

# Microphonics

T. Powers

# What is microphonics?

- Microphonics is the time domain variation in cavity frequency driven by external vibrational sources.
- A 1.5 GHz structure 0.5 m long will change in frequency by  $\sim 100$  Hz if the length is changed 33 nm.
- 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.
- We measure the microphonics on each series of cryomodules and on a fraction of the cavities in the field.
- When we measured the first cryomodule installed in the machine we found larger than expected microphonics noise.

# What is NOT microphonics?

- Static Lorentz force detuning
  - Note: 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.
- Low frequency pressure drifts with periods on the order of minutes to hours.
  - These can be addressed with your motor driven tuners.

# The math.

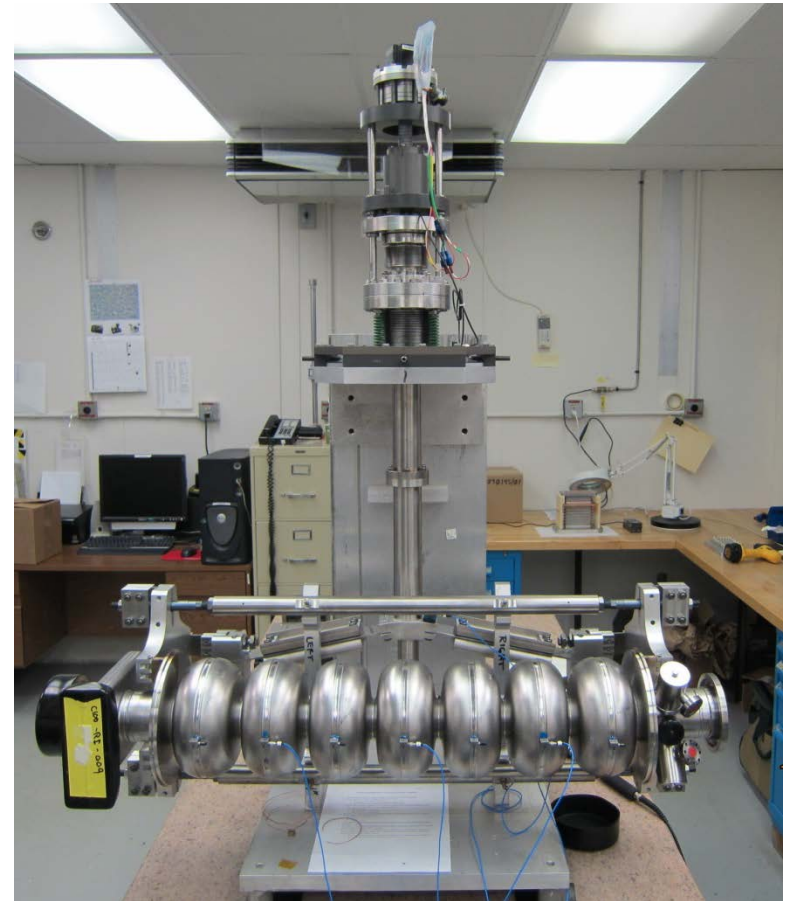
- Ignoring control loop gain and coupler bandwidth limitations the steady state amplitude and phase controls needed for microphonics is given by:

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

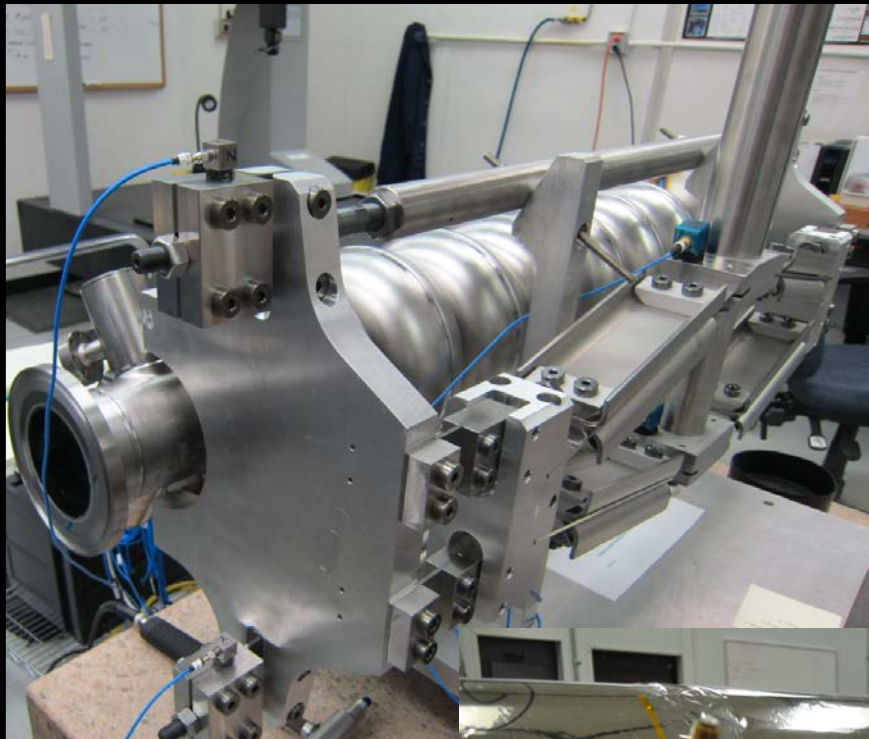
$$\varphi_{RF} = \arctan \left( \frac{2Q_L \frac{\delta f}{f_0} E + I_0 Q_L(r/Q) \sin \varphi_B}{E + I_0 Q_L(r/Q) \cos \varphi_B} \right)$$

# Modal Response Testing

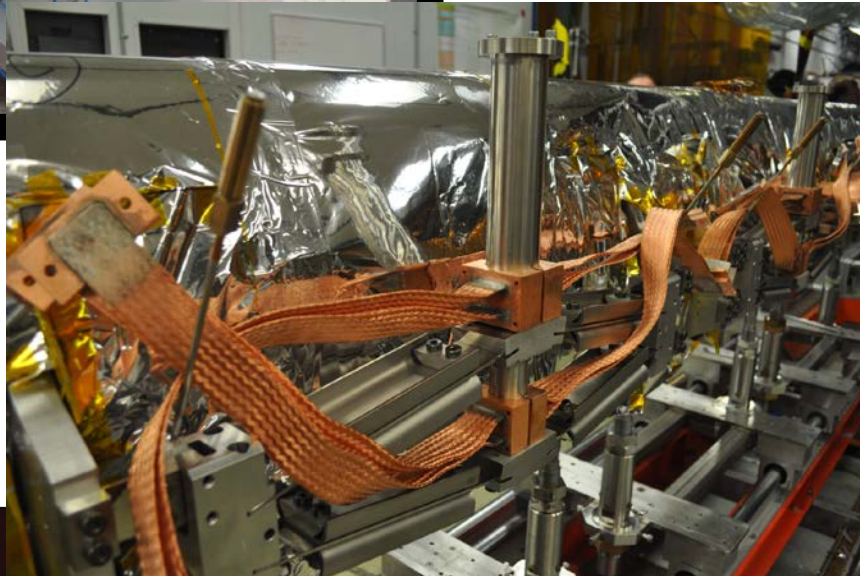
- A warm cavity was instrumented with 9 triaxial accelerometers
- A series of warm impulse hammer response tests were performed on structures ranging from bare cavities to a fully assembled cryomodule.
- This data was used in combination with finite element analysis to improve the design.



