RF heat load compensation with electrical heater for XFEL accelerator - measurements at CMTB, AMTF and FLASH

2015 IOP Conf. Ser.: Mater. Sci. Eng. 101 012159

(http://iopscience.iop.org/1757-899X/101/1/012159)

RF heat load compensation with electrical heater for XFEL accelerator - measurements at CMTB, AMTF and FLASH

V Ayvazyan, M Clausen, B Petersen, S Putselyk and T Schnautz

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

E-Mail: sergiy.putselyk@desy.de

A superconducting linac will provide electron bunches of 17.5 GeV beam energy for the operation of the European X-ray Free Electron Laser (XFEL) at DESY. 800 superconducting niobium 1.3 GHz nine cell cavities and 100 superconducting magnet packages will be cooled in a liquid helium II cooling bath at 2.0K temperature. Liquid helium II bath cooling at 2.0K is established by means of a 4 stages cold compressor system. For the stable operation of cold compressors sudden load changes should be avoided. Electrical heaters in the helium II bath will compensate dynamic heat load changes caused by the radio frequency (RF) operation of the cavities in the XFEL linac. The complementary load operation of electrical heaters is studied at the existing facilities at DESY. Measurements performed at Cryo Module Test Bench (CMTB), Accelerator Module Test Facility (AMTF) and FLASH accelerator are reported.

1. Introduction

The superconducting XFEL-linac is currently under construction at DESY, Hamburg. The XFEL-linac consists of 100 cryomodules, each of 12m length. Each cryomodule contains 8 superconducting 1.3 GHz radio frequency (RF) cavities, one superconducting quadrupole magnet package and two thermal shields at temperatures of 5-8K and 40-80K respectively [1-3]. The 2K supply of the cryomodules is subdivided in ‘strings’ of 12 cryomodules separated by string-connection-boxes (SCB.) All cryomodules of the linac contain a common 2K helium gas return tube (GRT.)

The cavities and the magnet packages will be cooled in a liquid helium II bath at 2.0K temperature, corresponding to a vapour pressure of 3100 Pa. Because of the extreme narrow RF bandwidth of the superconducting cavities, even small pressure changes will detune the cavities. Hence, any pressure fluctuations have to be limited during operation of the linac. In addition, the subatmospheric helium vapour pressure is maintained by operation of a 4 stages cold compressor (CC) set. For the stable operation of CCs without trips, sudden GHe flow rate changes across the CCs should be avoided. As a consequence, electrical heaters in the heliun II bath are applied to compensate sudden dynamic heat load changes, which are induced by RF load changes.

In view of the XFEL linac operation, also organisational and logistical aspects have to be addressed. Since about a decade, the RF and cryogenic systems for the superconducting FLASH linac are operated successfully. One of the former HERA refrigerators is in use for the cryogenic supply of the FLASH linac and robust warm subatmospheric helium pumps are in service for the 2K circuit. As a result, there is a huge amount of overcapacity available to deal with any possible load change of the RF system without compensation. Both systems are operated quite independently from each other. In case of the XFEL, both systems need much more coordination and matching. The different process control systems have to exchange the required information and implement the related algorithms. During the run of the reported measurements, first steps were taken to establish these links.

The present paper presents our first results on the development of the *RF heat load compensation scheme* (shorty – *compensation scheme*). Experiments were conducted at CMTB, AMTF facilities and FLASH accelerator. In the first part, requirements on pressure and GHe flow stability are considered. In the second part, experimental results are presented. In the last part, the case of XFEL accelerator is discussed.

