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Status of the SRF Cavities Resonance Control R&D Work at FNAL

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in behalf of FNAL resonance control team

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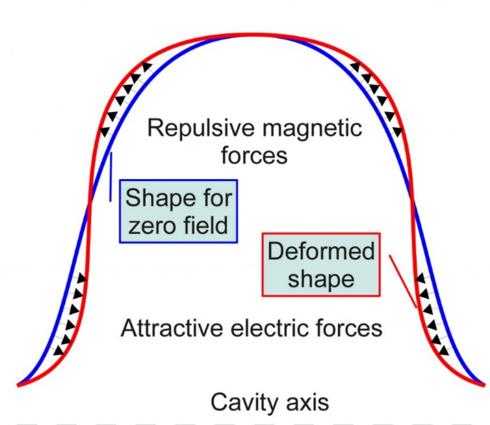
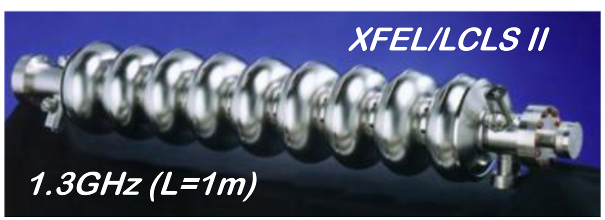
SRF Cavity Detuning

- SRF cavities manufactured from thin sheets of niobium to allow them to be cooled to superconducting temperatures
- Thin walls make cavities susceptible to detuning from
  - Pressure variations in the surrounding helium bath (dF/dp)
  - Radiation pressure from the RF field (Lorentz Force Detuning - LFD)
  - External vibration sources (microphonics)



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

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

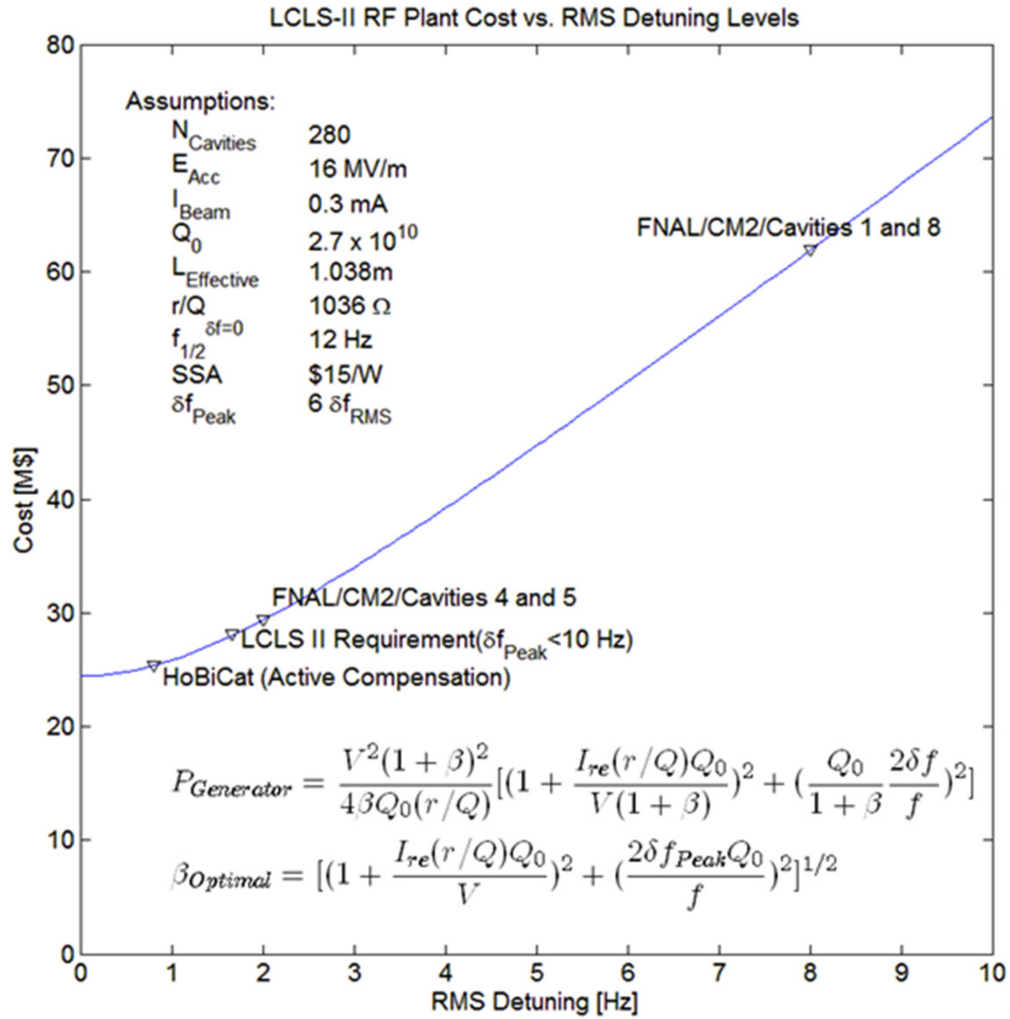


At the FNAL CM 2 cavity run with RF-pulse (Eacc~20-25MV/m)
Piezo is working as a sensor… recording cavity vibrations induced by LFD

