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Loss of insulation vacuum tests on an EuXFEL cryomodule

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Abstract. Many Free Electron Lasers (FEL) are nowadays based on linear superconducting accelerators (linacs). The typical layout of such a linac consists of a number of cryomodules (CMs) arranged in strings. Each cryogenic circuit in a string is protected by safety valves (SVs) in case of failure of the system or a catastrophic event. A typical worst-case scenario considers the venting of the insulation vacuum, causing a fast and uncontrolled warm up of the cryogenic circuits. Such venting can for example take place across a pump port belonging to a string. The amount of heat deposited on each circuit is a very important parameter to correctly size the safety devices.

This paper describes the tests performed at DESY on an EuXFEL cryomodule to evaluate the heat input to the three cryogenic circuits of the CM while venting the insulation vacuum. Test results are given with a particular focus of their application to long strings.

1. Introduction

The European XFEL Free Electron Laser (EuXFEL) [1] is in operation at DESY since 2017 [2]. The EuXFEL superconducting linac consists of 96 CMs arranged in nine strings. Every string of CMs is equipped with safety valves for each cryogenic circuit: the 40/80K, 5/8K and 2K one. The SVs were sized according to the test results reported in [3] considering as worst-case scenario venting the insulation vacuum with air across one DN100 pump port. Additional design and standardisation considerations determined the present configuration of the SVs in the facility.

Safety components like safety valves need regular verification with a certified authority. To avoid unnecessary warm ups of the entire facility, it was decided to double during the next shutdown foreseen in 2025 all safety valves in the EuXFEL cold linac and cryogenic distribution to allow the future verification of the SVs while keeping the facility in cold state. A precise evaluation of the heat input to the single circuits could help to verify the required amount and size of the safety valves.

Several publications [4-8] describe the heat load measurements to cold components, while venting the insulation or beam vacuum. The tests were however conducted on simple cryogenic components like e.g. cavities, cryostats, etc. The results reported in [3] were obtained on a "TTF-Type2" CM differing from the EuXFEL CMs by larger dimensions of thermal shields and absence of multi-layer insulation (MLI) on some pipes. Furthermore, all test results were released in the form of heat flux [W/m²]. The approach based on using heat flux values for sizing of SVs for long strings should be called into question since the approach suggests that the heat input to a circuit may exceed the heat input introduced by air across a vent port, which is physically impossible. Using all these results to size the EuXFEL SVs could hence cause the application of unreasonably large safety margins.

It was then decided to perform a test campaign aiming to establish patterns of the heat input evaluation to single circuits in long strings of EuXFEL CMs while venting the insulation vacuum.

2. Experimental setup

The CM XM-3 chosen for the venting tests is a pre-series EuXFEL cryomodule containing the 40/80K, 5/8K and 2K circuits (see figure 1). The 40/80K circuit consists of a thermal shield, and a forward (40KF) and return (80KR) pipe. The outer surface of the 40/80K thermal shield and the 40KF pipe are covered by 30 layers of MLI. The 5/8K circuit contains also a thermal shield, and a forward (5KF) and return (8KR) pipe. The outer surface of the thermal shield and the 5KF pipe are covered by 10 layers of MLI. The main components of the 2K circuit are a DN300 return pipe (2KR), eight superconducting cavities, a pipe for two-phase He II, one superconducting magnet, a 2.2KF forward pipe and a cooldown/warmup (WU) pipe. All the components of the 2K circuit are covered with 10 layers of MLI.

The CM XM-3 was installed in the CryoModule Test Bench (CMTB) [9] like for the test described in [3]. The air inlet unit (see figure 2) was located at the DN100 pump port of the End Cap (EC) bellows and contained a DN100 remotely controlled electro-pneumatic butterfly valve followed by a ~400 mm long intermediate DN100 pipe terminated by an aperture with variable DN.

The catastrophic venting across only one pump port is considered as the worst-case scenario for a string of cryomodules, even if each EuXFEL CM is equipped with a pump port.

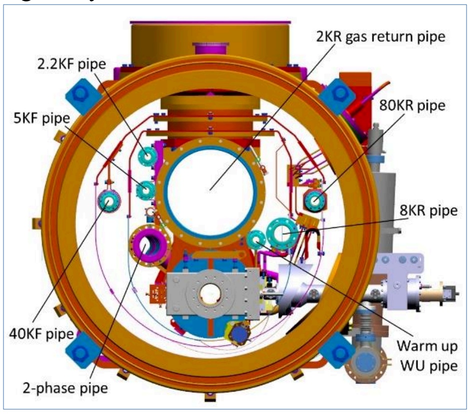

Figure 1. Layout of piping in EuXFEL CM.

