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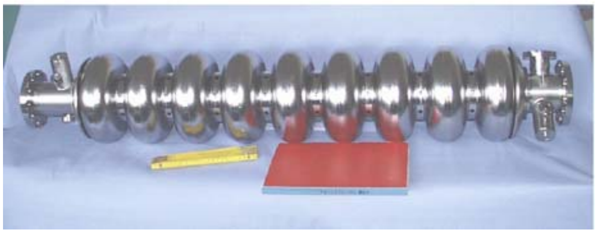

APPLICATION OF MULTILAYER PIEZOELECTRIC ELEMENTS FOR RESONANT CAVITY DEFORMATION IN VUV-FEL DESY ACCELERATOR

A. Napieralski, P. Sekalski

Department of Microelectronics and Computer Science, Technical University of Lodz, Politechniki 11, 93-590 Lodz, Poland

Abstract

The resonant cavities used for VUV-FEL accelerator, during pulsed operation might be deformed in range of micrometers. Its resonant frequency depends on the geometry therefore a compensation system is required. Active elements have to work at liquid helium temperature in radioactive environment for more than 10^{10} cycles without significant degradation. The paper presents current development on tuning system based on multilayer piezoelectric stack, which fulfils inter alia above requirements.

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Application of multilayer piezoelectric elements for resonant cavity deformation in VUV-FEL DESY accelerator.

Andrzej NAPIERALSKI, Przemysław SĘKALSKI

Department of Microelectronics and Computer Science, Technical University of Lodz, Politechniki 11, 93-590 Lodz, Poland

Abstract: The resonant cavities used for VUV-FEL accelerator, during pulsed operation might be deformed in range of micrometers. Its resonant frequency depends on the geometry therefore a compensation system is required. Active elements have to work at liquid helium temperature in radioactive environment for more than 10^{10} cycles without significant degradation. The paper presents current development on tuning system based on multilayer piezoelectric stack, which fulfils inter alia above requirements.

Key words: multilayer piezostack,

1. INTRODUCTION

A Free Electron Laser (FEL) that provides tunable radiation from the vacuum-ultraviolet (VUV) to soft X-rays is built at Deutsche Elektronen-Synchrotron (DESY) laboratory in Hamburg, Germany. It is a 260m-long extension of previous accelerator called TESLA Test Facility (TTF I) additionally equipped with undulators, in which the accelerated electrons are induced to emit flashes of X-ray laser light [1]. The first system ended FEL operation in March 2002 with great success. The SASE (self amplified spontaneous emission) principle has been proven for wavelengths from 180 nm to 80 nm. Next step is to upgrade energy to 1 GeV what will finally allow to reach wavelengths down to about 6 nm in the first harmonic of the SASE FEL.

Simultaneously, the VUV-FEL is an experimental facility for future generations of lasers and accelerators. After success of SASE operation, the construction of European X-Ray Free Electron Laser (X-FEL) is scheduled for year 2007-2012. It will consist of almost 3000m long accelerator ended with several undulators. The beam energy is planed to be around 20GeV. To reach such a value either a longer accelerator needs to be built or a technology, which will allow to obtain higher gradients in each cavity needs to be used (or at least combination of both parameters).

A resonant cavity is the main part of accelerator. In technology developed at DESY, it is a nine-cell structure build of pure niobium (see figure 1), which when cooled below 9.2K becomes a superconductor. The cavity operation temperature is set to 1.8K to eliminate temporary surface warm up (called quench), caused by imperfection of surface. The theoretical limit of gradient, which might be obtained in this type of cavity, is around 50MV/m. The VUV-FEL operates with much smaller gradients – 20MV/m, due to the technological processes connected with cavity preparations and due to the RF losses described below.

