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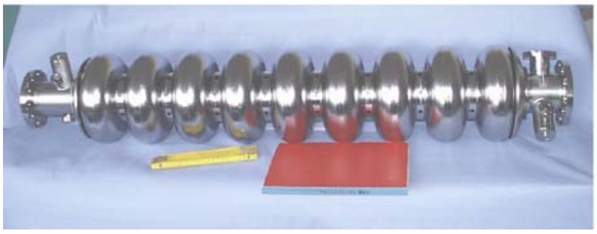

Smart materials based system operated at 2K used as superconducting cavity tuner for VUV-FEL purpose

P. Sebalski, A. Napieralski
Technical University of Lodz, DMCS, Poland
S. Simrock, C. Albrecht, L. Lilje,
DESY-Hamburg, Germany
P. Bosland, and all
CEA-Saclay, France
M. Fouaidy, and all
IPN-Orsay, France
A. Bosotti, R. Paparella, and all
INFN Milan, Italy

Abstract

The multilayer piezoelectric stacks are suitable for high precise tuning system system for superconducting cavities designed for next generation of linear accelerators. They may work at ultra low temperatures (even 2K), high vacuum ($<10P^{-5}$mBar) and radioactive environment. According to the author's investigation the may be operated for more than 10^{10} cycles without significant decrease of efficiency. The paper will describe the recent developments on fast tuning system dedicated to cavity shape compensation. 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 prototype of tuner is tested in linear accelerator VUV-FEL, which is constructed at DESY in Hamburg, Germany. The presented solution after minor modification might be used also for next generation of superconducting linear accelerators as X-FEL and ILC.

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SMART MATERIALS BASED SYSTEM OPERATED AT 2K USED AS A SUPERCONDUCTING CAVITY TUNER FOR VUV-FEL PURPOSE

P. Sekalski, A. Napieralski, Technical University of Lodz, DMCS, Poland
S. Simrock, C. Albrecht, L. Lilje, DESY-Hamburg, Germany
P. Bosland, and all, CEA-Sacley, France
M. Fouaidy, and all, IPN-Orsay, France
A. Bosotti, R. Paparella and all, INFN Milan, Italy

Abstract:
The multilayer piezoelectric stacks are suitable for high precise tuning system for superconducting cavities designed for next generation of linear accelerators. They may work at ultra low temperatures (even 2K), high vacuum (<10^{-5}mBar) and radioactive environment. According to the author's investigation they may be operated for more than 10^{10} cycles without significant decrease of efficiency. The paper will describe the recent developments on fast tuning system dedicated to cavity shape compensation. 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 prototype of tuner is tested in linear accelerator VUV-FEL, which is constructed at DESY in Hamburg, Germany. The presented solution after minor modification might be used also for next generation of superconducting linear accelerators as X-FEL and ILC

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

Introduction

The cavity is the one of the most important elements of each linear accelerator used for high-energy physics purpose. The resonant frequency of the cavity depends on its shape. In case of Vacuum Ultra Violet Free-Electron Laser VUV-FEL a frequency of the forced wave is fixed to 1.3GHz. Any cavity deformation detunes it from master oscillator frequency [1].
A technology called TESLA is used for VUV-FEL cavities. It relays on superconducting SC niobium nine-cell cavities. As the result of SC the cavities are ultra high quality resonators (unloaded Q factor over 10^{10}). However, because of power couplers and antennas the quality factor of operating system is limited to 3 10^{6}. Nevertheless, it implicates a very narrow bandwidth, which varies from cavity to cavity but remains around 230Hz [2, 3].
According to the experiment the just-over-1m-long cavity used for the purpose must be controlled with micrometer resolution. The length change of 1μm causes a frequency detuning of 300Hz. As a consequence there is need to use an electromechanical tuner [4].
The pure niobium became a superconductor when cooled below 9.2K. However, the operation temperature of VUV-FEL cavities is set to 2K. To reduce the complexity of tuner the active elements must operate at desired environment. Moreover, they must survive in a radiation environment for more than 10^{10} cycles (it corresponds to 10 years of operation with repetition rate of 20Hz).
The piezoelectric elements or magnetostrictive rods are used as an actuator for compensation system. Both types of elements fulfil these strict requirements [5, 6, 7].

Source of detuning and methods of compensation

The cavity might be deformed either by dynamic Lorentz force LF caused by pulsed accelerating electromechanical field and by vibration, which comes from surrounding environment (commonly called microphonics). The static LF is proportional to the square of accelerating field gradient (see Fig. 1). For gradients around 25MV/m the compensation system is highly recommended, but for higher ones is almost obligatory. The LF depends only on the parameters of forward field and therefore is repetitive. Proper system not only saves the input power, but also allows obtaining a stable beam.
The second source of perturbations is microphonics. These unpredictable vibrations are much smaller than LF and cause a detuning up to few tens of Hertz.
One compensation system is used for both effects. It is a double-lever system attached between one end of the cavity and the Helium tank. The second end of the cavity is fixed directly to the container [8, 9].

