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First operation of the XFEL linac with the 2 K cryogenic system

T Paetzold², B Petersen¹, T Schnautz¹, C Ueresin³ and J Zajac³

¹Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

²Lindekryotechnik/Engie, Hamburg, Germany

³Lindekryotechnik, Pfungen, Switzerland

E-mail: tobias.schnautz@desy.de

Abstract: The RF operation of the about 800 superconducting 1.3 GHz 9-cell cavities of the XFEL linac requires helium II bath cooling at 2 K, corresponding to a vapor pressure of 3100 Pa. After the first cool-down of the XFEL linac to 4 K in December, 27th 2016 the operation of the 2 K cryogenic system was started in January, 2nd 2017. The 2 K cryogenic system consist of a 4-stage set of cold compressors to compress helium vapor at a mass flow of up to 100 g/s from 2400 Pa to about 110 kPa and a full flow bypass with an arrangement of heat exchangers and control valves.

This paper describes the XFEL refrigerating plant, especially the 2 K cryogenic system, the tuning of the cold compressor regulation to adapt to the XFEL linac static and dynamic heat loads and experience of about 6 months of operation.

1. Introduction

The about 800 superconducting 9-cell 1.3 GHz niobium cavities of the XFEL linac are cooled in a helium II liquid bath at a temperature of 2 K. Two existing helium refrigerators at DESY were modified to supply the XFEL linac, in particular, a set of cold compressors was added to compress the helium vapor of the helium II bath from 3100 Pa to 0.11 MPa. The general arrangement of the XFEL cryogenic system was already introduced in [1]. The cold compressors (CCs) are placed in an additional cold box (CB44). The CB44 is located in the XFEL shaft building XSE, close to the valve box XLVB, the XFEL linac and the injector in order to reduce the distance induced pressure drop in the 2K return flow. The CB44 is connected to the XFEL refrigerator by the transfer line XRTL [1]. 2 K operation of the XFEL linac started in January 2017.

Process description of the XFEL 2 K refrigerator circuit:

1. In the 2 K supply line for the XFEL linac, helium at a pressure of 0.55 MPa and a temperature of about 4.5 K, is expanded to 0.1 MPa via a Joule-Thomson valve (JT) into a phase separator in CB44 (44S1140). The liquid fraction is transferred to the linac via a counter flow heat exchanger in XLVB [1]. The vapor fraction can be used to feed the CCs. The remaining vapor is mixed with the 4 K return flow from the injector and returns to the coldbox (4 K return).
2. The 2 K vapor return flow from the XFEL linac passes also the counterflow heat exchanger in the XLVB and enters the CB44 at a minimum pressure of 2400 Pa. The helium is compressed by the CCs from 2400 Pa at 3.4 K to 0.11 MPa at 25 K.



The CB44 contains four stages of cold compressors in series, wherefore three different types of motors with variable speed and ceramic ball bearings are used for pressure regulation in the 2 K circuit of the XFEL linac/injector. Figure 1 shows the main components of the cold compressor box CB44.

