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EXTENDED RANGE SRF CAVITY TUNERS FOR LCLS-II HE PROJECT*

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Abstract

The off-frequency detune method is being considered to be applied in the LCLS-II-HE superconducting linac to produce multi-energy electron beams for supporting multiple undulator lines simultaneously [1]. To deliver off-frequency operation (OFO) requirements for SRF cavity tuner must be changed. Tuner design modifications and results of the testing new tuner installed on the single dressed cavity and eight cavity/tuner system, deployed in verification cryomodule (vCM), will be presented.

INTRODUCTION

Tuner for LCLS II project developed as part of broad R&D program [2,3]. 250 units have been built, installed in into more than 40 cryomodules [4]. All tuners successfully tested as part of cryomodule qualification program [5]. LCLS II HE project is considering option for multi-energy operation that call for much more demanding parameters for SRF cavity tuners.

SRF tuners, that will be deployed into LCLS-II-HE linac, must be capable to bring 100% cavities to operational frequency 1.3GHz and at least 62% of the cavities of the linac need to be retuned to 1.299,535kHz (F_{OFO}=1.3GHz-465kHz) [6]. One more demanding requirement is regularity of cavity re-tuning from 1.3GHz to F_{OFO}=1.3GHz-465kHz. It must be done approximately twice a month, that will be required exceptional longevity for SRF cavity tuner.

TUNER MODIFICATIONS

Tuner Frame

To deliver OFO specification required to increase slow tuner range must be increase in almost 2,5 times. During LCLS II cryomodules testing, as first step after cooling-down CM to T=2K frequency of each cavity was measured. We called this frequency $F_{T=2K\_Landing}$. Cavity frequency $F_{T=2K\_Landing}$ is different from frequency $F_{T=2K\_non\text{-}restrained}$ on ~150kHz, that could be explained by initial preload of the cavity by tuner during installation and different thermo-contractions of the dressed cavity/tuner system components. Distribution of the $F_{T=2K\_Landing}$ for 160 cavities (20 CMs) equipped with tuner and tested at FNAL presented on the Fig. 1. Average of this distribution is Fig. 1. The LCLS II tuner range, required to bring cavities after cool-down to T=2K, is from 30kHz up to 250kHz. We are expecting that vendor will use similar procedure for LCLS II HE cavities during production and distribution of the $F_{T=2K\_Landing}$ will be similar. To tune LCLS II HE cavities to OFO slow tuner range need to be increase from 250kHz to 720kHz (or ~3 times).

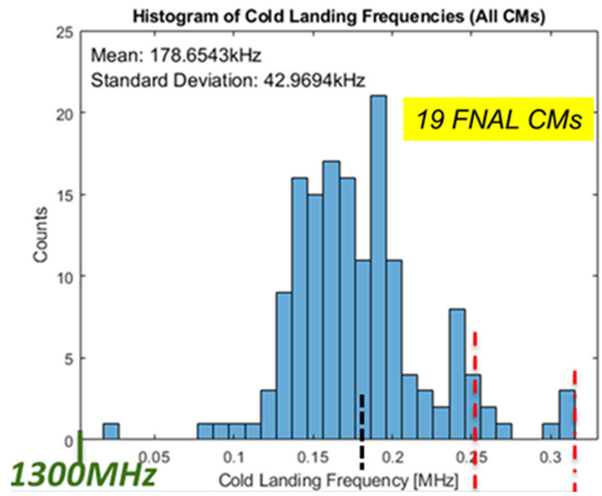

Figure1: Distribution of the values $F_{T=2K\_Landing}$ for 152 cavities assembled into 19 FNAL's cryomodules. Mean value is 1.3GHz+178kHz. 95% of the cavities have value of $F_{T=2K\_Landing}$ <1.3GHz+250kHz.

To be tuned to OFO cavity (with $F_{T=2K\_Landing}$ =1.3GHz+250kHz) must be compressed on 2.7mm from non-restrained position. LCLS II Tuner is double lever tuner with lever ratio 1:20 [2]. Review of the 3D model of the tuner and experience of tuner installation on the dressed cavity demonstrated that LCLS II tuner "as is" could not deliver required stroke/cavity compression.