Controlling cavity resonance to less than <u>20Hz</u>
Equivalent to control cavity length to <u>60nm</u>

The Cost of Cavity Detuning

- Operating detuned cavities is more expensive
  - If sufficient RF power is not available to maintain a constant gradient during the peak expected cavity detuning, the beam will be lost
- Cavity detuning can be a major driver of the cost of a narrow-band machine
- The cost is driven by the PEAK detuning



Some Future SRF Accelerators

Pulsed SRF accelerator, existing and projects	Cavity Half-bandwidth, Hz	LFD, Hz	LFD/HBW
SNS	550	300	0.6
ESS	500	400	1
XFEL	185	550	4
PIP II	30	300	10

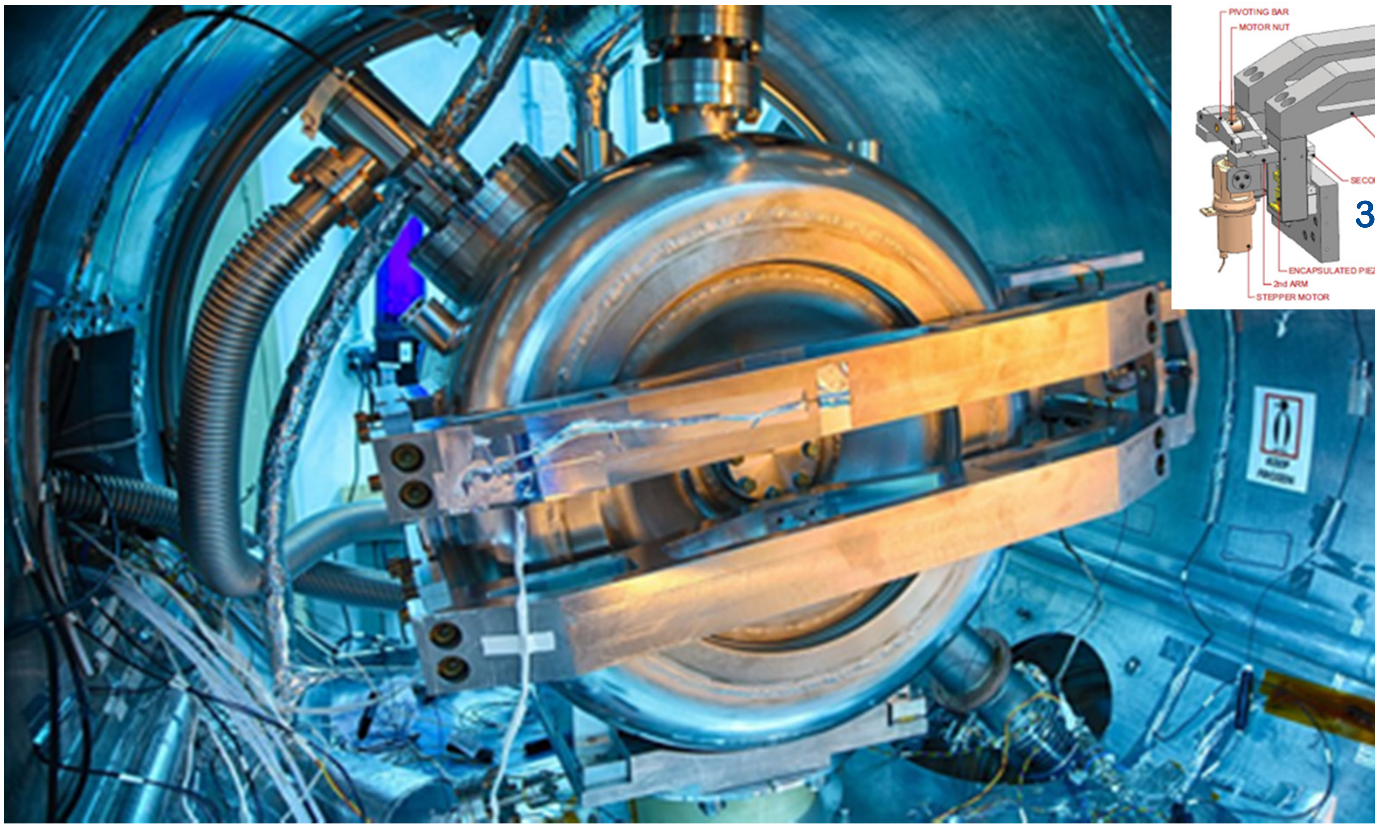
PIP-II presents a unique challenge because of the narrow bandwidths and pulsed operation

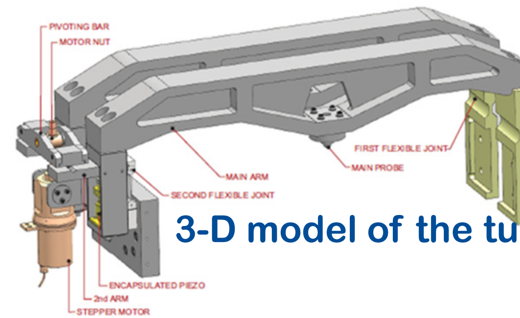
PIP II specific requirements for SRF Cavities Resonance Control:

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

PIP II (SSR1 cavity)resonance control progress

Dressed Single Spoke Resonator (f_{BW}~60Hz) with tuner and high-power coupler installed in the Spoke Test Cryostat at Fermilab.





