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Resonance Control State of the Art at FNAL

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First Microphonics Workshop

Thursday, October 8th, 2015

FNAL Facilities/Experience

- Over the years, FNAL has developed experience working with several different styles of cavities for different applications
  - ILC
    - HTS @ MDB / S1G @ KEK / CM1&CM2 @ NML
    - Challenging pulsed application with large bandwidths
    - Dominated by LFD
  - LCLS-II
    - HTS @ MDB / HTC @ Cornell
    - Mostly CW application with narrow bandwidth (30 Hz)
  - PIP-II
    - STC @ MDB
    - Even more challenging pulsed application with narrow bandwidth

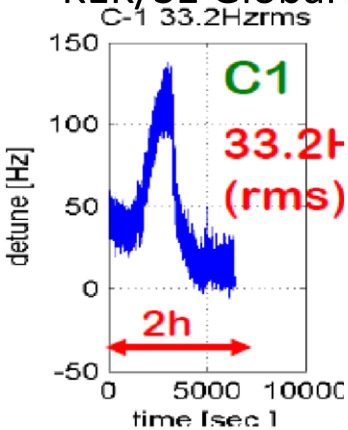
ILC Work – Adaptive Algorithm

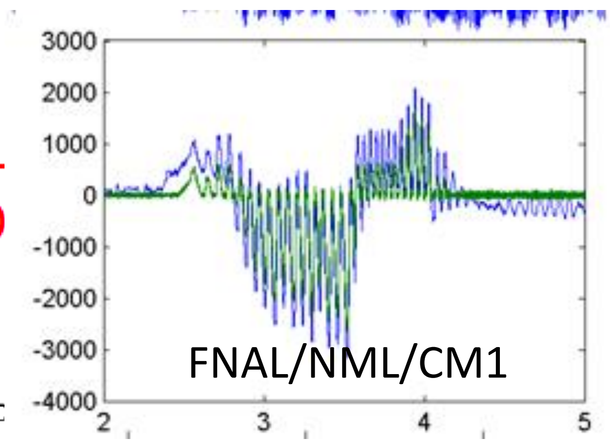
- Training pulses from the piezo characterize the cavity mechanical system (VIDEO)
- This characterization is inverted and used to shape the pulse structure (VIDEO)
- Pulsed operation causes significant mechanical vibration that is coupled through the cryomodule (RECORDING)

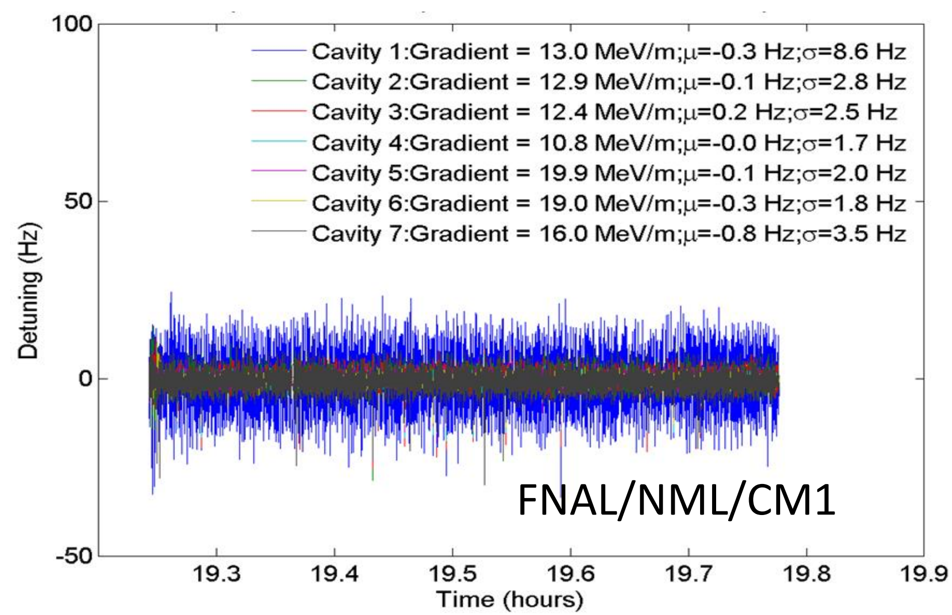
Feed-forward Resonance Stabilization in Pulsed Cavities

- Cavities sensitive to changes in He pressure df/dP ≅ 50 Hz/Torr
  - Can lead to large shifts in resonance frequency
- Adaptive algorithm can adjust piezo bias based on running average of detuning during previous pulses
  - Resonance can be stabilized to better than 1Hz on average
- Residual pulse-to-pulse detuning (microphonics) small in FNAL/NML/CM1
  - Lower in the middle (<2 Hz>
  - Higher at the ends (9 Hz)
    - Vacuum pumps
- Microphonics compensation requires feedback

KEK/S1 Global

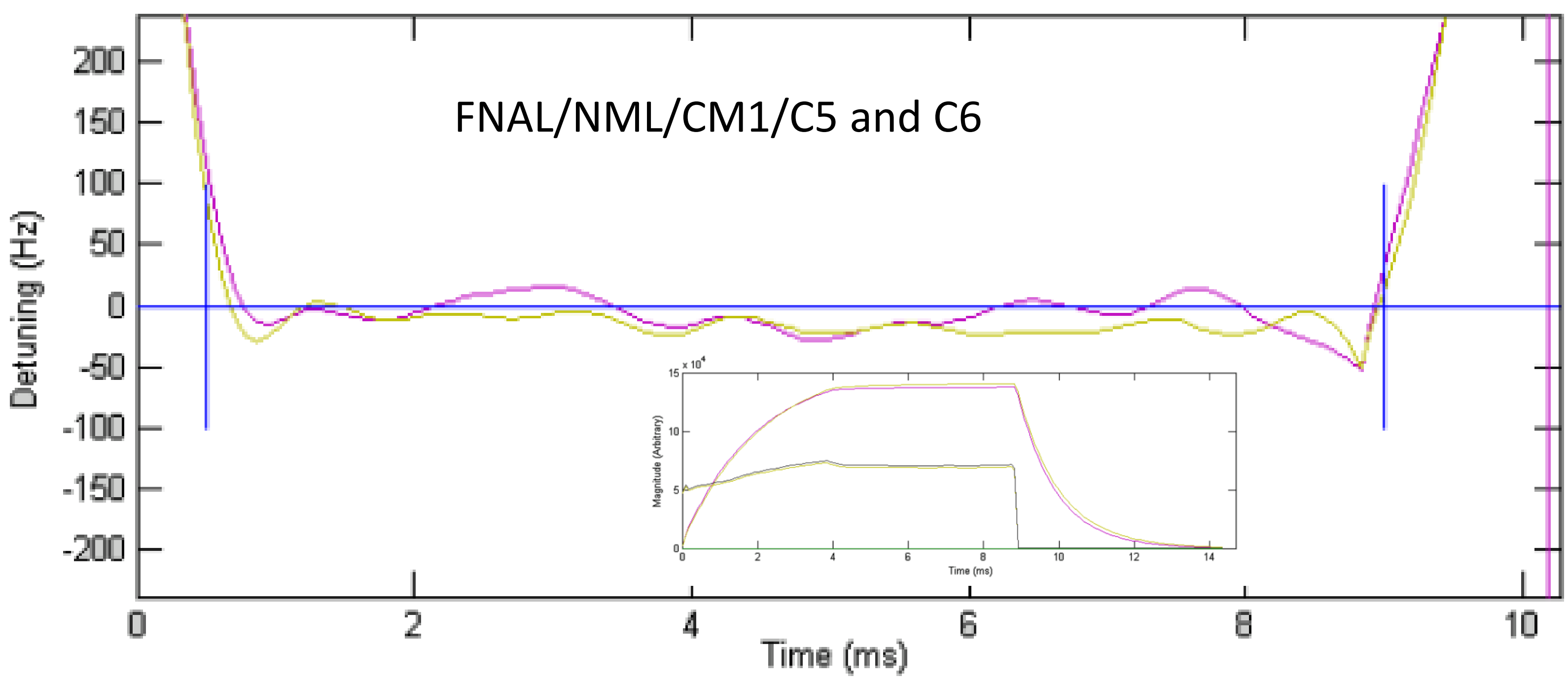




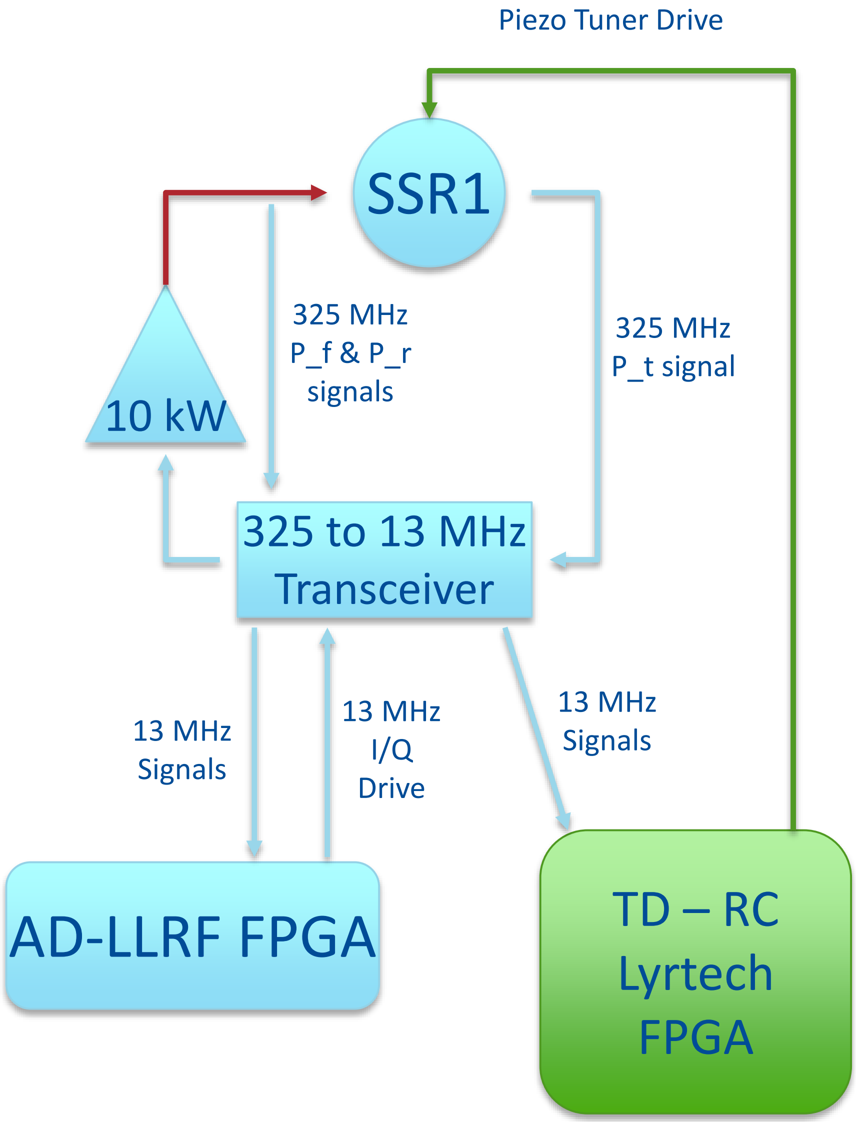


Narrow Bandwidths and Long Pulses

- For some applications longer pulses and narrower bandwidths may be useful
  - 2011 Test using 9ms pulses in FNAL/NML/CM1/C5 and C6 for Project X
    - Q_L ranged between $3x10^6$ and $3x10^7$
  - Adaptive LFD control able to limit detuning to better than 50 Hz across the flattop and most of the fill



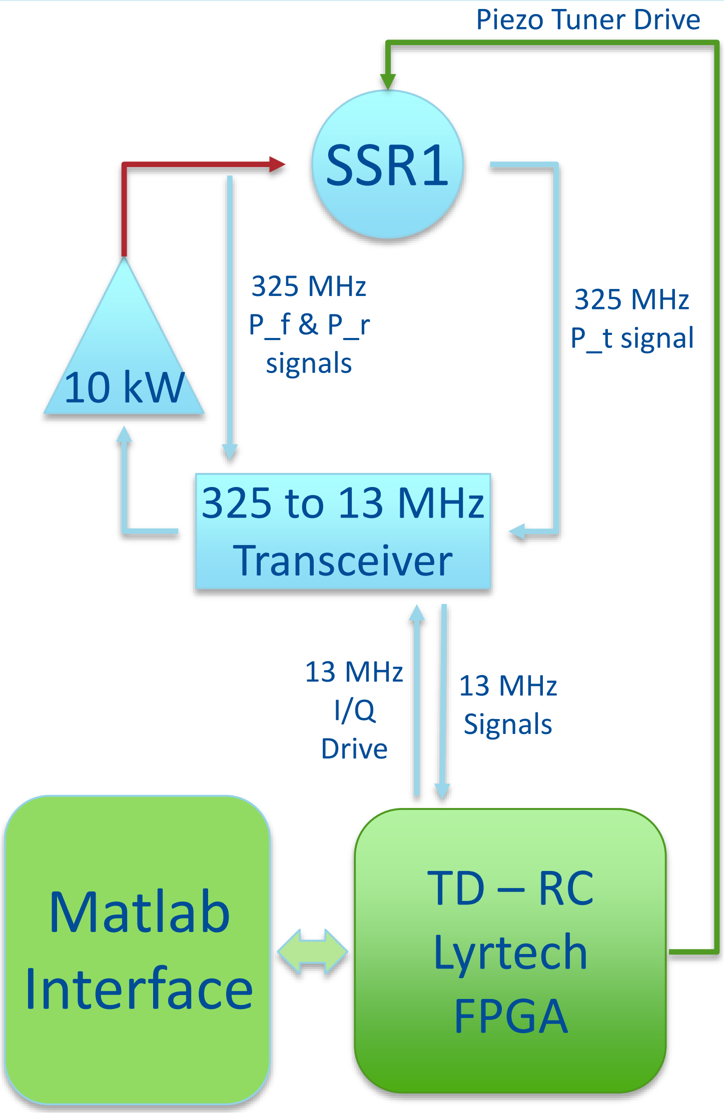
FNAL Control System Improvement



- Existing digital control system was passively monitored by the compensation system
- This was process and used to apply compensation signal to piezo controller
- Double peaked detuning distribution suspected to be from the difference between FPGA clocks

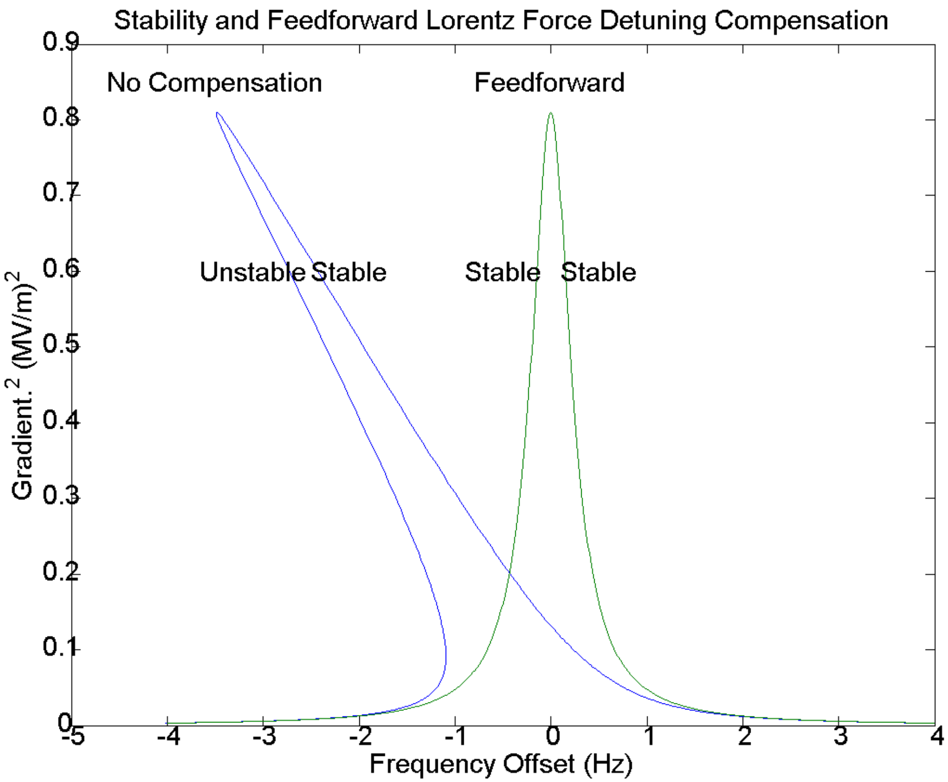
FNAL System Improvement (2)

- Now, compensation system also controls cavity drive
- In the FPGA:
  - Numerically down-convert signals from 13 MHz to baseband
  - Calculate detuning
  - Output 13 MHz drive I/Q
  - Output Piezo Tuner Drive
- Common clock, common data output and recording system



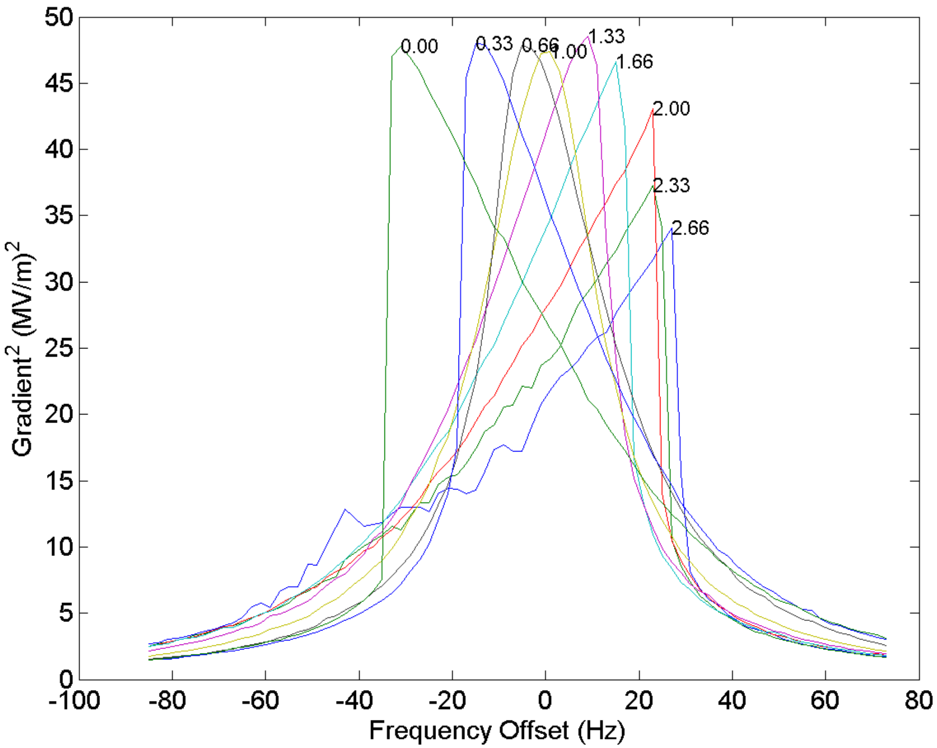
Ponderomotive Instabilities

- Lorentz force detunes cavity
- If detuning is more than several bandwidths cavities can become unstable
  - Small perturbations can cause the cavity field to suddenly crash to zero



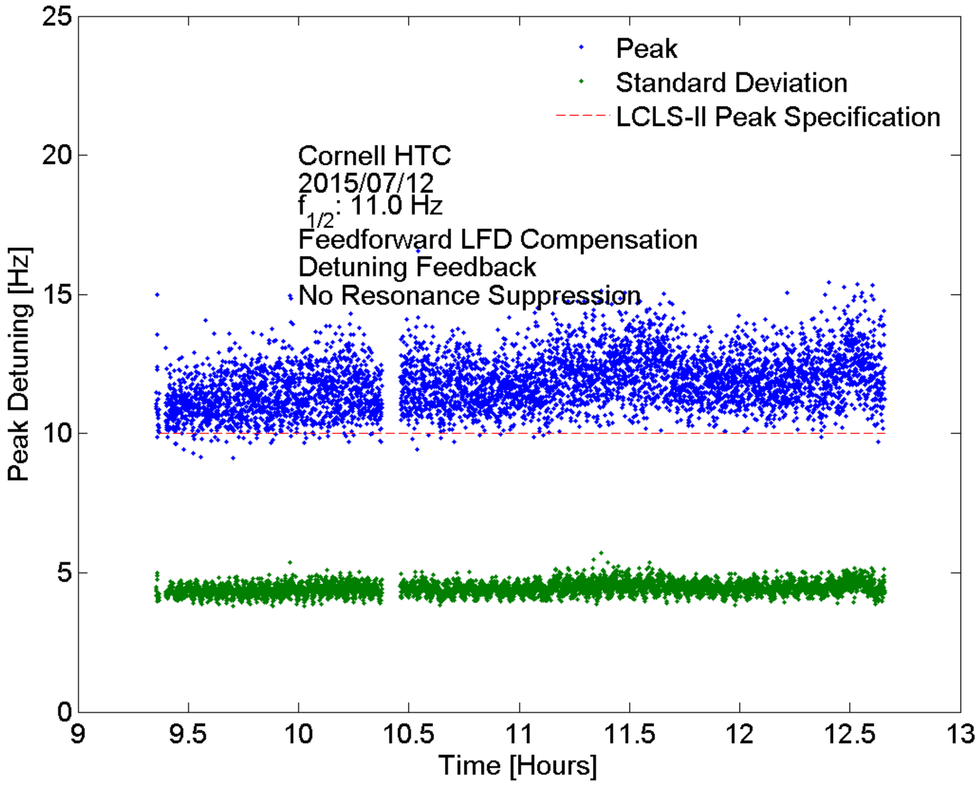
Feed-Forward LFD Compensation

- Possible to remove the instability using piezo feed-forward tied to cavity square of gradient
  - Previously shown for SSR1 spoke resonator
  - Now demonstrated for multi-cell elliptical cavities



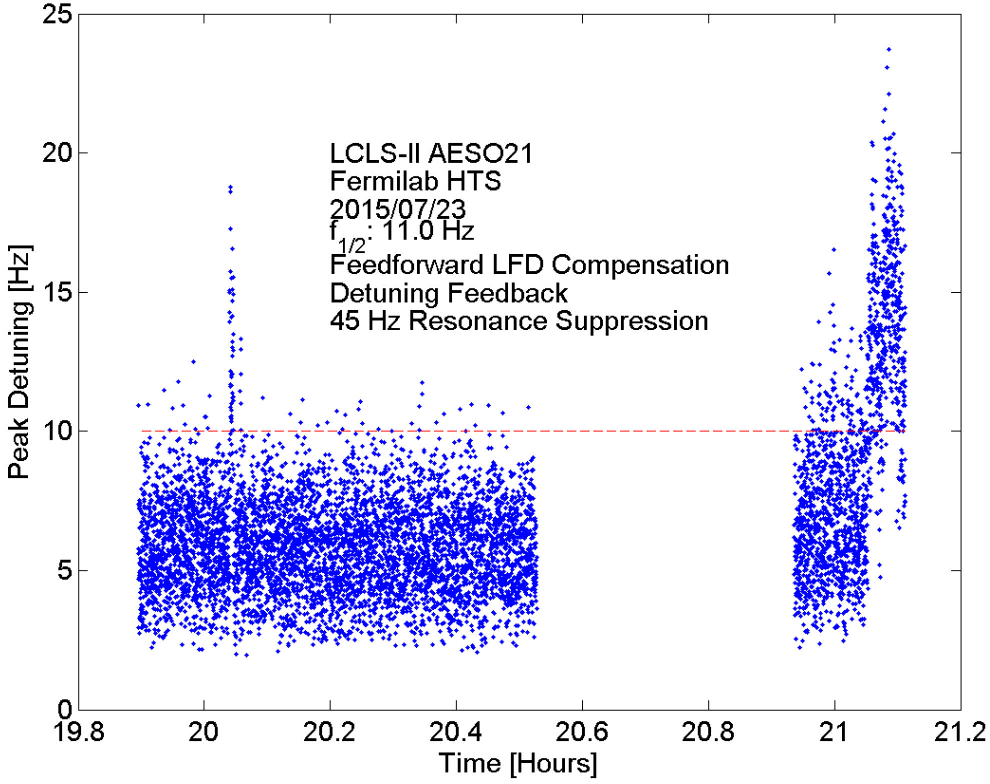
Proportional Feedback

- For CW operation, it is desired to stabilize the cavity resonance in the presence of detuning
- These factors include df/dP, vibration, and LFD
- Combination of LFD feed-forward and proportional feedback on the piezo tuner
- Detuning is calculated on the fly in FPGA and applied
- Detuning calculation implementation is incomplete, work ongoing



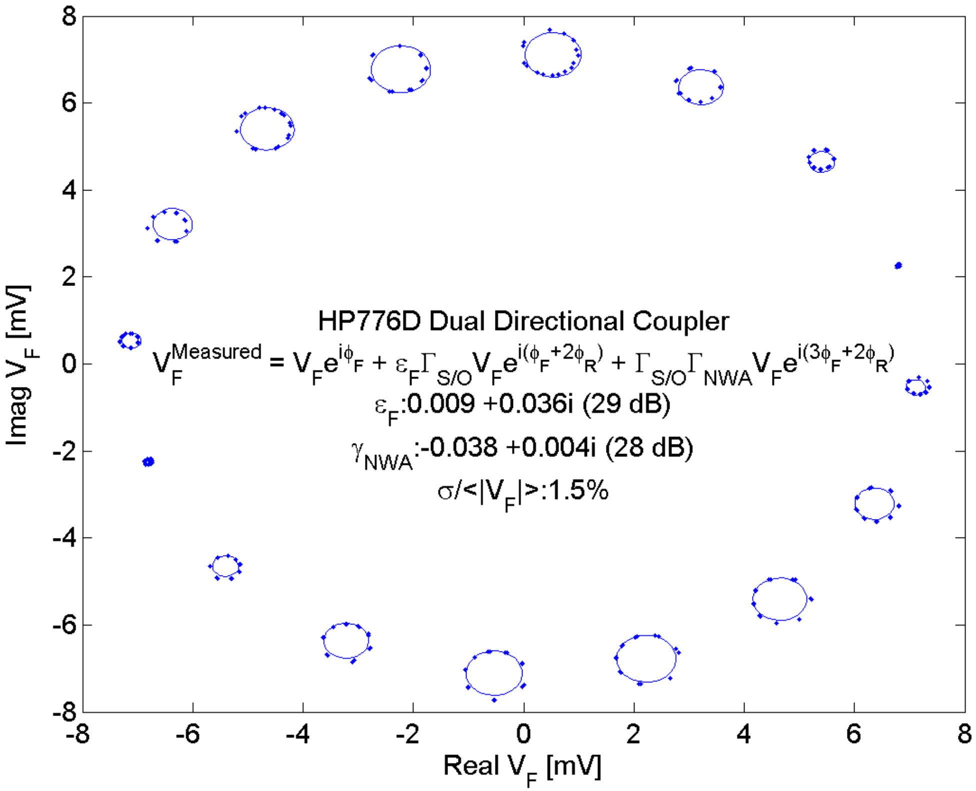
Proportional Feedback with Narrowband Compensation

- In addition to proportional feedback, narrowband compensation has been demonstrated to suppress specific sources
- Locks and cancels specific resonances
- Work is in progress to improve this implementation and extend to multiple frequencies

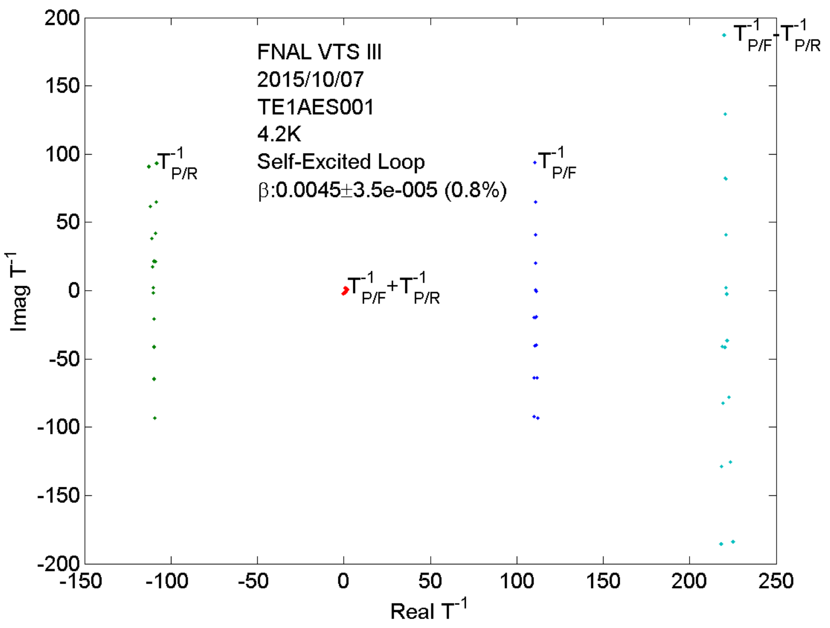


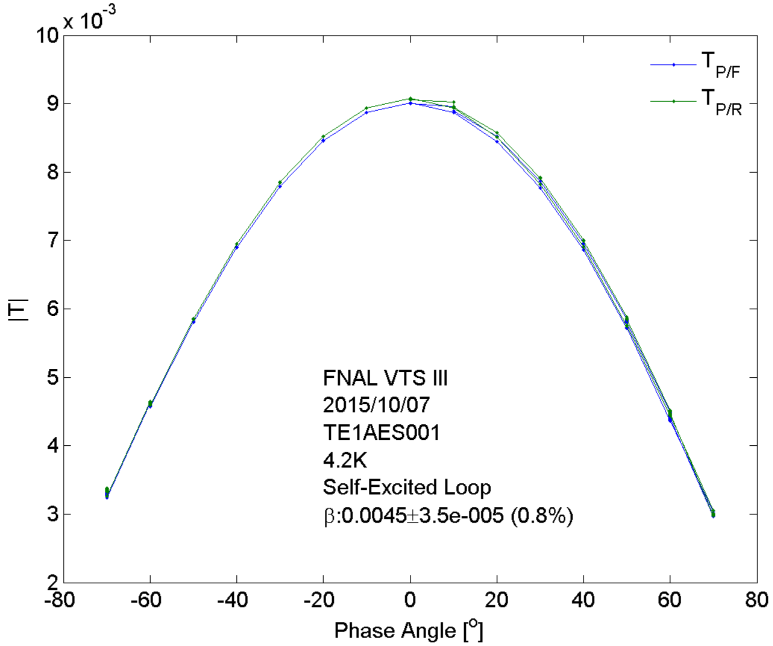
Directivity/Mismatch Errors

- Work continues on the source and mitigation of systematic errors associated with cavity measurements
- Imperfect Directivity
- Circulator Mismatch
- Measurements and compensation of these errors open exciting possibilities for making accurate measurements of very poorly coupled cavities



Precision Cavity Measurements using Transfer Functions



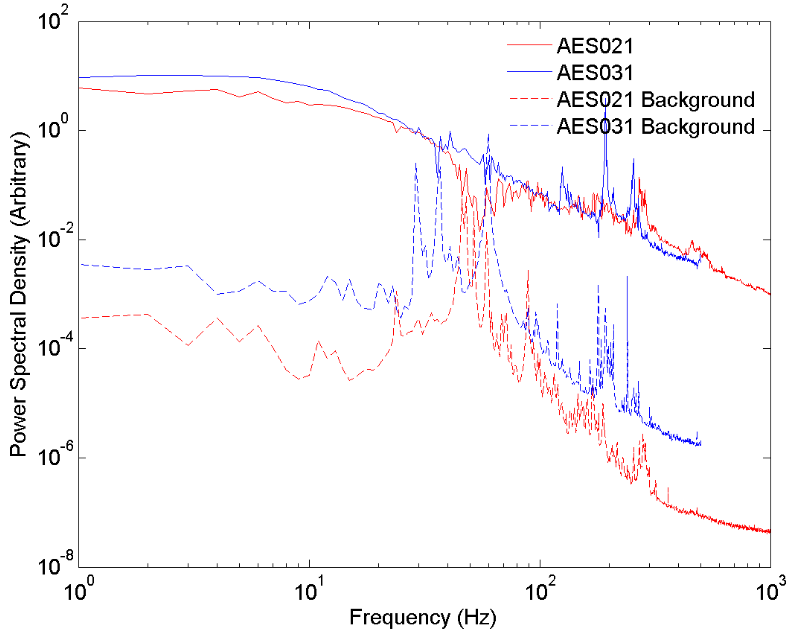


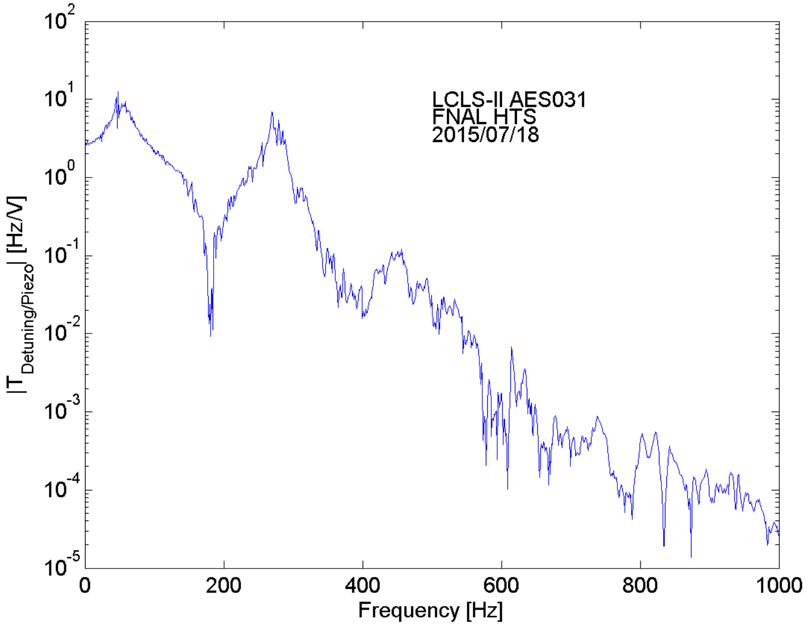
Single Cell cavity set in VTS III

4.5 K operation means very poor coupling

Working on porting self-excited loop and calibration functionality to a broadband transceiver/FPGA for ultra-flexible cavity testing

Cavity Characterization





Cavity Field Modulation Transfer Function

Piezo-Cavity Transfer Function

Summary

- Advanced tools have been developed at FNAL
  - Adaptive algorithm for pulsed operation
  - Pondermotive Feed Forward
  - Proportional Feedback
  - Narrowband Compensation
  - Precision measurement techniques
  - Cavity characterization
- The next goal is to integrate this all into a combined controller
- Take cavity characterization and use that data to build a combined electromechanical controller (Kalman Controller)