Challenges in the Building Reliable SRF Cavity Tuners for Future Higher Energy and Higher Intensity Accelerators

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Outline

- Role of the SRF cavity tuner
- Impact of tuner failures on the overall parameters of the SRF LINAC
- Tuner design:
  - ✓ robust; non-expensive; maintainable
- Tuner reliability/reliability of the active components
  - ✓ electromechanical actuator /stepper motor
  - ✓ piezo-electric actuator

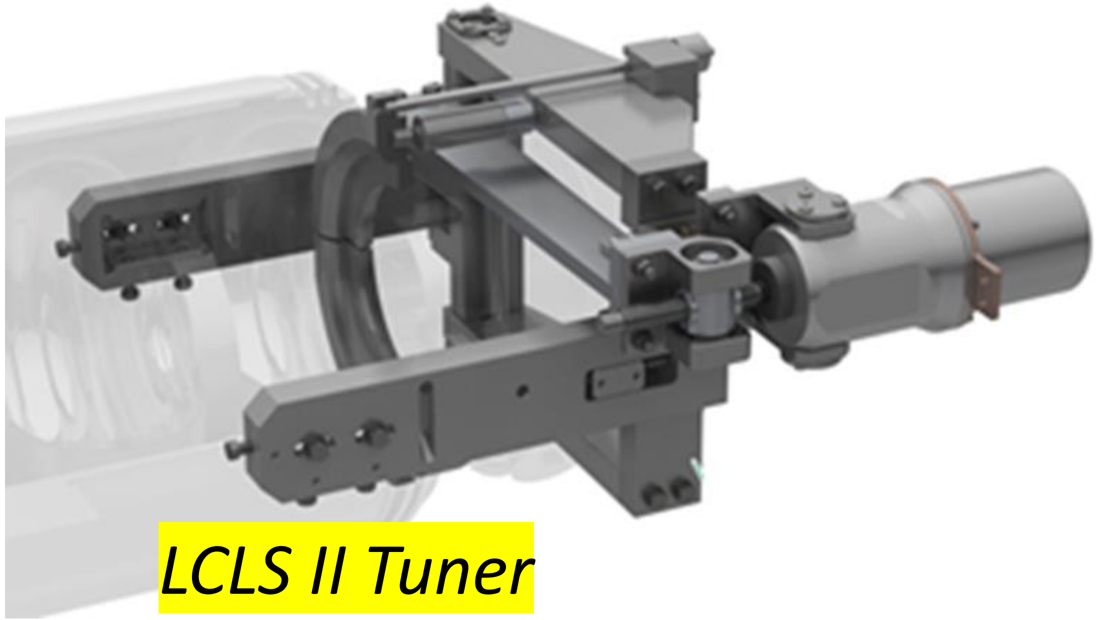
Role of the SRF cavity tuner

- To protect cavity during all steps of the production of the SRF cryomodules and operation
- To tune cavity to operational frequency after cool-down to T=2K and return to “elastic deformation region” before warm up (slow/coarse tuner/ range is 100’s kHz)
- To keep cavity in the resonance- compensate for microphonics and Lorentz Force Detuning (fast/fine tuner… range is 1-10 kHz)

Impact of tuner's failures on the overall parameters of the SRF LINAC

- Failure of the slow tuner:
  - Cavity could not be tune to operational frequency (SRF cavity became expensive 1 m long beampipe)
  - Cavity tune to operational frequency and developed problems (quenching) but tuner break down and cavity could not be retuned → problems with beam dynamics
  - Tuner failed and cavity could not be brought back before warm… likely cavity will be permanently non-elastically retuned… (cavity will be lost)
- Failure of the fast/fine tuner:
  - Microphonics and/or LFD could not be compensated → gradient of the cavity must be decreased to operate with available RF-power
  - For narrow bandwidth cavities that have large slow tuner hysteresis failure of the fine tuner will lead to problems with brining cavity to resonance (control problems)

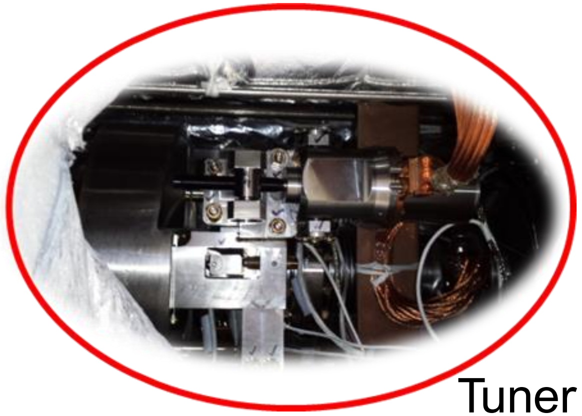
Maintainability of the SRF cavity tuners



Tuner design has capability to easily replace active components (piezo & stepper actuators) through designated "tuner access port" into vacuum vessel of the cryomodule.

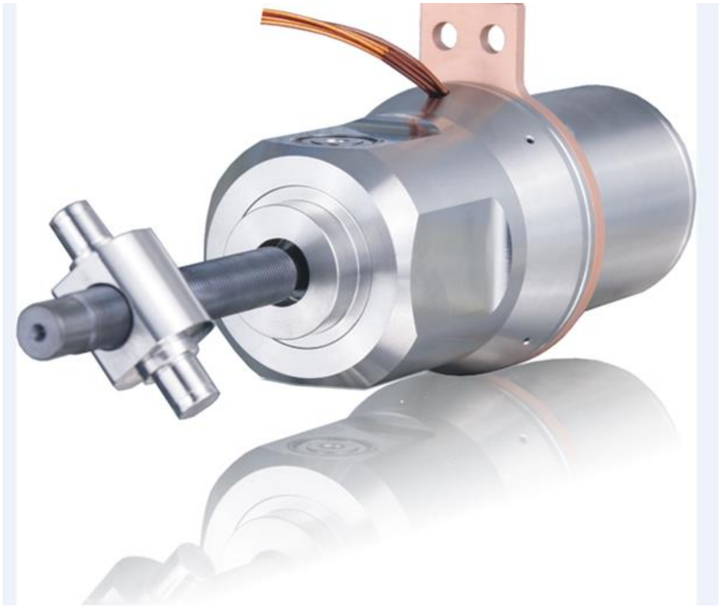
Otherwise, to fix tuner following steps need to be done:

