Resonance Control of Cavities

Jeremiah Holzbauer
PIP-II Machine Advisory Committee
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Resonance Control Group

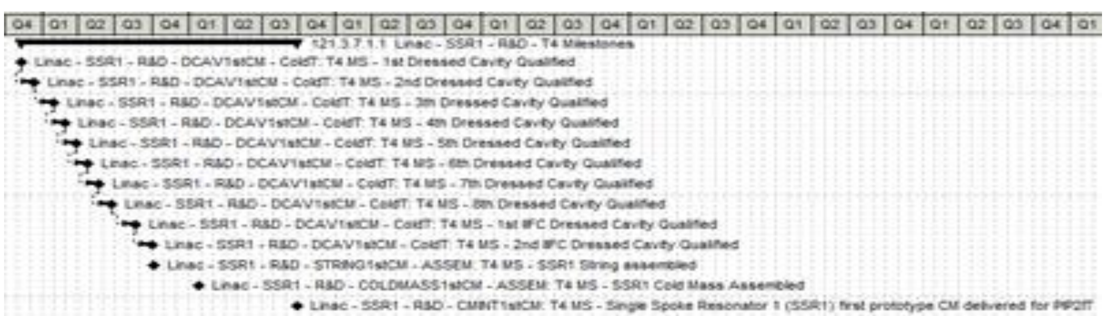
- Group Members:
  - Warren Schappert
  - Jeremiah Holzbauer
  - Yuriy Pischalnikov (group leader)
- PIP-II Role:
  - SRF/TD Resonance Control Group
- Relevant Experience
  - Developed adaptive LFD algorithms for ILC cavities
  - Extensive experience with resonance control in a variety of cavities

Relevant Group Publications (Inspirehep.net)

1) Investigation of Thermal Acoustic Effects on SRF Cavities within CM1 at Fermilab
2) Systematic Uncertainties in RF-Based Measurement of Superconducting Cavity Quality Factors
3) Performance of the Tuner Mechanism for SSR1 Resonators During Fully Integrated Tests at Fermilab
4) Reliability of the LCLS II SRF Cavity Tuner
5) Resonance Control for Narrow-Bandwidth, Superconducting RF Applications
6) Systematic Uncertainties in RF-Based Measurement of Superconducting Cavity Quality Factors
9) Progress at FNAL in the Field of the Active Resonance Control for Narrow Bandwidth SRF Cavities.
10) Design and Test of the Compact Tuner for Narrow Bandwidth SRF Cavities
12) RF Tests of Dressed 325 MHz Single-Spoke Resonators at 2 K
13) Application Investigation of High Precision Measurement for Basic Cavity Parameters at ESS
15) RF Control and DAQ Systems for the Upgraded Vertical Test Facility at Fermilab
16) Phase Method of Measuring Cavity Quality Factor
21) Recent Progress at Fermilab Controlling Lorentz Force Detuning and Microphonics in
22) Results Achieved by the S1-Global Collaboration for ILC
23) Lorentz Force Detuning Compensation Studies for Long Pulses in ILC type SRF Cavities
24) A Highly configurable and scriptable software system for fully automated tuning of accelerator cavities
26) Lorentz Force Compensation for Long Pulses in SRF Cavities
27) Adaptive compensation of Lorentz force detuning in superconducting RF cavities
28) S1-Global Module Tests at STF/KEK
29) Tuner Performance in the S1-global Cryomodule
30) RF Test Results from Cryomodule 1 at the Fermilab SRF Beam Test Facility
31) Operating Experience with CC2 at Fermilab's SRF Beam Test Facility
32) Tests of a Tuner for a 325 MHz SRF Spoke Resonator
33) Vibrational Measurements for Commissioning SRF Accelerator Test Facility at Fermilab
34) Cryomodule Design for 325 MHz Superconducting Single Spoke Cavities and Solenoids
35) 1.3 GHz Superconducting RF Cavity Program at Fermilab
36) Resonance control in SRF cavities at FNAL
37) Microphonics control for Project X
38) Test of a coaxial blade tuner at HTS FNAL
39) First high power pulsed tests of a dressed 325 MHz superconducting single spoke resonator at Fermilab
40) Control System Design for Automatic Cavity Tuning Machines
43) A tuner for a 325 MHz SRF spoke cavity
47) Development of SCRF Cavity Resonance Control Algorithms at Fermilab

Resonance Control R&D Goals and Program

- Goal:
  - Stabilize resonance to <20 Hz PEAK in presence of microphonics and LFD
    - Assumption Peak<6σ
- Program:
  - Develop required combination of passive measures + active control
- Milestone:
  - Demonstrate control algorithms + Hardware with Beam in SSR1 at PIP-II Injector Test in 2019
- Resources
  - Test Time allocated during upcoming production tests (1 week/test)



