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Heat loads measurements at the XFEL cold linac

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Abstract. The European X-Ray Free Electron Laser (EuXFEL) at DESY is in operation since the beginning of 2017. The free electron laser is based on a superconducting linear accelerator that delivers electrons to the undulator section with beam energy up to 17.5 GeV. The linear accelerator consists of 96 cryomodules; each 12 m long module is an assembly of 8 superconducting cavities and one superconducting magnet. This paper focusses on the measurement of the static and dynamic heat loads of the cryomodules assembled in the linac. Heat loads are an important parameter to evaluate the efficiency of the refrigerator system, the quality of the cryomodule assembly and installation and the accelerating cavity performances, being the dynamic heat loads proportional to the cavity quality factor (Q_0, the ratio of the stored energy to the dissipated energy). The paper describes at first the procedure to measure the static heat load without beam energy and the dynamic heat loads at different beam energy levels. The measurement results are then summarized and compared with the XFEL design values.

Keywords: European XFEL, Thermal performance, Superconducting accelerator.

1. Introduction

The heat loads at different temperature levels are an important parameter to evaluate the cryomodule performances and the thermal stability during operation of the XFEL linac system from the cryogenic point of view. The total heat load is the summation of static and dynamic heat loads. The static heat loads contribution includes conduction through cryomodule supports, fundamental power couplers, tuners, pressure relief pipes, beam line pipe, valves, magnet power supply leads, instrumentation wires, radiation to the shields and the cold mass. On the other hand, the dynamic heat load contributions are mainly from the RF losses in the accelerating cavities and the ohmic heating of the power couplers.

This paper first presents the methodology applied to determine the XFEL linac static heat loads (without beam energy) and dynamic heat loads at different beam energy levels and the summarizes the results for the 2 K cavity environment, 5/8 K intermediate and 40/80 K outer thermal shields circuits measured since the beginning of XFEL linac operation.

2. Methods of heat load calculation

The heat loads presented in this paper are calculated in two different ways, depending on the temperature level and facility considered.

The first method is the so called “delta enthalpy” method: from the measured temperature and pressure values the enthalpy of the helium is calculated (using tabular data from the HePak database [1]) at the inlet and outlet of the circuit. The enthalpy difference is then multiplied by the helium flow to obtain the heat load on the considered circuit. This is the standard method applied during linac operation and testing of single cryomodules at the AMTF (Accelerating Module Test Facility) during the construction phase of the XFEL.

The second method is the so called "latent heat" or "isothermal" method. This method evaluates the heat load deposited in the liquid helium in a closed system: the heat load $\dot{Q}$ can be obtained by multiplication of the helium latent heat (L) at the considered temperature level (in our case 2 K) by the measured flow rate ($\dot{m}$). This method has been used to calculate the 2 K heat load during the single cryomodule testing at AMTF.

Both methods are based on the total flow in the circuit and calculate therefore the total heat load. The contribution of the static and dynamic heat loads has been measured as follows. The static heat load has been measurement by switching off all the heaters and the RF power to the cavities. The static heat load contribution is then subtracted from the total heat load to evaluate the dynamic heat load

Dynamic heat load measurements at 5/8 K and 40/80 K at the AMTF were skipped because of time constraints.

3. Heat load of single cryo modules tested at Accelerator Module Test Facility (AMTF)

The Accelerator Module Test Facility (AMTF) at DESY in Hamburg is dedicated to test of RF cavities and accelerating cryomodules for the European X-ray Free Electron Laser (XFEL). The AMTF hall is equipped with two vertical cryostats, which are used for single RF cavities testing and three horizontal test benches that are used for testing the fully assembled accelerating cryomodules. Each test bench is connected to a valve box via a transfer line. Each XFEL cryomodule was tested at the AMTF horizontal test stand to verify the RF performances of the cavities and the overall performances of the cryomodule. A measurement of the heat load performances was part of the standard test procedure for the XFEL cryomodule qualification. More technical and measurement details can be found in the reference [2]. The heat load of the 2 K, 5/8 K and 40/80 K circuits has been measured as described at the section 2 and the results has been summarized in the table 1. During the 2 K dynamic heat load measurement, the average cavity gradient of 23 MV/m was maintained. These values are compared in chapter 9 with the average values calculated for the cryomodules once installed in the XFEL linac.

