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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 over-heating. 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 for both materials. The results obtained are in the temperature range of 10 K to 300 K.

Slim Blade Tuner

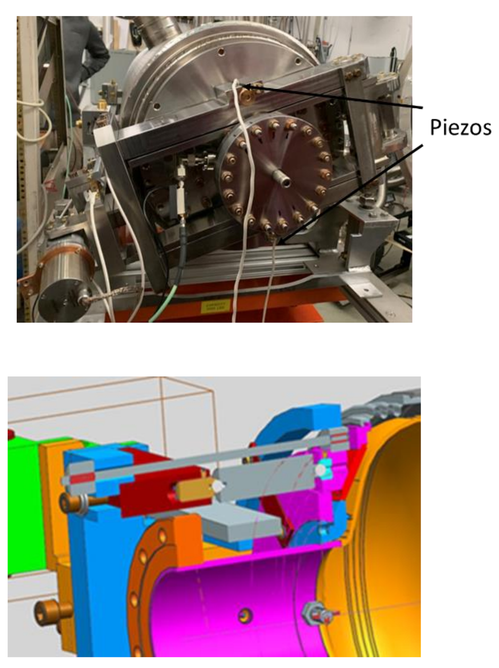

Figure 1: Top: example of piezo location in double lever tuner of 650 MHz elliptical cavity. Bottom: cross-sectional view.

- 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 to -3 kHz depending on the cavity .
- 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.

- 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 which makes heat transfer difficult.

Novel Piezo Design

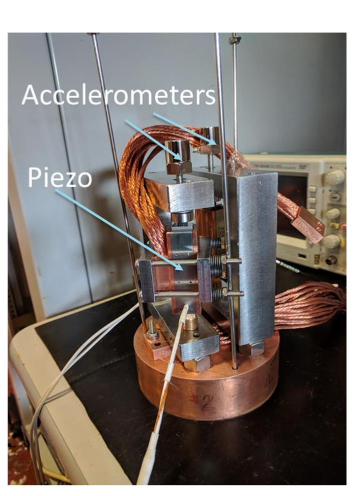

Figure 2: Setup of piezo on the copper disk. The temperature sensors are located inside the actuators. Two heat sinks are used and two accelerometers.

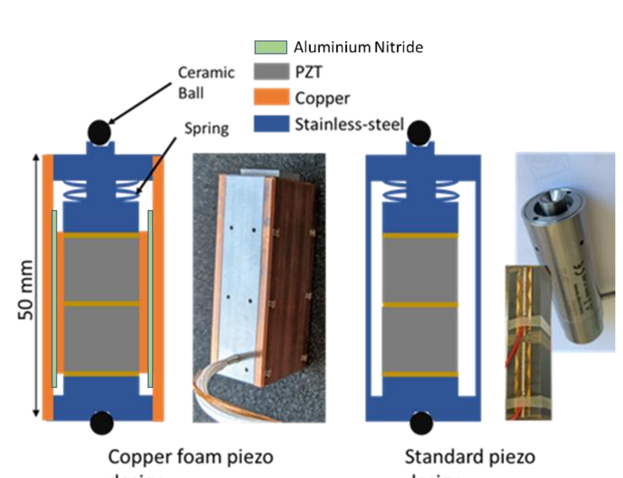

Figure 3: Cross-sectional view of the two piezo designs. One is the new piezo design with copper foam and the other is the standard design.

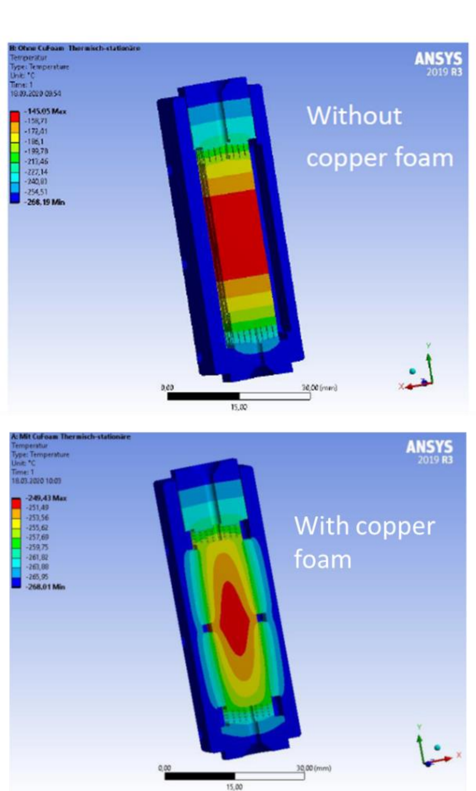

Figure 4: Simulation of heating of piezo with and without copper foam in contact with the ceramic (courtesy of PI).

