PIEZO CONTROL FOR LORENTZ FORCE DETUNED SC CAVITIES OF DESY FLASH*

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Abstract

Free-Electron LASer in Hamburg (FLASH) accelerator is dedicated for various high energy physics experiments. The superconducting (SC) cavities, the main parts of RF linac, are Lorentz force detuned when operated in pulse mode with high accelerating field gradients. The cavities of FLASH linac have been equipped with piezo tuners allow compensating of dynamic detuning during the RF pulse. In order to assure the simultaneous control of all available piezo tuners a distributed, multi-channel digital and analog piezo control system was designed. The paper describes the main parts of the system as well as its efficiency measurements obtained during high current, high gradient beam acceleration (9 mA) performed in Deutsches Electronen SYnchrotron (DESY).

FLASH FACILITY

The FLASH facility is comprised of main RF linac, undulator magnet sections as well as FEL diagnostics, as seen in Fig. 1. The RF gun is a photo injector, where

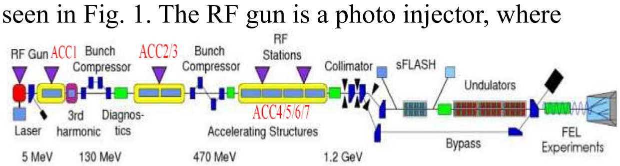

Figure 1: The block diagram of DESY FLASH accelerator.

electrons are generated by means of the photo effect. Particles passed thru RF Gun, are further accelerated downstream the SC linac to the required energy of 1.2 GeV. In long undulator sections, due to interaction with the alternating magnetic field, the electrons are redistributed to so called micro-bunches which can radiate coherently as a brilliant stream of photons. The beam energy for desired Free-Electron Laser (FEL) operation is achievable using four RF stations: ACC1, ACC2/3, ACC4/5, ACC6/7. The single RF station is powered by 5 MW klystron. The klystron is capable of generating RF wave of frequency of 1.3 GHz. The typical RF pulse duration is 2 ms length and its repetition rate is of order of 10 Hz. The RF stations are composed of accelerating modules. The each accelerating module contains 8 superconducting resonant cavities. The SC cavities are pulsed operated with high accelerating field gradients up to 30 MV/m. During the pulse operation, the cavities are detuned from its main resonance frequency, mainly due to their narrow bandwidth of 300 Hz and high quality factor of order of $3 \cdot 10^6$ [1]. The corresponding accelerating modules: ACC1, ACC3, ACC5, ACC6, ACC7 have been equipped with fast frequency tuners based on piezo translators to compensate the Lorentz force detuning as well as minimize the RF control efforts. The double stack piezos have been installed for cryomodules: ACC1, ACC6 and ACC7. Since, the first piezo is operated as an actuator, the second piezo element can be used as a spare part or a cavity mechanical vibrations sensor.

PIEZO CONTROL IN FLASH

The distributed, multi-channel analog and digital control system for fast frequency tuners was designed to meet piezo tuners configuration in FLASH. The piezo control system is divided into digital and analog parts. The digital part of the system consists of Sparc CPU machine, LLRF control board (SimconDSP), DAC/ADC board (Piezo Control Board) and LLRF timing board. The Sparc CPU machine, LLRF control board and timing board are placed inside VME crate. The Sparc CPU machine communicates with other industrial computers using Ethernet interface. The data transfers are performed using a dedicated client-server application – Distributed Object Oriented Control System (DOOCS) of FLASH [2]. The LLRF control board with powerful FPGA device of Virtex II Pro from Xilinx communicates with Sparc computer using VME interface. The FPGA device is used for driving vector modulator of RF klystron as well as sensing raw data from probes located close to the each cavity. The raw data is converted to intermediate frequency of 250 kHz using a dedicated mixers and RF down-converters. Furthermore, the SimconDSP board communicates with Piezo Control Board using fast serial interface (RocketIO) and optical links. The optical link connection was chosen in order to make the communication interfaces robustness to the hardness radiation environment as well as to eliminate the negative impact of the cables length. The timing board is connected to the triggering event of RF pulse and it is used for interrupts generation on the VME bus.

The analog part of the system is composed of 8-channel piezo driver unit with dedicated power amplifiers PB51 from Cirrus Logic [3]. The PB51 amplifiers are used to drive the piezo actuators with high voltage signals of order of ±100 V. In order to protect the piezo actuators, the piezo drivers are powered using external power supply unit of 200 W from Vicor. Additionally, the overvoltage and overcurrent protection circuits have been included inside piezo driver box.

