RF HEAT LOAD COMPENSATION FOR THE EUROPEAN XFEL

European XFEL

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Abstract

The European XFEL is a 3.4km long X-ray Free Electron Laser. The accelerating structure consists of 96 cryo modules running at 1.3 GHz with 10 Hz repetition rate. The injector adds two modules running at 1.3 and 3.9 GHz respectively. The cryo modules are operated at 2 Kelvin. Cold compressors (CCs) pump down the liquid Helium to 30 mbar which corresponds to 2 Kelvin. Stable conditions in the cryogenic system are mandatory for successful accelerator operations. Pressure fluctuations at 2 K may cause detuning of cavities and could result in unstable CC operations.

The RF losses in the cavities may be compensated by reducing the heater power in the liquid Helium baths of the nine cryogenic strings. This requires a stable readout of the current RF settings. The detailed signals are read out from several severs in the accelerator control system and then computed in the cryogenic control system for heater compensation. This paper will describe the commissioning on the cryogenic control system, the communication between the control systems involved and first results of machine operations with the heat loss compensation in place.

1987 Villars-sur-Ollon
My first ICALEPCS

30 Years ICALEPCS*

2017 Barcelona
My last ICALEPCS

* sorry I missed 2011 Grenoble

THE XFEL CRYOGENIC SYSTEM

The cryogenic system for the European XFEL consists of two cold-boxes with the associated warm compressors. One cold-cox is enough for cryogenic operations up to the desired operation point of 17.5 GeV in the linac. The cold-boxes were refurbished from the former hadron electron ring HERA. Both cold boxes are connected by a distribution box which feeds a transfer line into the XFEL shaft. The four stage cold compressors are located in the shaft followed by a valve box from where the Helium is fed into the XFEL tunnel and the injector section.

COLD COMPRESSOR OPERATIONS

The cold compressor box is housing four cold compressors which are running in sequence. The pressure in the 2 Kelvin areas of the injector and the XFEL tunnel is pumped down to 30 mbar which corresponds to 2 Kelvin. The pressure rise from 28 mbar at the entry of the cold compressor box (CB44) to 1 bar at its outlet is necessary to feed the helium back into the cold-boxes of the cryo plant. Cold compressors are necessary to improve the total efficiency of the cryogenic process. There is one limiting factor in cold compressor operations which is the small operation range for the individual compressor stages. Small fluctuations on mass flow or temperature may move the operation point closer to the surge line. This could cause the compressors to trip and the whole system to stop.

To avoid such a dramatic consequence the cold compressors have been equipped with a sophisticated bypass line. This bypass together with the speed control of the cold compressors helps to keep the mass flow changes within certain margins.

CRYOGENIC CONTROLS FOR A CRYO STING IN THE XFEL

A cryogenic string of the XFEL typically consists of twelve cryo modules with eight cavities each. The superfluid helium is covering all of the cavities and ending in two helium baths at both ends.

The basic control loop for such a cryo string is the level control by the Joule-Thomson (JT) valve. Fig.2 (red circle) The valve is used to control the Helium level on the opposite side ensuring that the level on both ends will stay within the defined margins.

The heaters run at constant value. The value must be set to be large enough to leave a minimum margin (e.g. 10%) after reducing the value by the dynamically calculated heat load compensation. Namely: $Q_{const} - Q_{heat\ load\ dynamic} > 10\%$ Fig. 1.

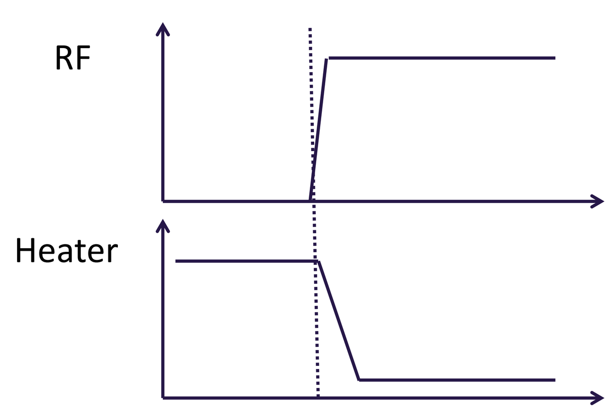

Figure 1: Heater power decreasing while RF power increases and thus dissipates the same amount of heat into the LHe bath. The overall energy balance stays constant.

