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Superconducting RF: Resonance Control

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PIP-II Machine Advisory Committee

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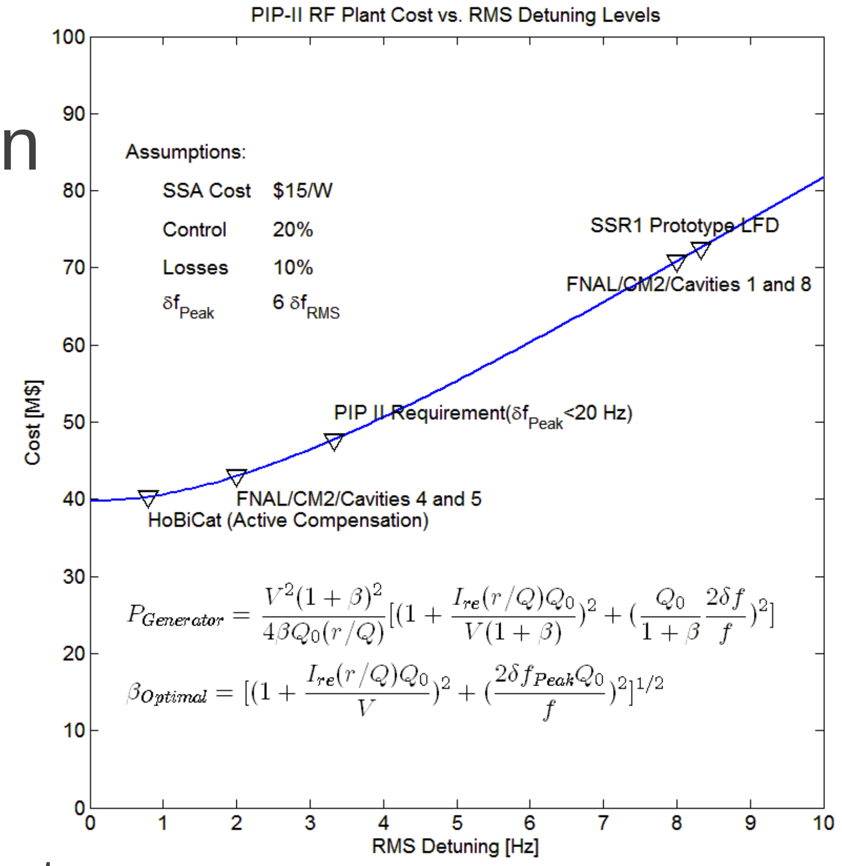
SRF Cavity Detuning

- SRF cavity cells often formed from thin (2-4mm) sheets of pure niobium to allow them to be cooled below superconducting transition temperature
  - Thin walls make cavities susceptible to detuning from vibration
  - Detuned cavities require more RF power to maintain accelerating gradient
  - Providing sufficient RF reserve power to overcome cavity detuning increases both capital and operational cost of machine
- Controlling cavity detuning critical for current generation of machines, (LCLS-II, PIP-II, ERLs, etc.) that employ very narrow bandwidth cavities
  - For machines with very narrow bandwidth cavities, e.g. ERLs, detuning can be the major cost driver for the entire machine

Cost of Cavity Detuning

- Detuned cavities require more RF power to maintain constant gradient
- **PEAK** detuning drives the RF costs
    - Beam will be lost if RF reserve is insufficient to overcome PEAK detuning
    - Providing sufficient reserve increases both the capital cost of the RF plant and the operating cost of the machine



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

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

Controlling Cavity Detuning

- Cavities may be detuned by either deterministic sources or non-deterministic sources
  - Deterministic sources include
    - Radiation pressure on cavity walls (Lorentz Force)
  - Non-deterministic sources include
    - Cavity vibrations driven by external noise sources
    - Helium pressure fluctuations

- Cavity detuning can be controlled using either passive or active measures
  - Passive measures include
    - Suppressing external vibration sources
    - Reducing cavity sensitivity to sources of detuning, e.g. df/dP, LFD,…
  - Active measures include
    - Sensing cavity detuning in real-time and using piezo or other actuators to actively cancel detuning
      - Deterministic sources may be cancelled using feed-forward
      - Non-deterministic sources require feed-back