- disconnect CM from LINAC;
- remove CM outside tunnel;
- Take out cold-mass from vacuum vessel;
- Fix tuner
- Repeat all steps in opposite order…



LCLS II cryomodule
Tuner as it seen from access port

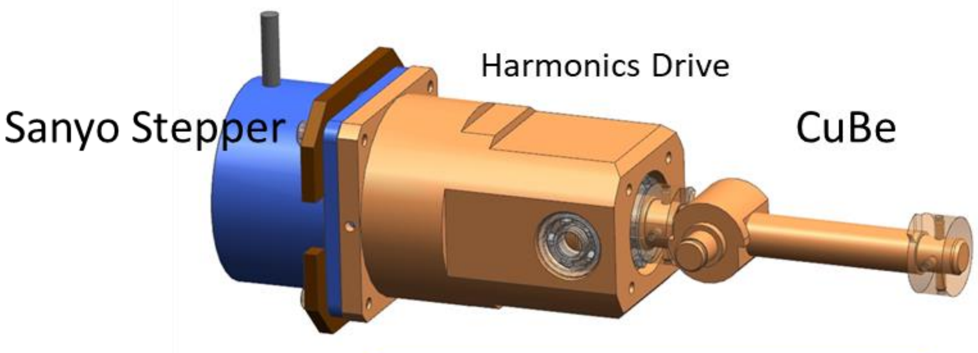
Tuner Reliability
Lifetime and rad. hardness of the active components
(electromechanical actuators & piezo-actuators)



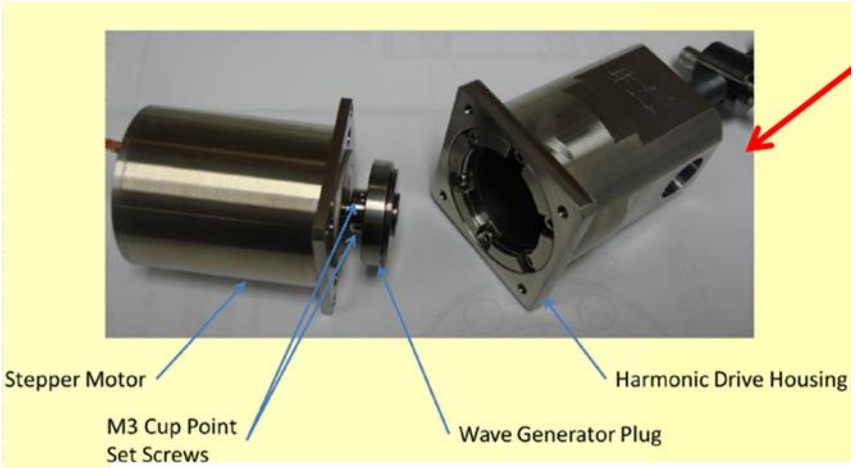
Stepper motor actuator

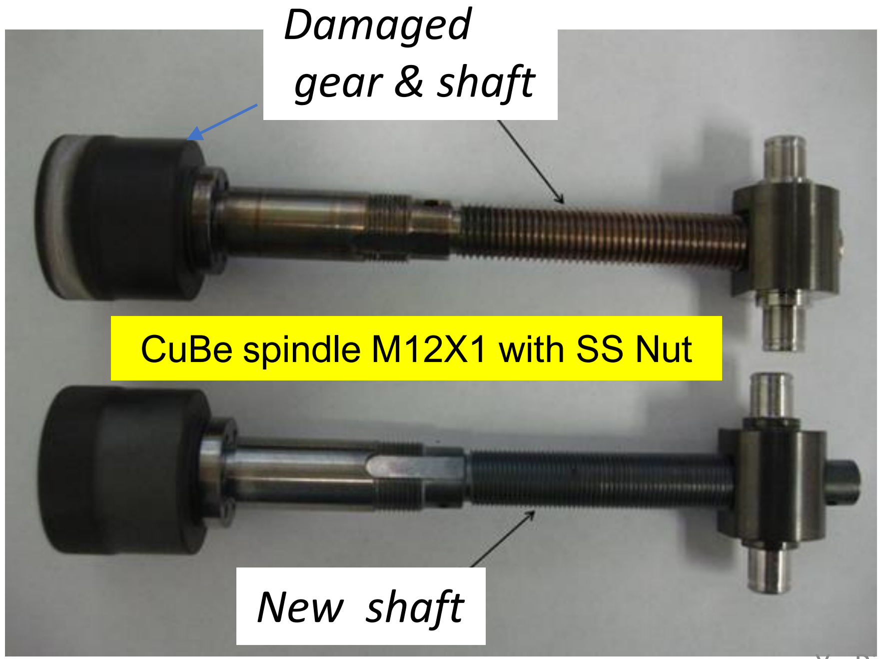
One the major issue with operation/longevity of electromechanical systems at cryogenic temperature and insulated vacuum – selection of the materials/gear and lubricants