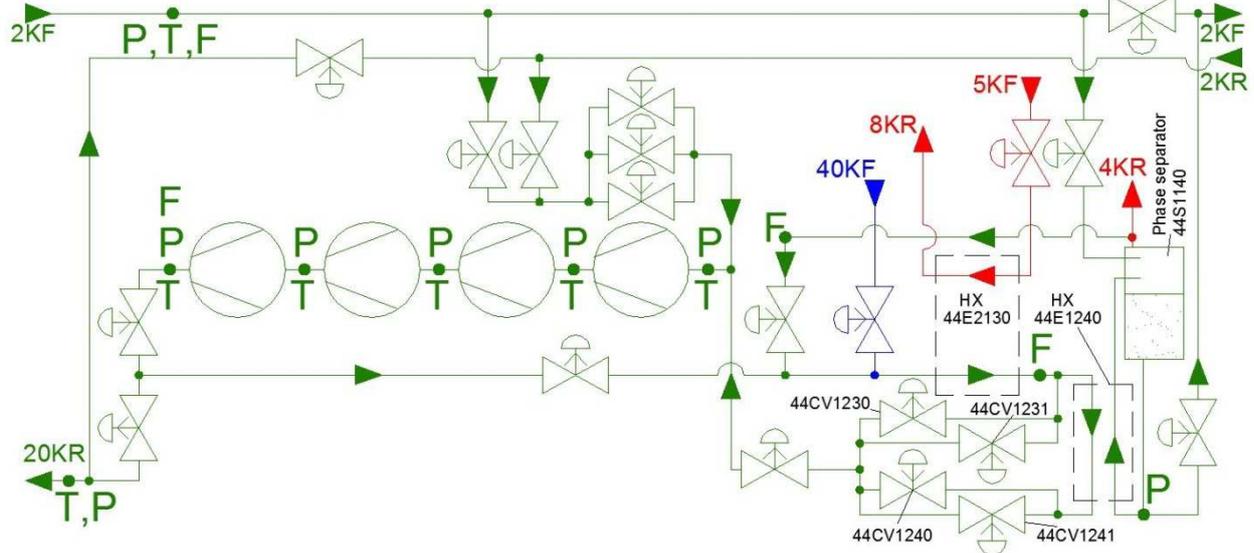


Figure 1. CB44 flow scheme.

The 40 K supply and 80 K return flows are transferred through the CB44. Besides, the 40 K supply flow can partly be diverted to the cold compressor bypass (CC-bypass) to support the cool down of the CC-bypass piping as well as the four cold compressor stages themselves.

Also the supply and the return flow of the 5-8 K shield pass the CB44. A counter flow heat exchanger 44E2130 is linked to the 5-8 K circuit to pre-cool a CC-bypass flow. The CC-bypass is used to ensure stable operating conditions related to the helium mass flow along the four cold compressor stages as well as the helium temperature at the inlet of the first cold compressor stage. The operation of the CC-bypass is explained in detail later on.

The cold compressors can be operated with a pressure ratio of about 46. The inlet pressure is adjustable considering the pressure drop of the 2 K return flow from the linac/injector. The discharge pressure can be adjusted by means of reducing the screw compressors inlet pressure down to 0.0650 MPa, leading to a turndown capacity of > 30%.

The cold compressors are optimized for the 17.5 GeV linac. In normal operation mode all four stages are controlled within a unified operating field, which dedicates predefined speed values to each machine. Based on the total pressure ratio of the four cold compressor stages, the set-pressure as well as the deviation to the measured suction pressure, four reduced speeds without units are calculated. These values are continuously converted to real speed set-points, which can be adjusted by using the frequency converters of the compressor motors.

2. CC-bypass operation: mass flow and temperature adjustment

At a given fixed pressure ratio the dynamic range of operation is quite limited [2]. Thus, CC-operation is very sensitive towards mass flow-, pressure- and temperature changes in the 2K return flow. The reduced mass flow versus the pressure ratio of each cold compressor stage can be charted to evaluate the current operating conditions. If the reduced mass flow becomes too high, the choke area is reached, where the compressors do not work efficiently any more. Contrarily, if the reduced mass flow is too low, the surge area is reached and the cold compressors stop operating immediately.

The required mass flow for the operation of the CCs is calculated by a PLC process control and supplied by the 2 K return flow from the XFEL linac/injector plus the CC-bypass flow. The CC-

bypass can be fed by gas, extracted at the discharge side of the four cold compressors as well as by the vapor from the phase separator 44S1140. The required inlet temperature varies with the inlet pressure from 15 K at 0.1 MPa to 3.4 K at 2400 Pa. A flow controller determines the total required bypass flow to be supplied. The temperature of CC-bypass mass flow is adjusted by using the counterflow heat exchanger 44E2130 and the heat exchanger 44E1240, connected to the phase separator in CB44. The heat exchanger 44E1240 can be partly bypassed for accurate temperature adjustment. A temperature controller determines, how the 4 bypass valves 44CV1230/31 and 44CV1240/41 are to be positioned in order to have a suitable mixing and to match the temperature set point, which itself is a function of pressure as stated above. The CC-bypass operation is regulated by four control loops integrated in a 'split range controller'.

By means of the CC-bypass, CC operation can be adapted to any return flow from the XFEL linac/injector within the specified range. The CC-bypass compensates flow changes of the XFEL linac/injector and contributes 30% design overcapacity in stationary operation for the time being. In particular, the CCs can be operated in full flow stand-alone mode by use of the CC-bypass.

Different operating parameters for CC-bypass operation had to be determined for different operating modes. During pump-down fast operating parameters have to be used, while for the steady state operation of the XFEL linac/injector another set of operating parameters had to be found. The mass flow adjustment can be seen in figure 2.