# Background Microphonics Testing



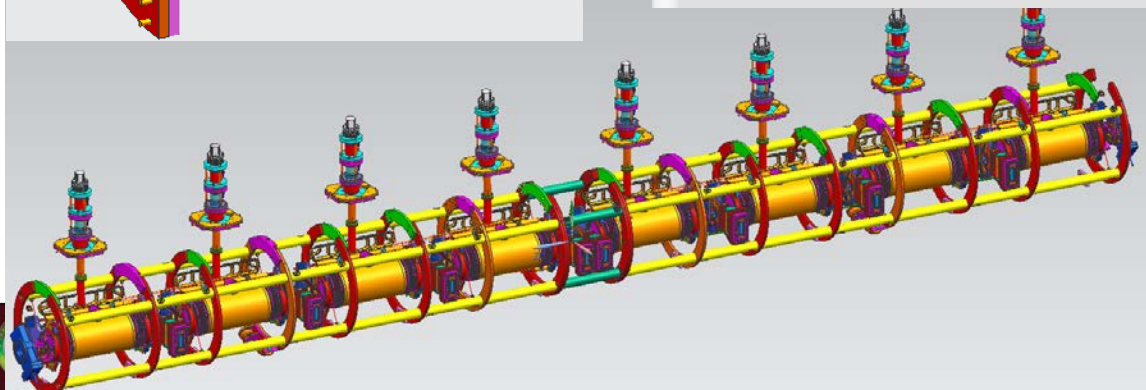
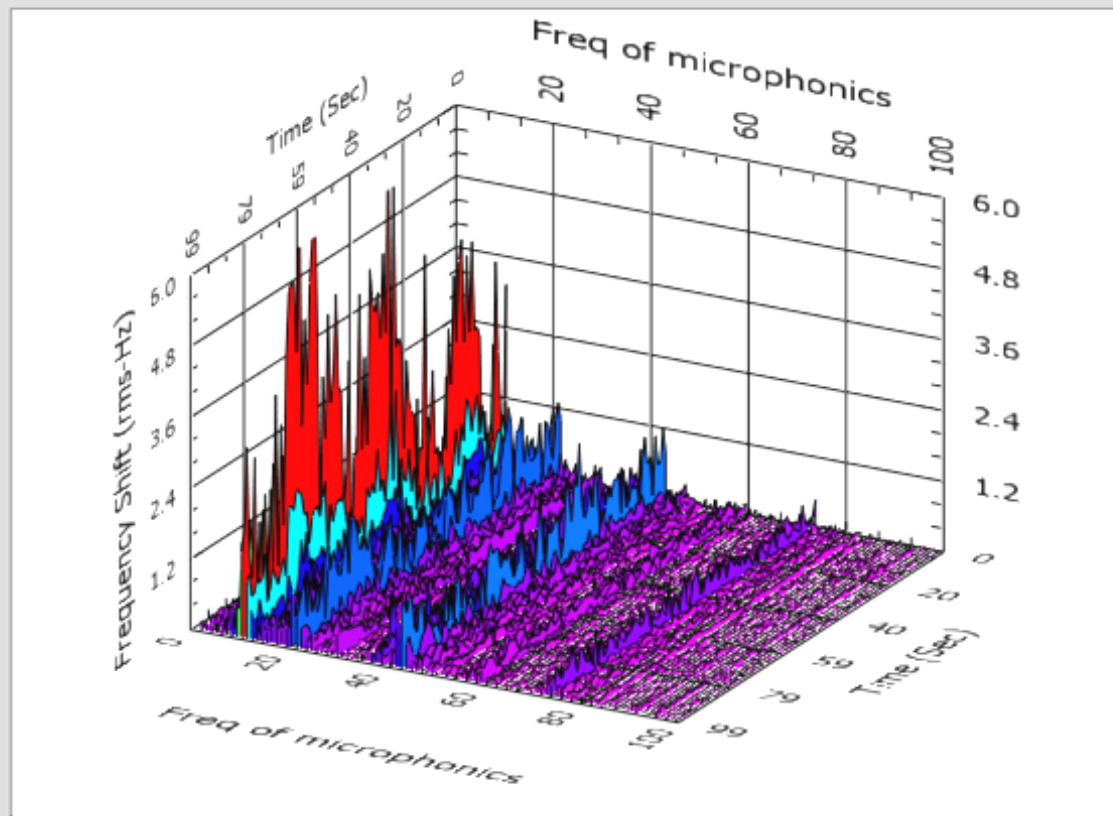
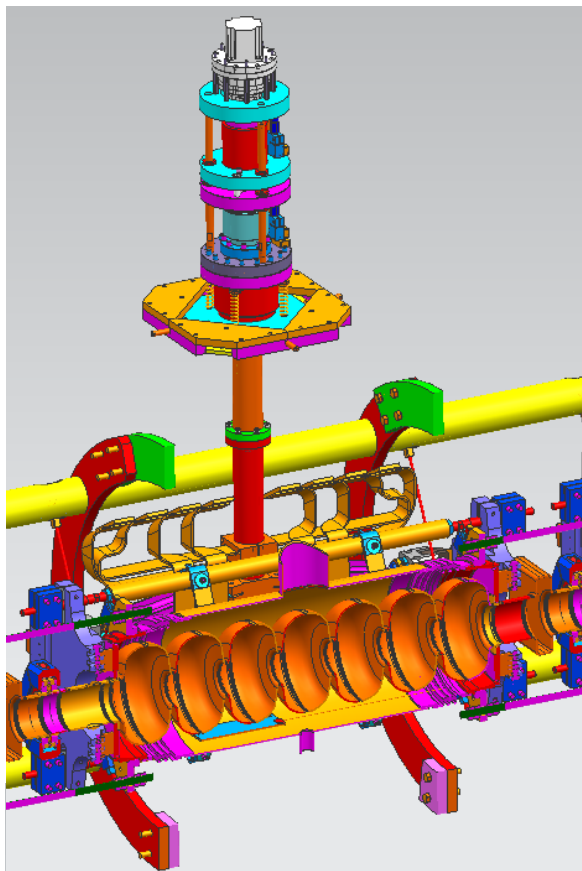
- Data taken using digital low level RF system operated in a fixed frequency mode at 1497 MHz
- The RF phase angles between the incident power and the cavity field probe readings were recorded at 1000 S/sec for 100 seconds.
- Phase angle and cavity loaded-Q used to calculate the detune frequency
- 8 channels of data were acquired synchronously.



