# RELIABILITY OF THE LCLS II SRF CAVITY TUNER

Y. Pischalnikov[#], B. Hartman, J. Holzbauer, W. Schappert, S. Smith, J.C. Yun
FNAL, Batavia, IL 60510, USA

*Abstract*

The SRF cavity tuner for LCLS II must work reliably for more than 20 years in a cryomodule environment. Tuner's active components- electromechanical actuator and piezo-actuators must work reliably in an insulating vacuum environment at low temperature for the lifetime of the machine. Summary of the accelerated lifetime tests (ALT) of the electromechanical and piezo actuators inside cold/ insulated vacuum environment and irradiation hardness test (dose level up to $5*10^8$ Rad) of tuner components are presented. Methodology to design and build reliable SRF cavity tuner, based on "lessons learned" approach, are discussed.

## INTRODUCTION

Description of the design and measured parameters of the SRF cavity tuner for LCLS II project were presented at the IPAC2015 conference [1] (Figure 1).

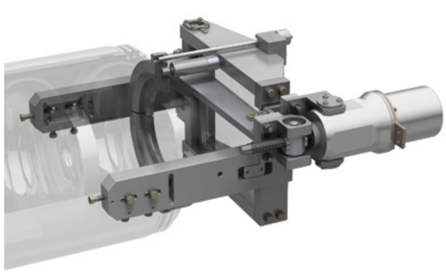

Figure 1: 3-D model of the LCLS II Tuner.

Tuner must work reliably for 20 years. Tuner will be assembled on the cavity inside the cryomodule (CM) and will work inside of the insulated vacuum vessel at cryogenic temperature. In Table 1, longevity (lifetime) requirements specifications for tuner components are presented.

Table 1: Tuner Active Components - LCLS II Lifetime Requirements (Operation for 20 Years and 40 Thermal Cycles)

| | |
|---|---|
| Coarse Tuner/ Electromechanical Actuator | 1,000 spindle rotations |
| Fast Tuner / Piezo-electrical Actuator | $2*10^{10}$ pulses ($V_{pp}$=2V, f=40Hz) & $6*10^6$ pulses ($V_{pp}$=50V, f=0.01Hz) |

The tuner was designed such a way that the electromechanical actuator and piezo-stack are accessible and replaceable through special ports in the cryomodule vacuum vessel. As the last remedy, active components of the tuner can be replaced through designated port in the CM vacuum vessel without removing the CM from the SLAC tunnel.

## RELIABILITY OF THE ELECTROMECHANICAL ACTUATOR

The electromechanical actuator is the active element of the slow/coarse tuner. The electromechanical actuator translates rotation of the stepper motor to linear motion of the tuner arms. The tuner is equipped with a Phytron actuator (LVA 52-LCLS II-UHVC-X1) [2] designed for the FNAL linear SRF project (Table 2).

Table 2: Four Main Components of the Electromechanical Actuator LVA 52-LCLS II-UHVC-X1

| | |
|---|---|
| Stepper Motor | LVA-52, 200step/revolution, Imax=2,5A |
| Gear Box | type:planetary; stainless steel; dry lubrication |
| Spindle | Titanium; M12X1; dry lubrication |
| Traveling Nut | stainless steel with TECASIN-1041 insert to mates 12X1 thread |

### *ALT of the LVA 52-LCLS II-UHVC-X1 Actuator at the FNAL HTS*

As a part of the R&D efforts actuator ALT conducted during several weeks of continuous operation of the blade tuner installed on the 9-cell elliptical cavity at the FNAL HTS [3,4]. Several parameters were monitored during long test: SRF cavity frequency, temperature of the stepper motor, etc.

The motor was operated with current I=0.7A ($I_{nom}$=1.2 A). During the test of the actuator, the tuner pushed & pulled the cavity, the load on the actuator changed from-1200N to +1200N. Total steps accumulated by the motor during ALT test was 5000 spindle rotations or 5 LCLS II lifetime requirements (Table 1). There was no observed degradation of actuator performance. Visual inspection after ALT shows no damage or loss of lubrication to the spindle and traveling nut.

