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MITIGATION OF DIELECTRIC HEATING OF PIEZOELECTRIC ACTUATORS AT CRYOGENIC TEMPERATURES*

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Abstract

The new generation of low beam intensity superconducting linacs will require high accelerating gradients for new scientific discoveries. The high accelerating gradient cavities in pulsed SRF linacs will experience large (~1000's of Hz) detuning caused by Lorentz force detuning (LFD). The piezo actuators that will be used to compensate large LFD must operate at a nominal voltage of 120V to 150V to deliver the required stroke to the cavity. In this high voltage range, the piezo is expected to warm up drastically due to its location in an insulating vacuum environment. Overheating of the piezo will significantly decrease the longevity of the actuator. A collaboration between FNAL and Physik Instrumente (PI) developed a novel piezo actuator design that mitigates piezo overheating. The design consists of using a metal foam in contact with the piezoelectric ceramic stack for heat removal. The second solution used lithium niobite as an alternative material. A comparison of the temperature stability will be presented and discussed. This study characterizes the dielectric properties of both materials. The results obtained are in the temperature range of 10 K to 300 K.

INTRODUCTION

Piezoelectric (piezo) actuators are used for resonance control of superconducting radio frequency (SRF) cavities in linacs. Linacs with cavities of narrow bandwidth caused by low beam current are especially dependent on the reliability and lifetime of piezo actuators. 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. For resonance control of a cavity, a voltage is applied to the piezo to deform the cavity which results in a change of frequency. The amount of frequency shift depends on the voltage that is applied, a higher voltage will lead to a larger frequency shift of the cavity. The amount of voltage needed for resonance control depends on the linac operation.

During CW operation the main source of vibration noise is caused by microphonics which can result in a detuning of the cavity of ~10-20 Hz and the worst-case scenario 100-150 Hz [1, 2]. The frequency of the microphonics vibration sources is found to be less than 100 Hz. This level of detuning can be compensated with a low voltage on the piezo and by driving it at a frequency less than 100 Hz. The reliability and lifetime of the encapsulated piezo stacks PI PICMA® were tested at Fermilab. During these tests it was shown that the piezo sustained 2×10^{10} cycles (equivalent to 20 years of LCLS-II operation) with a peak-to-peak voltage (V_{pp}) of 2 V on the piezo [3]. During this study, the temperature rise of the piezo was on the order of 5 K. In the case of a linac in pulsed operation a larger voltage is needed to compensate the detuning of the cavities.

For a linac in pulse operation the main source of detuning is caused by radiation pressure known as Lorentz force detuning (LFD). The detuning is given by $\Delta f = k_L E_{acc}^2$ where k_L is the Lorentz force detuning and E_{acc} is the accelerating gradient. This can result in a frequency shift of --500 Hz to -3 kHz depending on the cavity [4-6]. To compensate for this type of detuning a larger voltage must be used. The RF pulse will also excite the mechanical frequencies of the cavity which can be greater than 100 Hz. To compensate for pulse linac operation detuning a larger V_{pp} on the order of 120 V-150 V and frequencies of 200-300 Hz is needed [4-6].

At large V_{pp} and high driving frequency the piezo actuator heats up drastically as shown in Ref. [7]. The piezo actuators are made from lead zirconate titanate (PZT). PZT has a thermal conductivity of 4 W/(m·K) at room temperature and this drops to 0.02 W/(m·K) at 20 K [8] which makes heat transfer difficult. In this paper a novel design for heat dissipation demonstrates that large temperature fluctuations are prevented. Additionally, a lithium niobate ($LiNbO_3$) which has small permittivity was tested for the first time for use in resonance control of SRF cavities. This material exhibits small temperature increases at high voltage.