SSR1 Dressed Cavity Testing Schedule

PIP-II in the Context of Other Future SRF Accelerators

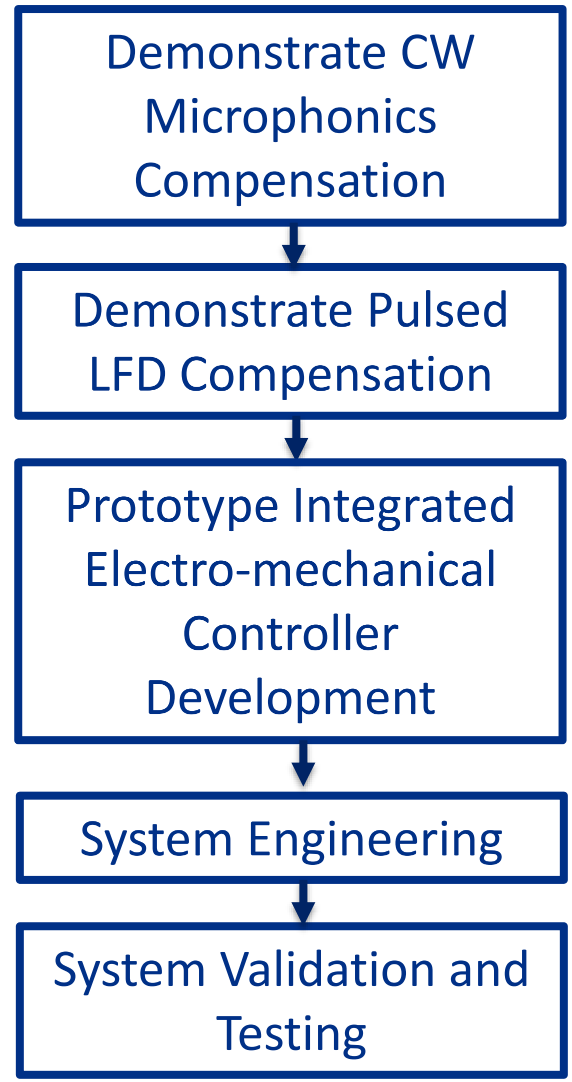
- As cavity gradients rise matched bandwidths narrow
- Minimizing detuning is critical for narrowband machines
- PIP-II presents a unique challenge because of the combination of narrow bandwidths and pulsed operation

				Mode	Gradient	Current	Frequency	Half Bandwidth	LFD	Peak Detuning	Peak Detuning/BW	LFD/BW
					MV/m	mA	MHz	Hz	Hz	Hz		
Wideband CW												
ARIEL	TRIUMF		e-	CW	10	10	1300	220				
SPIRAL-II		30 MeV, 5 mA protons -> Heavy Ions	Ion	CW	11	0.15-5	88	176				
Wideband Pulsed												
XFEL	DESY	18 GeV electrons – for Xray Free Electron Laser – Pulsed)	e-	Pulsed	23.6	5	1300	185	550			**3**
ESS	Sweden	1 – 2 GeV, 5 MW Neutron Source ESS - pulsed	p	Pulsed	21	62.5	704	500	400			**1**
Narrowband CW												
CEBAF Upgrade	JLAB	Upgrade 6.5 GeV => 12 GeV electrons	e-	CW	20	0.47	1497	25		10	**0.40**	
LCLS-II	SLAC	4 GeV electrons –CW XFEL (Xray Free Electron Laser)	e-	CW	16	0.06	1300	16		10	**0.63**	
FRIB	MSU	500 kW, heavy ion beams for nuclear astrophysics	Ion	CW	7.9	0.7	322	15		20	**1.33**	
cERL	KEK											
Narrowband Pulsed												
PIP-II	Fermilab	High Intensity Proton Linac for Neutrino Beams	p	Pulsed	17.8	2	650	30	300	20	**0.67**	**10**

http://accelconf.web.cern.ch/AccelConf/IPAC2015/talks/thzms3_talk.pdf

PIP-II Resonance Control Program Deliverables

- A set of fully documented, fully tested real-time implementation of algorithms capable of meeting the PIP-II specs for combined resonance frequency, phase, and amplitude stability.
  - Support for the production implementation of an integrated electromechanical controller by the AD/LLRF group
  - System validation and testing in conjunction with the AD/LLRF group



Recent Progress on Active Control

- Resonance Control has had an extended set of test time at STC while waiting for the next SSR1 cavity to be ready for testing. We received 80 working days of testing time, an up time of 60%.
- This extended testing time allowed extensive studies of:
  - Signal qualities/RF circuit
  - Detuning calculation and implementation
  - Feedback/Compensation techniques
- Development of a complementary Self-Excited Loop testing system
- These techniques were developed, coded, and refined first in CW operation, then in pulsed operation.
- This work gives a solid foundation for further testing going forward, including different cavity geometries.