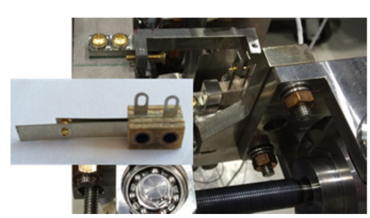

Figure 2: Limit switches mounted on the tuner.

*This manuscript has been authorized by Fermi Research Alliance, LLC under Contract N. DE-AC02-07CH11359 with U.S. Department of Energy.
[#]pischaln@fnal.gov




ISBN 978-3-95450-178-6

The tuner will be equipped with two limit switches to limit the range of motion (Figure 2). The role of the limit switches is to avoid having the tuner arm hit a “hard stop”. Limit switches will be wired to the stepper motor driver. If the tuner arm is allowed to reach the end of the motion, the forces on the traveling nut can reach 2-4kN. This is above the force limit of the actuator (+/-1.3kN). Excessive forces will damage TECASIN-1041 insert of the traveling nut (Figure 3).

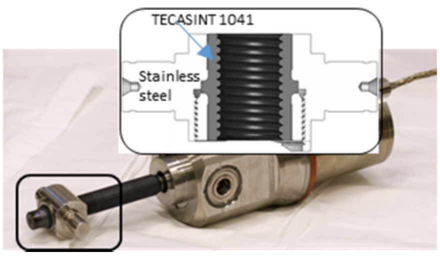


Figure 3: Traveling nut on the Ti spindle. Schematic design of the nut made from the stainless steel with TECASIN-1041 insert.

## RELIABILITY OF THE PIEZO-ELECTRICAL ACTUATOR

Encapsulated piezo-stack (Encapsulated piezo unit P-844K075) was designed by PI (Physik Instrumente, Inc) per FNAL specifications. Each capsule is made from two butted PICMA$^{TM}$ low –voltage piezo stacks (P-885.51) (Fig. 4) [5]. P-844K075 unit designed with several design features to extend lifetime of the piezo-tuner:

- Encapsulation (and translation of the forces/stroke from piezo to cavity/tuner arms system through ball couplings) [1]
    - to minimized shearing forces on the piezo-ceramic element
    - to deliver required internal preload on the piezo stack / - important for dynamic operation of the piezo
    - to significantly increased value of the piezo-capsule breaking forces (to withstand catastrophic events)
- Construction of the P-844K075 unit from two butted together piezo 10*10*18mm$^3$
    - Failure of the one piezo (HV breakdown in one of the ceramic layer) will not lead to loss of all units.

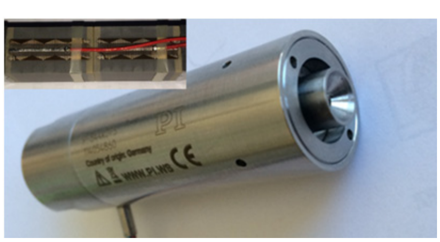

Figure 4: Encapsulated piezo actuators P-885.51.

- Wiring of the piezo-units done with Kapton insulated wires
    - Requirements to withstand high level of the radiation.

### *ALT of Piezo in Cold/Insulated Vacuum Environment*

Designated facility was developed at FNAL to conduct ALT of the piezo at cold/insulated vacuum environment (Figure 5). Piezo-stacks were mounted on the massive copper disk. Several temperature sensors were glued to the piezo-ceramic elements and to the copper disk. Geophones were attached on the top of the each encapsulated piezos to monitor response of the piezo during long (several months) automated test. The disk with piezos and instrumentation installed inside a vacuum enclosure. The enclosure was inserted into a LHe dewar. Data was collected through LabView based data acquisition system.

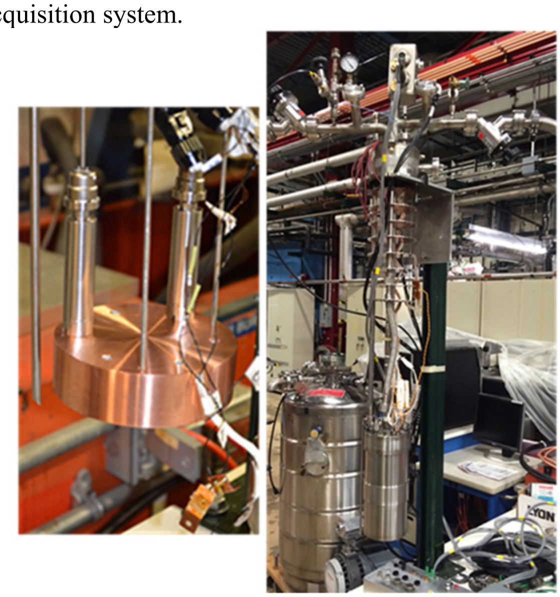

Figure 5: Facility for piezo-stacks ALT. Right: Helium Dewar and vacuum insert. Left: Two encapsulated piezo (with geophones) mounted on the heavy copper plate.

