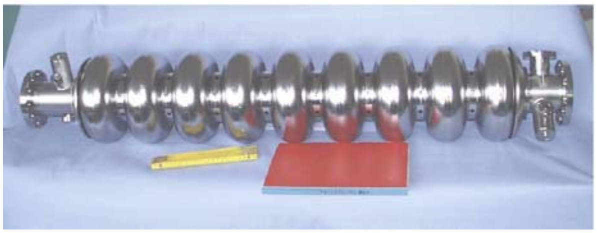
SRF



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

P. Sekalski, A. Napieralski, Technical University of Lodz, DMCS, Poland
S. Simrock, DESY, Hamburg, Germany

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 and 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 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.

Contribution to the SRF 2005, Ithaca, New York, 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).

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

P. Sekalski, A. Napieralski, Technical University of Lodz, DMCS, Poland
S. Simrock, DESY, Hamburg, Germany

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 and 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 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

A superconducting (SC) technology is a promising alternative for next generations of linear accelerator like already constructing VUV-FEL (Vacuum Ultra Violet Free Electron Laser), developed X-FEL (X-Ray Free Electron Laser) or even planed ILC (International Linear Collider) [1]. It not only allows obtaining high-energy particle but also it helps significantly reducing power consumption. The superconducting structure efficiency of energy transfer from acceleration field to beam might reach even close to 100%. It is important to remark, that an additional power consumed by cryogenic system is required to cool down the cavities to 1.8K. However, this extra energy is still much smaller than losses generated in normal conducting machines.

The cavities used in SC TESLA technology are extremely efficient resonators with quality factor above 10^6, when mounted into modules with couplers and tuners (Q factor of free cavity might reach even 10^{10}). The resonance frequency for niobium cavities developed at DESY-Hamburg is set to 1.3GHz.

To operate with such a good efficiency, the frequency of radio frequency (RF) field must fit precisely the resonance frequency of the cavity [2]. The distance end to end of nine-cell 1m long cavity, must be controlled in range of micrometers. From measurements, one can find that 1μm cavity length change causes 300Hz of detuning. As a consequence a high precision positioning system is needed.

The electromechanical system has to operate in very tough and unfriendly environment. First of all, it will be operated in vacuum (10^{-5} mBar) in cryogenic temperature (1.8K). Moreover, it is assumed that it will be exposed to 2MGy radiation dose during 10 years of operation. However, the most demanding requirement is MTBF factor. Dedicated tuner system should work without breakdown for at least 10 years (any service for parts mounted inside cryomodule is foreseen). It is very challenging, because each cavity needs to have its own tuner (for 2km 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. These elements might operate for more than 10^{10} cycles, which is predicted for the case.

MAIN PURPOSES OF CAVITY TUNER

The cavity tuner should realize three main objectives presented below. First of all, it should allow pre-tuning process, and then it ought to be able to compensate both LF and microphonics [3-6].

Pre-tuning is a necessary stage to reach proper frequency in which cavity will be operated. The cavity with couplers is assembled at room temperature, during cooling down to 1.8K and helium pumping the cavity shape is deformed, what causes resonance frequency shift. However, the master oscillator is set to constant frequency (in case of VUV-FEL it is equal to 1.3GHz). Hence, cavity-master oscillator system might be detuned by few MHz just after initial procedure. It corresponds to several millimetres change of the cavity length. Required tuner structure for this purpose might work slow 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. (such a complicated mechanical system might be relaxed in long time, therefore there is need to control length of the cavity). One part of tuner should be dedicated to this purpose. It is often called slow tuner, because it is operated when there are no beam and there are no time limitation.

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 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 more or less predictive. The system needs to act quite fast (up to 2kHz, slew rate should be higher than 1µm/100µs @1.8K) mainly during RF pulse. It will be operated with the same repetition rate as the beam (according to plan it might be even 20Hz).

