Control of Microphonics for Narrow Control Bandwidth Cavities

SRF Conference 2017

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What is Microphonics

- Microphonics is the time domain variation in cavity frequency driven by external vibrational sources as well as control instabilities and transients.
- For single cavity single source systems you get the same microphonics at low power as high power. Thus one can use 100 mW RF systems and work locally to investigate and solve problems.
- Vector sum systems have "cross talk" issues due to Lorentz force effects as part of the control algorithm and are field dependent.
- It can be due to fixed frequency sources such as motors and equipment.
- When the source is white noise the results shows up as the natural vibrational frequencies or modes of the structure.
- When fixed frequency sources are NEAR resonances in the structure things can get really bad as the resonance "amplifies" the effects of the fixed frequency sources.
- Increasing the loaded-Q of a system, decreases the control bandwidth which makes your system more sensitive to microphonics.

What is Not Microphonics

- **Static Lorentz force detuning**
  - **There are dynamic Lorentz force detuning effects that can effect the cavity frequency shifts in time scales consistent with vibrational modes of the cavities. Proper gradient regulation can be used to address this. Lorentz force is an issue for cavities operated with pulsed RF or in vector sum mode.***
  - **In vector sum systems a detuned cavity has its gradient decreased while the others are increased by 1/(N-1), the vector sum of gradient and phase is stable while individual cavities have time varying gradient and phase due to microphonics.**
- **Low frequency pressure drifts with periods on the order of minutes to hours.**
  - **These can be addressed with your motor or PZT driven tuners with minimal effects on RF power requirements.**

The Math

- The steady state amplitude and phase controls needed for microphonics is given by:

$$P_{RF} = \frac{(\beta+1)L}{4\beta Q_{FPC}(r/Q)}\left\{(E + I_0 Q_{FPC}(r/Q)cos\varphi_B)^2 + \left(2Q_L\frac{\delta f}{f_0}E + I_0 Q_{FPC}(r/Q)sin\varphi_B\right)^2\right\}$$

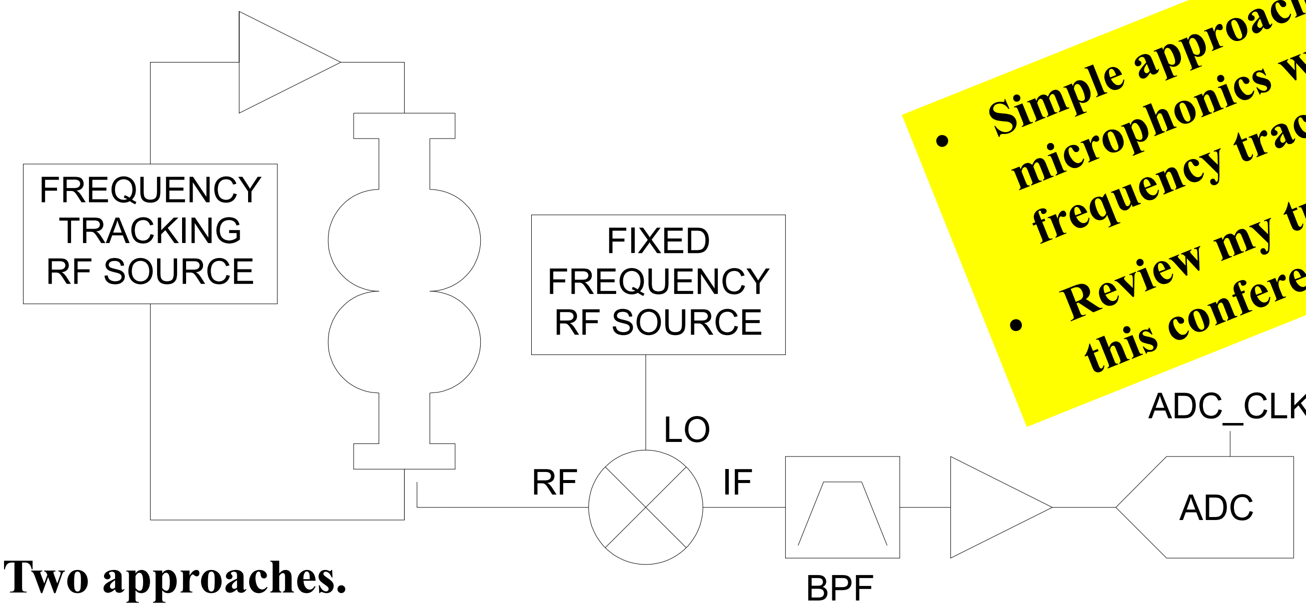
$$\varphi_{RF} = arcTan\left(\frac{2Q_L\frac{\delta f}{f_0}E + I_0 Q_{FPC}(r/Q)sin\varphi_B}{E + I_0 Q_{FPC}(r/Q)cos\varphi_B}\right)$$

- **One interesting outcome of the math is that beam loading reduces the control requirements due to microphonics.**

***Frequently folks use the loaded-Q, Q_L in place of the fundamental power coupler-Q, Q_{FPC}.**

Simple Sampled I/Q Receiver

- Simple approach for measuring microphonics when using a frequency tracking system.
- Review my tutorial talk from this conference



Two approaches.

1. **Band pass filter with ADC CLK that is either 4X the band pass filter center frequency (BPF_CF) signal or BPF_CF/1.25.**
2. **Low pass filter with ADC filter = 4X Low pass filter cutoff – 10 kHz (or so)**
3. **In both cases care has to be taken that the ADC clock frequency is precisely set or phase locked to the IF frequency.**

In low frequency systems there is a second low pass filter between the IF filter and the BPF I used a 5 MHz filter. I did this because the xxx kHz filters does not work well at RF frequencies.

What is Impulse Response Testing?