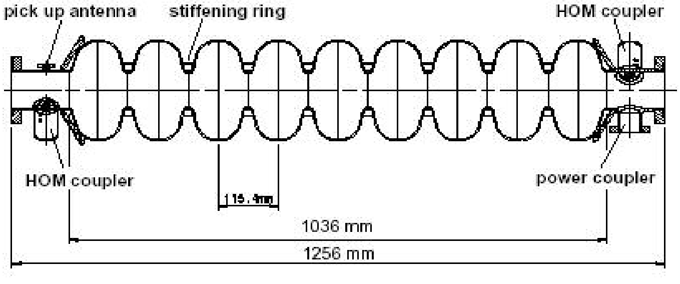


Figure 1. Nine-cell cavity used at VUV-FEL. [1]

The cavity is powered by 1.3GHz radio frequency wave, supplied from klystrons via couplers. Its shape is adjusted in such a way, that the given RF field creates a standing wave inside cavity. The quality factor of such a system is over 10^{10} (without load) or more than 10^{6} (when equipped with couplers and pick-up antenna)[2]. However, any geometry disturbance changes the frequency of cavity resonance, which causes system detuning and, as a consequence, quality factor reduction.

Shape of cavity might be changed by two main groups of effects: vibration, which comes from environment (called microphonics) and by Lorentz force caused by electromagnetic field, which fills cavity during pulse operation. The first phenomena is unpredictable and causes less than 20Hz detuning from resonance frequency, the second one is repetitive and its strength depends on the square of accelerating field gradients (for 20MV/m is around 170-200Hz). It is very important to mention that the resonance bandwidth of described cavity is only around 200 Hz. To sum up, an electromechanical system for cavity shape compensation is necessary for high gradients operation. The common active elements of such a system are multilayer piezostacks [4].

2. DESCRIPTION OF ELECTROMECHANICAL SYSTEM FOR CAVITY SHAPE COMPENSATION

Current electromechanical system base on a double lever mechanism. The handle ratio is 1 to 17. One side of tuner is attached to helium tank and the second to the cavity flange. Special bellow is used between cavity end and the container to allow flexible pushing and pulling operation. The system overview is presented in figure 2. One of the tuner supports is exchanged by piezoelectric stack fixture.

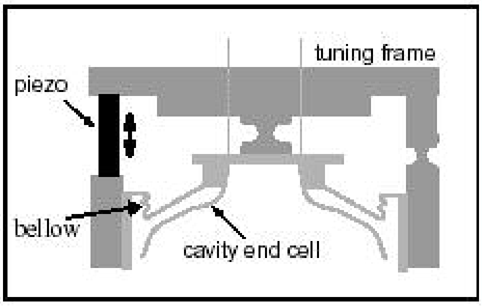


Figure 2. Overview of tuner.

As it was mentioned before, the tuner must perform two different types of operations. On one hand, it must be able to tune cavity, just after cooling down and pumping, in wide range. On the other hand, it must be able to act very fast during pulse duration (1.3 ms). It is very hard to design electromechanical system, which will be able to fulfil both requirements using only one active device. Therefore, in the presented solution, a stepping motor and piezostack are assembled together. The mechanical design was done by CEA-Sacley in France.

The slow tuner, based on stepping motor and Harmonic Drive gearbox, is used for pre-tuning stage. The engine is made by PHYTRON. Due to some special modifications (i.e. dedicated ball bearings), it might work at LHe temperature. It allows to move cavity by ±5mm, which corresponds to frequency shift of ±2.6MHz. The theoretical resolution is 1.5nm for one step, but because of a mechanical backlash of system, any results is visible only when stepping motor is moving by thousand of steps. Moreover, the device is too slow for fast tuning, which is necessary for microphonics and Lorentz force deformation. As a consequence, a fast tuner based on smart materials is combined.

The previous described part of tuner was designed for low gradient cavities used before. During these time the most important thing was to be close enough to the resonance frequency (bandwidth of these cavities was wider). However, with field gradient improvement and cavity bandwidth narrowing, other effect like Lorentz force and microphonics become more and more important. Currently, not only cavity initial frequency needs to be controlled, but also its shift during RF pulse needs to be reduced. The old tuner was slightly modified. Instead of one support, a fixture for a piezostack was assembled. Depending of its type it may hold one or two piezoelements (see figure 3). Elongation of piezoelements is too small to use them for pre-tuning stage, however they are enough fast for Lorentz force and microphonics compensation.

