Experience with Microphonics in the CBETA Main Linac Cryomodule

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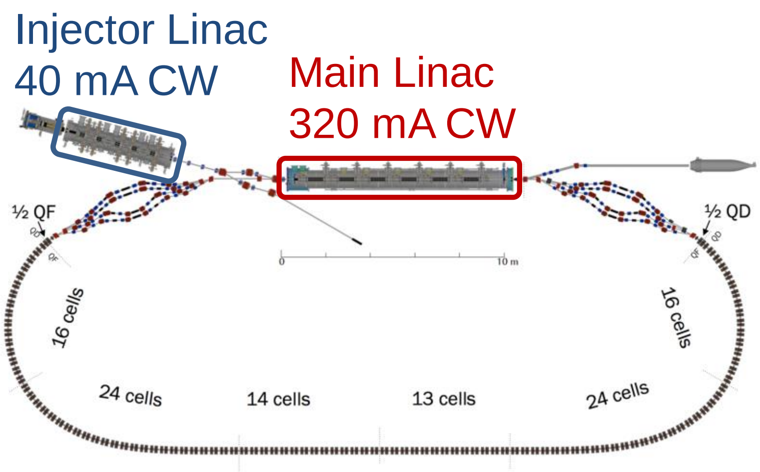
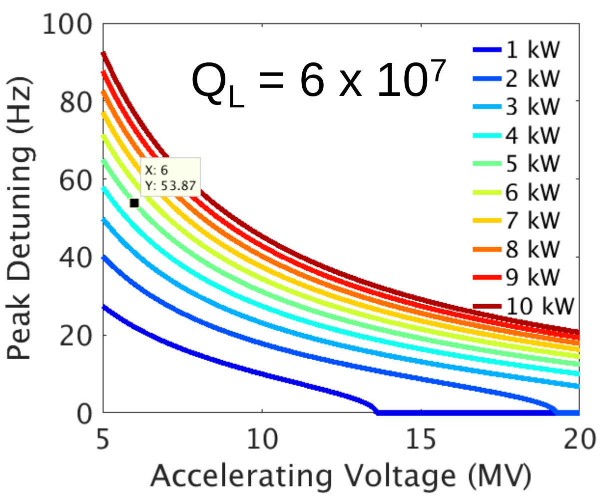
Overview

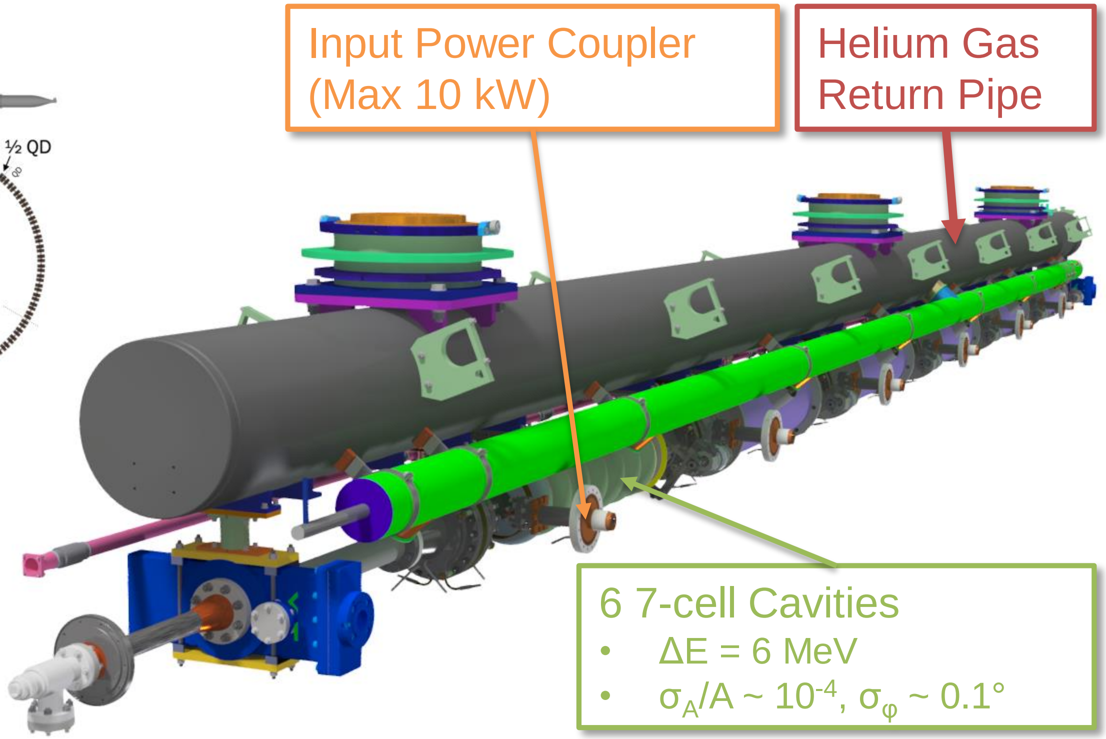
- Introduction
- Initial Measurements
- Vibration Sources
- Mitigation Results
- Active Resonance Control
- Results
- Conclusion

Introduction

The **Cornell-BNL ERL Test Accelerator** is a 4-turn energy recovery Linac with a FFA return loop.