- Impulse response testing is done to determine and quantify the resonant vibrational frequencies (or modes) of a structure.
- Modal response testing is typically done using two methods.
  - Impulse response excitation
  - Swept sine wave excitation
- Impulse response testing.
  - A force instrumented hammer is used to excite the structure and the force sensor is used to measure the excitation.
  - The frequency content of the impulse drive signal depends on the hammer and tip material.
  - For cavity work we generally use a 300 gm hammer with a tip that provides excitation out to about 1 kHz.
  - This method is very good for survey of systems.
- For swept sine measurements a magnet/coil system (speaker) is used to apply a measured sine wave force to the structure. This is used for detailed mode identification. Can be difficult to properly couple to the structure.

Transfer Function Math

- The motion or frequency shift of the cavity is measured using an accelerometer, or cavity resonance monitor or digital receiver.
- A complex FFT is taken of the excitation, $\vec{X}(\omega)$, and the system response, $\vec{Y}(\omega)$, the transfer function is given by.

$$\vec{H}(\omega) = \frac{avg\left(\vec{Y}(\omega)\right)}{avg\left(\vec{X}(\omega)\right)}$$

- Averaging is used to separate background motion from the excitation.
- Coherence is a measure of the effect of the excitation on the response. A coherence of 1 means that the response signal is due to the excitation. A coherence much less than 0.7 indicates that the response signal is driven by some other source. It is given by:

$$C(\omega) = \frac{avg\left(\vec{X^*}(\omega)\vec{Y}(\omega)\right)^2}{avg\left(\vec{X}(\omega)\vec{X^*}(\omega)\right) avg\left(\vec{Y}(\omega)\vec{Y^*}(\omega)\right)}$$

- Where the * symbol indicates the complex conjugate of the transformed signal.

Multiple Strike / Multiple Sensor Testing

- Since we are measuring transfer functions with both phase (time delay from the strike) and transfer function amplitude (magnitude of the response) the results of multiple sensor locations and single strike location can be combined to provide a picture of the motion of the entire structure.
- The other approach is multiple strike locations and single sensor location.
- Both approaches provide information about the modal motion of the structure.
- We use software called ME-CAD to preform the analysis.
- In general the software uses the phase and amplitude information at a given frequency band and translates it into a relative displacement as a function of time.

Why Are Modal Resonances Important?

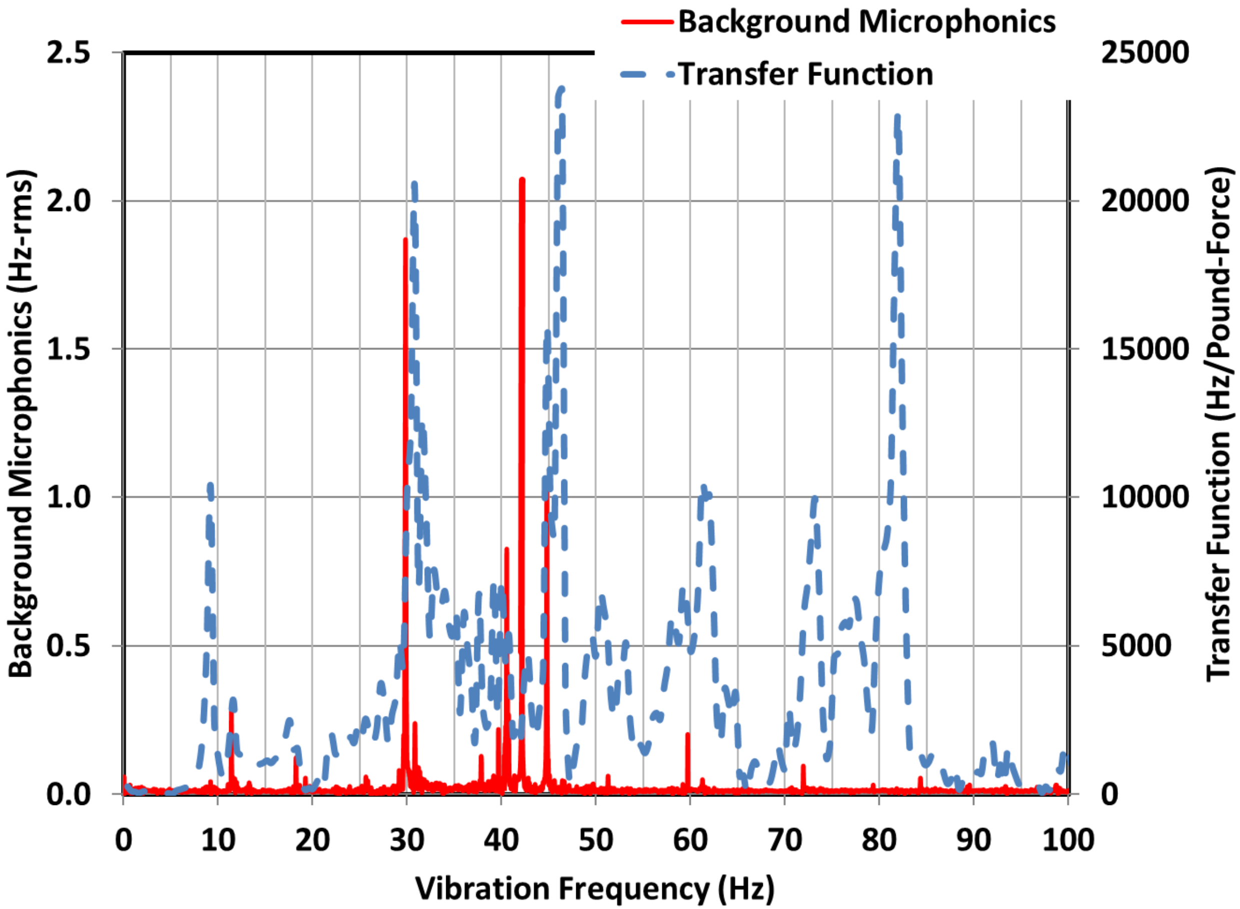
(Think pushing a child in a swing)

- If even a small excitation is at the same frequency as the modal resonance it can excite the mode and effectively amplify the effect of the external vibrational source. (Think of pushing a swing right at or near the top of the arc of motion.)
  - The microphonics will "phase lock" with the diving term even if is just near the resonance.
  - In CEBAF we had the 10 Hz string mode of 4 out of 5 cryomodules in the north linac lock to a 10.75 Hz vibration produced by a failing motor in a cooling tower that was 50 m from the linac. The remaining cryomodule had a resonance at 9.75 Hz which was to far away.
- Random noise will come both in phase and out of phase with the vibration created at the mode of the structure and the microphonics will build up and down over time. (Think of pushing a swing at random times.)

