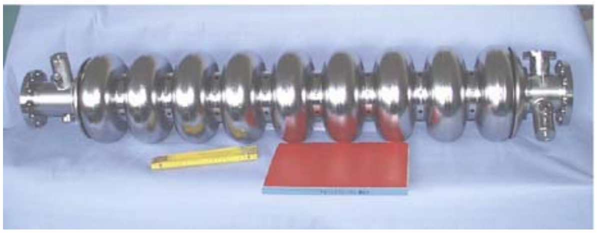
EU contract number RII3-CT-2003-506395 CARE-Conf-06-080-SRF

SRF



Electromechanical System for Lorentz Force Compensation

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Abstract

The cavity is the main element of each linear accelerator used for high-energy physics purpose. The resonant frequency of cavities depends on its shape. Due to the pulse operation they are deformed by dynamic Lorentz force caused by accelerating eletromechanical field. The paper will describe the recent developments of tuning system dedicated for cavity shape compensation. The system base of multilayer piezoelectric stacks. The active elements will work at temperature of 2K, high vacuum and irradiated environment. Hitherto, the performed experiments shows that the actuators might successfully work in such a demanding surrounds for requested lifetime of 10^{10} cycles. The presented detuning system is not only strongly desirable but also mandatory when the superconducting cavities will be operated with accelerating field gradient above 25MV/m. The experiments of the system are done in linear accelerator VUV-FEL which is founded at DESY-Hamburg, Germany. The results of work will be used also fort next generation of superconducting linear colliders as X-FEL and ILC.

Contribution to the NSTI Nanotech, Boston (USA)

Work supported by the European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area” programme (CARE, contract number RII3-CT-2003-506395)

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ABSTRACT

The cavity is the main element of each linear accelerator used for high-energy physics purpose. The resonant frequency of cavities depends on its shape. Due to the pulse operation they are deformed by dynamic Lorentz force caused by accelerating electromechanical field. The paper will describe the recent developments of tuning system dedicated for cavity shape compensation. The system base on multilayer piezoelectric stacks. The active elements will work at temperature of 2K, high vacuum and irradiated environment. Hitherto, the performed experiments shows that the actuators might successfully work in such a demanding surrounds for requested lifetime of 10^{10} cycles. The presented detuning system is not only strongly desirable but also mandatory when the superconducting cavities will be operated with accelerating field gradient above 25MV/m. The experiments of the system are done in linear accelerator VUV FEL which is founded at DESY-Hamburg, Germany. The results of work will be used also for next generation of superconducting linear colliders as X-FEL and ILC.

Keywords: piezoelectric stack, cryogenic, Lorentz force, tuning system

1 INTRODUCTION

The superconducting (SC) technology is a promising alternative for the next generation of linear accelerators like the VUV-FEL (Vacuum Ultra Violet Free Electron Laser) under construction at DESY, the European X-FEL (X-Ray Free Electron Laser) in the approval phase or the planed ILC (International Linear Collider) [1]. All these machines bases on TESLA shape, niobium cavities, which are operated in pulse mode. The width of RF pulse is 800µs, whereas the rise time is 500µs. The resonance frequency is fixed to 1.3GHz.

To reduce RF power losses the operating frequency must precisely match the resonance frequency of the cavity [2]. The distance end to end of nine-cell over-1m-long cavity must be controlled in range of sub-micrometers. From performed measurements, one can conclude that 1µm cavity length change causes 300Hz of detuning, whereas the bandwidth of the cavity is "only" 230Hz. As a consequence a high precision positioning system is needed [3].

The main source of distortion is Lorentz force (LF). During pulsed operation the cavity is reloaded with frequency of 1.3GHz. The current, which flows through cavity walls, interacts with electromagnetic field inside cavity. The mechanical force causes the cavity shape change and simultaneously it shifts the resonant frequency. The LF detuning depends on accelerating field gradient ($\Delta f_{static} \sim E_{acc}^2$) and might be equal even 1000Hz or above (if field gradient is 30MV/m and higher see Figure 1). The LF distortion is very repetitive and periodic.