Active Compensation Components

- Cavity/System Characterization
  - Calibrate RF signals/Systematic Errors
  - Lorentz Force Detuning (LFD) Calibration
  - Electromechanical Transfer Function
- Feed-Forward LFD Compensation
  - Drive piezo with signal αE^2
- Adaptive Algorithm (deterministic)
  - Calibrated compensation for RF impulse driven detuning
- Fast Detuning Feedback (non-deterministic)
  - Data-Driven Filter Bank for external microphonics

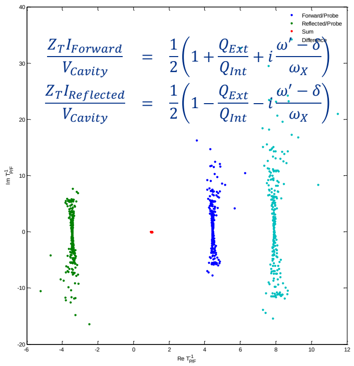
Measuring Cavity Detuning

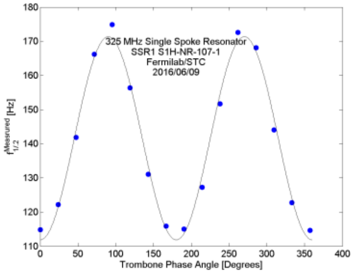
- Cavity detuning can be determined from complex baseband cavity signals
- Complex equation for baseband envelope can be separated into two real equations
  - Half bandwidth can be extracted from the real component
  - Detuning can be extracted from the imaginary component
- Precise compensation requires accurate measurements of the cavity baseband signals
  - Techniques developed to
    - extract accurate calibration from the baseband signals themselves
    - Measure and correct for systematic effects
      - Directivity
      - Reflections from the circulator
- Online implementation in FPGA

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

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

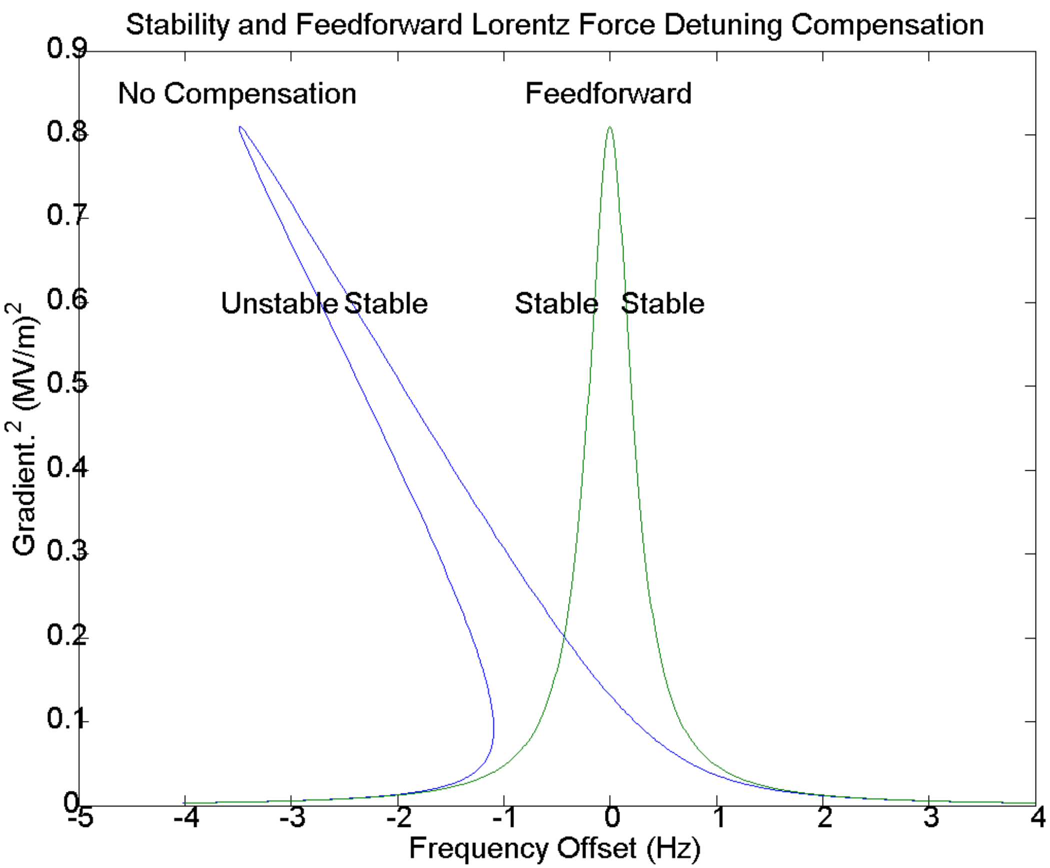
$$\delta = -\frac{\mathrm{Im}\left(P^*\left(\frac{dP}{dt} - 2\omega_{1/2}F\right)\right)}{P^*P}$$





