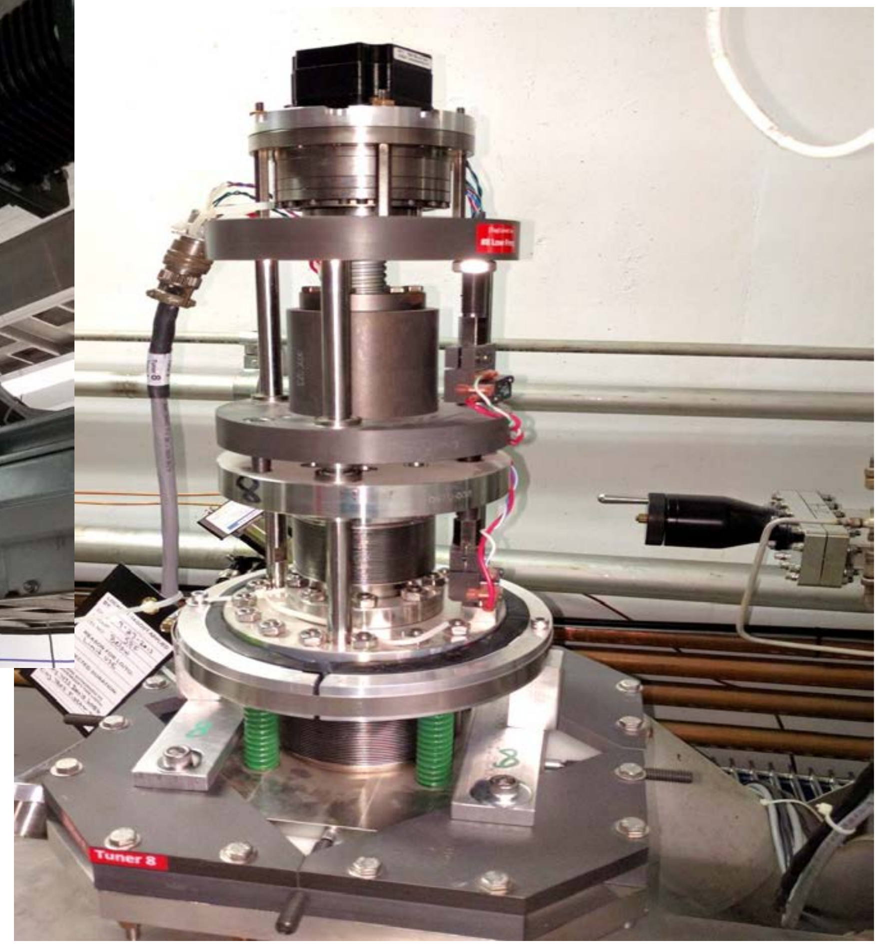
Passive Microphonics Control at JLAB



Tom Powers

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Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Why Do I Care About 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. Generally narrow band microphonics.
  - Think pushing a swing always when it stops near the top.
  - The vibrational modes will “phase lock” with the diving term even if they are just near the resonance.
- Even if there are not fixed frequency sources to excite the modes, they can be excited by broad band noise. Generally the width of the mode is broad if the Q of the mode is moderate.
  - Imagine pushing a swing at random times. From time to time you will push at just correct time to make it go higher. Other times you will make it slow down.
- Once the structure is displaced from its rest position it will ring down in one of its natural modes.
  - Think displacing the swing, letting go and watching what happens.
- If you damp the mode the it will ring down faster and oscillate less.
  - Think lightly placing your finger on a guitar string.

What To Look at With Microphonics

- **Identify the system resonances**
  - **Modal resonances, also called modes of the structure, in the mechanical structure can be excited by narrow or broad band sources.**
  - **Two of the standard approaches for measuring the modes of a structure is impulse hammer testing or swept sine excitation of the structure with a modal shaker.**

- **Identify the coupling mechanisms between the vibrational source and the structure.**
  - **For cryomodules think: What touches the structure such as piping, waveguides, and stands?**
  - **Reduce the coupling.**

- **Look for knobs you can control.**
  - **Can you damp the natural modes of the structure?**
  - **Do any of the modes couple out to something you can touch?**
  - **Can you reduce the source term before it effects the structure?**
  - **Can you redesign the cold mass to reduce the resonance of the mode?**
  - **Can you shift the frequency of the mode away from the excitation?**

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.

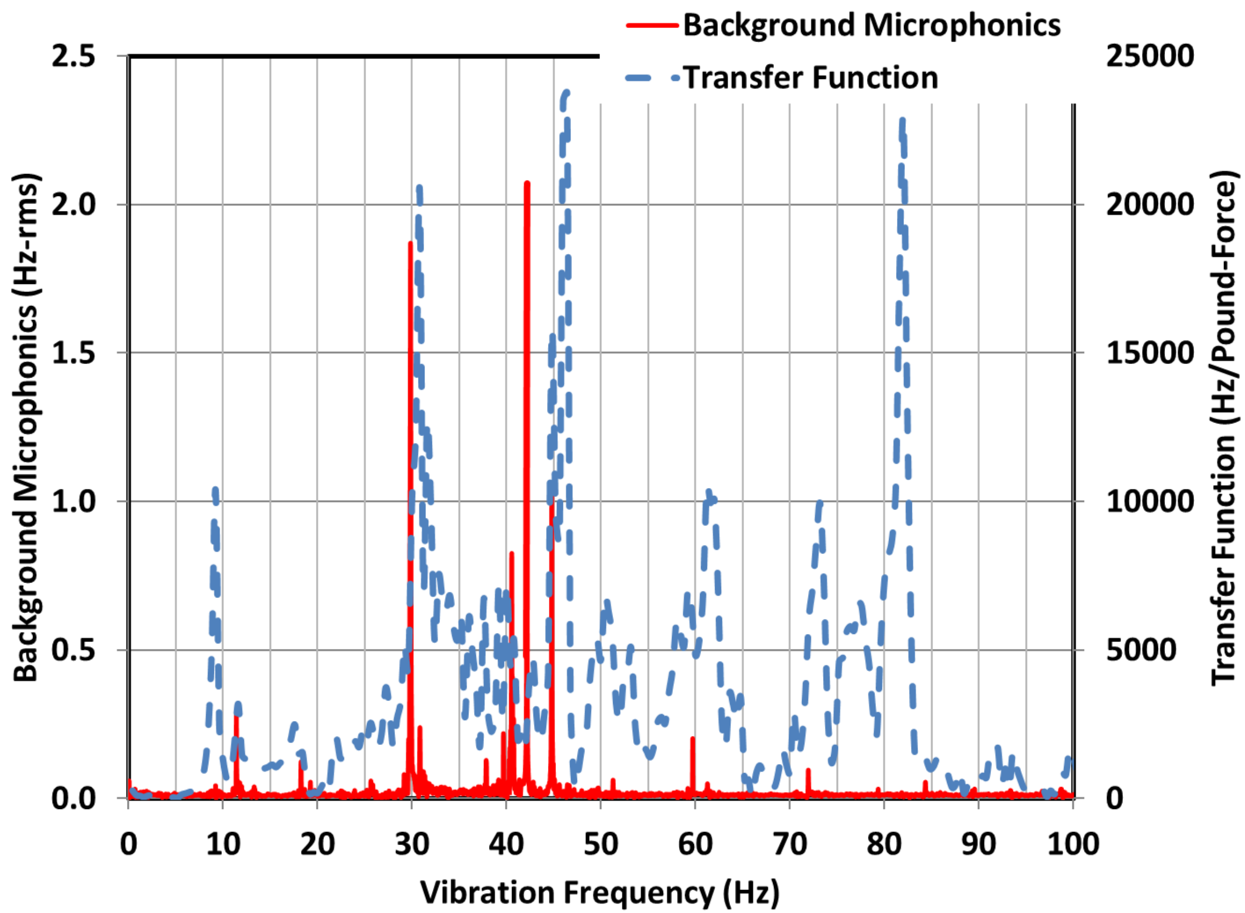
What is Impulse Response Testing?

- 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.

Example Excited Modal Resonances

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.