DIELECTRIC HEATING

The study of dielectric heating of the piezoelectric material is important since large temperature fluctuations can affect the coercive field (the critical electric field that changes the polarization of the material). Additionally, the effects of large temperature fluctuations can cause stress on the ceramic which can result in piezo failure. The first material to be discussed is PZT since this is the most widely used material for actuators due to the large stroke it provides. At room temperature, the PI piezo actuator can operate from -20 V to 120 V (unipolar operation). Below 77 K the voltage range of operation can go down to -120 V. The displacement stroke of the piezo can be doubled when the piezo is operated in the bipolar regime, but the heating

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must be monitored to ensure the temperature will not go above 77 K.

$$\dot{Q}_G = \frac{\pi}{4}(Cf\tan\delta)V_{pp}. \tag{1}$$

The heating of the piezoelectric actuator can be estimated using Eq. 1. The heating estimated from this equation is proportional to the temperature rise $\dot{Q}_G \propto \Delta T$. It was demonstrated that this Eq. 1 is only valid at a small voltage (1 to 50 V). At large voltage, the heating of the PZT ceramic deviates from this formula as shown in Refs. [7, 9]. This deviation is caused by positive thermal feedback [9] and an increase in permittivity at high voltage [10]. The data acquisition and cryogenic setup for the experimental data in this paper are the same as in Ref. [9]. A can is used to keep the piezo under vacuum and this can is then placed inside a Dewar and filled with liquid helium or liquid nitrogen.

Novel Piezoelectric Actuator Design

To prevent the piezo from reaching large temperature fluctuations a collaboration between PI, the manufacturer of PZT piezos, and Fermilab was started to develop a piezo actuator with a high heat dissipation factor. When operated in the cryomodule setting the standard PICMA® piezo has only two contacts through which heat can flow. These are the top and bottom points where the piezo contacts the cavity and tuner (see Fig. 1). Before contacting the cavity and tuner the piezo has ceramic balls (Silicon Nitride) to prevent shearing forces on the piezo.

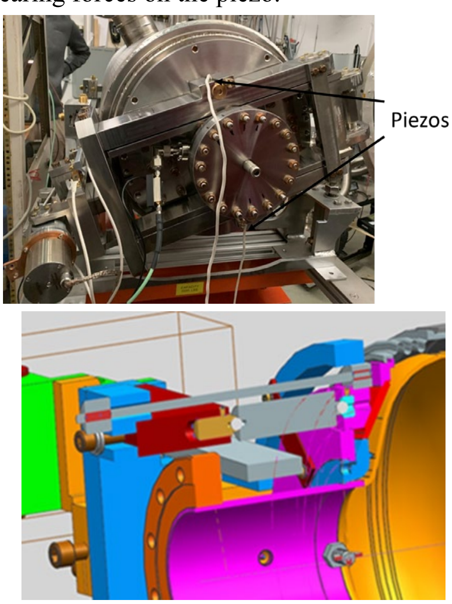

Figure 1: Top: example of piezo location in double lever tuner of 650 MHz elliptical cavity. Bottom: cross-sectional view.

These ceramic balls have a low thermal conductivity so heat flow is not efficient. In the first trial with the standard PICMA® piezo actuator design, these ceramic balls were not considered [7]. The setup up was modified to accommodate the piezos with the ceramic balls to replicate the same configuration in the cryomodule. Testing of the heat dissipation for the copper foam piezo actuator design was done with two piezos of the same model as shown in Fig. 2. Changes were made to the previous setup to accommodate the copper foam actuators and to also consider the effect of the silicon nitride balls since they have low thermal conductivity. In this setup, two heat sinks were used compared to one in the previous setup and two stainless-steel C-brackets to hold the piezos. The same number of temperature sensors and two accelerometers were used.

