

## Frequency Measurements on the Prototype SNS Medium- $\beta$ Cryomodule under Pulsed and CW Operation

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### Introduction

In June and July 2002, a series of tests were performed on the prototype SNS medium- $\beta$  cryomodule. One purpose of those tests was to measure the amount of microphonics and the dynamic Lorentz detuning during pulsed operation, and to assess the effectiveness of the piezo tuners in compensating the dynamic Lorentz detuning. The results of those tests are presented here.

There are four main classes of contributions to variations of the frequency of a superconducting cavity.

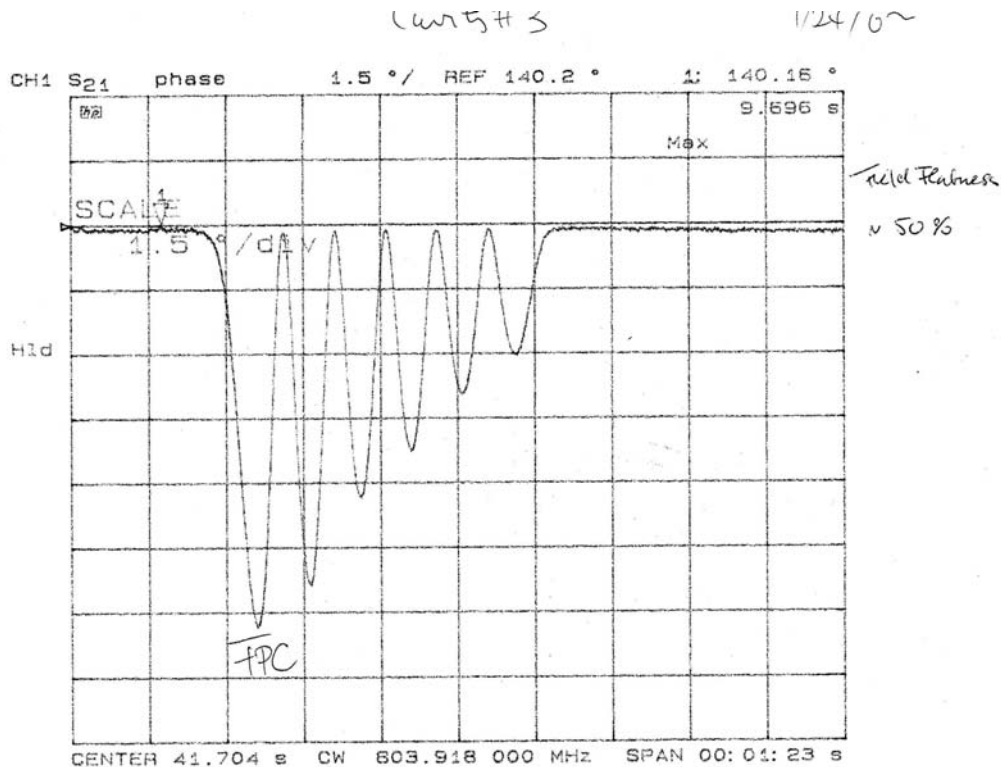
- Slow environmental effects. These include drifts induced by changes of temperature or pressure of the cryogens, and are usually compensated by tuners, mechanical or otherwise.
- Fast environmental effects. These can be either stochastic (ambient vibrations with a white or pink noise frequency spectrum) or composed of some well-defined frequencies. The former result in a gaussian probability density for the frequency deviation; the latter result in a double-peaked probability density and are more pronounced when a driving term is close to a mechanical resonance of the cavity. These effects, referred to as microphonics, are usually compensated by the low-level RF (LLRF) control system.
- Coupling between the electromagnetic and mechanical modes of the cavities through the radiation pressure. This is the origin of the Lorentz detuning which can also lead to ponderomotive instabilities. There is, at present, little experience with Lorentz detuning under pulsed operation and an important aspect of these tests was to measure its magnitude to determine whether the LLRF control system would be sufficient to compensate for it or whether a fast piezo tuner would be needed and, in that case, if it was effective.
- Tuners (mechanical, piezo, etc.). These are tools that are at our disposal to counteract the three sources listed above.

Specifications for the SNS medium- $\beta$  cryomodules were a microphonics-induced frequency deviation of <16 Hz rms and a Lorentz-induced total variation of <470 Hz during the 1.3 msec rf pulse at a design gradient of 10 MV/m.

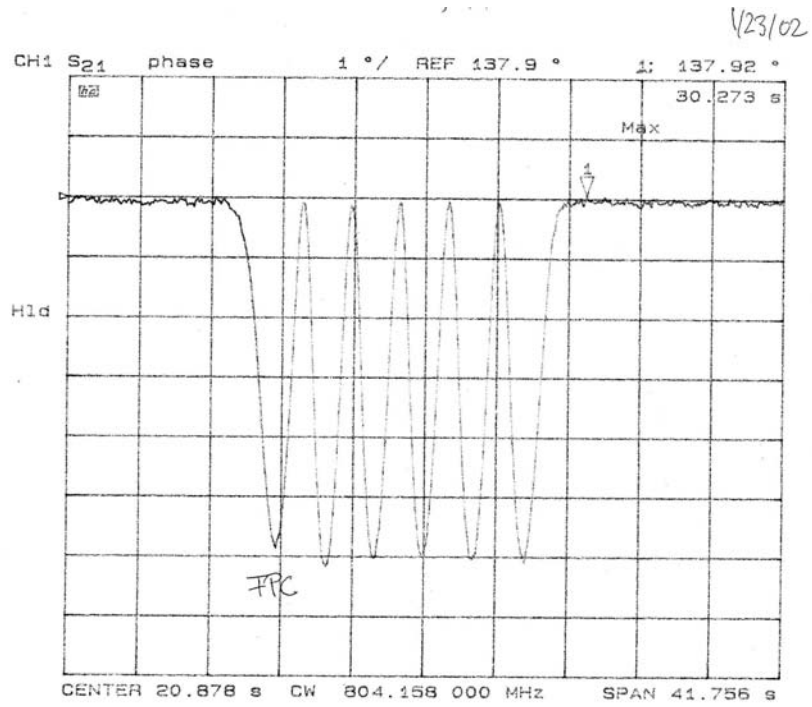
The cryomodule included three cavities that, because of differences in their fabrication procedures, had significantly different field profiles. Cavity 2 had a flat field profile while cavity 3, and especially cavity 1 had a tilted field profile. This makes some of the results difficult to

interpret. The differences in behavior of the cavities could be due to either the fact that their field profile was different or to the fact that the boundary conditions under which they operate are different. Cavity 2 is located in the middle, having another cavity on each side, while cavities 1 and 3 have another cavity on only one side.

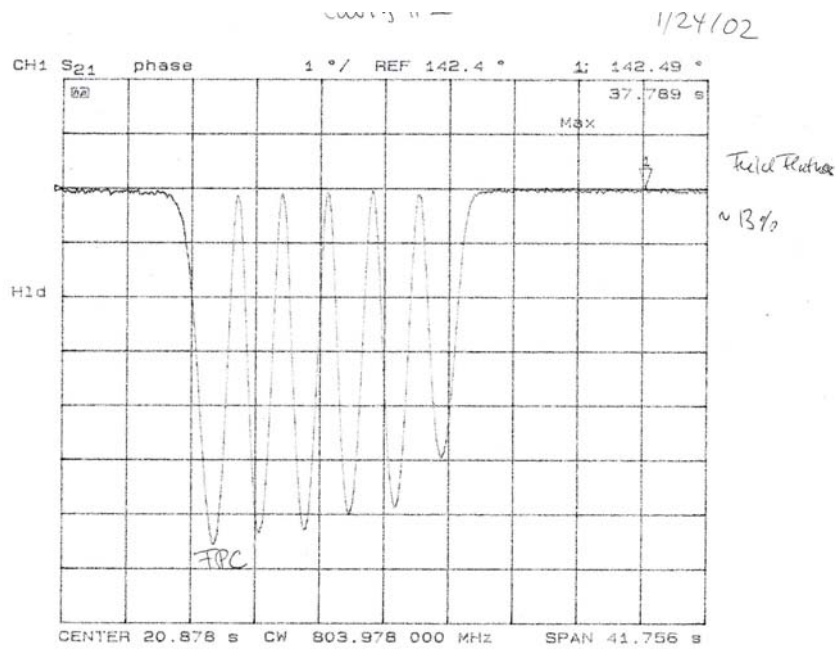
The behavior of the cavities under pulsed operation is, of course, most important for SNS; some measurements, however, could only be done under cw operation. Furthermore, the SNS cryomodules are under consideration for use in RIA, which is a low-current cw machine, with much stricter requirements for frequency stability. Some of the measurements were directed at assessing the suitability of the SNS cryomodules for use in RIA. Because of the large difference in the mechanical properties of the three cavities further measurements on production cryomodules will be needed to arrive at a firm conclusion.



Field Profile Cavity 1



Field Profile Cavity 2



Field Profile Cavity 3

## Microphonics

Microphonics measurements were performed using a Cavity Resonance Monitor (CRM) optimized for 805 MHz [1] and a stable phase reference. The CRM produces an output voltage proportional to the instantaneous frequency difference between the cavity and the reference with a choice of two sensitivities: 10 Hz/V and 100 Hz/V. The output voltage is available from two independent low-pass filters with corner frequencies of 1 kHz and 1 Hz. The latter allows removal of the microphonics to measure slow drifts, and the difference between the two allows removal of the slow drifts to extract microphonics.

