FERMILAB-CONF-22-829-TD
20th Int. Conf. on RF Superconductivity SRF2021, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-WEPTEV007

REVIEW OF THE APPLICATION PIEZOELECTRIC ACTUATORS FOR SRF CAVITY TUNERS*

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Abstract

Large SRF Linacs and HEP experiments require accurate frequency control, which is achieved using cavity tuners typically actuated by the piezoelectric ceramic stacks. The piezoelectric ceramic stacks become "standard" components of the SRF cavity tuner, and depending on the application, could be operated in different environments: in air, at cryogenic temperature, in vacuum, and submerged in liquid helium. Different applications place different requirements on the piezo actuators, but the important parameters common to all applications are the lifetime and reliability of the actuators. Several R&D programs targeting the development of reliable piezo actuators are reviewed in this contribution.

INTRODUCTION

For many years piezoelectric ceramics have been widely used in a variety of industrial applications and have proven to be highly reliable. There are many applications in space exploration research that have also demonstrated the capability of piezo actuators to tolerate up 109 cycles when operated in cold and vacuum environments [1]. The ability of the piezo actuator to generate large forces (3-4kkN for a stack with cross-section 10*10mm2) and withstand pressure up to 200MPa have made these actuators a good choice for deployment in SRF cavity tuners.

Recently, thousands of piezo actuators have been deployed as fast/fine tuning elements in several large SRF linac that are in or close to being in operation. In large machines (e.g., EuXFEL, LCLS II, ESS) piezo actuators are typically deployed close to the SRF cavity, inside insulated vacuum volume and at cryogenic working temperature. Operations of the piezo both cold and inside the vacuum has some advantages, especially for CW SRF linacs where the specifications for piezo are to deliver sub-micrometre stroke to compensate for microphonics. For pulsed SRF linacs, the piezo is utilized to compensate for the cavity's Lorenz Force Detuning (LFD). To compensate for LFD, the piezo must be driven with stimulus pulses with large voltage and frequencies of several 100' Hz. The piezo stack will experience significant acceleration forces that could quickly lead to cracks inside the piezo that result in failure. When operated in AC mode the piezo will heat up. Limited heat transfer from the piezo when inside a vacuum could generate additional challenges for reliable piezo operation.

The reliability of the piezo installed inside the SRF cryomodule became the most critical parameter, considering complexity and cost of replacement in cases of failure.

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.

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There are examples of the utilization of piezo as part of SRF cavity tuners in an ambient environment. In these applications, there are another set of challenges that need to be considered to extend the lifetime of the piezo tuner: humidity, temperature, and the DC voltage applied to the piezo.

There are applications when the piezo must operate while submerged in liquid Helium (LHe). Several examples of projects when the piezo is operated inside LHe are presented at the end of this review.

MECHANICAL INTEGRATION OF THE PIEZO ACTUATORS INO FAST TUNERS

A fast tuner is installed between the slow tuner and cavity. When slow tuner bring cavity to operational frequency it delivered on the piezo actuator preload on the order of several kN. It is important that the design of the fast tuner and the mechanical integration of the piezoceramic stack as part of SRF cavity tuner are done according to piezo manufacturer recommendations.

There are many examples of when "in-house" integration of the piezo is done incorrectly, which leads to fast tuner failures. Several unsuccessful examples of piezo stack integration that the FNAL tuner team experienced are also presented.

One of the first single piezo actuators built and tested at FNAL's CC2 cavity [2] is presented in Fig. 1. It was modified copy of the first DESY fast tuner. There were efforts with design to mitigate and measure shearing forces experienced by piezo stack while the cavity was cooled down to T=2K and tuned to operational frequency. This example demonstrated: (a) efforts to minimize the shearing forces on the piezo stack with a stainless-steel bullet didn't work as expected; and (b) the piezo stack experienced significant shearing forces that considerably shorten it's longevity.

The second example shows assembly of the Slim Blade tuners on the two dressed cavities FNAL sent to KEK for the S1Global project. The picture of the piezo installed into tuner demonstrates that there is a significant angle between forces applied to the two ends of the piezo stack (Fig. 2). Significant shearing forces have been observed that led to development of cracks on the piezo ceramics, resulting in the piezo failing after just a couple days of operation (Fig. 3).

