Resonance Control of the PIP-II SC Cavities
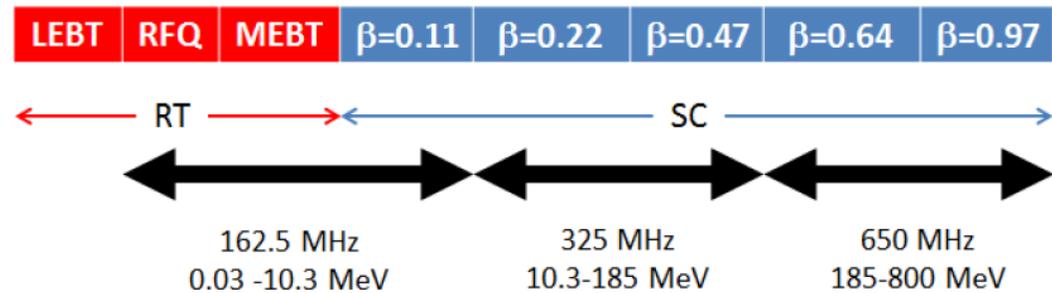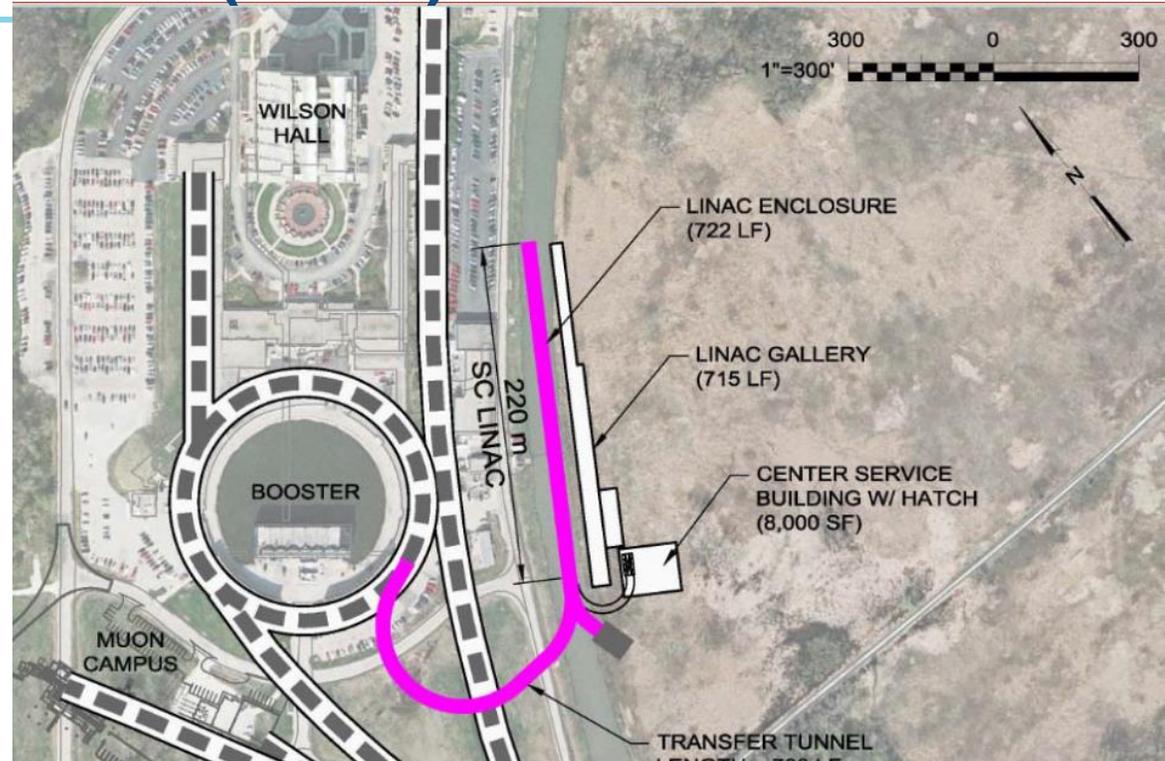
Warren Schappert

for the

TD Resonance Control Group
Fermilab, Batavia, IL, USA

The 59th ICFA Advance Beam Dynamics
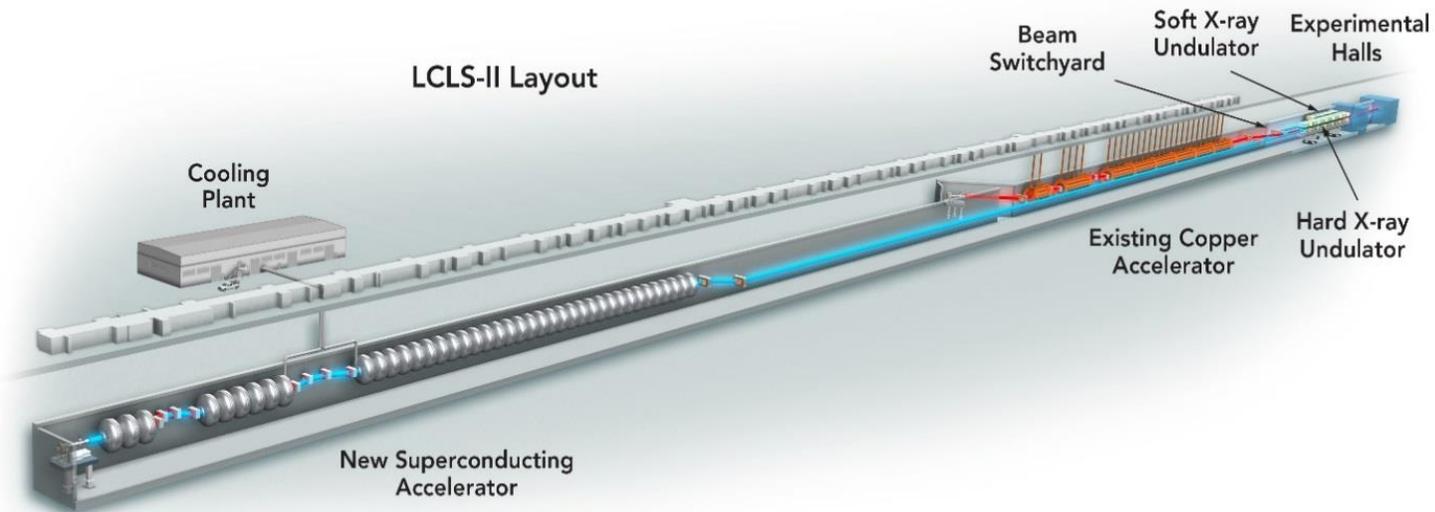Workshop on Energy Recovery Linacs
CERN June 17-24 2017