Another source of perturbation are the mechanical vibrations caused by environment, commonly called microphonics, i.e. helium pumps or even human activity. Detuning caused by this distortion is rather small and 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.

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, the system for pre-tuning is mandatory, Lorentz force compensation is strongly required and cancellation of microphonics is advisable. It is necessary to fight with microphonics especially when the repetition rate of RF pulse will increase, due to phase stability of accelerating field.

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.

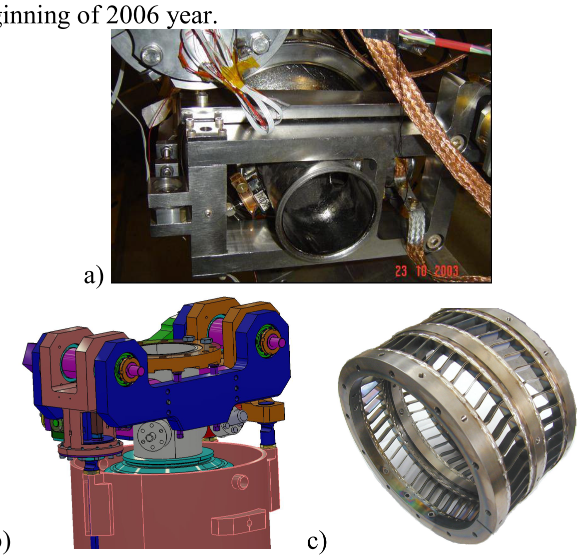
The first mentioned solution, which is mainly developed by CEA-Sacley, France, bases on a double lever mechanism (see Figure 1a). A stepping motor (PHYTRON) with harmonic gearbox is used for pre-tuning stage. One of three supports, which hold system to helium tank, is replaced by fixture in which a piezostack 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 (Figure 1b) was designed in such a way, that the neutral point is avoided [9]. 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. 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 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. The reduction of so-called "dead zone", in which beam is not accelerated, causes, that total length of accelerator might be shorten 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 is its price, which is three times higher than CEA one. 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.



a) b) c)

Figure 1. Variety of cavity tuners: a) CEA-Sacley old tuner; b) CEA-Sacley new prototype; c) coaxial tuner

ACTIVE ELEMENTS

The main parts of 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 [11].

Currently for VUV-FEL purpose, three different multilayer piezostack from EPCOS (PZT Nd34), PI (P-888.90 PIC 255) and NOLIAC (PZT pz27) suppliers are taken under investigation [8]. All actuators are the low voltage elements, which may be powered only up to 150V. 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 (1.8K) 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).

It is possible to conclude from experiments, that stroke at LHe environment is reducing by factor of 8 in comparison with room temperature test. A 4µm stroke @1.8K might be achieved by piezostack, which @RT has maximum elongation at least 30µm. All three groups of elements fulfil this requirement.

Another important feature of piezoelectric element is radiation hardness. A special set of experiment was performed 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 4K inside the small cryostat and then irradiated by Be neutron source (1-15MeV). 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.

The radiation hardness is also proved by EPCOS piezostack, which was inserted into module ACC1 of VUV-FEL one and half years ago – till now no degradation was seen.

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. A 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 the tested element was cooled down only to 77K because of cost of experiment [10].

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 optimal preload is assumed to be around 1/3 of blocking force, what stands for 1.2÷1.5kN 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 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 [7]. It is possible to use an external sensor based on a piezoresistive element or a strain gauge. However, these methods require an extra element, which might fail during 10 years of operation. Another attempt to force estimation is an investigation of piezostack parameters. 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, they are strongly depended on mechanical boundary conditions. An experiment performed at INFN-Milan shows that the resonance position is in logarithmic function of applied preload force (see Figure 2). 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 3).

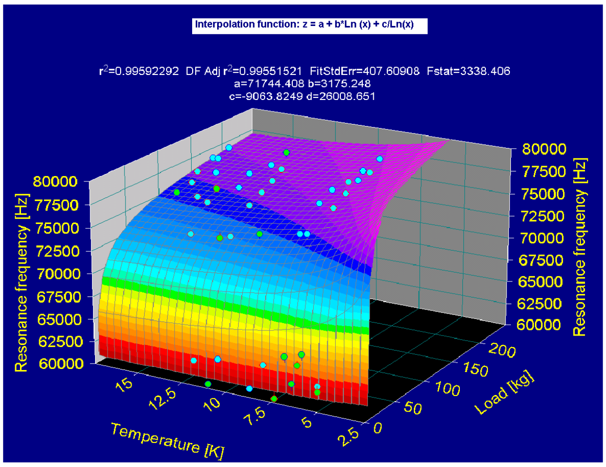


Figure 2. 3D interpolation of position of resonance versus applied force and temperature for EPCOS piezo.

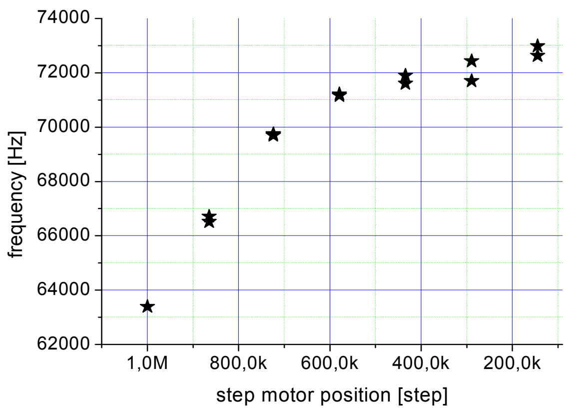


Figure 3. Resonance frequency of EPCOS piezo versus position of step motor.

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 0,7kN for 0 step motor position to 70N for 1 million steps movement (1 step≈1.7nm).

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 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.

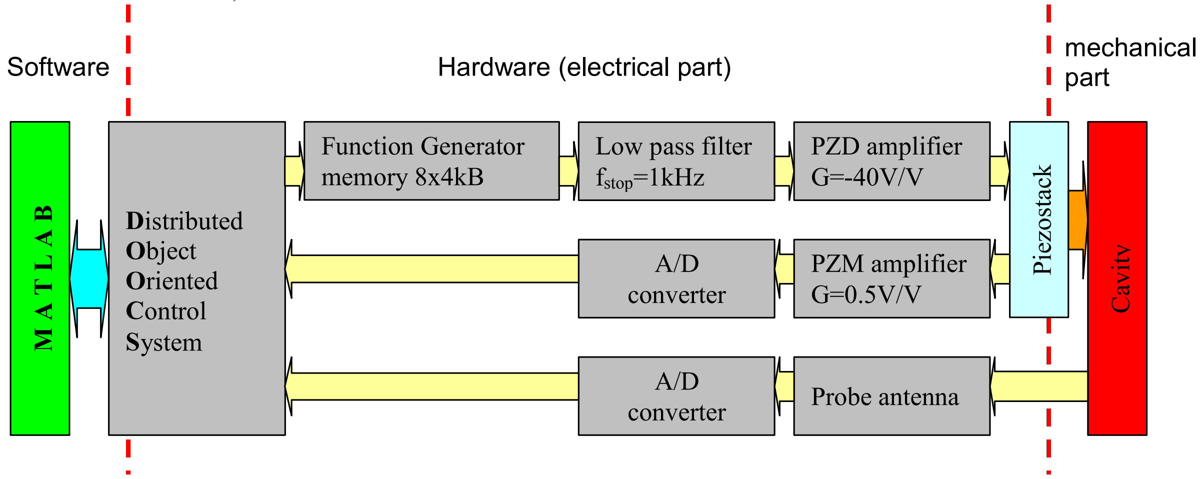


Figure 4. Control system for piezoelement assembled in tuner.

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 5. 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. Currently, 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 might operate improve its lifetime.

