EXPERIENCE WITH SINGLE CAVITY AND PIEZO CONTROLS FOR SHORT, LONG PULSE AND CW OPERATION

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Abstract

We present a compact RF control system for superconducting radio frequency (SCRF) single cavities based on MicroTCA.4 equipped with specialized advanced mezzanine cards (AMCs) and rear transition modules (RTMs). To sense the RF signals from the cavity and to drive the high power source, a DRTM-DWC8VM1 module is used equipped with 8 analog field detectors and one RF vector modulator. Fast cavity frequency tuning is achieved by piezo-actuators attached to the cavity and a RTM piezo-driver module (DRTM-PZT4). Data processing of the RF signals and the real-time control algorithms are implemented on a Virtex-6 and a Spartan-6 FPGAs within two AMC's (SIS8300-L2V2 and DAMC-FMC20). The compact single cavity control system was tested at Cryo Module Test Bench (CMTB) at DESY. Software and firmware were developed to support all possible modes, the short pulse (SP), the long pulse (LP) and CW operation mode with duty cycles ranging from 1% to 100%. The SP mode used a high power multi-beam klystron at high loaded quality factor (Q_L) of $3 \cdot 10^6$. For the LP mode (up to 50% duty cycle) and the CW mode a 120 kW IOT tube was used at Q_L up to $1.5 \cdot 10^7$. Within this paper we present the achieved performance and report on the operation experience on such system.

INTRODUCTION

The 1.3 GHz SCRF cavities in linear accelerators (linacs) such as Free Electron Laser in Hamburg (FLASH) and European X-Ray Free Electron (E-XFEL) are typically driven in a short pulse (SP) mode, at high Q_L above $3 \cdot 10^6$. When a SCRF cavity is operated in the SP mode, duration of the single RF-pulse is 1300 μs, and a repetition rate is up to tens of Hz. A 650 μs part of the RF driving pulse (generated by a multi-beam klystron) is efficiently used to accelerate up to $27 \cdot 10^3$ bunches per second (grouped in 10 successive RF pulses repeated with 10 Hz frequency), with a minimum bunch spacing of 222 ns and a maximum charge per bunch of 1 nC. Since the full width at half maximum (FWHM) bandwidth of a RF cavity resonator operated in the SP mode, with a nominal operating gradient of 23.6 MV/m, is 433 Hz for the FLASH and 283 Hz for the E-XFEL ($Q_L \sim 4.6 \cdot 10^6$), the leading source of the RF field disturbance is a Lorentz force detuning (LFD). The required cavity detuning for the E-XFEL is to be less than 10 Hz, and for this purpose cavities are equipped with the piezo tuners. The LFD can also lead to undesirable cavity oscillations, when operated in the LP mode at Q_L above $1.5 \cdot 10^7$, a duty cycle ranging from 10 to 50% and the gradients higher than 15 MV/m. A microphonics noise, which is unpredictable phenomena, is the main source of the RF field disturbance in the continuous wave (CW) mode of operation. In the CW mode, the RF cavities are driven by an IOT tube, and operated with Q_L greater than $1.5 \cdot 10^7$, which leads to a 5 time decrease of the bandwidth with respect to the SP mode. In order to achieve a stable acceleration of $100 \cdot 10^3$ bunches per second, with a nominal operating gradient up to 15 MV/m (which is foreseen after upgrade of the E-XFEL machine), the accelerating RF field stability should be better than 0.01% amplitude and 0.01 degrees phase.

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SINGLE CAVITY AND PIEZO CONTROLS

The pulse (SP and LP) and CW modes of operation of the SCRF cavity are enabled by the RF and piezo feedbacks. The RF feedback is based on the proportional (P) controller. The piezo feedback is composed of the ANC and a proportional-integral (PI) controllers. Its main purpose is a compensation of the microphonics noise. A piezo adaptive feedforward (AFF) controller is introduced, in order to compensate for the repetitive LFD.