The frequency was measured every 2 msec for up to 800 seconds in order to accumulate significant statistics.

Results of microphonics measurements follow.

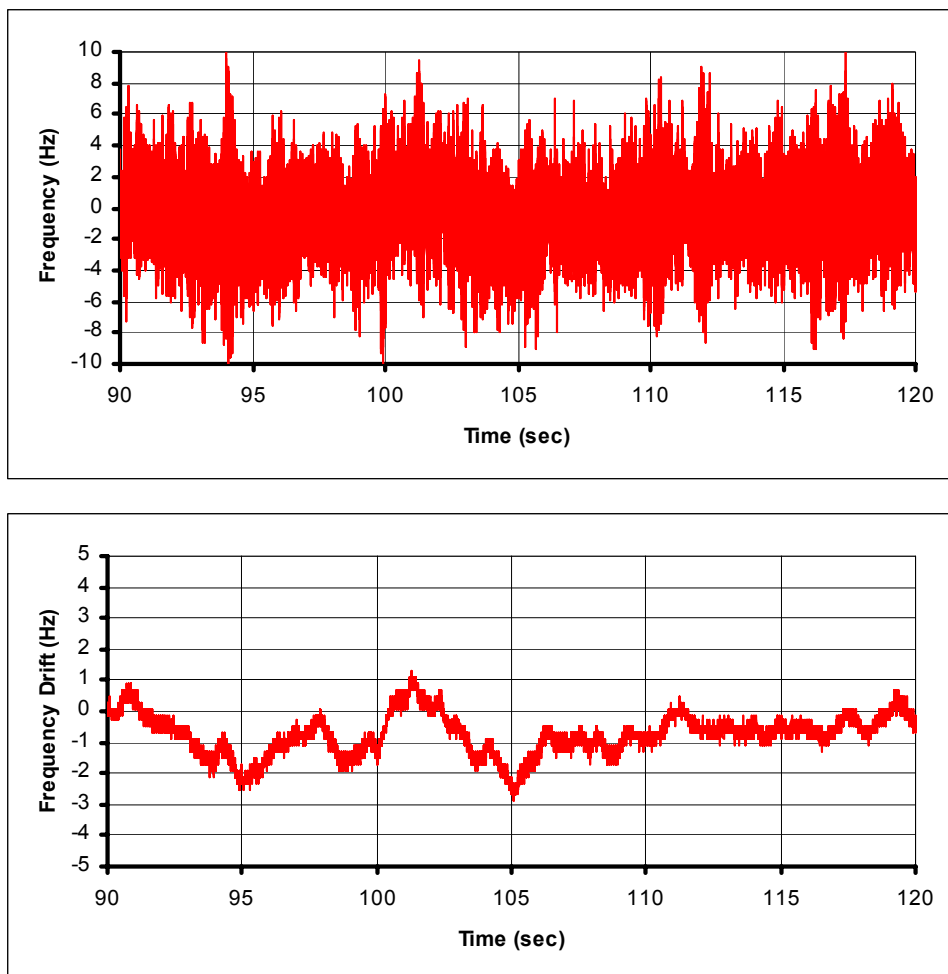


Figure 1: 30 seconds snapshot of the instantaneous frequency of cavity #2 operating CW at 1 MV/m (upper), and average frequency (1 Hz low-pass filtered) during the same time period (lower).

Figure 2: Typical probability density for microphonics-induced frequency deviation.

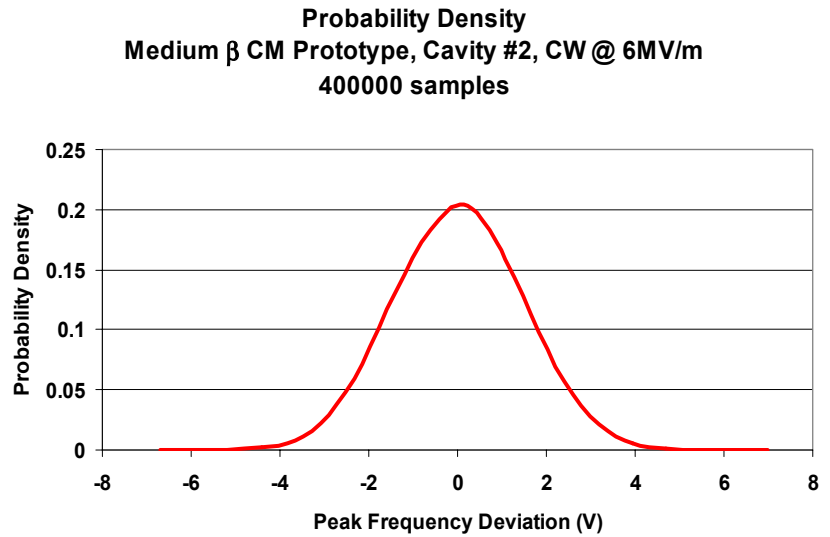
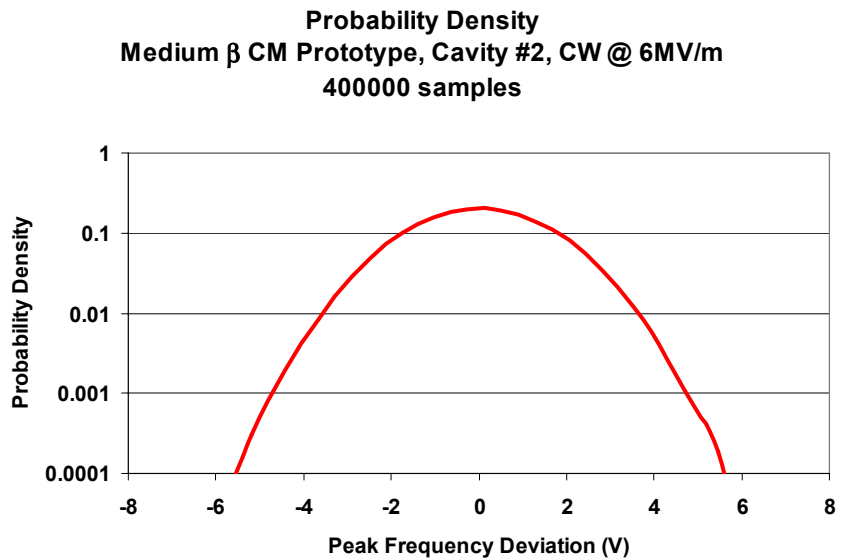


Figure 3: Same as figure 2 but as a log-linear-plot. A gaussian-like distribution is clearly visible.



The measurements were done with the piezo driver amplifier both energized and deenergized. No significant effect on the magnitude of the microphonics was observed.

Similar measurements were made on cavities 1 and 3, although with a much smaller sample (50000 measurements over 120 seconds). Some deviation from a gaussian distribution is observed; this could be due to the fact that the sample is smaller or that a mechanical mode was preferentially driven by an external frequency source.

A significant difference in the magnitude of the microphonics is observed between the cavities.

