



U.S. DEPARTMENT OF  
**ENERGY**

Office of  
Science

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# Resonance Control for Future SRF Accelerators

Warren Schappert  
Resonance Control Group  
Fermilab

# Some Future SRF Accelerators

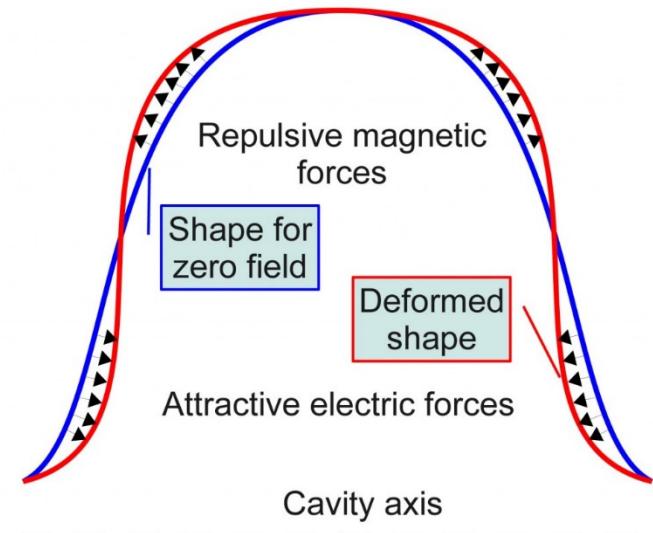
- As cavity gradients rise matched bandwidths narrow
- Minimizing detuning is critical for narrowband machines
- PIP-II presents a unique challenge because of the narrow bandwidths and pulsed operation

				Mode	Gradient	Current	Frequency	Half Bandwidth	LFD	Peak Detuning	Peak Detuning/BW	LFD/BW
					MV/m	mA	MHz	Hz	Hz	Hz		
<b>Wideband CW</b>												
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				
<b>Wideband Pulsed</b>												
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
<b>Narrowband CW</b>												
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	
FIRIB	MSU	500 kW, heavy ion beams for nuclear astrophysics	Ion	CW	7.9	0.7	322	15		20	1.33	
cERL	KEK											
<b>Narrowband Pulsed</b>												
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](http://accelconf.web.cern.ch/AccelConf/IPAC2015/talks/thzms3_talk.pdf)

