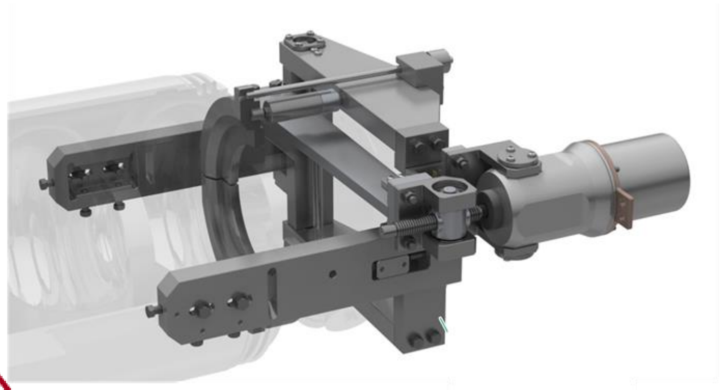

Tuner System For Dual Frequency Operation

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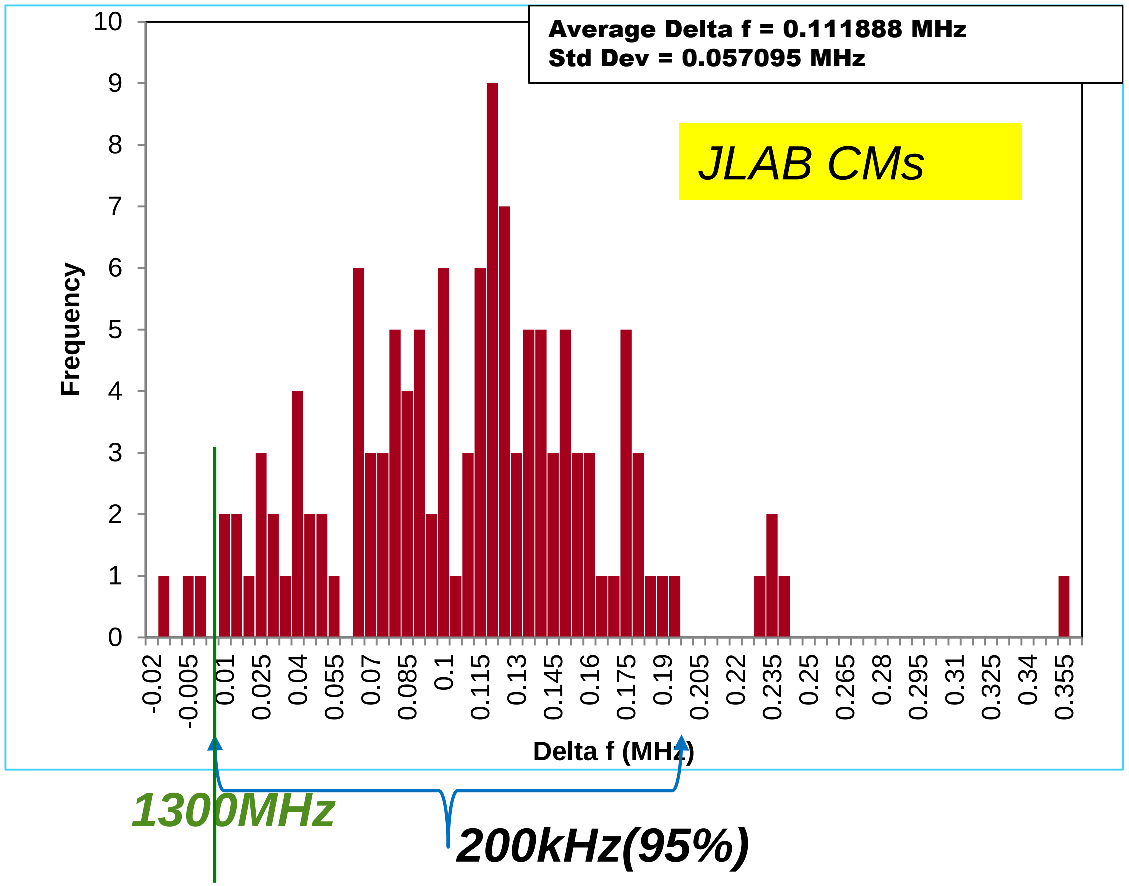
U.S. DEPARTMENT OF ENERGY | Stanford University