**Probability Density - Cavity #1 at 1 MV/m, 50000 measurements**

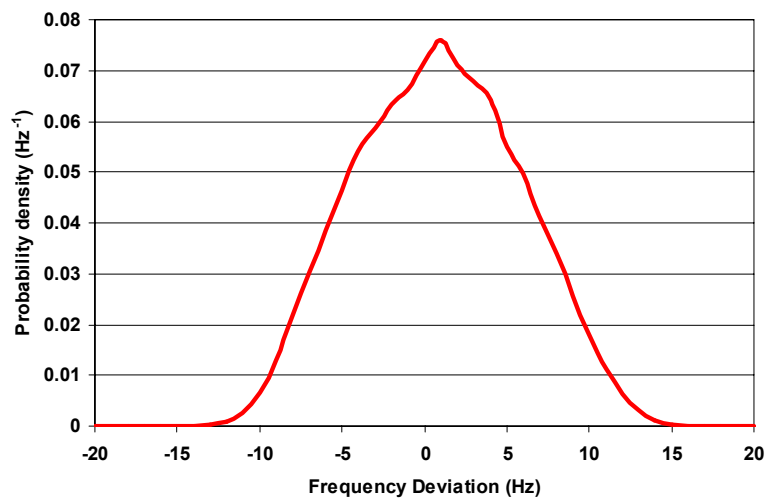


Figure 4: Probability density for cavity 1

**Probability Density - Cavity #3**

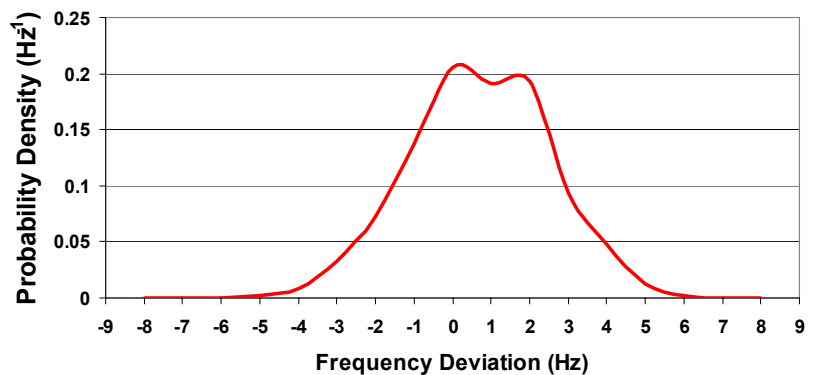
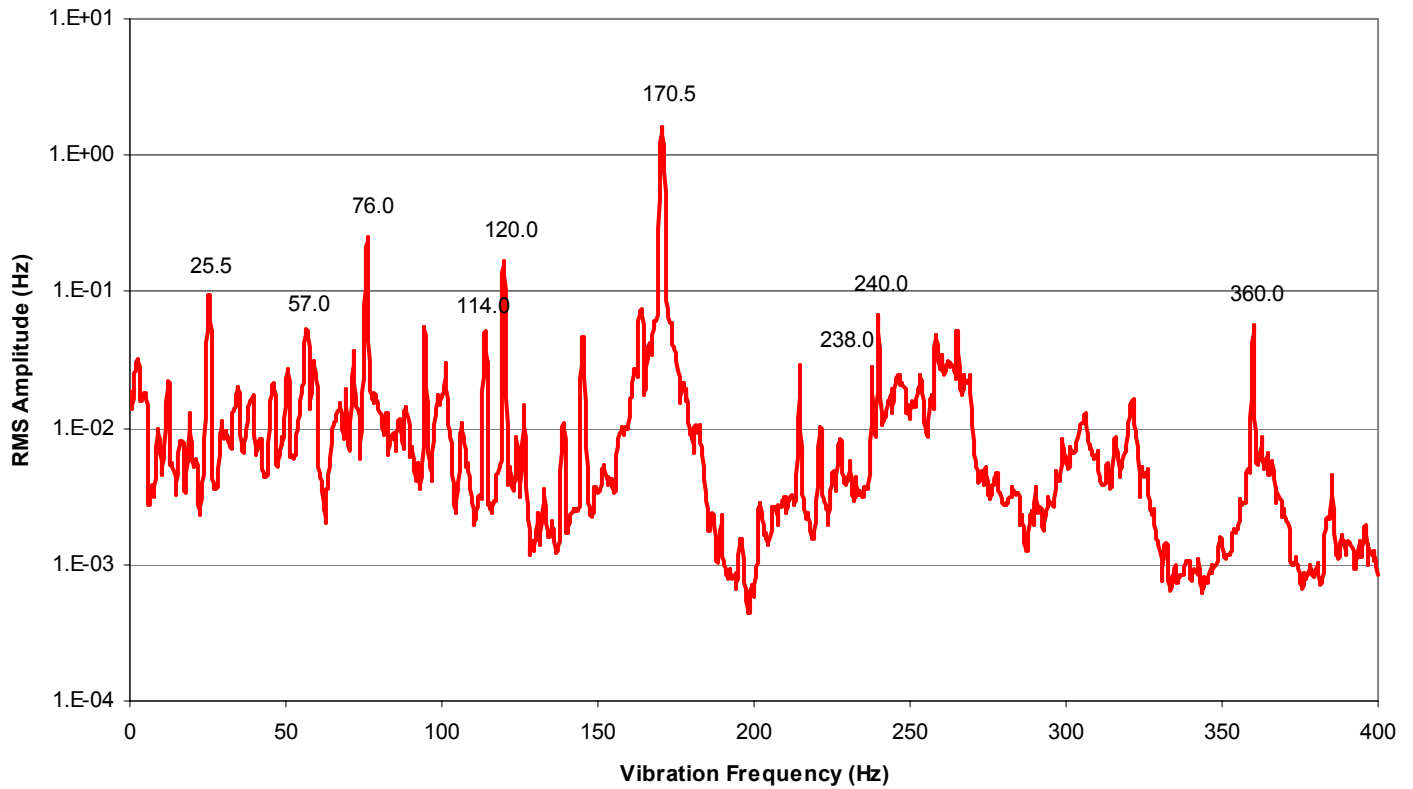


Figure 5: Probability density for cavity 3

We also measured the frequency spectra of the microphonics. As expected they were dominated by a few well defined frequencies corresponding to normal modes of oscillation of the cavity system including its connections to the outside world. Somewhat unexpected was the fact that the frequency spectra were substantially different between cavities. Further measurements on other cryomodules will be necessary to resolve whether these differences are due to random effects, differences in the boundary conditions for the different locations in the cryostat, or the different mechanical properties of the prototype cavities. Note the difference in the spectra between cavities 1, 2, and 3 (figures 6, 7 and 8). In particular cavity 1 has a much stronger response at lower frequencies while cavity 2 has a strong response at 170 Hz, and cavities 1 and 3 at 114 Hz.

Background Microphonics, Med B Cryomodule Prototype, Cavity Position 2 @ 1MV/m CW



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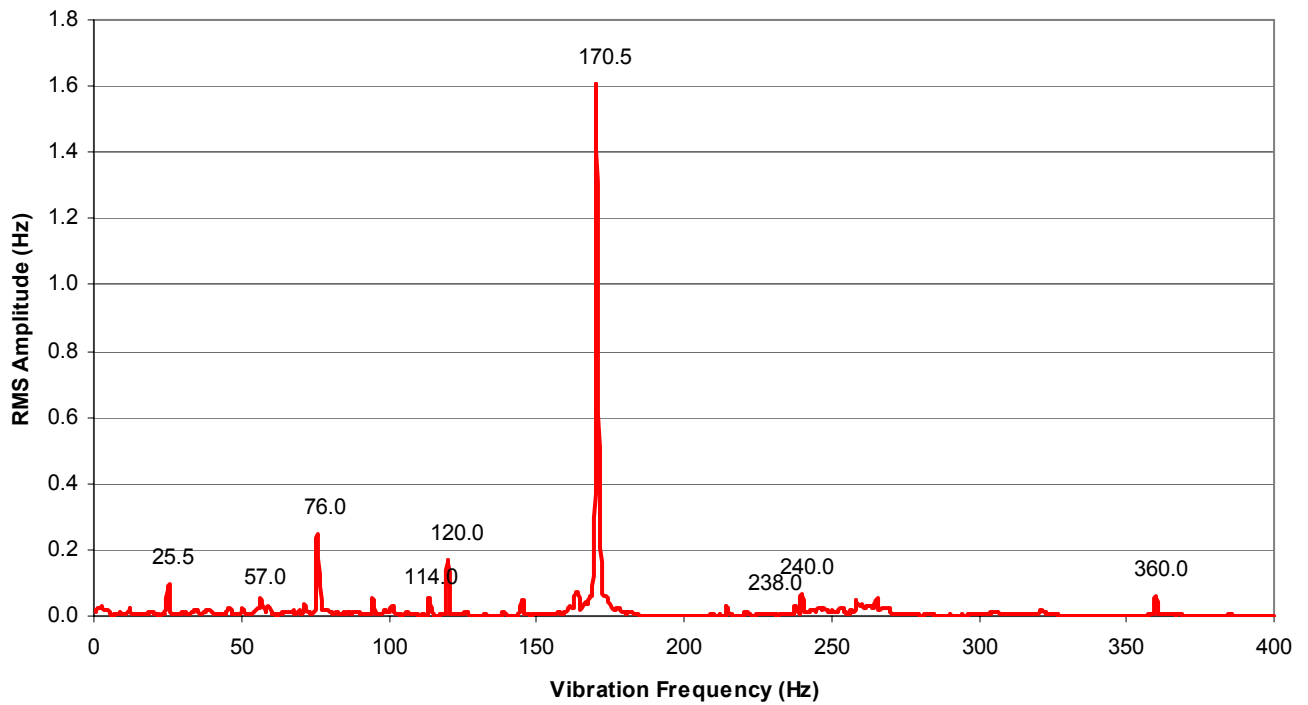


Figure 6: Frequency spectrum of microphonics in cavity 2. Log scale (upper) and Linear scale (lower). Microphonics are dominated by a mode at 170 Hz.

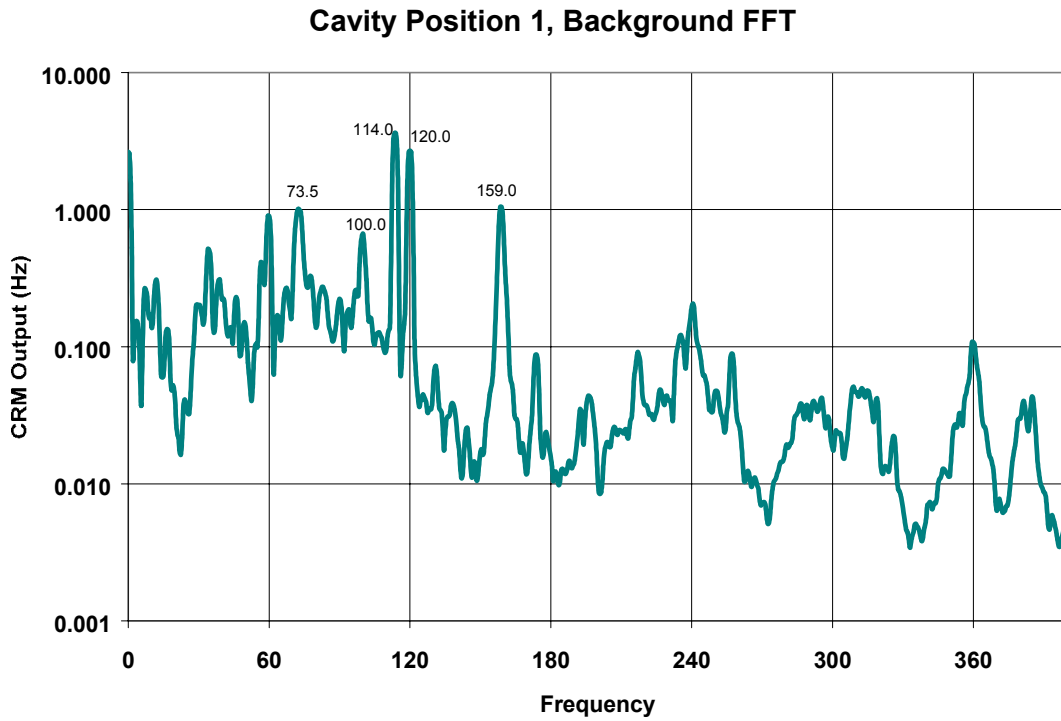


Figure 7: Frequency spectrum for microphonics in cavity 1. Dominant mode is at 114 Hz.

