

RF HEAT LOAD COMPENSATION FOR THE 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 Helium vapour 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 sensors 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.

THE XFEL CRYOGENIC SYSTEM

The cryogenic system for the European XFEL [1] consists of two cold-boxes with the associated warm compressors. One cold box 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.

RF OPERATIONS

The XFEL RF systems may be operated independently of the cryogenic system as long as the impact on the cryogenic system is limited to minimal values. This approach was used for commissioning the RF components at very low load.

As soon as the heat dissipated due to the dynamic load reached 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 ($\sim 3\text{K @ } 1.5\text{bar}$) and in the return flow ($2\text{K @ } 30\text{mbar}$)

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 COMPENSATION

Implementation

There are several ways to calculate the dissipated heat load into the cryo system:

1. Calculating the dissipated heat from the initial measurements of the individual cavities before theses got installed into the cryo modules.
2. Calculating the dissipated heat from the measurements of the individual modules (with eight cavities) before they got installed into the XFEL tunnel.
3. Calculating the dissipated heat from the measured RF and the boundary parameters of the cryogenic string.

The basic implementation in the XFEL case is version three (3) where version two (2) is used to cross check the results of three.

Before we describe this kind of implementation we'll have to understand the existing cryogenic control implementation of a cryogenic string in the XFEL.

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: $Q_{\text{const}} - Q_{\text{heat load dynamic}} > 10\%$ Fig. 1.

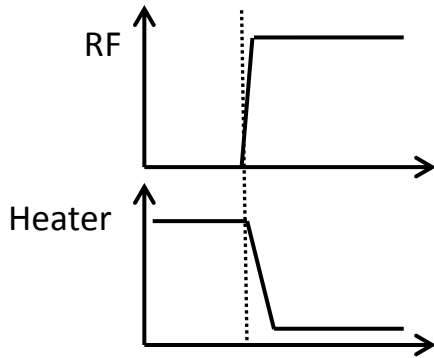


Figure 1: Heater power decreasing while RF power increases and thus dissipates the same amount of heat into the LHe bath. The overall energy balance stays constant.

As RF operations improve and modules will be tuned to run close to their limits the dynamic losses will rise. Therefore the constant values must be adjusted accordingly before a new run starts.

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 in tune (ON) and thus have their share on the total dissipated heat into the Helium. ($LF = \text{sum of ON cavities} / 16$)
- The repetition rate of the RF pulses (Rep) Fig.3.
- The form of the RF pulse itself Fig. 3.

The resulting formula is:

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

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

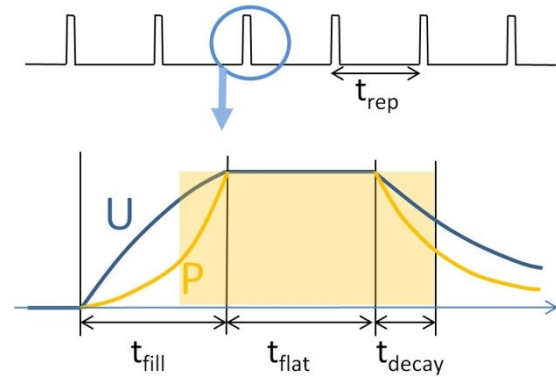


Figure 3: Repetition rate and pulse form.

Figure 3 also describes the resulting integral of the RF power during fill time and decay time and the expected voltage curve.