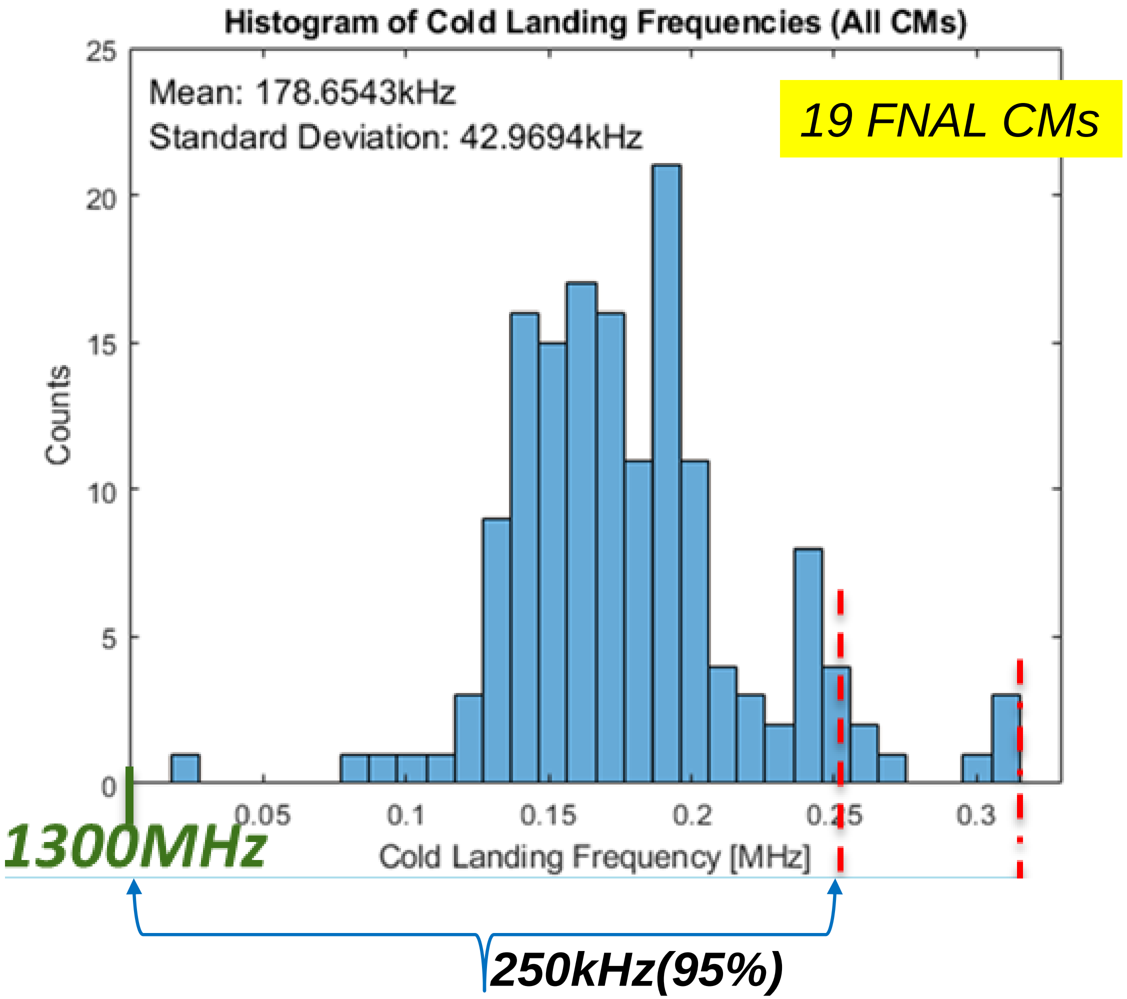
Outline

- Required range of the Tuner for Dual Frequency Operation
- New Specs for Tuner: LCLS II HE vs LCLS II
- *tuner range*
- *specs for the Phytron electromechanical actuator*
- *specs for the piezo-actuators*
- Modification of the slow tuner frame to deliver extended range
- Capability of the Phytron actuator (LVA 52-LCLS II-UHVC-X1) to preserve required reliability with new specifications.
- Capability of the PI piezo-actuator P-844K075 (or some other piezo-actuator) to preserve required reliability with new specifications.

Frequency of the cavities when CMs first time cool down to T=2K

Difference between 2K landing frequencies for FNAL & JLAB is ~ 66kHz (178kHz-112kHz)
This difference could be explained by a) back-filled .VS. vacuum beam, b) slightly different initial piezo preload ?





Required Tuner range for LCLS II HE

Assuming that

- cavities will be under vacuum during installation of the tuners
- piezo preload during initial tuner installation will be in the range of 50kHz

Required tuner range (for 95% of the cavities) will be 200kHz + 465kHz = 665kHz *(accounting from "T=2K landing frequency").*

To tune cavity on **ΔF_{TUNER}= -665kHz** cavity need to be compressed on **ΔX~ 2mm** *(from T=2K landing position)*

** For 1.3GHz cavity df/dx~330kHz/mm*

Frequency of the non-constrained cavity (at T=2K) .VS. “T=2K Landing frequency”

To determine overall compression (tuning) of the cavity required to bring it to F=1.3GHz-465kHz we need to know (in addition to “T=2K Landing frequency”) frequency of the “non-constrained” cavity.

Procedure for testing of the LCLS II CMs had not required to measure these values.

We could refer to our measurements with 3 dressed cavities at HTS during R&D program.

ΔF_0 between “T=2K landing” & “non-constrained” cavities (based on these measurements) is ~200kHz.

The difference is combination of the a) cavity compression when beam line at vacuum; b) cavity/piezo preload during tuner installation and c) difference in thermal contractions of the components of the dressed cavity/tuner system.

Overall compression (tuning) of the cavity (to bring to F=1.3GHz-465kHz)

$\Delta F = \Delta F_{TUNER} + \Delta F_0 = (-665kHz) + (-200kHz)$

$\Delta F = -865kHz$ or $\Delta X = 2.6$ mm

Specifications for Tuner system
LCLS II vs LCLS II HE (for Dual Freq. Operation) (I)

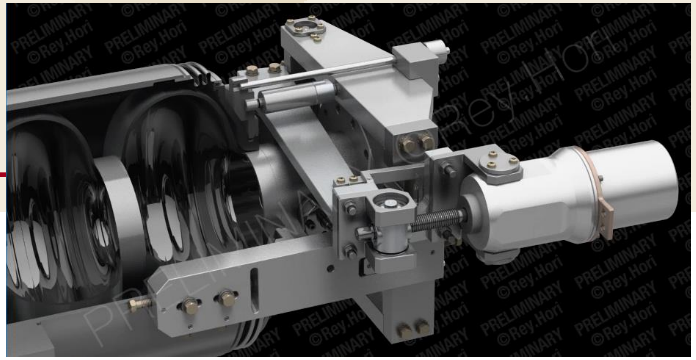
	LCLS II	LCLS II HE
Cavity frequency target, GHz	1.3GHz	1.3GHz-465kHz
Cavity frequency tuning from T=2K landing position, kHz	200 kHz	665 kHz
Forces on the Phyton Actuator	300 N	600 N
Forces on the each PI piezo-actuator from compressed cavity at operational point	3 kN	6-7 kN

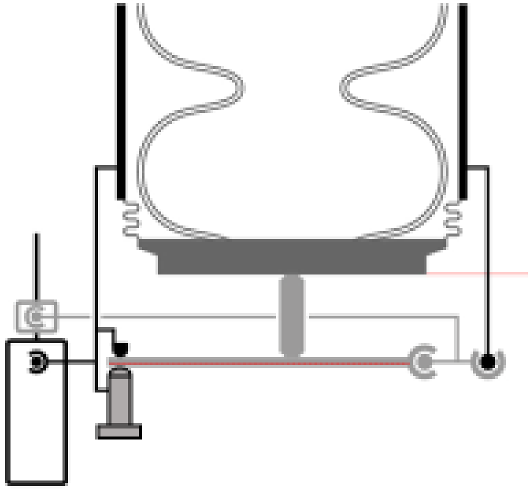
Specifications for Tuner system
LCLS II vs LCLS II HE (for Dual Freq. Operation) (II)
Estimations of the required range/running hours by stepper actuator

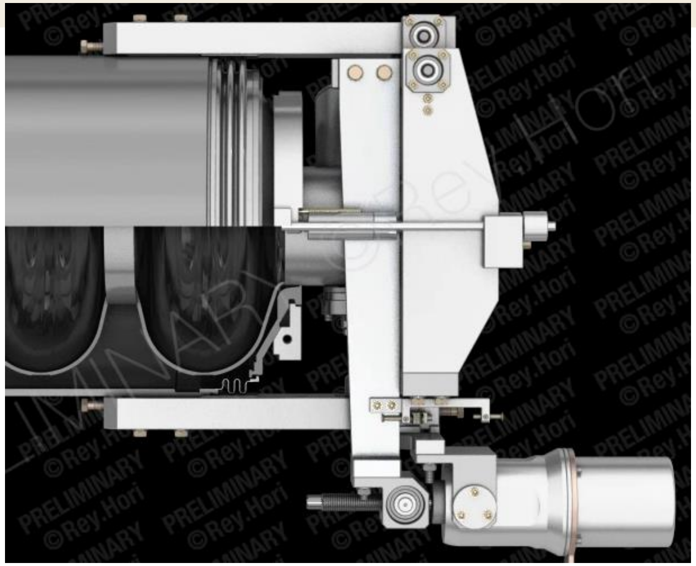
	Range during one year period			Hours of operation during life of LINAC (25 years)
	Frequency, MHz	Msteps	Hours (speed -200steps/sec)	
twice a year to tune "landing freq." to 1.3GHz and back	**1**	**0.56**	**0.8**	**20**
One time/month to tune to 1.3GHz-465kHz & back	**11**	**6**	**8**	**200**
Twice/month to tune to 1.3GHz-465kHz & back	**22**	**12**	**16**	**400** !