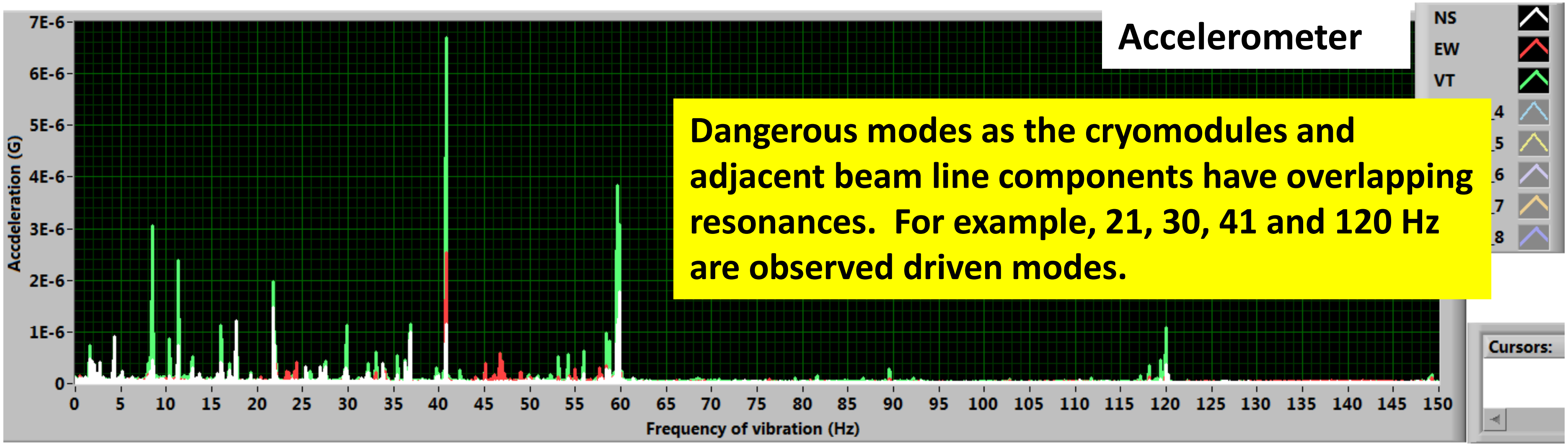


- Overlay of background microphonics (RED) and transfer function (BLUE) for Cavity 1 of the LCLS II string. Data taken with cryogenics in a quiet state.
- End effects and adjacent cryogenic piping vibrations transmitted from machinery are suspects.
- 29.8 and 41 Hz were driven by machinery vibrations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

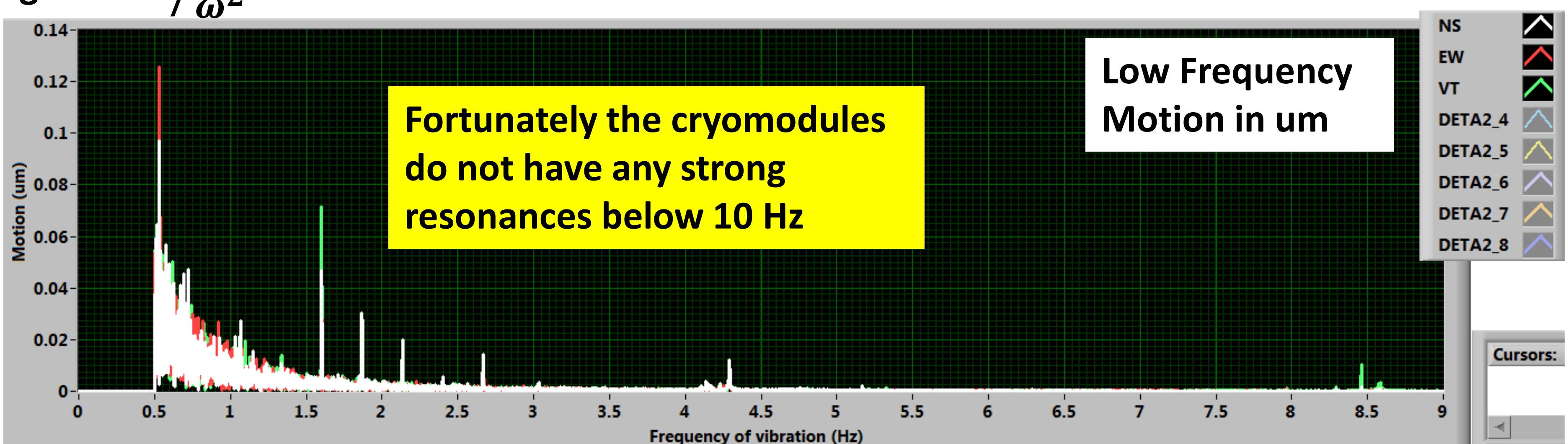
*Cavity 1, LCLS II Prototype Cryomodule In JLAB Cryomodule Test Facility, Low Power Test Data

Jefferson Lab

CEBAF South Linac Background Floor Motion in Tunnel
Background Vibrations WILL find your modes



Conversion from acceleration to motion is a double integral. Which means that it goes as $^{1}/_{\omega^2}$



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.

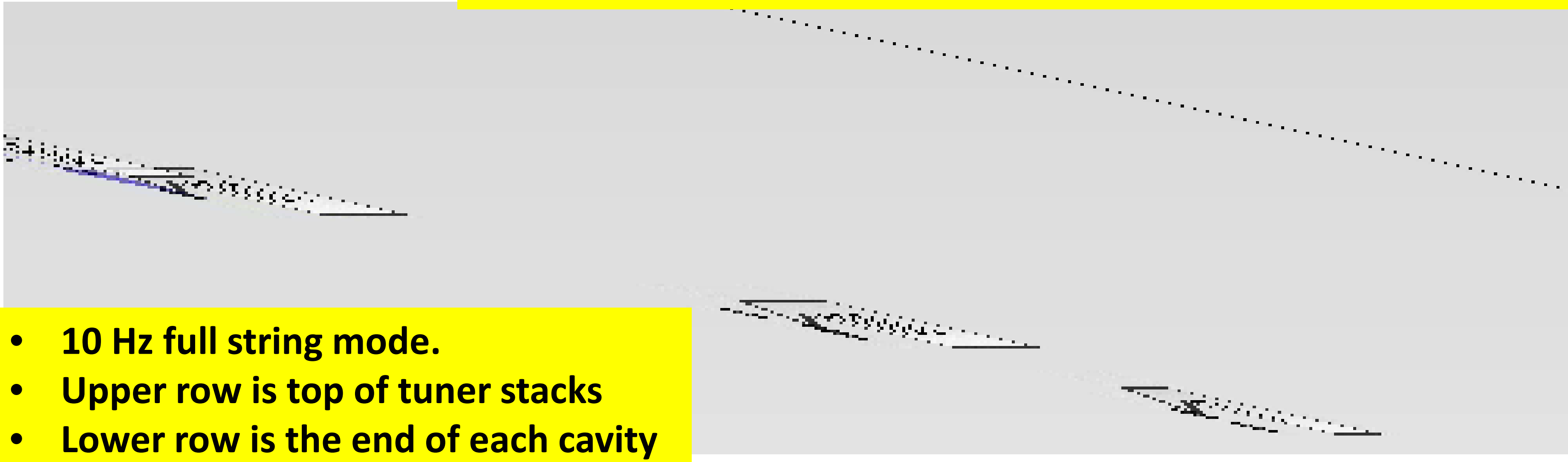
- Both approaches provide information about the modal motion of the structure.

- We use software called ME-CAD to preform the analysis.

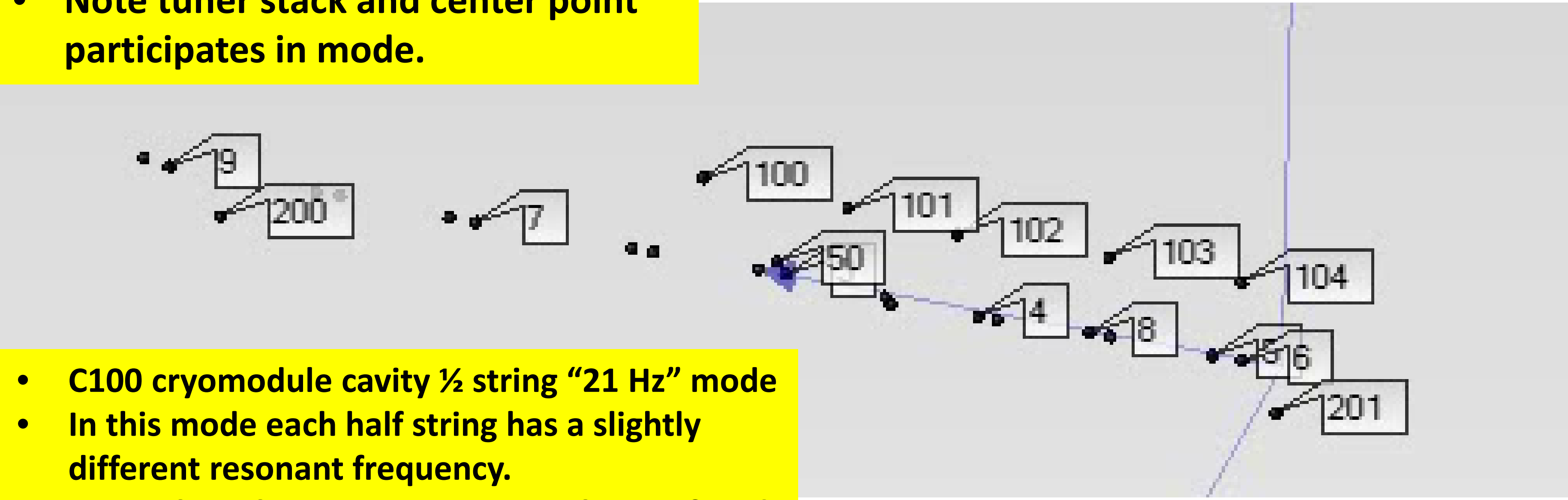
- In general the software uses the phase and amplitude information at a given frequency band and translates it into a relative displacement as a function of time.