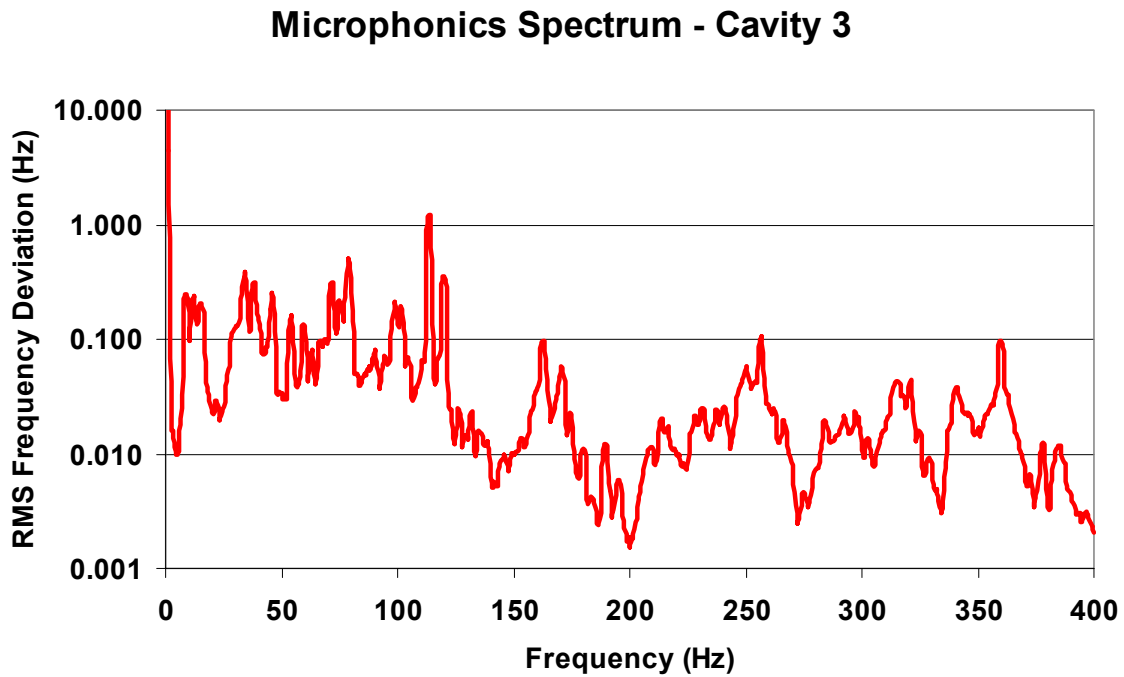


Figure 8: Frequency spectrum for microphonics in cavity 3. Dominant mode is at 114 Hz.



## Lorentz detuning

Static Lorentz detuning was measured in some cavities by slowly increasing the gradient and measuring the cavity frequency. This method requires a very stable system since it is subject to the drifts of the cryogen pressure. This was measured at 95 Hz/torr. A more accurate method is to run the cavity cw at high gradient and to apply a slow ( $\sim 0.2$  Hz)  $\sim 10\%$  amplitude modulation. The same 0.2 Hz modulation of the cavity frequency is measured using the 1 Hz low-pass output of the CRM.

The measured static Lorentz detuning coefficients were:

Cavity 1:  $-10.1$  Hz/(MV/m)<sup>2</sup>

Cavity 2:  $-3.9$  Hz/(MV/m)<sup>2</sup>

Cavity 3:  $-5.8$  Hz/(MV/m)<sup>2</sup>

The frequency dependence of the Lorentz detuning was measured as above by sweeping the frequency of the rf drive modulation, and measuring simultaneously the phase and amplitude of the rf field and frequency modulations.

Because of time constraint this measurement was made only on cavity 1. This data, however, contains, in principle, all the information needed to predict the dynamic behavior of the cavity and should be performed on the other cavities in this cryomodule, if possible, and in future ones, and extended to higher frequencies.

### Cavity Pos 1; Lorentz Transfer Function (delta Freq/transmitted power); AM Modulation Test

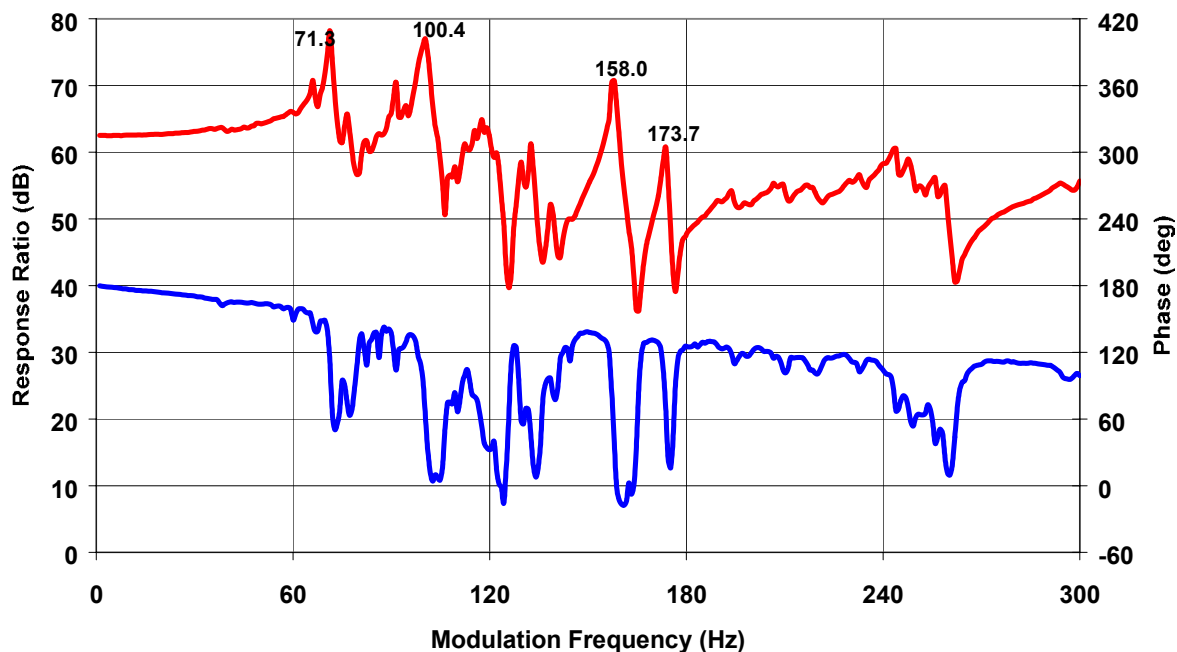


Figure 9: Phase and amplitude of the transfer function from rf field amplitude modulation to cavity frequency modulation.

The total transfer function exhibits the expected behavior. All the contributions to the detuning from the individual mechanical modes are additive *i.e.* the transfer functions of all the modes are in parallel. At each resonance the phase shift increases but recovers and never exceeds  $\pi$ .

Of great interest to SNS is the dynamic behavior of the Lorentz detuning under pulsed operation. The CRM has a 50 dB dynamic range, so it can measure the cavity frequency during the rise and decay of the fields, but we do not have, at present, the ability to measure the frequency between pulses. This would require maintaining a small but finite rf field in the cavity.

A typical measurement of the dynamic Lorentz detuning for an “SNS” pulse is shown in figure 10. In that figure, and all similar ones, the transients at the beginning and the end are associated with the phase-lock loop acquiring and losing lock and are not significant.

The static Lorentz detuning is quadratic with gradient and, all else being held constant, this ought to be true also in pulsed operation. This was confirmed on cavity 1 and shown in figures 11 and 12.

Med  $\beta$  CM, Cavity 2, Pulse Response, 60Hz, 1.3mS, 10MV/m

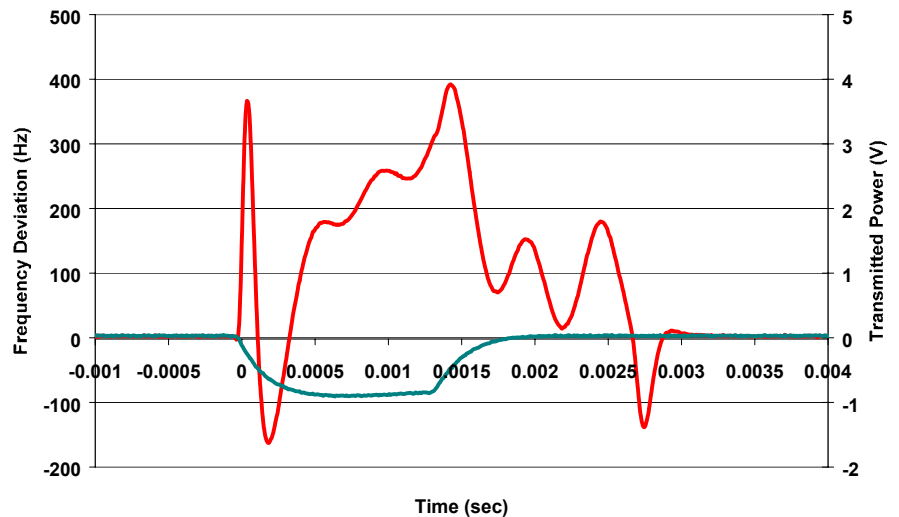


Figure 10: Typical response of the cavity frequency to an SNS pulse at design gradient. Curve is for cavity 2.