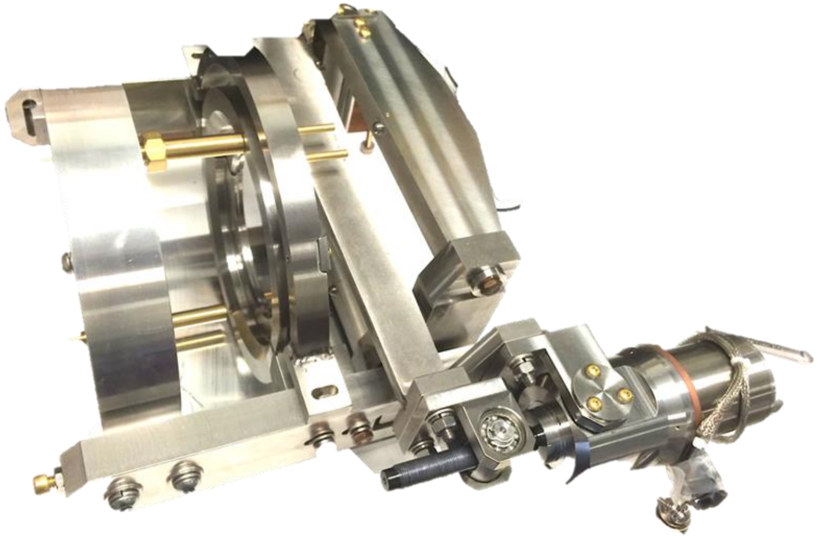
LCLS II Compact Double Lever Tuner

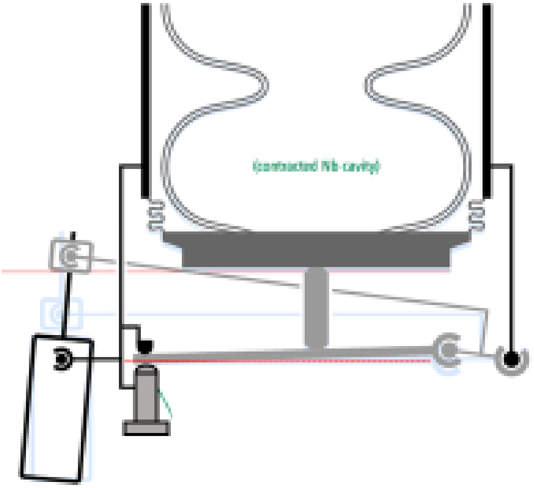
(principle of operation)

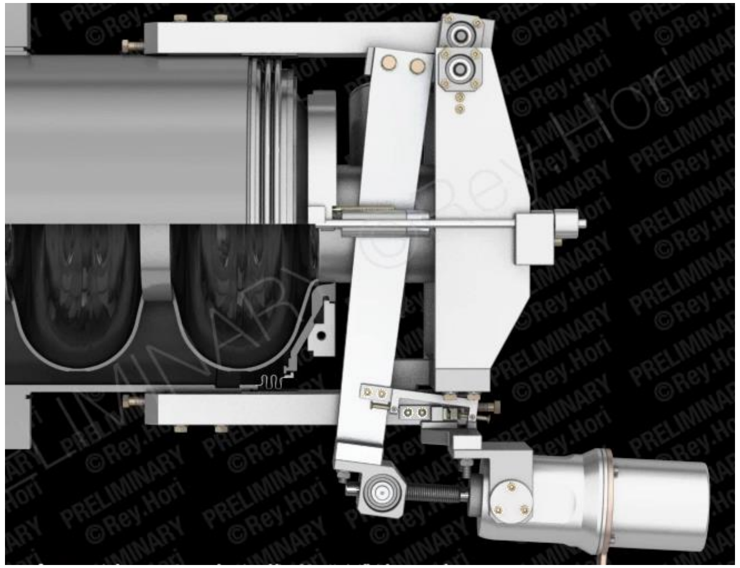










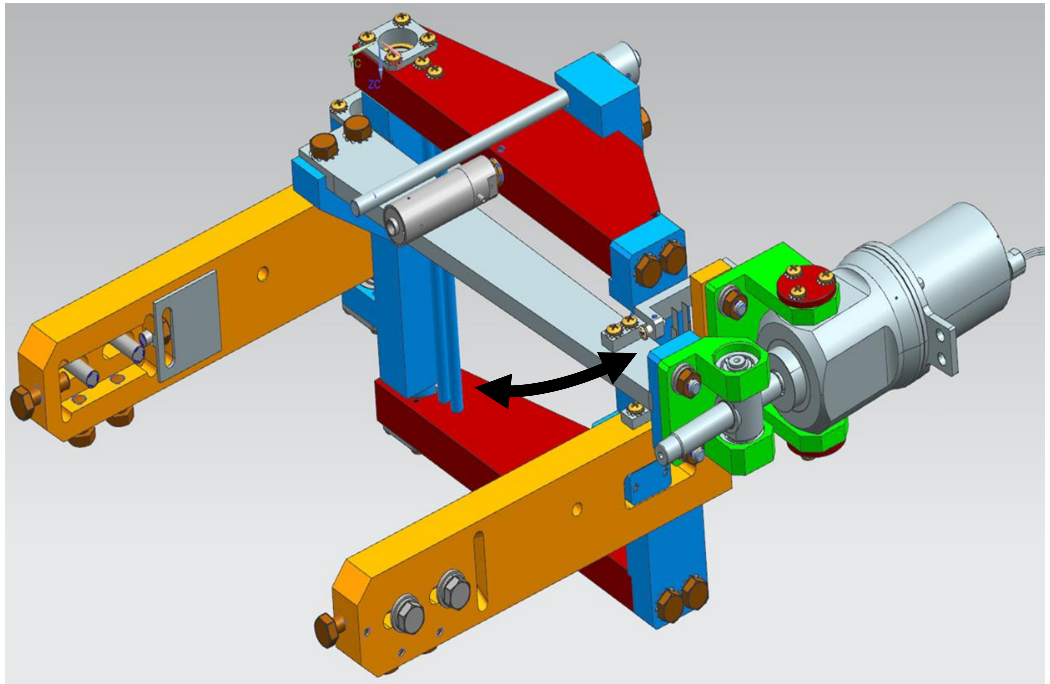


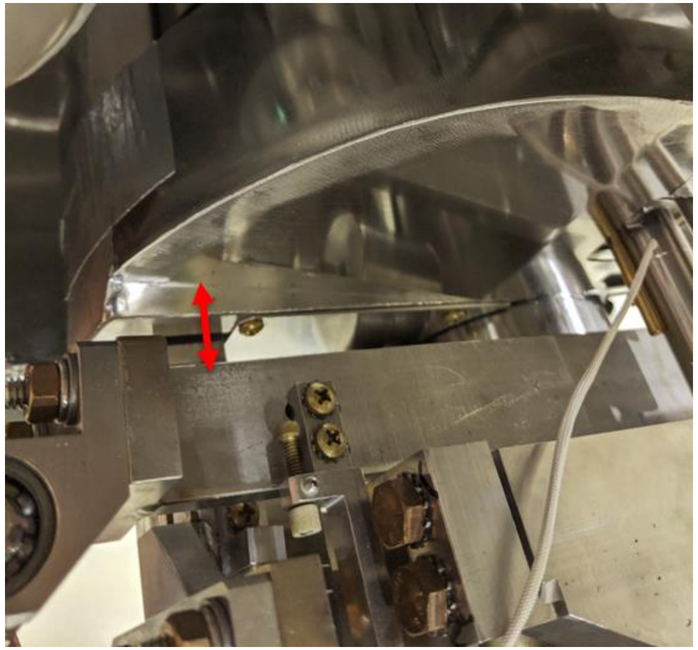
Can the Slow Tuner "as-is" deliver 700kHz tuning range?

