Caps (EC1-2), 6 String Connections Boxes (SCB1-6) and 1 Terminal End Cap (EC3). Each box contains thermal shields and process pipes similar to those at XLTLs. The 5KF, 2KF and 8KR process pipes are equipped each with a safety valve exhausting into a ~1200 m long DN200 recovery manifold located in the XFEL tunnel. Additionally each box has a cooldown CDN and a 3 kPa two-phase 2PH process pipe, and a beam pipe. The 2PH pipe contains a small liquid helium vessel equipped with a heater and instrumentation to control pressure and level inside the superconducting cavities. Two process valves (only one for SCB4) are installed within each box (except for EC1-2) – one JT valve and one bypass valve used during cooldown/warmup.

The String Connection Boxes are connected at each side to a string of cryomodules. A vacuum barrier VB separates the insulation vacuum of each string. The beam pipe contains a gate valve with pump ports at both sides. The design of SCBs is slightly different depending on the position inside the XFEL tunnel – on the downhill (SCB1-3, see figure 3), uphill (SCB5-6) or the lowest point (SCB4).

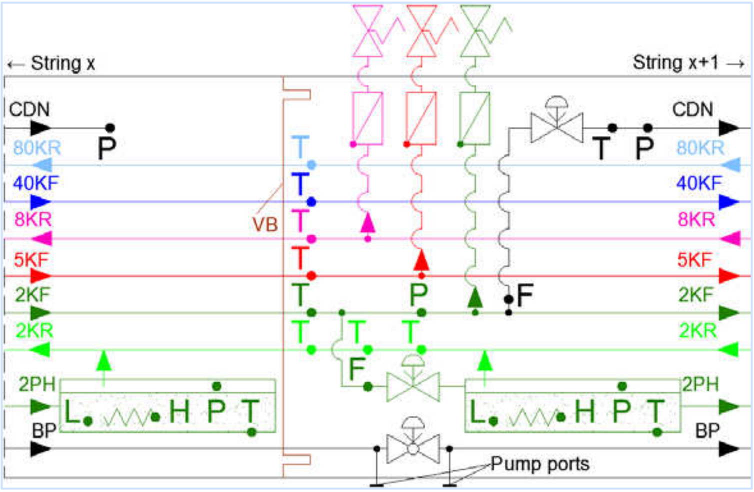


Figure 3. Flow scheme of SCB1-3.

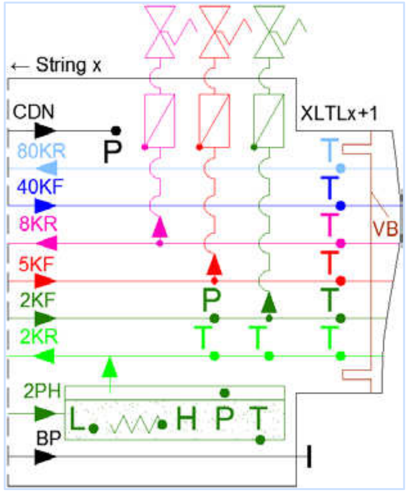


Figure 4. Flow scheme of EC1-2.

The Bunch Compressor End Caps (see figure 4) connect a string of cryomodules at the beam entering side of the EC to the respective XLTL at the beam exiting side of the EC. A vacuum barrier separates the insulation vacuum of the XLTL from that of the string.

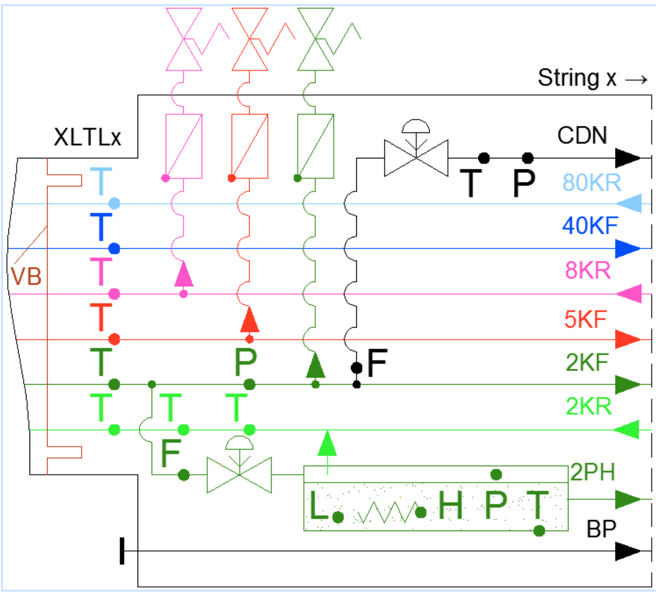


Figure 5. Flow scheme of FC1-3.