3-D model of the tuner

Resonance Control of the SRF cavities operated in CW mode
Synergy of the two projects: LCLS II & PIP II

Before start to discuss recent efforts/results in the PIP II resonance control let me briefly outline efforts and results of controlling resonance of 1.3GHz LCLS II cavity accomplished by FNAL resonance control team in the scope of SRF cavity tuner design verification program.

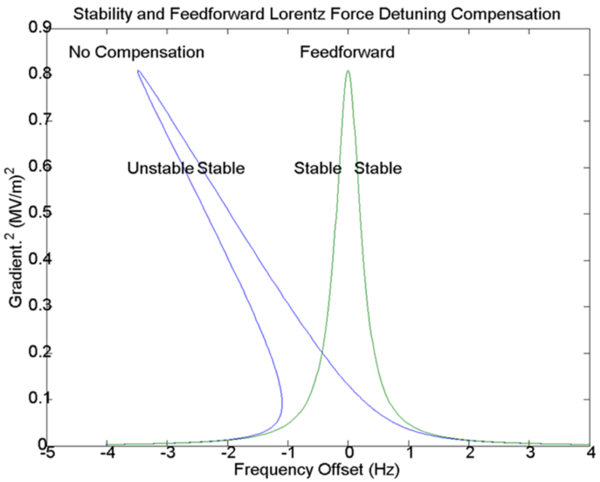
FNAL designed and tested slow/fast tuner and several dressed cavities were tested at FNAL's HTS.

LCLS II machine will operate in CW mode (with narrow bandwidth cavities $\mathbf{f}_{bw}$ **~ 30Hz** and reqs **peak** detuning less than **10 Hz**)

Active resonance control (CW operation)

Synergy of the two projects (LCLS II & PIP II)

Lorentz Force in Narrow Bandwidth Cavities

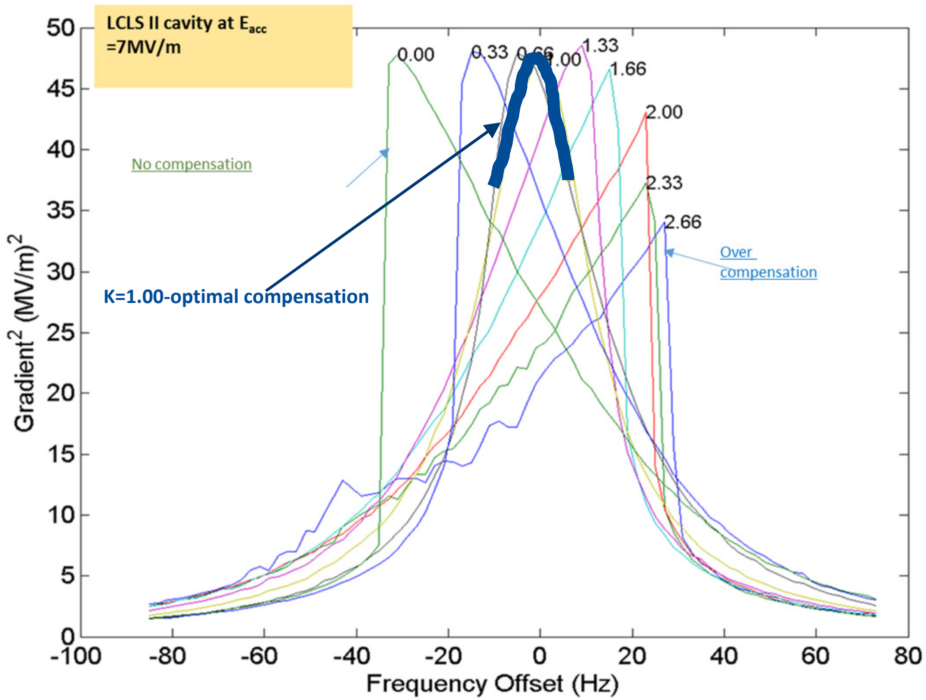


- **Lorentz force detunes cavity and for narrow bandwidth cavities resonance becomes a double valued function of the frequency (stable & unstable branches)**
- **If detuning is more than several bandwidths cavities can become unstable**
  - **Small perturbations (microphonics) can cause the cavity field to suddenly crash to zero**

For SSR1(325MHz) $\Delta F_{(at\ Eacc=12MV/m)}$ ~250Hz (f_{BW}~60Hz)
For LCLS II (1.3GHz) $\Delta F_{(at\ Eacc=12MV/m)}$ ~200Hz (f_{BW}~30Hz)

First demonstrated at Cornell

Possible to remove the instability using piezo feed-forward tied to cavity square of gradient