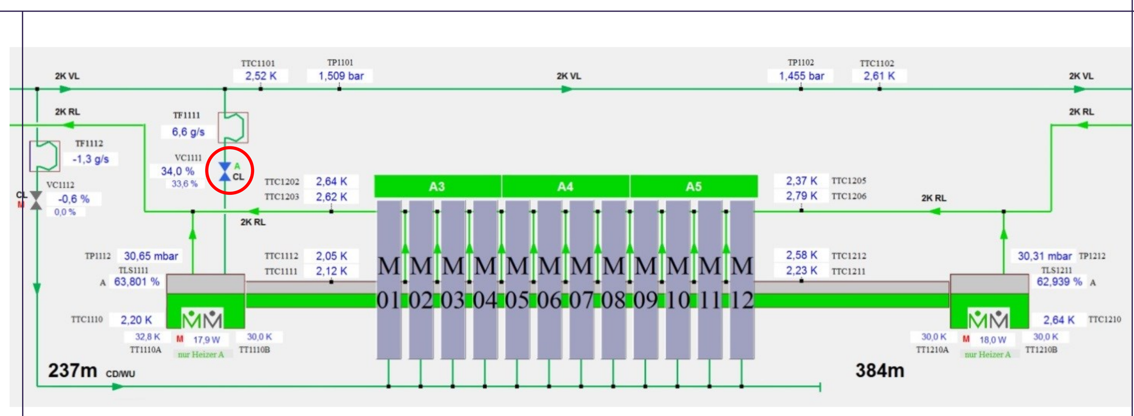

Figure 2: A cryo string in the XFEL consists of twelve cryo modules. The main control loop is configured to keep the LHe level constant by setting the JT valve accordingly.

RF OPERATIONS

As soon as the heat dissipated due to the dynamic load reaches certain limits it will cause liquid helium in the helium bath of the cryo modules to evaporate at higher rates. This will cause the level to drop and the level control valve to open for more mass flow. These changes will result in changes in both the forward direction (~3K @ 1.5bar) and in the return flow (2K @ 30mbar)

In the end the total mass flow in the whole system will be increased. This change must be compensated by the control loops implemented in the cold compressor box. As described this compensation may only occur within certain limits before the cold compressors will trip. This is the first reason why a compensation of the dissipated heat into the cryo system should be implemented.

The second reason to compensate the heat load is the resulting pressure fluctuation in the 2 Kelvin regime of the cryo modules. These fluctuations may cause a detuning of the superconducting cavities in the modules. This would disturb RF and thus machine operations and must be avoided. So there are two good reasons to compensate the dynamic heat load into the cryogenic system.

HEAT LOAD CALCULATION FROM RF PARAMETERS

To calculate the expected dissipated heat we have to observe the following parameters:

- The power from each klystron which is spread over two times two modules. Three sets of modulator / klystrons produce the RF power for one cryo string. (P_{12} and P_{34})
- The number of cavities which are actually on and thus have their share on the total dissipated heat into the Helium. (LF = sum of ON cavities/ 16)
- The repetition rate of the RF pulses (Rep) Fig.3.
- The form of the RF pulse itself Fig. 3.

The resulting formula is:

$$Q=(P_{12}*LF_{12}+P_{34}*LF_{34})*Rep*(t_{fill}*0,35+t_{flat}+t_{decay})*CF$$

Where CF is the experimentally determined so called 'cryo factor' to adjust the resulting value to the observed heat load.