"As is" LCLS II slow tuner could not deliver ΔF=700kHz

– Tuner motor arms motion will be limited by existing space between tuner and end-cup magnetic shielding of the cavity.

- In addition length of the Phytron actuator shaft will be not enough for required travel of the nut.





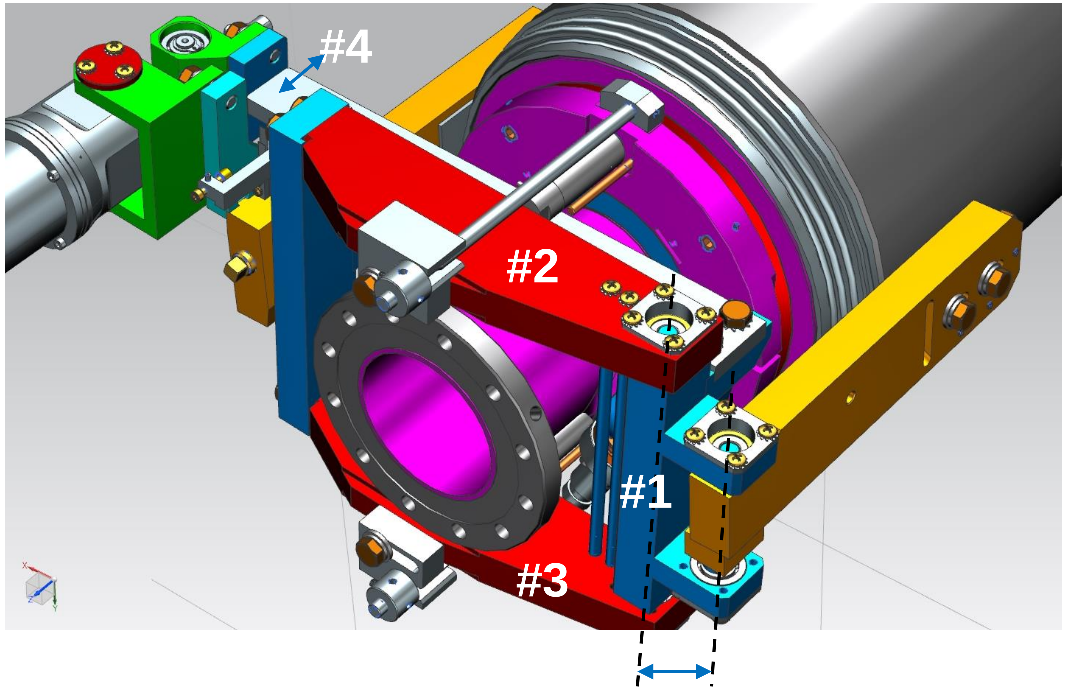
Modification of the Slow Tuner frame to deliver 700kHz tuning range

Change of the double-lever tuner ration from 1:20 to 1:16

We took following approach:

- make minimal tuner modifications (preserve all tuner/cavity/He Vessel interfaces);

-change the length of lever L1 from 30mm to 37.5mm we delivered tuner ratio 1:16 (instead of 1:20)



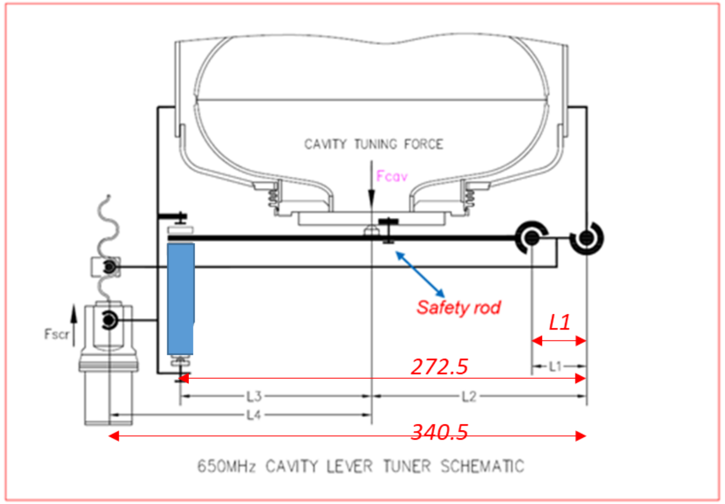
37.5mm (vs 30mm)

Four components of the existing need to be changed. (see labels)

All other components (part of the tuner frame and active elements) do not required any modifications.

No any interreferences with cavity components.

This design modifications will work for all cavities, including special design tuner for cavity#1.



L1, mm	**30**	**37.5**
Tuner Ration	**20**	**16**
Hz/step	**1.4**	**1.75**

Maximum forces on the Phytron actuator will be increased on ~ 25% and will be reached up 600N, that is below 1300N (Phytron specs).

First prototype of modified/ extended range Tuner for LCLS II HE

- Four new components have been machined.
- Modified tuner assembled by replacing these new components in tuner removed from CM5.
- New tuner has been installed on the dressed LCLS II cavity for VTS test.
- Results of the test will presented later in separate talk.

Tuner reliability

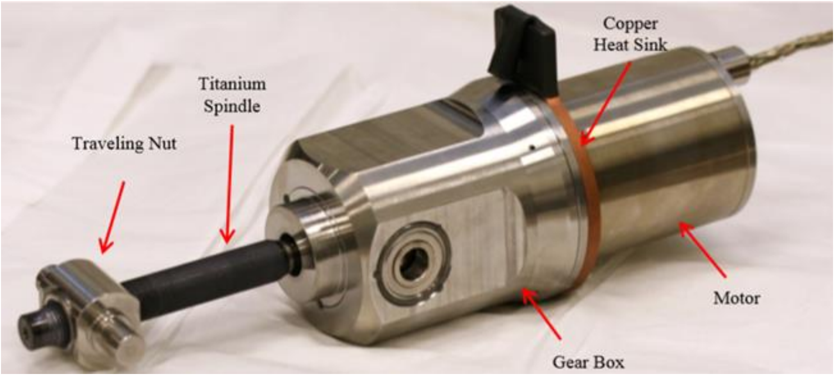
Tuner team went through several vigorous R&D programs to make sure high reliability of LCLS II tuner.

All tuner's components went through ALT (Accelerated Lifetime Tests) in real working conditions (at cryogenics temperature and insulated vacuum) to demonstrated longevity of the components.

Radiation hardness tests of the tuner's components performed by irradiating with gamma source up to expected level during 25 years of LINAC operation.

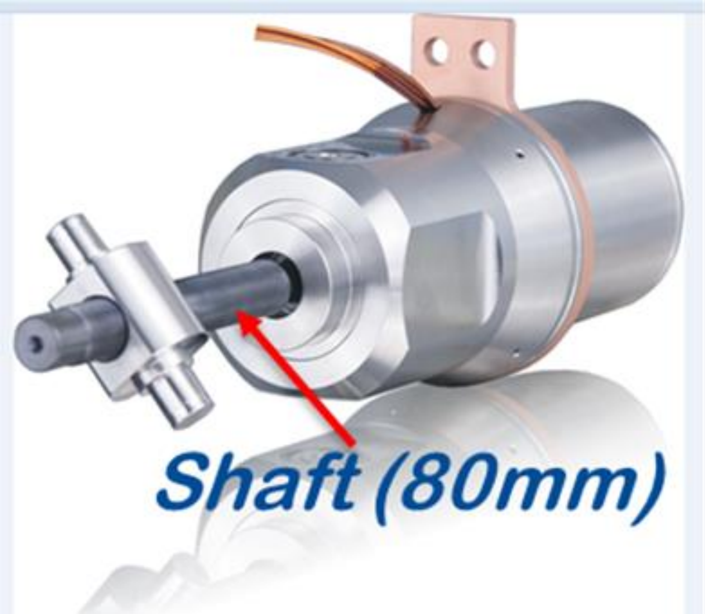
New specifications for tuner (for Dual Freq. Operation) will extend longevity requirements for active components: Phytron (stepper) and PI (piezo) actuators.

