Resonance Control in SRF Cavities at FNAL

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FERMILAB

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Resonance Control in SRF cavities.

The walls of SCRF cavities are deliberately kept **thin** (<=several mm) to allow the cavities to be kept **cool** but the thin walls make the cavities susceptible to **mechanical deformations** induced by:

- **The force of the accelerating electromagnetic field on the cavity walls (the Lorentz force);**
- Fluctuations in the pressure of the surrounding helium bath;
- Mechanical vibrations induced by external mechanical noise sources (e.g. pumps, cranes, etc.).

These mechanical deformations can change the resonant frequency of the cavity. For high-gradient, pulsed cavities operating in super-fluid helium, **the Lorentz force is the dominant source of cavity detuning.** If no efforts are made to compensate for LFD, cavities can dynamically detune by several bandwidths. Maintaining the accelerating gradient under these conditions would **require considerable excess RF power.**

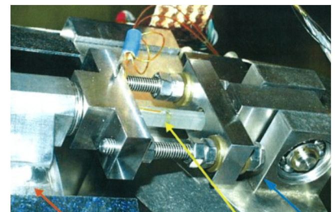
FAST TUNER/Piezo Actuators

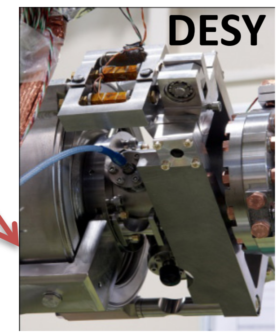
The use of piezo actuators to compensate LFD was pioneered at DESY:

M. Liepe, et. al., "Dynamic Lorentz Force Compensation with Fast Piezoelectric Tuner", PAC2001, Chicago, USA

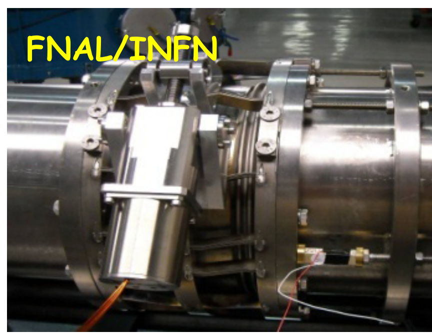
Piezo-actuators connected to the beam flange of the cavity. Piezos are driven by short electrical pulse, generate acoustic impulse. This impulse cancels detuning of the cavity induced by Lorentz forces.

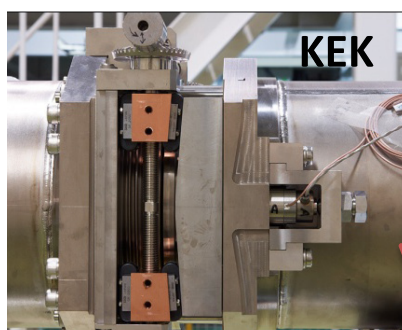
Tuner Designs





Many different implementations of Fast Tuner for SRF cavities done (just few examples).





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…

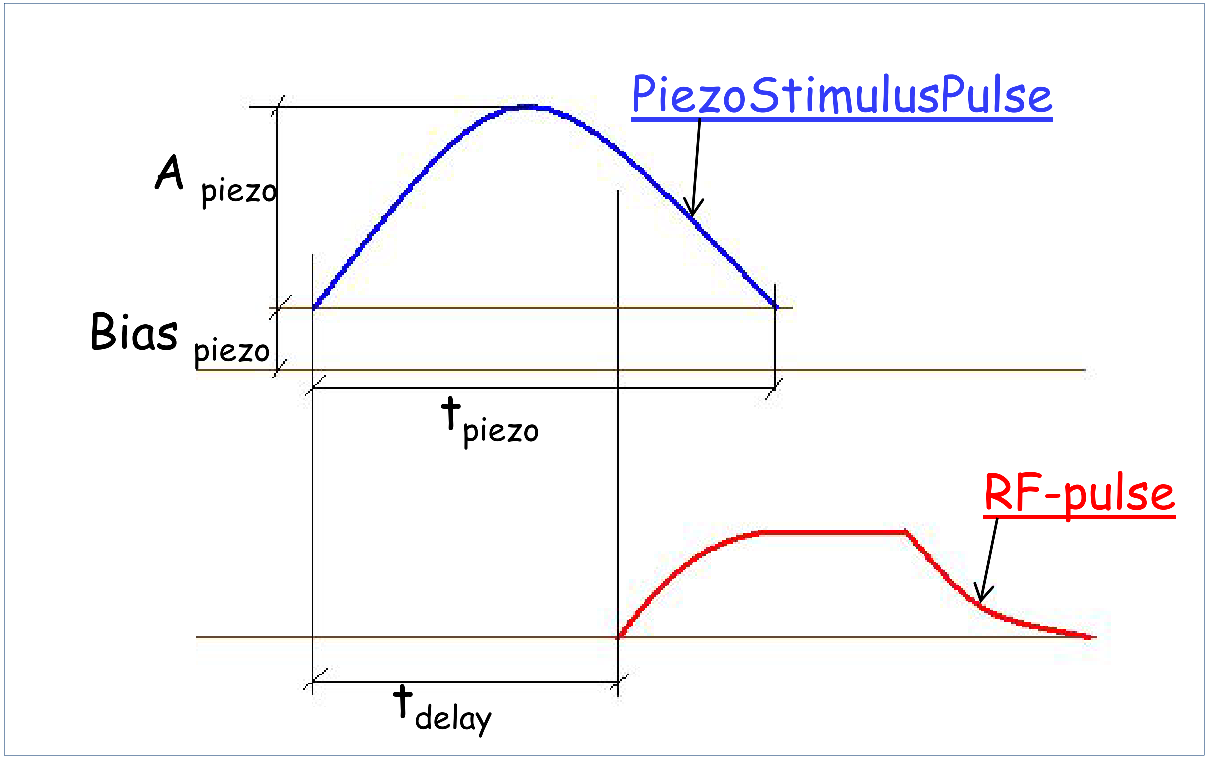
-delay between Piezo's and RF-pulses;

