SRF Tuner developed by FNAL for LCLS II Project is **strong candidate for ILC**

.

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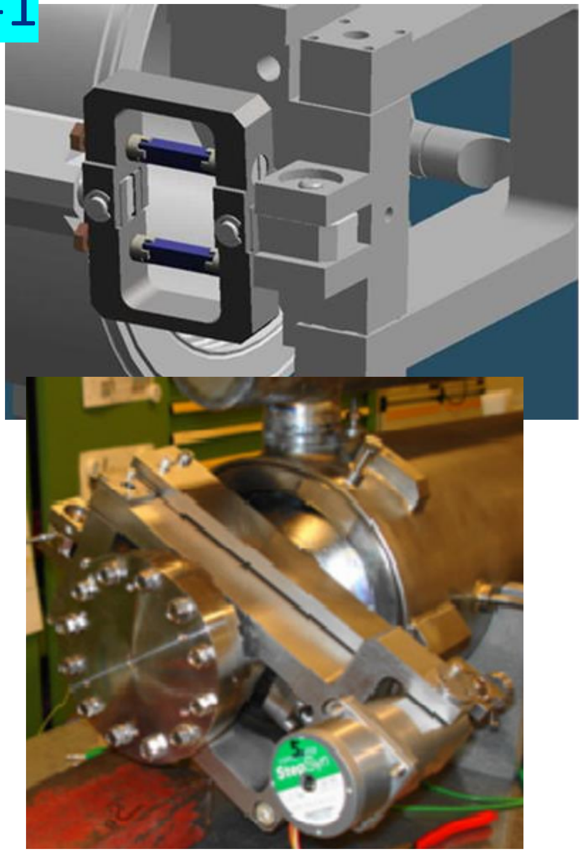
Tuning System (Tuner) specs for 1.3GHz 9-cell elliptical cavity for future large scale SRF LINAC/ ILC

- Must protect cavity during multiple steps of cryomodule assembly and testing “warm and cold”, during operation of the LINAC; during accidental events.
- Must have high level of the reliability/lifetime for 30+ years; and must be easy to maintain (capability to repair tuner without dis-assembly cryomodule)
- Must fit on the “short-short” cavity
- Must have simple, robust and non-expensive design, that easy to assemble and test warm
- Slow/coarse tuner must have range ~600kHz
- Fast/fine tuner must have range (for LFD compensation) > 2kHz

Tuners serving *(significant amount of)*1.3GHz elliptical cavities

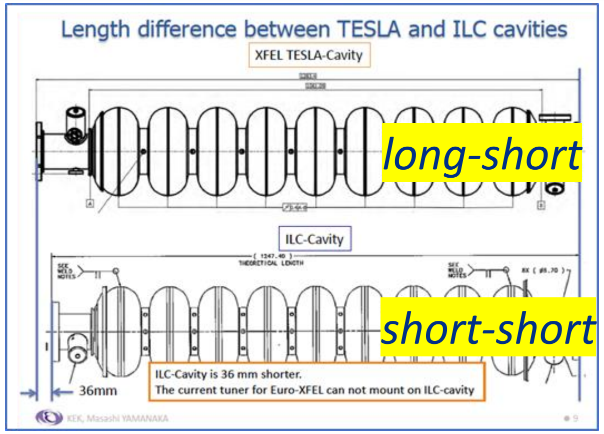
XFEL/Saclay I
N=800 units

#1



#4

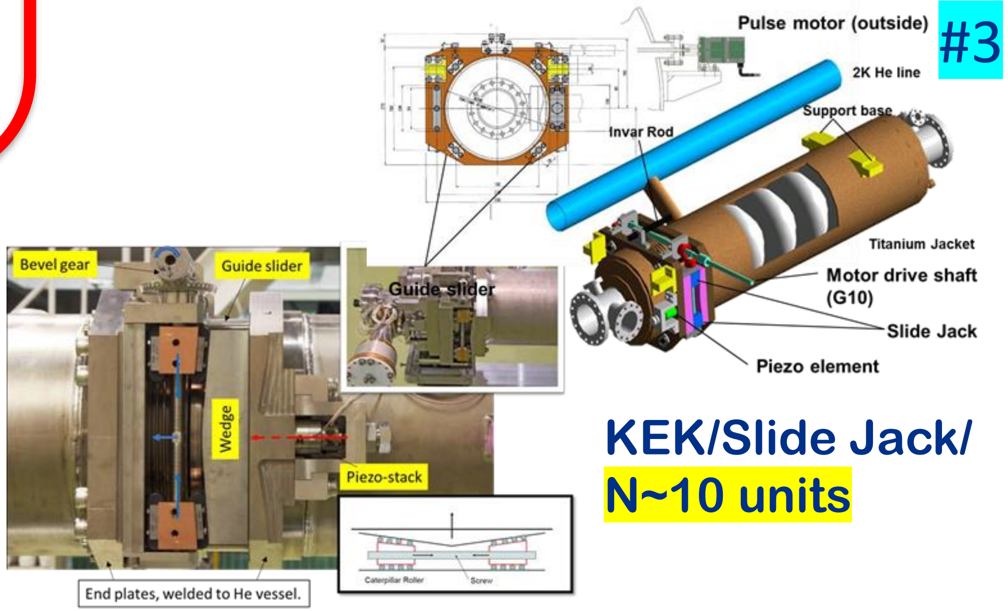
LCLS II (HE)/FNAL's
N=320 units+ 180units



SLIM Blade Tuner
(N=10 units at FNAL's CM2/FAST)

#2

#3



KEK/Slide Jack/
N~10 units

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Different designs of the Tuners for 1/.3GHz elliptical cavities

	(SLIM) Blade tuner *[1]*	Saclay/DESY tuner *[2]*	Slide-jack tuner *[3]*	Double-lever tuner *[4]*
Type	Coaxial	Lateral-Pick-up side	Coaxial and lateral coupler side	Lateral-Pick-up side
(fit to) Beampipes of TESLA Cavity	short-short, short-long	short-long	short-short, short-long	short-short, short-long
Cavity/Tuner system stiffness	30 kN/mm	30 kN/mm	~~290~~ 70 kN/mm	40 kN/mm
Drive unit	Inside vessel: Stepper motor + Harmonic Drive	Inside vessel: Stepper motor + Harmonic Drive	Outside vessel: both manual or stepper motor actuation	Inside vessel: Stepper motor + Planetary Gear Drive
Nominal frequency	1.3 GHz	1.3 GHz	1.3 GHz	1.3 GHz
Nominal tunable range	600 kHz	500 kHz	900 kHz	800 kHz
Nominal sensitivity	1.5 Hz/step	1 Hz/step	3 Hz/step	1.4 Hz/step
Coarse tuner hystersis	*100Hz*	*100Hz*		*45Hz*
Piezo	2, thin-layer (0.1 mm), dim. 10 x 10 x 40 mm^3	2, thin-layer (0.1 mm), dim. 10 x 10 x 36 mm^3	1, thick-layer (2 mm), dim. diameter 35 x 78 mm^2	2 , thin-layer (0.1 mm), dim. 10x 10 x 36 mm^3
Piezo Voltage	200 V	120 V	1000 V, operated at 500 V	120 V
Nominal piezo stroke at R.T.	55 μm	40 μm	40 μm	40um
Nominal piezo capacitance at R.T.	8 μF	13 μF	0.9 μF	13 μF
Nominal tunable range (tested at 2K)	2,000 Hz	800 Hz	~600 Hz @500 V	3,000 Hz
Capability to repair (motor + piezo)	No	No	OK	OK
# of tuner operated in accelerators	8 @FNAL/FAST	800 @E-XFEL	14 @STF-2, Quantum Beam	320+180 @LCLS-II (HE)
# of tuner operated in S1-Global	2	2	4	

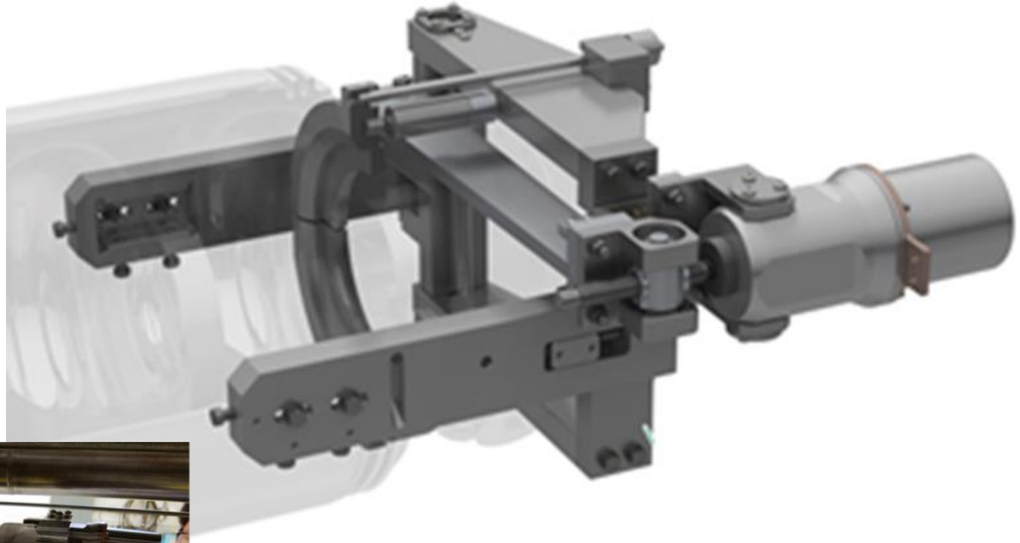
[1] https://lss.fnal.gov/archive/2011/conf/fermilab-conf-11-101-td.pdf

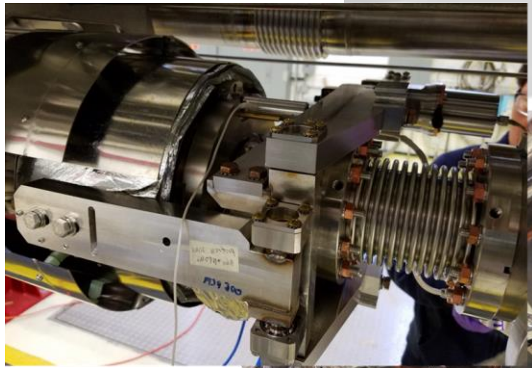
[2] LLRF Tests of XFEL Cryomodules at AMTF: First Experimental Results (cern.ch)

