Resonance Control in SRF cavities

SRF Tuners

Lorentz Force Detuning & Microphonics Compensation

Piezo Control System

September 19, 2011

CM1 Operation Meeting

Presented by Yuriy Pischalnikov

Outline

Slow Tuner
- why SRF required slow tuner
- design of CM1 & CM2 tuners for CM1 & CM2

Fast Tuner
- why SRF required fast tuner:
  - Lorentz Force Detuning(LFD)- (play sound of LF inside CM1)
  - Microphonics;
- Piezoelectric actuator/sensor – (aka piezo)
  - Typical piezo parameters;

LFD/microphonics compensation with piezo tuner
- Adaptive algorithm to control LFD
- Results from CC2; HTS(CM2 cavities) & CM1

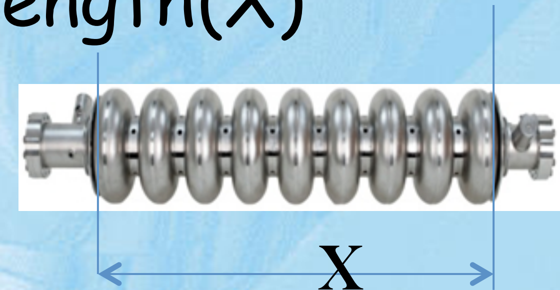
SLOW TUNER

- Tune cavity resonance to operating frequency
  - during initial and subsequent cool-down
  - compensate slow drift of frequency
- De-tune cavities to bypass for operation

Typical Parameters for 1.3GHz 9 cell ILC/Tesla cavities

- Cavity frequency (F) VS. cavity length(X)

  $\Delta F/\Delta x$ ~300 Hz/um;



- Slow tuner range (DF &DX):

  ΔF ~500 kHz == Δx ~+/-1 mm

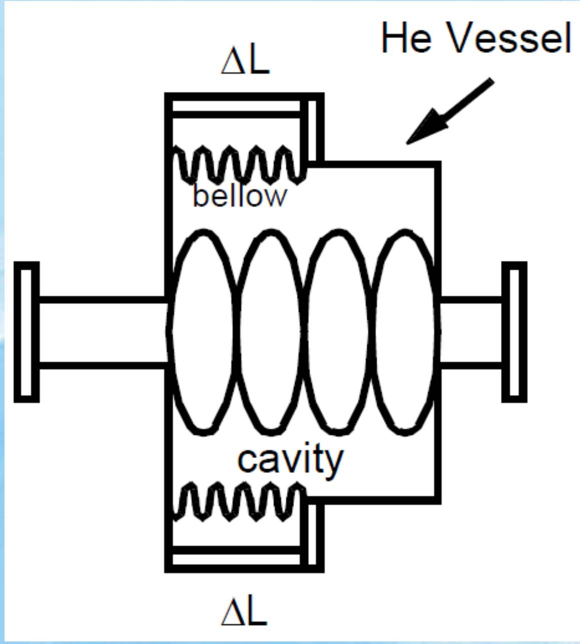
- Cavity bandwidth ($F_{1/2}$ at Q_L~3*10^6)

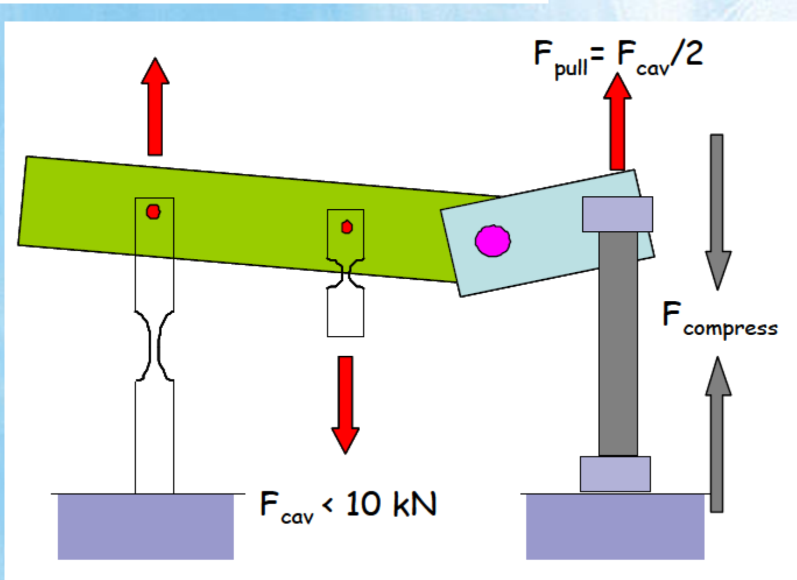
  $F_{1/2}$~400 Hz;

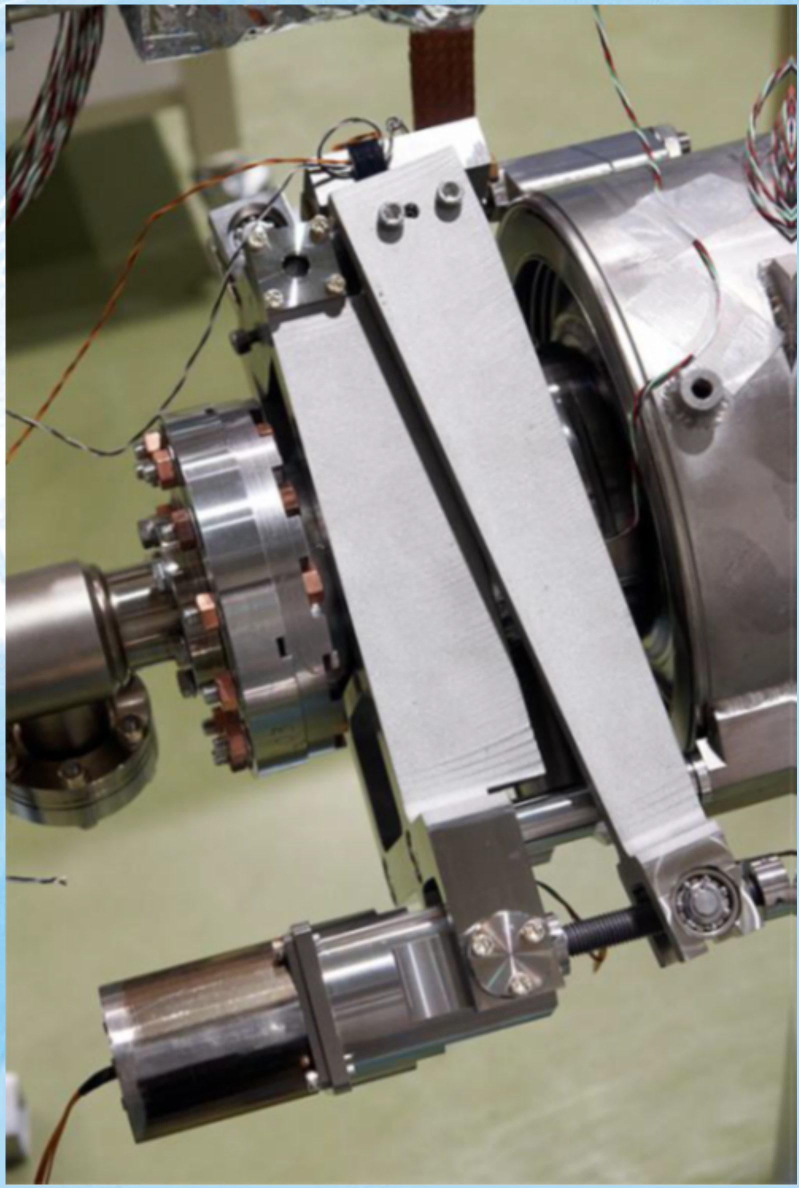
- Requirements to slow tuner to tune cavity within +/-10Hz to nominal value (1.3GHz) limit hysterezis of mechanical system

  +/-30 nm;

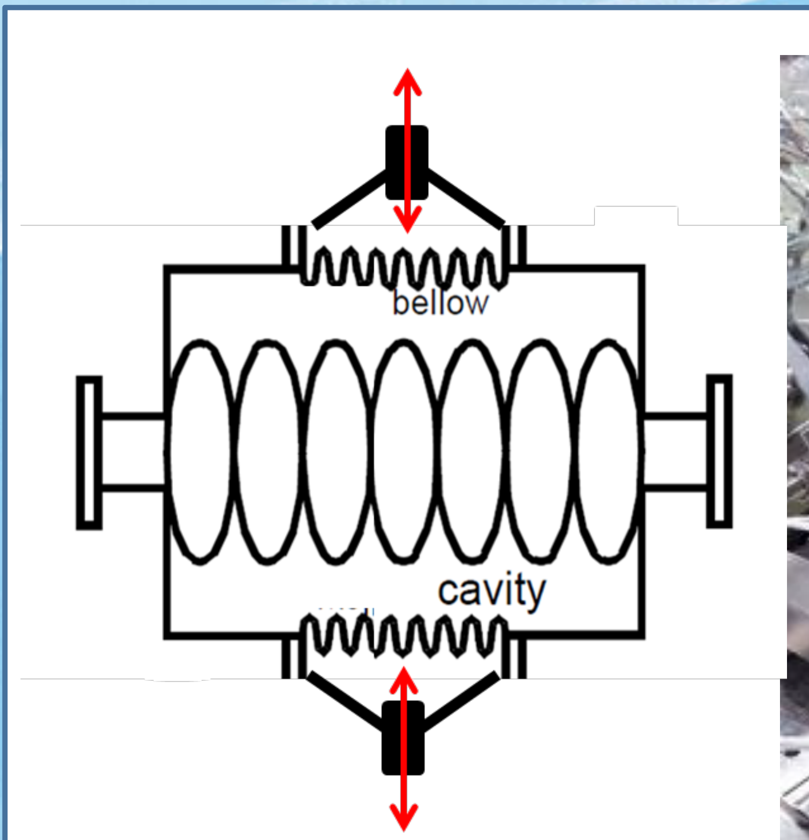
CM1 – DESY/Saclay (XFEL) Tuner







CM2- Blade Tuner (INFN/FNAL)