# 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)

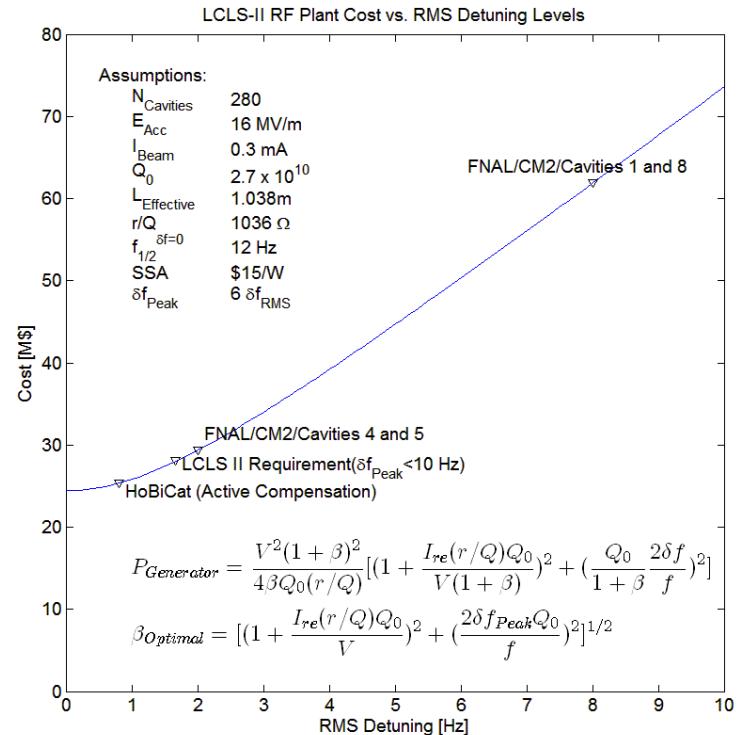


$$P_s = \frac{1}{4} (\mu |\vec{H}|^2 - \epsilon_0 |\vec{E}|^2)$$

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

# The Cost of Cavity Detuning

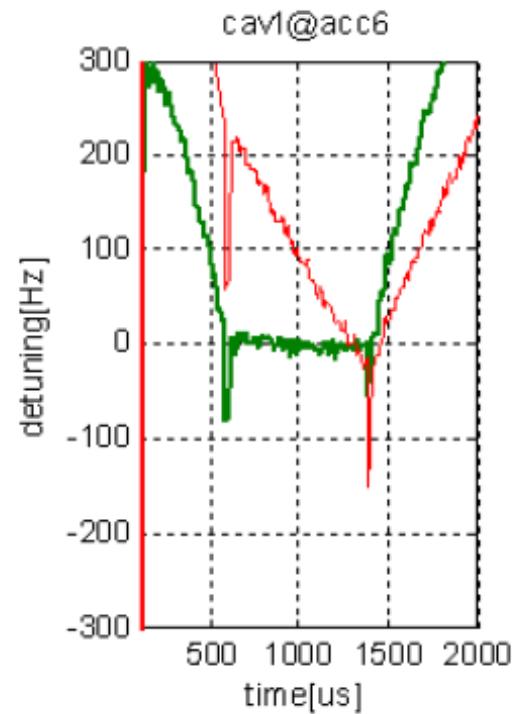
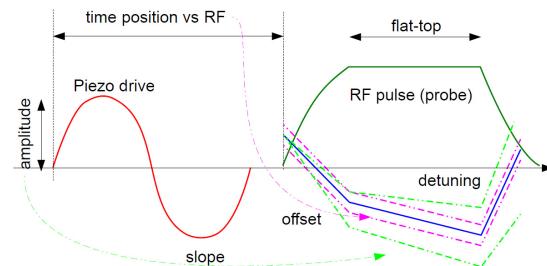
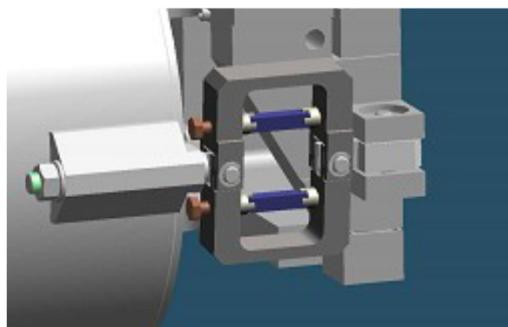
- Operating detuned cavities is more expensive
  - If sufficient RF power is not available to maintain a constant gradient during the peak expected cavity detuning, the beam will be lost
- Cavity detuning can be a major driver of the cost of a narrow-band machine
- The cost is driven by the PEAK detuning



Delayen and Merminga, Unpublished CEBAF Report

# Active Control

- Use of piezo actuators to compensate for cavity detuning pioneered at DESY  
–(to my knowledge)
- Piezo pulse cancels out Lorentz force detuning



<http://cds.cern.ch/record/1259235/files/EuCARD-PRE-2009-005.pdf>

# Measuring Cavity Detuning

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- 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

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

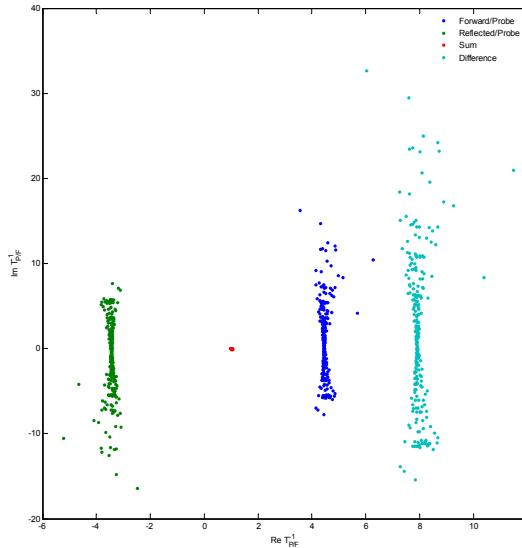
$$\omega_{1/2} = -\frac{\left\langle \text{Re}\left(P^*\left(\frac{dP}{dt}\right)\right) \right\rangle}{\left\langle \text{Re}(P^*(P - 2F)) \right\rangle}$$