The conventional methods of cooling a piezo ceramic such as using oil or forced air were not pursued due to the piezo's location in an insulating vacuum and at cryogenic temperature. The best method for heat dissipation was to use a heat sink attached to the actuator. The design of the new piezo consists of placing a high thermal conductivity material in contact with the piezo ceramic. The temperature of the piezo actuator will be in the range of 10 K to 20 K when cooled to 2 K with the cavity. The materials with high thermal conductivity in that range are copper, diamond, and sapphire. Copper foam is used to contact the ceramic and the outer encasing of the piezo actuator. Since the piezo ceramic will be operated at high voltage, a dielectric is used as a buffer between the connections of the copper foam in the ceramic and outer actuator encapsulation (see Fig. 3). Aluminum nitride has similar properties to sapphire, it has high thermal conductivity and small electrical conductivity. The design copper foam piezo actuator is shown in Fig. 3 along with the standard PICMA® design to contrast the designs.

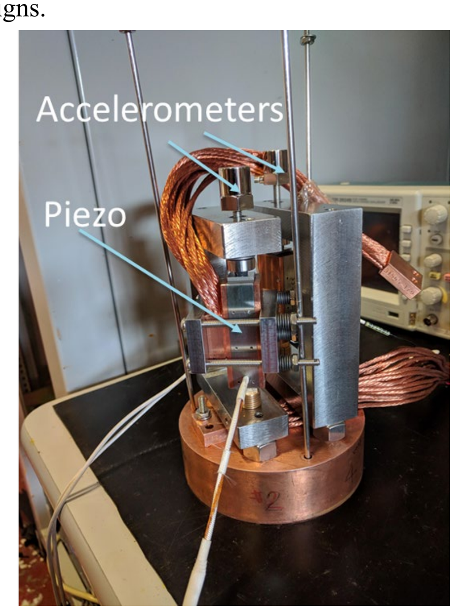

Figure 2: Setup of piezo on the copper disk. The temperature sensors are located inside the actuators. Two heat sinks are used and two accelerometers.

In this design, the encapsulation of the piezo has two copper plates and the inside has copper foam with a dielectric material as an interface between the copper foam and the ceramic. A copper heat sink is attached to the piezo encapsulation. To attach the heat sink the cylinder shape was changed to a rectangular one. Additionally, the encapsulation was optimized for heat transfer and include a preload

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integrated with the housing. This copper foam piezo design has 4 paths ways in which heat can flow compared to the standard PICMA® design which only has two. Additionally, the encapsulation is kept close to the cooling liquid temperature since the copper braid is connected to the rod in the cooling liquid.

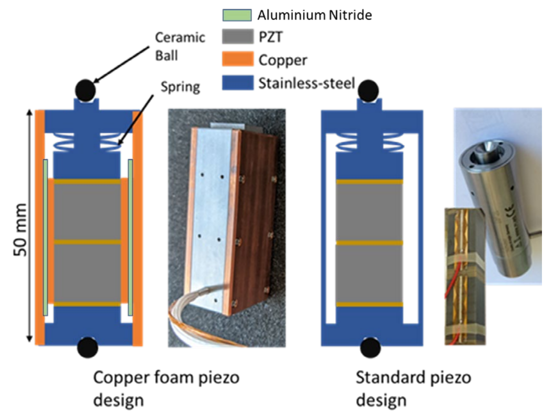

Figure 3: Cross-sectional view of the two piezo designs. One is the new piezo design with copper foam and the other is the standard design.

The simulation of the copper foam piezo design demonstrates that there is better heat dissipation compared to the one without copper foam as shown in Fig. 4. The copper foam piezo design was tested when cooled to 77 K and later to 4 K. In this iteration one of the copper foam design piezo has a heat sink attached while the other does not. The comparison of the new piezo design with the standard PICMA® design results obtained from an earlier section is summarized from plots like in Fig. 5 where the voltage and frequency of the driving waveform are varied. The results are shown in Tables 1 and 2. The ceramic material used is PZT which is used for both the standard PICMA® design and the copper foam design. The table gives the temperature rise of the piezo ΔT and the voltage used. All these trials were done with a driving frequency of 100 Hz.

