

LLRF R&D TOWARDS CW OPERATION OF THE EUROPEAN XFEL

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Abstract

The ever growing request for machines with a higher average beam pulse rate and also with a relaxed (< 1 MHz) pulse separation calls for superconducting linacs that operate in Long Pulse (LP) or Continuous Wave (CW) mode. For this purpose the European X-ray Free Electron Laser (European XFEL) could be upgraded to add the ability to run in CW/LP mode. Cryo Module Test Bench (CMTB) is a facility used to perform tests on superconducting cavity cryomodules. Because of the interest [1] in upgrading European XFEL to a CW machine, CMTB is now used to perform studies on XM-3 [2], a 1.3 GHz European XFEL-like cryomodule with modified coupling that is able to run with very high quality factor ($Q_L = 10^7 \dots 10^8$) values. The RF power source allows running the cavities at gradients larger than 16 MV/m. Because of the Q_L and gradient values involved in these tests, detuning effects like mechanical resonances and microphonics became more challenging to regulate. The goal is then to determine the appropriate set of parameters for the LLRF control system to keep the error to be less than 0.01° in phase and 0.01% in amplitude.

A POSSIBLE CW UPGRADE AT EUROPEAN XFEL

XFELs are important tools of discovery that allow unprecedented brightness and spectral purity. In 2017 the European XFEL came into operation, producing the brightest and hardest X-ray FEL light in the world. At the moment European XFEL can produce a maximum of 2700 pulses with a temporal distance of 220 ns and a repetition rate of 10 Hz. Because of the advantage (from the experimental point of view) of having a bigger temporal separation between the pulses and simultaneously increasing the average number of pulses per seconds, a CW upgrade of European XFEL could be made. For such upgrade the duty cycle would change from the actual value of 1.4% at 17.5 GeV for Short Pulse (SP) to a maximum value of 100% at 8.6 GeV, for CW, or 10% to 50% at 12.8 GeV for LP [1]. For CW/LP operations, IOT amplifiers, along with the existing klystrons, will be installed in European XFEL tunnel to allow both SP (high gradient) and CW/LP (reduced gradient) with minimum downtime between the switch of the two modes. To limit the required RF power, the Q_L could be increased to values higher than 10^7 . To meet the field quality requirements inside the cavities with an increased Q_L and to decide the optimal set of parameters of the Low Level RF (LLRF) controller, further studies have to be done both on European XFEL and dedicated test facilities.

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CHALLENGES OF CW OPERATION

Increasing the Q_L from the current European XFEL value of $4.6 \cdot 10^6$ to values bigger than 10^7 results in a full bandwidth less than 100 Hz that will make the cavities more susceptible to detuning effects. In order to keep the cavities on resonance with the required field stability but, at the same time, to limit the required peak RF power, these effects must be canceled out using a LLRF control system that acts on the fast piezoelectric tuners.

Lorentz Force Detuning

Lorentz force detuning effects on a TESLA cavity
 $Q_L = 6.1$, $K_{Lfd} = -1.59\text{Hz}/(\text{MV})^2$ and $\frac{R}{Q} = 1038$
 Measured vs computed

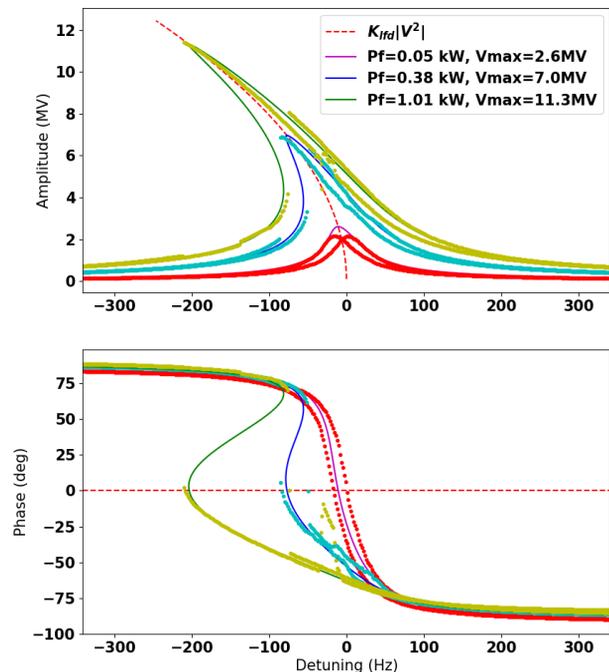


Figure 1: Resonance scan of a TESLA-like superconducting cavity at different values of the forward power using piezoelectric actuators. Computed (lines) vs. measured (points) values are shown. Tests were taken on cavity 2 of XM-3 module.