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

# Calibration

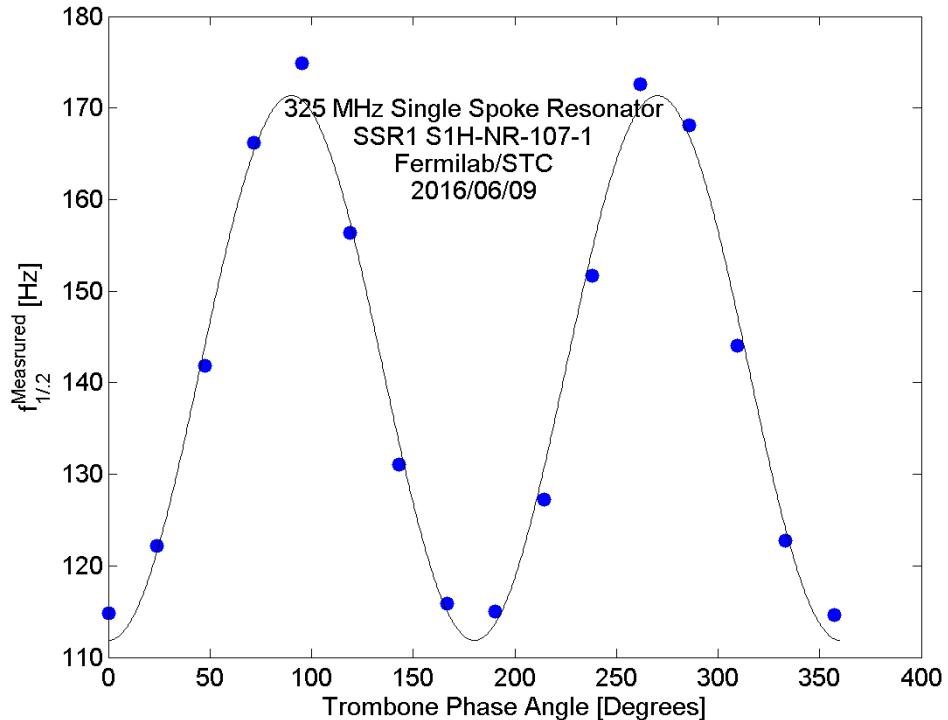
- Ratios of forward/probe and reflected/probe complex I/Q baseband signals are linear functions of detuning
- Relative calibration can be determined from self-consistency of signals
  - Sum of ratios add to unity
  - Slopes are purely imaginary and equal and opposite

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



# Systematic Effects

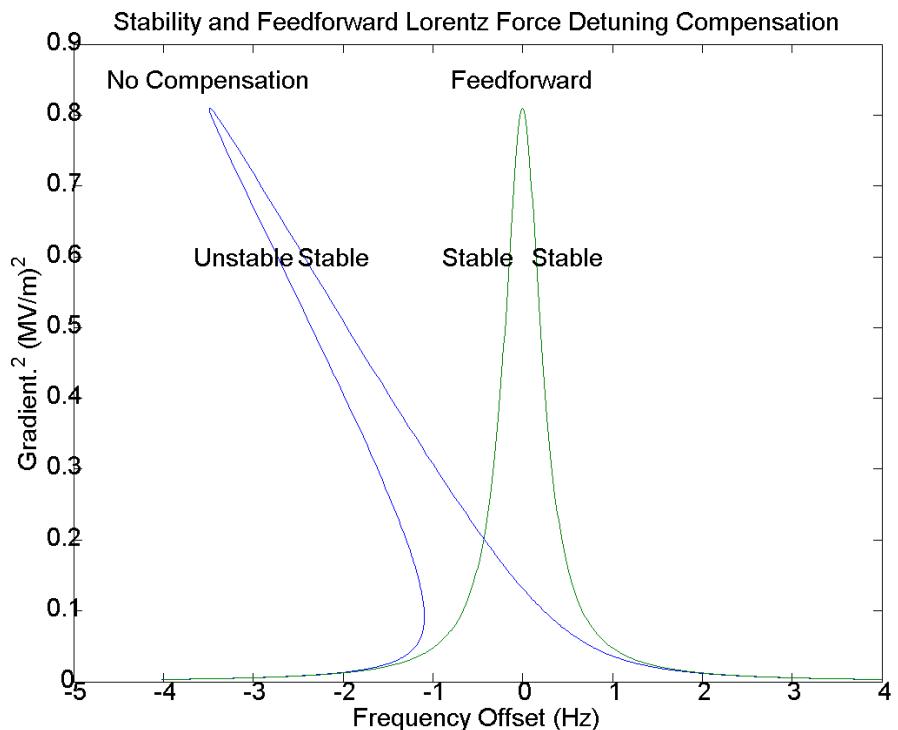
- Reflections from circulator can bias measurements of cavity bandwidth and resonant frequency
- Finite directivity of directional coupler used to separate the forward and reverse waves leads to cross-contamination of the signals