Cavity 1, LCLS II Prototype Cryomodule In JLAB Cryomodule Test Facility, Low Power Test Data

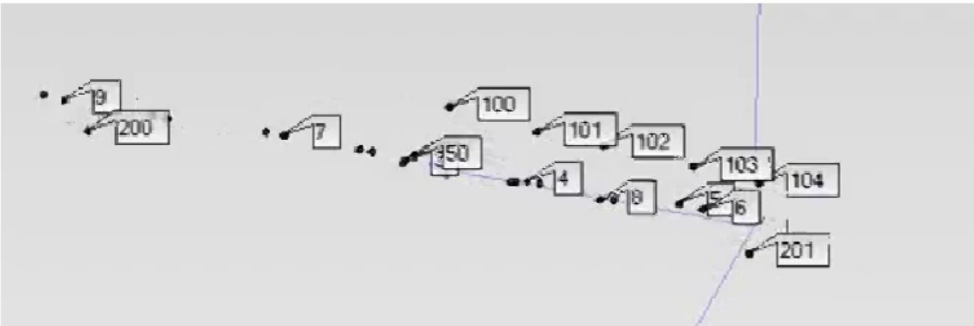
Overlap of high Q transfer functions and narrow band excitation is problematic, even if they do not exactly overlap

Transfer function source term location was beam pipe at cavity 8 end of cryomodule.



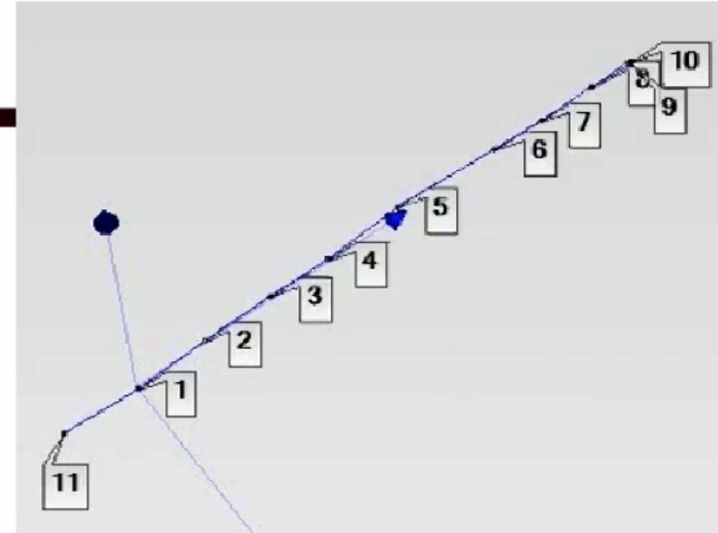
- Overlay of background microphonics (RED) and transfer function (BLUE) for Cavity 1 of the LCLS II string. Data taken with cryogenics in a quiet state.
- End effects and adjacent cryogenic piping vibrations transmitted from machinery are suspects.
- 29.8 and 41 Hz were driven by machinery vibrations coupled through the cryogenic piping.

Examples of Multi Sensor Single Strike Measurements

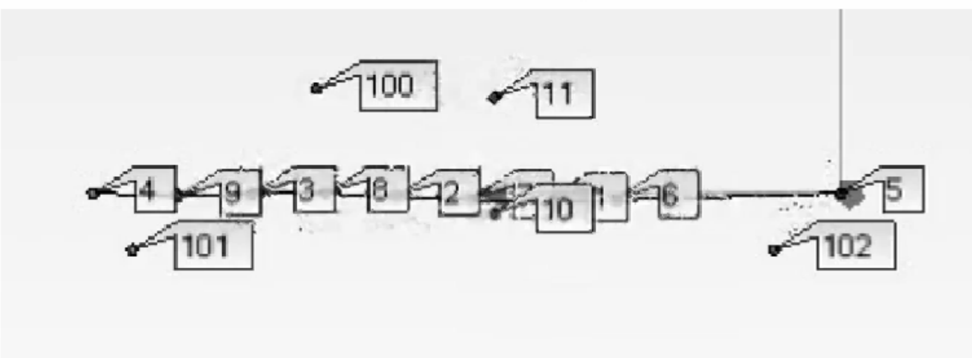


C100 cryomodule cavity string 10 Hz mode.

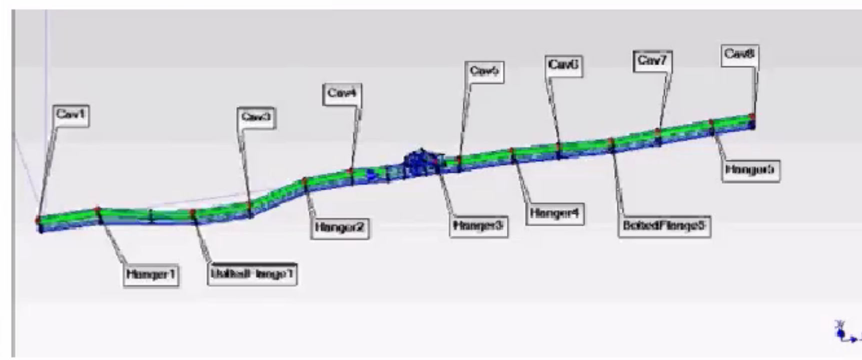
- Hammer strike point cryogenic U-tube.
- Upper row is top of tuner stack
- Lower row is the end of each cavity
- Note tuner stack participates in mode.



LCLS II cavity string when installed in the cryomodule 39 Hz mode (x1.1 for cold.) Note that cavities 5, 6 and you see the majority of detuning forces.



C100 cryomodule cavity string 33 Hz mode (x1.1 for cold). Note that cavities 1 and 8 see the majority of the detuning forces.