Proportional RF Feedback Controller

The 1.3 GHz RF signals are downconverted to an intermediate frequency (IF) of 54 MHz, and are next digitized using fast ADCs with 81.25 MHz frequency. The IF signals are band filtered in order to acquire the digital representation of their envelope, composed of the in-phase and quadrature (I and Q) components. Two P controllers are applied separately for the I and Q signals as shown in Fig. 1. An input of each controller (ERR_I, ERR_Q) is compared with an user defined setpoint (SP_I, SP_Q) and next multiplied by a proportional gain (GP_I, GP_Q). Outputs of the controllers are protected using a hardware coded limiters (CTL_I_LIMIT, CTL_Q_LIMIT), and are finally summed with feedforward signals (FF_I, FF_Q). A calibration of the RF signals is performed with IIR filters for the I and Q channels, a vector sum and output rotation matrices (IQ ROT, VS ROT, OUT ROT). Driving signals (VM_I, VM_Q) are next used for controlling the high power RF source using a 1.3 GHz analog vector modulator. A detailed description of the corresponding controller blocks can be found in [1].

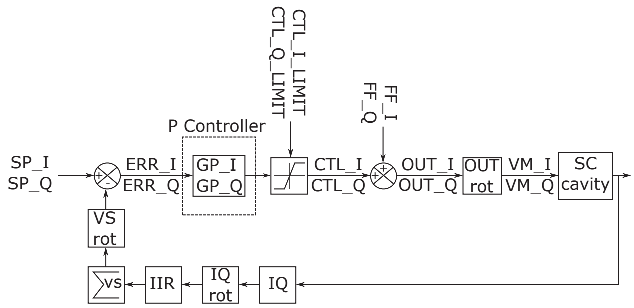

Figure 1: Block diagram of the proportional RF feedback controller.

Piezo Feedback Controller

The SC cavity detuning (CD) can be estimated using a cavity model [2], or alternatively approximated as a phase difference of the cavity voltage and forward wave measurements. The CD is applied to the piezo feedback (PI and ANC) controllers as an input error source (ERR_P). The current used implementation of the ANC filter can cancel disturbances having up to 4 different frequency components. To enable this, a corner frequency (CF) and bandwidth (BDW) have to be provided. The PI controller input is subtracted from a setpoint (SP_P), multiplied by an integral (K_I) gain and accumulated with a previously stored controller output. The proportional controller path (K_P) is not applied. The output (CTL_P, OUT_P) of the piezo feedback controller is protected using limiters ($LIMIT\_P$), next it is summed with a feedforward signal (FF_P), and is finally applied to a drive signal (DRV_P) of an analog power amplifier. The high voltage, high current output is generated to control the CD using the piezo based tuners. In addition, user defined control tables (CTABLE) can be activated and added to the final controller output, in order to apply a custom excitation, as shown in Fig. 2. More details can be found in [3].

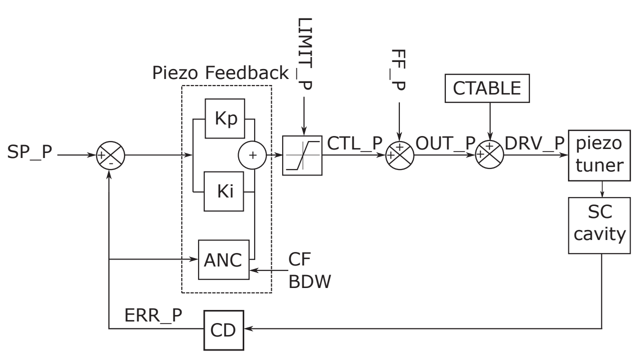

Figure 2: The block diagram of the Piezo feedback controller.

Adaptive Feedforward Piezo Controller

The piezo AFF controller has been implemented as a part of a high level software [4]. In the SP mode, the input error signal is calculated using the CD during the flattop of the RF pulse, as shown in Fig. 3.

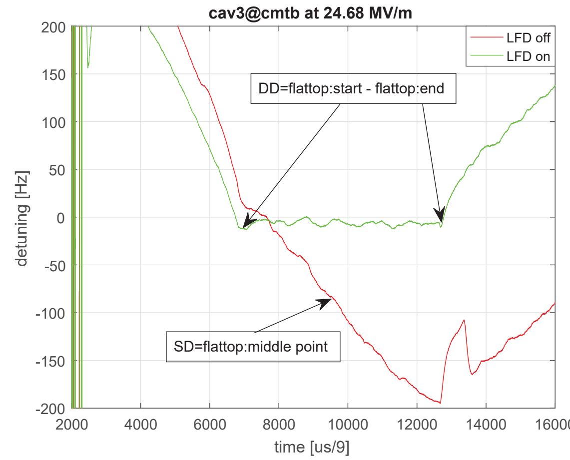

Figure 3: The SC cavity detuning calculated in the SP mode of operation.

In the next step, the least mean square (LMS) optimization method is applied to control the AC amplitude and DC bias level of the generated piezo excitation. The AC amplitude is minimized according to a dynamic detuning (DD) criteria, while the DC bias is optimized to minimize a static detuning (SD). The DD is calculated as a difference of the CD between a flattop start time (end of RF pulse filling process) and an end time (start of RF pulse decay process). The SD is calculated in a middle point of the flattop region. Piezo excitation frequency and delay parameters are setup with use of a simple system identification procedure. The parameters are identified before starting the AC and DC voltages adaptation. First, a piezo sensor voltage is read, without any piezo excitation applied (only the RF is active), and analyzed in the frequency domain. The beat frequency value is than applied as the first fixed parameter of the piezo controller. Next, a small AC voltage is applied to the piezo, with a varying time advance in respect to the RF pulse. The delay scan procedure is applying the piezo pulse a few ms before the RF pulse, and finishes when the RF pulse duration is reached. The described optimization methods can be also applied in the LP operation mode with the varying duty cycle.

RESULTS

The single cavity RF and the piezo controls have been tested at the CMTB in DESY. The E-XFEL accelerating module (XM-3) equipped with the 8 SCRF cavities has been connected, first to the 120 kW IOT tube for the CW/LP operation, and next switched to the 10 MW klystron (for the SP operation). The CW/LP experiment has been performed with Q_L of the cavities higher than $1.5 \cdot 10^7$. For the SP mode, the coupler antennas have been adjusted so that Q_L was less than $4 \cdot 10^6$.

CW/LP Experiment

During the CW/LP experiment, single cavity controllers have been setup for operation with 1 Hz repetition rate. The

ISBN 978-3-95450-182-3

monitoring ADCs have been calibrated for 80% of their dynamic range using the programmable attenuators. The tested cavity has been coarsely tuned to the resonance frequency of 1.3 GHz using step motor tuners. Next, the fine tuning has been applied using the piezo tuners. The microphonics disturbance has been located at 49 Hz using the FFT of the piezo sensor readout, and has been cancelled using the correctly adjusted ANC filter. Finally, the RF and piezo feedbacks have been setup together and their performance has been measured at 14 MV/m as shown in Fig. 4.

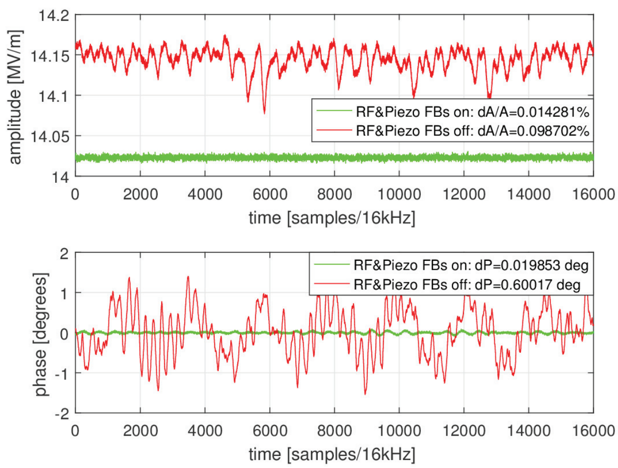

Figure 4: The RF and piezo feedbacks activated for the cavity 1 at the CMTB during the CW experiment.