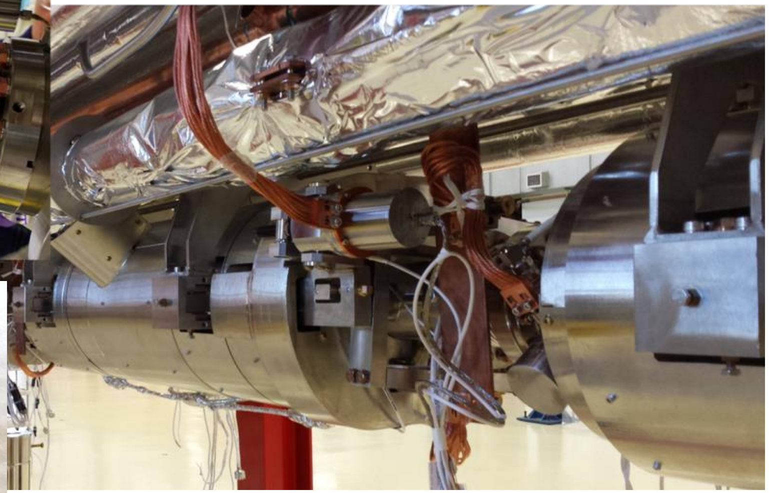
[3] Cryomodule Tests of Four Tesla-Like Cavities in the STF Phass-1.0 for ILC (cern.ch)

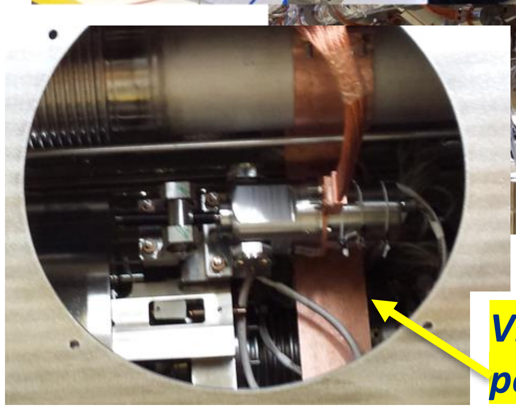
[4] https://accelconf.web.cern.ch/IPAC2015/papers/wepty035.pdf

SRF Cavity Tuner developed by FNAL for LCLS II project satisfied all ILC specs









View of the Tuner through designated port in CM vacuum vessel

- ✓ Compact double-lever Tuner that fit on <u>the “short-short” </u>cavity.
- ✓ Robust/Low-cost tuner frame design.
- ✓ High tuner stiffness for minimization of LFD
- ✓ Tuner design allow to replace actuators (stepper & piezo) through designated CM port without tuner dis-assembly
- ✓ Slow tuner range more than 800kHz
- ✓ Encapsulated piezo actuators translated stroke directly to the cavity (piezo stroke >3kHz and low group delay– important for active LFD compensation)
- ✓ <u>More than 320 tuners that built and deployed at 40 LCLS II have been cold tested/qualified for LINAC operations… now LCLS II HE project is building additional 180 more tuners (500units)</u>

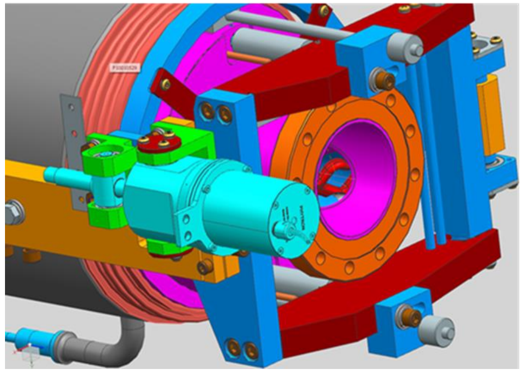
Some history behind development of Tuner for LCLS II (during last 6 years)

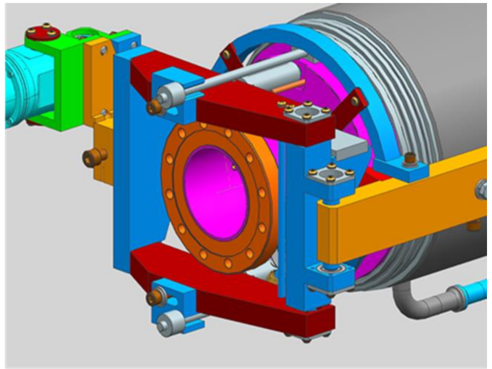
New tuner / need to be developed quickly for LCLS II project -- (first publication/results) in 2015… In 2021 40 LCLS II CMs (320 cavity/tuner systems) assembled/cold tested and delivered to SLAC

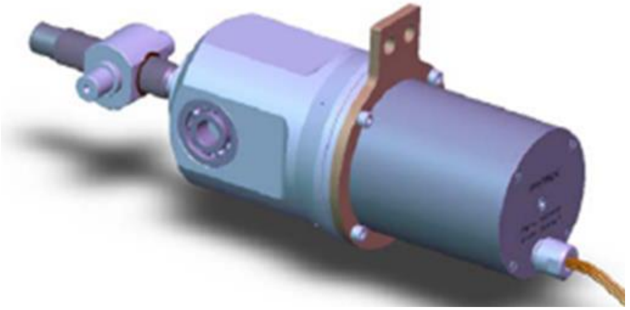
Task was to use best design's features from Saclay I/ XFEL (double lever) tuner

At the same time tuner design must be modified to:

- fit on the "short-short" cavity
- increase cavity/tuner system stiffness
- develop capability tuner maintenance/ stepper & piezo actuators replacement through designated port in vacuum vessel
- newest active components (stepper & piezo actuators) with significantly increased longevity have been developed in collaboration with industrial partners (Phytron & PI)







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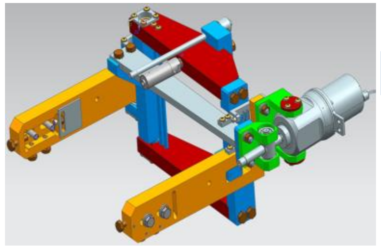
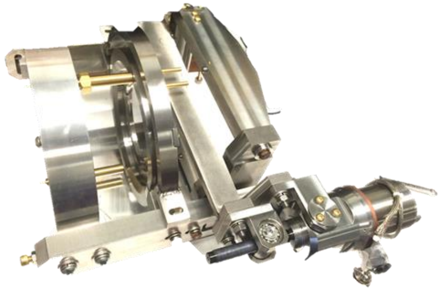
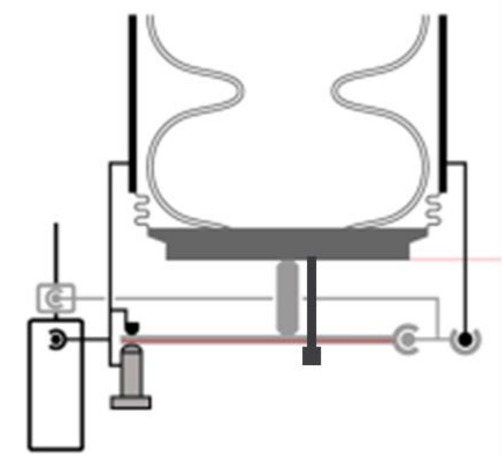
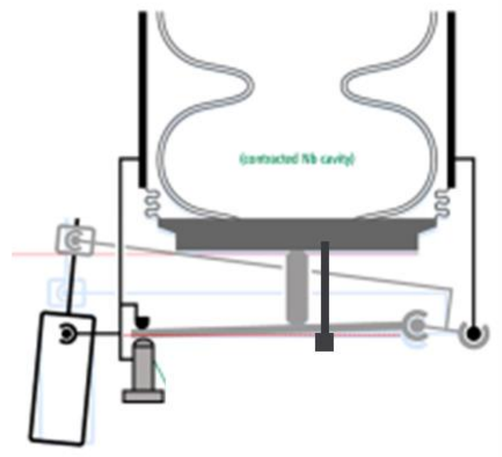
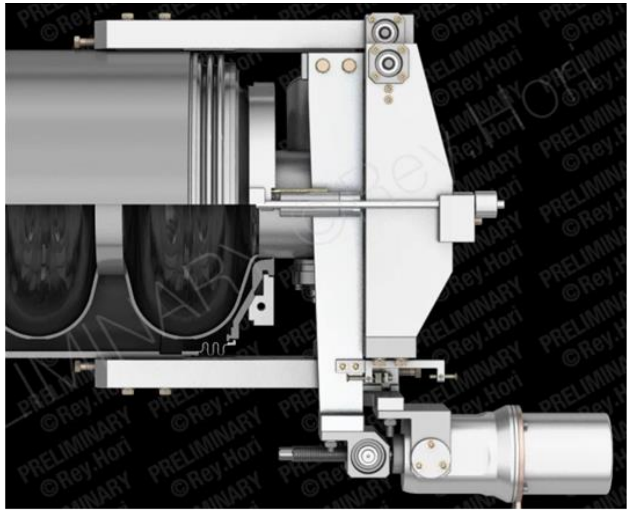


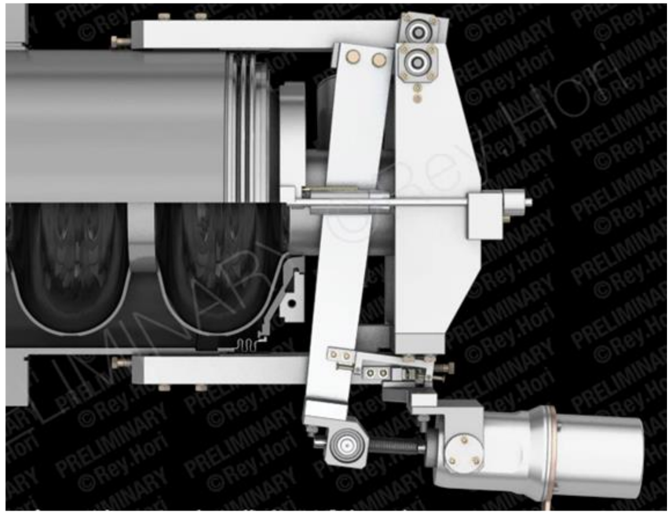
Double Lever Tuner (LCLS II/FNAL) principle of operation