Controlling Detuning in the PIP-II Cavities

- PIP-II design calls for narrow bandwidth ($f_{1/2} \cong 30$ Hz) cavities operating in pulsed mode
  - Narrow bandwidth makes cavities susceptible to vibration induced detuning
  - Pulsed mode LFD can excite vibrations
- PEAK detuning of PIP-II cavities must be limited to 20 Hz or less
  - PIP-II cavities will require active detuning compensation of both LFD and microphonics during routine operation
    - Will require combination of
      - best LFD compensation achieved to date
      - AND best active microphonics compensation achieved to date
      - AND 24/7 operation over hundreds of cavities for several tens of years
- **No examples of large machines that require active detuning control during routine operation currently exist**

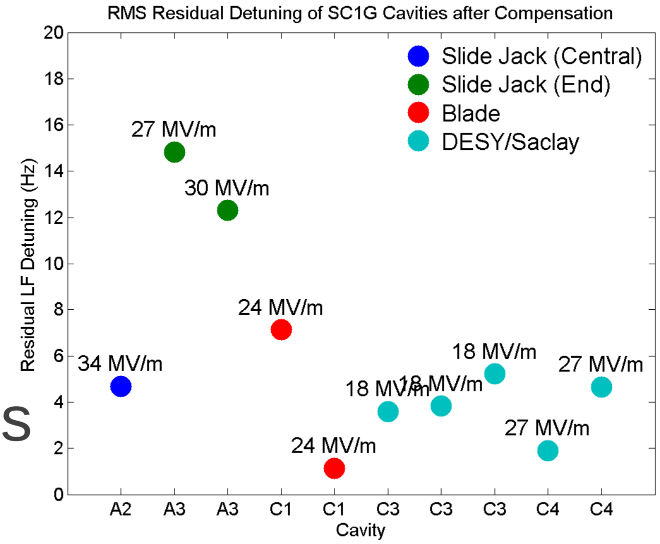
	N	f	Q_0	r/Q	E	$L_{Effective}$	Voltage	Current	Control	Losses	P_{Beam}
		MHz	10^9	Ω	MV/m	m	MV	mA	%	%	kW
HWR	8	162.5	5.0	275	9.7	0.21	2.01	2	20	10	4.02
SSR1	16	325	6.0	242	10.0	0.21	2.05	2	20	10	4.10
SSR2	35	325	8.0	296	11.4	0.44	4.99	2	20	10	9.99
LB650	33	650	15.0	375	15.9	0.75	11.86	2	20	10	23.72
HB650	24	650	20.0	609	17.8	1.12	19.92	2	20	10	39.84

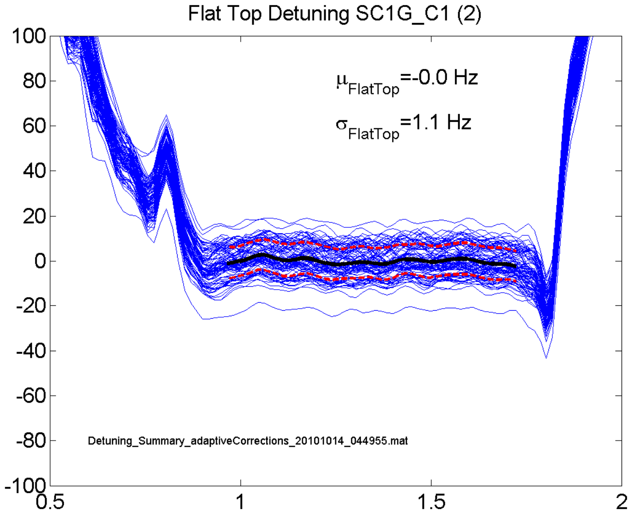
LFD Compensation at FNAL

- Adaptive feed-forward LFD compensation system developed at FNAL for ILC cavities

- System tested with four distinctly different cavity designs during S1G tests at KEK in 2010
  - Uncompensated detuning ranged between several tens to several hundreds of Hz depending on the desi
  - Compensated detuning limited to <20 H in all four cavity types

