LFD and Microphonics Suppression for PIP-II

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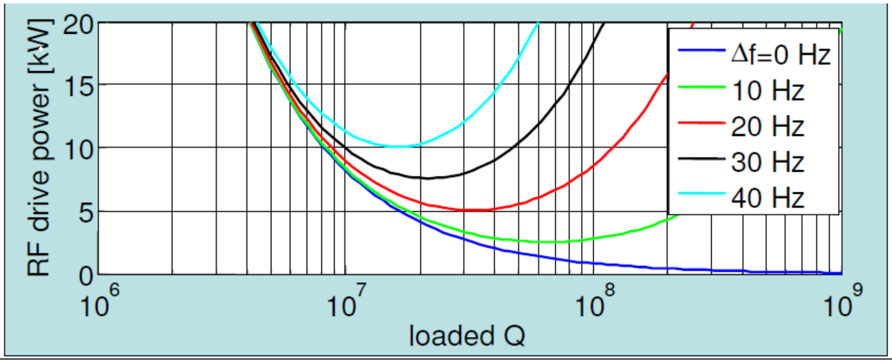
Cost of Cavity Detuning

- Narrow BW cavities with high microphonics levels require more RF power
  - Beam can be lost if sufficient reserve RF power to compensate for detuning is not available
- **PEAK** (not average) microphonics levels are important
- For machines with very low beam loading (XFELs, ERLs) microphonics can actually **drive the design of the machine**
- Effects of microphonics must be considered in the design of the entire project from the start



$$P_g = \frac{V^2}{8\frac{r}{Q}Q_L}\left(1+\left(\frac{\Delta f}{f_{1/2}}\right)^2\right) \qquad Q_{opt} = \frac{1}{2}\frac{f_0}{\Delta f} \qquad P_{g,\min} = \frac{V_{acc}^2}{2r/Q}\frac{\Delta f}{f}$$

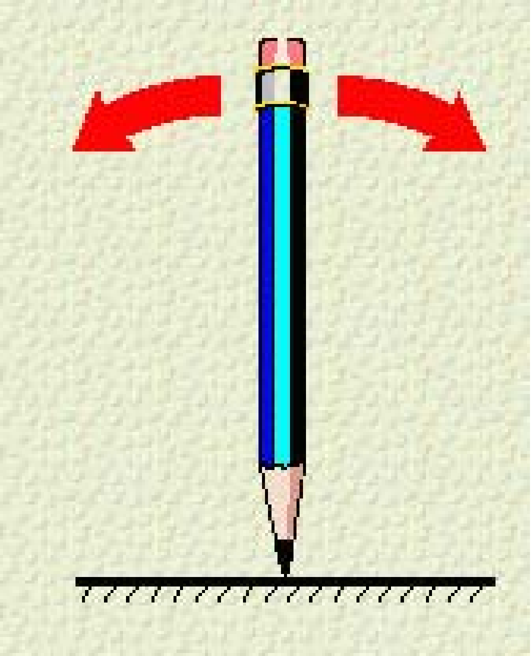
http://erl.chess.cornell.edu/papers/2005/ERL058.pdf

Sources of Cavity Detuning

- Pressure variations
  - Important in both CW and pulsed operation
  - Dominant source of detuning in CW cavities
    - CCII (4K) shows swings in resonance frequency of up to 500 Hz over periods of several minutes
- Mechanical vibrations
  - Excitation of cavity modes by external vibration sources
    - Mechanical
    - Geophysical
  - Relatively small (several Hz) for carefully designed systems
- Lorentz Force Detuning
  - Not important for CW cavities (except during turn-on)
    - Dominant source of detuning in pulsed mode cavities (~500 Hz in Tesla Style Elliptical Cavities at 35MV/m)