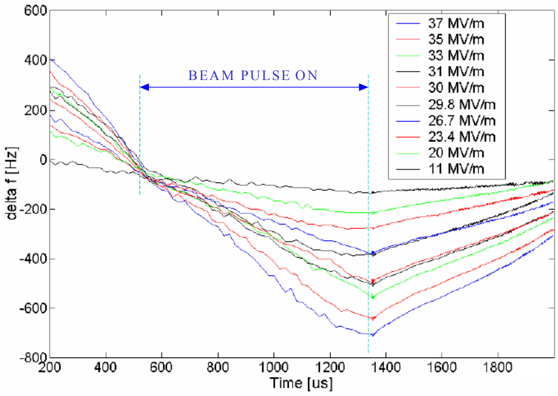

Fig. 1: *The Lorentz Force detuning for different accelerating field gradients*

Currently as active element multilayer piezostacks are used. Several models from three different manufacturers are tested – EPCOS (PZT/Nd34), NOLIAC (Pz27 and Pz29) and PI (PICMA 888 series). The main parameters of used actuators are collected in table 1.

Table 1*. Parameters of used piezoelectric actuators*

Parameter name	Units	EPCOS	NOLIAC	PI
Material		PZT-Nd34	PZT pz27	PZT 25
Young Module	kN/mm^2	51	45	35
Cross-section	mm^2	7x7	10x10	10x10
Length	mm	30	30	36
Stroke (300K)	µm	40	42	30
Main resonance frequency	kHz		66	70
Stiffness	N/µm	83	150	97
Blocking force	kN	3.2	6.3	3
Max voltage	V	160	200	120
Slew rate	V/ms	1.6		
Load current	A	20		
Capacitance (F=0N)	µF	2.1	5.7	12
Capacitance (F=850N)	µF	3.4		
Capacitance @10K	µF			3.4

All of the actuators were successfully tested at cryogenic environment [6]. From experiments we have found that the elongation at 2K decreases by factor of 8 in comparison to the stroke at 300K. This is the reason to use a stack, which have nominal elongation over 30µm (@300K).
The active elements might be assembled in single or double actuators fixtures. Due to the force unbalancing problems the single piezo fixture is used nowadays.
The overview of control system is presented in Fig. 2. Shape of the signal is calculated in Matlab environment and then transmitted to function generator, which is connected with actuator through dedicated amplifier. Feedback information is collected by antennas and/or by second piezostack. Because the Lorentz Force is very repetitive, therefore a feed forward algorithm is used to drive a system.

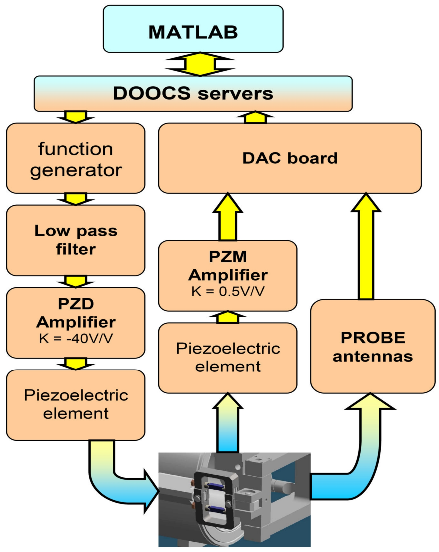

Fig. 2: *Overview of control system for VUV-FEL piezoelectric tuner*

The performed experiments shows that the current system might fully dump Lorentz force detuning up to 200Hz. Some preliminary test indicates that it is possible to compensate the detuning also for higher accelerating field gradients (up to 35MV/m ó700Hz) but there is need to use higher elongation piezostacks.
The result from measurement done in VUV-FEL is presented in Fig. 3. The detuning during the flat top of pulse is almost completely compensated. It means that the given cavity is kept in resonance during whole pulse. As a consequence, the energy of the beam accelerated in such a cavity is higher by 600keV, whereas almost no additional power is consumed (only the one to drive the control system). The Lorentz Force detuning is proportional to the square of accelerating field gradient; therefore for higher gradients the advantages of the system will increase. Current investigation are focused on new piezoelectric stack, which allows to obtain more stroke and more force.
A feed-forward automatic algorithm was recently implemented. The actuator is driven using a sine-wave pulse. Its 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, called resonance excitation one, 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.

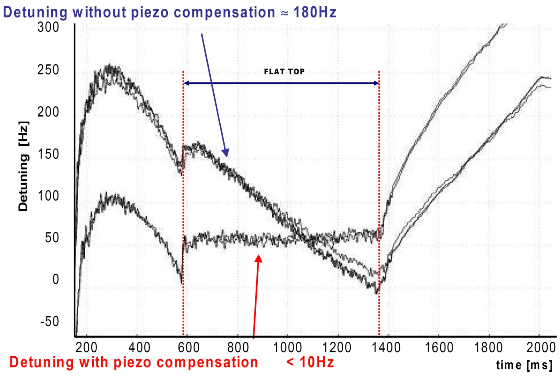

Fig. 3: Detuning with and without piezostack-based system. The accelerating field gradient is 20MV/m

Static force measurement at LHe temperatures

According to literature the lifetime of the piezoelectric actuator depends on the preload force. Thus, it is necessary to introduce a static force measurement. The commercial available strain gauges might work at cryogenics temperatures after minor modifications of used materials. Especially, the used glue must be elastic at 4K.