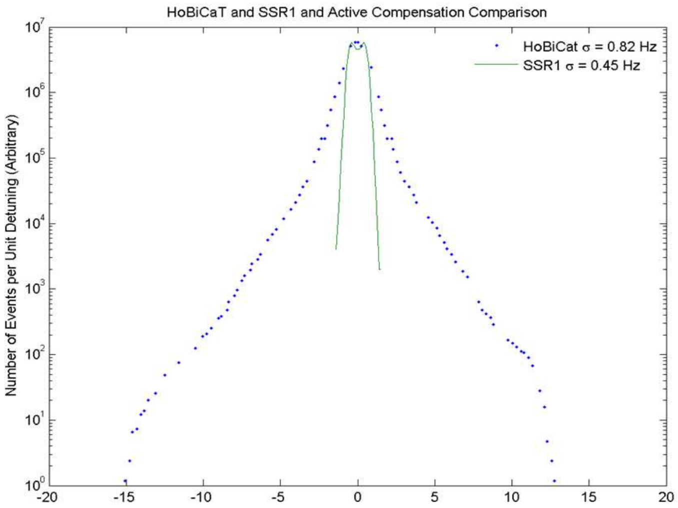
- System is in routine use in NML/CM2 and HTS

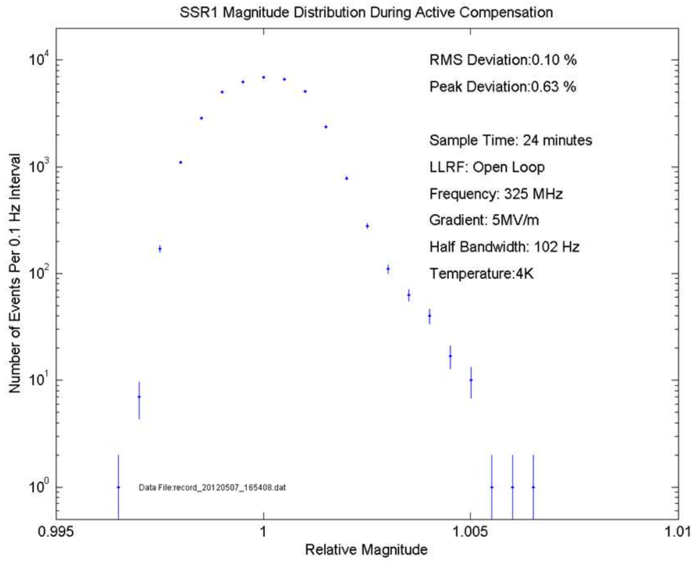

RMS Residual Detuning of SC1G Cavities after Compensation


Flat Top Detuning SC1G_C1 (2)

Microphonics Compensation at FNAL

- 1.3 GHz elliptical cavities
    - Damp individual mechanical resonance lines by 15 dB
- 1st SSR1 prototype
    - Fixed frequency/ fixed amplitude RF with piezo feedback
    - Frequency stability
        - 0.45 Hz RMS
    - Magnitude stable to
        - 0.10% RMS
        - 0.63% Peak over 20 minutes


HoBiCaT and SSR1 and Active Compensation Comparison


SSR1 Magnitude Distribution During Active Compensation

RMS Deviation:0.10 %
Peak Deviation:0.63 %

Sample Time: 24 minutes
LLRF: Open Loop
Frequency: 325 MHz
Gradient: 5MV/m
Half Bandwidth: 102 Hz
Temperature:4K