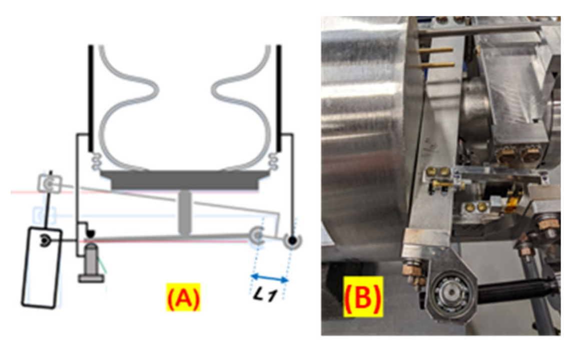

Figure 2: (A) Kinematic model of the double lever tuner. For demonstration purposes motor arm fully open/maximum compression of the cavity (up to limit by hard stop on the dressed cavity). (B) Close up picture of tuner/motor arms and cavity's endcap magnetic shield. This picture of the LCLS II, before arms extension on 7mm.

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There were two reasons that limited existing tuner stroke: motor arm stroke could be not open wide enough by interfere with cavity magnetic shielding and stepper motor shaft is short to deliver required stroke.

Two major tuner design modification have been introduced: (a) slow tuner lever ratio changed to 1:16 and (b) length of the tuner arms was increased on 7mm, allowing to shift tuner frame from cavity magnetic shielding and increase room for motor arm (Fig. 2). To change double lever ration from 1:20 to 1:16 length of the lever L1 was changed from 30mm to 37,5mm (Fig. 3). In addition, design of the several small components of the tuner (length of the safety rods, length of the silicon brass screws preloading piezo, etc.) need to be changed to accommodate extended tuner arms. Changes in tuner's lever ratio led to changes in tuner's sensitivity from 1.4Hz/step to 1.8Hz/step.

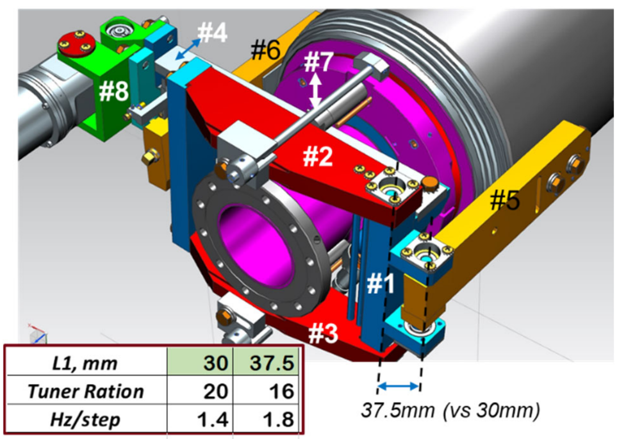

Figure 3: 3D-Model of the LCLS II/LCLS II HE tuner. For extended range tuner length of the arms #5&#6 were increased on 7mm.

Specification for Stepper Motor Actuator

The electromechanical actuator (stepper motor actuator) Phytron LVA 52-LCLS II-UHVC-X1 (Fig. 4) developed in collaboration between FNAL & Phytron [7] for ILCTA project. This actuator was successfully adopted for LCLS II and PIP II project. Major actuator parameters required to serve both LCLS II and LCLS II HE projects presented on the Table 1. Force on the actuator's traveling nut/shaft to bring cavity to OFO is 690N that is 2,5 time larger than LCLS II specs but still inside 1300N specification.

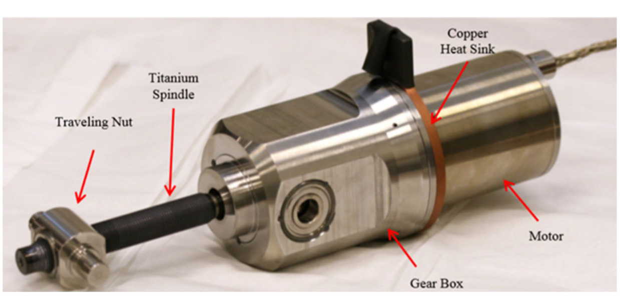

Figure 4: Phytron stepper motor actuator.

Actuator's longevity for LCLS II HE is much more demanding. Estimated longevity is based on assumption that HE part of the linac need to be re-tuned from 1.3GHz to 1.3GHz-465kHz twice a month. Lifetime specification for stepper motor actuator for LCLS II HE OFO is at least 30 times longer than for LCLS II. Reliability of the Phytron actuator already was measured during several ALTs (Accelerated Lifetime Test) but for smaller forces and shorter operational time [8]. It has been demonstrated that actuator withstand high radiation (up to $5*10^8$Rad) [3] and worked at real operational conditions (vacuum and cryogenic temperature) for longer than 10 lifetimes of the LCLS II linac. To demonstrate capability of the Phytron actuator to serve LCLS II HE OFO the designated ALT with dressed cavity/extended range system was conducted at FNAL HTS facility. Tuner has been operated 600 cycles by compressing cavity on ~800kHz. During this ALT test, that run for 1,5-month, tuner exercised for 1.5 lifetimes of the LCLS II HE linac or 45 lifetimes of LCLS II. No degradations of the stepper motor actuator have been observed. Details of stepper motor ALT test will be presented in separate paper.