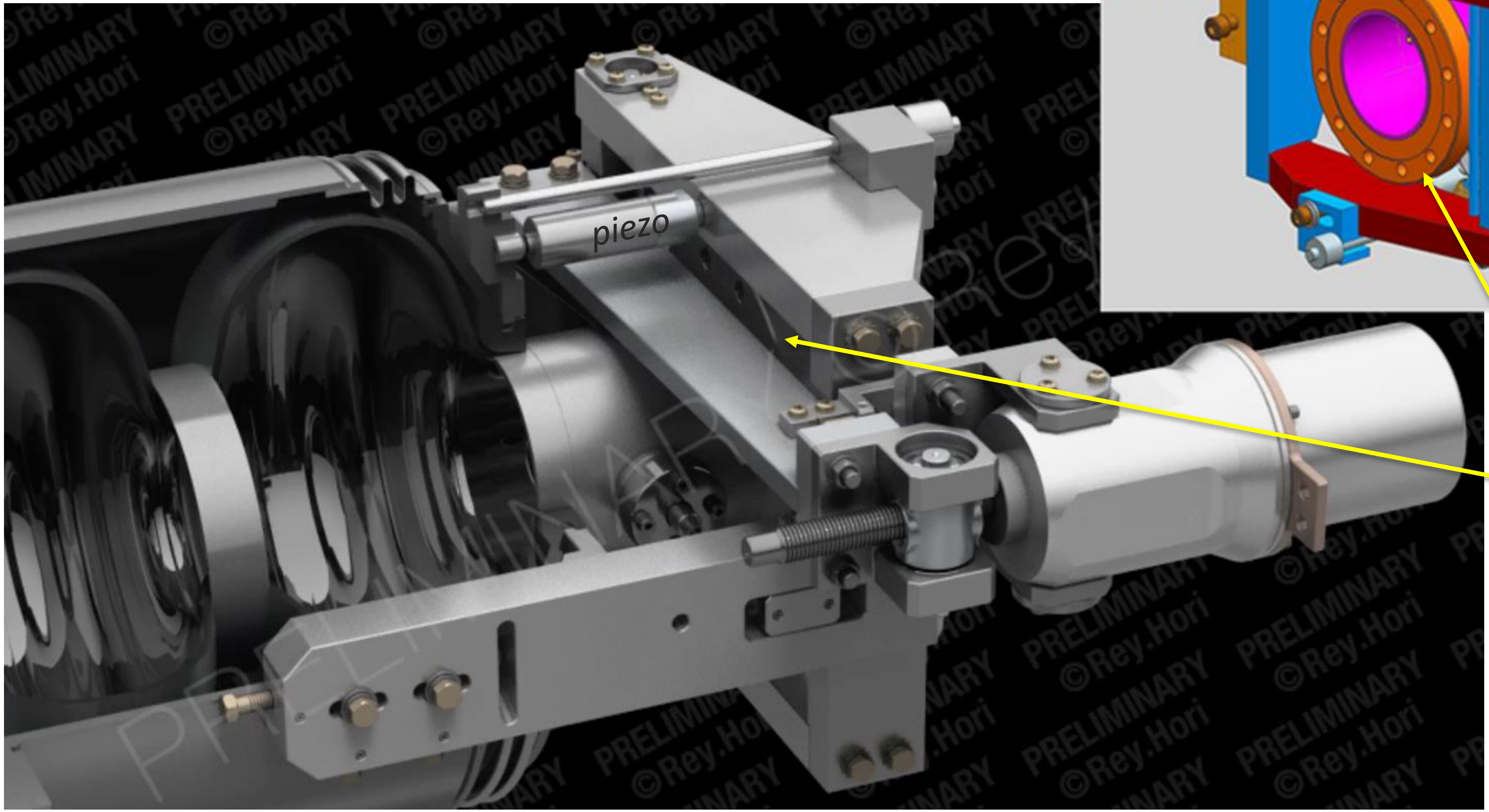


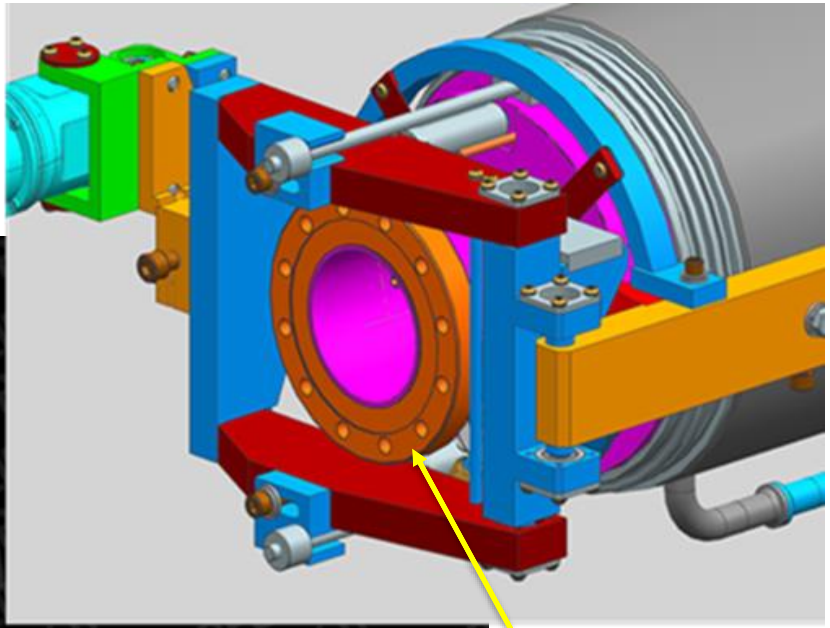




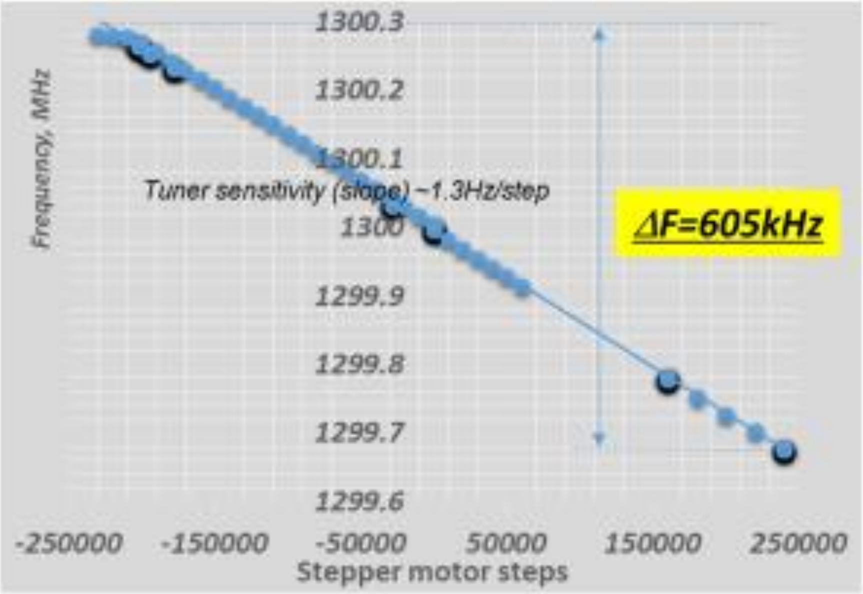
- Slow/Coarse Tuner is double Lever Tuner (close to design of the SACLAY I) with ration 1/20
- Tuner working in cavity compression (push)
- Solid tuner arms (instead of flex) significantly increase tuner stiffness
- Fast Tuner – two piezo-actuators installed close to cavity split ring – increased fast tuner stroke & minimum group delay (important for LFD compensation)
- Cavity/piezo actuator interface through ceramic balls to minimize shearing forces on piezo
- Tuner designed with features that allowed easily replaced motor & piezo through designated port
- Newly designed highly reliable stepper motor and piezo actuators

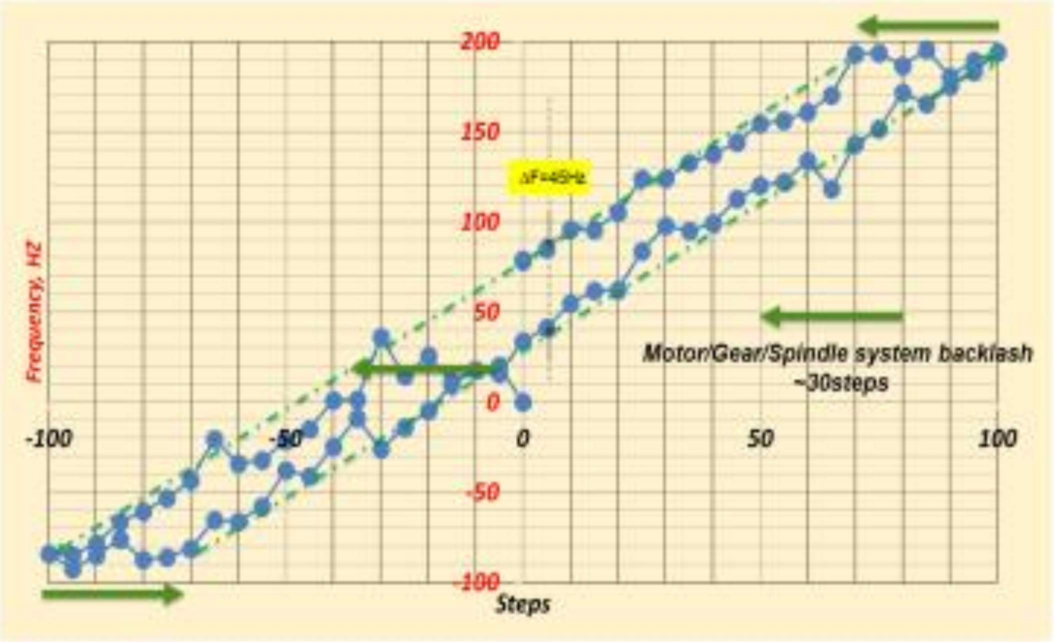
LCLS II Double Lever Tuner designed to be installed over cavity's beamline flange/bellows… could be assembled on the "short-short" cavity