The heating of a single stack at 77 K of the standard PICMA® design piezo stimulated at 100 Hz and voltage of V_{pp}= 100 V resulted in a temperature increase of 105 K on the ceramic. The same modulation was done to the copper foam piezo with a heat sink with both stacks active, the temperature rise was 18.92 K, demonstrating that the heat sink and the new design improved heat dissipation by a factor of 11. For comparison, the temperature rise was divided by two since both stacks were operated in the copper foam design. The copper foam design piezo without a heat sink had a ceramic temperature increase of 41.73 K with the same modulation. The heat dissipation of the copper foam piezo without a heat sink improved by 3.75 times compared to the standard PICMA® design. The piezos will operate when the cavity is cooled to 2 K and the temperature of the piezos will be around 10 to 20 K. The same tests performed at 77 K were performed when the piezos were cooled with liquid helium. The results are shown in Table 1, the heat dissipation improves by a factor of 14 when comparing the standard PICMA® design to the copper foam with a heat sink. The copper foam design without the heat sinks improves the heat dissipation by a factor of 6 compared to the standard PICMA® design.

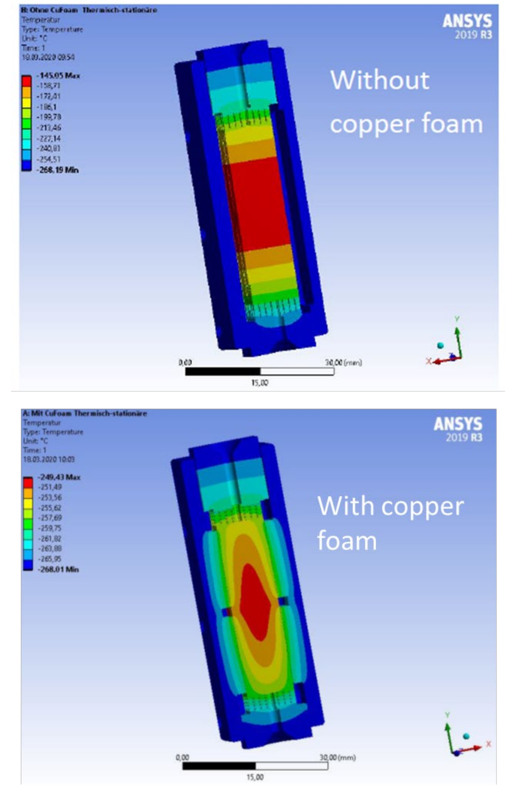

Figure 4: Simulation of heating of piezo with and without copper foam in contact with the ceramic (courtesy of PI).

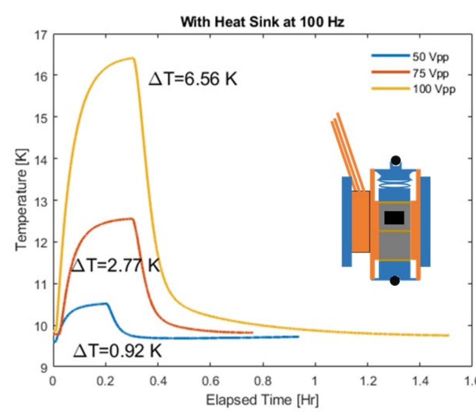

Figure 5: Temperature rise of copper foam piezo modulated with 100 Hz sine wave at different voltages.

The results for the copper foam without the heat sink at both 4 K and 77 K operation are shown in Table 2. The temperature difference between the sensor on the ceramic ($T_{max}^{Ceramic}$) and the one on the capsule shell (T_{max}^{Shell}) is another proxy for calculating the heat transfer improvement. A small temperature difference between the capsule shell and the piezoceramic indicates that there is good heat flow. For the standard PICMA® design cooled with liquid helium and operated at 100 Hz at V_{pp}= 100 V the temperature difference from the inside to the outside encapsulation is 40 K.

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Table 1: Data for trials with liquid nitrogen (LN2) and liquid helium (LHe). The temperature rise on the ceramic is given when the piezo is stimulated with a 100 Hz sinewave at different voltages.

