Resonance Control of the PIP-II SC Cavities

Warren Schappert
for the
TD Resonance Control Group
Fermilab, Batavia, IL, USA

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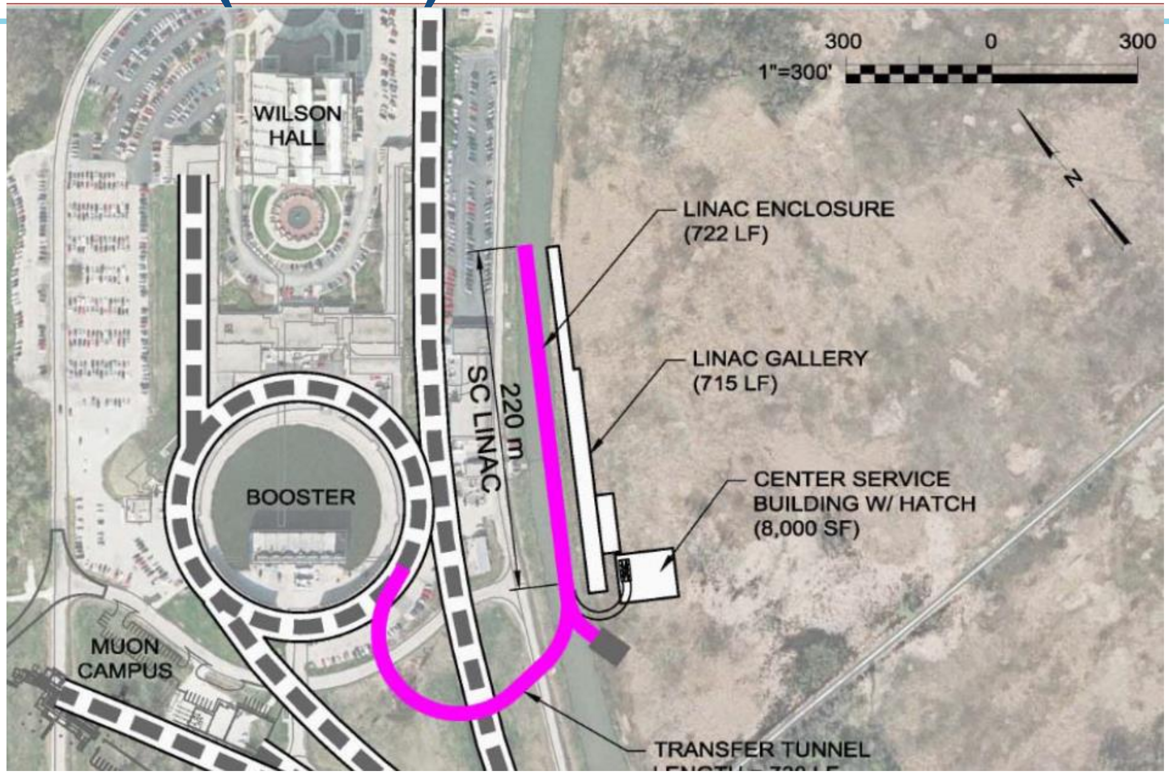
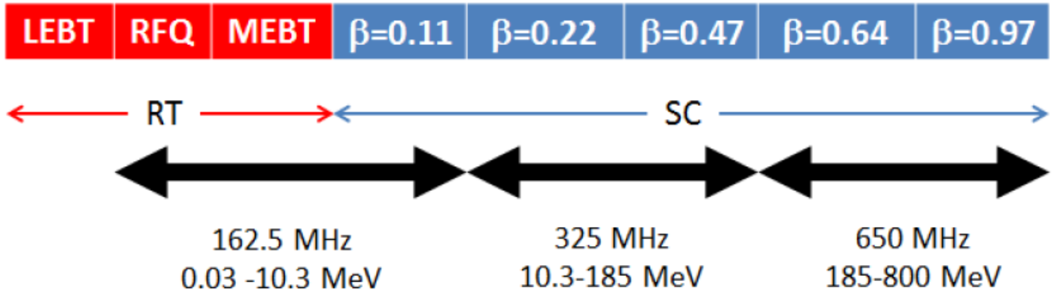
Fermilab Proton Improvement Plan II (PIP-II)

- 800 MeV pulsed superconducting linac injecting 2mA peak into the existing Booster
- Increase final beam power to 1.2 MW @120 GeV for Long Base Line Neutrino Facility (LBNF)
  - –Upgradeable to 2.4 MW
- 116 SRF Cavities with half bandwidths between 28 and 43 Hz
- Peak Detuning 20 Hz
- Lorentz force ~ $10 \times f_{1/2}$
- Active resonance stabilization will be required for successful operation

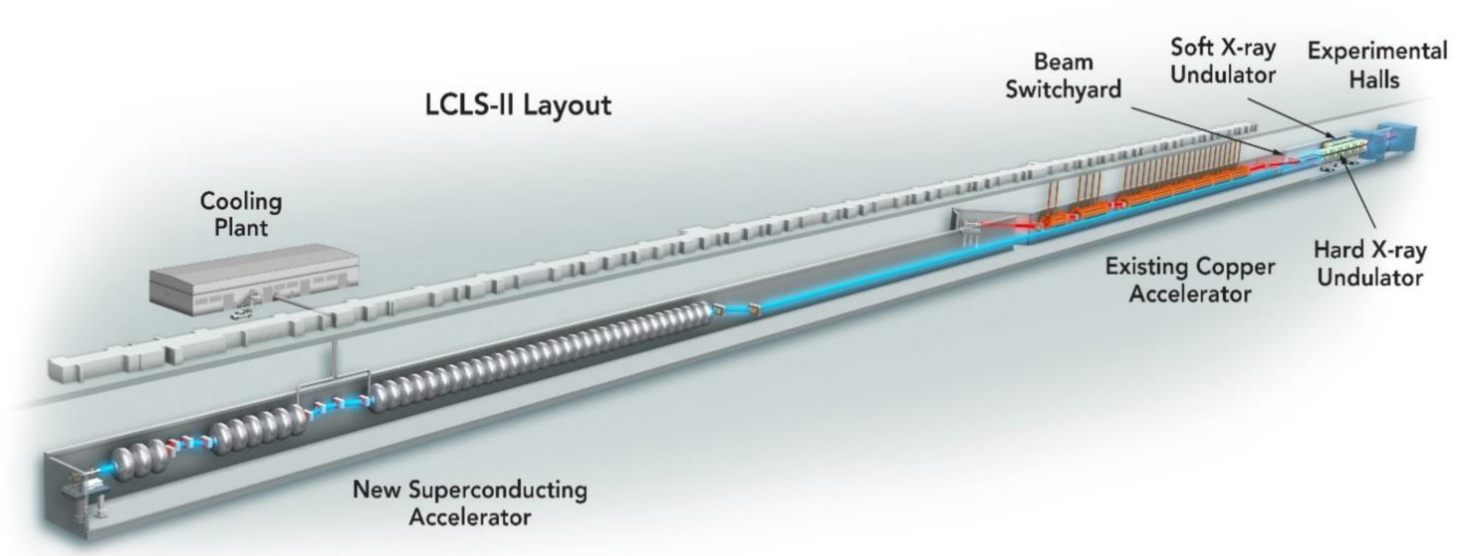




SLAC Linear Coherent Light Source II (LCLS-II)