C100 CM Example of Multi Sensor Single Strike Measurements

- Note there is a 10% increase in F at low temperatures



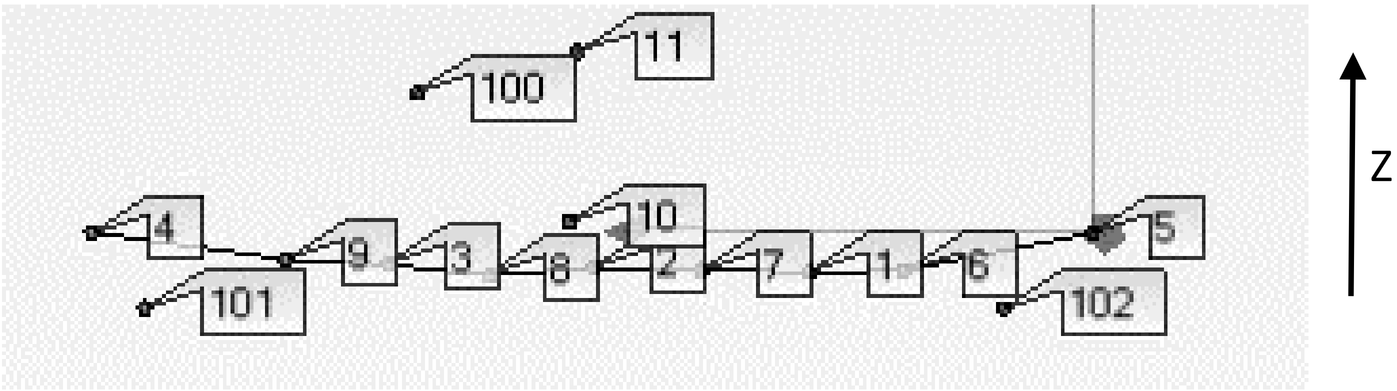
- 10 Hz full string mode.
- Upper row is top of tuner stacks
- Lower row is the end of each cavity
- Note tuner stack and center point participates in mode.



- C100 cryomodule cavity ½ string "21 Hz" mode
- In this mode each half string has a slightly different resonant frequency.
- Note that the center point is almost fixed

Examples of Resonances Giving us Trouble in CEBAF

- 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. It was only discovered when they shut the pump off at 8 PM on a Saturday.
- In the south linac we have several cryomodules that tended to vibrate at 21 Hz. We applied waveguide struts and dampers and it continued to vibrate. In the end we had to put a jack under the center of the cryomodule and apply a few hundred pounds of upward force. It seemed that the vibrations were exciting an insulating vacuum vessel beam constrained near the ends mode.



C100 Vacuum vessel 23 Hz mode

Initial Improvement to C100 Design (2010/11)*

- Design allows for 25 Hz Peak Detuning

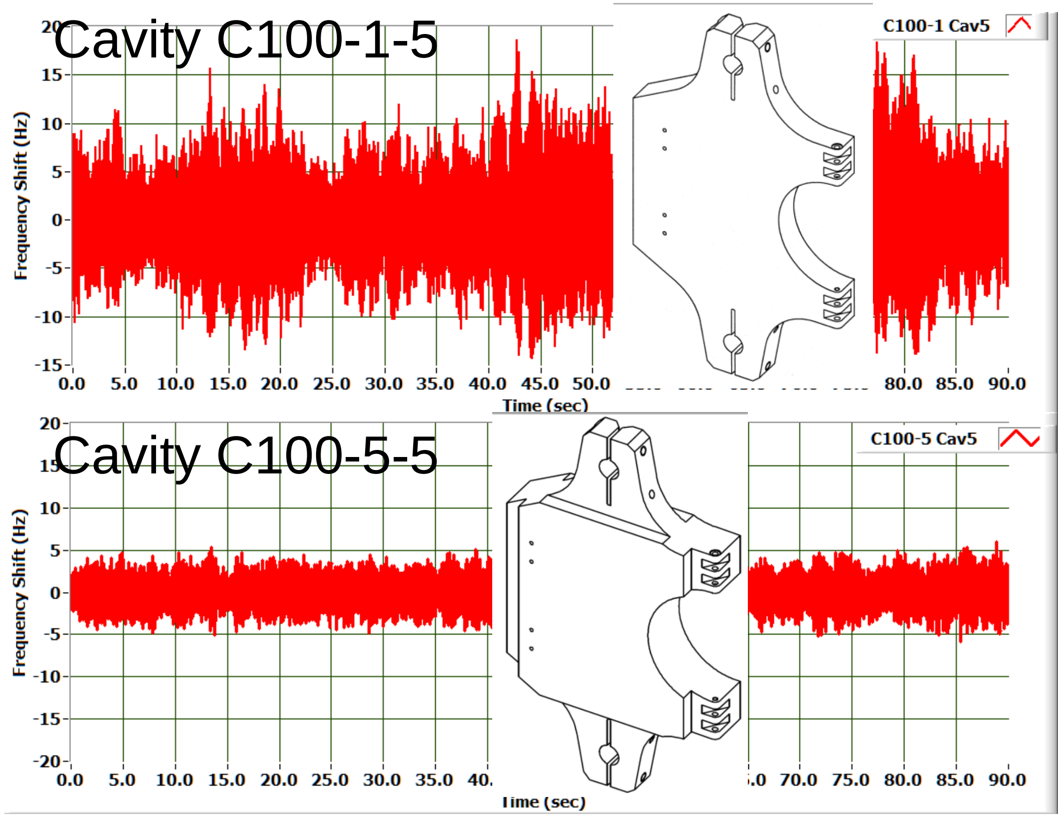
- Actual peak detuning (21 Hz) was higher than expected in first cryomodules

- A detailed vibration study was initiating which led to the following design change.

- A minor change to the tuner pivot plate substantially improved the microphonics for the CEBAF C100 Cryomodules.

- While both designs meet the overall system requirements the improved design has a larger RF power margin

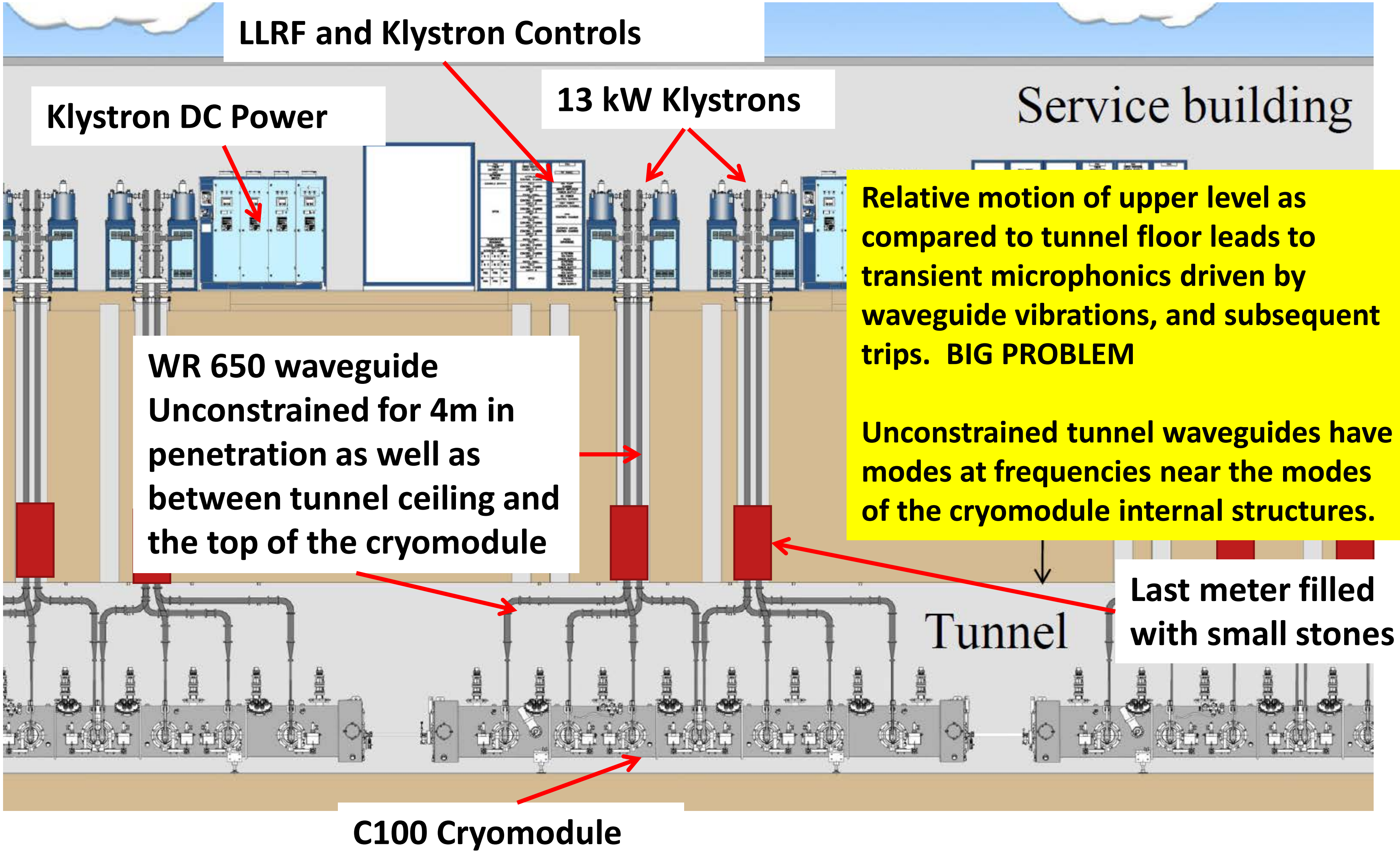
Microphonic Detuning*	C100-1	C100-4
RMS (Hz)	2.985	1.524
6σ(Hz)	17.91	9.14