2. Requirements on stability and general background

At stationary operation conditions of the XFEL linac cavities, heat will be dissipated in the helium II bath and evaporation of vapour will result. The vapour will flow to the inlet of the CCs via the GRT of the cryomodules. The flow will be driven by the pressure drop between the cavity helium vessels and the suction pressure at the inlet of the CCs. A stable vapour pressure of 3100 Pa at the cavity helium vessels will be maintained by the operation of the CCs at constant mass flow (the pressure drop across the GRT is neglectable.) The stable RF operation of the cavities requires a relative pressure stability smaller than +/- 1%. Any change of the dynamic RF loads at the cavities will result in a change of evaporation rate and vapour flow. The resulting pressure change will trigger the regulation of the CCs. Hence, the regulation of the CCs has to adapt to the flow change in order to keep the vapour pressure constant within the specified bandwidth. In case of the XFEL helium refrigerator regulation can be applied in different ways: the helium mass flow across the CCs could be varied within the dynamic range, the CCs bypass regulation loop could be adjusted or regulation valves in front of the CCs inlet could be used at fixed inlet pressure of the CCs. Any of these regulation scenarios will require a more or less complex response of the cryogenic plant, they have to be considered as slow and could cause CC trips. Therefore, CCs operation conditions should be kept constant and sudden RF load changes should be compensated by the complementary operation of electrical heaters during XFEL beam runs. During the steady-state operation mode of CCs, two cases related to RF operation must be considered, i.e. switching on/off of RF power, and large RF power variation, e.g. due to simultaneous quench of several cavities. For convenience of the discussion, consider the operation conditions of the CCs as fixed. As a consequence, any RF load changes would result in a helium vapour pressure change. Investigations were conducted during cryomodule operations at FLASH, at single Cryomodule Test Bench (CMTB) and at Accelerator Module Test Facility (AMTF), to study these boundary conditions, to understand the basic parameters and to develop concepts for the XFEL-linac operation. In contrast to the XFEL-linac cryogenic system, warm helium pumps are used at these facilities to operate the helium II bath at 3100 Pa. At first sight, the concept of complementary switching of RF load end electrical heaters seems to be simple. In reality, electrical heaters in liquid helium II baths show time constants in the order of several minutes in contrast to much shorter time constants of the RF system. Strategies have to be developed to deal with this mismatch.

3. Measurements

3.1 Heaters

For effective operation of electrical heater, it is important to measure two parameters: i) time constant, and ii) energy needed for the heater warm-up/cool-down. These parameters are investigated by monitoring the GHe flow rate. The performance of power supply, which has very short time constant, could be neglected for the further discussion.

For the AMTF cryomodule test stands [4], the time constant of electrical heaters was roughly estimated to be approximately constant in the range of 300-500s, while for the CMTB[5] it was ca. 200-300s for heating power above 20W and increasing up 1000s if heating power is decreasing to zero. The reason of this behaviour is attributed to the mechanical and thermal installation of the

IOP Conf. Series: Materials Science and Engineering **101** (2015) 012159 doi:10.1088/1757-899X/101/1/012159

heating cartridge inside the tube, which is welded into LHe (Liquid Helium) vessel (i.e. around this tube is LHe). For the case of AMTF, there was vacuum grease, which facilitated the heat transfer at low heating power. At CMTB, there was no vacuum grease, and at ca. 20W heating power, thermal expansion of heating cartridge leads to the better thermal contact between surfaces of the tube and heater cartridge.

We also tried to estimate the energy, which is needed to supply the heater in order to increase heating power. As an example, ca. 3 kJ is required to be supplied for heater at AMTF in order to "warm-up" heater from its initial steady-state value of 0W to the final one of 10W. Unfortunately, due to limitation on available time, only few measurement points were taken for CMTB and at FLASH accelerator, it was not possible due to hardware and available time limitations.

In order to improve the heater performance, in some cases we can operate them with overshot (short initial time moment, when heating power has to be increased), or undershot (short initial time moment, when heating power has to be decreased). Operation with over-/undershot allowed decrease time constant till required heating power and corresponding GHe flow reaches equilibrium value from range of 100÷400s to 30÷80s.