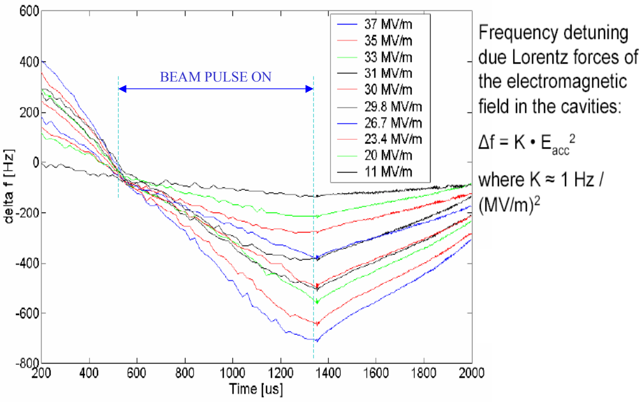

Figure 1. Lorentz Force Detuning measured in VUV-FEL cavities for different accelerating field gradients

The active elements of electromechanical system might be attached to the cavity directly (i.e. VUV-FEL), inside the cryomodule or might be fixed outside it (i.e. CEBAF [4]). In first case, the authors' work on, the tuner will be operated in vacuum (10^{-5} mBar) and at cryogenic temperature (2K). Moreover, it is assumed that it will be exposed up to 2 MGy radiation dose during 10 years of operation [3]. At least, it will be closed inside the cryomodule therefore it should be reliable (no service is foreseen). It is very challenging issue, because each cavity needs to have its own tuner, which has to work for at least 10 years without breakdown (i.e. for 2 km accelerator used for X-FEL purpose around 2000 cavities will be used).

Such a demanding environment indicates that either a piezoelectric stack or magnetostrictive rod might be used as an active element for the cavity tuner. According to performed test [5], these elements might operate for more than 10^9 cycles, which is predicted for the case.

Preliminary test with piezostack-based compensation system were done before in CHECHIA test stand in DESY [6]. The paper presents the recent results obtained by authors in VUV-FEL system, which might be operated by end-user.

2 MAIN PURPOSES OF CAVITY TUNER

Beside the LF compensation the VUV-FEL cavity tuner should realize two other objectives. First of all, it should allow pre-tuning process, and then it ought to be able to compensate microphonics [6-10].

Pre-tuning is a necessary stage to reach the desired resonance frequency. The cavity with couplers is assembled at room temperature but need to operate at 2K. Between these two stages the cavity shape is deformed, what causes the resonance frequency to shift (by i.e. cooling down, cavity and isolation vacuum pumping). However, the master oscillator is set to a constant frequency (in case of TESLA cavities - 1.3 GHz). The reproducibility of the resonance frequency after installation and cooldown is in range of ±20kHz. It corresponds to several tens of micrometers change of the cavity length. Required tuner structure for this purpose (so-called 'slow tuner') might work unhurried but must be able to compensate deformation in this range. The pre-tuning phase is planed to be performed rather rarely, i.e. once a week or even month.

In opposite, so-called fast tuner should realize LF and microphonics compensation. The last deformation is caused by environment, i.e. helium pumps and flows or even human activity. Additionally, a crosstalk between nearby cavities and the one between next macro-pulse might appear. Detuning caused by this distortion is rather small and usually do not exceed 20Hz. However, it is fully stochastic, hence a feedback loop is required for the control system. The algorithm for microphonics compensation should work permanently, during RF pulse and between them. The microphonics is mostly an issue for low current machines like X FEL, but might be omitted for ILC one. Moreover, microphonics causes a higher phase error rather than amplitude one, which is reasonably small.

At the end there is need to mention that resonance bandwidth of the cavity is extremely narrow comparing to resonance frequency, and it is around 230Hz (slightly varies from cavity to cavity). Thus, for VUV-FEL, the system for pre-tuning is mandatory, Lorentz force compensation is strongly required and cancellation of microphonics is advisable.

3 ACTIVE ELEMENTS

The main parts of VUV-FEL fast tuner are elements made of smart materials. Two types of actuators are investigated nowadays: magnetostrictive rods and piezoelectric stacks. First of them are driven by magnetic field, the second by electric one. Magnetostrictive tuner investigation is not as well advanced as piezoelectric one, however it might be an interesting option for future design [13].

Currently for VUV-FEL purpose, the authors use three different multilayer piezostack from EPCOS (PZT Nd34), PI (P 888.90 PIC 255) and NOLIAC (PZT pz27) [14]. All actuators are the low voltage elements, which may be powered only up to 150V (in contrary, for SNS purpose a high voltage piezos are used). The length of piezostack varies from 30mm (EPCOS, NOLIAC) to 36 mm (PI). The smallest cross-section has EPCOS piezostack (7x7mm). Two others are slightly bigger (10x10mm).

All active elements were tested in pumped liquid helium temperature (2 K) with success. All layers of elements are co-fired during production. Elimination of glue is necessary to avoid cracks caused by cooling down (different TCE of materials cause stresses).