- 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…

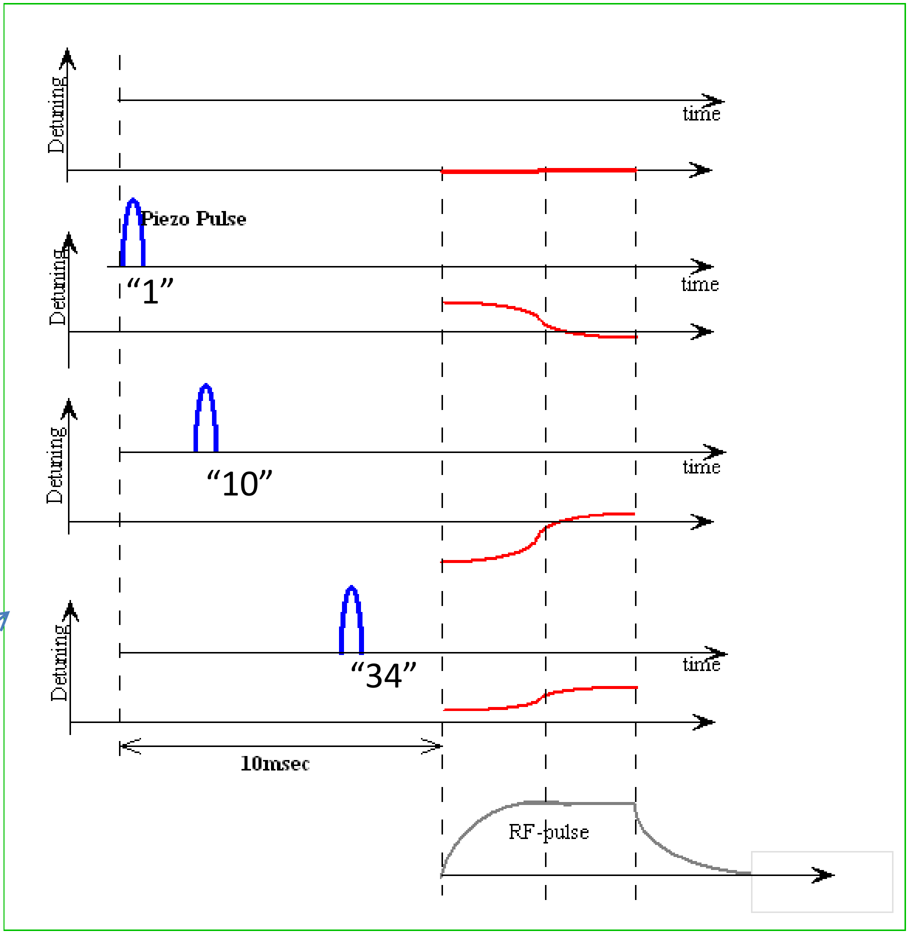
Also "short unipolar pulse" approach will not work for cavities where the length of the RF pulse is comparable or greater than the period of the dominant mechanical resonance

Adaptive Least Square LFD Algorithm

has been developed at Fermilab as a part of SRF Resonance Control R&D program
(Developed by 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.

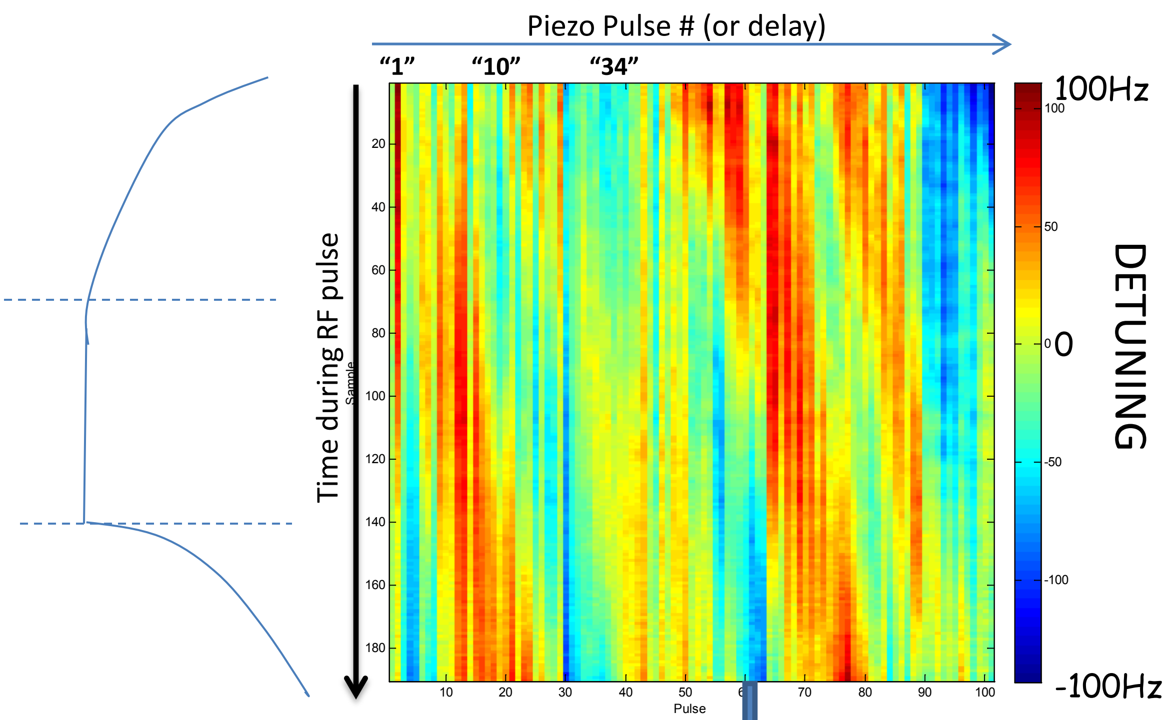
Piezo/cavity excited be sequence of small (several volts) narrow (1-2ms) pulses at various delay.
The forward, probe and reflected RF waveform recorded at each delay and used to calculate detuning.
[Response Matrix]



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

Adaptive LS LFD Algorithm

Response Matrix

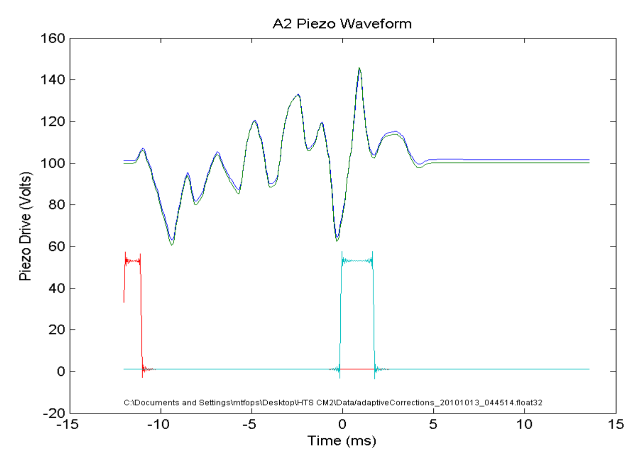


As operating conditions vary, the RF waveforms can be used to measure any residual detuning. The response matrix can then be used to calculate the incremental waveform required to cancel that residual detuning.