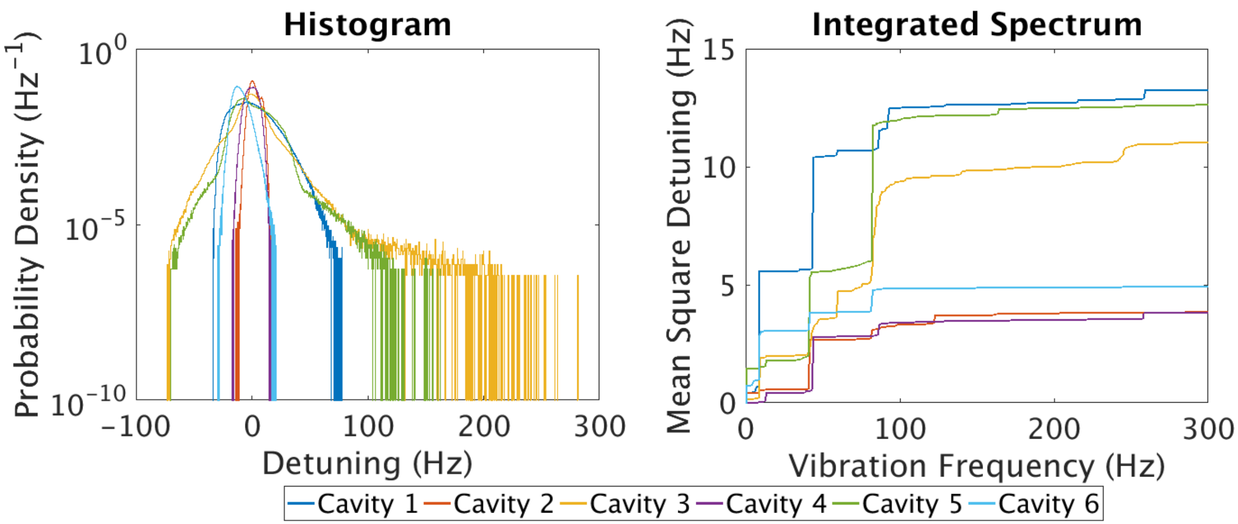


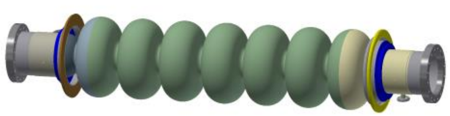


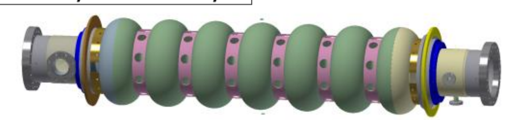


The peak detuning of the cavity must be less than **54 Hz** in order to sustain a cavity voltage of 6 MV using a power amplifier capable of delivering **5 kW**.

Microphonics Detuning







Cavity Number	1	3	5	2	4	6
Peak Detuning (Hz)	78	280	163	18	18	33
Major Vibration Frequencies (Hz)	8, 40, 80	8, 40, 80	40, 80	40, 80	40, 80	8, 40, 80

RF Power Constraint Mitigation

- We relax the peak detuning limit by using 10 kW power amplifiers for unstiffened cavities.
- We can further relax the limit by changing the loaded quality factor to $Q_L \sim 2 \times 10^7$ using a 3 stub tuner.

Vibration Sources

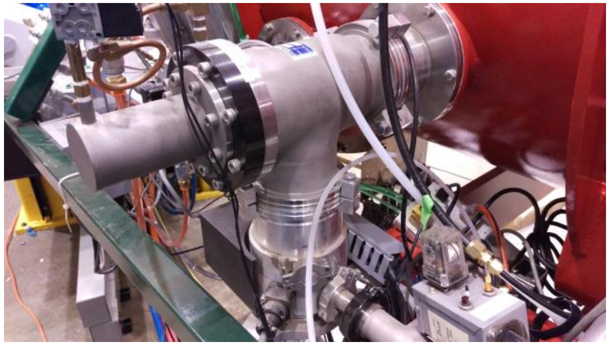
Vibrations can couple into the cryomodule from outside sources.