From authors' experience, the active elements stroke at LHe environment is reduced by factor of 8 in comparison with room temperature test. A 4 μm stroke at 2 K might be achieved by piezostack, which at RT has maximum elongation at least 30 μm. All three groups of elements fulfil this requirement.

Another important feature of piezoelectric element is radiation hardness. A special set of experiment was performed with assistance of authors at CERI-Orlean in France to check the influence of neutron radiation on electrical and mechanical parameters of active elements. The element was cooled down to 4 K inside the small cryostat and then irradiated by Be neutron source (1-15 MeV). The total acquired dose is $1.76 \div 3.09\ 10^{14}$ n/cm². Only effects connected with heating caused by beam was observed during 20h of irradiation [15].

Moreover, the EPCOS piezostack proved that it is radiation tolerant. During its 2 years operation in ACC1 module of VUV-FEL no degradation of parameters were observed. However, it is hard to measure accumulated dose, because the piezostack cannot be removed from module and the machine was running with varying parameters.

In general, it is foreseen that active element has to work without breakdown for 10 years without any service, what stands for lifetime of 10^{10} cycles. The research performed at INFN Milan shows that PI piezostack after $1.5\ 10^{9}$ cycles has no significant degradation of mechanical (stroke) or electrical (capacitance, resonance frequency, hysteresis) parameters. However, it is important to notice that only one element was tested and it was cooled down only to 77 K [5].

One of the important issues, which have to be solved, is correct initial boundary condition for piezoelement. From manufacturers, one can find, that lifetime of such actuator strongly depends on preload force. If element is too strongly squeezed, then not only its elongation is decreased, but also additional mechanical stress causes faster degradation of material. Contrary, if element is free or almost relaxed then it is not controllable. The manufacturer recommendation for preload is usually 1/3 of blocking force [16], what stands for 1.2÷1.5 kN in case of elements used for VUV-FEL purpose.

One of challenges, which were solved, was the measurement of static force applied to piezoelement at 2K. The authors propose to use a self-developed method based on the investigation of resonance frequency shift on impedance curve. [16]

4 DEVELOPED CONTROL SYSTEM

Nowadays, only one cavity in VUV-FEL accelerator is equipped with both the slow and the fast tuners. Only one active element is hold by fixture. It is a relatively small piezostack of 7x7 mm cross-section and 30 mm length from EPCOS. However, the control system is built in such a way, that any other elements might be operated and also an option for two elements is foreseen (one will work as a sensor, the second as an actuator).

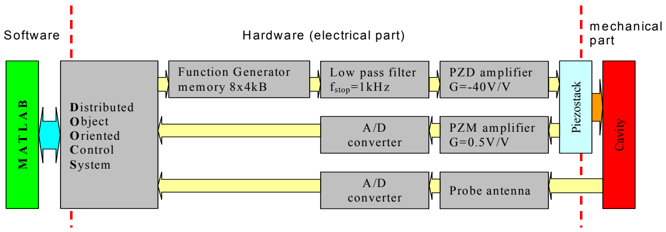

Figure 2. Control system for piezoelement assembled in tuner

Overview of control system is presented in figure 2. The voltage signal is formed in Function Generator (FG), which is driven using Distributed Object Oriented Control System servers (DOOCS) by MATLAB script. Then, given wave is transmitted by low pass filter, which smooth discrete steps of FG, to piezo driver (PZD) in which it is amplified with gain –40V/V. Afterwards, such prepared signal is applied to piezoelectric actuator.

It is possible to read feedback information from sensor by PZM amplifier, which adjusts the impedance of active element using MATLAB and DOOCS servers. It is also possible to get information about detuning change from RF field parameters change (forward and reflected power probes are used).

The second method has been implemented in MATLAB GUI presented in Figure 3. The top graph shows magnitude of reflected and forward power and probe signal. Just below a calculated detuning is presented. Two bottom figures illustrate a voltage signal at FG output and the one applied directly to piezostack.

The same panel, using given sliders, allows driving the piezoelement manually. However a feed-forward automatic algorithm was recently implemented. The actuator is driven using a sine-wave pulse. It frequency hits one of mechanical resonances of cavity. Hence, it allows building up a vibration and increasing the amplitude of oscillation caused by single piezoelement in one shot. It is important to correctly adjust the phase between the RF field and piezostack action. The wrong settings amplify detuning and might cause instability.

Presented method allows reducing voltage applied to piezoelement down to 40-50V. As a result, the actuator works far from its own limits, and therefore its lifetime will be extended.