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

| LEBT | RFQ | MEBT | β=0.11 | β=0.22 | β=0.47 | β=0.64 | β=0.97 |

RT ◄──────► SC ◄──────────────────────────►

162.5 MHz
0.03 -10.3 MeV

325 MHz
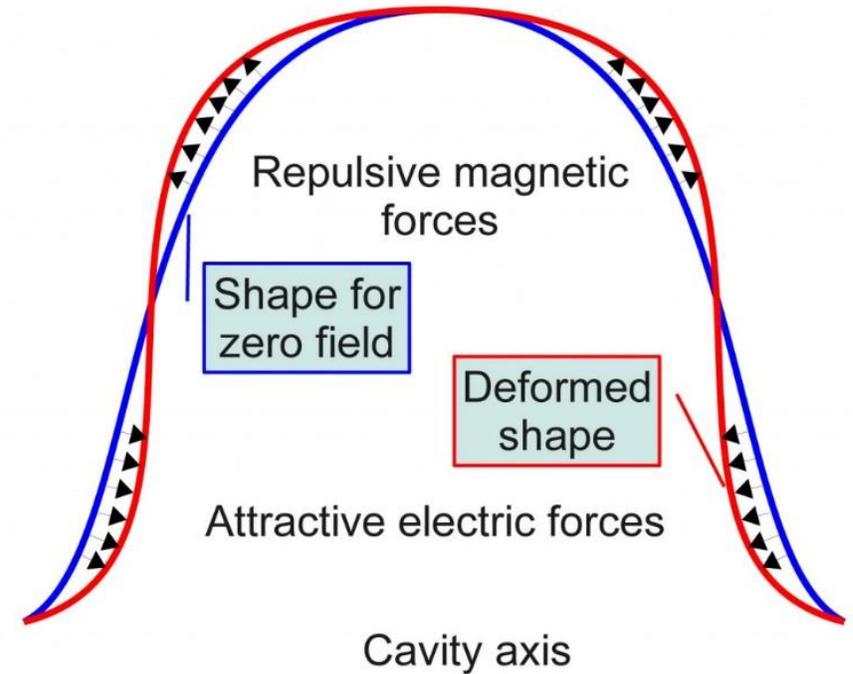10.3-185 MeV

650 MHz
185-800 MeV

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

LCLS-II Layout

Cooling Plant

Beam Switchyard

Soft X-ray Undulator

Experimental Halls

Existing Copper Accelerator

Hard X-ray Undulator

New Superconducting Accelerator

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)
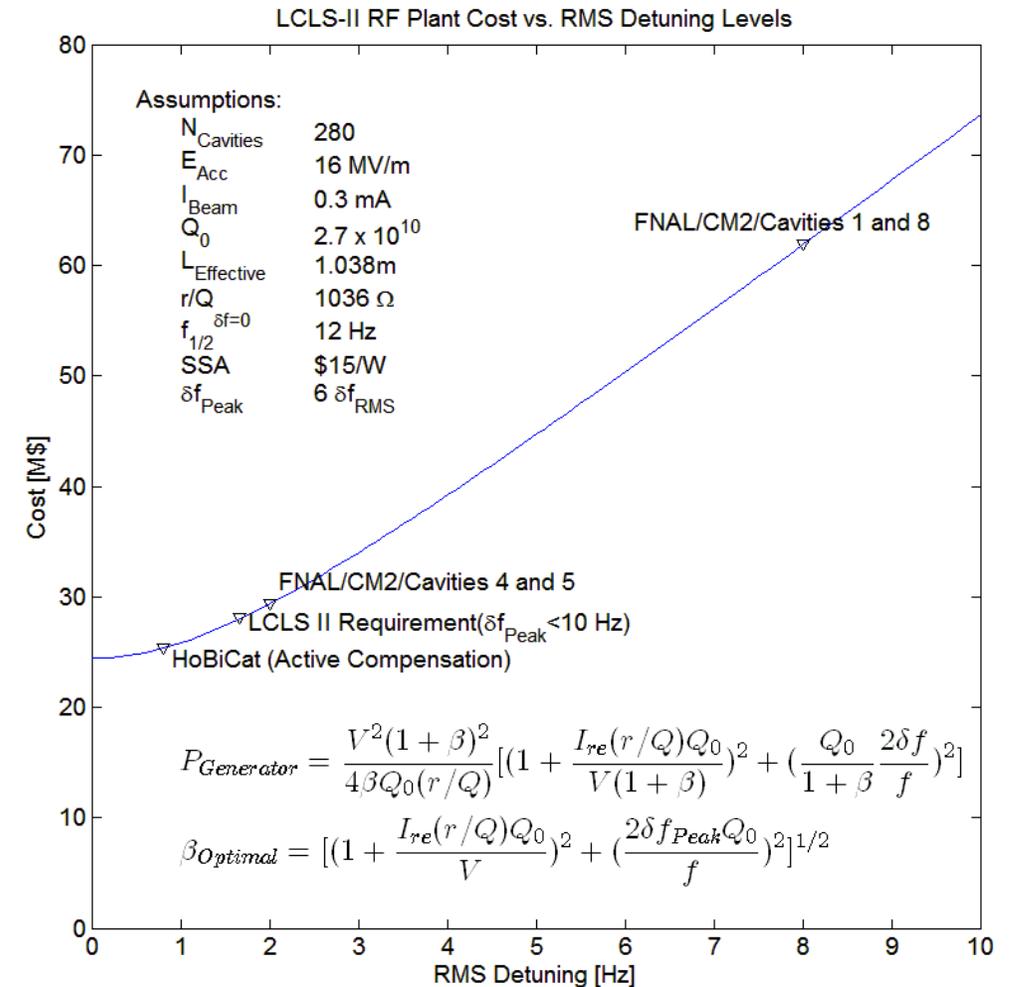

Repulsive magnetic forces

Shape for zero field

Deformed shape

Attractive electric forces

Cavity axis

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

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

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

LCLS-II RF Plant Cost vs. RMS Detuning Levels

Assumptions:

$N_{Cavities}$	280
E_{Acc}	16 MV/m
I_{Beam}	0.3 mA
Q_0	2.7×10^{10}
$L_{Effective}$	1.038m
r/Q	1036 Ω
$f_{1/2}^{\delta f=0}$	12 Hz
SSA	\$15/W
δf_{Peak}	6 δf_{RMS}

FNAL/CM2/Cavities 1 and 8

FNAL/CM2/Cavities 4 and 5

LCLS II Requirement(δf_{Peak}<10 Hz)

HoBiCat (Active Compensation)

$$P_{Generator} = \frac{V^2(1+\beta)^2}{4\beta Q_0 (r/Q)} \left[(1 + \frac{I_{re}(r/Q)Q_0}{V(1+\beta)})^2 + (\frac{Q_0}{1+\beta} \frac{2\delta f}{f})^2 \right]$$

$$\beta_{Optimal} = \left[(1 + \frac{I_{re}(r/Q)Q_0}{V})^2 + (\frac{2\delta f_{Peak}Q_0}{f})^2 \right]^{1/2}$$

Cost [M\$] vs RMS Detuning [Hz]

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

Helium Vessel

Piezo Stack

Stepper Motor

LCLS-II Fast/Slow Tuner
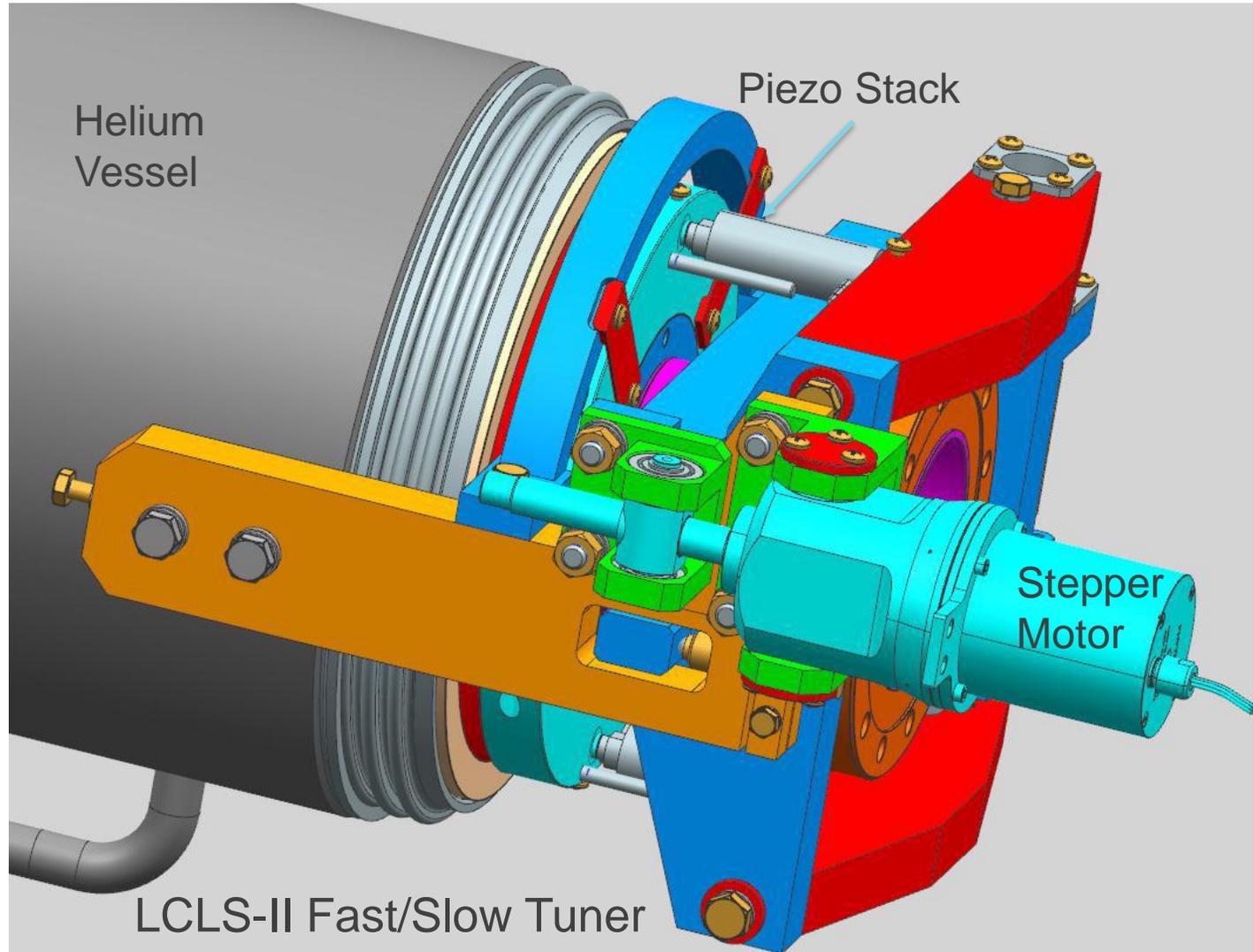
Measuring Cavity Detuning

- 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

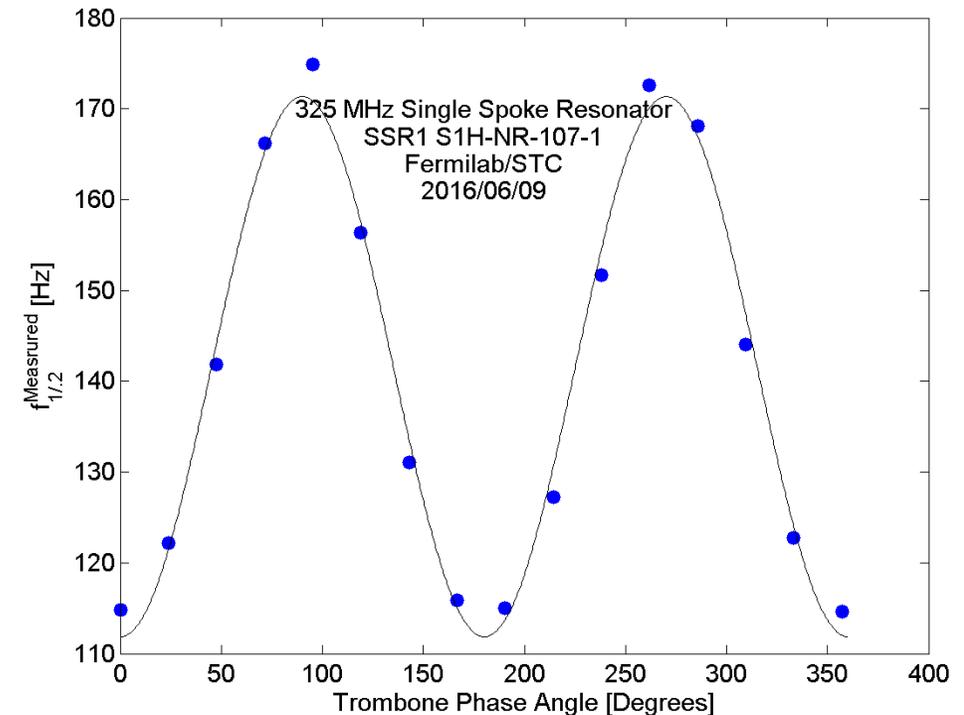$$\frac{dP}{dt} = -(\omega_{1/2} + i\delta)P + 2\omega_{1/2}F$$