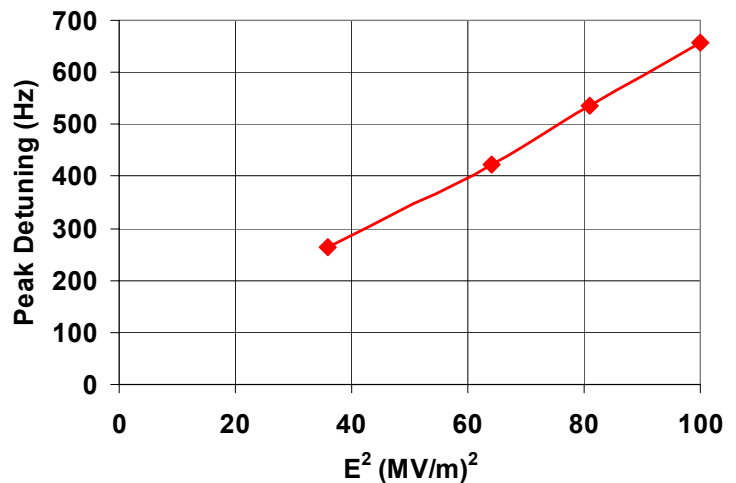


Figure 11: Peak detuning as function of gradient from figures 12.

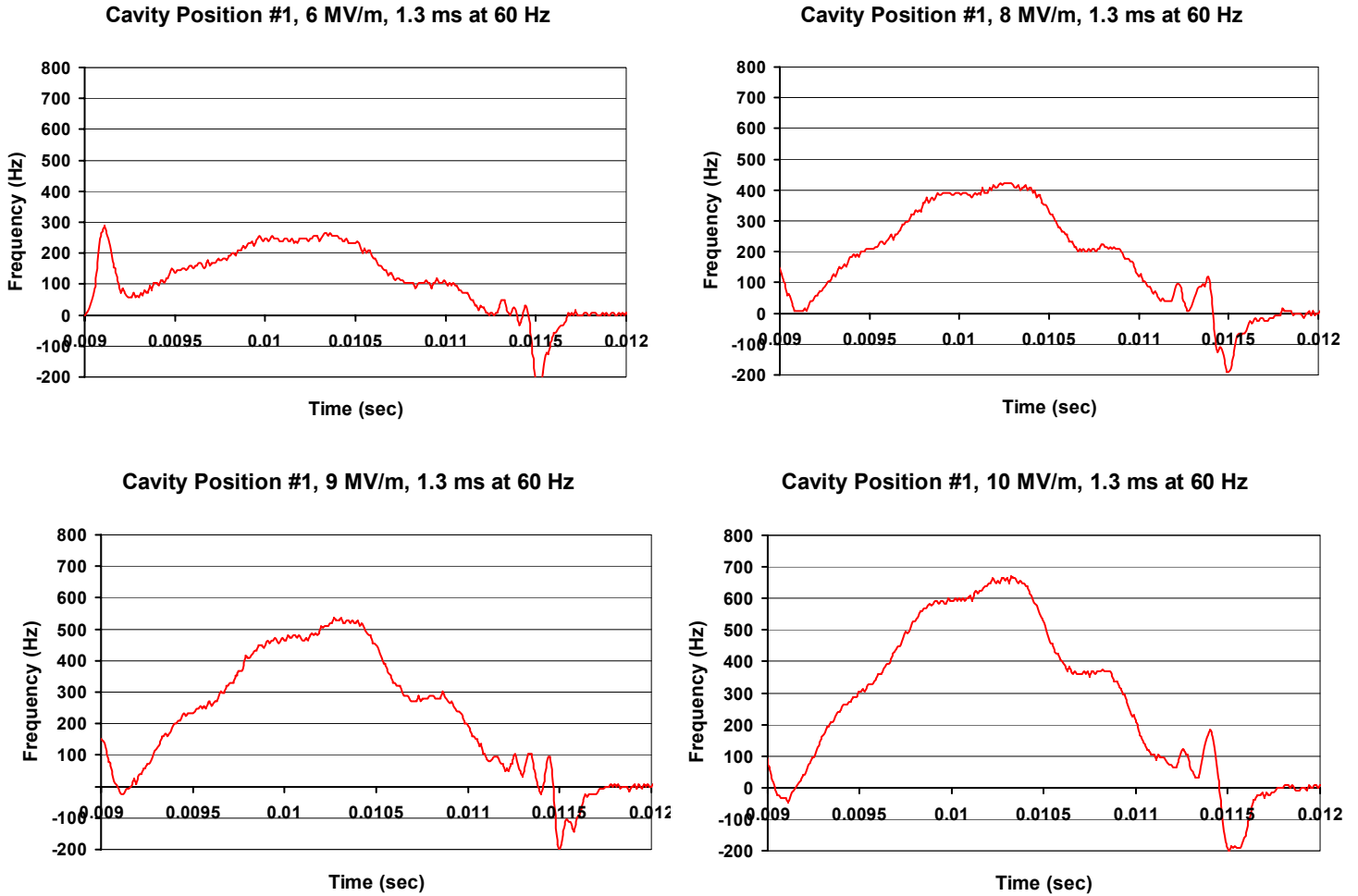


Figure 12: Time dependence of the dynamic Lorentz detuning for identical pulse shapes and peak fields of 6, 8, 9, and 10 MV/m. Data is for cavity position 1.

Present in all the dynamic measurements, although with different magnitudes, was an oscillation at  $\sim 2$  kHz.

Dynamic Lorentz detuning for 1.3 msec, 60 Hz pulses at 10 MV/m were:

- Cavity 1: -650 Hz
- Cavity 2: -380 Hz
- Cavity 3: -400 Hz

With the exception of cavity 1, which was the one with the extreme field unbalance, the SNS requirement of 470 Hz was achieved.

## Piezo tuners

The effectiveness of the piezo tuners in compensating for the Lorentz detuning is shown in figure 13. A reduction by a factor of 3 was easily achieved. The critical parameter was the timing between the rf pulse and the piezo pulse. Similar reduction was achieved by changing the polarity of the piezo drive signal by adjusting the timing. It should be noted that this compensation takes place only during the short rf pulse. Although we do not have the ability to measure it, it is likely that the cavity frequency undergoes large transients between the rf pulses.

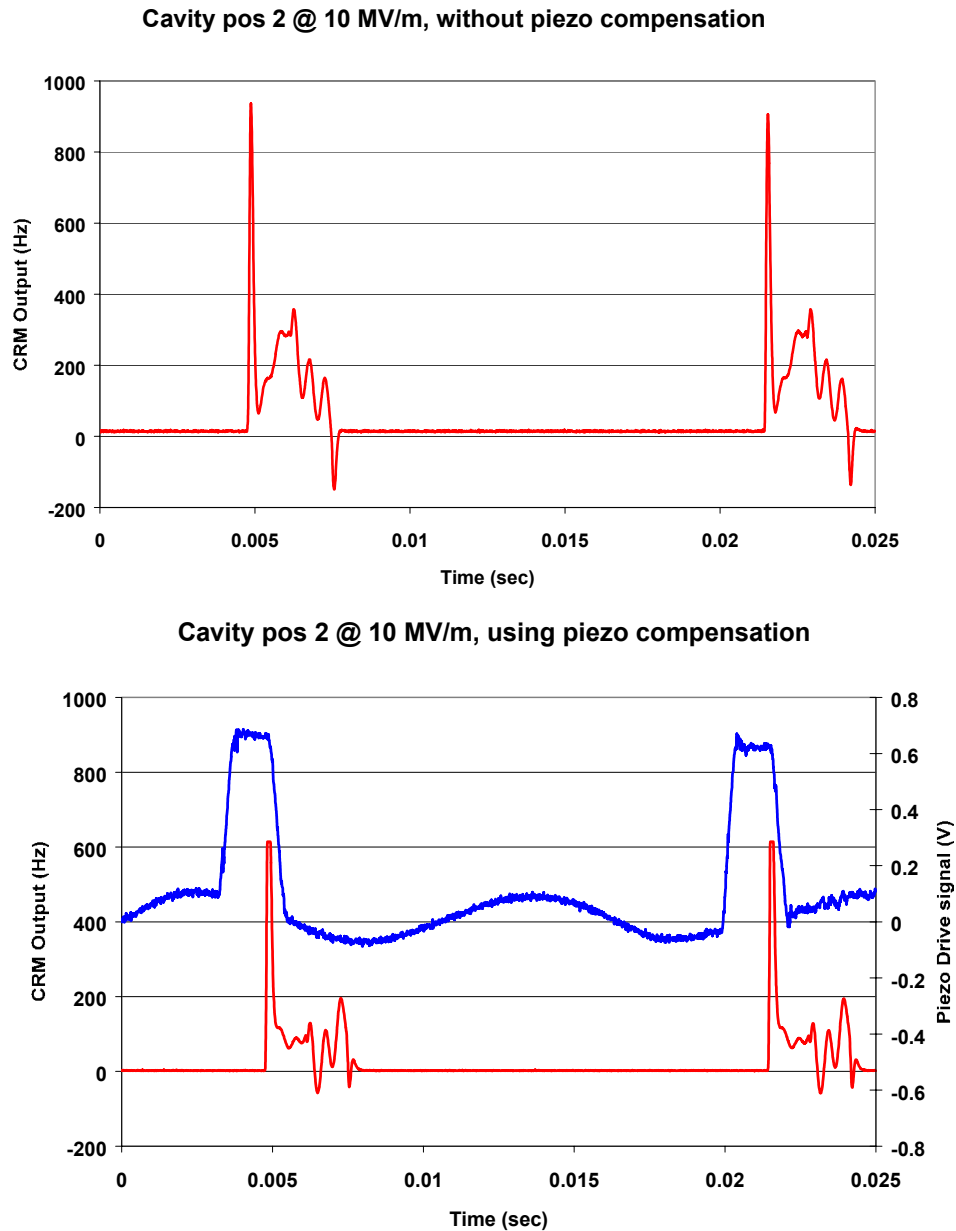


Figure 13: Dynamic Lorentz detuning with and without piezo compensation. Measurements are for cavity 2 operating at 10 MV/m for a 60 Hz train of SNS pulses.