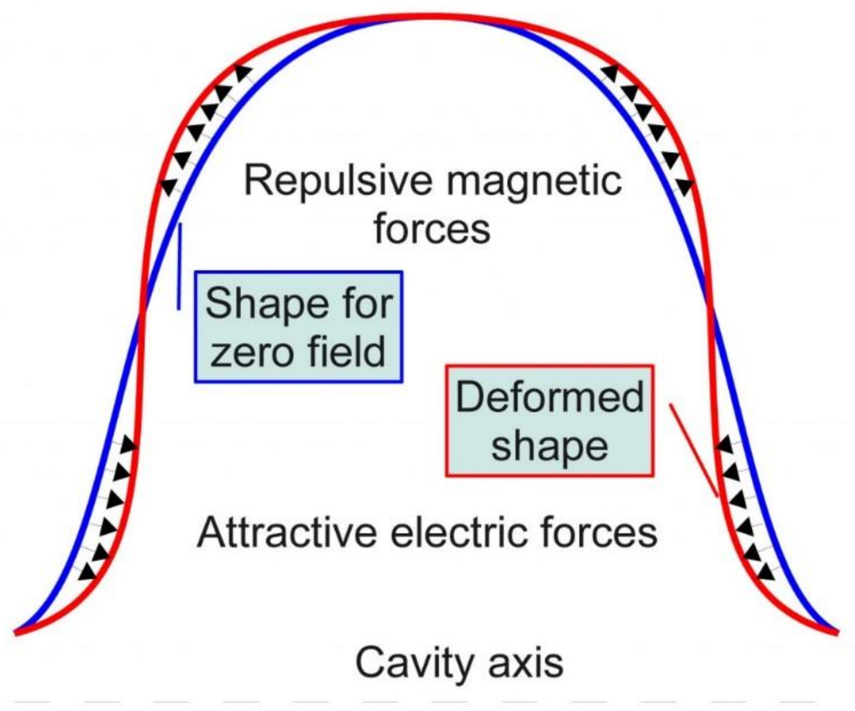
- 4 GeV superconducting linac to be installed in exisiting SLAC tunnel
- 0.2 to 5 keV X-rays at 1M Pulse/s
- 10^{11} Photons/Pulse in 10^{-3} Bandwidth (20W)

- 35 1.3 GHz XFEL style cryomodules modified for CW operation at 16 MV/m
- Cryomodules being constructed and tested at Jlab and Fermilab
- 8 Cavities/CM with 16 Hz Half-bandwidth
- 10 Hz peak detuning requirement



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
  - –Radiation pressure from the RF field (Lorentz Force Detuning)
  - –External vibration sources (microphonics)

