SC Cavities Fast Tuning System Based on Piezoelectric Actuators

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ABSTRACT

Free Electron Laser in Hamburg (FLASH) accelerator is composed of 40 superconducting (SC) cavities equipped with both single and double piezoelectric actuators. The piezo tuners are used to tune the cavity to its main operating frequency. Dedicated multichannel analog and digital control system has been designed, fabricated and connected to all accessible piezo tuners to meet such a large scale machine configuration [1]. The fast tuning system has been used to support high gradient, high current beam acceleration experiment (9 mA tests) carried out in Deutsches Elektronen Synchrotron (DESY). During the studies the DC and AC modes of piezoelectric actuators control have been applied and preliminary tested.

Keywords: Free Electron Laser, superconducting cavity, piezo tuner, control system

1 INTRODUCTION

The FLASH accelerator is operated in pulse mode with repetition rate up to 10 Hz. The typical time duration of a radio frequency (RF) pulse is about 2 ms. The electromagnetic wave, transmitted to the cavity as a set of successive pulses, causes strong mechanical stresses inside the cavity. The mechanical deformations of thin cavity walls are typically caused by repulsive magnetic forces as well as attractive electric forces, mainly due to the Lorentz forces. The Lorentz force detuning (LFD) is RF field gradient depended and can be sufficient especially for high gradient operation that reach or even exceed the nominal operating conditions foreseen for single SC cavity (~25 MV/m) [2]. The detuned cavity reflects more input power, and as a result, it needs more RF power to achieve a desired operation conditions. The cavity can be tuned to a resonance frequency of 1.3 GHz using slow tuners (based on stepper motors) and fast tuners (based on piezoelectric elements).

2 FREQUENCY TUNERS

The cavity resonance frequency should be kept close to the resonance range as long as possible, especially at the time when the electron beam is accelerated (flattop region). To achieve this goal, the special mechatronic devices, frequency tuners, are applied [3]. The usual tuning method for superconducting cavities is to change the cell length by adjusting mechanically the overall length of the cavity. Since all the cavity cells are very similar mechanically, each cell changes by the same amount that means the overall field profile is not affected. A consideration with respect to the extent of the tuning range is the elastic limit of niobium material. Keeping the elastic limit gives a tuning range of several hundred kHz.

TTF[1] tuner (Saclay I and II model) is accomplished by a mechanical device that modifies the cavity length driven by a stepper motor unit (see Fig. 1 right). The leverage system is designed in order to reduce stresses on the stepper motor and to enhance enough sensitivity. The stepper motor drives a copper-beryllium alloy (CuBe) screw through an harmonic drive gear box what leads to final sensitivity below 1 Hz per step and to total static tuning range above 500 kHz. The stepper motor tuners are commonly used for pre-detuning process what means cavity tuning in steady-state conditions. Since, the step motor tuners are too slow to counteract the cavity deformation caused by 2 ms RF pulse, the fast frequency tuners based on piezo translators have been added. The piezoelectric actuators have been chosen in order to provide a nanometer resolution, high dynamic operation (several kHz), high forces (100 N) and high reliability [4], especially for operation in the radiation environment. The piezo integration of the TTF tuner has been obtained avoiding a complete redesign of the mechanical assembly itself. The mechanical part of TTF tuner, has been equipped with a compact titanium frame with 2 piezo parallel stacks – Saclay II tuner (see Fig. 1 left).

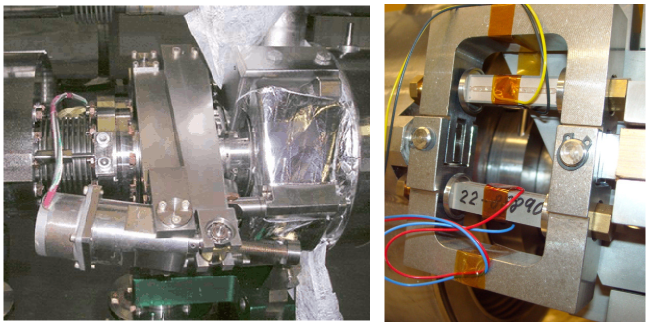

Figure 1: TTF tuner (left) equipped with 2 piezo elements (right).

