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STUDY OF DIFFERENT PIEZOELECTRIC MATERIAL STROKE DISPLACEMENT AT DIFFERENT TEMPERATURES USING AN SRF CAVITY*

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Abstract

Piezoelectric actuators are used for resonance control in superconducting linacs. The level of frequency compensation depends on the piezoelectric stroke displacement. In this study, the stroke displacement will be measured with a 1.3 GHz SRF cavity by measuring the frequency shift with respect to the voltage applied. The entire system was submerged in liquid helium. This study characterizes the PZT piezoelectric actuator (P-844K093) and a lithium niobate (P-844B0005) piezoelectric actuator. All these actuators were developed at Physik Instrumente (PI). The piezoelectric displacement was measured at different temperatures.

INTRODUCTION

Piezoelectric (piezo) actuators have a wide array of applications such as in resonance control in SRF linacs and various experiments in dilution refrigerators. In a dilution refrigerator the cooling capacity is on the order of µWs. In these applications a large stroke and small heat dissipation are crucial, two piezo materials will be compared with these characteristics. Piezo actuators exhibit the piezoelectric effect which occurs below the Curie temperature. Materials exhibiting this effect experience a mechanical deformation when an electric field is applied to the material. The opposite effect is also possible where a mechanical deformation of the material will induce an electric field. Lead zirconate titanate (PZT) is the most widely used material for actuators, it provides larger stroke but it heats up rapidly. Lithium niobate ($LiNbO_3$) produces 0.3 % of heat dissipation of PZT but has a stroke of 8.3 % of PZT at room temperature. This comparison uses the nominal voltage of each piezo, see Table 1 for properties of both. From the literature, it is known that $LiNbO_3$ doesn't decrease the displacement stroke as drastically compared to PZT. Thus, when both are at cryogenic temperature the stroke difference won't be as large.

In this experiment, an SRF cavity was used to measure the piezo stroke. The piezo stroke for PZT is cited in the literature as being 10 % of the room temperature value at 4 K [1, 2] and by piezoelectric companies [3, 4]. As reported in [5], LCLS-II cryomodule commissioning showed that the piezo stroke was larger than this value. A more thorough measurement of the piezo stroke is done in this paper to validate the results from the cryomodule commissioning. An SRF cavity was used due to its extreme sensitivity to longitudinal deformation. A 1 nm deformation on the cavity will result in a 2.3 Hz frequency deviation which can be easily recorded. The PZT piezo actuator used in this experiment (P-844K093) consists of two stacks with dimensions given in Table 1. The $LiNbO_3$ actuator (P-844B0005) dimensions are also listed in Table 1. The main results from this paper are that the PZT stroke at 4 K is greater than 10 % of the room temperature value and the piezo stroke of the $LiNbO_3$ actuator is measured with an SRF cavity for the first time. For the PZT piezo actuator the stroke measurements were done from 4 K up to 91 K.

Table 1: Piezoelectric properties of $LiNbO_3$ and PZT actuators used in this paper. For PZT the voltage to obtain the stroke is 0 V to 100 V and for $LiNbO_3$ it is from -500 V to 500 V.

	PIC 050	**PIC 255/252**
Material	$LiNbO_3$	PZT
Length [mm]	36	18
Cross-section [mm^2]	100	100
Stroke (300 K) [μm]	3	15
Stiffness [N/μm]	195	200
Blocking Force [N]	585	3600
Curie Temperature [K]	1423	623
Density ρ [g/cm^{-3}]	5	7.80
Relative Permittivity ϵ_{33}/ϵ_0	28.7	1750

CAVITY FREQUENCY TUNER

The dark-photon search experiment setup [6] was used to conduct the measurements. This setup consists of an LCLS-II tuner that uses a stepper motor and piezos. The cavity-tuner system is supported by an aluminum frame. There are two piezos capsules used to control the frequency, in this case, the PZT and $LiNbO_3$ capsules were

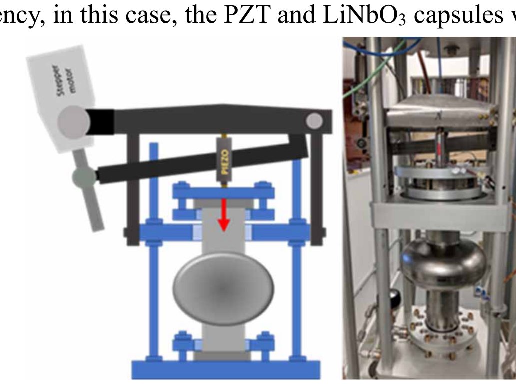

Figure 1: Left: schematic of one cell 1.3 GHz cavity with tuner installed. Right: Picture of the cavity.