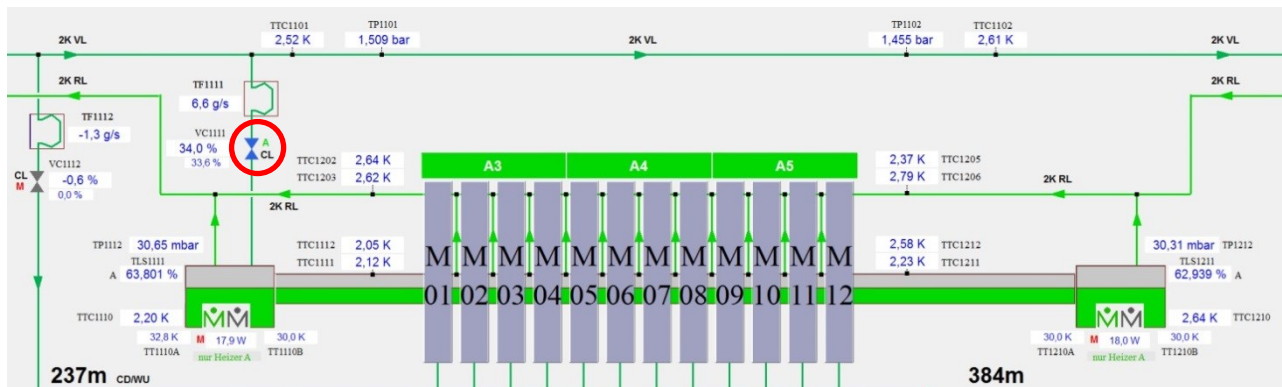


Figure 2: A cryo string in the XFEL consists of of twelve cryo modules. The main control loop is configured to keep the LHe level constant by setting the JT valve accordingly.

Separation of Concern

The continuous controls like control loops and the heat load calculation belong closely together. The runtime requirements are different. While the continuous controls have to fulfil the 24/7 operation requirement of the cryogenics the heat load compensation has to be flexible to react on new / changing requirements or new experience.

We decided to separate the two functionalities from each other Fig. 4. While the control loops run in the designated EPICS IOC with the direct connection to the I/O through Profibus [2], the heat load calculation runs on a virtual Linux host in a so called ‘soft’ IOC (IOCs without direct connection to hardware I/O are called ‘soft’ IOC. They run the same EPICS IOC code software and process EPICS records in the same manner as any other IOC)

The communication between the two systems is the standard EPICS communication protocol called Channel Access (CA). Special precautions have been implemented to handle network interruptions.

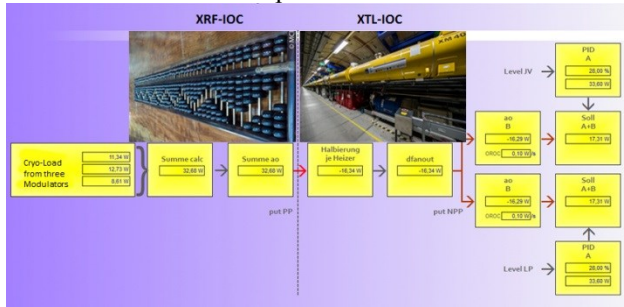


Figure 4: Soft IOC(left) for heat loss calculation and cryo control IOC (right)

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.5.

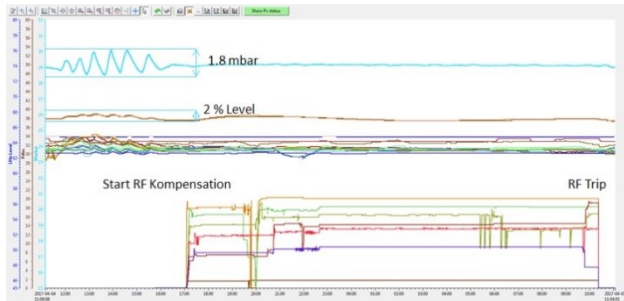


Figure 5: First run with heat load compensation switched on. And first RF trip the next day.

In the morning of the next day a trip caused the RF to be switched off instantaneously, an operation which did not happen before. A trip at 10GeV could be compensated without major level and pressure fluctuations.

After this successful ‘spontaneous test’ the development of the heat load calculation went on.

Figure 5 also shows some instability in the 30 mbar lines at 2 Kelvin. These are only partly caused by uncompensated RF operations.

Ongoing developments

In the last months the algorithm was optimized. The information about detuned cavities had to be incorporated. Also the precise calculation of the pulse form and the resulting power had to be improved.

This process is ongoing and will continue to be optimized.