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:
<u>“Fill+FlatTop”</u> only <u>“FlatTop”</u>

Optimal Compensation Pulse

<u>for 1.3GHz 9cell cavity equipped with KEK tuner</u>



Applications of Adaptive LS LFD Algorithm:

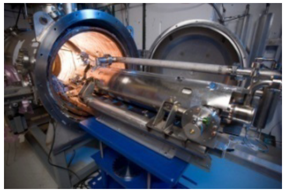
at HTS (9-cell 1.3GHz cavity with Blade tuner);

at CM1-NML facility (9-cell 1.3GHz with DESY tuner);

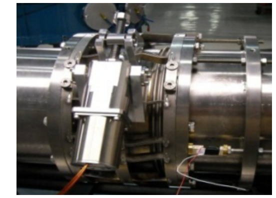
S1-Global(9-cell 1.3GHz with 4 different type of tuners);

9-cell 1.3GHz cavity with RF-pulse 8ms long;

SSR1- single spoke cavity.

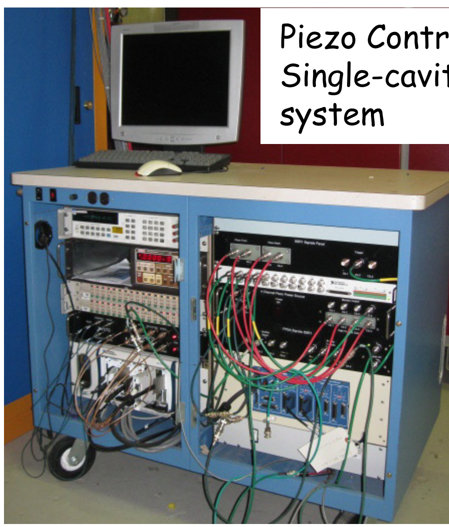


Horizontal Test Stand
at MDB FNAL



Objectives: to test dressed 1,3GHz cavity for construction of cryomodules #2 to #6 for NML Accelerator Physics R&D Facility
Cavity's selection criteria – capability to operate at E_{acc}>35MV/m

LFD during 0.8ms pulse cold be **more than 1000Hz**
LFD compensation goal: ΔF less than 20Hz



Piezo Control System routinely used for QA tests of cavity/tuner system with Eacc up 35MV/m

10 dressed cavities have been tested

Cavity	Max gradient
TB9AES004	31 MV/m
TB9ACC013	> 35 MV/m
TB9AES009	35 MV/m
ACCEL8	32 MV/m
TB9AES010	> 35 MV/m
TB9AES008	> 35 MV/m
TB9ACC016	19 MV/m
TB9RI029	29 MV/m
TB9AES007	33 MV/m
TB9RI018	> 35 MV/m

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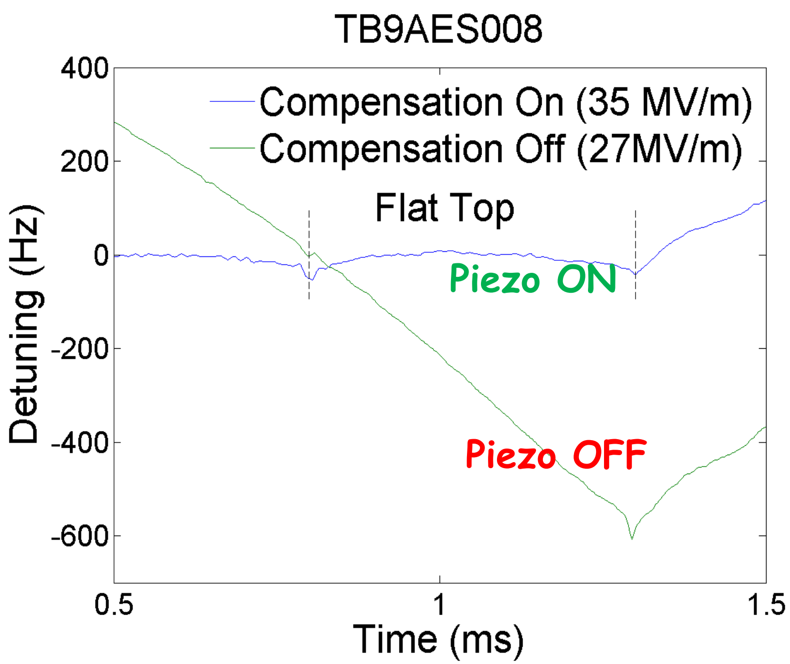
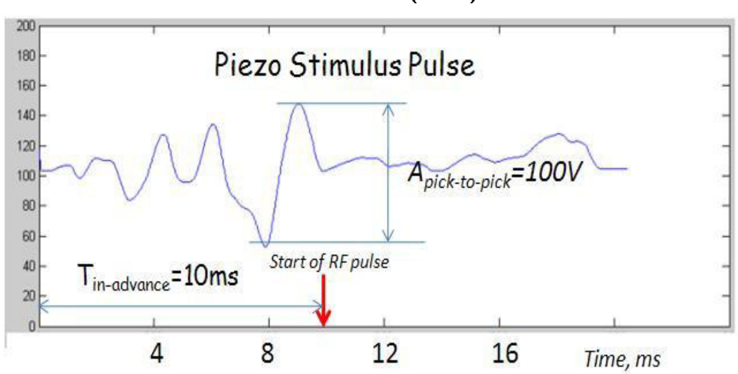
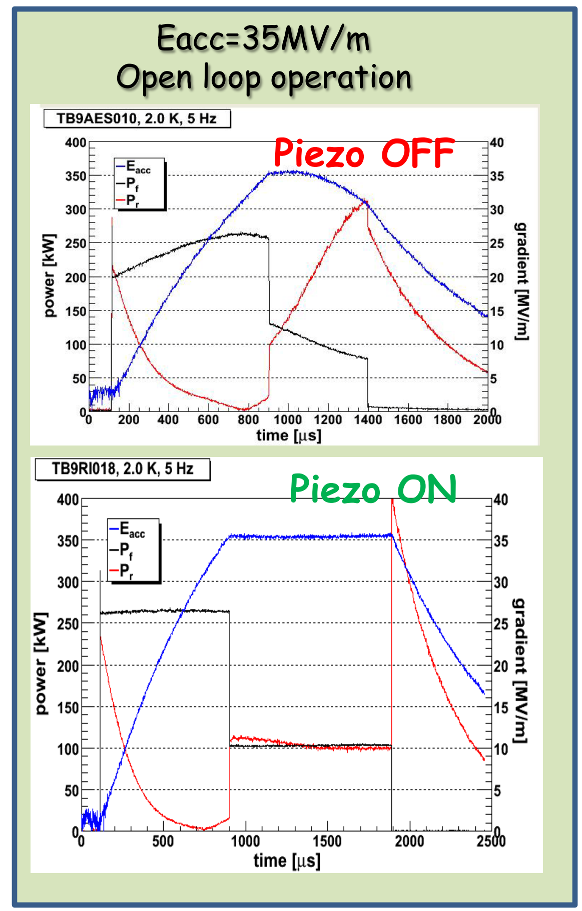
HTS at MDB FNAL