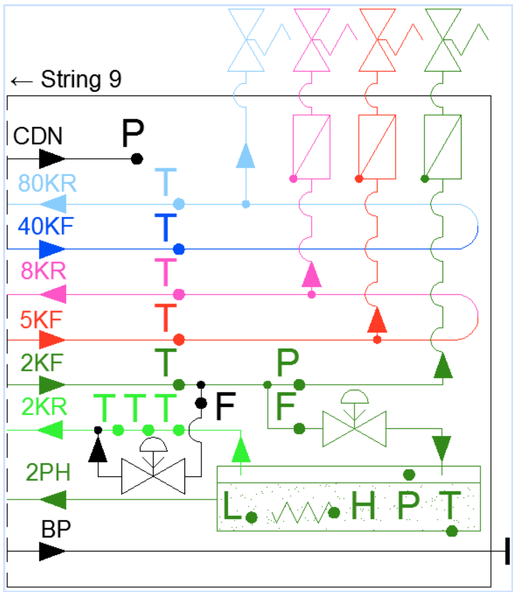


Figure 6. Flow scheme of EC3.

The Feed Caps (see figure 5) connect a string of cryomodules at the beam exiting side of the FC to the respective XLTL at the beam entering side of FC. A vacuum barrier separates the insulation vacuum of the XLTL from that of the string.

The Terminal End Cap closes the insulation vacuum of the last XFEL string and shorts the forward and return pipes of the 5/8 and 40/80 K circuits (see figure 6.) An additional safety valve is installed at the 40/80 K circuit in case of an extension of the XFEL linac to 120 cryomodules.

Cold masses of the XFEL linac are shown in table 2. The helium inventories for transient and stationary conditions are also presented. The transient filling of the DN300 gas return tube at 4.5 K and about 0.1 MPa requires additional helium.

Table 2. Cold masses of the XFEL linac and helium inventory for transient and stationary states.

Process circuit	Cold mass [kg]	He mass transient [kg]	He mass stationary [kg]
2 K	161000	5600	3600
5/8 K	44000	1100	1100
40/80 K	61000	200	200

2. Cooling down of the XFEL linac and injector

Boundary conditions of the XFEL linac cooldown were investigated earlier in [3]. The cooldown rates are limited by the maximum thermal stresses in the cryogenic circuits of the cryomodules: thermal gradients ΔT for the helium supply and return temperatures must not exceed 50 K. In addition radial ΔT for the 2 K vapour return pipe must not exceed 20 K. Parallel cooling down of XFEL linac and injector was accomplished in several steps (see figure 7.)

Step 0: The cooldown was started by operating CB41 in the 80 K mode and cooling the 2KF, 5KF, 4KR and 40/80 K circuits including the 40/80 K thermal shields of DB54, XRTL, CB44, XLVB, XITL and XIVB down to roughly 85 K. The 2KF and 5KF pipes were short-circuited with the 4KR piping respectively in CB44 and XIVB through the corresponding sub-coolers. Depending on the temperature the return gas was either sent back to CB41 (if T<200K) or heated to room temperature in an external oil heat exchanger and returned to the suction side of the screw compressors.

At the same time warm helium gas was blown through all the XFEL linac and injector circuits, returned to the screw compressors and purified in XLTP.