LCLS II cryomodule coupler vacuum pipe 45 Hz mode. Ion pump in middle of line.

Mitigating Modal Resonances

- Add damping materials to the structure.
  - Damping materials are materials that have a relatively high loss tangent. Compressing and releasing them absorbs energy.
  - When damping remember that a flat pad damps better in the compression mode not in the shear mode.
  - The compressive modulus is a function of frequency and compression. This complicates analysis especially when operating with systems like waveguides.
  - We have chosen to use Sorbothane® material which has a loss tangent between 0.3 and 0.7 between 10 Hz and 150 Hz.
- Stiffen the structure. This will generally shift the resonant frequencies higher or introduce other modes.
- Change the resonant frequency to by adding weight. This can be useful for addressing driven modes.

Complications With SRF Cavities

- For a 0.7 m long CEBAF C100 cavity 10 nm of change in length is about a 20 Hz change in cavity frequency.
- You are dealing with complicated structures that are difficult to fully simulate to the 10 nm level.
- Thermal isolation generally means weak mechanical coupling to the outside world.
- Some difficult part about damping resonances that affect cavity microphonics are:
  - The environment that you are concerned about is your accelerator.
  - You will not know all of the source terms until the machine is built and operating.
  - By the time you know what the problems are due to the machine environment, the cryomodule design is probably complete and you are well into production.

Complications With SRF Cavities

- Common damping materials do not work at cryogenic temperatures.
- Cryogenic lines are made of isolated pipes within pipes. While one can damp the outer pipe using conventional methods it is difficult to damp the inner pipe.
- The cryogenic plant and water systems in accelerators are great sources of background vibrations and they have pipes which can get the vibrations to the cryomodule.
- Coupling paths from the sources to the cryomodule are often difficult to understand.
- Multiple cavities with a single source have the potential for microphonics driven / Lorentz force driven instabilities.
  - Detuning a cavity up in frequency will cause its gradient to be reduced.
  - Lorentz effects will cause the frequency to be increased
  - Runaway is a “product” of loaded-Q, peak microphonics and gradient.

What To Do When You Discover a Problem

First . . . If possible . . . deal with it mechanically.

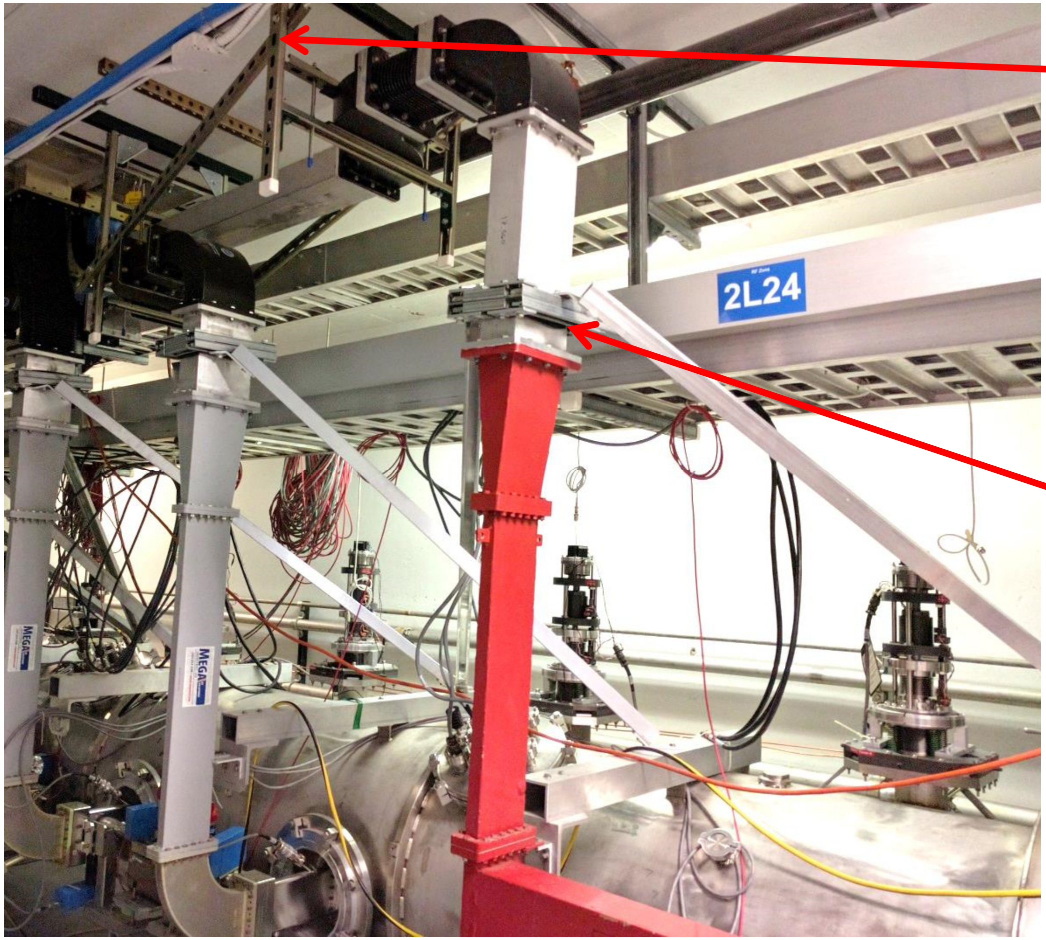
- It is important to understand the modes of your structure that impact cavity microphonics, if you are going to have any hope of fixing them mechanically after the fact. At JLAB we will do modal testing of
  - The bare cavities,
  - Dressed cavities,
  - Cavity string (before and after installation into the cryomodule),
  - The structures surrounding/touching the cryomodule.
- Determine the source term and reduce it by isolating motors, damping pipes, etc. . . . . Not always possible or practical.
  - Reduce the coupling terms.   Constrain and damp the waveguide, piping, vacuum hoses, that are touching the cryomodule.
  - Get rid of corrugated vacuum hoses and use either rubber or braided jacketed hoses.
  - Separate the backing pump from the turbo pump with a rubber hose.
  - Thermo-acoustic oscillations (correlated to vibrations on the JT valves)
- Plan construction activities and limit heavy vehicle traffic around your accelerator.