LFD during 1,3ms RF-pulse (Fill+FlatTop) was ~**2300Hz**

LS LFD compensation -- to less than **20Hz** during 1,3ms pulse

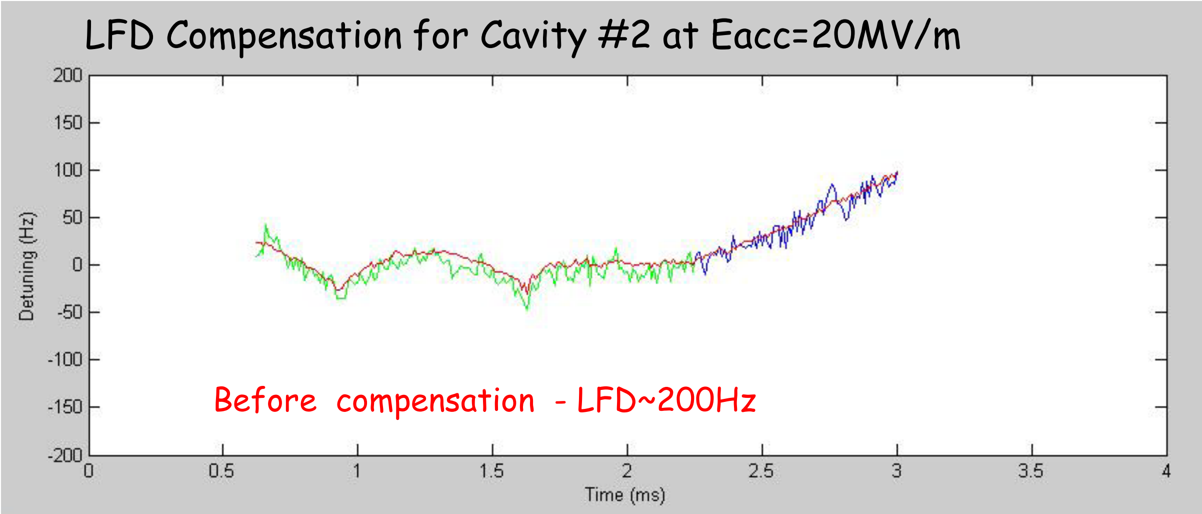






CM1 at NML

- Commissioning of the CM1 in under way. LFD compensation on the cavities with "single cavity FNAL's compensation system".



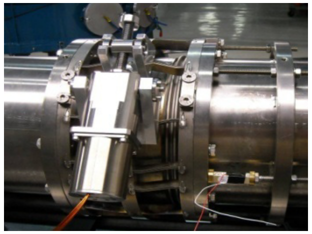
- We are working to deploy a multi-cavity compensation system as a part of LLRF:

    resonance control task will run on MVME5500LLRF controler

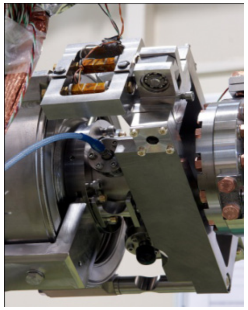
    transfer Matlab code to C (using Embedded Matlab Compiler)

S1-Global

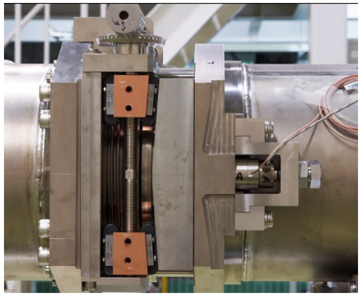
FNAL's team built and delivered to KEK piezo control system (copy of HTS system). LS LFD algorithm has been used for LFD compensation on 4 different type of cavity/tuner systems...



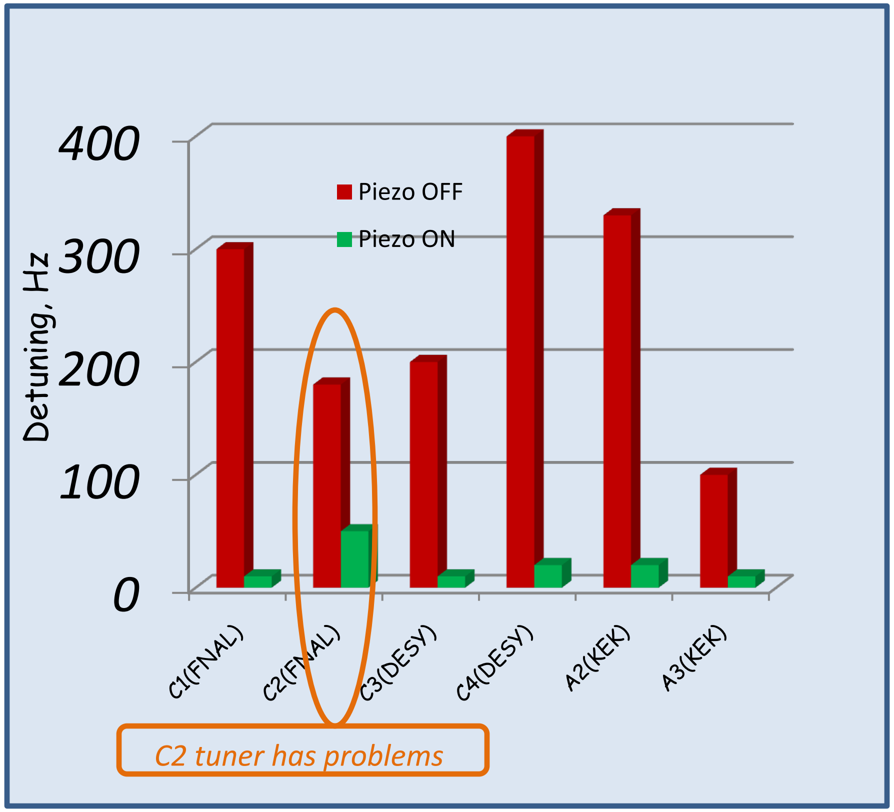
Blade Tuner(FNAL/INFN)