Electromechanical actuator with Harmonic Drive



Axial load on spindle = 200N





Multiple failures at SNS

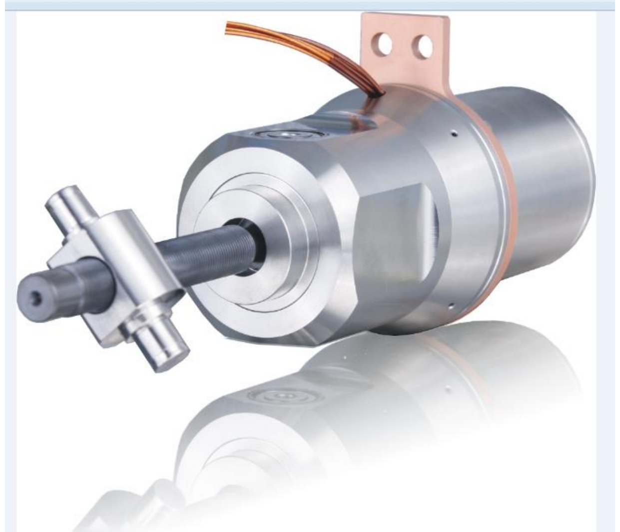
Harmonic Drive

Pros: smaller size
smaller backlash

Cons: low forces ~200N
short lifetime

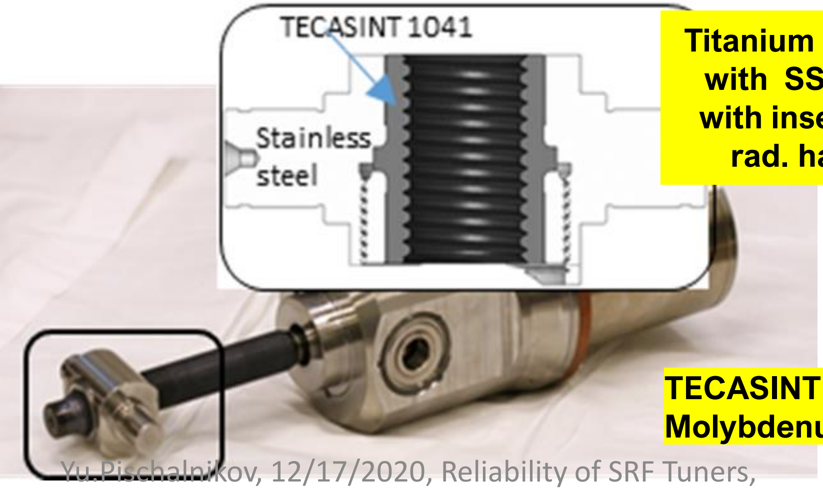
Electromechanical Actuator for Project X. FNAL/Phytron Collaboration
It was adopted by LCLS II (and now by PIP II & LCLS II HE)

- -High Vacuum/Cryogenic Stepper motor (52mm diameter; 200steps/360O; I=1A)
- -Planetary Gear 1:50 (no Harmonics Drives)
- -Titanium shaft 12x1 (dry lubrication)
- -Traveling nut made with TECASIN insert (provide additional dry lubrications)
- -Tested in cryo/vacuum environment for 10 lifetimes of the LCLS II/ILC LINACs without any failures.
- -Tested for radiation hardness up to 5*108Rads (no issues)



Planetary Gear Box 1:50

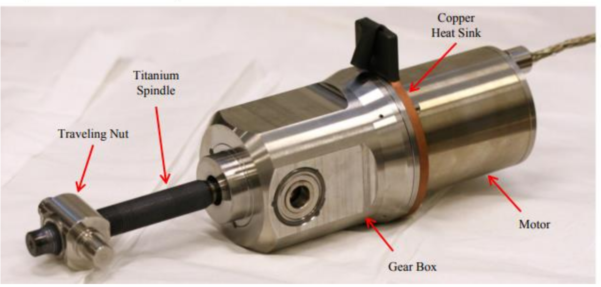
Testing actuators inside LN2 on the vendor site



Titanium spindle M12X1 with SS traveling nut with insert made from rad. hard material

TECASINT 1041 (polyimide; fillers 30% Molybdenum disulfide (MoS2)

Accelerated Lifetime Test



Continuously running at cryo temperature inside insulated vacuum for 14 days→

350MHz=12liftimes of LCLS II

No failure

Operation during, **Years**	25
Warm up cycle per year	2
Warm up cycle per life of LINAC	50
Average (slow) tuning range (300kHz * 2), MHz	0.6
Expected tuning range for the lifetime of the LINAC, MHz	**30**

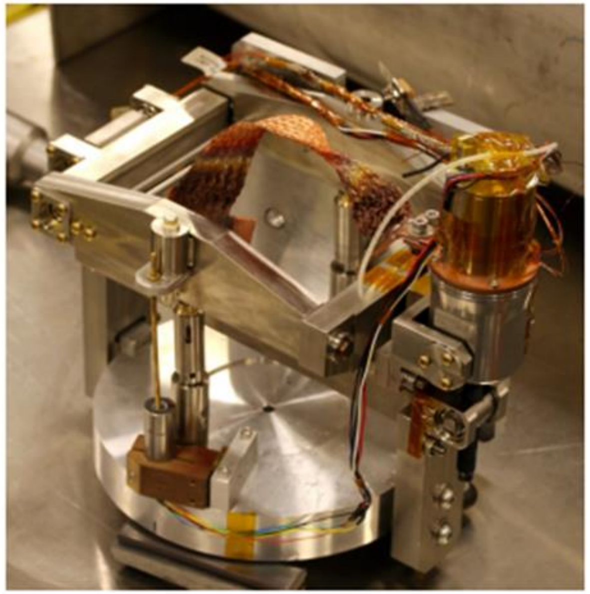
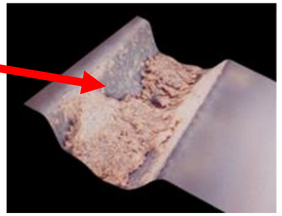


Figure 2: Tuner assembly attached to Aluminium base plate and spring stack for testing