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[1] TTF – Tera-eV Superconducting Linear Accelerator (TESLA) Test Facility

This double stack configuration allows for keeping a spare actuator as redundant. If no replacement is needed, it can be used as a sensor of cavity mechanical vibrations [5].
The piezo tuners require special control system able to drive capacity of piezo (of order of few microfarads) with high curent and voltage pulses (up to 1 A and 100 V). The parameters of the compensating pulse must be calculated for each cavity separately basing on the cavity detuning during RF field pulse [6].

3 CAVITY DETUNING

Measuring the Lorentz force detuning is the most important part for the fast frequency tuners control. LFD is used for estimating the cavity response to the applied drive. The SC cavity detuning can be measured by various methods. Since the modern control systems are generally based on DSP or FPGA devices, the digital computation of cavity detuning is strongly recommended [7]. The principle of digital detuning computation is to measure the cavity input and output RF signals. The cavity detuning equation can be derived using equivalent circuit model described in [8]. The SC cavity can be modeled using LCR circuit. The input coupler is used for feeding a cavity with RF power. The coupling from the klystron output of the transmission line and from the transmission line to the cavity side is represented by the lossless transformer. The study of cavity behavior is possible when the circuit model is transferred to the cavity side of the directional coupler as shown in Fig. 2.

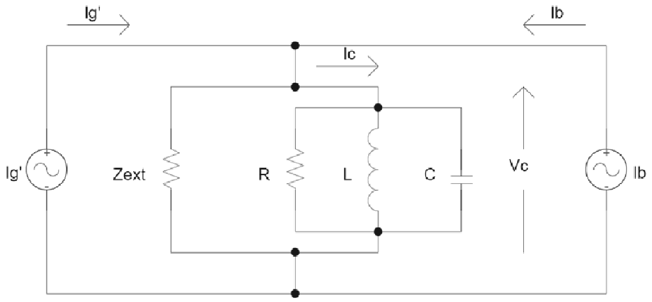


Figure 2: The circuit model of the RF system converted to the cavity side using the ideal transformer equations.

Using this circuit topology, the following differential equation can be derived [9]

$$\frac{d^2V_c}{dt^2}+\frac{1}{R_LC}\cdot\frac{dV_c}{dt}+\frac{1}{LC}\cdot V_c=\frac{1}{C}\frac{dI_c}{dt} \quad (1)$$

where R_L, Z_{ext}, V_c and I_c mean loaded shunt impedance, external load impedance, cavity voltage and cavity current, respectively. When studying the cavity behavior with klystron power and beam current, small terms in second order derivatives as well as carrier frequency term of (1) may be neglected and the cavity baseband equation can be derived as [10]

$$\frac{dV_c}{dt}+(\omega_{1/2}-j\Delta\omega)\cdot V_c=2\omega_{1/2}\cdot V_{for} \quad (2)$$

where $\Delta\omega$ means the cavity detuning paremeter. The above equation is true only for the steady-state conditions. When accelerator is operated with high gradient, high current electron bunch, the beam induced voltage needs to be added to formula (2). The Lorentz force detuning parameter computed using the cavity baseband equation is depicted in Fig. 3.

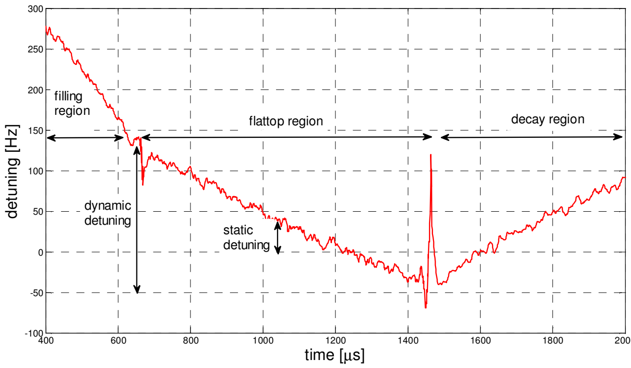


Figure 3: Lorentz force detuning measurement.

The detuning curve can be divided into three time slots. During the first 600 µs the cavity is filled in with expotentionally arising power from the klystron (filling region). The next 800 µs corresponds to the constant level of the power delivered from RF generator (flattio region). During the last 600 µs the RF gate is closed and there is no power from the RF generator (decay region). The static and dynamic detuning paremeters are the main input signals to the digital control system that is used to tune the cavity to the resonance frequency.