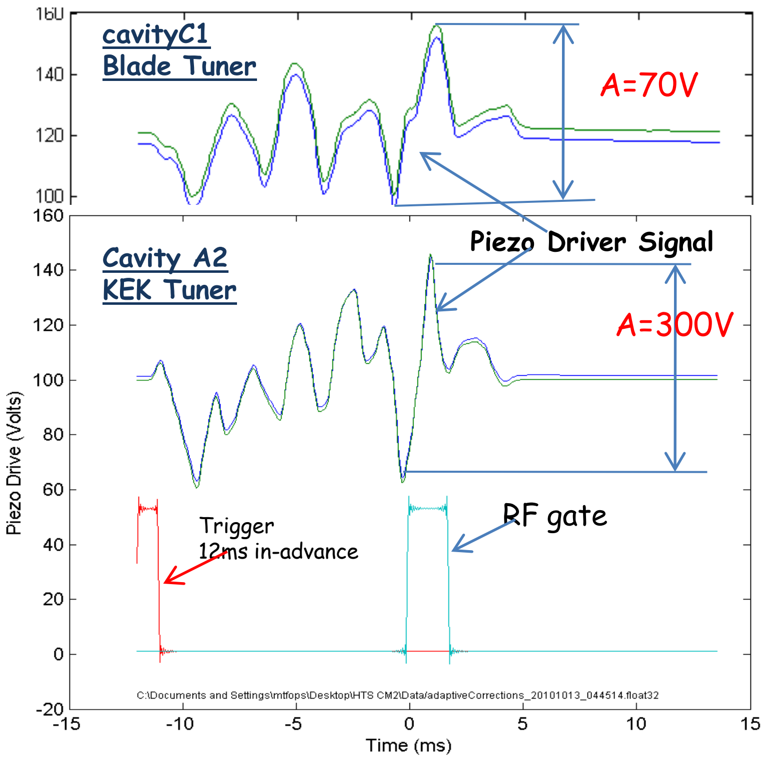
DESY/Saclay Tuner



Slide-Jack Tuner (KEK)