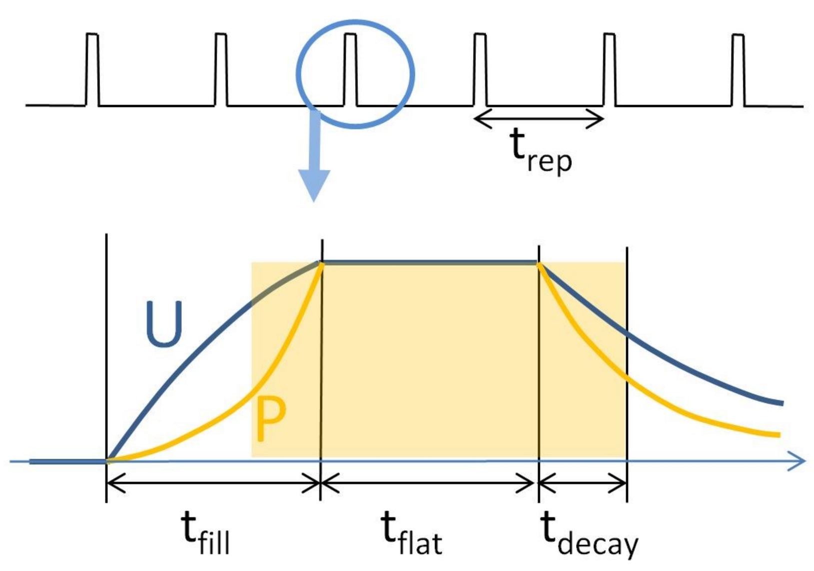

Figure 3: Repetition rate and pulse form.

FIRST RESULTS

After thoroughly testing the initial implementation of the heat load compensation the first version went into operation in the evening of the 4th of April. At this day the RF commissioning team wanted to run several RF stations in parallel. This new operation scheme was possible with the heat load compensation in place Fig.4. The next day a trip was stopping the RF abruptly. The cryo system continued without major impact. – success! -

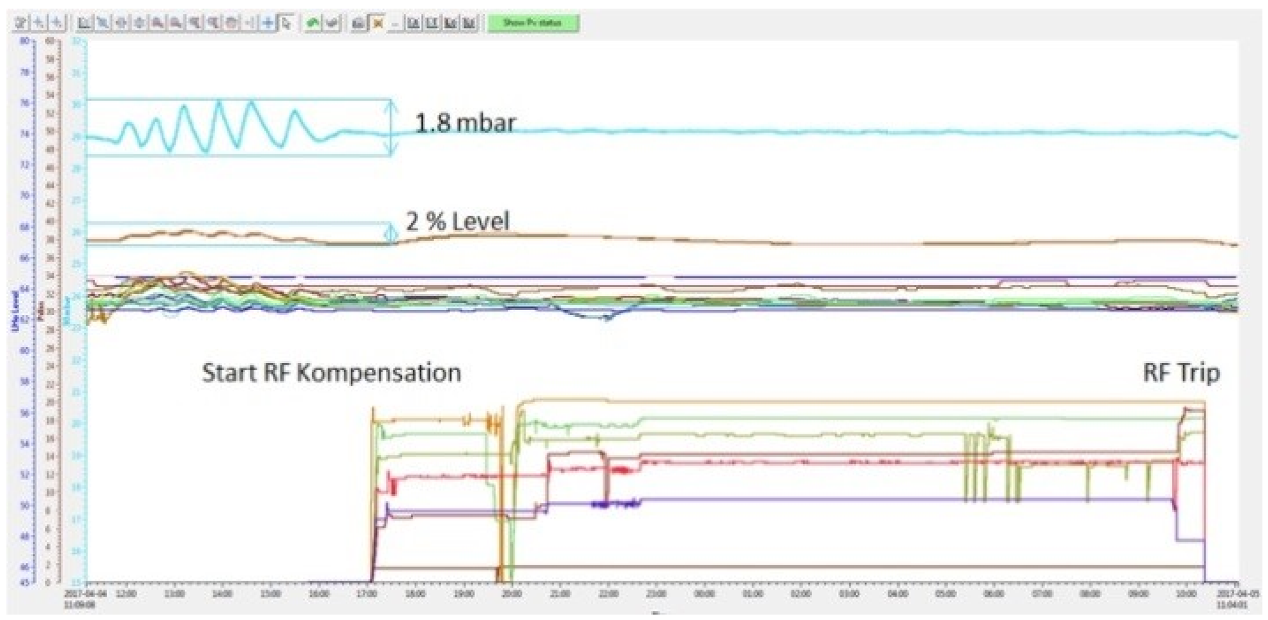

Figure 4: First run with heat load compensation switched on. And first RF trip the next day.