Table 1. Average Heat loads of 103 cryomodules tested at AMTF

Circuit	Average heat load per cryomodule [W]
40/80 K Static	92.7
5/8 K Static	10.6
2 K Static	5.6
2 K Dynamic	4.2

4. Overview of XFEL Cryogenic System

A detailed description of the XFEL cryogenic system was given in [3,4]. For the completeness of this paper a short overview of the XFEL cryogenic system is presented in this chapter. The XFEL system consist of the linac, the injector and the refrigerator infrastructure (see figure 1). The main linac is divided into three linac sections L1, L2 and L3 and consists of 96 1.3 GHz cryomodules in total. Each linac section has its own feed cap (FC) and end cap (EC) for the supply and return of the cryogens. The cryogen is supplied to each linac section with the transfer lines XLTL1, XLTL2 and XLTL3. Each string in the linac section L3 is connected via a string connection box (SCB). The cryogenic plant located in building 54 feeds the XLVB distribution box which cools down the linac on one side and the injector through distribution box (XIVB). The XLVB box receives back all the cryogenic circuits from XFEL linac and the injector. The 2 K return vapor is then processed either by the cold compressors or by warm He-pumps in the AMTF.

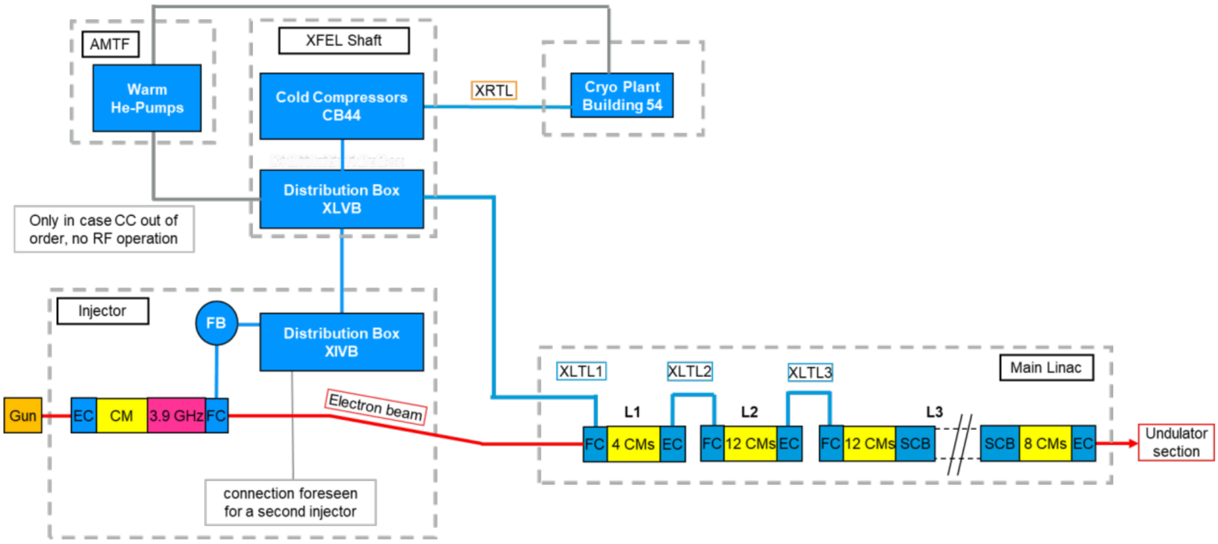

Figure 1: XFEL System Overview [3]

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

The enthalpy method has been used to measure the static and dynamic heat loads as described in section 2. Accurate temperature has been calculated using an additional method that has been explained in [4]. For the 2 K circuit, the flow has been calculated as the sum of all flow meters that has been installed at the inlet side of the JT valves of each string. The contribution of the electrical heater heat load in the 2 K helium bath is then subtracted during the enthalpy balance.