Cold/vacuum environment is almost ideal environment for piezo actuators [6] except the problem of removing the heat dissipated inside ceramics [7,8,9]. In vacuum heat dissipated inside piezo ceramics can be transferred to outside the ceramic volume through the piezo-stack end plates to piezo-tuner metal fixture. Major concerns are that heating up center layers of the piezo-stack will create positive feedback loop. Capacitance and dissipation factor of the center layers of piezo-stack will increase with temperature and as a result will lead to more heat dissipation inside the center layers. It will lead to “run-away” conditions.

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

$$P_{av}=\pi C U^2 f * D,$$

where C is piezo capacitance, U (V) is amplitude, f is frequency of piezo stimulus pulse, and D is dissipation factor (typical value 5-20 %).

Measurements of the PI piezo capacitance and dissipation factor during cool-down cycle are presented on the Figure 6.

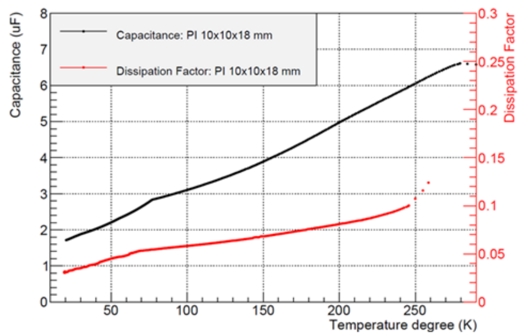


Figure 6: Dependency of the capacitance and dissipation factor of the PICMA TM piezo-stack versus temperature

Major objective of the piezo ALT test was to run piezo for $2*10^{10}$ pulses with amplitude of the stimulus pulse $V_{pp}$=2V and frequency f=5kHz (see Table 1 and Table 3). Even though the LCLS II piezo operational requirement is f=40Hz, we decided to increase frequency of ALT to 5kHz to accomplish lifetime test in a 2 month period. Shortening lifetime test of the piezo to just two months (instead of 20years) led to increase of the heat dissipation into the piezo ceramics up to 6mW (instead of 50uW during LCLS II operation) (Table 3). During ALT test, temperature of the piezo rose ~2K over an hour and stayed stable after that for the rest of ALT (two months). There was no "run-away" observed. We monitored piezo operation by monitoring amplitude of the geophone. Two PI piezo stacks accumulated $2*10^{10}$ pulses without any degradation of the performances and without over-heating "run-away" events.

It is important to emphasize that during the ALT piezo operation the applied stroke was that of LCLS-II operation however piezo-stack motion acceleration was several thousand times larger (Table 3) due to higher frequency. Appropriate preload on the piezo-stack helped to mitigate development of cracks on the ceramics layers even with quite large piezo acceleration. Cracks are one the major cause for piezo HV breakdown.

After main LCLS II ALT we conducted an additional study with much higher power dissipation inside piezo (Figure 7). Test objectives were to explore impact of heat dissipation on the piezo operation in much more demanding operational conditions (like XFEL). We ran piezo up to $P_{av}$ ~300mW or ~2 times higher than that of XFEL operational condition ($V_{pp}$=26V and f=1kHz). Temperature of the piezo-stacks typically stabilized in 1-2 hours after piezo operation started (Figure 8.) Piezos were operated within XFEL parameters ($P_{av}$~100mW) for several days. We did not observed any degradations of piezo parameters or piezo overheating conditions.

