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PIEZO CONTROLS FOR THE EUROPEAN XFEL

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Abstract

The European X-Ray Free Electron Laser (E-XFEL) accelerator is a pulse machine. The typical time duration of a radio frequency (RF) pulse is about 1.3 ms. The RF power transmitted to the superconducting RF (SCRF) cavity as a set of successive pulses (10 Hz repetition rate), causes strong mechanical stresses inside the cavity. The mechanical deformations of the RF cavity are typically caused by the Lorentz force detuning (LFD). The cavity can be tuned to 1.3 GHz resonance frequency during the RF pulse using the fast piezo tuners. Since the E-XFEL will use around 800 cavities (each cavity with double piezos), a distributed architecture with multi-channel digital and analog control circuits seems to be essential. The most sought-after issue is high-voltage, high-current piezo driving circuit. The driving electronics should allow a maximum piezo protection against any kind of failure. The careful automation of the piezo tuners control and its demonstration for the high gradient conditions is also a real challenge. The first demonstration of the piezo controls applied for chosen RF stations of the E-XFEL linear accelerator (linac) are presented and obtained results are briefly discussed within this paper.

INTRODUCTION

The 1.3 GHz SCRF cavities of E-XFEL linac are typically operated in a short pulse (SP) mode. In SP mode a duration of a single RF-pulse is about 1300 μs repeated typically ten times per second. Due to the fact the full width at half maximum (FWHM) bandwidth of a cavity resonator in such mode (E_{acc}~23.6 MV/m; Q_L~4.6·10^6) is 283 Hz, the leading source of the RF field disturbance is the 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 piezo tuner of each cavity is equipped with redundant piezo element. The one piezo can be used as an actuator while the second one as a mechanical vibrations sensor. The E-XFEL linac is composed of 25 RF stations. The each RF station is driven by its own high power RF source (10 MW klystron). The single RF station consists of 32 cavities controlled by vector sum based low-level RF (LLRF) controller [1]. The first 16 cavities are sensed by the master controller. The next 16 cavities are probed by the slave system. The partial vector sum of both systems is summed and the final drive is generated. In addition, each of the master and slave system is calculating detuning from 32 cavities. The detuning information is used to control resonance frequency of each cavity individually. As a result the piezo controls must provide a reliable high voltage, high current drive for 800 piezo elements in total. In order to fulfill this requirement a 16-channel piezo driver module (PZ16M) has been delivered.

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PIEZO CONTROL SYSTEM OVERVIEW

The piezo control system for the E-XFEL consists of PZ16M module. It is 16-channel, 19 inch unit supporting driving and sensing up to 16 piezo actuators and sensors simultaneously (see Fig. 1). The PZ16M communicates with

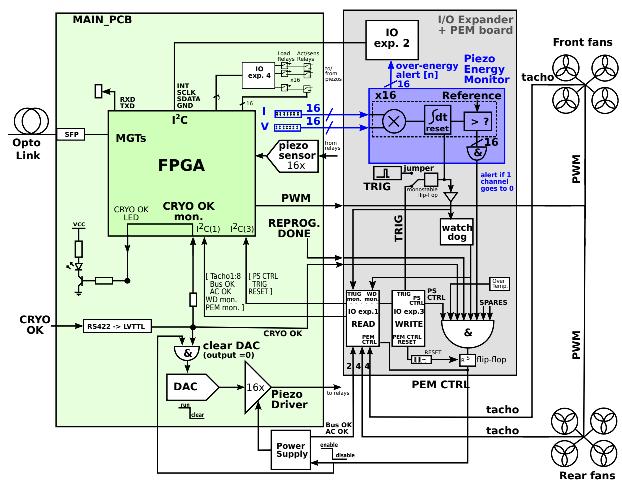

Figure 1: The block diagram of PZ16M module.