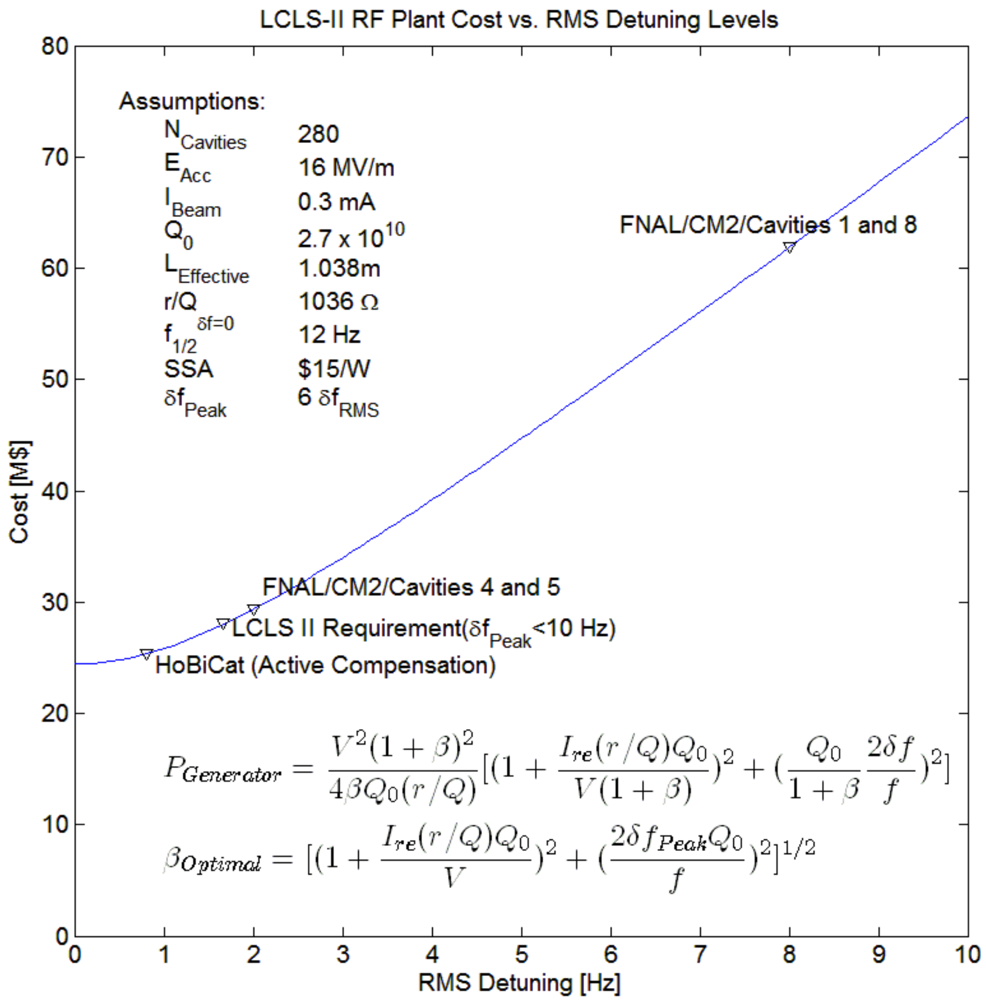


$$P_s = \frac{1}{4}\left(\mu|\vec{H}|^2 - \varepsilon_0|\vec{E}|^2\right)$$

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

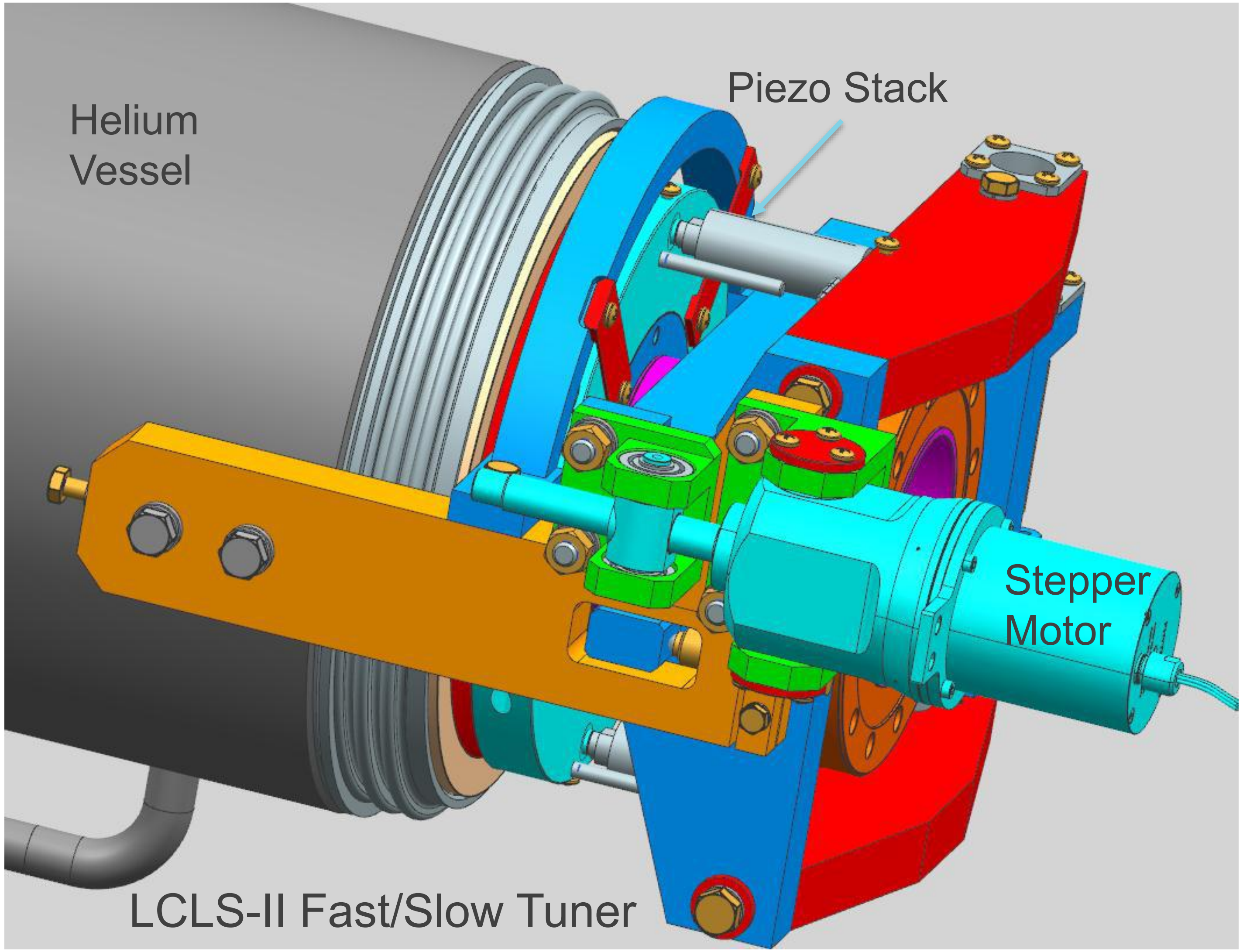
The Cost of Cavity Detuning

- Detuned cavities are more expensive to build and to operate
  - 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-bandwidth machine
- The cost is driven by the **PEAK** detuning



Active Resonance Stabilization

- Use of piezo actuators to actively compensate for cavity detuning pioneered at DESY (to my knowledge)
- Piezo pulse cancels out Lorentz force detuning
- Some of the earliest work on active microphonics compensation done by Carcagno et. al. at Fermilab



Measuring Cavity Detuning

- Cavity detuning can be determined from complex I/Q baseband cavity signals
- Complex equation for baseband envelope can be separated into two real equations
  - –Half bandwidth can be extracted from the real component
  - –Detuning can be extracted from the imaginary component
- Precise compensation requires accurate measurement of the cavity signals
  - –Accurate calibration
  - –Corrections for systematic effects

$$\frac{dP}{dt} = -\left(\omega_{1/2} + i\delta\right)P + 2\omega_{1/2}F$$

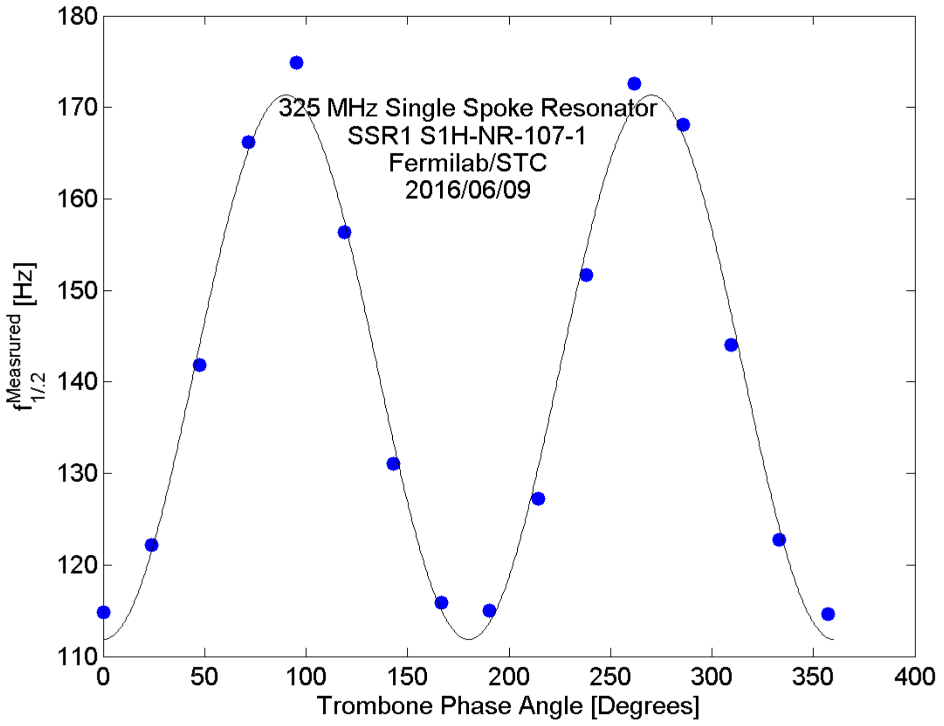
$$\omega_{1/2} = -\frac{\left\langle \mathrm{Re}\left(P^{*}\left(\frac{dP}{dt}\right)\right)\right\rangle}{\left\langle \mathrm{Re}\left(P^{*}\left(P-2F\right)\right)\right\rangle}$$

$$\delta = -\frac{\mathrm{Im}\left(P^{*}\left(\frac{dP}{dt} - 2\omega_{1/2}F\right)\right)}{P^{*}P}$$