FNAL built CM2 [3] which was the FNAL SRF team's first experience in SRF cryomodule construction. Piezo's failure at S1Global cryomodule led to decision modified fast tuner design. Encapsulation was added onto the piezo stack (Fig. 4). Although encapsulation helps address some of the shearing force problems it does not entirely resolve all of the issues associated with piezo cracking.

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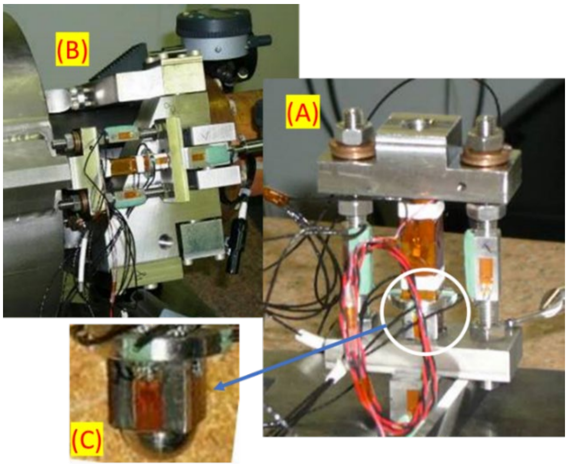

Figure 1: (A) Single piezo fast tuner for CC2. Tuner instrumented with strain gages to measure tensile forces on the piezo stack. (B) Tuner installed on cavity as part of double lever tuner (Saclay I). (C) Stainless steel bullet with strain gauges.

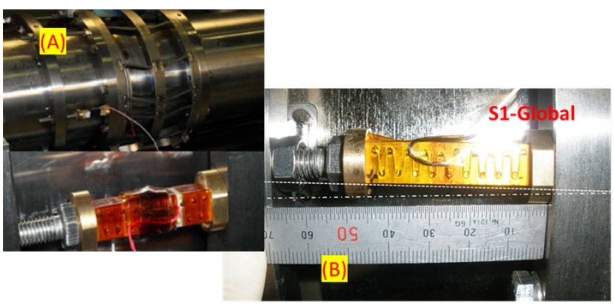

Figure 2: (A) Slim Blade Tuner for S1Glbal project. (B) Picture demonstrating piezo misalignment, that led to significant tensile stress on the piezo stack.

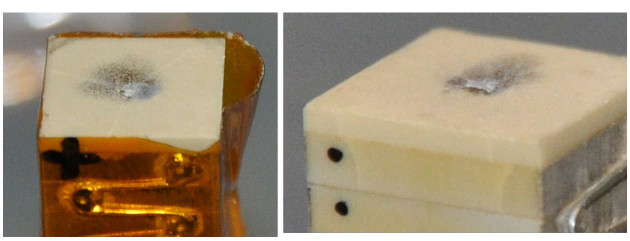

Figure 3: Piezo damage (with cracks on piezo layer).

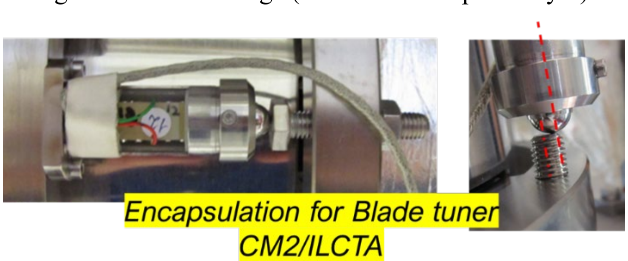

Figure 4: Picture of simple capsulation for piezo actuator.

Considering all previous experience, the FNAL tuner team reached out to the R&D team from Physik Instrumente [4], when starting the design of the SRF cavity tuner for the LCLS II project.

The result of joint FNAL/PI efforts was the encapsulated piezo actuator P-844K075 (Fig. 5). The encapsulated piezo actuator built from two PZT (lead zirconate titanate) PICMA® stacks P-888.51 butted together. The two piezo stacks located inside one capsule are electrically independent. In case one of the stacks failure (HV-breakdown) the second could still work independently as a fast tuner.