outside world using optical link connectivity. The piezo driver module has been equipped with piezo energy monitor (PEM) unit in order to protect piezos against failure [2]. The idea of the circuitry is to generate alarm if piezo energy safety threshold is reached. In addition, the PEM has been equipped with external over-current protection to avoid damage of the power electronics. The piezo driver outputs are disconnected from the load by default using a set of relay switches. In addition, the lifetime of each piezo element is extended by use of an actuator and a sensor relay switches. The heat dissipation of PZ16M is supported by a dedicated cooling system composed. The top FANs are used to dissipate heat from the power amplifiers matrix. The bottom FANs are provided to dissipate heat from integrated power supply units. The high voltage power supply unit of 170 V_{pp} is controllable by PEM logic. The PEM is switching off the high voltage supply unit when any kind of alarm is triggered. The PZ16M device after power cycle cannot drive piezos. The high voltage power supply is off by default. The normal operation of the module is only possible when all alarms and an external input from cryogenic plant (CRYOK) are inactive.

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CONTROL ALGORITHM

The piezo control algorithm has been developed to compensate for the cavity detuning. The cavity detuning consists of static and dynamic parts as shown in Fig. 2. The static detuning (SD) part is controllable mainly by DC bias voltage applied to the piezo element. It also slightly depends on the piezo excitation phase. The dynamic detuning (DD) is composed of linear detuning (LD) and curvature detuning (CD) parts. The DD is coupled with AC amplitude and phase of the piezo compensation pulse (PCP). The AC amplitude parameter mainly acts on LD while the phase compensate mostly for the CD.

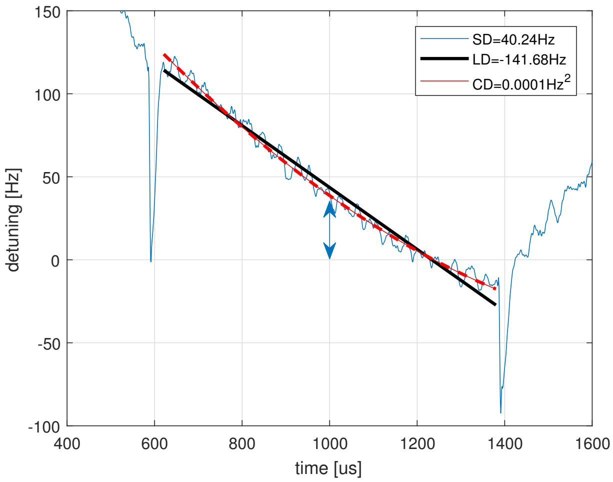

Figure 2: The cavity detuning and its sub-components overview. The 600 us peak is the point of the RF feed-forward power change (start of the flat-top region when the beam is accelerated). The 800 us peak is the end of RF power. The SD is defined as a detuning at the center of the flat-top signal. The LD is measured from the maximum (+110 Hz) to a minimum (-25 Hz) deviation during the flat-top. The CD is showing how many degrees the flat-top detuning is curved.

Piezo Controller Calibration

The piezo controller calibration is performed with two stages. In the first stage the cavity response to the RF pulse (without PCP applied) is measured using piezo element operated as a cavity mechanical vibrations sensor. The set of successive RF pulses is recorded, averaged and analyzed in a frequency domain. The dominant beat frequency is searched in the obtained spectrum and used to setup the piezo excitation period. In the second stage a small piezo excitation of specified frequency and a small AC amplitude (10 percent of a full dynamic range) is generated and its phase is scanned in an iterative way. The LD response is recorded for each iteration step. The obtained nonlinear function is analyzed and searched for the minimum. Finally, the piezo excitation phase is scanned again with CD taken into account. As a result of the calibration, the PCP is precisely set in time advance to the RF pulse and perfectly matched to the dominant frequency of the system dynamics as shown in Fig. 3.