		Standard PICMA® Design	Copper Foam Design
Trial	Voltage [V]	ΔT [K]	ΔT [K]
LN2	50	6	2.01
	100	105	18.92
LHe	50	2.47	0.92
	75	10.52	2.77
	100	91.14	6.56

Under the same operation, the copper foam piezo with the heat sink had a temperature difference is 8 K. A smaller temperature difference from the ceramic to the piezo encapsulation show that the thermal heat transfer improved.

Table 2: Maximum temperature of the standard PICMA® and the copper (cu) foam actuator without a heatsink attached.

	Standard PICMA® Design		Cu Foam Design W/O Heat Sink	
Initial Temp [K]	20	77	14	77
$T_{Ceramic}^{max}$ [K]	110	183	29	120
T_{Shell}^{max} [K]	71	131	21	96

The large dielectric heating observed in the standard PICMA® design was due to the positive thermal feedback of the piezo. The copper foam piezo with a heat sink matches the expected temperature rise from Eq. 1 for modulation below V_{pp}= 75 V. At higher voltage, there is a deviation but not as large compared to the standard PICMA® design result which was 4.5 times larger than the dielectric heating formula. The piezo temperature increase during liquid helium operation and with a driving waveform of 100 Hz at V_{pp}= 50 V was 0.92 K. At 100 Hz and V_{pp}= 100 V the temperature increase is 6.56 K, the expected temperature increase from the formula is 3.68. These results indicate that there is still a discrepancy from the formula by a factor of 1.68. This difference is due to the increase in permittivity of the ceramic at high voltage [10].

Lithium Niobate Piezo Actuator

The piezo heat dissipation can be improved by changing the design and adding a heat sink as shown in the previous section. Another way to minimize dielectric heating is by using a different piezo material with a smaller dissipation factor and constant dielectric properties with respect to the driving voltage. Lithium niobate ($LiNbO_3$) exhibits a small permittivity and dissipation factor as shown in Table 3. The piezo was developed by PI and it is a single crystal. The measurements for the $LiNbO_3$ material were done with the same setup as shown in Fig. 2. A temperature sensor was attached to the metal encasing of the $LiNbO_3$piezo to infer the temperature inside. This piezo did not include a sensor directly attached to the crystal compared to the PZT design. This material can operate in bipolar mode reaching a maximum of V_{pp}= 1000 V at any temperature. It is also a ferroelectric like PZT but exhibits a smaller hysteresis.

Table 3: Piezoelectric properties for $LiNbO_3$ and PZT actuators used in this paper.

	PIC 050	PIC 255/252
Material	$LiNbO_3$	PZT
Length [mm]	36	18
Cross-section [mm^2]	100	100
Stroke (300 K) [μm]	3	18
Stiffness [N/μm]	195	200
Blocking Force (300 K) [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

The maximum stroke displacement is 3 µm at room temperature from -500 V to 500 V. This is 12 times smaller than the stroke produced by the PZT piezo which is 36 µm at room temperature for the same length. Note that this is comparing two stacks of PZT glued together to be the same length as the $LiNbO_3$ piezo. This larger difference decreases when the piezo is cooled down.

The lithium niobate piezo was first cooled down with liquid nitrogen to reach a temperature of 77 K. Using the dielectric heating Eq. 1 the power generated by the piezo is estimated to be on the order of µW with driving voltage of V_{pp} = 500 V and at 200 Hz. The results from stimulating the piezo at V_{pp} = 500 V and at 200 Hz yielded no temperature increase on the metal shell of the piezo encapsulation. This is due to the small heat generated from the piezo. It is possible that the temperature on the crystal might have gone up but only the temperature on the outside of the encapsulation was measured. Further testing at higher voltages was left for the cooldown to 4 K.