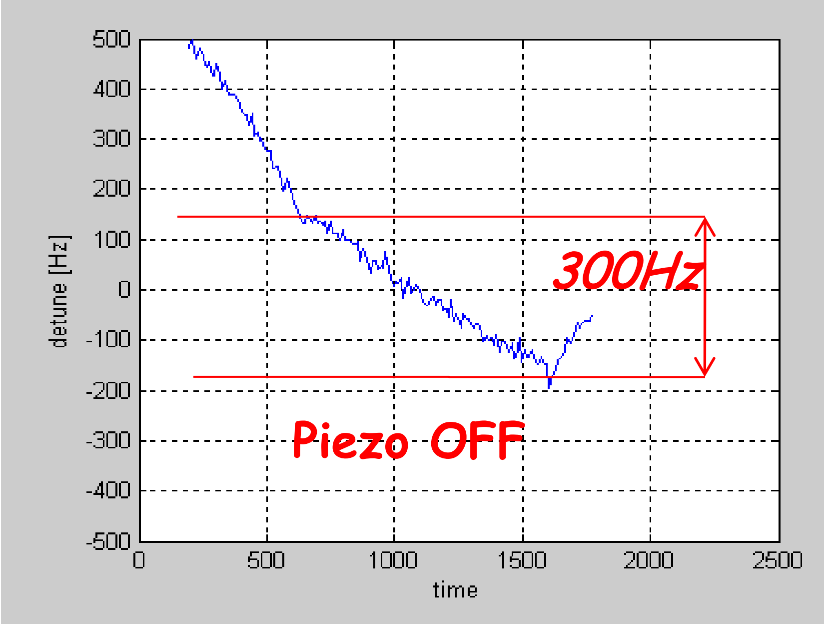


Piezo Impulse Calculated by LS LFD algorithm

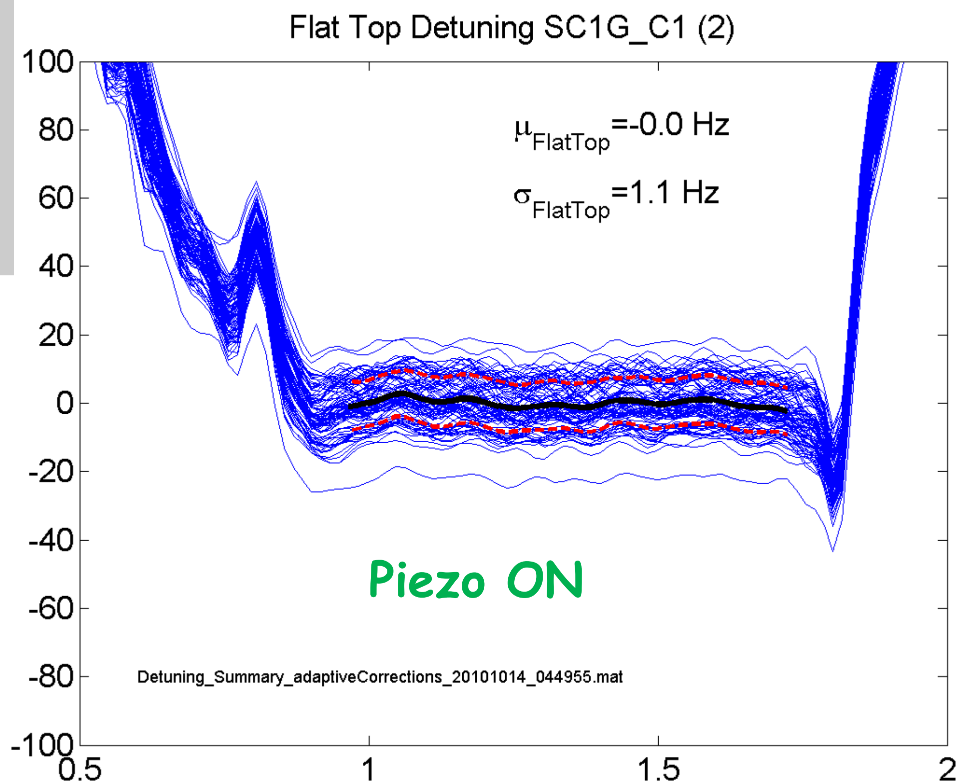


S1-Global

Eacc=27MV/m
S1-G C1 (Blade Tuner) cavity
LLRF feed back ON



Compensation only during Flat-Top

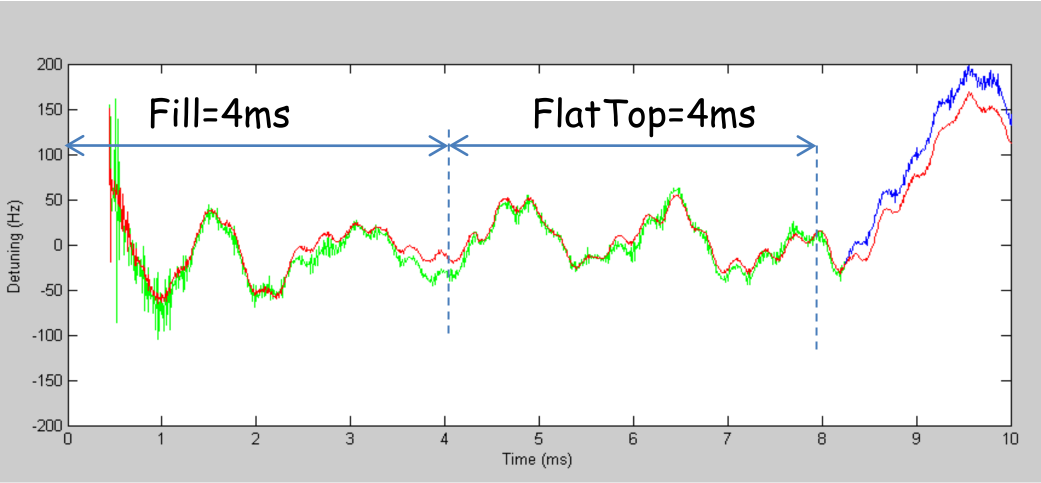


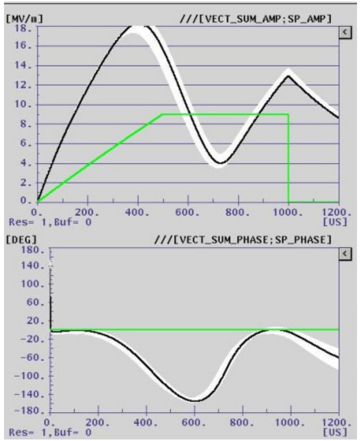
Application of Adaptive LS LFD algorithm

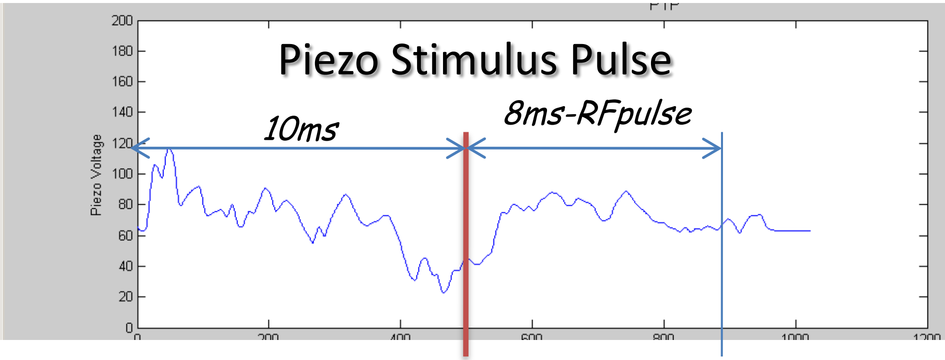
for long RF Pulse

("proof-of concept" test 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 aprox. several kHz.
This was sufficient to drive cavity completely off resonance.