LCLS II cavity (f_{BW}~40Hz).
Cavity E_{acc}^2 .VS. Frequency Offset
(when Forward Power driving frequency swing near cavity resonance)
Piezo driving voltage $V=K*k1*E_{acc}^2$.
K=0.00-no compensation; ***K=1.00-optimal compensation***

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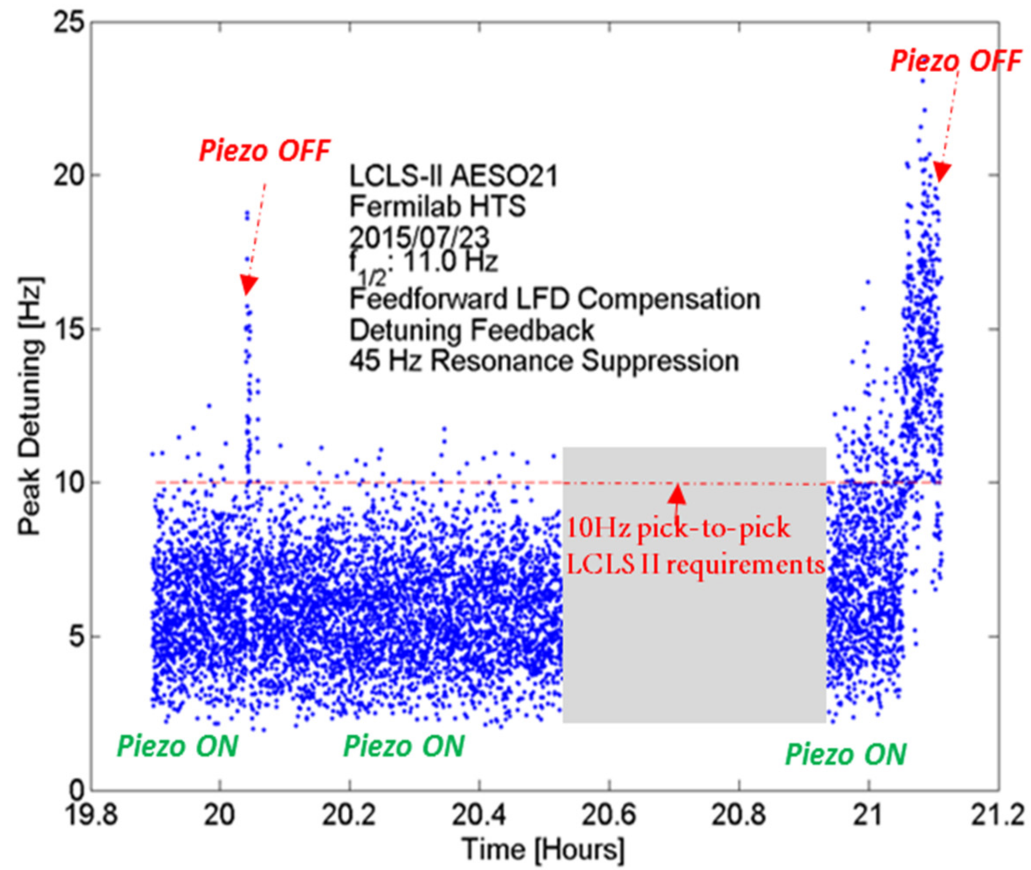
Resonance Control of LCLS II cavity at HTS (FNAL)

LCLS II (SLAC, CW) E_{acc}=16MV/m, f_{BW}=16Hz; Reqs for Peak Detuning 10Hz

1. Feedforward LFD compensation:
Cavity stabilized against ponderomotive forces by driving piezo with voltage proportional to the magnitude squared of the cavity gradient (E_{acc}^2)

2. Feedback microphonics compensation:
Feedback proportional to the phase difference between the incident and transmitted signals was added to the piezo drive waveform generated by FPGA and added a narrow band resonance stabilization (locked to the most prominent resonance line -45Hz)

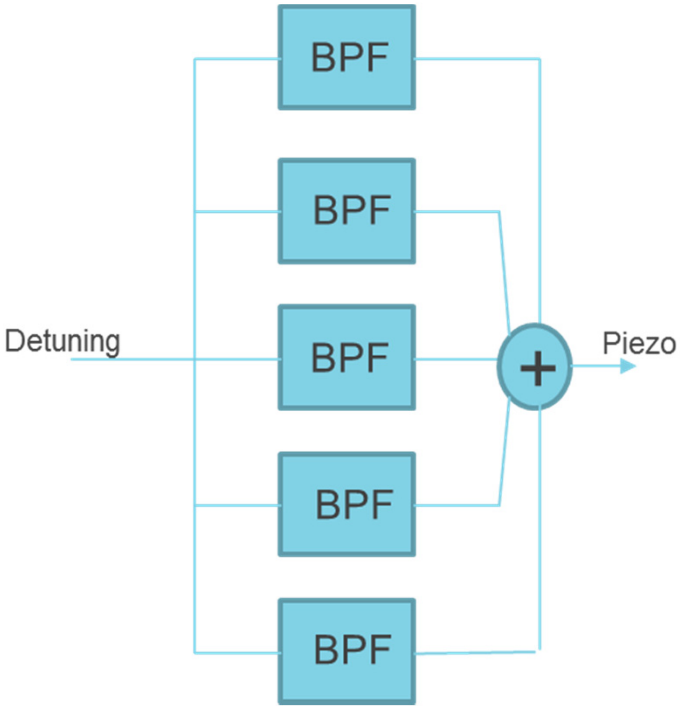
Active Resonance Control of the LCLS II Cavity (HTS/FNAL)