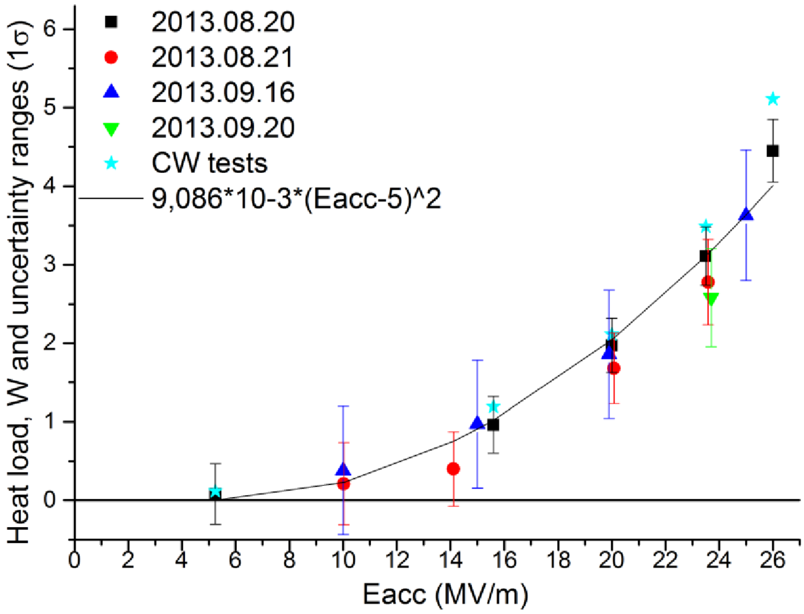

Figure 1. RF dynamic heat load and standard deviation for the XM-3 cryomodule.

3.2 CMTB

Measurements on XM-3 prototype cryomodule were performed in September 2013. Figure 1 shows dynamic heat loads on 2K system performed over two months. All measurement points coincide within the measurement uncertainties. We also plotted data continuous wave (CW) tests of single cavities in bath cryostats assuming duty factor 0.013.

The experimental results on *compensation scheme* are shown in Figure 2. At the first time period, heating power of 3.5W was applied and after that heater was switched off, while RF power was switched on. One can note that the averaged GHe mass flows with heater on

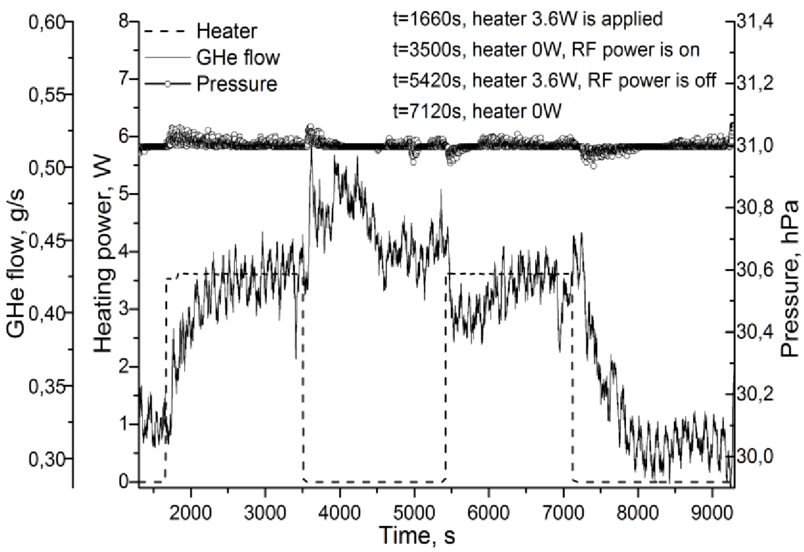

Figure 2. Measurements on XM-3 on 20 September 2013.

