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Heat load measurements of XFEL cryomodules using helium evaporation method

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Abstract. The European XFEL Free Electron Laser (EuXFEL) at DESY is at 2K operation since January 2017. User operation with a maximum beam energy of 17,5 GeV began in September 2017. Studies are ongoing for a possible upgrade to operate XFEL at higher duty factors and lower cavity gradients. For this purpose, dynamic heat loads should be measured precisely to evaluate the cryomodules performances and the needed cooling capacity of refrigeration plant. This paper describes a heat loads measurement method based on measurements of the amount of helium evaporated from LHe II bath during a certain time period. A distinctive feature of this method is its insensitivity to eventual leaks across the seats of JT-valves. Furthermore, possible errors in the LHeII level readings can be minimized using this method. This paper summarizes the experience gained so far with this method at the EuXFEL linac and the CryoModule Test Bench (CMTB). Issues that have arisen during the measurements are discussed and conclusions are drawn. Results of the heat load measurements in CW mode are presented for a single cryomodule at CMTB.

1. Introduction

The main linac of the EuXFEL [1] consists of three linear accelerators sections– L1, L2 and L3 (Figure 1) including cryomodule strings. The L1 and L2 sections contain 4 and 12 cryomodules (CMs) respectively. The L3 section contains seven cryogenic strings; six with 12 CMs each and one string (Str. 9) with eight CMs. All strings are separated by connection boxes (SCBs).

The main components of the 2K circuit of each CM are eight superconducting niobium 1.3 GHz nine cell cavities and one superconducting magnet package. These components are cooled at 2 K in LHe II bath. The 2K circuit is surrounded by a 5/8K and a 40/80K thermal shield.



Figure 1. Arrangement of the main components in the EuXFEL linac

Currently EuXFEL operates at beam energies up to 17.5 GeV with a duty factor DF around 1%. It is planned to upgrade the EuXFEL for HDC (High Duty Cycle) operation featuring longer



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accelerating pulses (i.e. higher duty factors) at lower accelerating gradients V_{acc} . The L1 and L2 linac sections will get new HDC-designed CMs, while the existing L1 and L2 cryomodules will be rebuilt into an additional string 10 in L3.

The HDC operation will result in larger heat loads for all circuits and will require the installation of an additional refrigerator, whereas the partially re-use of the existing cryogenic infrastructure also has to be considered. A fundamental parameter for the cryogenic design of the upgraded linac are the cryomodule RF heat loads at low cavity gradients and high duty factor.

A test campaign has started at DESY to measure the RF heat load Q_{RF} for all cryomodules at low accelerating gradients with the available duty factor. Such measurements shall be as accurate as possible in order to keep uncertainties in the heat loads at a reasonable level and allow a proper design of the future beam operation parameters as well as the HDC cryogenic system. The helium evaporation method seems to be a suitable one to provide a sufficient accuracy.

2. The 2K circuit of an EuXFEL string

The 2K circuit of each EuXFEL string consists of a DN40 2.2KF, DN300 2KR (GRP) and a DN65 two-phase pipe (2PP) as seen in Figure 2. The 2.2KF and 2KR pipes run uninterrupted through the whole linac (L1, L2, L3) while each string has a separate 2PP. Subcooled helium is delivered to each string by the 2.2KF pipe at 1.5 bara and expanded at 31 mbara by means of a JT valve. The helium temperature in the 2.2KF pipe upstream of the JT valve depends on the position of the string within each linac section and ranges from 2.3 to 3.8 K for the first and last string respectively. The 2PP contains two LHe II vessels located at opposite sides of the pipe within the SCBs. Each vessel is equipped with two heaters and two superconducting level sensors and has a connection to the GRP to pump helium vapor by cold compression. Furthermore, the 2PP between neighbouring CMs also contain such connections to GRP.