*Kirk Davis, Joe Matalevich

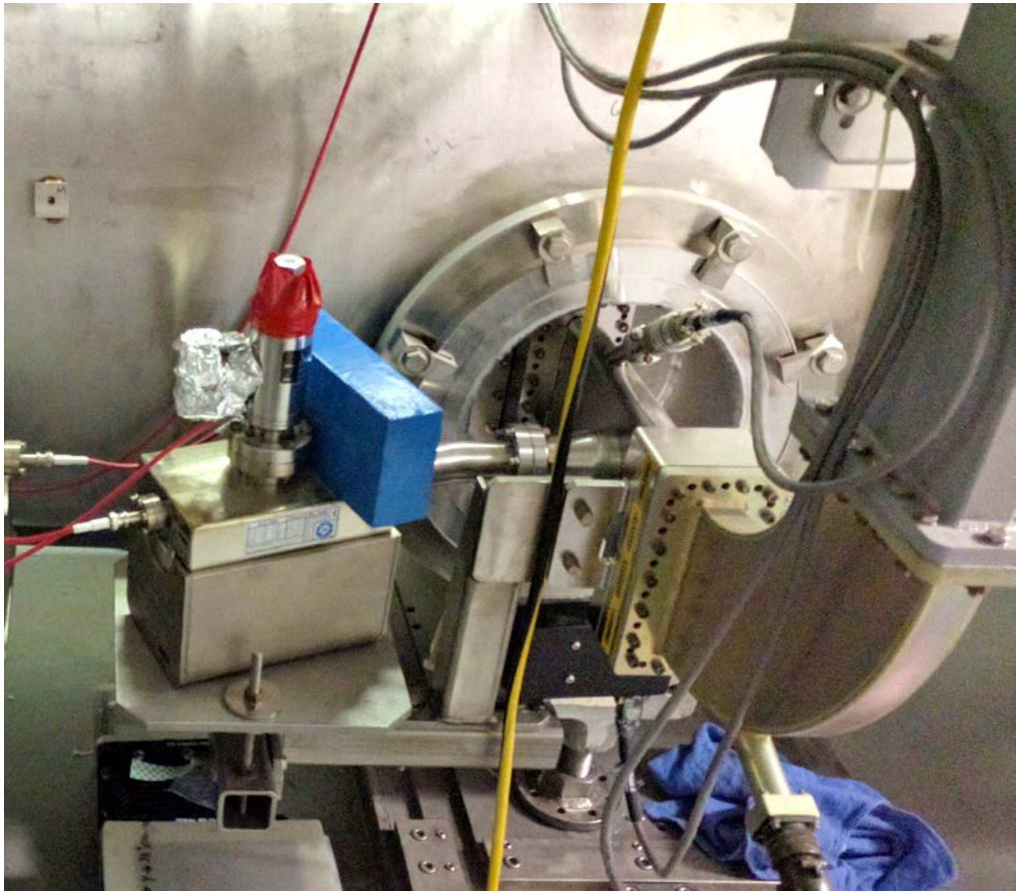
Jefferson Lab

Vertical Slice of CEBAF 12 GeV Zone Without Hardening

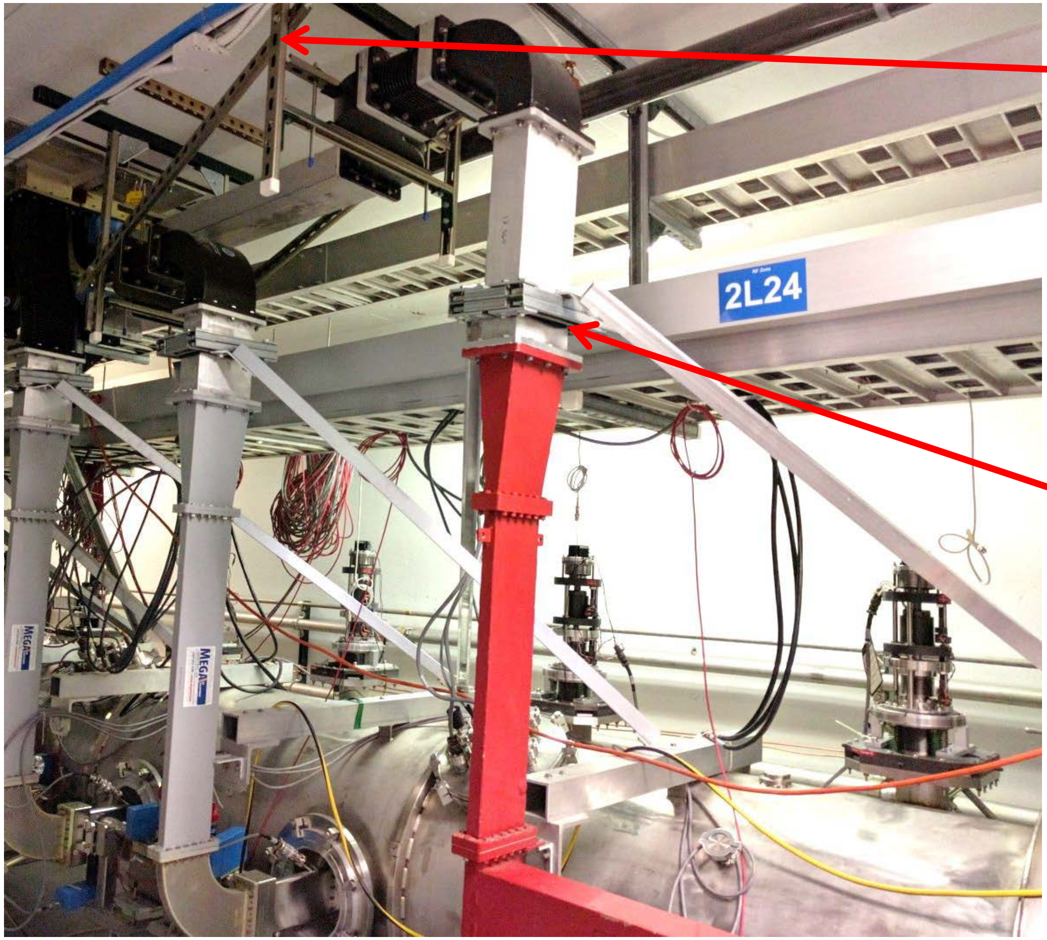


Simple Fix, Move the Frequency of the Mode

- After installing tuner dampers, waveguide struts and waveguide dampers we found that there was a 41 Hz vibration on all of the cavities in SL24.
- 41 +/- 1 Hz is a known excitation the source being a very large compressor in the central helium liquefier.
- The first approach was to move an accelerometer around the structure looking for excessive 41 Hz. We found it on some of the waveguide window vacuum ion pumps.
- We did impulse transfer function measurements of the ion pump assembly and found a ~40 Hz resonance.
- After insuring that they were properly installed, torqued, etc. we added a lead brick to each pump in order to move the resonance.