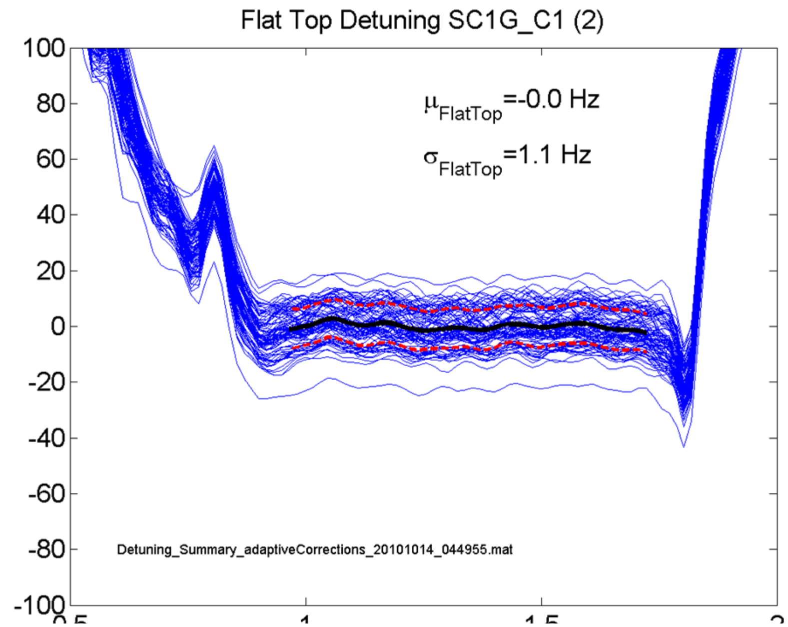
Controlling Cavity Detuning

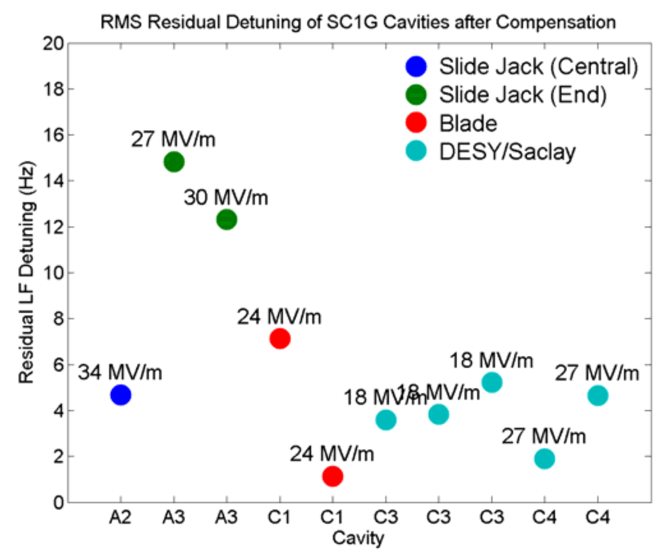
- Passive measures should be exploited first
  - Active control only after all passive measures deployed
- Controlling detuning in narrow bandwidth cavities requires careful coordination of
  - Cavity and Cryomodule Mechanical Design
  - Cryogenic System Design
  - Civil Engineering
  - RF Power and Control System Design