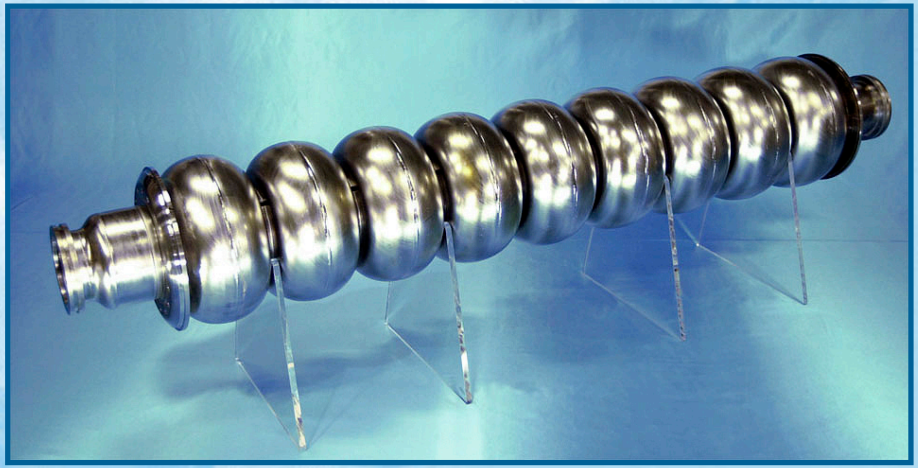


FAST (PIEZO) TUNER

- Compensate Lorentz Force Detuning (static and dynamic)
- Control of Microphonics (typically up to few 10 Hz)

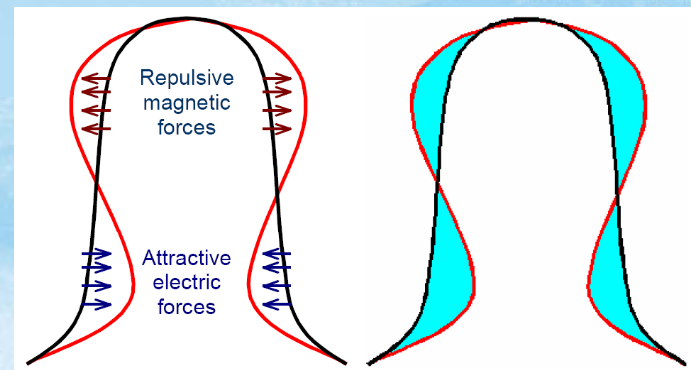
Resonance Control in SCRF Cavities

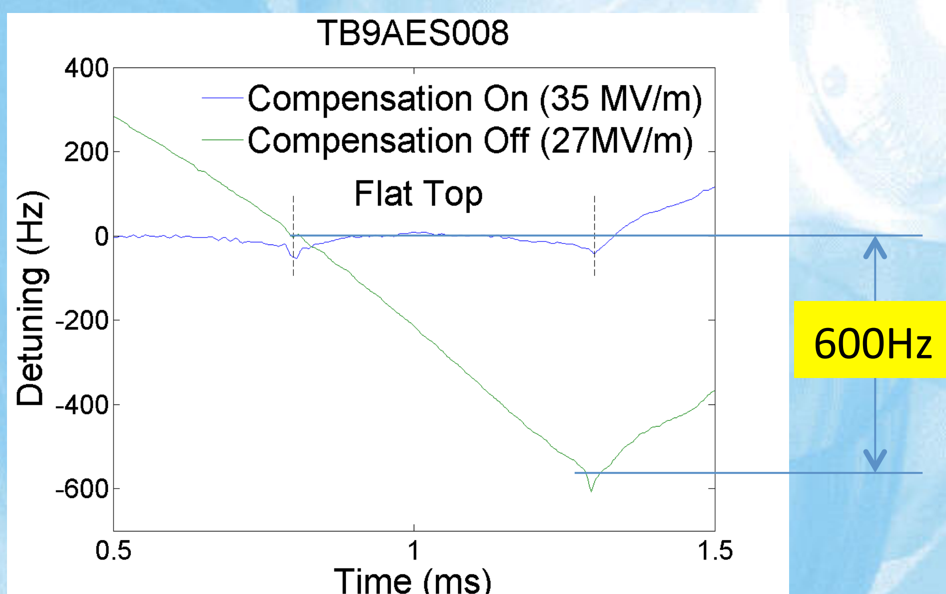
- SCRF cavities are designed with thin walls to maximize heat transfer to liquid He bath
- The thin walls lack stiffness making the cavities susceptible to mechanical oscillations
- Longitudinal oscillations can change the resonance frequency of the cavity
- Oscillations can be excited
  - Deterministically (**Lorentz Force**)
  - Non-Deterministically (Microphonics)



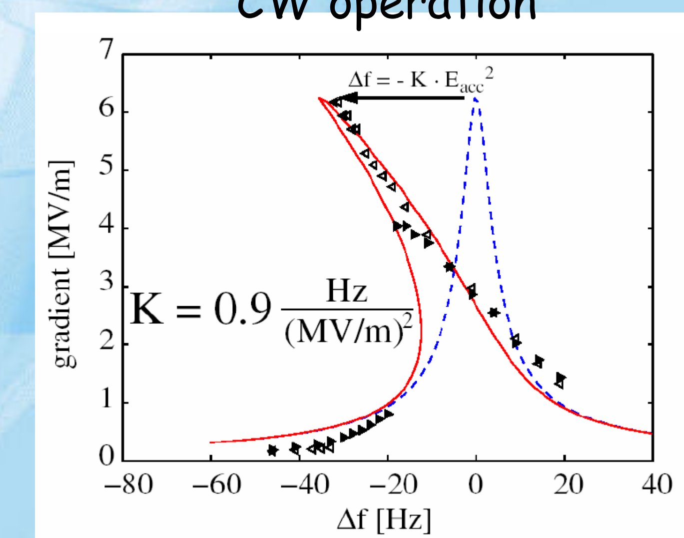
Lorentz Force Detuning

- Accelerating Electromagnetic fields in the cavity (radiation pressure) cause the cavity wall to distort
- Distortion changes the resonance frequency of the cavity
- Effect proportional to the square of the field strength ($\sim E_{acc}^2$)





Effect of Static LFD
CW operation



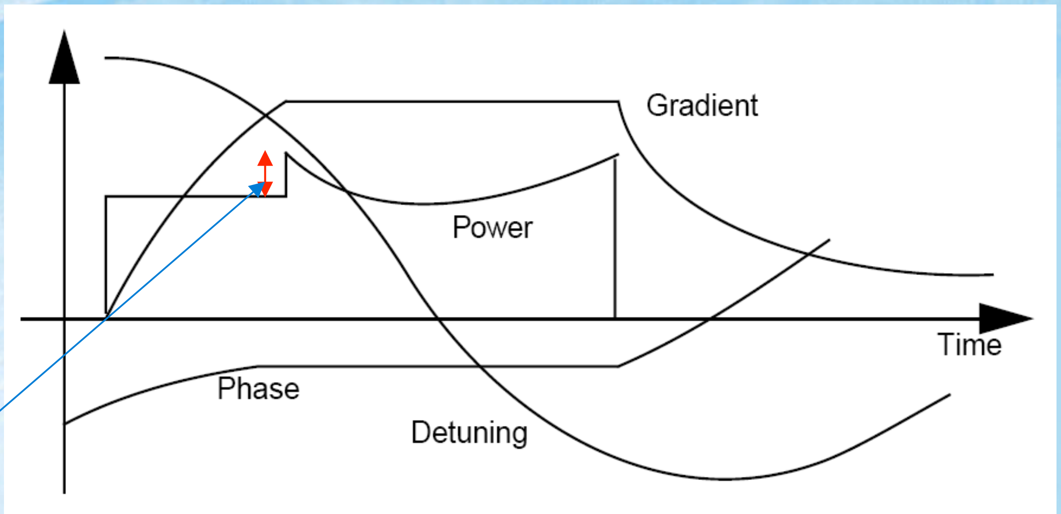
Lorentz Force Detuning

and RF Power Requirements

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

$$\Delta f_{FT} = -K_{FT} \cdot E_{acc}^2$$

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



$-K_{FT} \approx 0.5$ (for FlatTop~800us)

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

Example: **for Eacc=35MV/m up to 100-150% extra RF power:**

-Over-sized Klystron

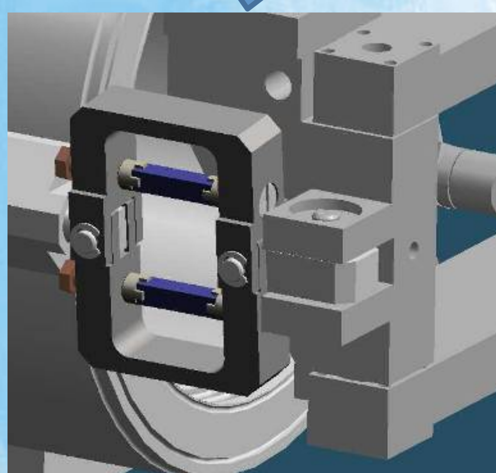
- More difficult control of RF (LLRF)