# Ponderomotive Instabilities

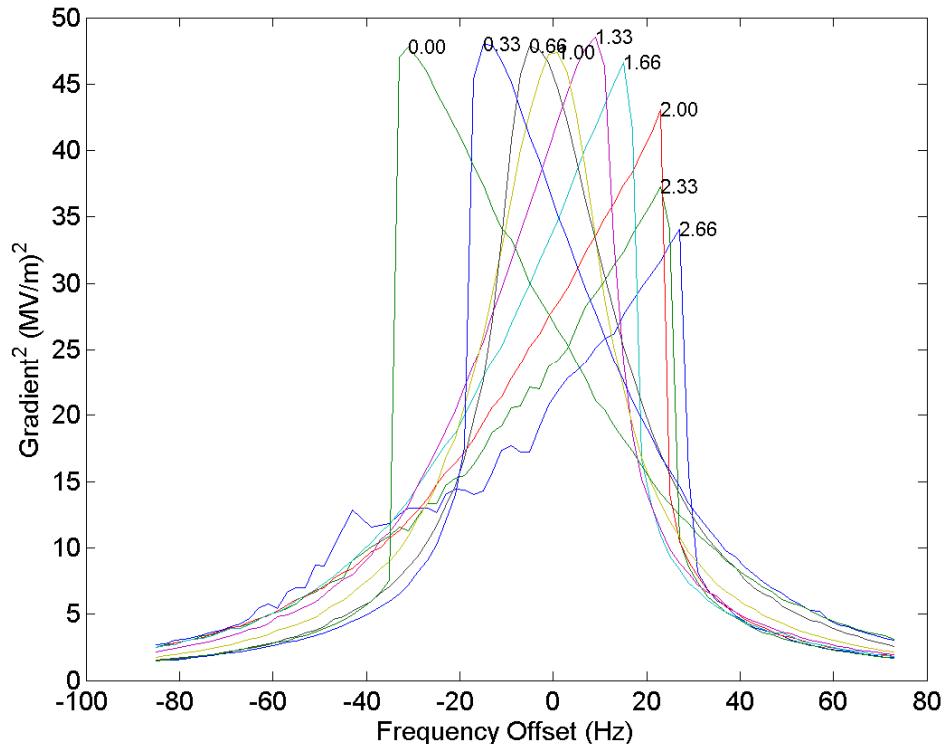
- Lorentz force detunes cavity
- If detuning is more than several bandwidths cavities can become unstable
  - Small perturbations can cause the cavity field to suddenly crash to zero