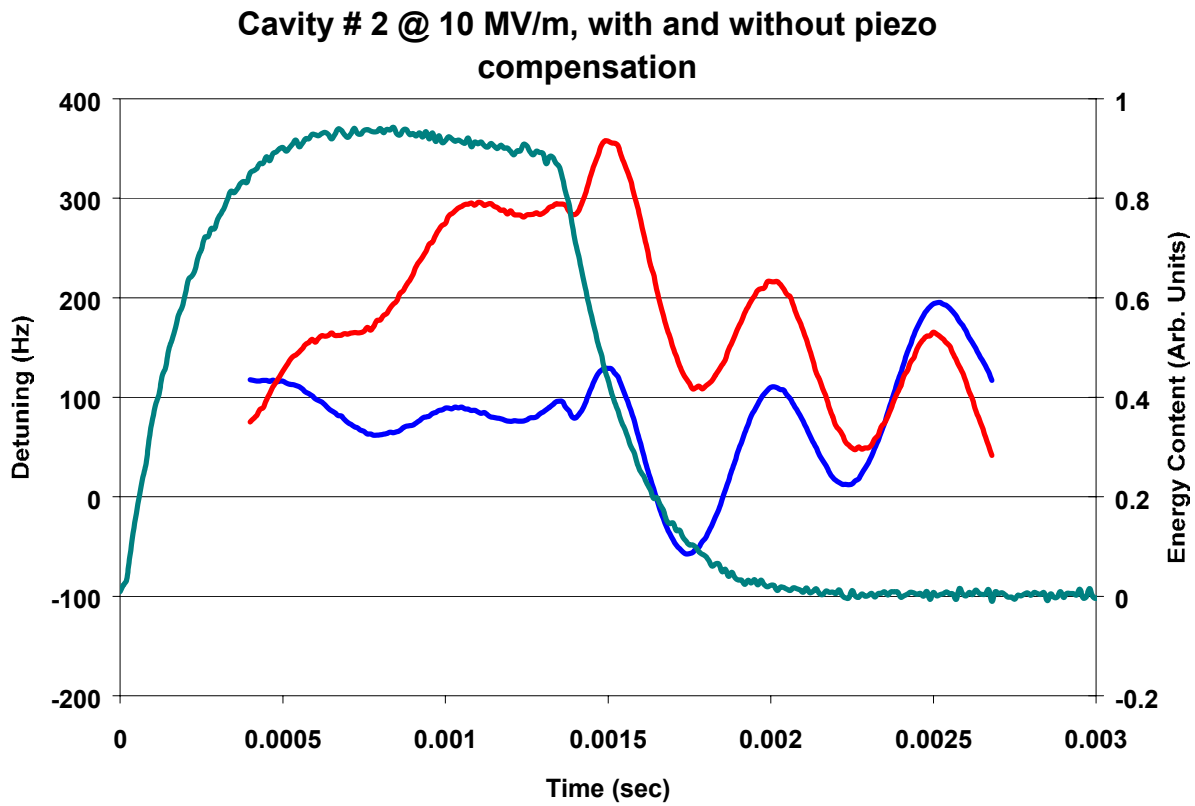
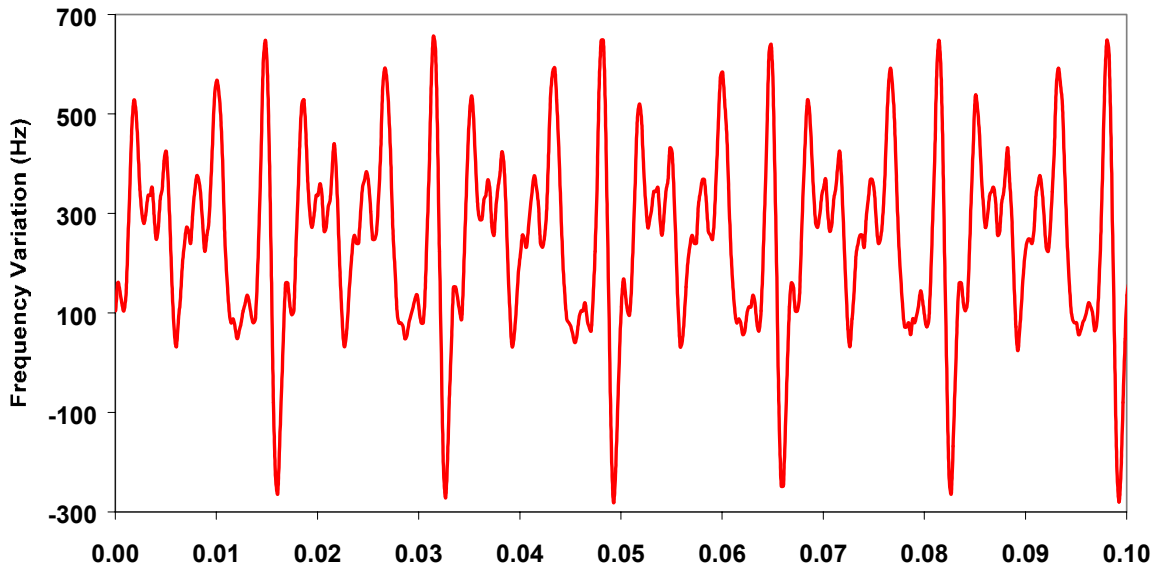


Figure 14: Cavity frequency without (upper) and with (lower) piezo tuner compensation.

The length of the rf and piezo pulses are much shorter than the period of the dominant mechanical modes so it would be expected that the detail of the pulse shape would have relatively little effect on the dynamic behavior of the cavity frequency. Furthermore the decay time of the dominant modes is much larger than the spacing between the pulses, thus it would be expected that the cavities would be in a perpetual state of “ringing”. This is demonstrated in the following figures. Cavity 2 was operated cw and the piezo tuner was activated at 60 Hz, in a similar fashion and amplitude that would be needed to compensate for the Lorentz detuning. Note that the response of the cavity frequency is relatively insensitive to the rise time of the piezo pulse, but that it is also essentially periodic. It is for this reason that, for the short duration of the rf pulse, the piezo pulse can be used to compensate for the Lorentz detuning which would have a similar complex, but periodic, behavior by carefully adjusting the timing between the two.

**Cavity Position 2 Response to Piezo Pulses at 1.28 ms  
pulse width; 160 usec rise time; 60 Hz**



**Cavity Position 2 Response to Piezo Pulses at 1.28 ms  
pulse width; 320 usec rise time; 60 Hz**

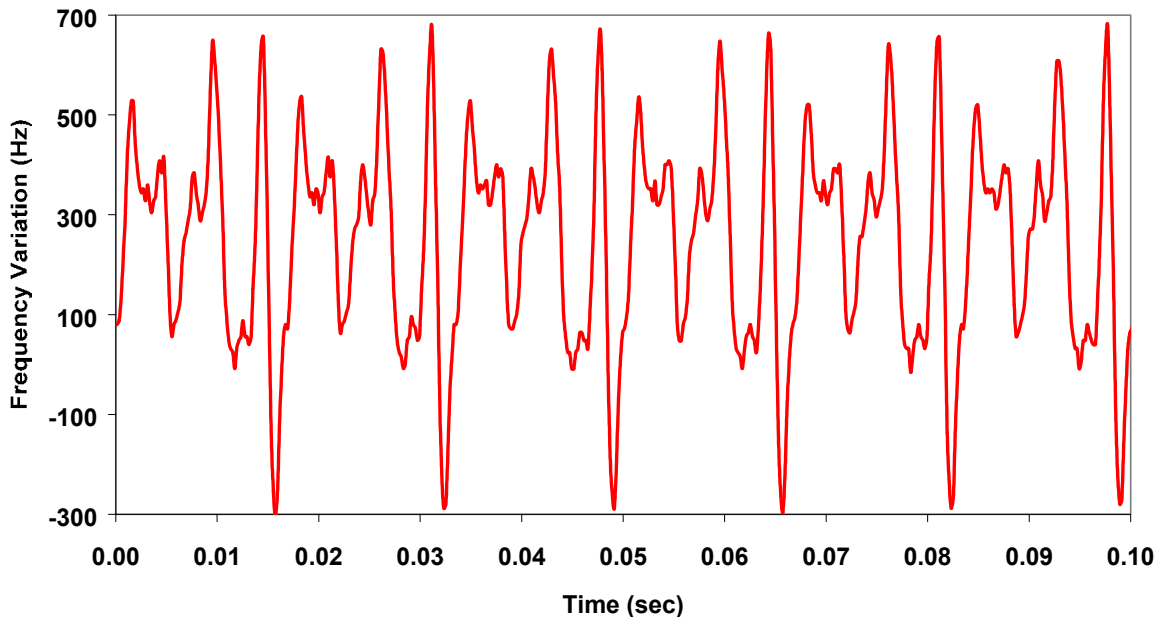


Figure 15: Cavity frequency variation induced by a 60 Hz excitation of the piezo tuner similar to that which would be needed to compensate for the rf-induced Lorentz detuning. Note the periodic behavior and the insensitivity to the shape (rise time) of the piezo drive. The frequency swing is  $\sim 1$  kHz.