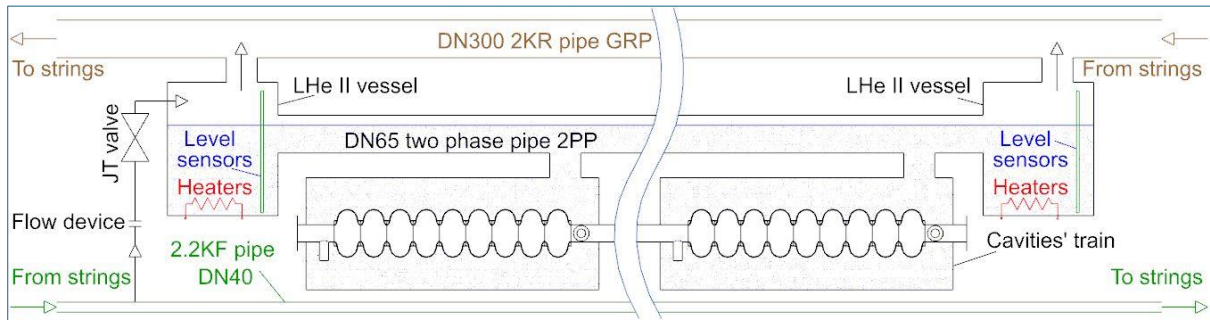


Figure 2. The 2K circuit of the EuXFEL strings

3. Description of the helium evaporation method

The method is based on measuring the mass of helium Δm evaporated from the 2PP during the time period $\Delta \tau$. The evaporated mass is proportional to the applied heat load Q causing the evaporation:

$$Q = L \cdot \Delta m / \Delta \tau \quad (1)$$

where L is the latent heat of LHe II. For a liquid with density ρ the evaporated mass can be defined as the change of volume ΔV in the 2PP during the evaporation time times the density of the liquid:

$$\Delta m = \rho \cdot \Delta V \quad (2)$$

The volume of liquid helium contained in a horizontal 2PP can be calculated as:

$$V = A_L \cdot Length \quad (3)$$

where $Length$ is the 2PP length and A_L is the cross-sectional area of the liquid helium. For a circular pipe with the internal diameter D and a liquid level h_L the cross-sectional area of liquid A_L (Figure 3) is:

$$A_L = (D^2/4) \cdot \left(\arccos(1 - 2 \cdot h_L/D) - (1 - 2 \cdot h_L/D) \cdot \sqrt{1 - (1 - 2 \cdot h_L/D)^2} \right) \quad (4)$$

Thus, the task of measuring the heat load Q is reduced to measurements of the liquid levels h_{L1} and h_{L2} at the beginning and end of the test period in order to calculate ΔV .

In general, the heat load Q includes a static heat load Q_{stat} , a virtual heat load Q_{virt} caused by a leak of liquid across the JT valve and a dynamic heat load Q_{dyn} . The latter can be produced either by an electrical heater Q_{heat} or by RF power Q_{RF} , hence:

$$Q = Q_{stat} - Q_{virt} + Q_{dyn} \quad (5).$$

Therefore, to be able to measure Q_{dyn} , a calibration of the system with $Q_{dyn} = 0$ is necessary to determine the value $Q_{stat} - Q_{virt}$. If the volume of the liquid changes by the value ΔV_{stat} during the time period $\Delta \tau_{stat}$, then:

$$Q_{stat} - Q_{virt} = L \cdot \rho \cdot \Delta V_{stat} / \Delta \tau_{stat} \quad (6).$$

Once $Q_{stat} - Q_{virt}$ is known, $Q_{RF} = Q_{dyn}$ can be calculated measuring the volume change ΔV_{RF} during the time $\Delta \tau_{RF}$ while RF power is applied to the cavities of a cryomodule. Being

$$Q_{stat} - Q_{virt} + Q_{RF} = L \cdot \rho \cdot \Delta V_{RF} / \Delta \tau_{RF} \quad (7),$$

the applied heat load Q_{RF} will be defined as:

$$Q_{RF} = L \cdot \rho \cdot [(\Delta V_{RF} / \Delta \tau_{RF}) - (\Delta V_{stat} / \Delta \tau_{stat})] \quad (8).$$

The drawback of equation (8) is the necessity to calculate volumes of liquid using geometrical characteristics of the system h_L and $Length$. As pointed in [2], level sensors are not always installed as prescribed by drawings. The calibration method proposed in [2] helps to define the reading of the level sensor corresponding to the bottom edge of the 2PP. This partially solves the problem but not completely since some errors in absolute readings of the level still remain. For inclined 2PPs (the EuXFEL case) the exact definition of the volume of the liquid helium contained in the 2PP requires the application of two level sensors installed at opposite sides of the 2PP. This further increases the error in the determination of the liquid helium volume. Furthermore, the definition of the 2PP length $Length$ is also not free from errors.

