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RF-ENERGY MANAGEMENT FOR THE EUROPEAN XFEL

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Abstract

The European XFEL is in its commissioning phase at this time. One of the major tasks is to bring up all the 25 installed RF-stations, which will allow for a beam energy of up to 17.5 GeV. It is expected, that a klystron may fail every 1-2 month. The accelerator is designed at the moment with an energy overhead corresponding to 2-3 RF-station, as the last 4 accelerating modules will be installed in a later stage. This will allow recovering the missing energy with the other functioning RF-stations to keep downtime as short as possible in the order of seconds.

The concept and corresponding High-Level software accomplishing this task will be presented in this paper.

XFEL RF LAYOUT

The European XFEL consists of four linac sections to accelerate the electron beam. The injector I1 accelerates the beam to 130 MeV and uses a 3.9 GHz module to linearize the beam profile. This beam is injected through a dogleg into the second section called L1, which is build of one RF-station of four modules each containing eight 1.3 GHz superconducting cavities. After L1, the beam reaches energy of about 700 MeV, gets compressed in the bunch compressor B0 and then further accelerated in the section L2 to approximately 2400 MeV with three RF-stations again with four modules each. After passing bunch compressor B1, the beam enters the long L3 section, where the beam reaches its final energy of up to 17.5 GeV. This section contains of 20 RF-stations, in a later stage with 21, and is laid out with an energy overhead of 10 % to compensate for an outage of up to 3 RF-stations in the final configuration [1][2].

Every RF-station in the sections L1 to L3 is build of a 100 kV pulse transformer driving a 10 MW klystron. This klystron powers via two waveguide arms 4 accelerator modules containing 8 cavities. So 32 cavities are feed by one klystron giving a possible energy gain of such a RF-station between 600 and 900 MeV depending of the gradient of the individual cavities.

Table 1: XFEL Energy Gain Configuration

Linac Section	*ΔE* [GeV]	*N*	*ΔE / N*	*V* [MV/m]
Injector	0.13	1	130	16.5
Linac 1 (L1)	0.57	1	570	17.8
Linac 2 (L2)	1.7	3	567	17.7
Linac 3 (L3)	15.1	21/20	719/755	22.5/23.6

DESIGN MATTERS

There are several reasons why a RF-energy management is required. Some of them are the following:

One klystron tube is expected to break once per month and needs to be exchanged, which takes several hours so that it should be possible to postpone it to the next maintenance day.

There are other sources of failures like coupler interlocks or broken computer hard disk and electronic devices, which resides inside the XFEL tunnel in restricted areas. In order to get those failures repaired, experts are required and may not be available at a time.

So in case of any kind of failure, the RF-energy management should help to reduce the time to recover beam operation in an automated way.

DESIGN IDEA

The purpose of the RF-energy management is to control the overall energy gain in the L3 section of the XFEL. The operator should just set the energy for the whole XFEL. So the required energy in L3 is simply given by:

$$E_{L3} = E_{total} - E_{I1} - E_{L1} - E_{L2}$$

The energy E_{L3} has to be distributed now to the active RF-stations along L3. Active RF-stations are stations, which are marked as operational by the Finite State Machine FSM and when the timing trigger is set in a way to allow this station to accelerate the beam or may shifted into this position.

There are in principle two ways to change the beam energy:

- Change the amplitude of the RF-stations [3]
- Change the phases in counter-rotating way [4]

Changing the amplitudes seems the more obvious way of doing it, but has the disadvantage, that several LLRF tuning parameter, like cavity tuning or klystron linearization need to follow. So bigger amplitude changes may make the LLRF regulation unstable. Changing the phases is much easier to handle by the LLRF regulation, but may have an impact to the beam dynamics, as the beam is accelerated off-crest at every station and only the total phase of L3 becomes zero. So the beam could develop a chirp, which may harm SASE performance.

Both methods are implemented to study its feasibility.

Use cases

The RF-Energy Management should fulfil the following use cases:

- Allow to change the overall Linac energy by one property

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- Switch all 25/26 RF-stations on/off with one command
- Standardize the energy distribution by an reproducible algorithm
- Recover the overall energy from a trip of a RF-station within few seconds
- Should run contiguously as a DOOCS [5] middle-layer server process in the background

SUB-SYSTEMS

The RF-Energy Management server is designed as a DOOCS middle-layer server. In DOOCS terminology a middle layer server is a process that uses only control system network communication, but has no direct connection to hardware. As a consequence, this system relays on several sub-systems. The three most important ones are described here:

LLRF System

The LLRF system [6] provides the drive to the klystrons in order to regulate the RF field inside the cavities. A vector sum is computed in real-time from probes of all 32 cavities by firmware. The hardware is based on the MicroTCA.4 crate standard [7] and completely located inside the XFEL tunnel. Per RF-station one master and one slave crate are required to be connected with a dedicated fibre optic link for the real-time communication. DOOCS server on these crates allows controlling amplitude and phase.

Timing System

The XFEL timing system [8] is in charge to synchronize the whole XFEL. It is based on the MicroTCA.4 AMC standard to fit into every LLRF, coupler-interlock or diagnostics crate. A master timing crate in the injector area generates event numbers with an update rate up to 10 Hz. These events are distributed via fibre optic links to slave timer boards where these events may create local trigger. A dedicated event number is configured at the master timer for every RF-station to allow shifting the trigger at such a station for the LLRF, coupler interlock, klystron interlock and modulator simultaneously from one machine pulse to the other at a central place.