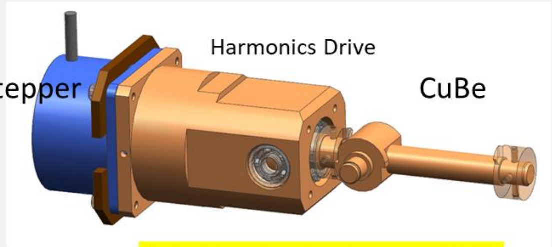
Titanium Shaft TECASIN Nut

Molybdenum disulfide (MoS2) dust



Traveling nut could be easy replaced

Next test for LCLS II HE OFO specs at FNAL soon.
LCLS HE OFO specs for longevity is ~ 700MHz



Axial load on spindle = 200N

XFEL stepper actuator longevity specs *is 25MHz*

Piezo actuator

Active Resonance Control

Development/implementation of the piezo control algorithms in large systems

Pulsed SRF accelarators, existing and projects	Cavity Half-bandwidth, Hz	LFD, Hz	LFD/HBW
ESS	500	400	0.8
XFEL	141	550	4
PIP II	30	330	11
ILC (50-60MV/m)	55	2500-3600	40-60
ILC(35-40MV/m)	—	—	10-15

Lorentz Force Detune is an issue!

(df_{LFD}/df_{HWR}~$gradient^3$)

When machine operate at high rep rate (10-25Hz) residual vibration from previous pulse will contribute into detuning…

Requirements to the piezo for operation in XFEL/ ILC and LCLS II
Impact on the longevity of the piezo

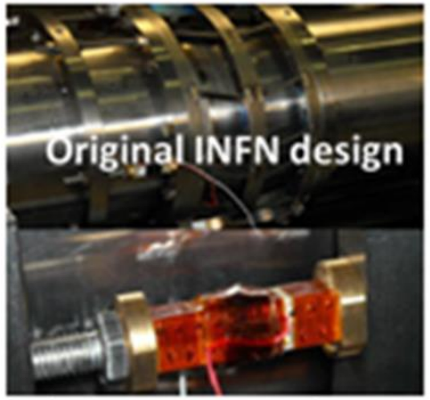
	XFEL /ILC	LCLS II	FNAL-test-stand *(2month)*
Operation	10/20 pulses/sec	CW	CW
stimulus pulse, Hz	200 *(2 sinewave per pulse)*	40	5000
Vpp, V	120	2	2
piezo stroke,[um]	5	0.2	0.2
number pulses for 20 years	7E+10	2E+10	2E+10
total stroke of piezo for 20years, [km]	60/ 500	5	5
Piezo-stack motion speed (rms) (mm/s)	4.5	0.02	2.2
Piezo-stack motion acceleration (rms)(g)	0.6	0.0004	7
Heat dissipation, [mW]	90/200	0.05	6
Piezo ΔT raised	20K/ ~100K	0.1K	2K

*$P_{av}=\pi CU^2 f$ *D, where D is dissipation Factor (~5-20%)*

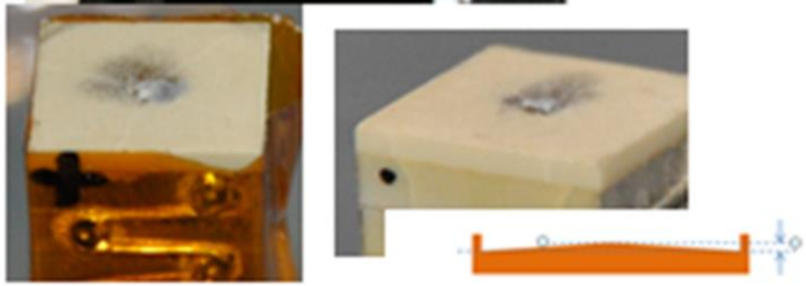
estimated
measured

Operational voltage for ILC piezo *(when operated at RF-pulse mode)* will be 60 times higher that for LCLS II. Power dissipation inside piezo-ceramic actuator for ILC is several 1000 large than for LCLS II. <u>Overheating of PIEZO could be a serious problem.</u>

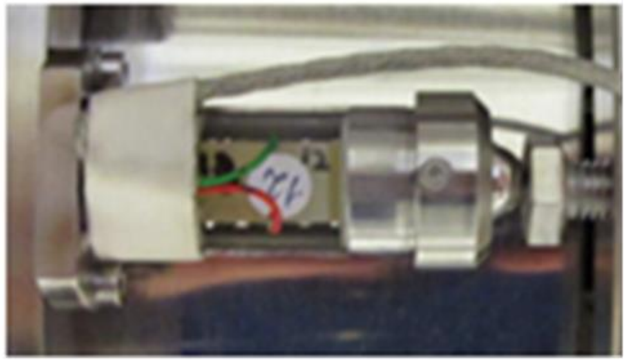
Many project have their “bad” experiences with piezo failure.
Examples of FNAL’s Tuner team experience
(failures of the “in-house” integration of the piezo-ceramic stack into fast tuner.
Shearing Forces on the piezo-stack led to quick piezo failures.