5 EXPERIMENTAL RESULTS

The experimental results, showed in figure 3, were obtained in the cavity 5 in module ACC1 of the VUV-FEL accelerator. When the fast tuner is switched off, during the RF flat-top, the detuning is almost 180 Hz (for 20 MV/m field gradient inside cavity), which is a value comparable with cavity bandwidth. However, when the automatic feed-forward piezostack compensation system is activated, the change of frequency remains below 10 Hz (the offset of 50 Hz might be easily compensated by stepper motor system). Sudden decay of detuning, which is visible in the beginning of the flat-top is caused by the calculation method and has no physical justification.

The system was initially tested for different gradient from 8 to 20MV/m. The higher gradients are not accessible in current module. However, preliminary test performed by authors in CHECHIA test stand showed that using manual settings for resonance excitation there is possible to compensate LF for gradients up to 35MV/m [17].

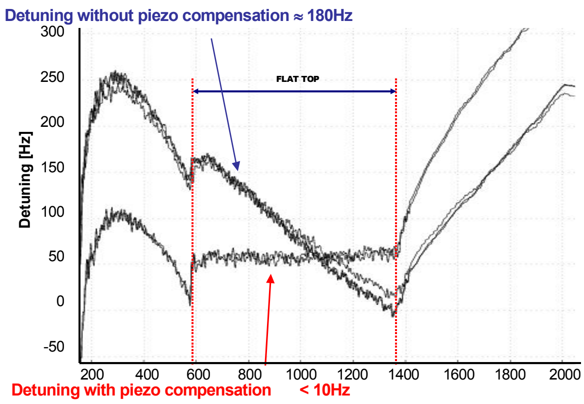

Figure 3. Detuning with and without piezostack based system. The accelerating field gradient is 20MV/m.

Such type of shape compensation allows saving up to 50 per cent of consumed RF power depending on accelerating field gradient.

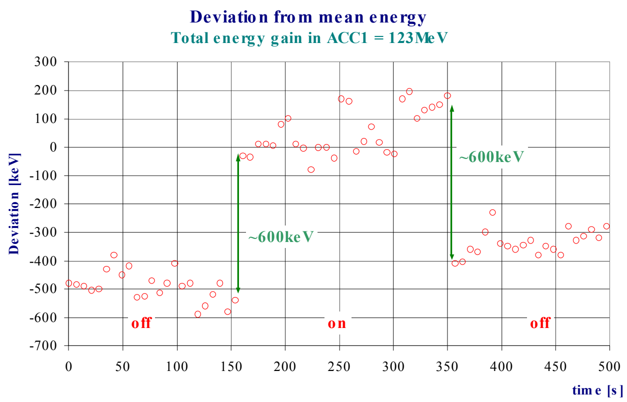

Figure 4. Beam energy change. Total energy of module is 123MeV. An energy increase by 600keV corresponds to 0.5% of full energy

The figure 4 presents the beam energy change when piezostack system is switched on and off. The eight cavities module of total energy gain of 123MeV improves its efficiency by a half percent (600keV). It is important to notice that only one cavity is equipped with fast tuner and the accelerating gradient was relatively low (20MV/m). To conclude the system works correctly but further test are foreseen in nearest future with new cryomodule in which all cavities will be equipped with piezostack tuner.

6 SUMMARY

There are several options for cavity tuners (UMI – coaxial tuner, CEA tuners – the old and the new ones and KEK). There are two types of actuators: magnetostrictive and piezoelectric one. The second one has been tested with cavity with success. The detailed study needs to be performed to compare both solutions and choose the best one. Both of types were tested successfully at LHe temperature.

The first generation of the CEA tuner with EPCOS piezostack is already mounted in ACC1 cavity 5 (VUV-FEL). It is possible to reduce detuning caused by LF from 180 Hz to 10 Hz during flat-top (above 90%) using a feed-forward algorithm. The adaptation of parameters is performed in few steps therefore the same system might be used for thousands of cavities. However, there is need to perform more test to prove advantages of proposed control system.

Currently, due to the fact that inserted piezostack from EPCOS is weak, the resonant compensation is used. The next generation of CEA tuner will be equipped with PI and NOLIAC piezostack, which are twice stronger. It will allow developing the method for single pulse compensation.

7 ACKNOWLEDGEMENT

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area” program (CARE, contract number RII3-CT-2003-506395), and Polish National Science Council Grant ”138/E-370/SPB/6.PR UE/DIE 354/2004-2007”.

We also acknowledge and appreciate the important contributions of the individuals from INFN-Milan, CEA-Saclay, IPN-Orsay and DESY-Hamburg laboratories, who helped us during the research.

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