Tuner frame assembled around cavity beam-line flange





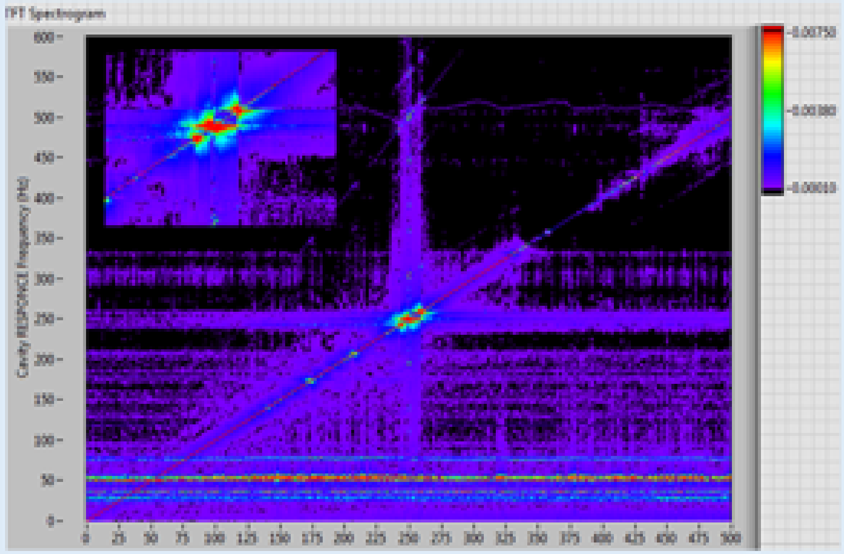
Slow/Coarse Tuner Parameters

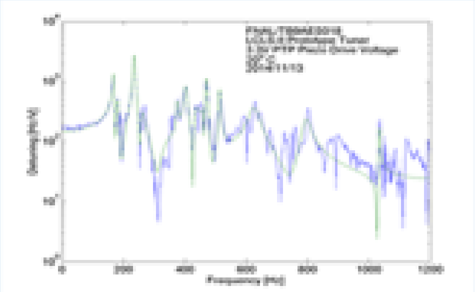
TUNER PARAMETERS OPTIMIZATION

- Slow tuner range >600kHz
- Small hysteresis (45Hz) and backlash 30(steps) for slow tuner
- Slow tuner sensitivity - 1.3Hz/step

Fast Tuner Parameters

Drive piezo actuator with stepped frequency sine wave

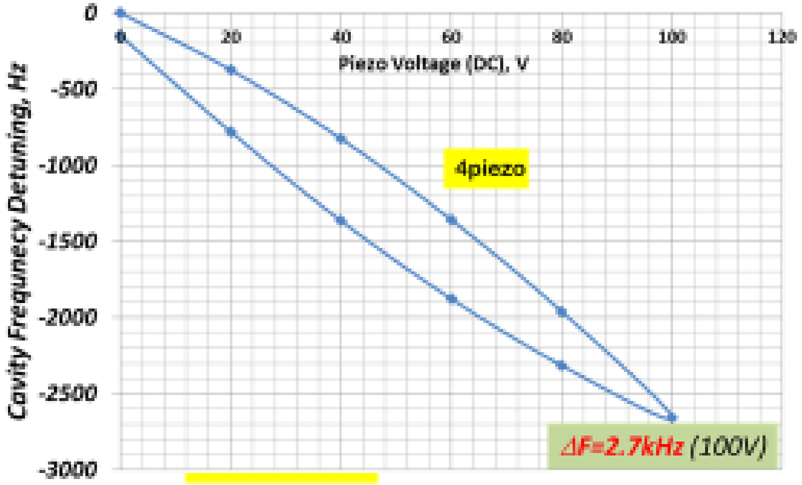




#	f(Hz)	tau(ms)	kappa(Hz/V)	Strength
1	235	49	14.5	0.65
2	168.1	41	6.86	0.1
3	471.2	46	5.79	0.09
4	402.2	17	1.29	0.04
5	232.6	126.4	1.29	0.03

TUNER PARAMETERS OPTIMIZATION

- Fast (piezo) tuner range is ~3kHz (at $V_{nominal}$=120V)
- Measured piezo resolution ~0.15Hz (limited by noise in HTS)
- Lowest mechanical resonances of the tuner/cavity system is 170Hz with major resonance at 235Hz
- Piezo tuner range will not be changed with cavity tuned up to 600kHz



Even Tuner never operated in RF-pulse arrangement (LCLS II is CW LINAC) we measured transfer function and resolution. Based on our experience in S1G and other projects this tuner designed for optimal LFD compensations.

Development of the newest active components:

highly reliable electromechanical (stepper motor) actuator

and piezo electric actuators

Collaboration with industrial partners:
Phytron, Inc and Physik Instrumente, Inc

Reliable Tuner's actuators, that were developed in collaboration with industrial partners, are one the important innovation that drastically changed reliability of the SRF cavity's tuning system

Development started long before LCLS II… as part of ILCTA program at FNAL… Systems that we built "in-house" using design from INFN/DESY had very low reliability system

-Electromechanical Actuator is results of collaboration of the FNAL and Phytron Inc.

-High Vacuum/Cryogenic Stepper motor (52mm diameter; 200steps/360^{O}; I=1A)

-Planetary Gear 1:50 (no Harmonics Drives)

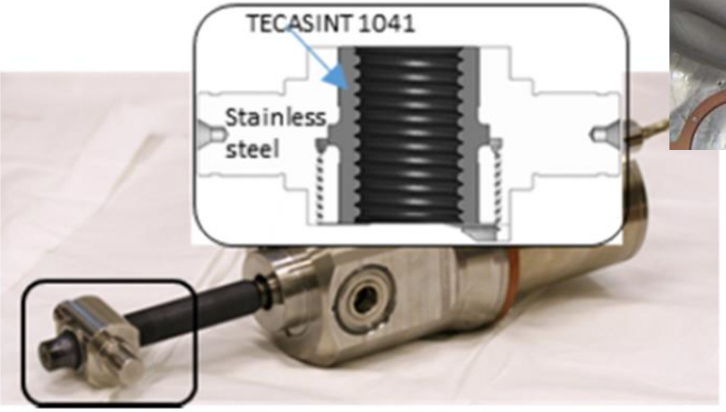
-Titanium shaft 12x1 (dry lubrication)

-Traveling nut made with TECASIN insert (provide additional dry lubrications)

- Forces (on the traveling nut) up to 1300N (for ILC cavities maximum req. forces if just 400N for 600kHz)

-Tested in cryo/vacuum environment for **10 lifetimes the LCLS II/ILC LINACs without any failures**.

-Tested for radiation hardness up to 5*10^{8}Rads (no issues)



Harmonics Drive

Piezo Actuator P-844K075

Designed by Physik Instrumente (PI)

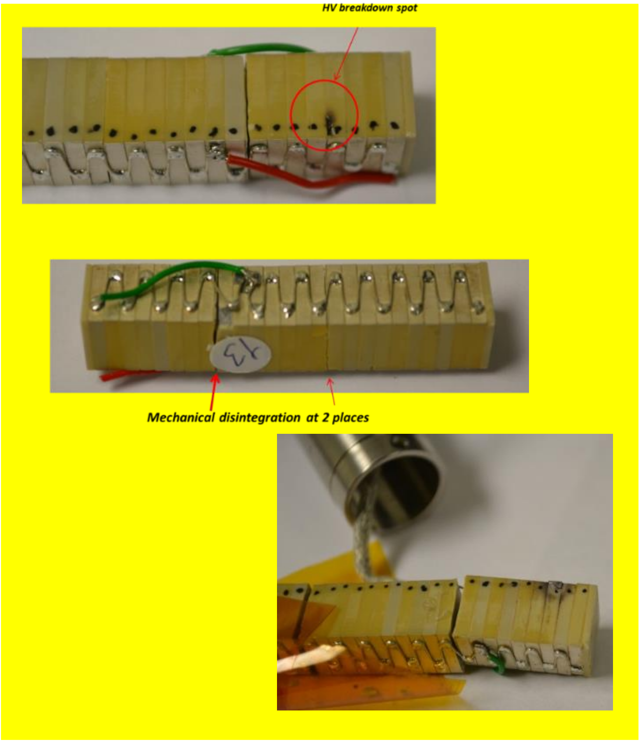
(with contribution from FNAL) for LCLS II Project.

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

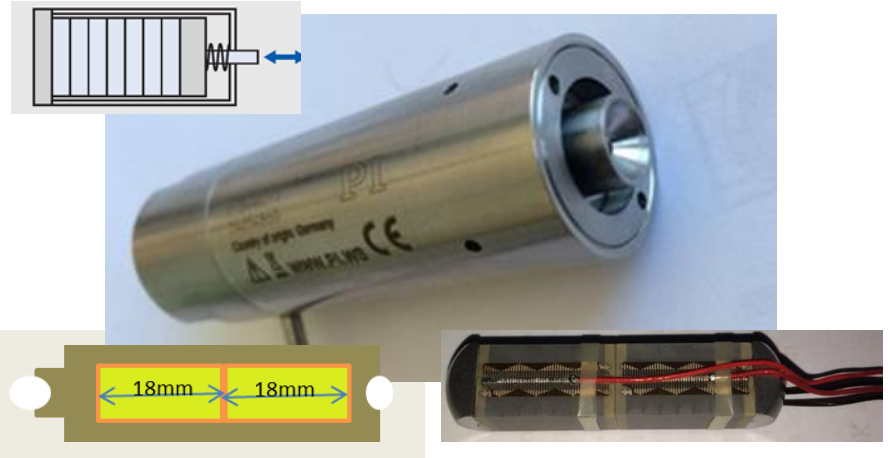
Each Cavity/Tuner system has 4 (four) electrically separate piezo-stacks.
Tuner could operate even after failure of 2 stacks

Shearing Forces on the piezo ----Piezo-stack capsulation
Lessons Learned from CM2(FNAL); S1Global; SSR1(FNAL)