Lorentz Force Detuning (LFD) is a detuning effect that arises from the electromagnetic pressure that the accelerating field exerts on cavity walls. The detuning produced by LFD is proportional to the square value of the field.

$$\Delta f_{Lfd} = K_{Lfd} \cdot (\Delta V)^2$$

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Because for European XFEL TESLA-like cavities $K_{Ifd} \approx -1\text{Hz}/(\text{MV})^2$ [3], when driving the cavities at accelerating fields higher than 10 MV, the resulting detuning becomes comparable to a full bandwidth of 130 Hz, equivalent to a $Q_L = 10^7$.

With even higher fields and Q_L s (eg. in Fig. 1) the resonance curve becomes metastable and shows a strong hysteretic behaviour [4] Fig. 1. When driving cavities near resonance with such conditions, a transient effect, like cavity oscillations driven by microphonics, or forward RF power oscillations, can trigger a jump of the field to low gradients. The LLRF controller should then be able to prevent static drops and automatically adjust the tune correction to be applied when the accelerating gradient is changed or the forward power is switched on.

Microphonics and Mechanical Properties of Fast Tuners

External disturbances, commonly referred to microphonic noise, produce a detuning that can be periodic (the noise produced by turbopumps, air conditioning, 50 Hz electric hum) or temporary (vehicle passing near the facility, routine activation other acceleration devices). Also long time drifts of the spectral properties of the noise have to be taken in account. This is particularly important because our current LLRF control system for CW uses an Active Noise Compensation unit (ANC) [5] to compensate the microphonic noise detuning. This unit, using the detuning information as input signal, locks on a particular microphonic frequency and produces a signal to actuate the fast tuner. The result of such operation is the cancellation of the locked noise component. Because the capture bandwidth is limited and has to be set up with a fixed central frequency, the stability of time-dependent spectral properties of the noise has to be measured. Additionally, the mechanical properties of the fast piezoelectric tuners has to be modeled. This is particularly important because the control algorithms that use these tuners have to take into account mechanical resonances in order to work in a correct way.

MEASUREMENTS AT EUROPEAN XFEL

Microphonic and mechanical studies during shutdown periods were conducted even if European XFEL is not operated in CW mode. These measurements were done only using the installed piezoelectric sensors/tuners. Because of the limitations of the system during the measurements, the length of the acquired signals was only 100 ms, thus producing a separation between the recorded frequency components of 10 Hz. The measurements on the first module of European XFEL station 15 are shown in Fig. 2. The main noise component frequency is at 160 Hz with a possible second and third harmonic components at 320 Hz and 470 Hz. The origin of this signal is at the moment still unknown. Also a 50 Hz signal was detected.

Mechanical resonances were also measured exciting the cavities with the fast piezoelectric tuner and reading back

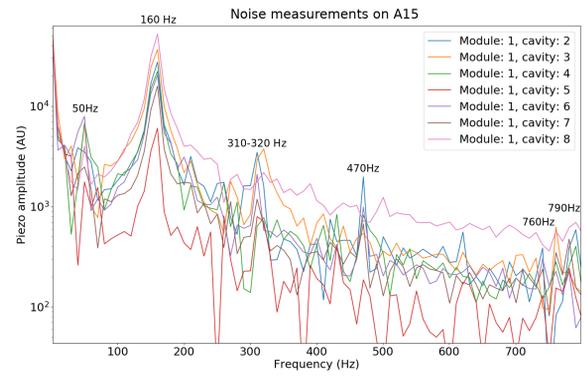


Figure 2: Microphonics recorded at European XFEL RF station A15 cryomodule 1 with piezoelectric sensor. Cavity 1 is not shown.

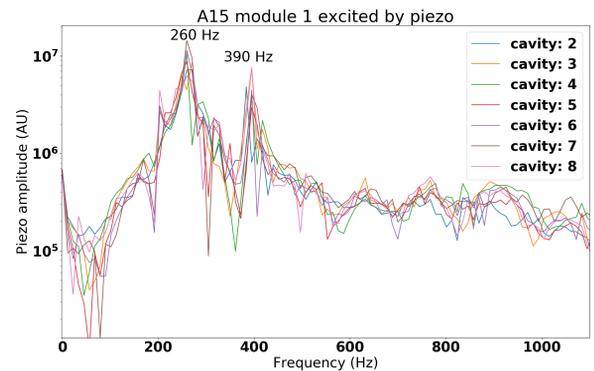


Figure 3: Transfer function between excitation produced by the fast tuner and piezo sensor.

the produced signals with the piezoelectric sensor. In Fig. 3 such measurements were displayed for RF station A15 for a periodic excitation of 10 Hz. For each cavity resonance peaks were observed at 260 Hz and 390 Hz.

MEASUREMENTS AT CMTB

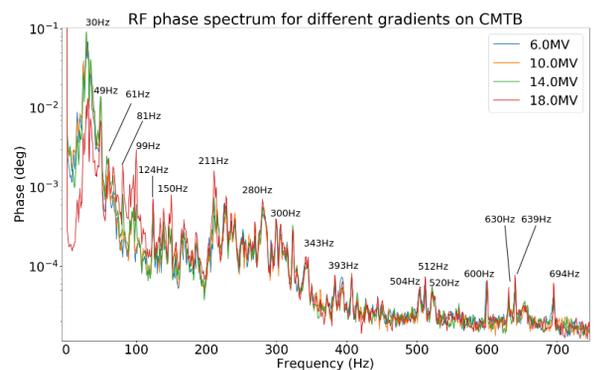


Figure 4: Microphonic noise recorded on the probe signal of cavity 1 at different accelerating voltages. $Q_L = 5 \cdot 10^7$.

