ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLM64

HIGH DYNAMIC VOLTAGE RANGE STUDIES OF PIEZOELECTRIC MULTILAYER ACTUATORS AT LOW TEMPERATURES

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Abstract

Piezoelectric actuators are used for resonance control in superconducting linacs. In high accelerating gradients linacs, such as those operated in a pulsed mode, require a large operating piezo voltage. This is due to the Lorentz forced detuning which causes a large frequency shift and is compensated with an active piezo-tuning system. In this high dynamic voltage range the piezo is expected to warm up drastically due to it being in an insulated vacuum The capacitance, dielectric losses, piezo stroke (based on geophone), and thermal properties such as heating are obtained in the temperature range of 20K to 300K of the piezo actuator P-844K075 that was developed at Physik Instrumente will be presented and discussed.

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. The reliability and lifetime of the encapsulated piezo stacks PICMA P-844K075 were tested under a continuous wave (CW) operation for the LCLS-II project. 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 [1]. 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.

Piezo actuators use the piezoelectric effect which occurs when an electric field creates a mechanical deformation on the crystal. The opposite effect is also possible where a mechanical deformation of the crystal will induce an electric field. For resonance control 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 results in a detuning of the cavity of ~10-20 Hz and in the worst-case scenario 100-150 Hz [2]. The frequency of the microphonics vibration sources is found to be less than 100 Hz [2]. This level of detuning can be compensated with a low voltage on the piezo and by driving it at frequency less than 100 Hz. For a linac in pulse operation the main source of detuning is caused by radiation pressure known as Lorentz force detuning (LFD). This can result in a frequency shift of -500 Hz. In order 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. In order to compensate for pulse linac operation detuning a larger V_{pp} on the order of 120 V-200V and frequencies of 200-300 Hz is needed.

The piezo actuators are made from lead zirconate titanate (PZT). PZT has a thermal conductivity of 4 $W/(m \cdot K)$ at room temperature and this drops to 0.02 $W/(m \cdot K)$ at 20 K [3] which makes heat transfer difficult. At large V_{pp} and high driving frequency the piezo actuator is expected to heat up dramatically. The majority of the SRF linacs such as SNS, Eu-XFEL, LCLS-II, and ESS employ tuner system with piezo-actuators located inside a cryomodule (CM) at insulated vacuum. In this configuration the stroke of the piezo is maximized by being closer to the cavity. Additionally, a humid free environment increases the overall lifetime of the piezo by preventing voltage breakdown due to water creeping into the ceramic. In order to increase overall lifetime of the piezo actuators for a pulsed linac this study will characterize the piezo heating at large V_{pp} values at cryogenic temperatures and in an insulated vacuum.

THEORY

Self-heating Generation Model

The temperature dependence of the piezo with respect to time can be model with a 1-D self-heating equation based on the first law of thermodynamics. The behaviour of the temperature rise for different voltages and frequencies shows that the rise is proportional to $\left(1 - e^{-\frac{t}{\tau}}\right)$ [4]. Additionally, this model can be used to estimate the internal heat generation of the piezo when an empirical formula is not known. For this derivation a uniform temperature distribution and isotropic material is being assumed, the equation then can be written as

$$\dot{Q}_G - \dot{Q}_d = mC_p \frac{dT}{dt} \tag{1}$$

where $\dot{Q}_G$ is the internal heat generation due to dielectric losses and $\dot{Q}_d$ is the heat dissipation; m is the mass; and C_p is the specific heat capacity of PZT. At low electric field (voltage) the heat generation can be approximated by

$$\dot{Q}_G = \frac{\pi}{4}(C \tan\delta) f V_{pp}^2 \tag{2}$$

where C is the capacitance of the piezo; $\tan\delta$ is the dissipation factor; f is the driving frequency of the piezo; and

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. Additional support provided by award number DE-SC0018362 and Michigan State University.

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V_{pp} is the peak-to-peak voltage drive of the piezo. Eq. (1) can be used to fit the data and obtain the heat dissipation from the fit since Eq. (2) no longer holds at large values. A measurement of the heat generation must be made to find the value as discussed in [4].

In order to solve Eq. (1) it is assumed that the specific heat capacity of the piezo as well as the dielectric losses are not dependent on temperature. As it will be shown later this is not true but it's a good approximation. The heat dissipation for the piezo is modelled by

$$\dot{Q}_d = R_{Th}(T - T_o) \tag{3}$$

where R_{Th} is the modified heat transfer coefficient which is assumed to be independent of T; T_o is the initial piezo temperature; and T is the temperature of the piezo. The modified heat transfer coefficient is defined as $R_{Th} = h_{eff}A$ where h_{eff} is the effective heat transfer coefficient seen by the piezo and A is the area where the heat is transferred. Solving Eq. (1) gives the following solution

$$T = T_o + T_\infty\left(1 - e^{-\frac{t}{\tau}}\right) \tag{4}$$

$$\tau = \frac{mC_p}{R_{Th}} \tag{5}$$

$$T_\infty = \frac{(\dot{Q}_G + R_{Th}T_o)}{R_{Th}} \tag{6}$$

where Eq. (5) is the time constant and Eq. (6) is the steady state temperature reached after a long time. The heat generated by the piezo ($\dot{Q}_G$) can be obtained by Eq. (5) and (6). In order to obtain R_{Th} to solve for $\dot{Q}_G$ the heat capacity of PZT at the steady state temperature T_∞ is used. This model is then used to measure $\dot{Q}_G$.