The DAC/ADC board is operated as a bridge between analog and digital parts of the piezo control system. The Piezo Control Board and 8-channel piezo driver units are connected using backplane and they are located inside

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single Euro crate. The piezo sensors are connected to DAC/ADC board using front panel connectors. The differential signals from piezos are initially conditioned using instrumentation amplifiers AD8222 from Analog Devices. The single-ended signals from conditioning circuits are connected to external multiplexer circuit and next sensed using successive approximation (SAR) ADC converter. The piezo driving circuit consists of a dedicated multi-channel DAC converter AD5373 from Analog Devices. In order to isolate the DAC outputs from power amplifiers inputs, the quad buffers have been added. The block diagram of the designed piezo control system is shown in Fig. 2. The control system is capable of simultaneous compensation of up to 64 cavities, but currently only 40 channels are actively used in FLASH.

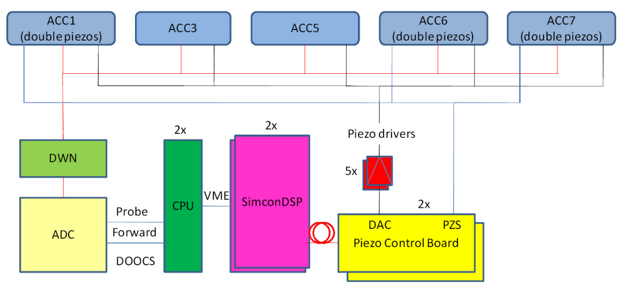

Figure 2: The block diagram of piezo control system in FLASH (the timing board is not presented).

Control Application

The control application was coded in C++ programming language. It is composed of two main applications integrated into DOOCS control framework. The first application is used for detuning computation (middle layer server). It takes data from monitoring ADCs using shared memory access (see Fig. 2). The raw data from ADCs are demodulated to I and Q components and further computed according to the Lorentz force detuning equation. The calibration of the coupler directivities is performed for cavity side of the coupler and it is used for forward and reflected power crosstalk elimination.

The second application is used for compensation pulse parameters computation (front-end server). The re-calculated new parameters of feedforward table as well as feedback table are sent/receive to/from the hardware using DMA transfers on the VME interface bus. The feedforward table is composed of sine like waveform of variable changed amplitude, frequency, number of pulses as well as time advance to the RF pulse. For the user defined shapes of the compensation signal, the custom table was added. The data transfers are synchronized to the RF pulse using interrupts generated by timing board. The piezo driving as well as the piezo sensing circuits are synchronized using the same timing events – the start of RF pulse for each accelerating module. For more sophisticated control schemes the both circuits can be easily applied in advance to the start of RF pulse.

PIEZO CONTROL EFFICIENCY MEASUREMENTS

The piezo control system was installed in FLASH facility to support 9 mA experiment performed in DESY in September 2009.

Table 1: RF Control Efforts with Piezo Compensation

cavity no.	forward power [kW]	accelerating field gradient [MV/m]	reflected power [kW]
	diff. [%]	diff. [%]	diff. [%]
1	-11.3%	+7.7%	-7.3%
2	-6.2%	+3.4%	-9.6%
3	-6.6%	+3.5%	-10.1%
4	-7.5%	+10.6%	-10.9%
5	-7.7%	+14.4%	-18.6%
6	-9%	+7%	-8.7%
7	-3.5%	+8.5%	-12.2
8	-4%	+6%	-8.6%
average	-7%	+7.6%	-10.8%

The compensation system was switched on and used to tune the corresponding cavities to desired resonance frequency of 1.3 GHz, which means the flattop detuning less than 10 Hz. The FLASH linac was operated with 1500 bunch trains of frequency of 3 MHz. The achieved beam current was close to 7.5 mA. The accelerating modules ACC2/3 and ACC4/5/6 were operated with 5 Hz repetition rate of RF pulse. The forward power of ACC2/3 and ACC4/5/6 klystrons was measured to be closed to 309 kW and 426 kW, respectively. The cavity voltage as well as forward and reflected power were measured first without and next with compensation system, after the piezo feedforward control tables setup. It is clearly visible that RF control efforts for single accelerating module can be reduced by 10% when Lorentz force detuning is compensated from 200 Hz up to less than 10 Hz (see Tab. 1 and Fig. 5 right). The Lorentz force detuning compensation is also visible in the piezo sensor readout made for cavity 2 in ACC6, (see Fig. 5 right). The mechanical vibrations induced by RF pulse (red) are actively attenuated using piezo compensation pulse (green).

The RF linac was upgraded with new accelerating modules: ACC1 and ACC7 equipped with double piezos after FLASH machine shutdown which was scheduled from Sept. 2009 up to March 2010. The LLRF control system was exchanged from DSP system to SimconDSP system. The RF pulse repetition rate was increased up to 10 Hz. Authors find out that the first piezo compensation pulse applied to actuator generates additional microphonics noise which is visible before the start of the next RF pulse, see Fig .3.