In next step, an investigation of more complicated shape of driving voltage is foreseen. Also interesting option is a signal, which will hit simultaneously more than one resonance.

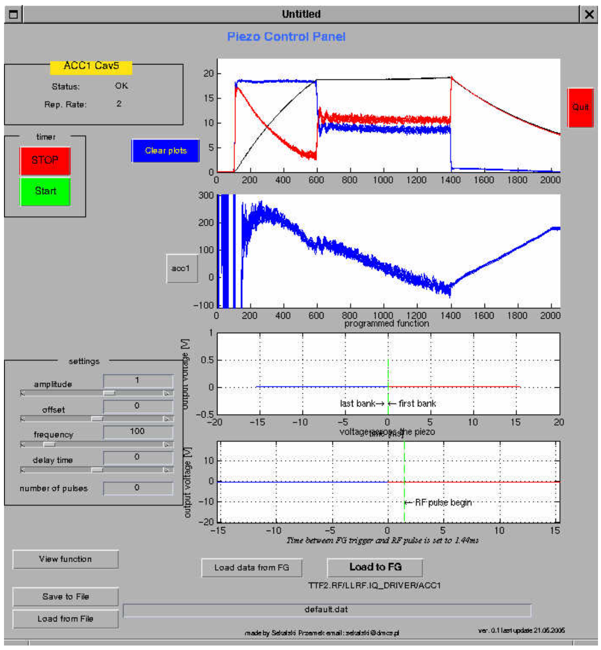


Figure 5. MATLAB GUI for LF compensation

EXPERIMENTAL RESULTS

The experimental results obtained in cavity 5 in module ACC1 of VUV-FEL accelerator is presented in Figure 6. When the fast tuner is switched off, during flat-top the detuning is almost 170 Hz (for 20MV/m field gradient inside cavity), which is a value comparable with cavity bandwidth. However, when piezostack compensation system is activated, the detuning is less than 20Hz.

Sudden fall down of detuning, which is visible in the beginning of flat-top is caused by calculation method and has no physic justification.

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

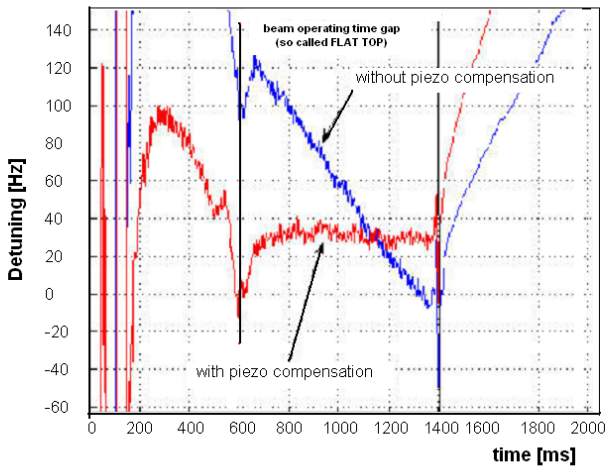


Figure 6. Detuning caused by Lorentz force with and without piezostack based tuner system

SUMMARY

There are several options for cavity tuners (UMI – coaxial tuner, CEA tuners – the old and the new ones). All tuners are simultaneously developing by CEA Sacley in France and University of Milan in Italy. 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 plenty difficulties, which need to be worked out.

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.

First generation of CEA tuner with EPCOS piezostack is already mounted in ACC1 cavity 5 (TTF II). It is possible to reduce detuning caused by LF from 170 to 20Hz during flat-top (almost 90%).

The control signal is set manually nowadays. However, LF is very repetitive from pulse to pulse (according performed test the same settings are adequate for months). The feed-forward and feedback algorithm are under developing.

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-Sacley, IPN-Orsay and DESY-Hamburg laboratories, who helped us during the research.

REFERENCES

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

[4] 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

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

[6] 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

[7] 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

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

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

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

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