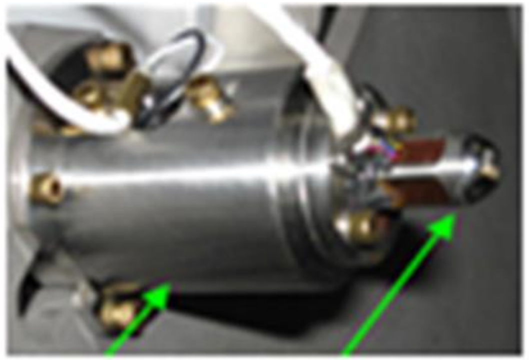


1) Shearing Forces applied to piezostack



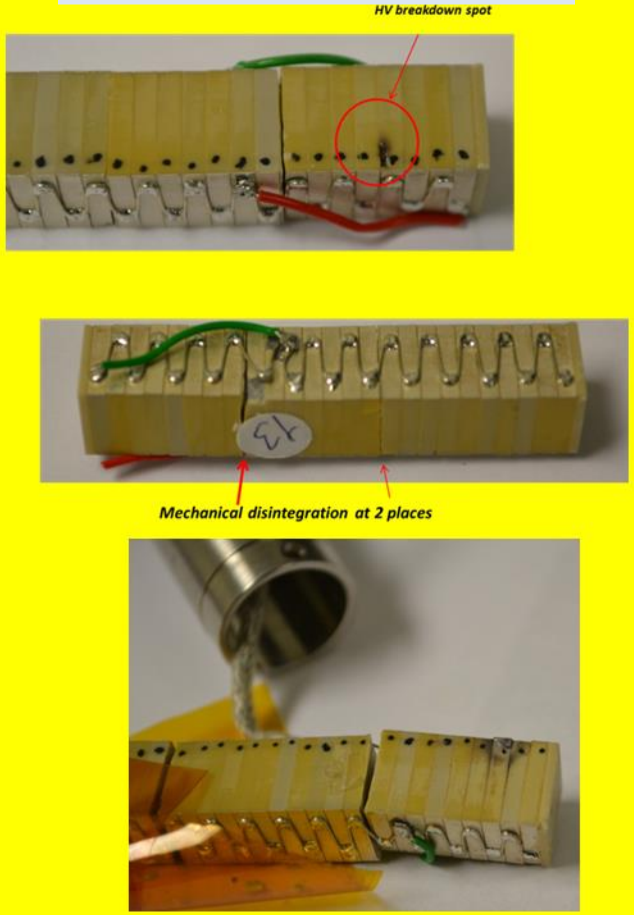
No any encapsulations





“in-house” capsulations

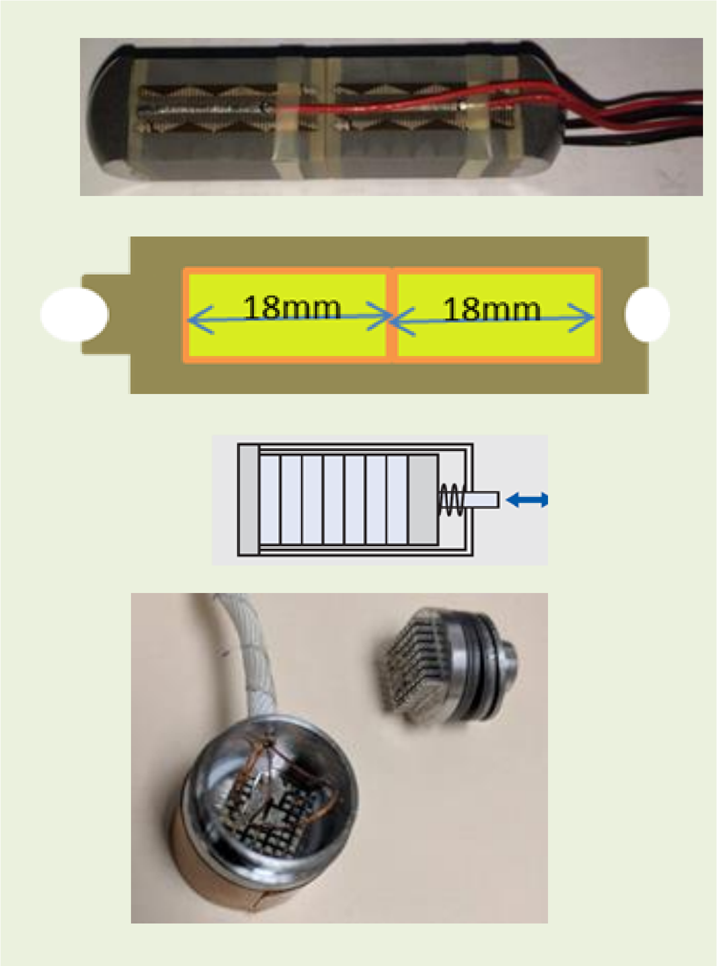
Typical Failure
cracks → HV breakdown

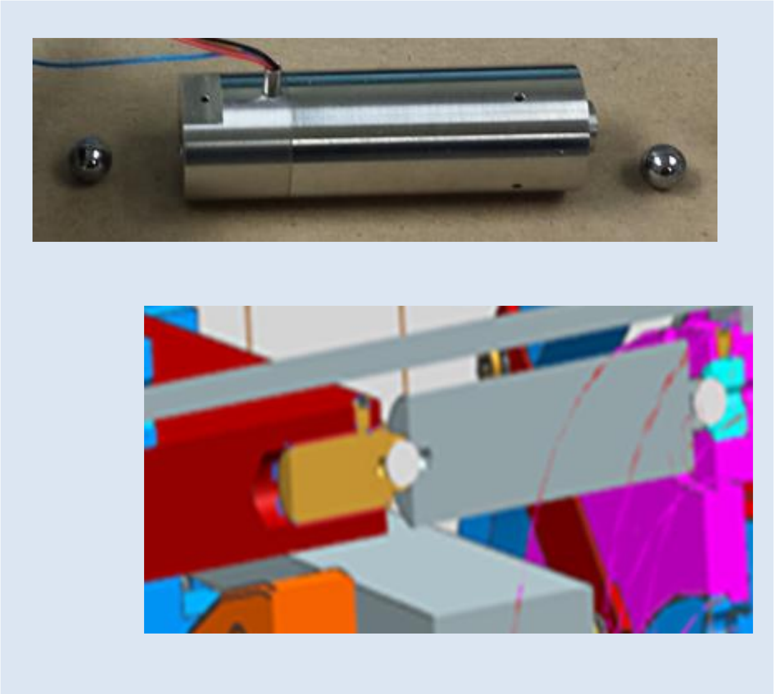


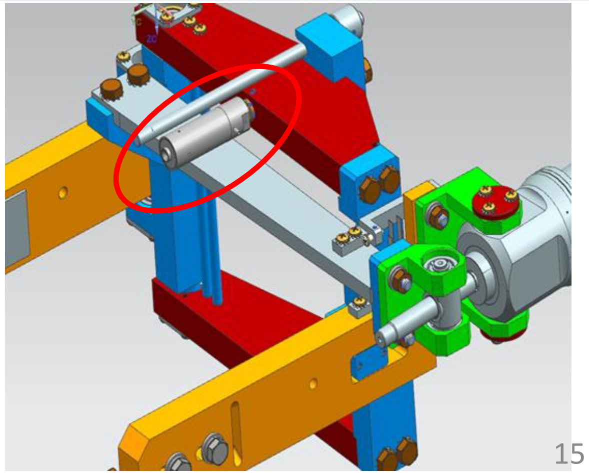
Join FERMILAB/ Physik Instrumente (PI) efforts to build piezo-actuator (for LCLS II .. and now for PIP II)

Physik Instrumente P-844K075

- Two glued PICMA piezo-stacks 10*10*18mm
- Capsulation with best technology
- Internal preload of piezo-stack
- Interface with ceramic balls to minimize sharing forces
- Wires that withstand high radiation







Piezo-actuator reliability study (Accelerated Lifetime Test ALT)