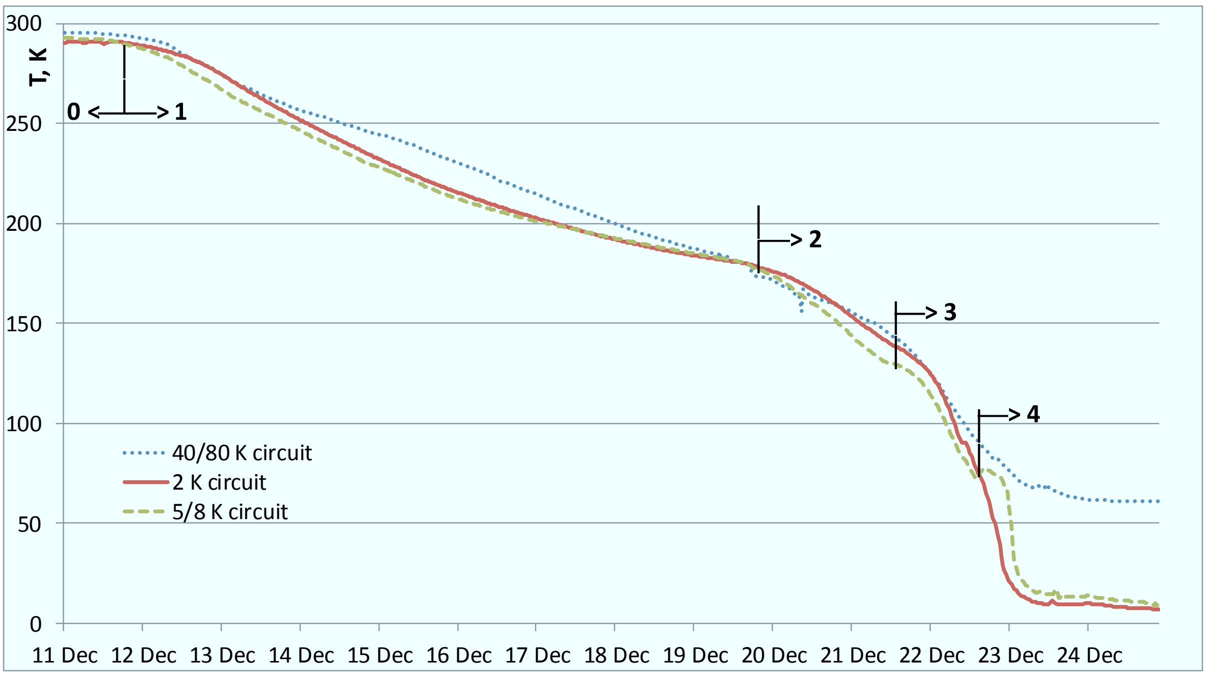


Figure 7. Outlet temperatures of the XFEL linac 2, 5/8 and 40/80 K circuits during cooldown.

Step 1: Starting cooling down the XFEL linac and injector by opening the corresponding cold valves in XLVB and XIVB and gradually adding cold gas to the warm gas flow to avoid exceeding the ΔT =50 K limit for all circuits. During cooldown, the return gas from all the circuits was collected by an external low pressure manifold, heated up by ambient air, handled by the screw compressors and purified. In order to prevent the gas temperature at the inlet of compressors from being too low, a part of flow was redirected to CB41.

Step 2: CB43 was started to boost the cooldown. CB43 took over the cooldown of the 40/80 K shield circuits. CB41 continued with cooling down the 5/8 and 2 K circuits.

Step 3: Closing one after another the supply of warm helium in XLVB and XIVB and cooling down all circuits only with cold helium. As the cooldown progressed, the CB41 and CB43 got back colder gas helping the cold boxes to further reduce the temperature of the cooling helium. At the end of the step the cooling temperature achieved its ultimate value of 40 K.

Step 4: Switching CB41 in the 4.5 K mode.

Liquid helium appeared in the first strings in the night between December 24th and 25th. Stable 4.5 K operation of the XFEL linac and injector was established starting from December28th. As soon as stable operation was established, the operation of CB43 was stopped and CB41 took over cooling of all circuits.

First 2 K operation will be reported in a separate continuing paper [4].

3. Determination of static heat loads to the XFEL linac 2, 5/8 and 40/80 K circuits

All XFEL linac components starting from XLVB – the transfer lines XLTL1-3, all cryomodules and connection boxes in L1, L2 and L3were considered to determine the static heat loads of the XFEL linac 2, 5/8 and 40/80 K cooling circuits.

3.1 40/80 K thermal shield circuit

The heat load Q_{40K} at the 40/80 K circuit of XFEL Linac is defined as the difference between the enthalpies of the helium flow coming out from and entering the circuit multiplied by mass flow of helium across the circuit. The flowmeter TF3113 of Coriolis type was used for measuring mass flow rates. To determine the enthalpies the pairs of temperature sensors TTC3110 and TTC3220 installed in XLVB, and TTP3102 and TTP3202 installed in XLTL1 (see figure 8) were used. Since the heat load values are very sensitive to measurement errors of the temperature sensors, and the temperature sensor TTC3110 was out of order for some time, an additional method to improve the accuracy/reliability of the heat load measurements was applied:

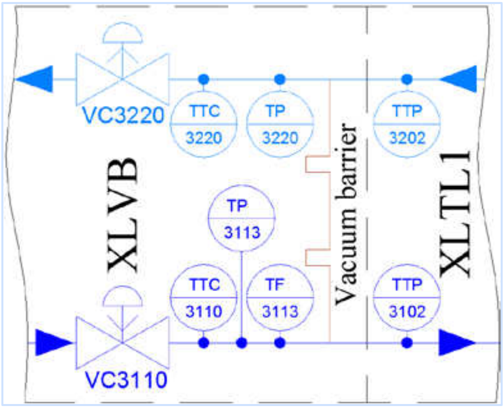
All XLTLs and all connection boxes have temperature sensors installed on the 40 K forward and 80 K return pipes. Assuming the heat load per unit of length of the concerned pipe (40 K forward and (separately) 80 K return) is roughly the same, then the plot of temperature readings in function of the XFEL linac length can be approximated by a linear function or by a small order (2) polynomial. The value at the crossing of the chosen function at X=0 m (coordinate of the sensors in XLVB according to the figure 7) would give a more accurate value of the temperatures for the 40 K forward and 80 K return flows and would partially exclude their systematic errors. For the 40 K forward pipe an additional temperature sensor located in CB44 was also involved into the evaluation.

Table 3. Results of static heat load measurements of the XFEL linac 40/80 K circuit.

	1	2	3	4	5	6	7	8	9	Average
Flow rate, g/s	111,1	65,8	93,2	81,2	80,7	85,0	80,8	81,3	84,9	
Heat load seen by XLVB,W							9813	9616	9826	**9751,5**
Heat load seen by XLTL1,W	9224	8689	9606	9128	9364	9249	9424	9192	9374	**9250,1**
Heat load XLVB calc.,W	9916	8879	9892	9396	9609	9523	9691	9482	9676	**9562,6**

Table 3 summarizes the results of the heat load measurements to the XFEL Linac 40/80 K circuit using different pairs of sensors as well as “the fitted pair of sensors” for 9 periods of stable operation. An average value over the period was calculated for each sensor/instrument. The static heat load to the XFEL linac 40/80 K circuit amounts to 9.5 kW with the standard deviation 1σ of ±0.3 kW. Given that the total surface area of the 40/80 K thermal shield is about 3560 m^2, this results in the heat load per unit of surface of 2.67 W/m^2. The value includes heat loads of all XLTLs, connection boxes and cryomodules due to thermal radiation, supports, vacuum barriers and heat sinks. It is practically difficult to estimate contributions of single sources of heat into the total heat load.

The temperature profiles along the XFEL linac for the 40 K forward and 80 K return circuits together with the corresponding fits for the set 9 are shown in figure 9. The temperature set for the 80 K return flow contains no rejected sensors while for the 40 K forward flow 4 temperature sensors were excluded from consideration. The fits allow calculating the heat load at the 40/80 K thermal shield of the cryomodules. In fact, the XFEL linac L3 consisting of 80 cryomodules begins at FC3 at 435m distance from XLVB. Substituting the distance into the fits one gets L3 input and output temperatures of respectively 43 and 58.3 K. It results in the heat load of 86 W per cryomodule. This measured value is in good agreement with earlier calculations of the 40/80 K static heat loads of the cryomodules [5].



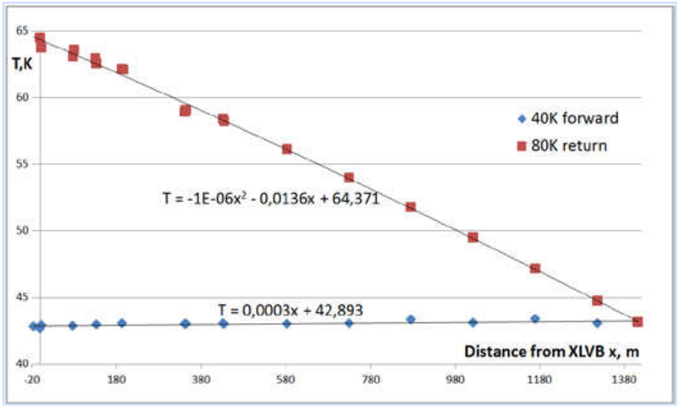


Figure 8. Instrumentation layout at XLVB.

Figure 9. Temperature profiles along XFEL linac.

3.2 5/8 K circuit

The basic principles described in 3.1 were also applied to determine the static heat load at the 5/8 K circuit. However, temperature profiles along the XFEL linac showed significant scattering with respect to linear fitting for both the 5 K forward and 8 K return flows and were not considered reliable. Instead three pairs of temperature sensors were used to determine the heat load: TI2191 and TI2291 in CB44, TTC2130 and TTC2240 in XLVB and TTC2101 and TTC2201 in XLTL1 (see figure 10.) These three pairs were installed by different manufacturers using different technologies. The flowmeter TF2131 of Coriolis type was used for measuring mass flow rates.