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

$$\delta = -\frac{\text{Im}\left(P^*\left(\frac{dP}{dt} - 2\omega_{1/2}F\right)\right)}{P^*P}$$
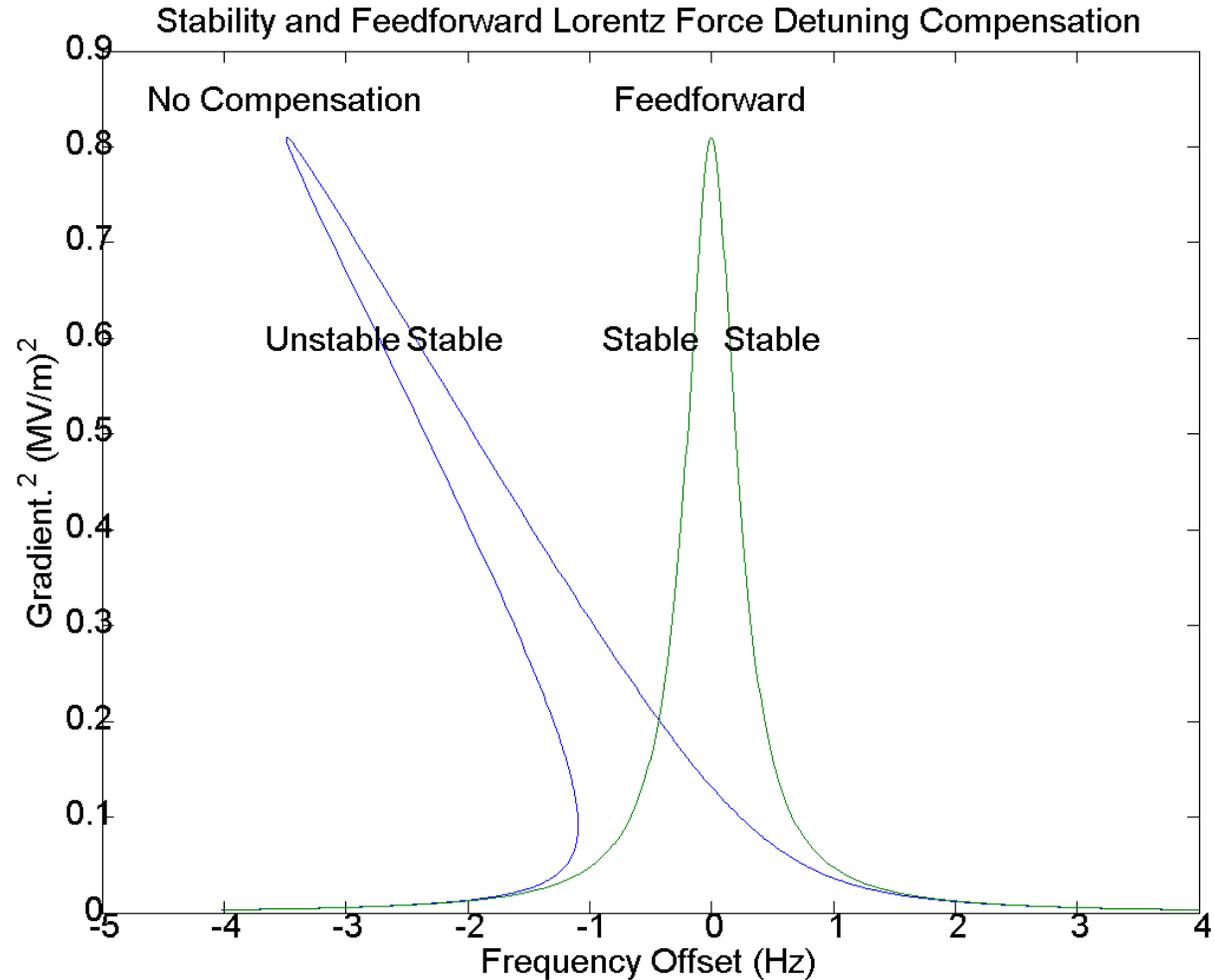
Calibration and Systematic Effects

- 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

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

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

325 MHz Single Spoke Resonator
SSR1 S1H-NR-107-1
Fermilab/STC
2016/06/09

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

Stability and Feedforward Lorentz Force Detuning Compensation

No Compensation

Feedforward

Unstable Stable

Stable   Stable

$Gradient.^2 (MV/m)^2$

Frequency Offset (Hz)