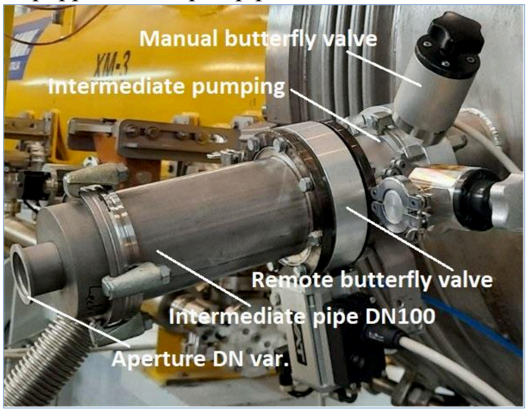

Figure 2. Air inlet unit.

The venting of a string with a different number of cryomodules can be simulated venting the same cryomodule through ports with different cross-section A_{virt}. If a string of N CMs is vented across one port with the cross-section A_{str}, each CM gets 1/Nth of the total air flowing through the port. This corresponds to venting each cryomodule of the string through a virtual port with the cross-section $A_{virt}=A_{str}/N$. If the heat input Q_{virt} to a circuit is measured while venting one single CM across a port with the cross-section A_{virt}, then the heat input Q_{str} to the same circuit in a string of N cryomodules will be $Q_{str}=Q_{virt}*N$. Thus, the heat input Q_{str} to a circuit of a string equipped with a vent port of cross-section A_{str} can be predicted by measuring the heat input Q_{virt} to this circuit of a single CM vented across a vent port with the cross section A_{virt}.

It was observed in the previous test [3] while venting the vacuum insulation space of a CM that the vacuum pressure remains roughly constant before the 2K and 5/8K SVs opened. This gives the evidence that the cold surfaces of the CM are able to cryo-pump for some time the whole heat input introduced by the air flowing through the vent port. This effect could be explained if the heat input to the coolant Q_{virt} would be directly proportional to the cross-section of the vent port A_{virt}. This hypothesis was verified venting one cryomodule through a series of orifices with different diameter.

3. Test procedure

The heat input to the vented piping for each circuit was calculated assuming isochoric heating. In order to extend the duration of the isochoric heating, the SVs protecting the process circuits were set to open at pressure values corresponding to the design pressures of the circuits, i.e. 19 barg for the 5/8K and 40/80K circuits and 3 barg for the 2K circuit. Furthermore, the operation pressure values in the process circuits before venting were set as low as possible, i.e. 31 mbara, 2.4-2.5 bara and 12-14 bara for the respectively 2K, 5/8K and 40/80K circuits. The 2-phase pipe was filled with liquid to circa half. The process valves separating all process circuits of the CM from the Feed Box (FB) were closed shortly before each venting cutting the air supply to the pneumatic actuators.

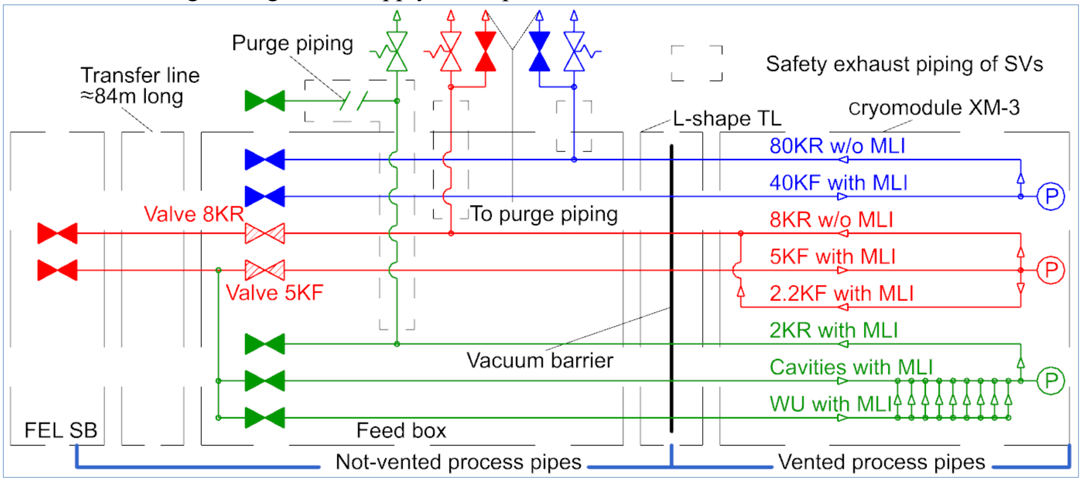

Figure 3. Flow scheme of the experimental setup.