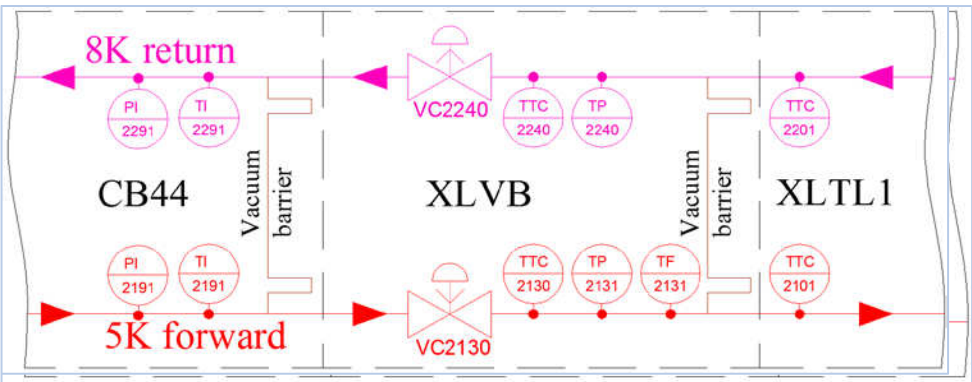


Figure 10. Layout of the 5/8 K instrumentation in CB44, XLVB and XLTL1.

Table 4 summarizes the results of the heat load measurements at the XFEL Linac 5/8 K circuit using different pairs of sensors for 9 chosen periods. As a result, the heat load at the XFEL linac 5/8 K shield is 830 W with the standard deviation 1σ of ±40 W. This results in 0.59 W per 1 m of the 5/8 K circuit (both, 5 K forward and 8 K return flows) and 0.28 W/m^2 per unit of surface of the XFEL linac 5/8 K thermal shield. Considering temperature readings at FC3 and XLTL3, the heat load at the 5/8 K thermal shield of L3 can be estimated as 630 W or 7.9 W per cryomodule. As for the 40/80 K circuit these measured values are in good agreement with earlier calculations for the 5/8 K static heat loads of the cryomodules [5] and lower than the design values.

Table 4. Results of static heat load measurements at the XFEL linac 5/8 K circuit.

	1	2	3	4	5	6	7	8	9	Average
Flow rate, g/s	62,1	91,3	49,7	91,0	47,7	62,0	78,7	58,0	61,4	
Heat load seen by CB44,W	815,4	850,0	805,6	859,6	803,4	814,9	836,2	810,2	811,4	**823,0**
Heat load seen by XLVB,W	803,1	794,8	781,1	809,5	788,6	796,7	794,7	796,4	787,2	**794,7**
Heat load seen by XLTL1,W	851,3	897,0	816,1	946,3	803,3	853,4	932,9	857,7	859,3	**868,6**

3.3 2 K circuit

The static heat losses at the XFEL linac 2 K circuit were measured in a similar way as described in 3.1 and 3.2 but using only one pair of XLVB temperature sensors. Since the 2 K circuit does not have one single general flowmeter, the flow rate across the circuit was calculated as a sum of flow rates across all flowmeters installed upstream of the JT valves of each string. The total power dissipated by all electrical heaters in the linac 2 K helium bath was then withdrawn from the enthalpy balance. The static heat load of the XFEL linac 2 K circuit averages to 610 W with the standard deviation 1σ of ±20 W. This would correspond to roughly 6.35 W per cryomodule (this is the upper limit since heat loses in XLTL1-3 are included) and is in good agreement with the results obtained in [5].

4. Summary

Both the XFEL linac and injector are in stationary cold operation since beginning of 2017. During operation no serious faults were discovered so far. The measured heat losses in the 2, 5/8 and 40/80 K circuits correspond to earlier calculations and are significantly lower than the design values. As a result, no margins are eaten up by the static loads. This allows operating the XFEL cryogenics using only one cold box, leaving the second for redundancy.

Acknowledgements

Design and construction of the superconducting XFEL linac is based on the achievements of the international TESLA (Technology) Collaboration. H. Edwards (†2016, Fermi National Accelerator Laboratory, FNAL, USA) was a main supporter of the collaboration from the start. In particular, the authors thank our colleagues from FNAL for their contributions to TESLA cryogenics. The basic concepts for cryogenics were developed about 25 years ago by G. Horlitz (†1997, DESY.) B. Wiik (†1999, DESY) started it all.

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