and RF on coincide within 10% (with RF on, it is a bit higher.) Initial overshot of GHe mass flow after switching off of electrical power and switching on RF, we attribute to heater performance, i.e. heater stored some energy (ca. 1 kJ) and it needs some time to release it. At the third period, RF was off and heater was on, and similar to previous periods, averaged values of GHe mass flows coincide within 10%. Initial undershot in GHe flow we again attribute to the heater effect, i.e. heater need some time and energy (ca. 1kJ) for the "warming-up" before all heating power was being released into LHe. Another measurement was performed under the same conditions to the previous one with one difference – "background" heating power of 7W was added in order to increase total GHe flow (this simulates some GHe flow toward CC at XFEL for the case if one cryomodule is switched on or off). Measurement results were similar to the previous one. Process of switching off of heater and switching on of RF power could be also considered as following: due to longer time constant of electrical heater in comparison to the RF one, the RF heat load is released in liquid helium (LHe) in a shorter time, while residual heating from cooling of electrical heater after switching off is longer process and as a consequence, the some additional heat release of few kJ occurs. The longer time constant could be also interpreted as following (for example for heater): due to relatively poor thermal contact between heater cartridge and enclosing tube, the CMTB heater temperature is in the range of 40-120K depending on operation range, and it takes longer to release this "stored" energy into the LHe.

3.3 AMTF

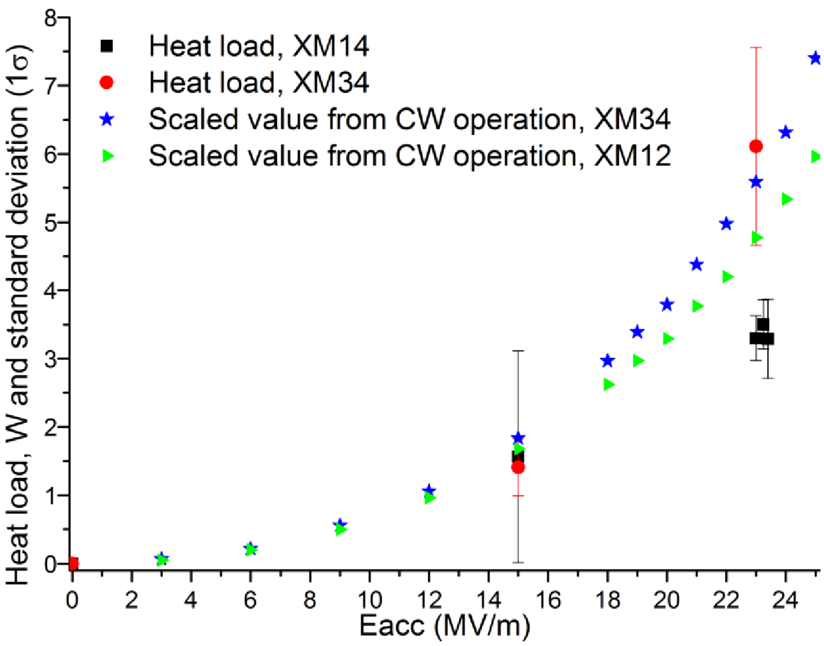

Figure 3. RF dynamic heat load and standard deviation for the XM14 and XM34 cryomodules.

Measurements at AMTF were performed on modules XM14 and XM34 and were very similar to the ones performed at CMTB. The only difference was that for the measurements on XM34, shortly (ca. 10 min) before changing of heating and RF powers, the pressure regulation loop was set into the manual mode. This was done in order to exclude its influence on GHe flow.

The dynamic heat loads on 2K system for different cryomodule and CW values scaled with duty factor 0.014 are shown in Figure 3.

IOP Conf. Series: Materials Science and Engineering **101** (2015) 012159 doi:10.1088/1757-899X/101/1/012159