The whole tuner attached to the end of the cavity is presented in figure 4. On the right photo a bellow is also visible, which is interconnections between two nearest cavities. It allows to adjust shape of each cavity without significant interference to the other ones.

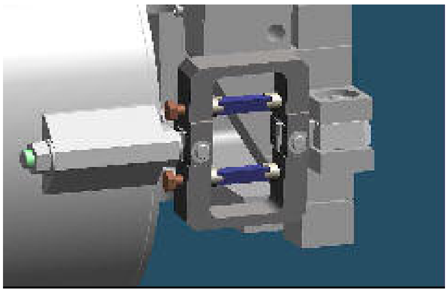
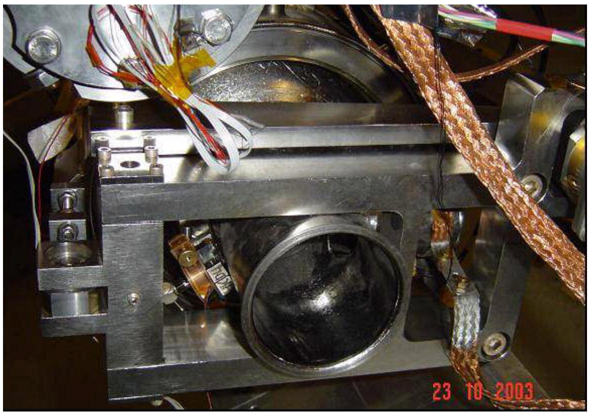


Figure 3. Fixture for two piezoelements attached instead of old tuner support.



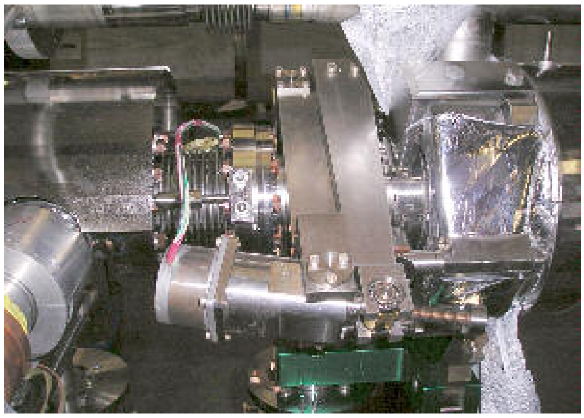


Figure 3. Photographs of cavity tuner.

Simultaneously, another type of tuner is developed in University of Milan. It is attached around cavity, therefore it is called coaxial one. As before a stepping motor is used for pre-tuning phase, and piezoelements are used as a fast tuner. There is possibility to implement the same type of piezostack as in the previously described solution. However, in this type of tuner is quite easy to assembly longer piezos (currently up to 72mm, quickly upgradeable). The biggest advantage of coaxial system is reduction of a dead zone (a space without accelerating gradient) between nearest cavities from 350mm to 283mm. On the other hand, it means that the total length of accelerator might be shorter by 5%. The main disadvantage is its cost, which is 3-4 times higher than the current system.

3. PIEZOELEMENT SPECIFICATION

Generally, for both type of tuners – CEA's and coaxial ones, the same piezoelements might be used. At the beginning of the experiment only one kind of multilayer piezostack from EPCOS was available. Nowadays, three other suppliers are taken under considerations – PI, NOLIAC and PiezoMechanik. The detailed material characterisation and what is more important - comparison are currently performing at DESY, IPN-Orsay and INFN-Milan laboratories under leadership of paper authors [8].

The piezoelectric elements must meet several though requirements. From mechanical point of view, the maximal displacement (stroke) must be in range of 40 microns at room temperature. The stack is required to fit into the tuner fixture, thus its length cannot exceed 40 millimetres. The cross-section is not as strict parameters, but thicker active elements are more expensive. The blocking force of piezoelectric element is obligated to be higher than 3kN, whereas its stiffness should be in range of hundreds N/µm. It should be also relatively fast thus the slew rate of elongation have to be higher than 100µm/µs. From electrical point of view, the piezostack might be supplied with voltage up to 150V to reduce Joule heating. The supplied current ought to be smaller than 2Amps. Usually the piezoelements are modelled as a pure capacitor. All proposed for our design active elements has a capacitance in range from 3µF up to 12µF.