State of the Art LFD Control

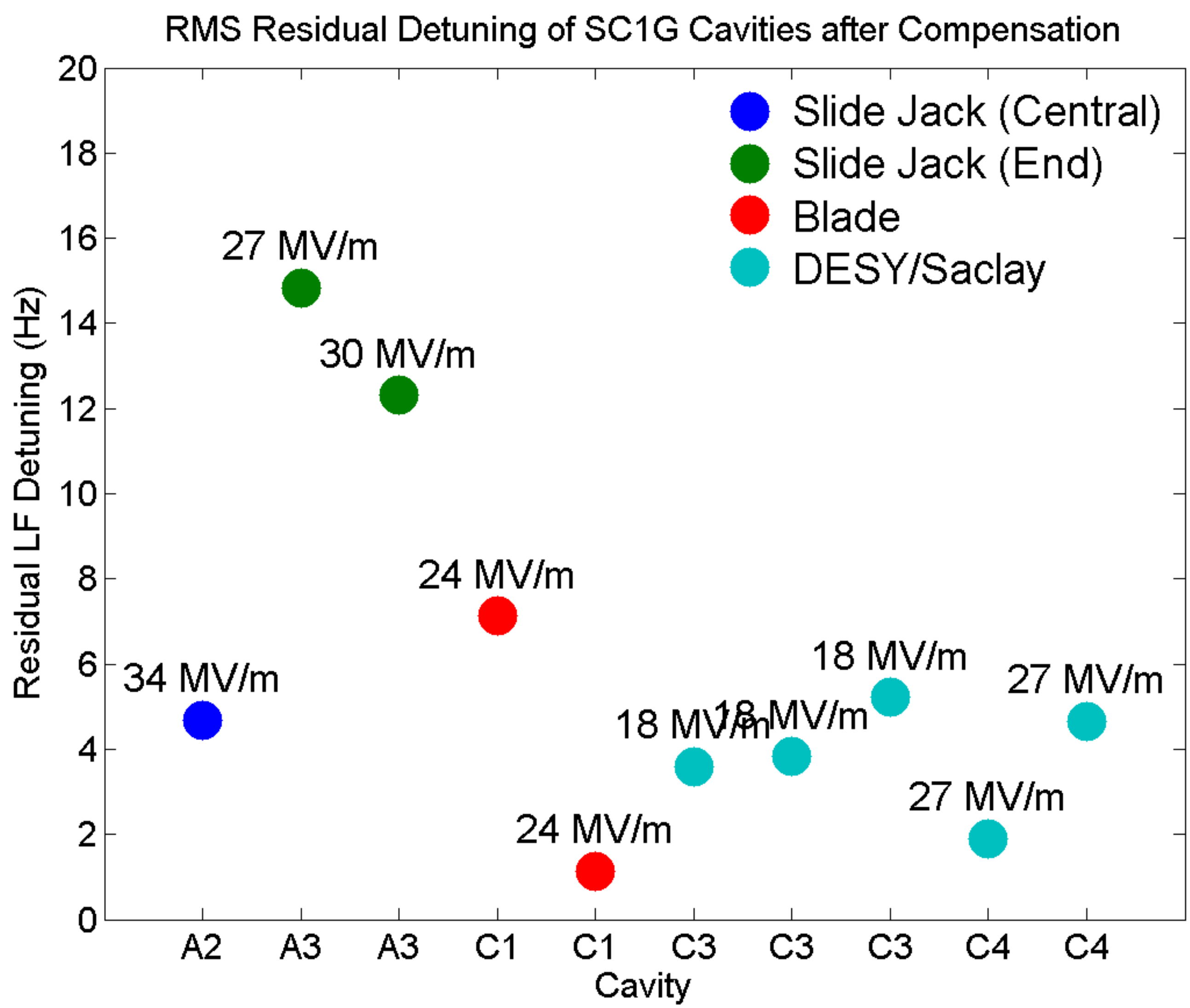
- Adaptive LFD compensation
  - Developed at FNAL
  - Tested with
    - Four different 1.3 GHz cavity designs at S1G
      - RMS residual detuning variation between 2 and 16 Hz
    - SSR1 spoke resonator