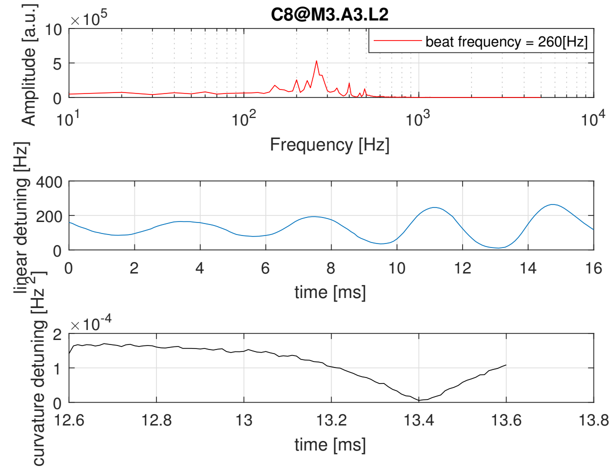

Figure 3: The piezo compensation pulse calibration stages. The top curve shows Fast Fourier Transform (FFT) of the RF field to cavity response recorded using piezo sensor. The middle curve shows LD versus the piezo excitation pulse time scan in advance to the RF pulse duration (located at 16 ms). The bottom curve shows CD versus the piezo excitation pulse time scan for the found minimum of the previous scan with a total range of 1 ms.

Piezo Adaptive Feedforward Operation

The piezo adaptive feedforward operation consists of two least means square (LMS) optimizations. The LMS of LD is trying to optimize AC amplitude of the PCP. The LMS of SD is optimizing piezo DC bias voltage. The controllers are acting on piezos till a threshold of 10 Hz for both LD and SD is reached [3]. The gain of both filters can be adjusted with a value mainly to regulate the speed of an adaptation. The sign of each filter gain can differ from cavity to cavity and from module to module and strongly depends on the phase relation of the PCP to the start of the RF pulse. The example tuning process is depicted in Fig. 4.

PIEZO CONTROLS COMMISSIONING

The first pre-series of piezo controls have been installed for the following E-XFEL linac sections: C[1..8].M[1..4].A[3,4].L2 and C[1..8].M[1..4].A21.L3. The each installed PZ16M unit has been first checked for the cabling correctness using an automated script. The idea was to apply small DC bias voltage for each cavity (C[1..8]) and build a cavity SD matrix response over an accelerating module (M[1..4]). The example cable check report is shown in Table 1.

As a next step a single RF station has been setup with LLRF feedback controllers to a demand SP of 21 MV/m per cavity and the piezo compensation system has been activated

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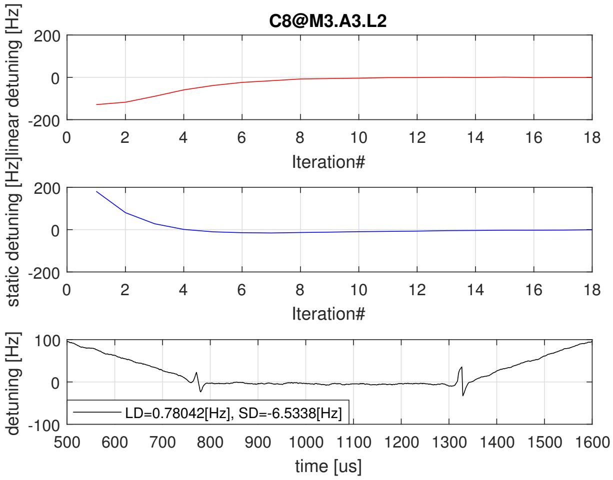

Figure 4: The linear and static detuning correction for chosen E-XFEL cavity operated at 21 MV/m.

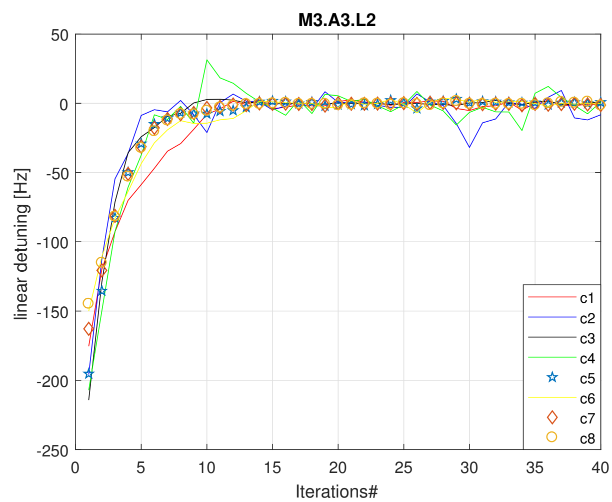

Figure 5: The linear detuning correction applied for a single accelerating module composed of 8 SCRF cavities (c[1..8]).

