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TESTING OF THE PIEZO-ACTUATORS AT HIGH DYNAMIC RATE OPERATIONAL CONDITIONS

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Abstract

Reliability of the piezo-actuators deployed in SRF cavity tuners operated at high dynamic voltage range rate conditions can lead to a significant impact on the overall performance of the SRF linacs. We tested at FNAL piezo-actuators P-844K075 that were developed at Physik Instrumente (PI) for LCLSII project. Although these actuators were developed for a CW linac we tested them at high dynamic rate inside a cryogenic/insulated vacuum environment. Results of the tests will be presented. Different modes of the piezo-actuators failure will be discussed.

INTRODUCTION

Operation of the facilities that deploy narrow bandwidth SRF cavities significantly depend on the reliability of the tuner's system and particularly longevity of the piezo-actuators.

Piezo-ceramic actuators are reliable devices that operated in different industrial applications. It was demonstrated that piezo-actuators could operate without failures for many years and many (10^{10}) cycles if design of the system follow best practices [1]. One important aspect that needs to be addressed, especially important for piezo-actuators when operated at high dynamic rate, is management of the heat transfer from the surface of the piezo-ceramic stack. The typical solution is to use flow of the gas/dry air to remove heat from the piezo surface [2]. Piezo-ceramic is a poor heat conductor and center of the piezo-stack will quickly warm up when heat removal managed only through endplates of the stack (Fig. 1).

Majority of the SRF linacs (SNS, EXFEL, LCLS-II, ESS) employed tuner system with piezo-actuators located inside cryomodule (CM) at insulated vacuum. There are no convection cooling and capsulated piezo-actuator separated from tuner frame with ceramic balls [3, 4]. Typical operating temperature of the piezo-ceramic stack deployed in the piezo-tuner, when SRF cavity at T=2 K, is near T=20 K.

Four years ago we tested reliability/longevity of the encapsulated piezo-stack (Encapsulated piezo unit P 844K075) was designed by PI (Physik Instrumente, Inc) per FNAL specifications [4, 5]. During previous studies our objective was to demonstrate ability of the piezo-actuator P-844K075 to serve LCLS-II project.

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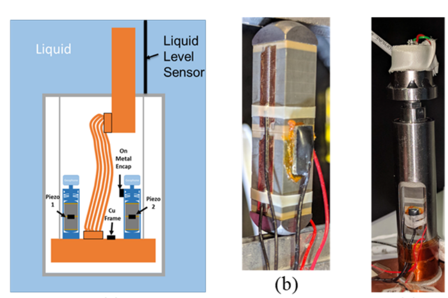
We operated for $2*10^{10}$ pulses (equivalent to 20 years of LCLS-II operation) with amplitude V_{pp}~2V. LCLS-II linac will operate in CW-mode and piezo-actuators must compensate (if it will be necessary) microphonics of the SRF cavities. Typical frequency of the microphonics are below 100 Hz with small amplitude.

Objective of our recent studies was to evaluate capability of the PI piezo-ceramic actuator P-844K075 to serve SRF linac that will operate in RF-pulse mode. Major source of cavities detuning in RF-pulse mode is Lorentz Forces (LF). Typically to compensate cavity LF detuning piezo-actuators must run at nominal voltage V_{pp}=120-200 V with stimulus pulses up to f=200-300 Hz [6]. At these operational conditions power dissipation inside piezo-ceramic will be up to 1000 times higher than during tests described in our previous paper [4].

TEST SETUP

The experiment was conducted at a specialized facility constructed at FNAL for testing instrumentation inside insulated vacuum at cryogenic temperature [4]. For the experiments liquid nitrogen (LN2) and helium (LHe) were used to cool down the setup. Two piezo capsules each consisting of two 10 × 10 × 18 mm stacks glued together were placed on top of a thick copper plate which acted as the base for vibrating piezo and as the heat sink. Each double piezo-stack was preloaded with spring inside capsule. Capsule made from thing wall stainless steel tube. The copper plate was connected to a copper braid which contacted the liquid via a copper rod. This setup ensured that the copper plate would reach temperatures close to the liquid. The copper plate along with the piezo capsules was enclosed in a can as shown in Fig. 1 (a) and kept under vacuum at 10^{-3} Torr.



(a) (b) (c)

Figure 1: (a) Schematic view of the inside of the can, (b) Ceramic stack with Cernox sensor attached, (c) Picture of encapsulated piezo with geophone on top.