Table 1: Stepper Motor Actuator Parameters

	LCSI II	LCLS II HE
Forces on the shaft/nut system to tune 95% of cavity to 1.3GHz, [N]	270	340
Forces on the shaft/nut system to tune 95% of cavity to 1.3GHz-465kHz, [N]	N/A	690
Longevity of the actuator/Number of the motor kSteps to tune cavity from 1.3GHz to "safe" position before warm-up (twice a year) during 20 years, [MSteps]	7.2	5.6
Longevity of the actuator/Number of the motor kSteps to tune cavity from 1.3GHz to "1,3GHz-465kHz" and back 20 times a year during 20 years, [MSteps]	N/A	206
Longevity for 20 years operation, [Msteps]	7.2	210

Specification for Piezo Actuator

Encapsulated piezo actuators, deployed in the tuner, developed in collaboration with Physik Instrumente, Inc (PI) [9] specifically for LCLS II project. Actuator (P-844K075) is encapsulated PICMA© piezo-stack with dimensions: cross-section $10*10mm^2$ and length 36mm. Inside stainless-steel capsule piezo-stack preloaded for 800N (Fig. 5).

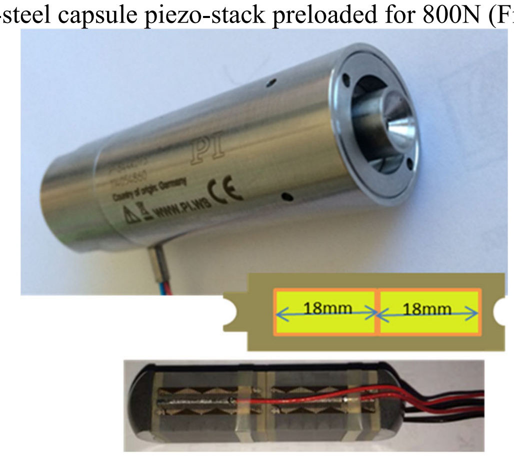

Figure 5: P-844K075 encapsulated piezo actuator. Inside capsule two butted PICMA© piezo-stacks.

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On the both ends actuator has grooves that used for ceramic ball interface between tuner main arm and cavity's end-group flange. Balls interface help to minimize built-up of the shearing forces on the piezo-stack when compressing/tuning cavity. According to manufacture specifications blocking forces of the PI actuator is 3.8kN.

One more parameter specified for PICMA© piezo-stacks, "maximum preload for constant forces" that specified in PI catalogue, is 30MPa, that is 3kN for P-844K075 [9]. Estimation of the piezo preloading, when slow tuner compressed cavity to F=1.3GHz, is ~ 3kN. Preload on the piezo-stack, when cavities will be tuned to F_{OFO}=1.3GHz-465kHz, will reach ~6kN that exceed in two times recommended by manufacture. Project considered several options to overcome potential problems with large preload on the PI actuator at OFO tuner position: to increase numbers of the piezo actuators per tuner from two to four in parallel; to develop piezo with two times larger cross-section. As mentioned previously, production schedule for LCLS II HE does not permitted for comprehensive R&D program that will guarantee that newest piezo actuator will have the same high level of reliability as P-844K075 [3]. Comprehensive risk analysis to reliably operate piezo P-844K075 with preload up to 6kN conducted in collaboration with PI engineers. Short summary of the analysis presented in next paragraph.

Piezo ceramics offer compressive strength well above 200MPa. P-844K075 actuators equipped with PICMA stacks 10*10mm2 can take at least 20kN pressure without been destroyed. We conducted destructive test of the P-844K075. Actuator was installed inside heavy metal jig and cool-down with jig inside liquid Nitrogen bath. After cool-down jig with actuator installed in the Instron device and forces applied on piezo till piezo-stack crushed. Actuator withstand forces up 28kN before collapsed. (Fig. 6). Most critical from piezo actuator point of view is generation of local tensile stress, e.g. caused by bending stack. Local tensile stress can lead to cracks and in an AC operation mode eventually to failure of the actuator. Existing design of the P-844K075 and interface of actuator inside tuner already optimized in respect of decoupling the actuator from any lateral force or torque. Factory recommendation of keeping preload ~30MPa applied to un-capsulated (bare) piezo-stack with assumption that customers will conduct "in-house" installation of the piezo-stack.