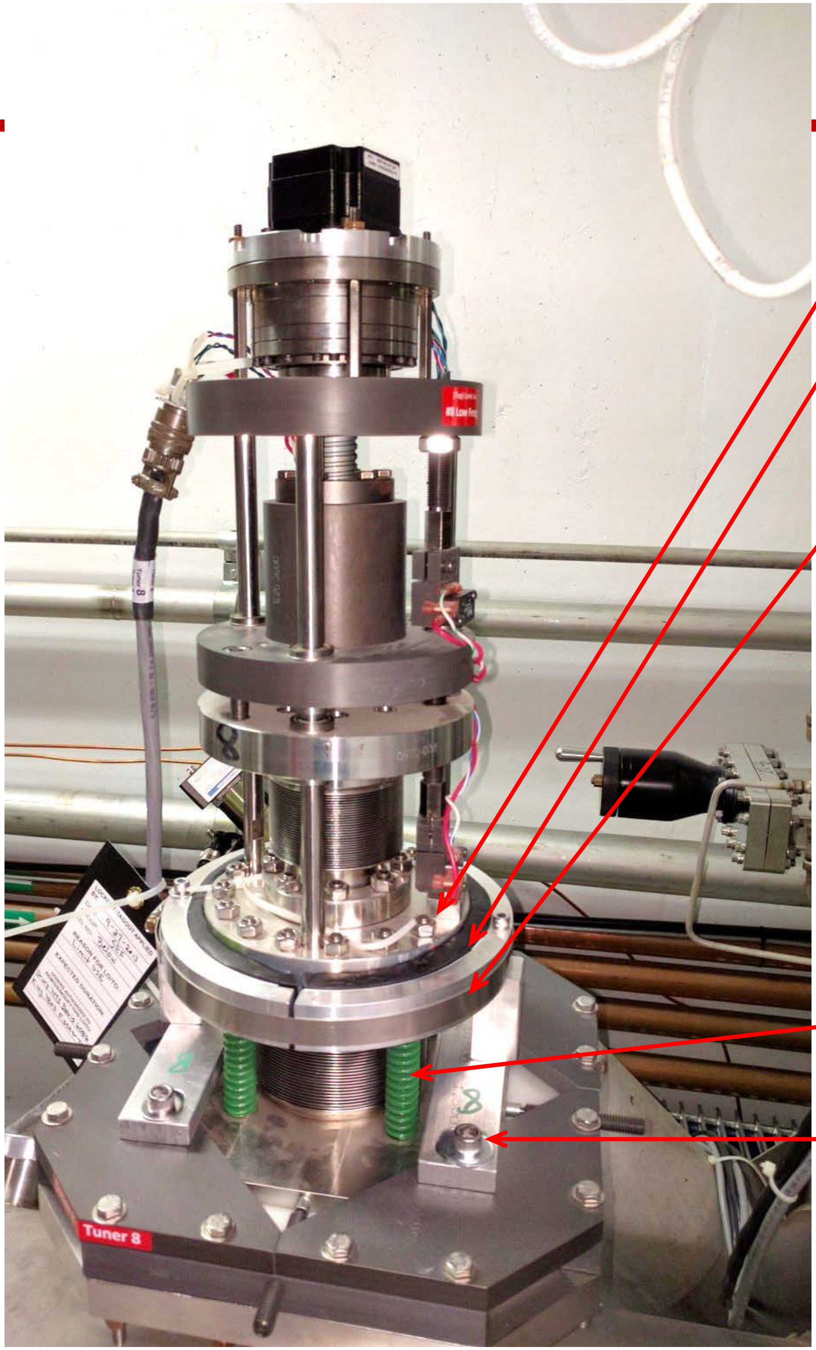


CEBAF C100 Hardening Waveguide Ceiling and Strut Bracing/Damping



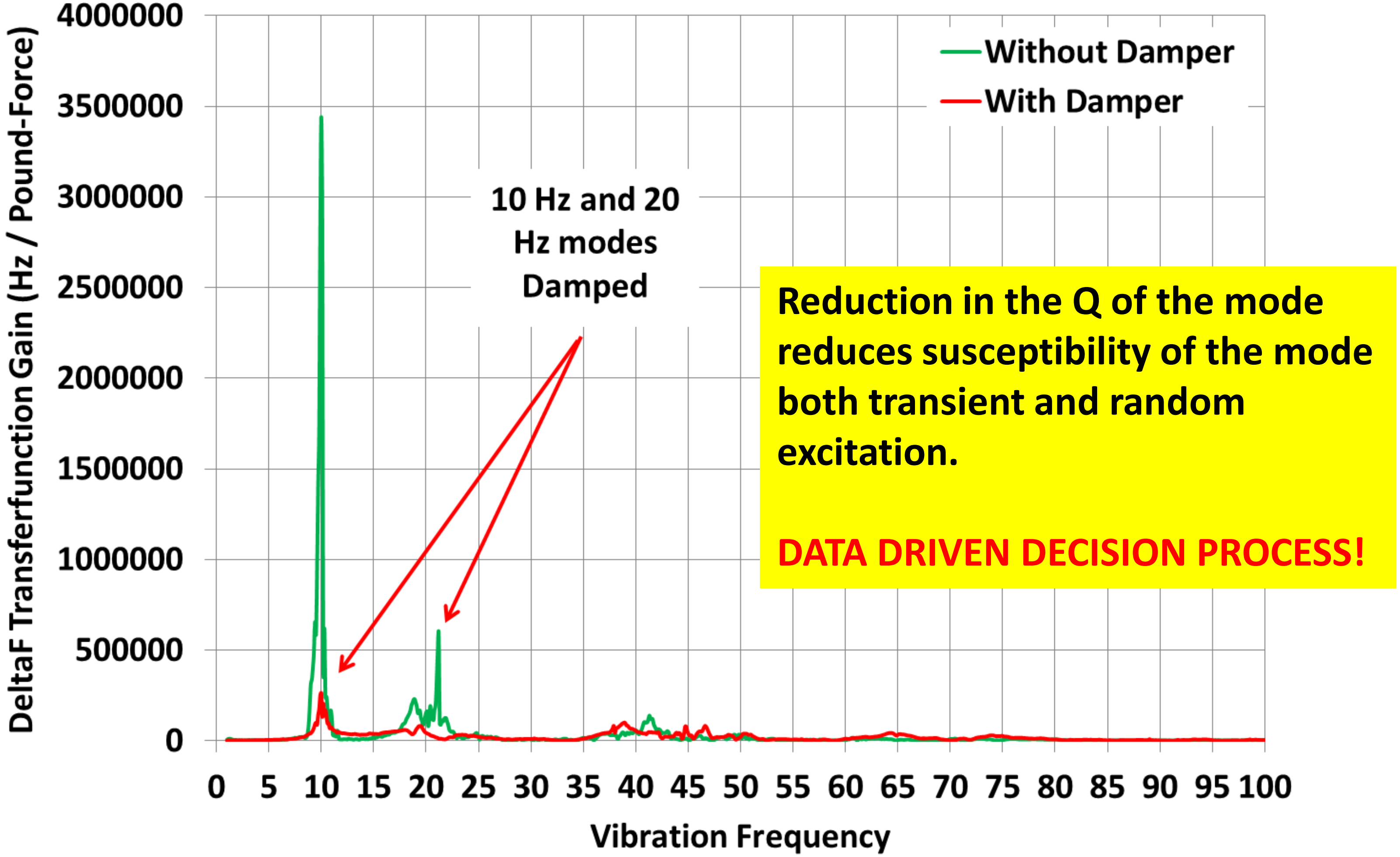
- Ceiling bracing improved
  - provides 3-axis constraint.
  - Has 1/8” 50 durometer Sorbothane® to damp vertical motion and to a lesser extent EW/NS motion.
- Waveguide struts back to existing bolts on the cryomodule
  - Provides 3-axis constraint of upper end of waveguides.
  - Waveguide bracket uses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

CEBAF C100 Tuner Damper Ring



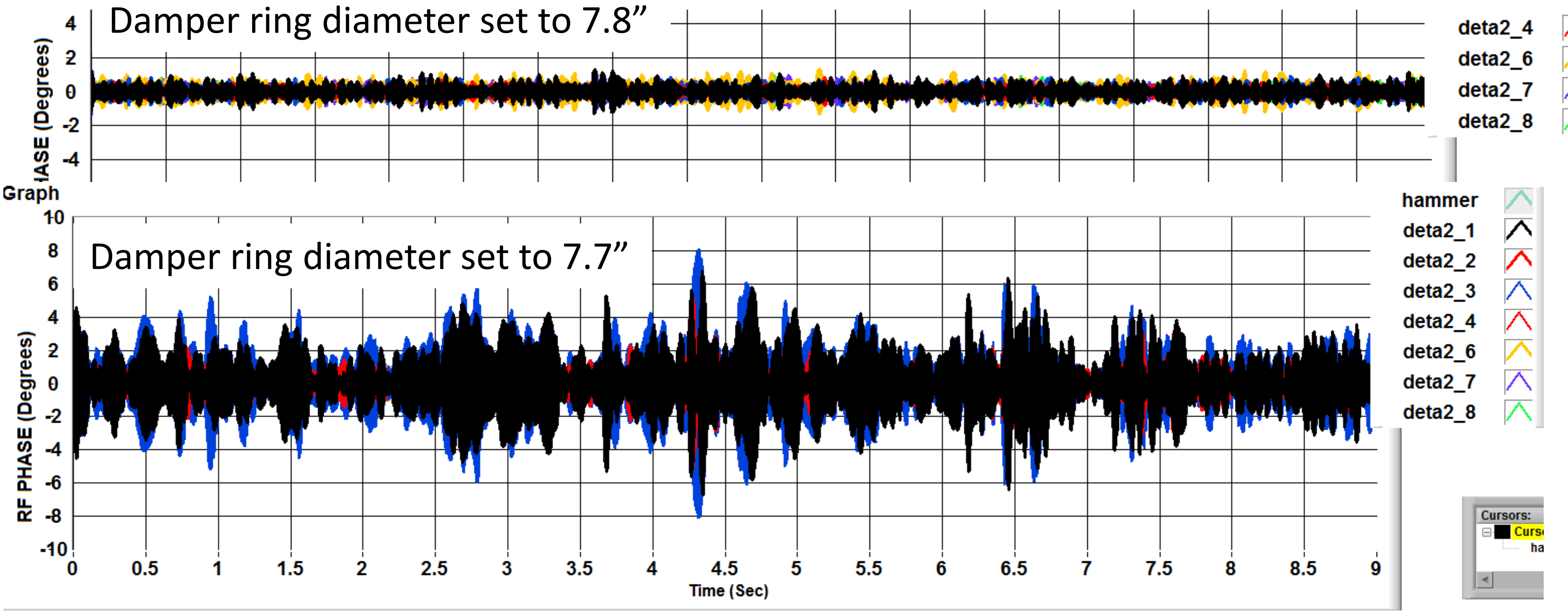
- Lower tuner flange 6” OD, 1.5” thick.
- 30 durometer, 1/2” x 1” sorbothane with polyethylene tape on the inner surface in order to allow vertical motion.
- Split ring with a nominal ID of 7” and with two 3/8” gaps for adjustment.
  - Compression adjustment made by tightening the hose clamp while measuring 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