What To Do When You Discover a Problem

Second compensate for microphonics using some type of active controls.

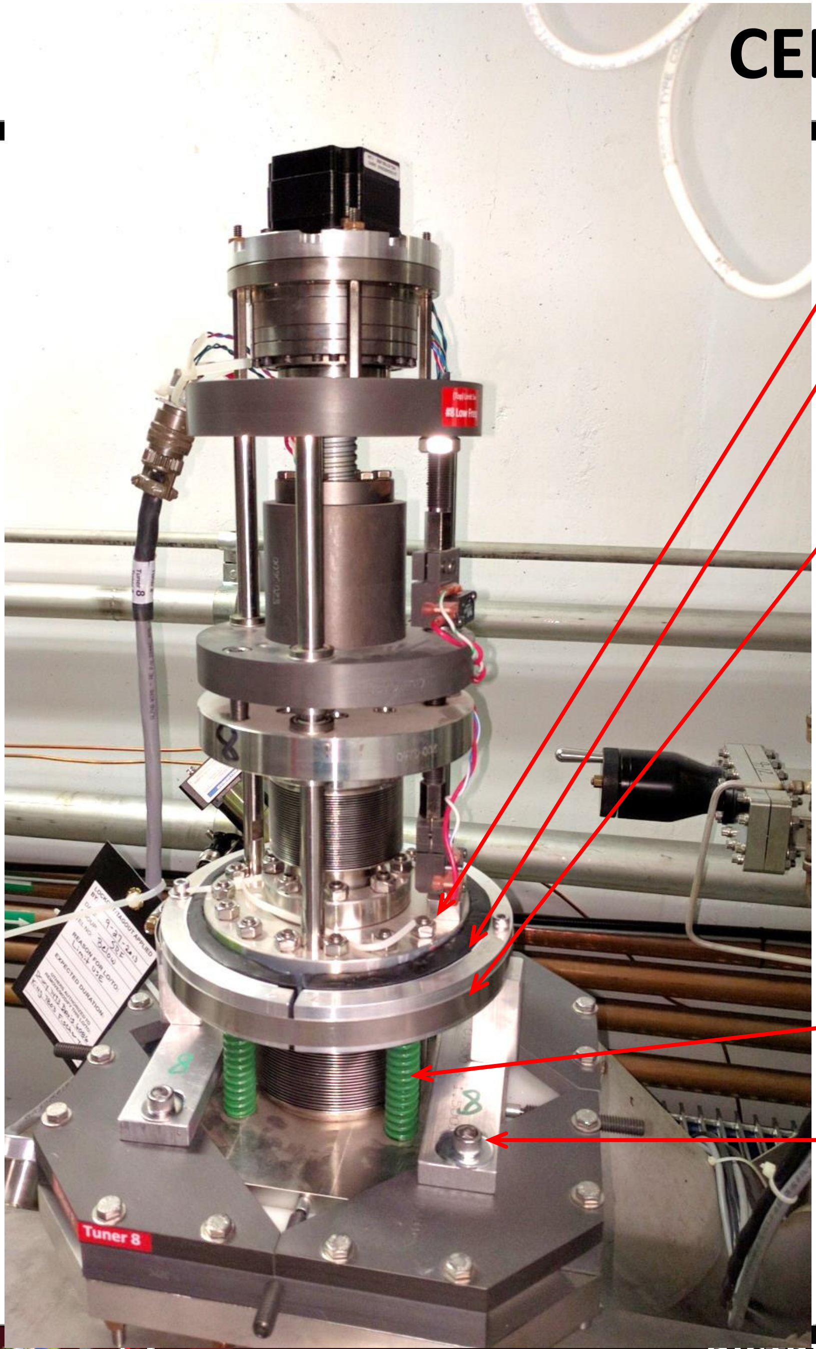
- **PZT tuners**
  - **Most labs are focusing on attacking the narrow band excited modes using adaptive dynamic feed forward PZT based systems.**
  - **It becomes difficult if there is strong mechanical coupling between tuning from cavity to cavity.**
  - **Becomes more difficult if there is a node in the PZT transfer function at the same location as a critical source term and structural resonance.**
- **Lower the loaded-Q, decrease the operating gradient and buy more RF power as necessary.**
- **Insure that LLRF systems have options that address situations of excessive microphonics with minimum interruption of beam delivery.**