Electromechanical Actuator
Phytron LVA 52-LCLS II-UHVC-X1



Phytron Electromechanical Actuator

Dual frequency operation of the LCLS II HE will required much more demanding specifications for electromechanical actuator:



1. Larger operational FORCES – up to 600N

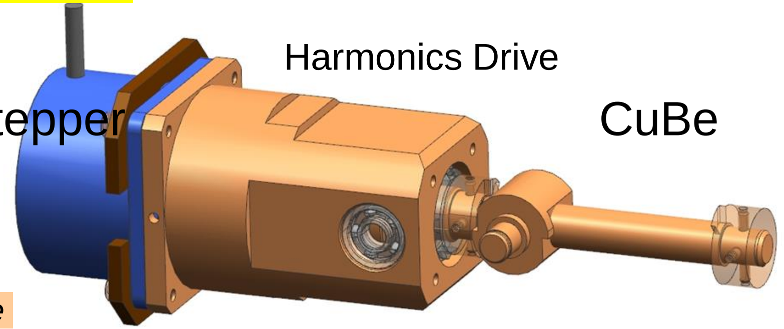
(Specifications of the Phytron actuator is 1300N)

2. Required LIFETIME of the actuator is 160MSteps (for 1 time a month re-tuning) or 310Msteps (for 2 time a month re-tuning).

With typical speed of stepper motor 200steps/sec it is 220Hours (or 420Hours) of running.

Lifetime of Electromechanical Actuators:
20 hours .VS. 220 hours .VS. 420 hours

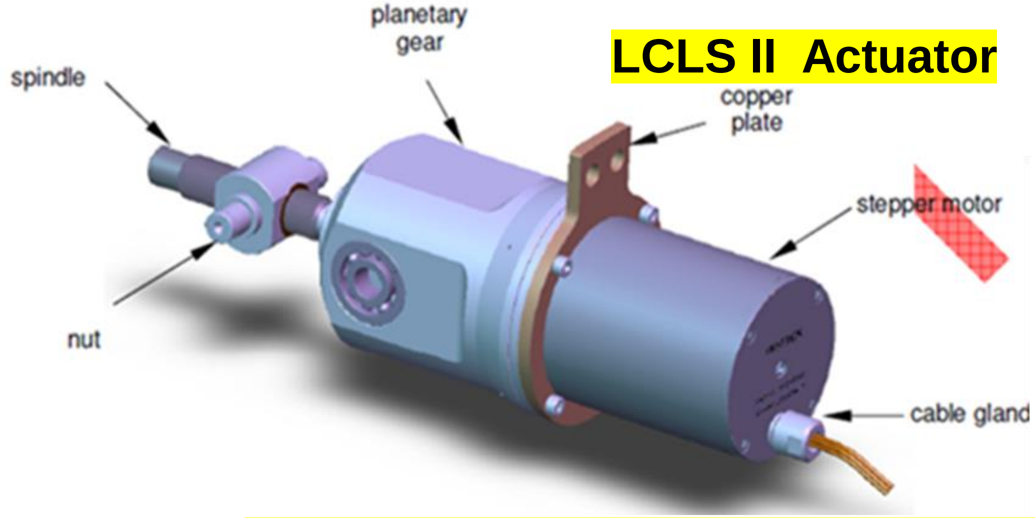
XFEL Actuator



Lifetime of the XFEL actuator is ***30Hours***

Axial load on spindle = 200N

LCLS II Actuator



Axial load on the spindle up to 1300N

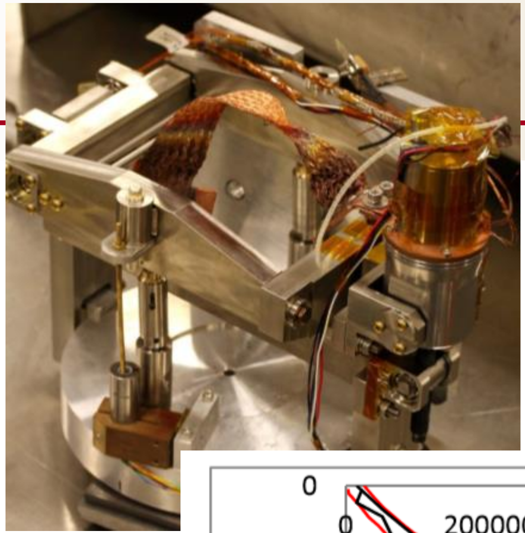
Longevity tests of the LCLS II (Phytron) actuator by JLAB/FNAL team:

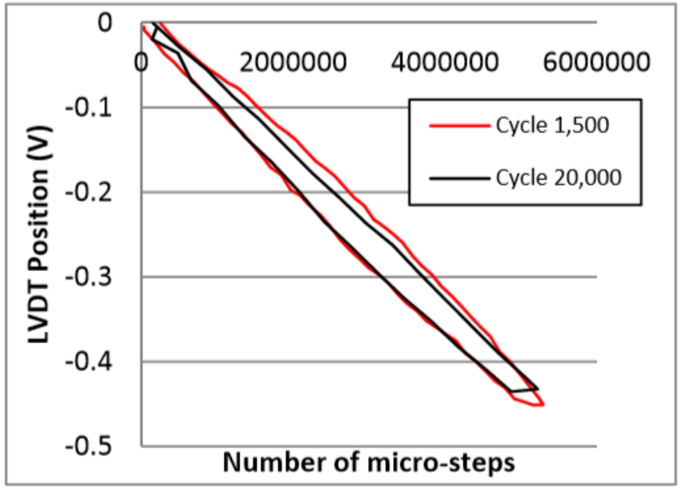
http://accelconf.web.cern.ch/AccelConf/SRF2015/papers/thpb062.pdf

https://accelconf.web.cern.ch/AccelConf/srf2017/papers/mopb110.pdf

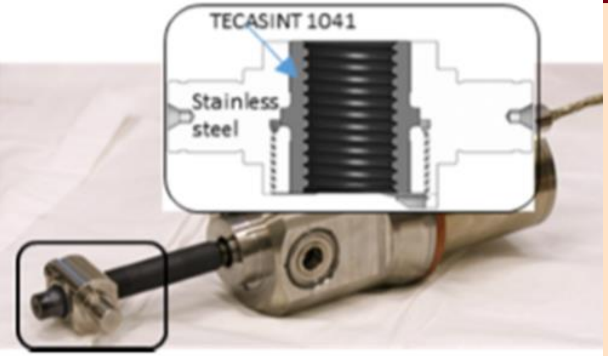
Actuator has been tested when installed on the LCLS II tuner. Tuner mounted on aluminum frame/dummy cavity. Setup has been cool-down inside JLAB VTS and actuator run (inside insulated vacuum and cryogenic temperature) for 14days (or **330 hours**)

Brief summary of the Accelerated Lifetime Test of the Phytron (LCLS II) actuator

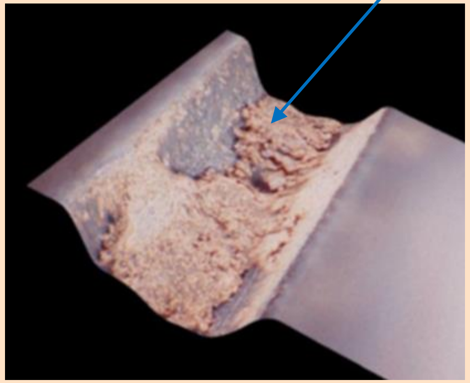




Despite of the degradation of the TECASINT 1041 nut material there was no change in the actuator performance at the end of ALT tests (14days/330hours of continuous operation)



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



Material found between spindle threads (X400 magnification).