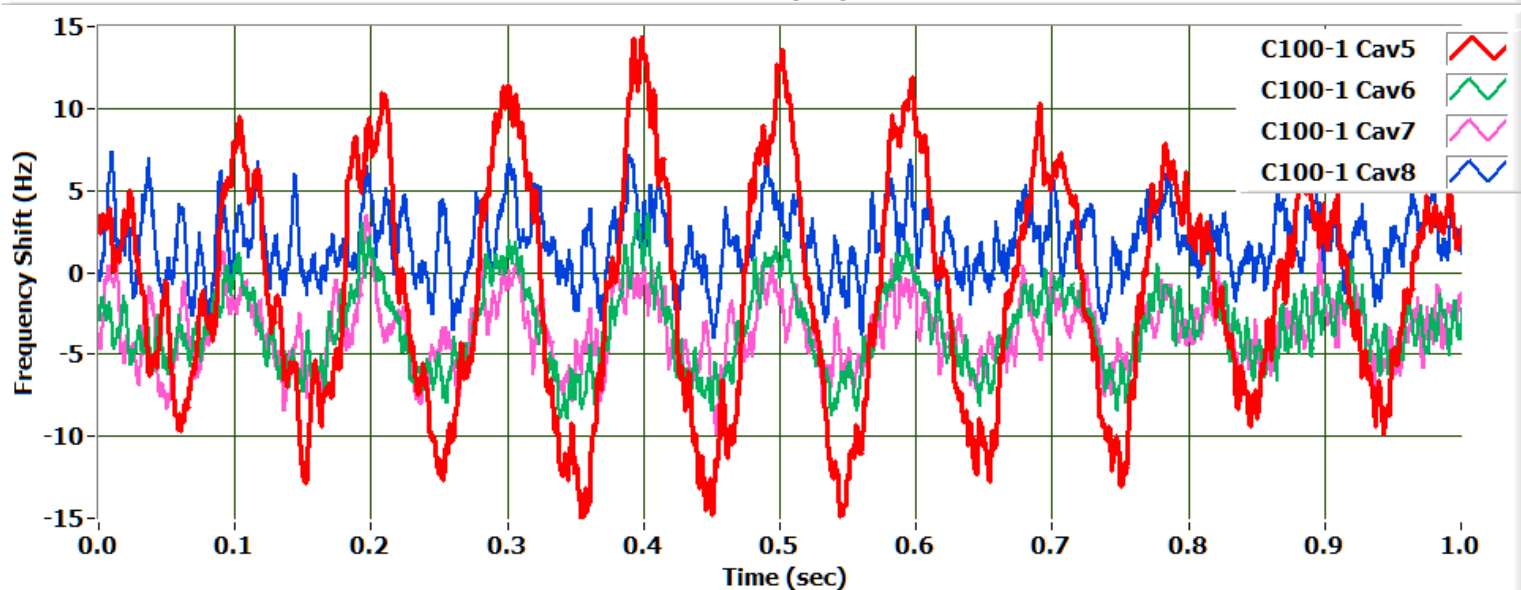
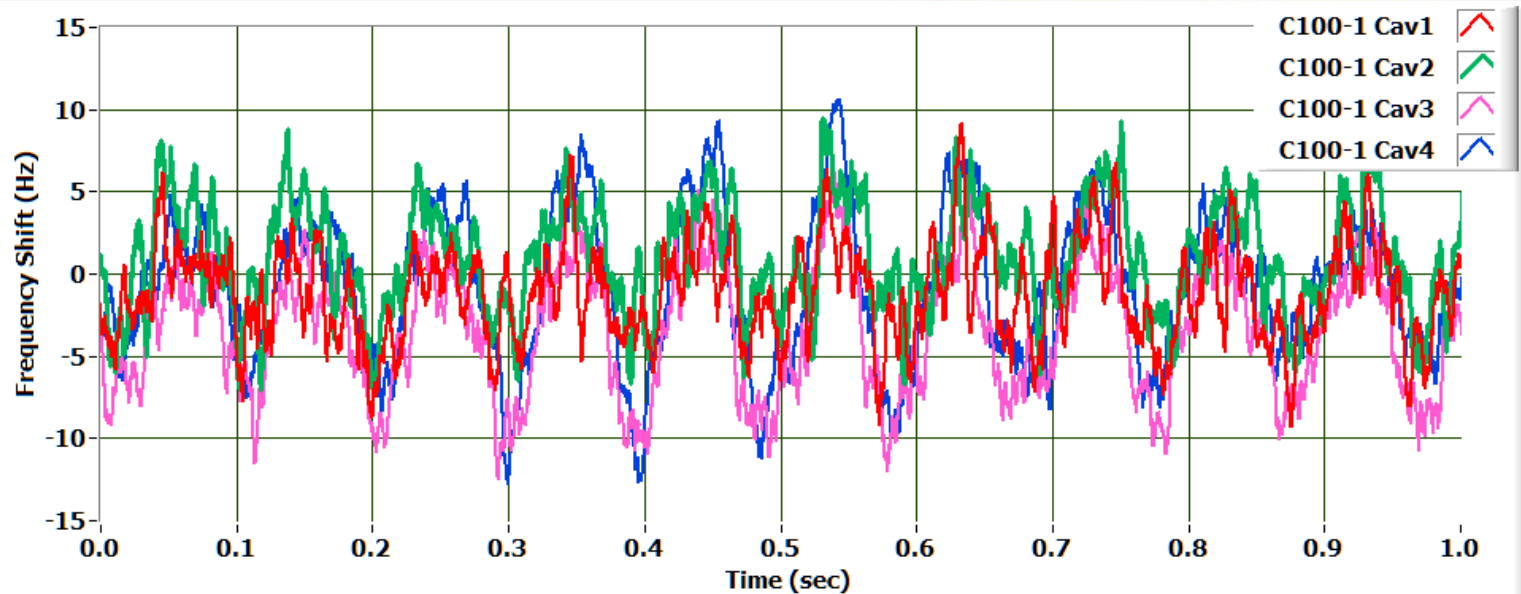