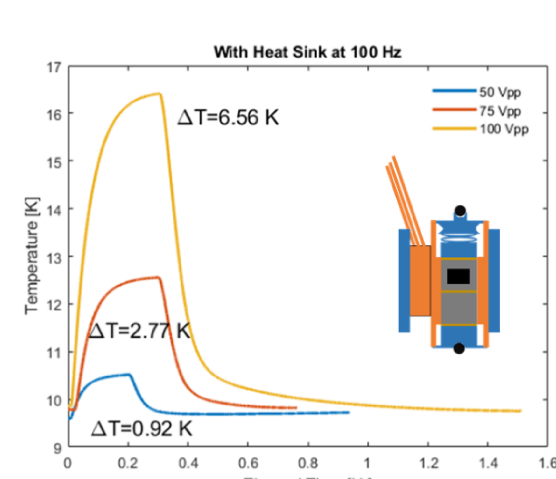

Figure 5: Temperature rise of copper foam piezo modulated with 100 Hz sine wave at different voltages.

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]	$\Delta T\ [K]$	$\Delta T\ [K]$
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

- The design of the new piezo consists of placing copper foam 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

Novel Piezo Design

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 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.
- 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.

$LiNbO_3$ Piezo Actuator

Table 3: Piezoelectric properties for $LiNbO3$ 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

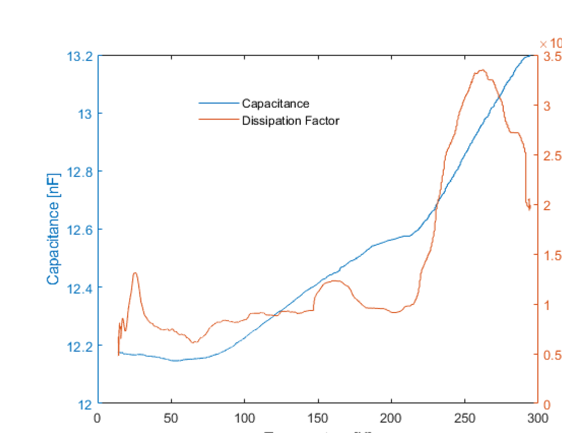

Figure 6: The capacitance and dissipation factor are measured with an LCR for the lithium niobate piezo at 1 kHz at Vpp= 1 V.

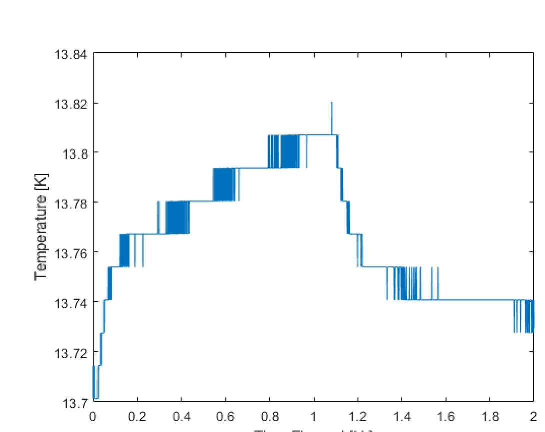

Figure 7: Temperature rise of the $LiNbO3$ piezo with a sine wave Vpp = 1000 V and 200 Hz.

- At V_{pp} = 1000 V with a sine wave of 200 Hz the temperature on the outside of the capsule increased by 0.1 K as shown in Fig. 6.
- 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.
- 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.

Conclusion

- A novel piezoelectric actuator design was developed and tested yielding a reduction of heating by a factor of 14 at liquid helium temperatures.
- This new design also succeeded in stopping the positive thermal feedback. 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.

Acknowledgements

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