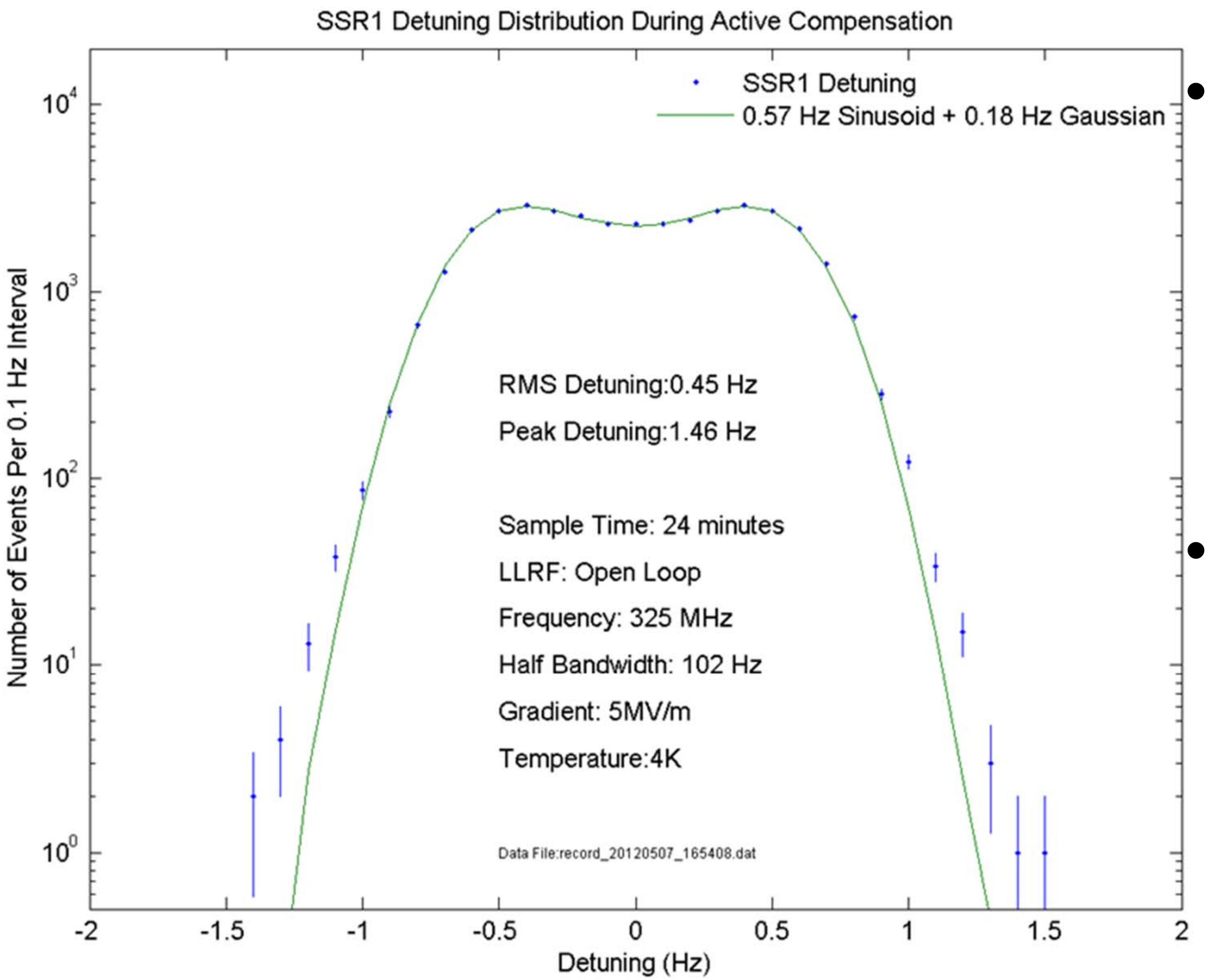


S1G Back-to-Back Comparision

- All tuners respond very well
- Detuning control limited by adaptive bias correction rather than cavity/tuner design



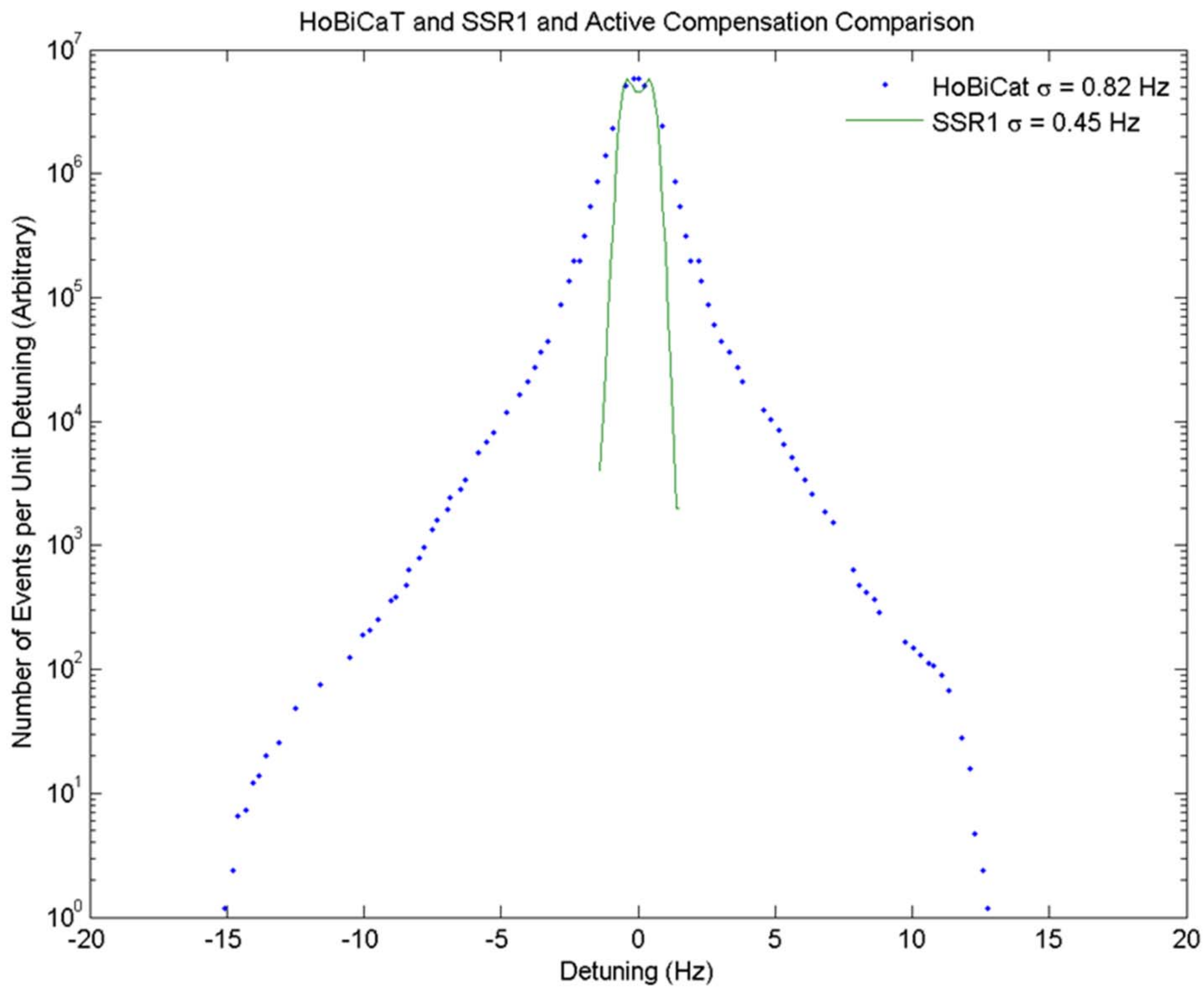
State of the Art Microphonics Control



- Bimodal distribution
  - Consistent with feed-through of some unwanted harmonic
- Further improvements possible if feed-through can be suppressed

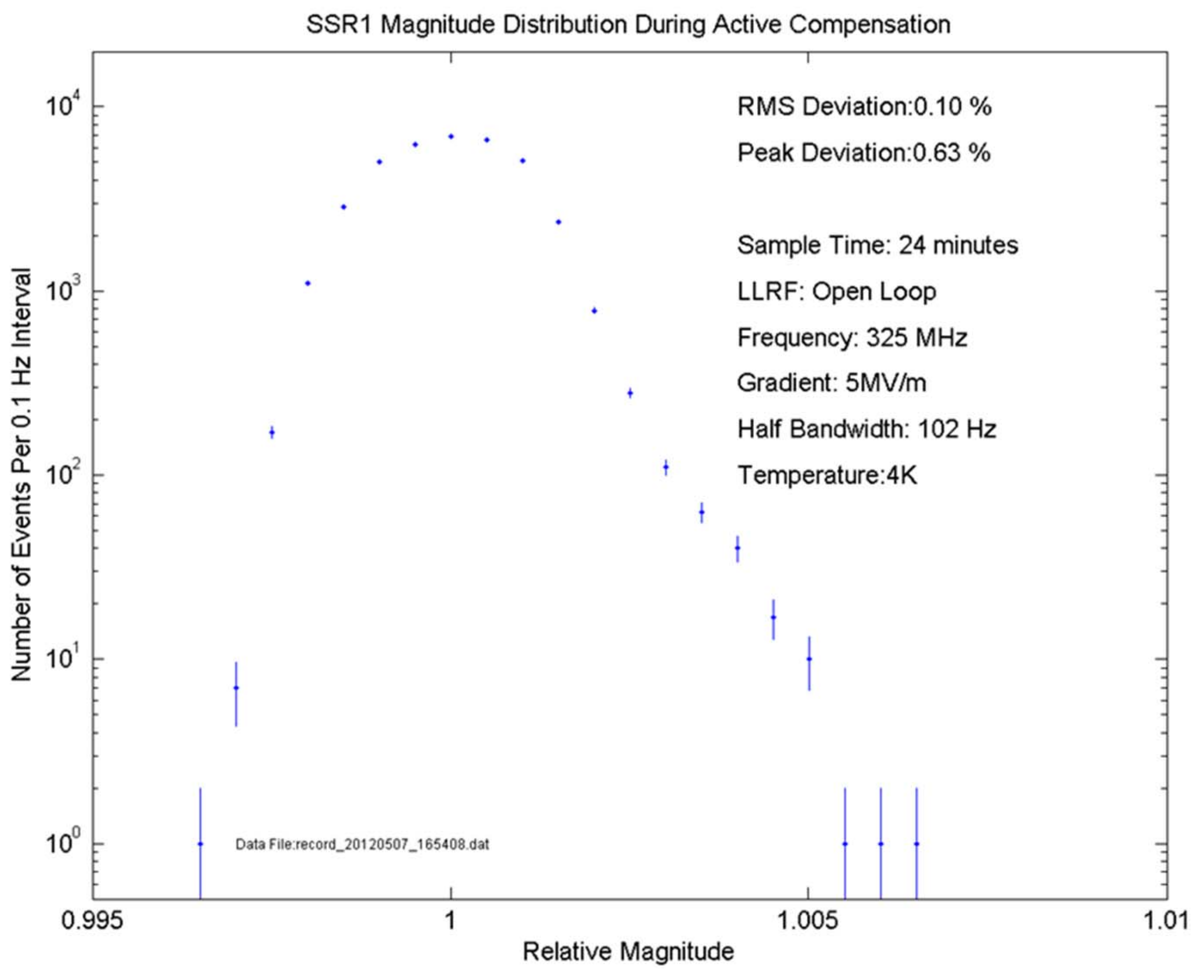
Comparison with HoBiCaT

- Narrower peak
- No evidence of large tails
  - HoBiCaT
    - 2K
  - SSR1
    - **4K**



Field Magnitude

- **OPEN LOOP at 4K**
- Magnitude stable to
  - 0.10% RMS
  - 0.63% Peak over 20 minutes



Microphonics Plan for Project X

- Brian Chase, Ruben Carcagno, and Gustavo Cancelo were asked to develop a plan to deal with microphonics in Project X
- Tried to look at the project as a whole
  - Survey literature
  - Discuss with FNAL experts
  - Discuss with experts at other laboratories
- Primary expertise of group members is active compensation of cavity detuning and LLRF
  - Able to draw on considerable outside expertise
- Goal
  - Identify potential sources of cavity detuning
  - Estimate possible detuning of Project X cavities by each source
  - Develop a microphonics error budget for Project
- Project X Document 629-v1

Project X Cavity Detuning Under Various Scenarios

- Scenario 1
  - Attack detuning on all fronts
    - Cavity pressure sensitivity and variation < 5 Hz/mbar
      - measurement uncertainty at FNAL VTS
    - Maintain pressure to within $\pm$ 100 ubar (SNS)
    - Limit vibration to $\sigma < 3$ Hz (HoBiCaT)
    - No pressure transients
- Scenarios 2-6
  - Successively relax each of the above assumptions
    - Pressure Sensitivity Variation => 50 Hz/mbar (CEBAF)
    - Pressure Sensitivity => 100 Hz/mbar (CEBAF)
    - RMS vibration level => 10 Hz (FNAL HTS)
    - Peak pressure variation => 500 ubar (Linde)
    - Peak pressure transients => 2 mbar (CEBAF)
- For all scenarios
  - Compare no active compensation to active compensation of 15 dB (CCII, HoBiCaT)
    - To date suppression at this level has only been demonstrated in short term tests involving single cavities

Total Microphonics Levels

- Apply microphonics to baseline design
  - Project X Document 450-v (Nikolai Solyak,March 29 2010)
- Many other scenarios possible
- Levels are intended to be reasonable orders of magnitude
  - not best possible
  - not worst possible
- Numbers may change as design continues to evolve and our understanding improves but general trends should persist

	Scenario					
Detuning Parameter	All Fronts	No Minimization of Sensitivity Variation	No Minimization of Pressure Sensitivity	No Vibration Minimization	Status Quo/ No Transients	Status Quo/CEBAF Transient Levels
Peak Presssure Variation (mbar)	0.1	0.1	0.1	0.1	0.5	2
Mean Pressure Sensitivity (Hz/mbar)	5	5	100	100	100	100
Peak Pressure Sensitivity Variation (Hz/mBar)	5	50	50	50	50	50
RMS Detuning due to Mechanical Vibrations (Hz)	3	3	3	10	10	10
Peak Pressure Related Detuning (Hz)	1	6	15	15	75	300
Peak (6 Sigma) Mechanical	18	18	18	60	60	60
Peak Microphonics (Hz)	19	24	33	75	135	360

Effect of Microphonics on RF Power

Cavity Type	Cavity Parameter					Scenario					
	Cavity Bandwidth (Hz)	Power Consumption (kW)	Supply (kW)	Available Power (%)	Active Compensation (dB)	All Fronts	No Minimization of Sensitivity Variation	No Minimization of Pressure Sensitivity	No Vibration Minimization	Status Quo/ No Transients	Status Quo/CEBAF Transient Levels
Peak Microphonics (Hz)						19	24	33	75	135	360
SSR0	50	0.63	1	159%	0	113%	119%	133%	208%	325%	772%
					15	100%	101%	101%	107%	119%	187%
SSR1	50	1.9	5	263%	0	113%	119%	133%	208%	325%	772%
					15	100%	101%	101%	107%	119%	187%
SSR2	30	4	5	125%	0	131%	144%	171%	305%	503%	1251%
					15	101%	102%	104%	117%	144%	269%
LB650	20	14	30	214%	0	157%	180%	222%	428%	727%	1851%
					15	103%	104%	108%	133%	180%	374%
HB650	19	23	30	130%	0	162%	186%	231%	448%	762%	1945%
					15	103%	105%	109%	136%	186%	391%
ILC	76	20	30	150%	0	106%	109%	116%	161%	235%	526%
					15	100%	100%	101%	103%	109%	148%

Coupling optimized for detuning according to Eqn. 16 of JLab TN-96-022
Red cells indicate that detuning due to microphonics will require more power than baseline design (Project X Document 450-v) provides

PIP-II Cavities

CM	Frequency	Eacc_min	Eacc_max	CM	Cav/CM	Eacc	deltaE	Q0	Static Loss per CM	Total Loss per CM	Kappa_LFD	LFD	Q_L	Δf	f_{1/2}=f/(2 Q_L)	Δf_Microphonics
	MHz	Mev	Mev			MV/m	MeV		W	W	Hz/(MV/m2)^2			Hz	Hz	Hz
HWR	162.5	2	11	1	8	8.2	1.7	5.00E+09	14	24			3.30E+06	50	**24.6**	**20**
SSR1	325.0	11	38	2	8	10	2.05	5.00E+09	16	27	1.5	**150**	5.80E+06	56	**28.0**	**20**
SSR2	325.0	38	177	7	5	11.2	5.32	1.20E+10	8.8	52			7.20E+06	45	**22.6**	**20**
LB 650	650.0	177	480	5	6	16.5	11.6	1.50E+10	8.1	153	1	**272**	1.40E+07	46	**23.2**	**20**
HB 650	650.0	480	800	4	6	17.5	17.7	2.00E+10	6.2	153	1	**306**	1.40E+07	46	**23.2**	**20**

- Current PIP-II detuning requirements are **EXTREMELY AGRESSIVE**
  - Active compensation would almost certainly be required for every cavity type even in CW operation
  - Pulsed operation leads to significant complications
    - LFD drives mechanical resonances
    - Only able to measure microphonics accurately when RF in cavity
- **Not clear that even state of the art active control will be good enough**

Conclusion

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  - Cavity and Cryomodule Mechanical Design
  - RF Control System Design
  - Cyrogenic System Design
  - Civil Engineering
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