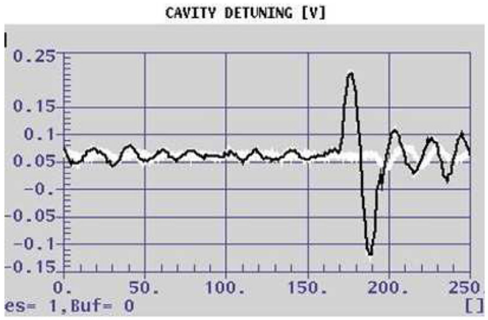

Figure 3: The piezo sensor readout with (black) and without (white) applied Lorentz force detuning compensation signal.

The second piezo pulse compensation method was applied for active attenuation of mechanical vibrations induced by the LFD compensation pulse. The optimal parameters of the second piezo pulse were discovered using standard deviation of measurement from the piezo sensor readout before RF pulse (first 100 samples) for different delay and amplitude scan. The obtained results are shown in Fig. 4.

CONCLUSIONS

The all available piezo tuners of FLASH facility are controllable using design piezo control system. The system efficiency was tested with high gradient, high current beam acceleration tests. The average RF control efforts has been reduced by 10% for tuned cavities. The novel approach for active attenuation of cavity mechanical vibrations induced by Lorentz force detuning compensation pulse was initially tested and improved using second compensation pulse method.

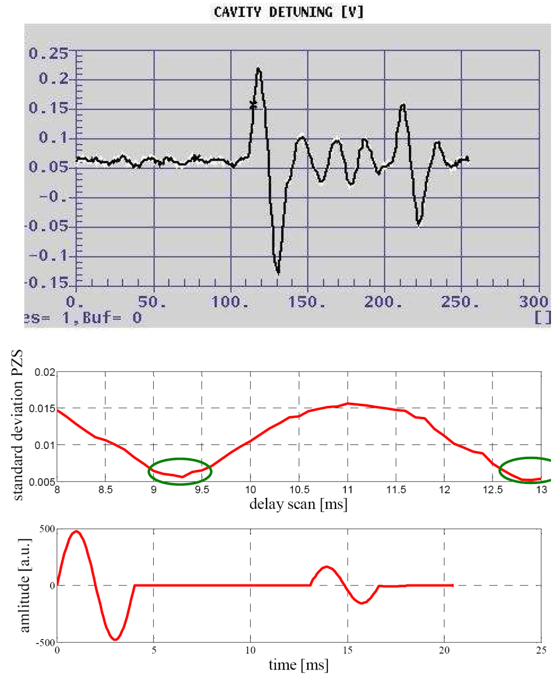

Figure 4: Piezo sensor readout with both compensation pulses (upper), standard deviation of measurement from the piezo sensor readout before RF pulse for different delay scan (middle) and the compensation signal shape (lower).

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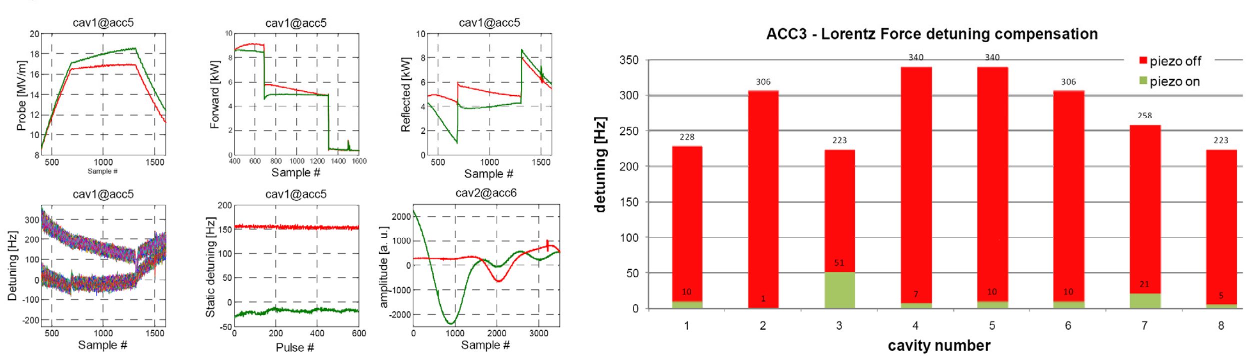

Figure 5: Example results of cavity parameters measurements with (green) and without (red) piezo compensation. On the left side, there is a accelerating field gradient, forward and reflected power, cavity detuning, static detuning and piezo sensor readout. On the right side, there is a detuning histogram for ACC3 cryomodule.