TECASINT insert inside the traveling nut

Brief summary of the meeting with Phytron experts

Some of the questions that discussed (with concentration on the lifetime of the unit):

1. Request to review possibility to use newest material for Traveling Nut. Phytron engineers design TECASINT insert almost 10 years ago… Maybe, there are new material that will better match to our demanding specs.
2. Unit that went through ALT has been sent to Phytron (more than 3 years ago) for post-test dis-assembly/evaluations. We were extremely satisfied with longevity more that 12 lifetimes of the LCLS II and didn't follow up with Phytron. Phytron will try to locate this unit… but not clear how successful they will be.
3. Phytron will share with us design/drawings of the fixture they used for test each unit at LN2. We will work with Phytron on the details/specifics of the required forces/stroke… to allocate right spring, etc. We will conduct our incoming ALT with close collaboration/consulting with Phytron
4. Phytron will send us quotes for ALT test : 400 hours/ insulated vacuum/T=70-100K. Very likely it will be expensive … we need to find facility/opportunity to conduct this ALT at FNAL/JLAB/SLAC.
5. Important for extended actuator longevity to use multi-stepping mode for stepper (even we operate in full-step). Multi-stepping will significantly reduce stepper motor vibration that will worn more quickly the dry-lubrication coating on the first stage of the planetary gear.

Summary.
The capability of Phytron stepper actuator to longevity required for Dual Freq. operation

- ALT test of the one unit for 330hours demonstrated that cavities could be re-tuned up to 3-time in two month.

- At this moment weakest element is traveling nut /TECASINT insert.

- Additional ALT tests will be conducted during next 1-2 month (in close collaboration with Phytron engineers).

- One of the options could be considered:
  - Traveling nut is not expensive components that could be easy replace through tuner access port … in case of nuts will be failed in several tuners after 10(?) years of the LINAC operation.

Piezo Actuator P-844K075

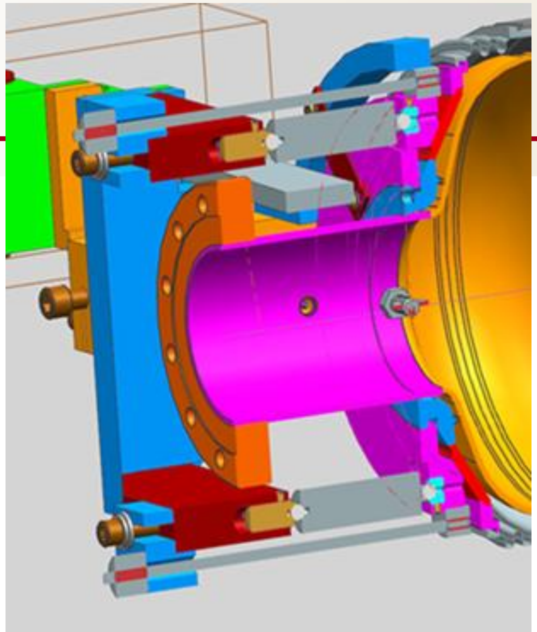
Designed by Physik Instrumente (PI)

(with contribution from FNAL) for LCLS II Project.

Each capsule has inside two (glued) 10*10*18mm PICMA piezos. Piezo, during assembly into capsule, internally preloaded with 800N.

Piezo-Actuators

P-844K075



Physik Instrumente (PI) manual recommended maximum constant forces that could be applied to PICMA piezo-ceramic stack is 30MPa.

For our actuator P844K075 with cross-section 10*10mm2 it is just 3kN.

PICMA® Stack Multilayer Piezo Actuators (10*10*36mm3)	
Blocking force, kN	3.8
Recommended Preload for dynamic operation, kN	1.5
Maximum preload for constant force, kN	3

We have two piezo-actuators per Tuner. Stroke/forces from slow tuner transfer to cavity through piezo-actuators. To minimize shearing forces, applied to piezo, ceramic balls used as interface.

When cavities will be tuned on 1.3GHz-465kHz constant forces on the each piezo-actuator will reach up **to 6-7kN** (or double compare with "standard" LCLS II operation mode).

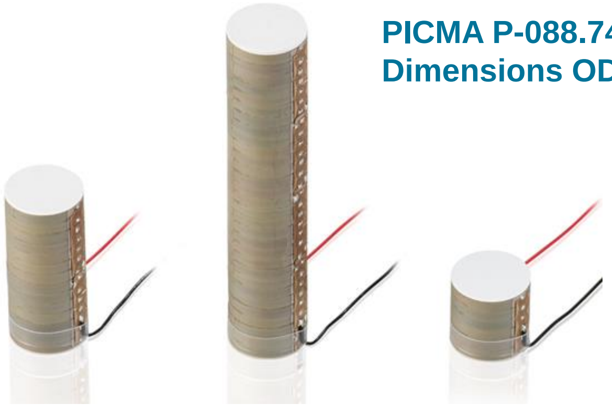
Question: how constant forces up 6-7 kN could impact on the longevity of the piezo-actuator ?

Piezo-actuator for large forces (search for optimal solution)

During last couple month intense communications with PI experts took place to review different options for reliable piezo-actuator for LSLC II HE (to handle 7kN of constant forces and preserve the same level of reliability as LCLS II unit):

#1. Keep the same P844K075 piezo-actuator (PREFERABLE)

#2. Develop (and thoroughly test) new piezo-actuator with larger cross-section (based on 16mm diameter (200mm2);



PICMA P-088.741
Dimensions OD*L 16*36mm

#3. To design multi capsules system, where several PICMA stack-stack) worked in parallel to decrease forces per mm2.

Piezo-actuator for LCLS II HE Tuner (Option#1- P844K075)

Piezo-ceramics experts from PI explained reasoning to published 30MPa value/limit in company catalog:

1. There is small probability that **warm** piezo-ceramic stack ***could start to de-polarized*** at the compressive stress above ***30MPa.*** For cold piezo (at cryogenics temperature) piezo depolarization process will start at significantly higher values of the forces on stack.

2. Second reason for publishing in PI catalog 30MPa value is liability. PI want to limit allowable compressive stress that users/customers will apply to non-capsulated PICMA piezo-stack. Especially, when customer installed bare piezo-ceramics stacks in their equipment (sometimes/often do not follow exact PI recommendations).

These are slides from PI .

On my request to provide PI “semi-official” response on the use of the P-844K075 in the range of the forces up to 7kN.