# Microphonics Spectra as a function of Time

C100-1-5 deltaF



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

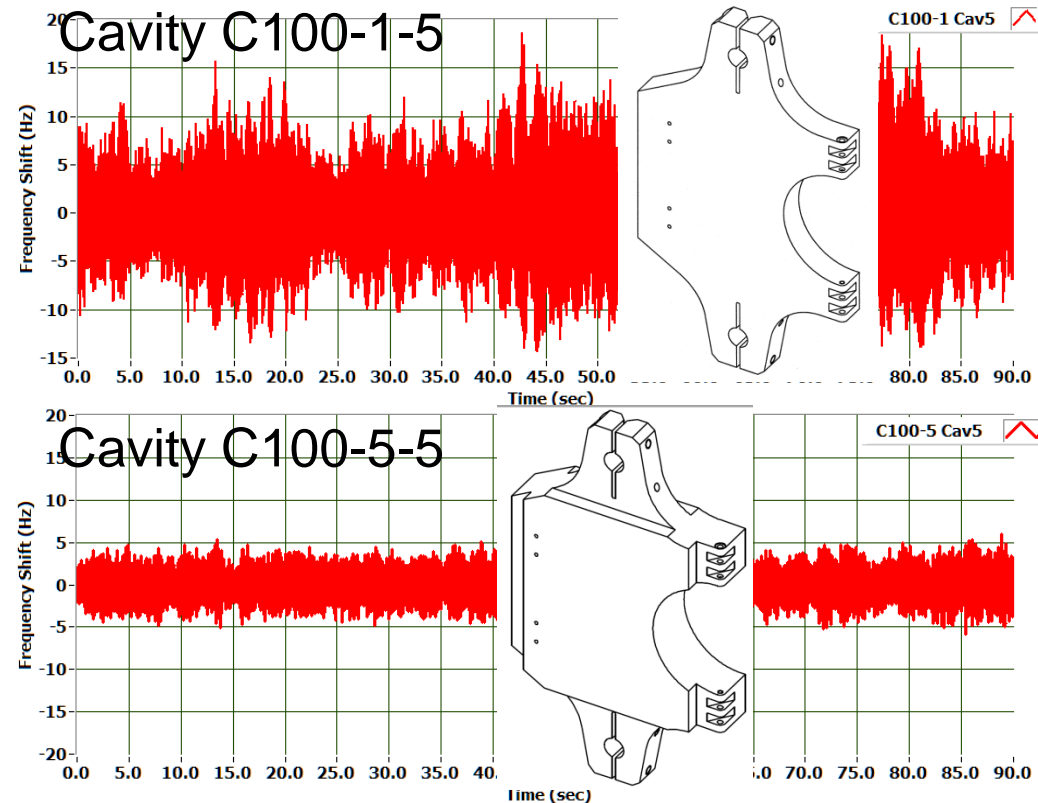




# Microphonics

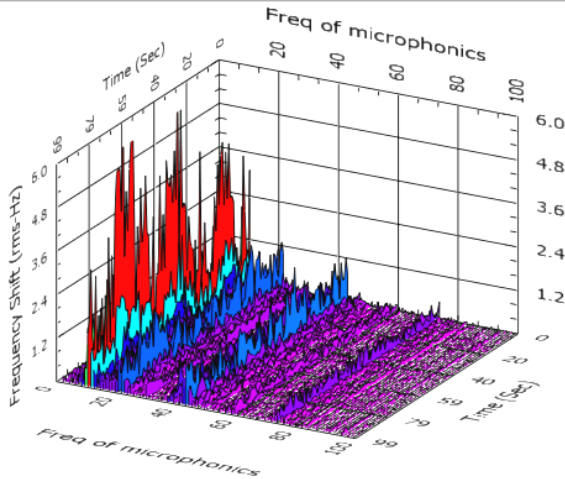
- Design allows for 25 Hz Peak Detuning
- Actual peak detuning (**21 Hz**) was higher than expected in first cryomodules
- A detailed vibration study was initiating which led to the following design change.