Proper load cell was developed at INFN-Milan with collaboration of CELMI (see Fig. 4). Several performed run shows that the sensitivity is constant and equal to 0.02mV/kg (~0.2mV/N). Moreover, what is also important the same sensitivity is for room temperature and only offset value varies with temperature.

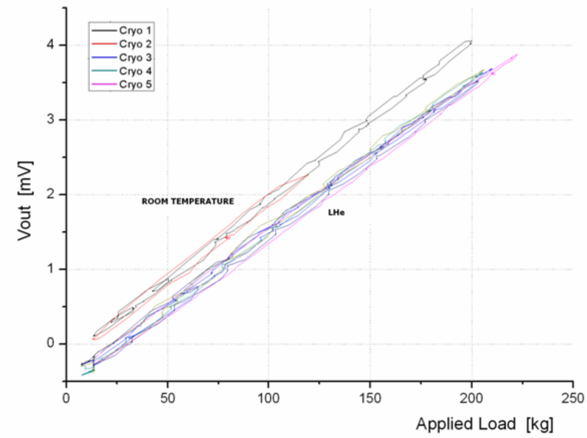

Fig. 4: Response of load cell in function of applied load

One of disadvantages of proposed method is a necessity of additional wiring. Moreover, the sensor should be evaluated for lifetime issue.

Another method proposed by authors is to use a piezoelectric device itself [12]. Since, the generated voltage is proportional to dynamic force change, some parameters of actuator are depending only on the stress. Especially, two parameters were investigated – capacitance and impedance.

The typical impedance curve of used multilayer piezostacks are presented in Fig. 5. Several resonances are visible for frequencies in range of kHz. From measurement, the authors found that their positions depend on the load applied to piezoelement.

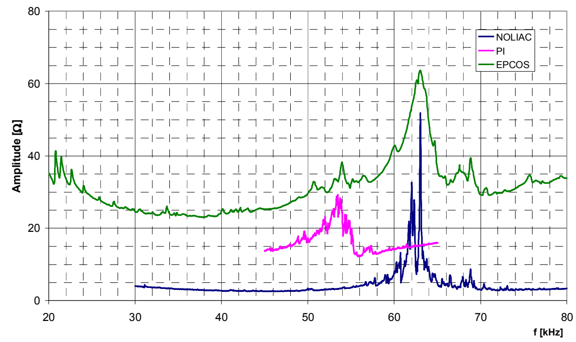

Fig. 5: Multilayer piezostacks impedances. EPCOS (blue line), PICMA (green dotted line) and NOLIAC (red dashed line).

A change of one of the resonance frequency of EPCOS piezo for different applied force measured at 4K is presented in Fig. 6. This measurement comes from special test stand developed at INFN-Milan.

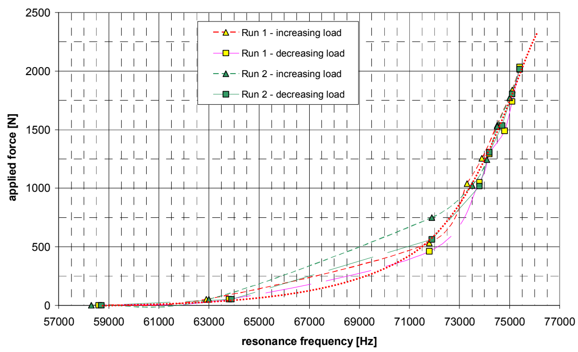

Fig. 6: Resonance shift of EPCOS piezostack at 4K in function of applied force

The measurement presented above might be used for estimation of force applied to piezoelement mounted in tuner assembled in the module. By comparison of the position of frequency it is possible to judge that the force applied to piezoelement was 0.8kN. According to manufacturers the maximal lifetime is reached when static force is around 1/3 of blocking force (3.2kN for EPCOS piezo). Thus, the piezostack should be preloaded more.

Another method based on capacitance measurement is developed at IPN-Orsay. It is also promising one, because it also relays on the piezoelement itself. The behaviour of change is exponential, the same manner as it was with impedance resonance shift. The main disadvantage of this method is small change of capacitance (few hundreds of pF per 1 N) caused by applied force in comparison to capacitance of the active element (usually around 4 F). During measurement there is need to minimize all noises.

Conclusion

The piezoelectric based tuner is successfully used for VUV-FEL purpose to compensate the Lorentz force. It allows tuning the cavity by 200Hz with reasonably low voltage applied to actuator (up to 50V). To guarantee the proper lifetime a preload force need to be set correctly.
Three methods of static force measurement are investigated. One of them is based on strain gauges and two others on characterization of physical parameters of piezoelectric element. The capacitance change and resonance position shift are very interesting because there is no need to use additional sensors and wiring.

Acknowledgement

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