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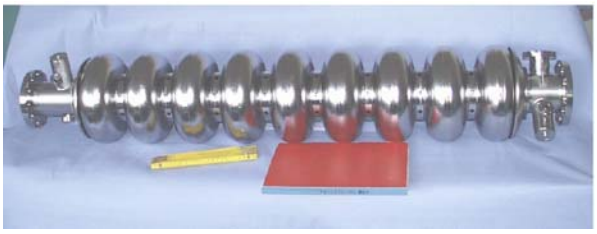

PERFORMANCE OF MAGNETOSTRICTIVE ELEMENT AT LHe ENVIRONMENT

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Abstract

The paper describes preliminary tests of magnetostrictive rod at LHe temperature (4K). This kind of material elongates due to applied magnetic field in a range of several microns. The device might be an option for an electromechanical system, which is necessary for VUV-FEL accelerator to compensate cavity deformation caused by Lorentz forces and by microphonics. Hitherto, piezoelectric stacks were used. However, according to the observation of behaviour of both types of materials at room temperature, one can find that the magnetostrictive elements are more reliable and more immune to wrong mechanical preloads.

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KEYWORDS: **Magnetostriction, Smart material, VUV-FEL tuner**

ABSTRACT: The paper describe preliminary test of magnetostrictive rod at LHe temperature (4K). This kind of material elongates due to applied magnetic field in a range of several microns. The device might be an option for an electromechanical system, which is necessary for VUV-FEL accelerator to compensate cavity deformation caused by Lorentz forces and by microphonics. Hitherto, piezoelectric stacks were used. However, according to the observation of behaviour of both types of materials at room temperature, one can find that the magnetostrictive elements are more reliable and more immune to wrong mechanical preloads.

INTRODUCTION

In superconducting accelerators, like in existing VUV-FEL (Vacuum-Ultraviolet Free Electron Laser), a cavity deformation caused by Lorentz force was observed [1,2]. Resonant frequency of cavity is a function of its shape. As a consequence, if it changes dimensions then this frequency is shifted and system consisted of master oscillator and cavity is detuned. In result, the efficiency of acceleration dramatically decreases.
An electromechanical system is designed to compensate Lorentz force [3-7]. Hitherto the piezoelectric actuators were used to balance the cavity shape. However some issues, i.e. lifetime, suggest that other smart materials like magnetostrictive rods ought to be taken under consideration. These kinds of elements change its length due the applied magnetic field. The common magnetostriction constant is usually in range of several per miles.
Requirements and material samples description are presented below. Additionally, the first experimental results of magnetostriction rod operation at 4K are presented.

ACTUATOR REQUIREMENTS

An active element must accomplish several very strict and tough requirements. First of all the actuator has to work at cryogenic environment. The operation temperature of cavity is set to 1.8K (Liquid Helium under tens mBars pressure). However, the tuner itself is mounted in high vacuum environment (less than 10^{-5} mBar). As a result, the element may not generate too much heat (<0.01W), because in one hand it will be hard to disperse it from device itself, and on the other it will be additional load for cryogenic system.
The stroke of actuator must be in range of 10 microns. Then, it will allow to compensate detuning of around 800Hz, depending on force transposition of mechanical part of tuner. The blocking force is required to be higher than 6kN and the Young modulus of material higher than 45kN/mm^2. Nevertheless, the total dimension of actuator may not exceed 20x20x40mm.
Moreover, the active element should act with control speed of 10µm/100µs. It will be operated in pulse mode by up to 20 percent of the period. However, it must be able to resist 10^{10} of cycles in radioactive area and consume total dose of 2MGy.
At last but not least, the magnetic stay field around the actuator must be lower than 100µT (10 cm from tuner) to keep the superconduction in the niobium cavity.

POSSIBLE MATERIALS

At the current state two types of magnetostrictive elements seem to fulfil above requirements - one of them is fabricated by ENERGEN INC, the other by ETREMA. Material from first company is called KELVIN ALL, the other GALFENOL. There is need to use special materials because the ones commonly used at room temperature i.e. Terfenol-D does not work at LHe environment (see figure 1). The others like TbDyZn are extremely expensive (even 5-10 times more than the described).