4 PIEZO CONTROL

The current control system can be operated in DC and AC modes. The DC operation mode of piezo control is used to compensate the cavity static detuning that means the offset of the cavity detuning curve from 0 Hz on the vertical axis, see Fig. 3. The DC operation corresponds to the constant voltage pedestal directly applied to the piezoelectric actuator between two consecutive RF field pulses. The example transfer function of DC voltage scan versus static detuning change for chosen cavity is depicted in Fig. 4.

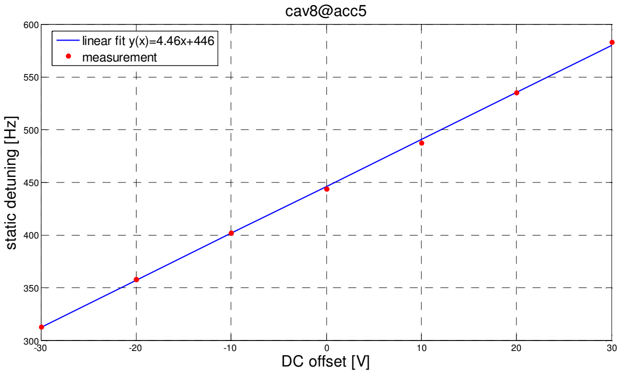


Figure 4: The linear fit of DC offset voltage scan versus static detuning parameter.

The AC operation mode is applied to compensate the cavity dynamic detuning. The dynamic detuning is measured for the flattop region (the region when the beam is accelerated) see Fig. 3. This region can be approximated with good agreement using linear function fit. The compensation effect is achieved by means of the slope correction of the considered linear function as it is presented in Fig. 5.

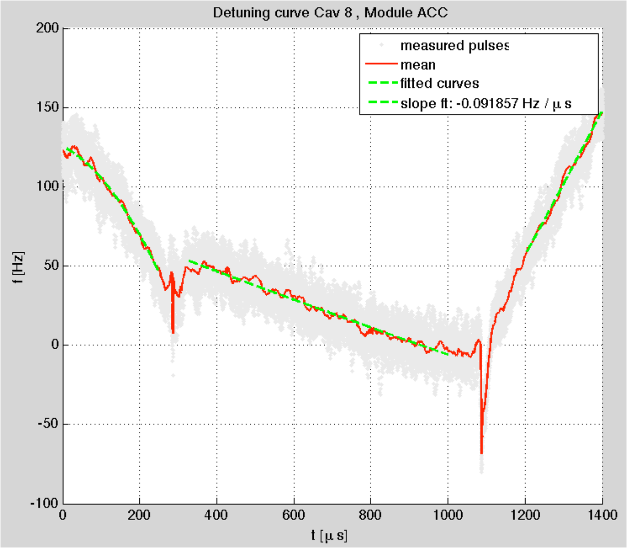


Figure 5: The dynamic detuning measurements with and without AC correction.

The both control modes have been applied to support the high energy physics experiments carried out at DESY FLASH accelerator.