Water Pumps
(6 m away)
No contribution

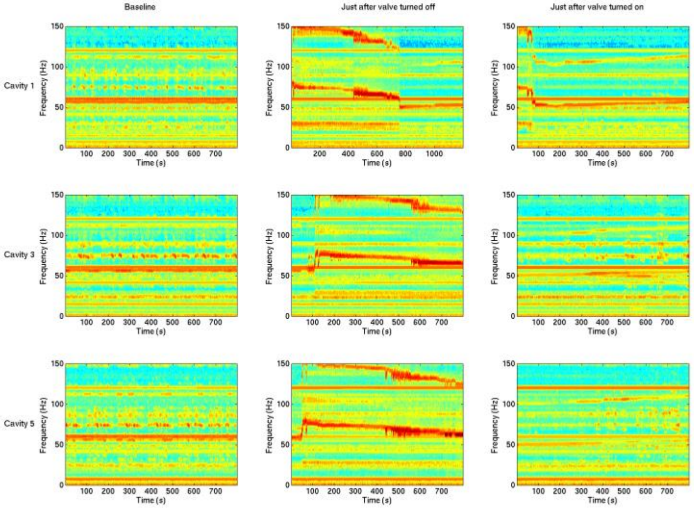
Blower Pumps
(4 m away)
No direct contribution

Klystron Platform
59 Hz vibrations coupled in through waveguide suspended from platform.

Vibrations can also come from inside the cryomodule.



Turbomolecular Pump with Backing Pump
Weak source

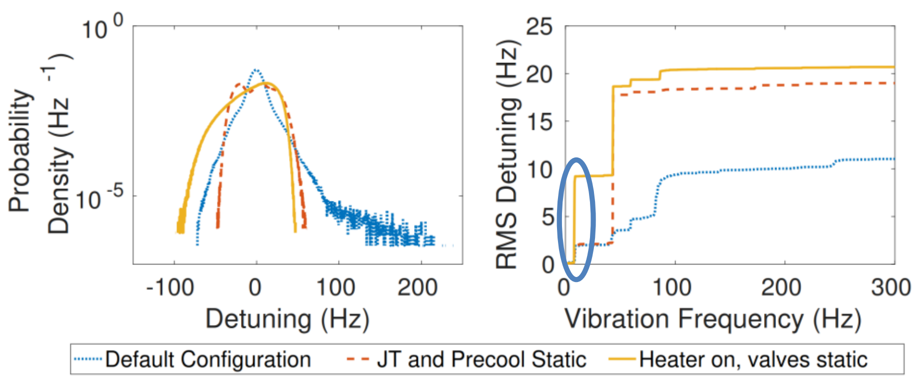


5 K Helium System
Turning off gas flow changes vibration spectrum quite a bit!

Mitigation

1. Valve Actuation

- Actuation of the JT valve correlates with peak detuning events of as much as 280 Hz in cavity 3.
- Valves made static and the Helium level control done using 2 K 2 Phase heater.



Addressed!

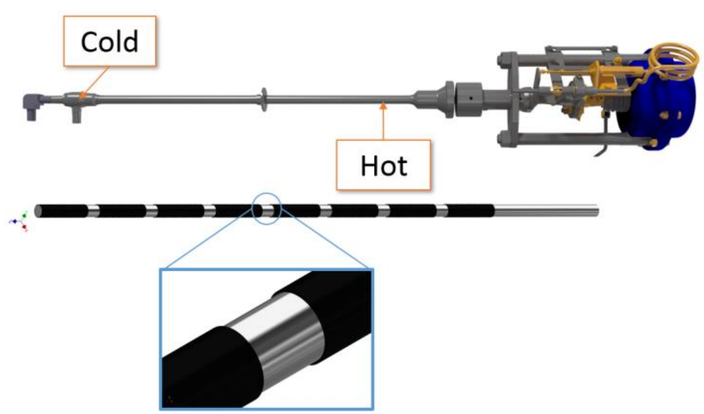
2. Excited Structural Resonances

- The gas flow due to pump skid excites 8 Hz. The amplitude of this line increases when heat load is high.
- Impulse response testing will be done to ascertain this effect and steps will be taken to damp it.

3. Thermo-acoustic Oscillations[1]

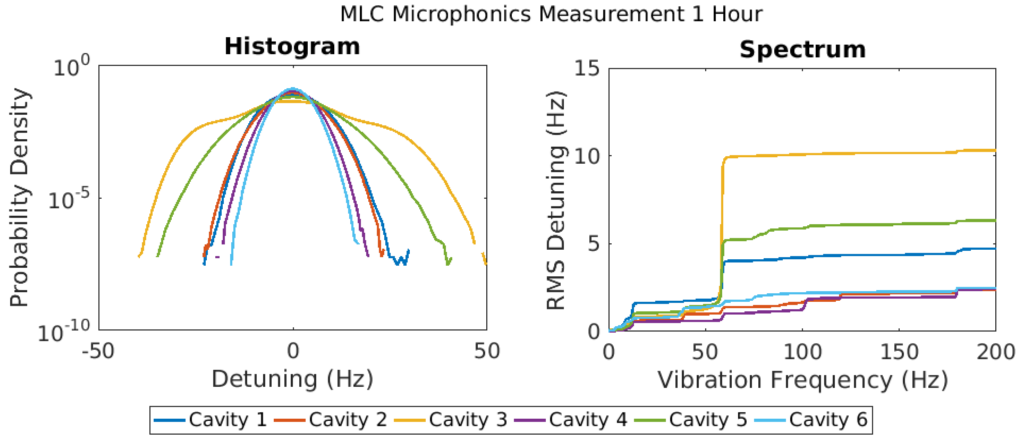
- Thermo-acoustic oscillations in the needle valve produce 40 Hz and 80 Hz.
- Fit PEEK plastic sleeves on the 5K adjust valve stem to reduce the gas flow and damp the instability.

Addressed!



[1] LCLS – II cryomodule commissioning in FermiLab

Mitigation Results



Cavity	Stiffened	Old Peak Detuning (Hz)	New Peak Detuning (Hz)	Field (MV)	Nominal Amplitude Stability
1	No	78	30	6 (9.5)	4.0×10^{-4}
2	Yes	18	25	6 (10)	3.9×10^{-4}
3	No	280	**50**	6 (8)	4.0×10^{-4}
4	Yes	18	20	6 (10)	4.1×10^{-4}
5	No	163	41	6 (8.5)	3.1×10^{-4}
6	Yes	33	18	6 (11.3)	2.9×10^{-4}

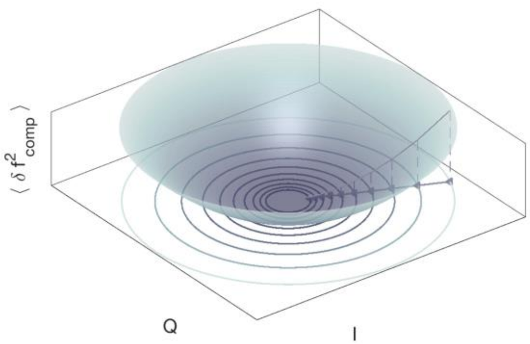
Valve modification was highly successful! Exceeded design energy gain by 50 %!

Narrowband Active Noise Control

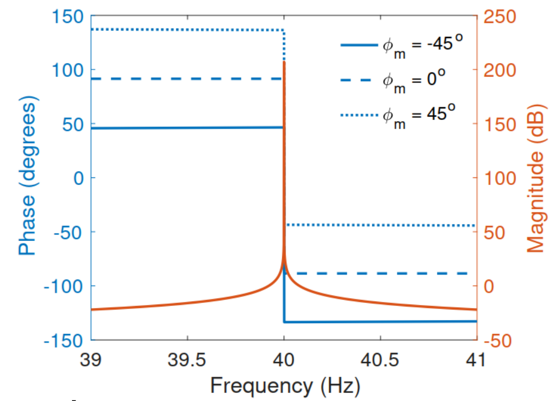
Besides mitigation of vibration sources, an active control system is also necessary!

We can compensate for narrowband microphonics detuning by applying a sum of sine waves on the actuator. (Narrowband Active Noise Control (ANC))

Problem: Adjust I_m and Q_m to modulate the carriers at frequencies ω_m to reduce detuning.



Equivalent to a set of IIR Notch Filters

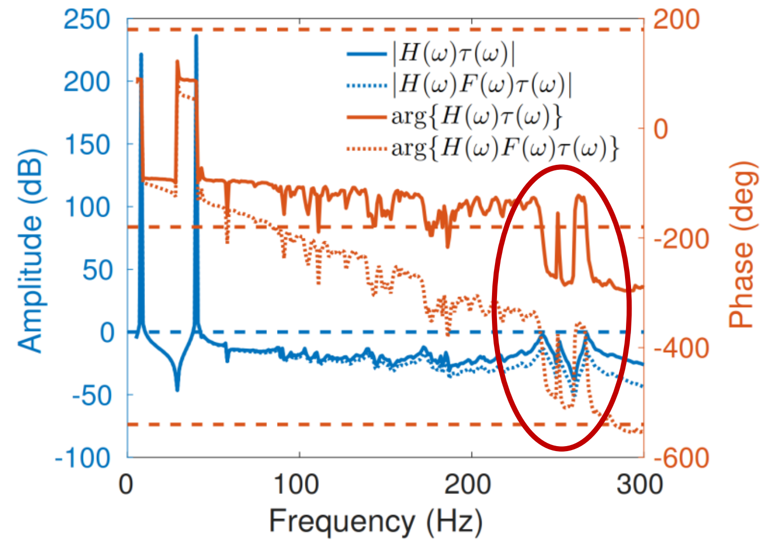


Fixed Parameters: Learning Rate (gain) μ_m and Controller Phase φ_m

Stability:

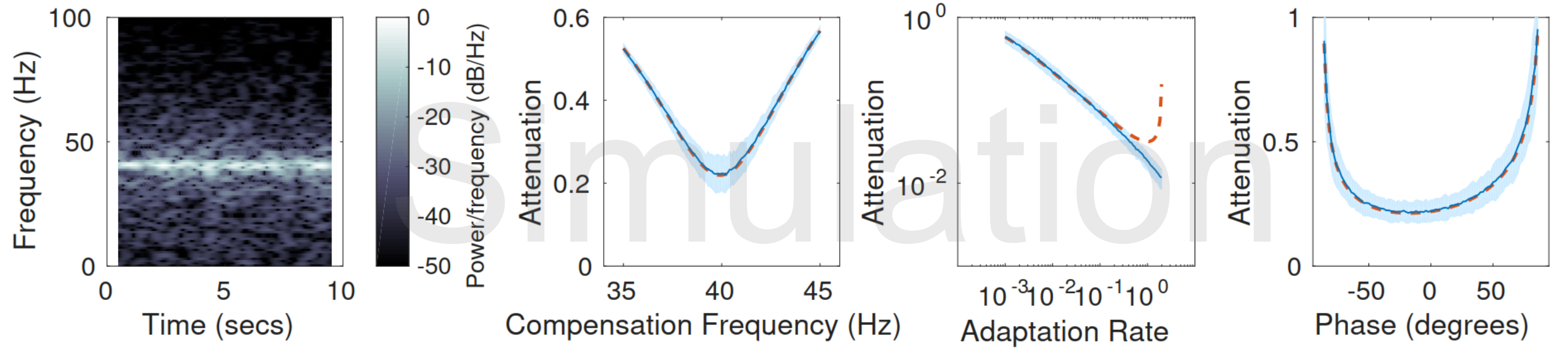
1. There is a range of controller phase φ_m within which the system is stable. As the gain increases this span decreases.
2. There is an upper limit to gain μ_m inversely proportional to group delay and tuner transfer function amplitude.
3. Tuner resonances also affect stability.

We use a FIR low pass filter to suppress resonances above 200 Hz.

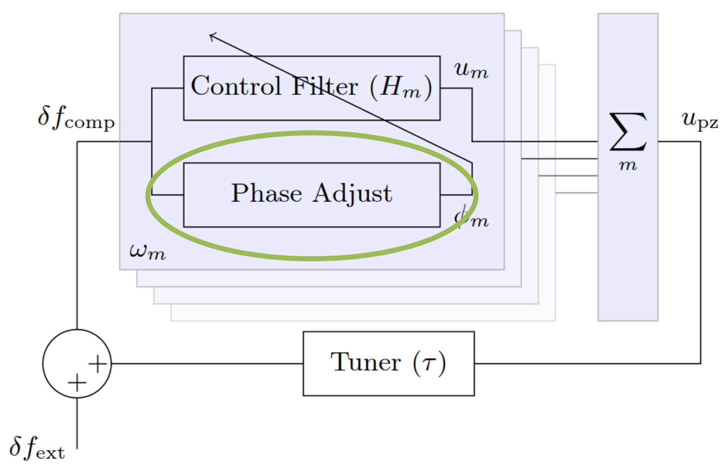


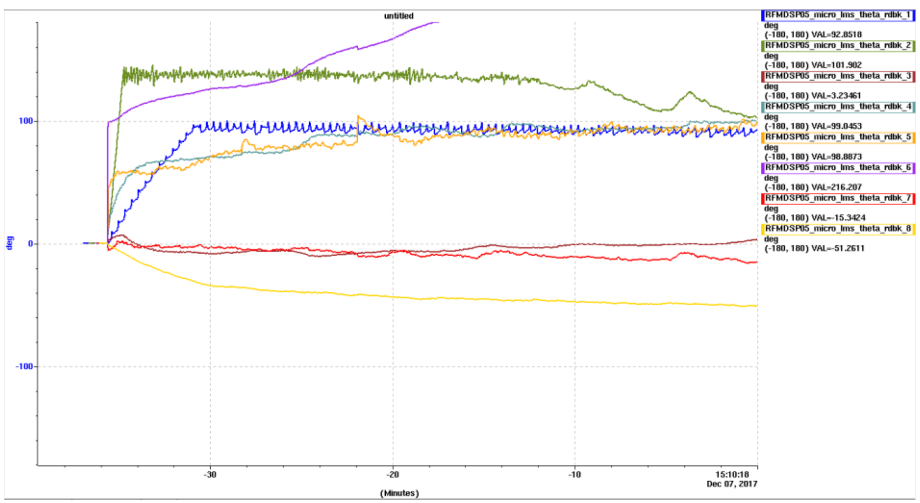
Phase Adaptation

How to choose controller parameters?



Instead of depending on transfer function measurements, use Least Mean Square (LMS) to determine optimum controller phase in-situ and introduce η_m





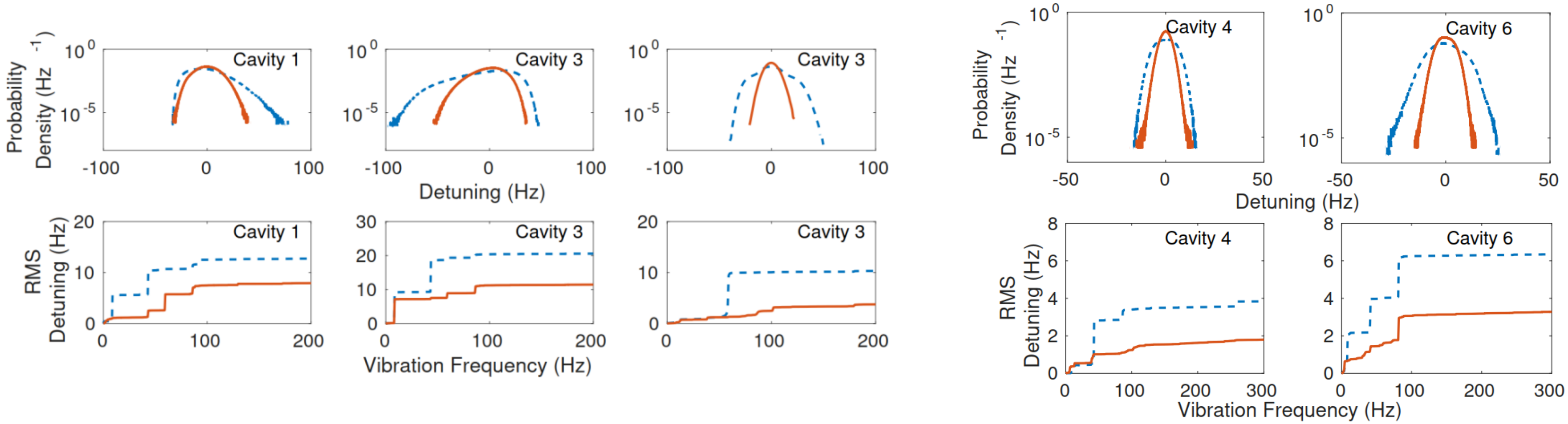
The modified ANC algorithm estimates the phases and keeps them in the stable region even if the transfer function changes.

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

Results

CBETA Cornell-BNL ERL Test Accelerator

The modified narrowband ANC was tested on some cavities of the main linac.



Run Description	Peak Detuning (Hz)		RMS Detuning (Hz)	
	ANC Off	ANC On	ANC Off	ANC On
Cavity 1 with JT and precool static	78	45	13.6	9.1
Cavity 3 with JT and precool static	100	57	20.8	11.7
Cavity 3 with JT and precool static and 5 K valve modified	50	22	10.7	4.6
Cavity 4 with JT and precool static	17	19	4.4	2.4
Cavity 6 in original configuration	30	15	6.4	3.4

The algorithm is effective and stable over hours of operation! No mechanical coupling with neighboring cavities because of bellows in our cryomodule.

Conclusions

- Initial Measurements

  The peak detuning for un-stiffened cavities were more than **100 Hz** compared to the 54 Hz maximum which a 5 kW system can tolerate while maintaining the CBETA design energy gain of 6 MeV. Microphonics was mainly **dominated by 40 Hz and 80 Hz** vibrations along with **sudden impulses of large amplitude**.

- Cryogenic System Modifications

  We made the JT and precool valves static to prevent large impulsive detuning. We fit the 5 K adjust valve stem with plastic sleeves to damp thermo-acoustic oscillations at 40 Hz and 80 Hz. After the modifications, **maximum peak detuning was 50 Hz** on cavity 3 primarily caused by 59 Hz vibrations coupled in through the waveguide.
  We exceeded our required energy gain by 50% during beam operations.

- Active Resonance Control

  We developed a modified narrowband Active Noise Control algorithm which optimizes the controller phase parameter online and requires three parameters frequency ω_m, gain μ_m and adaptation rate η_m. These parameters along with the mechanical eigenmodes determine the stability and we used additional filtering to attenuate the eigenmodes.

- Results

  We demonstrated stable and effective operation of the algorithm with beam over multiple hours with almost a factor of 2 reduction in the peak detuning on both stiffened and un-stiffened cavities.

Acknowledgements

Peter Quigley, Vadim Vescherevich, Adam Bartnik, John Dobbins, Fumio Furuta, Colwyn Gulliford, Georg Hoffstaetter, Roger Kaplan, Matthias Liepe, Dan Sabol, James Sears, Colby Shore, Eric Smith

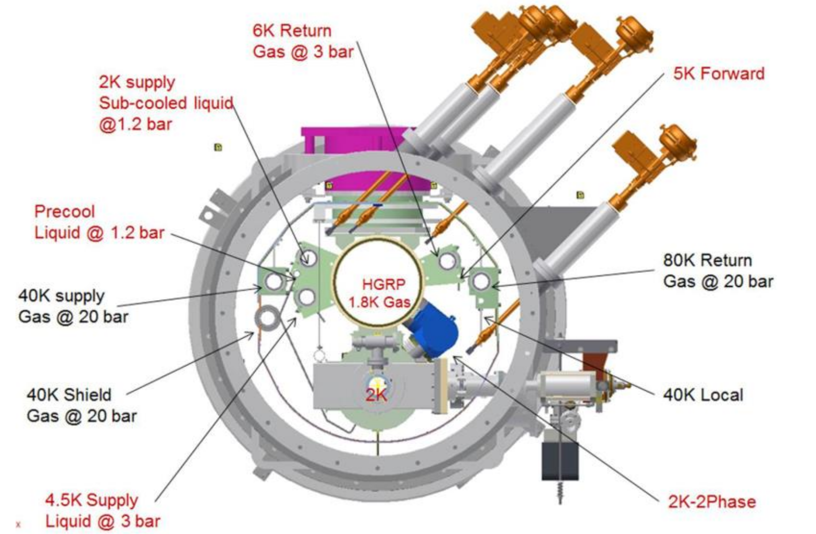
We would also like to thank Warren Schappert and Ben Hansen for discussing their experience with LCLS-II cryomodule commissioning at FNAL, prompting us to look for it in our Main Linac.

Thank you!

Cryogenic System

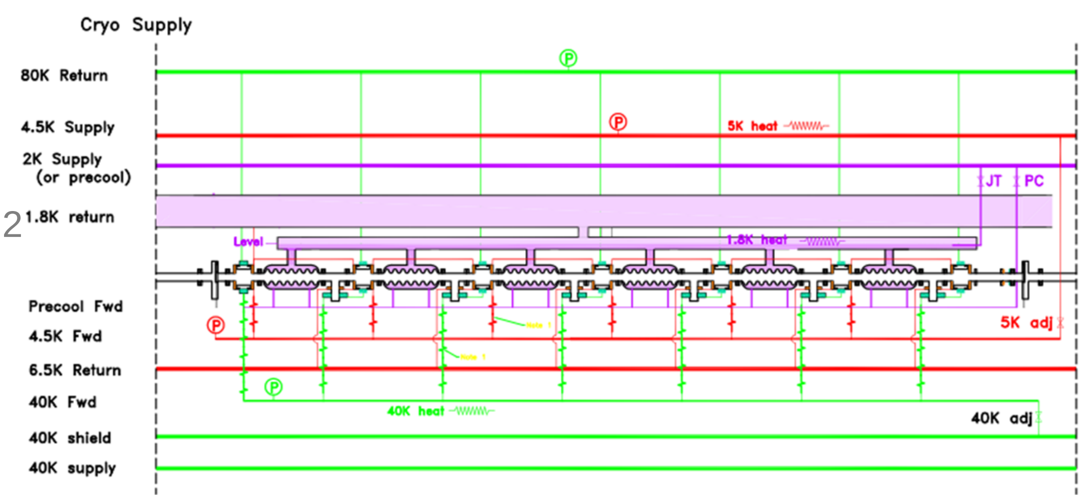
Three subsystems:

1. 40 K / 80 K
   Thermal shield, input couplers, HOM loads.
2. 4.5 K/ 6.5 K
   Input couplers, beam pipe.
3. 2 K/ 1.8 K
   Cavities.