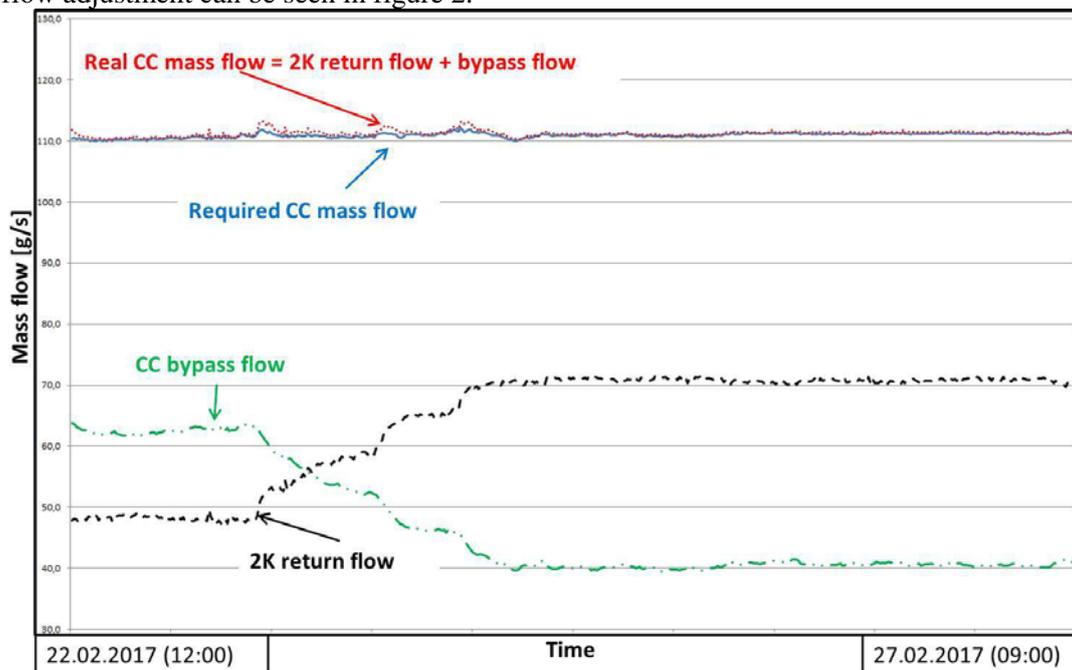


Figure 2. Cold compressor bypass operation – mass flow adjustment.

Regarding to this example, the required mass flow for CC-operation was roughly 110 g/s. Beginning with a 2 K return flow of about 48 g/s, the CC-bypass flow delivered roughly 62 g/s in order to produce the required mass flow for CC-operation. For test purposes of the CC-bypass functionality, the 2 K return flow from the XFEL linac/injector was permanently increased by heating in the 2 K bath of the linac until 70 g/s had been reached. This mass flow corresponds to the calculated heat load of the 2 K circuit at 17.5 GeV beam operation.

It can be seen, that the CC-bypass operation leads to an automatic reduction of the CC-bypass flow, avoiding a critical deviation from the required mass flow. Finally the CC-bypass operation produced a bypass flow of 40 g/s, resulting in a perfect match of the required and the real mass flow for cold compressor operation.

But of course the functionality of the CC-bypass operation has limits referring to fast changes in the 2 K return flow. Figure 3 shows another situation, where significant changes in the 2 K return flow occur.