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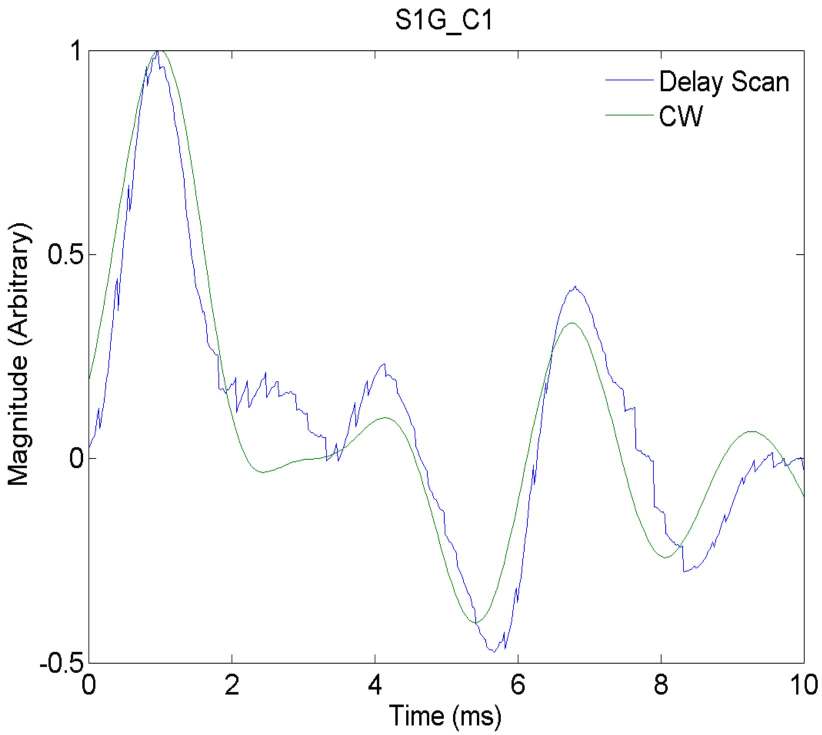
Adaptive Feedforward LFD Compensation

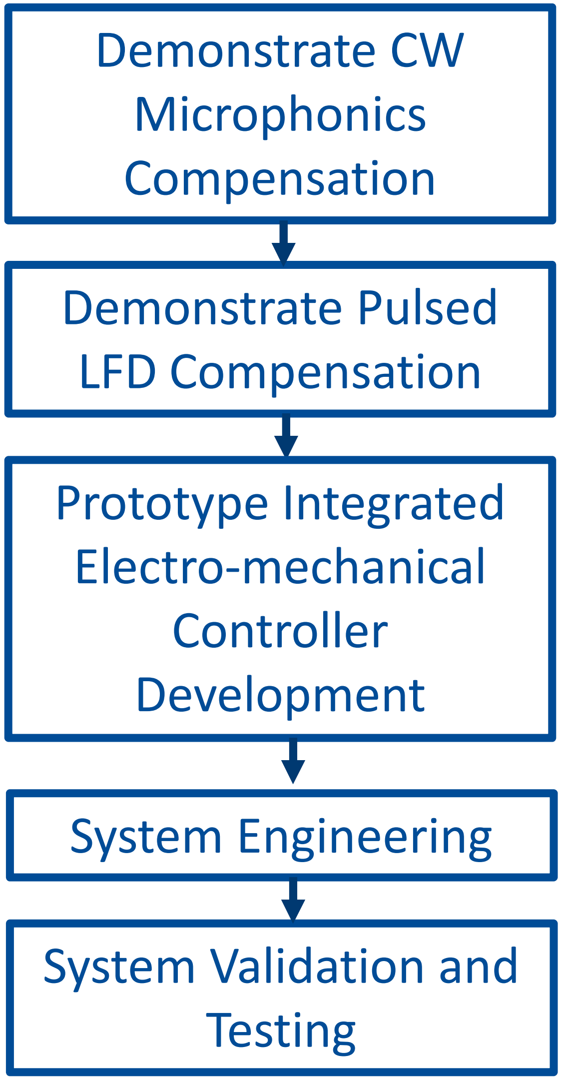
- Learning phase
  - Apply a series of short stimulus pulses to the piezo at different delays with respect to the RF Pulse,$S(t_{Piezo},n_{Pulse})$
  - Measure the detuning response of the cavity during the flattop, $R(t_{Flattop},n_{Pulse})$
  - Calculate the transfer function, $T = (S^TS)^{-1}(S^TR)$
    - Equivalent to CW measurement of piezo impulse response