Physik Instrumente

P-844K075 actuators for LCLS II HE – Reliability under increased preload

MOTION | POSITIONING

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Overview

Consequences of a high preload on piezo performance

- Material strength of piezo ceramics
  - Compressive strength
  - Tensile strength
  - Design relevant aspects for P-844K075 actuator
- Changes in stroke
  - Due to changed preload
  - Due to changed external stiffness
- Conclusion: Lifetime of P-844K075 under high preload

Consequences of a high preload on piezo performance

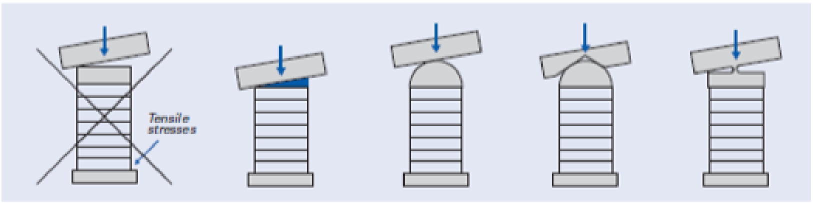
Material strength

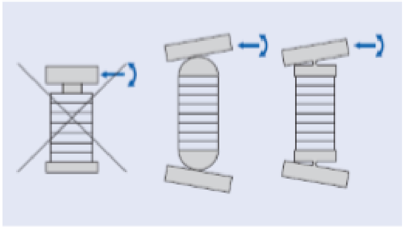
- Compressive strength
  - Piezo ceramics offer compressive strengths well above 200MPa.
  - P-844K075 actuators are equipped with PICMA stacks that feature a 10mm x 10mm cross-section. They can take at least 20kN of pressure without being destroyed.
- Tensile strength
  - Tensile strength of a piezo stack can be as low as 5MPa.
  - To protect the ceramics from external pulling forces – especially as long as they are not integrated in the final assembly – the P-844K075 actuator is designed with an internal preload of about 800N at room temperature.

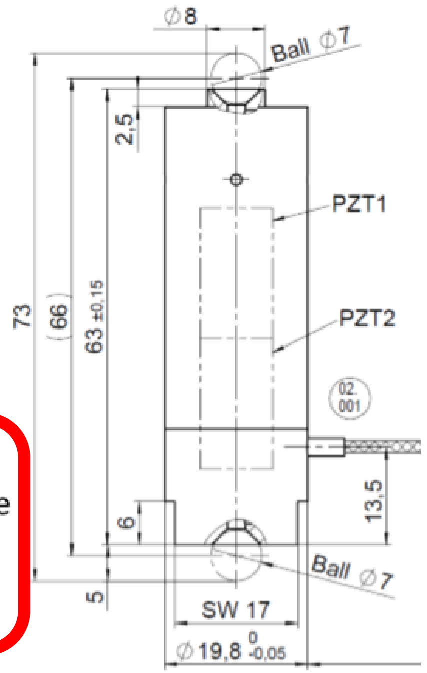
Consequences of a high preload on piezo performance

Material strength: Design relevant aspects for P-844K075

- Very high external preload forces can locally exceed the tensile strength of the piezo material, especially if the force is not applied near the axis within the core cross-section of the actuator.





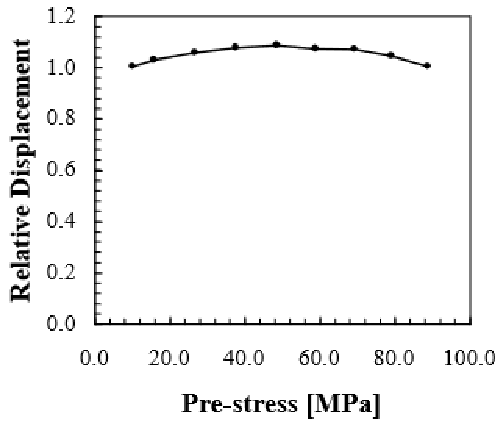


- The design of the P-844K075 is already optimized in this respect:
  - Mechanical interfaces are prepared to connect the actuator via balls and avoid lateral forces, e.g. due to parallelism tolerances.
  - Internally all components are aligned with respect to these interfaces.

Consequences of a high preload on piezo performance

Changes in stroke when increasing preload

- The actuator begins to mechanically depolarize already at a few 10 MPa. But large-signal control repolarizes the actuator and this actually causes the induced displacement to increase by up to 10%.
- Measurements at room temperature show that the maximum stroke can be reached with a preload in the range of 60MPa. At around 70 - 80MPa the available stroke is about the same as in an unloaded state.
- For dynamic operation it has to be taken into account that effective capacity and loss values increase as well.
- There is no measurement data available for low temperatures. In cryogenic applications these effects will be much smaller due to the fact that depolarization effects are reduced at very low temperatures.



PI

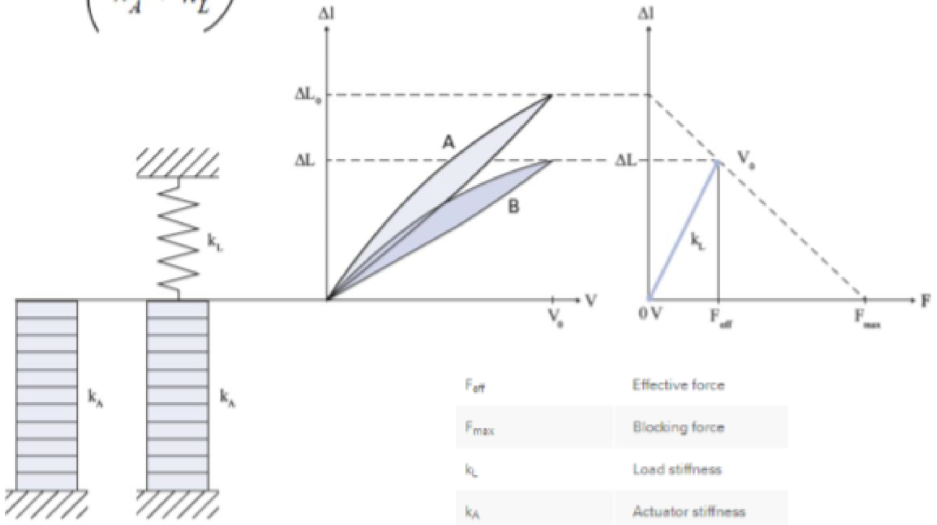
Consequences of a high preload on piezo performance

Changes in stroke when increasing preload stiffness

- The load stiffness for the P-844K075 will not change in the LCLS II HE project. Therefore, this slide is only for information and the sake of completeness.

