PIEZOELECTRIC STACK BASED SYSTEM FOR LORENTZ FORCE COMPENSATION CAUSED BY HIGH FIELD IN SUPERCONDUCTING CAVITIES

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Abstract

The superconducting cavities based on TESLA technology will operate at high gradients up to 37MV/m. However, during pulsed operation, its resonant frequency is changing due to the Lorentz force (LF). A fast tuning system, which contains smart materials such as piezoelectric stack or magnetostrictive rod, is needed. Simultaneously, this tuner must be fully integrated with stepper motor and its gearbox, used for pre-tuning stage (commonly named slow tuner). The paper presents the current status of development at DESY-Hamburg of a tuner system based on piezoelectric elements. In particular, the estimation of the mechanical preload force applied to the piezostack at LHe temperature is presented. Furthermore, the control loop is described.

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]. The resonance frequency for niobium cavities developed at DESY-Hamburg is set 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. As a consequence a high precision positioning system is needed [3].

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 [15]). In first case, the authors' work on, the tuner will be operated in vacuum (10^{-5} mBar) and at cryogenic temperature (2 K). 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 [11], 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 [4]. The paper presents the recent results obtained by authors in VUV-FEL system, which might be operated by end-user.

MAIN PURPOSES OF CAVITY TUNER

The VUV-FEL cavity tuner should realize three main objectives. First of all, it should allow pre-tuning process, and then it ought to be able to compensate both LF and microphonics [1-7].

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 1.8K. 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 two other purposes. It must react during RF pulse and compensate detuning caused by LF and microphonics. The dynamic LF is an issue in pulsed machines like the ones developed at DESY.

The source of first mentioned distortion is RF field itself. 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 (so-called Lorentz force LF). The mechanical force causes the cavity shape change and simultaneously shift of it 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). The LF distortion is very repetitive and periodic and what is the most important predictive. The system needs to act quite fast (up to 2 kHz, slew rate should be higher than 1 µm/100 µs at 1.8 K) mainly during RF pulse. It will be operated with the same repetition rate as the macro-pulse (up to 10 Hz for VUV-FEL).

Another source of perturbation are the mechanical vibrations caused by environment, commonly called microphonics, i.e. helium pumps or even human activity. Additionally, a cross-talk between nearby cavities and between previous 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.

TUNERS VARIETY

Currently, there are two main groups of cavity tuners developed for TESLA technology based accelerator. First of them are mounted at the end of the cavity. The second type of tuner is assembled around the cavity in the middle of it.

The first mentioned solution, which is mainly developed by CEA-Saclay, France, bases on a double lever mechanism. A stepping motor (PHYTRON) with harmonic gearbox is used for pre-tuning stage. One of three supports, which hold system to helium tank, is replaced by fixture in which a piezostack or a magnetostrictive rod might be assembled. There is also option to put two active elements in parallel to have a sensor-actuator configuration.

The first generation of such solution, has been used for all test described in this paper. However, several problems occur during exploitation. One of the most important is appearance of neutral point. It may happen that if stepping motor is in wrong position, the forces in system will be in the equilibrium and then piezoelement lose a preload force. As a consequence, there will be no possibility to control it. It is also dangerous for active element itself because non-preloaded element reduces its lifetime.

The second generation of CEA tuner was designed in such a way, that the neutral point is avoided [10]. The preload force is applied directly by cavity elasticity. The first tests are scheduled for end of 2005.

A coaxial tuner, mainly developed by INFN Milan in Italy, is another option [12]. It consists of three coaxial rings connected by blades. The side rings are fixed to the helium tank, which is cut between them. The middle ring might rotate and then, using declivous blades, it pushes the two others. As previously, for pre-tuning stage the stepping motor is used and for fast tuning a piezostack is mounted. The main advantage of this type of tuner is decreasing of space between cavities from 350 to 283mm [12]. The reduction of so-called “dead zone”, in which beam is not accelerated, causes, that total length of accelerator might be shortened by 5%. Another benefit of this solution is a possibility of using, if necessary, bigger and more reliably (and also more expensive) piezostacks without significant change of tuner design.