- Compensation Phase
  - Measure the detuning during the flattop, $D(t_{Flattop})$
  - Determine piezo pulse required to cancel out detuning,
    - $P = -(T^TT)^{-1}(T^TD)$
  - Iterate to suppress any residual detuning

Detuning Control Program for PIP-II

- Demonstration of feasibility is current focus
- Focus must shift at some point to engineering a robust integrated electro-mechanical control system
- Reliable operation can only be ensured by extensive program of testing of both components and integrated system



Demonstrate CW Microphonics Compensation

Demonstrate Pulsed LFD Compensation

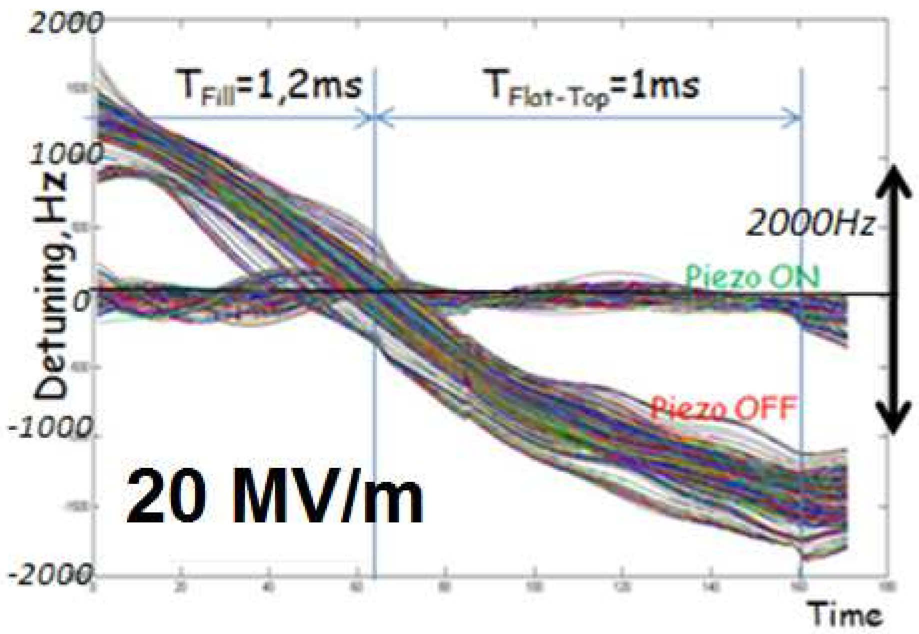
Prototype Integrated Electro-mechanical Controller Development

System Engineering

System Validation and Testing

Feasibility of LFD Compensation for PIP-II

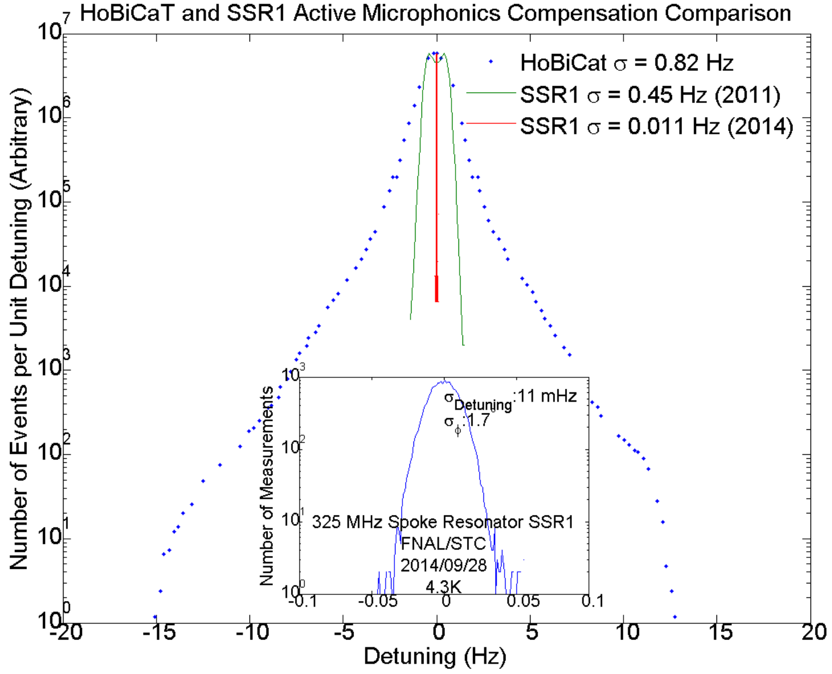
- LFD compensation measurements using previous SSR1 prototype
  - Short test
  - Good results but do not meet PIP-II specs
- SSR1 Pulsed mode studies with prototype tuner and prototype coupler will commence shortly
  - Slower fill
  - Improved understanding