Not only could the piezo tuners be used to compensate for the Lorentz detuning during pulsed operation, they could also conceivably be used for compensation of the microphonics in cw operation. The issues are quite different in this case since microphonics are, by their nature, essentially stochastic and the piezo tuner would be used continuously in a feedback mode as opposed to for short times in a periodic feedforward mode in pulsed operation.

The transfer function (phase and amplitude) from input voltage of the amplifier driving the piezo to cavity frequency was measured. This was done in a similar fashion to that of the transfer function from rf field modulation to cavity frequency. For cavity 2 we measured the transfer function for the two extreme positions of the slow mechanical tuner (Figure 16). Subtle but real differences in the responses were observed

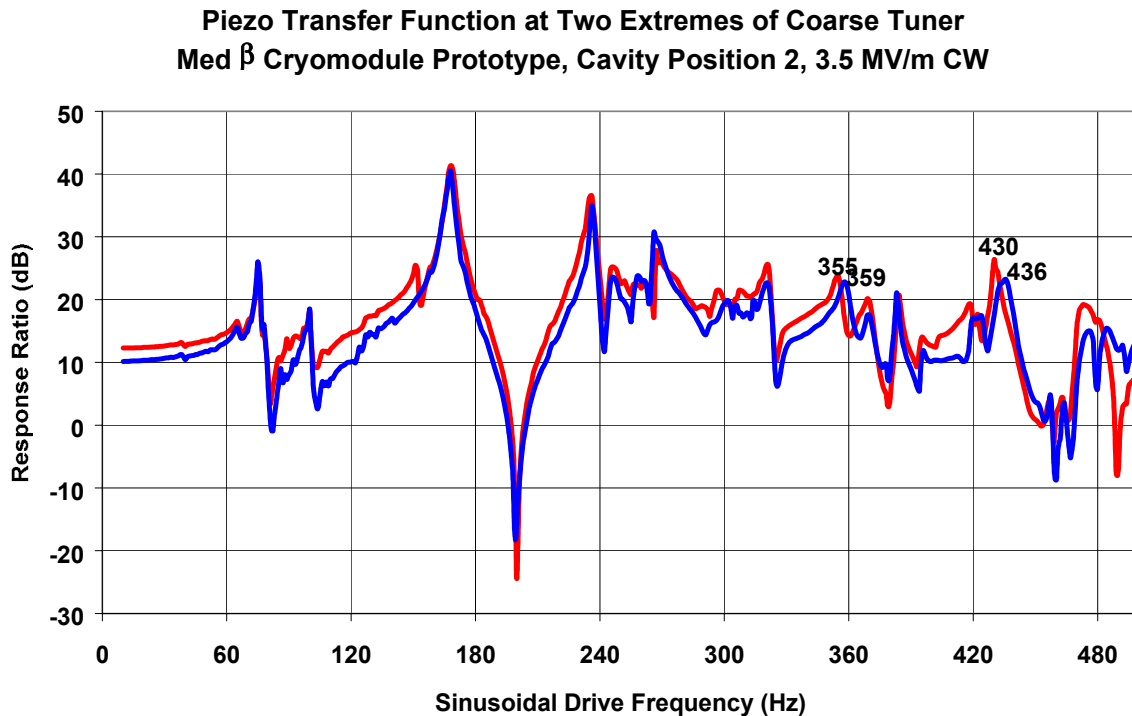
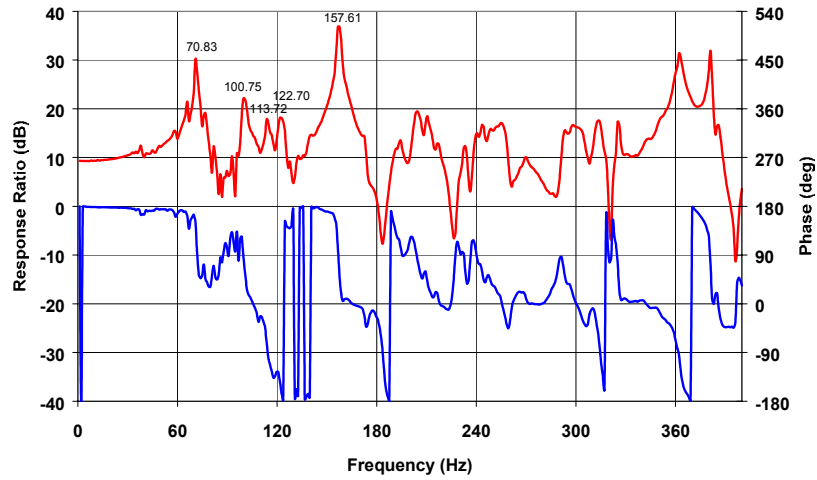


Figure 16: Amplitude of the piezo transfer function in cavity 2 for the two extreme positions of the coarse mechanical tuner. Blue: 804.612 MHz; Red: 805.06 MHz

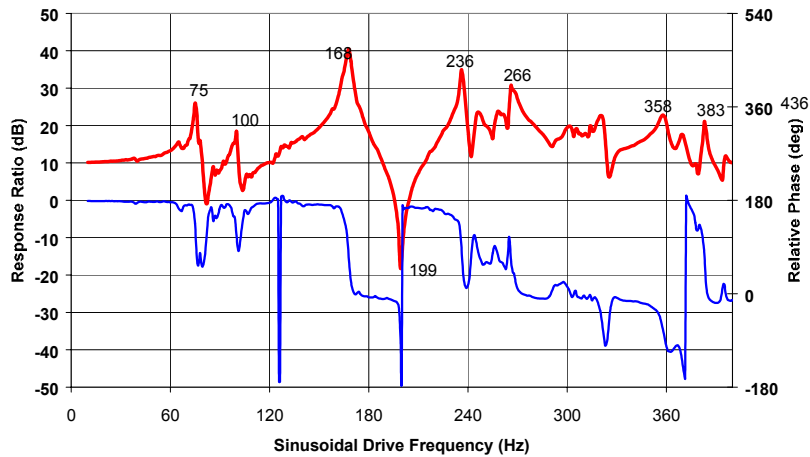
The behavior of the piezo tuner transfer function was unexpected and is not, at present, fully understood. Similar results were obtained at DESY with no better understanding.

First, the transfer functions of the 3 cavities were substantially different one from the other; some strong resonances that were present in one cavity were absent in others (Figure 17). Most surprising was the fact that each resonance seems to add  $2\pi$  in the phase shift; more than  $20\pi$  had accumulated at 500 Hz. It is as though the resonances were in series as opposed to being in parallel. It should be pointed out that the transfer function includes the driver amplifier for the piezo, the piezo itself, and the mechanical modes of the cavity. Separation of the various contributions will require further testing.

### Cavity Pos 1, Piezo Transfer Function



Cavity Response to Piezo, Swept Sinusoid, Drive Amplitude = 26Vpp  
Med B Cryomodule Prototype, Cavity Position 2, 804.612MHz, 3.5 MV/m CW



### Cavity Position 3, Piezo Transfer Function

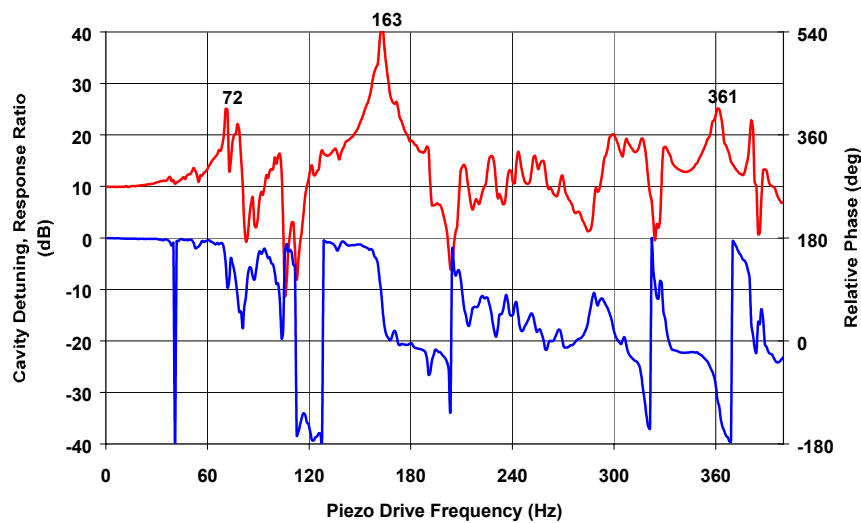


Figure 17: Phase and amplitude of the piezo transfer functions for the 3 cavities.