Table 3: Requirements of the piezo for operation in XFEL and LCLS II Linacs. Impact on the longevity of the piezo (20 years operation). "Piezo ΔT raised" is measured value.

| | XFEL | LCLS II | FNAL-test-stand *(2month)* |
|---|---|---|---|
| Operation | 10 pulses/sec | CW | CW |
| stimulus pulse, Hz | 200 *(2 sinewave per pulse)* | 40 | 5000 |
| Vpp, V | 120 | 2 | 2 |
| piezo stroke,[um] | 5 | 0.2 | 0.2 |
| number pulses for 20 years | 1E+10 | 2E+10 | 2E+10 |
| total stroke of piezo for 20years, [km] | 60 | 5 | 5 |
| Piezo-stack motion speed (rms) (mm/s) | 4.5 | 0.02 | 2.2 |
| Piezo-stack motion acceleration (rms)(g) | 0.6 | 0.0004 | 7 |
| Heat dissipation, [mW] | 90 | 0.05 | 6 |
| Piezo ΔT raised | 20K | 0.1K | 2K |

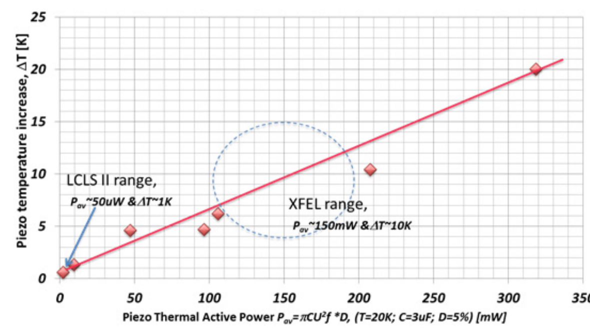


Figure 7: Increase of Piezo temperature (ΔT) versus power dissipated into piezo-ceramics.

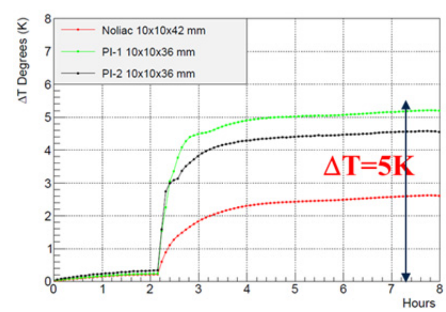


Figure 8: Piezo-ceramics temperature increase after stimulus pulse $V_{pp}$=10V and f=1kHz turned ON.

## RADIATION HARDNESS OF THE TUNER COMPONENTS

Based on simulation [10], tuner components will experience irradiation assuming 10nA continuous dark current for 20 years (with 300 annual days of beam operation) to the dose level of 2-4*$10^8$ Rad.

Major concerns are radiation damage of the tuner active components: the piezo-electrical stacks and the electromechanical actuator. Both stepper motor windings and piezo-electrical stacks lead wires will have insulation made from Kapton. The measured threshold for Kapton degradation is between 1-10 *$10^8$ Rad [11].




ISBN 978-3-95450-178-6

### *Irradiation Hardness Test of the Piezo-stacks*

FNAL team conducted measurements of the PI piezo-stack characteristics after the irradiation with gamma source ($Co^{60}$).

Several piezo-stacks (slightly different configuration) irradiated with gamma-source (Table 4).

Table 4: Description of the Different Samples of the Piezo-stacks Irradiated during "rad-hardness" Test

| LABEL | Description of the piezo-stack | Irradiation Dose , Rad | |
|---|---|---|---|
| | | *session #1* | *session #2* |
| A | non-capsulated piezo 2X10*10*18mm$^3$ -butted (wires with teflon insulation) | 1*10$^8$ | 5*10$^8$ |
| B | non-capsulated piezo 2X10*10*18mm$^3$ -butted (wires with teflon insulation) | 1*10$^8$ | 5*10$^8$ |
| C | non-capsulated piezo 2X10*10*18mm$^3$ -butted (wires with teflon insulation) | 0 | 0 |
| E1 | Enapsulated piezo 2X10*10*18mm$^3$ -butted (wires with Kapton insulation) | | 5*10$^8$ |
| E2 | Enapsulated piezo 2X10*10*18mm$^3$ -butted (wires with Kapton insulation) | | 0 |