	Detuning		
	Uncompensated		Compensated
Gradient	Flattop	Full Pulse	Flattop
MV/m	Hz	Hz	Hz
13	450	900	30
22	1450	2500	75

Feasibility of Microphonics Compensation for PIP-II

- Very encouraging results from recent test of SSR1 prototype in STC provide reason for CAUTIOUS optimism
  - σ_{Detuning}=11 mHz in open loop RF over 2 hour period
    - Piezo but no slow tuner
    - Narrow bandwidth power coupler
    - Resonance frequency stabilized using a combination of
      - Feed-forward LFD compensation
      - Fast feed-back on forward/probe phase
      - Slow feedback on detuning
      - Synchronous down-conversion
  - Almost two orders of magnitude improvement compared with best previously published results (HoBiCaT)
  - More than an order of magnitude compared to best previous results at FNAL



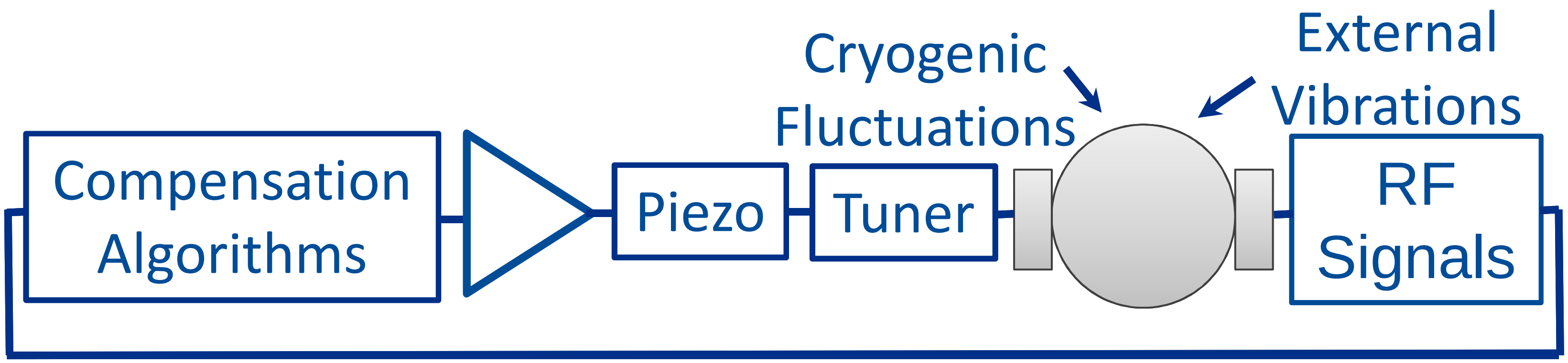
- More tests in immediate future using prototype tuner and power coupler

Integrated Electro-Mechanical Controller

- Measure SSR1 mechanical transfer functions
  - Detuning response to mechanical and LFD excitations as a function of frequency
- Extract low order approximation to transfer mechanical functions
  - Minimal State Space Realization (MSSR) algorithm of Kalman and Ho
- Construct optimal coupled electro-mechanical filters and controllers from low-order transfer functions
  - Kalman filter
  - Linear Quadratic Gaussian Regulator
    - Recursive, weighted, least-squares fit at each point in time minimizes quadratic cost function that depends on transfer-functions and noise covariance