Jean Delayen Caltech Thesis



# Stabilizing the Resonance

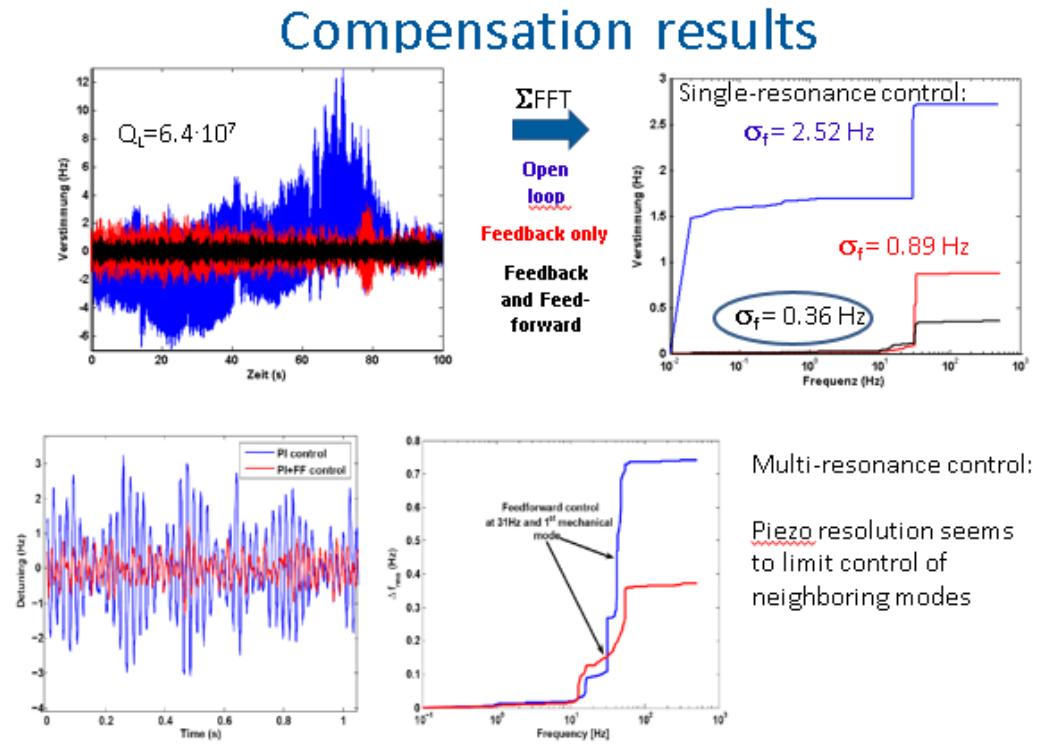
- Cavity can be stabilized against ponderomotive forces can be by driving piezo with voltage proportional to the magnitude squared of the cavity gradient
  - First demonstrated at Cornell



# Feedback

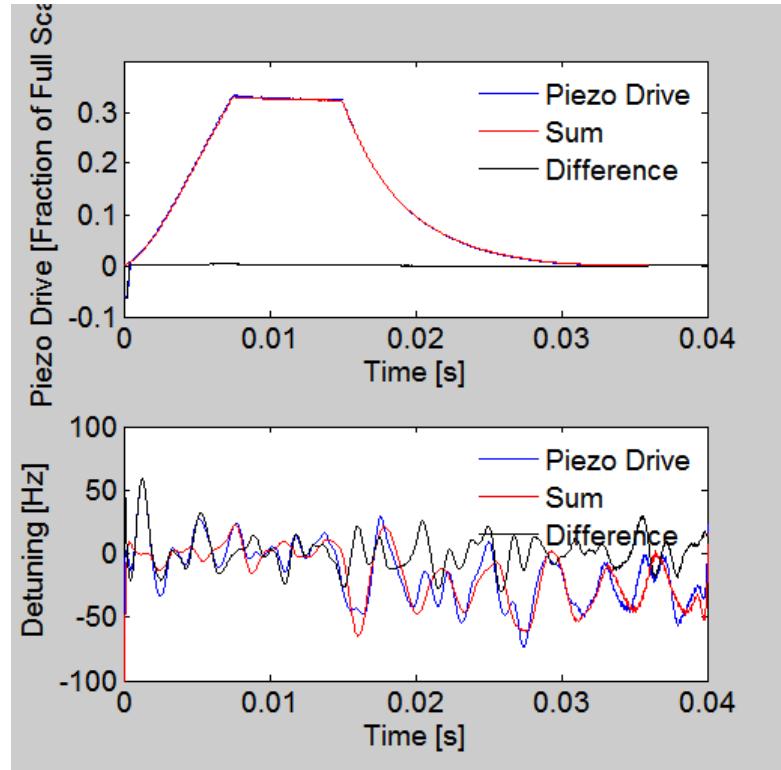
- Initial microphonics suppression studies at Fermilab
  - <http://lss.fnal.gov/archive/2003/conf/fermilab-conf-03-315-e.pdf>
- Extensive studies of microphonics at BESSY
  - Phys. Rev. ST Accel. Beams 13, 082001

Courtesy Axel Neumann



# 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

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- Piezo to 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