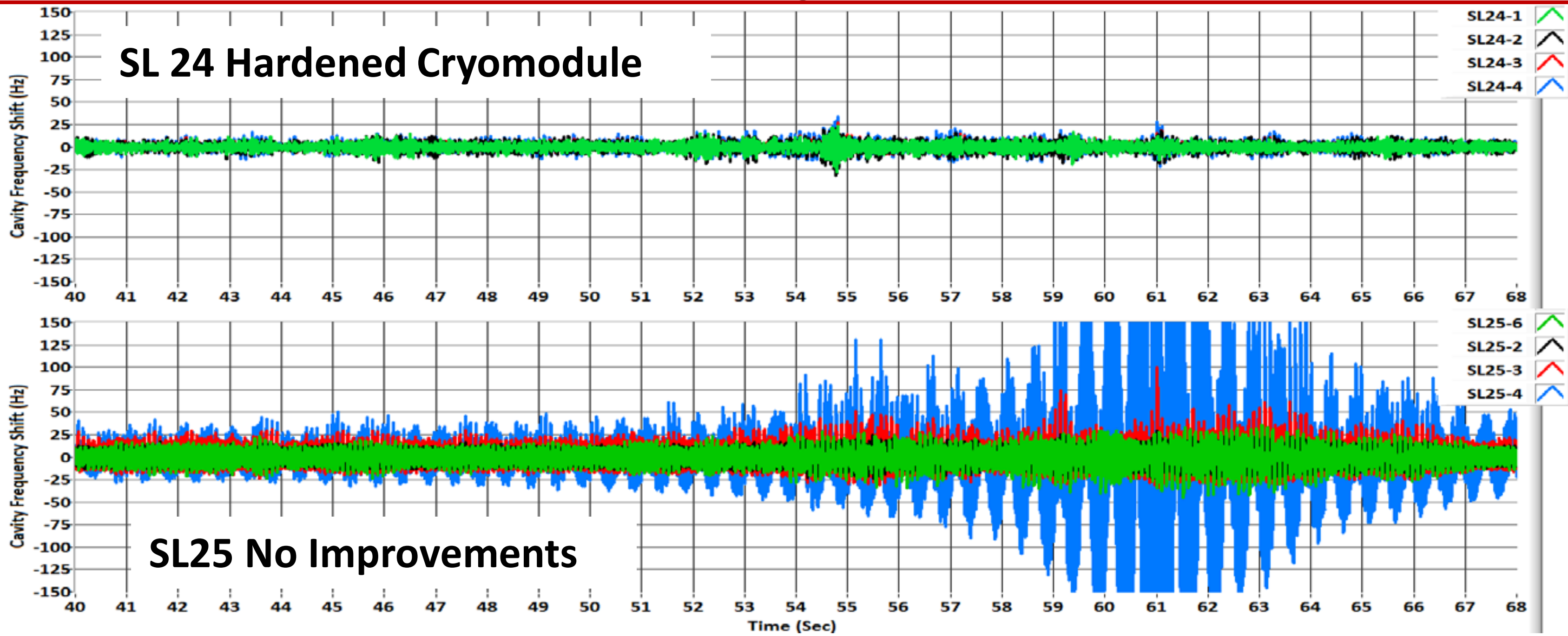
- **Tuner damper compression "tuned" to reduce the Q of the 10 Hz mode.**
- **Reducing the 20 Hz mode was an unexpected bonus.**

Damping Materials Have Their Own Resonances



- A damper system has frequency dependence that is a function of the amount of compression. The dependence has resonances. This is nothing new.
- When we set the damper reduced the damper ring diameter from 7.8” to 7.7” we say a dramatic increase in the frequency content at 180 Hz.
- Further data analysis of all of the C100 cryomodules, with no tuner rings, indicated that low levels of 180 Hz content would turn on and off “randomly” when the tuners were operated and would stay on/off when the motor stops. The hypothesis is that it is an oscillation in the motor driver.

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.

Tuner Correlated Microphonics

- **Microphonics is a linear problem.**
- **We improved the background noise by a factor of 2 and then saw a stepper motor correlated issue.**
- **The noise is worse after two motors are operated at the same time.**
- **The initial noise is about 200 Hz but it often excites the 10 Hz mode.**

Summary and Acknowledgements

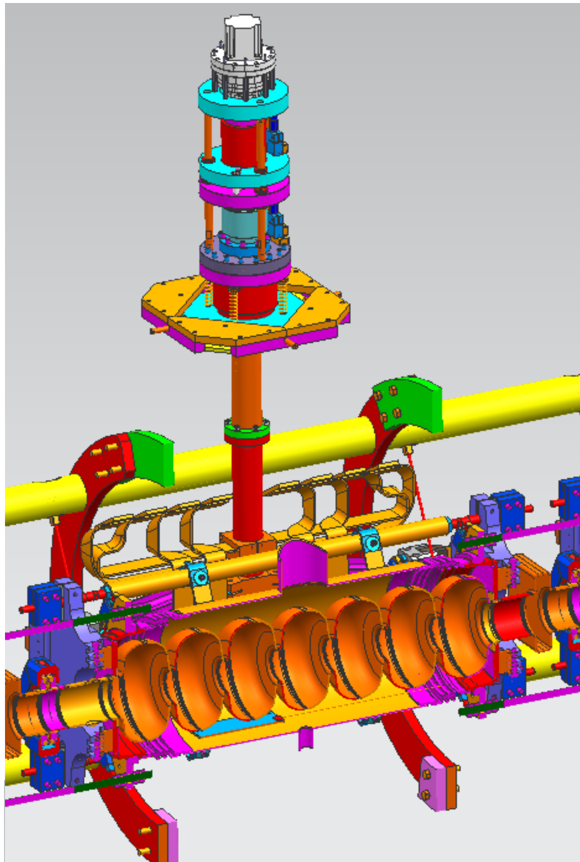
Mechanically damping of the cryomodule structure can be an effective way to address microphonics. The key issue is to determine a location where damping material can be applied to the structure.

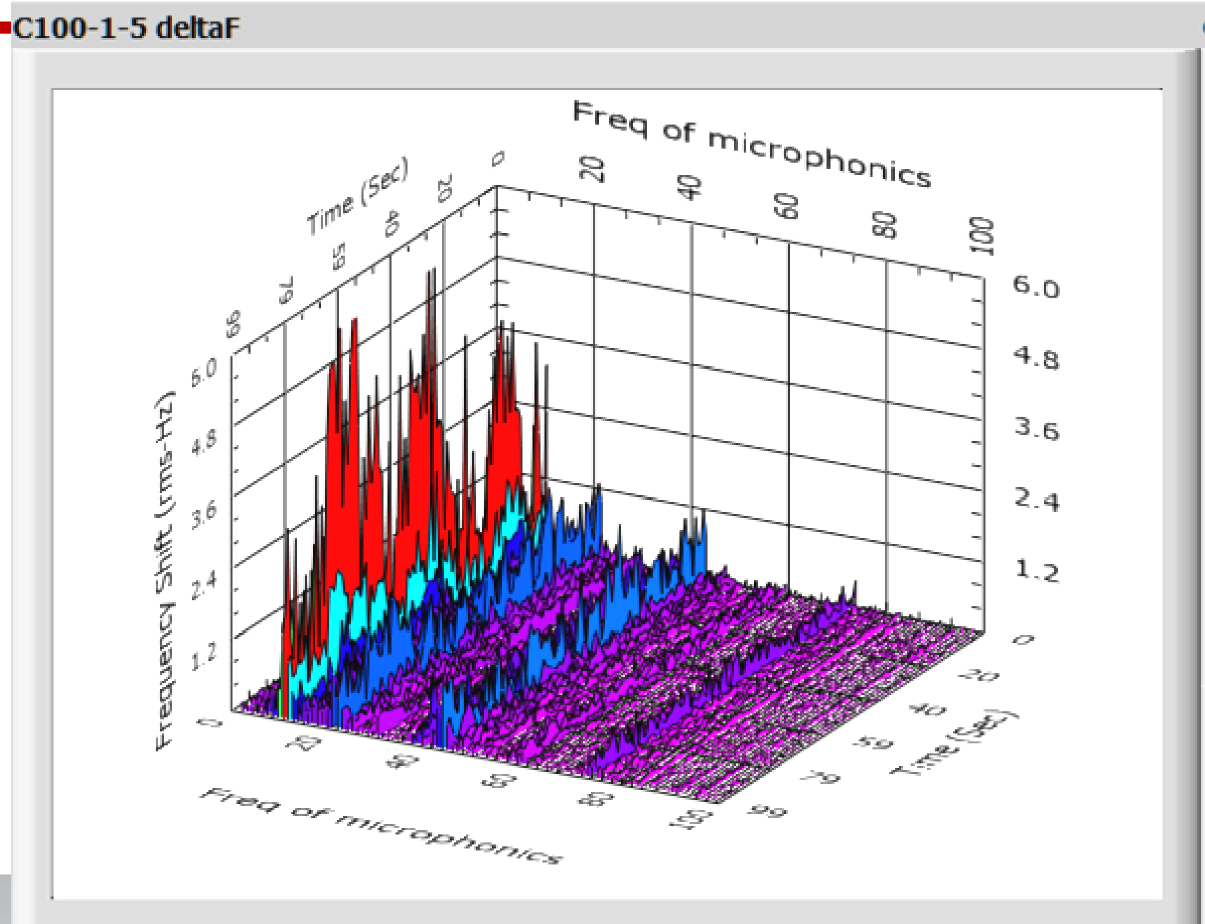
Independent of the approaches used it is recommended that one perform transfer function measurements to the cavity frequency shift and if possible to the vibrational modes of the structure, with the goal of making data driven decisions.