Overheating piezo-ceramic actuators when operated at cryogenic temperature & insulated vacuum

Power dissipated inside piezo-stack

$$P = \frac{\pi}{4} \cdot f \cdot C \cdot tan(\delta) \cdot U^2_{p-p}$$

- **Thermal conductivity of the piezo-ceramics is low.**
- **Removing heat from the actuator is necessary to avoid overheating at large amplitude and high operating frequency.**

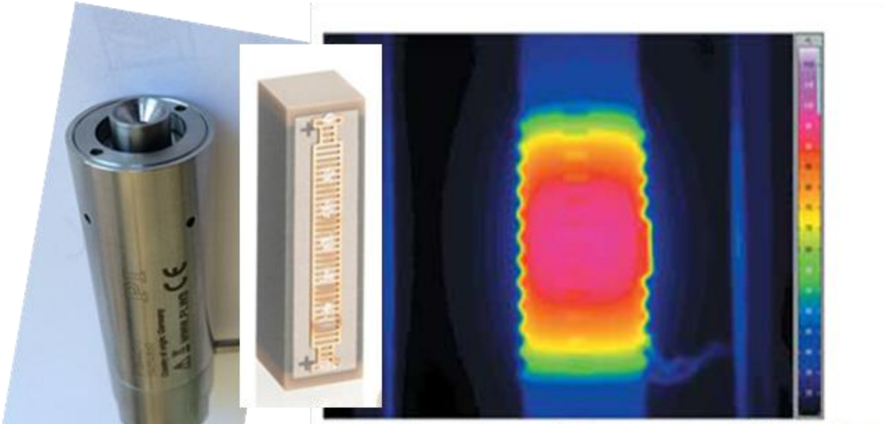
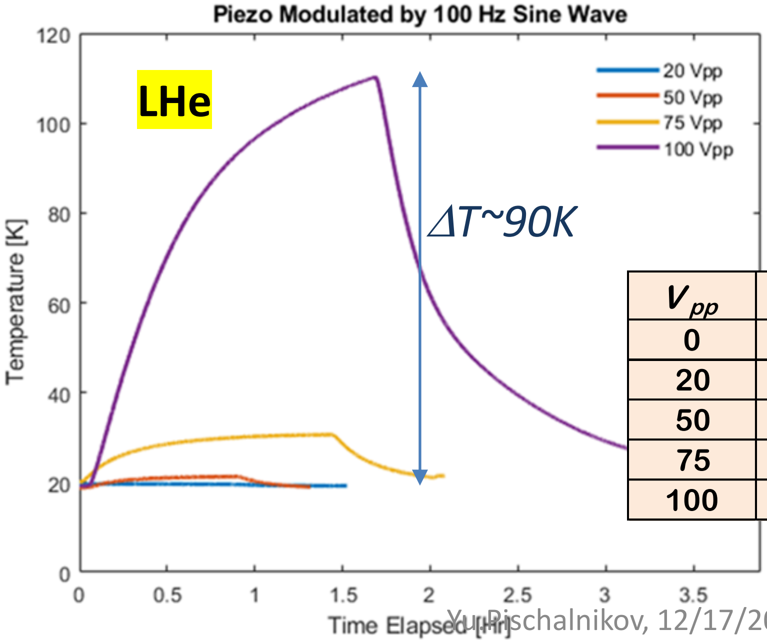
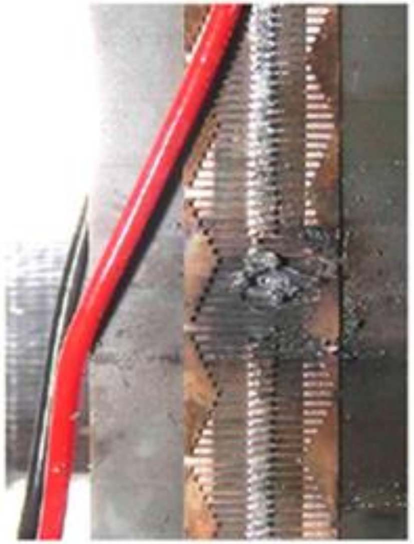


Fig. 5.1: Thermal image of a dynamically cycled high voltage actuator, clamped at its end faces. Environment: ambient air convection. Notice the cooling effect at the end-faces due to the clamping mechanics

