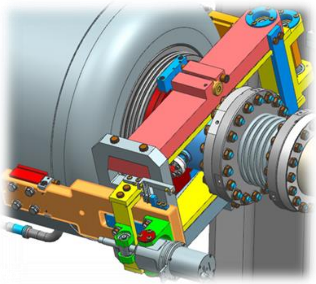
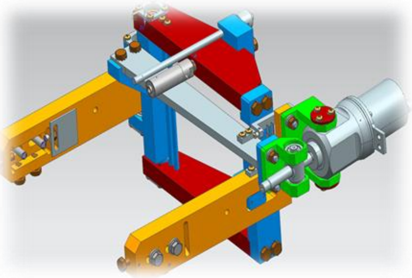
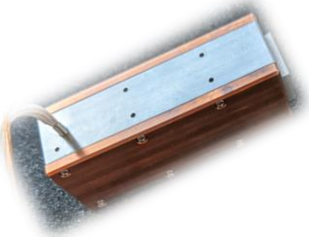
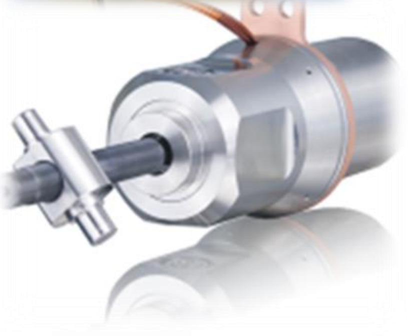
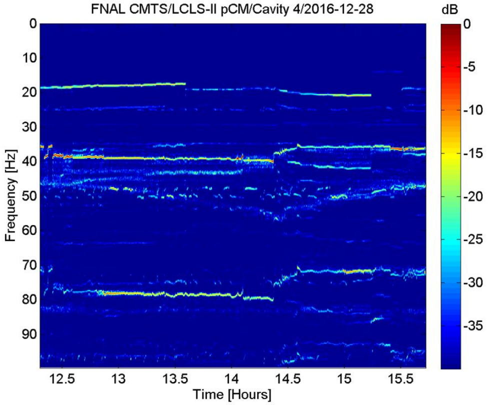





Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

SRF CAVITY RESONANCE CONTROL

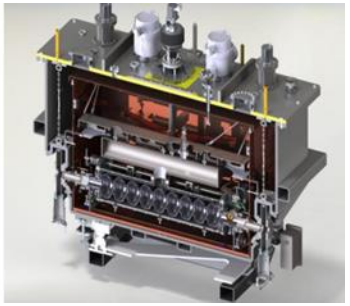
MSU/FRIB Accelerator Physics/Engineering Seminar



Yuriy Pischalnikov
FNAL
March 22, 2024

SRF CAVITY to accelerate the beam



High β:
mostly various elliptical shape structures.

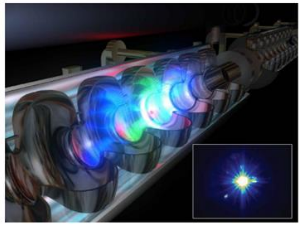
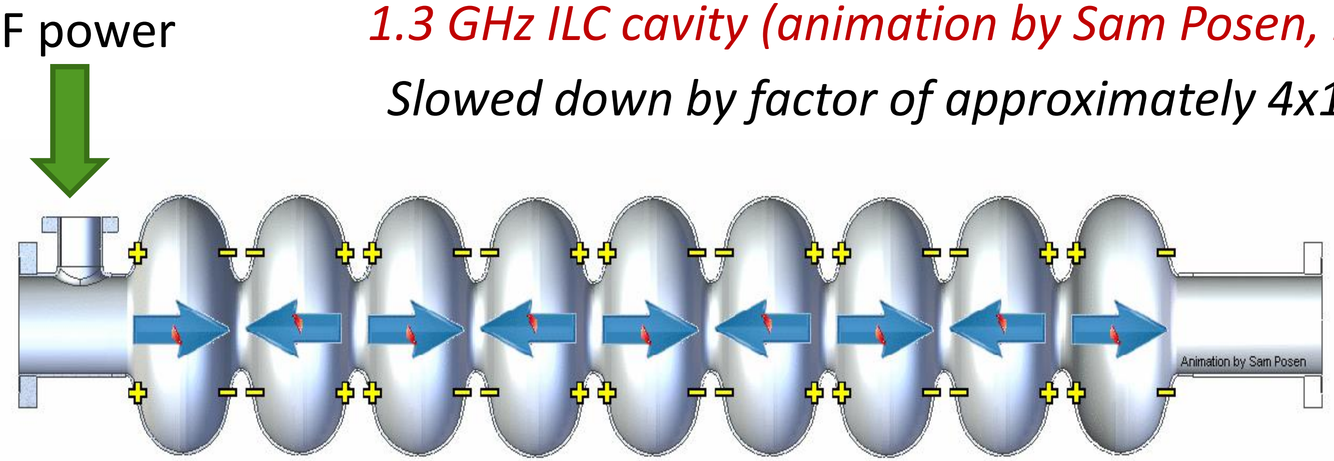


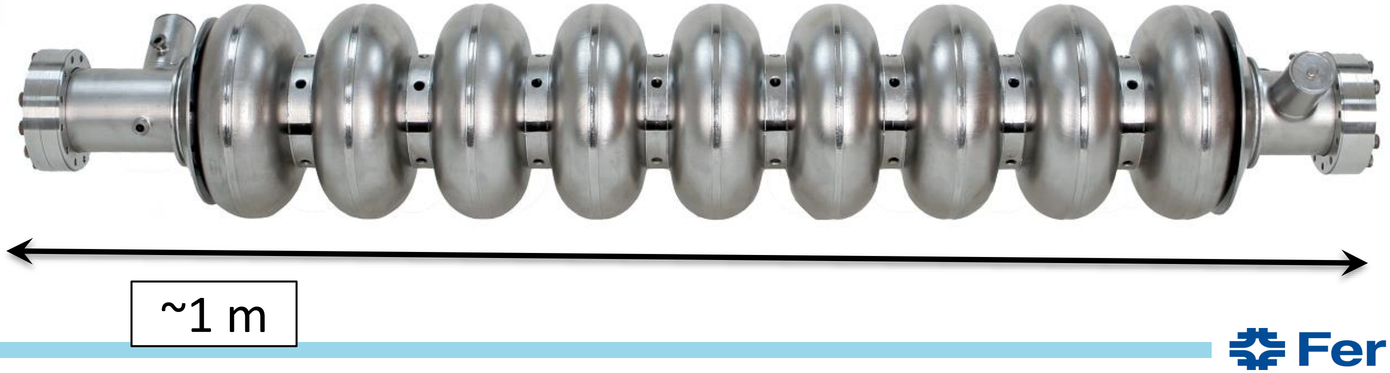
Illustration of synchronism

1.3 GHz ILC cavity (animation by Sam Posen, FNAL)

Slowed down by factor of approximately 4x10^9

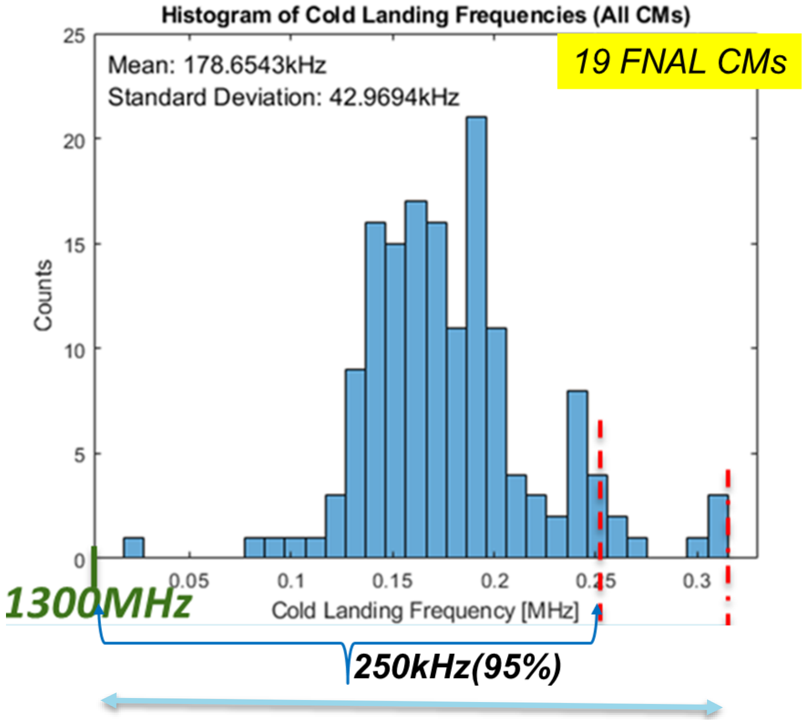
Fermilab 1.3 GHz CM for LCLS-II at SLAC





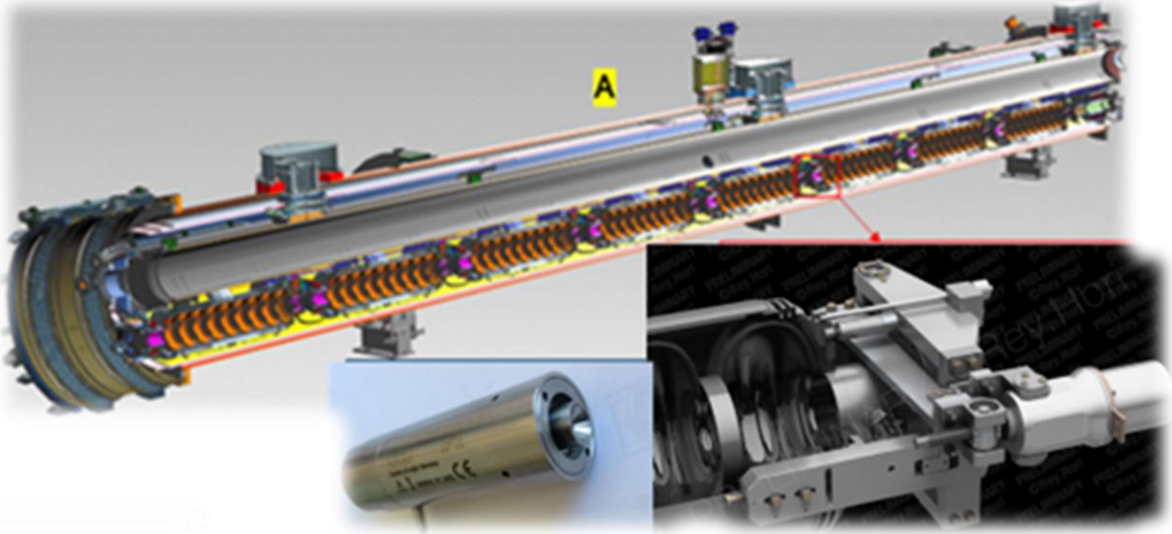
Resonance Control for SRF Cavities (Slow/Coarse Tuner)

- **Even cavities could be manufactured with small spread of resonance frequencies, after cool-down to T=2K (4K) each cavity will be required tuning to operational frequency. To be tuned each cavity must has slow/coarse tuner that capable to compress cavity on several mm and deliver required forces (up to 10kN). Typical slow tuner is *mechanical system with stepper motor.***



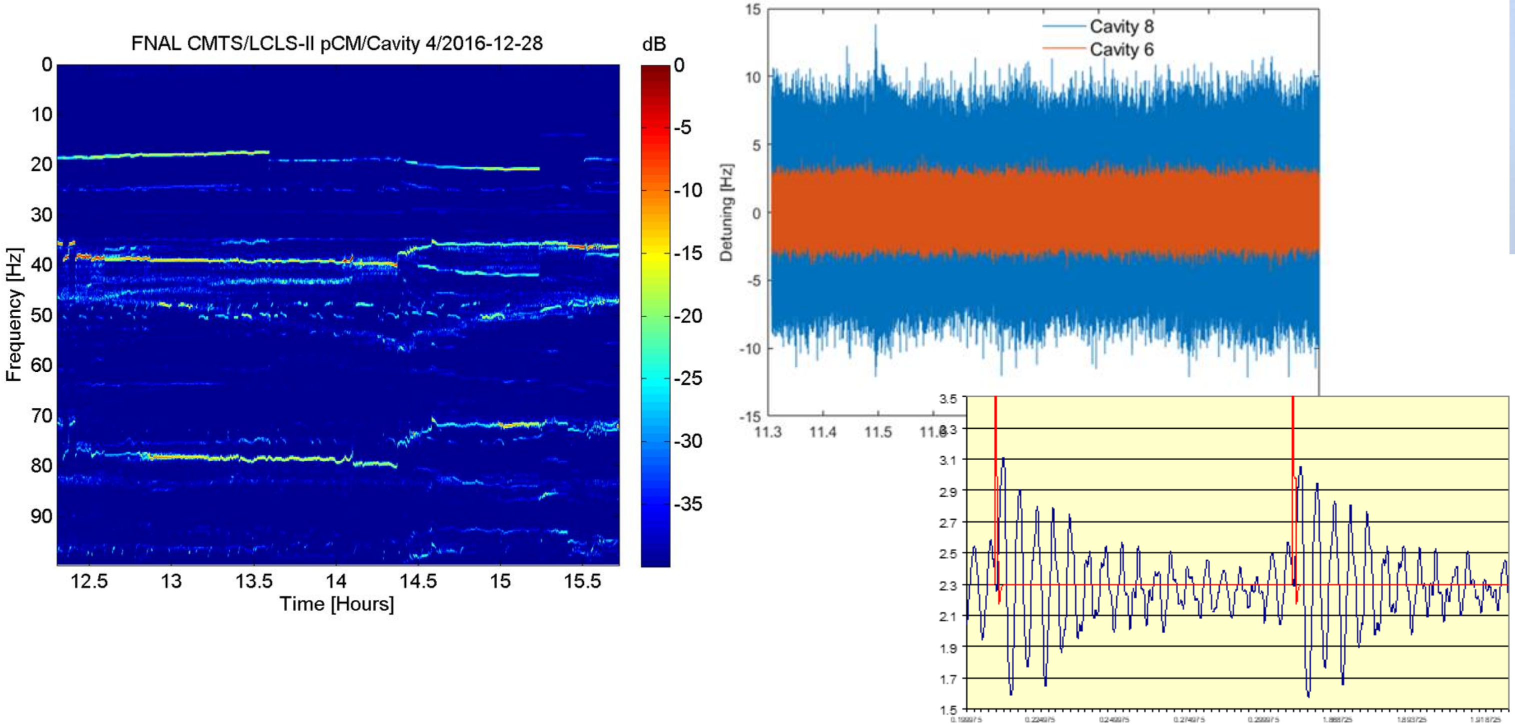
dX~1mm

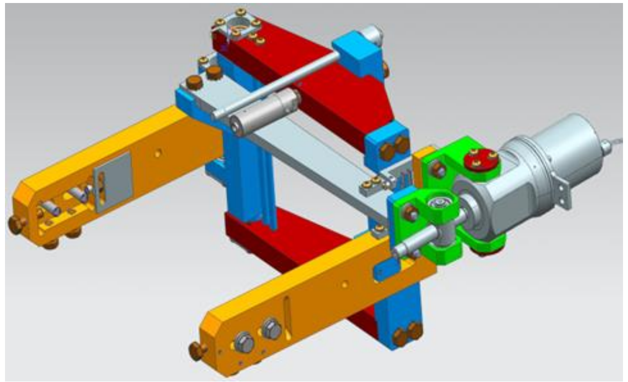
df/dL ~300kHz/mm



Resonance Control for SRF Cavities (fast/fine tuner)

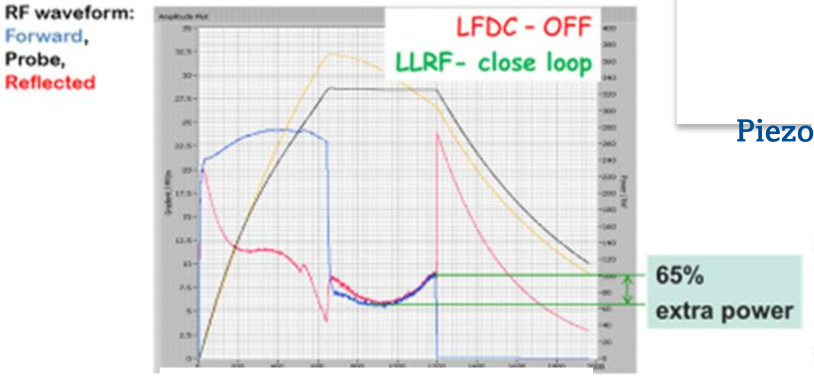
- **Cavity made from thin Nb sheets (cooling down at high gradient). External vibration (microphonics) or/and Lorentz forces (LF) will change cavity shape ➔ frequency. To compensate microphonics and LF detuning fast/fine tuner, that deployed piezo-ceramic actuator, must be added in serious with in slow/coarse tuner.**





Resonance Control for SRF Cavities (control algorithms)

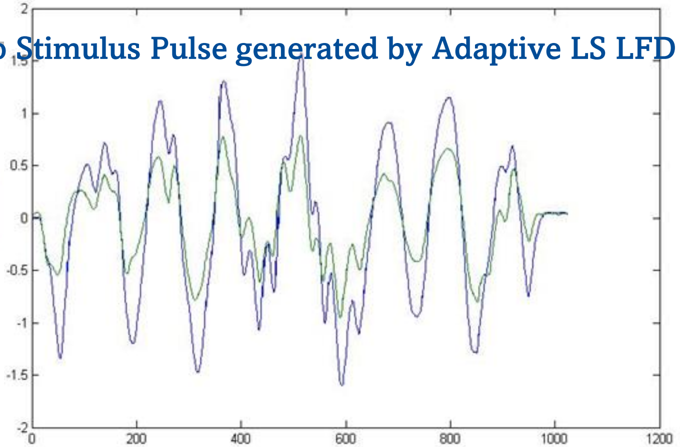
- **To keep SRF cavity's accelerating gradient at required level LLRF (Low Level RF) system could overcome cavity's resonance shift by pumping from High Power RF source more power. This approach very expensive and could not be applied to operate SRF LINAC. To keep cost of RF-plant at reasonable level sophisticated control algorithms that will through piezo-actuator actively compensate LFD and slow frequency drift & microphonics .**

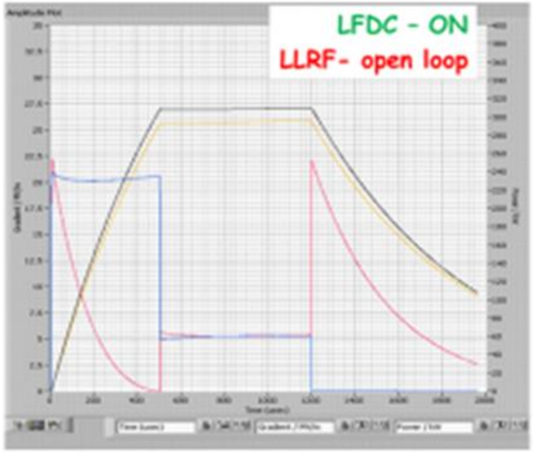


$$\frac{\Delta P}{P_0} = 0.25\left[\frac{K}{f_{1/2}}\right]^2 E_{acc}^4$$

Peak power increases with the fourth power of accelerating gradient

Piezo Stimulus Pulse generated by Adaptive LS LFD





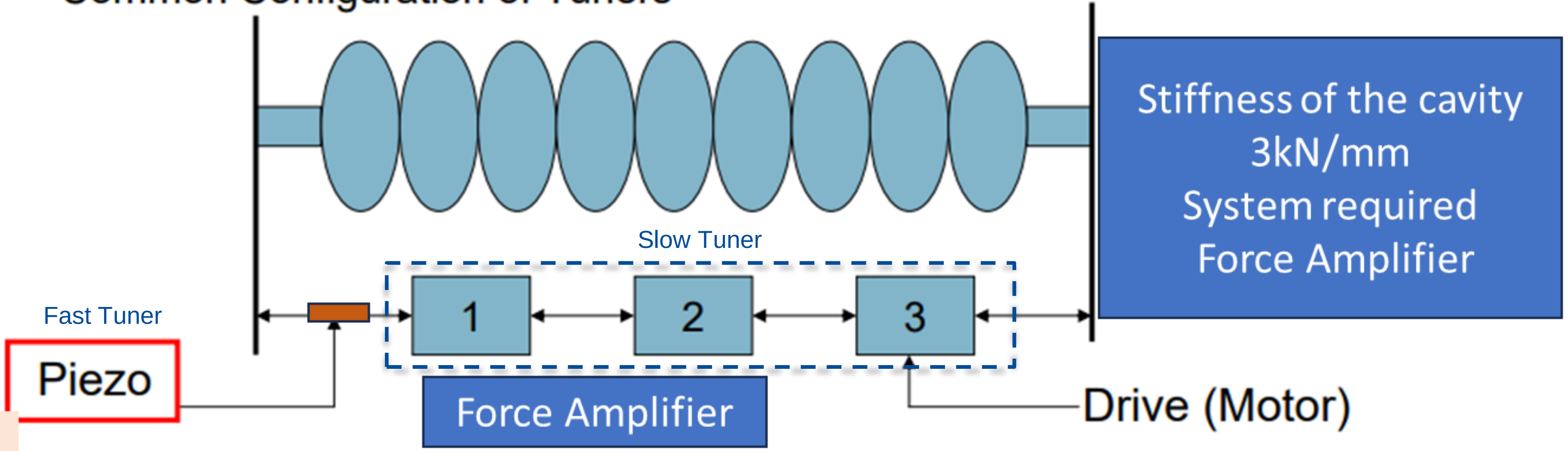
SRF Cavity Tuners

- **Protect cavity during CMs assembly and cool-down & warm-up**
- **Tune cavity to operating frequency after cool-down to 2K (4K)**
- **Tune cavity to "warm position" before CM warm up** (to prevent cavity's non-elastic deformations… elastic deformation range at T=2K is 5 time large that at T=300K)
- **Retune cavity (that malfunctioning) ~100BW away from operating frequency**
- **Keep cavity on the resonance during acceleration of the beam (active resonance control)**
- **Tuner reliability/lifetime must be longer than life of SRF Linac (30+ years)**

Common Configuration of the SRF Cavity Tuner

Tuning Principle:

Volume Change of ΔV→
Frequency Change of Δf


Common Configuration of Tuners

Stiffness of the cavity
3kN/mm
System required
Force Amplifier

Force Amplifier → Gear Box/Lever/Screw

Compression/stretching cavity on 2mm required F~6kN

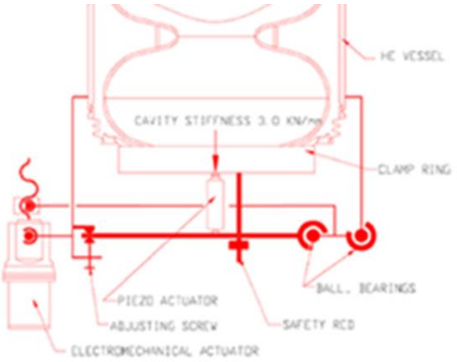
Piezo-stack 10*10*40mm will withstand forces up to 5(8)kN and could deliver stroke (at T=20K) dX~5-8um (or df~1.5-3kHz)

SRF Cavity Tuners

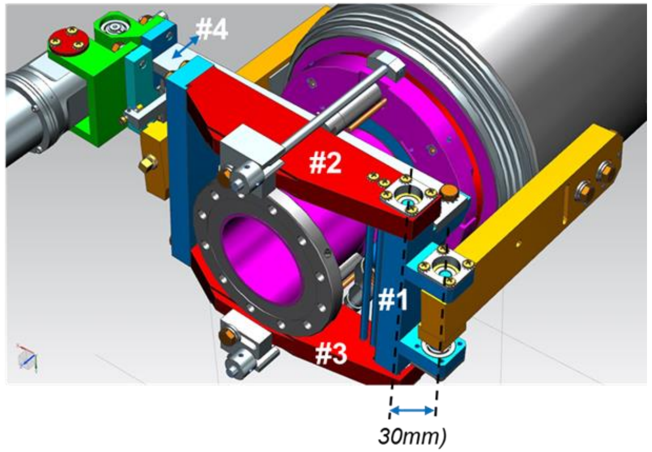
- Slow/Coarse Tuner (changing volume of the SRF cavity)
  - Mechanical
    - Compressing/stretching cavity
    - Insertion (plunger)
  - *Pressure (FRIB)*
  - SC electromagnetic
- Fast/Dynamic/Fine Tuner
  - Piezoelectrical actuator
  - Magnetostrictive actuator
  - SC electromagnetic
  - Ferroelectric Reactive

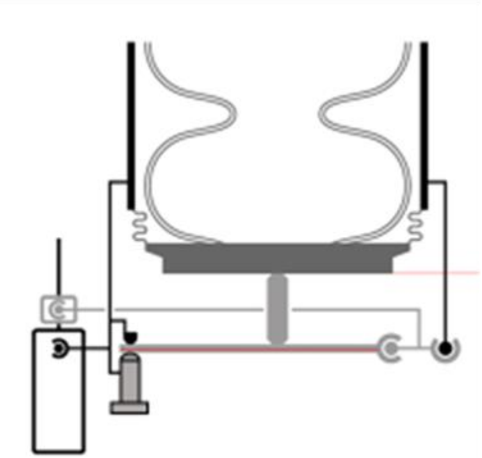
LCLS II Compact Double Lever Tuner

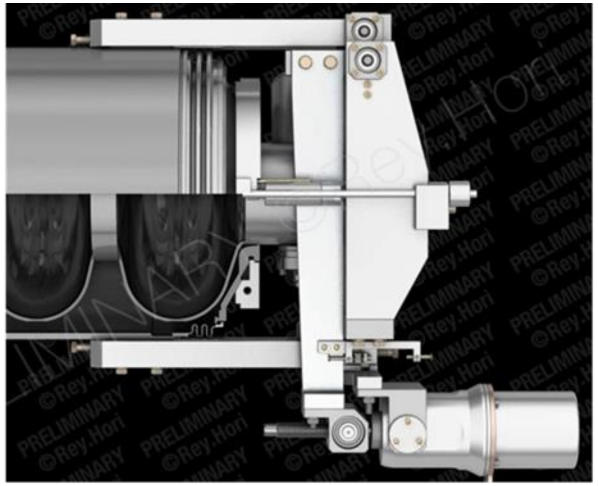
(double lever mechanical amplifier like SACLAY-I tuner)

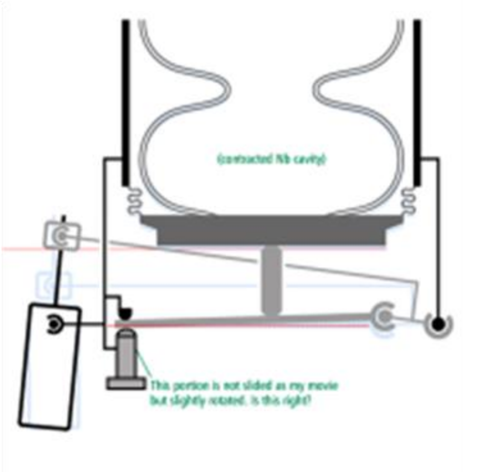


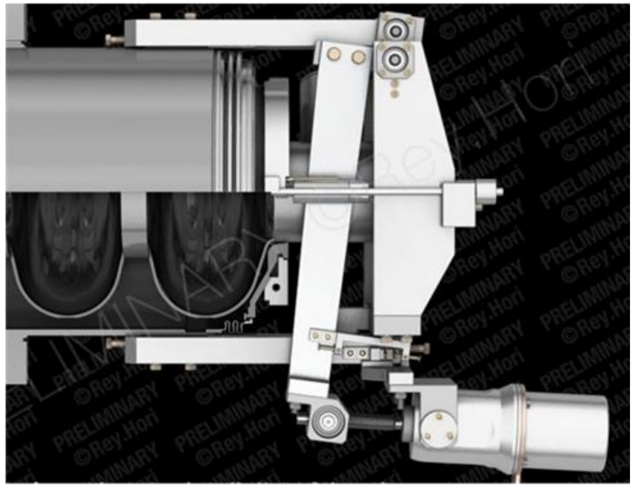
L1, mm	30
Tuner Ration	20
Hz/step	1.4











Specs:
Slow/coarse tuner range – 600kHz
Slow tuner resolution – 1-2Hz/step
Slow tuner hysteresis – less that 100Hz
Fast/fine tuner range - 2kHz
Fast/fine tuner resolution – better than 1Hz

Tuner remnant magnetic field not impact Q0 of the cavity;
Active components of the tuner (stepper & piezo) must be maintained/replaced through designated port into vacuum vessel;
Lifetime of tuner must be 30+ years

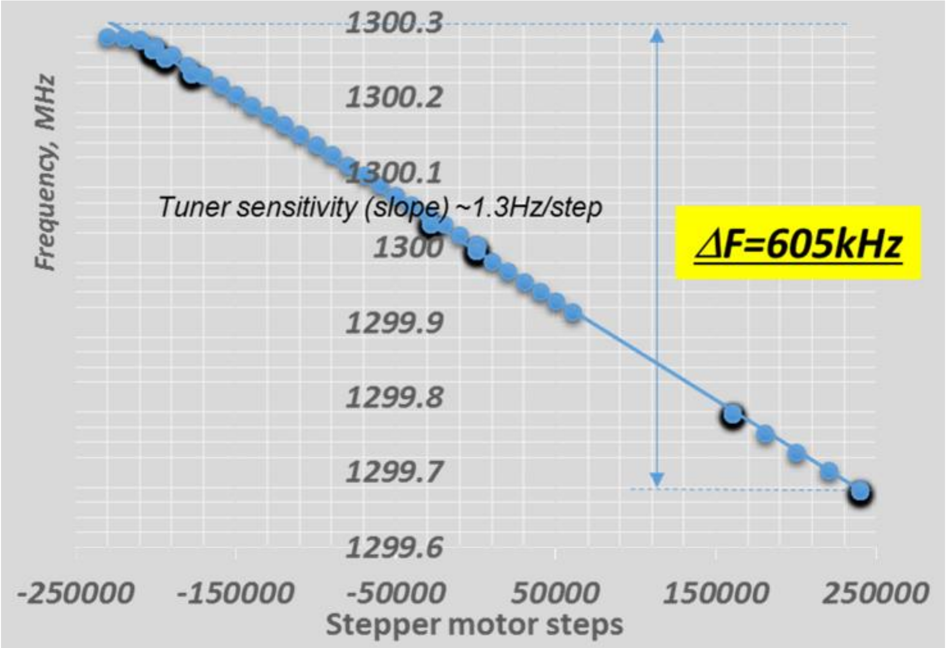
Measured parameters of the LCLS II Tuner (slow)

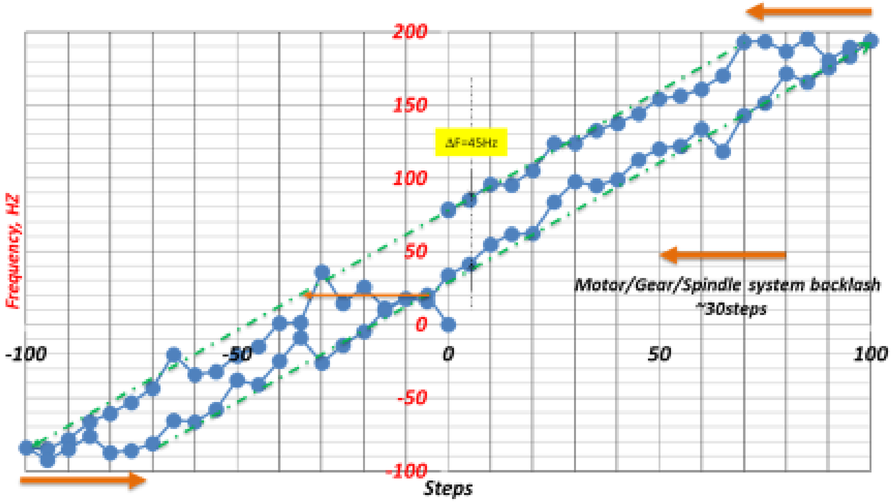
Coarse (Slow) Tuner parameters (measured)

1. *Range* ***ΔF~600kHz***

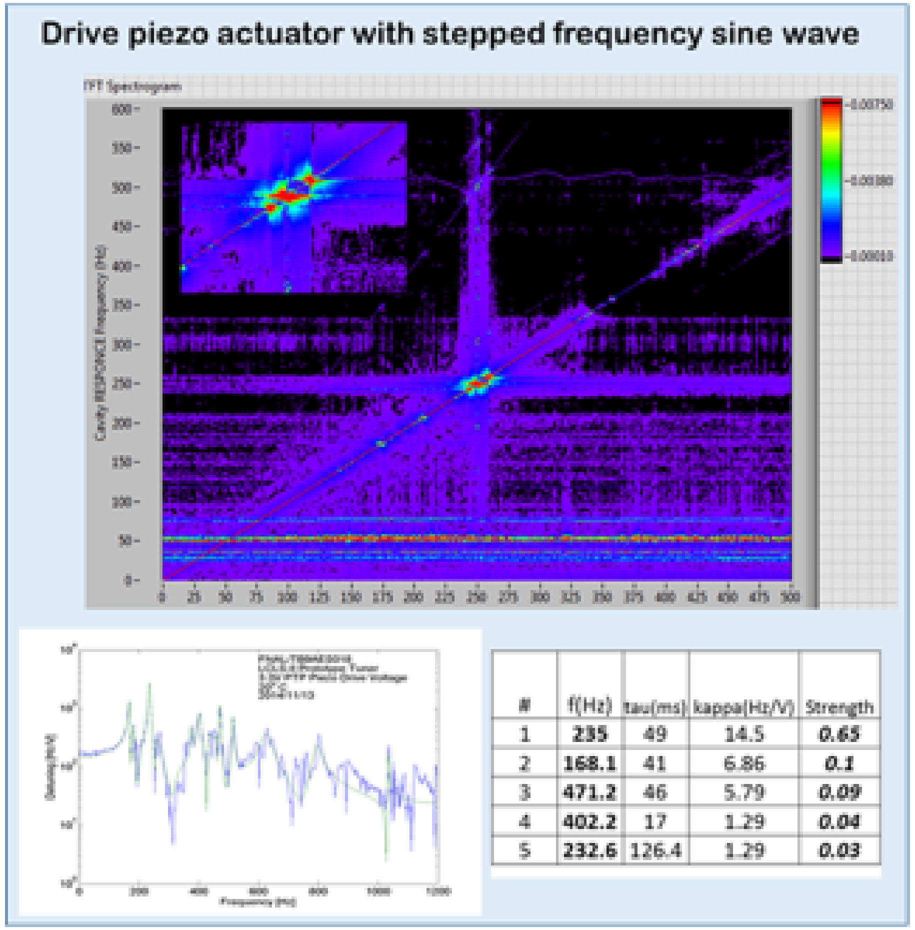
2. *Slope for coarse tuning* ***k=1.3Hz/step***

3. *Short range hysteresis* ***ΔF~45Hz*** *(or 30steps of backlash)*





Fast/piezo tuner parameters

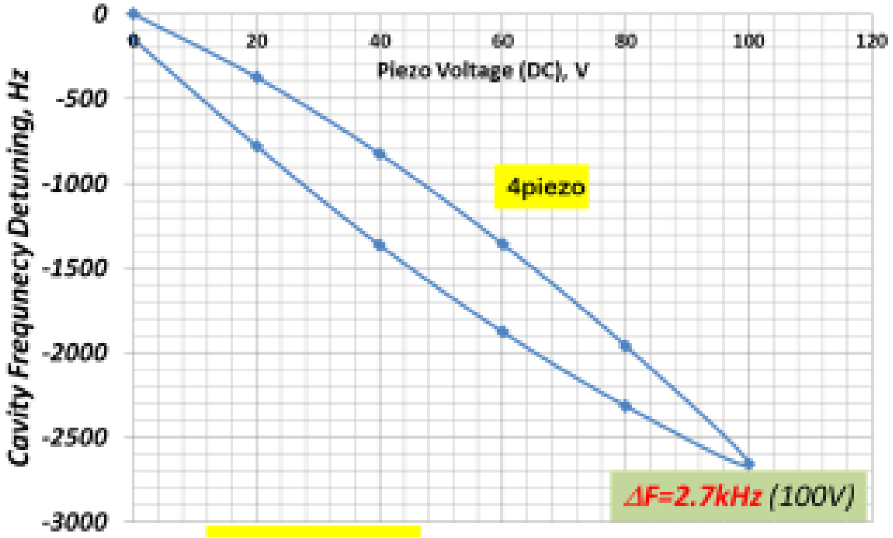


Drive piezo actuator with stepped frequency sine wave

#	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

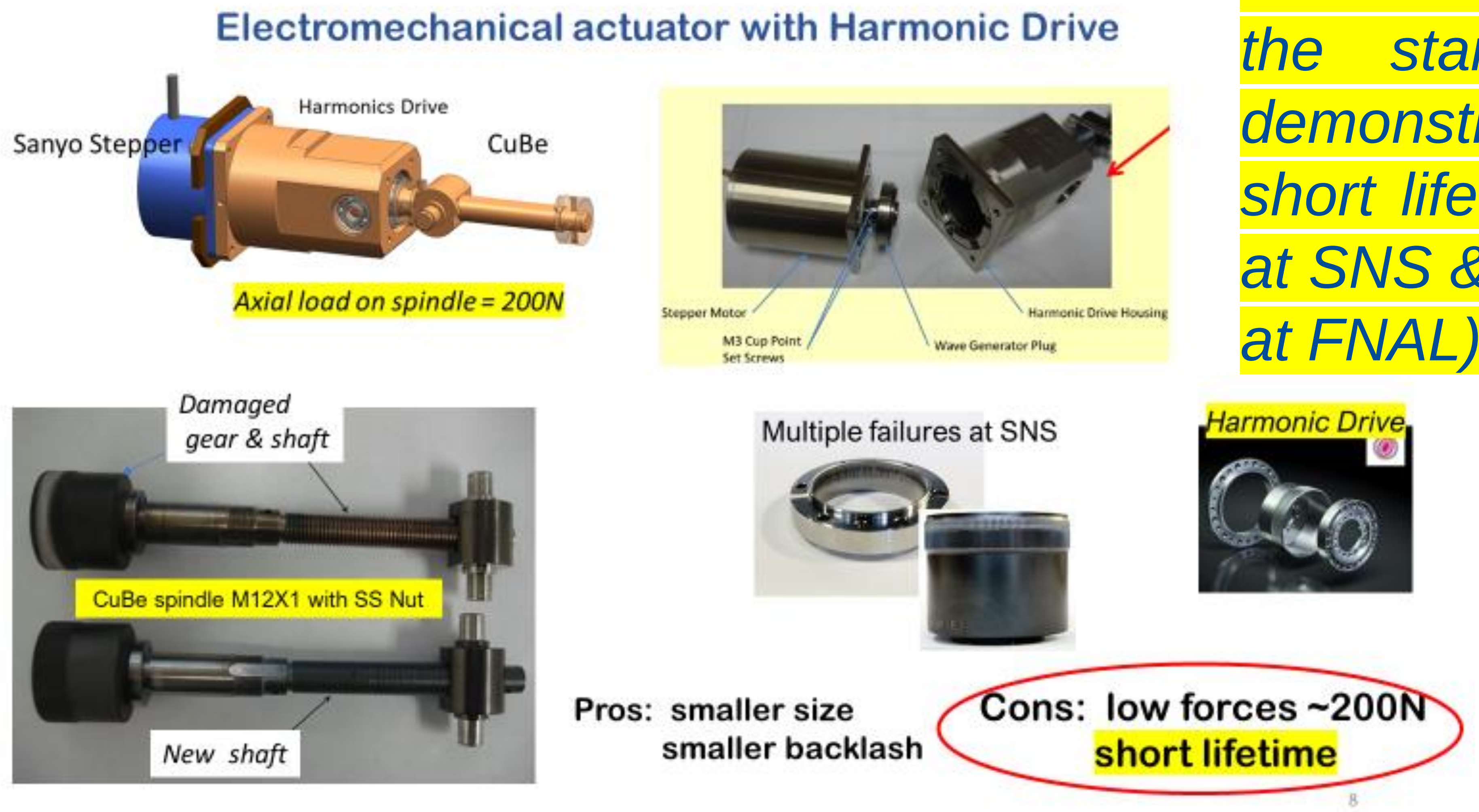
- **Fast (piezo) tuner range is ~3kHz** (at $V_{nominal}$=120V)
- Measured piezo resolution ~0.15Hz (limited by noise in HTS)
- Lowest mechanical resonances of the tuner/cavity system is 170Hz with major resonance at 235Hz
- Piezo tuner range will not changed with cavity tuned up to 600kHz



Fast Tuner resolution is better than 0.15Hz

Special R&D program initiated to develop reliable electromechanical actuator

actuators (available at the start of project) demonstrated very short lifetime (operation at SNS & longevity tests at FNAL)

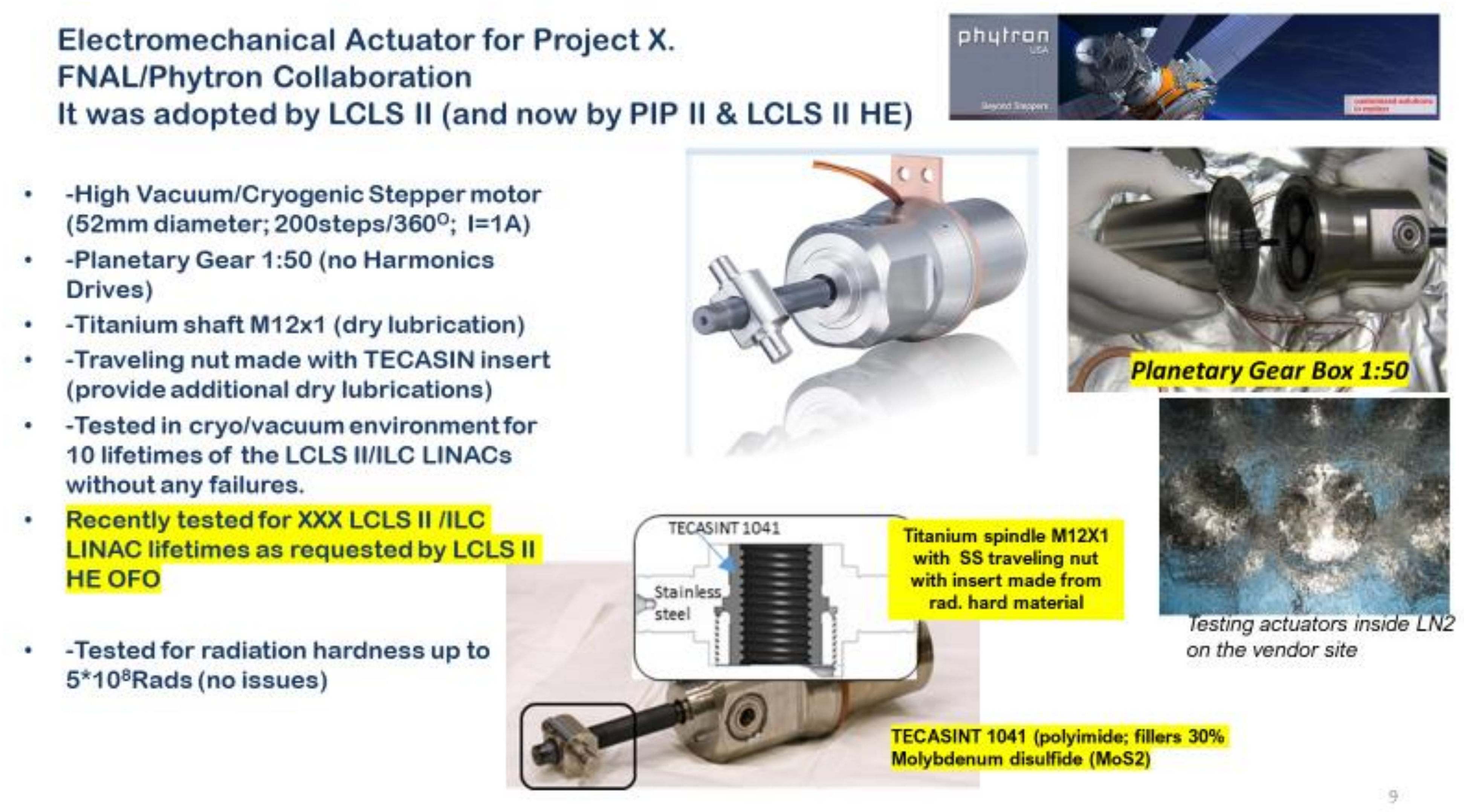


Electromechanical actuator with Harmonic Drive

Pros: smaller size
smaller backlash

Cons: low forces ~200N
short lifetime

Joint efforts of the Phytron& FNAL led to development reliable unit with lifetime up to 500+ years of ILC/LCLS II/EuXFEL SRF LINACs operation



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/360°; I=1A)
- -Planetary Gear 1:50 (no Harmonics Drives)
- -Titanium shaft M12x1 (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.
- Recently tested for XXX LCLS II /ILC LINAC lifetimes as requested by LCLS II HE OFO
- -Tested for radiation hardness up to $5*10^8$Rads (no issues)

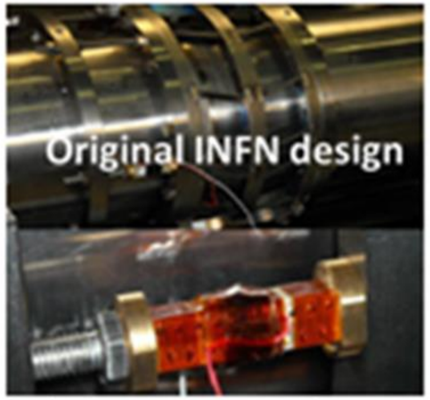
Planetary Gear Box 1:50

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

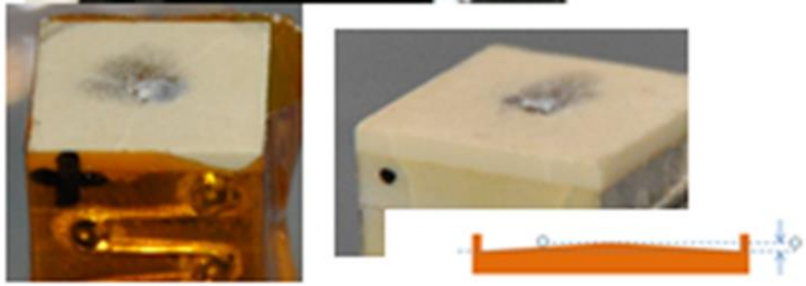
Testing actuators inside LN2 on the vendor site

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

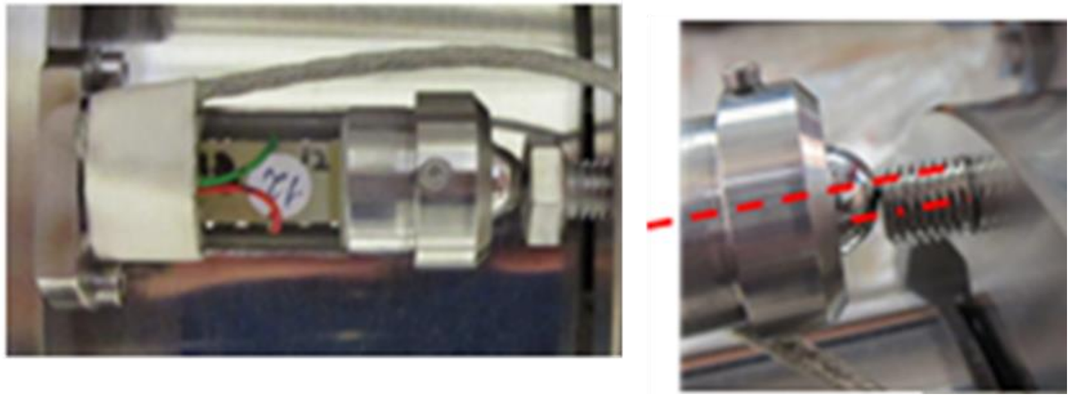
Many project have their “bad” experiences with piezo failure.
Examples of FNAL’s Tuner team experience
(failures of the “in-house” integration of the piezo-ceramic stack into fast tuner.
Shearing Forces on the piezo-stack led to quick piezo failures.

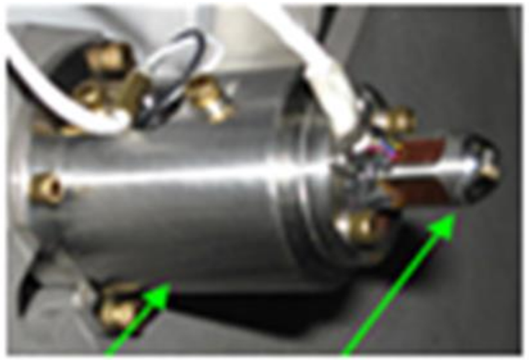


1) Shearing Forces applied to piezostack



No any encapsulations

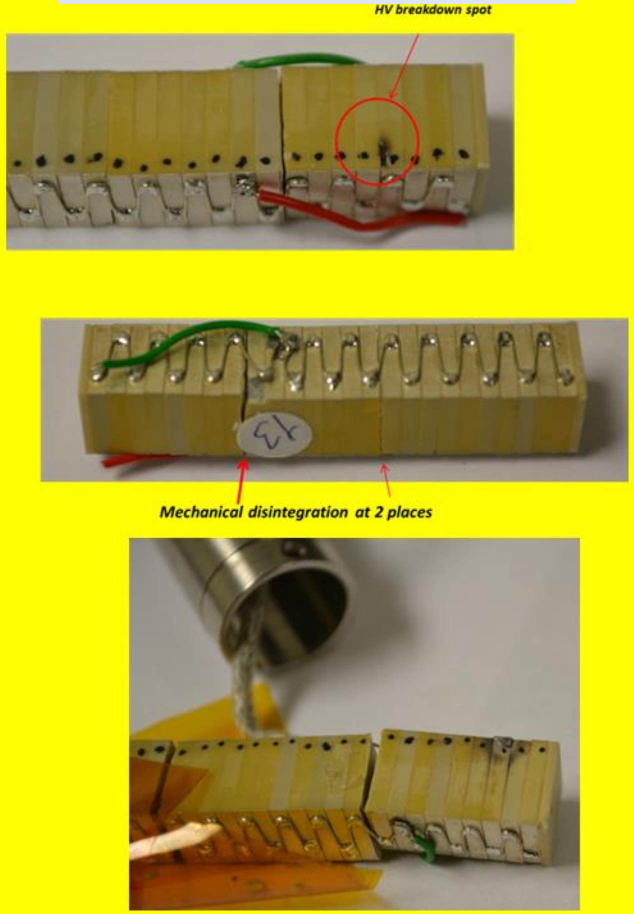




“in-house” capsulations

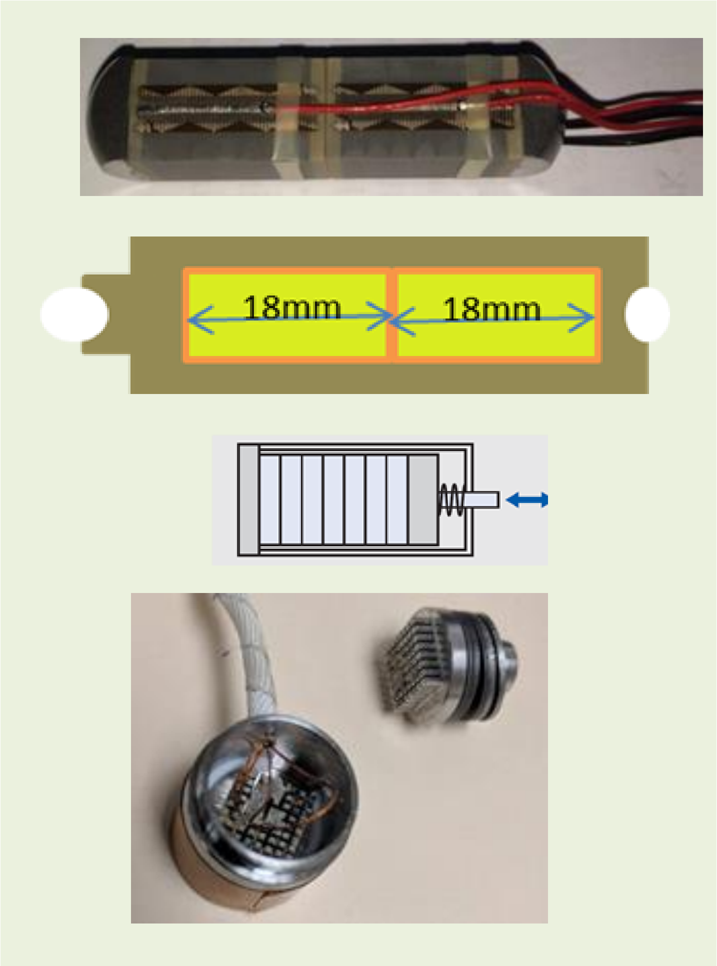
Forces could be up to 5-10kN

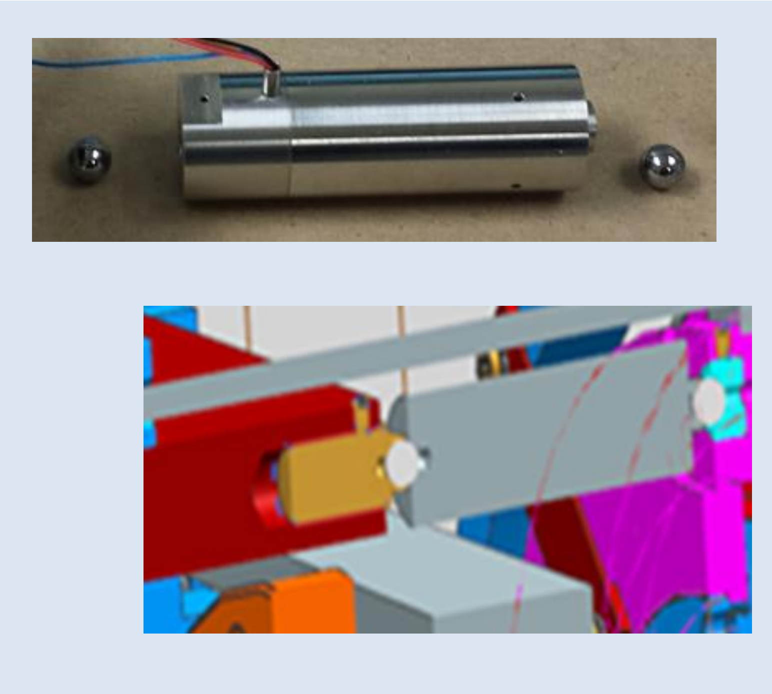
Typical Failure
cracks → HV breakdown

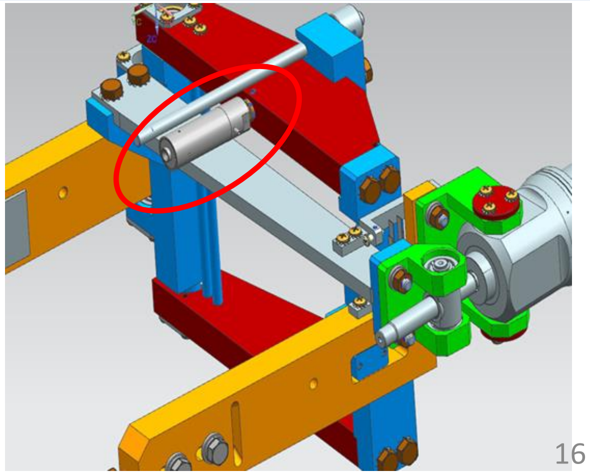


Join FERMILAB/ Physik Instrumente (PI) efforts to build piezo-actuator (for LCLS II .. and now for PIP II)

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

High reliability of tuner components (piezo-actuator)
Accelerated Piezo Lifetime test & Radiation hardness at FNAL

Designated facility at FNAL to test piezo at the CM environment (insulated vacuum and LHe)

Insert into LHe dewar with cryo/vacuum and electrical connections

Capsules (up to 5) with Piezo-stacks Mounted on the copper block

- **RTD (Cernox) –to mount on Piezos**
- **Geophones (to monitor piezo stroke)**

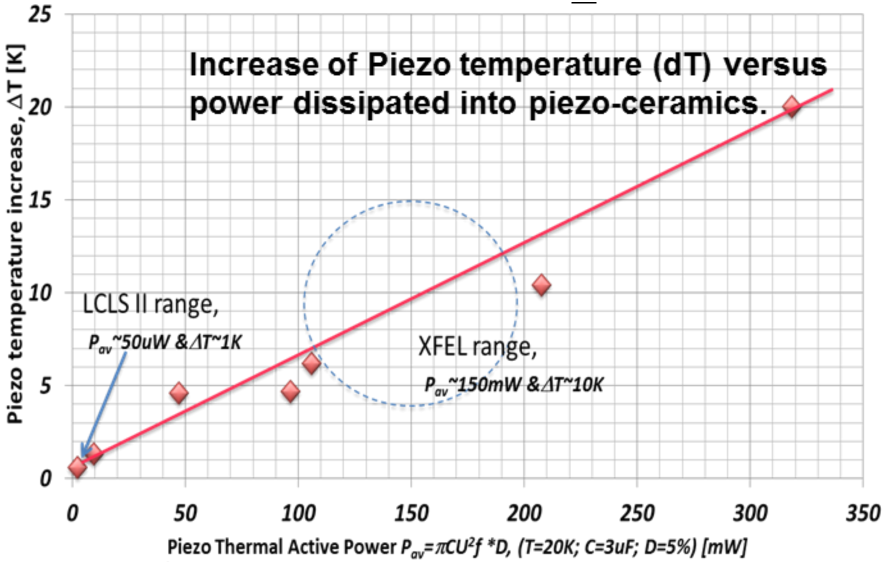
Accelerated piezo-stack lifetime test

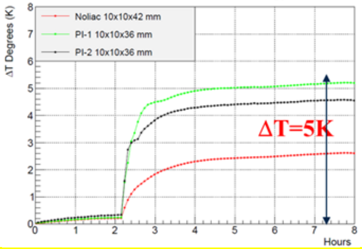
$2*10^{10}$ pulses ($V_{pp} = 2V$ & $F = 40Hz$)

20years → 2 month (40Hz→5kHz)

<u>LCLS II --- P_{av}~ 50µW (40Hz, 2V)</u>

<u>During ALT at 5kHz P_{av}~ 6mW (ΔT~2K)</u>

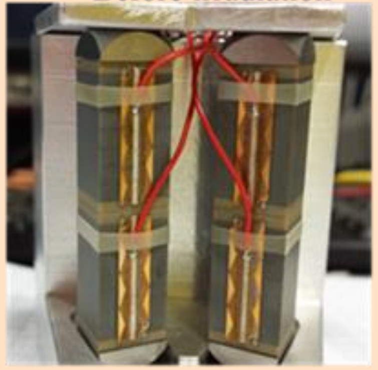


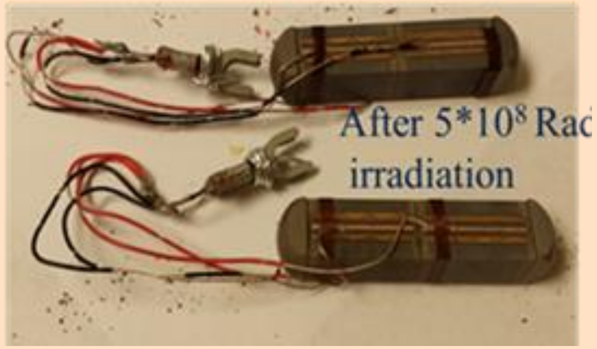


LCLS II Tuner piezo-stacks run for <u>$2.5*10^{10}$ pulses (or 125% of LCLS II expected lifetime</u>) without any degradation or overheating

Radiation Hardness Test up to $5*10^8$ Rad

Before irradiation





Piezo Stroke decreased on 10%

Piezo-actuator reliability study (Accelerated Lifetime Test ALT)

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

Power dissipated inside piezo-stack

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

- 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.

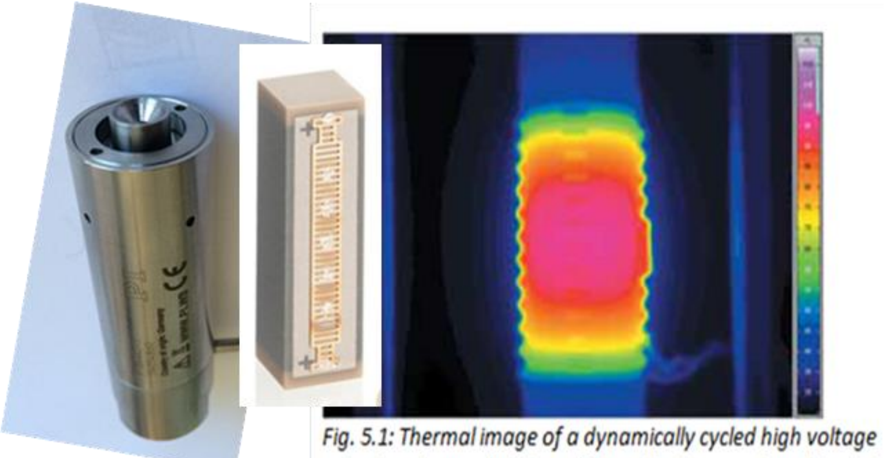
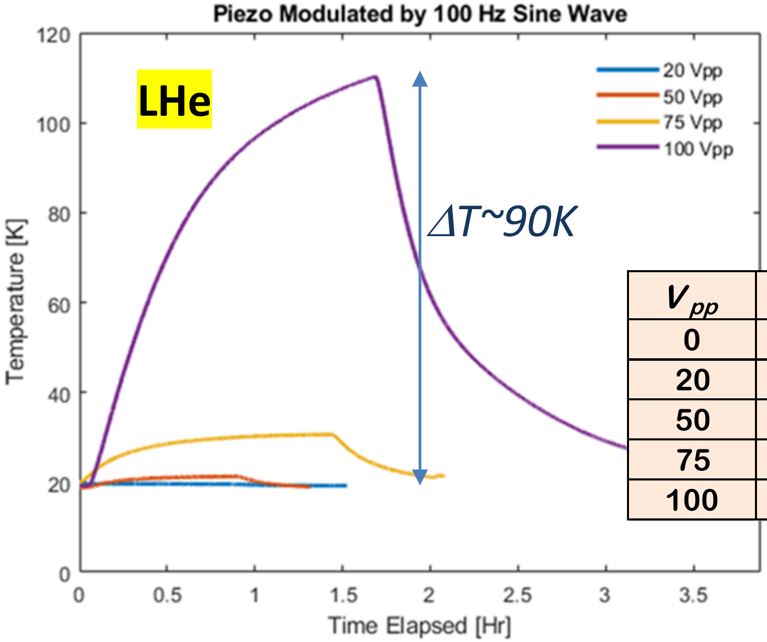
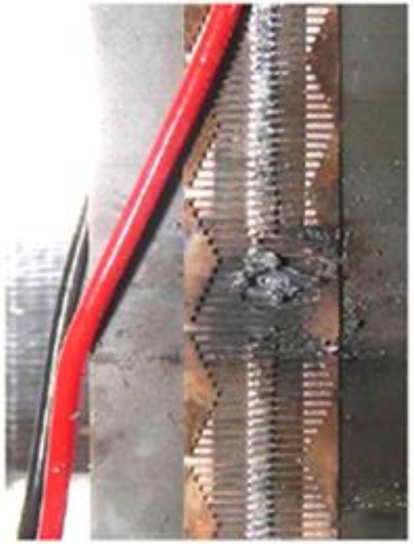


Fig. 5.1: Thermal image of a dynamically cycled high voltage actuator, clamped at its end faces. Environment: ambient air convection. Notice the cooling effect at the end-faces due to the clamping mechanics

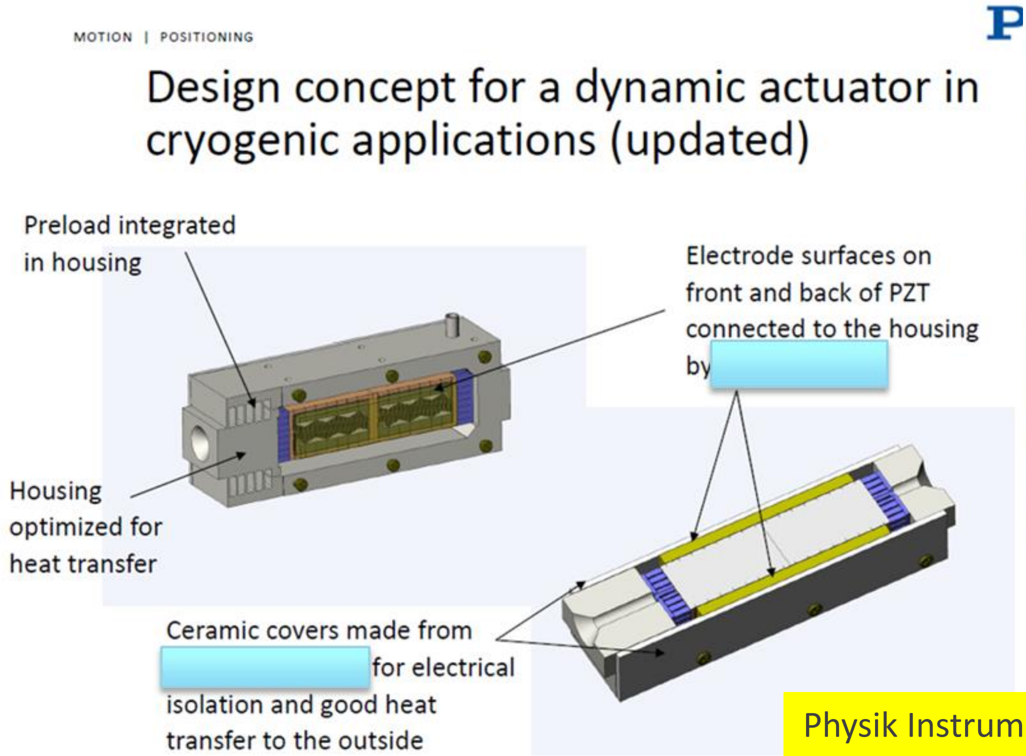
FNAL ALT Study



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



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



MOTION | POSITIONING

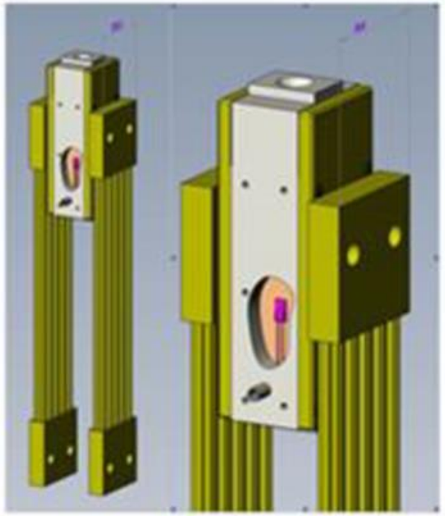
Design concept for a dynamic actuator in cryogenic applications (updated)

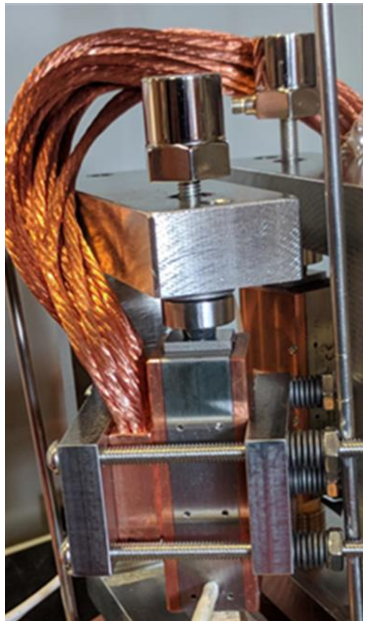
Preload integrated in housing

Electrode surfaces on front and back of PZT connected to the housing by [redacted]

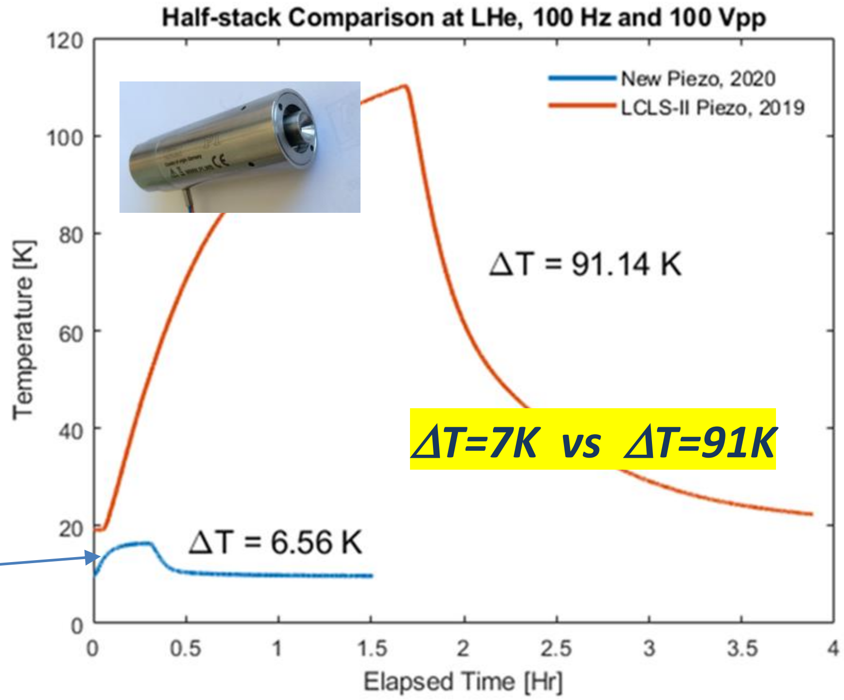
Housing optimized for heat transfer

Ceramic covers made from [redacted] for electrical isolation and good heat transfer to the outside





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

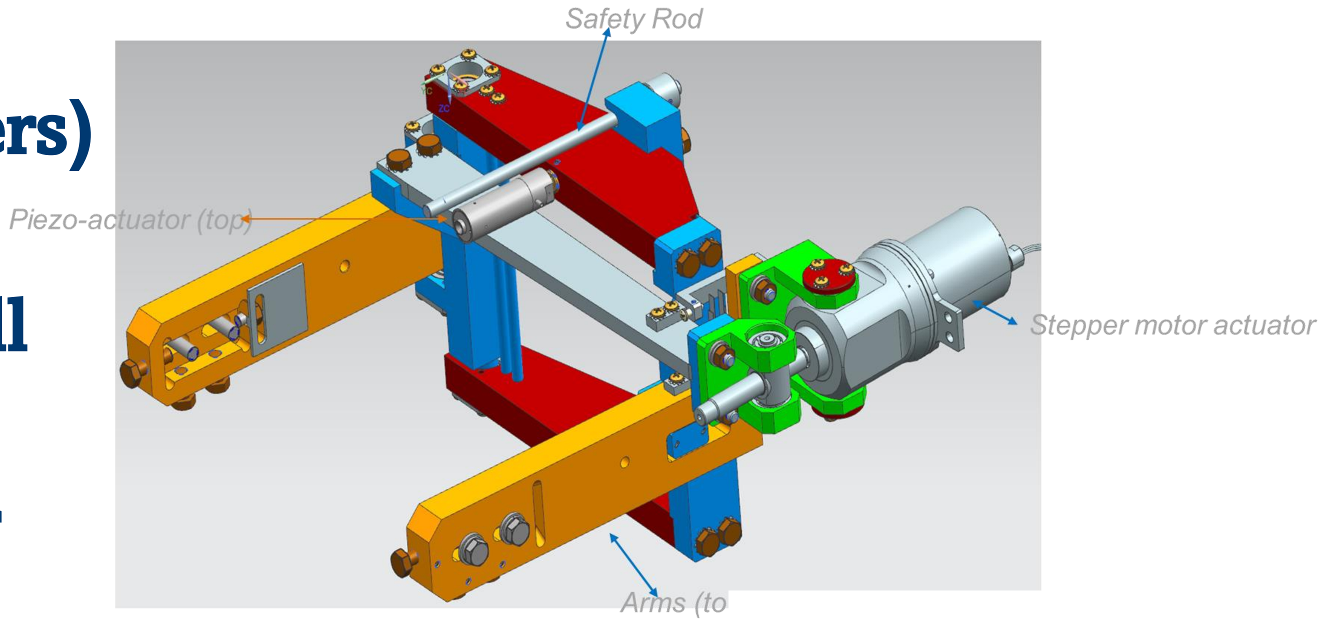


ΔT=7K vs ΔT=91K

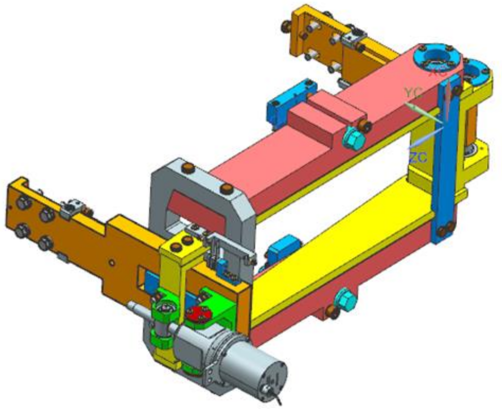
Physik Instrumente (PI)
GmbH & Co. KG
Auf der Roemerstrasse 1
76228 Karlsruhe
Germany

LCLS II TUNER (from prototype to many SRF LINACs)

- **Built and installed for LCLS II LINAC (in operation ~320 Tuners)**
- **Built and cold tested ~ 100+ Tuners for LCLS II HE (total will be 200 Tuners)**
- **Approved as baseline Tuner for ILC (KEK)**



- **Copied (without any modifications) for China SRF LINAC (future Light Source)**
- **Desing of LCLS II tuner modified to fit for 650MHz cavities for PIP II LINAC (& 644MHz FRIB upgrade)**

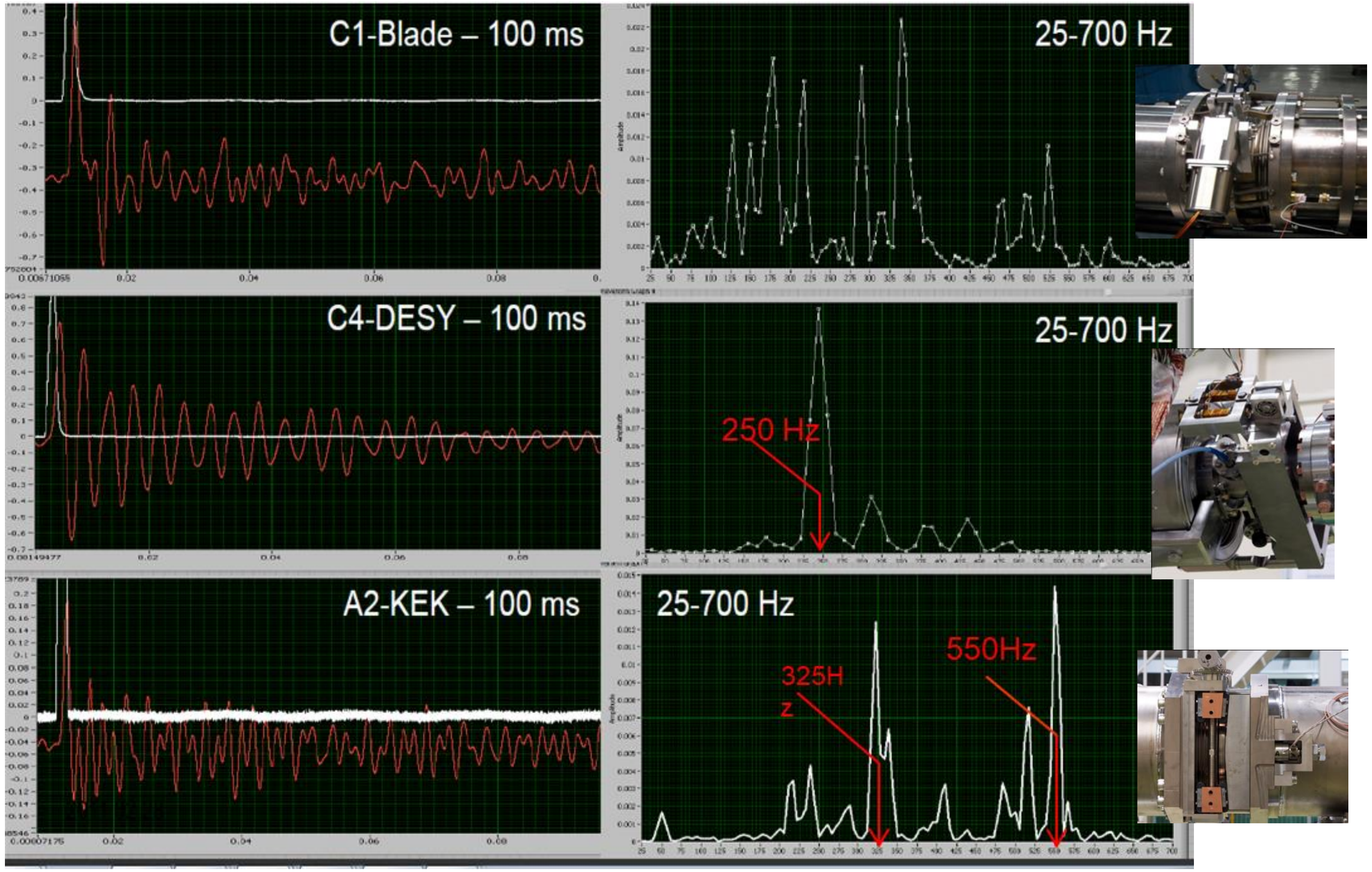


Control Algorithms to compensate Lorentz Force Detuning and Microphonics

Dynamic LFD (for operation at RF-pulse mode) … XFEL/ILC/SNS/ESS

- Short RF-pulses → “strong dynamic Lorentz forces” will lead for mechanical vibration of the cavity (cavity will respond vibrating with main mechanical resonance frequency of cavity/tuner system)…

(like a hitting with hammer into drum)

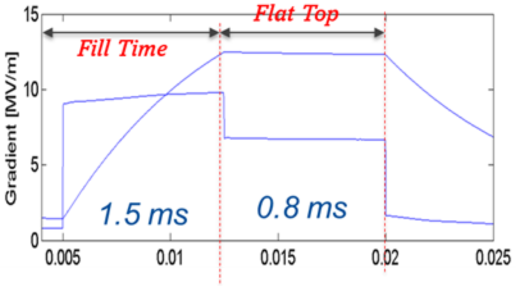


Time

Frequency

Cavities powered with RF (in CW-mode) and short pulse applied to piezo (white pulse) …Red line - cavity detuning responses

RF-Pulse



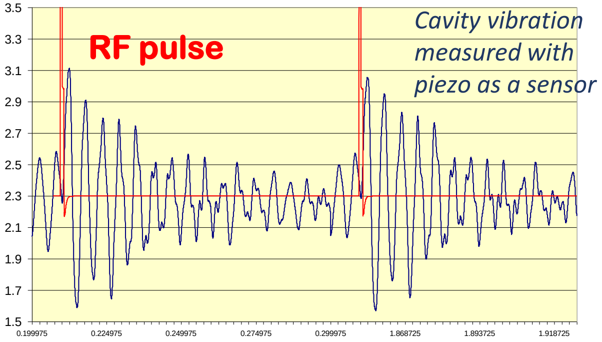
piezo_cavity_4.wav

piezo_cavity_7.wav

zo_cavity_5.wav

piezo_cavity_6.wav

Cav#4 under RF power
Cav#5,6,7 RF is OFF
(mech. Cross talk between cavities



SRF cavity detuning (RF-pulse mode)/ require considerable excess RF power

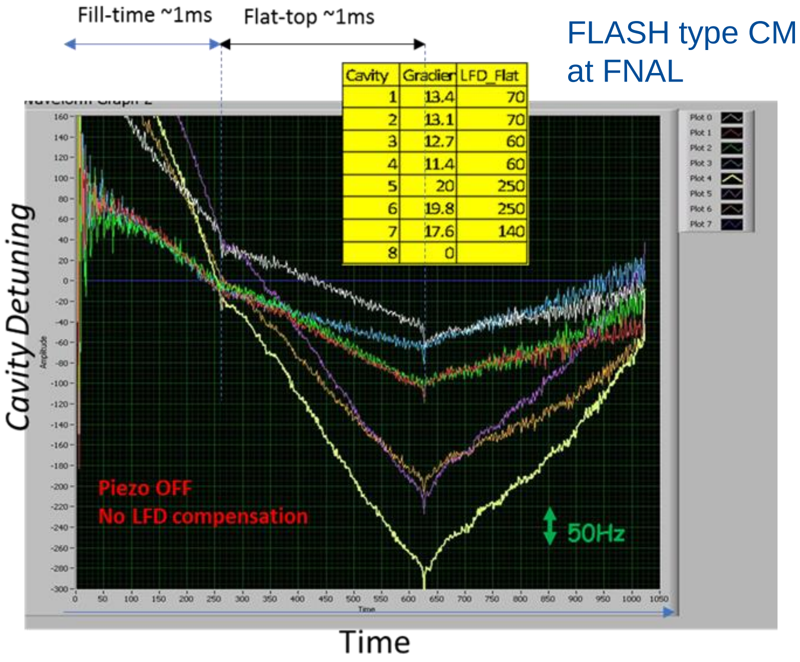
$$\Delta f_{LFD} = - K_{LFD} * E_{ACC}^{2}$$

As results of LF cavity will be detuned when “flat top” – time when cavity must accelerate beam…

To keep cavity at the resonance fast /piezo tuner must compensate/mitigate vibration during RF pulse (or deliver excessive amount of RF power). If LFD compensation will not work RF-plant must be built with larger than required (expensive) power … reflected power will be waisted- used to warm water…)

$$\frac{\Delta P}{P_0} = 0.25\left[\frac{K}{f_{1/2}}\right]^2 E_{acc}^4$$

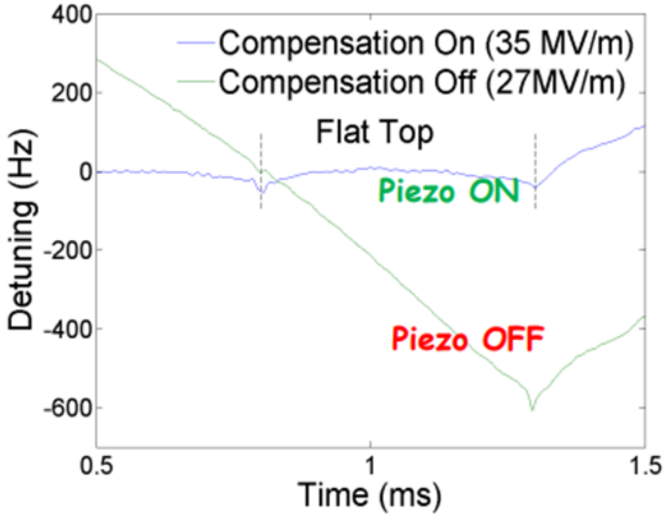
Peak power increases with the ***fourth*** *power of accelerating gradient*



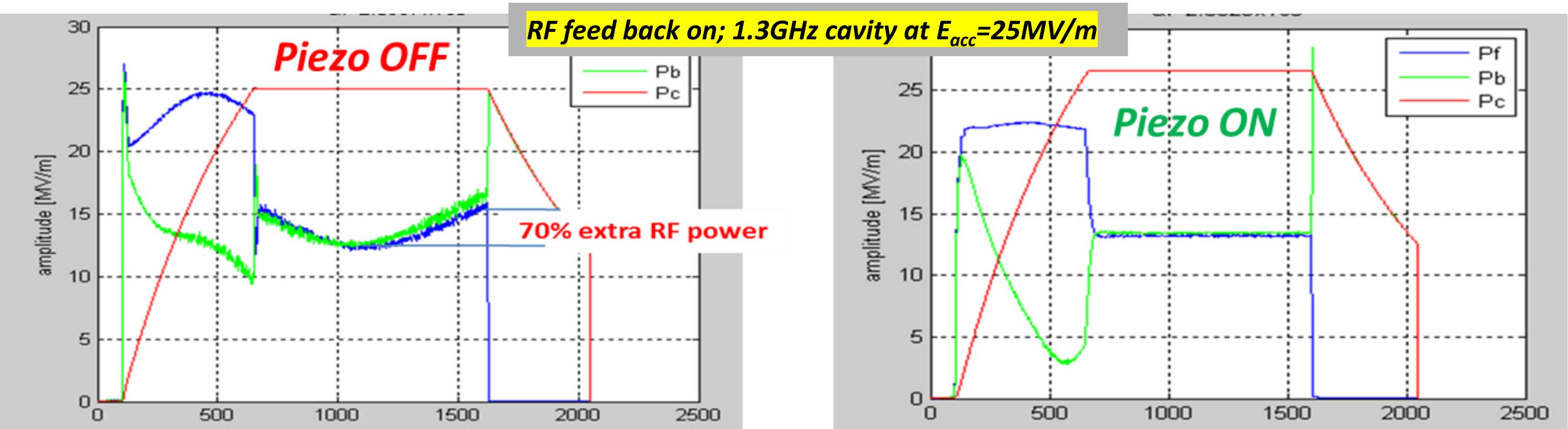
Cavity	Gradien	LFD_Flat
1	13.4	70
2	13.1	70
3	12.7	60
4	11.4	60
5	20	250
6	19.8	250
7	17.6	140
8	0	

FLASH type CM at FNAL

1.3GHz 9-cell cavity

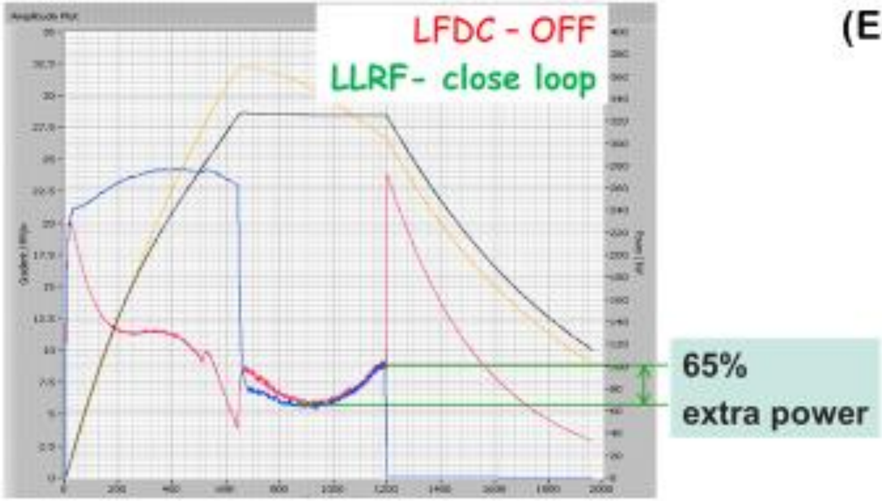


RF feed back on; 1.3GHz cavity at E_{acc}=25MV/m



LFD required to keep RF power at minimum and decrease impact on the LLRF system operations

RF waveform:
Forward,
Probe,
Reflected



RF Power for 1.3GHz 9-cell (TESLA) cavity
(Eacc=23MV/m) ΔF_{LFD}=450Hz

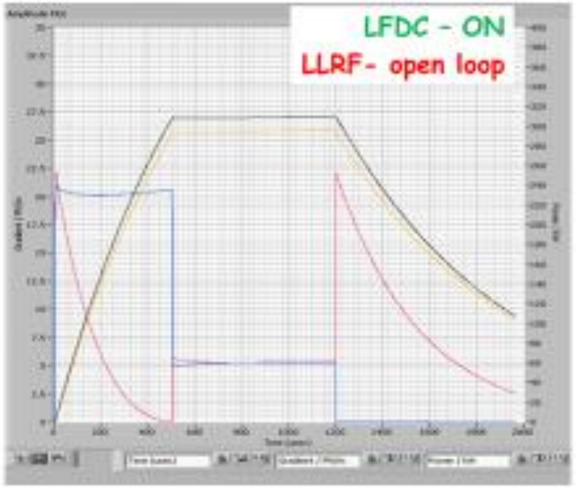
$$\frac{\Delta P}{P_0} = 0.25\left(\frac{\Delta f}{f_{1/2}}\right)^2$$

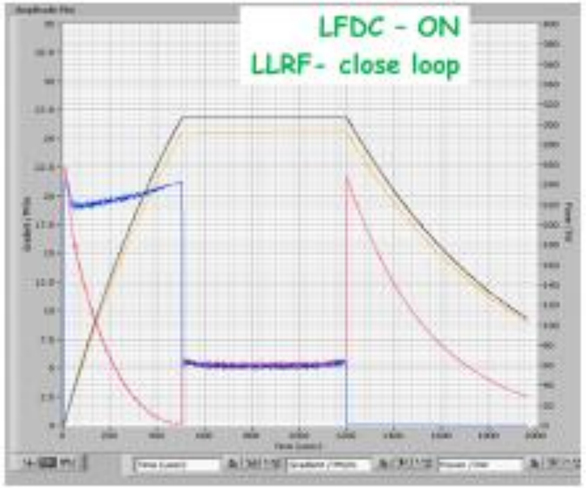
Δf = cavity detuning (Hz)

$f_{1/2}$ = cavity half bandwidth

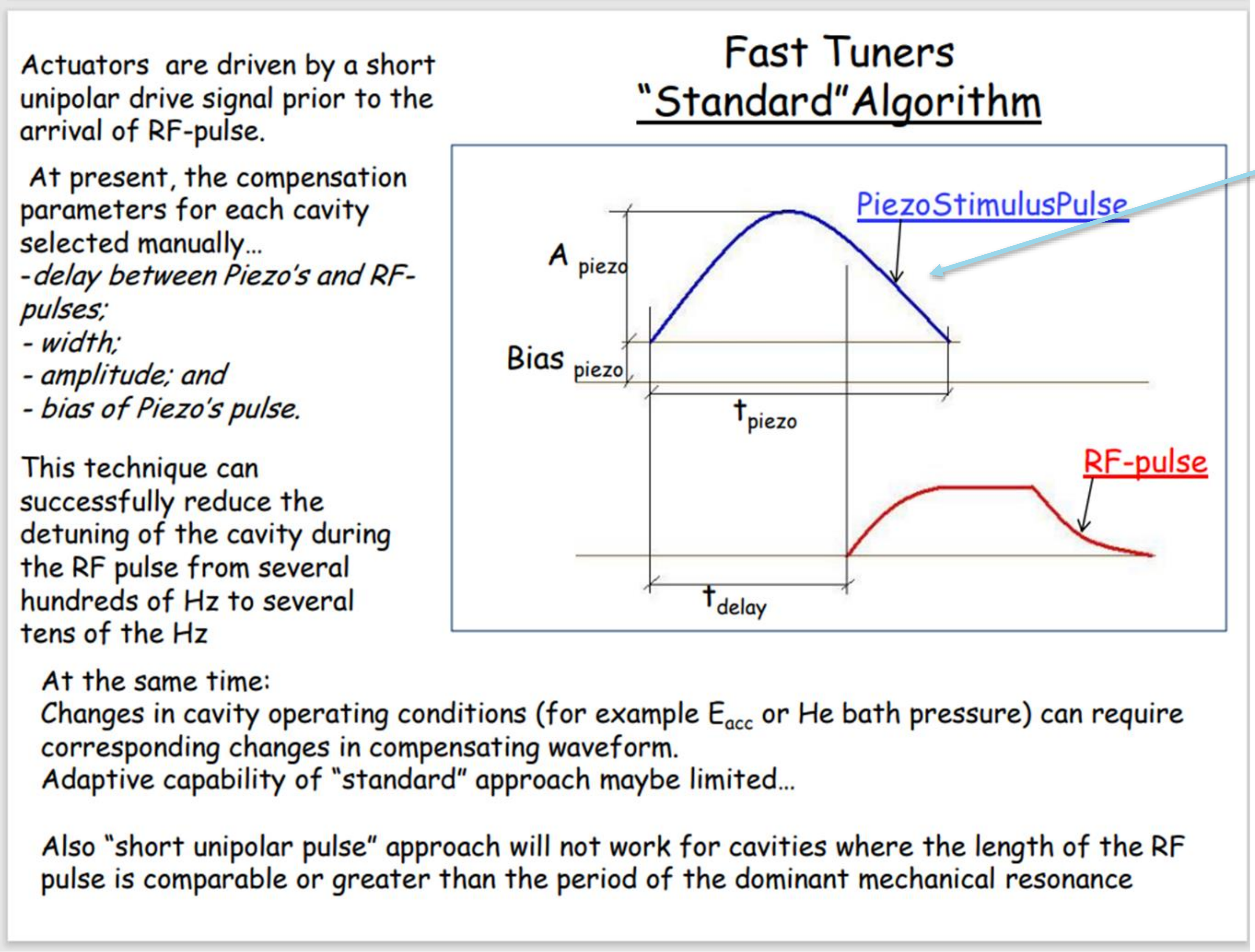
$$\frac{\Delta P}{P_0} = 0.25\left[\frac{K}{f_{1/2}}\right]^2 E_{acc}^4$$

Peak power increases with the fourth power of accelerating gradient





Compensation of the LFD (in RF-pulse mode) Feed-Forward algoritm



Fast Tuners
“Standard”Algorithm

Actuators are driven by a short unipolar drive signal prior to the arrival of RF-pulse.

At present, the compensation parameters for each cavity selected manually…

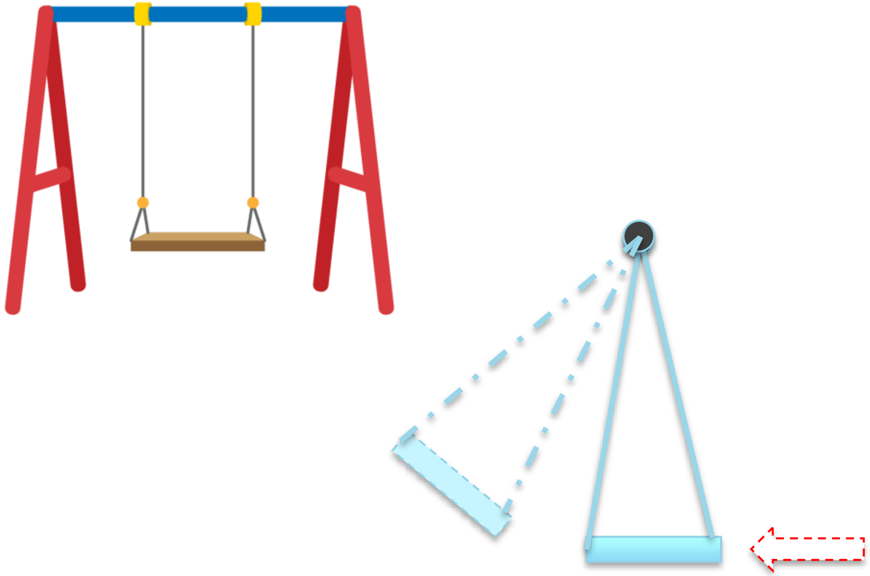
- *delay between Piezo's and RF-pulses;*
- *width;*
- *amplitude; and*
- *bias of Piezo's pulse.*

This technique can successfully reduce the detuning of the cavity during the RF pulse from several hundreds of Hz to several tens of the Hz

At the same time:
Changes in cavity operating conditions (for example E_{acc} or He bath pressure) can require corresponding changes in compensating waveform.
Adaptive capability of “standard” approach maybe limited…

Also “short unipolar pulse” approach will not work for cavities where the length of the RF pulse is comparable or greater than the period of the dominant mechanical resonance

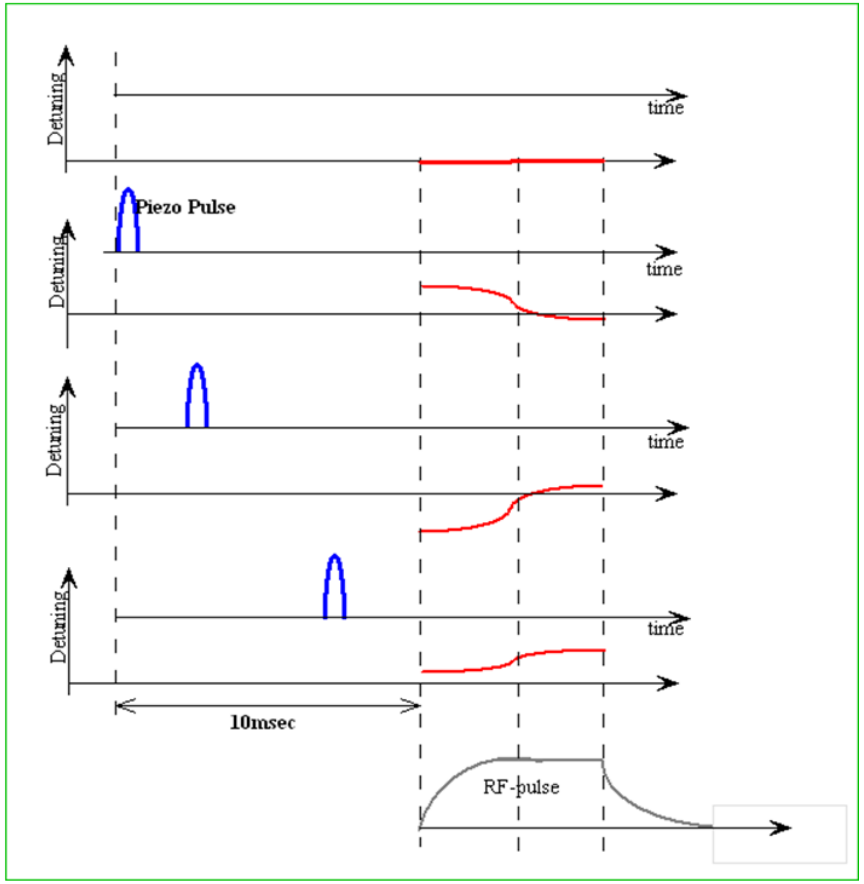
Sinewave (1/2 period) with frequency closed to the frequency of main mechanical resonance cavity/tuner system.
Disadvantage of algorithm:
- manual selection of Amplitude & Delay (advance)
- adjustment (manual) required vs Eacc & during time of operation



Adaptive Least Square LFD compensation algorithm (author Warren Schappert)

The response of the cavity frequency to the piezo impulse (TF) can be easily measured when cavity operated in CW-mode.
Since it is often not convenient to connect a pulsed cavity to CW source, we developed alternative technique to measure this response (TF) when cavity operated in RF-pulse mode.

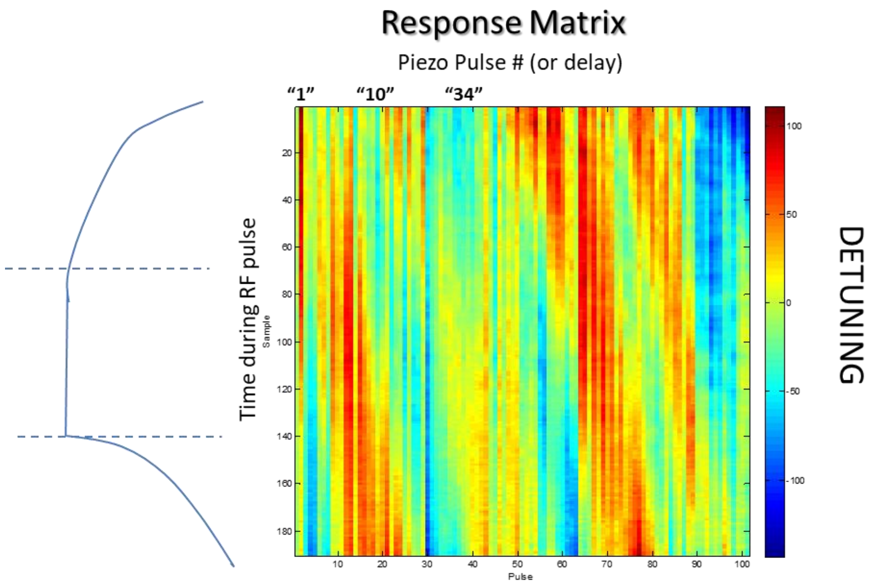
Piezo/cavity excited be sequence of small (several volts) narrow (1-2ms) pulses at various delay.
The forward, probe and reflected RF waveform recorded at each delay and used to calculate detuning.
[Response Matrix]



Details of Adaptive LS LFD Algorithm at :
"W. Schappert, Y.Pischalnikov, "Adaptive Lorentz Force Detuning Compensation".
Fermilab Preprint –TM-2476-TD.

Adaptive Least Square LFD compensation algorithm (author Warren Schappert)

Adaptive LS LFD Algorithm

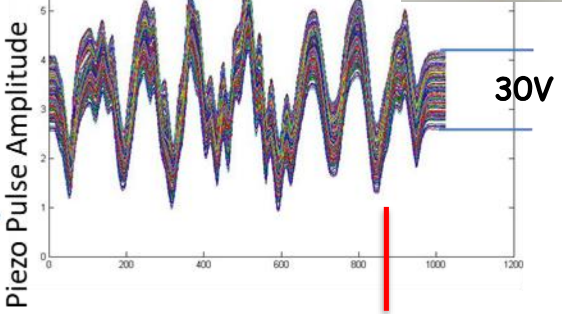


As operating conditions vary, the RF waveforms can be used to measure any residual detuning. The response matrix can then be used to calculate the incremental waveform required to cancel that residual detuning.

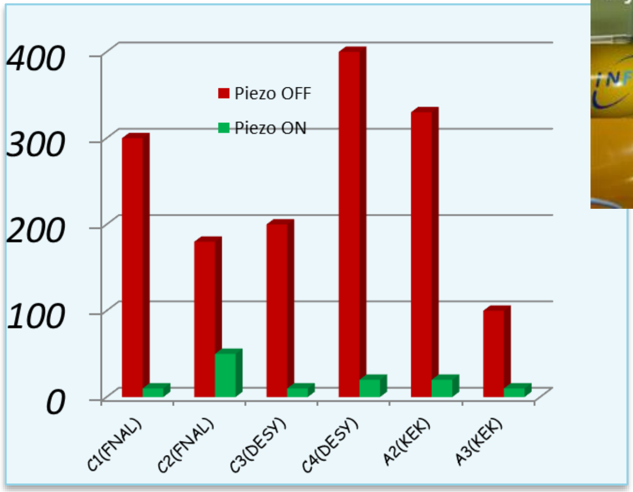
Invert the response matrix and determine combination of pulses needed to cancel out the LFD using LS
Any part of RF pulse could selected for Compensation: "Fill+FlatTop" only "FlatTop"

4,5 K LiqHe bath pressure compensation

Piezo Stimulus pulses
Eacc=34MV/m during 180sec operation
Bias changed on 30V
(dV=30V → dF=600Hz)

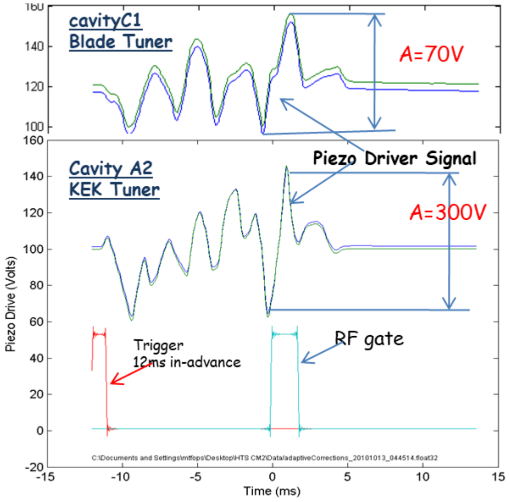


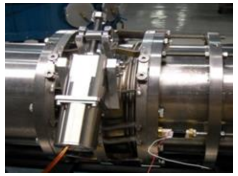
Start of RF pulse

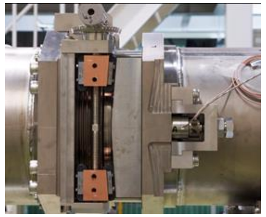


LS LFD algorithm has been used for LFD compensation on 4 different type of cavity/tuner systems…

Piezo Impulse Calculated by LS LFD algorithm

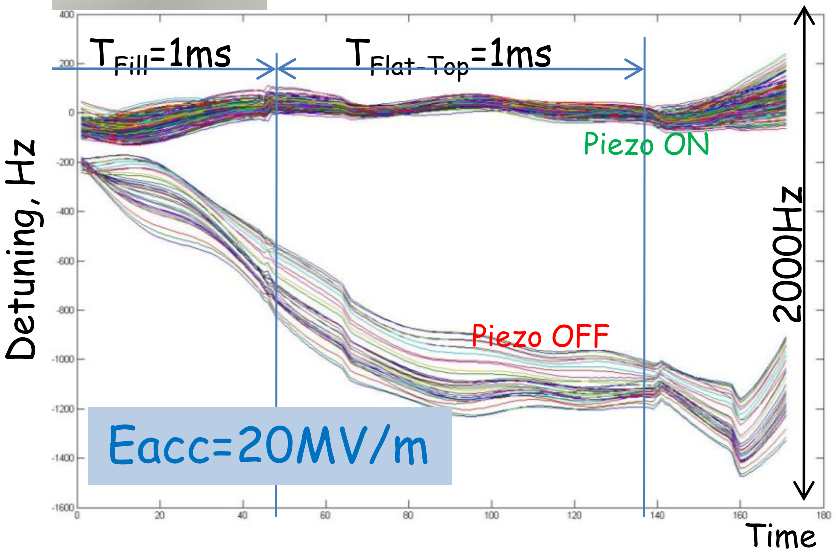


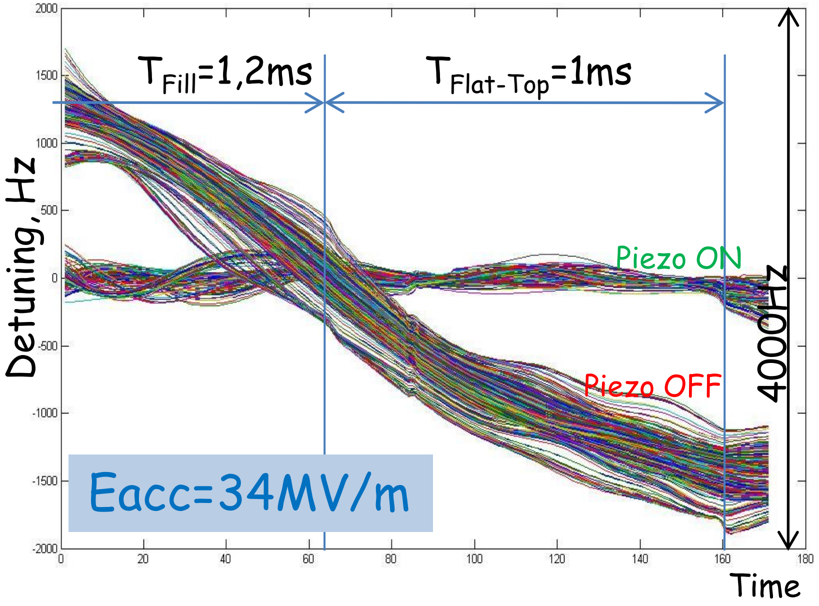




325MHz Spoke Cavity (SSR1)

(designed for HINS: 4,5K & 10MV/m ; RF-pulse 1ms-FlatTop)

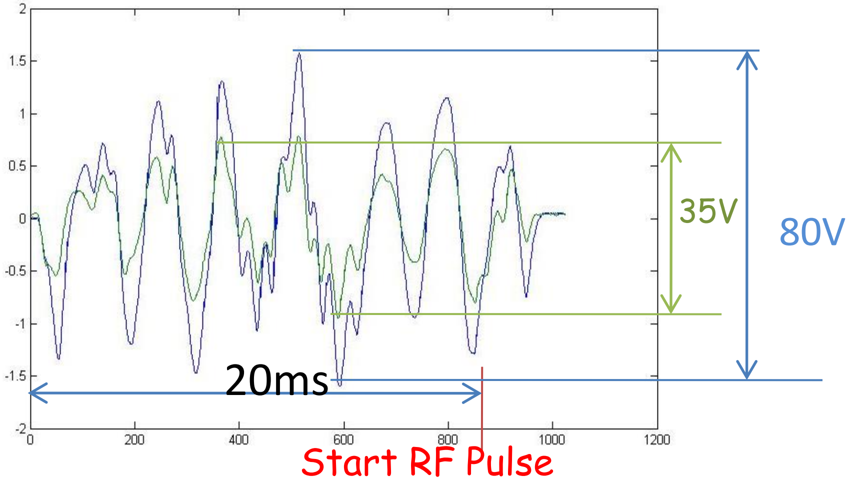




Eacc	Piezo OFF	Piezo On	(ApiezoV)
14MV/m	500Hz(1000Hz)	30Hz	35V(18%)
23MV/m	1500Hz(3500Hz)	75Hz	80V(40%)

$\Delta F=-kE_{acc}^2$ K~1,2Hz/(MV/m)^2

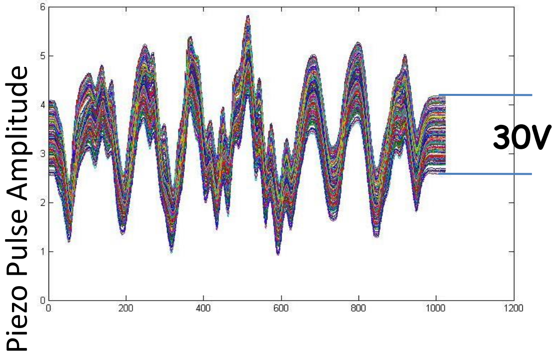
Piezo Stimulus Pulse generated by Adaptive LS LFD



X

4,5 K LiqHe bath pressure compensation

Piezo Stimulus pulses Eacc=34MV/m during 180sec operation Bias changed on 30V (dV=30V → dF=600Hz)



Microphonics … critical for narrow bandwidth SRF (operation in CW-mode)

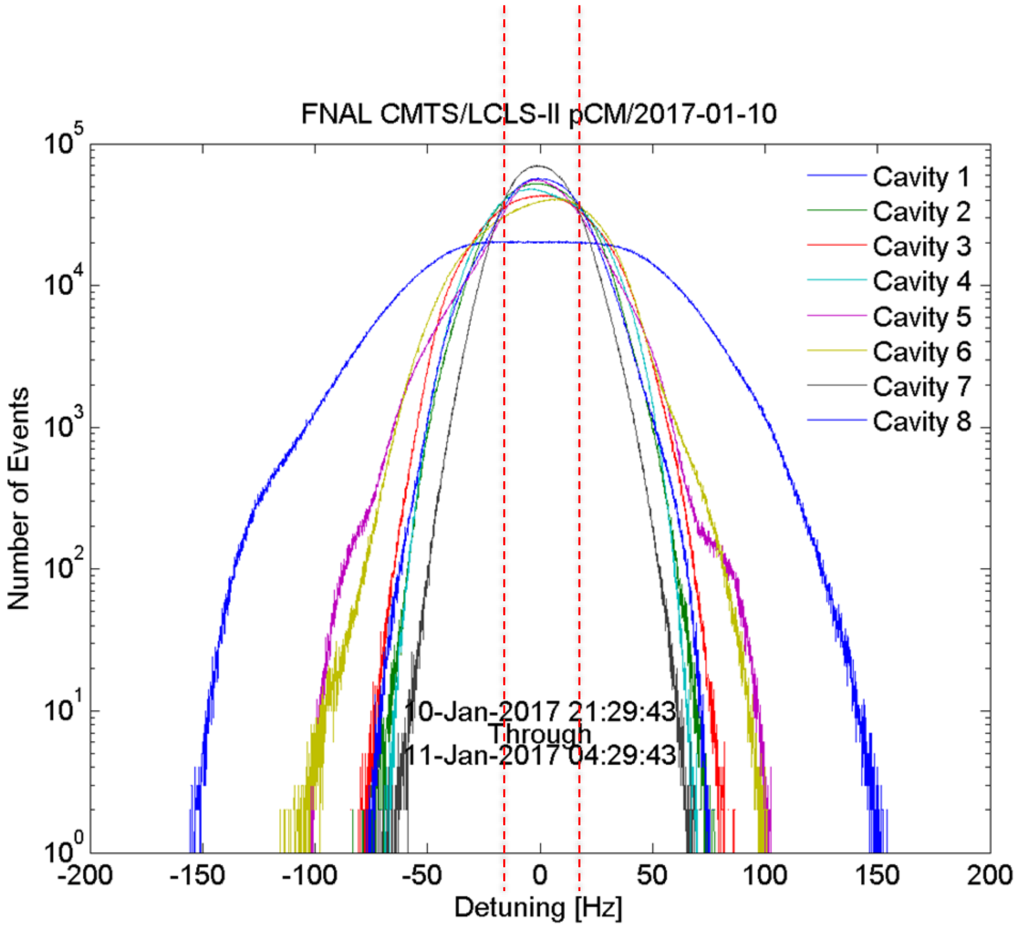
- Microphonics are mechanical vibrations from many different external sources that propagate to the cavities
  - *SRF cavities have very high sensitivity df/dL(V) (300Hz/um -1.3GHz TESLA cavity)..*

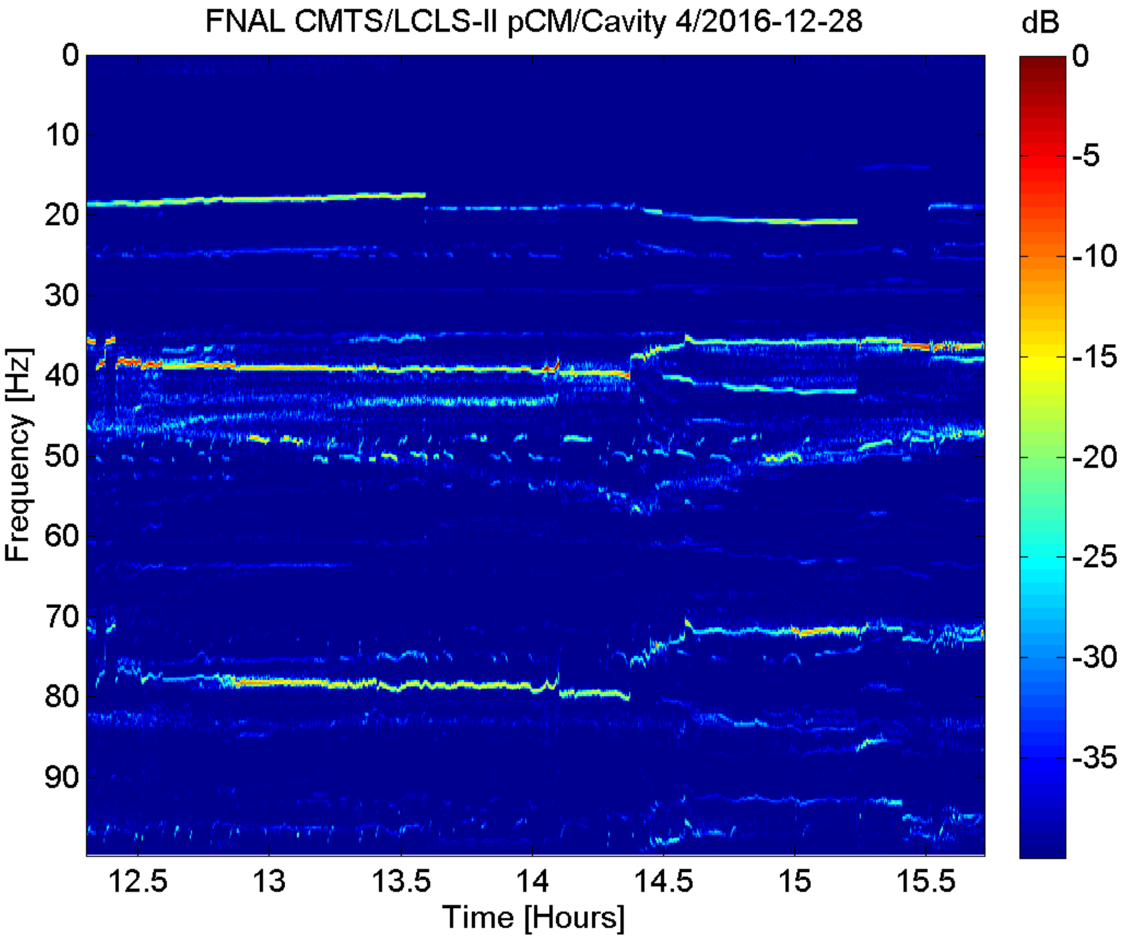
  With spec like 10Hz (p-to-p) cavity vibration ~10nm will trip LCLS II cavity

- For LCLS II project (pCM at FNAL) main sources of microphonics were cryogenics flow induced vibrations: TAO & vibrations generated by liquid He flow
- Additional sources contributed cavity vibrations are the motors& pumps that located close to cryomodules

Disclaimer: SRF LINAC (with narrow bandwidth cavities) must be designed to address as best as possible passive compensation/mitigation of the microphonics… active compensation must be last line of defense

SRF cavity operation at CW-mode ... Microphonics (LCLS II experience)





Peak detuning was up to 150Hz (with 10Hz spec)

Vibration lines shift rapidly in frequency and amplitude

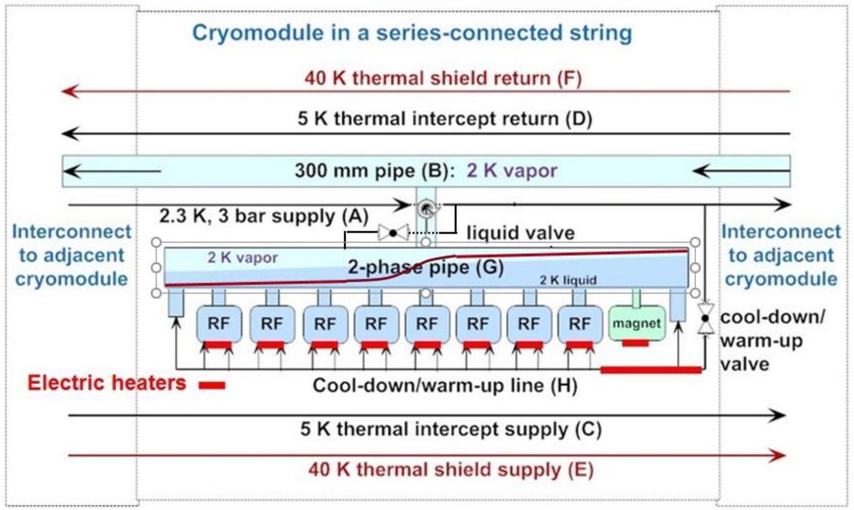
- *Not mechanical resonances*
- *Narrow-band cryogenic source(s) exciting wide-band, low frequency mechanical response*

Possible Sources microphonics that were addressed

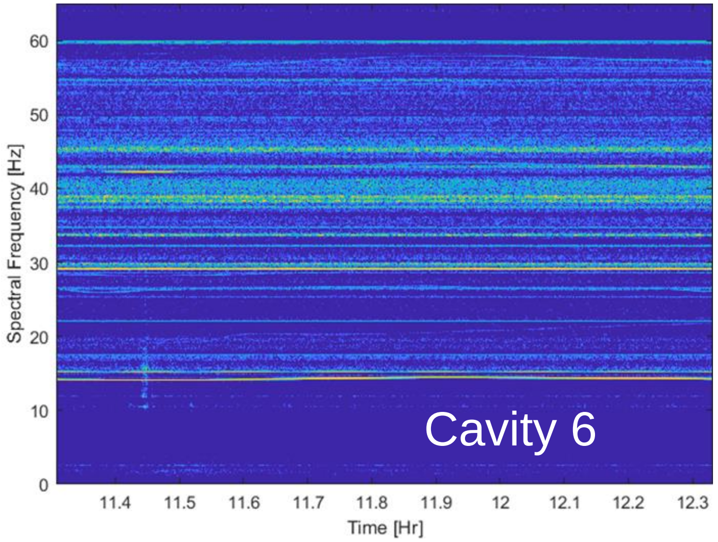
JT valve stem was modified to incorporate a graphite loaded Teflon wiper similar to valves used in the Tevatron

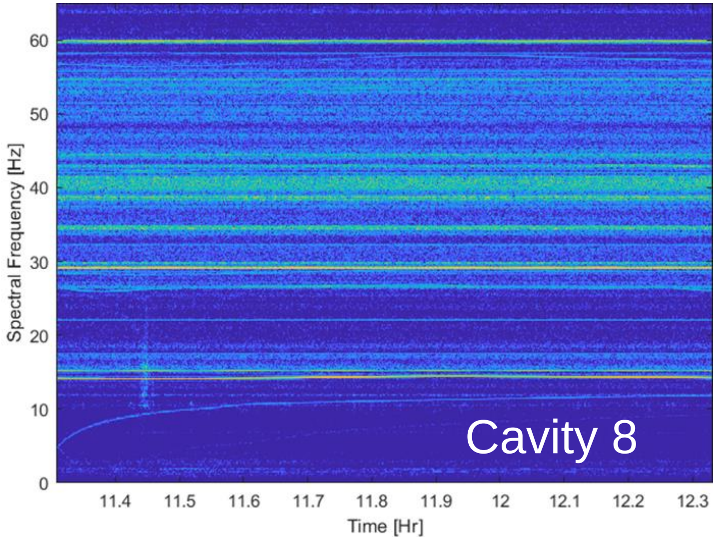
- Cryogenic
  - Liquid quality
  - High gas velocities
  - Thermo-Acoustic Oscillations
- Mechanical
  - Bellows vibration
  - Gate valve attached to Cavity 1
  - Ground motion/vibration from pumps/motors

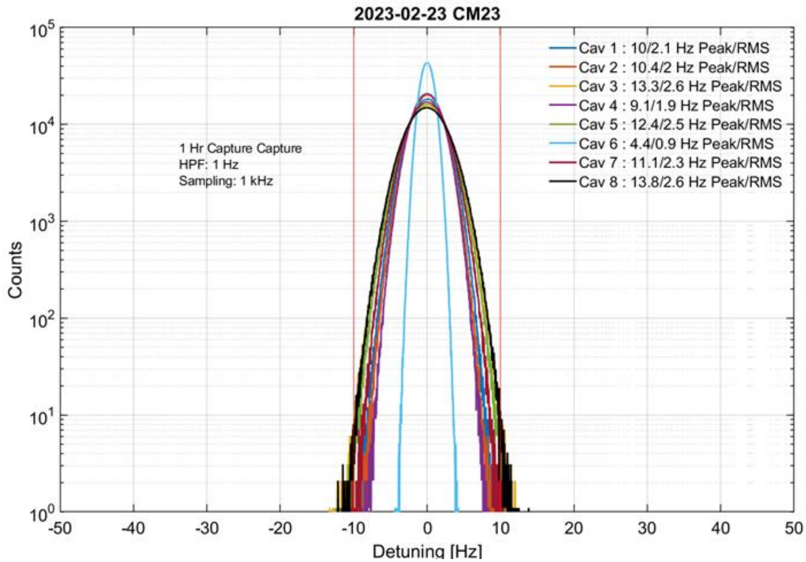
Tuner for cavity#1 modified to support Gate Valve

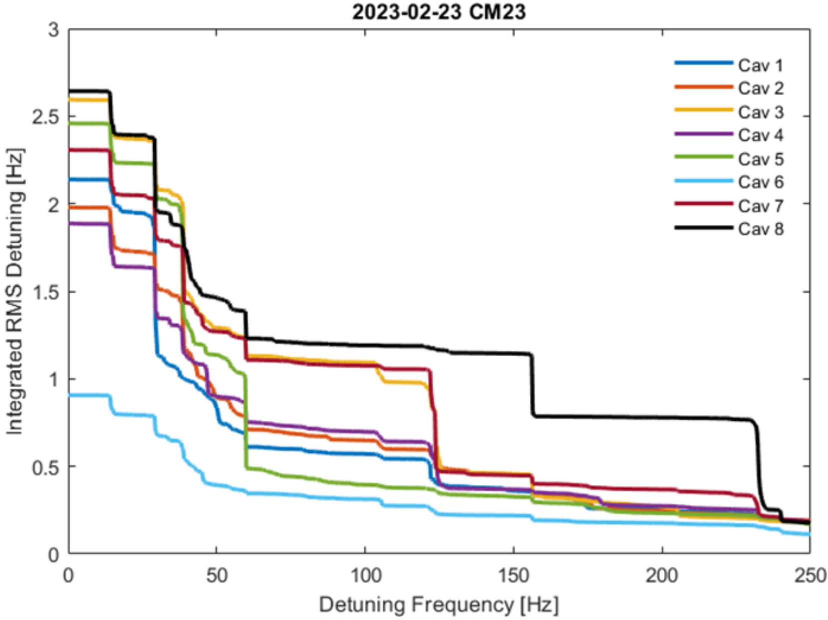


LCLS II /LCLS II HE CMs testing at FNAL (CMTF)

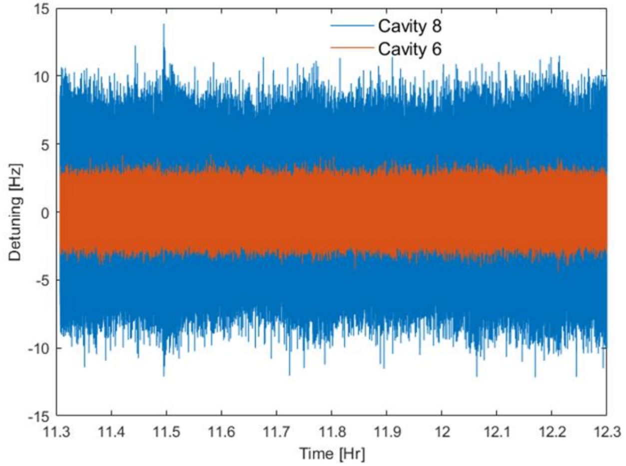








- *Cavities 4 and 6 have no events higher than 10 Hz*



- *Largest contribution from 30 Hz*
- *Cavity 8 still has contributions from 156 Hz and 230 vibrations.*

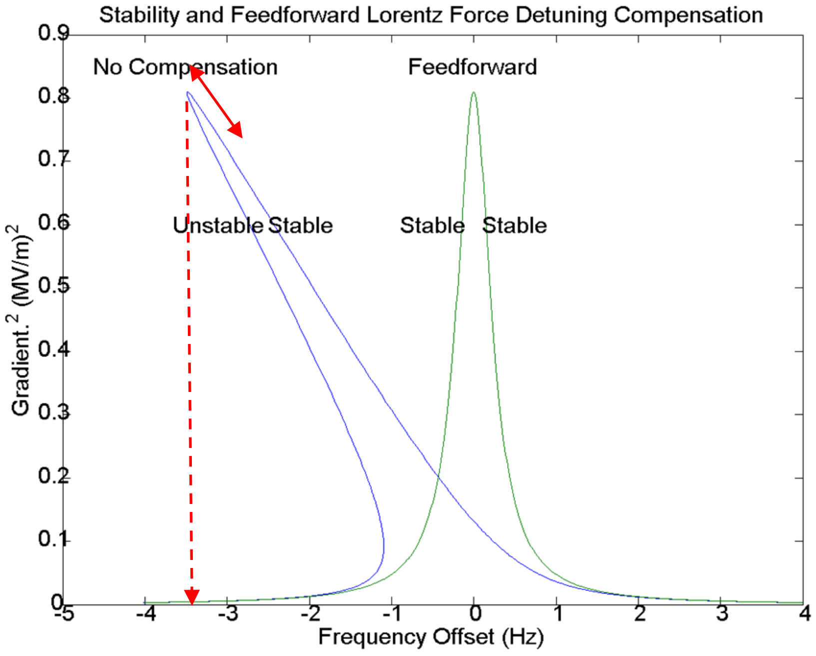
Active microphonics compensation (with piezo-tuner) (feed-back algorithms)

- Compensation of the slow microphonics (He pressure non-stability) is working well on the large machine..

- Compensation of the stable (in frequency & amplitude) microphonics with frequency of vibrations the range of 10’s of Hz has been successfully demonstrated by many team (including FNAL)

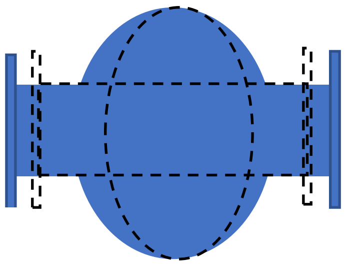
- BUT compensation of the microphonics for lines that non-stable in frequency and amplitude of vibration in real machine *(not just suppression during several minute)* is a real challenge

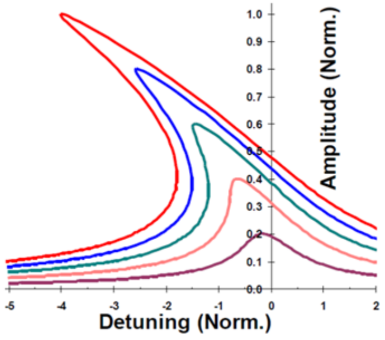
Lorentz Force in Narrow Bandwidth Cavities (CW operation)

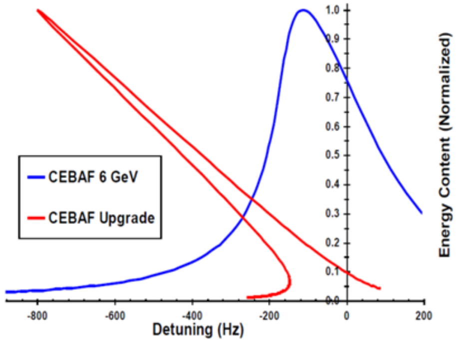


Pondermotive Instability

E_{ACC} ↑ → Frequency ↓

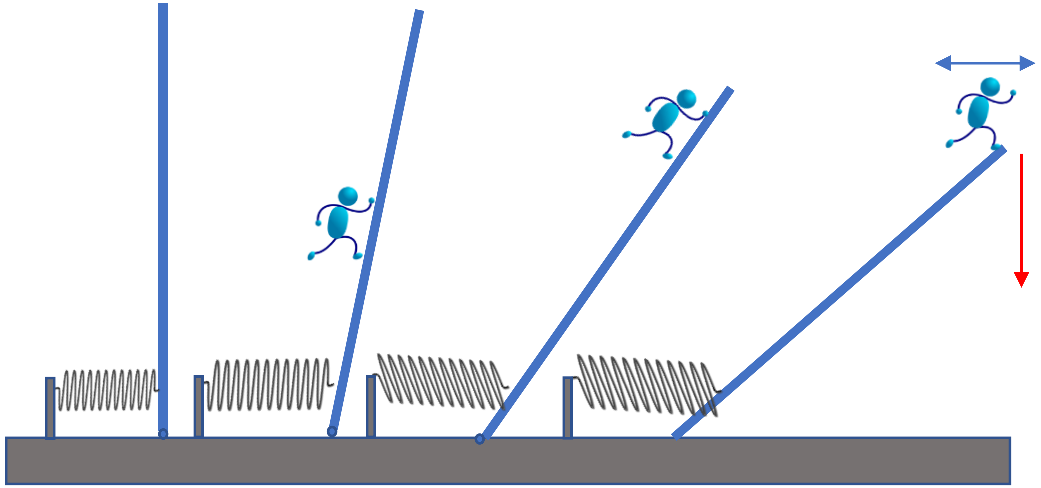






In narrow bandwidth cavities LFD can lead to instabilities

- *Resonance curve becomes a double valued function of the frequency*
  - ✓ *(stable & unstable branches)*
- *If detuning is more than several bandwidths cavities can become unstable*
- *Vibrations (microphonics) can drive cavity form stable side of resonance to unstable side*
  - ✓ *Cavity field crashes to zero*



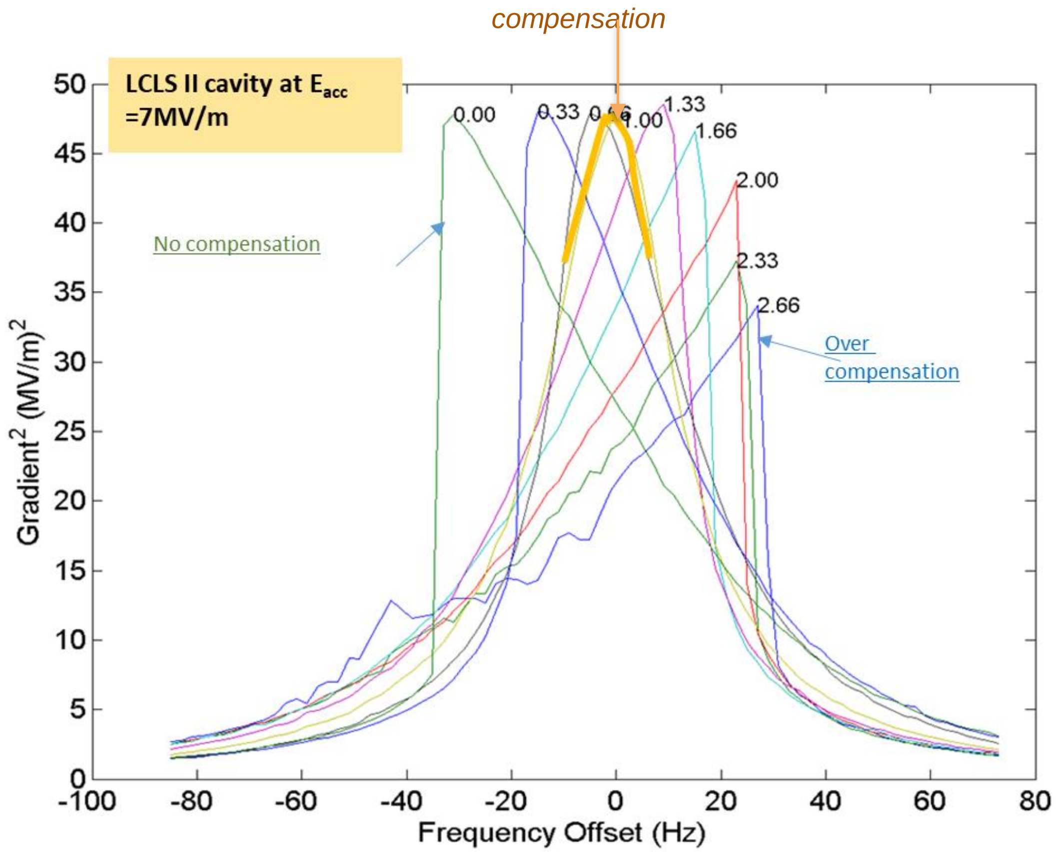
Possible to remove the instability (compensate LFD) using piezo feed-forward tied to cavity square of gradient

LCLS II cavity – 1.3GHz 9-cell elliptical cavity with $f_{1/2}$~20Hz.

This plot presented square value of the Field inside the cavity (Probe signal, Eacc) [$Eacc^2$] when Forward Power driving frequency swing near cavity resonance.

Piezo driving voltage $V=K*k1*Eacc^2$.

K=0.00-no compensation;
K=1.00-optimal compensation;
K>1.00 – over compensation.



PIP II and LCLS II Projects

- PIP II (Fermilab Proton Improvement Plan II)- pulsed linac
  - RF pulse structure (20Hz rep-rate; 15% duty factor; 0.5ms flattop)
  - 116 SRF Cavities with half bandwidths between 29 and 43Hz
    - Spoke -325MHz (SSR1&SSR2) and 5 cells elliptical -650MHz
      - Peak Detuning 20Hz
      - Lorentz forces ~17 X $f_{1/2}$

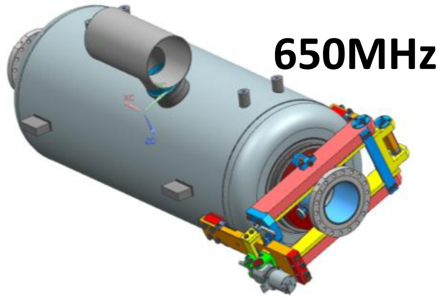
Active resonance stabilization will be required for successful operation of PIP pulsed linac.