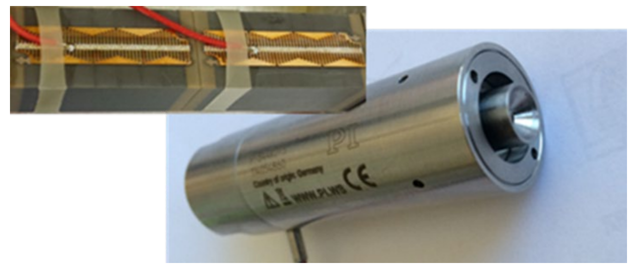

Figure 5: P-844K075 encapsulated piezo actuator. Inside the capsule there are two butted PICMA© piezo stacks.

The capsule is made from stainless steel (SS). The piezo stack is glued with epoxy to the SS endplates. The SS endplates have cuts to prevent the layer of glue from cracking while the actuator is cooled down to cryogenic temperature. The piezo is preloaded inside the capsule with a bevel washer spring to 800N. To minimize shearing forces, the actuator has grooves in both ends that allow 7mm ceramic balls to be installed between cavity's conical flange and slow tuner main lever (Fig. 6). The utilization of ceramic balls helped minimize build-up of shearing forces on the piezoelectric stack.

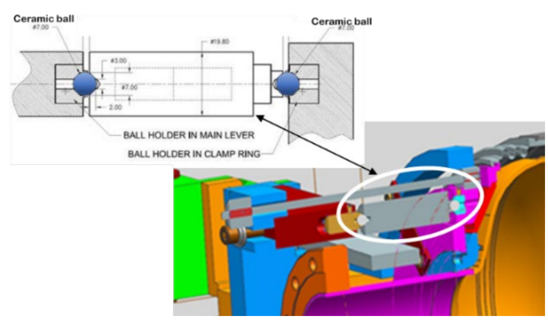

Figure 6: Ceramic balls help prevent development of tensile stress on the piezo. 3D-model of the LCLS II tuner pictured. Piezo actuator installed with 7mm ceramic balls.

The most critical factor that impacts piezo actuator longevity is the generation of local tensile stress (e.g., stress caused by bending the stack). Local tensile stress can lead to cracks, and in an AC operation mode eventually lead to failure of the actuator. The existing design of the P-844K075 and interface of actuator inside tuner are already optimized with respect to decoupling the actuator from any lateral force or torque.

During cryomodule production and operation the piezo must withstand forces up to 7kN. To find the limit (breaking force) of the destructive test of the P-844K075 has been conducted. The actuator was installed inside of a heavy metal jig and the cooled-down inside a liquid Nitrogen bath. The jig was installed on the Instron device and forces

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applied on piezo until the piezo stack was crushed. The actuator was able to withstand forces up to 28kN before it collapsed (Fig. 7).

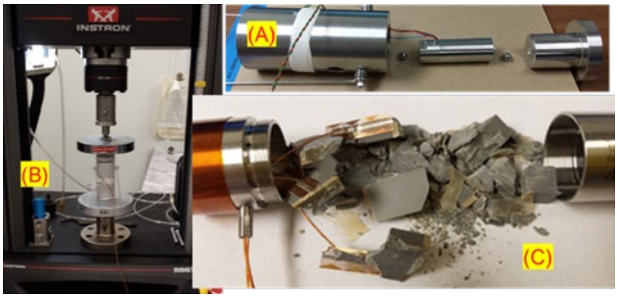

Figure 7: Destructive test of the piezo actuator. (A) Actuator installed inside heavy jig to minimize shearing force development and keeping piezo ceramic at temperature T~80K during test at Instron (B). (C) Crushed piezo-ceramic stack.

CHALLENGES OF OPERATION PIEZO ACTUATORS AT CRYOGENIC TEMPERATURE AND VACCUM

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

$$P_{av}=\pi/4 * C*V_{pp}^2*f*D,$$

where C is piezo capacitance, V_{pp} (V) is amplitude, f is frequency of piezo stimulus pulse, and D is the dissipation factor (typical value 5-20 %). The FNAL team found [5-7] that this formula for the PZT piezo results in correct estimation for V_{pp} up to ~50V. When the piezo operated near nominal voltage (120V-150V), the estimated heat dissipation more closely follows $V_{pp}{}^3$ or even $V_{pp}{}^4$. The FNAL team built a designated facility to conduct studies of piezo heating operated at cryogenic temperature and in a vacuum environment [5, 6].