The main disadvantage of last solution might be its price. However, there is need to investigate and compare all parameters of all two types of tuners to decide which solution will be used in final design (i.e. a cost of extra 5% long tunnel). Such a comparison for X-FEL accelerator is planned for beginning of 2006 year.

Alternative to the European efforts are the KEK’s tuners [18]. The uniqueness of the slide jack tuner is that the motor is placed at room temperature outside of the vacuum vessel. Second system is the coaxial ball screw tuner in which both, the motor and the piezo are placed at intermediate temperature inside of the vacuum vessel.

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) [9]. 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 piezo (7x7mm). Two others are slightly bigger (10x10mm).

All active elements were tested in pumped liquid helium temperature (1.8 K) with success. All layers of elements are cofired 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 1.8 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÷3.09 10^{14}

n/cm². Only effects connected with heating caused by beam was observed during 20h of irradiation [14].

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 piezo 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 [11].

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 is a measurement of static force applied to piezoelement at 1.8K. The authors propose to use a self-developed method based on investigation of internal parameters of active elements itself.

Static force measurement at LHe temperature

Several methods of static force measurement at LHe environment were developed. It is possible to use an external sensor based on a piezoresistive element or a strain gauge. However, these methods require an extra element. Another attempt to force estimation is an investigation of piezostack parameters. The authors finds that the applied preload force might be evaluated by a capacitance change or a shift of resonance frequency on the impedance curve of the element. The second method is more precise, but also more equipment demanding.

The impedance curve indicates, that multilayer piezostack has several resonance frequencies and, what is more important, all of them are strongly depended on mechanical boundary conditions. An detailed experiment performed at INFN-Milan shows that the resonance position is in logarithmic function of applied preload force (see Figure 1) [8]. Unluckily, it also depends on temperature.

Obtained results might be used for estimation of preload force applied to piezoelement assembled in tuner fixture. As it was mentioned before, using old CEA tuner interference between slow and fast tuner was observed. Any movement of stepping motor causes a change of preload applied to piezostack (see Figure 2).

Comparison of both results allows estimating preload force of element, which operates in accelerator module (test stand CHECHIA in this case). The value of applied force has been changed from 0,7 kN for 0 step motor position to 70 N for 1 million steps movement (1 step ≈ 1.7nm).

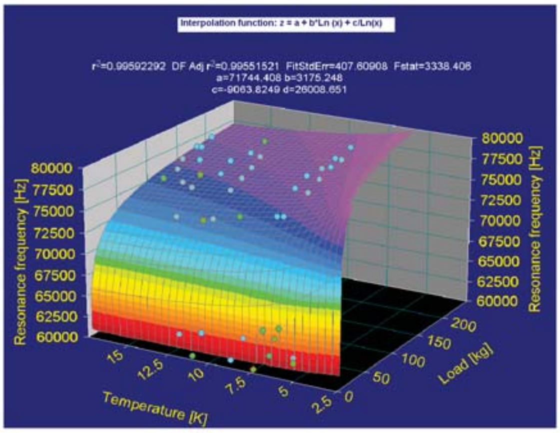


Figure 1. 3D interpolation of position of resonance versus applied force and temperature for EPCOS piezo [8].

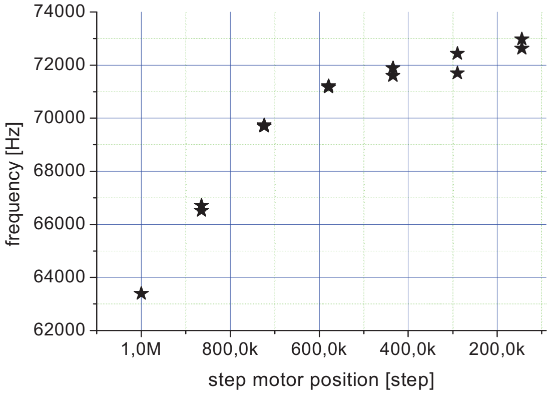


Figure 2. Resonance frequency of EPCOS piezo versus position of step motor [8].