The flow scheme of the experimental setup is shown in figure 3. The L-shape transfer line connecting the FB with the FC contains a vacuum barrier. The FB is connected to FEL Sub-cooler Box (FEL SB) by an 84m long transfer line. Geometrical data of each circuit are summarized in Table 1.

Table 1. Geometrical data of the circuits

		40/80K circuit	5/8K circuit	2K circuit liquid	2K circuit gas
Vented volume of the process piping, m³		0.0942	0.102	0.188	0.955
Not vented volume of process piping, m³		0.00226	0.0093	0.00394	0.107
Volume of the safety exhaust pipe, m³		0.00025	0.0028	-	0.17
Vented surface area of He, m²	with MLI	3.44	5.13	9.0	16.6
	w/o MLI	2.56	2.6	0	0

The instantaneous heat to the coolant was calculated as the time derivative at constant density of the total internal energy U of the coolant contained in the circuit. The time derivative at any point in time t_i was calculated by fitting the measured values of the internal energy with a linear function within the time period $t_i - \Delta t$. The time interval Δt was set to 20 seconds for the 40/80K circuit and 1 second for the 2K and 5/8K circuits. The helium properties were calculated with HEPAK [10].

In total, 4 apertures/orifices were used for the venting experiments – 40, 50, 60 and 80 mm. The "zero" timestamps in all the following plots correspond to the beginning of the opening of the gate valve. The sampling rate was 5 Hz for the venting tests using the 40 mm and 50 mm orifices, and 10 and 20 Hz for the respectively 60 mm and 80 mm orifices.

4. Calibration of the air inlet unit

With CMTB being in warm state, the CM vacuum vessel was vented sequentially through all the orifices used for the cold tests. An additional venting test was conducted directly through the electro-pneumatic butterfly valve. The air flow rate was calculated as the weight of the air inside the vacuum vessel at 0.5 bara and 290 K divided by the time necessary to fill the vessel from 0 to 0.5 bara. The vented volume of the vessel was ~9.3 m³. The sampling rate for all tests was 20 Hz.

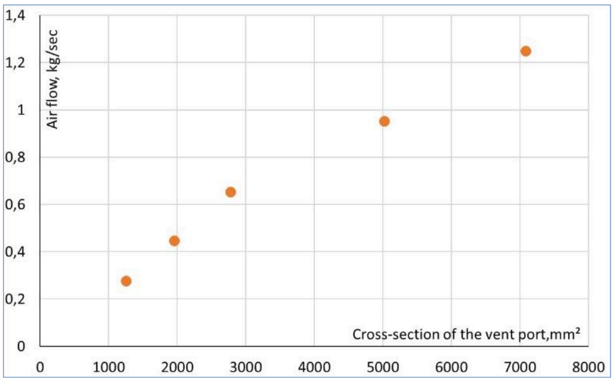

Figure 4. Air flow rate versus cross-section of vent port.

The results of the warm tests are shown in figure 4 and summarized in Table 2. Deviations from the linear relation observed for the 80 mm orifice and for the direct venting through the electro-pneumatic butterfly valve, having the internal diameter of 95 mm, are likely caused by hydraulic resistance of the manual and remote butterfly valves integrated into the vent port. Therefore, the cross-section of the vent port is not an adequate unit for the heat input representation and shall be replaced by the air flow rate.