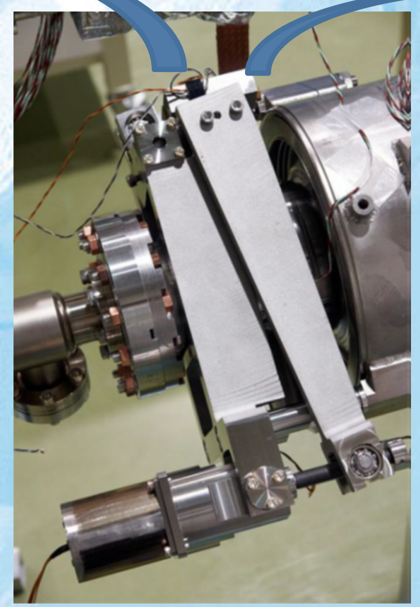
Fast (Piezo) Tuner

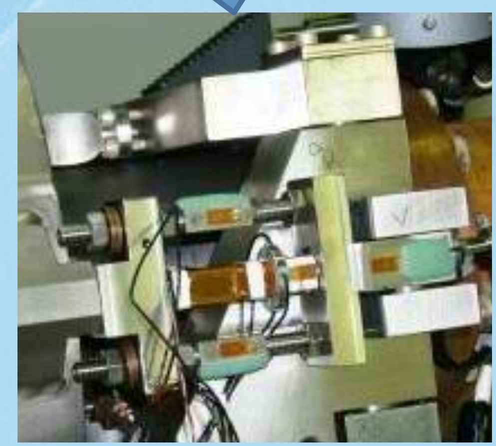
The use of piezo actuators to compensate LFD was pioneered at DESY:

<u>*M. Liepe, et. al., "Dynamic Lorentz Force Compensation with Fast Piezoelectric Tuner", PAC2001, Chicago, USA*</u>

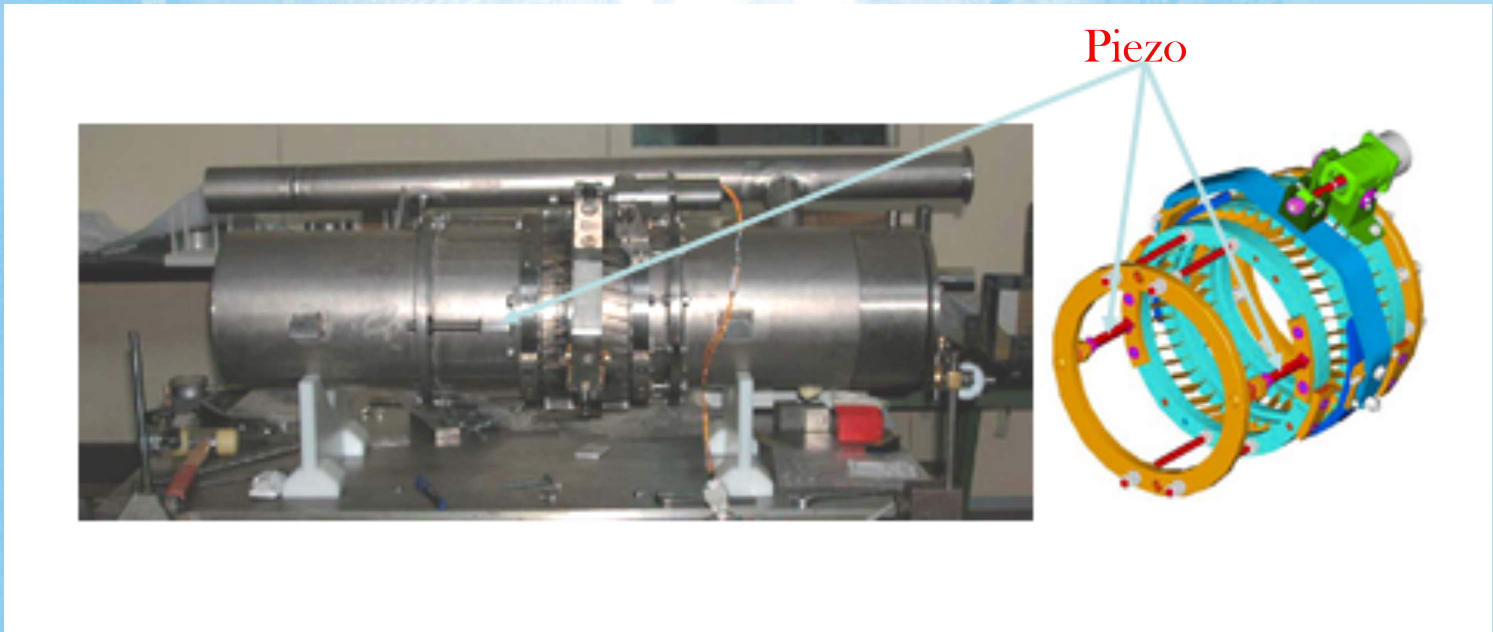
Piezo-actuators connected to the beam flange of the cavity. Piezos are driven by short electrical pulse, generate acoustic impulse. This impulse cancels detuning of the cavity induced by Lorentz forces.







Fast Tuner Integration into Blade Tuner (CM2)



Piezoelectrical actuators

PIEZOELECTRIC ACTUATORS

- ***Commercially available from multiple sources***
- ***Typically used at room temperature (stroke~50μm for 50mm long Piezostack at RT)***
- ***Work at cryogenic temperatures with reduced stroke (6-10% of RT stroke ~ 4-5μm at 4K)***
- ***Deliver high forces ~5000N for 10*10mm² cross-section***
- ***Low voltage (150-200V) actuators used for fast tuner***
- ***~10uF for stack 10*10*50mm (at RT) and 10% at LiqHe***
- ***Actuator of main choice at many labs for detuning compensation studies***
- ***Piezo can work as a sensor***
- ***Widely used in different industrial applications (diesel engine , etc…)***

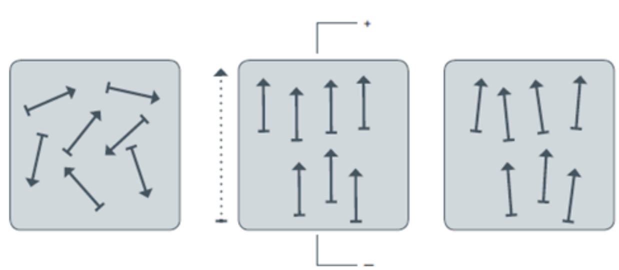
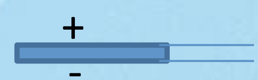


Fig.2 Electric dipoles in piezoelectric materials before, during and after poling.

Stacked multilayer piezoelectric actuators are made of two or several linear actuators glued together. The purpose of the stacking is to obtain more displacement than can be achieved by a single linear actuator.



250um

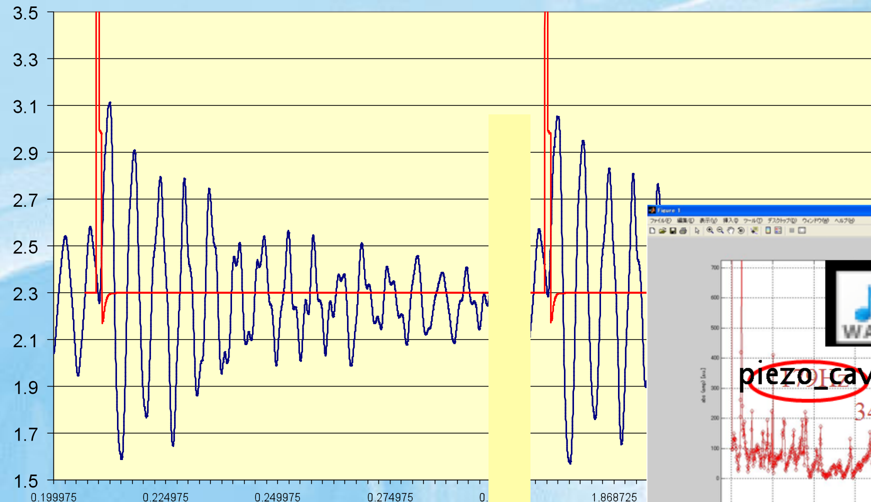
Sound of cavity vibration excited by Lorentz Force– sensor is piezo (auxialiry piezo)