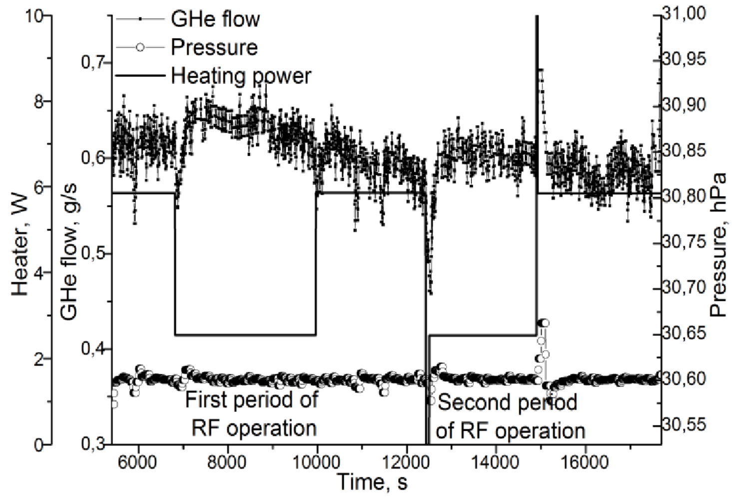

Figure 4. Measurements on XM14.

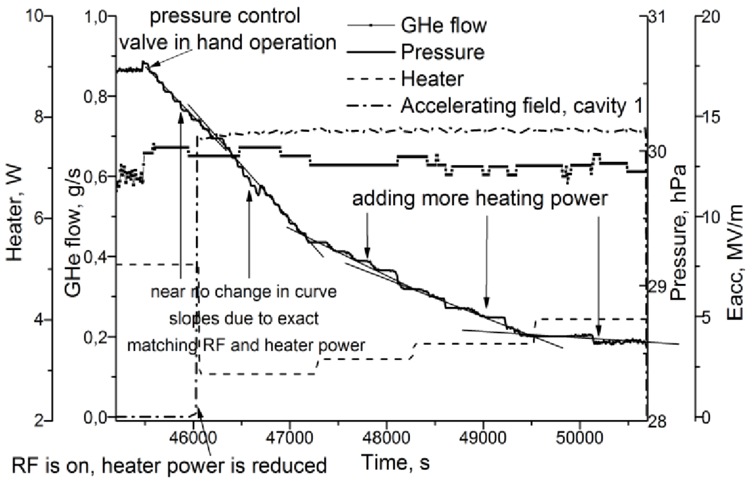

Figure 5. Measurements on XM34.

Figure 4 shows the measurements performed at XM14, where two periods of RF operation were applied (during second period, heater was operated with over-/undershot, i.e. overshot with 26W for. 10s, and undershot with 0W for 100s). Averaged values of the heat loads before and after variation of heater and RF powers are within the range of 0.025÷0.06 g/s, which we consider as a very promising result, because it indicates that matching of RF heat load of cryomodules measured at AMTF would be possible. Maximal variation between peaks of GHe flow (ca. 0.1 g/s) during the first time period (without over-/undershot) was comparable with other fluctuations. Time period of GHe flow variation was in the range of 200-300s, which is also very promising, because the control system should have sufficient time to react in order to further smooth the GHe flow, e.g. by applying *fine-tuning*. We conservatively consider value of 0.06 g/s as *residual error* for the process of switching on/off of RF power for one cryomodule, and e.g. for 4 cryomodules, it would be 0.24 g/s. It is worth also to mention that residual heating after switching off/on of RF power was observed, e.g. after switching off/on of RF power at FLASH accelerator (we note that for single module measurements at CMTB or AMTF, residual heating is also observed). We attribute this effect to the fact that some parts, which are connected to cavities, e.g. HOMs or couplers, do not have direct contact with LHe and therefore are not cooled immediately (and *vice versa*). So, during these measurements, e.g. switching off of RF power and switching on of heater, two effects somehow compensate each other, i.e. residual heating from RF, and “missing” energy required for the heater to be “warmed-up” and to operate at full power (*vice versa* is also valid). This could be observed during the second RF period, when heater operation with over-/undershot allowed compensation the heater performance, i.e. heater power to LHe was at the set point quite fast, while the residual RF heating was still present. In that case, the variation of GHe flow was larger, ca. 0.10÷0.15 g/s, and some pressure fluctuation (max. 0.08 hPa) were also noticed. GHe fluctuations for this case are also relative small, maximal 0.15 g/s (for 4 cryomodules - 0.6 g/s.)