Calibration and Systematic Effects

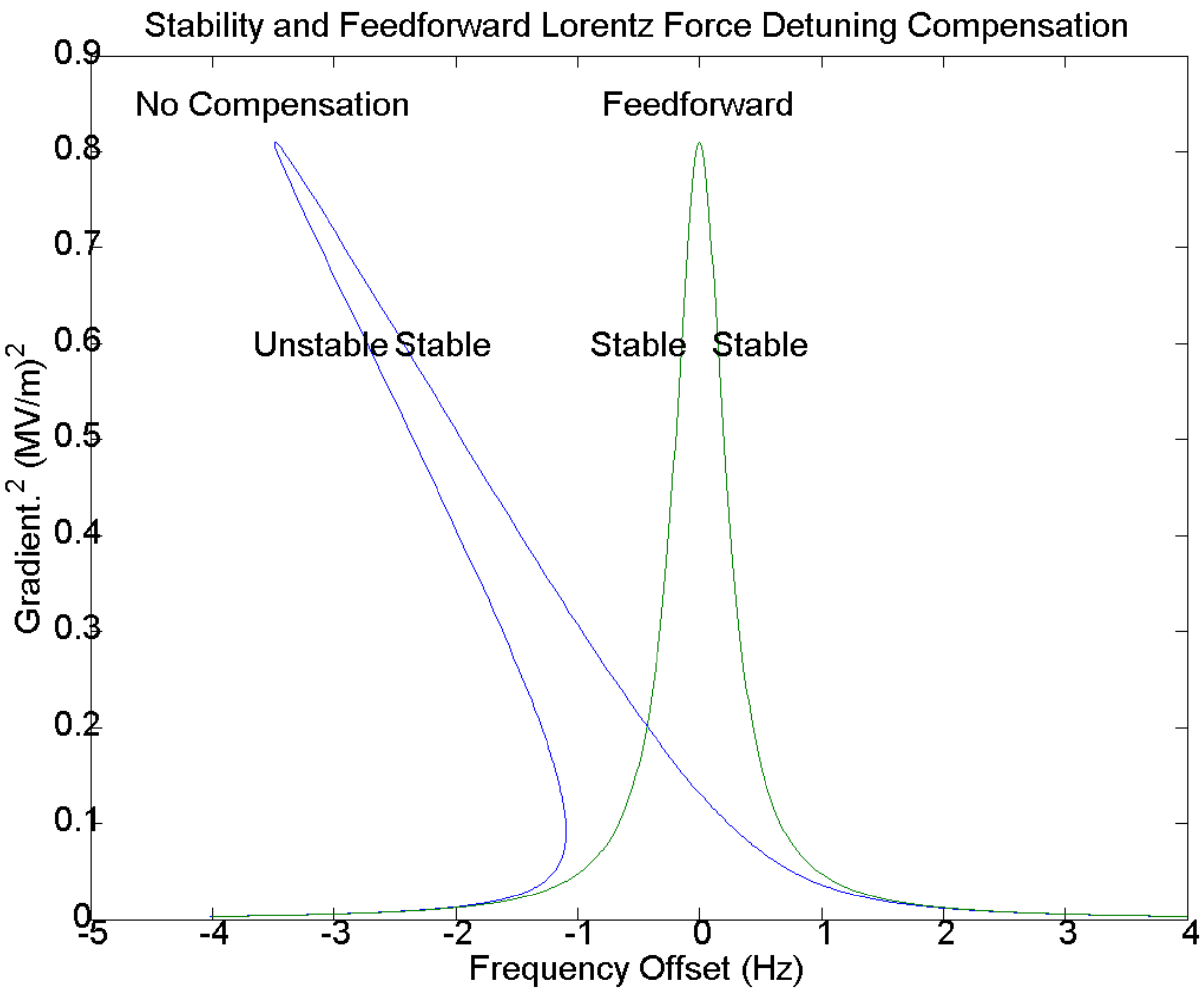
- Relative calibration can be determined from self-consistency of the complex baseband signals
- Reflections from circulator can bias measurements of cavity bandwidth and resonant frequency
- Finite directivity of directional coupler used to separate the forward and reverse waves leads to cross-contamination of the signals
- Reflections between the cavity and the directional coupler bias the signals from even the best directivity couplers

$$\frac{Z_T I_{Forward}}{V_{Cavity}} = \frac{1}{2}\left(1 + \frac{Q_{Ext}}{Q_{Int}} + i\,\frac{\omega' - \delta}{\omega_X}\right)$$
$$\frac{Z_T I_{Reflected}}{V_{Cavity}} = \frac{1}{2}\left(1 - \frac{Q_{Ext}}{Q_{Int}} - i\,\frac{\omega' - \delta}{\omega_X}\right)$$