Improvement of Feedback algorithm applied to SSR1 cavity

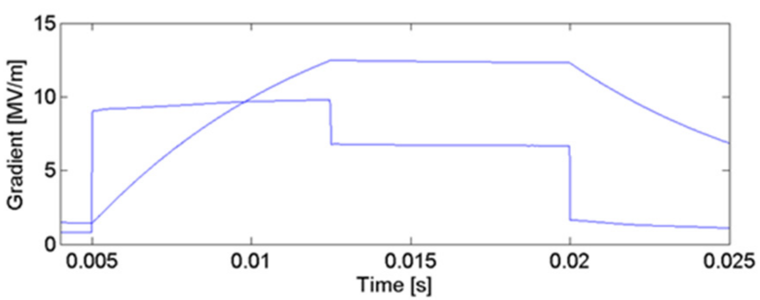
(SSR1 cavity operated at CW mode)

- Initial efforts of simple proportional detuning feedback were successful, but further improvements required a filter bank.
- Detuning signal is run through a series of bandpass filters, summed, and applied to the piezo. Bandpass filter frequency, decay time, and gain are set manually.
- Filters targeted pressure drift (0 Hz) as well as dominant driving terms (20, 200 Hz).
- Upgrade plans include automating setting of filter bank parameters based on the cavity transfer functions.



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

- 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** (to better measure and understand LFD)



RF-pulse shape during study at STC

As next step in addition to two algorithms (feed-forward tied to E_{acc}^2 & feedforward (20Hz & 200Hz)) Adaptive Least Square Lorentz Force Detuning Algorithm (LS LFD) has been implemented to control cavity resonance.

Adaptive LS LFD Algorithm originally developed at FNAL for ILC successfully applied to different type of SRF cavities (9-cell elliptical and spoke cavities) working at different operating conditions: S1Global, Project X, HINS

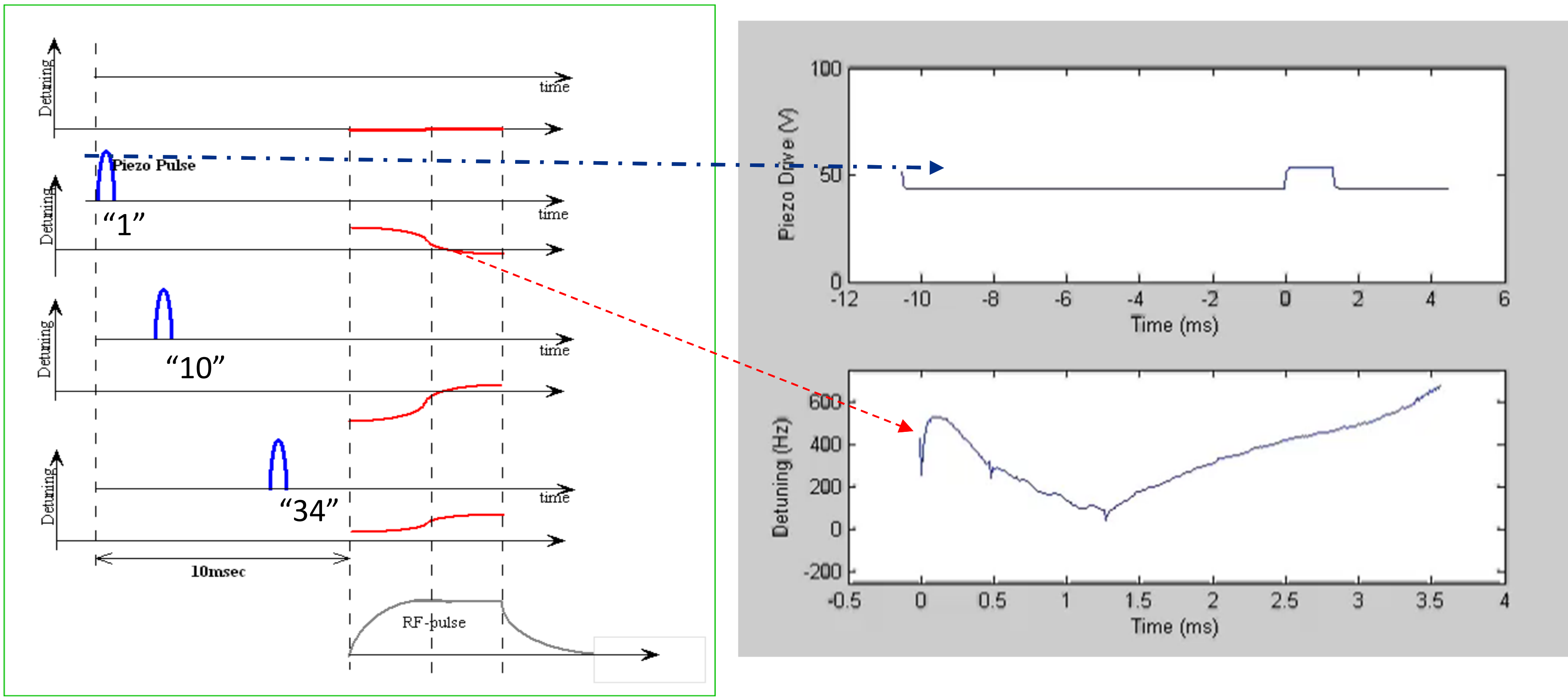
Details of Adaptive LS LFD Algorithm at :

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

W. Schappert, Y.Pischalnikov, "Adaptive Compensation for Lorentz Lorentz Force Detuning in Superconducting RF Cavities". SRF2011, Chicago, USA

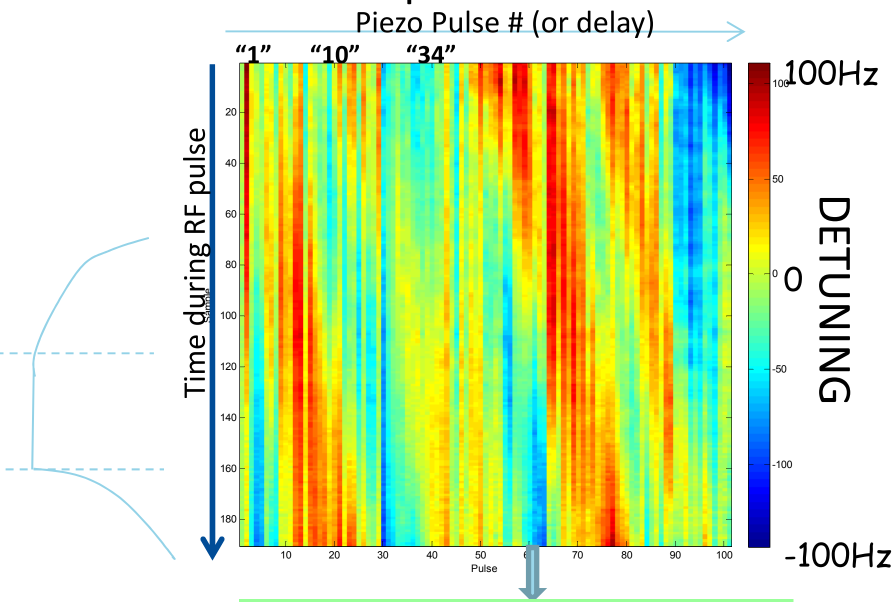
Adaptive LS LFD Algorithm (how it is works) #1

Narrow (1-2ms) small amplitude (several volts) stimulus pulses drive piezo tuner. First pulse starting 10-20ms before cavity RF-pulse. Each next pulse delay between piezo pulse and RF-pulse decreased (with 1ms increment). Piezo scan will stop after scanning through RF pulse.
The forward, probe and reflected RF waveform recorded at each delay and used to calculate detuning. [Response Matrix]



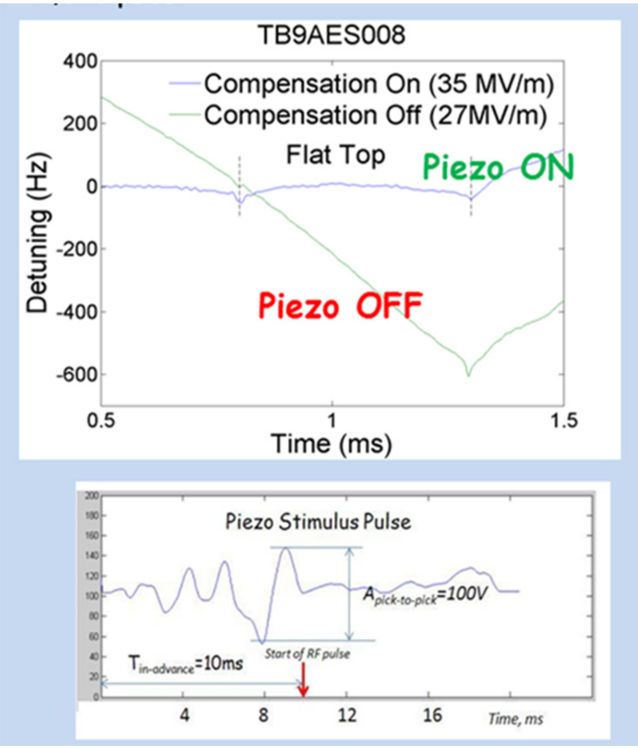
Adaptive LS LFD Algorithm (how it is works) #2

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: <u>"Fill+FlatTop"</u> only <u>"FlatTop"</u>

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.



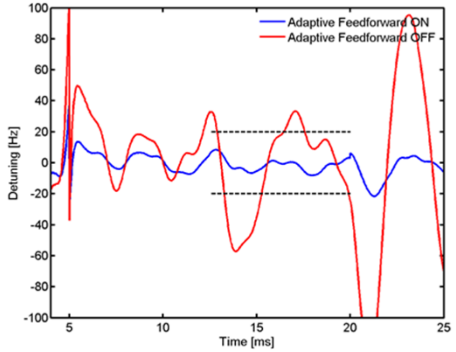
1.3GHz tesla style cavity tested at HTS FNAL (for CM2)

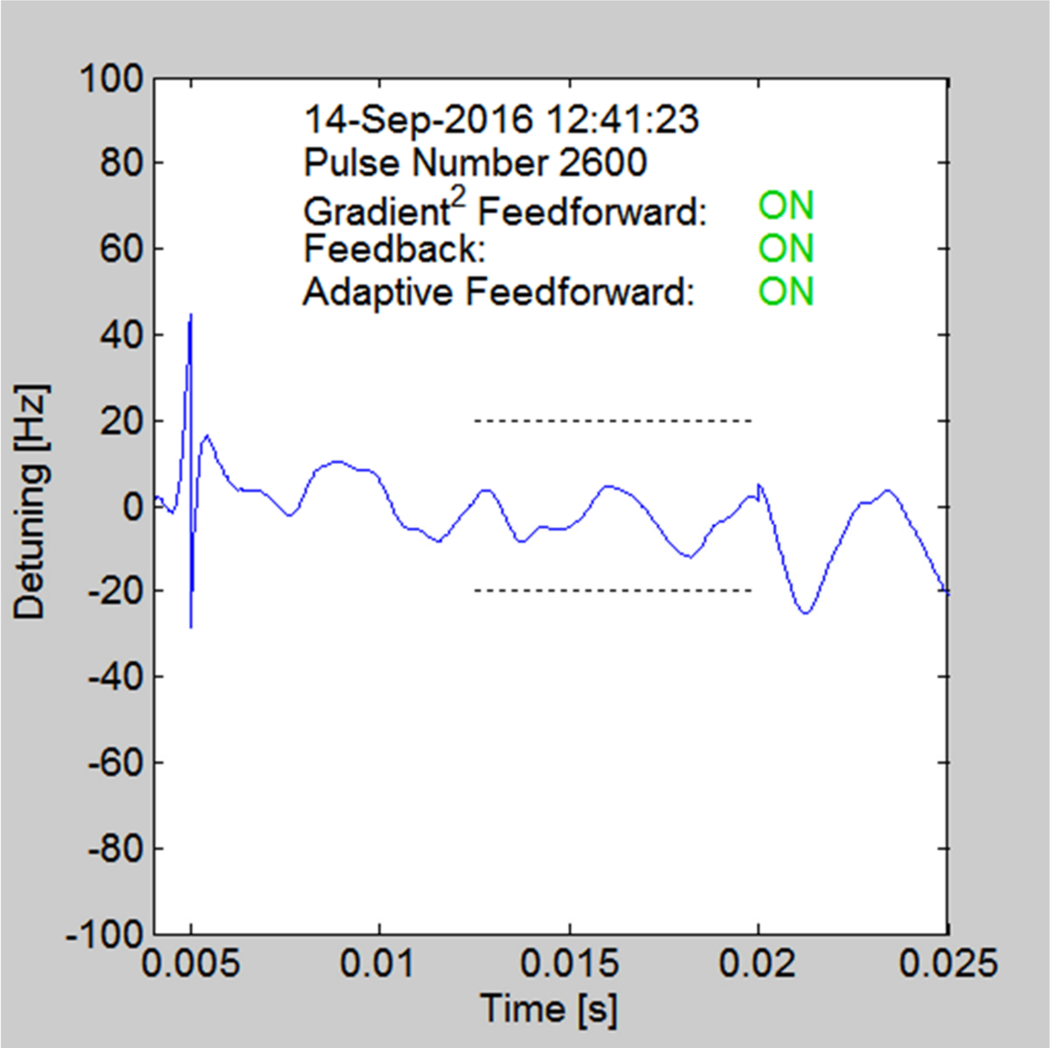
LFD during 1,3ms RF-pulse (Fill+Flat Top) ~2,300Hz

After LS LFD compensation – less than 20Hz during 1.3ms pulse

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)