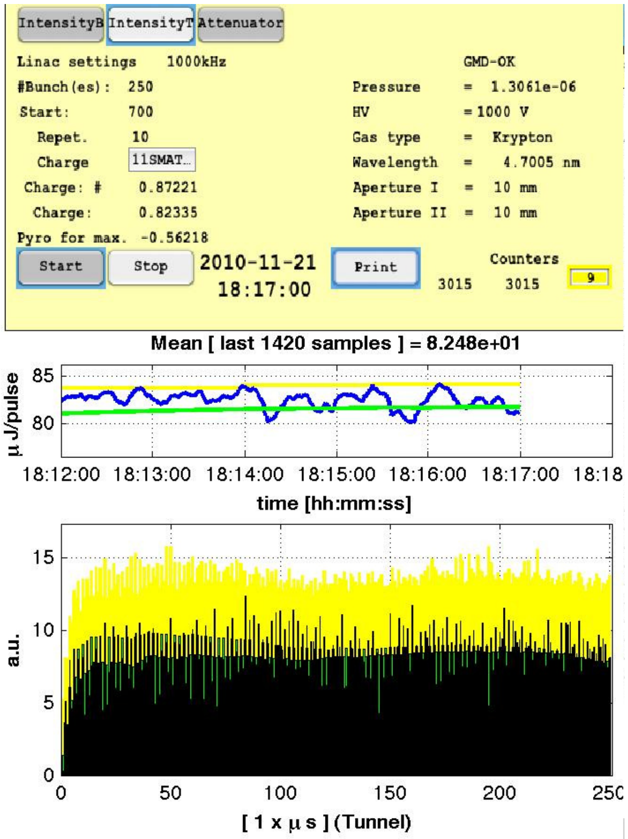
5 EXPERIMENTS

The control system of fast frequency tuners has been used during 9 mA experiment to support the Self-Amplified Spontanouse Emission (SASE) tuning. Since the total beam energy delivered from the accelerating modules was enough for the tests, the module ACC1 has been baypassed from LFD compensation. The modules ACC3 and ACC5 have been operated only in DC mode and ACC6 and ACC7 with both AC and DC modes of piezo control. The tuning setup for ACC7 is summerized in Tab. 1.

ACC7 module	DC Voltage [V]	AC Voltage [V]	Delay [ms]
cav1	30.5	-30.0	19.0
cav2	10.3	-21.0	19.9
cav3	3.00	-27.0	19.5
cav4	-13.7	-27.0	19.7
cav5	-11.2	-26.0	19.7
cav6	3.6	-28.0	19.4
cav7	-25.8	-20.0	19.7
cav8	-40.8	-19.0	19.7

Table 1: Piezo tuners setup for ACC7 module during the experiment.

During the FLASH studies, accelerator has been operated with high gradient (more than 30 MV/m), high current (beam trains of 250 bunches each one repeated with frequency of 1000 kHz) conditions. The main goal for such an operation was to achieve the desired beam energy as seen in Fig. 6.



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Linac settings    1000kHz                                 GMD-OK
#Bunch(es):   250                    Pressure       =  1.3061e-06
Start:        700                    HV             = 1000 V
  Repet.       10                    Gas type       =  Krypton
  Charge                             Wavelength     =   4.7005 nm
 Charge: #     0.87221               Aperture I     =  10 mm
  Charge:      0.82335               Aperture II    =  10 mm
Pyro for max.  -0.56218
                2010-11-21                          Counters
                 18:17:00                    3015    3015      9
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Figure 6: Beam energy monitor during SASE experiment.

The SASE tuning studies have been run simultanously with piezo tuners control. The control signal has been automatically adjusted using the proportional gain control scheme. The setup of gain parameter for each cavity has been searched experimentally. The LFD compensation for accelerating module ACC7 is shown in Fig. 7.

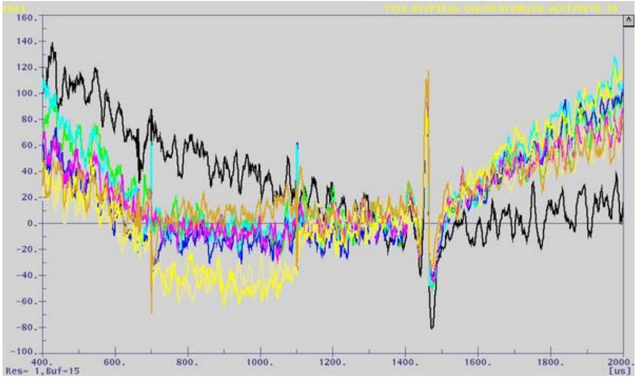

Figure 6: Lorentz force detuning for cav[1..8]@acc7. Cavity 1 is not compensated due to unexpected failure of piezo no. 1 (due to unkown reasons).

6 SUMMARY AND CONCLUSIONS

The LFD compensation system has been successfully demonstrated with SASE tuning during 9 mA tests. The static and dynamic detuning has been reduced from hundred up to single Hz for the chosen cavities. The DC and AC piezo control modes have been preliminary tested and valided with total voltage applied to piezo tuner less than 70 V. The usage of DC voltage allows reducing the AC voltage and as a result decreasing the mechanical vibrations transferred to the system by piezo compensation itself [11]. During the experiment the stable beam energy of order of more than 80 μJ has been achieved. This energy spread allows generating the long light pulses of less than 5 nm wavelength that corresponds to the soft X-ray range of FLASH machine operation.

7 ACKNOVLEDGMENTS

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