FNAL ALT Study



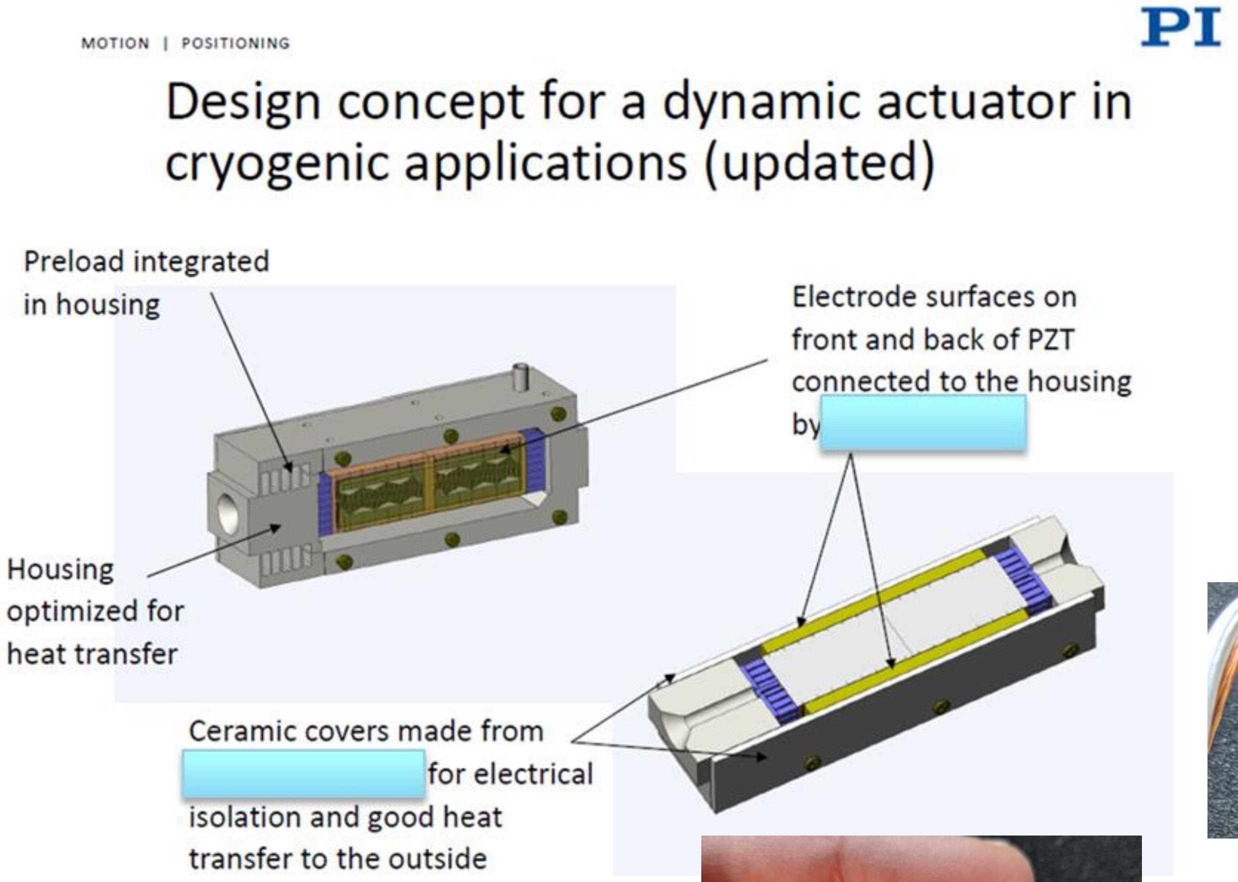
V_{pp}	ΔT
0	0
20	0.1
50	2
75	10
100	90

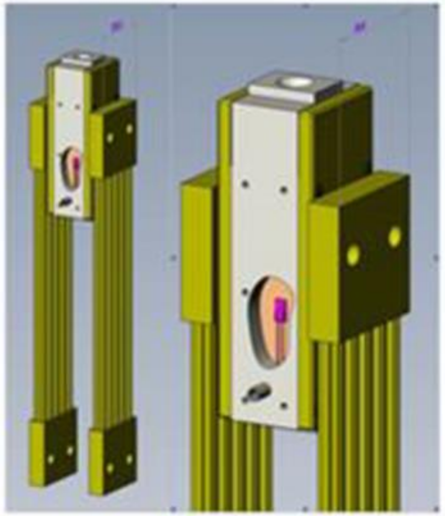


With the goal to develop newest High dynamic rate & high amplitude piezo-actuator FERMILAB engaged in R&D work with industrial partner to address following Task

- Develop technology to remove heat from the whole stack of the piezo-actuator (encapsulated & preloaded) when it is operating at cryogenics temperature (from 2K to 20K) and inside insulated vacuum.
  - *piezo continuously stretching/compressing (any thermo-conducting paste will be solid at this temperature)*
  - *Surface of the piezo under HV (any connections /heat sink to cryomodule's thermo-shield must be electrically insulated)*

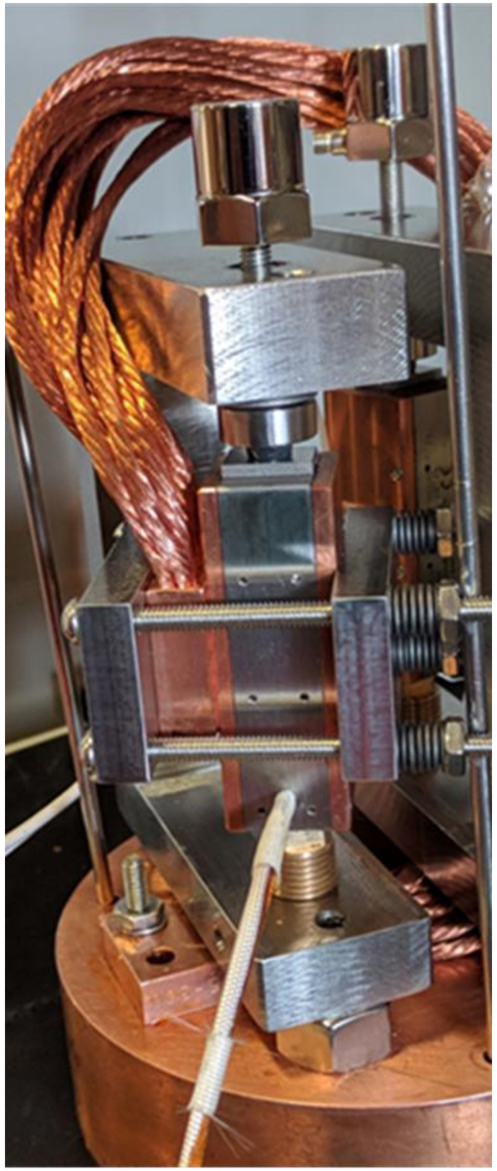
Design of the PI High Dynamic Rate encapsulate piezo actuator (patent pending)