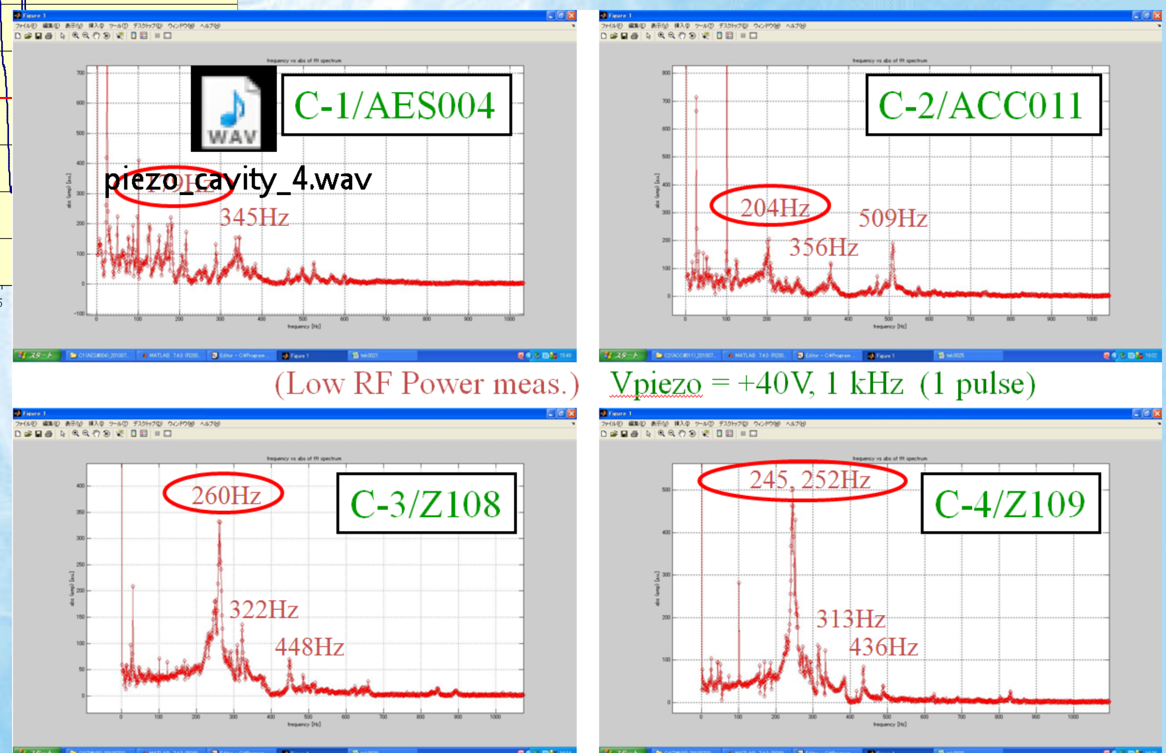
1. Cavity #4 under RF power

piezo_cavity_4.wav

2. Cavities #5,6,7… RF is Off (mechanical cross talk between cavities)

piezo_cavity_5.wav piezo_cavity_6.wav piezo_cavity_7.wav





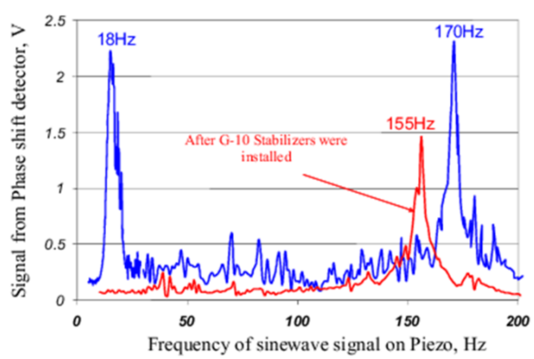


Figure 5: CC2 mechanical transfer function before and after installation of G-10 stabilizer.

LFD compensation Algorithms

- . “Standard” – exciting cavity with 1/2sine-wave form
  - Manual selection of 4 parameters:
    - Length of the piezo drive stimulus pulse (pdsp);
    - Amplitude of pdsp;
    - Delay (time in advance)
    - Piezo bias
- “Adaptive Least Square LFD compensation algorithm” – introduced and developed by Warren Schappert

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…

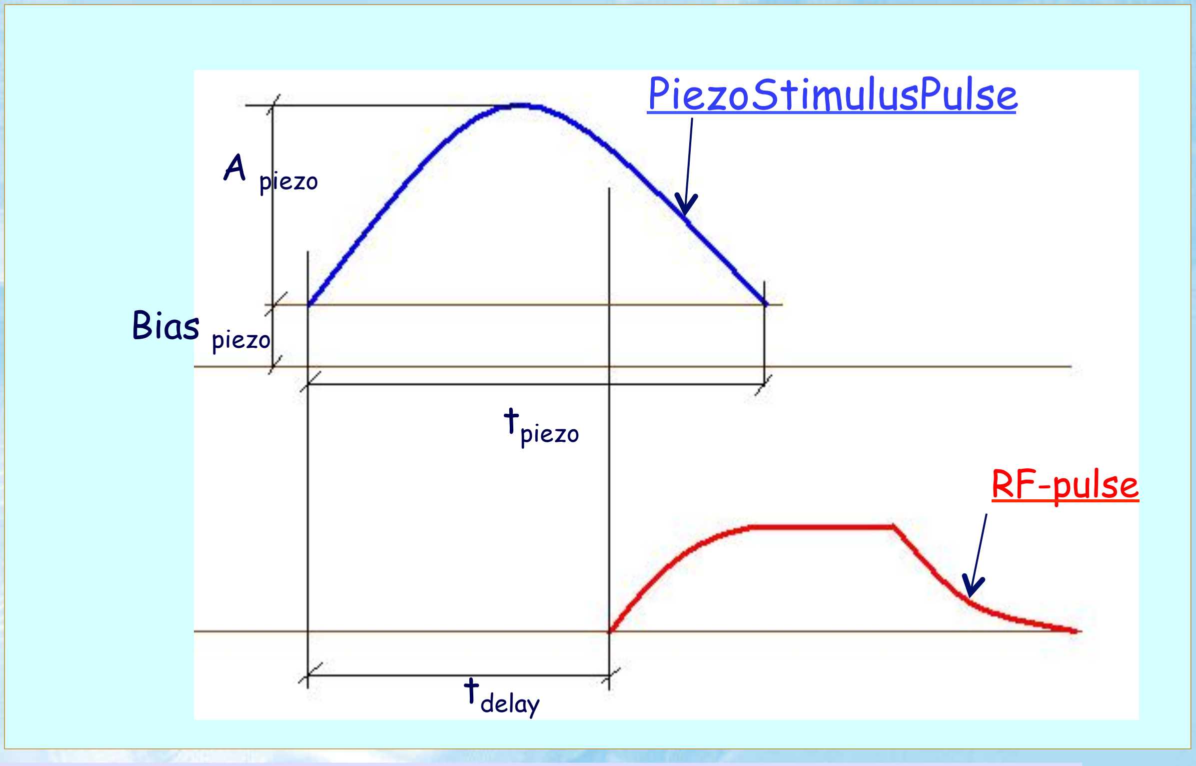
-delay between Piezo's and RF-pulses;

- 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

Adaptive Least Square LFD Algorithm

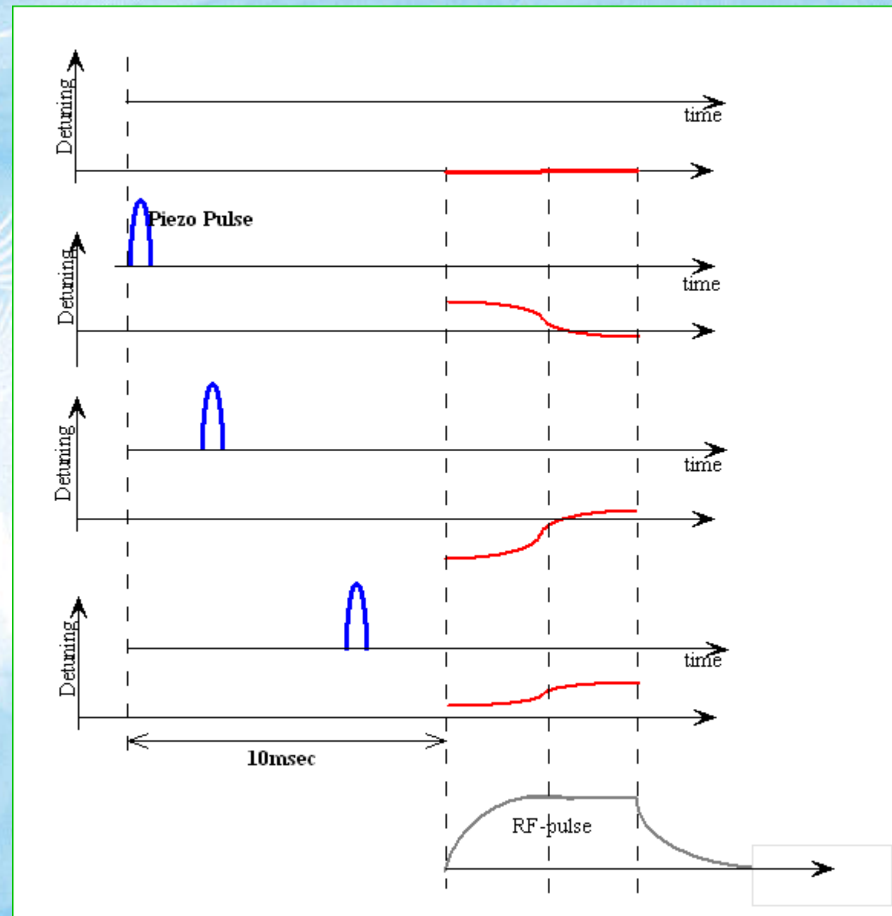
The response of the cavity frequency to the piezo impulse (TF) can be easily measured when cavity operated in CW-mode.