A total of four Cernox temperature sensors were used. One was placed on the copper plate, the second one was placed on the side of the piezo capsule encasing. The other

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two sensors were placed in the middle of the two piezo stacks. The location of the temperature sensors is shown in Fig. 1. The temperature sensors for the piezos were placed in the middle of the stacks for three reasons. The primary reason was that most of the heat is concentrated in this region. The second reason was to avoid the possibility of the sensor falling off during operation, placing it in the middle allowed us to have one $10 * 10 * 18$ mm stack which did not come in contact with the sensor. During all our test only the stack which did not make contact with the sensor was used. The last reason was to avoid the heating of the sensor due to the piezo rubbing against it during operation.

In order to verify that the piezos were being stimulated by a sine wave a geophone was placed on top of each of the capsules as shown in Fig. 1 (c). We also monitored the liquid level of the Dewar for the test with LHe. This allowed us to estimate the LHe consumption. The data was collected via the data acquisition (DAQ) module NI PXI-1031. This DAQ was also used for driving the piezo with a sine wave pulse. The schematic of this setup is shown in Fig. 2. The lakeshore relayed the resistance of the Cernox sensors which was then calculated to give temperature. An LCR meter was used to measure the capacitance of a stack as well as the dissipation factor, the pulse used for this measurement had a frequency of 1 k Hz and 1V.

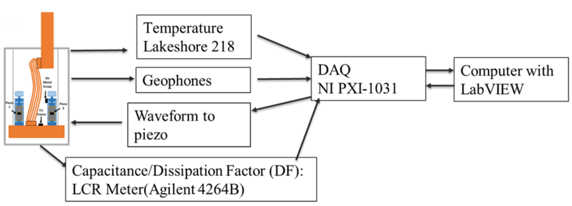

Figure 2: Schematic of data acquisition.

During the initial cooldown with liquid helium the capacitance and dissipation factor were recorded with the LCR meter. The results shown on Fig. 3 that the capacitance drops with temperature as well as the dissipation factor.

OPERATION OF THE PIEZO AT LN2

We started our test when Dewar was filled with liquid N2. After temperature of the large copper disc was stabilized at T=77 K we subjected piezo #2 to several different tests when piezo run with continuous sinewave stimulus pulse for several hours. Figure 4 shows changes of the temperature of all 4 RTDs mounted inside vacuum enclosure when piezo run for 5 hours with sinewave f=100 Hz and V_{pp}=100 V (from 0 V to 100 V). Temperature of the centre of the piezo#2 increased by ΔT~100 K and the top of the stainless-steel capsulation on for piezo#2 on ΔT~45 K. At the same time centre of the piezo#1 changed on just ΔT~2 K, that is just confirmation of the poor thermo-conductivity of the piezo-ceramic stack.

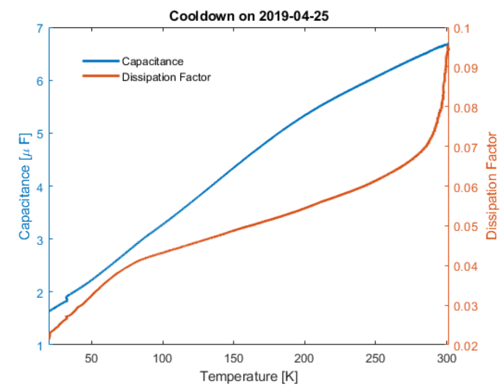

Figure 3: Dependency of the capacitance and dissipation factor of the PICMA^{TM} piezo-stack versus temperature.

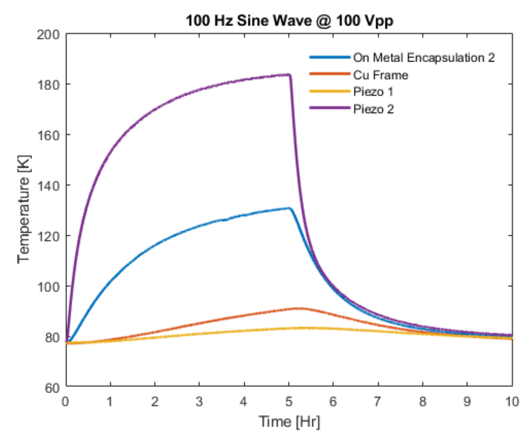

Figure 4: First test with liquid nitrogen. Piezo run with sinewave pulses with f=100 Hz and amplitude 100V_{pp}.

OPERATION OF THE PIEZO AT LHE

We were more interested to study high dynamic rate operation of the piezo when Dewar filled with liquid Helium (LHe). Piezo heating when operated at 100 Hz@100Vpp presented on the picture 5A. After temperature of the enclosure was stabilized copper disc cool down to 5 K and but temperature piezos remained close to 20 K. This situation is similar to temperature distribution in the real tuner inside SRF cryomodule. Typically, when SRF cavity cool down to 2-4 K temperature of the piezo-stack stabilized near T=20 K.