Piezo Ceramics stack is fragile system   It can be damage very easily …
If design of the fast-tuner system done without taking into account "right" techniques.
Many "poor" fast/piezo tuner designs created "impression/opinions" that piezo tuner is not reliable system…



LCLS II piezo-stack (designed and built in collaboration with PI)

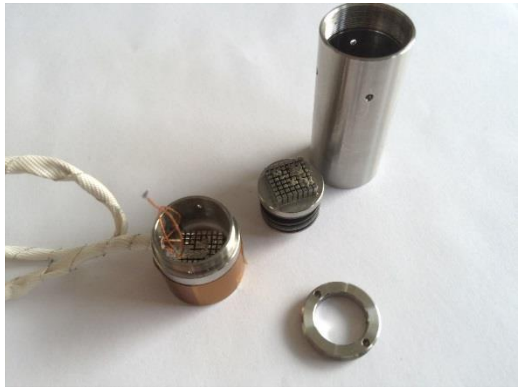


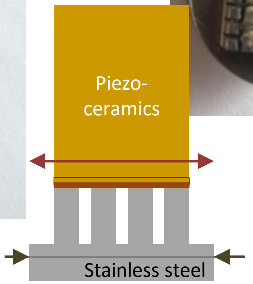
LCLS II configuration allowed for max. length 36mm piezo
Piezo capsule build with piezo stack made from 2*18mm piezo
LCLS II fast tuner can deliver 3kHz (V=120V) (all 4 piezo)

- *Internal preload (800N at 10-20K)*
- *Minimization of the shearing forces through balls connections*
- *Piezo-ceramic stack glued to substrates (as recommended by all piezo companies)*
- *PI using patented technology … taking into account different thermo-expansion coefficient for piezo-ceramics and stainless steel*
- *316L stainless steel construction (High Q0 reqs)*
- *Wiring with kapton insulation wires (rad.hard)*

Fixture with piezo-capsule was cool-down inside LN2, installed into INSTRON and measured S vs Forces

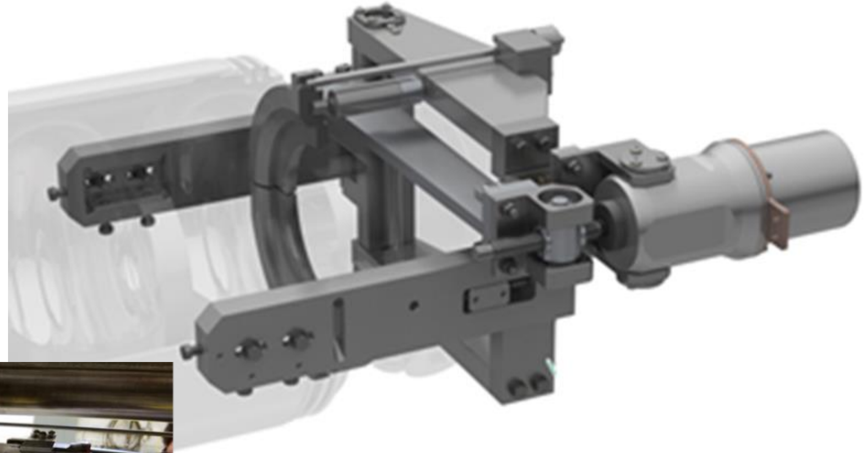
Piezo Survived 25kN test
2Piezo-stacks ==50kN (10kN requirements)

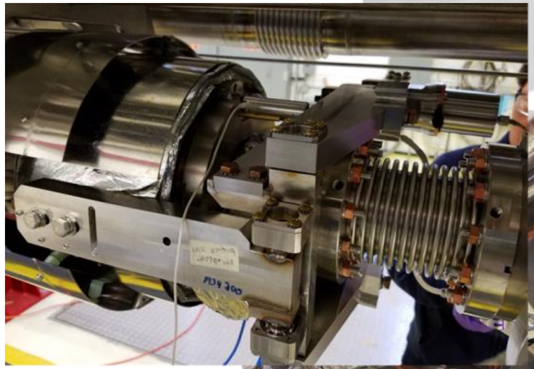


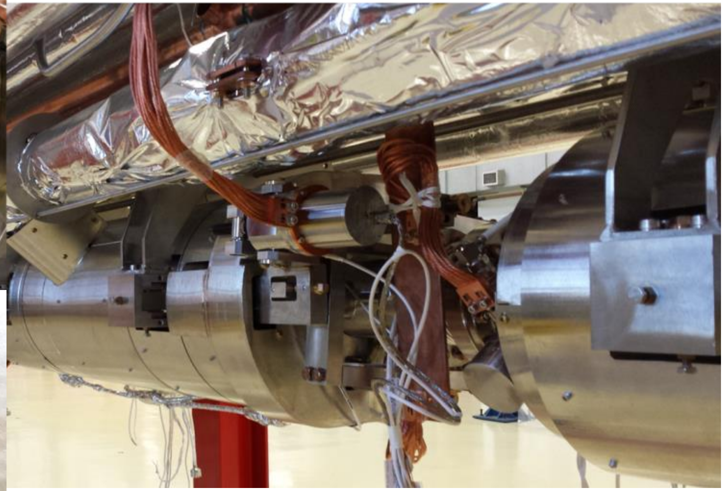


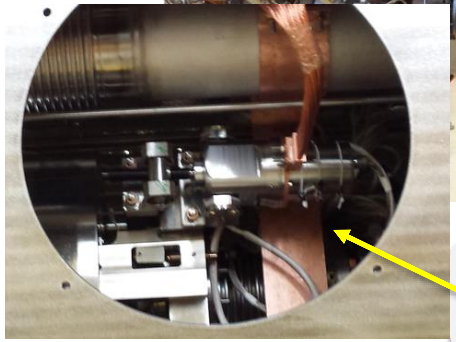
Conclusion: Developed by FNAL for LCLS II SRF cavity tuner met all ILC specs

(during design of this tuner FNAL team has advantage to apply experience gained by other teams from all previously designed tuners; SACLAY I; SLIM Blade, Slide Jack, etc.)









View of the Tuner through designated port in CM vacuum vessel

- ✓ Compact double-lever Tuner that fit on <u>the “short-short”</u> cavity.
- ✓ Robust/Low-cost tuner frame design.
- ✓ High tuner stiffness for minimization of LFD
- ✓ Tuner design allow to replace actuators (stepper & piezo) through designated CM port without tuner dis-assembly
- ✓ Slow tuner range more than 800kHz
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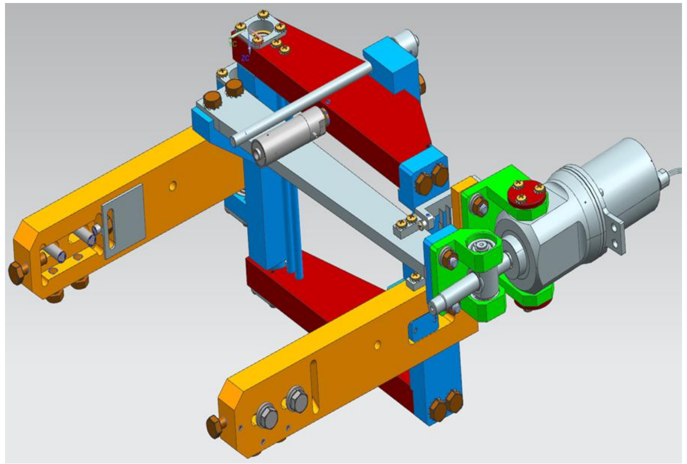
- ✓ <u>More than 320 tuners that built and deployed at 40 LCLS II have been cold tested/qualified for LINAC operations (additional 180 tuners will be built for LCLS II HE)</u>

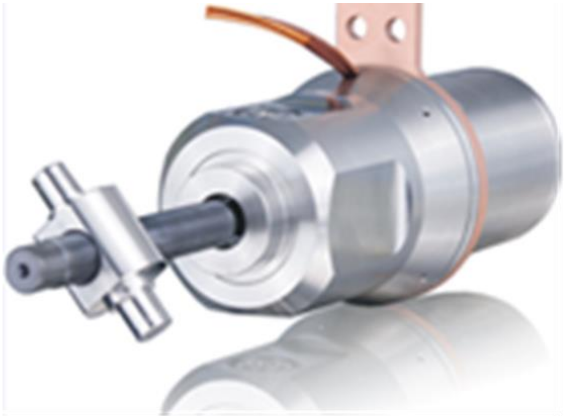
Improvement of the LCLS II Tuner for ILC

- Based on the LCLS II project experience there are list of modifications that could significantly improve/simplify tuner cost/ assembly labor/improve reliability
- Fermilab team is extending collaboration with industrial partners to decrease cost of the active components (stepper and piezo actuators)
- ILC requirements to piezo-actuators are much more demanding and R&D need to be done to demonstrate capability of the PI actuator to operate without possible piezo-ceramics overheating
- Fermilab is pursuing development of the newest encapsulated piezo-actuator with unique technology to remove heat from piezo-ceramics. ILC requirements for could be significantly benefit from new technology.



