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LONG PULSE OPERATION OF THE E-XFEL CRYOMODULE

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Abstract

The CW operation becomes more attractive mode of beam and RF operation, even for infrastructures initially developed as pulsed experiments. Compared to the short (single ms) pulse the CW or long pulse (LP) operation allows for a more relaxed bunch scheme and enables higher bunch quantities during the experiment run. The Long Pulse operation scenario is one of the possible EXFEL modes of work in the future. LLRF systems that work in CW (and LP) are in operation worldwide. Most of them are dedicated to single cavity control. The XFEL dedicated system is capable of multi-cavity cryomodules vector-sum operation. In such a configuration switching from short-pulse operation into long-pulse with the existing limitations from the allowed cryo heat load level, average input power per coupler (and others) can be extremely challenging. For this setup the support from the dynamic resonance control system is essential. This paper summarizes efforts towards the successful vector-sum operation of the X-FEL type cryomodule in the LP operation mode. Modifications to the original LLRF setup together with challenges of narrow bandwidth operation in moderate and high gradients are discussed.

INTRODUCTION

Current Low Level Radio Frequency (LLRF) control systems offer more and more versatility and flexibility that can cover a wide scope of applications to be realized by the same set-up.

The system designed and developed initially for accelerating field parameters regulation in short (millisecond scale) pulse operation fulfills CW operation requirements too.

One such example is the LLRF system of the EXFEL project. The facility is in operation since 2017. Although the design nominal operation parameters foresee up to around 1,4 ms pulses with a 10 Hz repetition rate the work on the CW and LPO upgrade possibilities started already in 2011. Over last years, different studies have taken place to determine the necessary modification for the controller system. At the same time, the work continued on system usage limitations determination and environment restrictions.

Majority of the CW and LPO work took place at the Cryo Module Test Bench (CMTB) facility at DESY (Hamburg, Germany). This facility operates single TESLA cavities cryo module that comprises 8 niobium structure. It can operate either the short pulse (using klystron) or CW/LPO (using an IOT prototype) in 2K temperature conditions.

LLRF SYSTEM STRUCTURE

The LLRF system of the DESY facilities (like FLASH or EXFEL) [1] is the controller capable of multi-cavity operation configuration. It optimizes the electro-magnetic field in 8 up to 32 resonators (4 cryomodules) strings. The implementation diagram with the simple proportional feedback loop configuration is summarized in Figure 1. The single

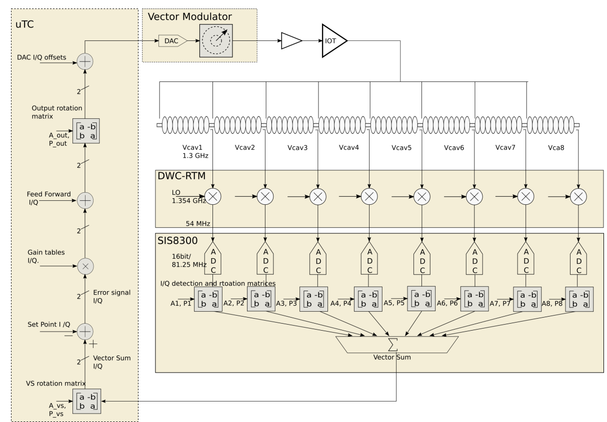

Figure 1: Overview of the LLRF system main RF control loop.

RF controller generates a command signal for all resonators simultaneously. Based on the vector sum information, the error signal reflects the difference between the desired pulse shape and the actual field in cavities. The system allows for different resonator impact adjustments using single rotation and scaling parameters configurations. The other control loop dedicated and more engaged during the CW and LPO operation is the one that provides fine frequency tuning of each cavity (see Figure 2).

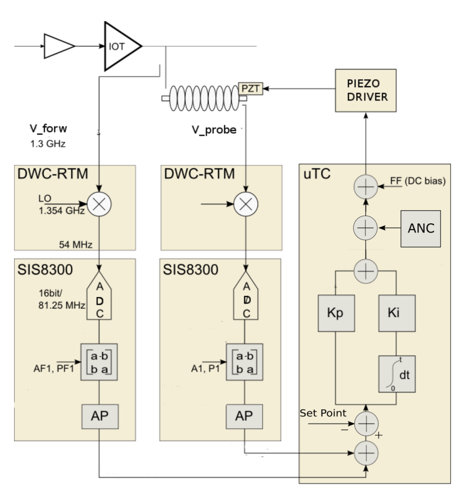

Figure 2: Overview of the cavity resonance control structure.

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The piezoelectric-based system takes care of the dynamic compensation of the resonator frequency shifts from the required value [2]. The controller structure for the piezo operation incorporates different mechanisms capable of cavity tuning excitation generation:

- Integrator controller,
- Active Noise Cancellation (ANC),
- custom feed-forward tables.
- Proportional controller.