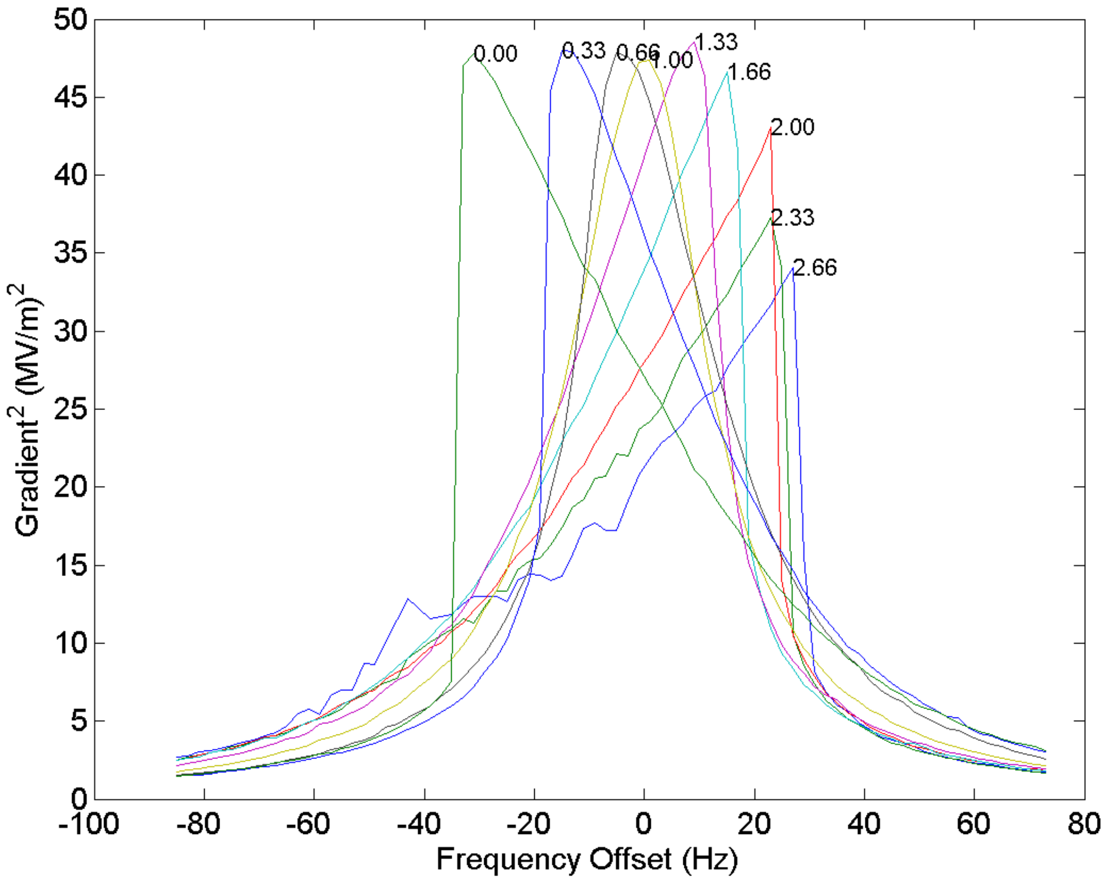
Ponderomotive Instabilities

- Lorentz force detunes cavity proportional to the square of the gradient
- If detuning is more than several bandwidths cavities can become unstable
- Small perturbations near the peak can cause the cavity field to suddenly crash to zero
- Cavity becomes very difficult to control



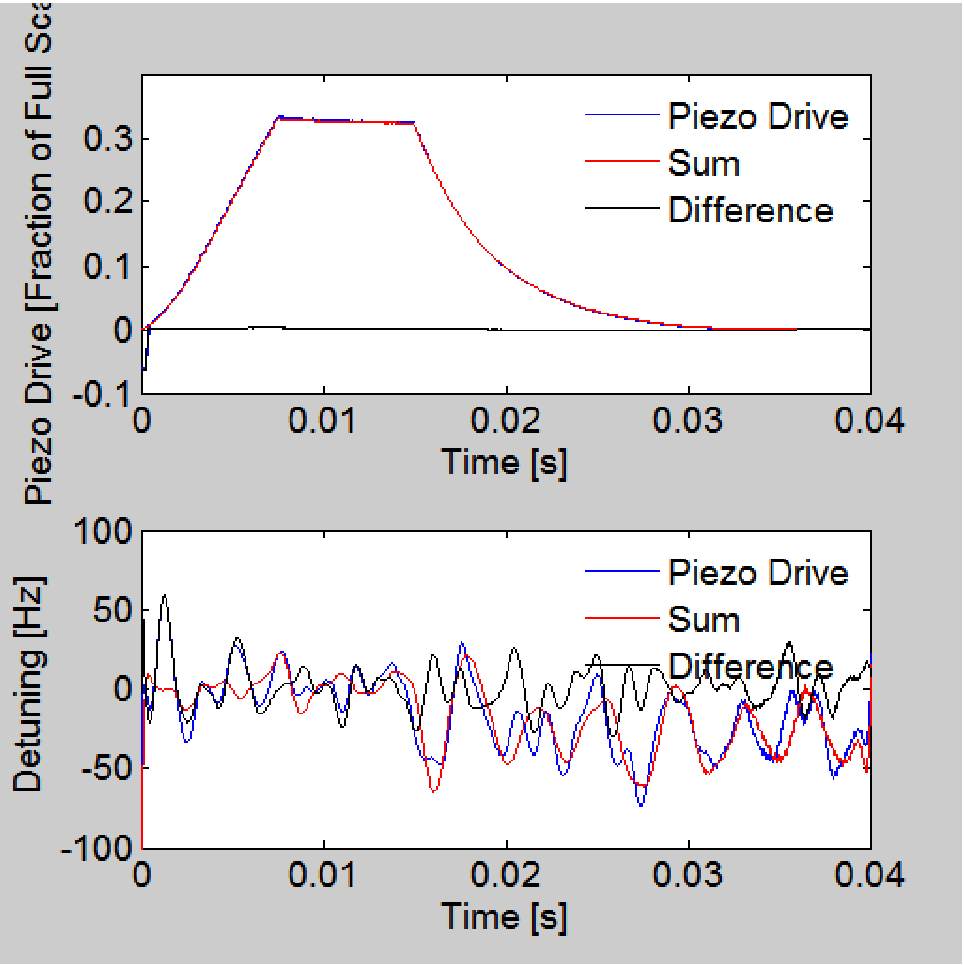
Feed-Forward Ponderomotive Stabilization