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]

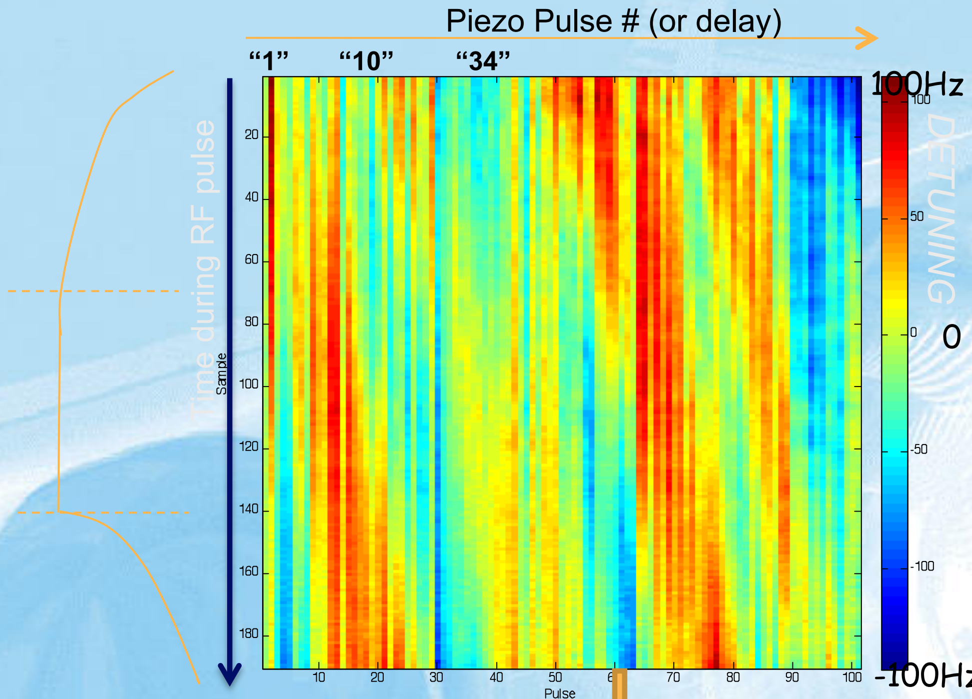


Details of Adaptive LS LFD Algorithm at :

"W. Schappert, Y.Pischalnikov, "Adaptive Lorentz Force Detuning Compensation". Fermilab Preprint –TM-2476-TD. And at PAC2011.

Adaptive LS LFD Algorithm

Response Matrix



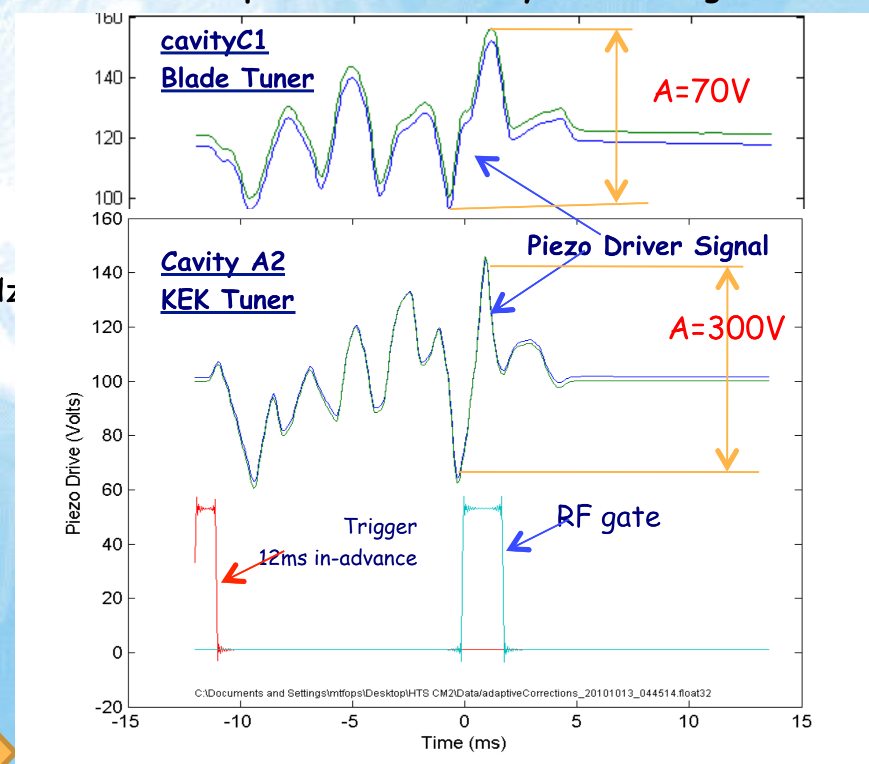
Invert the response matrix and determine combination of pulses needed to cancel out the LFD using LS

Any part of RF pulse could selected for Compensation:

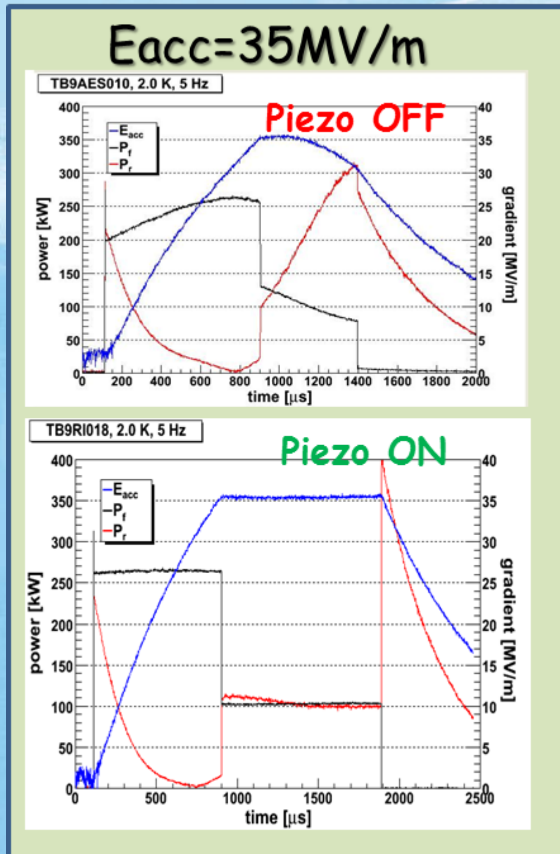
"Fill+FlatTop" only "FlatTop"

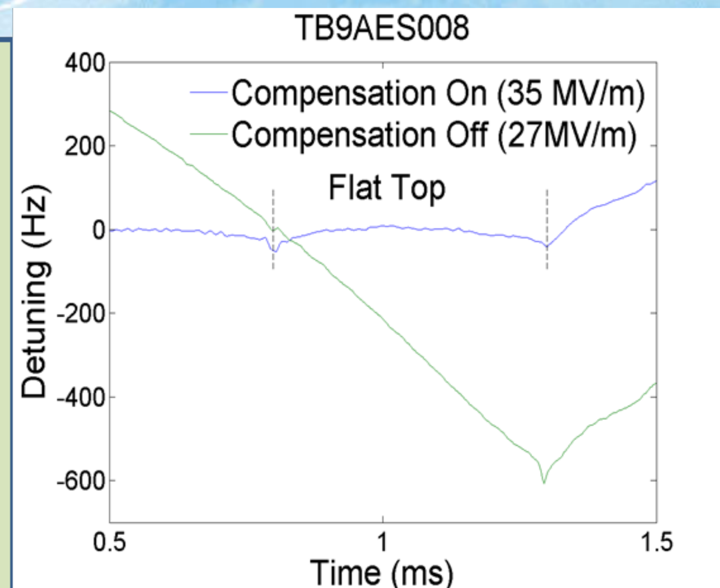
As operating conditions vary, the RF waveforms can be used to measure any residual detuning. The response matrix can then be used to calculate the incremental waveform required to cancel that residual detuning.

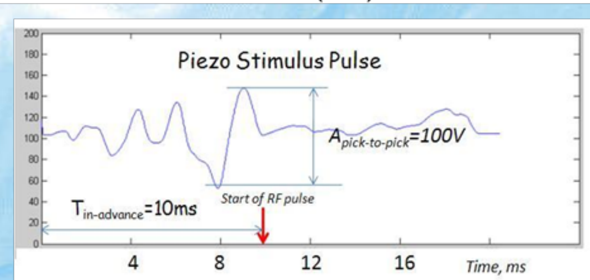
Piezo Impulse Calculated by LS LFD algorithm



Results from HTS (cavities for CM2)