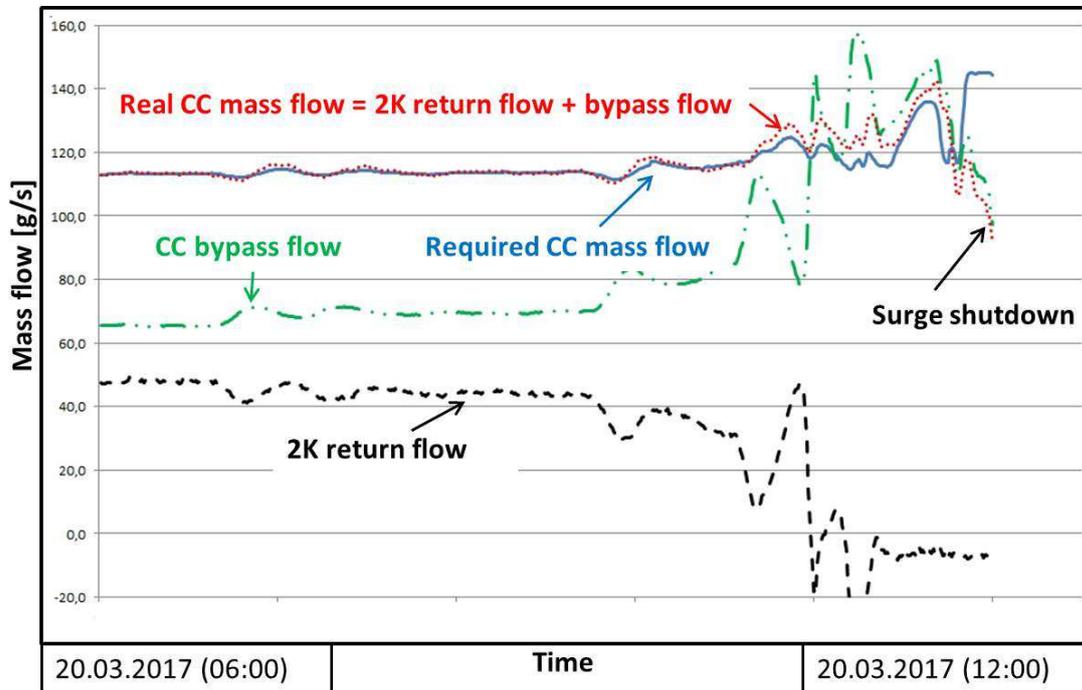


Figure 3. Cold compressor bypass operation – surge.

Initially the CC-bypass operation created a CC-bypass flow, which compensated the behaviour of the 2 K return flow perfectly well. But at a certain point, the CC-bypass operation was obviously not able to compensate the strong changes in the 2 K return flow in time, which resulted in a surge shutdown of the cold compressors.

Surge shutdowns, caused by limited bypass-reactions with regard to the currently used operating parameters, should be avoided. Especially dynamic load changes applied by RF operation to the helium II bath of the cavities shall be compensated before leading to critical deviations from the required CC mass flow. Therefore the electrical heaters in the cryo-strings shall be used. The heater power can be adjusted simultaneously to the RF operation, if the RF parameters are known and the resulting dynamic heat load can be estimated. Finally, an automatic heat load compensation function could be implemented in the cryogenic control system, as the dynamic loads of each XFEL cryomodule were measured during the acceptance tests in the AMTF [3].

So far, the XFEL linac was operated up to 13 GeV beam energy. Within this beam energy range the heater control algorithms operate successfully, resulting in a stable vapor helium mass flow in the return to the CCs. Figure 4 shows the mass flow stability during a significant RF load change. Here, heat load changes in the 2 K circuit were induced by a sudden RF-shutdown from 10 GeV beam operation. The heat load compensation functionality could be verified during this event.

Critical deviations between the required mass flow and the real mass flow did not occur and the 2K return flow as well as the CB44-bypass flow remained stable within a certain range. As a result, the stable CC operation was not affected.