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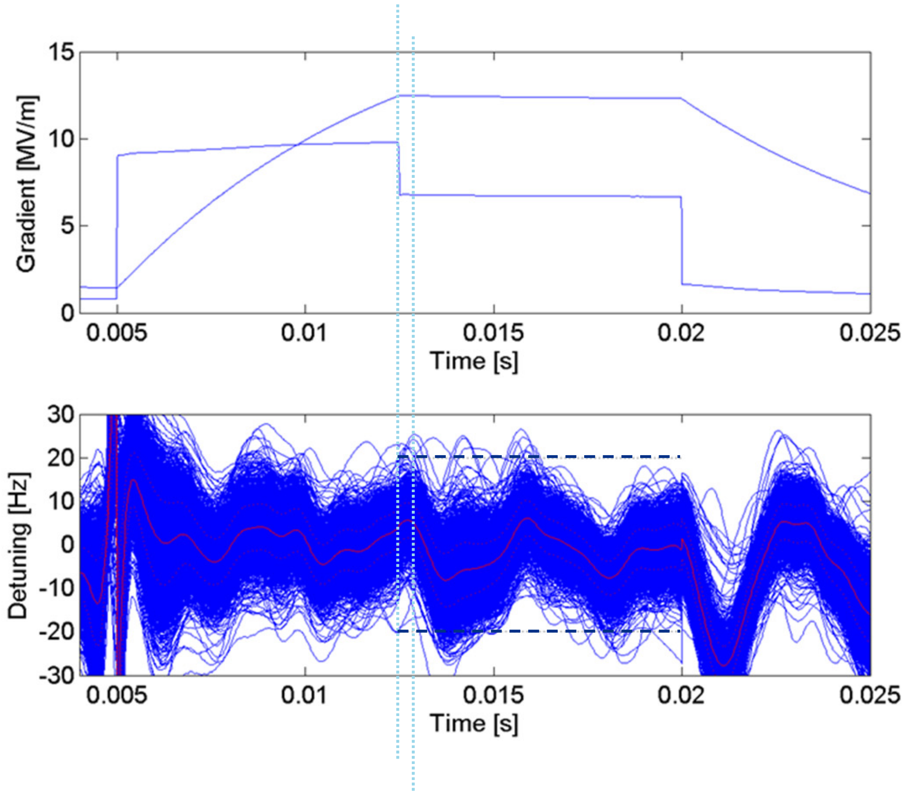
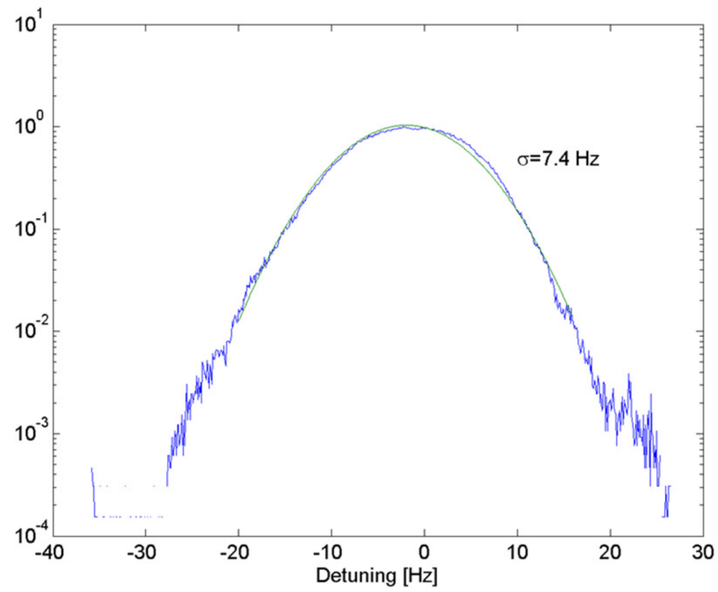
Resonance Control of the SSR1 cavity (2)



At this stage we are within factor of 2 of PIP-II specs → Peak 20Hz (σ~3.5Hz) (for flat-top 7,5ms)

If we take into consideration only first 0.5ms detuning will definitely smaller than σ~7.4Hz



General important for SRF cavities resonance control issues

(that not discussed in this presentations but presented in several talks by team members in different conferences/workshops)

- How to accurately measure cavity detuning (including accurate calibration of the cavity signals and correction for systematic effects)

W.Schappert "Resonance Control for Future Accelerators", LINAC2016

- SRF cavities Resonance Control task is multidisciplinary
  - Optimization of the cavity design (dF/dP; LFD);
  - Optimization of the cryomodule design;
  - Cryo-system stability;
  - Civic engineering;
  - Active piezo control.
- Active Resonance Control is last resort (so far there are no any working accelerator that relay on active/piezo control)

Summary

- Resonance control of narrow bandwidth SRF cavities is challenging task (especially for cavities that will operate in RF-pulse mode)
  - FNAL's PIP II Project is one of the example
- FNAL team controlled LCLS II cavity frequency with peak detuning **10 Hz**
- Significant progress with resonance control for PIP II (narrow bandwidth spoke cavity SSR1 that operates in RF-pulse mode). SSR1 cavity frequency controlled with peak detuning ~**40 Hz** (or better) with target **20 Hz**
  - *Feedforward proportional to E_{acc}^2 can stabilize ponderomotive effects*
  - *Feedback can stabilize against pressure variations and microphonics*
  - *Improvement using adaptive feedforward indicates that dominant source of vibration is radiation pressure from the RF pulse*
- Next tests (as a part of 10 SSR1 cavities qualifications) should allow definitive statement about our ability to compensate SSR1 cavities to required levels
- FNAL resonance control team has significant experience to address complex (sometime even aggressive -like PIP II) SRF cavities control tasks