C2Po2A-01: Six' years experience of the XFEL 2K operation

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General information about the European XFEL

- Length of accelerator: 1500m
- Accelerator modules: 96 1.3GHz accelerator modules, each of them equipped with 8 superconducting 9-cell cavities + 1 superconducitng quadrupole, cooled in a He II bath at 2 K.
- Linac: 9strings, most of them with 12 accelerator modules, connected to each other by string connection boxes (including JT-valves)
- Design electron energy: 17.5GeV
- First cooldown: December 2016
- Start of 2K beam operation: January 2017
- Start of user runs: September 2017
- 2K cooling capacity: 1.9KW

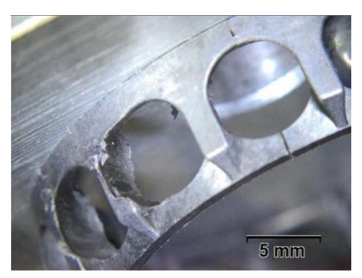
Cold compressors

Cold compressor design:

- 4 stages in series
- Max. mass flow: 110g/s
- Lowest suction pressure: 24mbar
- Pressure stability: < 2%
- CC-motors with ceramic ball bearing for radial suspension (specified lifetime 16000 hours)

Cold compressor issues:

- In total, more than 30 motor failures caused by damaged ceramic ball bearings
- Average lifetime of motors far below specification
- During exchange of damaged CC-motors XFEL linac and injector can be kept cold at 2 K (31 mbar) by means of the AMTF warm He pumps



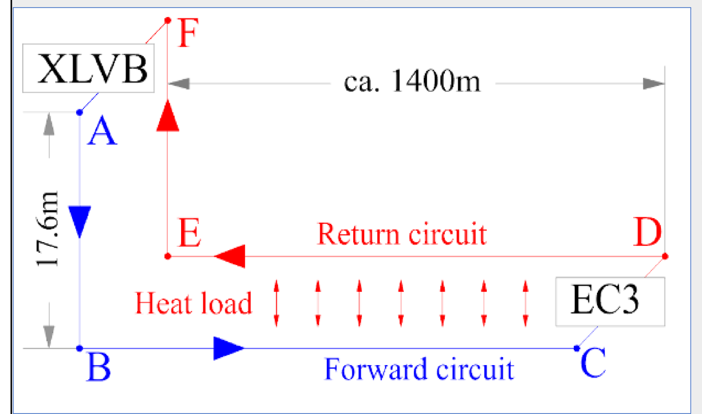
Cold compressor measures:

- Several design upgrades could improve the situation but not solve the problem
- Preventive maintenance of the motors after 4000 hours was established to improve the operating reliability
    - Unplanned downtime during user runs could nevertheless not be avoided completely as bearing failures still occurred within the maintenance time interval
- ➢ Ceramic ball bearings seem not to be a suitable technology for CC-motors
- In December 2022 a prototype motor from Linde Kryotechnik using active magnetic bearings was installed.
- Since then, the motor has been operated for more than 4500 hours without any sign of noticeable problems

Application of helium guards

- Despite all valves in the XFEL linac are equipped with helium guard systems, neither the valves nor the 31mbar pressure transmitters are helium guarded in the tunnel.
- One helium guard at distribution box XLVB is installed at a manifold for 2KR safety valves
- All components cold compressor box CB44 at sub atmospheric pressure are helium guarded
- Since the beginning of the 2K operation two cases of contamination of the 31mbar system with air were registered. The cases were presumably caused by blackouts. These provoked opening of the helium guarded buffer to atmosphere. The buffer was then not thoroughly purged.

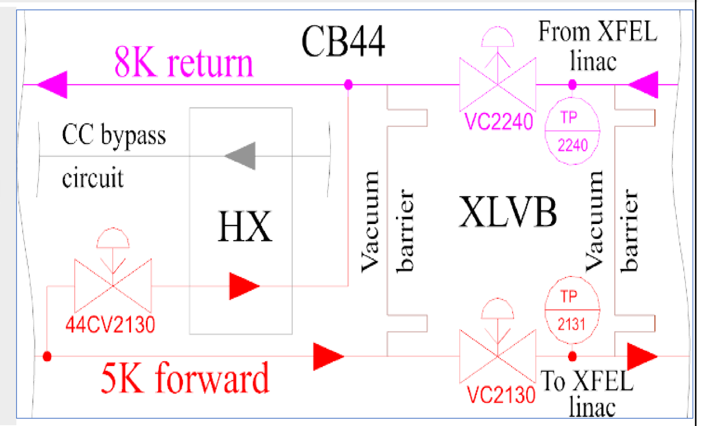
Influence of hydrostatic head



- The XFEL linac is ~17.6 m below XLVB → delta enthalpy $i_B - i_A = 9.8 m/sec^2 * (h_A - h_B) = 173$ Joules/kg
- Assuming isentropic flow ($ds=0$) it follows from $T*ds = di - v*dp$ → $p_B - p_A = 9.8 m/sec^2 * (h_A - h_B)/v$
- Heat load causes appearance of a positive difference of hydrostatic pressures in the arms A-B and E-F → $\Delta p_{hydr} = 9.8 m/sec^2 * (h_A - h_B) * (1/v_{AB} - 1/v_{EF})$

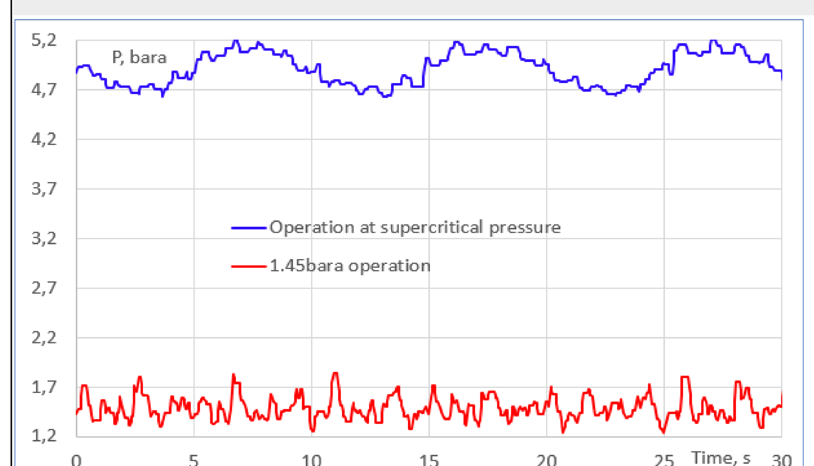
The outlet pressure $p_F = p_A + \Delta p_{hydr} - \Delta p_{frict}$, where Δp_{frict} is the pressure loss due to friction.

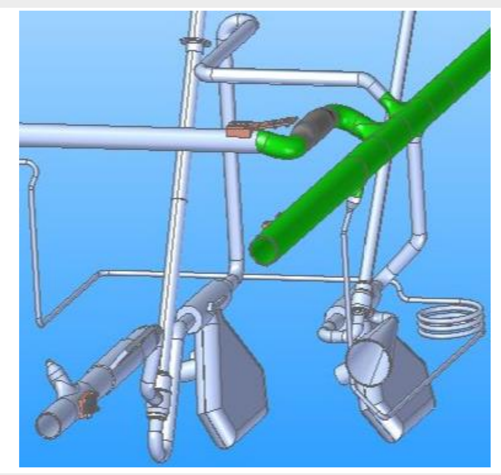
- The 40/80K circuit: $\Delta p_{hydr} \approx 10$ mbar, $\Delta p_{frict} \approx 85$ mbar → $p_F < p_A$ → "normal" pressure profile
- The 5/8K circuit: $\Delta p_{hydr} \approx 93$ mbar, $\Delta p_{frict} \approx 14$ mbar → $p_F > p_A$ → outlet pressure is **larger** than the input one!!! This has caused instabilities in the 5/8K and the CC bypass circuits and **CC trips**. → Valves' lifts were rearranged so as pressure in the 8KR circuit has become smaller than that in the 5KF circuit



- ➢ CB44 can provide the XLVB 2.2KF circuit either with supercritical or saturated LHe at 4.4K.
- ➢ The hydrostatic head increases the 2.2KF pressure at the linac entrance by $p_B - p_A \approx 0.25$ bar
- ➢ The enthalpy increase of 173 Joules/kg decreases the LHe II contents after JT valves by 0.73%
- ➢ For the 2KR circuit the pressure loss caused by the hydrostatic head amounts to ~1.2 mbar