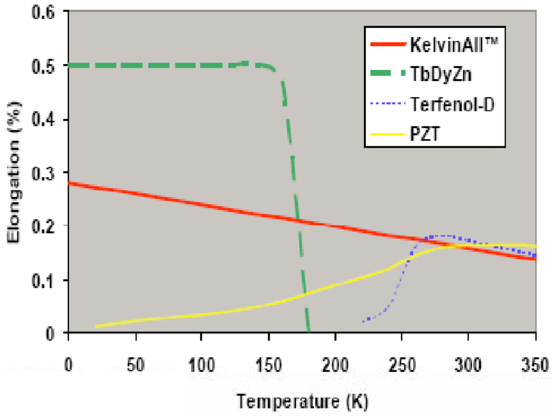

Figure 1. Magnetostriction of different materials in function of temperature (courtesy of ENERGEN).

First of magnetostrictive element rod is made of material called KELVIN All. Its magnetostriction is range of thousands of ppm (see figure 2) [8]. Manufacturer claims that the 18mm length rod has a stroke around 20μm. The full-length elongation takes only 250μs, which stands for control speed of 8μ/100μs. It may operate in radioactive, high vacuum environment. However, currently there is no data about degradation in time caused by radiation. Assumed lifetime is higher than 10^{10}, but a proper test needs to be performed to verify this statement.

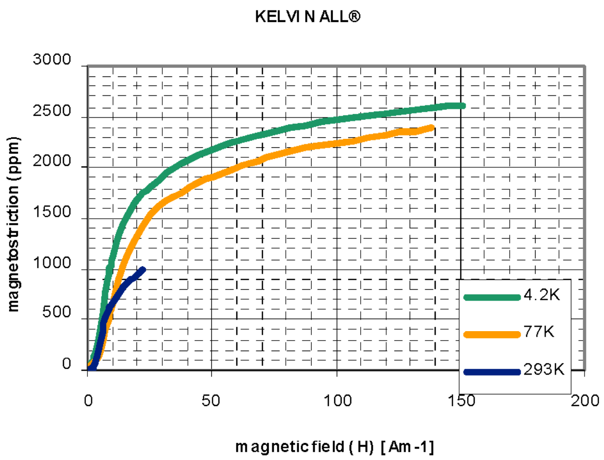

Figure 2. Magnetostriction of KELVIN ALL® material (courtesy of ENERGEN)[2]

The company ENERGEN, INC provide a tuner with magnetostrictive rod inside. The draft view with dimensions and its photo are presented in figure 3.

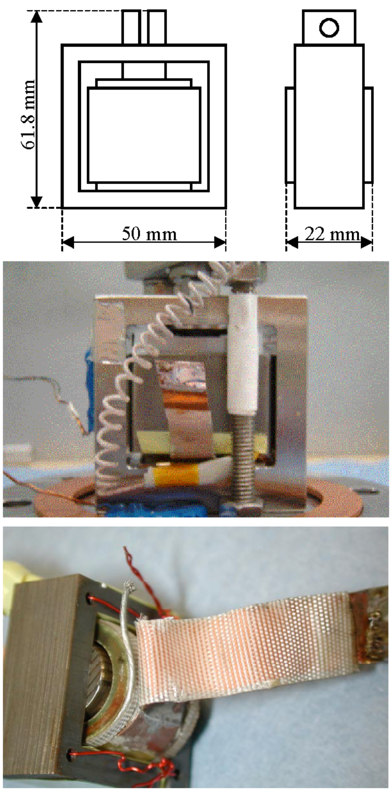

Figure 3. Magnetostrictive element with metal frame - the draft view with dimensions (top) and its photo (middle). At the bottom a magnetostrictive rod with Nb3Sn coil and ferrite ring is presented.