Warren Schappert

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
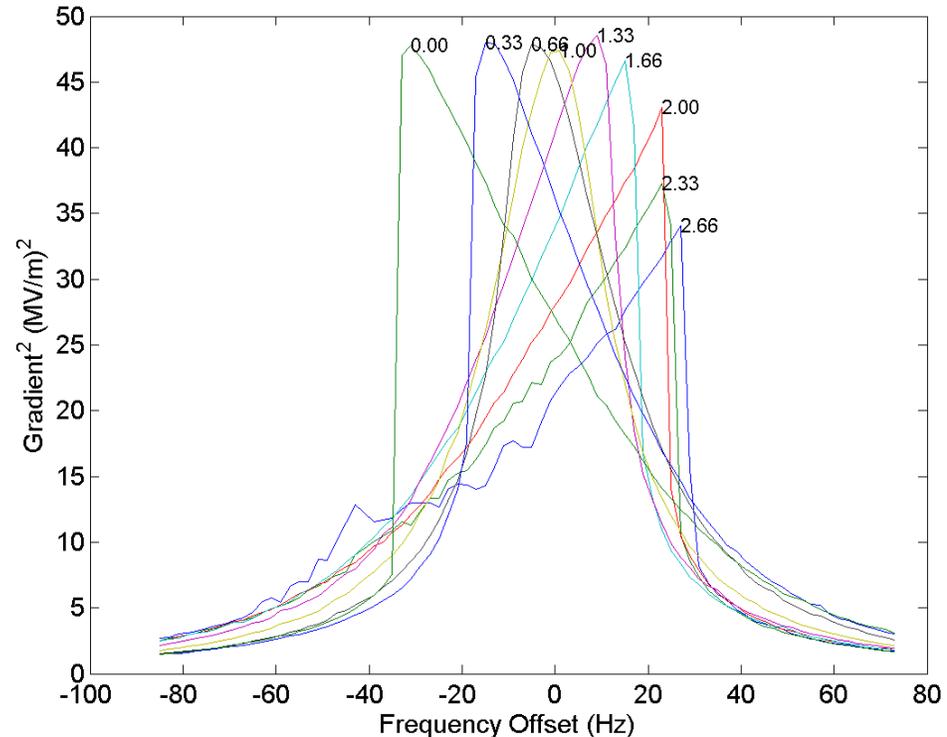
Adaptive Feedforward

- 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
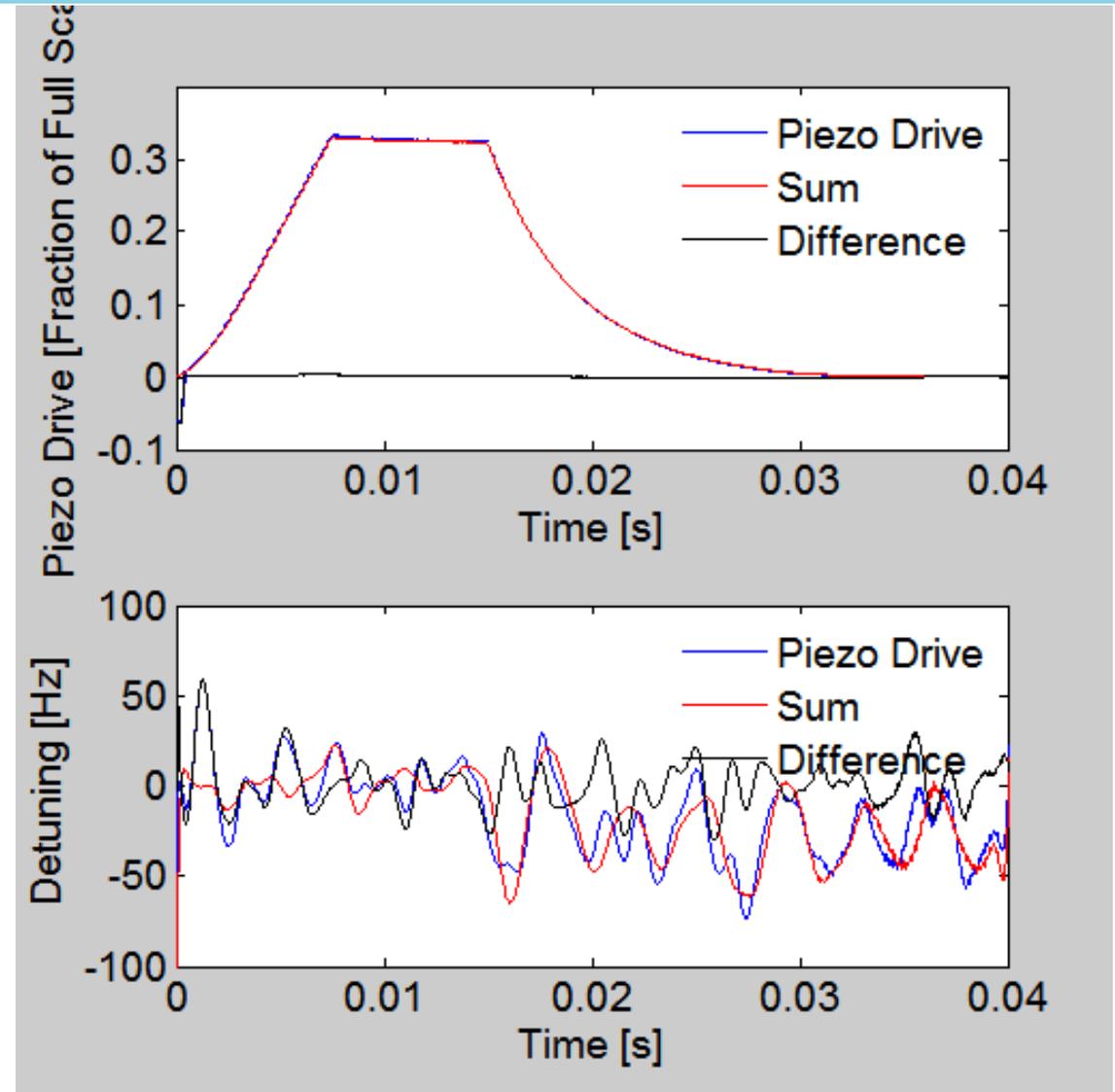
(Inverse) Piezo/Detuning Transfer Function