- Possible to remove the instability using piezo feed-forward tied to cavity square of gradient
- Demonstrated for both
  - 325 MHZ Single-Spoke Resonator
  - 9-Cell 1.3 GHz Elliptical Cavities



Cavity Mechanical 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



(Inverse) Piezo/Detuning Transfer Function

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

- Measure response to piezo pulses

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

- Extract Transfer function from measured data

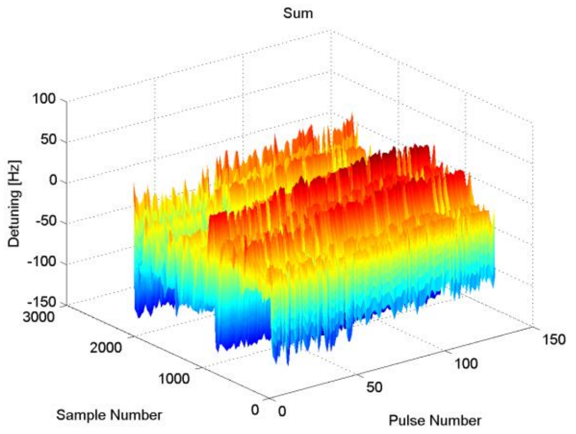
$$T_{\delta/PZT} = \delta V^T_{Piezo} (V_{piezo} V^T_{Piezo})^{-1}$$

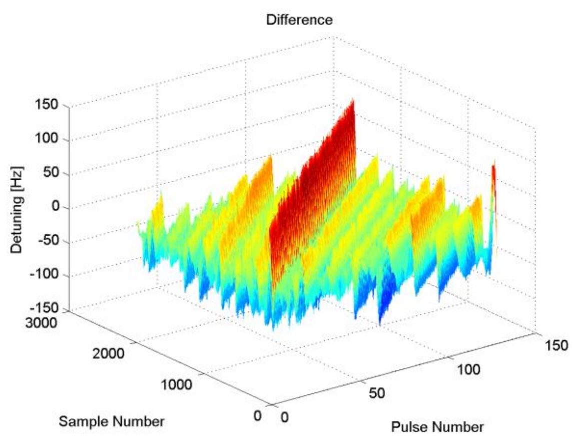
- Any deterministic detuning can be cancelled using the appropriate waveform

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

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

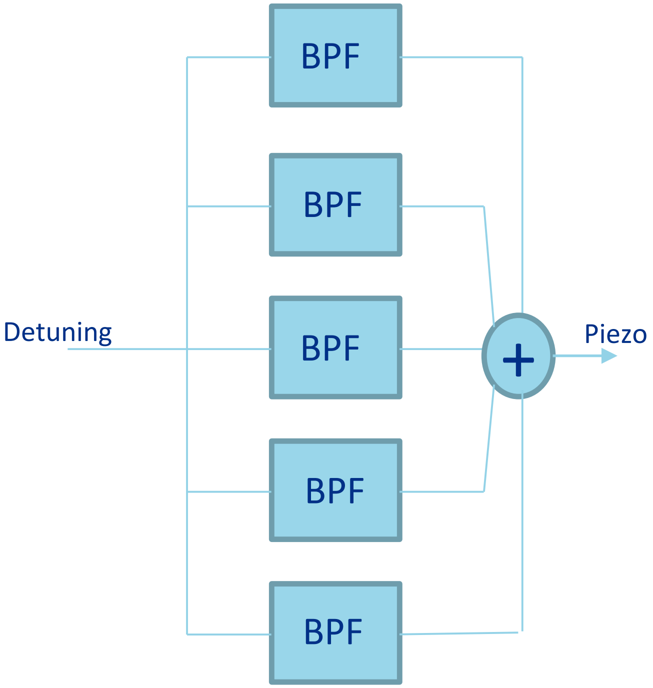
- Numerical instabilities can be suppressed using SVD or Tikhonov Regularization