Table 2 summarizes the results of the static heat load measurements to the XFEL Linac at 2 K, 5/8 K and 40/80 K circuits. For the operation period of 2017-2021, the average static heat load to the XFEL linac has been measured to be 9.7 kW, 773 W and 587 W with the standard deviation 1σ of ±0.165 kW, ±44 W and ±46 W for 40/80 K, 5/8 K and 2 K circuits respectively. Hence the average static heat load per cryomodule can be approximately ~102 W, ~8 W and ~6 W for 40/80 K, 5/8 K and 2 K circuits respectively. The average heat load per cryomodule that has been reported in the table 2 should be considered as a conservative value as it includes the contributions of cryomodules (CM), transfer lines (TL), feed caps (FC), end caps (EC) and the string connection boxes (SCB).

Table 2. Measured average static heat loads and average heat load per cryomodules of XFEL linac for 2 K, 5/8 K and 40/80 K circuits

Circuit	Static heat load [W]	Average heat load per cryomodule [W]
40/80 K	9777 ± 165	~ 102*
5/8 K	773 ± 44	~ 8*
2 K	587 ± 46	~ 6*

**Conservative values include contributions of CM, TL, FC, EC, & SCB*

6. Contributions to the 2 K static heat load

It has been observed from the table 2 that the measured average 2 K static load amounts to 587 W; this value is the sum of a sothermal part from the 2 K helium bath and a non-isothermal contribution for the 2 K forward and return pipes. The following paragraphs evaluate the contribution of each component individually.

6.1. Isothermal contribution of the 2 K bath.

The isothermal heat load contribution to the 2 K bath which includes the cavities and magnets has been measured using the "latent heat "method as explained in section 2. This measurement was performed during a dedicated study time at the XFEL linac in 2020. The XFEL Injector was also involved into the experiment.

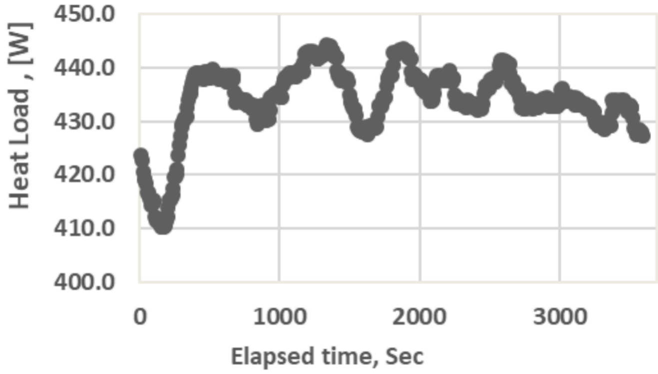

Figure 2: Trend of the 2 K isothermal static heat load in the XFEL experiment.

Figure 2 shows the calculated 2 K isothermal heat load measured during the test time. At time zero all JT valves were closed. Though the system had not yet reached steady state, the heat load can be estimated to be around 430 W. Since XFEL consists of circa 97.5 cryomodules (96 1.3 GHz linac cryomodules, one 1.3 GHz injector cryomodule and one 3.9 GHz injector cryomodule that counts for ½ a 1.3 GHz module), the average heat load per cryomodule is 4.4 W. For the XFEL linac the 2 K isothermal static heat load would be then be 4.4 * 96 = 423 W. If we subtract this value from the total 2 K static heat load measured above we obtain a non-isothermal 2 K static heat load for the XFEL linac of 587 – 430 = 157 W.

