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LORENTZ FORCE DETUNING COMPENSATION SYSTEM FOR ACCELERATING FIELD GRADIENTS UP TO 35 MV/M FOR SUPERCONDUCTING XFEL AND TESLA NINE-CELL CAVITIES

P. SEKALSKI[1], S. SIMROCK[2], L. LILJE[2], C. ALBRECHT[2]
1) TECHNICAL UNIVERSITY OF LODZ, DMSC, POLAND
2) DEUTSCHES ELEKTRONEN-SYNCHROTRON, HAMBURG, GERMANY

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ABSTRACT: During the last decade superconducting resonant cavities have became an attractive option for a variety of linear accelerators under construction or in planning. For the X-FEL and TESLA projects, nine-cell 1.3 GHz cavities have demonstrated gradients up to 35Mv/m. Because of the high quality factor, they have very narrow bandwidth. They are susceptible to small changes of dimension caused by high gradient RF field. This effect is called the Lorentz force detuning. The system for dynamic Lorentz force detuning compensation is presented.

INTRODUCTION

Both projects, the TeV-Energy Superconducting Linear Accelerator (TESLA) and the X-ray Free-Electron Laser (XFEL) have the same principle of operation. Nine-cell superconducting resonant cavities (see figure 1) will be used to accelerate electrons and/or positrons.

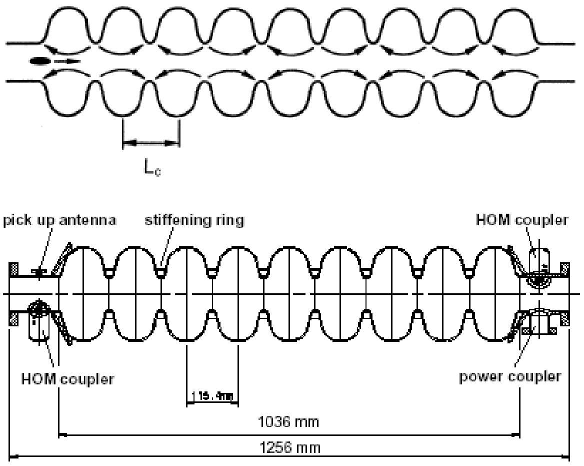

Fig.1. Top: schematic cross section of the 9-cell TESLA cavity with electric field lines. The resonant frequency is 1,3GHz. The cell length equals 1/2 the RF wavelength.
Bottom: Technical layout of the TESLA Cavity with stiffening rings, two higher-order mode (HOM) couplers and flanges. (from [1])

The cavities are made of pure niobium, which is a weak II-type superconductor below 9.2K. Moreover, it has no hysteresis, therefore the heat produced by RF field is low. The main advantage of using superconducting cavities (SC) instead of the normal conducting (NC) ones is their energy efficiency. While in NC about 50% of power is dissipated in the conductors surface and finally transferred to heat. This effect is reduced in SC cavities by six orders of magnitude. Still, RF losses cause heating, which need to be dissipated. In reality 1W of heat deposited at 2K requires almost 1kW of primary AC power in the refrigerator. In spite of this need to cool the whole accelerating system to the cryogenic temperature, still a superconducting system has a better efficiency. Operating temperature of XFEL and TESLA cavities is around 2K.

The cavities are powered by the RF wave with constant frequency of 1.3GHz. The cavities are operated in pulse mode with a RF pulse duration of 1.3ms and a repetition rate of up to 10Hz. During the first 500μs the field inside cavity rises, then during the last 800μs of beam acceleration a constant gradient is kept. Therefore, the RF field has a duty cycle of 1%. The efficiency of accelerating system proposed for XFEL and TESLA projects is so high that almost all energy from RF pulse is directly transferred to the bunch of particles during flat-top. Because the walls of cavity are made of superconductor thus the lost power in the surface is negligible. The quality factor of unloaded cavity is around $Q=10^{10}$. The quality factor of loaded cavity is $3*10^6$, what causes very narrow cavity bandwidth ($f_{1/2}$ is around 200Hz). To reach the resonant frequency the sophisticated system was build. It consists of a step motor, which adjust the size of the cavity after cooling down and pumping. On the one hand this tuner is very effective because it can detune cavity for almost 300kHz. On the other hand it is very slow and needs more than one cycle of machine to change the cavity resonance frequency. Because of the second reason, it cannot be used to compensate fast changes of cavity resonance frequency caused by microphonics or Lorentz forces. The principle of effect is described below.

LORENTZ FORCES DESCRIPTION

The RF electromagnetic field results in radiation pressure, which acts on the cavity walls [2]. As a consequence the cavity deforms, leading to a change in the resonance frequency. The forces act inward near the cell equator and outward near the cell bore. The radiation pressure may be calculated from equation (1):

$$P_s = \tfrac{1}{4}\left(\mu_0\left|\vec{H}\right|^2 - \varepsilon_0\left|\vec{E}\right|^2\right) \tag{1}$$

From calculation and experiments one can develop that the static detuning is proportional to square of the magnitude of accelerating field gradient, what can be written as:

$$\Delta f \sim -kE_{acc}^{2} \qquad (2)$$

where k is a Lorentz force detuning constant equal to 1 Hz/(MV/m)^2 for TESLA/XFEL cavities.

The detuning for different gradient field is shown in figure 2.

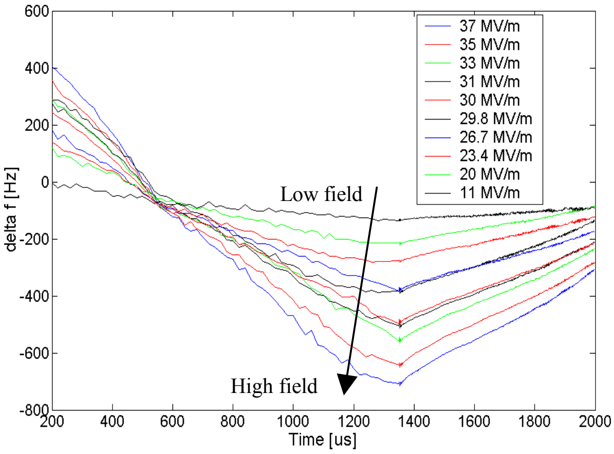

Figure 2. Lorentz force detuning for different accelerating field gradients.

To reduce influence of Lorentz force, it is possible to increase the wall thickness to enhance the cavity rigidity, however this solution increases the cost and what is more important it also reduces the efficiency of cooling by liquid helium. The wall thickness of the XFEL and TESLA cavities has been chosen to be 2.8 mm, and the individual cells are stiffened with rings. As a consequence, the total change of the volume can be compensated by a cavity length change. It was calculated and then measured in the CHECHIA cryomodule that Lorentz forces which appear during pulse operation causes a reduction in cavity resonance frequency. To compensate this effect there is a need to apply the force in opposite direction. Therefore piezoelectric devices are assembled in such way that they pull the cavity when the voltage is applied.

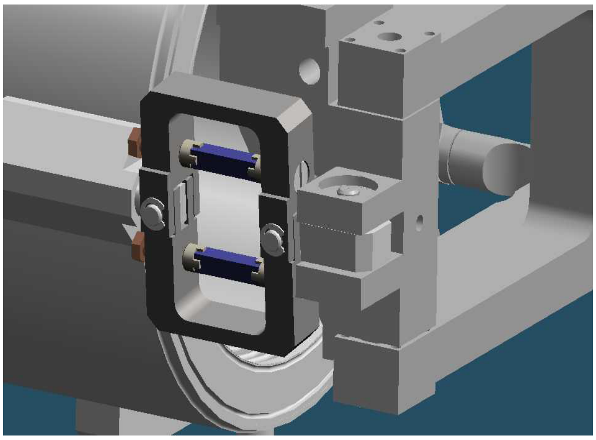

Figure 3. The fixture for two piezoelements used in current Lorentz force tuner (made by H.B. Peters)

The scheme of the fixture is presented in figure 3. One of the piezoelement is used as a sensor, while the second is an actuator.

PIEZOELECTRIC ELEMENTS

At this moment there are four different piezoelectric elements under investigation, which are from the NOLIAC, EPCOS, PiezoMechanik and Physical Instruments (PI) corporations. The overview of their parameters is presented in table 1.

Table 1. Parameters list of piezoelements

	Properties	Units	EPCOS	NOLIAC	Piezo Mechanik	Physical Instruments
	Material name		PZT-Nd34	PZT pz27	PZT 5H	PZT 25
Mechanical	Young modulus:	kN/mm2	51	45	55	35
	Cross Section:	mm2	7x7	10x10	7,5x7,5	10x10
	Length:	mm	30	30	55	36
	Stroke (RT)	µm	40	42	60	30
	Resonance frequency	kHz		66	14	70
	Initial preload		*No*	*No*	400	*No*
	Calculated properties:					
	Stiffness:	N/µm	83	150	56	97
	Blocking force	kN	3,2	6,3	4,0	3,0
Electrical	Max voltage	V	160	200	150	120
	Control speed	V/ms	1,6			
	Charge current	A	20			
	Capacitance(unload)	µF	2,1	5,7	11	
	Capacitance (850N)	µF	3,4			

All piezostacks are low voltage piezoelectric devices. The maximum voltage is around 200V at room temperature (RT), however according to experiments it is possibly to supply piezoelement with higher voltage at cryogenic temperature (according to PiezoMechanik company: the voltage at 2K can be twice as high as at room temperature).

Piezoelements from PI company was delivered with special cryogenic option. The manufacturer assures that the special technique was used to guarantee the flexibility at low temperature. It is important because on the other hand during cooling down the piezo can be destroyed by the internal stresses that is caused by different temperature coefficient of the expansion (TCE) of stack and glue.

THE EXPERIMENT DIAGRAM

The experiment diagram is presented in figure 4. The shape of the applied pulse is generated in the MATLAB environment. Using the DOOCS server (Distributed Object Oriented Control System) it is transmitted to function generator (FG). The drive voltage for is up to 100V. The FG output voltage is in the range ±5V, so that there was need to use an piezo amplifier (PZD) with gain 40V/V. The output signal is discrete in time and in the amplitude. Because the piezoelement behaves more or less as a capacitor, therefore 1kHz low pass filter between PZD and FG is used to reduce current, which flows during rapid voltage change between each step. PZD amplifier drives the piezo actuator, which interacts with cavity in the CHECHIA stand test. The second piezoelement acts as a sensor. It measures the response from the cavity. A second amplifier (PZM) witch gains equal to 1V/V is working as a buffer. Its output is connected to A/D converter. Then the data through the DOOCS server are collected and processed in MATLAB environment.

The detuning system is synchronized with the master oscillator, which triggers all system, including the RF pulse generator.

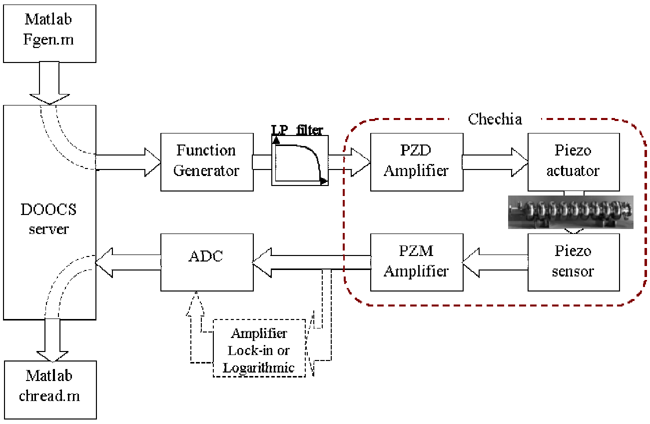

Figure 4. Circuit diagram for Lorentz force compensation.

Two types of experiments were performed, which are described in detail below. In first of them the single pulse compensation was used. In the second, the multipulse signal was generated to compensate the Lorentz force with resonance excitation.

RESULTS OF EXPERIMENT

Single pulse compensation

Firstly, the single pulse compensation was used. Several shape of signal were tested such as triangle, trapezoid and sine wave. The best results was achieved for the sinusoidal shape.

At the beginning, using the sensor piezoelement the main mechanical resonance frequency of cavity with tuner were determined to be 219Hz. Furthermore, from the same sensor the delay time between the FG triggering and the RF pulse has been measured (840µs). This time also includes the delay from signal path. The amplitude of applied voltage is 100V (FG output is set to 2.5V). Using these parameters the half sine wave was set as a driving pulse (see figure 5).

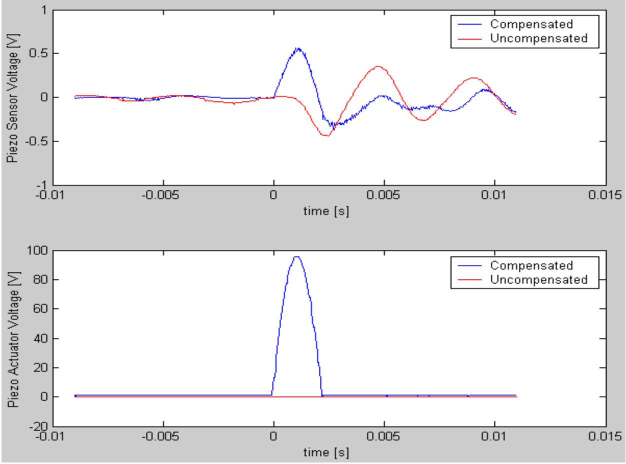

Figure 5. Piezo driver input signal (bottom) and the response from piezo sensor (top). Red line when the piezo actuator was off, Blue one when the piezo actuator is on.

As it is shown in figure 5, if the piezo compensator is switched off, the mechanical ringing excited by Lorentz force detuning appears after the RF pulse (red curve). But if the piezo driving signal is applied the ringing is reduced.

Notwithstanding, the main advantage of the used system is the Lorentz force detuning compensation. In figure 6 is shown the detuning for both possibilities: when the compensation is turned on and off.

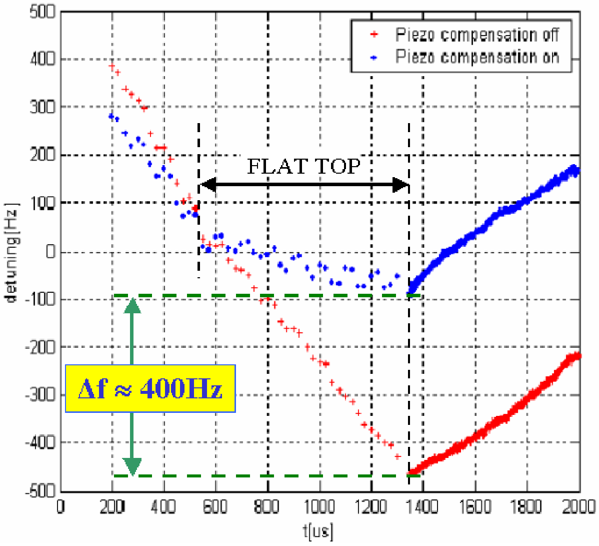

Figure 6. Detuning reduction by single pulse.

Using this simple half sine-shaped pulse, more than 400Hz of the Lorentz force detuning during the flat top was compensated. Additionally, the stability of the phase and amplitude of field was also reached (see Figure 7). All of this measurements were done for an accelerating field gradient of 35MV/m. The cavity was operated stably with these settings without breakdown for more than 700 work hours. Furthermore, even after warming up and cooling down the cavity, the settings for piezo compensation were still effective.

However, there is need to compensate the last 100Hz of the detuning. Therefore we decided to use a multipulse compensation.

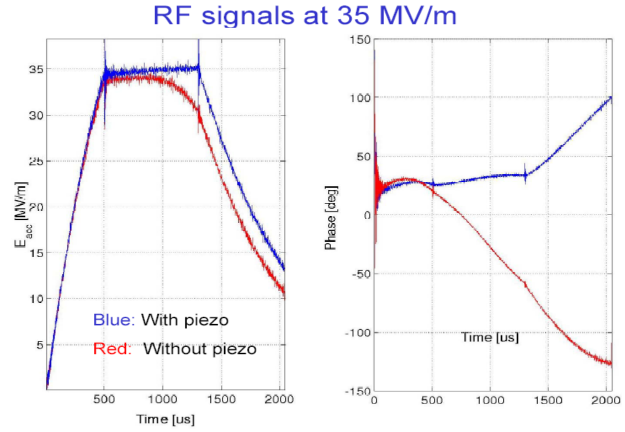

Figure 7.Amplitude and phase of RF signal at 35MV/m

Multi-pulse compensation

To increase the effect of piezoelectric device, the excitation of main mechanical resonance frequency was used. The applied signal is presented in figure 8. It is a three period sine wave of frequency 219Hz. The third period of the oscillation occurs during the RF pulse.

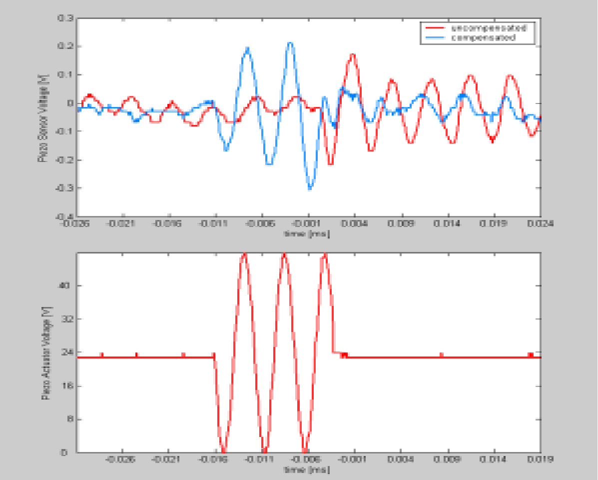

Figure 8. Piezo driver input signal (bottom) and the response from piezo sensor (top). Red line when the piezo actuator was off, Blue one when the piezo actuator is on.

As it is visible, before RF pulse the cavity is ringing with the frequency of signal applied to piezo. The Lorentz force caused by RF field partially cancels this ringing. As a consequence, more than 1kHz of compensation are achieved. Additionally, it is possible to reduce the amplitude of the applied voltage to 40V. This potentially increases the lifetime of the piezoelements, because it works only in narrow range of input signal.

When the RF field is lower, then also the detuning caused by Lorentz force is smaller. Therefore the overcompensation may occur. This effect is presented in figure 9. For 30.8MV/m gradient the compensation during flat top is overregulated.

The peaks in detuning curve come from microphonics. The upset caused by this effect is below 10Hz. However if the repetition of the RF pulse will increase, the microphonics should be also taken under consideration and ought to be compensated.

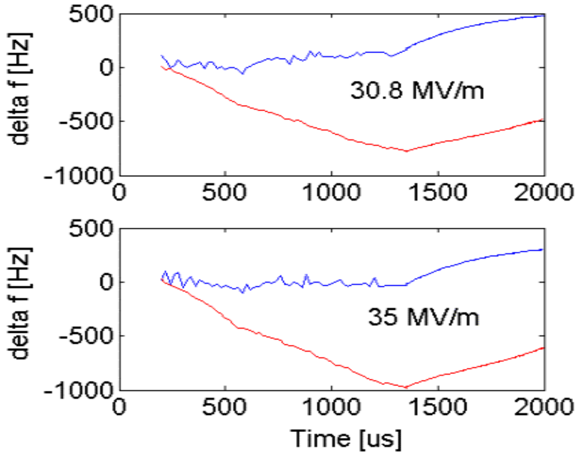

Figure 9. Detuning reduction by multiple pulses for different field gradients.

CONCLUSIONS

It is possible to compensate the Lorentz force detuning in superconducting nine-cells cavities for the TESLA and X-FEL projects using low voltage piezo elements. The principle of such a system is presented above. By a simple feed-forward signal applied to piezoelectric actuator, it is possible to compensate detuning from 400Hz (with single pulse) up to over 1kHz (with three pulses). Additionally, the stability for more than 700 hours of such a system was checked.

Still, there is a need to automate the process of choosing the parameters, because each cavity is slightly different.

ACKNOWLEDGEMENT

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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] P. Schmueser, "Superconductivity in High Energy Particle Accelerators", internal report DESY 2002
[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
[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.