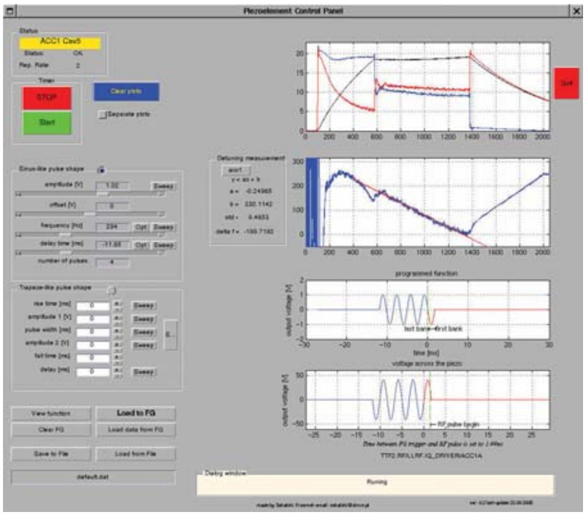
CONTROL SYSTEM

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).

Overview of control system is presented in Figure 4. 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.



Status: OK
Rep. Rate 2
amplitude [V] 1.02
offset [V] 0
frequency [Hz] 234
delay time [ms] -11.88
number of pulses 4
y = ax + b
a = -0.24965
b = 230.1142
std = 0.4653
delta f = -199.7192

Figure 3. MATLAB GUI for LF compensation

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.

EXPERIMENTAL RESULTS

The experimental results showed in Figure 5 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 detuning remains below 10 Hz. 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].

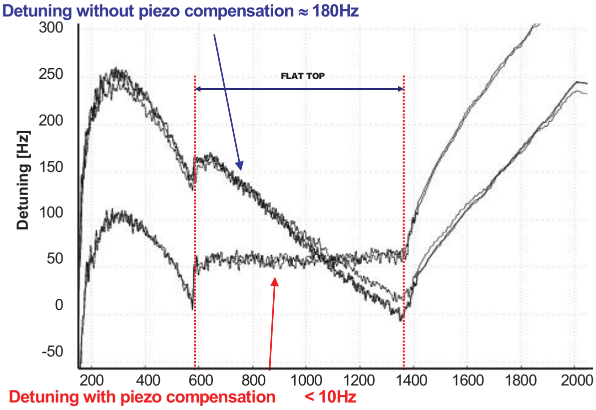


Figure 5. Detuning caused by Lorentz force with and without piezostack based tuner system

Such type of shape compensation allows saving up to 50 per cent of consumed RF power depending on accelerating field gradient [1].

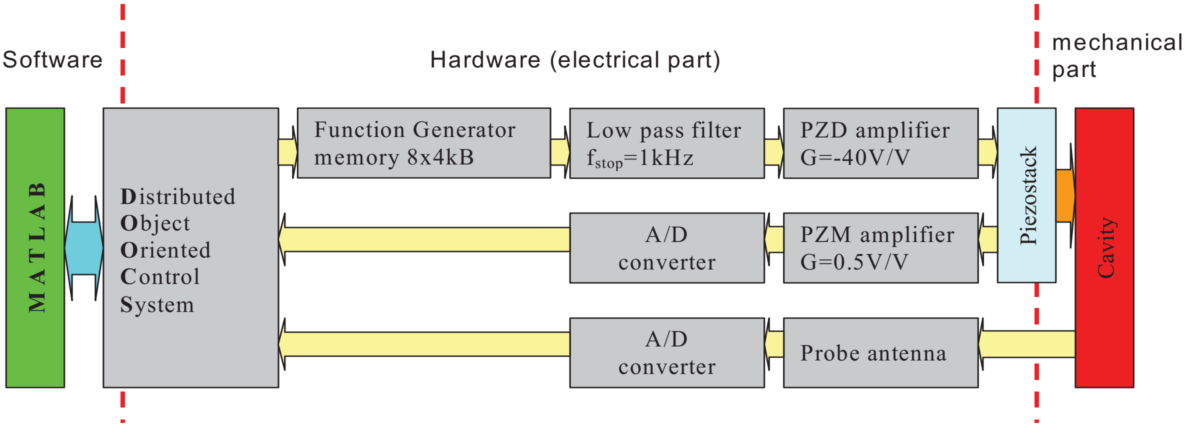


Figure 4. Control system for piezoelement assembled in tuner

SUMMARY

There are several options for cavity tuners (UMI – coaxial tuner, CEA tuners – the old and the new ones and KEK). A lot of problems are solved so far i.e. neutral point, force measurement at 2K (using i.e. resonance shift monitoring), but there are still some issues, which need to be verified (i.e. cross talk between cavities need to be investigated, possibility of microphonics compensation).