OPEN POINTS

Recognition and Compensation of 'Soft Quenches'

If a cavity is operated just 'at the edge' of the maximum gradient it will start quenching at the end of the RF pulse. If the cavity shows this kind of behaviour the RF power will slowly but increasingly heat the Helium. The point when this happens is difficult to detect. Due to the fact that the RF controls (for now) cannot detect this critical operation mode it is possible that a cavity is 'boiling' Helium in a module for a long time.

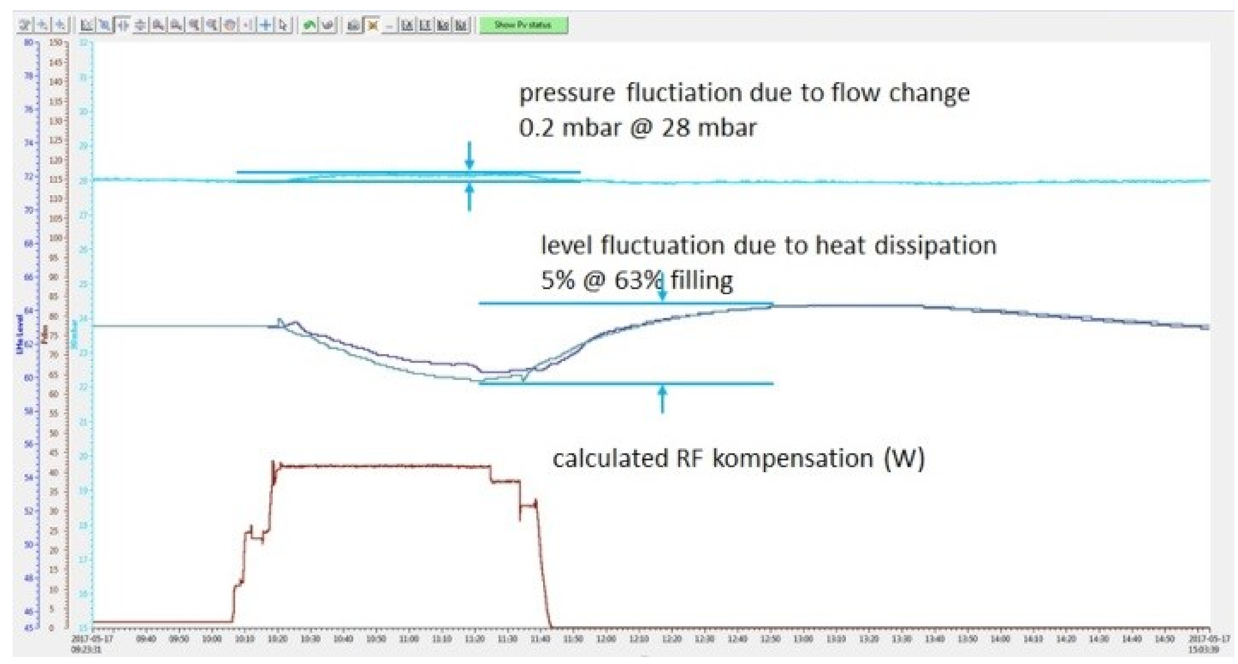

Figure 5: 'Soft quench' of just one cavity can cause major problems in a cryo string.

Figure 5 shows a long lasting so called 'soft quench'. RF heat loss compensation was turned on. It could only compensate for the heat losses during normal operations. The RF power was too high for at least one cavity. Even step wise reducing the RF did not cure the situation. The Helium level did not recover to normal. In the end the RF had to be switched off from the cryo module. Cryo operations recovered after about two hours from this incident.

OUTLOOK

A heat load compensation has been successfully implemented in the XFEL cryogenic control system. Changes in the RF operations of the linac have a minimum impact on the cryogenic system. Especially the impact on the operations of the cold compressors is negligible.

While the XFEL operations will move forward to higher energy we will have to continue our effort to improve the heat load compensation.

The special case of so called 'soft quenches' must be clearly identified. Special strategies must be implemented to continue machine operations while 'soft quenches' occur. Once 'soft quenches' can be identified the RF in these cavities must be reduced to get back to normal operating conditions.