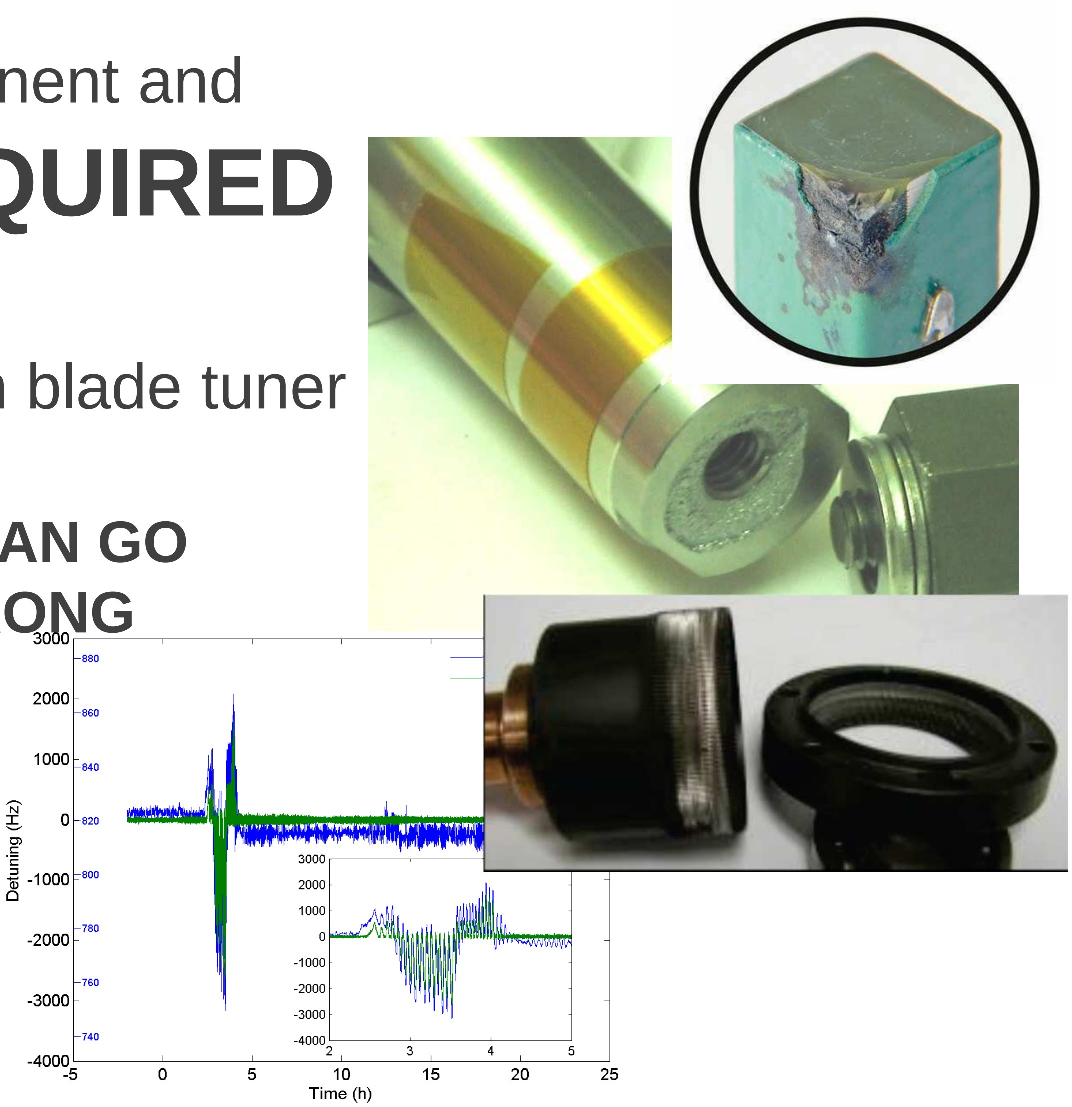
System Engineering for PIP-II

- Detuning control crosses boundaries between divisions and between disciplines
  - Robust system required for machine operation
- Focus must shift need to shift towards engineering high-reliability system
  - Integration of algorithms with LLRF control system
  - Will require extensive testing of all hardware, firmware, software