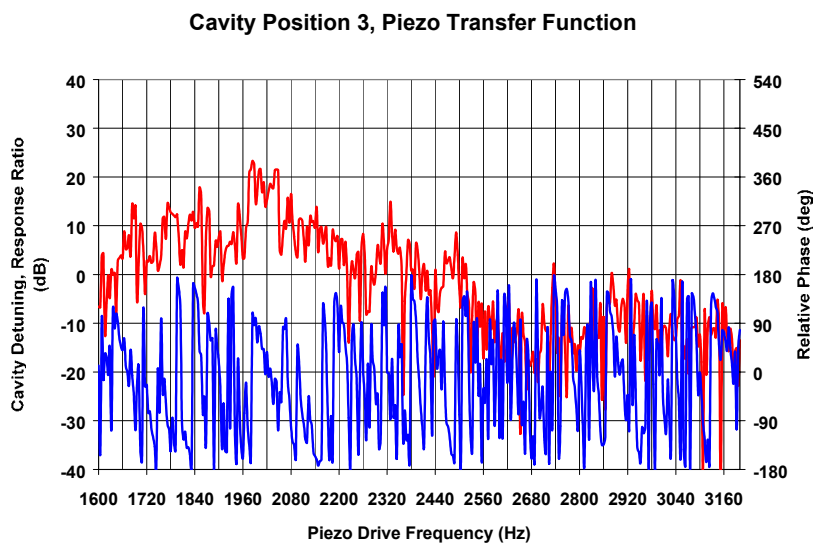
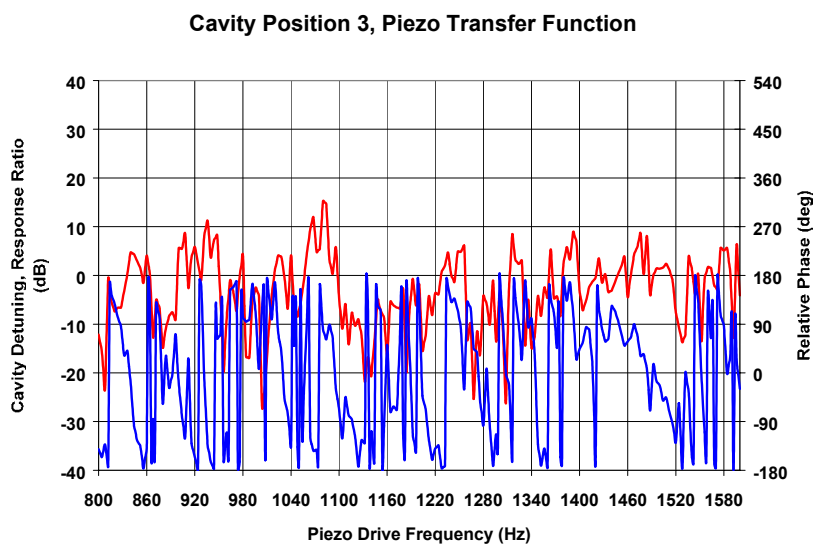
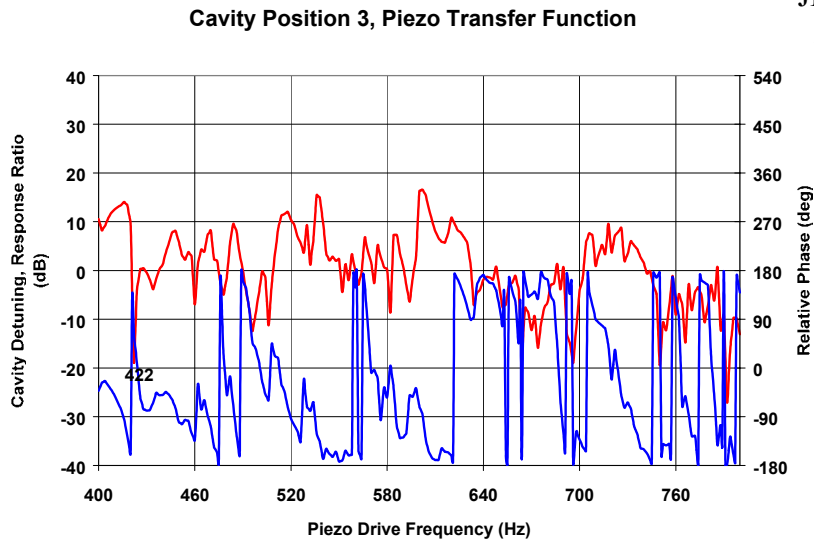


Figure 18: Amplitude and phase of the piezo transfer function for cavity 3 from 400 to 3200 Hz. Results up to 400 Hz are shown in figure 17.

A complete transfer function to 3.2 kHz was measured for cavity 3 (Figure 18). Note the continuous accumulation of phase shift and the broad peak around 2 kHz.

Of concern for use of the piezo tuner to control microphonics is the amount of microphonics that it can generate during activation. The frequency of cavity 2 was measured while activating the piezo tuner with a slow (1 or 2 Hz) trapezoidal signal with rise time of 0, 5, 10, and 20 msec. A square wave (0 rise time) generates microphonics of the same order of magnitude as the steady state displacement it induces; these microphonics then decay in about 400 msec. In order for the microphonics to be less than 50 % of the steady state displacement, the ramp time of the trapezoidal drive must be at least 5 msec.

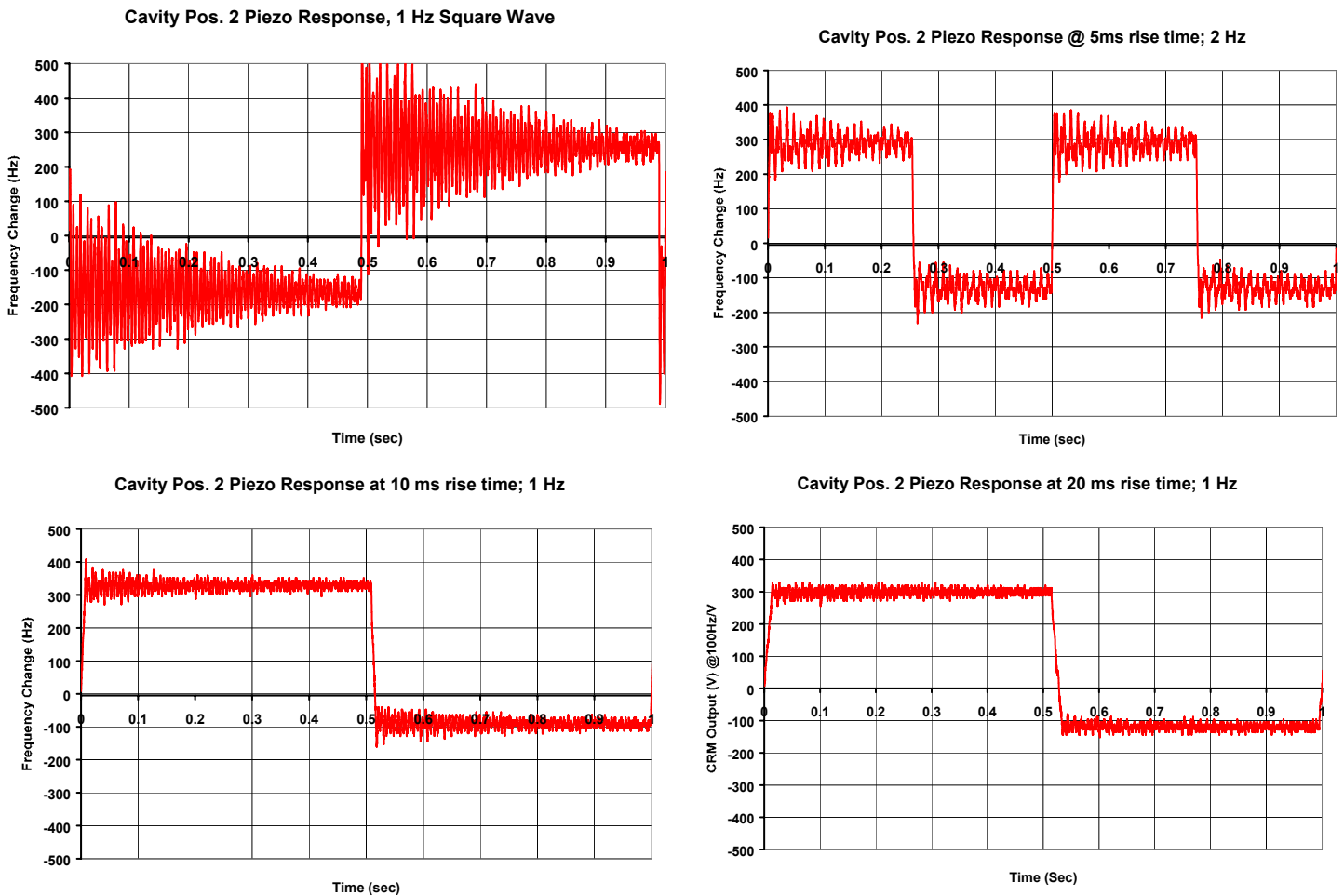


Figure 19: Cavity frequency response to trapezoidal excitation of the piezo tuner with ramp times of 0, 5, 10, and 20 msec.

The frequency of the oscillations generated by activation of the piezo tuner is 170 Hz, which is consistent with the frequency spectrum of the microphonics measured for this cavity and shown in figure 6.

## References

- [1] Microphonics Testing of the CEBAF Upgrade 7-Cell Cavity  
G. Kirk Davis, Jean Delayen, Michael Drury, Thomas Hiatt, Curt Hovater, Thomas Powers, Joseph Preble  
Proc. 2001 Particle Accelerator Conference, Chicago, IL, 18-22 June 2001.