CEBAF C100 Hardening Waveguide Ceiling and Strut Bracing/Damping



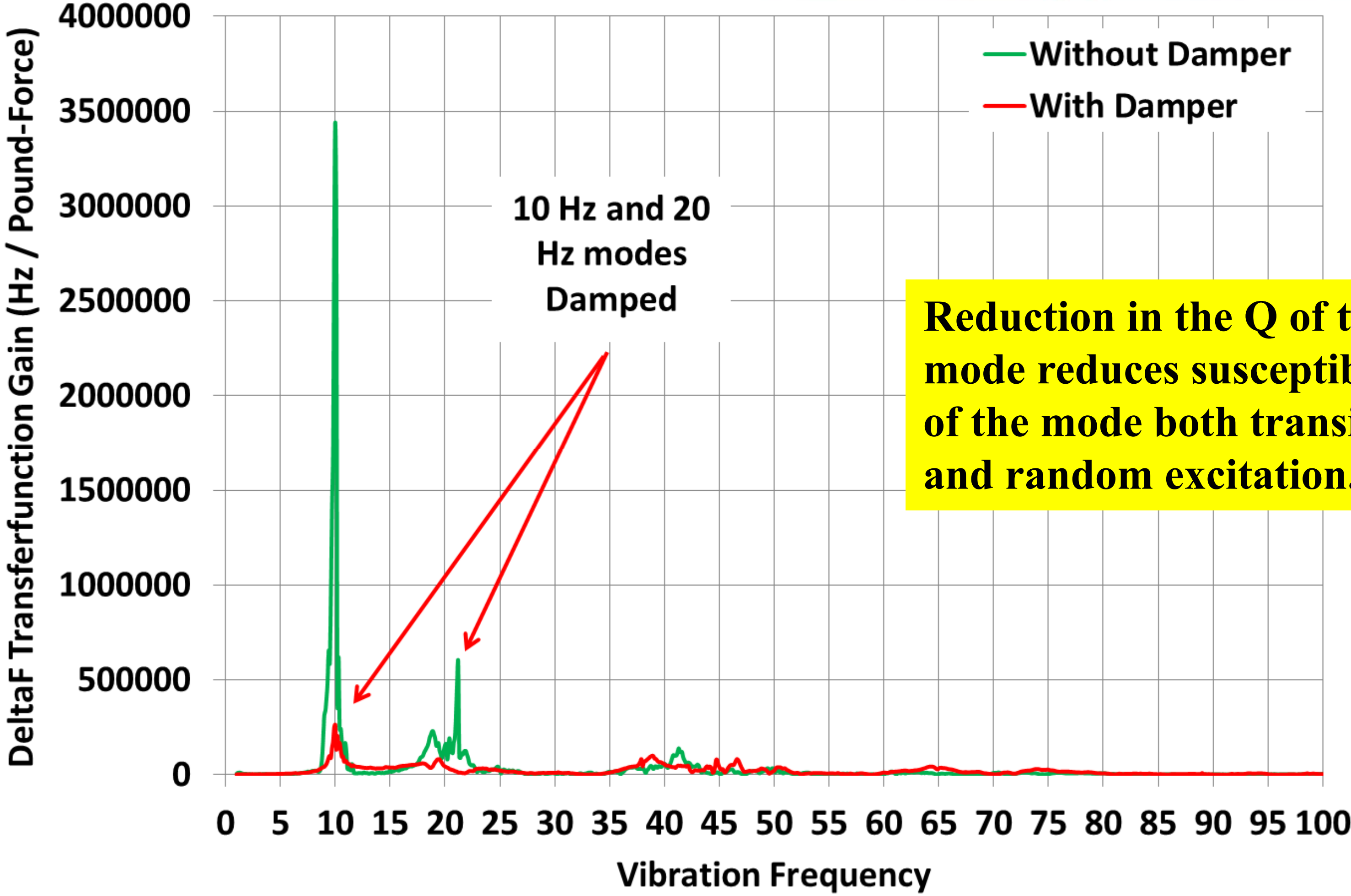
- Ceiling bracing improved
  - provides 3-axis constraint.
  - Has 1/8” 50 durometer Sorbothane® to damp vertical motion and to a lesser extent EW/NS motion.
- Waveguide struts back to existing bolts on the cryomodule
  - Provides 3-axis constraint of upper end of waveguides.
  - Waveguide bracket uses ¼” Sorbothane to damp EW and NS motion and to a lesser extent vertical motion.

CEBAF C100 Tuner Damper Ring



- Lower tuner flange 6" OD, 1.5" thick.
- 30 durometer, 1/2" x 1" sorbothane with polyethylene tape on the inner surface in order to allow vertical motion.
- Split ring with a nominal ID of 7" and with two 3/8" gaps for adjustment.
  - Compression adjustment made by tightening the hose clamp while measuring the OD of the short axis of the split ring.
  - Damper compression setting was tuned to minimize the transfer function from striking the cryomodule end can near the beam pipe to 10 Hz cavity vibration.
- Green springs adjusted to relaxed state after cavity is cold and tuned.
- Mounting plates fixed in place after compression adjustment insuring minimum lateral forces on tuner.

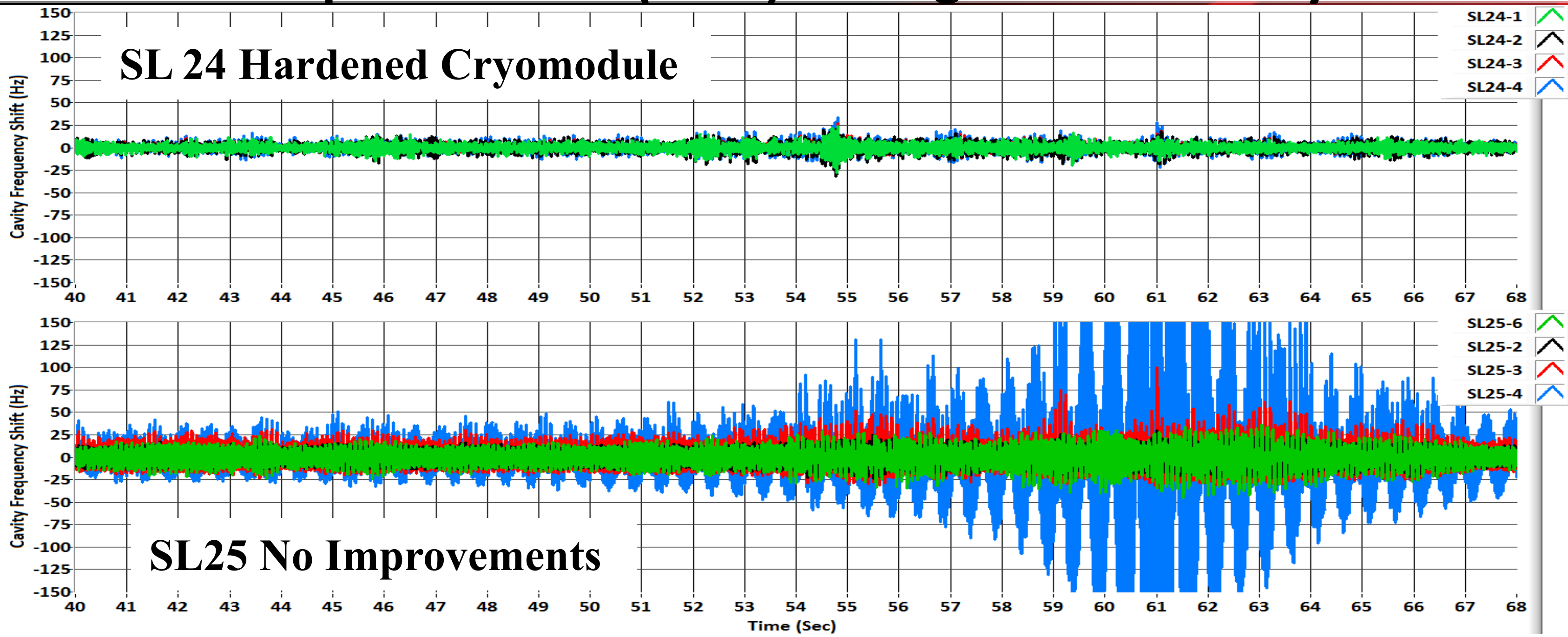
SL24 With and Without Tuner Damper, Waveguide struts Installed



Reduction in the Q of the mode reduces susceptibility of the mode both transient and random excitation.