One of the most difficult properties of piezostack is ability for low temperature operation. It has to work at cryogenic temperature of 1.8K. The different materials, from which it is build, should have a similar temperature coefficients of expansion (TCE) to avoid cracks during cooling down caused by mechanical stress. The manufactures commonly use a cofired process for ceramic packages. It is the technology used to join together various ceramic layers and metallization patterns screen printed onto those layers by simultaneous firing at high temperature. From our experience with this type of piezostack, all of them work correctly at liquid helium temperature. In opposite, when piezostacks from PiezoJena (assembled with different technology) were tested, all of them had cracks and shortcuts.

Moreover, according to performed test, properties of piezoelectric stack vary with temperature. The stroke, one of the most important parameter, is reduced by factor of 8. The other one, as capacitance changes less (2-3 times smaller at LHe than at room temperature). Moreover, the piezostacks, when cooled down, might be operated with bipolar voltage, even if in room temperature only an unipolar voltage was allowed. Furthermore, the operating voltage range is also increasing, but the damage test was not performed to avoid cryogenic system breakdown, thus it is hard to find how much it increases.

Piezoelectric stack needs to operate not only at LHe temperature but also in radioactive environment. The total foreseen dose is around 2MGy. Recently, proper test was performed in CERI laboratory in Orleans, France. A special insert for a small cryostat with holder for four piezostacks (see figure 4) was designed. The active elements from NOLIAC and PI were cooled down to 4.2K and then whole cryostat was exposured to 35μA neutron beams. The experiment persist around 20h, during which each piezostacks acquired total dose of 1.76-3.09 10^{14} n/cm^2. It corresponds to 20 years of operation inside the accelerator. During all experiment parameters of piezostacks like capacitance, loss tangent, displacement, etc were measured. Only small degradation in capacitance caused by neutron heating was observed.

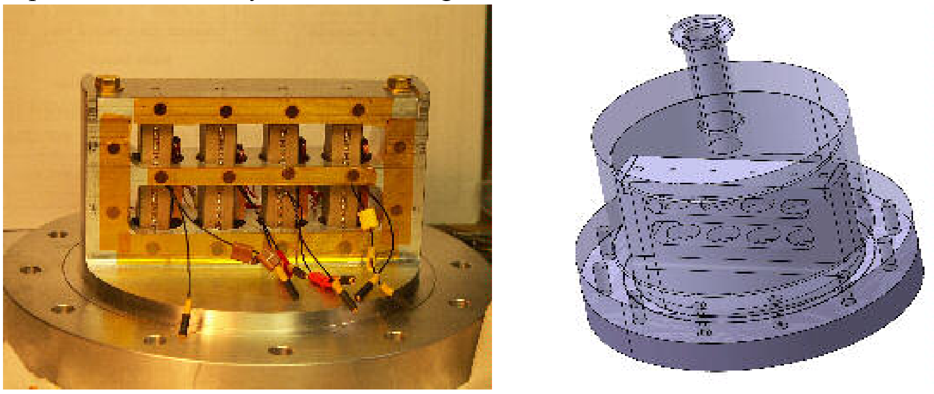


Figure 4. Piezostack holder for experiment insert for criostat (left photo). Black dots are the Ni foil plates used as an integraded dose sensors. Drawing of insert box (on the right).

The most crucial requirement is a lifetime. The piezostacks will be mounted in proper tuner frame and then will be closed in the cryomodule. It is not possible to open cryomodule, only exchange of it might be taken under consideration. However this operation will be extremely expensive. The piezoelement must therefore keep its properties for 10^{10} cycles. The static preload force, which is applied to piezostack, determines the lifetime. According to manufacturers to obtain maximal reliability of device, the active element should be stressed with one third of blocking force. In our case it corresponds to around 1.2kN.