Measurements on microphonics and on the fast tuner transfer function with CW fields were made on XM-3. Noise measurements were done recording the spectrum of the RF signal in open loop. Results are displayed in Fig. 4 for different gradients. As it was already found in previous measurements [5], the two main noise components are at 30 Hz and 49 Hz and are produced by the vacuum pumps installed in the facility.

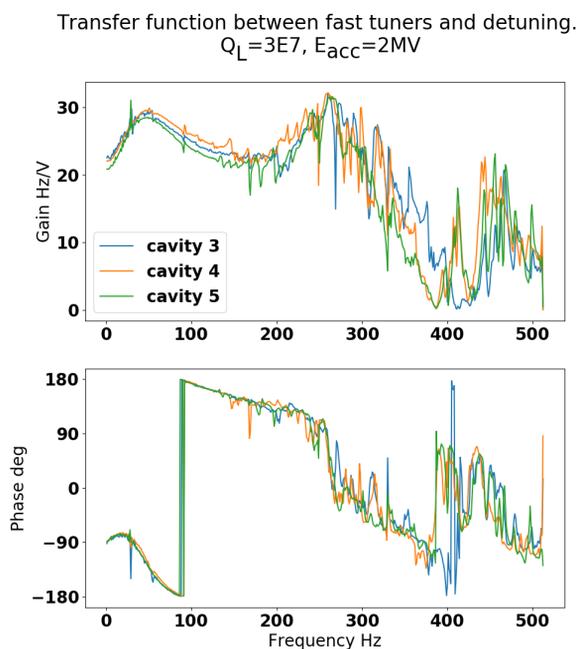


Figure 5: Mechanical transfer function between piezoelectric actuators of cavity 3,4,5 XM-3 and probe signals. The Y axis is the amount of detuning produced by a sinusoidal excitation from the piezoelectric actuators.

The mechanical transfer function between the fast tuners and the accelerating field was also measured (Fig. 5) using the piezoelectric actuators excited with a varying frequency sinusoidal signal. A central component of 260 Hz matches the measurement at European XFEL, whereas the 390 Hz component was not found.

To observe the long time stability of the microphonics, a 24 hours-long test acquisition of piezoelectric sensor signal (Fig. 6) was recorded. The spectrogram shows the stability of the microphonic spectrum over the entire measurement time.

CONCLUSION AND OUTLOOK

Previously done measurements [6, 7] demonstrated that it is possible to achieve high CW RF fields (>15 MV/m) while meeting the required stability (less than 0.01° in phase and 0.01% in amplitude). However a simple, automatic and reproducible way to achieve these results has to be developed. Furthermore the knowledge acquired at CMTB has to be adapted to large scale working facilities like European XFEL. Then some additional development should be done:

Technology
Low level RF

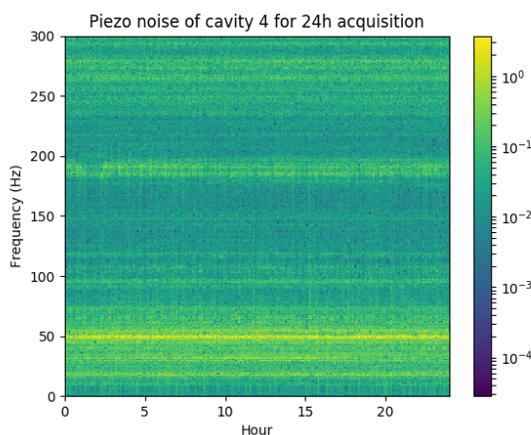


Figure 6: Noise spectrogram taken during a 24h data recording. The signal is recorded from a piezoelectric sensor.

- Develop a reliable detuning estimation.
- Simulate how beam loading affects the system.
- Estimate an RF plant model of a module driven by an IOT. Optimize the MIMO feedback controller parameters with the model.
- Develop algorithms that counteracts LFD related issues. A simple and reproducible way to achieve these results has to be found.
- Find a way to optimally and automatically setup ANC.
- Develop diagnostic routines to find out important information (Q_L , detuning, quench detection, etc.) about the system while minimizing the downtime.
- Find automated procedures to automatically raise CW gradient to a desired level while meeting European XFEL specifications. This should be proven with multiple long term studies.
- Update hardware/firmware/software stack to industrial quality level. The increased performance possibilities of new hardware has to be exploited to improve the LLRF system regulation ability.

The measurements done at European XFEL and CMTB will then be used to enhance the model used in our LLRF control system.

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