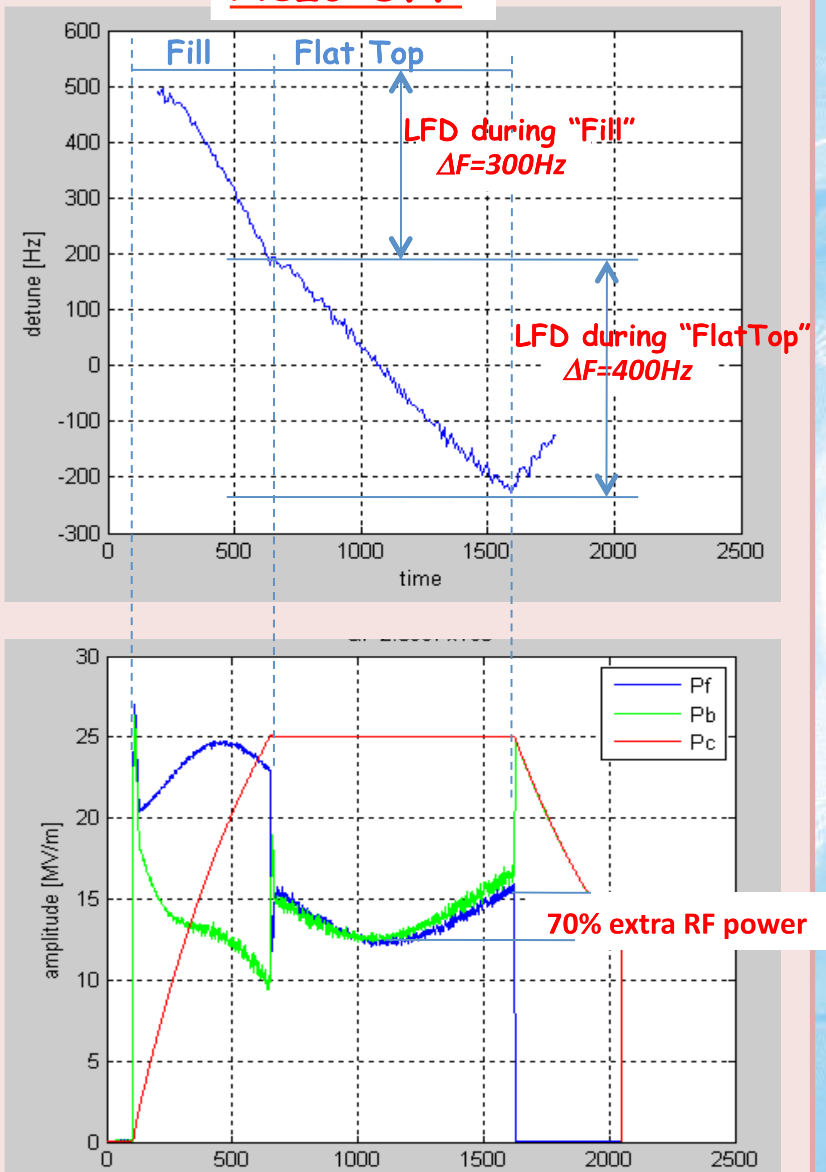




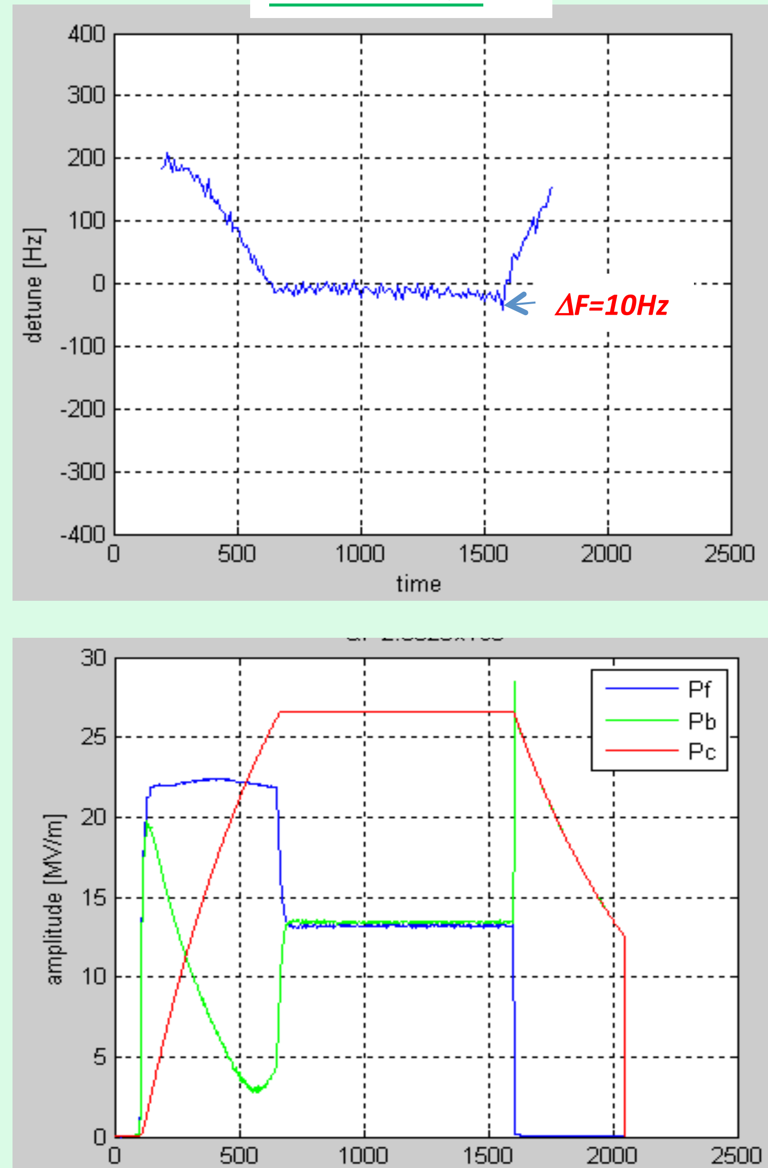
S1-Global

C4-DESY at Eacc=25MV/m
RF feedback ON; LFD Compensation “FlatTop” only

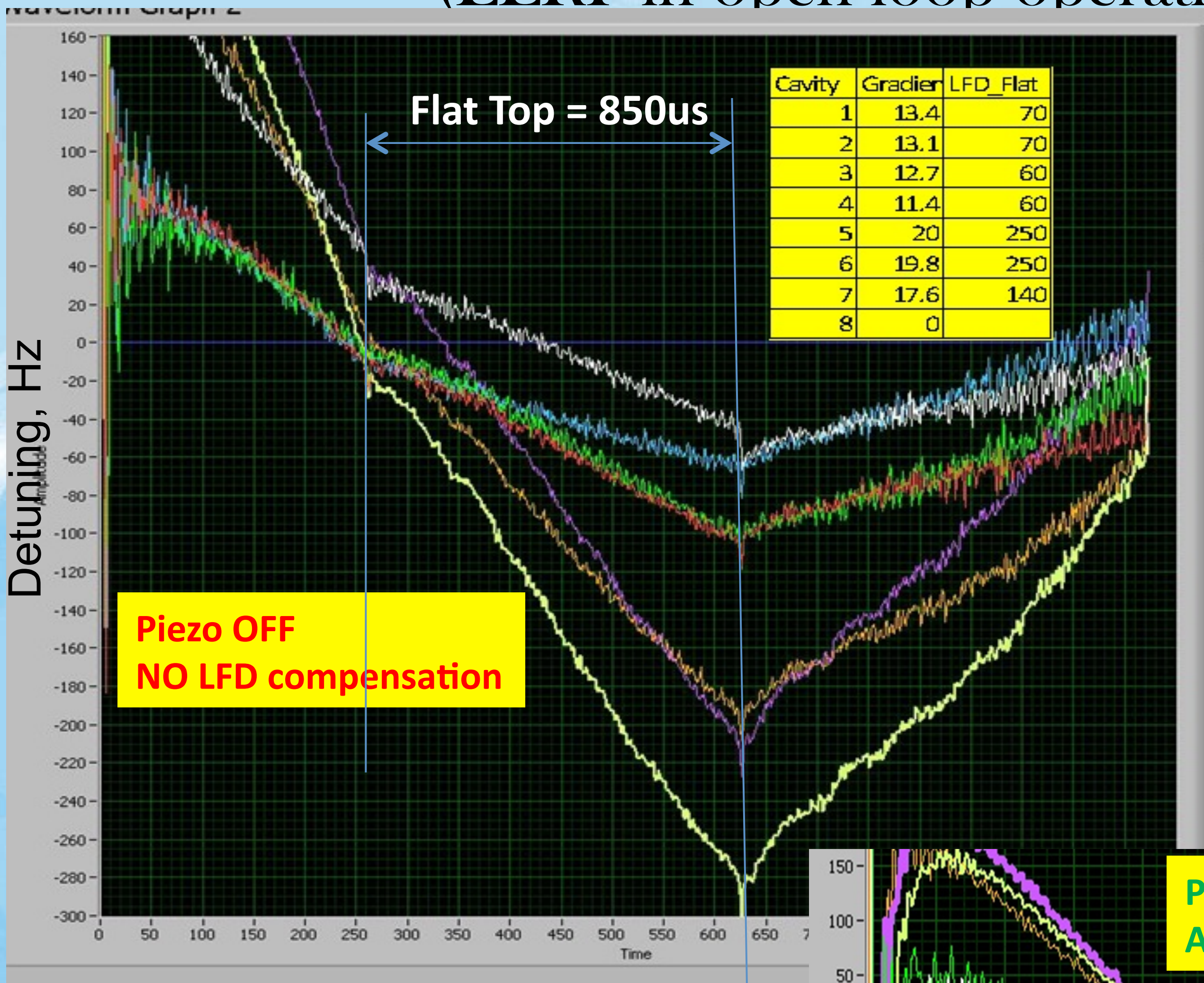
Piezo OFF



Piezo ON

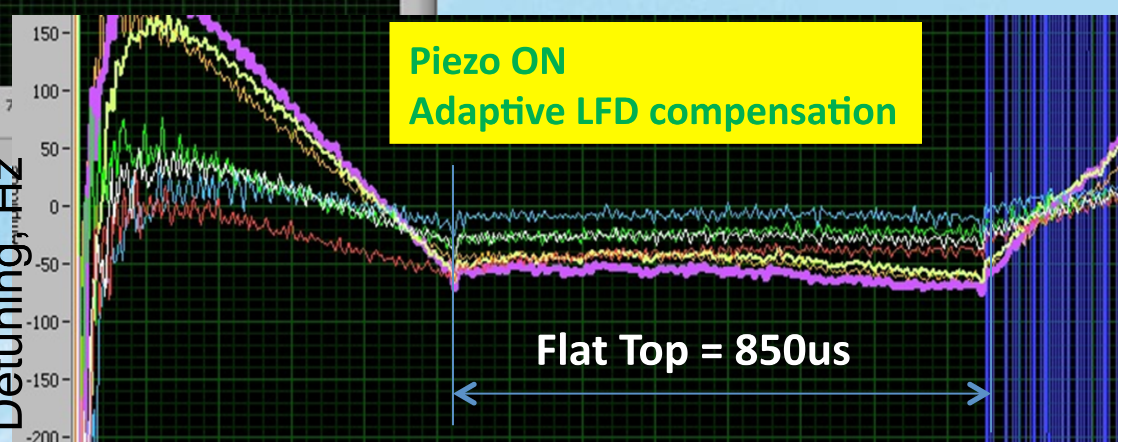


CM1- 8(7) cavities LFD Compensation (LLRF in open loop operation)



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	

Simultanious operation of 7 cavities CM1. Operating gradient range from 11MV/m (#4) up to 20MV/m (#5). Cavities tune (LFD) during "t=0.85ms flat-top" changed from 60Hz(#4) up to 250Hz (#5).