One of the most difficult issues is a measurement of the static force in the LHe environment. For our purpose we have developed three methods. First of all, it is possible to use a separate sensor, which will base on piezoresistive effect. Small gauge resistors are placed in Wheatstone bridge on a metal membrane. When membrane is deformed, a strain in resistors causes change of its resistance. One of complicated problem was to use proper material (i.e. glue, surface) to avoid a delamination of sensor. This technique has one great disadvantage – additional device is required, which needs to be implemented in the system. As a consequence, we have turned to piezoelectric stack properties, and began an investigation of its dependencies versus applied force [9].

Each piezoelectric material, when impedance is analyzed, has a resonance and anti-resonance frequencies. For multilayer piezostack, several of this kind of pairs might be observed. The positions of these resonances (sometimes called parallel and serial) are strongly depended on the applied force [9]. It is possibly to determine static force by measuring its shift. In example, a force of 900N applied to EPCOS piezostack (change from 100 to 1000N) causes a change of resonance frequency from 62kHz to 68kHz, what can be easily measured.

Further researches made possible to develop third the method of preload estimation. Using precise multimeter it is possible to find that also a capacitance depends on applied force. However, the change is in range of nF whereas a capacitance of active element is in range of μF. Moreover, any voltage applied to piezoelement causes its elongation and in results change in the measured parameter. To summarize, all three methods are under investigation and final method of preload measurement will be chosen after its comparison.

Parameters of four different multilayer piezostack are collected. All of them have been preliminary tested at LHe temperature with success. However, because of high blocking force and reliability for more advanced tests, as radiation influence, only PI and NOLIAC were chosen.

Parameter name	Units	EPCOS	NOLIAC	Piezo Mechanik	Physical Instrument
Material		PZT-Nd34	PZT pz27	PZT 5H	PZT 25
Young Module	kN/mm^2	51	45	55	35
Cross-section	mm^2	7x7	10x10	7,5x7,5	10x10
Length	mm	30	30	55	36
Stroke (300K)	µm	40	42	60	30
Main resonance frequency	kHz		66	14	70
Stiffness	N/µm	83	150	56	97
Blocking force	kN	3,2	6,3	4	3
Max voltage	V	160	200	150	120
Slew rate	V/ms	1,6			
Load current	A	20			
Capacitance (F=0N) @300K	µF	2,1	5,7	13,4	12
Capacitance (F=850N) @300K	µF	3,4			
Capacitance @10K	µF			1,43	3,4

Table 1. Summary of several piezostack parameters.

4. RESULTS

The control system for piezoelement used in presented tuner is given in figure 5. Shape of signal is nowadays calculated in MATLAB environment. Then, using dedicated m-function, proper tables are written in function generator memory via Distributed Object Oriented Control System (DOOCS). To eliminate current peaks caused by voltage digitalization a low pass filter is used. Such prepared signal is amplified and supplied to the piezoelement, which interacts with cavity. Because piezostack might be also used as a sensor, therefore measured signal is converted to digital representation and then transmitted to DOOCS and MATLAB. PZM amplifier is used as a buffer for impedance adjustment.