Table 1: The static detuning in Hz response matrix generated for cavities (c[1..8]) at M2.A3.L2 section of E-XFEL. The A means aggressor (the piezo driver channel) and V means victim (cavity static detuning response to this excitation). The response matrix shows that PZ16M channel 1 (ch1) acting on cavity 5 (c5), ch2 on c6, ch3 on c7 (weak coupling or cable problem) and ch4 on c8, ch5 on c1, ch6 on c2, ch7 on c3 and ch8 on c4. It means a cable trace of c[1..4] is swapped with a cable trace of c[5..8].

A/V	c1	c2	c3	c4	c5	c6	c7	c8
ch1	50.2	78.7	68.0	31.9	236.9	37.9	7.6	40.5
ch2	51.8	79.9	66.3	29.5	45.2	231.1	8.4	36.2
ch3	51.6	80.4	74.9	35.2	46.1	41.8	170.3	39.9
ch4	50.3	80.5	72.4	36.0	48.0	42.4	7.8	225.1
ch5	223.5	78.5	72.6	31.6	45.9	42.9	9.4	41.1
ch6	52.9	249.9	68.1	32.1	43.2	40.4	8.6	39.5
ch7	51.0	78.0	257.3	33.4	44.7	41.6	9.7	38.7
ch8	52.1	85.0	71.2	213.5	47.7	39.4	12.0	40.3

for all 32 cavities simultaneously. The active piezo compensation (APC) for a single accelerating module is presented in Fig. 5. For the proof of concept the RF signals (cavity voltage, forward and reflected power) without and with APC have been recorded and shown in Fig. 6.

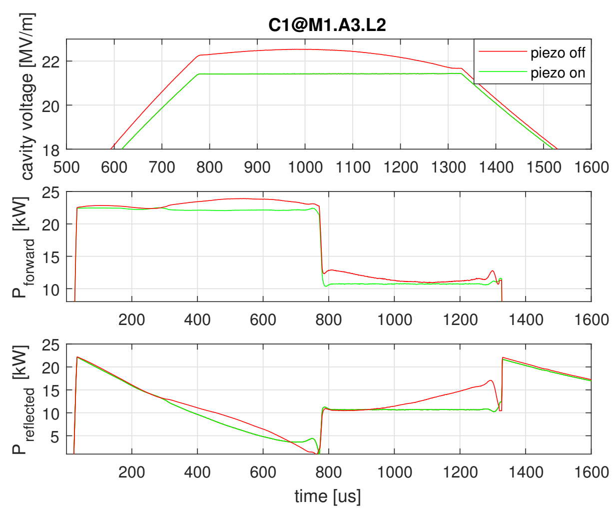

Figure 6: The RF signals analyzes with and without active piezo compensation pulse applied.

DISCUSSION AND FUTURE PLANS

The E-XFEL linac has been initially equipped with 6 pre-series of PZ16M. During commissioning stage a total of 2 cabling mistakes have been figured out and corrected during maintenance day. A total of 96 cavities have been tuned from initial detuning of around 200 Hz down to several Hz. The piezo control system allows minimizing the high power RF drive effort especially for the start of the RF pulse. The significant reflected power reduction has been also noticed at the end of the RF pulse. The system has been operated for several weeks without any piezo failure or driving electronics damage. Currently, we are in a stage of finishing the E-XFEL linac installation composed of 50 of PZ16M modules. The regular E-XFEL machine operation with piezos is scheduled for the second half of the 2019.

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