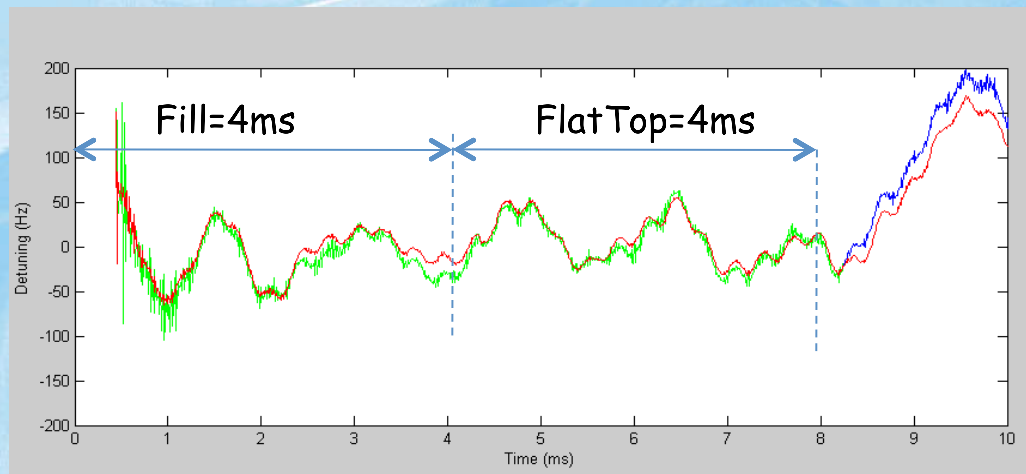


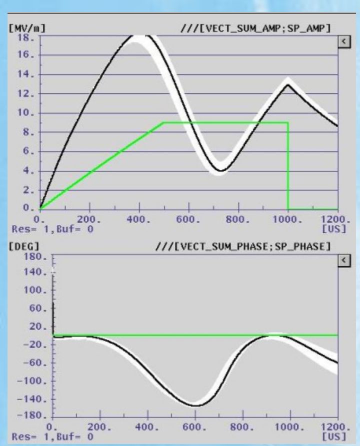
When adaptive LFD compensation system has been turn ON cavities frequency changes during "flat-top" were limited to below 10Hz.

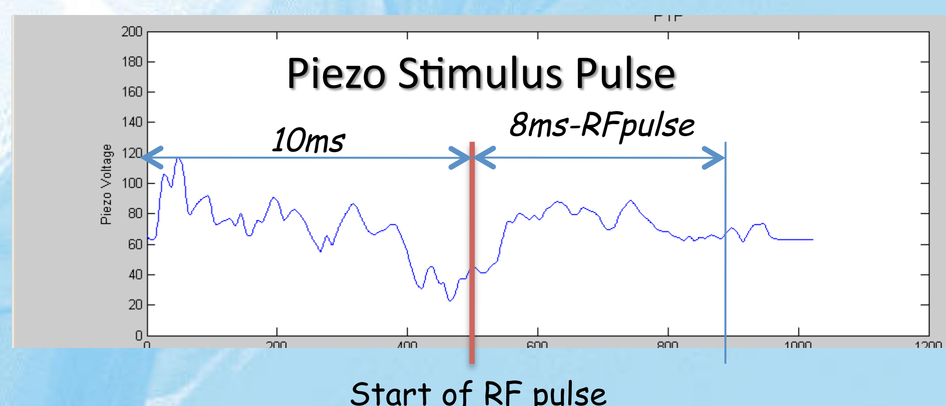
Application of Adaptive LS LFD algorithm
for long RF Pulse

(special task related to 3-8GeV pulsed linac-Project X)
test has been performed at HTS

Detuning of nine-cell elliptical cavity driven by an 8ms pulse With gradient **Eacc=22MV/m**. Cavity detuning without piezo compensation was several kHz. This was sufficient to drive cavity completely off resonance.