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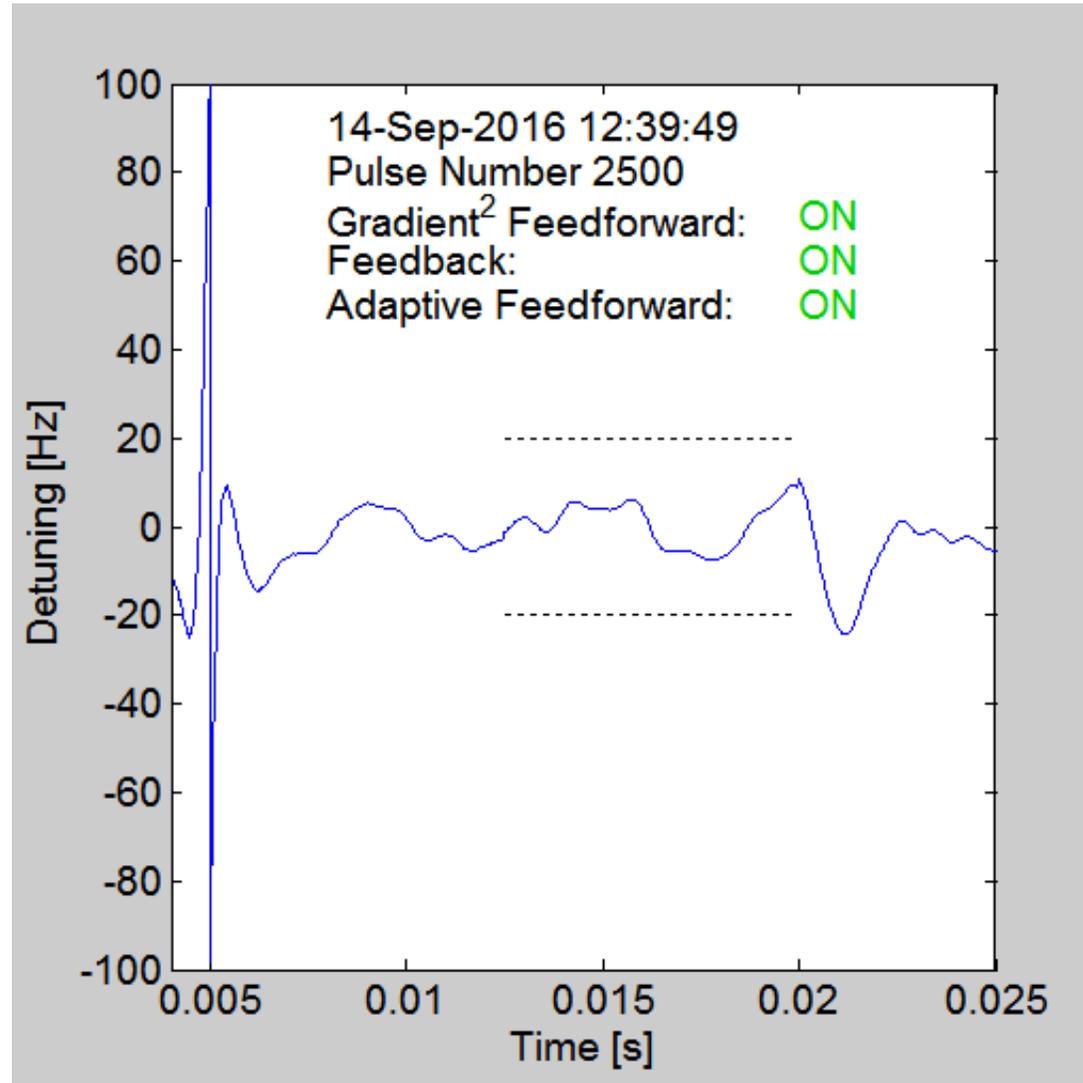
$$\delta - T_{\delta/PZT} V_{\delta} = 0$$

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

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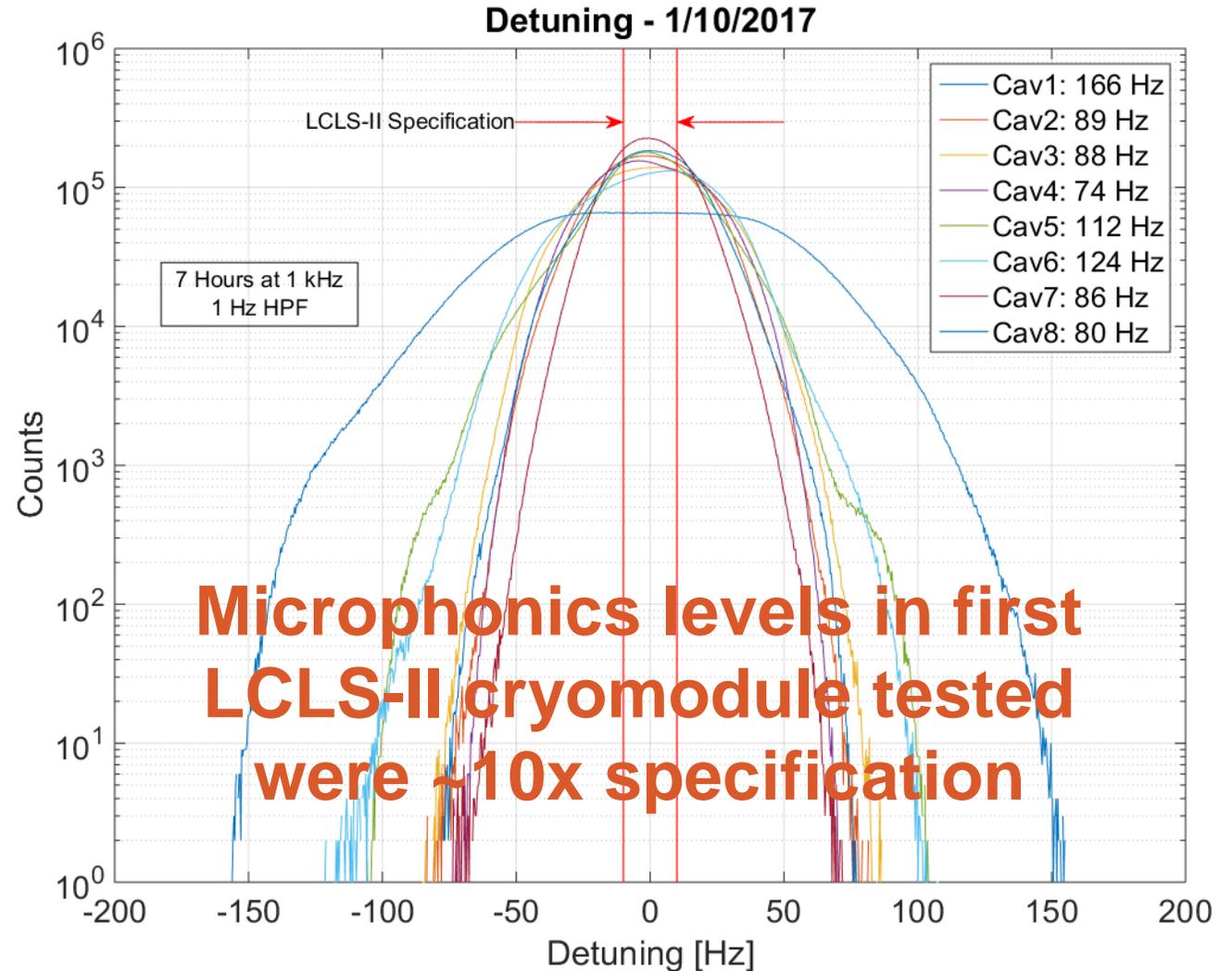
Adaptive Feedforward