Table 2. Calibration results of the air inlet unit

Orifice diameter	40 mm	50 mm	60 mm	80 mm	95 mm
Filling time to 0.5bara, sec	20.3	12.5	8.58	5.89	4.48
Air flow rate, kg/sec	0.275	0.446	0.651	0.949	1.25

5. Vacuum pressure trends during the cold venting tests

Figure 5 shows the evolution of the vacuum pressure for all cold venting tests. The measurements were taken with the sensor located within the 5/8K thermal shield in the EC, in vicinity of the air inlet unit. Unlike the results reported in [3], no considerable pressure drop in radial direction was observed. Similar to [3], there is for all tests a time period where the vacuum pressure remains almost stable. The values of this "stable" vacuum pressure (average value between the fifth and sixth second of venting) are plotted against the air flow rate in figure 6.

Figure 5 also shows the opening moments of the 5/8K and 2K SVs. The 5/8K SV always opened within the "stable" vacuum pressure period while the 2K SV reacted significantly later.

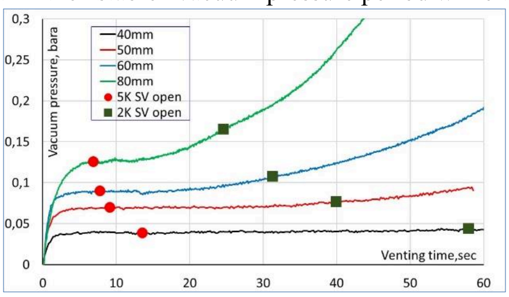

Figure 5. Trends of insulation vacuum pressure.

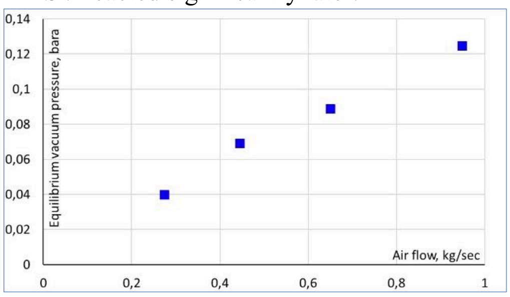

Figure 6. Vacuum pressure versus air flow rate.

6. Heat input to the 40/80K circuit

The temperature of the coolant before the venting tests ranged from 47 to 54 K resulting in the coolant weight of ~1.2 kg. In all tests the pressure increased almost linearly with the time. The slight deviation from linearity gives evidence to existence of a maximal value of the heat input (see figure 7 – venting across 80mm orifice). The values of the maximal heat input for all tests are plotted against the flow rate of air as shown in figure 8 and summarised in Table 3.

The heat input values from Table 3 shall be used for sizing the SVs protecting the 80KR pipe, not covered by MLI. The SVs for protection of the superinsulated 40KF pipe should be sized assuming the total heat input is shared between the 40KF and 80KR pipes according to the coolant surface areas as given in Table 1.

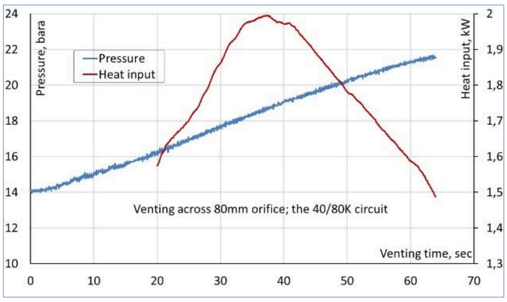

Figure 7. Pressure and heat input trends 40/80K.

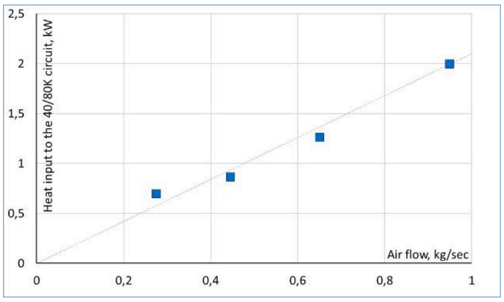

Figure 8. Heat input as a function of air flow.

7. Heat input to the 2K circuit

The pre-triggering conditions for the 2K circuit in all cold venting tests corresponded to a liquid-vapor mixture with the quality around 0.03 (27.9 kg of liquid and 0.84 kg of vapor) while the discharge across the 2K SV takes place in the one phase region at ~3 barg. The heat transfer mechanism changes from boiling inside the liquid/vapor dome to heat conduction and convection outside.