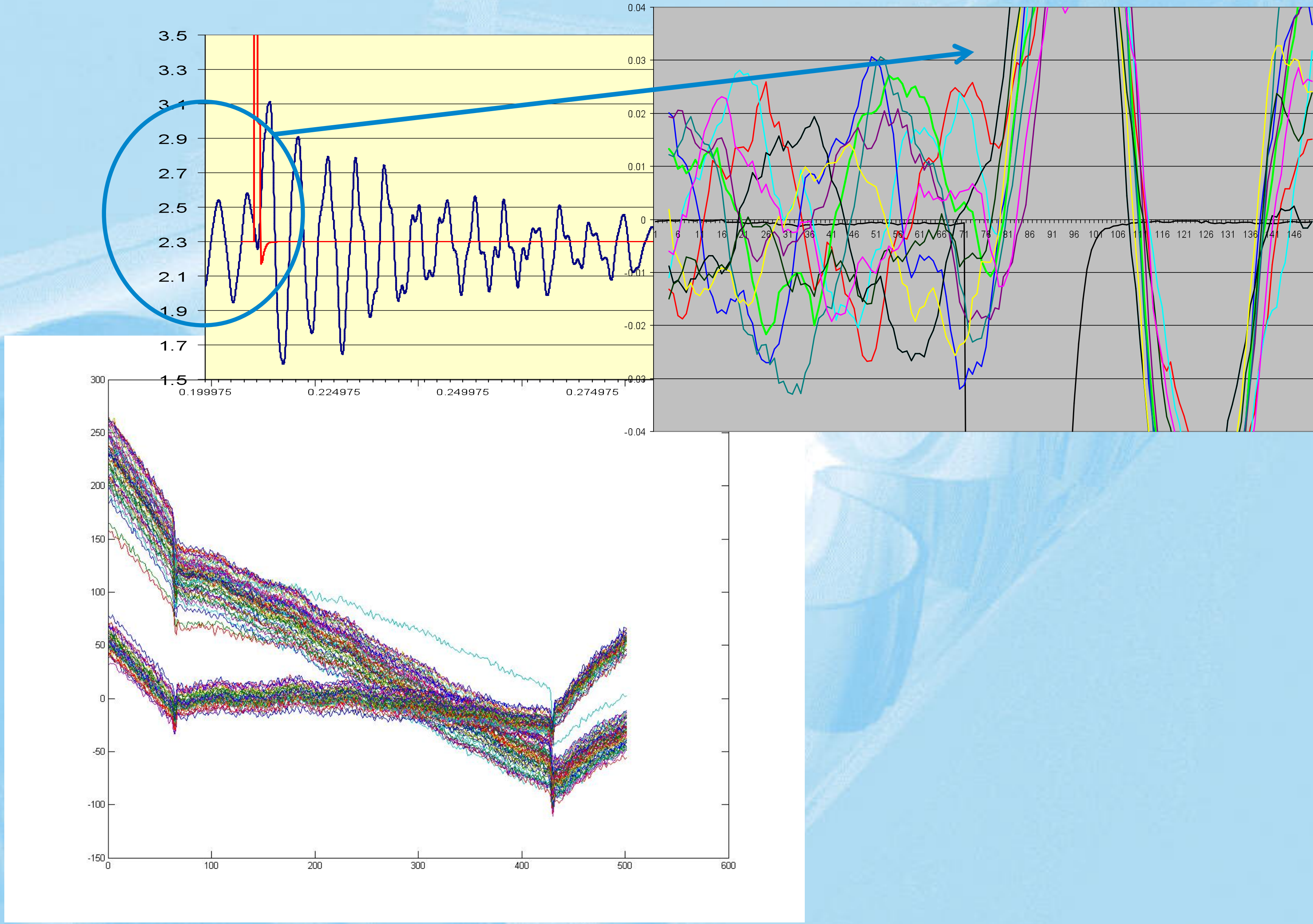


SOURCES OF MICROPHONICS

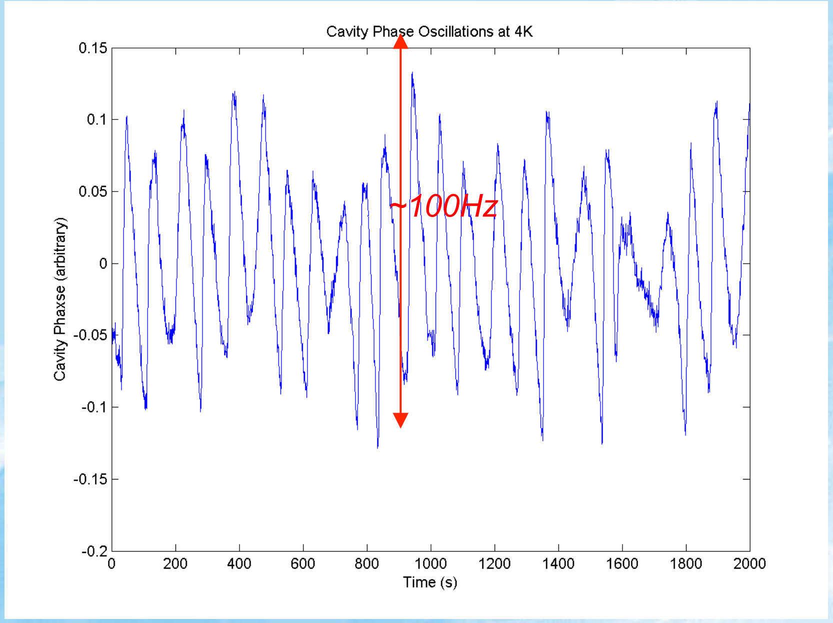
- Liquid helium pressure fluctuations can induce very slow vibrations (~1Hz-0.01Hz).
- At higher repetition rates, residual vibrations from previous RF pulses can be important.
- External noise sources such as vacuum pumps, motors, ground motion, cryo-flow induced vibration can be a significant source of detuning.

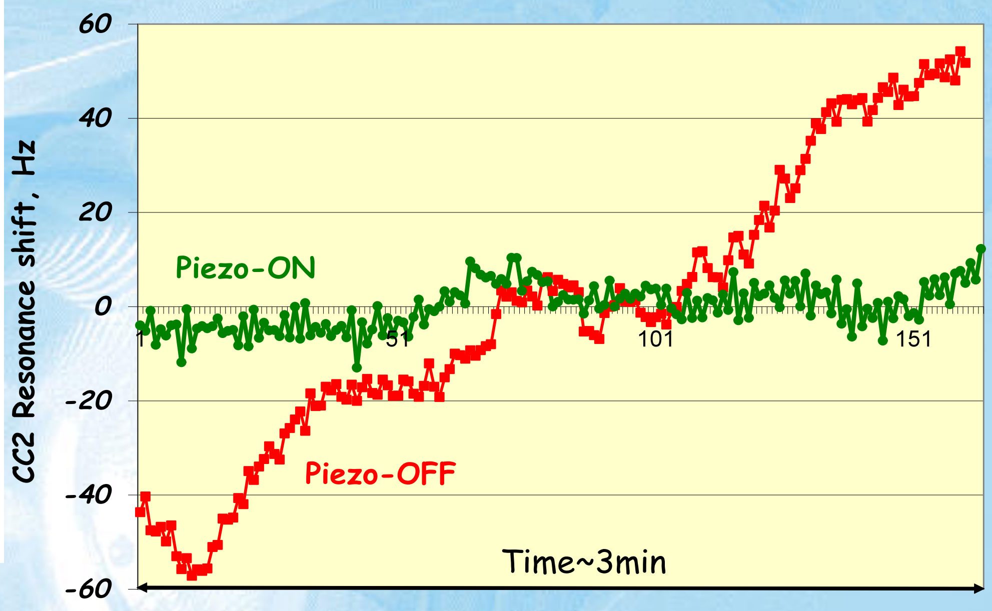
Microphonics

Effect of Cavity Residual Vibration on Resonance Stability at different repetition rates



Resonance stability -LHe Bath Pressure Fluctuations (results at 4K)





Resonance Stability of CC2 at 4K.

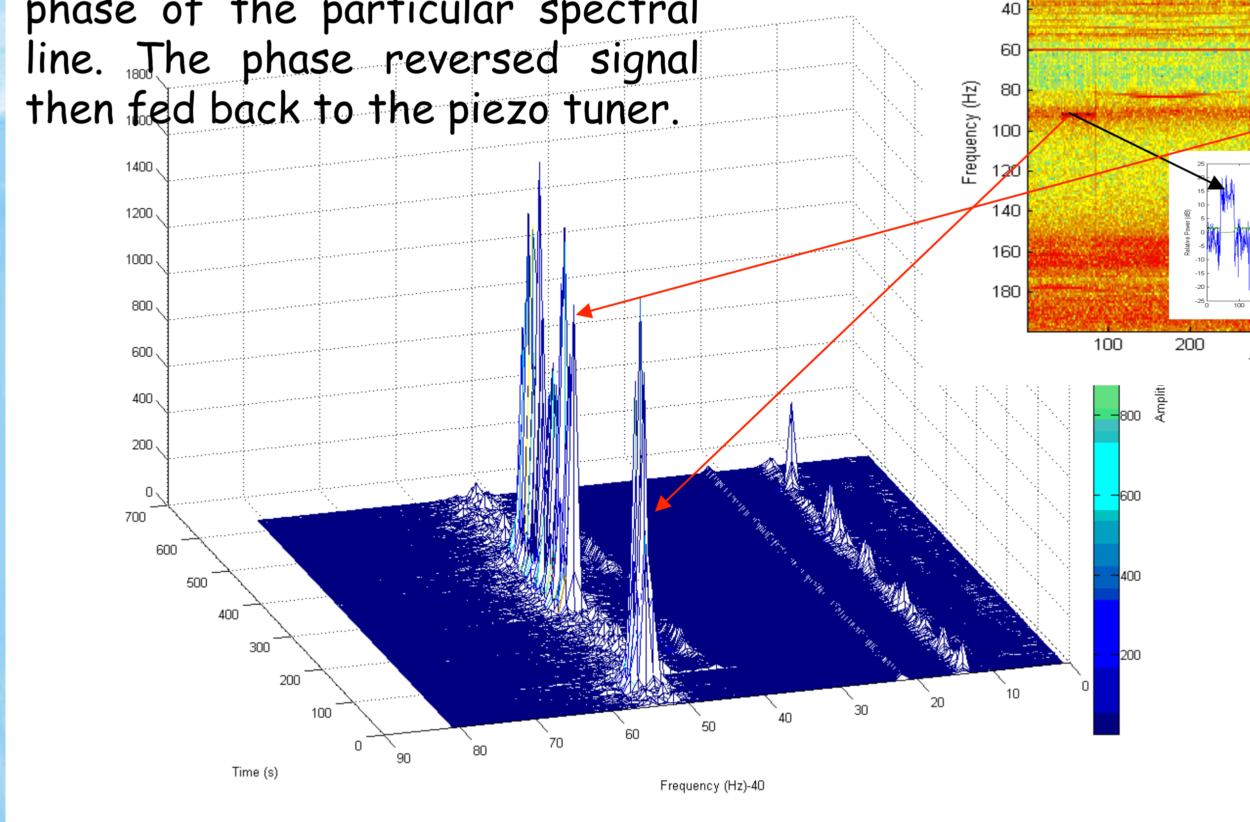
The resonance of the cavity was stabilized by
*Averaging the detuning at the center of the flattop over several pulses
*Adjusting the piezo bias voltage in a proportional loop based on the averaged detuning.

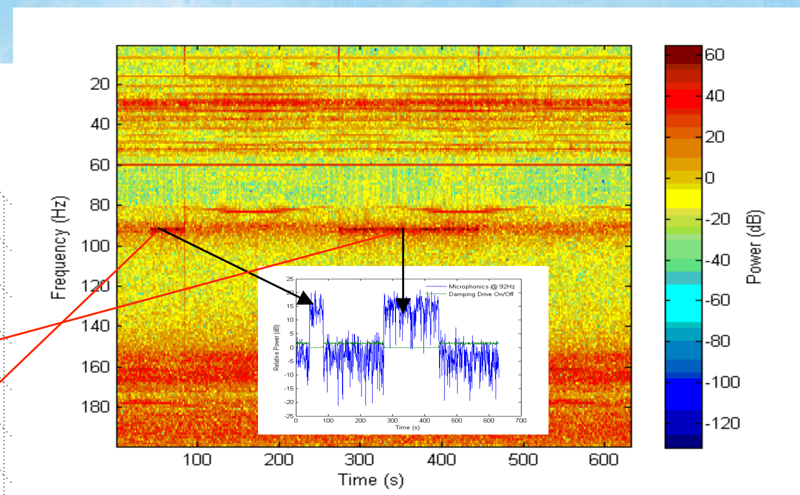
CC2 – FNAL SRF Cavity Resonance Control "sand box"

now is part of Photo-injector for NML Accelerator Physics R&D Facility

Compensation of mechanical vibrations induced by external mechanical noise sources (e.g. pumps, cranes, etc.).

The Piezo tuner actively damped vibrations induced by external sources. An IIR filter bank was used to isolate and reverse the phase of the particular spectral line. The phase reversed signal then fed back to the piezo tuner.





Active damping reduces the vibration at this frequency **by 15 dB.**

Summary

- Fast- Piezo Tuner technology for LFD is a well developed techniques with quite reliable hardware components (if design approariatly) and adaptive algorithms (feed-forward)….

  "Set it and forget it"…

- Microphonics compensation with Fast- Piezo Tuner is more in a R&D state … it is not is not yet a reliable mature technique.