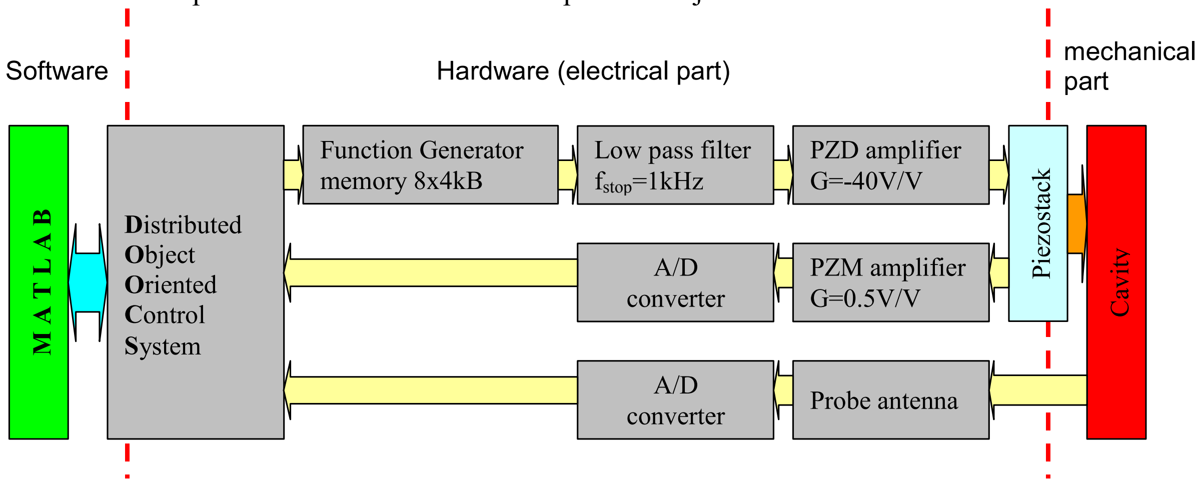


Figure 5. Control system for piezoelement assembled in tuner for cavity shape compensation

Recently, a new control panel for active elements driving was made. It allows to measure the detuning in each RF field pulse. Used algorithm bases on forward, reflected and probe power measurements. The main advantage of current system is possibility to apply given voltage to piezoelement and immediate result observation. Such a system allows to understand behaviour of presented electromechanical system and form proper automatic procedures.

At this moment in VUV-FEL only one cavity is equipped with tuner and piezostack, therefore a manual operation is sufficient. However, for future purposes, when thousands of piezostack will require independent driving settings an automatization is strongly required.

Up to now, using presented system fitted with piezostack from EPCOS a compensation of 90% of detuning caused by Lorentz force was obtained. Cavity resonance frequency change with piezoelement control system switch on and off is presented in figure 6.

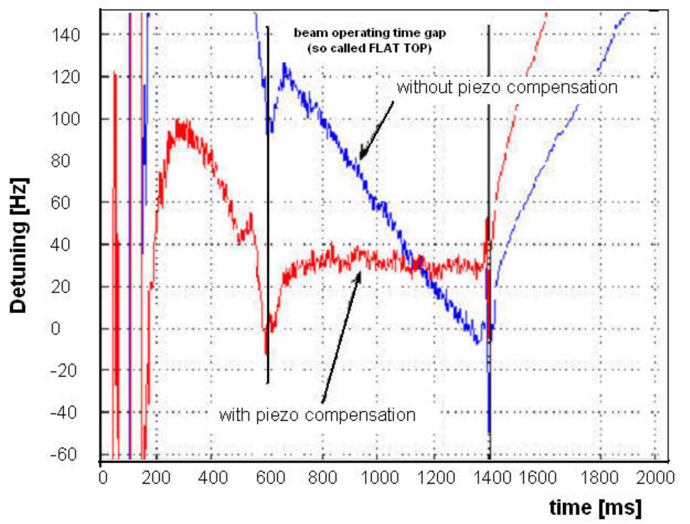


Figure 6. Detuning caused by Lorentz force with and without piezostack based tuner system.

5. CONCLUSIONS

VUV-FEL laser will be based on superconducting cavities technology. The shape deformation caused by Lorentz force, in range of microns, might be successfully compensated by electromechanical system, in which a multilayer low voltage piezostack will be implemented. Hitherto, performed experiment indicates that almost 90% of detuning from resonance frequency (1.3GHz) is remunerated. The system was working for more than one month constantly (almost one year operation with some breaks caused by other parts of accelerator) without any visible degradation.

Currently only one cavity of 32 has a piezostack actuator for fast compensation. A system presented in this paper is operated manually. An algorithm development for automatic control is undergoing. Some preliminary system identification test were performed, however it seems that structure consist of cavity-tuner-piezostack is nonlinear.

The piezostack used in the tuner are quite small (up to 10x10x40 mm), but might save up to half of power required for RF system operation, which is measured in MW range. According to performed experiment, the 10 years operation without breakdown might be foreseen, even in such demanding environment, where the temperature is close to absolute zero and there is a radiation.

6. ACKNOWLEDGEMENT

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