The technique to bypass these accuracy problems consists of two steps. Firstly, all experiments (with and without the dynamic heat load) shall be conducted so that the time periods $\Delta \tau$ are always measured between the same two level values h_{L1} and h_{L2} , resulting in the same volume change ΔV_0 for all experiments. In doing so the equation (8) takes the following form:

$$Q_{RF} = L \cdot \rho \cdot \Delta V_0 \cdot [(1/\Delta \tau_{RF}) - (1/\Delta \tau_{stat})] \quad (9).$$

Secondly, the change of volume ΔV_0 still unknown in (9), can be defined by conducting a second calibration experiment with a known power dissipated by a heater $Q_{dyn} = Q_{heat} \neq 0$ and measuring the time interval $\Delta \tau_{heat}$ necessary for the helium level to drop from h_{L1} to h_{L2} . Then,

$$Q_{heat} = L \cdot \rho \cdot \Delta V_0 \cdot [(1/\Delta \tau_{heat}) - (1/\Delta \tau_{stat})] \quad (10).$$

The volume change ΔV_0 can now be extracted from (10) and substituted in (9) to calculate the RF heat load

$$Q_{RF} = Q_{heat} \cdot (\Delta \tau_{heat} / \Delta \tau_{RF}) \cdot [(\Delta \tau_{stat} - \Delta \tau_{RF}) / (\Delta \tau_{stat} - \Delta \tau_{heat})] \quad (11).$$

In conclusion, the task of measuring the RF heat load is reduced to measuring the time periods $\Delta \tau_{stat}$ ($Q_{dyn} = 0$), $\Delta \tau_{heat}$ ($Q_{dyn} = Q_{heat}$) and $\Delta \tau_{RF}$ ($Q_{dyn} = Q_{RF}$) required by the system to evaporate the LHe II in the 2PP from level h_{L1} to h_{L2} . The absence of the need to conduct

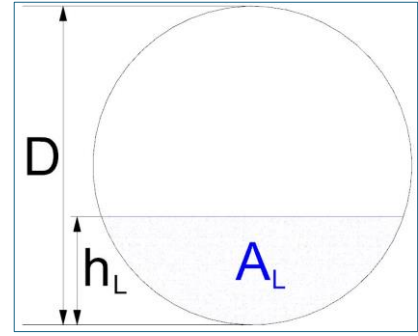


Figure 3. Cross section of the 2PP

geometrical calculations of the volume is reached at the expense of an additional calibration test. Since the level readings are not tied to the volume calculations, the method is insensitive to errors introduced by inaccuracy of the level sensors' installation inside the 2PP as well as length definitions of the respective pipe segment.

4. Measures to improve the accuracy

4.1 Using the reference curve

Substituting ΔV_{RF} , Q_{RF} and $\Delta\tau_{RF}$ in (8) by ΔV_0 , Q_{dyn} and $\Delta\tau_{dyn}$ respectively, the equation will represent a linear function with the intercept $-(Q_{stat} - Q_{virt})$, the independent variable $1/\Delta\tau_{dyn}$, the dependent variable Q_{dyn} and the slope $L \cdot \rho \cdot \Delta V_0$. Two points on the function curve shall be known to define a linear function. These points shall be obtained by measuring time periods needed for changing the level from h_{L1} to h_{L2} for two values of the heating power Q_{heat} .

The number of calibration experiments can be extended to consider possible random errors during the calibration experiments. The calibration data are plotted in a reference curve $Q_{heat}(1/\Delta\tau_{heat})$ as shown in Figure 4. The use of the reference curve brings the advantage in making further RF heat load measurements more trustful however at the expense of additional calibration time. Maximal and minimal values of the heating power Q_{heat} should overlap the expected Q_{RF} range.