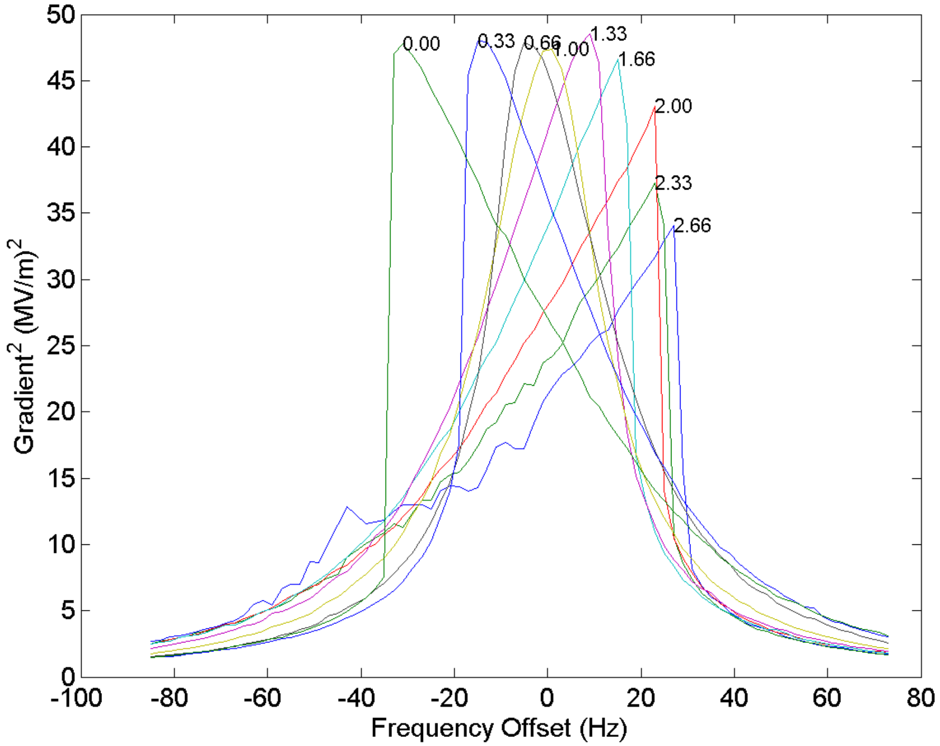
Ponderomotive Instabilities

- Lorentz force shifts cavity resonance frequency as gradient rises
- If detuning is more than several bandwidths cavities can become unstable
  - Small detuning perturbations can cause the cavity field to suddenly crash to zero



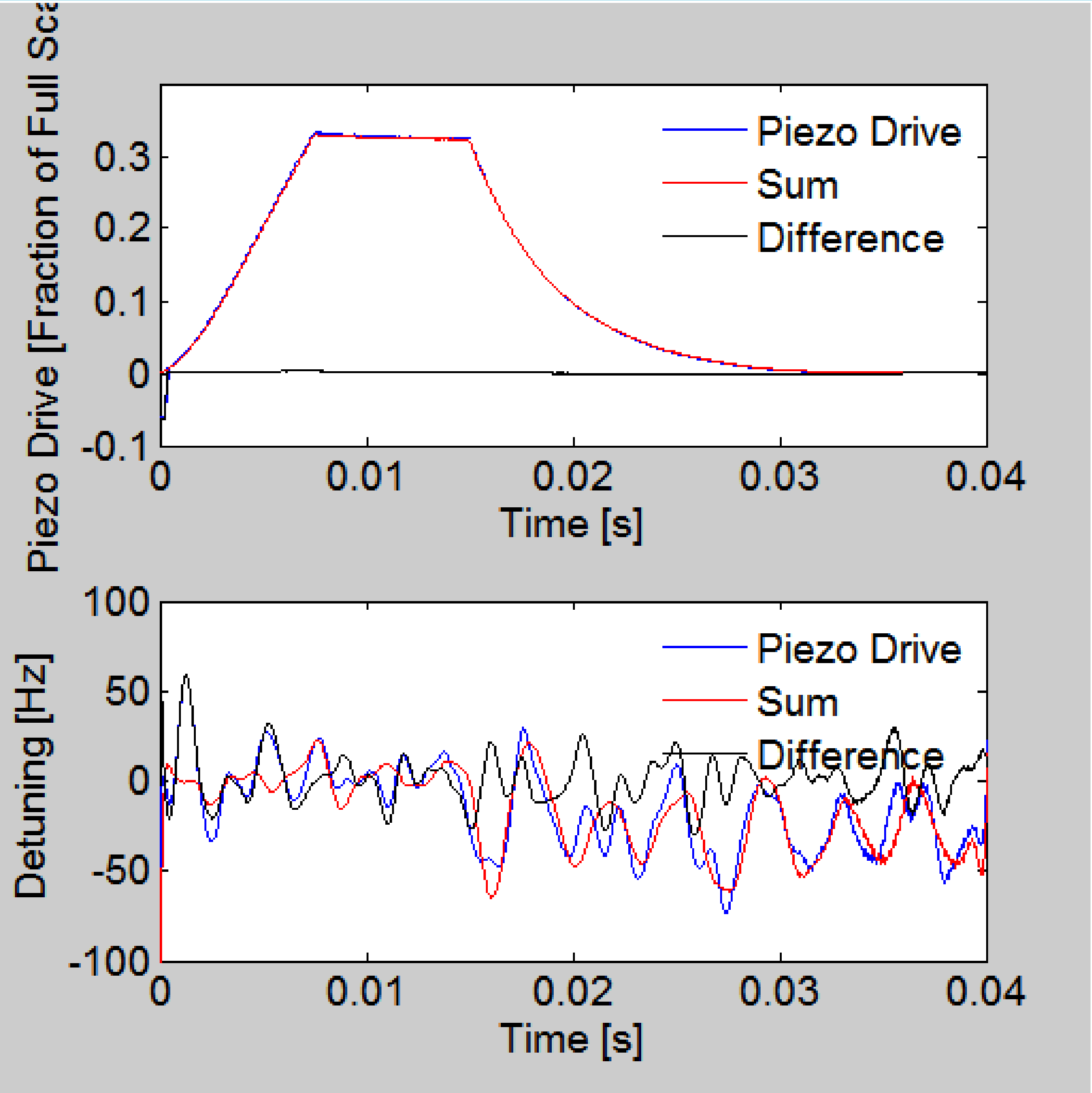
Stabilizing the Resonance: $|E_{acc}|^2$ Feedforward

- Cavity can be stabilized against ponderomotive forces can be by driving piezo with voltage proportional to the magnitude squared of the cavity gradient
  - –First demonstrated at Cornell



Adaptive Feedforward

- Cavity characterization
  - Piezo excited by series of positive and negative impulses at different delays with respect to the RF pulse
  - Sum and difference of detuning from positive and negative impulses allow impulse response to be separated from background detuning
- Compensation waveform tailored to the mechanical response for each individual cavity
  - Any pulse can be constructed from sum of impulses
  - Time domain equivalent of frequency domain transfer function



(Inverse) Piezo/Detuning Transfer Function

- Piezo/Detuning transfer function can be inverted to determine the piezo waveform needed to cancel any detuning waveform