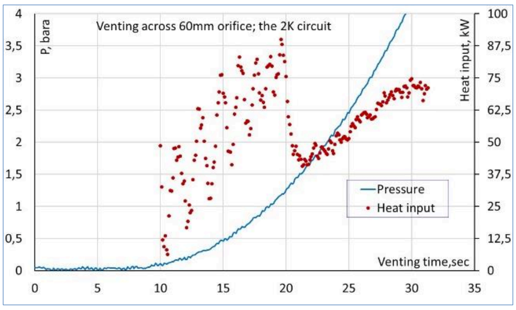

Figure 9. Pressure and heat input trends 2K.

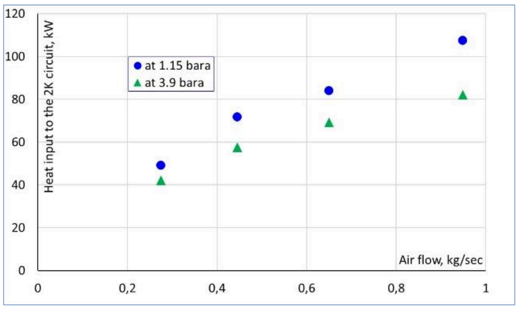

Figure 10. Heat input as a function of air flow.

Figure 9 shows the trends of pressure and heat input for the venting test with the 60 mm orifice. Within the liquid/vapor dome the heat input rises with time and reaches a maximum value just before the isochore curve 20.22 kg/m³ leaves the dome at the pressure of ~1.2 bara. After, the heat input drops to ~half its value, reaches a local minimum at the pressure of ~1.5 bara and then rises again. There are signs that the heat input reaches its maximal value in the one-phase region close to ~4 bara.

Points of particular interest are the maximal values of the heat input in the two-phase and one-phase regions. The corresponding values of the heat input are plotted against the flow rate of air as shown in figure 10 and summarized in Table 3. Unlike the 40/80K circuit, the heat input to the 2K circuit flattens with increase of air flow rate.

8. Heat input to the 5/8K circuit

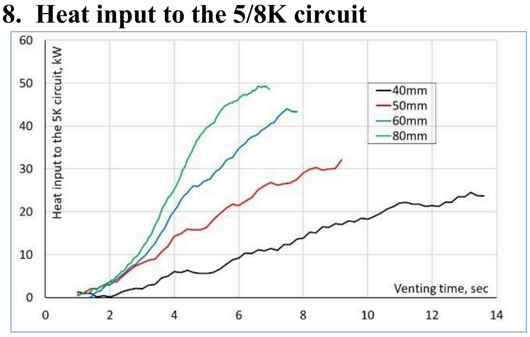

Figure 11. Heat input trends for all cold tests.

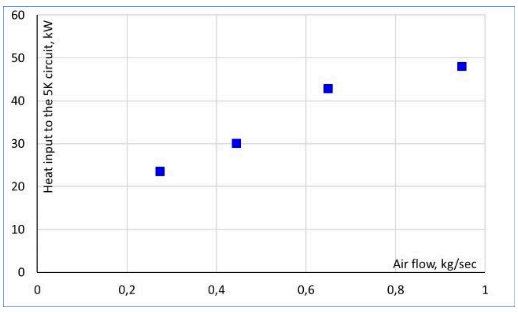

Figure 12. Heat input as a function of air flow.

The pre-triggering temperature of the 5/8K circuit was kept for all cold venting tests around 4.5 K resulting in the coolant weight of ~14 kg. The linear trend of the heat inputs for the 5/8K circuit (see figure 11) stems from the parabolic shape of the pressure rise curves.

The values of the heat input at the pressure of 19.5 bara are plotted against the flow rate of air as shown in figure 12. The heat input flattens with increase of air flow rate, like for the 2K circuit. The heat input values to all the CM circuits are summarized in Table 3.

Table 3. Heat inputs to the CM circuits

Air flow rate, kg/sec	0.275	0.446	0.651	0.949
Heat input to the 40/80K circuit, kW	0.697	0.864	1.26	1.99
Heat input to the 2K circuit at 1.15 bara, kW	49.1	71.8	84.0	107
Heat input to the 2K circuit at 3.9 bara, kW	42.2	57.6	69.2	82.0
Heat input to the 5/8K circuit at 19.5 bara, kW	23.4	29.9	42.8	48.0

8.1. Venting test simulating an EuXFEL string

The trends of the heat inputs for the 5/8K circuit (see figure 11) show that the heat input is rising during the whole duration of venting till opening of the 5/8K SV. There are no signs that the heat input slows down, except perhaps for the test with the 80 mm orifice. This indicates that the peak values of the heat input to the 5/8K circuit will likely be reached at pressures above the set pressure of the 5/8K SV. In the EuXFEL linac a vented string is surrounded by other not-vented strings or transfer lines resulting in an increased weight of the coolant involved in the isochoric process. This will slow down the pressure rise in the linac while keeping the same heat input to the coolant. Therefore, a higher heat input could be reached at the time of opening of the 5/8K SV.