After piezo #2 run continuously during ~1.5 hour with sinewave 100Hz@100Vpp temperature of the piezo#2 raised from 20K to 110K (DT=91 K). Temperature of the piezo #2 was not stabilized yet after 1.5hours but was quite close to saturation and we turn off stimulus pulse. Temperature trend for all 4 RTDs (inside enclosure), when Dewar filled with LHe, is similar to LN2 (Fig. 4). Increase of the piezo temperature during 1.5 hours test led to increase of the piezo stroke, presented in Fig. 2B. Amplitude of the geophone raised when piezo temperature (Fig. 5B).

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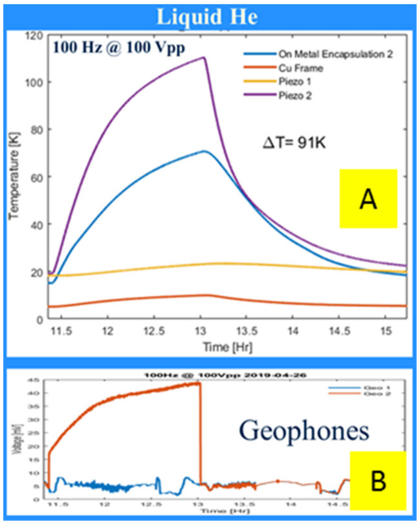

Figure 5: Test of the piezo warm-up, when piezo run with sinewave stimulus pulse with parameters: f=100 Hz and V_{pp}=100 V. (A) Temperature of all 4 RTD sensors inside enclosure, (B) Response of the geophone, mounted on the piezo.

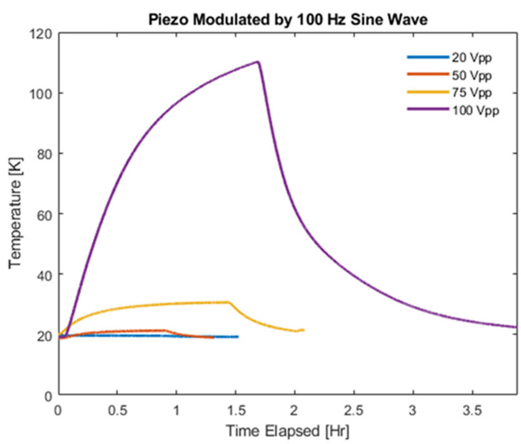

Figure 6: Piezo warm-up (from T=20K) versus amplitude of sinewave stimulus pulse (V_{pp}). Frequency of the sinewave f=100Hz.

Table 1 summarized described above tests. In addition we added in Table 1 values of the piezo capacitance and dissipation factor (Fig. 3) for the maximum temperature that piezo reached during test.

Figure 6 presents results of the several tests when we measured piezo temperature changes keeping the same frequency of the sinewave stimulus pulse f=100 Hz and for V_{pp} values: 20 V; 50 V; 75 V and 100 V. Before starting any new test (with new V_{pp}) we let piezo to cool down back to 20K. On the Fig. 7 presented piezo temperature when amplitude of sinewave kept V_{pp}=50 V but frequency of the stimulus sinewave changed (f=100 Hz; 200 Hz and 300 Hz).

The thermal active power P_{av} generated in the actuator can be estimated as follows:

$$P_{av}= * 4/\pi C*V_{pp}^2*f*D \qquad (1)$$

where C is piezo capacitance, V_{pp} (V) is amplitude, f is frequency of piezo stimulus pulse, and D is dissipation factor (typical value 5-20 %) [7]. Table 1 has value of the power P_{av} calculated for each test at the maximum piezo temperature.

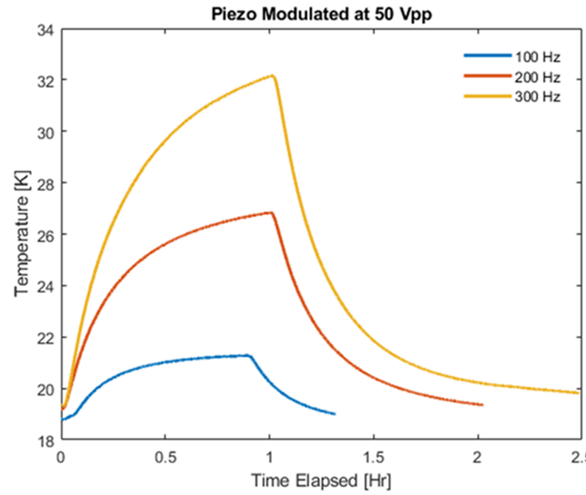

Figure 7: Piezo warm-up (from T=20 K) versus frequency of sinewave stimulus pulse (f). Amplitude of the sinewave V_{pp} =50 V.