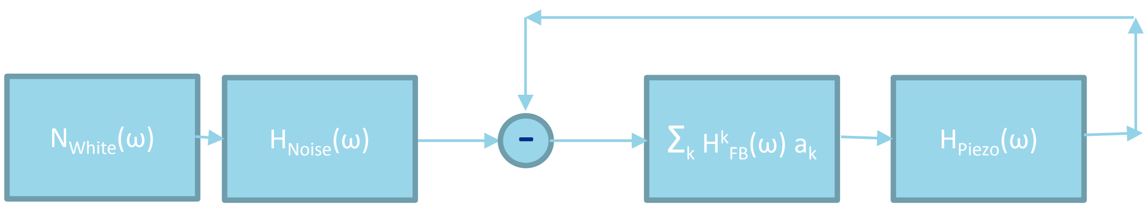
Feedback Compensation for Random Disturbances

- Online detuning calculation fed to bank of bandpass filters
  - Frequency, decay time can set for each filter in the bank to lock on to individual resonance lines
  - Gain and phase of each filter output set to compensate for detuning at that resonance line
- Outputs from filters summed and fed to piezo
  - 0 Hz stabilizes cavity against pressure drift
  - Dominant resonances observed at 20 and 200 Hz
- Filter parameters currently set manually



Data-Driven Filter Bank Coefficients

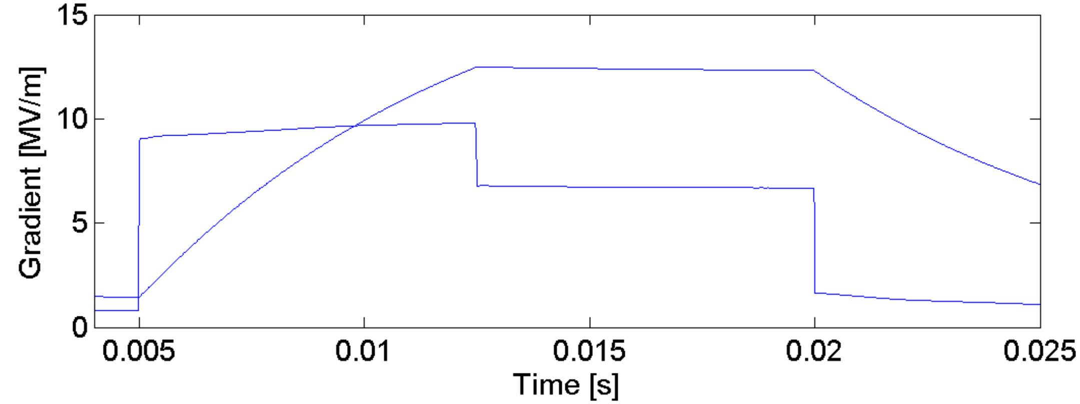
- The goal is to build a filter bank and set coefficients (frequency, tau, gain and phase of each filter bank) in an automated and optimal fashion.
- Detuning captures are used to build test signals and determine filter bank frequencies and taus.
- These test signals are then filtered and have piezo/cavity transfer functions applied.
- Fitting these outputs to the input gives an optimal gain and phase for each filter.
- This has been modeled extensively, but not demonstrated online.

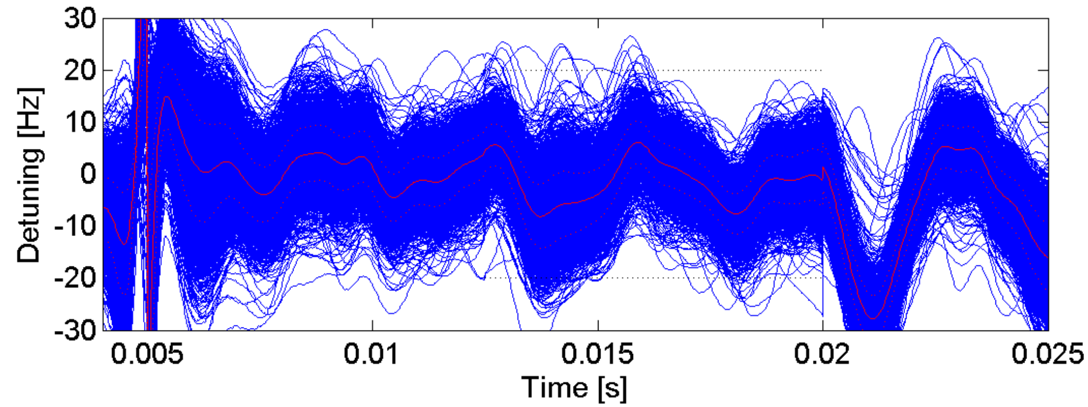


$$\chi^2 = \left(1 - \left(\sum_k H_{FB}^k(\omega) a_k\right) H_{Piezo}(\omega)\right)^{\dagger} \left(|H_{Noise}(\omega)|^2\right) \left(1 - \left(\sum_k H_{FB}^k(\omega) a_k\right) H_{Piezo}(\omega)\right)$$