Different components play different roles in frequency mismatch reduction. The proportional part handles rapid detuning changes while the integral one compensates for slow changes between 10 to 15 Hz. The ANC mechanisms incorporated in this solution provide tuning for mechanical disturbances originating from the microphonics. Finally, the feed-forward tables minimize the repetitive error determined during the pulse to pulse operation (not suitable for the CW scenario).

LPO CONDITIONS AND CHALLENGES

Used LPO approach defines the long pulse system excitation as 1Hz repetition rate pulses with defined duty factor. Typically, DF ranges from 10 to 50%.

The transfer from the short-pulse to the CW or the LPO has some consequences. Among the others, the changes impact the RF-related environment of the cavity. First, the high-power RF sources are not flexible enough to work in all regimes. The investigation is ongoing on the devices that can satisfy short-pulse and CW operation with enough power margin to cover cavity string consumption.

Moreover, the input couplers that deliver RF power to the cavity cannot sustain the high average power load required for the CW/LPO operation with comparable conditions (like 23-25MV/m field gradient). Although they can work with up to 400 kW excitation, it is only acceptable during the short time pulses (1-2 ms duration, 10 Hz repetition rate). The tolerable average power level should not exceed a couple of kilowatts. The average power reduction demands coupling change between the cavity and its input antenna. Resulted loaded quality factor modification allows for comparable field parameters achievement with less input power needed. The drawback of this is the resonator configuration, with a narrow bandwidth conditions (down to ca. 30 Hz in case of TESLA cavities). This situation makes the cavity more susceptible to the gradient reduction because of the mechanical microphonics sources present in the environment (see Figure 3). The dominant frequencies of 30 Hz, 40 Hz, 49 Hz and 57 Hz can be determined from this figure.

With the LPO operation also the Lorentz Force Detuning (LFD) plays a significant role in narrow-band setup (see Figure 4).

The resonance curve of the cavity bends because of the LFD pressure on the cavity walls. The walls stiffness determines the size of this effect. Narrow bandwidth conditions

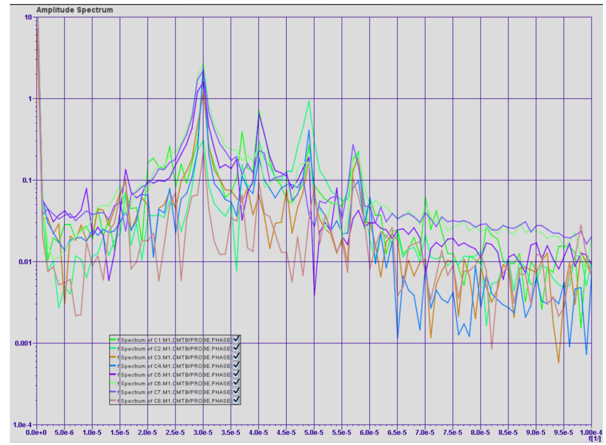

Figure 3: The cavity probe spectral density of 8 cavities in the cryomodule (in [MHz]) with the microphonics disturbances peaks visible.

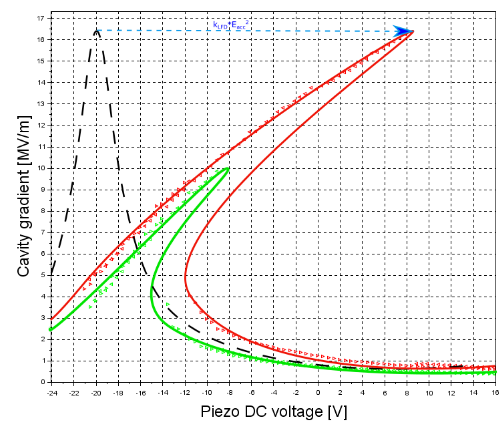

Figure 4: The cavity gradient (in red and green) in function of the cavity detuning (1V of piezo voltage corresponds to 8 Hz detuning).

and high gradient operation can lead to the ponderomotive drops of the field gradient. As depicted in the figure, the dynamic recovery mechanism may require an extensive range of the piezo tuner regulation to cope with this issue.

Taking above into the consideration the careful and sophisticated tuning control is required.

VARIOUS CONFIGURATIONS FOR IN-PULSE RESONANCE CONTROL

Different configurations of the detuning controller evaluation took place. The initial work included only the "I" controller usage for the detuning reduction. As first step the piezo tuner range optimization took place. This regulation overhead assured reliable system response even in the case of the monotonic (ponderomotive) drop. Still higher (above 15 MV/m) gradient operation was not possible due to the microphonics impact.

The unwanted mechanical resonance mode excitation occurred thanks to different disturbances introduced to the

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cavity from outside and the non-optimal cavity filling process in the presence of the LFD. The significance of resulting oscillations was high enough to block effective cavities operation.