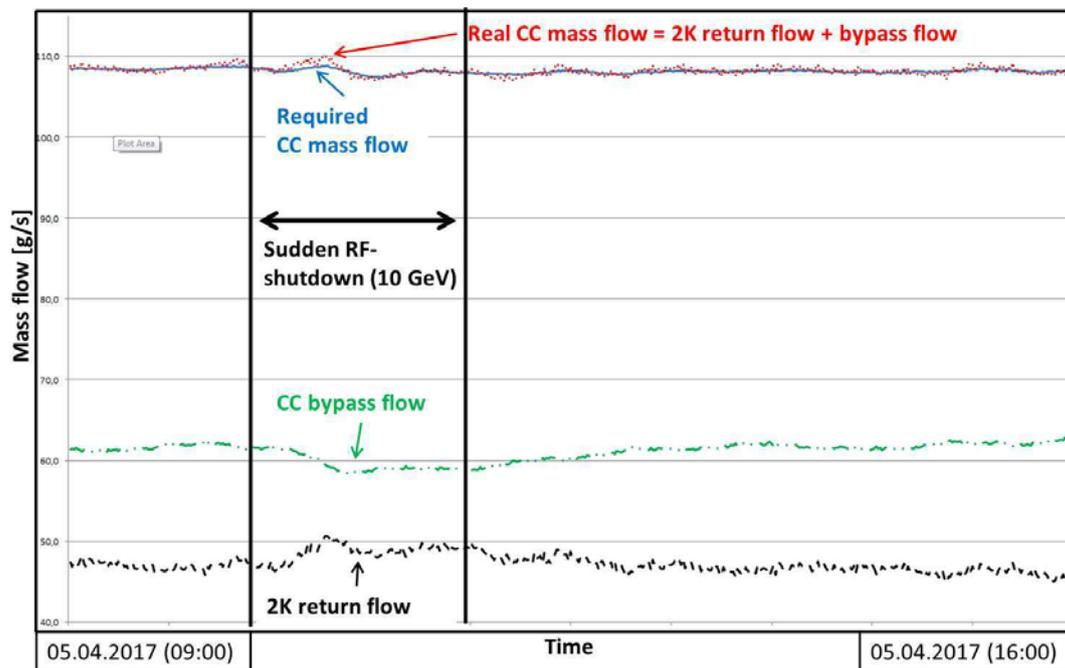


Figure 4. Cold compressor bypass operation – RF shutdown.

3. CC-bypass operation: 2K pressure adjustment

Mass flow changes in the 2 K return flow as well as the mass flow adjustment by CC-bypass operation as described above have an impact on the pressure stability in the 2 K circuit of the XFEL linac/injector. A relative vapor pressure stability of better than $\pm 1\%$ (e.g. ± 30 Pa @ 3060 Pa) is specified to avoid RF-phase shifts, caused by detuning of the cavities. Actually the vapor pressure of the 2 K helium II bath of the linac should be regulated by use of a pressure control loop actuating directly the speed set points of the cold compressors. Because of the time delays in the control loop and the large volume of the linac, cold compressor speed changes do not lead to fast reactions of the linac pressure. This results in continuing changes of speed set points until flow break-down. In order to avoid this problem a cascade pressure controller is implemented. The pressure controller of the linac determines the set point of another pressure controller, which regulates the suction pressure of the cold compressors by adapting the speed set points. As a result, the cold compressors regulate the linac pressure not directly, but indirectly by regulating their own suction pressure.

Finally, the specified pressure stability along the helium II bath of the linac could be exceeded significantly and a stable operation of the cold compressors, avoiding surge shutdowns, was established. The concept of the cascaded pressure regulation can be seen in figure 5.

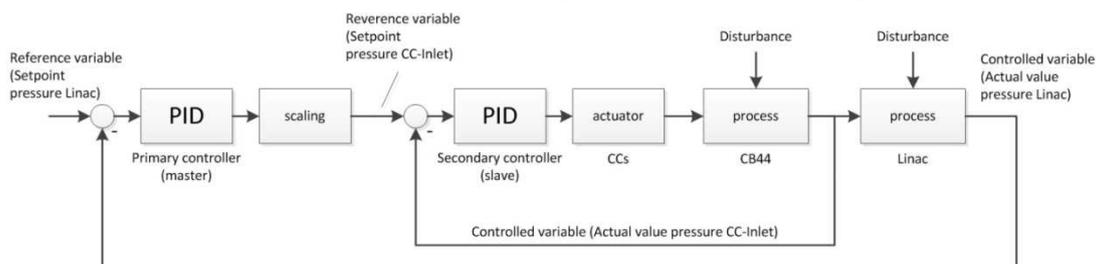


Figure 5. Cascaded regulation concept for 2K pressure adjustment.

The result of the cascaded regulation for the pressure adjustment in the 2 K circuit can be seen in figure 6.

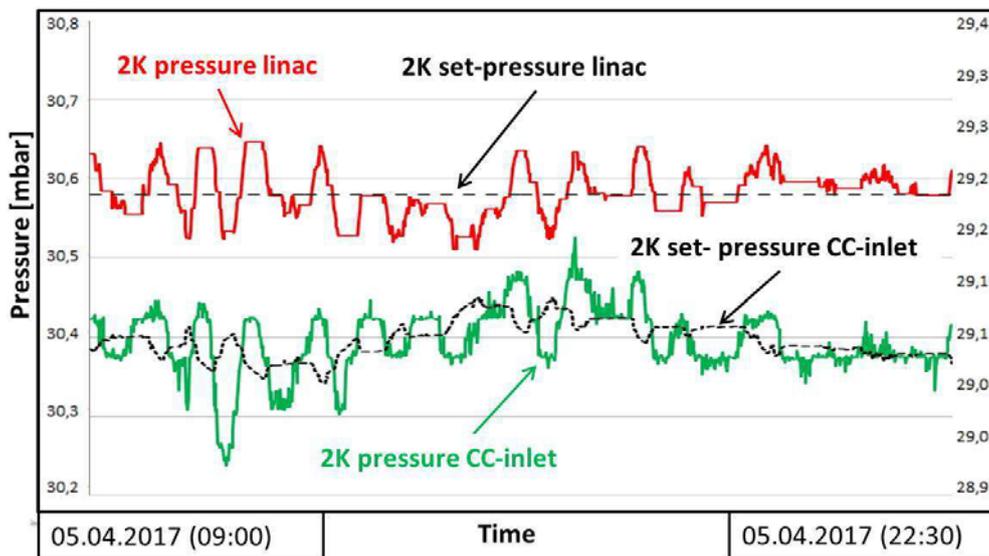


Figure 6. Cascaded regulation for 2 K pressure adjustment - linac vs. cold compressor inlet.

The constant set-pressure of 3058 Pa in the 2 K circuit of the linac can be seen (upper charts, left scale). On the other hand, the dynamic set-pressure at the inlet of the cold compressors, adapted as described above, can be seen (lower charts, right scale). The corresponding pressures can be seen respectively. Both are affected by the movement of Joule-Thompson valves in the string connection boxes, the 2 K heat load changes due to dynamic RF-operation as well as the mass flow compensation by CC-bypass operation.

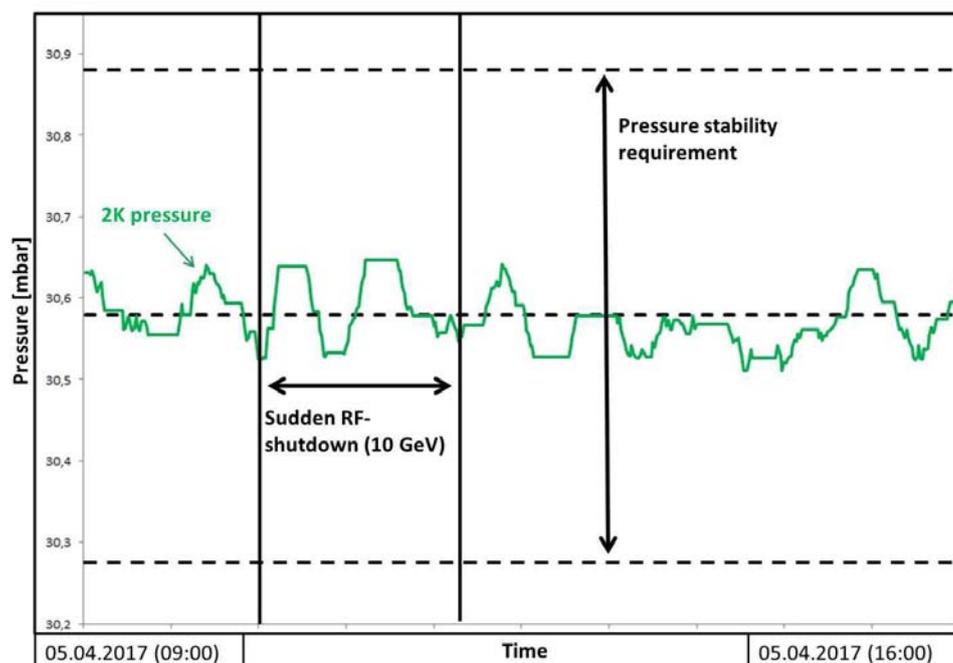


Figure 7. 2K pressure stability during RF shutdown.

Figure 7 shows the pressure in the 2 K circuit during the sudden RF-shutdown as described above. Here it has to be pointed out, that the heat load compensation functionality together with the CC-bypass operation is acting respectably well, so that the 2 K pressure adjustment by speed control of the cold compressor motors is not affected perceptibly.