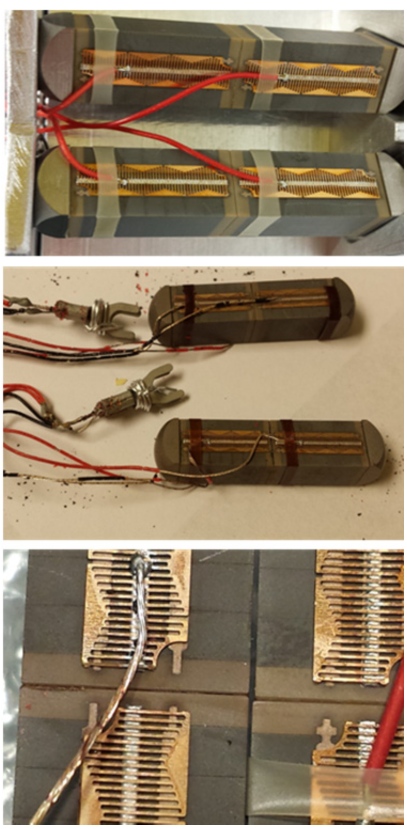

Figure 9: Top: sample A & B before irradiation test. Middle: sample A & B after 5*10$^8$ Rad dose. Bottom: Central part of the two piezo-stacks (epoxy layer between two 10*10*18mm piezo): left- sample B (after 5*10$^8$Rad) and right - sample C.

The first irradiation run with dose level ~1*10$^8$ Rad was done at FNAL facility (during 10days of continuous irradiation). The second irradiation cycle was conducted at Sandia Lab with accumulated dose ~5*10$^8$ Rad (during 7days of irradiation).

Before and after irradiation samples went through visual inspections (Figure 9). For all of the samples, including reference samples (C&E2), main parameters (capacitance, heat dissipation factor, and stroke) were measured before and after each irradiation session (Figure 10, Table 5). Strokes of the piezo-stacks were measured with Keyence LC-200 Laser Displacement Meter (Figure 10).

Table 5: Summary of the Piezo Samples Stroke Reduction after Gamma Irradiation

| Piezo sample | Level of the dose [Rad] | |
|---|---|---|
| | 1*10$^8$ | 5*10$^8$ |
| A | 3% | 7% |
| B | 8% | 10% |
| C | | |
| E1 | | 10% |
| E2 | | |

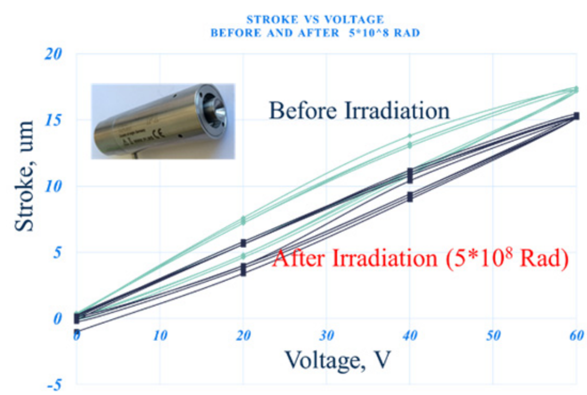


Figure 10: Piezo hysteresis curve for E1 sample before and after irradiation up to 5*10$^8$ Rad.

Piezo-stacks were irradiated at room temperature and in the air at extremely high radiation dose rate. There are some speculations that in real operational conditions (insulated vacuum and cryogenics temperature) radiation damage will be less than at our accelerated irradiation tests.

There is data of the piezo-stacks radiation hardness at cold/insulated vacuum conditions but these studies conducted with irradiation of piezo by neutrons to a total dose ~7*10$^{14}$ n/cm [12].

Visual inspection after irradiation tests do not reveal any serious damages to the piezo ceramics, except for Teflon insulation on the leads wires on the samples A&B. At the same time piezo-stack E1 (designed for LCLS II tuner) that has leads wire with Kapton insulation has no visible damage.

Most important parameter – stroke of the piezo-actuator has decreased only on 10% and that is acceptable to LCLS II requirements [1].

### *Electromechanical Actuator Irradiation Test*

During "5*10$^8$ Rad" cycle following components of the electromechanical actuator were irradiated: stepper motor, limit switches and "traveling nut".