The second actuator is made of GALFENOL (see figure 4). It is a composition of gal, iron and rare earth minerals. Its dimensions are 6x6x20mm. It has smaller magnetostriction than KELVIN ALL by factor of 2-3. Moreover, it has no lamination to reduce edgy current, as the previous one. On the other hand, it is at least twice cheaper than ENERGEN solution. According to the manufacturer, it will fulfil the requirement list, but till now it was tested only in liquid nitrogen.

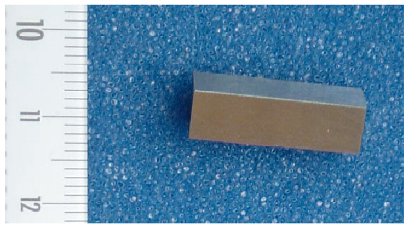

Figure 4. Magnetostrictive rod made of GALFENOL.

EXPERIMENT OVERVIEW

Current test was done to validate the KELVIN ALL materials itself. The experiment was performed in a vertical cryostat. The proper insert was designed (see figure 5). It consists of two main elements: the support with fixture for piezoelement and magnetostrictive tuner and the cover with two thermal cooper connectors. The last mentioned ones allow keeping the superconducting coil made of Nb_3Sn below critical temperature.

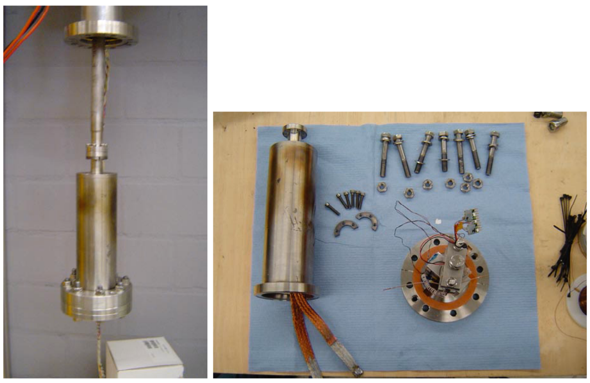

Figure 5. Photos of insert for the vertical cryostat.

Three temperature sensors were glued to base, to magnetostrictive tuner frame, and to metal block close to piezoelectric sensor. They allow controlling heat flow through the system during experiment. Additionally, they indicate if the insert is well thermal stabilized. The whole system was cooled down to 4K.

In the frame, two active elements were assembled in series: piezoelectric from NOLIAC, which works as a sensor, and magnetostrictive from ENERGEN as am actuator (see Figure 6). The special screw mounted on top allows adjusting the system compression. The preload force was set at room temperature to 1.2kN.

To superconducting coil was driven by voltage to current transducer. The device base on APEX PA93 linear power amplifier. The maximum output current is slightly over 8Amps. Over that value amplifier saturates. Remarkable is fact, that the inductance of the coil is 2.4mH, therefore also high voltage is necessary to reload coil with frequency of 1kHz. Due to the heat dissipation, the transducer works only in pulse mode. The input signal is set in Rhode & Schwartz function generator.

The magnetic field inside the coil elongates the magnetostrictive rod. Noliac's Piezo acts as a displacement sensor. When pressed it generates voltage, which was registered on the scope.

Similar experiment with two Noliac piezostacks was already performed (one piezo acted as a sensor, the second as an actuator).

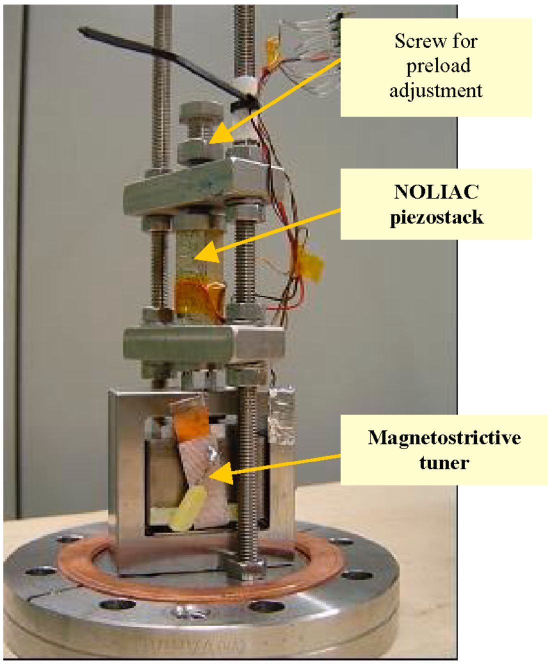

Figure 6. Test overview

EXPERIMENT RESULTS

First of all, the experiment indicates that KELVIN ALL material works at 4K. However, the elongation of the magnetostrictive rod is smaller than presented in datasheet. The coil was supplied by half-sine current wave. The current amplitude was changed from 0.4 to 8.3 Amps. The NOLIAC piezostack output voltage in function of supplied current is presented in figure 7.

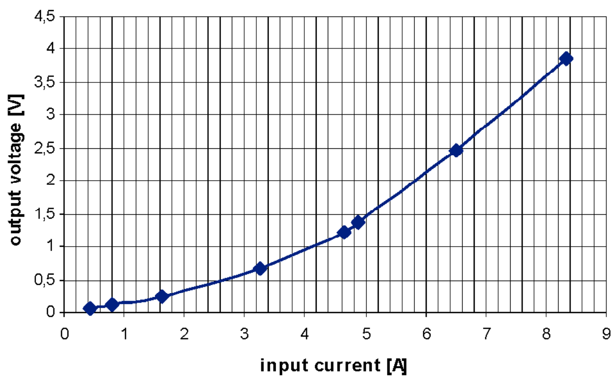

Figure 7. Piezostack output voltage versus applied current to superconducting coil of magnetostrictive tuner

Using algorithm, described in next chapter, the elongation of magnetostrictive rod was calculated, Results are presented in figure 8.

During the preparation of experiment, the 1 cm length wires protruding from shield was crumbled. To avoid future break of superconducting wires, simple string made of wire itself were used to improve elasticity of connection. It is important aims for future design, because small vibration might cause similar troubles in the machine.

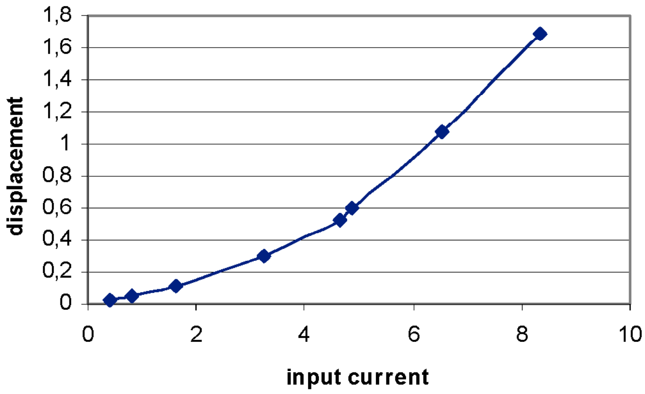

Figure 8. Calculated displacement of magnetostrictive rod versus applied current.

CALCULATION ALGORYTHM

From calculation and previous measurement with two Noliac Piezos connected in series we developed the displacement curve versus the applied current (see figure 9). Using this function, one can find the force applied by the magnetostrictive rod.

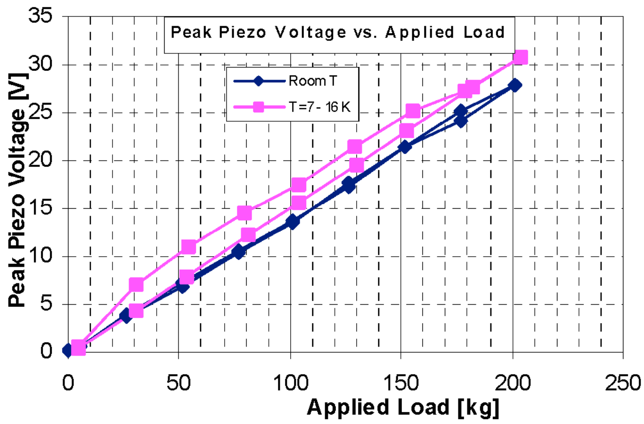

Figure 9. Measured piezo voltage response in function of applied load for NOLIAC piezo at room and cryogenic temperature.

The maximal output voltage was around 4V, therefore according to above curve, one can develop that almost 18kg was applied to piezostack. If we assume that the stiffness of frame was higher than piezo, then the entire load was applied to piezostack directly.

The piezo stack due to the applied force should shrink. Using formula given below, one can find how much piezo changes its length. This value should be equal to magnetostrictive rod enlargement (presented in figure 8):

$$\Delta l = \frac{l}{s} s_{33} F \qquad (1)$$

where:

l – piezostack length equal to 30mm

s – piezostack cross-section area equal to 100mm^2

s_{33} – elastic coefficient equal 23*10^{-12}

F – applied force

CONCLUSIONS

The maximal displacement of magnetostrictive tuner was less than 2um. The data might be not exact, because the preload force and boundary condition were not well controlled (It might happen that the preload force was higher than 1kN, because stiffness of fixture is unknown).

In figure 11, a sample of measured signal is presented. One can find that both signals have similar shapes. Small delay between input and output signal might be observed (around 70us). In principle it might be explained by the magnetostrictive element hysteresis (as it is observed in RT temperature).

Finally, performed experiment does not give the quantify results, but the main goal of test was reached: the tuner was run successfully at LHe temperature. On the other hand, the detailed magnetostrictive rod characterization is strongly required. Using the obtained experiences, the proper experiment will be prepared and performed soon.

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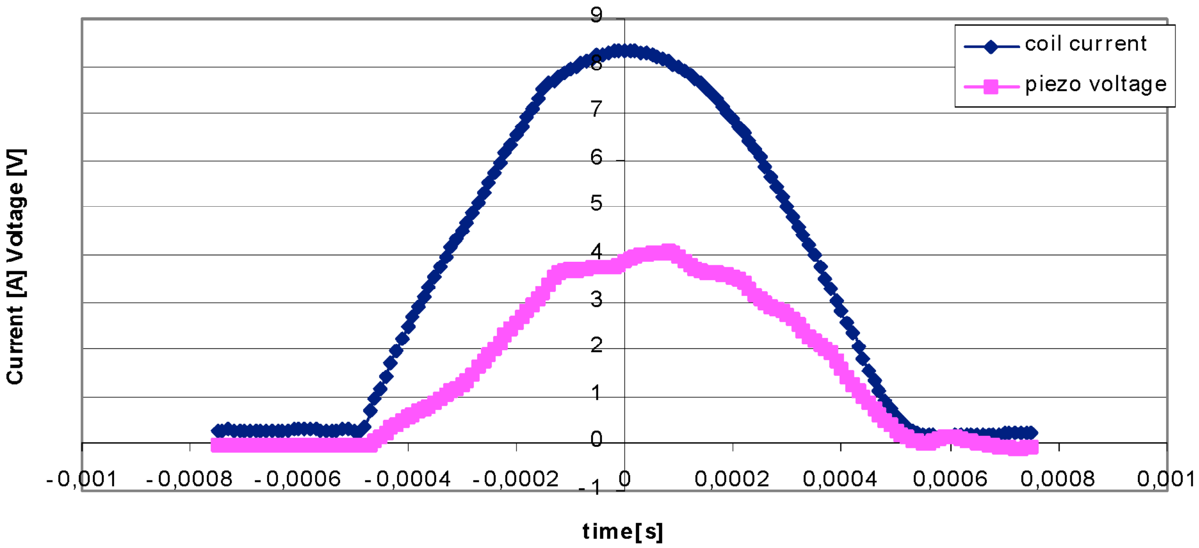

Figure 11. Sample of measured data – input coil's current and output piezoelement's voltage. Parameters of input current are following: frequency =1kHz, amplitude = 8,33A