6.2. Non-isothermal contribution of 2 K gas return DN300 pipe.

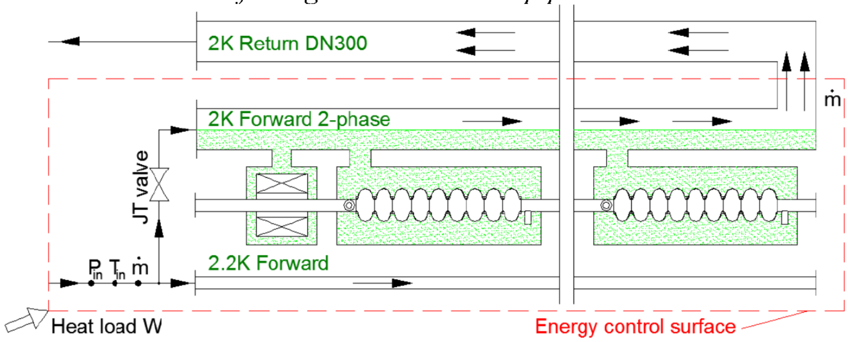

Figure 3: Flow scheme excluding the DN 300 pipe from the energy balance

Figure 3 shows the flow scheme excluding the 2 K return DN300 pipe from the energy balance. Here the total helium gas flow that leaves the system at the end of the 2 K 2-phase pipe is in saturated vapour state. Hence the energy balance equation can be written as

$$\dot{Q} = \dot{m}(h_{sat,V} - h_{in}(p_{in}, T_{in})) \quad (1)$$

Where $h_{sat,V} = 25.04\ J/g$ is the saturated vapour enthalpy, while $p_{in}, T_{in,} h_{in}$ are the inlet pressure, temperature and enthalpy respectively.

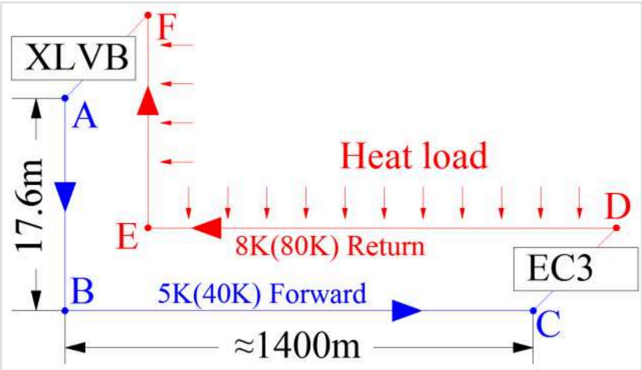

Figure 4. Location of the XFEL linac in reference to XLVB

The equation 1 is applicable if the inlet and outlet enthalpies are measured at the same height. In fact, the XFEL linac is located in the XFEL tunnel about 17.6 m below the XLVB (see figure 4), where the inlet measuring points are located. The hydrostatic head adds about 0.025 MPa to the pressure exiting XLVB making thus the operation pressure in the 2 K forward circuit of the XFEL linac of 0.145 MPa. Such a compression takes place at the expense of enthalpy increase by the value

$$g * \Delta height = 9.81\, m/sec^2 * 17.6\, m \approx 173\ Joules/kg.$$

So, if the inlet enthalpy h_{in} is measured at XLVB, then the equation of energy conservation would look as follows

$$Q = \dot{m} * (25.04 - h_{in} - 0.173) = (24.867 - h_{in}) \quad (2)$$

This is then the equation to use to calculate the average static heat load without the 2 K gas return pipe contribution. The calculated value is then 515 W. If the subtract this value from the total static heat load at 2 K shown in table 2, we obtain a static heat load contribution of the 2 K return DN300 pipe of about 587 – 515 = 72 W.

6.3. Non- Isothermal 2.2 K forward DN40 pipe contribution.

The contribution of the 2.2 K forward pipe (see figure 4) can now be obtained by subtracting the isothermal static heat load contribution of the 2 K bath (423 W) from the static heat load of the 2 K circuit without the DN300 gas return pipe (515 W). The 2.2 K forward pipe contribution is the 92 W.

It could be observed that the contribution of the 2.2 K forward pipe (DN40) is higher than the contribution of the 2 K gas return pipe (DN300). This is probably due to the pressure oscillations observed in the 2.2 K forward pipe.