Network Communication

All RF data are supplied by front end controllers of the machine control system [3]. Since the communication with the XFEL machine controls is essential for XFEL operations a dedicated fibre optical link has been established between the cryo- and the machine control systems.

ALTERNATIVE HEAT LOAD CALCULATIONS

Method Two (2)

As mentioned before there are two alternative methods to calculate the expected heat load. Method two (2) takes into account how the RF is distributed into the cavity couples of the four couples per module and this for the two modules which are connected to one of the two RF distribution arms from one klystron. A quadratic formula will calculate the expected heat load at a given RF power.

As a result his method computes qualitatively good results. The absolute values still need to be adjusted.

Method One (1)

The calculation of the expected heat load based on the individual measurements of the cavities still needs to be fully implemented. It might also help to identify the so called ‘soft quenches’ mentioned below.

OPEN POINTS

Recognition of so called ‘Soft Quenches’

RF operations of ‘normal’ cavities shows a clear signature. The Q_{load} stays constant during the whole RF pulse. If the RF reaches the maximum gradient such a cavity will quench from the beginning of the pulse. This kind of quench can be clearly identified by the LLRF controls. The modulator will switch off the RF for just a few pulses and normal RF operations will continue afterwards. In such a case the cryo system will not even recognize the quench and the dissipated heat is negligible.

If a cavity is operated just ‘at the edge’ of the maximum gradient it will start quenching during the 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. See the plots in Fig. 6 where cavity C5.M3.A14.L3 clearly shows a hard quench at 16 MV/m. Between 13 and 16 MV/m the cavity can

still be operated but the Q_{load} degrades dramatically. 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.

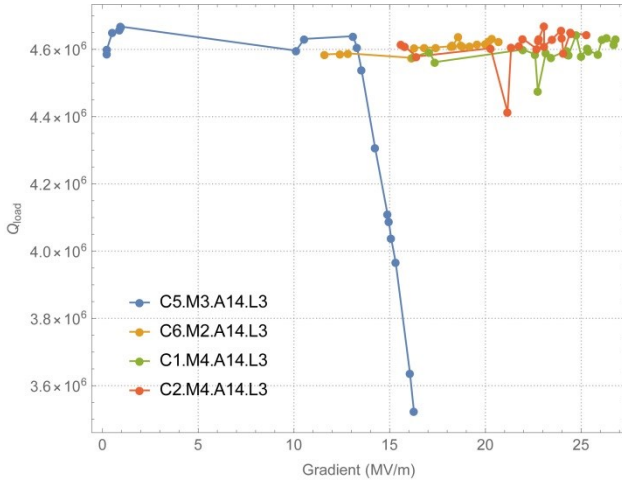


Figure 6: Q_{load} as a function of the gradient (MV/m)

In the end the dissipated heat will boil off Helium and the LHe level in the module will decrease dramatically.

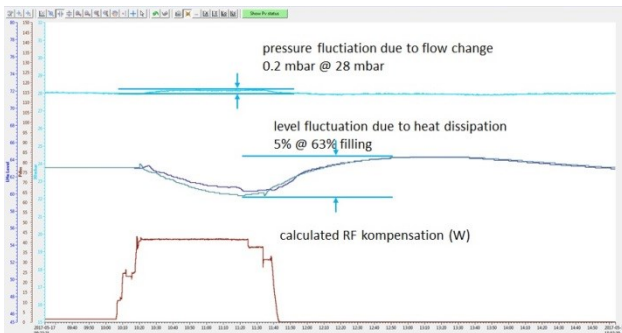


Figure 7: ‘Soft quench’ of just one cavity can cause major problems in a cryo string.

Figure 7 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 stepwise 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.

Even though the situation looks dramatically – we were still in safe mode. If the LHe level had gone below a certain safety margin, the RF would have been switched off automatically.

On the other hand it demonstrates the impact of ‘soft quenches’ on the cryo system. The dissipated heat in such a case can easily reach a factor of 100 above normal. The cryo system actually needs a long time to recover to the previous stable conditions while RF operations could

continue after a short interruption in the adjacent modules.

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 of 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.

REFERENCES

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