The capacitance and dissipation factor were measured with the LCR meter with V_{pp}= 1 V at 1 kHz during the cooldown of the setup. The results are shown in Fig. 6. The capacitance is 13.2 nF and the dissipation factor is estimated to be about 3×10^{-3} at room temperature. At a temperature of 12 K, the capacitance is 150 times smaller than the PZT and the dissipation factor is 28 times smaller compared to the PZT value. These small values indicate that the power dissipation will be small. Additionally, the capacitance only changes to 92 percent of the capacitance at 293 K when cooled to 12 K. The capacitance of the PZT changes to 27 percent for the same temperature change. The capacitance and stroke displacement are proportional, thus it is expected that the $LiNbO_3$ piezo will only decrease stroke to 92 percent of the room temperature value.

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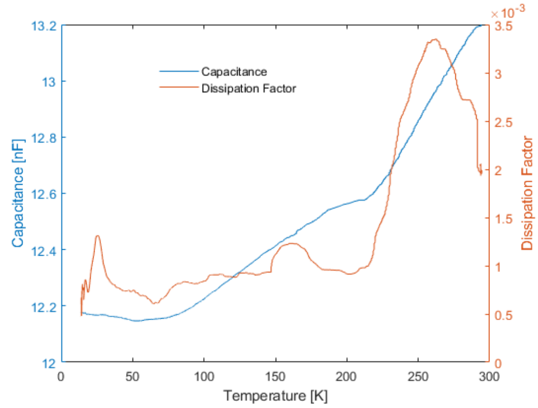

Figure 6: The capacitance and dissipation factor are measured with an LCR for the lithium niobate piezo at 1 kHz at V_{pp}= 1 V.

The $LiNbO_3$ piezo was cool down further with liquid helium to reach a temperature of 12 K. The voltage was increased to V_{pp} = 1000 V with a sine wave of 200 Hz since the temperature rise was small for smaller voltage. In this case the temperature on the outside of the capsule increased by 0.1 K as shown in Fig. 7. The temperature rise is small and thus shows that $LiNbO_3$ material is an alternative to PZT albeit with a smaller stroke size. The stroke of the PZT piezo with both stacks at a temperature of 12 K will be reduced to 9.72 µm at 100 V. At 1000 V and at 12 K the stroke of the $LiNbO_3$ piezo is reduced to 2.76 µm. This difference is now reduced by a factor of 3.5. The typical frequency sensitivity of an SRF cavity is 200 to 300 $\frac{Hz}{\mu m}$. The $LiNbO_3$ actuator can thus compensate up to 552 Hz of detuning.

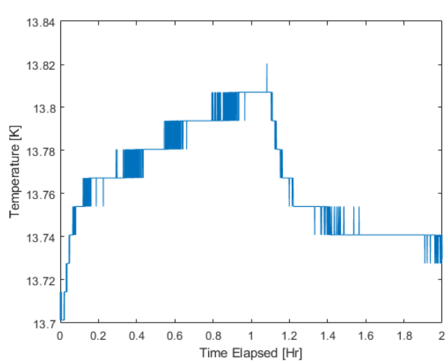

Figure 7: Temperature rise of the $LiNbO_3$ piezo with a sine wave V_{pp} = 1000 V and 200 Hz.

CONCLUSION

A novel piezoelectric actuator design was developed and tested yielding a reduction of heating by a factor of 14 at liquid helium temperatures. The copper foam design with and without the heat sink shows excellent heat dissipation improvement in both 77 K and 4 K environments. The results demonstrate that the copper foam piezo can be operated in bipolar mode when cooled with liquid helium to increase the stroke without reaching the 77 K threshold. This new design also succeeded in stopping the positive thermal feedback. The piezoelectric material with no copper foam undergoes expansion and contraction during large temperature fluctuations on the order of 100 K. These contractions cause stress on the ceramic, by preventing large temperature fluctuations due to heating the PZT copper foam design improves the lifetime. The properties of an actuator made from the lithium niobite piezo ceramic were studied for use in SRF cavity resonance control for the first time. The lithium niobate piezo ceramic actuator shows no heating but with a compromise of a smaller displacement stroke. Even with a smaller stroke this actuator can still compensate detuning up to 550 Hz which is in the range of most high gradient pulsed linacs.

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