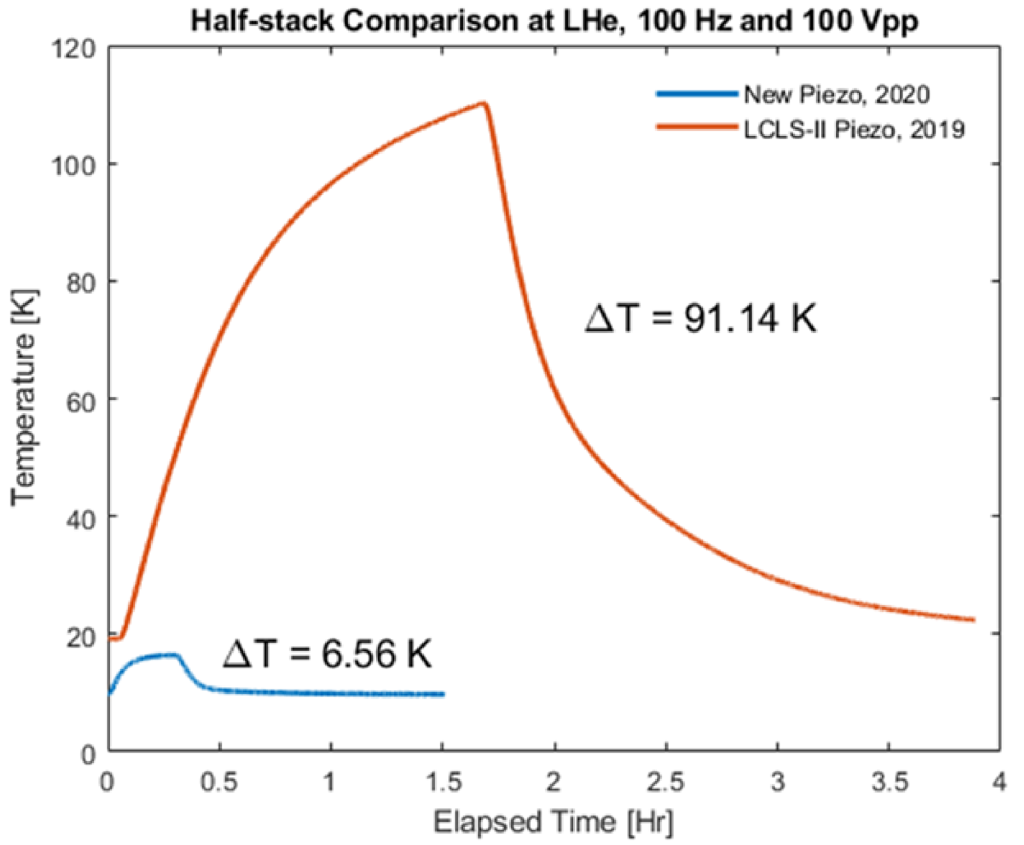




Physik Instrumente (PI) GmbH & Co. KG
Auf der Roemerstrasse 1
76228 Karlsruhe
Germany

New Piezo results at LHe





The same sinewave signal 100Vpp@100Hz warmed up the new (HDR) piezo on just ΔT=7K when "standard" piezo-actuators on ΔT=91K

ΔT=7K vs ΔT=91K

Development of the piezo-actuators with different piezo-electric ceramics … significantly decrease heat dissipation at high repetition rate and high amplitude

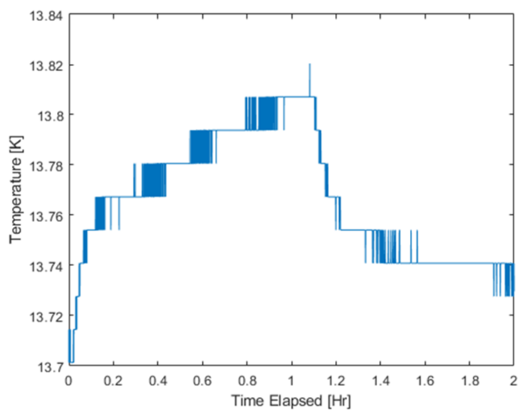
PI/FNAL development

Lithiumniobat piezo-actuator

dX~7um
T~20K

dX~3um
T~20K

dX~4-10 um
T~4K-45K



	ΔT
PICMA LCSI II actuator	90K
Heat Transfer piezo actuator	7K
LiNbO3 actuator	0.1K

Summary

- Longevity of the active components (stepper and piezo actuators) will limit reliability of SRF cavity tuners
- Reliable actuators could be built only in strong collaboration with industrial partners that have strong record of work with space programs (*“made in house” solution is usually non-reliable*)
- Available stepper motor actuators (example: Phytron unit for LCLS II) demonstrated longevity that satisfy reqs for future HEP SRF LINACs. Next step is work with industrial partners to minimize cost of unit
- FNAL in collaboration with PI built reliable piezo actuators for LCLS II project (CW-mode operation).
- FNAL is working with PI to develop reliable piezo actuators for high dynamic rate operation (to compensate LFD in future SRF machine to be run in RF-pulse mode – ILC; PIP III, etc)