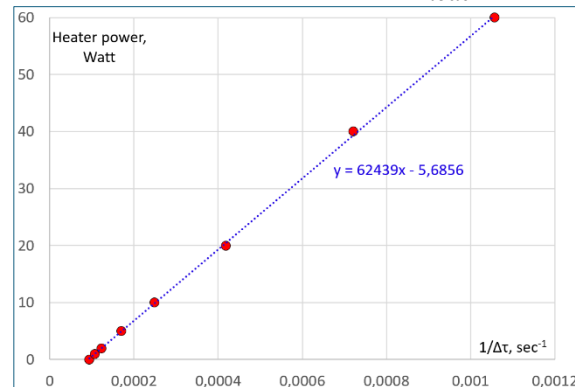


Figure 4. Example of the reference curve

4.2 Calculation of the time periods $\Delta\tau$

Each digitized level reading gets an assigned timestamp. The scan rate for cryogenic parameters is ~ 1 Hz. The digitized series of $h_L(\tau)$ readings may therefore not contain the exactly desired values of h_{L1} and h_{L2} . Thus, the timestamps corresponding to h_{L1} and h_{L2} cannot be precisely assigned. The problem can be solved by fitting the digitized series $h_L(\tau)$ by a second order polynomial using the least-squares method. The exact timestamps $\tau(h_{L1})$ and $\tau(h_{L2})$ can then be calculated using the resulting fitting function $\tau(h_L) = a \cdot h_L^2 + b \cdot h_L + c$. The fitting range within the digitized series $h_L(\tau)$ is not limited to $h_{L1} - h_{L2}$ but extended to $h'_{L1} - h'_{L2}$ so as $h'_{L1} > h_{L1}$ and $h'_{L2} < h_{L2}$.

Many level sensors experience a jumpy behaviour as noted in [2]. Presence of jumps within the digitized series $h_L(\tau)$ will result in an erroneous fitting function $\tau(h_L)$ and consequently in an incorrect calculation of the timestamps $\tau(h_{L1})$ and $\tau(h_{L2})$. All jumps and other doubtful readings are therefore excluded from the series $h_L(\tau)$ so as only trustful data are considered for establishing the fitting function. In some cases (Figure 5), two polynomials are required - one for definition of $\tau(h_{L1})$, the other for $\tau(h_{L2})$.



Figure 5. Fitting the level curve by two polynomials

4.3 Constancy of the $Q_{stat} - Q_{virt}$ value

The virtual heat load Q_{virt} is associated with a leak across the concerned JT valve. The incoming liquid slows down the level drop in the 2PP. Thus, the effect of slowing down the level drop can be seen so as if the system would be equipped with a heat sink with the capacity Q_{virt} .

It cannot be ensured that the leak rate across the JT valve being in open position and having the same valve lift will be the same for all single tests within the test run. Therefore, all tests should possibly be conducted with a closed JT valve equipped with a hard-wired end switch for the “closed” position. The eventual leakage across the valve seat is associated with an opening of a certain size between the high- and low- pressure sides of the valve. Supposing the size of the opening remains unchanged for all single tests throughout the test run, the constancy of the leak rate will be ensured if pressure and temperature upstream of the valve are kept constant. During RF heat load measurements in section L3 of EuFEL, all JT valves are kept closed independently on which string undergoes the tests. This is to retain the unique temperature distribution along the 2.2KF pipe throughout the tests.

The static heat load for the 2K system of a CM Q_{stat} depends on the LHe II level in the 2PP. The constancy of the integral value of the static heat load (i.e. the value between the h_{L1} and h_{L2}) during the whole run of tests is ensured by the method itself since the h_{L1} and h_{L2} values remain the same for all experiments. This is valid if cooling conditions (e.g. temperature of thermal shields) remain unchanged.

Good practice to check the constancy of the $Q_{stat} - Q_{virt}$ value for validating the conducted series of Q_{RF} measurements is to repeat the calibration test with $Q_{dyn} = 0$ at the end of the test run (Figure 6). If the resulting $h_L(\tau)$ curve is identical to the one obtained at the beginning, the series of Q_{RF} measurements are validated. Otherwise, a new test run should be initiated.

The time for the repeatability test can be shortened if the test is conducted with a known power Q_{heat} dissipated by the heater.