- **Tuner damper compression "tuned" to reduce the Q of the 10 Hz mode.**
- **Reducing the 20 Hz mode was an unexpected bonus.**

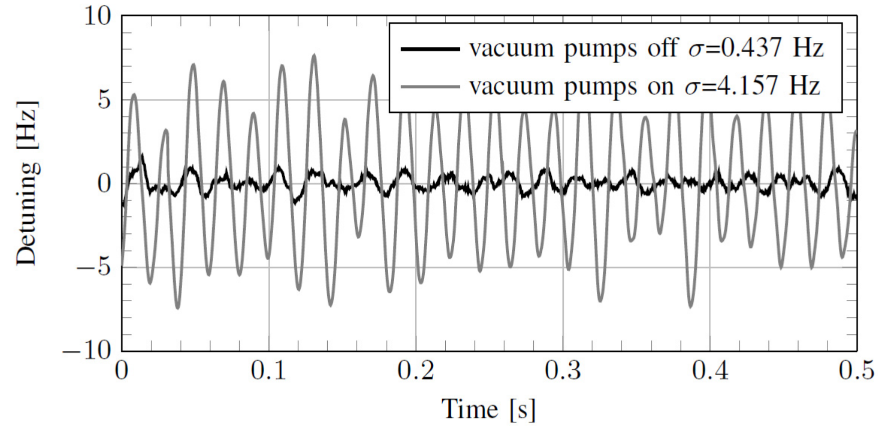
Comparison of a Hardened (SL24) and Zone With No Improvements (SL25) During Truck Drive By

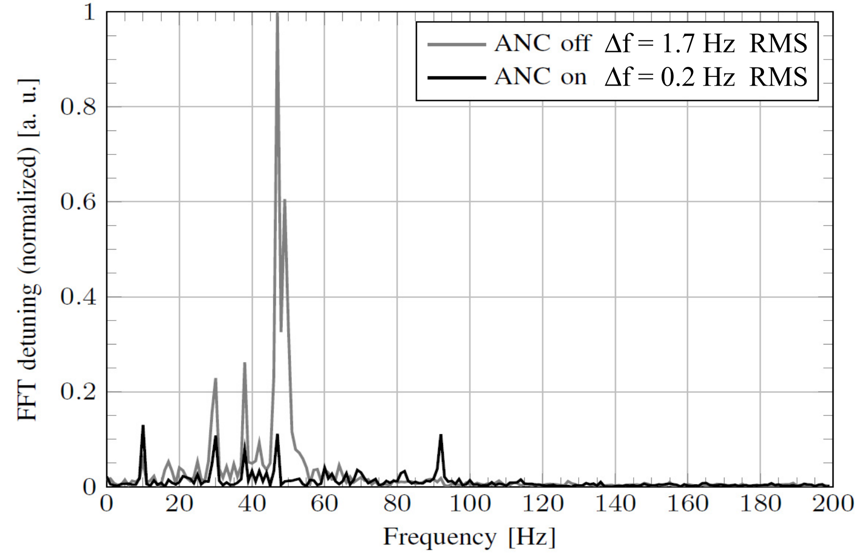


- A liquid nitrogen truck drove down the south linac service road at about 15 mph passing the zone at time equals about 60 seconds.
- Cavities operated in GDR mode at 3 MV/m in order to avoid trips.
- Improved both steady state microphonics and response to transient excitation.
- Vertical scale +/- 150 Hz of detune frequency, typical controls bandwidth 25 Hz.
- The truck was a problem because it produced ground vibrations at the same frequency as the 10 Hz string mode and 20 Hz half string modes.

CW Operation – Microphonics Suppression Effort at DESY

- **Dominant frequencies around 30 Hz and 49 Hz for most cavities**
- **Main contributor are vacuum pumps**
- **Pumps are essential for operation. They were turned off only for about 20 minutes to allow for microphonics measurements**
- **Active Noise Cancellation (ANC) techniques were applied to notch these frequencies (adjusted for individual cavities)**