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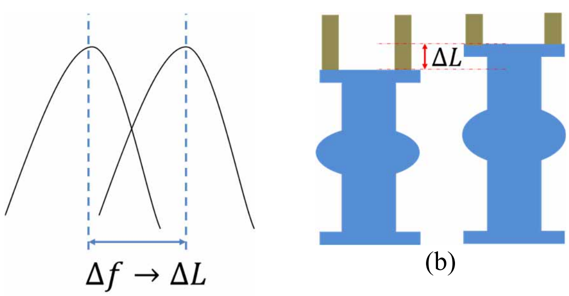
Figure 2: Close-up look at the location of the piezos on the cavity tuner.

used (See Figure 1 and Figure 2). The PZT capsule has a Cernox RTD attached to the PZT body, this is used to monitor the temperature (Figure 2). The piezo capsules are pre-loaded with the tuner to prevent any slack once cooled down. The motor can also be used to further compress the piezos. The whole setup is put in a dewar in the vertical test stand (VTS). The dewar is filled with liquid helium until the entire setup is covered. The frequency sensitivity of the cavity to the longitudinal deformation is 2.3 kHz/µm and the cavity stiffness is 23 kN/mm. The stiffness of the tuner is 20 kN/mm. The piezo stroke to cavity compression efficiency of the tuner is 40 % when both piezos are used, and 20 % when only one piezo is used. The method of the piezo stroke measurement is illustrated in Figure 3 where the frequency shift of the cavity is related to the piezo stroke. The cavity frequency is measured using a network analyzer (NA). The amount of compression ΔL is calculated using the cavity sensitivity of 2.3 kHz/µm. Note that this parameter does not change with temperature.



(a) (b)

Figure 3: (a) Depiction of cavity resonance curve when the cavity is compressed, this frequency shift is related to compression. (b) Schematic of cavity compression by the piezos.

MEASUREMENT AT 4 K

Once the piezos are cooled to 4 K a steady temperature measurement of both piezos is taken. Figure 4 shows the hysteresis from both piezos, the hysteresis of the $LiNbO_3$ is smaller than that of PZT. For the PZT the voltage applied was 0 V to 100 V and for $LiNbO_3$ it was -500 V to 500 V. The hysteresis is correlated with the loss tangent thus showing that the loss tangent of $LiNbO_3$ is smaller than the PZT loss tangent. A smaller loss tangent produces less dielectric heating. After cooling down to 4 K the stainless-steel frame becomes stiffer by 5% (using Young's Modulus) compared to room temperature value, this improves the tuner efficiency by the same amount since now more of the piezo stroke goes to the cavity. This effect is taken into consideration for the stroke calculations. After hysteresis measurements were completed the cavity was then warmed in a period of 24 hours.

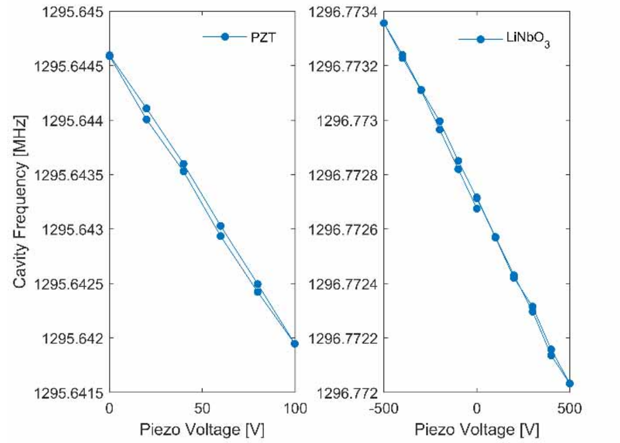


Figure 4: Piezo stroke measured by compressing the cavity and using a NA to measure the frequency shift at 4 K. Left plot is for PZT and the right plot is for $LiNbO_3$.

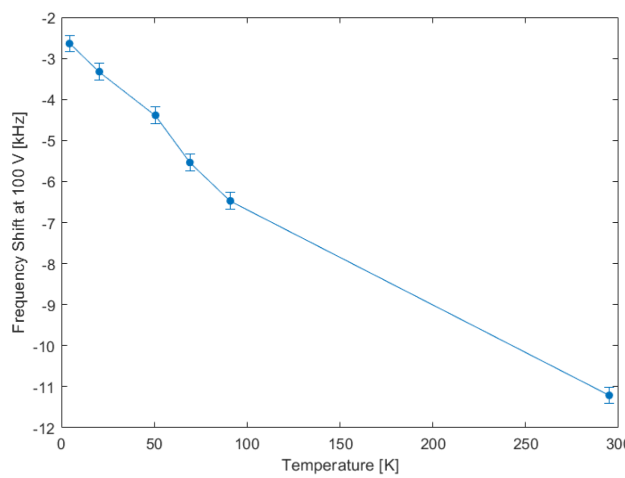


Figure 5: PZT stroke measured by compressing the cavity and recording the frequency shift with a NA during warm-up, the voltage applied to the piezo was 0 V to 100 V.