Other impact on the piezo performance at increased preload is possible mechanical depolarization of the actuator. In cryogenic applications this effect will be much smaller due to the fact that depolarizations effects are reduced at very low temperatures. We are expecting that P-844K075 actuator will exhibit similar performances and the same level of reliability with increased static external preload of about 6kN.

During ALT test of the tuner at HTS (see section stepper motor) compressed cavity 625 cycles that led to preloading piezo from ~2kN up to ~6kN. The performances of the two piezo actuators installed into tuner were not degraded after they subjected to 6kN preload for 625 times.

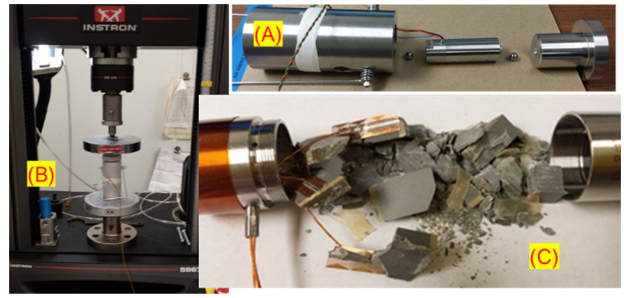

Figure 6: Destructive test of the piezo actuator. (A) Actuator installed inside heavy jig to minimize shearing force development and keeping piezo-ceramic at temperature T~80K during test at Instron (B). (C) Crushed piezo-ceramic stack. Actuator withstand forces ~28kN before collapsed.

TESTING OF THE MODIFIED TUNER

Goal for modification of the LCLS II HE tuner was to significantly increase slow tuner range and preserve major parameter of the tuner similar to LCLS II specifications. Details studied of the LCLS II tuner published early [2,5]. Tests objectives with first extended prototype tuner, assembled on the dressed cavity, were to demonstrate large range of the slow tuner and capability of the piezo withstand forces above 6kN.

First test conducted with dressed cavity equipped with tuner prototype that was submerged into liquid Helium in VTS (Vertical Test Stand). Operation of the LCLS II tuner when submerged into liquid Helium (LHe) demonstrated previously [10]. Major results, when tuner has been operated at 2K and compressed cavity on the ΔX=2.7mm (ΔF= 870kHz), presented on the Fig. 7. Slow tuner curve "frequency versus motor step" is linear with tuner sensitivity ~1.8 Hz/step. Piezo stroke vs forces on the piezo presented on Fig. 8. As expected, there are no piezo performances degradation with preload up to 6.2kN. VTS test also provided information about parameters of the 9-cell elliptical cavity when compressed on quite significant stroke ΔX~2.7mm. VTS test demonstrated that cavity do not experience of any non-elastic deformations. After two cycles of compression cavity on ΔF= 870kHz the cavity's field flatness changed less than on 0.01%.

As next step dressed cavity, equipped with extended range tuner, was installed at FNAL HTS with major objectives to conduct ALT test of tuner's components (stepper and piezo actuators). Tuner cycled 625 times, compressing cavity on 2,5mm from non-restrained position. During test performance of the tuner monitored. There were no observations of the changing tuner performance or dressed cavity fatigue.

Extended tuners installed on the verification cryomodule

First LCLS II HE cryomodule (verification cryomodule – vCM) assembled at tested at FNAL [11]. The vCM's cavities were equipped with extended range tuners. LCLS II tuner for cavity#1 has different design compare with tuners served cavities from #2 to #8 [12]. Frame of the tuner for cavity#1 is serving additional task: support Gate Valve of the cryomodule. Based on this functionality of the tuner

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for cav#1, decision was made to change cav#1 tuner lever ratio to 1:16 but keep the same distance between tuner main lever and cavity conical flange/ no extension for tuner's arms. There is plan during cryomodule assembly to select cavities with "lower" frequency (Fig. 1) to be installed on the position 1. If we assume that for some reason in ½ of cryomodules cav#1 could not be tune to OFO it will count to ~ 7% from all cavities in LCLS II HE linac.