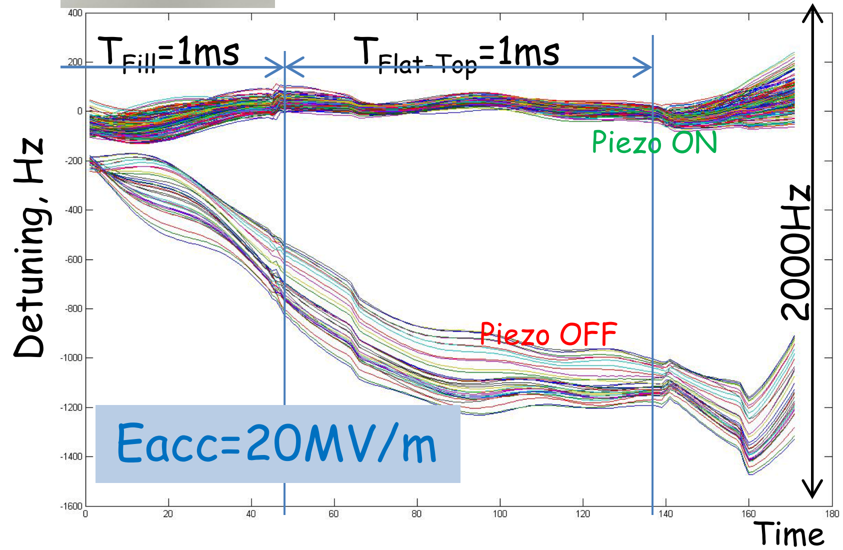
Start of RF pulse

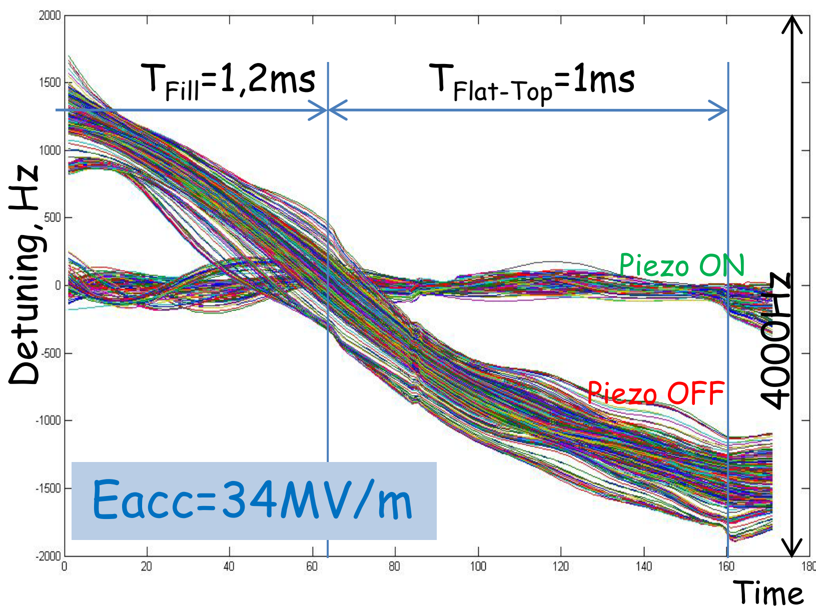
325MHz Spoke Cavity (SSR1)

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

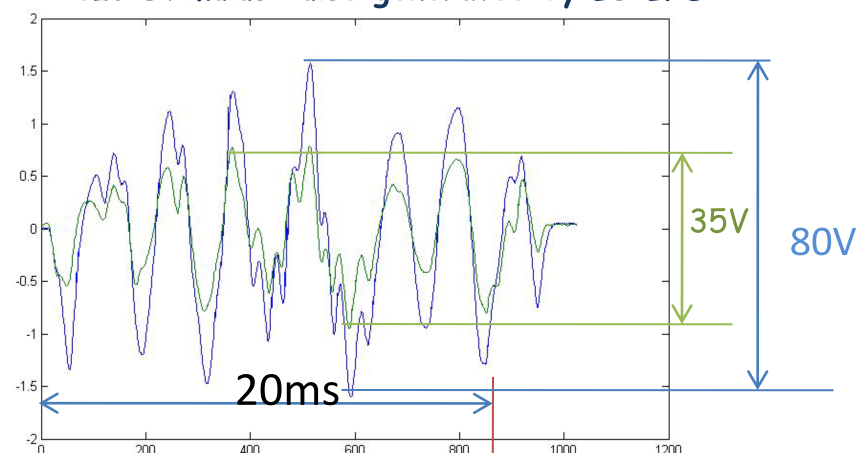
Eacc	Piezo OFF	Piezo On	(ApiezoV)
20MV/m	500Hz(1000Hz)	30Hz	35V(18%)
34MV/m	1500Hz(3500Hz)	75Hz	80V(40%)

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



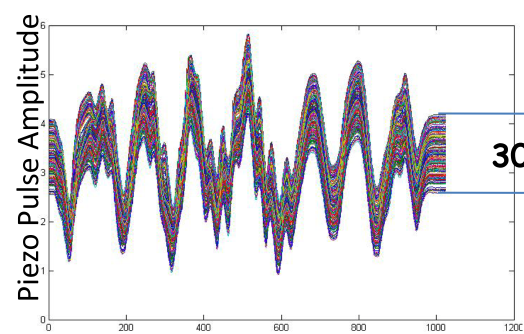


Piezo Stimulus Pulse generated by LS LFD



4,5 K LiqHe bath pressure compensation

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



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FNAL's Microphoncs Compensation R&D program
(for Project X)

Piezo actuators used to reduce microphonics in CKM cavities by 20 dB (Carcagno et al. 2003 (FNAL))

BESSY able to limit pressure related detuning in 1.3 GHz CW cavities to less than 1 Hz (Axel Neumann Thesis)

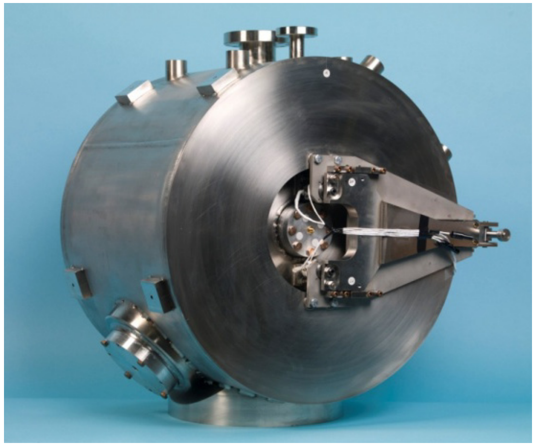
Other work by groups at MSU, Cornell, Argonne, JLab, …

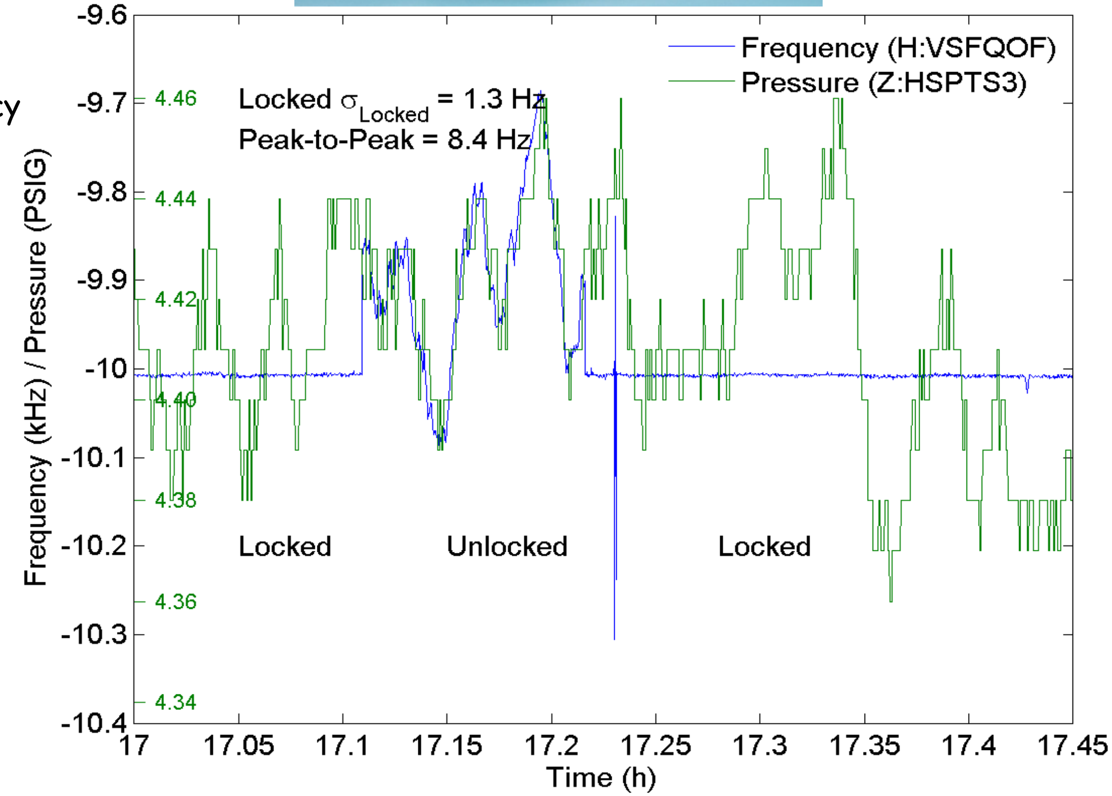
Compensation of fluctuations in the pressure of the surrounding helium bath;