7. Pressure oscillations in the 2 K forward pipe

As described in [1], the XFEL linac contains 12 connection boxes. The 2.2 K forward pipe in each box is equipped with an Ø6 x 1 mm capillary intended for measuring pressure mainly during XFEL cooldown / warmup. It was observed during the XFEL cooldown that pressure oscillations have appeared in the 2.2 K forward pipe after temperature of the pipe dropped below 6 K. In general, the oscillations were observed in all connection boxes and at SCB3 with the peak-to-peak amplitude around 50 kPa while the average pressure amounted to 150 kPa. Pressure oscillations in the 2 K forward pipe were also detected by a pressure transmitter located in XLVB however with the much smaller peak-to-peak amplitude (see figure 5).

A visual inspection in the XFEL tunnel has detected no signs of ice building typical of thermal acoustical oscillations. However, sounds generated by "opening-closing" of the check valve installed upstream of the 2.2 K forward safety valve were heard at each connection box. The FFT analysis of the oscillations has revealed two main frequencies around 0.22 Hz and 0.37 Hz (see figure 6). These are too slow to result from thermal acoustic oscillations. The exact reason for the pressure oscillation is not yet known.

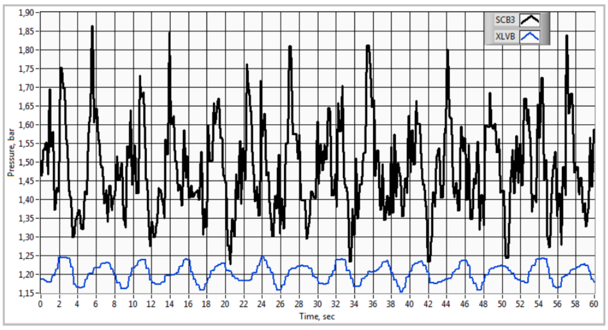

Figure 5. Pressure oscillations in SCB3 and XLVB

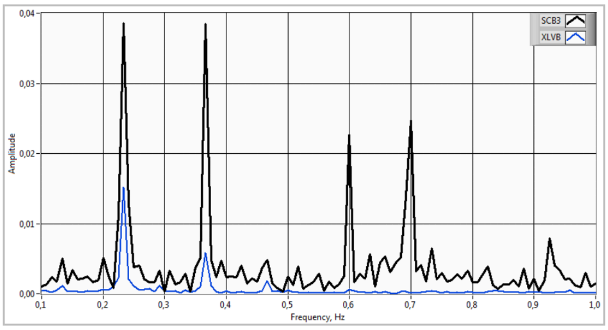

Figure 6. FFT spectrum of pressure oscillations

8. Measurement of dynamic heat loads of the XFEL linac 2 K, 5/8 K and 40/80 K circuits

When powered with RF, the superconducting accelerating cavities dissipate heat on the cavity walls. This energy is adsorbed by the LHe bath surrounding the cavity itself. The amount of heat is proportional to the accelerating gradient across the cavity and the quality factor of the cavity Q_0 (the ratio of stored energy to energy loss per cycle). This heat is the main contribution to the dynamic heat loads at 2 K, while the main contributions at 5/8 K and 40/80 K comes from the heating of the main coupler, bringing the RF energy to the cavities. The measurement methodology of the dynamic heat load has been explained in section 2.

Table 3 summarizes the dynamic heat loads of 2 K, 5/8 K and 40/80 K circuits for different energy levels. Figure 7 shows the static and total heat loads for varies energy levels for the 5/8 K and 40/80 K circuit and figure 8 shows the same values for the 2 K circuit during the operation time period 2017 to 2021. It could be seen that the static heat load measured for the three circuits are stable since the beginning of operation in 2017. The total heat load varies according to the RF energy levels at which the XFEL linac is being operated.