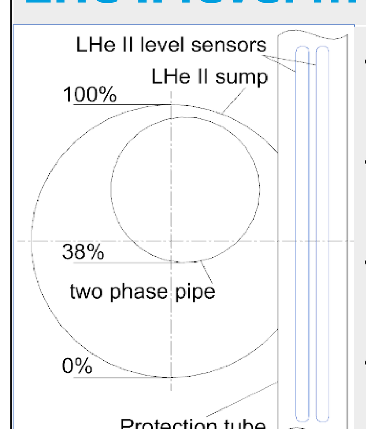
Pressure oscillations in the 2.2KF pipe





- Pressure oscillations with the peak-to-peak amplitude of 0.5 bar are being observed in the 2.2KF pipe
- The oscillations are too slow for TAO, also no ice blocks common to TAO were discovered
- The oscillations are likely caused by the design of capillaries for pressure measurements – these exit the 2.2KF pipe downwards and can provoke a thermosiphoning effect
- The total number of the capillaries (12) seams to be unnecessary high

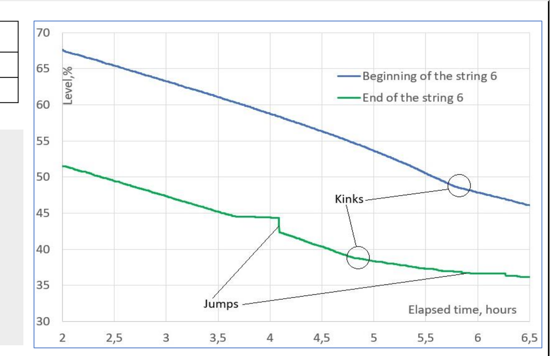
LHe II level meters



- Difference in the readings of level sensors placed in the beginning and at the end of each string can be predicted considering the "tunnel inclination"
- The detected deviations are caused by not accurate positioning of the sensors in relation to the two-phase pipe
- The level fall curves have a characteristic kink when the two-phase pipe becomes empty
- The absolute position of a level sensor can be adjusted by attributing to the kink the design value of the level of 38%

	Str. 1	Str. 2	Str. 3	Str. 4	Str. 5	Str. 6	Str. 7	Str. 8	Str. 9
Predicted level difference, %	+5.9	+13.5	+7.7	+2.9	+2.1	-3.3	+5.4	+4.3	+3.0
Adjusted level difference, %	+5.0	+14.7	+7.8	+4.1	+1	-5.9	+5.9	+6.7	+4.0

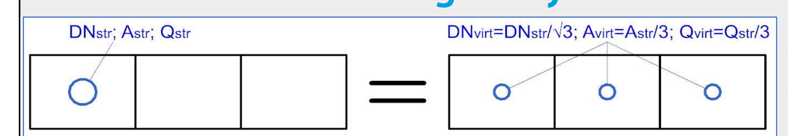
- Many of level sensors experience a jumpy behavior
- This could be caused by ice formations on NbTi wires (AMI)
- Could be remedied by using AMI firmware with a "Dirty-Mode" option



Doubling of safety valves in XFEL

- All safety valves in XFEL shall be doubled during shutdown in 2025
- The present design of the XFEL linac safety system is based on the results of venting tests conducted at DESY in 2008 on one cryomodule (CT1). However,
- The used cryomodule was not a XFEL-like one
- The test results were released in the form of heat flux [W/m²] → transfer of the results to long strings may cause the use of unreasonably large safety margins influencing not only size of safety valves but also their number

How to simulate a string of cryomodules ?

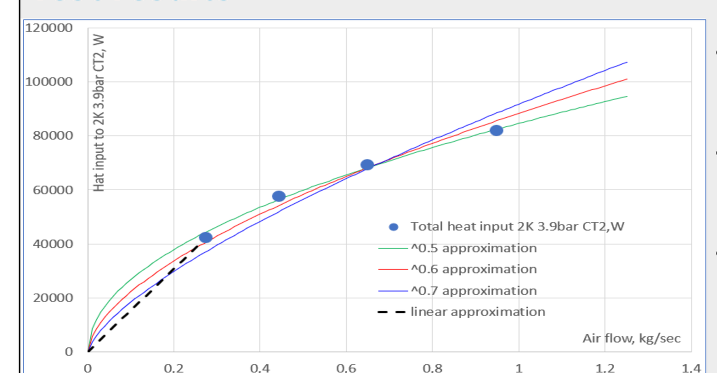


A string of N CMs equipped with one pump port of the cross section Astr can be replaced by a string where each CM is equipped with a virtual pump port with the cross section Avirt=Astr/N

Heat input Qstr to a circuit of a string equipped with one pump port Astr can be predicted by measuring the heat input Qvirt to this circuit of a single CM vented across a vent port Avirt → Qstr=Qvirt*N

The tests consisted of venting one cryomodule through a series of orifices with different diameter (CT2). Considering that vacuum pressure remained stable during CT1 venting tests in 2008, a linear dependence of heat input from cross section of the vent port was expected