As a result, stable operating conditions for the cold compressors are generated, avoiding surge shutdowns. At the same time, we reach a pressure stability better than 0.3%, which is better than internally specified. Even a worst case scenario like a sudden RF-shutdown from 10 GeV does not affect the quality of this pressure stability, which is quite remarkable.

4. CC-operation: Pump-down

For the time being frequent manual operator interventions are required for the pump-down procedure from 0.1 MPa – 2400 Pa in order to avoid surge shutdowns. The procedures are permanently optimized. An automated pump-down which is optimized in time and operational effort is highly desired.

5. CC-operation: Recovery after shutdown

In case of a cold compressor shutdown, the XFEL linac/injector can be kept cold at 3060 Pa at static heat loads using a system of warm helium pumps, located in the Accelerator Module Test Facility (AMTF), dedicated to be used for module and cavity performance tests. This pumping system is connected to the XLVB in the shaft building XSE. As soon as the operation of the CCs stops, all related valves to the XFEL linac/injector are closed, to avoid backflow of helium and pressure rise in the linac and the warm helium pumps in the AMTF take over pumping the 2 K return flow.

After the shut-down, the CCs are restarted in stand-alone bypass mode until the suction pressure is close to the linac pressure. Then, the cold compressor inlet valves are opened very cautiously, to re-connect the linac/injector at sub atmospheric pressure to the CB44. In order to stabilize this procedure, several parameters of the split range controller have to be adjusted manually during the re-connection. This procedure requires at least three well trained cryo operators, in order to minimize the risk of causing a surge shutdown. It takes roughly 5 hours until stable linac/injector-operation can be established again.

In the future, the endangering of shutdowns shall be reduced to a minimum by use of intelligent software, based on operational experience gained in numerous tests. Moreover the recovery time from failures shall be reduced to a minimum.

6. CC-operation: Bearing problems

The cold compressor motors are equipped with two pairs of ceramic ball bearings for radial suspension, one of them is located at the top (warm end) and the other one at the bottom of the rotor (cold end). Additionally a guide bearing, also designed as ball bearing, is installed at the warm end of the rotor, to allow a thermal expansion of the rotor.

A lifetime for the cold compressor motors of at least 16000 hours is specified. For the time being, the average lifetime of three of the four motors is far below the specification. The resulting availability does not correspond to the planned operation schedule of XFEL. Motor failures are usually caused by damaged ceramic ball bearings.

Linde Kryotechnik has conducted a systematic root cause analysis in cooperation with the supplier of the motors and DESY. In addition, separated from XFEL operation, a test stand was installed to investigate the ball bearing issues. Failure sources were identified and the relating counter measures were triggered. A new motor design was developed and successfully tested at the manufacturer. One motor equipped with a main feature of the new design is currently in operation at DESY since more than 2200 hours without any failures. As a result, the new motor design is very promising, but the final impact on the lifetime of the ceramic ball bearings still has to be verified.

7. Summary

The 2K helium II bath supply of the XFEL superconducting linac is continuously operated since about 6 months. In parallel to the beam commissioning of the XFEL linac, the procedures, algorithms and controls of the 4-stages cold compressor system were developed and optimized. A full flow bypass enables standalone operation of the cold compressors. After a cold compressor shut-down, the pressure in the linac/injector can be kept constant at 3060 Pa (static) by use of warm helium pumps in the AMTF. The CC-bypass system allows an internal pump-down and the linac/injector can be re-connected at sub atmospheric pressure in order to minimize downtime after a cold compressor shutdown.

The pressure stability of the helium II bath along the 1.5 km length of the linac is by far better than specified. Sudden changes of the RF loads do hardly affect the operational stability of the cold compressors. A pressure stability better than 0.3% can even be obtained during a sudden RF-shutdown from 10GeV beam operation. The elaborated CC-bypass operation in combination with the automatic heat load compensation equalizes instabilities in the 2 K return flow.

Some of the operational procedures have to be further automated to assist the cryo-operators. So far operating instruction for dynamic procedures as mentioned above are used, which have been developed continuously during commissioning. In case further automation is restricted to a certain level, these operating instructions have to be adapted and permanently optimized in order to simplify operation issues, where manual intervention is still essential.

The low average operation lifetime of the ceramic bearings is much below specification and not acceptable for the future operation of the XFEL linac. Main failure causes were identified and a promising upgraded design of one CC motor has been implemented by Linde Kryotechnik with the remaining machines to follow soon.

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