Figure 5 shows the data for PZT during warmup, the measurements stopped after 91 K because the frequency of the cavity was changing drastically due to the warming of the cavity. When the liquid inside the dewar is blown off and the temperature goes above 91 K the temperature rate of change is 25 K/hr compared to the stable 2 K/hr when the cavity is between 20 K and 91 K. The measurements could not be done for $LiNbO_3$ due to the large frequency shift caused by the thermal effects. Five measurements were taken at each temperature from 0 V to 100 V for PZT and averaged. The stroke of the piezo is calculated with the equation

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Table 2: The piezo sensitivity for 293 K is from 0 to 100 V. At 4 K it is from 0 V to 100 V. For $LiNbO_3$ it is from -500 V to 500 V at room temperature and 4 K.

Piezo Type	Capacitance [μF]		Piezo Sensitivity [Hz/V]		Calculated Stroke [μm]		Piezo Stroke Ratio 4 K/293 K [%]
	293 K	4 K	293 K	4 K	293 K	4 K	
PZT	14	4	-112	-26.4	24.3±1.7	5.4±0.4	22.4±2.2
$LiNbO_3$	.0013	.00125	-1.393	-1.323	3.0±0.3	2.7±0.2	90.4±11.2

$$D = \frac{\Delta f}{E * S}\,, \qquad (1)$$

where Δf is the frequency shift, E is the efficiency of the tuner at 20 % for a single piezo, and S is the cavity frequency compression sensitivity at 2.3 kHz/um. Each of these parameters has an uncertainty, the error for the stroke is given by

$$\frac{\delta D}{D} = \sqrt{\left(\frac{\delta S}{S}\right)^2 + \left(\frac{\delta E}{E}\right)^2 + \left(\frac{\delta \Delta f}{\Delta f}\right)^2}\,. \qquad (2)$$

At room temperature for PZT $\delta\Delta f/\Delta f = .04$, where $\delta\Delta f = 100$ Hz is the error in measurement of the frequency which in this case is due to microphonics and Δf is the total shift in frequency. For $\delta S/S = \delta E/E = 0.05$ at room temperature. At 4 K the error is the same for S and E but for $\delta\Delta f/\Delta f = .02$ where $\delta\Delta f = 20$ Hz. The same values are taken for the case of $LiNbO_3$. The calculated stroke for 293 K and 4 K is shown in Table 2. The calculated stroke at room temperature is within the specified values (10 % error) of PI for both actuators. At 4 K the increase of efficiency of the tuner is taken into account. The piezo stroke ratio from 4 K to 293 K is calculated based on the piezo stroke calculation. The results show that the piezo stroke at 4 K from PZT is reduced to 22.4 % from room temperature. This is twice the value found in the literature [1-4]. For $LiNbO_3$ the stroke from room temperature to 4 K is reduced to 90.4 %.

In comparing the stroke measurement to those found in the literature [1, 2] it should be noted that the actuator is 36 mm long compared to two 18 mm stacks glued together used in this study. The actuator in their study was also not submerged in liquid helium and instead was cooled via conduction. The cooling of the actuator and the size is not the reason why the stroke ratio is different. The displacement of the actuator was measured via a potentiometric displacement sensor. The model number is not provided in the paper, the error from this sensor is needed to determine if this is the source of error. Note also that the voltage applied to their piezo was from -10 V to 120 V. Based on the results from [1, 2], the stroke value they obtain is 5 % to 16 % from 293 to 4 K. Their results also show a variability of stroke with only a 1 K difference. The piezo stroke values for the piezo manufacturers from 293 to 4 K is only 10% [3, 4].

CONCLUSION

The piezo stroke was measured with a 1.3 GHz cavity. The results show that PZT stroke at 4 K is reduced to 22.4 % of the value at room temperature which is larger than the previously reported in the literature. The stroke of $LiNbO_3$ at 4 K is 90.4% of the room temperature value. The piezo stroke of $LiNbO_3$ is now close to that of PZT. The results show that the $LiNbO_3$ actuator can also be used for applications where low heat dissipation is required.

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