Next, ANC filters enhanced the controller functionality (implemented in the system). Both mechanisms working together allowed for microphonics impact reduction. Still, the cavity filling phase caused the detuning that required extensive compensation from the RF power side and strong LLRF feedback loop gain conditions.

Afterward, custom FF tables helped to reduce the repetitive detuning present during the initial filling phase. An adaptive algorithm helped to optimize initial excitation of the piezo actuator that released the unnecessary RF power overhead engaged in the resonator standing wave build-up.

Finally, the work focused on the controller application firmware settings adjustment. The goal was to extend the integral loop bandwidth. With this approach, the piezo actuator could follow the in-resonance filling of the cavity field and track the detuning changes over the whole RF pulse duration. The microphonics impact reduction was out of the "I" loop range, but the ANC could reduce these unwanted disturbances.

ACCELERATING FIELD REGULATION RESULTS

For the LPO study, the LLRF generated pulses with different (pre-defined) duty factor pulses with a 1 Hz repetition rate. The Figure 5 contains an example of the cavity response to this kind of pulse.

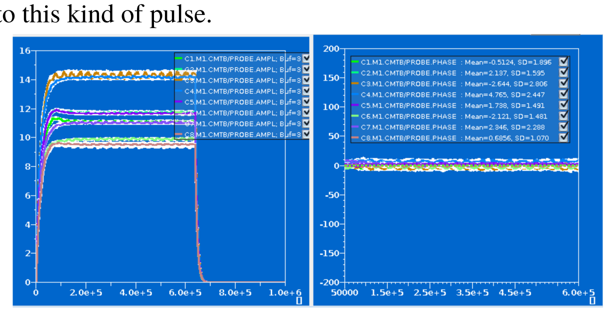

Figure 5: Long pulse operation of the 8 cavities (different colors) in single EXFEL type cryomodule (amplitude response - left, phase response - right).

The particular cavity may have different gradient level from the neighbouring structure. Still it is worth to underline that they are all controlled by a single LLRF system that provides a signal to all of them at the same time. Different loaded quality factor or waveguide distribution determine the power portion that goes to particular resonator. In the case of such multi-cavity systems, the regulation of the whole LLRF vector-sum field envelope parameters is taken into consideration.

The LLRF loop performance achieved for 13 MV/m average gradients and the duty factor of around 55% showed satisfactory results (see Figures 6 and 7).

The amplitude regulation level defined for the EXFEL system is at the level of dA/A = 0.01%. Achieved results

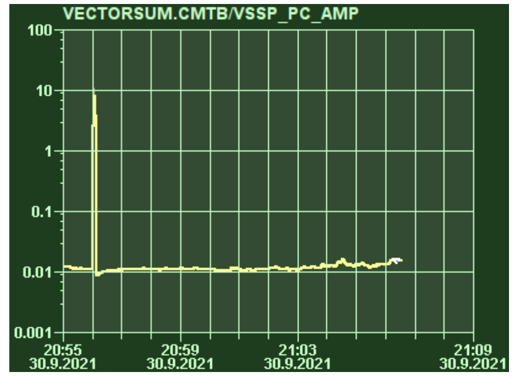

Figure 6: LLRF system vector sum amplitude regulation performance (dA/A in [%]) in time.

almost completely fulfill this requirement for the whole measurement period.

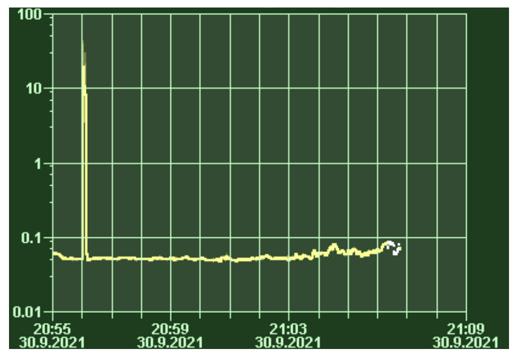

Figure 7: LLRF system vector sum phase regulation performance (dP in [deg]) in time.

The phase requirements are at the level of dP = 0.01 deg. Results at the level of 0.4 to 0.5 deg achieved during that study are not satisfying specified limits. The main error ingredient came from the oscillations caused by microphonics. The reason was not the optimal configuration of the ANC filters at the time of the study. We consider this to be a potential field of improvement for future work on that system.

Even though the achieved results did not fulfill tight regulation requirements in 100% we can already use the system in this configuration for the successful operation of the later stages (like EXFEL L3 section) of the long electron linac.

SUMMARY

The work summarizes efforts toward the LLRF system transformation between short-pulse and Long-pulse operation scenarios. The work on the system allowed to identify some of the potential risks and costs of such transformation (like narrow bandwidth operation).

Performed study provided clear recommendations about especially fine tuning system configuration and performance. Achieved results (from the accelerator in situ environment - CMTB) only slightly deviate from the defined limits and give some space for improvements in future design improvements endeavour.

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