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.

A 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 (almost 90%) using a feed-forward algorithm. However, the proposed control system should be checked with more than one cavity to prove its advantages.

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.

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REFERENCES

[1] M. Liepe; "Superconducting multicell cavities for linear colliders", PhD thesis, University of Hamburg, DESY-THESIS-2001-045, (2001). "TESLA Technical Design Report", DESY 2001-011, 2001

[2] T. Schilcher, "Vector Sum Control of Pulsed Accelerating Field in Lorentz Force Detuned Superconducting Cavities", PhD thesis

[3] "TESLA Technical Design Report", DESY 2001-011, 2001

[4] S.N. Simrock, "Lorentz Force Compensation of Pulsed SRF Cavities", Proceedings of LINAC 2002, Gyeongju, Korea

[5] M. Liepe, W.D.-Moeller, S.N. Simrock, "Dynamic Lorentz Force Compensation with a Fast Piezoelectric Tuner", Proceedings of the 2001 Particle Accelerator Conference, Chicago, USA

[6] L. Lilje, S. Simrock, D. Kostin, M. Fouaidy, "Characteristics of a fast Piezo-Tuning Mechanism for Superconducting Cavities", Proceedings of EPAC 2002, Paris, France.

[7] P. Sekalski, S. Simrock, L. Lilje, C. Albrecht, "Lorentz Force Detuning Compensation System for Accelerating Field Gradients Up To 35 MV/m for Superconducting XFEL and Tesla Nine-Cell Cavities", 11th International Conference MIXDES 2004, p398-402, ISBN: 83-919289-7-7

[8] P. Sekalski, A. Napieralski, S. Simrock, L. Lilje, A. Bosotti, R. Paparella, F. Puricelli, M. Fouaidy: "Static absolute force measurement for preloaded piezoelements used for active Lorentz force detuning system", LINAC 2004, Luebeck, Germany

[9] M. Fouaidy, N. Hammoudi, "Characterization of Piezoelectric Actuators Used for SRF Cavities Active Tuning at Low Temperature", SRF 2003.

[10] P. Bosland, Bo Wu, "Mechanical Study of The Saclay Piezo Tuner (PTS)", DAPNIA-CEA Saclay, internal report

[11] A. Bosotti et all, "PI piezo lifetime test report", INFN Milan, internal report

[12] A. Bosotti and all, "Report on Fast Piezo Blade Tuner (UMI) for SCRF Resonators Design and Fabrication", CARE Note

[13] P. Sekalski, M. Grecki, C. Albrecht, "Performance of Magnetostrictive Element at LHe Environment", 12th International Conference MIXDES 2005, Kraków, 22-25 June 2005, pp. 799-802, ISBN 83-919289-9-3

[14] M. Fouaidy, G. Martinet, N. Hammoudi, F. Chatelet, S. Blivet, A. Olivier, H. Saugnac "Electromechanical, Thermal Properties and Radiation Hardness Tests of Piezoelectric Actuators at Low Temperature", SRF 2005 Ithaca, USA

[15] S. Simrock, "Review of Fast and Slow Tuners", SRF 2005, Ithaca, USA

[16] PI web page, http://www.physikinstrumente.de

[17] P. Sekalski, S. Simrock, L. Lilje, C. Albrecht, "Lorentz Force Detuning Compensation System For Accelerating Field Gradients Up To 35 MV/m For Superconducting XFEL And TESLA Nine-Cell Cavities", 11th International Conference MIXDES 2004, p. 398-402, ISBN: 83-919289-7-7

[18] K. Saito, "ILC High Gradient Cavity Development Status", Asia Video meeting on 4 Aug 2005