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

- Any deterministic detuning can be cancelled using the appropriate waveform

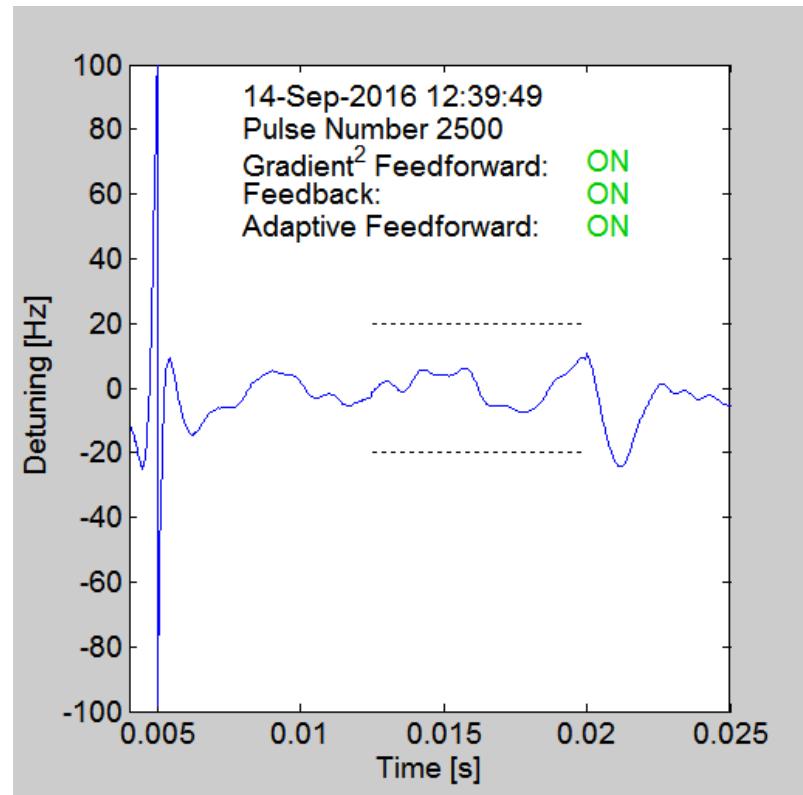
$$\delta - T_{\delta/PZT} V_{\delta} = 0$$

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

- Numerical instabilities can be suppressed using SVD or Tikhonov Regularization

# Adaptive Feedforward

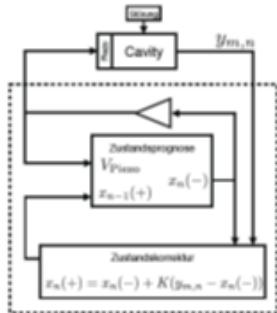
- Cavity run with
  - Gradient Feedforward,
  - Feedback manually tuned up in CW and
  - Adaptive Feedforward
- Adaptive Feedforward turned off at pulse 2706 and back on at pulse 2841



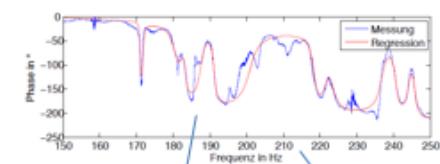
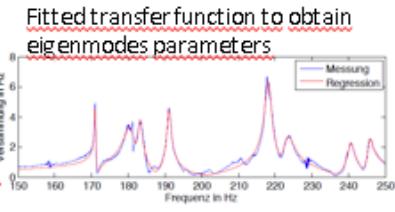
# Optimal Control

- Optimal control techniques pioneered by Kalman in the early 1960s
  - Recursive, weighted, least-squares fit at every point in time
- Will be first tested in SRF gun cavity at BESSY

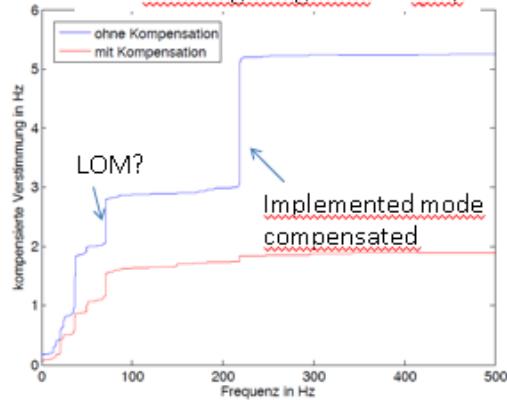
Plots here are from thesis (2014)



Scheme with simple Proportional state Feedback, Implemented on Labview FPGA Limited to one eigenmode



RMS detuning integrated vs. freq.