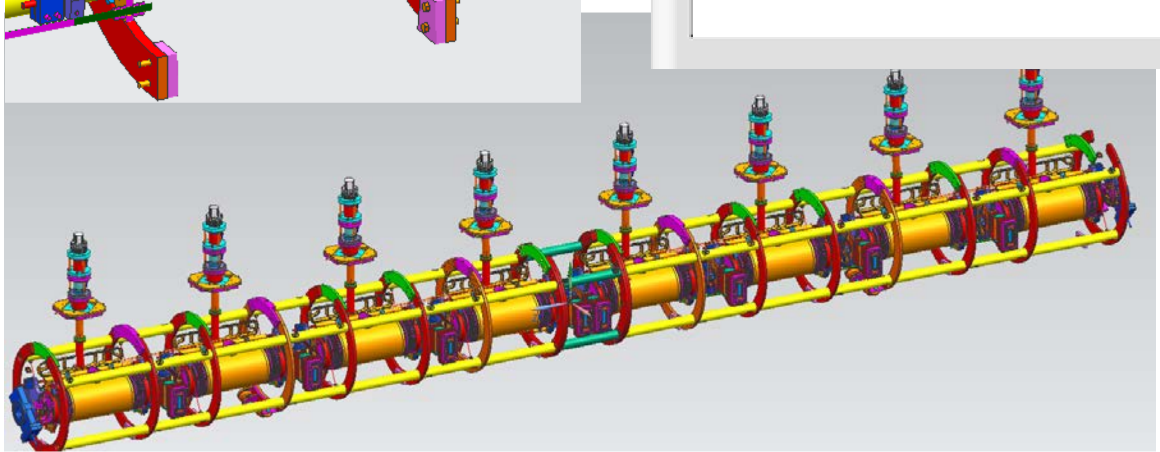
I would like to acknowledge the contributions made by Natalie Brock, Kirk Davis, Joe Matelivitch, Anna Solopova, and especially my partner in microphonic crime solving George Biallas. Their work is scattered throughout this presentation.

BACKUP SLIDES

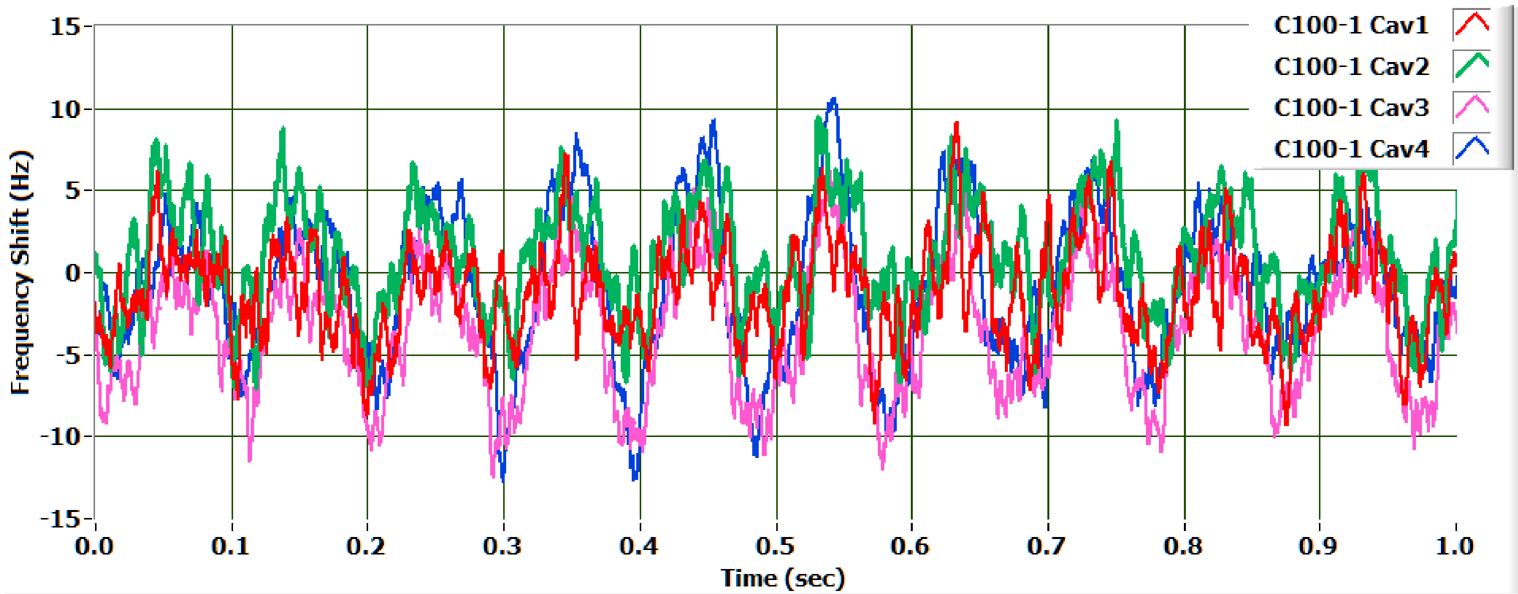
Microphonics Spectra as a function of Time C100 CM