- If the piezo actuator works against a spring force, its induced displacement decreases because a counterforce builds up when the spring compresses.
- Higher stiffness of the preload spring automatically reduces the available stroke.

$$\Delta L \approx \Delta L_0 \left(\frac{k_A}{k_A + k_L} \right)$$



F_{eff}	Effective force
F_{max}	Blocking force
k_L	Load stiffness
k_A	Actuator stiffness
ΔL_0	Nominal displacement
ΔL	Displacement
V	Operating voltage
V_0	Nominal voltage

PI

Conclusion

Lifetime of P-844K075 under high preload

Summary:

- Assuming a use case of the P-844K075 actuators for the LCLS II HE project which is similar to previous applications with an increased static external preload of about 6kN, a similar reliability can be expected.
- Most critical from piezo actuator point of view is the generation of local tensile stress, e.g. caused by bending of the stack, which can lead to cracks and in an AC operation mode eventually to failure of the actuator.
- In this respect decoupling the actuator from any lateral force or torque is most important and already taken care of in the existing design of the interfaces. Nevertheless, special care should be taken when installing the actuators. For more details please refer to PI_Handling_Piezo_Actuators.pdf

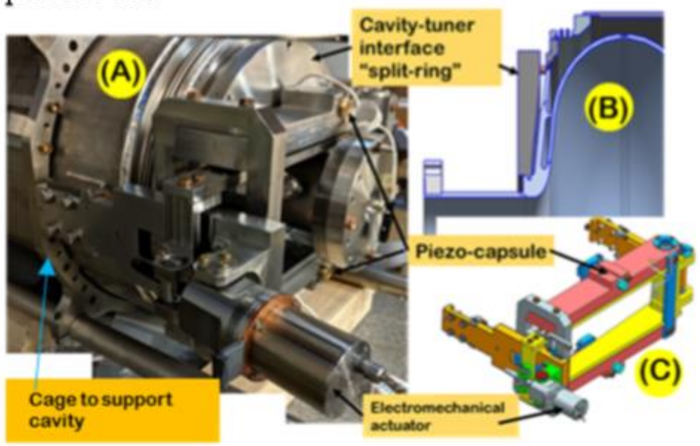
Ideas to further minimize the risks of failure:

- The internal preload of the actuators can be significantly reduced to take the increased load conditions into account.
- If a failure should happen it will be most likely in AC operation. Therefore, if possible, an accelerated lifetime test under operating conditions can help to prove reliability of the actuators.

Recent Tests of the P-844K075 with constant forces near 7kN

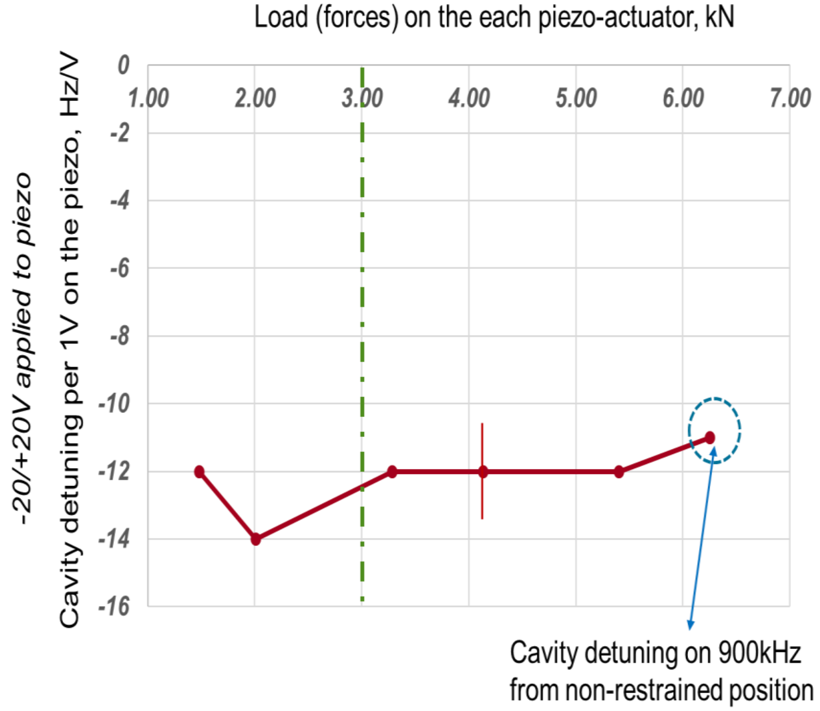
Tuner for PIP II 5 cell elliptical cavity is scale-up version of the LCLS II tuner with two P-844K075 piezo-stacks. Cavity stiffness is ~20kN/mm. Cavity has been retuned on 120kHz (compressed on 0.6mm). Forces applied to each of the piezo-stack was more than 7 kN. Piezo stroke slightly increased as predicted by PI.

pressure test.



Forces on the Piezo, kN	Cavity detuning, Hz/V
4	20
7	22

VTS test of the CAV0215



Piezo-actuators worked at forces up to 6.5kN without any problems

Piezo-actuators for LCLS II HE (Dual Freq. Operation)

Piezo actuator P-844K075 installed in the all LCLS II cryomodules (overall number is more than 600 units).
There was no any failure of the piezo-actuators during cool-down/testing CMs.
Many tests with piezo-actuators have been done: Rad-hardness test, ALT test, etc.

There was no doubt that P-844K075 is best (and only one) piezo-actuator for LCLS II HE. At the same time there were concerns about P-884K075 reliability when it will operate at double forces (6-7kN).

Based on information from PI and experimental data we could conclude that actuator P-844K075 will work reliably as part of the LCLS II HE tuner (Dual Frequency operation).

PI will pursue (as request from FNAL) development of the piezo-actuator with cross-section 200mm2 (Option#2). Major requestor for this new piezo is PIP II. And we will consider bigger cross-section piezo-actuator as just additional (back-up) option for LCLS II HE.

Any efforts for option#3 (several small cross-section piezo-actuators in parallel) will be stop immediately

Summary (I)

- ✓ Based on the existing for LCLS II cavities production tuning specifications, to deliver (for 95% cavities) required for Dual Freq. Operation cavity tuning target 1.3GHz-465kHz, tuner range must be not less than 680kHz.
- ✓ Overall cavity compression will reach ~2.6mm (or ~ -880kHz tuning from the cavity's non-restrained position)
- ✓ To deliver required range, small modification of the existing tuner design proposed. Modifying 4 components of the slow tuner frame tuner "ratio" changed from 1:20 to 1:16. Tuner will deliver extended range without changing position of the tuner vs cavity/He vessel.
- ✓ New parts machined and modified tuner assembled and installed on the dressed LCLS II cavity CAV0215. Dressed cavity/tuner system installed and tested at VTS.
- ✓ Tuner worked as expected. Measured slow tuner response was 1.75Hz/step (that consistent with 1:16 ration). During test cavity was tuned on ~880kHz, that delivered ~7kN forces on each of the piezo-actuator. Piezo-actuators performances do not compromised by large forces.

Summary (II)

- ✓ LCLS II HE Tuner for Dual Freq. Operation demand new requirements/specs for active components of tuner:
  - ✓ Electromechanical actuator (Phytron)
  - ✓ Piezo-ceramic actuator (PI)

- ✓ Phytron stepper actuator- required forces increased up to 600N that is just ½ of the design specs.
- ✓ Required longevity of the actuator (to re-tune LINAC twice a month) increased in 20times (or ~400 hours of stepper operation) compare with LCLS II specs. One Phytron unit went through ALT test up to 330hours with failure. This result provide confidence that Phytron unit could deliver required longevity. Additional ALT tests of the Phytron electromechanical actuator will be conducted.

- ✓ PI piezo-actuator P-844K075 will work at constant forces up to 7kN that required for LCLS II HE tuner. Based on the PI information & preliminary experimental results PI piezo-actuator will preserve that same level of reliability as for LCLS II (3kN max range preload).

Summary (III)

- ✓ Proposed small modification of the tuner design will deliver required range for Dual Frequency Operation

- ✓ The same tuner’s active components (Phytron & PI actuators) will deliver new (much more demanding) specifications to operate tuner in Dual Frequency mode.