- 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,…

Detuning - 1/10/2017

LCLS-II Specification

7 Hours at 1 kHz
1 Hz HPF

Cav1: 166 Hz
Cav2: 89 Hz
Cav3: 88 Hz
Cav4: 74 Hz
Cav5: 112 Hz
Cav6: 124 Hz
Cav7: 86 Hz
Cav8: 80 Hz

Counts

Detuning [Hz]

Microphonics levels in first LCLS-II cryomodule tested were ~10x specification
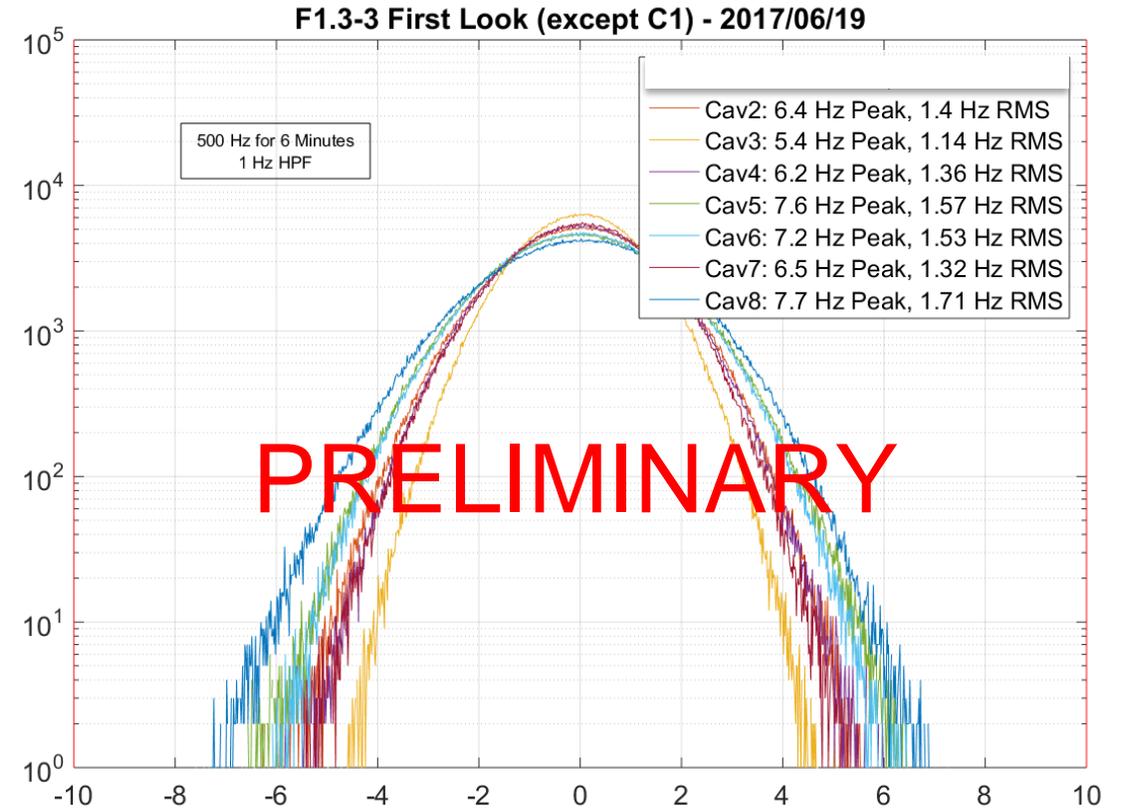
Thermo–Acoustic Oscillations

- 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

FNAL CMTS/LCLS-II pCM/Cavity 4/2016-12-28
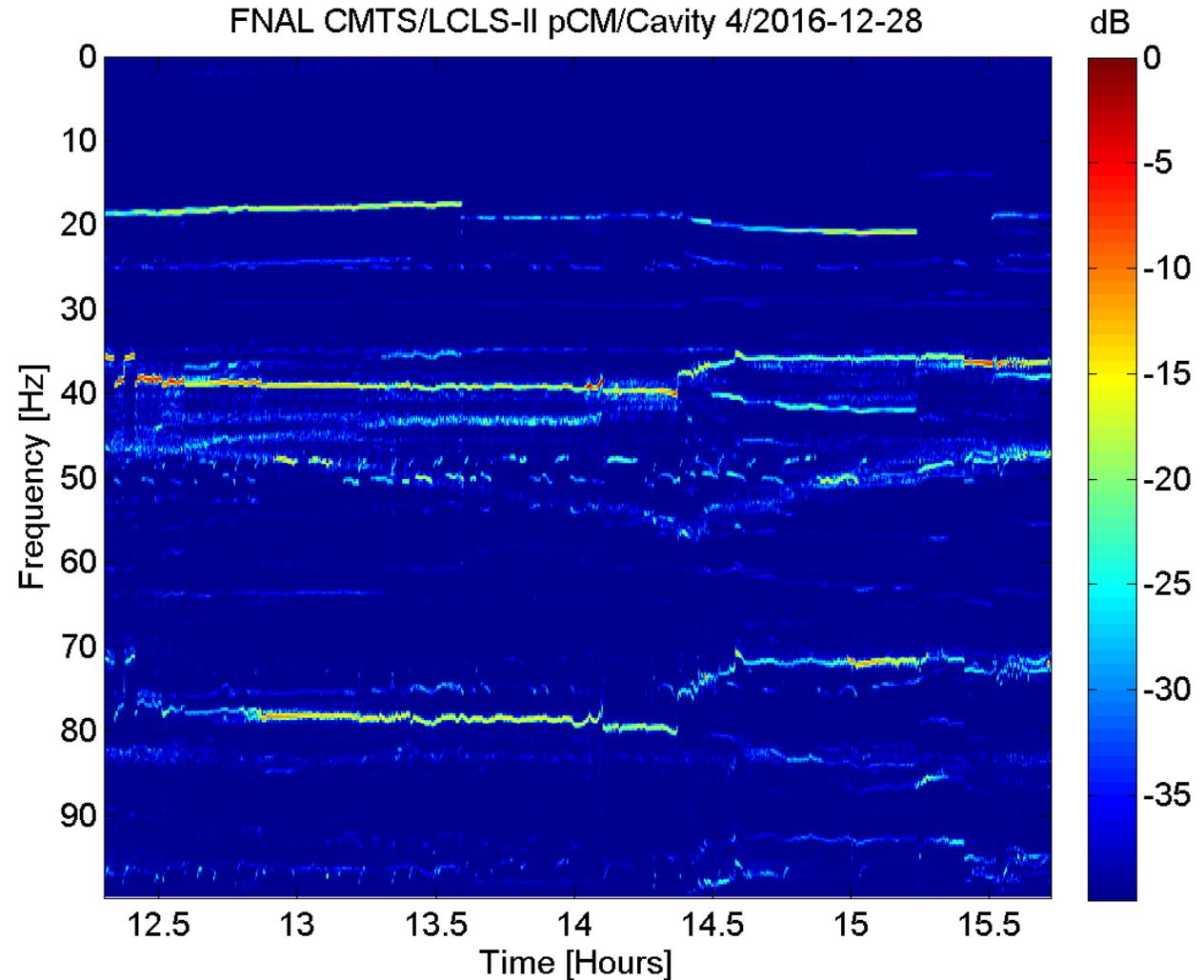
LCLS-II Detuning Following Mitigation of TAOs

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

F1.3-3 First Look (except C1) - 2017/06/19

500 Hz for 6 Minutes
1 Hz HPF

Cav2: 6.4 Hz Peak, 1.4 Hz RMS
Cav3: 5.4 Hz Peak, 1.14 Hz RMS
Cav4: 6.2 Hz Peak, 1.36 Hz RMS
Cav5: 7.6 Hz Peak, 1.57 Hz RMS
Cav6: 7.2 Hz Peak, 1.53 Hz RMS
Cav7: 6.5 Hz Peak, 1.32 Hz RMS
Cav8: 7.7 Hz Peak, 1.71 Hz RMS

PRELIMINARY

Warren Schappert

June 22, 2017

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

FNAL/CMTS/CM2/Cavity 2 - May 18,2017
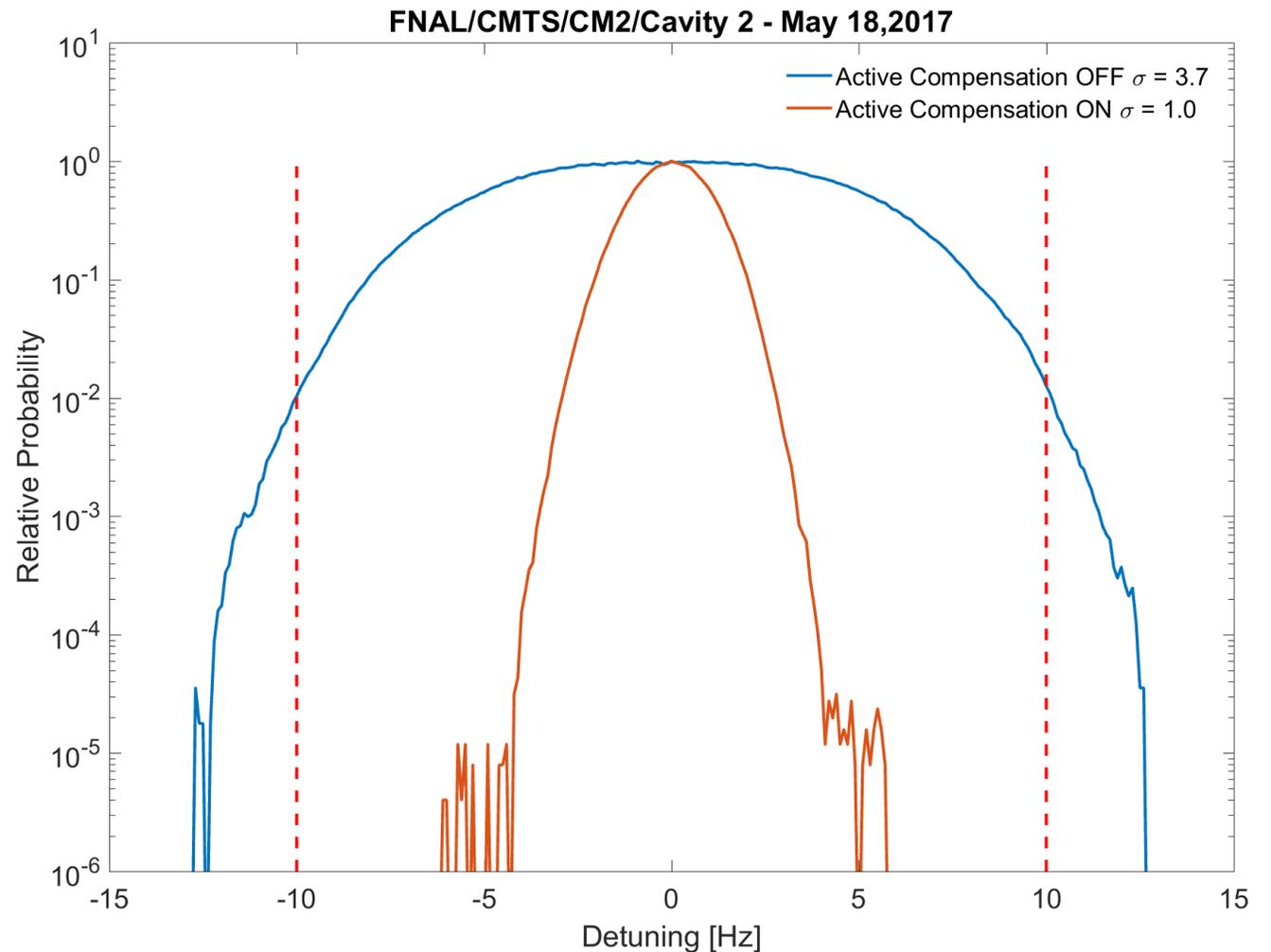
Conclusions

- 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