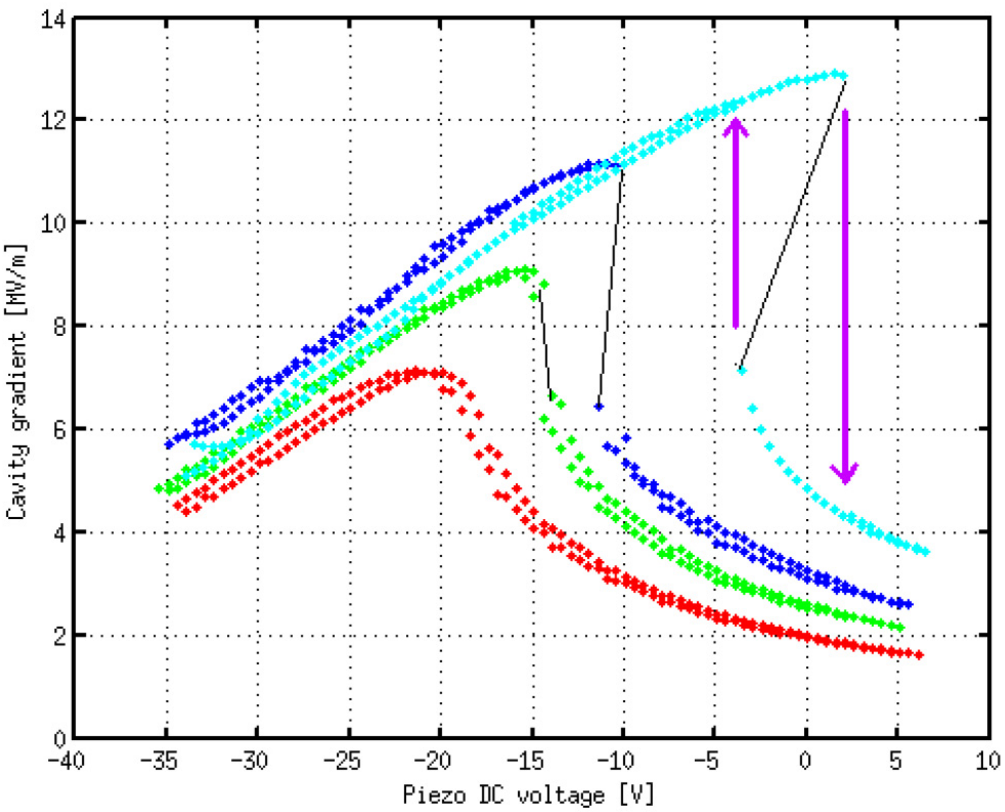


Julien Branlard, DESY
CW tests at CMTB

Reference: "***FPGA Based RF and Piezo Controllers for SRF Cavities in CW Mode***", R. Rybaniec *et al.* - IEEE Transaction on Nuclear Science, Jun. 2017 (DOI: 10.1109/TNS.2017.2687981)

CW Operation – Microphonics Suppression Effort at DESY

- Detuning as a function of piezo DC bias shows hysteresis behavior
- Effect increases with gradient
- Can lead to domino effect detuning in vector sum control
- Single cavity jump can cause extensive reaction of RF feedback, leading to instabilities



Julien Branlard, DESY
CW tests at CMTB

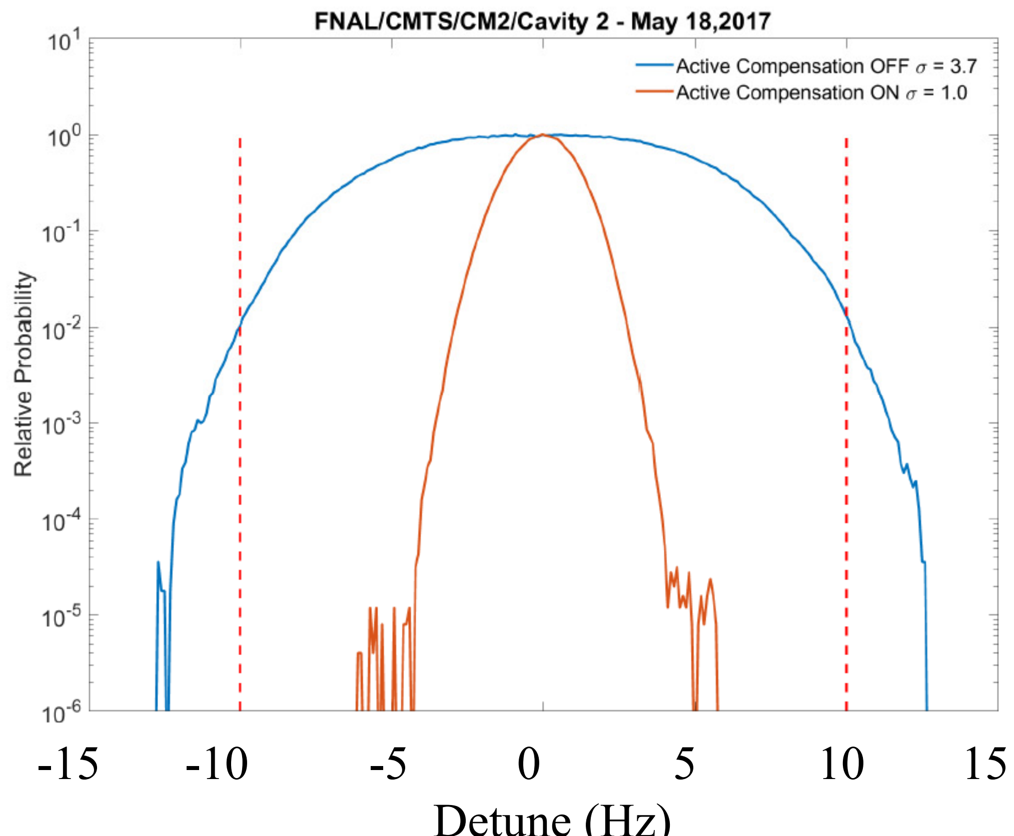
Data presented in "**Operation experience from CW/LPO at CMTB**"
W. Cichalewski *et al.* - SRF controls and CW operation workshop, Dresden, Nov. 2015

Fermi Lab Active Compensation of LCLS II Cavities

Cavities 1 and 2 were operated at the same time with active PZT compensation. They will expand to all 8 when controls are available.

Active Compensation

- Active compensation tests have been promising
- Intend to try new automated Least-Squares algorithm during up-coming tests next week
- Also pursuing optimal control (Kalman/LQGR) techniques



Conclusion

Microphonics can usually be managed. It becomes more difficult as cavity control bandwidths are decreased to levels of 20 Hz. It is best if the sources of narrow band vibrations which happen to overlap natural modes of the structrure can be reduced or that the coupling between the source and the structure can be reduced through isolation and damping. These studies are best done at low RF power with top where you can work local to the cryomodules.

Much progress is being made in the use of PZT controls for addressing quasi steady state microphonics such as that driven by narrow band sources. This can become complicated if there is a significant coupling between the PZT actuator on one cavity and an adjacent cavity. Any mitigation process should start with an understanding of the modes of the structure that couple to cavity microphonics.

Thank you for your attention

Acknowledgements: