Resonance Control for Superconducting RF Cavities

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Budker Seminar

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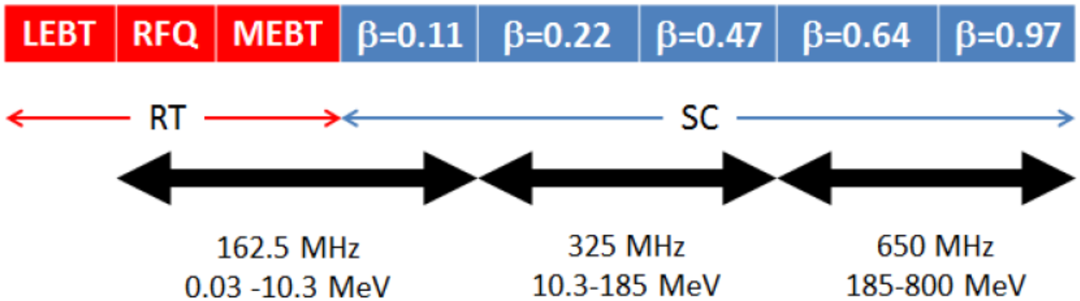
- **Status:** 5th year MSU graduate student, Physics and Astronomy Department
- **Research at Fermilab**
  - **Microphonics**
  - **Dynamic tuner/ Piezo Actuators/Reliability**
  - **Resonance Control Algorithm**
  - **DOE SCGSR**
    - **Date:** 10/30/2017-4/30/2018
  - **PIP-II**
    - **Date:** 5/1/2018-Present
  - **Joint University-Fermilab Doctoral Program in Accelerator Physics and Technology**
    - **Date:** 09/1/2018-Present

Outline

- Introduction
- Microphonics
  - Effects on detuning
  - Passive resonance control

Fast/Slow Tuner
  - Mode of operation
  - Requirements for cavity
  - Piezo Actuator/Reliability
- Resonance Control Algorithm
  - System Characterization

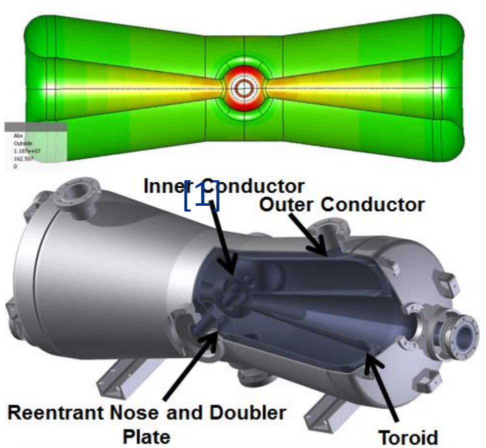
Superconducting RF Cavities

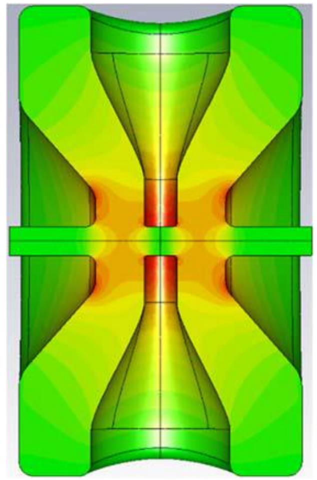


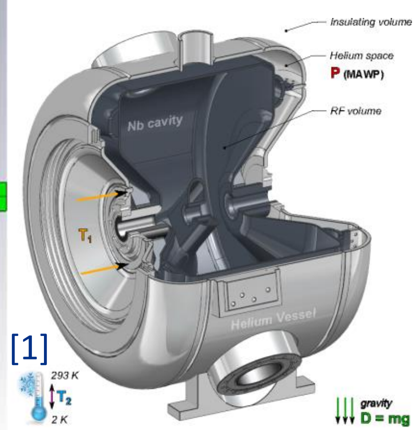
Multicell Elliptical Cavity
$f_o = 650\ MHz$
Low Beta (LB) $\beta_o = 0.64$
Low Beta (HB) $\beta_o = 0.97$

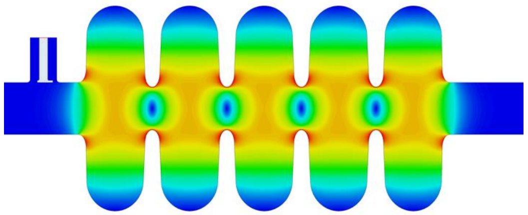
Single Spoke Resonator (SSR)
$f_o = 325\ MHz$
$SSR1\ \beta_o = 0.22$
$SSR2\ \beta_o = 0.47$

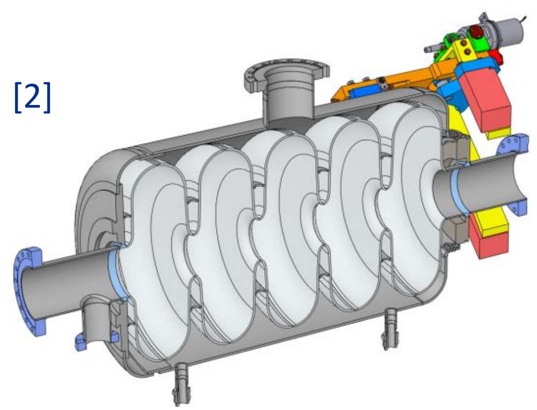
Half-wave Resonator
$\mathrm{f_o} = 162.5\ \mathrm{MHz}$
$\beta_o = 0.11$











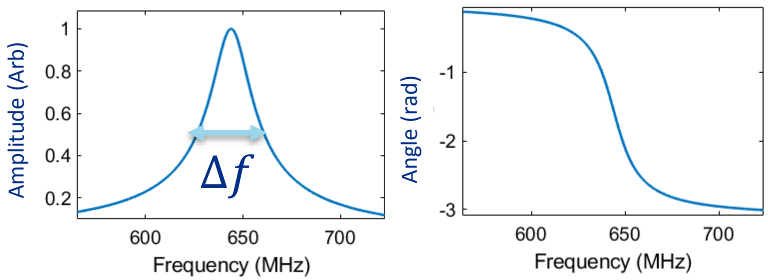
Superconducting RF Cavities

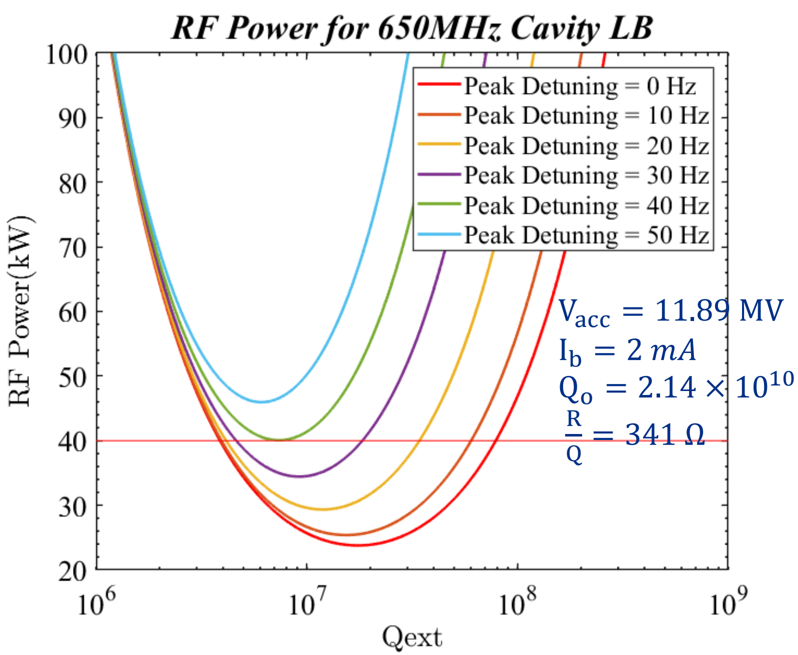
- Cavities are manufactured from thin sheets of Nb for efficient cooling to superconducting temperatures
- The thin walls make the cavities susceptible to deformation which in turn change the frequency

$$\frac{f - f_o}{f_o} = \frac{\int_{\delta V} \left(\mu_o |\vec{H}|^2 - \epsilon_o |\vec{E}|^2\right) dV}{\int_v \left(\mu_o |\vec{H}|^2 + \epsilon_o |\vec{E}|^2\right) dV}$$

- Low Beta (LB) 650 MHz tuning sensitivity $240 \frac{Hz}{\mu m}$
- **10 nm longitudinal deformation causes 2.4 Hz detuning**

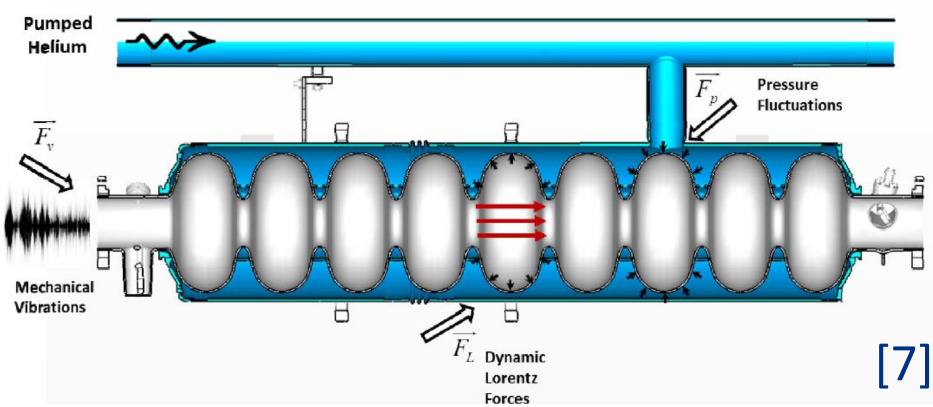
Why does detuning matter?

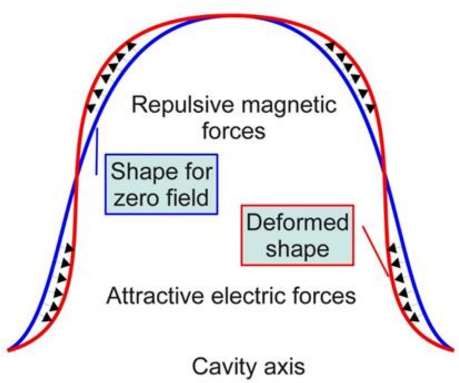




- To provide the desired accelerating gradient the cavity must be in resonance
- Narrow bandwidth of the cavities caused by low beam loading:
- $Q_L = V_{acc}/(I_b \frac{R}{Q})$ =$1.74 * 10^7$
- Cavity bandwidth: $\Delta f = f_o/Q_L$= 37 Hz
- RF power source can provide 40 kW
  - Provide power to the beam and cavity (RF power 23.8 kW)
  - Detuning from microphonics (~16 kW)
- Peak Detuning/Max RF power sets machine trip rate
- Reduce Linac trip rate
- Reduce RF power used thus reduce cost

Microphonics and Lorentz Force Detuning





$$P_s = \frac{1}{4}(\mu|\vec{H}|^2 - \varepsilon_0|\vec{E}|^2)$$

$$\Delta f_0 = (f_0)_2 - (f_0)_1 = -K\, E_{acc}^2$$

[7]M. H. Awida et. al, "Multiphysics analysis of frequency detuning in superconducting RF cavities for proton particle accelerators," *2015 IEEE MTT-S*

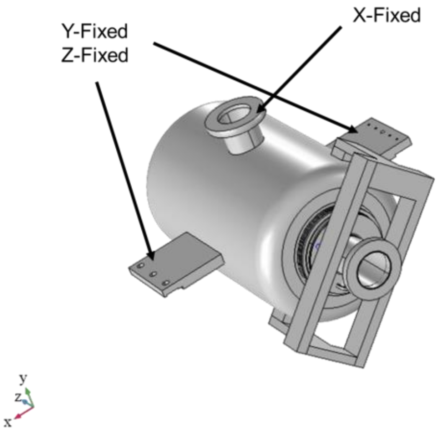
Continuous Wave Operation

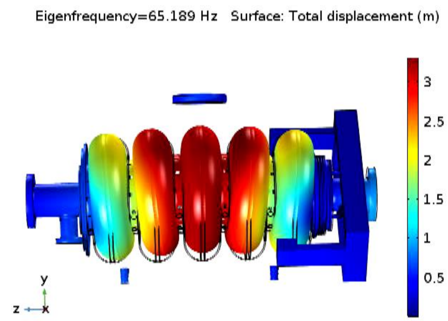
- Pressure variation in the surrounding He bath:
  - $\Delta f_{He} = \frac{df}{dP}\delta P, \delta P \sim 0.05 - 0.1\, mbar$ at 2 K.
- Internal and external vibration sources (microphonics)
- Cryogenic Valve Plumbing
  - Thermal acoustic oscillations

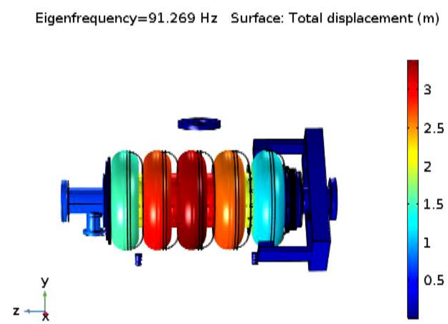
Pulse Mode Operation

- Radiation pressure from the RF field, Lorentz Force Detuning (in pulsed mode).
  - LFD LB: $-2\, Hz/\left(\frac{MV}{m}\right)^2$
  - At 16.9 MV/m, **Δf=-571 Hz**

COMSOL Simulations of Vibrational Modes

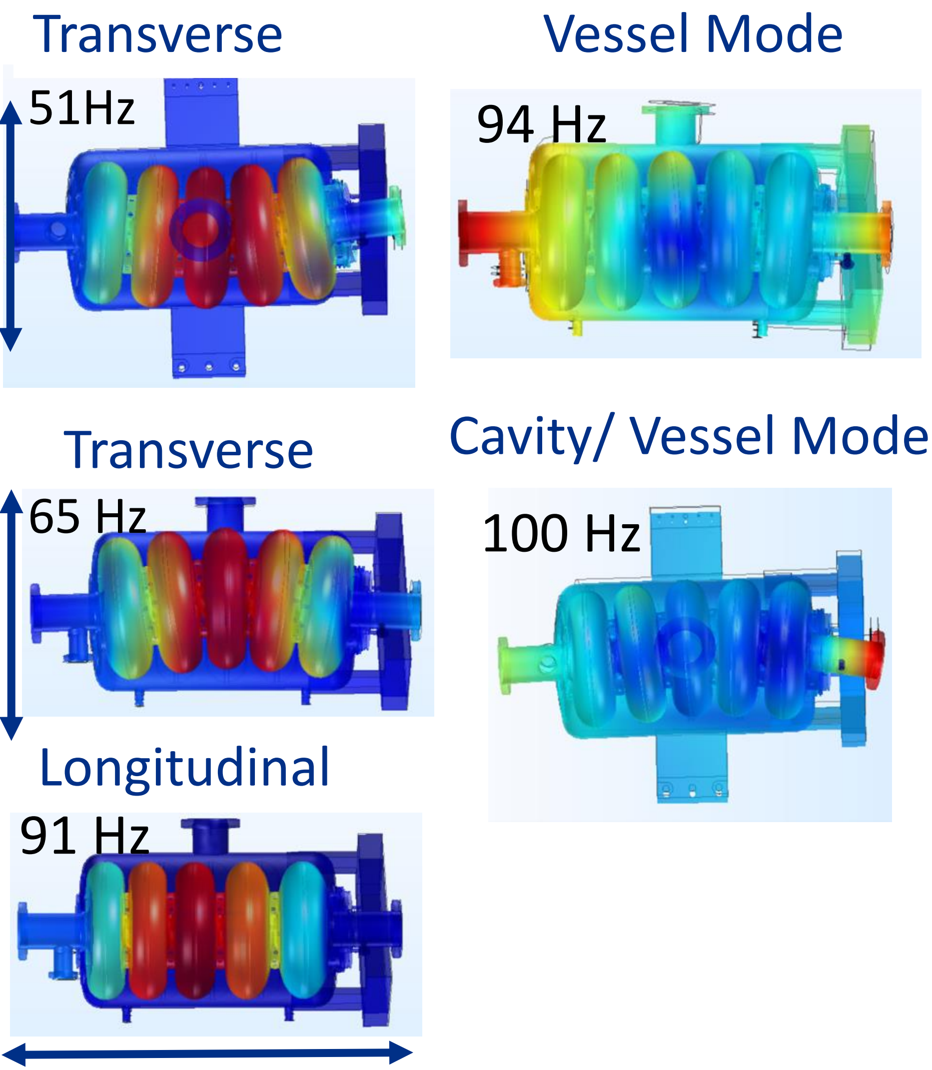




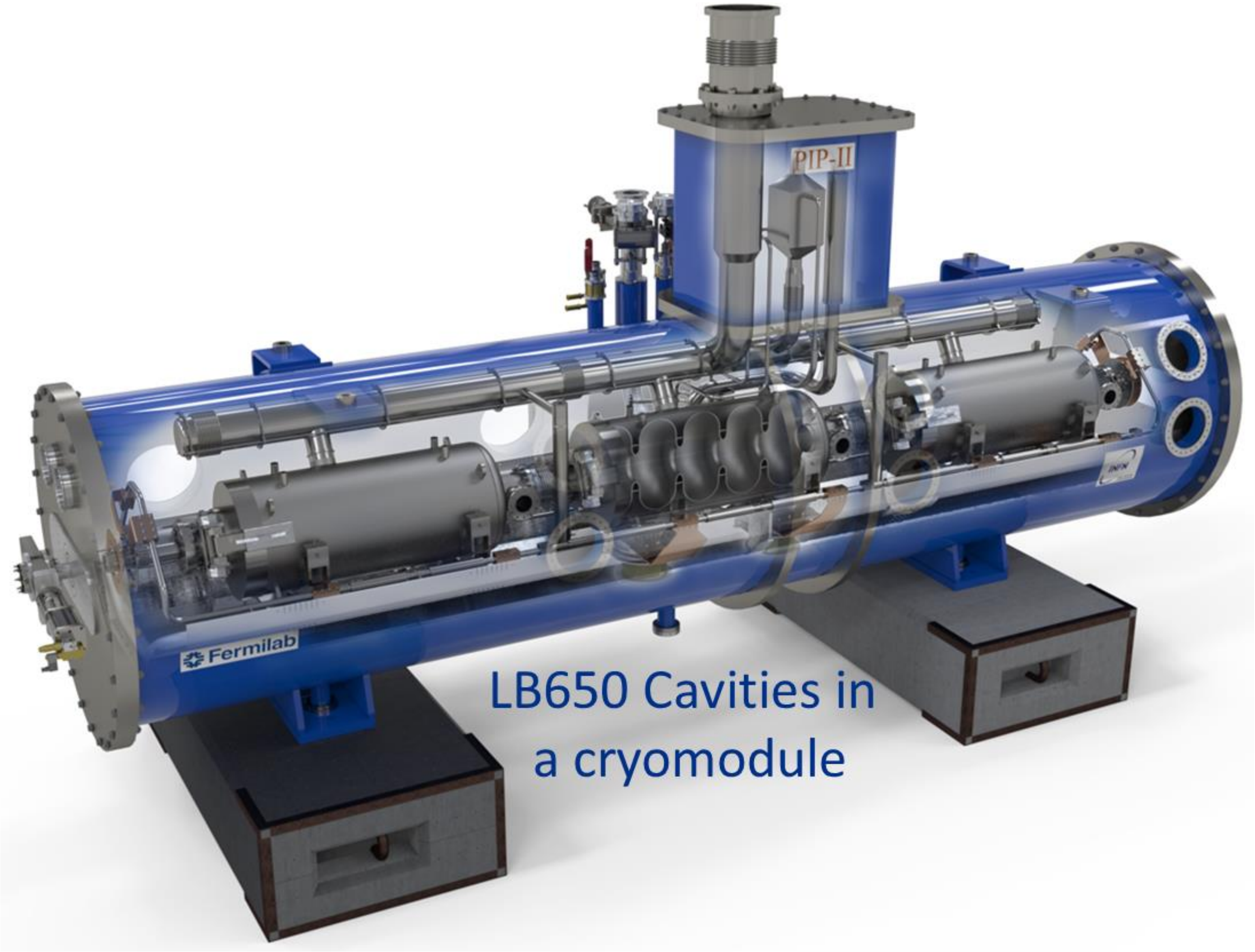


- FRIB cavity, similar to LB 650 MHz cavity
- Cavity detuning sensitivity 258 Hz/μm
- COMSOL was used to simulate the mechanical resonances of a single cavity and helium vessel
- Single cavity simulations can be done in commercially available software
- The cavity/Helium Vessel design needs to be optimized to limit resonances

Results from Simulations



- The longitudinal modes produce largest detuning
- Optimize to keep vibrational mode frequencies large
- Optimization for multiple cavities in a string along with all the components in the cryomodule is computationally demanding
- Conducting simulations will not be enough to mitigate microphonics


PIP-II
Fermilab
LB650 Cavities in
a cryomodule

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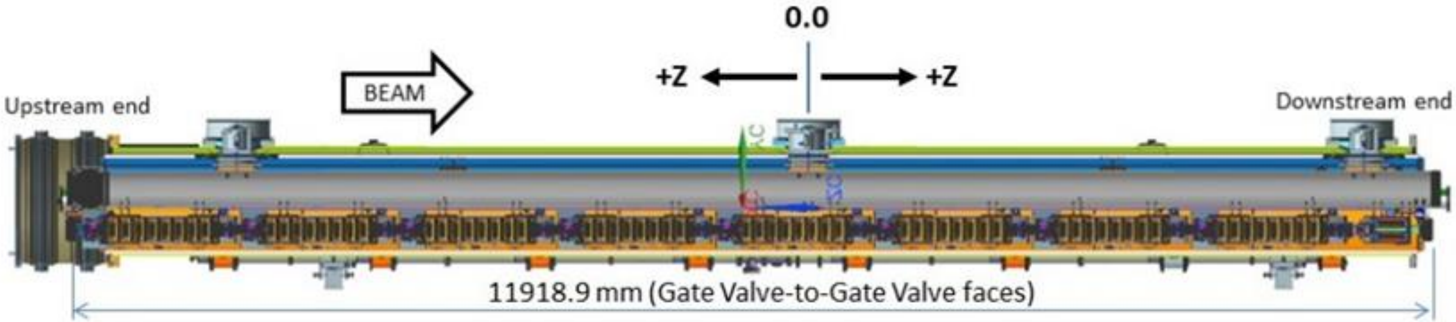
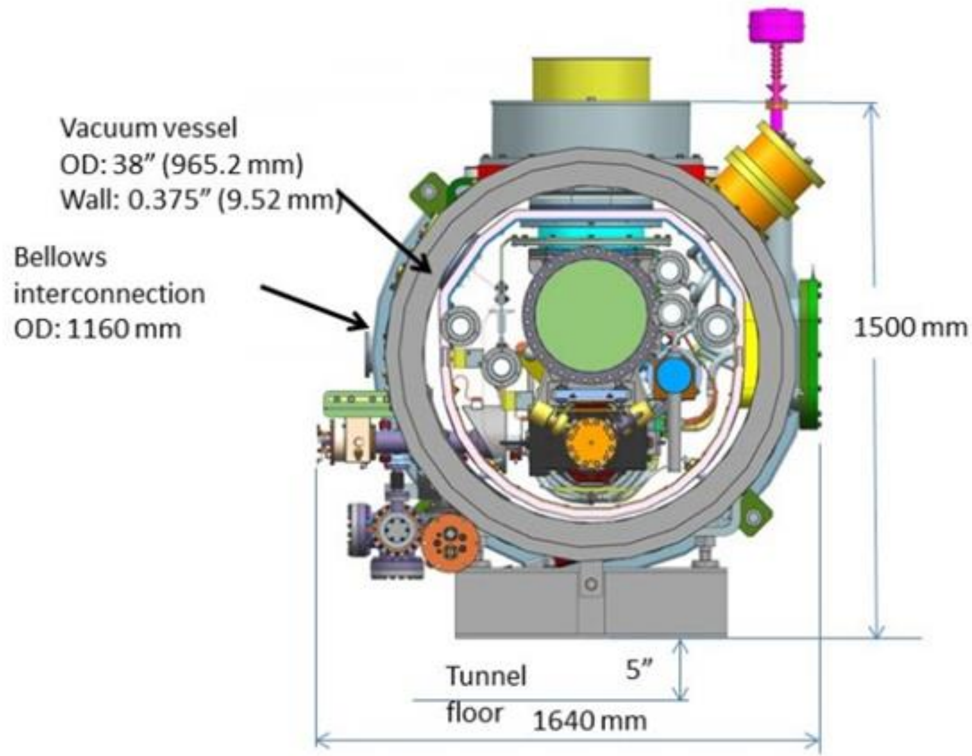
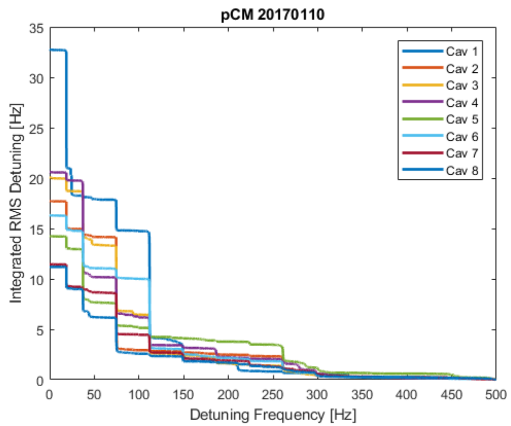
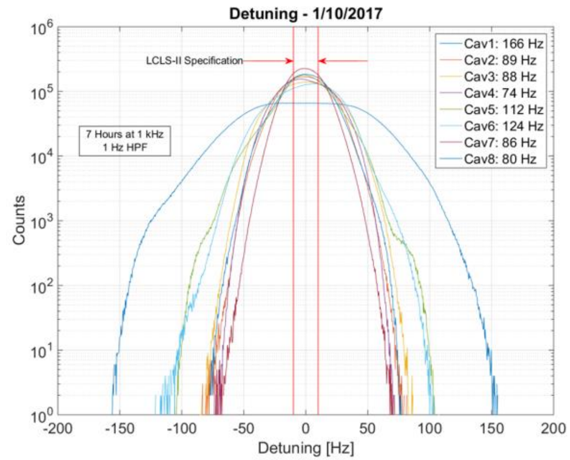
LCLS-II Cryomodule

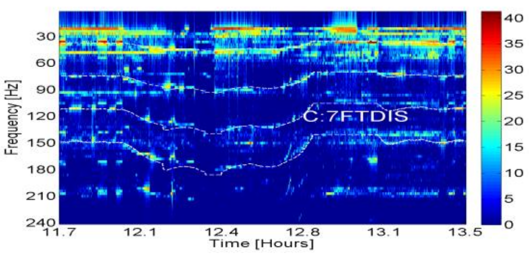


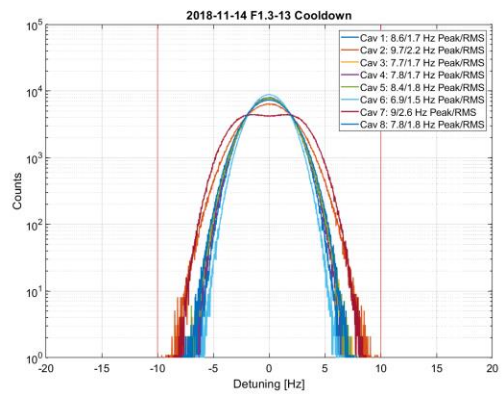


Passive Resonance control





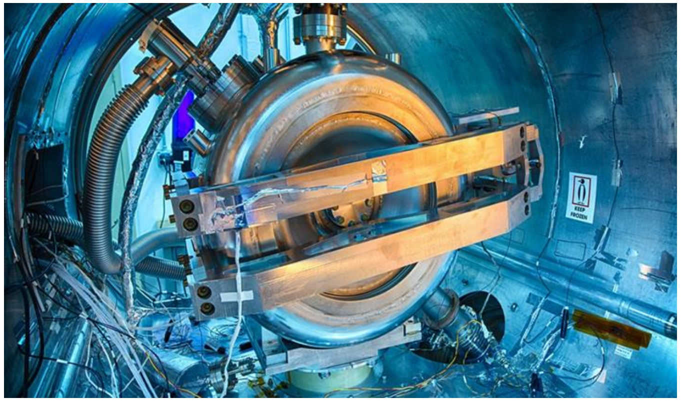


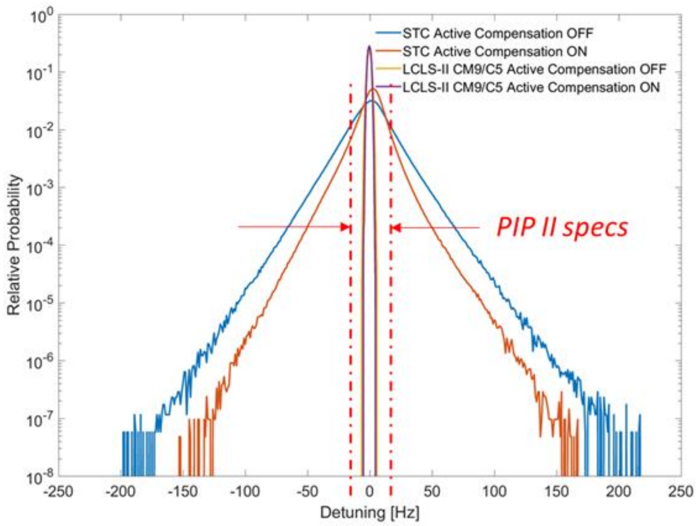


- LCLS-II Specification: 10 Hz peak detuning (excursion from 1.3 GHz)
- Initial cool down showed detuning was greater than the specification
- As is current resonance control algorithm cannot get into LCLS-II specification
- Changes in the cryogenic plumbing and mechanical were needed to get within specification

[] LCLS-II Microphonics Working Group

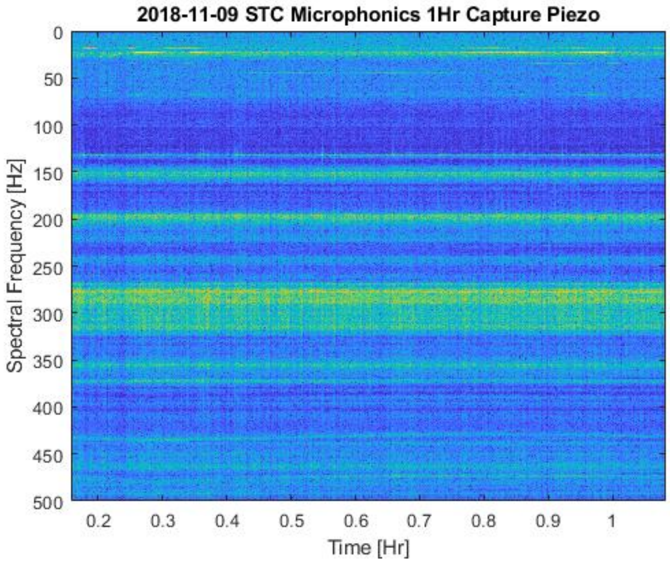
Method of Detecting Microphonics



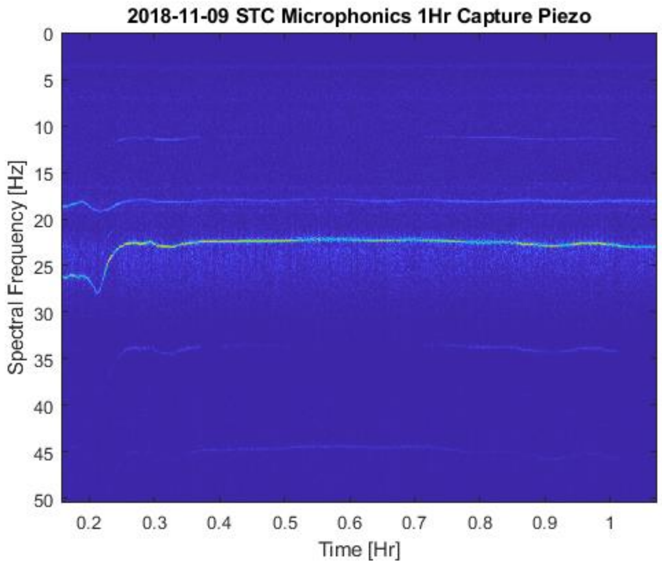


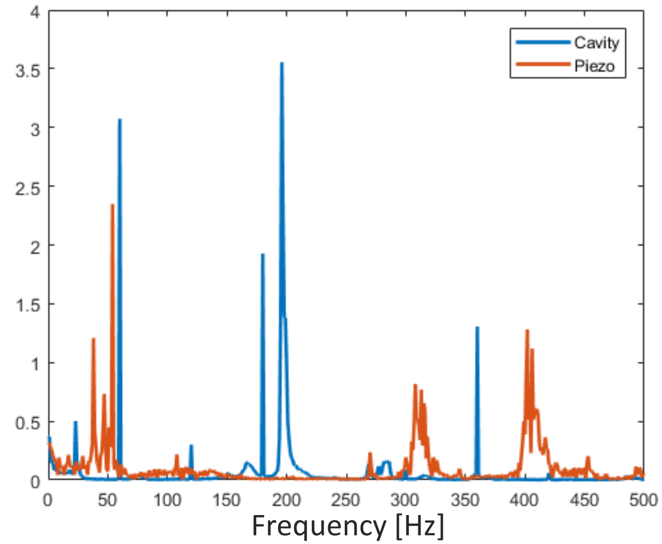
- Piezo Actuators
- Geophones
- Superconducting RF Cavity at 2 K is the most sensitive
- Specifications for PIP-II cavity is 20 Hz peak detuning
- With large detuning on the cavity the resonance control algorithm is not enough to get to PIP-II Specifications

Piezo as Sensor

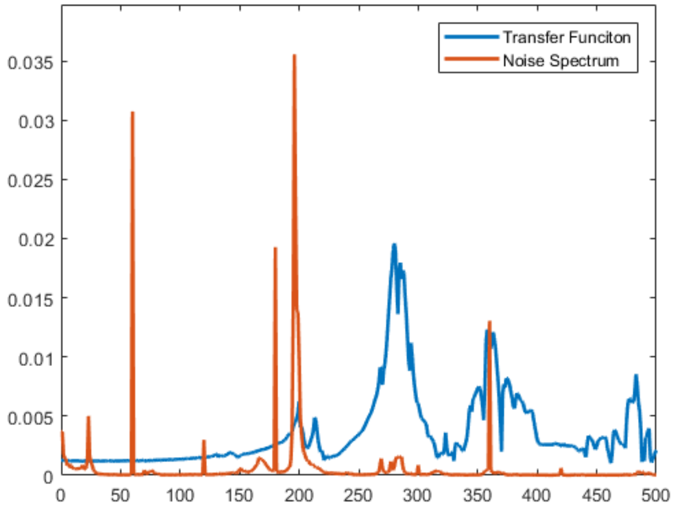


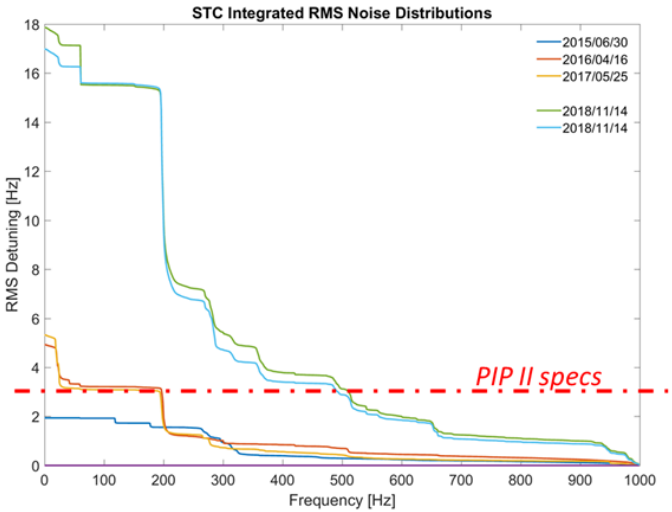
- When the piezo is compressed it will produce a voltage
- The voltage is recorded with sampling rate is 1 kHz
- Can be used when cavity is off
- Less precision
- Piezo





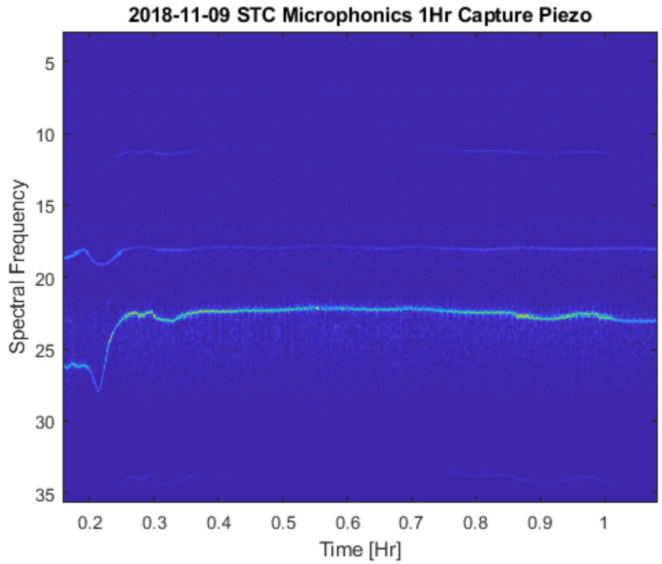
Comparison of Noise to Resonant Frequencies

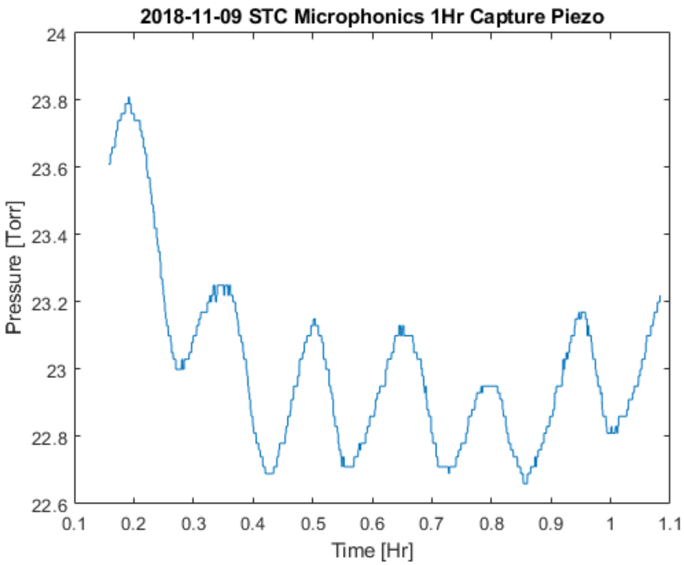




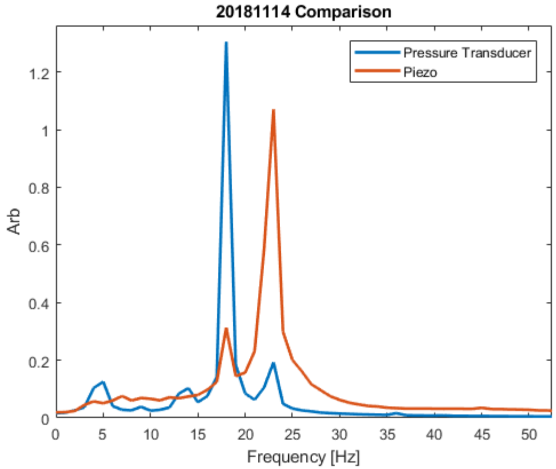
- Transfer function shows the eigenfrequencies of the cavity
- The noise spectrum shows there is a strong resonance speak around one of the eigenfrequencies

Helium Pressure Variation





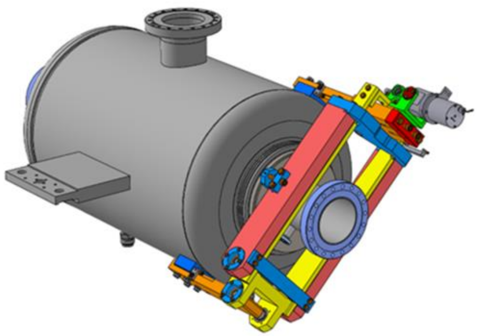
- Experience from Microphonics workgroup show that changing frequencies is related to cryogenic induced vibrations
- The only source changing frequency changing is from ~ 20 Hz source (pressure related)
- Task List
  - Analyze the data for the cavity
  - Identify where the 200 Hz source is coming from

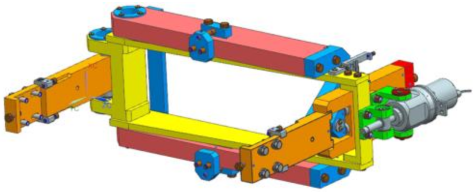


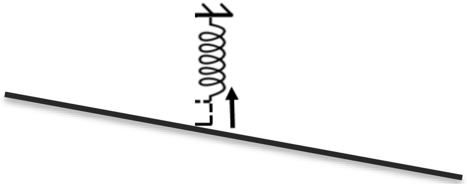
Microphonics Control Strategies

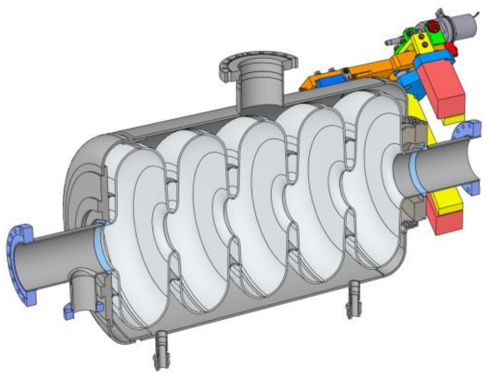
- Provide sufficient reserve RF power to compensate for expected peak detuning levels
- Improve the regulation of the helium bath pressure $\frac{df}{dp}$
- Reduce the sensitivity of the cavity resonant frequency to variations in the helium bath pressure, Lorentz Force, and external vibrations
- Minimize the acoustic energy transmitted to the cavity via external vibration sources.
- Actively damp cavity vibrations using a fast mechanical tuner driven by feedback from measurements of the cavity resonant frequency.

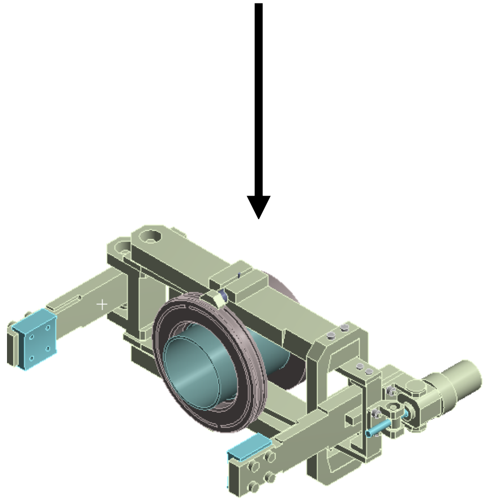
Fast/Slow Lever Tuner



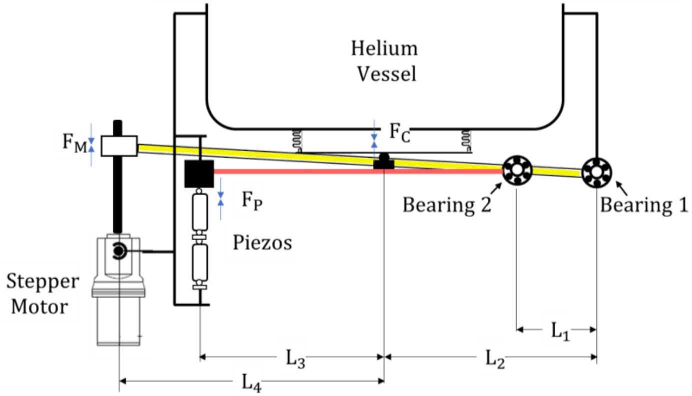




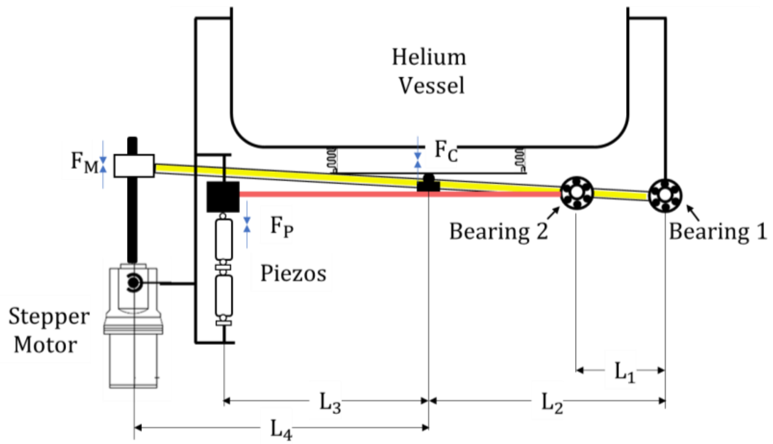


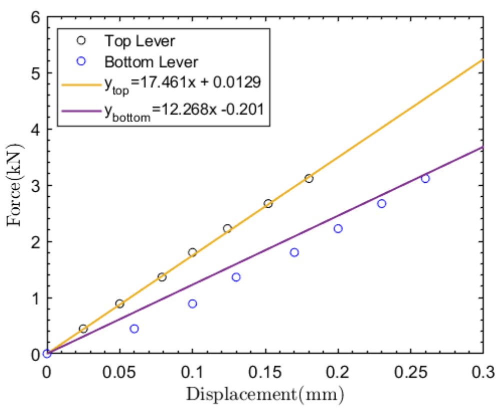


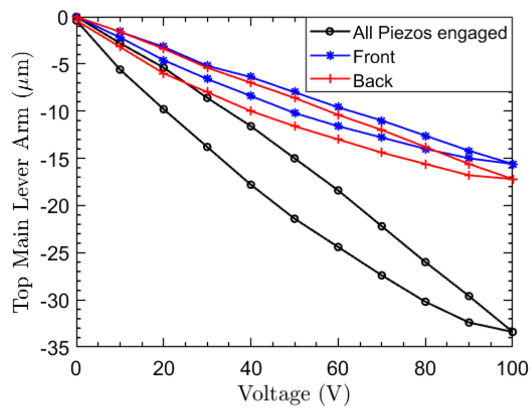
[3] S. Cheban



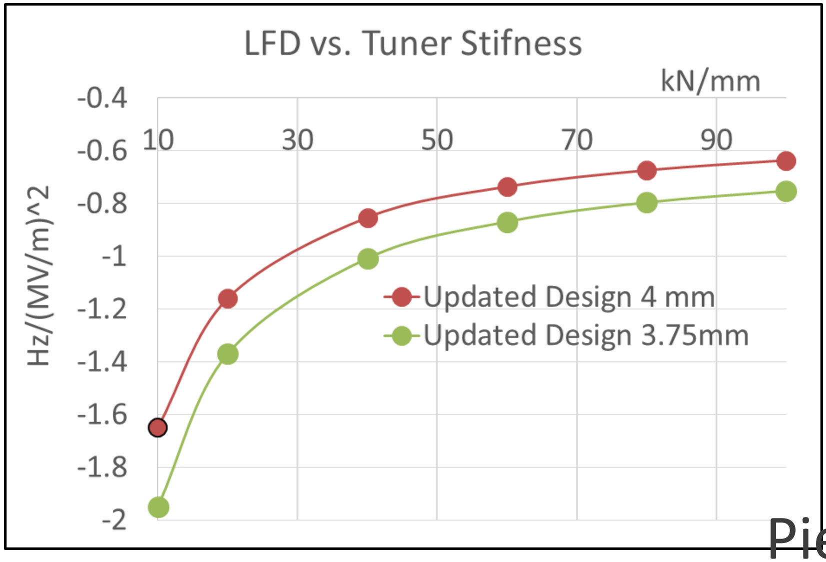
Tuner Properties







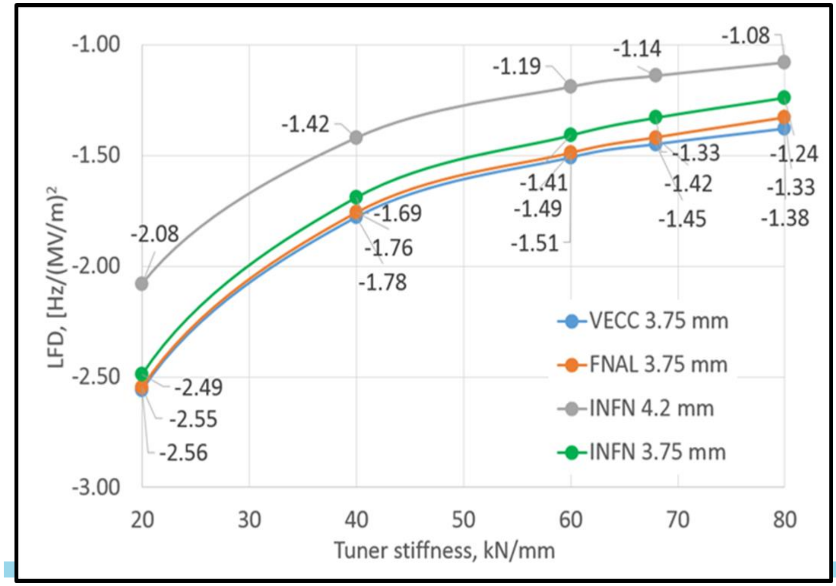
- The tuner test show that the stiffness is ~30 kN/mm
- Coarse tuning 200 kHz done by stepper motor
- Fine tuning 1 kHz done by piezos
- For a single piezo encapsulation the maximum detuning is ~430 Hz and for all the piezos ~1.6 kHz both at 100V



E_{ac}=18.8 MV/m

$K_{LFD\text{-}Static}$=0.8-1.0

Piezo Actuator



E_{ac}=16.9 MV/m

$K_{LFD\text{-}Static}$=1.4-1.8

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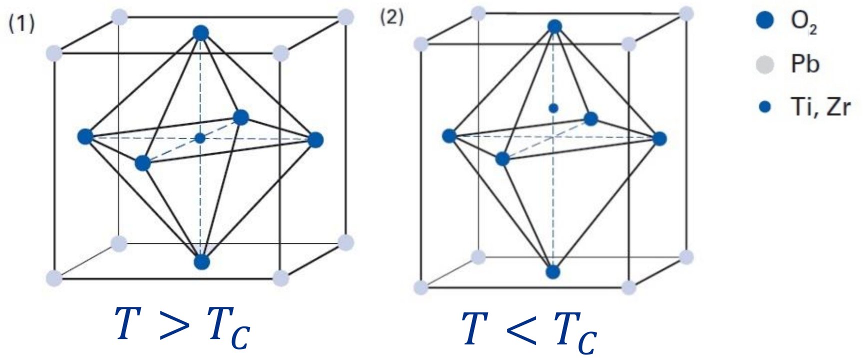
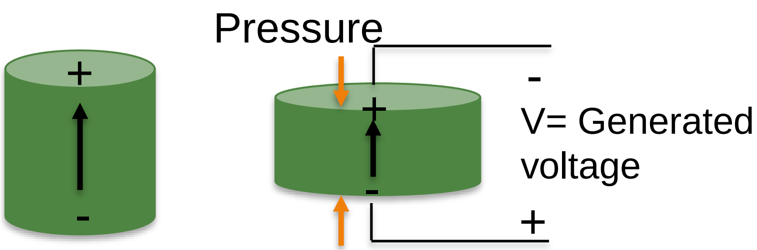
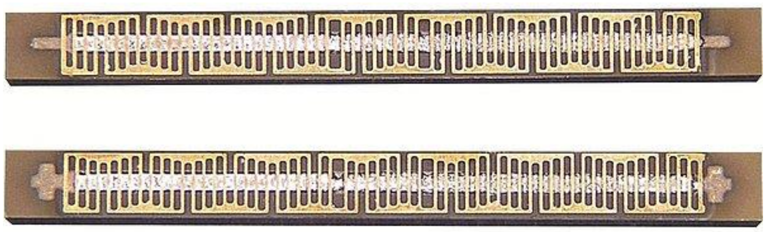
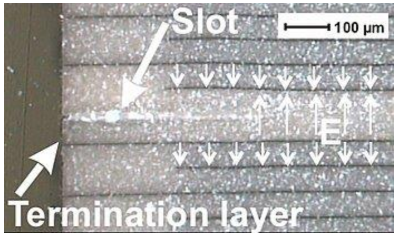
Piezoelectric Effect

- Piezoelectric Effect
  - Occurs below curie temperature
  - Material used is lead zirconate titanate (PZT)
  - Obtained after poled
  - Applying voltage will elongate or shrink the piezo depending on the sign
  - Applying pressure will generate voltage
- Piezo capsule built with two 18 mm long piezo stacks made



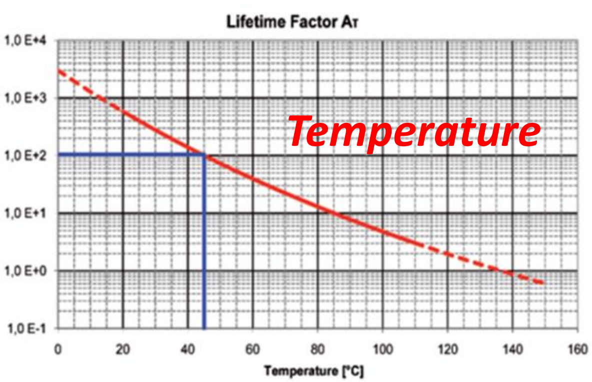


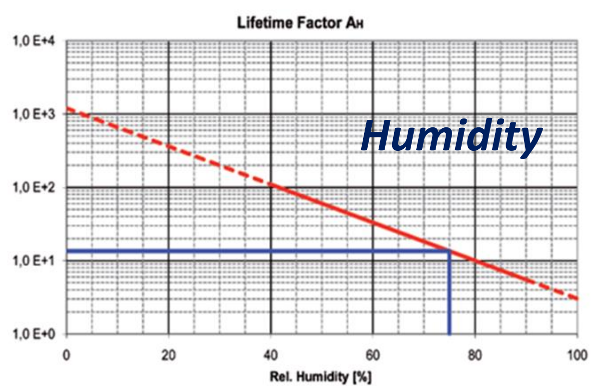


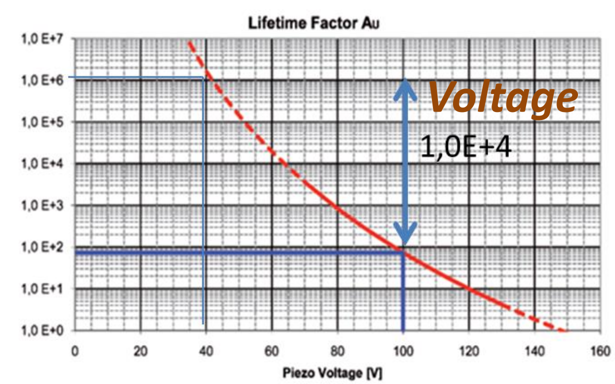


Piezo Lifetime R&D Program

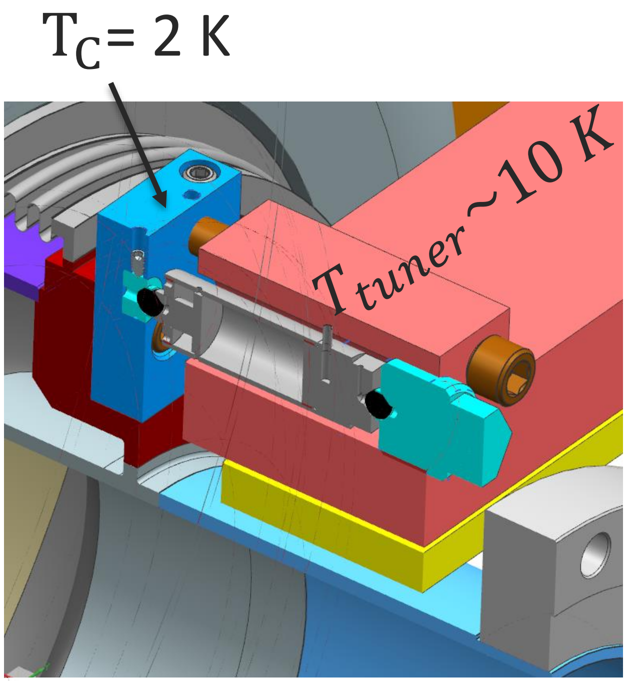
- Factors affecting lifetime
  - Temperature, Humidity, Voltage
  - Shear Forces
  - Radiation damage
  - Dielectric losses
- Decreasing operational voltage from 100V to 40V will increase lifetime in 10,000 time.
- Accelerated life time test for piezos for LCLS-II show run for $2.5 * 10^{10}\ pulses$ (or 125% of LCLS II expected lifetime) without any degradation or overheating [Pischalnikov, et al]







Piezo Reliability



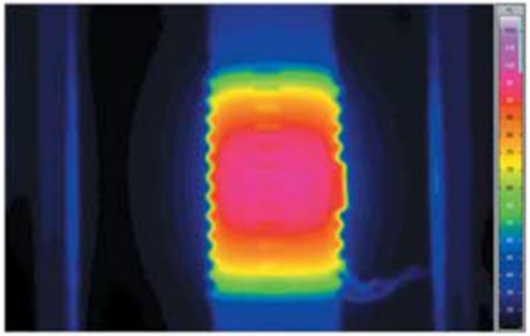
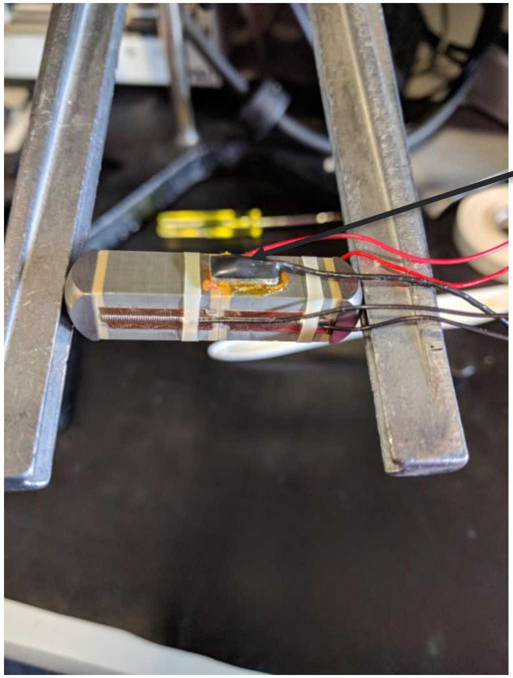
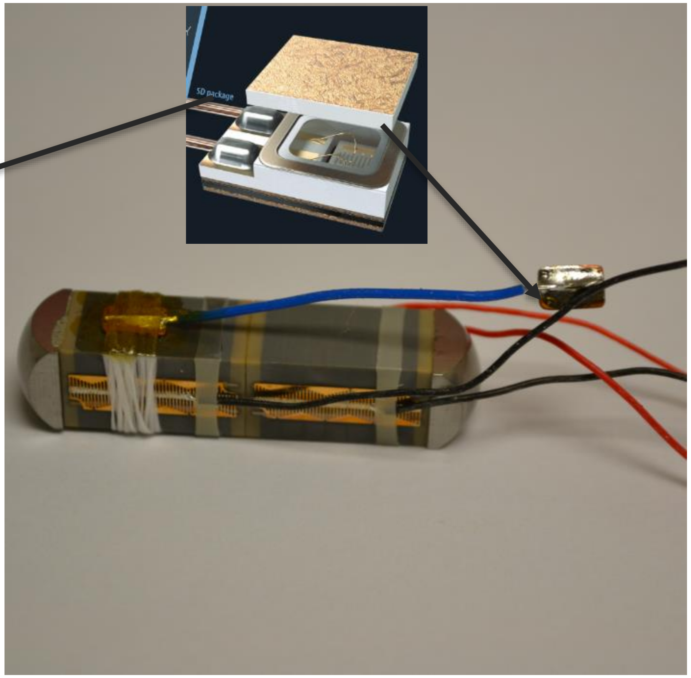


Fig. 5.1: Thermal image of a dynamically cycled high voltage actuator, clamped at its end faces. Environment: ambient air convection. Notice the cooling effect at the end-faces due to the clamping mechanics

- Dielectric losses in the ceramic creates heating
- PIP-II will require the piezo to operate at high voltage
- Outcome: Test whether piezo can withstand high dynamic operation

Changes to Experiment





- Cernox sensor attached directly to the piezo stack
- Previously a thin wire with thin copper plates were used
- Improve reliability of temperature readings

Experimental Setup

- Use geophones to verify piezo is being excited
- The setup will be dunked in a LHe dewar
- Task List:
    - Improve LabView data acquisition program
    - Verify all wires are connected correctly
    - Test at Liquid Nitrogen
    - Prove piezo will survive high dynamic pulse operation

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  - Compensation

Harmonic Oscillator

$$\Delta\ddot{\omega}_\mu(t) + \frac{2}{\tau_\mu}\Delta\dot{\omega}_\mu(t) + \Omega_\mu^2\Delta\omega_\mu(t) = k_\mu^{LFD}\Omega_\mu^2 E^2(t) + n_\mu^{Piezo}\Omega_\mu^2 N(t) + m_\mu\ \Omega_\mu^2 M(t)\ (1)$$

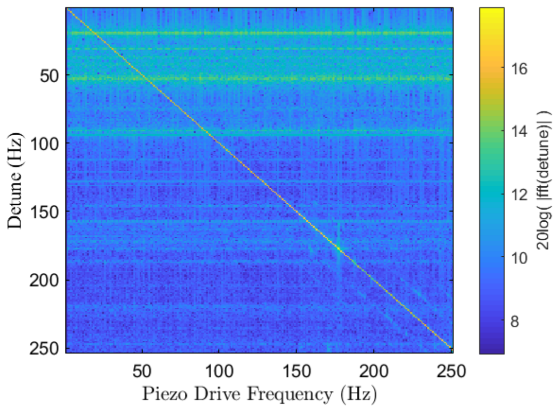
$$\Delta\omega(t) = \sum_{\mu=1}^{\infty}\Delta\omega_\mu(t)$$

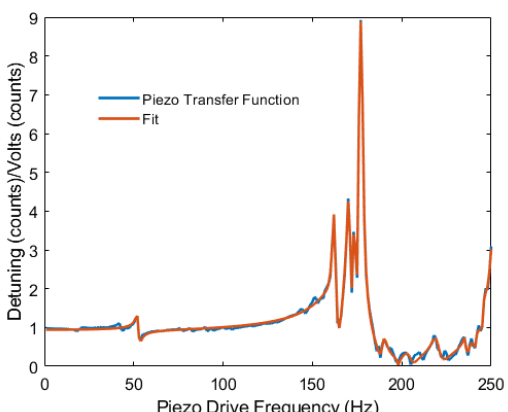
- $\Delta\omega_\mu$ detuning of the mode, detuning frequencies Ω_μ,and the coupling $(k_\mu^{LFD}, n_\mu^{Piezo})$
- To dampen a mode, the piezo drive is $N(t) \propto \Delta\dot{\omega}_\mu(t)$

Transfer Function

Response Detuning

Piezo Drive

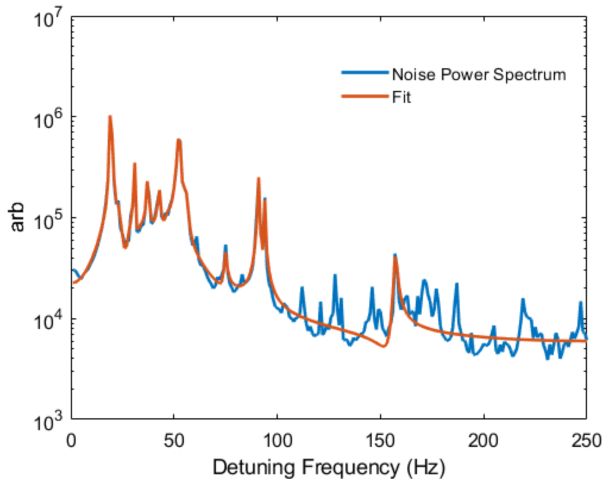


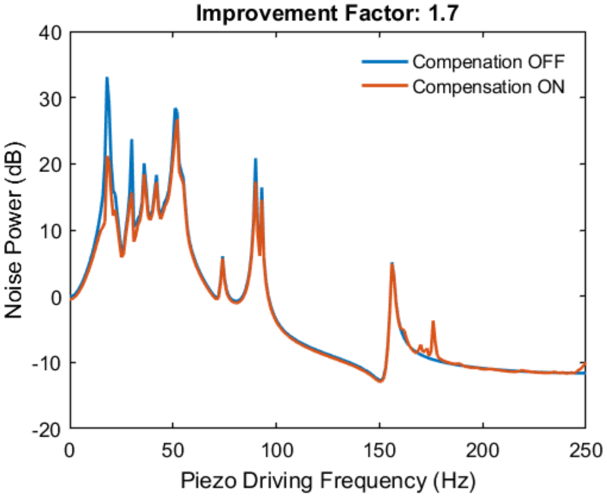


- Response of the cavity to a stimulus from the signal from the piezo
- A low order approximation can be obtained using the Kalman-Ho identification algorithm
- From the transfer function we want to obtain $Q_{\mu} = \frac{1}{\tau_{\mu}}$, the detuning frequencies Ω_{μ}, and the coupling k_{μ}

Microphonics Noise Spectrum

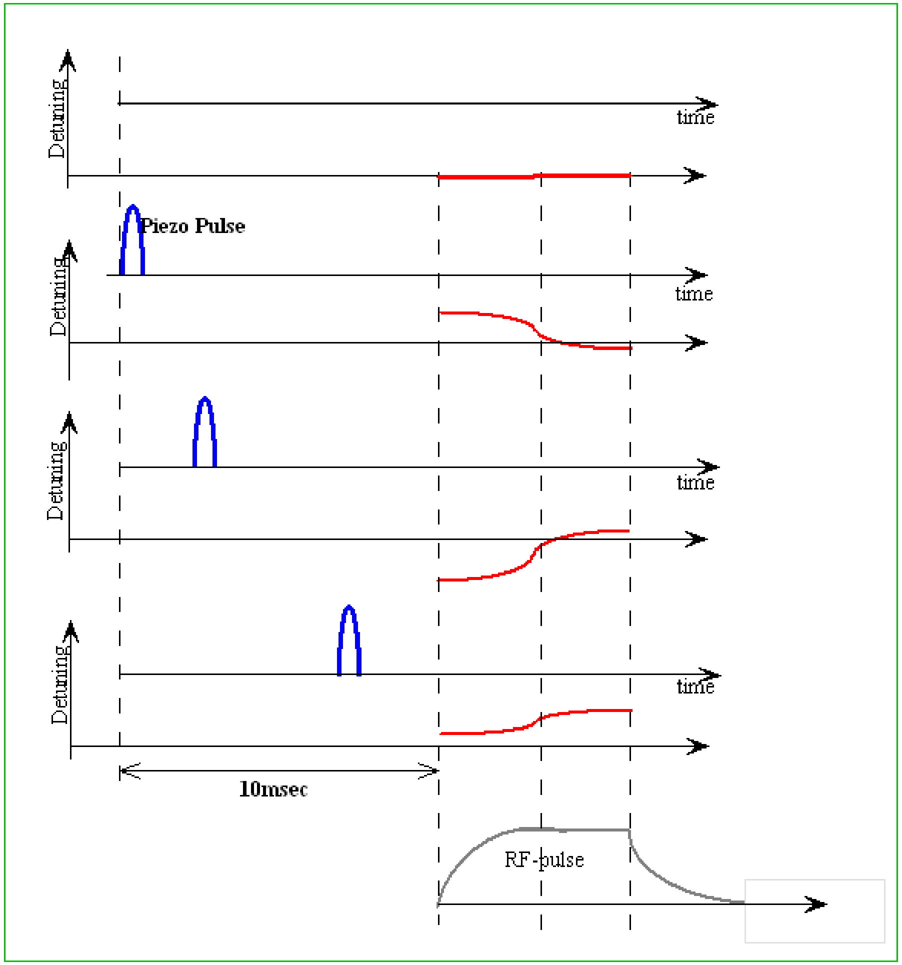
Background Noise





- Frequencies and bandwidths for microphonics can be determined using a combination of Kolmogorov Spectral Factorization and Kalman-Ho algorithm

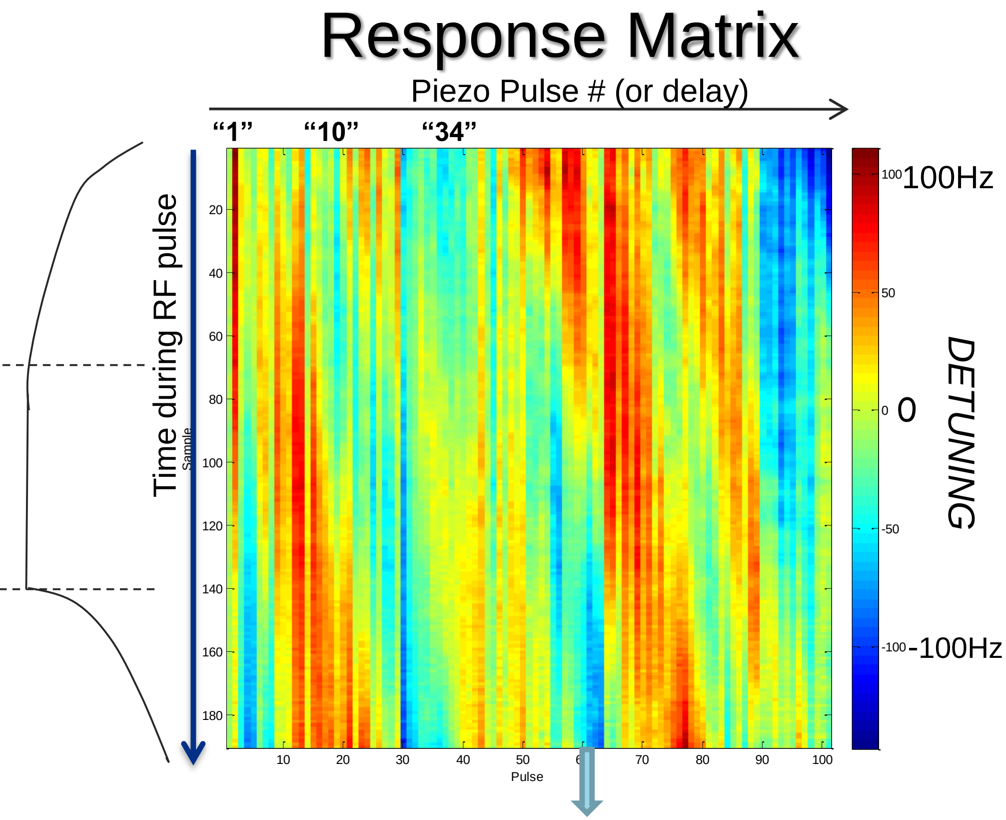
Response Matrix



- 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]

“W. Schappert, Y.Pischalnikov, “Adaptive Lorentz Force Detuning Compensation”. Fermilab Preprint –TM-2476-TD

Adaptive Least Square(LS) LFD Algorithm



- 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"

"W. Schappert, Y.Pischalnikov, "Adaptive Lorentz Force Detuning Compensation". Fermilab Preprint –TM-2476-TD

Summary

- Microphonics
  - I learned about the various sources that contribute to the detuning
  - The pinpointing the sources is not easy
- Fast/Slow Tuner
  - Measured the tuner stiffness and piezo stroke
- Resonance Control
  - I learned algorithm to model the system and obtain the modal frequencies
  - Resonance control algorithm studies are ongoing

Plan

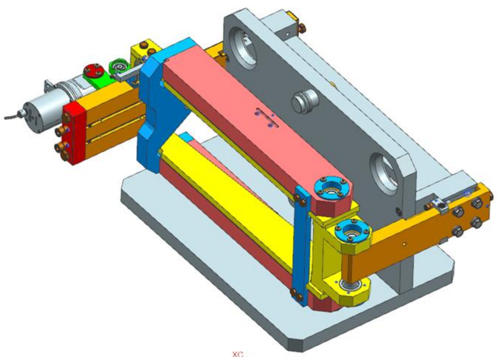
- 2019
  - Finish Piezo Experiment
  - Microphonics studies
  - Work on calculating the detuning of the cavity via probe, reversed, and forward signal
  - Work on resonance control algorithms
    - Adaptability with change in frequency of modes
- 2020
  - Microphonics studies
  - Work on resonance control algorithms
    - Adaptability with change in frequency of modes
  - Write Thesis
- 2021
  - Defend thesis

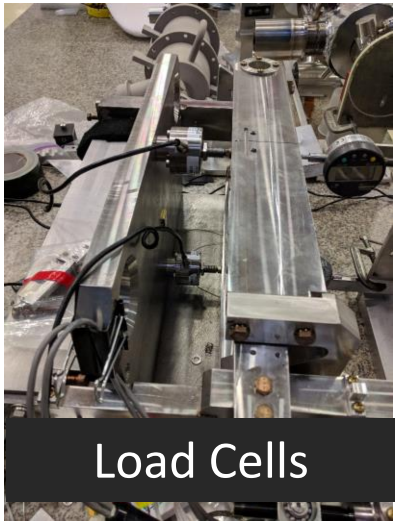
Acknowledgements

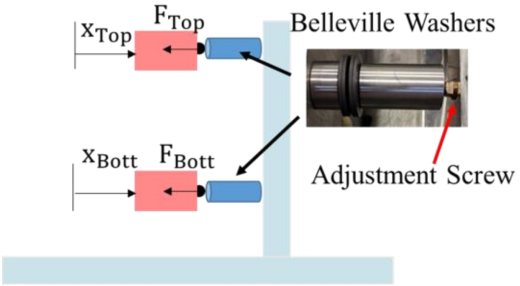
- Peter Ostroumov
- Slava Yakovlev
- Fermilab Resonance Control Group
  - Yuriy Pischalnikov
  - Warren Schappert
  - Jeremiah Holzbauer
  - J.C. Yun

Back Up

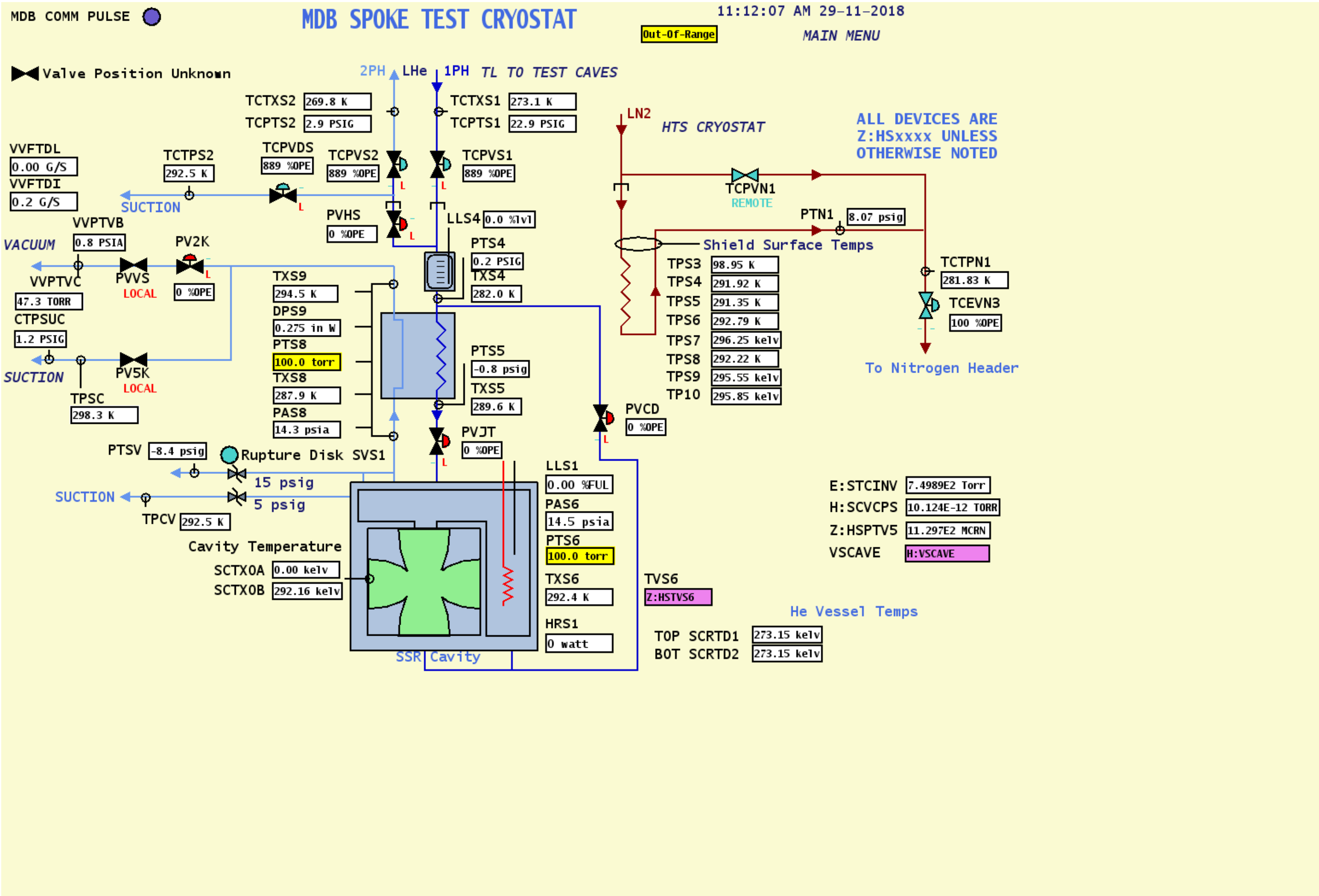
Stiffness/Piezo Stroke Setup







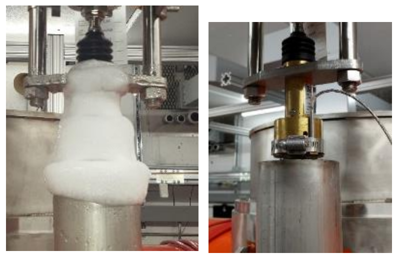
- The stiffness is measured by applying a force to the main lever arm via the adjustment screw and recording the displacement.
- Cavity simulated with Belleville washers (4.9kN/mm)
- There is error in the measurement since the stand is not stiff enough

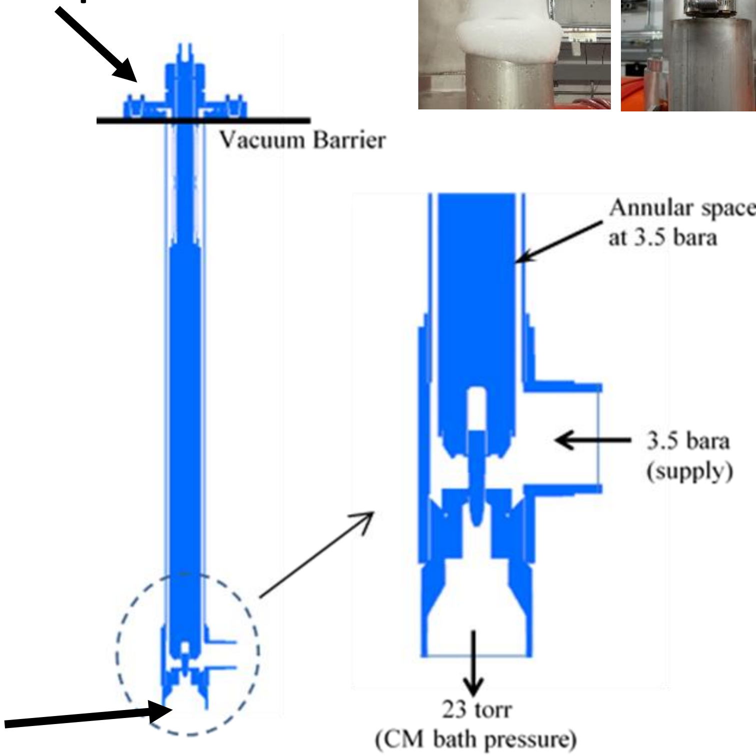

MDB COMM PULSE
MDB SPOKE TEST CRYOSTAT
11:12:07 AM 29-11-2018
Out-Of-Range
MAIN MENU
Valve Position Unknown
2PH
LHe
1PH
TL TO TEST CAVES
TCTXS2 269.8 K
TCTPS2 2.9 PSIG
TCTXS1 273.1 K
TCTPS1 22.9 PSIG
LN2
HTS CRYOSTAT
ALL DEVICES ARE
Z:HSxxxx UNLESS
OTHERWISE NOTED
VVFTDL 0.00 G/S
VVFTDI 0.2 G/S
TCTPS2 292.5 K
TCPVDS 889 %OPE
TCPVS2 889 %OPE
TCPVS1 889 %OPE
SUCTION
TCPVN1
REMOTE
PTN1 8.07 psig
VVPTVB 0.8 PSIA
PVHS 0 %OPE
LLS4 0.0 %lvl
VACUUM
PV2K
PTS4 0.2 PSIG
Shield Surface Temps
VVPTVC
PVVS
LOCAL
0 %OPE
TXS4 282.0 K
TXS9 294.5 K
TPS3 98.95 K
TPS4 291.92 K
TPS5 291.35 K
TPS6 292.79 K
TPS7 296.25 kelv
TPS8 292.22 K
TPS9 295.55 kelv
TP10 295.85 kelv
TCTPN1 281.83 K
TCEVN3 100 %OPE
47.3 TORR
CTPSUC 1.2 PSIG
DPS9 0.275 in W
PTS8 100.0 torr
TXS8 287.9 K
PAS8 14.3 psia
PTS5 -0.8 psig
TXS5 289.6 K
To Nitrogen Header
SUCTION
PV5K
LOCAL
TPSC 298.3 K
PVCD 0 %OPE
PTSV -8.4 psig
Rupture Disk SVS1
PVJT 0 %OPE
15 psig
5 psig
SUCTION
TPCV 292.5 K
LLS1 0.00 %FUL
PAS6 14.5 psia
PTS6 100.0 torr
E:STCINV 7.4989E2 Torr
H:SCVCPS 10.124E-12 TORR
Z:HSPTV5 11.297E2 MCRN
VSCAVE H:VSCAVE
Cavity Temperature
SCTX0A 0.00 kelv
SCTX0B 292.16 kelv
TXS6 292.4 K
TVS6 Z:HSTVS6
He Vessel Temps
HRS1 0 watt
TOP SCRTD1 273.15 kelv
BOT SCRTD2 273.15 kelv
SSR Cavity

Thermal Acoustic Oscillations (TAOs)

Joule-Thomson (JT) Valve

Room Temperature





2 K

- Lessons from Microphonics Working Group
- TAOs are an oscillatory instability that occur in long gas tubes with a large temperature gradient
- The temperature differential drives an acoustic like oscillation, where the cold cryogenic fluid rapidly moves up the warm end tube, warms, expands and drives back down to the cold end.
- Signs of TAOs:
  1. High heat loads
  2. Ice/condensation at warm side
  3. Mechanical vibration

[1] Microphonics working group

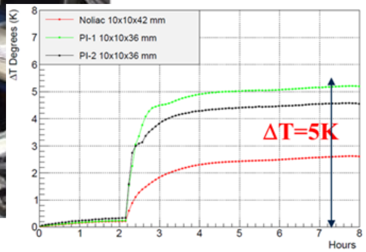
Accelerated Piezo Lifetime test at FNAL

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)



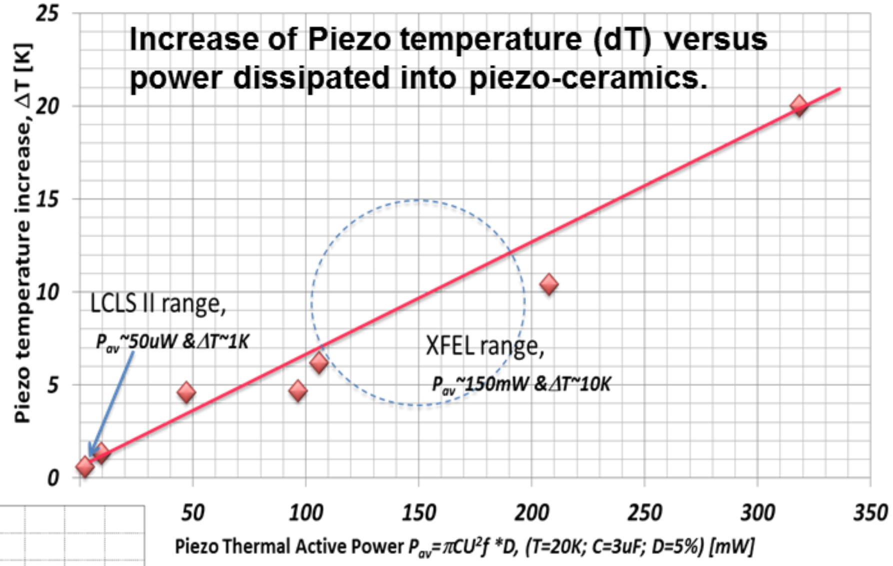
Accelerated piezo-stack lifetime test

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

20years → 2 month (40Hz→5kHz)

LCLS II --- ***P_{av}~ 50μW (40Hz, 2V)***

During ALT at 5kHz ***P_{av}~ 6mW (ΔT~2K)***



*Slide Y, Pischalnikov

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