SSR1 with Narrow Bandwidth Coupler

- Initial cold tests of SSR1 using CW provided an opportunity to gain experience with a very narrow bandwidth cavity
  - Test Conditions
    - 4.5K
    - Cavity bandwidth of about 1.5 Hz
    - df/dP **~= 140 Hz/torr**
    - dP_{PTP}~=**5 torr**
    - LLRF tracking resonant frequency of cavity
  - Detuning control system
    - 100 kHz digitizer measured RF frequency offset from an arbitrary set point
    - FPGA fed Δf back to fast tuner
- Reduced pressure related variations in cavity frequency from several hundreds Hz to

Δf <= 1.3 Hz RMS



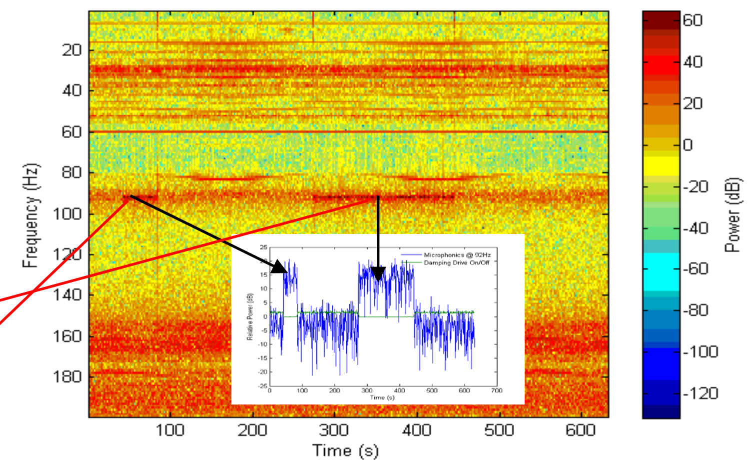


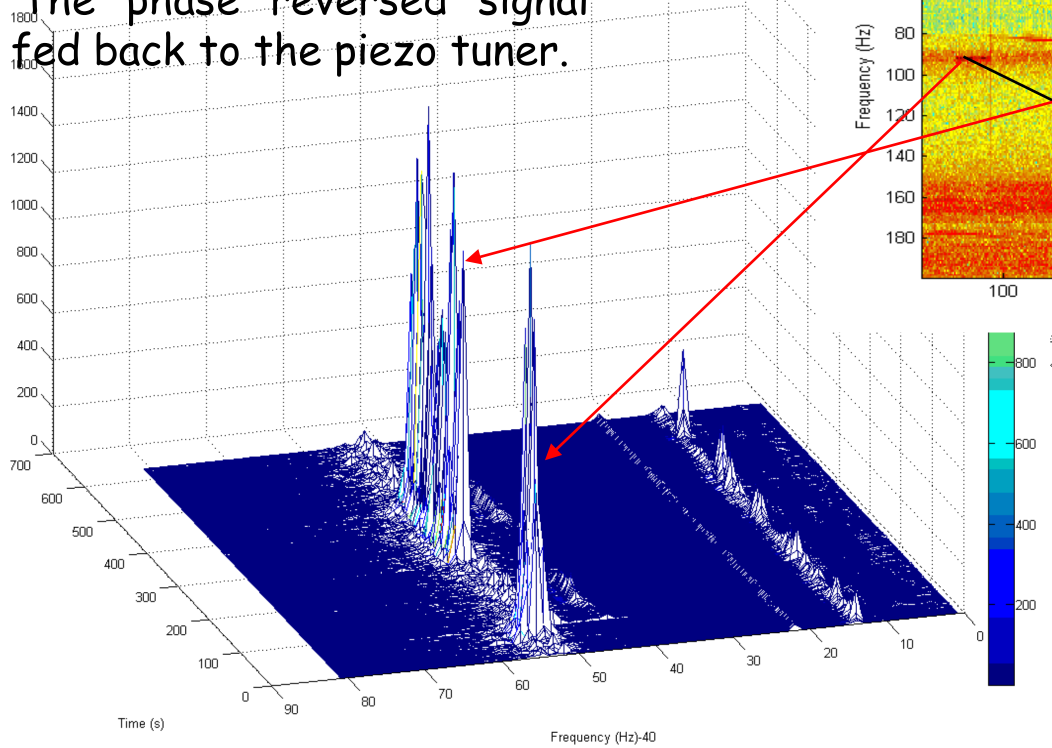
CC2 – FNAL SRF Cavity Resonance Control "sand box"

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 (1)

An adaptive procedure has been developed at Fermilab to compensate for Lorentz force detuning in SRF cavities.

The procedure can automatically characterize the response of individual cavities to the Lorentz force and to the compensation actuator.

The measured response is used to automatically calculate an appropriate compensation waveform and adapt that waveform to changing cavity operating conditions.

The procedure has been successfully used to compensate a variety of cavities at Fermilab and elsewhere.

Summary (2)

FNAL's Resonance Control group shifting efforts to Microphonics compensation R&D program.

Preliminary results:

- He bath pressure fluctuation could be reduce to less than σ~1Hz (even at 4,5K operation for cavity with dF/dP~140Hz/torr)
- Illustrated ~15d active compensation of detuning induced by external mechanical noise at particular frequency.