An ALT (accelerated lifetime test) of piezo actuator P-844K075 as part of the LCLS II project was conducted for $2*10^8$ pulses (with V_{pp} = 2V). Frequency of the stimulus sinewave pulse was increased to 5 kHz to accumulate $2*10^8$ pulses for 2 months. The piezo power dissipation throughout the ALT test was 6mW. During operation of LCLS II linac expected power dissipation will be less than 60uW. The resulting heating of the piezo was small (ΔT~ 1 K) and therefore did not create significant risk for piezo failure. Based on the LCLS II ALT test, one can conclude that heating of the piezo actuator when compensating microphonics during CW-linac operation, is a not a risk for piezo longevity.

When the cavity is operated in RF-pulse mode it is subjected to dynamic Lorentz force detuning (LFD) up to several kHz. To compensate for LFD, the piezo needs to be run at nominal voltage 120-150V. Power dissipation inside the piezo ceramic will reach a level of 500mW. As demonstrated in [6, 7], the temperature in the centre of the piezo stack could be raised by ΔT~100K (Fig. 8). Heating of the piezo when operating at the high dynamic rate that is required for LFD compensation could therefore decrease the lifetime of the actuator [6, 7, 8].

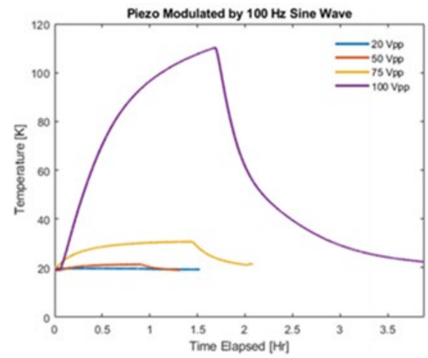

Figure 8: Temperature in the middle of piezo [6].

The FNAL and PI teams conducted a R&D program to develop a novel piezo actuator for high dynamic rate operation. The goal was to develop an encapsulated piezo actuator that has a solution for removing heat from the surface of the piezo-ceramic stack. Private industry addresses the need to remove heat from the surface of the piezo stacks through the flow of the dry air, nitrogen gas, or with oil. Existing techniques are shown to be effective when working in an ambient environment but not for vacuum or cryogenic temperature.

The result of this R&D program is actuator P-844K093 (Fig. 9 and Fig. 10). Capsulated and preloaded actuator utilized the same PICMA® stack 10*10*36mm. Copper foam was selected to remove heat from the side surfaces of the PICMA® stack.

Figure 9: Novel piezo actuator P-844K093.

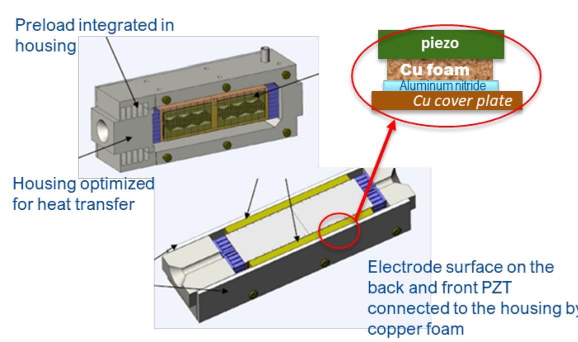

Figure 10: Internal design of the P-844K093 actuator

An aluminium nitride material, which is a good dielectric with excellent heat transfer properties, was installed between the under HV copper foam and outside copper plate. A heat sink must be connected to actuator's outside copper plate and anchored to a cryogenic pipe (2K, 4K, or 77K).

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Simulations of heating up the "copper foam" high dynamic rate P-844K093 actuator for two cases: when copper foam placed inside actuator and without copper foam, presented on Fig. 11. Simulations were performed by the PI team. According to the results of the simulation, copper foam is shown to significantly remove heat (ΔT ~20K with foam vs ΔT ~100K without foam) from the piezo ceramic stack. It is important to point out that during these tests it was possible to measure temperature on the surface of the piezo stack but not in the centre.