- Measure response to piezo pulses

$$\delta = T_{\delta/PZT} V_{Piezo}$$

- Extract Transfer function from measured data

$$T_{\delta/PZT} = \delta V^{T}_{Piezo} (V_{piezo}\, V^{T}_{Piezo})^{-1}$$

- Any deterministic detuning can be cancelled using the appropriate waveform

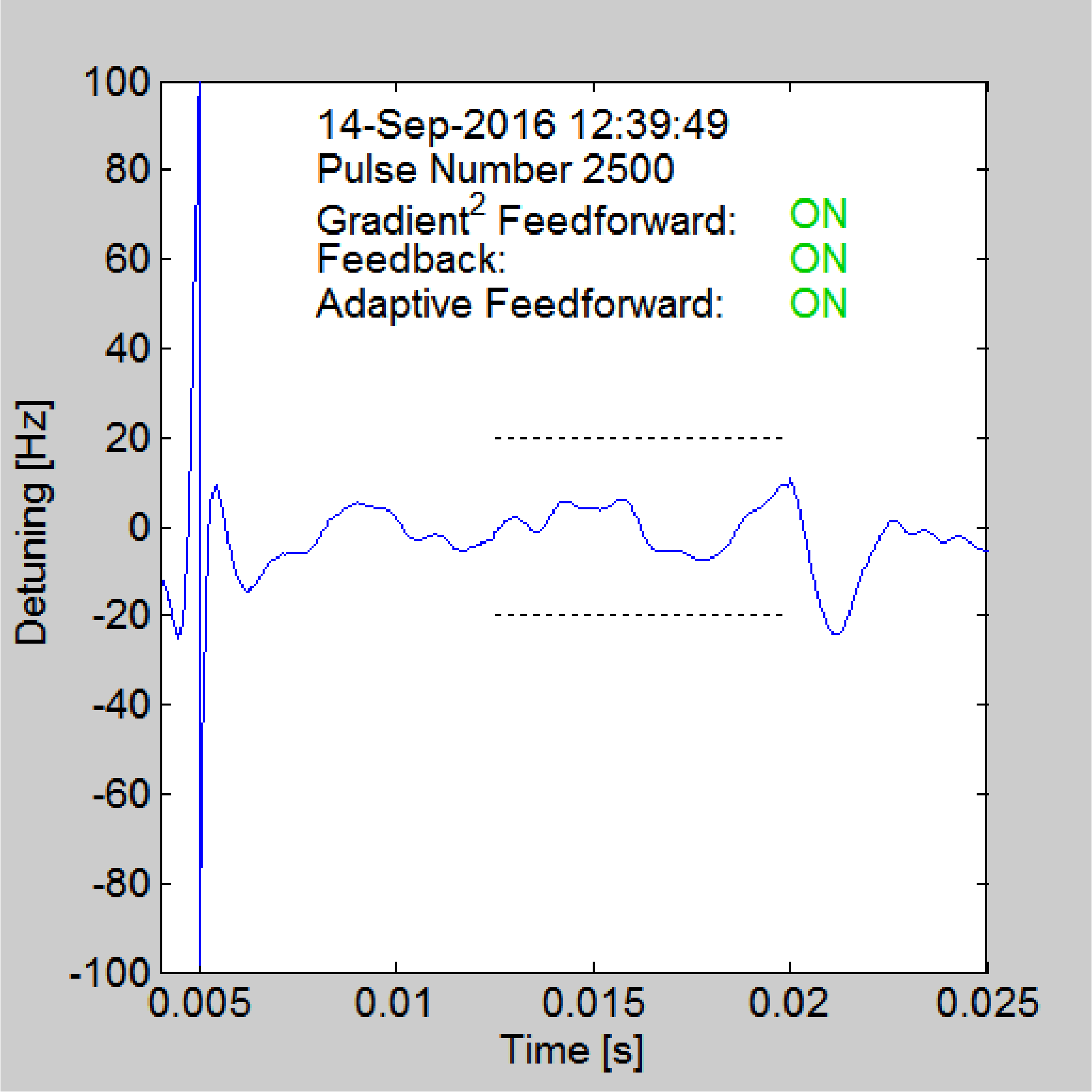
$$\delta - T_{\delta/PZT} V_{\delta} = 0$$

$$V_{\delta} = (T^{T}_{\delta/PZT}\, T_{\delta/PZT})^{-1} (T^{T}_{\delta/PZT}\, \delta)$$

- Numerical instabilities in underdetermined systems can be suppressed using SVD or Tikhionov Regularization

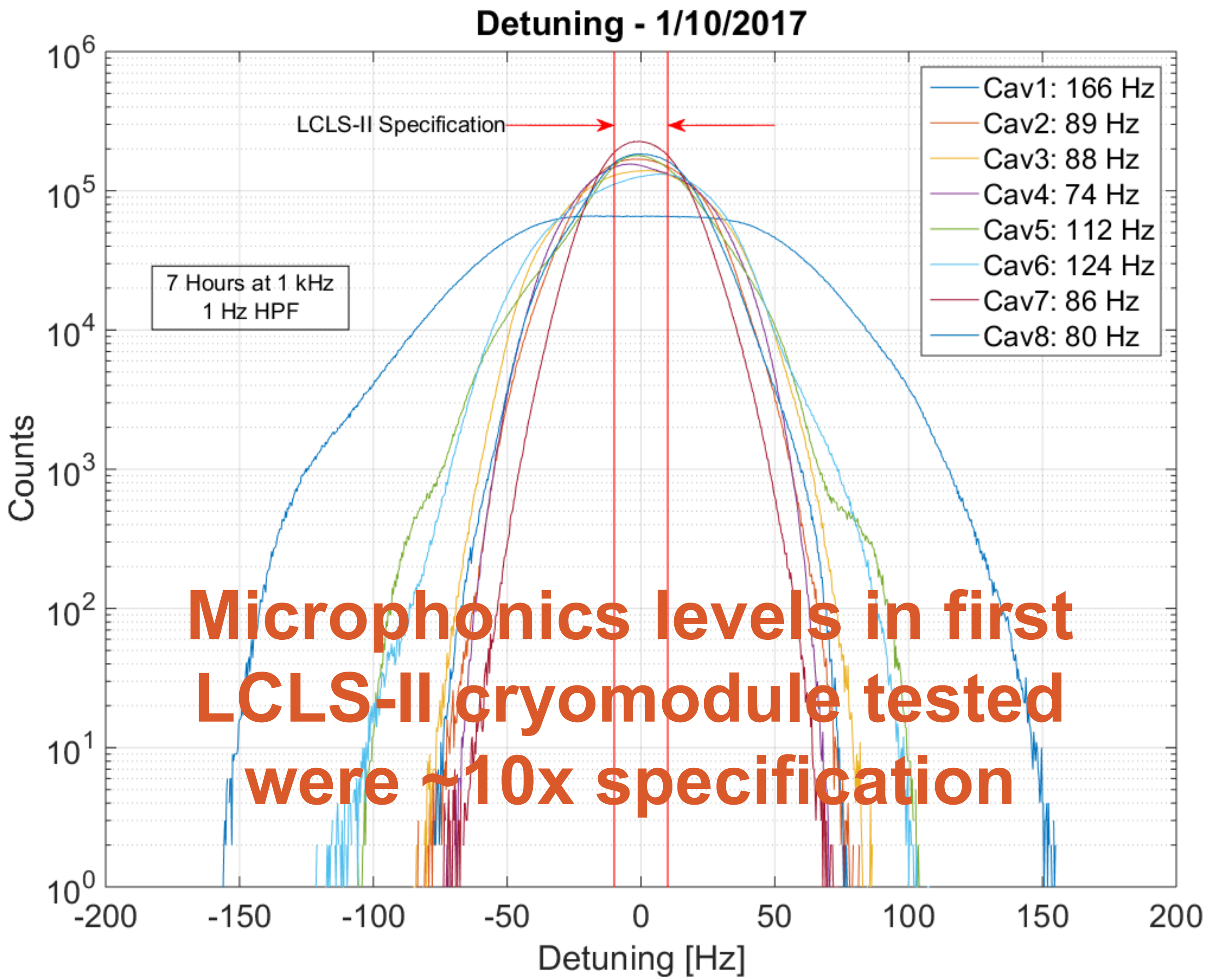
Adaptive Feedforward

- Cavity run with
  - $|E_{acc}|^2$ Feedforward,
  - Feedback manually tuned up in CW and
  - Adaptive Feedforward
- Adaptive Feedforward turned off at pulse 2706 and back on at pulse 2841