Prediction

$$x_n(-) = A_{n-1} \cdot x_{n-1}(+) + B_{n-1} \cdot u_{n-1}$$
$$P_n(-) = A_{n-1} P_{n-1}(+) A_{n-1}^T + Q_{n-1}$$

Kalman gain update  $K_n = P_n(-) H^T \cdot (H P_n(-) H^T + R_n)^{-1}$

$$P_n(+) = (1 - K_n H) P_n(-)$$

$$x_n(+) = x_n(-) + K_n (y_{m,n} - H \cdot x_n(-))$$

State correction

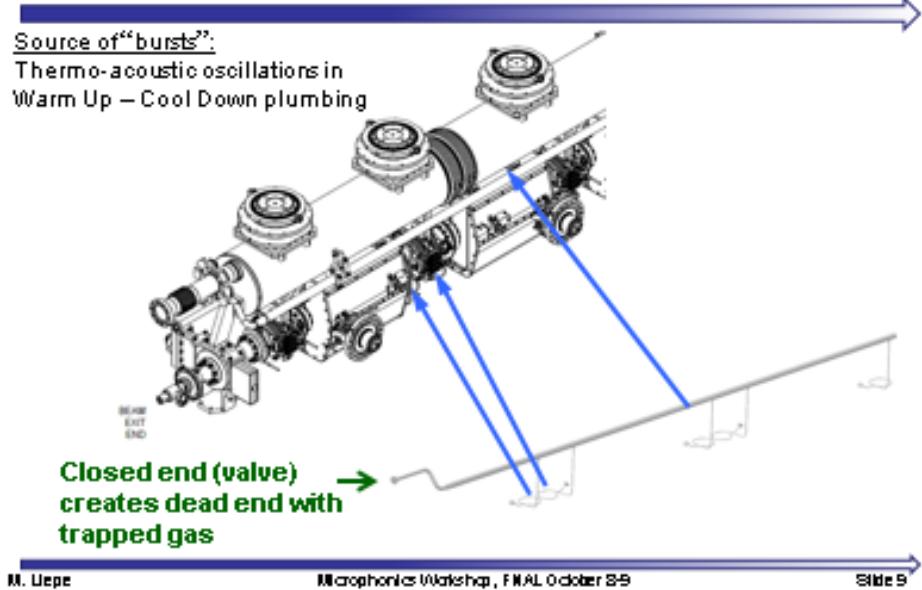
→ Implemented in Xilinx Artix-7, pipelined more than 9 eigenmodes at least possible to calculate (2016)

Courtesy Axel Neumann

# 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
  - SNS, DESY, BESSY, Cornell, FRIB,...

## ERL Injector: Source of Microphonics Bursts



# Passive Control

- Passive control measures suppress vibrations before they can reach the cavity
- Ensuring adequate implementation of passive control measures requires
  - Outreach
  - Education, and
  - Enforcement
- Organizational challenges may be more daunting than the technical challenges



## Effect of Microphonics

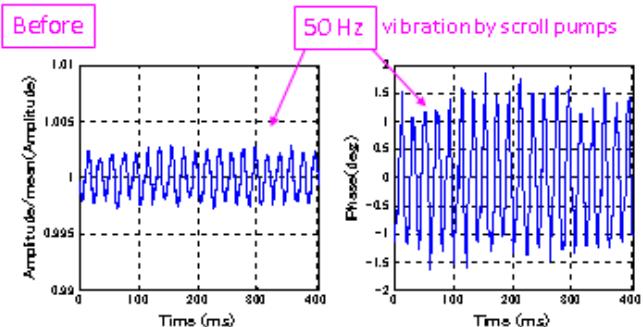
cERL



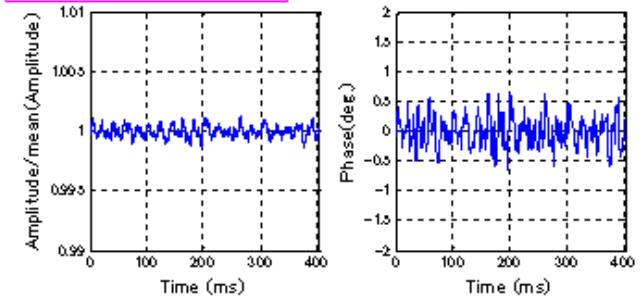
9-cell SRF cavity:  $Q_0=10^7$

Field gradient  
8.3 MV/m (Operation point)  
15 MV/m (Design)

$V_{cavity}$  against constant  $V_{forward}$



After vibration measures



## Conclusions

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- Cavity detuning can be a major cost driver for narrow-band SRF accelerators
- 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