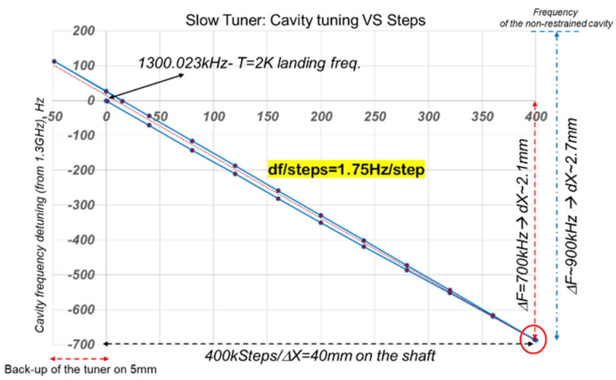

Figure 7. Slow tuner performance, when cavity and tuner submerged into LHe. Cavity was compressed on ~2.7mm.

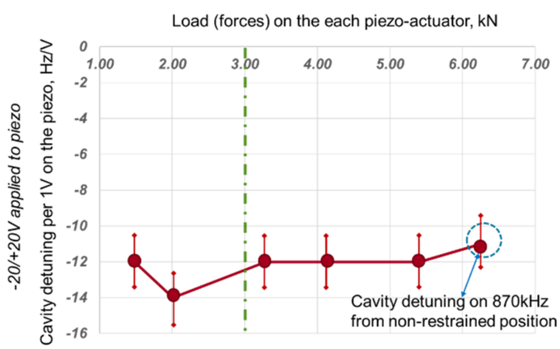

Figure 8. Piezo's tuning response vs preload (forces) on the piezo actuator. Piezo actuator was submerged into LHe at T=2K.

All modified tuners installed in the vCM worked as expected. The cavities $F_{T=2K\_Landing}$ and steps required for tuner to bring cavity to operational frequency 1.3GHz presented on the Table 2. Average value of $\Delta F=(F_{T=2K\_Landing}$-1.3GHz) for vCM is 52kHz that is lower than the same value for 19 LCLS II cryomodules (Fig. 1). Difference in ΔF=126kHz could be explained by (a) installation of the tuners on vCM cold-mass done with beamline under vacuum (in LCLS II/FNAL cryomodules installation done with backfilled with 1 bar N2); (b) cavities selected for vCM were tuned to "lower" frequency at vendor facility; (c) cavities were preloaded with piezo as part of tuner installation on 100kHz (instead of 50kHz for LCLS II). Fast tuner (piezo) response is 20Hz/V for all 8 cavities. All 8 cavities of vCM were tuned to OFO without any issues. All 8 fast/fine tuners of vCM have the same response 20Hz/V after tuned to OFO position.

Table 2: vCM Cavity Frequencies and Number of the Motor's Steps Required to Bring Cavities to 1.3GHz.

cavity#	F $_{T=2K\_Landing}$ - 1.3GHz, [kHz]	Number of the motor steps required to tune cavity to 1.3GHz	Slow Tuner sensitiviy, [Hz/step]
1	71	38730	1.83
2	32	17300	1.85
3	13	6460	1.97
4	28	14750	1.88
5	61	32950	1.84
6	93	54700	1.70
7	51	27780	1.84
8	69	37850	1.82
	52		***1.84***

CONCLUSION

LCLS II HE tuner is modification of the LCLS II tuner that addressed OFO requirements. Objectives were to introduce only necessary modifications of the proven to be reliable LCLS II design. To increase tuning range in 2,5 times tuner frame has two major changes: increase on 7mm the tuner arm's length and double lever ratio from 1:20 to 1:16. The modified tuner prototype was able to deliver OFO range without changing length of the stepper motor shaft and avoid interferences between cavity magnetic shield and motor arm. ALT testing at HTS demonstrated that Phyton stepper motor actuator operated for 400MSteps that is twice of required longevity of actuator for OFO. The PI encapsulated piezo actuators, used for LCLS II project, will be used for LCLS II HE. Testing tuner, when piezo preloaded at 6kN, that required to operate at OFO, demonstrated the same characteristics as at 3kN. ALT test at HTS confirmed that piezo performances do not changed after two piezo actuators were compressed up to 6KN 625 times. Based on the analysis performed by PI and FNAL experts we are expecting the same level of reliability of the P-844K075 actuator even at 6kN preload, as required by OFO. Multiple tests with extended range tuners installed on the dressed cavities demonstrated that tuner met LCLS-II-HE OFO specifications.

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