Additional Slides

(for more detail discussion of the Tuner's technical questions)



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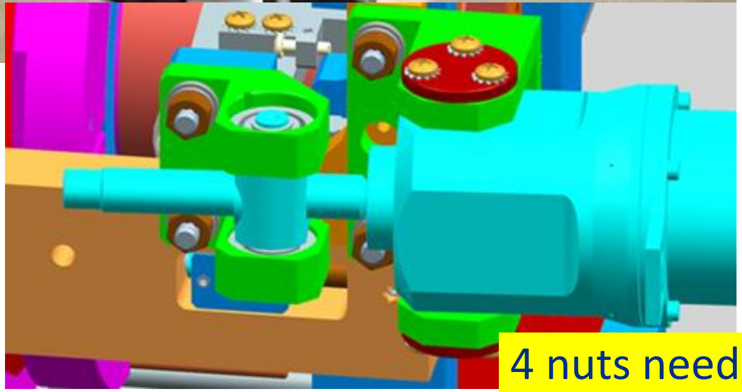
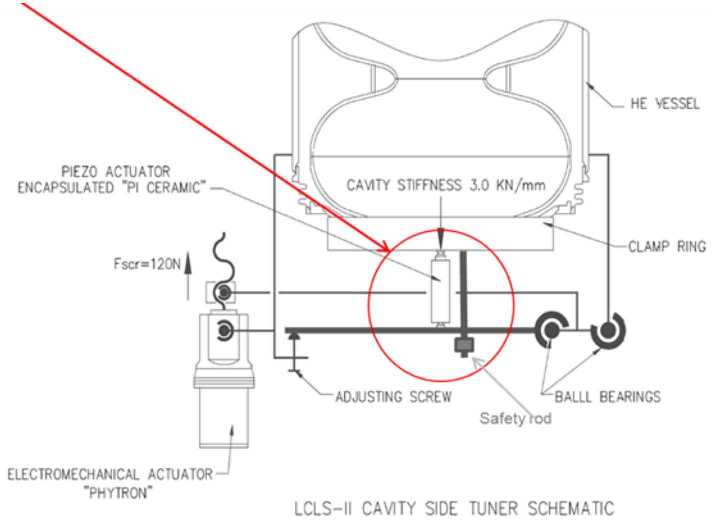
Design of the tuner allowed to release tuner/cavity preload, remove stepper motor cartridge, replace piezo-actuators

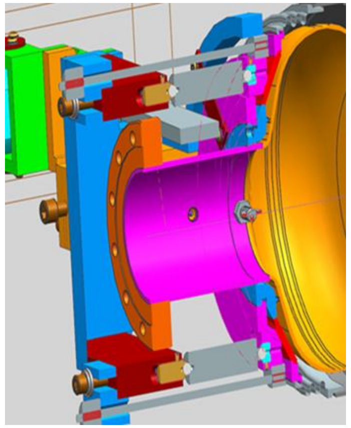


View of the Tuner through designated port in CM vacuum vessel



4 nuts need to be unscrewed to remove stepper motor actuator

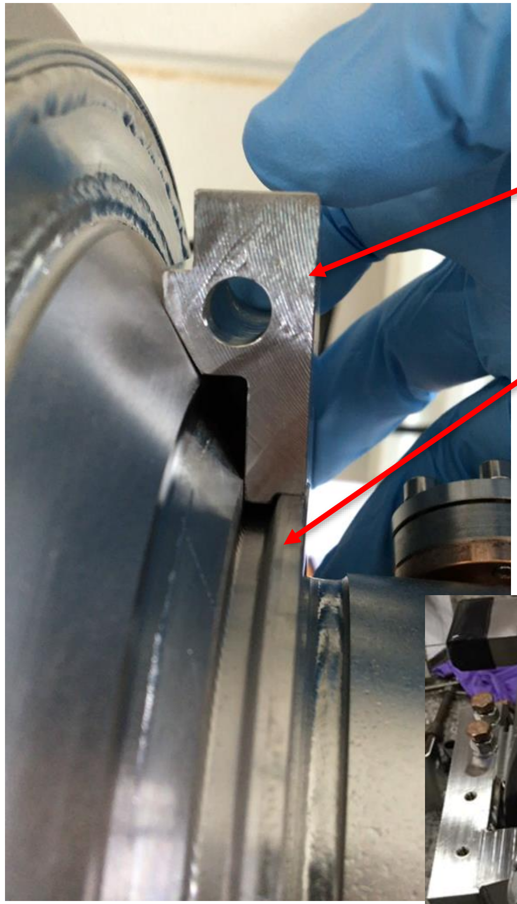
Piezo reachable through port … could be easily replaced



Ceramics balls minimized shearing forces

Important element of the dressed cavity-to-tuner interface " Split ring" & Ceramic Balls

Split-ring system must protect cavity during many steps of cavity testing. And be able translate nanometers stroke from tuner to the cavity

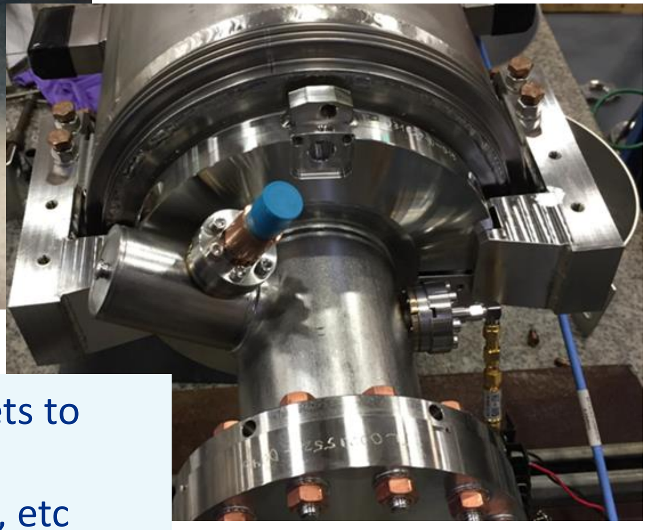


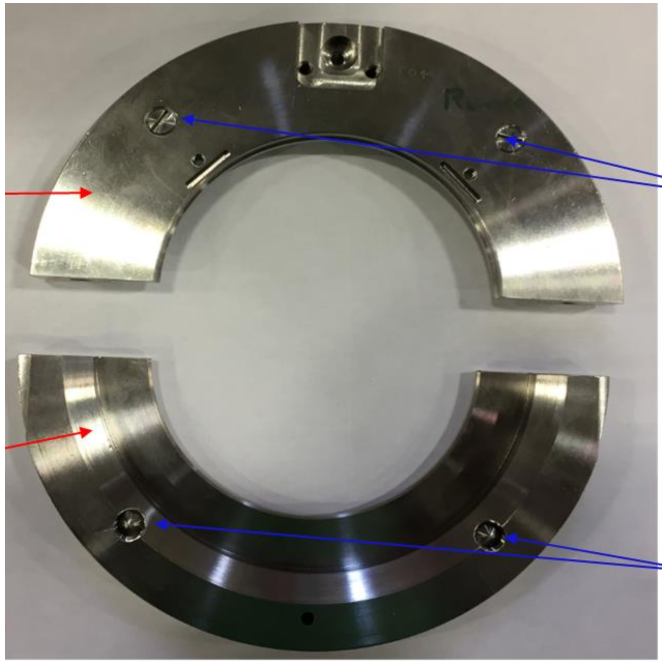
½ Split Ring

Cavity's end-group flange

Used to:

- Installed cavity into Tuning machine
- Secure split ring on the dressed cavity





Split ring & safety brackets to protect cavity during pressure/leak check test, etc

LCLS II Tuner required different (than XFEL) design of the dressed cavity-tuner interface (split ring). It is small components (and it is in the middle of borders… between tuner and dressed cavity). Need enough attention…

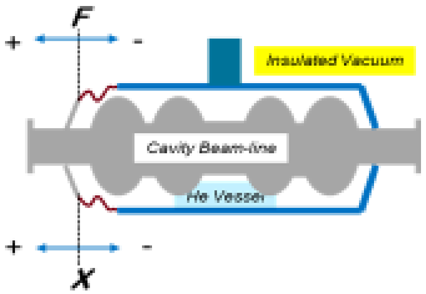
Requirements for the Tuner#1:

Must protect cavity during multiple steps of cryomodule assembly and testing “warm and cold”, during operation of the LINAC; during accidental events.

Impact on the Cavity/He Vessel/Tuner system for various pressure conditions during anticipated steps of assembly and operation of the CM.

Requirements: $|\Delta X_{T=300K}| < 0.6mm$

TEMPERATURE	PROTECTION		*The step* during cavity assembly or operations	Insulated Vacuum, bar abs	Cavity Beamline, bar abs	Helium Vessel, bar abs	Forces on cavity flange with absolutely restrained cavity, kN	Cavity length will change if flange non-restrained, mm
Tcav=300K	RESTRAIN BRACKETS	0	Cavity is relaxed after HV welding	1	1	1	0	0
Tcav=300K	RESTRAIN BRACKETS	1	Cavity/He Vessel Leak Check at MP9	1	1	0	-2.6	-0.6
Tcav=300K	RESTRAIN BRACKETS	2	Cavity/He Vessel Pressure test at MP9	1	1	3.3	6.0	1.4
Tcav=300K	RESTRAIN BRACKETS	3	Cavity/He Vessel Leak Check in CM/HTS	1	0	0	-3.8	-0.8
Tcav=300K	RESTRAIN BRACKETS	4	Cavity/He Vessel leak check in Clean Room	1	0	1	-1.2	-0.25
Tcav=300K	TUNER INSTALLED ON CAVITY	5	He Vessel pressure test in CM	1	0	3.3	4.9	1.1
Tcav=300K	TUNER INSTALLED ON CAVITY	6	Start of cooling down CM	0	0	1.5	3.9	0.8
Tcav=300K	TUNER INSTALLED ON CAVITY	7	Linac maintenance (e.g., tuner or interconnect access)	1	0	1.4	0	0
Tcav=300K	TUNER INSTALLED ON CAVITY	8a	Tuner access and disconnect (e.g., replace piezo), what is max cryo system pressure	1	0	0	-3.8	-0.8
Tcav=300K	TUNER INSTALLED ON CAVITY	8b		1	0	2.5	2.7	0.6
5K	TUNER INSTALLED ON CAVITY	9	End of cooling down	0	0	1.5	3.9	0.8
2K	TUNER INSTALLED ON CAVITY	10	Operating condition	0	0.03	0	0	0
5K	TUNER INSTALLED ON CAVITY	11	Worst case cold loss of vacuum accident. Will piezo and tuner survive?	0	0	4	10.4	2.2



Highlighted steps when cavity at 300K will go beyond elastic deformation if do not protected with tuner/safety brackets system.