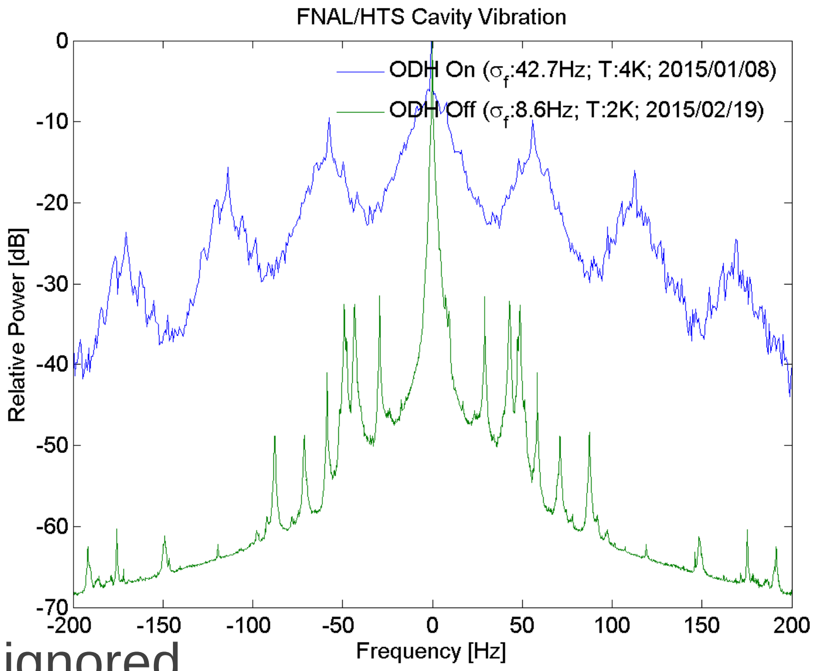
Component and Integration Testing

- **EXTENSIVE** component and integration testing **REQUIRED** for reliable operation
- Experience at FNAL with blade tuner for ILC cavities
  - **EVERYTHING THAT CAN GO WRONG WILL GO WRONG**
- Experience at other labs
  - MSU
  - JLab
  - SNS
  - Cornell
  - HoBiCaT



Cross-disciplinary Challenges

- Minimizing cavity detuning requires careful optimization across entire machine
  - Cavity design, cryomodule design, RF plant, cryogenic system design, civil engineering
    - Cross-disciplinary challenges may be more daunting than technical challenges



- Large potential costs if any aspect ignored
  - Small design changes may have large impact on cavity detuning
  - Cost of fixing microphonics afterwards could be very high
- Some structure within PIP-II organization will be required to coordinate effort amongst groups and disciplines
  - Education and communication
  - Vibration related reviews

Looking Forward

- Upcoming tests of SSR1 offer opportunity to
  - Finalize CW algorithms
  - Investigate pulsed mode operation
  - Measure expected RF and performance parameters
- Focus must then shift to integration of algorithms into an integrated electro-mechanical control system
  - Will require close collaboration between TD/RC and AD/LLRF groups
- Robust system will require careful system engineering and extensive testing of all hardware, firmware and software
- Need to arrive at consensus on mechanism(s) within PIP-II organization to coordinate detuning control efforts

Conclusions

- Controlling cavity detuning will be critical for successful operation of PIP-II because of narrow cavity bandwidths ($f_{1/2}$~ 30 Hz)
  - Narrow bandwidths would be challenging even with CW operation alone
  - Pulsed mode operation brings significant additional complications
- All possible passive measures must be exploited but active control will still be required
  - Will require both best LFD and best microphonics compensation achieved to date operating reliably over many cavities and many years
    - Early test results provide reason for **CAUTIOUS** optimism
  - There are no existing examples of large machines that require active control of detuning during routine operation
- Cross-disciplinary challenges may be more difficult to solve than technical challenges (which are still considerable)
  - Minimizing cavity detuning requires optimization of entire machine
  - Will require active coordination across divisions and across disciplines