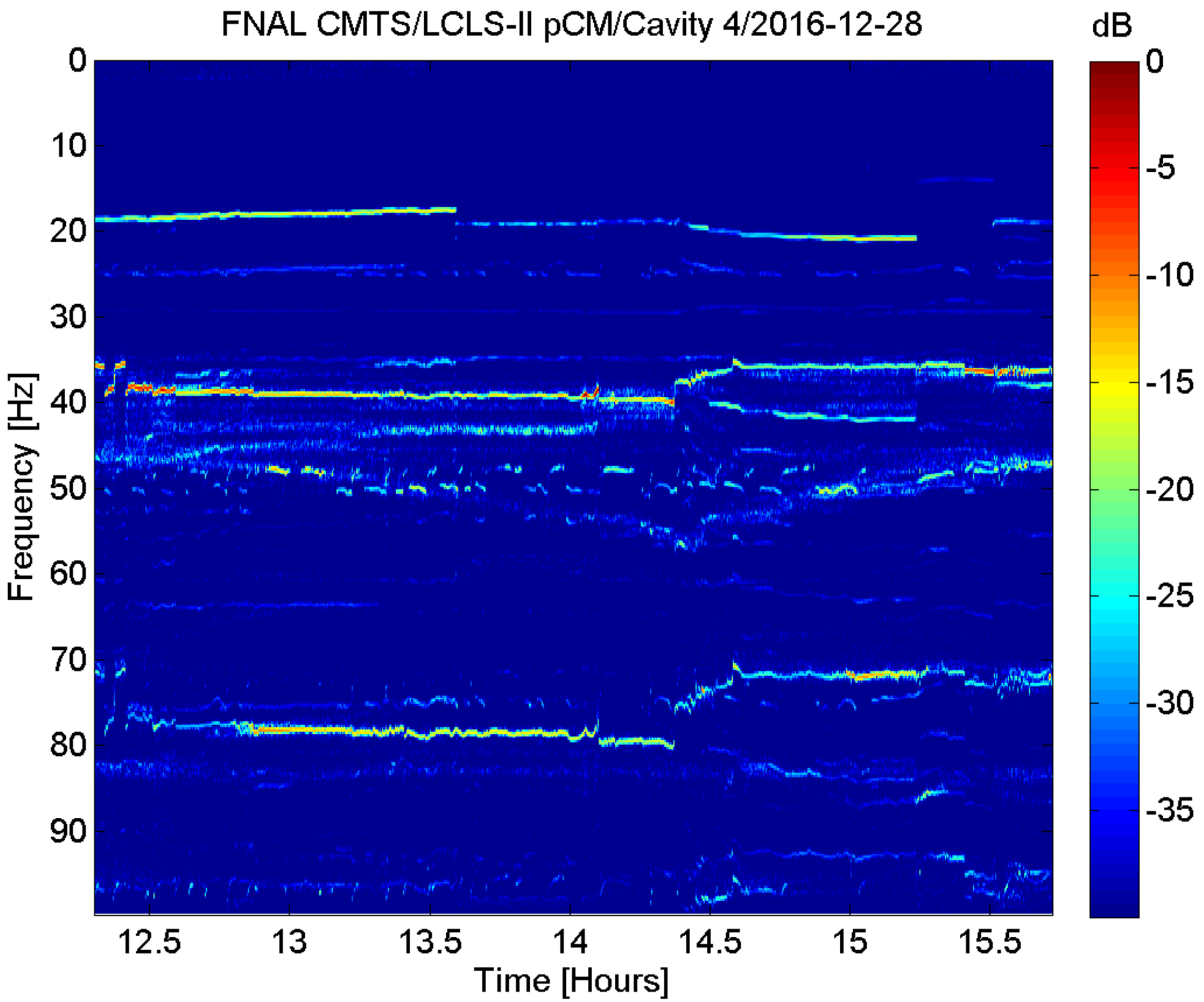
Limits of Active Control

- Active Control alone is NOT enough
- Suppressing cavity detuning in narrow-band machines requires trading off design elements across the entire machine
- Horror stories from every laboratory we talked to
  - –SNS, BESSY, Cornell, FRIB,…