EXPERIMENTAL RESULTS

The experiment was conducted at a specialized facility constructed at FNAL for testing instrumentation inside insulated vacuum at cryogenic temperature. For the experiments liquid nitrogen (LN) and helium (LHe) were used to cooldown the setup. Two piezo capsules each consisting of two $10\,mm \times 10\,mm \times 18\,mm$ stacks of PZT glued together were placed on top of a thick copper disk which acted as the base for the piezos and as the heat sink. The copper disk along with the piezo capsules was enclosed in a can and kept under vacuum at 10^{-3} Torr, the configuration is shown in Fig. 1. The data acquisition methods as well as other details of the set up are discussed in another paper [4]. A total of 4 Cernox sensors were used to measure the temperature. In order to verify that the piezos actuators were being driven geophones were mounted on each of the capsules.

At larger voltages the heat generation no longer follows Eq. (2). $\dot{Q}_G$ can be obtained by fitting the temperature rise of the piezo with Eq. (4). The value from the fit are then compared to that of Eq. (2) using the values of C and $\tan\delta$ from Fig. 2 at the steady state temperature (T_∞) during the rise. Figure 2 shows that C and $\tan\delta$ decrease with temperature.

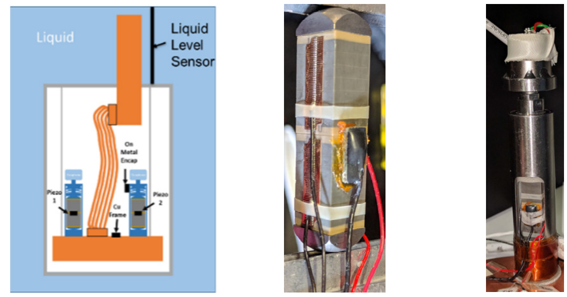

Figure 1: (a) Schematic view of the inside of the can. (b) Two piezo stacks with Cernox sensor attached. (c) Completed encapsulation of the piezo stack with geophone mounted on top.

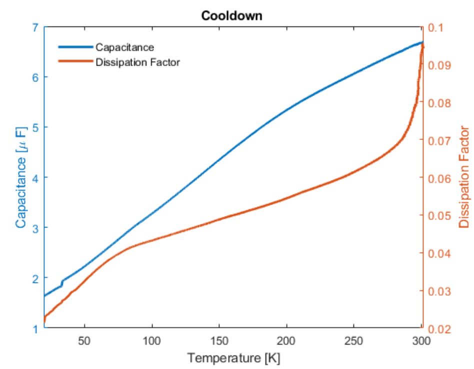

Figure 2: Capacitance and dissipation factor of the PICMA actuator with respect to temperature.

Piezo Heat Generation Model Comparison

Figure 3 shows the result of the fit for the trial with a sine wave of 100 Hz at 100 V_{pp}. The temperature rise from the initial value was of 91 K, the results shows that the temperature rise follows Eq. (4).

Table 1: Power Generated by the Piezo from Eq. (2) and from the Fit at the Steady State

$\dot{Q}_G$ (*Eq.* **4**) [mW]	$\dot{Q}_G$(fit) [mW]	f [Hz]	V_{pp} [V]
27.9	29.6	300	50
20.7	20.5	100	75
112.8	191.3	100	100
705.0	1178	300	100
1557.2	2205	400	100

$\dot{Q}_G$ is obtained from Eq. (2) at the steady state temperature as well from using Eq. (6). Eq. (6) is solved from the values obtained from the fit of Eq. (4). The results for various fits is shown in Table 1. The results show that at voltages below 75 V the $\dot{Q}_G$ from Eq. (2) at the steady state are similar to that of the fit. At voltages larger than 75 V the values start to deviate. This is due to the large temperature change of the piezo, in this case C, $\tan\delta$, and C_p change significantly. Additionally, C and $\tan\delta$ also increase with respect to the voltage applied [5]. This helps explain why the values are larger than then the ones predicted by Eq. (2). Comparing these values to the helium consumption given in [4] show that the ratio of helium to consumption to that of Eq. (2) and the fit are not in agreement.