A Detailed study of the effect of copper foam for heat removal with novel actuator P-844K093 is presented in Ref. [7]. The main results of heating the middle of the PICMA stacks in the two actuators P-844K075 and P-844K093 under the same stimulus pulses are presented in Fig. 12. The differences in the temperature increase of the piezo stacks are ΔT~91K for P-844K075 and ΔT~7K for novel actuator P-844K093. The novel actuator with the copper foam used as heat transfer media has worked well to remove heat from the piezo. This new design also succeeded in stopping positive thermal feedback. P-844K093, when anchored to 4K pipes, could be safely run in bipolar mode (-120V to +120V) without reaching the 77 K threshold the risks damage.

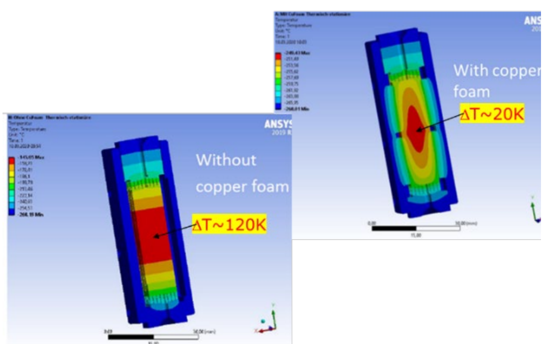

Figure11: A simulation of the heating up of two novel actuators when run at the same stimulus pulses. One actuator (top, with ΔT~20K) has copper foam and the other (bottom, ΔT~100K) without copper foam installed.

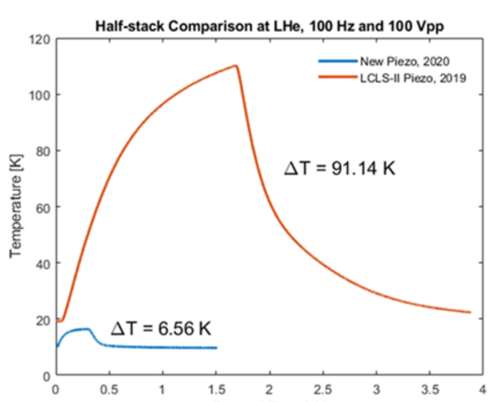

Figure 12: Actuators heating comparison when driven at the same stimulus pulse (f=100Hz, V_{pp}=100V). Red curve is for actuator P-844K075 and blue is for P-844K093.

The FNAL/PI team also considered piezo material with different properties than that of PZT for development of high dynamic rate actuators. Lithium niobate ($LiNbO_3$) material, which exhibits a small permittivity and dissipation factor, was selected for construction of the prototype actuator [7]. A lithium niobate actuator 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. The maximum stroke displacement for a 36mm long $LiNbO_3$ actuator is 3 µm at room temperature, when operated from -500 V to 500 V. In line with expectations, when cooled down to cryogenics temperature the stroke of $LiNbO_3$ actuator will not decrease significantly in cmparison to to PZT actuators. The stroke dependency of the $LiNbO_3$ piezo versus temperature still needs to measured.

The PI team built an actutor prototype from Lithium niobate ceramic. The heating characteristics of the prototype unit, when operated in AC mode, was measured by FNAL faculiy with the same methods as actutors P-844K093 and P-844K075. As predicted, FNAL tests demonstarted very small (ΔT <1K) changes in actuator temeprature when run with sinewave at 200Hz and Vpp=1000V. Lithium niobate actuators could be good alternatives to "standard" PZT actuators for high dynamic rate operation in a cryogenic/vacuum enviroment.

There are some applications when piezo actutors must work when submerged into liquid helium [9, 10]. Submerging actuators into liquied helium resolved the issue of heat removal from the actuators. The piezo stack was built from thin (~100um) layers of piezo ceramics glued or cofired together. Special precautions and preliminary tests need to be done to make sure that the media (liquid heluim) is able to withstand large electrical field applied to piezo without breakdown.