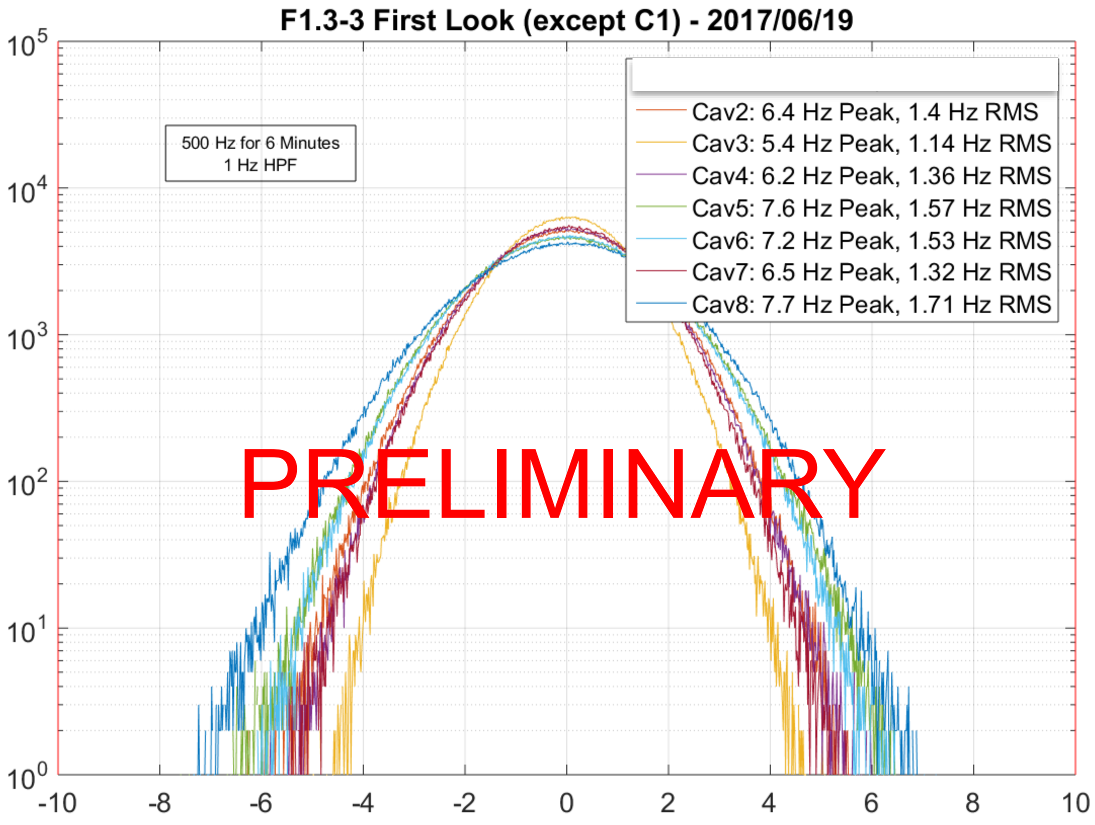
Thermo–Acoustic Oscillations

- Instability in frequency and amplitude indicate a narrow-band (cryogenic?) source driving a broad-band mechanical response
- Cryogenic valves had been installed by design with insulating gas column on the high pressure side to prevent contamination
  - –Reversed from manufacturer recommendation
    - not uncommon in practice
- High pressure gas susceptible to thermo-acoustic oscillations
  - –Warm gas acts as a spring
  - –Cold gas/liquid acts as a mass



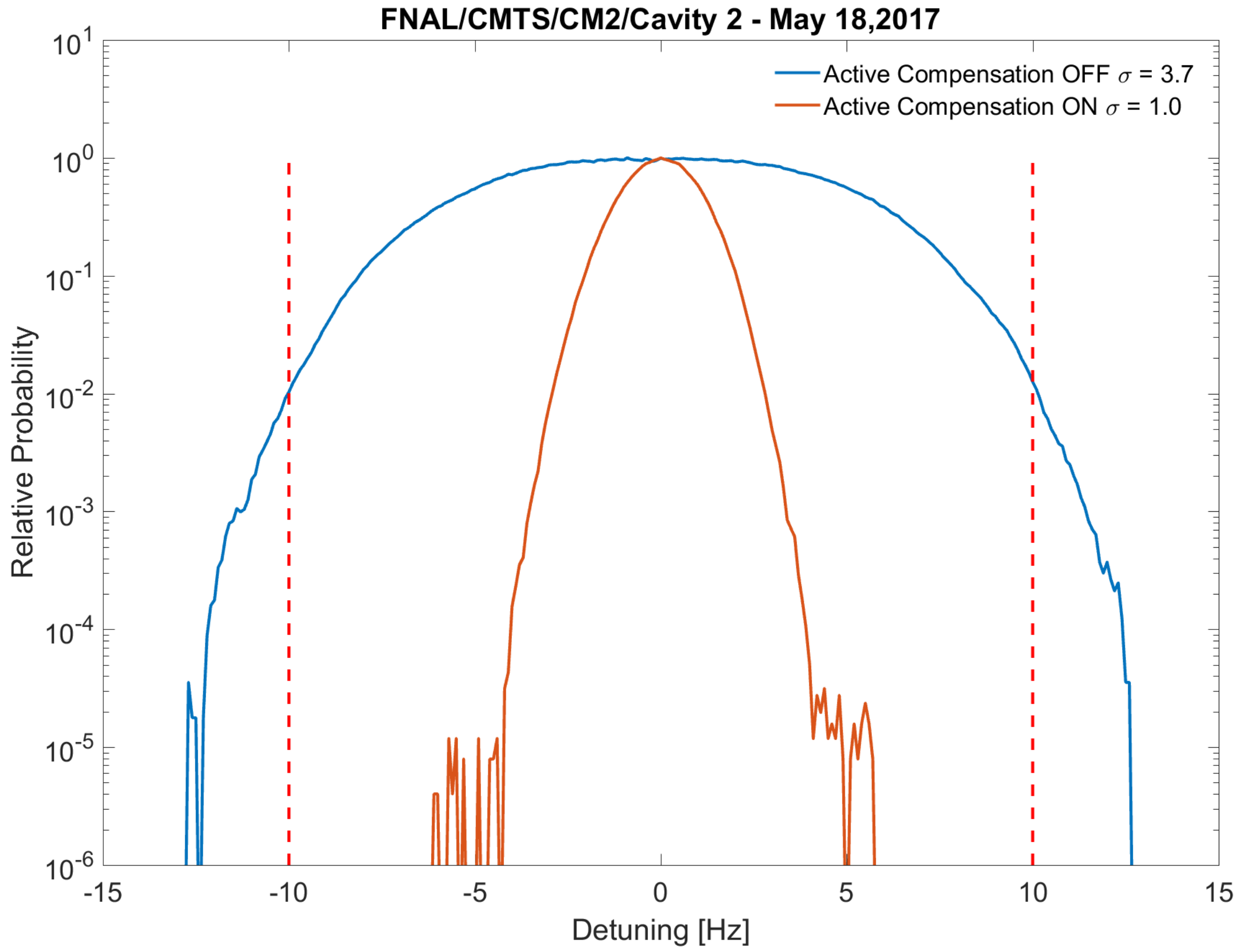
LCLS-II Detuning Following Mitigation of TAOs

- Unreversed valves installed in second cryomodule
  - –Permanent solution will require new guard-gas valves
- Valve stems also fitted with multiple wipers to damp TAOs



Active Compensation

- Active compensation tests have been promising
- Intend to try new automated Least-Squares algorithm during up-coming tests next week
- Also pursuing optimal control (Kalman/LQGR) techniques



Conclusions

- Cavity detuning can be a major cost driver for narrow-band SRF accelerators
  - PIP-II is particularly challenging because of the combination of
    - narrow bandwidth cavities
    - high Lorentz force detuning
    - pulsed operation
- Great strides have been made in active control
  - Ponderomotive effects can be suppressed using feed-forward proportional to the gradient
  - Deterministic sources (e.g. LFD) can be suppressed using adaptive-feedforward
  - Non-deterministic sources (e.g. microphonics) can be suppressed using feedback
- Active control alone is NOT enough
  - Suppressing cavity detuning requires trading off design elements of the entire machine
  - Organizational challenges may be more daunting than technical challenges