Figure 5 shows measurements performed on XM34 with fixed value of pressure regulating valve. The goal was to simulate the operation condition at XFEL accelerator, where no (or very slow) pressure regulation is foreseen. Due to very low opening of valve, ca. 3%, it was quite difficult to keep the pressure at the constant value, and therefore, initial pressure drift was present. After 10 minutes, the RF was switched on and heater power was correspondingly reduced. Due to good matching of the absolute values of heating powers, no changing of the curve slope was observed, which also confirmed that compensation scheme seems to be applicable for the case of no (or slow) pressure control. In case RF and heater loads are not exactly matching, there will be small pressure drift. In order to stabilize the pressure, heating power should be adapted adequately. See Figure 5, where heating power was increased in three steps.

3.4 FLASH

Fortunately, the concept of heat load compensation can be tested at a superconducting linac in operation. The set-up of FLASH at DESY [6] corresponds to about one half of a XFEL linac string.

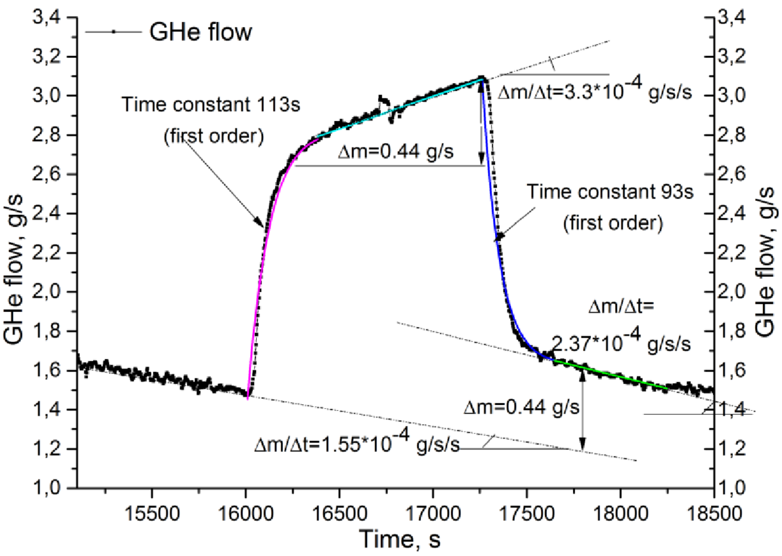

Figure 6. GHe mass flow evolution during RF operation (RF is on at time moment ca. 1600s and off at 1730s).

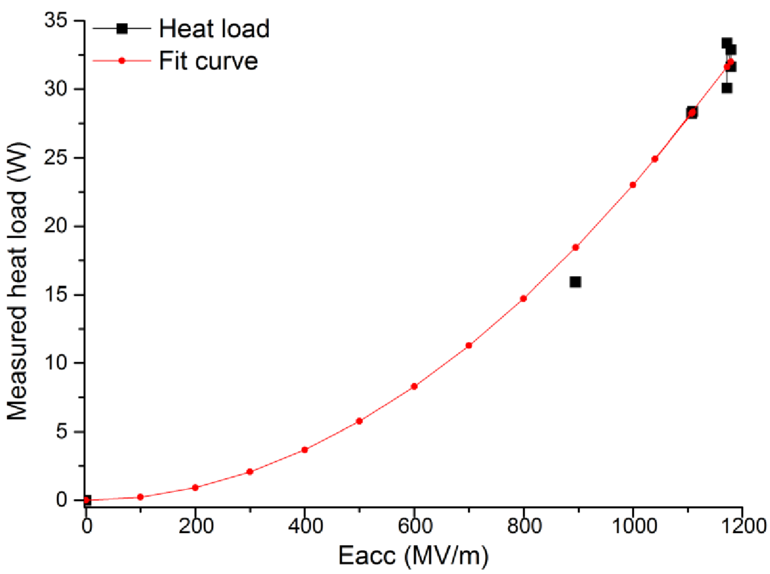

Figure 7. Heat load versus acceleration field for Flash accelerator (modules 1 to 7).