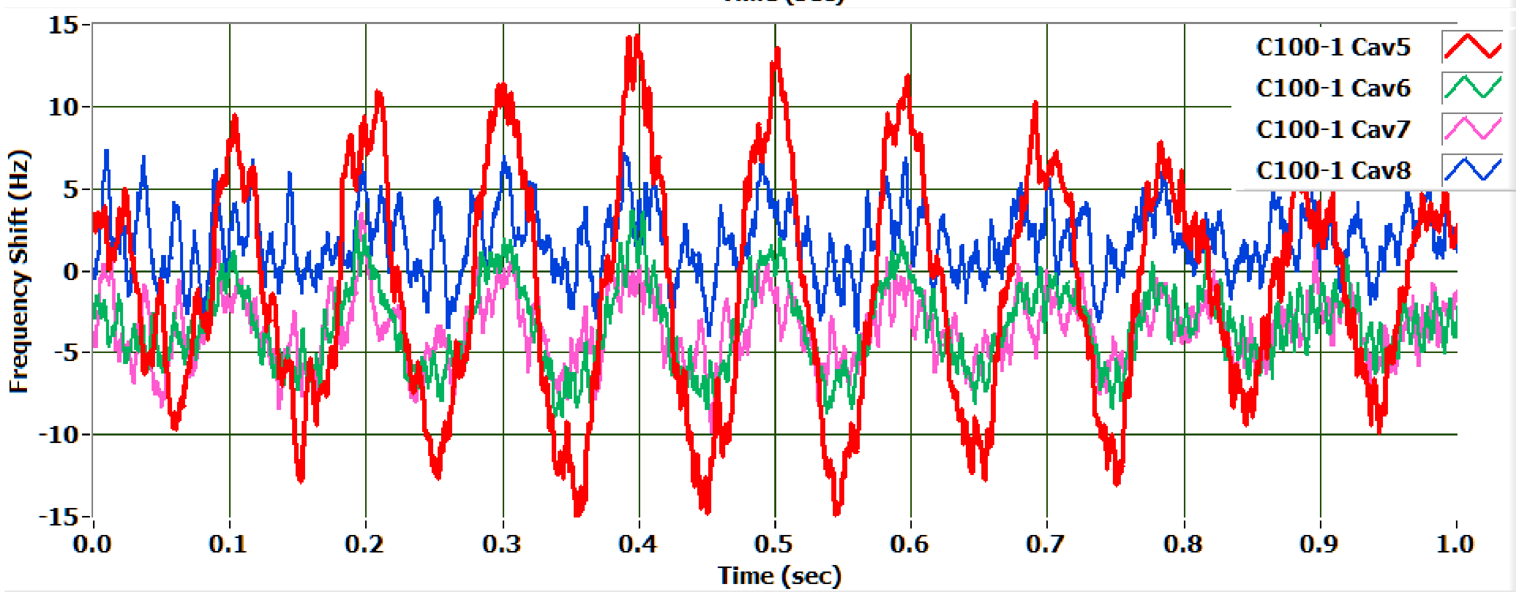






Time Domain Data for Cavities 1 to 4 and 5 to 8





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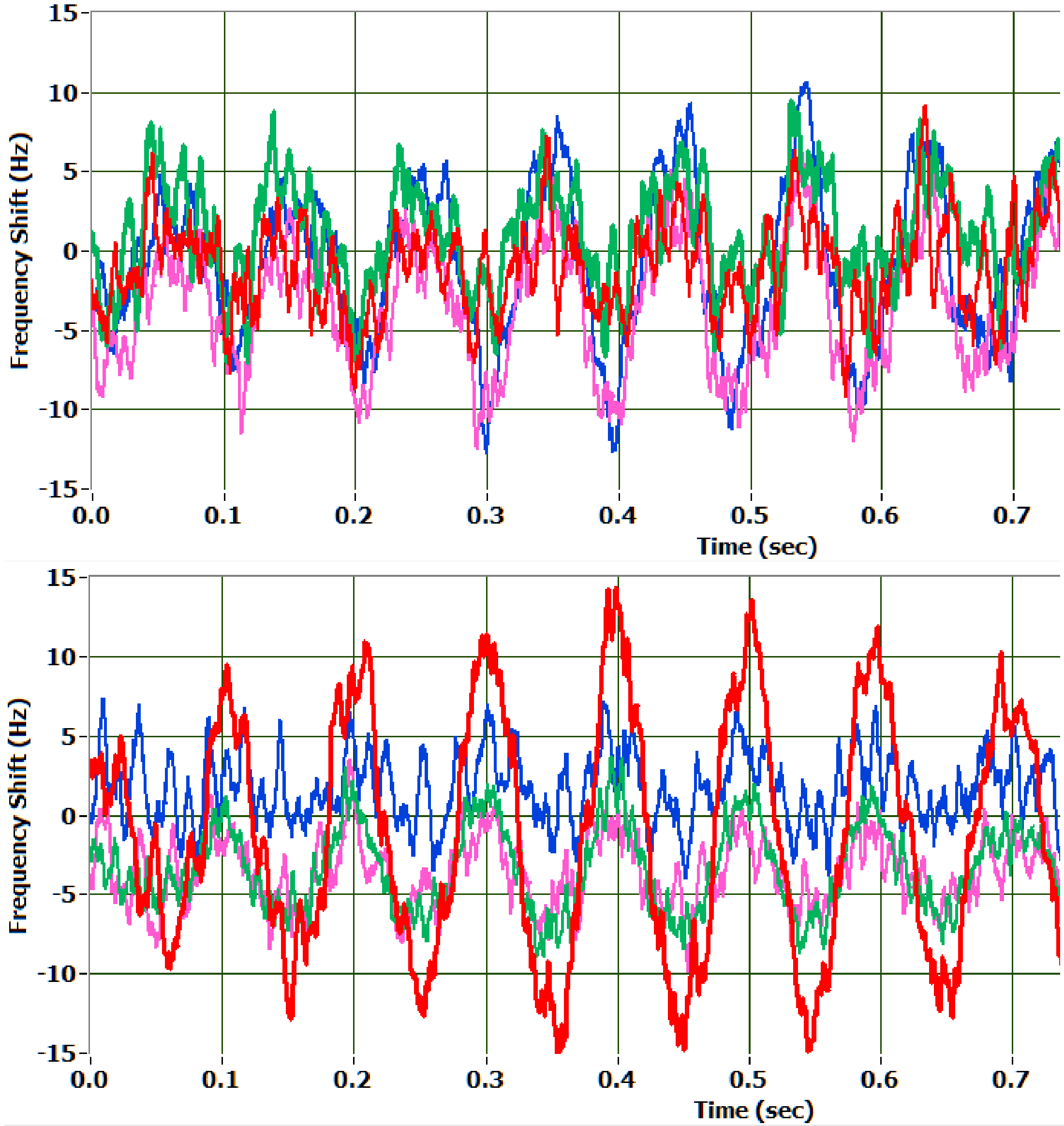
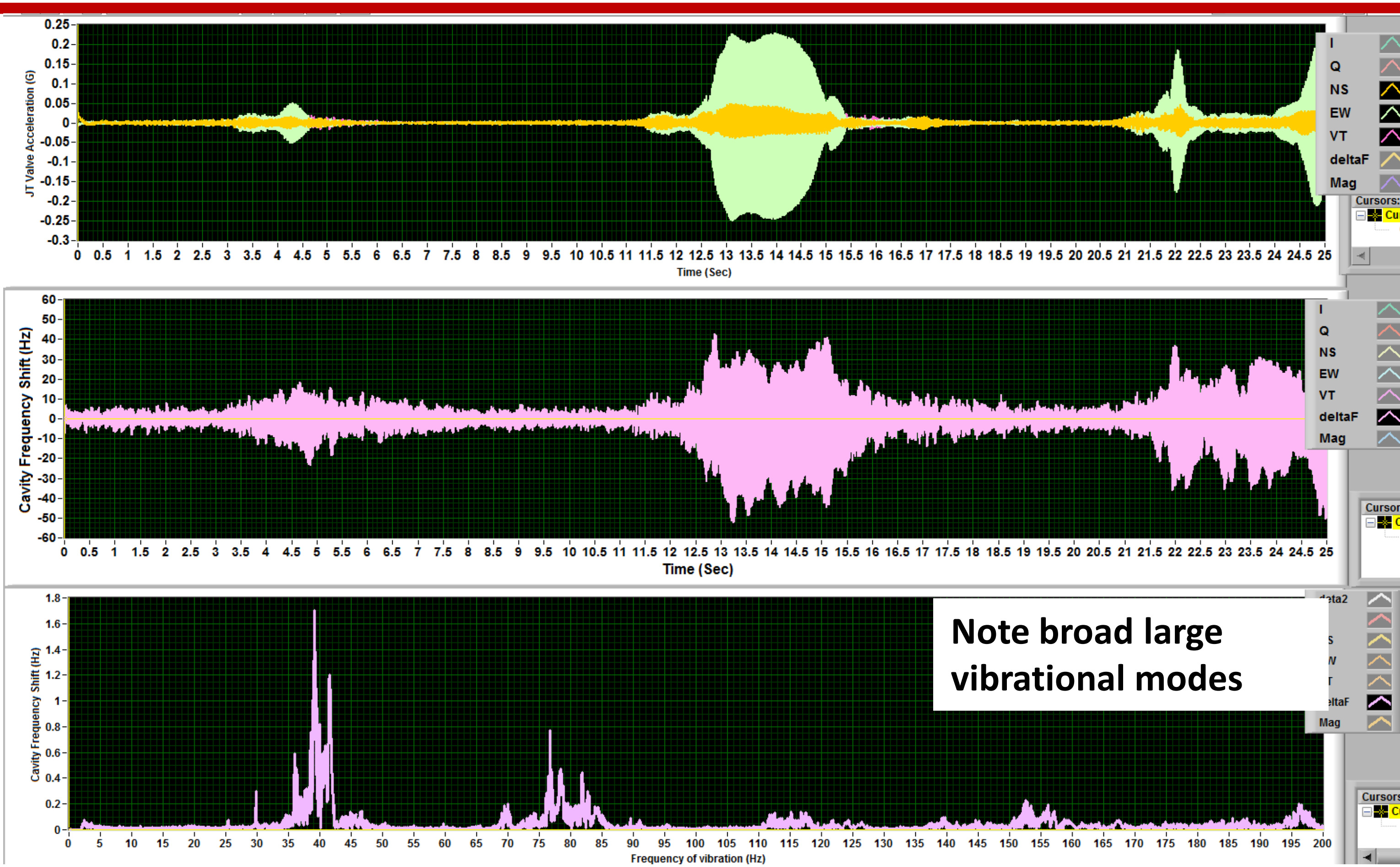


- Note that there is a 10Hz mode where half of the cavity string gets longer while the other half gets shorter.
- The halves swap energy back and forth in this mode.
- For some reason cavity 5 in each of the modules measured had the highest microphonics.
- This mode does appear in the finite Element Simulations.

LCLS II Microphonics and JT Valve Vibrations First Prototype Tests



Accelerometer on JT Valve +/- 0.2 G

Microphonics +/-60 Hz full scale.

Spectrum Peak harmonic 1.8 Hz-rms

Time scale 25 seconds, Frequency scale 200 Hz.

Thermo-Acoustic Oscillations caused excessive microphonics

JT valve design changes, etc. were implemented to address the issue

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.**
- **Microphonics can be induced by fixed frequency vibrations such as motors and equipment.**
- **When the source is white noise the resultant microphonics shows up as the natural vibrational frequencies or modes of the structure.**
- **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.**

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:

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

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