An additional venting test was therefore carried out to simulate venting of the insulation vacuum in one EuXFEL string. In the test, the ~84 m long transfer line between CMTB and the FEL SB was connected to the 5/8K circuit of the CM (see figure 3). During the venting test the 5/8K process valves in the FB were kept open while the 5/8K process valves in the FEL SB were kept closed. The 60 mm orifice was used for the test. The whole 5/8K circuit was filled with supercritical helium. The weight of the coolant involved into the isochoric process was thus increased by ~4 times.

Figure 13. Comparison of pressure trends.

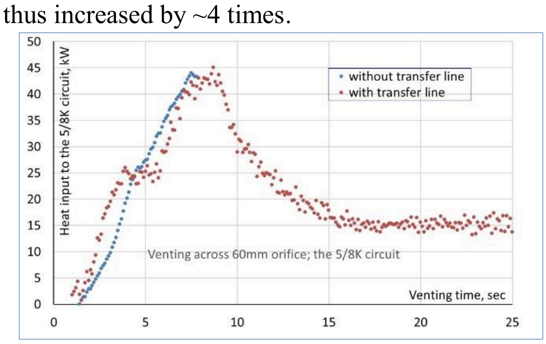

Figure 14. Comparison of heat input trends.

As expected, the pressure increase in the 5/8K circuit for the test with transfer line was significantly slower than for the test without the transfer line (see figure 13). The heat input (see figure 14) peaked at ~45 kW and dropped then by ~3 times. The value after the peak remained stable for a long time.

8.2. Influence of adiabatic compression

Considering that the peak values of the heat input to pipes covered by MLI (e.g. the 2K circuit) occur significantly later as those to pipes without MLI, one can assume that the peak heat input observed in figure 14 can be attributed essentially to the 8KR pipe with neglectable contribution from the 5KF and 2.2KF pipes. This leads to the appearance of two processes. On short time scale, the coolant confined in the 8KR pipe expands and causes the coolant in the 5KF and 2.2KF pipes to be adiabatically compressed to a pressure referred hereafter as a non-equilibrium pressure. On a long timescale, the expanded and compressed helium will mix resulting in a drop of the non-equilibrium pressure to an equilibrium one.

The volume of the 8KR pipe exposed to air by venting is 41.6 litres. The coolant contained in this volume will expand and compress the coolant inside the 5KF and 2.2KF pipes also exposed to air. Together with the remaining parts of the 5/8K circuit, that are not-exposed to air, these are 69.6 litres. Before venting, the system is in an equilibrium state at circa ~2.4 bara and ~4.57 K. Assuming the 19.5 bara to be a non-equilibrium pressure, the 5/8K circuit would then require ~120 kJ to reach 19.5 bara from 2.4 bara@4.57 K. The circuit would however require about 143 kJ assuming the 19.5 bara to be an equilibrium pressure. Thus, the assumption of considering the measured pressure as an equilibrium one causes an uncertainty of about +20% in the calculation of the heat input. The uncertainty increases with the increase of the ratio of the volumes of the compressed coolant to the expanded one and will be of the order of +75% for the test with the connected transfer line. Therefore, using the values of the heat input from Table 3 will not cause undersizing of the 8KR SVs.

8.3. Heat inputs to pipes with and without MLI

As noticed before, the maximal value of the heat input could be caused only by the 8KR pipe. Furthermore, comparing the tests with and without transfer line (see figure 14) one can conclude that the maximal values of the heat input reached in both tests are close to each other. Therefore, the values of the heat input at 19.5 bara from Table 3 can be considered as a good approach for sizing of SVs for the 8KR pipe.