Measurements on seven FLASH accelerator modules were carried out. Except at the last module, heat load measurements on individual modules had not been performed before installation. Also, the long-time constant of electrical heaters, in the order of 1000s, required quite extended time-period measurements. As a consequence, the test program had to be cut in order to fit in the available time slot at FLASH accelerator.

First measurements were performed with switching on/off of the RF power in order to find characteristic time constants, see Figure 6, and dependence of cryogenic heat load versus accelerating field, see Figure 8. The time constant is in the range of 110-140s (switching on of RF power) and for switching off – 90-100s. It is also worth to note that long-time drift on the GHe flow towards warm compressors was present, which we attribute to the slow warming-up/cooling-down of components, which are not directly cooled by LHe, e.g. HOMs and fundamental couplers.

Figure 7 shows the measurement points and quadratic fit curve assuming cavity Q_0 is constant.

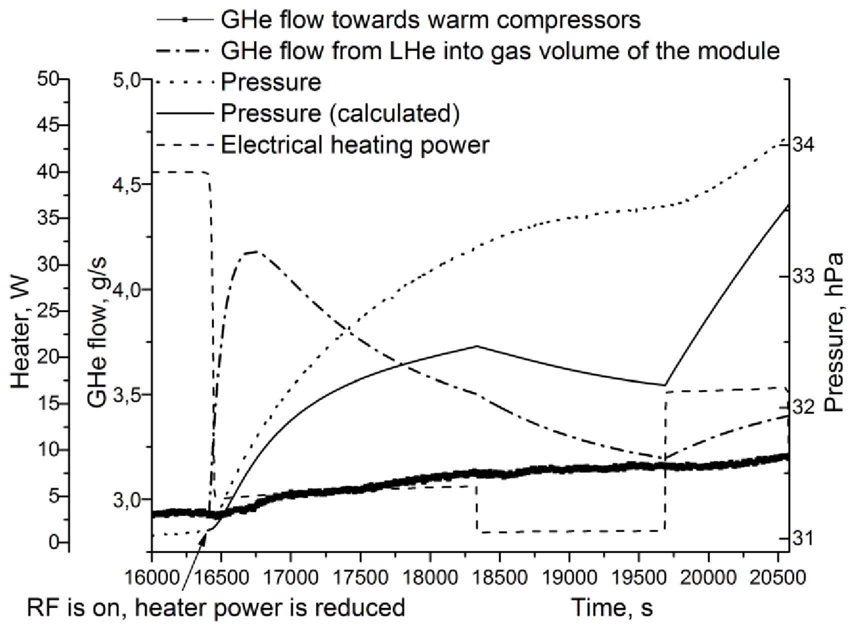

Figure 8. Pressure and GHe flow evolution inside the FLASH accelerator.

Figure 8 shows the pressure evolution inside the FLASH accelerator for the case if no (or slow) pressure regulation, similar to XFEL, will be present. Shortly before the reduction of heater power and switching on RF (t=16400s), the pressure control valve was taken out of control. Two competing processes occurs, one is relative fast increase of RF power with time constant of ca. 110-140s, and slow reduction of heater power with time constant of ca. 1000s. During that time, the net positive release of heating power occurs into LHe, which leads to evaporation of LHe and GHe flow into gas volume of accelerator module, see dash-dot curve in Figure 9. The calculated pressure increased is shown by the solid line, see Figure 9. In order to be able to influence the pressure, e.g. to stabilize or increase/decrease, heater power was decreased at t=1830s or increased at t=1970s, which led to required pressure evolution. The deviation between measured and calculated pressure variation is with ±40%, which we consider as very good result. This deviation could be reduced if one includes the dead-time for the time constants as well as long-time drift of GHe mass flow in our simplified model. It was also to note that relative pressure increase over whole measurement time was ca. (34hPa-31hPa)/31hPa ≈10%, which led to the same ratio of GHe flow increase at the warm compressors. We consider it to be also very encouraging result.