As today… PIP II is CW LINAC

- LCLS II CW linac (4Gev)
  - ~300 Tesla style (1.3GHz) SRF cavities
    - cavities $f_{½}$ ~16Hz
    - cavity detuning requirements (microphonics) less than10Hz peak

PIP II specific requirements for SRF Cavities Resonance Control:

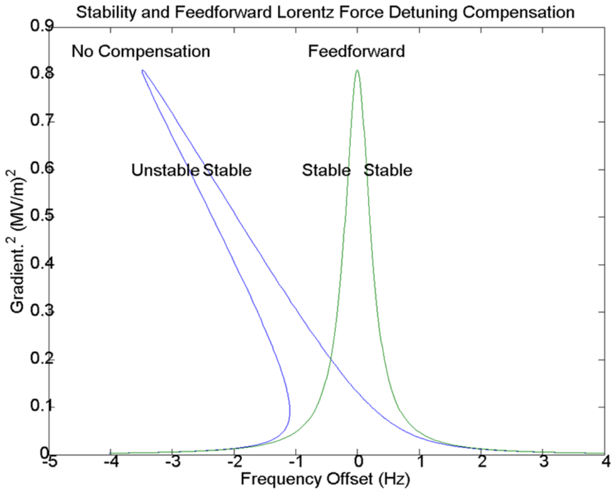
- *Low beam loading → narrow bandwidth of the cavities*
- *High accelerating gradient (~20MV/m)*
  - *→ large Lorentz Force Detuning*
  - *→ significant residual vibration/ excessive microphonics*



Resonance control of the PIP II (SSR1) cavity operated at Pulse mode

Lorentz force detunes cavity and for narrow bandwidth cavities resonance becomes a double valued function of the frequency (stable & unstable branches)

1. **Removing the instability driving piezo feed-forward with amplitude proportional to E_{acc}^2**



Large dynamic detuning of the cavity by RF-pulses (LFD)

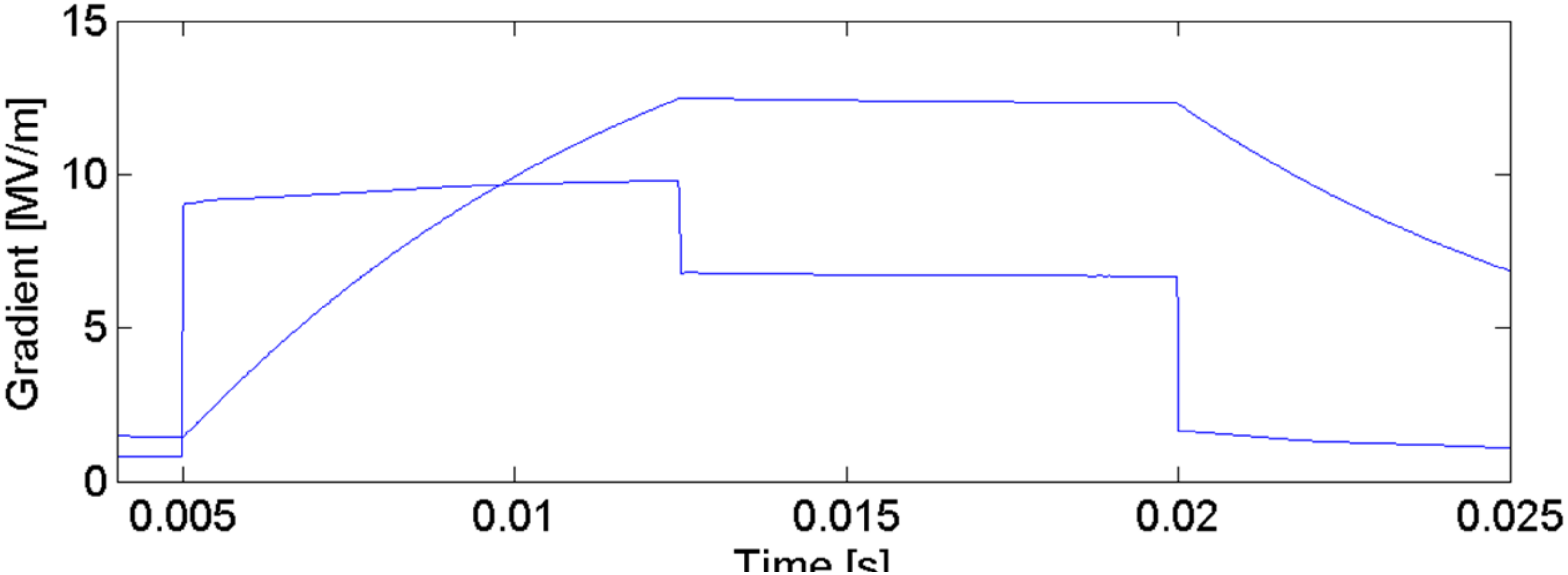
2. **Adaptive LS LFD algorithm (feed-forward)**

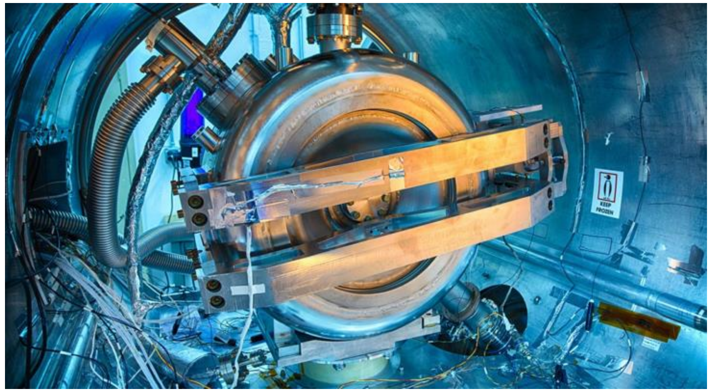
significant residual vibration/excessive microphonics

3. **Feed-back ..bank of filters targeting dominant driving terms (20Hz&200Hz)**

Resonance Control for Narrow Bandwidth PIP II Cavities

- 325 MHz
- Single Spoke Resonator
- Slow Motor Tuner
- Piezo Tuner
- 2 K operation
- 12.5 MV/m
- 20 Hz pulse structure
- 15% duty cycle
- 0.5 ms flattop
- 30 Hz Half bandwidth



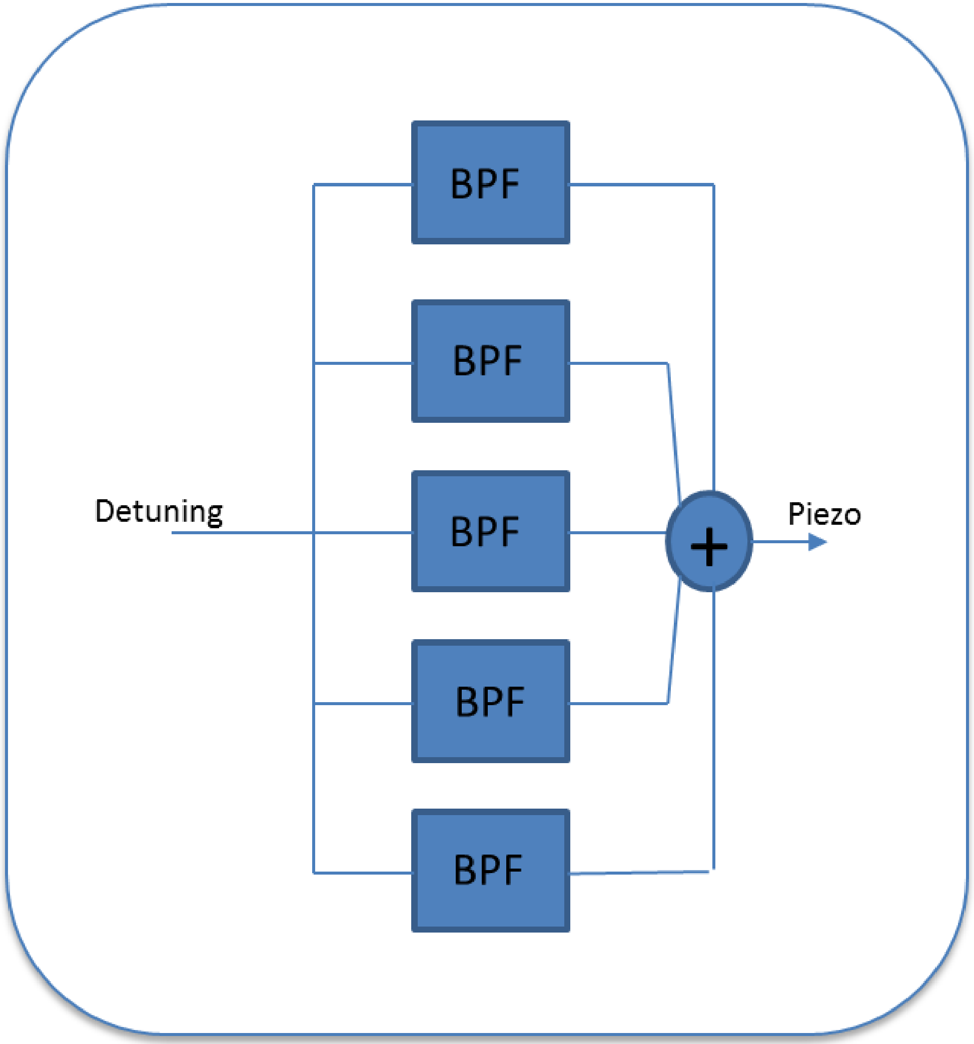


Testing was done at the Spoke Test Cryostat at Fermilab. RF was driven open loop, with no feedback on phase and amplitude except piezo for detuning.
>12.5 MV/m (spec)
25 Hz rep rate
7.5 ms fill
7.5 ms flattop
Longer flattop was done to help diagnose flattop performance.

Feedback

Non-Deterministic (Microphonics)

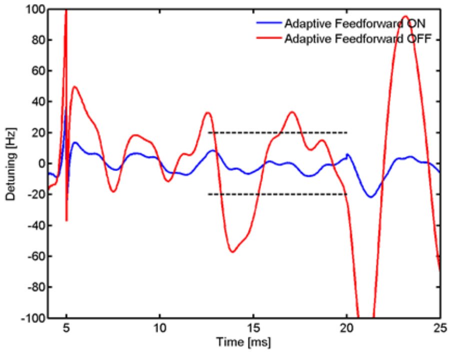
- Online detuning calculation fed to filter bank
- Frequency, decay time and gain can set for each filter in the bank
- Outputs summed and fed to piezo
- 0 Hz stabilizes cavity against pressure drift
- Dominant resonances observed at 20 and 200 Hz
- Filter parameters set manually

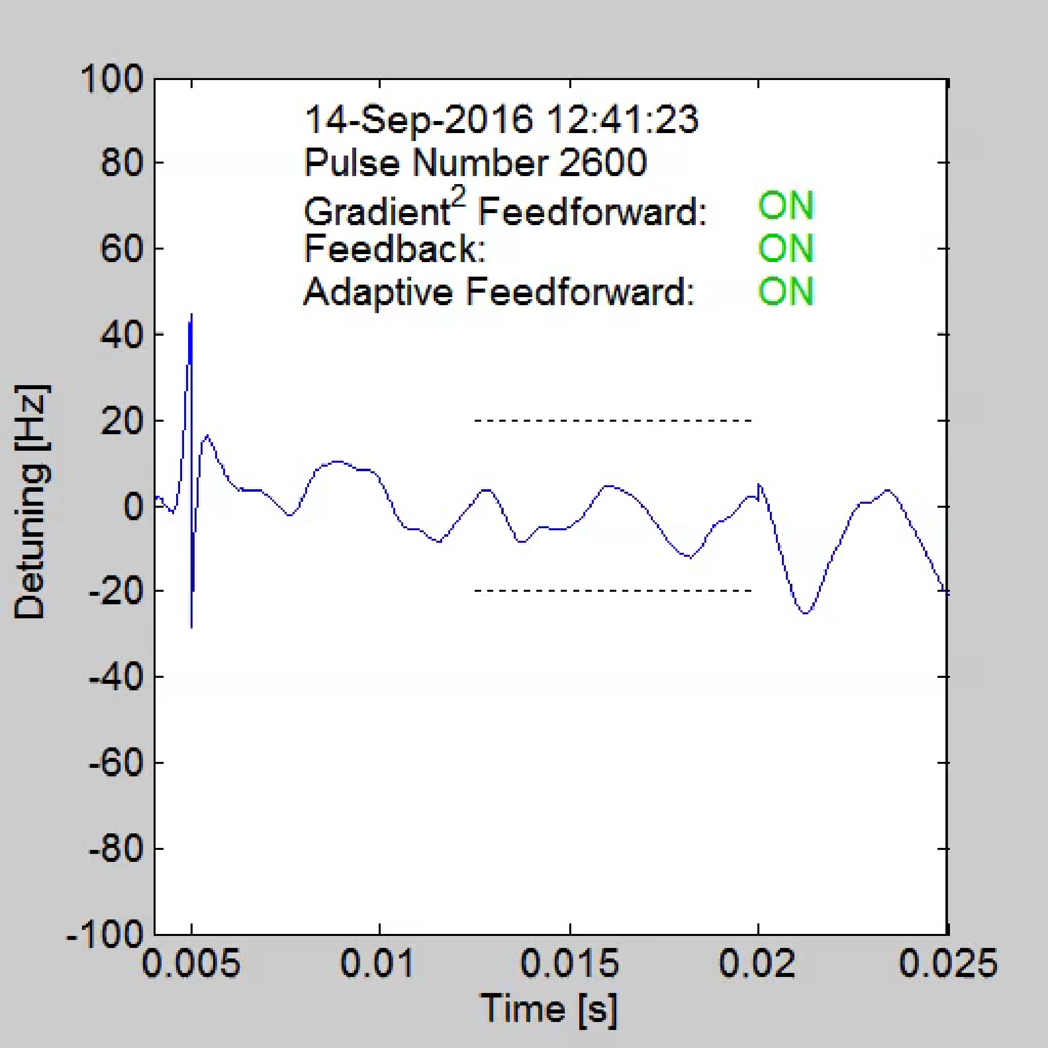


Resonance Control of the SSR1 cavity

- Cavity run with
  - ✓ Gradient Feedforward,
  - ✓ Feedback manually tuned up in CW and
  - ✓ Adaptive Feedforward

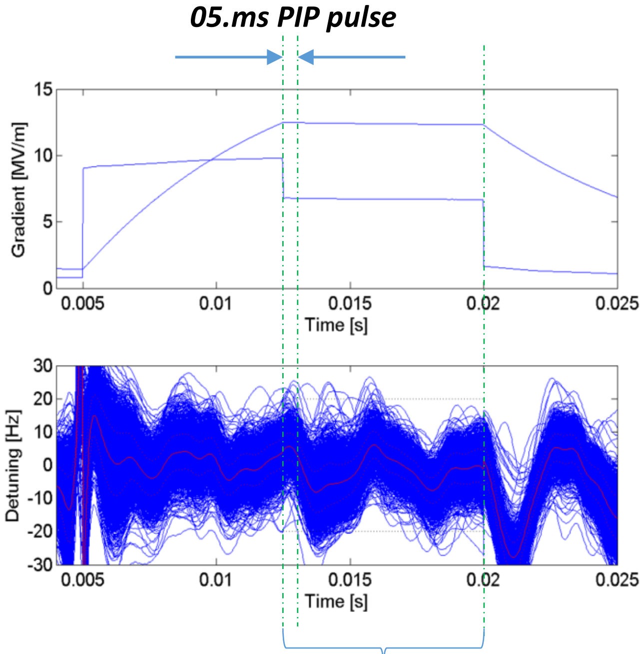
- Adaptive Feedforward turned ON and OFF (during this short -21sec run)

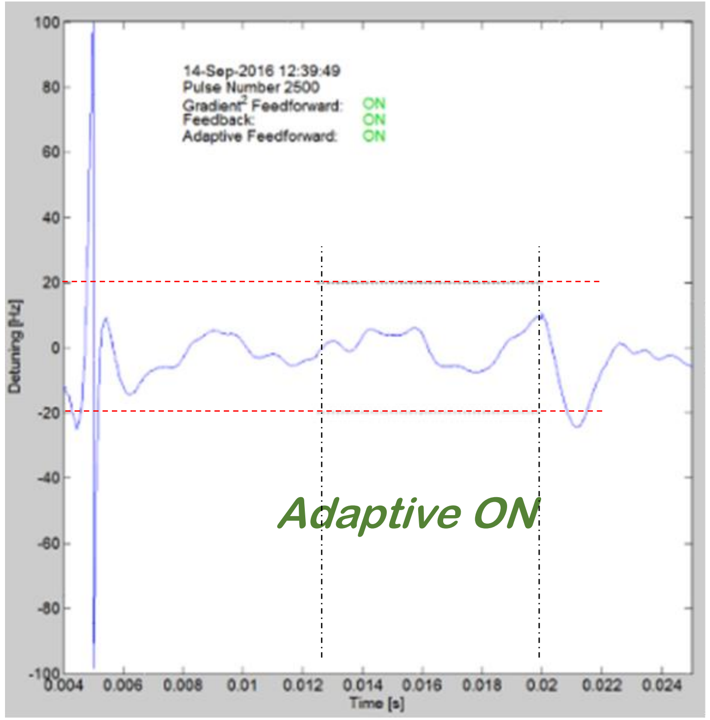


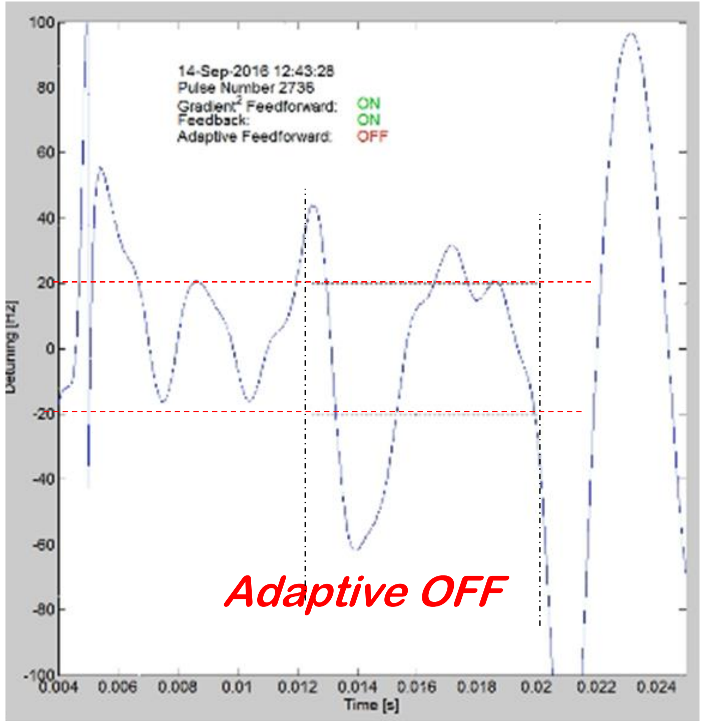


Results

- PIP-II nominal operating conditions
    - 12.5 MV/m
    - 20 Hz repetition rate
    - 15% duty cycle
    - 0.5ms flattop
- STC operating condition
    - >12.5 MV/m
    - 25 Hz repetition rate
    - 7.5 ms fill
    - 7.5 ms flattop

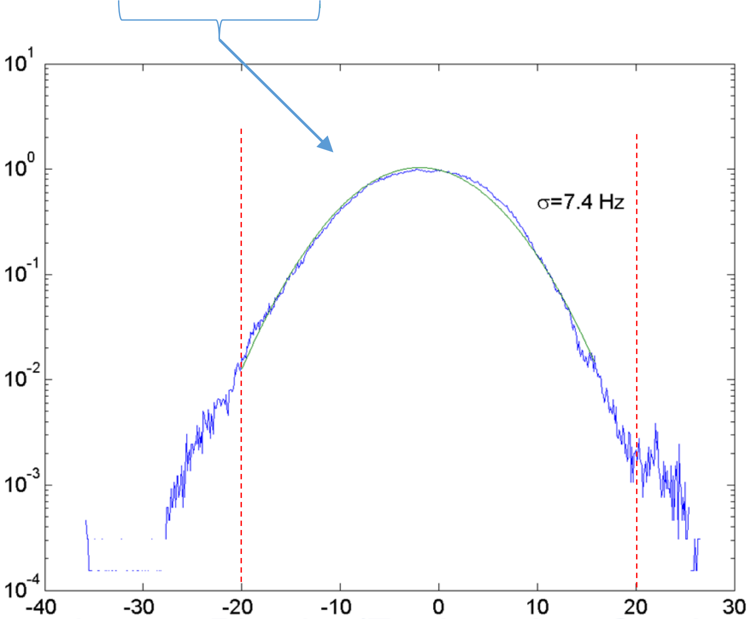






~7.4 Hz RMS detuning on the flattop.

Specification is a peak detuning of 20 Hz, so a further improvement in RMS of ~2 is needed.



Without the adaptive compensation on , the detuning was almost an order worse. Without the other two compensation methods, the cavity rapidly fell off resonance.

Significant progress has been made toward PIP-II specification of detuning.

~~***Work is in progress at Fermilab at this moment***~~

PIP II LINAC is CW machine… no any work for development of resonance control algorithms at FNAL at this moment

Summary (I)

- Combination of the expertise of physicists, mechanical, electrical, RF, control, and software engineer required to deliver “solid” SRF cavity Resonance control system
- In the SRF community Tuners often called “auxiliary” system… but no questions that non-reliable “auxiliary=tuners” will lead to significant problems:
  - When slow tuner failed cavity could not be tuned to operational frequency and in best case SRF cavity will be just 1m long beampipe (that cost several hundred thousand $). In some case it could be even bigger impact on beam dynamics of accelerators
  - If tuner broken after cool-down and tuning cavity to operational frequency failure to return cavity back to “warm position“ frequency will permanently be retuned cavity … cavity could not be recovered (non-elastic deformation range)

Summary (II)

- Failures of fast/fine tuner (and/or non-stable resonance control algorithms) also will make big impact on the SRF LINAC operation:
    - In case of RF-pulse operation failure to compensate LFD will lead to “disastrous” option to decrease operational field (accelerating gradient) of the cavity
    - For narrow bandwidth cavities with not working fast/fine tuner & with limited RF-power & “non-ideal” cryo-plant LHe pressure control there are no other solution as significantly decrease cavities' accelerating gradient…
    - Non-stable resonance control will lead to large number of the SRF cavities “trips” that will significantly complicate SRF LINAC operation and efficiency.

Summary (III)

- Despite of the efforts that SRF Resonance control community invested into the development of reliable and stable control algorithms this task is far from to be solved.
- This complex task is left for new generation of the scientist and engineers….that could be address with new (probably AI) approaches…