Accident at cold CM Impact on the Tuner/piezo

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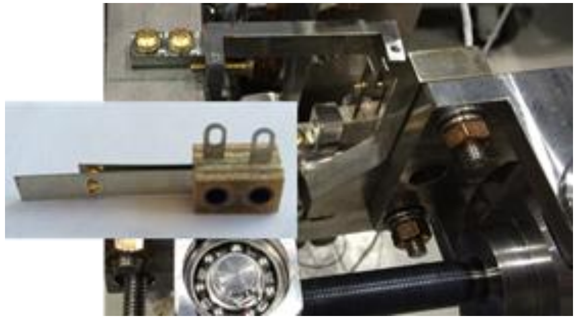
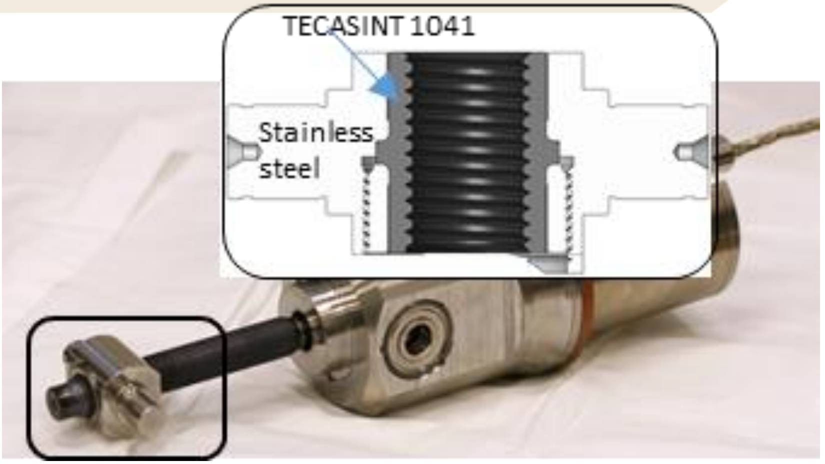
Accelerated Lifetime tests
& Rad. Hard tests
of the stepper motor & the piezo actuators

Radiation Hardness tests of the Electromechanical Actuator (up to $5*10^8$ Rad)

Phytron stepper motor internal windings after irradiation with dose $5*10^8$ Rad



Limit switches mounted on the tuner.

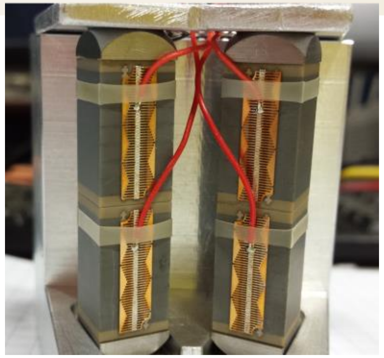


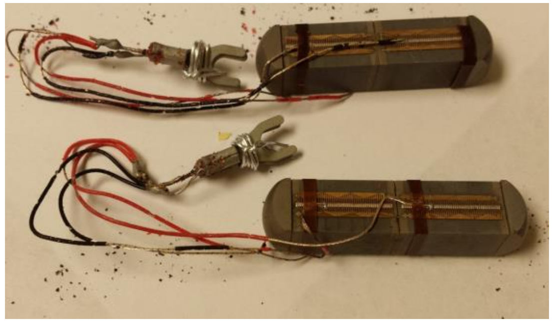
Traveling nut on the Ti spindle. Schematic design of the nut made from the stainless steel with TECASIN-1041 insert. TECASINT 1041 is a high temperature polyimide with 30% MoS2. This material has excellent radiation resistance properties (1-$10*10^8$ Rad).). Large radiation dose will cause material to “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.

There was no any degradation in the electromechanical actuator components:

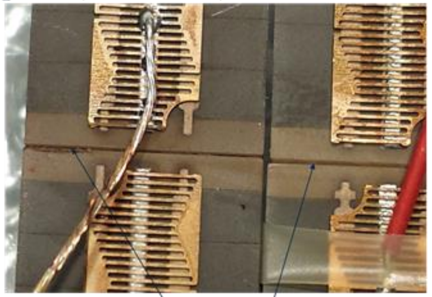
- ***Windings of the stepper motor***
- ***Limit switches***
- ***Traveling nut***

Irradiation of the Piezo-stacks up to 10^9Rad (gamma)

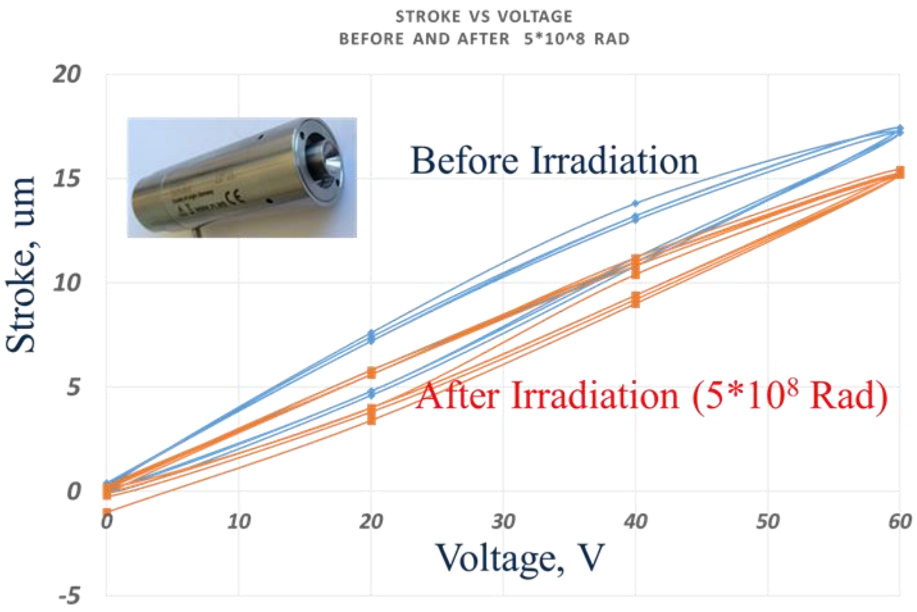




Sample A($5*10^8$ Rad) Sample C (0 Rad)

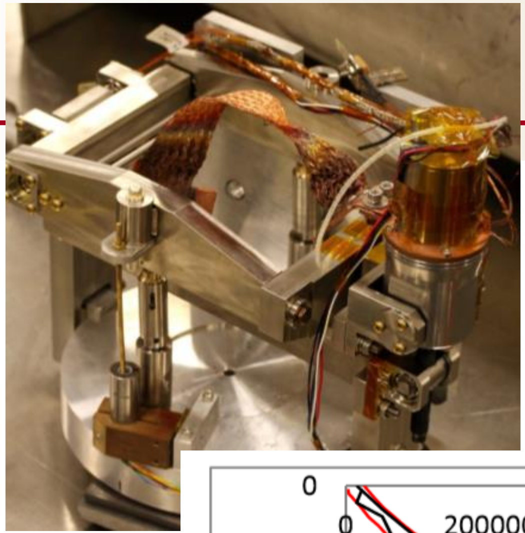


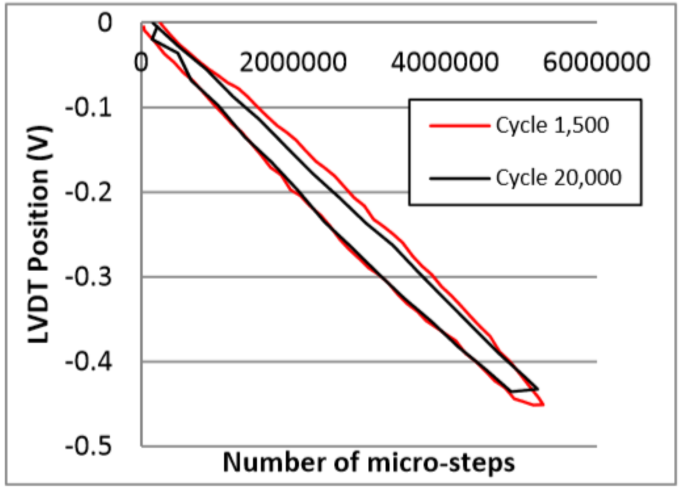
Discoloration of the thing layer of Epoxy



Stroke of the piezo-stack decreased only on 10% after irradiation up to 10^9 Rad

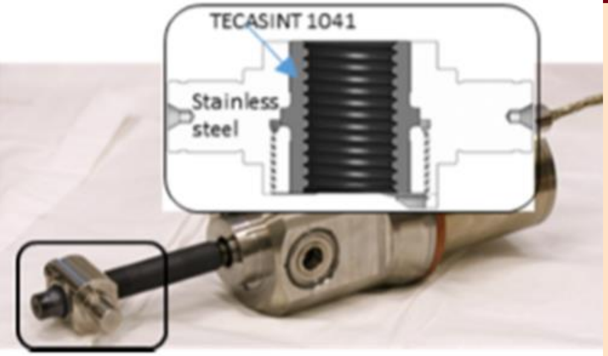
Brief summary of the Accelerated Lifetime Test of the Phytron (LCLS II) actuator





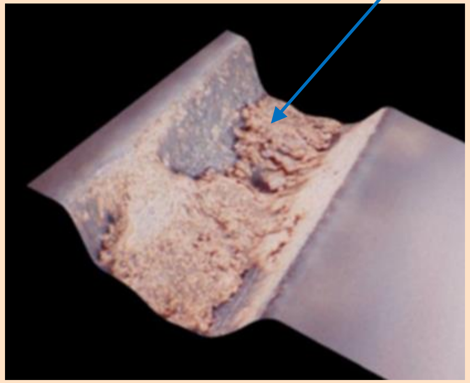
Despite of the degradation of the TECASINT 1041 nut material there was no change in the actuator performance at the end of ALT tests (14days/330hours of continuous operation)

10 lifetime of ILC

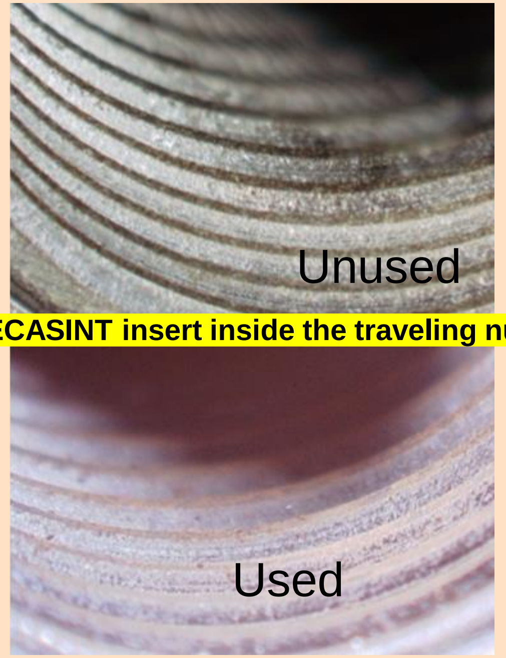


Traveling nut on the Ti spindle. Schematic design of the nut made from the stainless steel with TECASIN-1041 insert.