The simplified model and corresponding calculated curve is obtained by linearization around operating point, i.e. keeping 1st derivative term and linear terms related to RF and heater with corresponding time constants. For our case it implies that at steady-state, i.e. at the operating point, the helium flow to the system through JT-valve is balanced by helium flow to warm compressors. Due to variation of RF and heater power, there will be small deviations around this point, which leads to the changing of total stored heat inside the system (and corresponding pressure), which is proportional to total amount of helium. So, this small variation around the operating point can be described by isochoric process.

During the measurements at FLASH, an algorithm was implemented in the process control system, which automatically adjusted heating power according to the actual value of acceleration field.

4. Discussion

Experiments at CMTB, AMTF and FLASH showed that the heat load compensation scheme for XFEL is feasible and will be based on two issues:

- Establishing the curve *cryogenic heat loads versus acceleration field (E_{acc})*: This curve could be based either on 4 cryomodules (one RF station), or one string (12 cryomodules – 3 RF stations). The final choice will depend on the available commissioning time for cryogenic and RF systems. The cross-check of the curve according to the single module testing at AMTF will be also carried out.

- The heater power will be adjusted according to the acceleration field. It is expected that the heater time constant will be similar (or better) to the AMTF, i.e. in the range of 100-300s, which significantly simplified the operation. During the commissioning of cryogenic system, the heater time constants will be measured.

During the XFEL operation, some minor pressure variation will be present, which we attribute to the total uncertainties, e.g. ±40%. The *fine-adjusting* will be done by other methods, e.g. some other heaters or slowly varying pressure control valves or internal control of box with cold compressors (above mentioned *fine-adjusting* methods as well as general control of GHe flow and pressure of XFEL accelerator including the cold box with CC is out of the scope of present paper).

5. Conclusion

In the present paper, the measurements related to the *RF heat load compensation scheme* are presented.

RF heat load compensation with electrical heaters seems to be feasible and will be based on: i) establishing curve for the cryogenic heat load versus acceleration field, and ii) operation of electrical heater according to the acceleration field. For the practical implementation at XFEL it will be necessary to devote some time to the specific measurements, e.g. establishing the curve, time constants, which hopefully will be done in parallel to the commissioning of RF and cryogenic systems.

At present, automatic program, which control heater power according to the acceleration field at FLASH was established and for the future some other communication protocols between RF and cryogenic groups will be also tested.

Acknowledgment

The authors are also thankful for all colleagues working in the MKS group for their contribution over the whole project, e.g. J. Eschke (CMTB operation), T. Böckmann (Instrumentation and Automation). Particular thanks for the colleagues from the IFJ-PAN, Poland, for their possibility to perform measurements at AMTF. The last but not the least, the authors express their gratitude to FLASH run coordinators K. Honkavaara and S. Schreiber for their approval to perform the measurements.

References

[1] *The European X-Ray Free-Electron Laser*, Technical Design Report (TDR), Hamburg, DESY 2006-096, July 2007
[2] Bozhko Y, Lierl H, Petersen B, Sellmann D, Zolotov A, 2007 *Requirements for the cryogenic supply of the European XFEL project at DESY*, Advances in Cryogenic Engineering, **51B** 1620-1627
[3] Pagani C *at al* 1999 *Further improvements of the TESLA test facility (TTF) cryostat in view of the TESLA collider*, Advances in Cryogenic Engineering **45A**, 939-946
[4] Bozhko Y *at al* 2011 *Test Stands for Testign Serial XFEL accelerator modules*, Advances in cryogenic Engineering **57** 1100-1107
[5] Bozhko Y *at al* XFEL 2006 *Cryomodule Test Bench* Proceedings of the 21th International Cryogenic Engineering Conference **21** 125-128
[6] FLASH accelerator, DESY, Hamburg, see www.flash.desy.de