Stepper motor was disassembled to visually inspect inside windings before and after irradiation. Our interest was wire insulation on the stepper windings. Visual inspection and "short-circuit test at 40V" do not revealed any damage from the irradiation.

We requested from vendor to fabricate limit switches with insulation made from fiber-glass material G11 (Figure 2). This material is often used for construction of the accelerator magnets. Visual inspection do not reveal any damages from radiation. We were informed by Sandia radiation facility personnel that during quite strong radiation dose rate, the temperature of the samples was above room temperature. We observed some discoloration and oxidation on the limit switch contacts. In real tuner operation at cold/insulated vacuum environment this will not be an issue.

Figure 11: Phytron stepper motor internal windings after irradiation with dose 5*10$^{\mathbf{8}}$ Rad.

Traveling nut from stainless steel has a TECASIN 1041 insert which mates to the M12X1 thread (Figure 3). TECASINT 1041 is a high temperature polyimide with 30% MoS2. This material has excellent radiation resistance properties (1-10*10$^8$ Rad ). Large radiation dose will cause material to "swell" [13]. This can lead to increased friction for Ti-spindle/traveling nut system. We conducted after-irradiation visual inspection and measurements of mechanical dimensions of the insert. No damages or size changes have been found.

## CONCLUSION

During design of the SRF cavity tuner for LCLS II project we followed couple major ideas: 1) used as much as we can from previous tuner design experience, 2) worked with companies to create most advanced and reliable active components for the tuner. Avoid "in-house" assemblies of the electromechanical and piezo-electrical actuators.

Reliability of the SRF cavity tuner is one of the major concerns. Active components of the SRF cavity tuner for LCLS II project were subjected to a battery of the reliability tests. Each tuner components went through ALT in real operating conditions (cold/insulated vacuum).

Our electromechanical actuator and piezo-actuator meet the LCLS II lifetime requirements.

SRF cavity tuner will be irradiated during lifetime of the accelerator with a dose of ~2-4*10$^8$ Rad. All components of the tuner were irradiated up to 5*10$^8$ Rad. The post irradiation tests /visual inspections of the components confirmed capability of the SRF tuner to withstand required radiation dose.

## REFERENCES

[1] Y. Pischalnikov et al., "Design and Test of Compact Tuner for Narrow Bandwidth SRF Cavities", WEPTY035, IPAC2015, Richmond, VA, USA.
[2] http://www.phytron.eu/antrieb/index.php?Set_ID=165&PID=72
[3] Y. Pischalnikov et al., "Tests of a Coaxial Blade Tuner at HTS/FNAL", TUP082, PAC2011, New York, USA.
[4] Y. Pischalnikov et al., "Tests of Electromechanical Actuators for SRF Cavity Tuner", IPAC2014, Dresden, Germany.
[5] http://www.piceramic.com/product-detail-page/p-882-p-888-100810.html
http://www.physikinstrumente.com/product-detail-page/p-844-101210.html
[6] http://www.pi-usa.us/pdf/Piezo_Actuator_Lifetime_Tests_Picma.pdf
[7] M. Fouaidy et al., "Full Characterization at Low Temperature of Piezoelectric Actuator Used for SRF Cavities Active Tuning", FOAA010, PAC2005, Knoxville, Tennessee, USA.
[8] M. Grecki et al., "Piezo Characterization, Tests and Operation at FLASH", LLRF13, Lake Tahoe, CA, USA.
[9] P. Pertsch et al., "DC- and AC-Signal Reliability of the Piezoelectric Multilayer Actuators", proceeding ACTUATOR 2010, p 55-58, Bremen, Germany.
[10] M. Santana Leitner, L. Ge, "Radiation Fields from Field Emission at the SCRF cavities of LCLS II", SLAC Radiation Physics Note RP-15-13.
[11] C.L. Hanks, D.J. Hamman "Radiation Effects Design Handbook", Section 3. Electrical Insulating Materials and Capacitors, NASA-CR-1787.
[12] M. Fouaidy et al., "Radiation Hardness Tests of Piezoelectrical Actuators with Fast Neutrons at Liquid Helium Temperature", CARE-Note-07-004-SRF.
[13] http://www.ensinger-inc.com/downloads/lit_brochures/TECASINT-handbook.pdf




ISBN 978-3-95450-178-6