Test Conditions

- 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

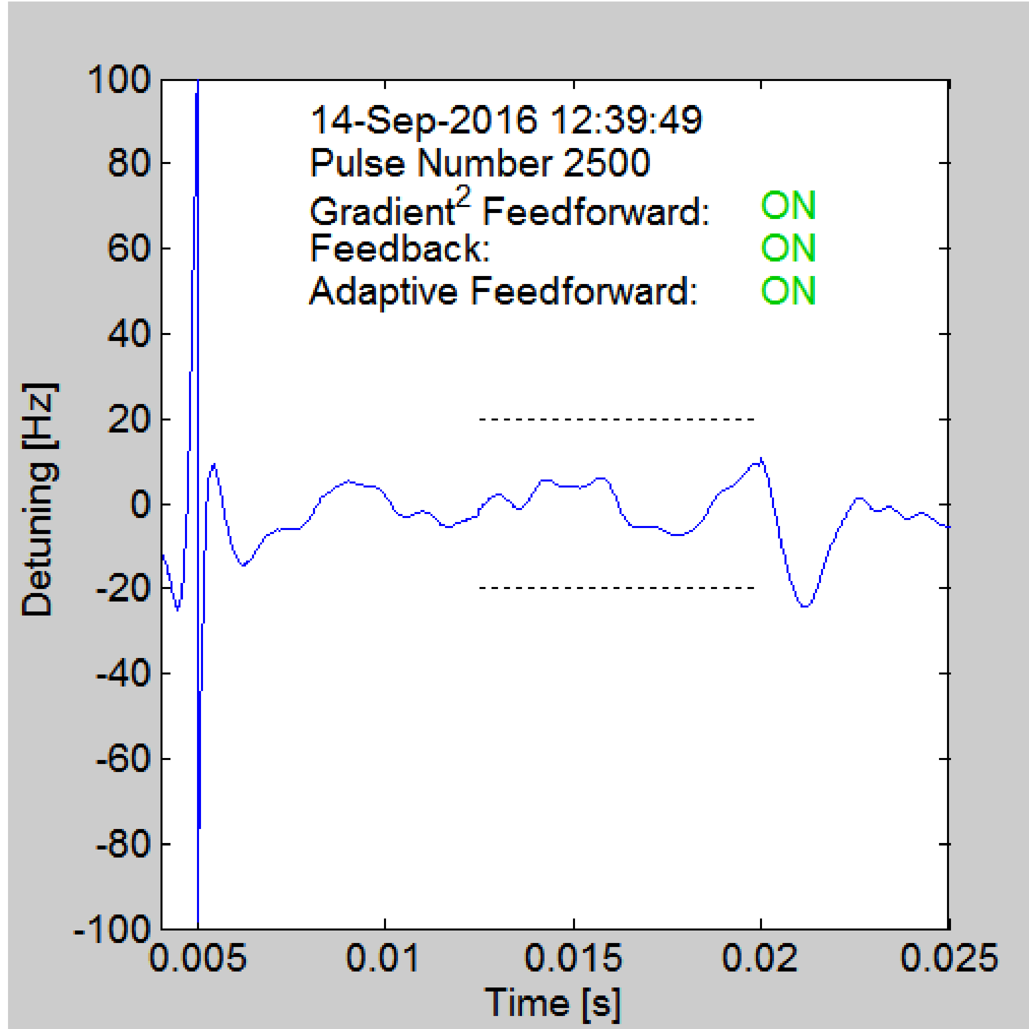




Fermilab PIP-II

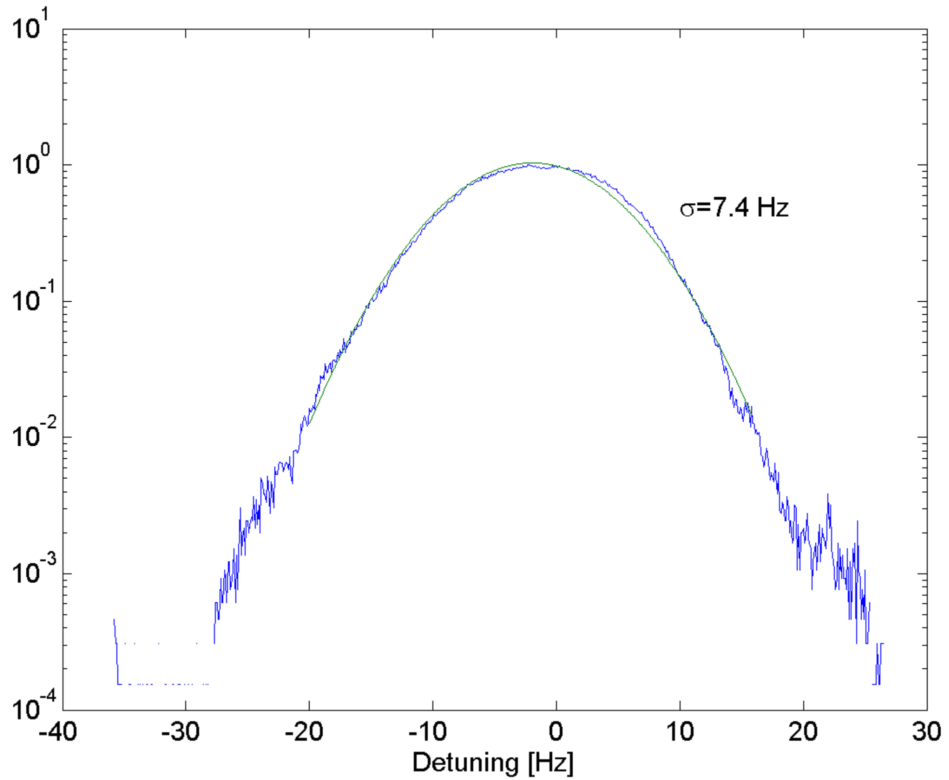
Real-time Detuning Waveforms

- Cavity run with gradient Feedforward, feedback tuned up (by hand) in CW and adaptive Feedforward
- Adaptive turned off at pulse 2706 and back on at pulse 2841
- This data was taken in open loop, no cavity tracking at all



Preliminary Offline Analysis

- Within a factor of 2 of PIP-II specs
- Improvements in feedback may help
  - Next goal is to deploy automated filter bank during testing
  - Improvements in firmware will improve detuning calculation



Plans for the Future

- Major improvements in firmware and software including
  - Improved internal diagnostics
  - Improved detuning calculation
  - More clearly defined collection of viable compensation algorithms
- Next test
  - Improve feedback filter-bank coefficient generation
  - Comprehensive performance measurements
    - Gradient calibration
    - LFD coefficients
    - Long term stability
  - Definitive statement about our ability to compensate SSR1 cavities
- Move to next step of program (Development of integrated electro-mechanical controller)

Conclusion

- Extended test time provided opportunity to try new approaches
  - Clearer path forward
    - Feedforward proportional to resonance can stabilize ponderomotive effects
    - Feedback can stabilize against pressure variations
    - Improvement using adaptive feedforward indicates that dominant source of vibration is radiation pressure from the RF pulse