OPERATION OF PIEZO ACTUATORS AT AMBIENT ENVIROMENT

There are designs of the SRF cavity tuners when piezo actuator is installed outside of the cryomodule at an ambient environment. The principals of mechanical integration of the piezoceramic stacks inside fast tuner described in the previous section need to be followed during design of the "warm" piezo tuner. There is obviously some advantage for the "warm" piezo: it can be replaced much easier in the case of failure. The drawback of the "warm" fast tuner is that the piezo's stroke translated to the cavity through rod, that must penetrate into insulted vacuum volume. This type of mechanical system could have large group delays that limit fast response from the piezo.

The lifetime of the piezo actuator strongly depends on the DC voltage applied to the piezo, temperature, and the humidity at which the piezo operates (Fig. 13). As an example, decreasing DC voltage on the PICMA® piezo from 150V to 100V will increase MTTF (mean time to failure) from 2 month to 10 years [11]. The DC-degradation mechanism of the piezo inside of high humidity is presented in Fig. 14. To mitigate the effect of high humidity one could

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select a piezo with ceramic coating (like PICMA®) (Fig. 15). If a conventional piezo (with polymer insulation) is selected, a fast/fine tuner needs to be located inside the container with dry air or nitrogen gas.

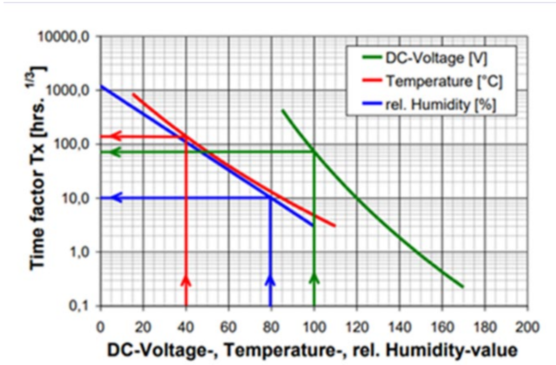

Figure 13: PICMA® piezo longevity dependency versus DC Voltage, Temperature and relative humidity (courtesy of PI).

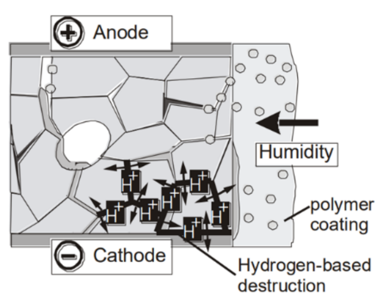

Figure 14: DC-degradation mechanism of piezoceramic (courtesy of PI).

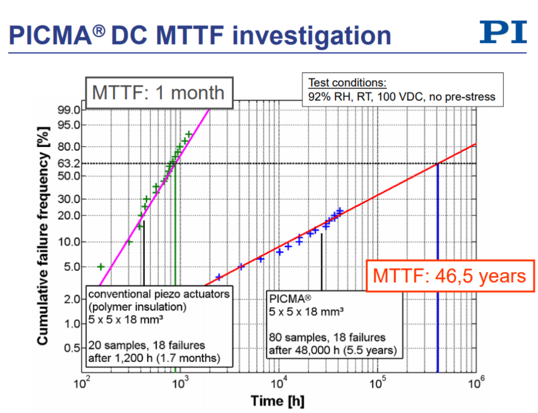

Figure 15: Summary DC MTTF investigation by PI. Run for 2 years with more than 1,000 piezo samples.

CONCLUSION

The longevity of modern piezoelectrical actuators can easily cover 20-30 years, which is the typical lifetime of SRF linac. To preserve this longevity, the tuner's designers must follow piezo vendors recommendations during the process of integrating the piezo stack into the SRF cavity tuner. Collaboration with applications engineers from piezo production companies can help ensure reliable tuner design.

The FNAL/PI joint R&D program led to the development of the P-844K075 actuator, that was successfully deployed in LCLS II and will also be used in PIP II and LCLS II HE.

The novel piezo actuator P-844K093 was developed for high dynamic rate operation. Copper foam heat transfer techniques resolved piezo overheating problems. The prototype actuator from lithium niobite piezoceramic demonstrated good potential for SRF tuner's application.

Recommendations for selection of the piezo actuator for "warm" tuner's is presented.

ACKNOWLEDGEMENTS

The author would like to acknowledge the PI R&D team for successful collaboration over the last 7 years.

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