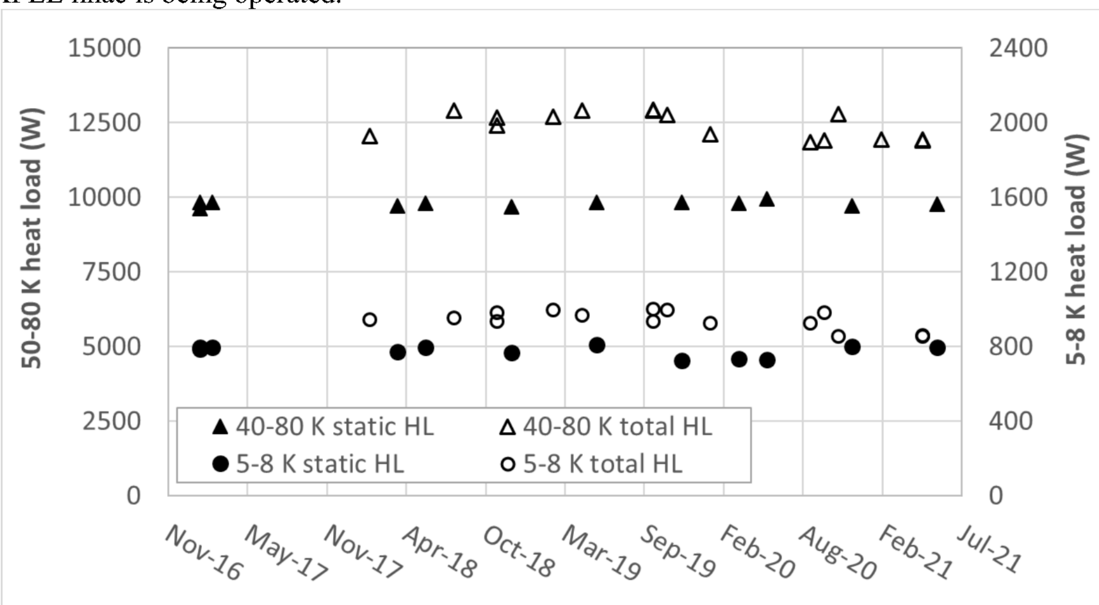

Figure 7: Static heat load without RF power and total heat load at different energy levels of 5/8 K and 40/80 K circuits.

Table 3 Dynamic heat loads of 2 K, 5/8 K and 40/80 K circuits for different energy levels

Circuit	Dynamic Heat load for different RF energy [W]	
	14 GeV	16.5 GeV
40-80 K	2707	3047
5-8 K	177	198
2 K	464	688

Figure 9 shows the total 2 K heat load variation as a function of RF energy levels. The total heat increases quadratically as expected for the varying energy levels. For the energy level of 16.5 GeV, the 2 K dynamic heat load that has been measured is 688 W.

9. Comparison and conclusions

Table 4 summarizes the average static and dynamic heat loads of a XFEL cryomodule and the single cryomodules tested at AMTF for the 2 K, 5/8 K and 40/80 K circuits and compares them with the XFEL design values [6].

Table 4 Comparison of the static and dynamic heat loads of 2 K, 5/8 K and 40/80 K circuits for different energy levels with XFEL design value

Circuit	Static Heat Loads [W]			Dynamic Heat Loads [W]		
	Measured XFEL	Measured AMTF	XFEL Design Value	Measured XFEL (16.5 GeV)	Measured AMTF (23.5 MV/m)	XFEL Design Value (23.5 MV/m)
40-80 K	102*	92.7	83	32	-	40
5-8 K	8*	10.6	13	2	-	2.3
2 K	6.1*	5.6**	4.8	7.2	4.2	8.6

**Conservative values include contributions of CM, TL, FC, EC, & SCB*
*** Only isothermal contribution*

As a general conclusion it can be affirmed that the measured XFEL static and dynamic heat loads for all the three circuits are in line with the XFEL design values. Only the deviation from the design value of the 2 K static heat loads is quite significant. This deviation could be explained remembering that the measured values at the XFEL linac are conservative values, since they include the contribution of the transfer lines, feed and end caps, and string connection boxes. The measured AMTF values are also in good agreement with the XFEL values.

Moreover, when considering the total 2 K measured value of 13.3 W (6.1 + 7.2 = 13,3 W) this is still in good agreement with the 2 K total XFEL design value of 13.4 W (4.8 + 8.6 = 13.4 W).

It can be also concluded by looking at the summary graphs shown in figure 7 and 8 that the static heat loads measured since the beginning of the XFEL linac operation are quite stable.

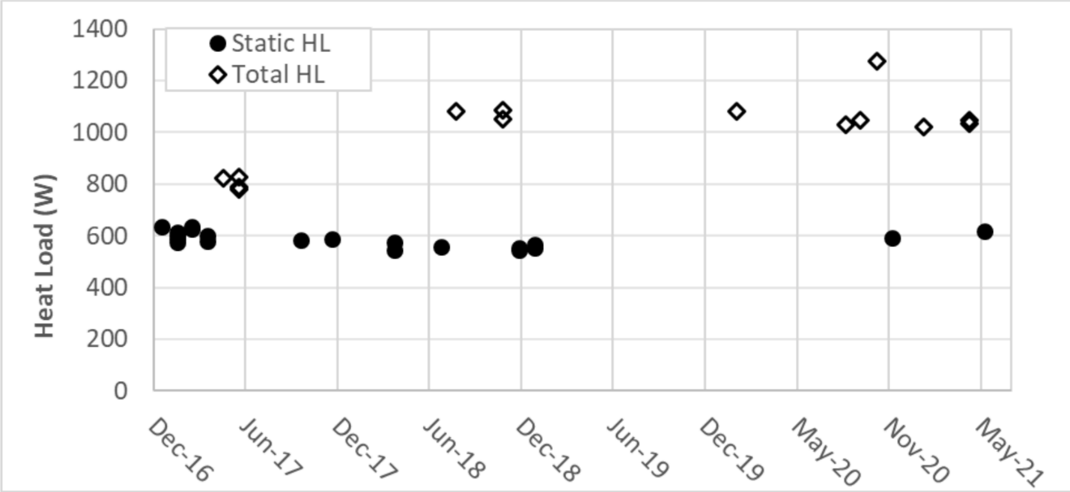

Figure 8: Static heat load without RF power and total heat load at different energy levels of 2 K circuit

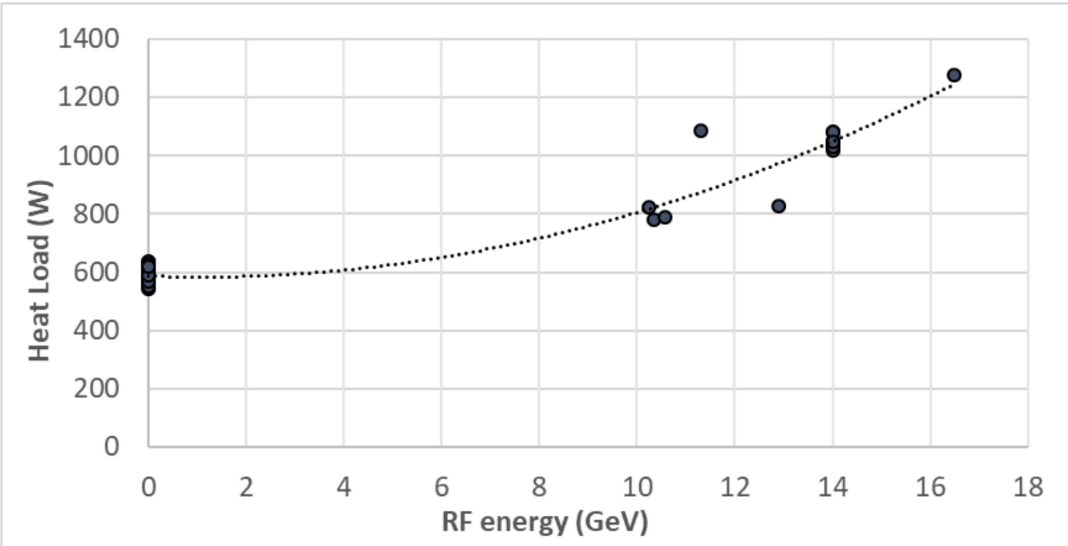

Figure 9: Total heat load of 2 K circuit as a function of RF energy level.

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