The heat inputs to the superinsulated part of the 5/8K circuit are estimated in the terms of heat flux [W/m²] and summarised in Table 4 using the following assumptions:

- Assumption A: The heat flux to the superinsulated part of the 5/8K circuit is calculated as 1/6th of the heat flux to the 8KR pipe (see [5] and [8]).
- Assumption B: Since all components of the 2K circuit are covered by MLI, the results for the 2K circuit in one-phase region are applied to the superinsulated part of the 5/8K circuit.
- Assumption C: The flat part of the heat input curve in figure 14 represents the heat input contribution of the superinsulated part of the 5/8K circuit.

Table 4. Heat flux to the superinsulated pipes of the 5/8K circuit

Air flow rate, kg/sec	0.275	0.446	0.651	0.949
Heat flux assumption A, kW/m²	1.5	1.92	2.74	3.08
Heat flux assumption B, kW/m²	1.65	2.25	2.71	3.21
Heat flux assumption C, kW/m²	1.52	1.95	2.78	3.12

9. Spreading the test results to long strings

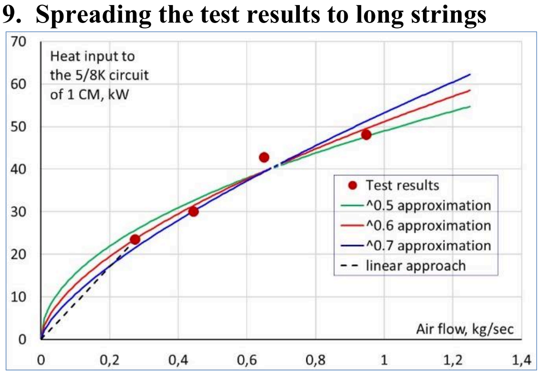

Figure 15. Examples of approximation curves.

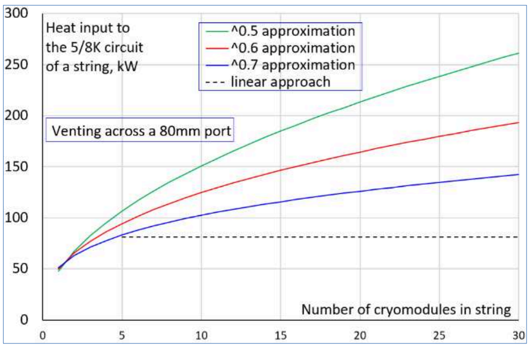

Figure 16. Heat input versus number of CMs.

Each string in the EuXFEL linac is equipped with a DN100 pump port with the maximal air throughput of 1.25 kg/sec. In the case of catastrophic venting of a regular string of 12 CMs, each CM gets on its own the air flow rate of ~0.1 kg/sec. This flow rate is far below of the minimal measured one of 0.27 kg/sec. The values of heat input at low flow rates of air could be predicted approximating the experimental results by functions originating from zero. The plots in figure 15 show different approximation curves for the 5/8K circuit of one CM calculated using a linear and exponential relations to the power 0.5, 0.6 and 0.7. The resulting heat input plots versus the number of CMs in a string for different approximations are shown in figure 16 for the case of venting the string across an 80mm port.

10. Conclusions

While venting the vacuum vessel across ports ≤80 mm, the pressure in the vacuum insulation space of the EuXFEL CM remains roughly constant, at least until the 2K and 5/8K SVs open. The equilibrium vacuum pressure and the heat input are proportional to the air inflow – the larger the air inflow the larger the equilibrium vacuum pressure and the larger the heat input.

The heat input to the coolant in the 40/80K circuit is directly proportional to the air inflow. The size of SVs protecting the circuit in a string will not depend on the number of CMs in the string but only on the size of the pump port. The heat input to the coolant in the 2K and 5/8K circuits flattens with increase of the air inflow indicating that the total heat input is disproportionally distributed between cold components and the 2/5K coolant – the smaller the air inflow the higher the contribution of the total heat to the coolant. Correct sizing of the 2K and 5/8K SVs for long strings requires the knowledge of the heat input to one CM measured for the corresponding air flow rate. The term “heat flux [W/m²]” is little applicable to sizing of SVs for long strings.

The measured values of the heat input to the circuits shall be seen as the result of a collective action of all cold components together and are therefore applicable only to EuXFEL CMs. Changing the cryo-pumping capability of a component (e.g. covering the 8KR pipe by MLI) will result in a different value of the equilibrium vacuum pressure and change the heat input to the remaining cold components.

Acknowledgments

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