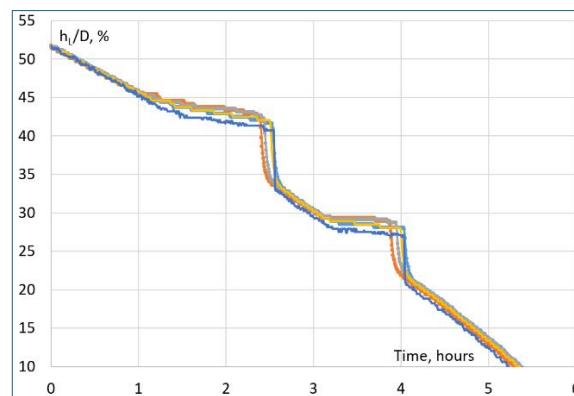


Figure 6. Repeatability check curves

4.4 Choice of h'_{L1} and h'_{L2} values

From a mathematics point of view, the h'_{L1}/D and h'_{L2}/D values should be as close as possible to respectively 100 and 0% since eventual errors in the level readings at these filling grades will have smaller impact onto the volume value. Considering however that the larger the filling grade the larger the flow tendency to transition into non-stratified flow, the h'_{L1}/D value shall be chosen so as smooth stratified flow will have to take place in the 2PP for the maximum expected heat load. The h'_{L2}/D value should possibly not fall below 10% because of RF interlock limitations.

4.5 Measurements in inclined strings

The LHe II “liquid-vapor” boundary in the 2PP follows the earth curvature. Inclined strings result in different level readings at opposite sides of each string. This however has no effect on the method accuracy since only one level sensor is used for the whole test run – the volume change caused by the level drop from h_{L1} to h_{L2} will be exactly the same from one experiment to another. The choice of the level sensor at the EuXFEL strings takes place before the test run by conducting one evaporation test involving all sensors and choosing the best suitable one on the basis of smoothness criterion.

4.6 Impact of heaters on level readings

Heaters are located at the bottom of the LHe II vessels containing also the level sensors. A temperature gradient along the LHe II column between the bottom and the “liquid-vapor” boundary will depend on power dissipated by the heaters. Even if the temperature gradient is small, this can affect the level readings since the work principle of the used superconducting level sensors is based on the heat exchange effect between the superconducting wire and the fluid. In order to exclude eventual inaccuracy of the level readings introduced by the heaters, all heat load measurements in the EuXFEL linac are conducted using the heaters in one LHe II vessel and the level sensors in the other LHe II vessel at the end of the string of cryomodules. Such solution is not applicable at the test facilities since they are equipped with only one LHe II vessel.

5. Measurements of the RF heat load at CMTB

The evaporation method was validated at CMTB [3] on a spare EuXFEL cryomodule (XM46.1). Firstly, the reference curve was created (Figure 4). Then, the RF heat loads were measured in CW and long pulse (50% duty factor) mode. The RF power was applied simultaneously to all cavities. The accelerating gradient V_{acc} of the cavities ranged from 3.5 to 10 MV/m and was kept constant during the measurements. All cavities within the cavities’ train had the same gradient. The experimental data and corresponding fitting curves are shown in Figure 7.

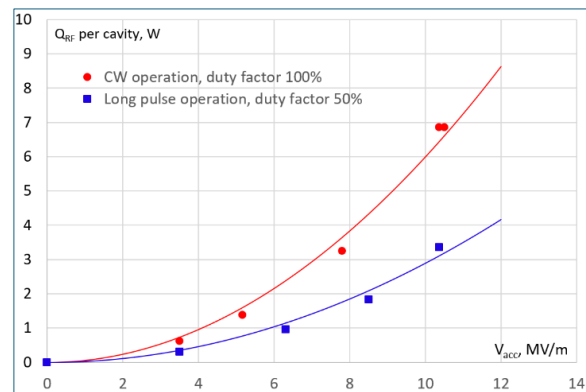


Figure 7. Q_{RF} vs V_{acc} for the XM46.1 CM at CMTB

The fitting curves follow the quadratic dependency of the RF heat load from the accelerating gradient $Q_{RF} \sim V_{acc}^2$. Also, as expected, reducing the duty factor by two times results roughly in the same decrease of the RF heat load.

6. Conclusions and next steps

Results of the RF heat loads measurements obtained at XM46.1 are promising. The minimal measured heat load value was around 2.4 W with $Q_{stat} - Q_{virt}$ being ~ 5.7 W. The results are repeatable.

During the EuXFEL shutdown times the reference curves for all L3 strings are being measured. After having created all reference curves, the RF heat loads measurements relevant for HDC operation will commence during next shutdowns.

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