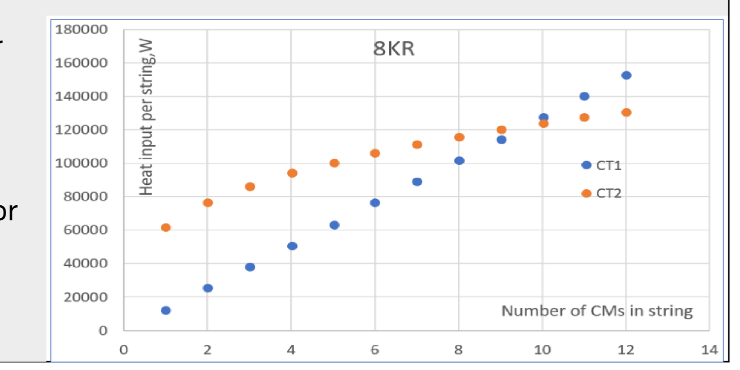
Test results



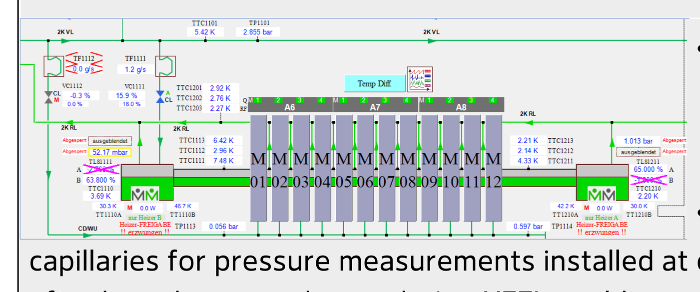
- 40/80K circuit: as expected, linear dependence of the heat input from air inflow (≡vent port cross section)
- 5/8K and 2K circuits: heat input flattens with the increase of the air inflow
- The heat input to 5/8K and 2K circuits for small flow rate of air can be predicted extrapolating the test results by functions originating from zero

Application of the test results to the safety system of the XFEL linac

- The 8KR safety valves shall be larger for strings with a number of cryomodules ≤10 and smaller for longer strings
- The 5KF SVs shall be smaller almost for all strings (3.5 times smaller for the regular XFEL strings of 12 CMs)
- The 2.2KF SVs shall be smaller for all strings (9 times smaller for regular XFEL strings)
- Total number of safety valves in the XFEL linac was reduced from 30 to 12



Excessiveness of some instrumentation



- Only one of 18 pressure transmitters in the 31mbar region is used for the pressure regulation of the cold compressors (plus a redundant one). 16 capillaries out of total 18 are closed by valves to minimize the contamination risk
- The cooldown/warmup pipe in each string is equipped with capillaries for pressure measurements installed at opposites ends of the pipe. All 18 capillaries are closed by valves after have been used once during XFEL cooldown. Even for the cooldown/warmup procedure the necessity to have pressure measurements in the cooldown/warmup circuit should be questioned.
- Warm flowmeters are intended for measurements of flow rates of warm helium during cooldown/warmup. These flowmeters can be replaced by virtual ones. One way uses energy balance with the full mixture enthalpy, the other is based on calculation of flow rate across a valve with known Kvs and valve lift.
- Cold Coriolis flowmeters are installed in the cooldown circuits inside the string connection boxes. They can be replaced by virtual ones calculating the flow rate using the the valve lift, pressure and temperature.
- Cold Coriolis flowmeters are installed upstream of the JT valves inside the string connection boxes. Despite the transmitters for the flowmeters are protected by a radiation protection shielding, several failures were detected manifested in slow degradation of readings. Such failures cannot be detected in time. The quality of the measurements can hence being questioned. The better way would be to use a single Coriolis flow meter installed in a radiation free area. Heat loads to single strings can be measured using the LHe II level fall curves.

Conclusions

- Despite several failures of cold compressors, the 2K XFEL operation was not jeopardised. The failures were bridged over by processing the 2KR flow by AMTF warm pumps (compensating static heat loads)
- Motors with magnetic bearings seem to be a suitable alternative to the motors with ceramic bearings
- Influence of the hydrostatic head should rather be considered for future designs
- Despite poor application of helium guards, the 2KR circuit did not seriously suffer from air contamination
- The newly conducted venting tests (CT2) have resulted in a significant reduction of the number of the safety valves to be doubled in the XFEL linac
- The number of pressure transmitters and flow meters seem to be far too excessive
- Pressure oscillations in the 2.2KF pipe and jumpy level sensors still remain open issues

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