Table 1: Summary of the Six Piezo Tests, When Piezo Run with Sinewave Stimulus Pulses with Different Frequencies (f) and Amplitude (V_{pp})

f, Hz	Vpp, V	C,uF	Dis. factor	Pav, mW	ΔT, K
100	20	1.8	0.022	1.2	0.1
100	50	1.8	0.025	9	2
200	50	2	0.026	21	7
300	50	2	0.027	32	13
100	75	2	0.026	23	10
100	100	3.5	0.047	140	90

Piezo temperature change (ΔT from T=20 K) versus the calculated thermal active power for all six tests from Table 1 presented in Fig. 8.

Important to note that value of the C and D that presented on the Fig. 3 (and these values consistent with vendors datasheets) are measured for small signals. For high V_{pp} (or high electrical field), the product C*D is typically 7 to 10 times higher [7]. It could be meant that values of the thermal active power P_{av} generated in the piezo-actuator that calculated using formula (1) and presented in Table 1 could underestimated, especially at large amplitude (V_{pp}).

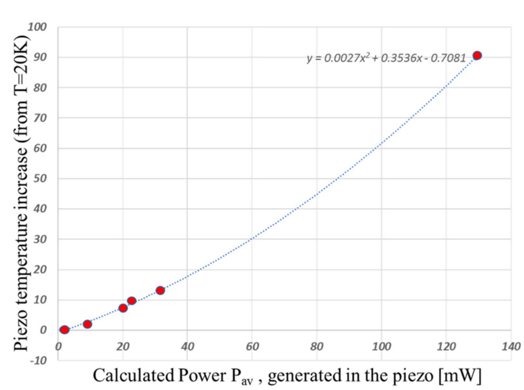

Figure 8: Piezo warm-up (temperature raised from T=20 K) versus calculated power P_{av} (formula 1).

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Using liquid level we monitored LHe consumption when we run piezo at different amplitude V_{pp}. Considering that static losses (when no driving signal on the piezo) was near 0.13 L/hour we can estimated amount of LHe consumed during couple tests: 1) piezo run at 100 Hz@75V_{pp} and 2) 100 Hz@100V_{pp} (Fig. 6). Summary of the both tests presented in Table 2. Power deposited inside enclosure, estimated from amount of boiled LHe and P_{av} calculated from formula (1) different in factor 6 to 12, that is consistent with statement in the reference [7].

Also, we conducted several piezo tests to evaluate piezo heating for bipolar sinewave stimulus pulses (Fig. 9). We do not observe any differences in piezo heating between unipolar and bipolar stimulus pulses (Fig. 9). When piezo run at f=100 Hz and V_{pp}=50 V with three different wave form: sine, square and triangular (Fig. 10).

Table 2: Power Generated by Piezo

	100Hz@75Vpp	100Hz@100Vpp
Test duration, Hours	2	2
LHe consumption, kg	0.105	1.18
Power calculated from LHe consumption, mW	300	3500
Power calculated from formula $P_{av}=\pi/4$ $[C*D*V_{pp}^2*f]$, mW	50	250

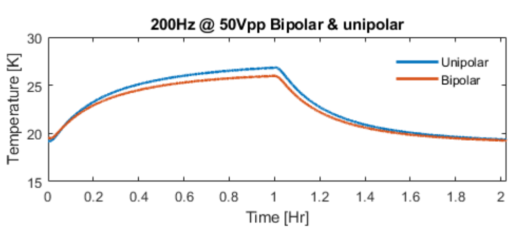

Figure 9: Piezo driven with sinewave stimulus pulses V_{pp}=50V: unipolar (0Vto 50V) and bipolar (-25 V to 25 V).

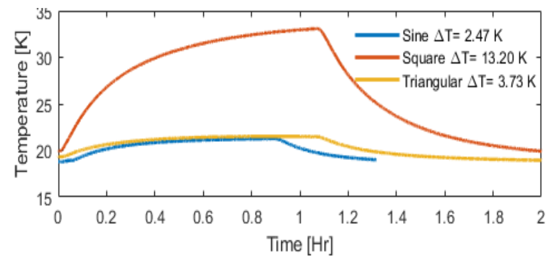

Figure 10: Piezo driven at f=100 Hz and V_{pp}=50 V with three different wave form: sine, square and triangular.

CONCLUSION

Longevity of the piezo-actuators when operated at high dynamic rate inside cryogenic/insulated vacuum environment need to be address in the initial stage of the tuner design.

We demonstrated that PI piezo-actuator when operated at high rate (100 Hz) and at V_{pp} close to nominal voltage (V_{pp}=100 V) will be quickly heated above T=100 K (from T=20 K when idle).

When piezo-actuator operated at high amplitude (V_{pp}) energy deposited inside piezo-ceramics will be large than predicted by formula (1). As results center of the piezo-stack could be quickly overheated that will significantly decrease piezo-actuator longevity.

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