2 K liquid Helium system controlled by:

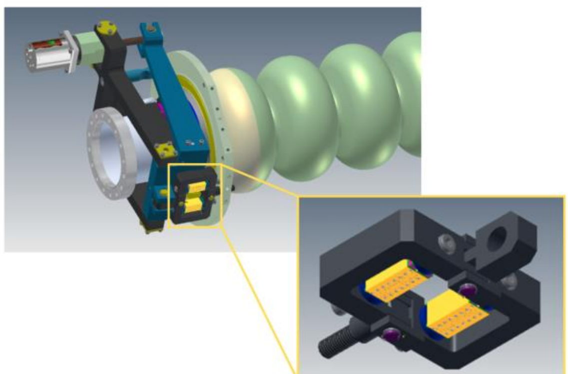
1. Pneumatic Joule-Thomson (JT) and precool valve.
   Controls amount of LHe entering the 2 K 2 phase pipe.
2. 2 K 2 Phase heater
   Adds heat load if necessary.
3. Pump Skid
   Controls vapor pressure in 2 K 2 phase pipe supplying to the Helium vessels thus controlling bath temperature.

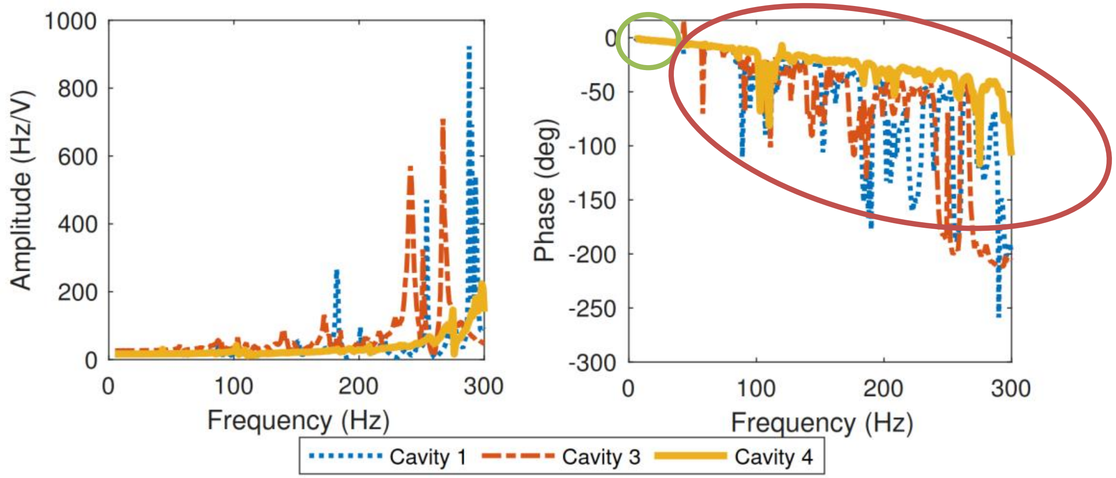


Active Resonance Control

Mitigation of vibration sources is the preferred method of reducing peak microphonics detuning, but having an active control system is also necessary!

The Main Linac 7 cell cavities are attached to a tuner based on the Saclay I design with added fast actuators.





Observations:

1. Phase response is almost 0° up to 30 Hz, this makes it ideal for proportional integral feedback control.
2. For higher frequencies of the phase response is very noisy, especially for un-stiffened cavities.
3. The mechanical eigenmodes of stiffened cavity starts at a higher frequency and in general has a smaller response amplitude.

Modified Narrowband ANC

Idea: Treat this as a real time least squares optimization problem.

Actuator Signal: $$u_{pz}(t_n) = \sum_m I_{mn}\cos\omega_m t_n + Q_{mn}\sin\omega_m t_n$$

Assuming that the tuner is a LTI system the detuning can be written as:

$$\delta f_{\text{comp}}(t_n) = \delta f_{\text{ext}}(t_n) + \sum_m \alpha_m\{I_{mn}\cos(\omega_m t_n - \phi_m) + Q_{mn}\sin(\omega_m t_n - \phi_m)\}$$

Where, α_m and φ_m describe the transfer function from actuator to detuning at the frequency ω_m.

Mean Square Detuning: $F_n = E[\{\delta f_{\text{comp}}(t_n)\}^2] \sim \{\delta f_{\text{comp}}(t_n)\}^2$

Minimize the mean square detuning using a gradient descent algorithm.

$$I_{m,n+1} = I_{m,n} - \mu_m \delta f_{\text{comp}}(t_n)\cos(\omega_m t_n - \phi_m)$$
$$Q_{m,n+1} = Q_{m,n} - \mu_m \delta f_{\text{comp}}(t_n)\sin(\omega_m t_n - \phi_m)$$

ω_m ,μ_m and φ_m are fixed by the operator.

$$\phi_{m,n+1} = \phi_{m,n} - \eta_m \delta f_{\text{comp}}(t_n)\{I_{m,n+1}\sin(\omega_m t_n - \phi_m) - Q_{m,n+1}\cos(\omega_m t_n - \phi_m)\}$$

FAT Microphonics