- Currently within a factor of 2 of PIP-II specs for SSR1
  - We expect that the implementation of integrated electro-mechanical controller will improve the performance (better reproducibility of LFD kicks)
- Next test should allow definitive statement about our ability to compensate SSR1 cavities to required levels
- Progress justifies cautious optimism but SSR2 and 650 cavities are still to be addressed
- Can begin to move to next step of program
- Progress on active compensation should not overshadow necessity of passive microphonics mitigation
  - In particular analysis and mitigation of thermoacoustic oscillations, LCLS-II experience is going to be very helpful here

Backup Slides

Measuring Cavity Detuning

- Cavity detuning can be determined from complex 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

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

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

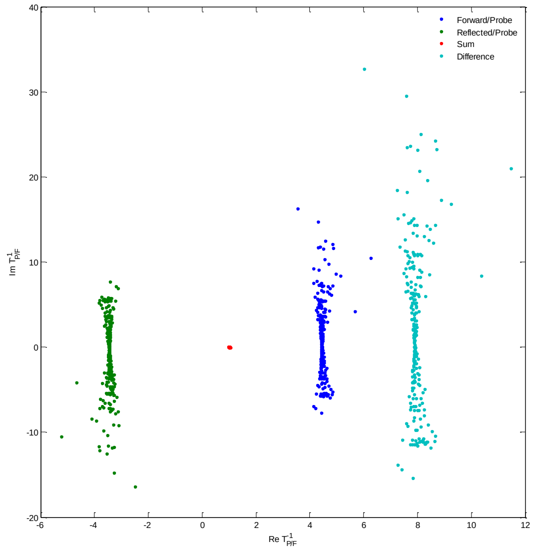
$$\delta = -\frac{\mathrm{Im}\left(P^* \left(\frac{dP}{dt} - 2\omega_{1/2}F \right) \right)}{P^* P}$$

Calibration

- Ratios of forward/probe and reflected/probe complex I/Q baseband signals are linear functions of detuning
- Relative calibration can be determined from self-consistency of signals
  - Sum of ratios add to unity
  - Slopes are purely imaginary and equal and opposite

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

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



Fermilab PIP-II

Systematic Effects

- 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