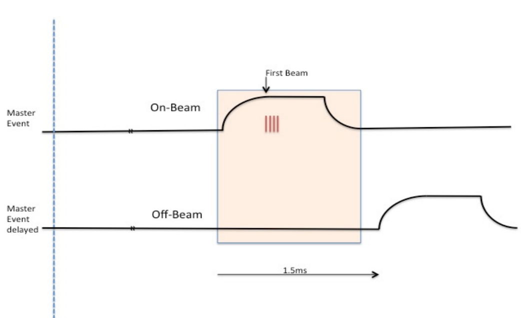

Figure 1: Timing shift of the RF pulse.

In case, one station is shifted “off-beam”, it is in maintenance mode and maybe operated independent from the beam operation.

Finite State Machine FSM

The Finite State Machine FSM is in charge for the automation of one RF-station. Its main purpose is to switch the whole RF system including modulator, klystron and LLRF on/off, monitor its proper operation and recover the system as fast as possible after a trip or interlock. One independent instance of the FSM is running per RF-station. If a station is fully operational, it is indicated by the FSM with the message “RF running”. The message “RF-station shifted off beam” indicates, that the master trigger is delayed by 1.5 ms, but this station is ready for operation and may be included by the RF-Energy Management.

OPERATION

The main purpose of the RF-Energy Management is to recover the beam operation from a failure of a RF-station as quick as possible in order to minimise the downtime of the XFEL facility. In case of a failure, the FSM shifts this particular station off the beam via a command to the timing system master. This shift is active from the next machine pulse on. As this station does not contribute to the beam energy anymore, the RF-Energy Management may immediately start to distribute the lost energy to the remaining RF-stations. It checks with 10 Hz rate the status of every FSM location to monitor for a failure indication. In case, there is a RF-station in standby mode (off-beam) available, the RF-Energy Management sends a command to the master timer to shift it back “on-beam”. After this, the software calculates a new energy distribution and applies it to all RF-stations. In case the amplitudes are changed, it may take some seconds to allow for the LLRF system to come back to stable regulation. If the phases are set everything should operational immediately. This phase algorithm sets the phases in a counter-rotating way. So if the first station gets a positive phase, the next gets a negative and so on. In case there is an odd number of RF-station operational, the last one will be set to on-crest (zero) phase.

Switching back on the electron beam is an operator task for the time being, but maybe automated later.

Another task, the RF-Energy Management could be used for, is to change the overall energy of the electron beam. One set-point property is provided to the user to do this task. Every 600 MeV energy change, the RF-Energy Management shifts a RF-station ON or OFF the beam accordingly in order to keep the amplitude or phase change to individual stations as low as possible. When a station is taken “off-beam”, a station at the end of the XFEL-Linac is chosen and vice versa to keep the impact to the beam dynamic low.

One may mask a RF-station to be ignored by the RF-Energy Management in case it is broken, in maintenance or should stay “off-beam” for special tests. A RF-station may even be masked when operating “on-beam”, but

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should not change its gradient. E.g. that beam dynamics consideration requires the same gradient in any case.

USER INTERFACE

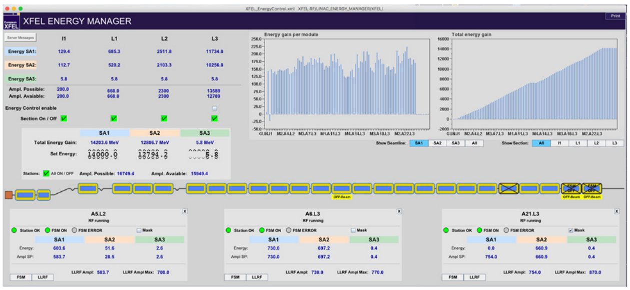

Figure 2: jDDD operator interface for the RF-Energy Management.

There are only a few knobs required to operate the RF-Energy Management in standard mode like the overall energy set points or switching all RF-stations on or off. In certain situations an expert view may required which is shown in Fig. 2. The jDDD [9] Editor is used to create this panel. In the middle one sees the XFEL indicated with its RF-stations. Clicking on one of these blue/yellow areas opens a more detailed view of one RF-station below of the Linac line allowing to go even further to LLRF or FSM expert panels. Above the Linac line are some statistics values shown and the actual controls are placed. The graphs are showing the gradients per module and the accumulated energy gain along the XFEL.

STATUS

The implementation of the RF-Energy Management is finished and the software is installed and configured at the European XFEL. Most of the internal logic could be tested on our software test bed called Virtual XFEL. It allows simulating most of the XFEL operation like beam tracking or RF operation and enables us to save lot of software testing time at the real XFEL accelerator.

For the first tests at the XFEL, the amplitude algorithm was used and worked fine for small changes of some 100 MeV, but failed for large steps of 1 GeV and then tripped several RF-stations as the LLRF regulation could not follow that fast. When simulating a trip at one station, a spare one was shifted “on-beam” as expected and the electron beam was back within seconds. But the SASE level increased by more then 100 %, so it seems that the beam dynamics changed considerably and may not be as relaxed as the calculation indicated. Changing the energy by adjusting the phases could not be tested yet.

CONCLUSION

First tests have already shown, that the RF-Energy Management may become a valuable tool to ease XFEL operation and to reduce the time to recover beam operation. Now one need to gain operational experience to detect issues for further improvements and eventually systematic beam optics studies are required to understand electron beam parameter changes.

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