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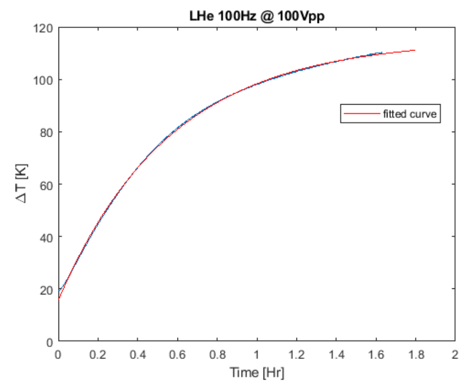

Figure 3: Fit of Eq. (4) for temperature rise of piezo driven by 100Hz and 100 V_{pp} sine wave.

The behaviour of the temperature rise of the piezo for several trials with different voltage, frequencies, and starting temperatures are shown in Fig. 4. Figure 4 also shows the time constant for each of the trials. To reach the steady state temperature of the piezo can take several hours. This is due to the small thermal conductivity of the piezo. The time constant τ can be used with Eq. (4) to predict the temperature rise of the piezo once the value of $\dot{Q}_G$ is known.

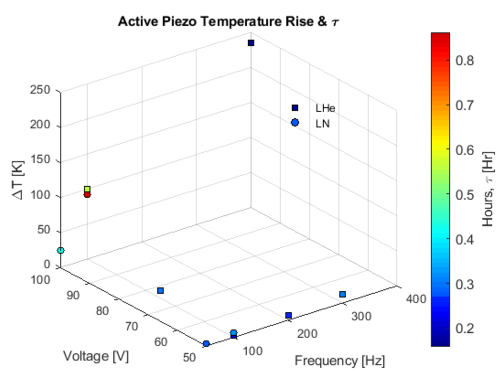

Figure 4: Temperature rise of the piezo with respect to voltage and frequency. The time constant calculated from the fit of Eq. (4) is show for each trial.

For each of these trials the temperature increment of the copper disk is shown in Fig 5. The temperature rise of the copper disk can range from 1 K to 16 K. In the case of 50 V_{pp} the temperature rise of the copper disk is small on the order of 2 K for the largest frequency. At large values V_{pp} heat transfer from piezo could lead to cavity quench. The piezo heat generation model can be used during tuner design to prevent heat spreading to the cavity.

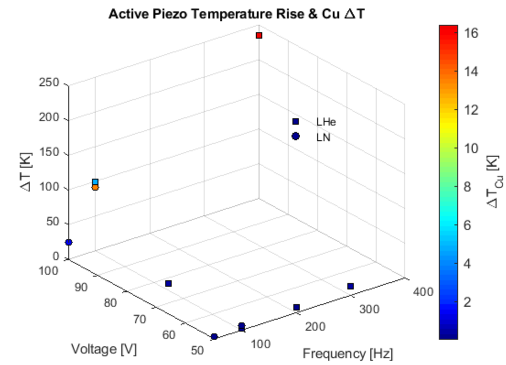

Figure 5: Temperature rise of the piezo with respect to voltage and frequency with the rise of temperature of the copper disk.

The results from the geophone shown in Fig. 6 demonstrate that the piezo stroke also increases with temperature. The increase of the piezo stroke can also be modelled with Eq. (4) but instead of temperature the stroke is used. Modelling the piezo stroke this way will be beneficial since the piezo stroke can increase 2.58 times with a temperature increase of 91 K as shown in Fig. 6.

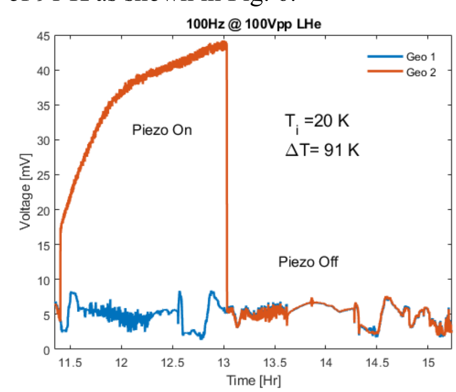

Figure 6: Voltage of geophone during the trial at 100 Hz at 100 V_{pp}.

CONCLUSION

During a pulsed linac operation the piezo electric actuators must deliver large stroke by being driven with large amplitude voltage. The dielectric and thermal properties of the PI P-844K075 piezoelectric actuator were study at cryogenic temperatures with large V_{pp}. The results show that the capacitance and dissipation factor decrease with respect to temperature. A model derived using the first law of thermodynamics shows that during operation the piezo actuators temperature rise dependence follows Eq. (4). This model can be used to predict the temperature rise of the piezo. Additional studies are needed to explain the discrepancy between power needed for the helium consumption and the power generated by the piezo. Lastly the parameters obtained from Eq. (4) can also be used to model the piezo stroke.

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