SP Experiment

The SP operation has been demonstrated for 17 MV/m gradient and repetition rate of 10 Hz. The step motor tuners have been setup to minimize SD of the cavity. The piezo excitation parameters have been identified, and finally the piezo automation has been activated. The RF closed loop feedback operation has been adjusted using 8/9pi mode notch filters at a corner frequency of 830 kHz and a bandwidth of 40 kHz. The performance of the RF and piezo controllers has been measured and compared to the E-XFEL requirements as shown in Figures 5 and 6.

CONCLUSION

During the SP mode of operation, the RF feedback supported by the piezo AFF controller has been used to obtain the amplitude and phase stabilization (dA/A~0.014% and dP~0.011 degrees), which meets the E-XFEL requirements. The active LFD compensation was run for several hours, and measured DD and SD were both less than 2 Hz RMS. For the CW/LP experiment, the RF feedback controller has been supported by the ANC filter acting on the piezo. The ANC was suppressing the dominant frequency of the microphonics noise (49 Hz) by a factor greater than 3. The peak performance stabilization of the accelerating field was: dA/A~0.014% amplitude and dP~0.019 degrees phase.

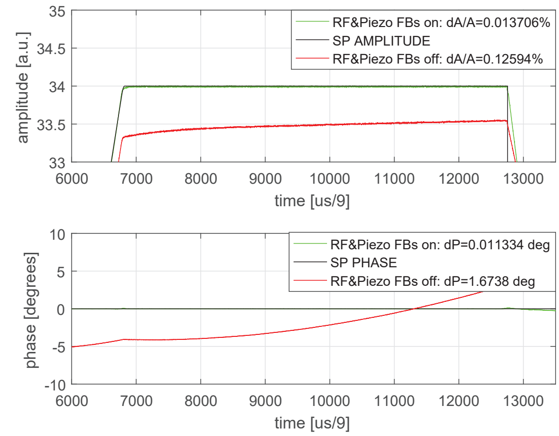

Figure 5: The RF feedback and piezo AFF controllers activated for cavity 1 at the CMTB during the SP experiment.

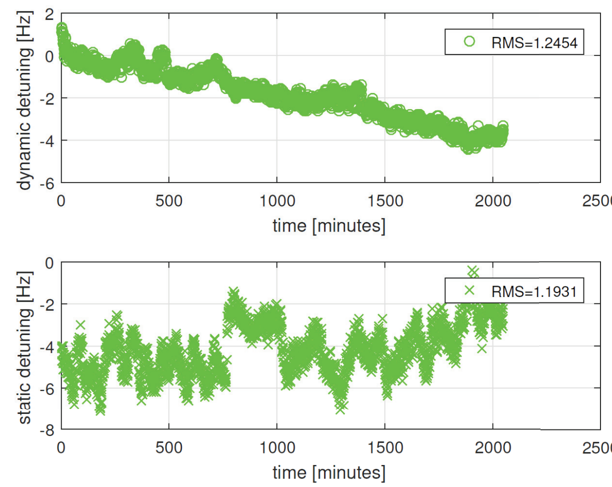

Figure 6: The long term measurements of the AFF piezo controller.

ACKNOWLEDGEMENT

We would like to express our gratitude to Colleagues from the MSK LLRF team and other groups at DESY. Special thanks are also addressed to T. Kozak, M. Hierholzer, L. Butkowski, W. Cichalewski, J. Branlard, D. Kostin, W. Merz, R. Onken because without their everyday support the presented results would never be possible to achieve.

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