Molybdenum Disulphide



Material found between spindle threads (X400 magnification).



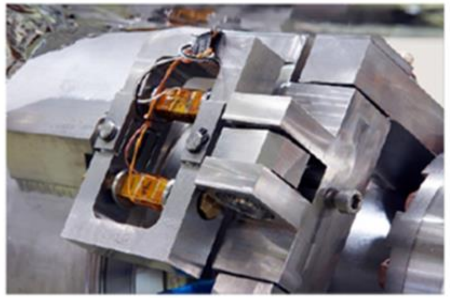
TECASINT insert inside the traveling nut

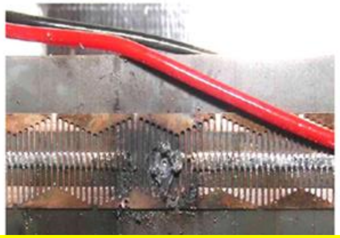
Overheating the piezo-actuator during operation at high dynamic rate/high amplitude

Studies of the INFN/DESY team in the frame of the ILC/XFEL projects.

M. Grecki, et al. LLRF13 Lake Tahoe.

Temperature rise in function of pulse amplitude, single pulse, 10Hz repetition rate



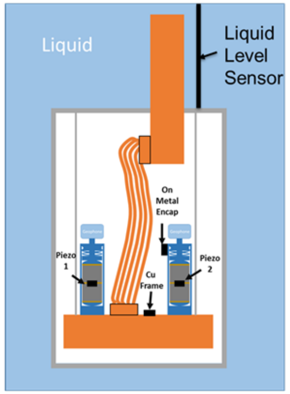


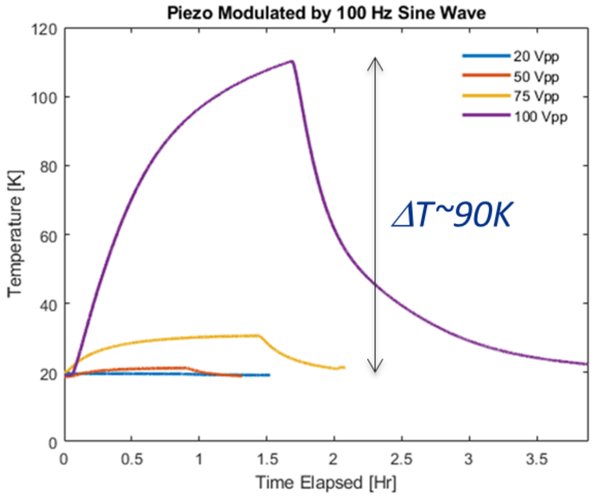
LN2 Test. Overheating and failure of the piezo

Removing heat deposited inside piezo-stack is crucial to preserve longevity of the piezo-actuator

FNAL Studies in the frame of LCLS II/ PIP II & ILC (and the future RF-pulsed LINACs)

SRF2019, Y. Pischalnikov et al., TESTING OF THE PIEZO-ACTUATORS AT HIGH DYNAMIC RATE OPERATIONAL CONDITIONS





.....cold vacuum is an almost ideal environment for piezo actuators…
except the problems to heat transfer from piezo inside insulated vacuum…

Piezomechaniks ΔT~70Degree

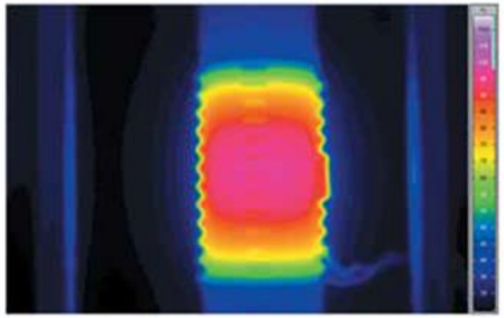
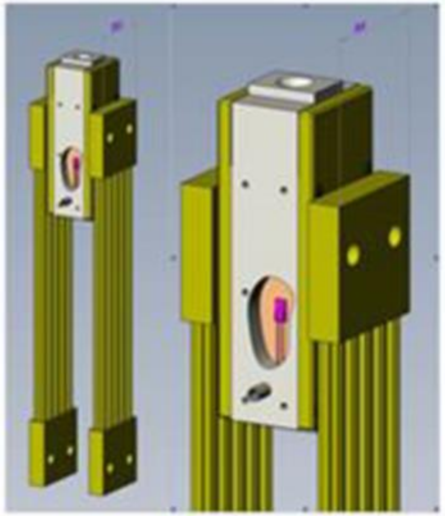
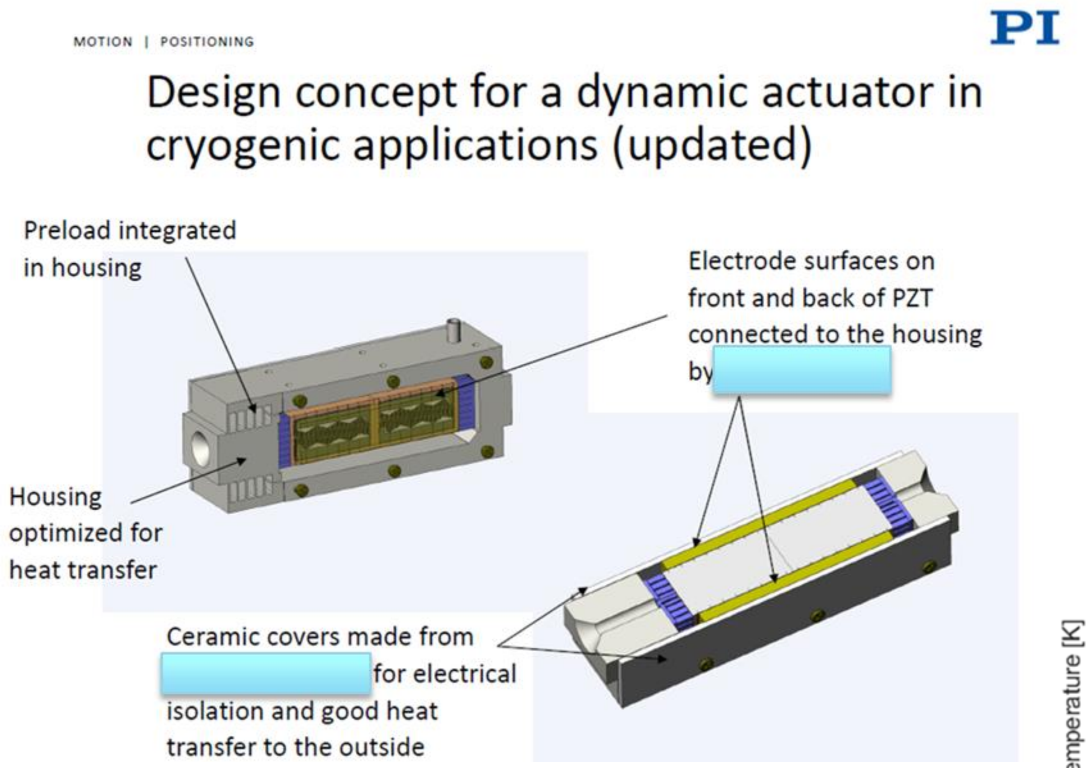


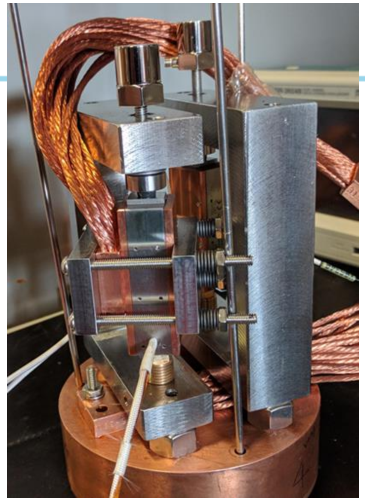
Fig. 5.1: Thermal image of a dynamically cycled high voltage actuator, clamped at its end faces. Environment: ambient air convection. Notice the cooling effect at the end-faces due to the clamping mechanics

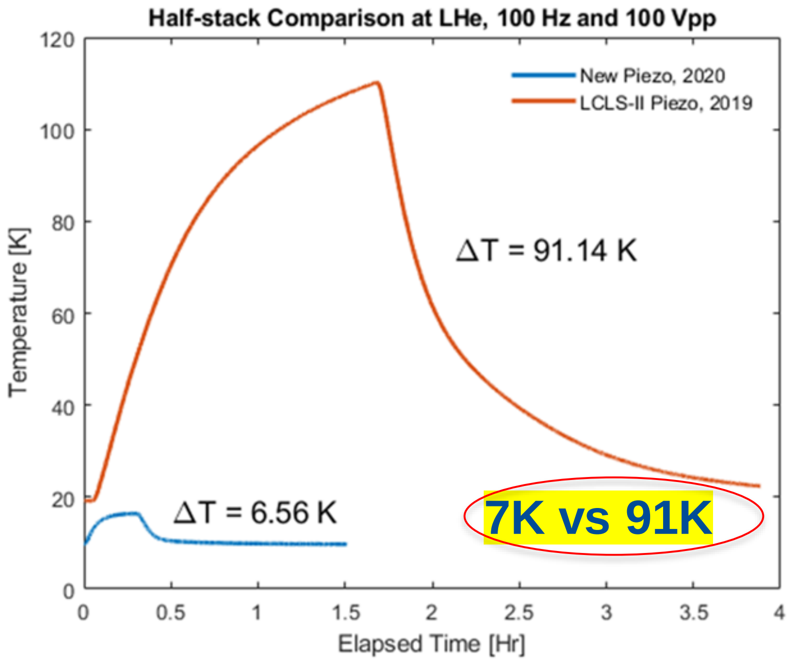
Design of the High Dynamic Rate encapsulate piezo actuator



Physik Instrumente (PI)
GmbH & Co. KG
Auf der Roemerstrasse 1
76228 Karlsruhe
Germany







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