- A minor change to the **tuner pivot** plate substantially improved the microphonics for the 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
6 $\sigma$ (Hz)	17.91	9.14

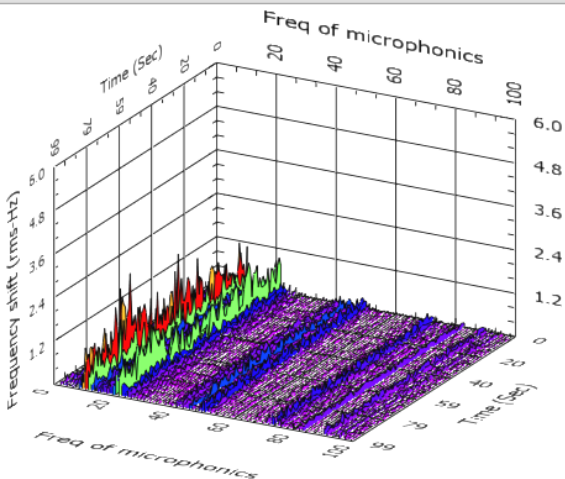


# Spectra with old and new tuner plates

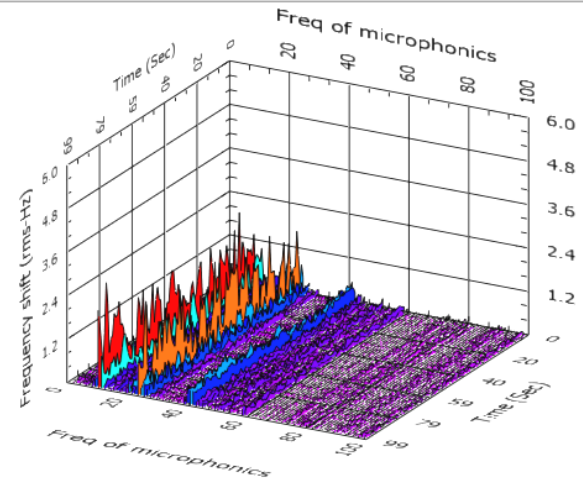
C100-1-5 deltaF



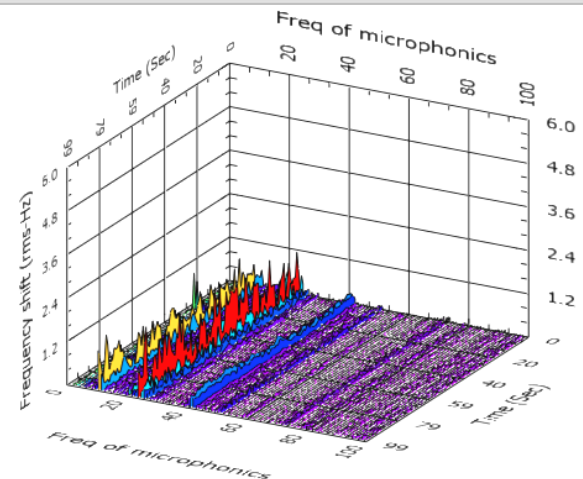
C100-1-6 deltaF



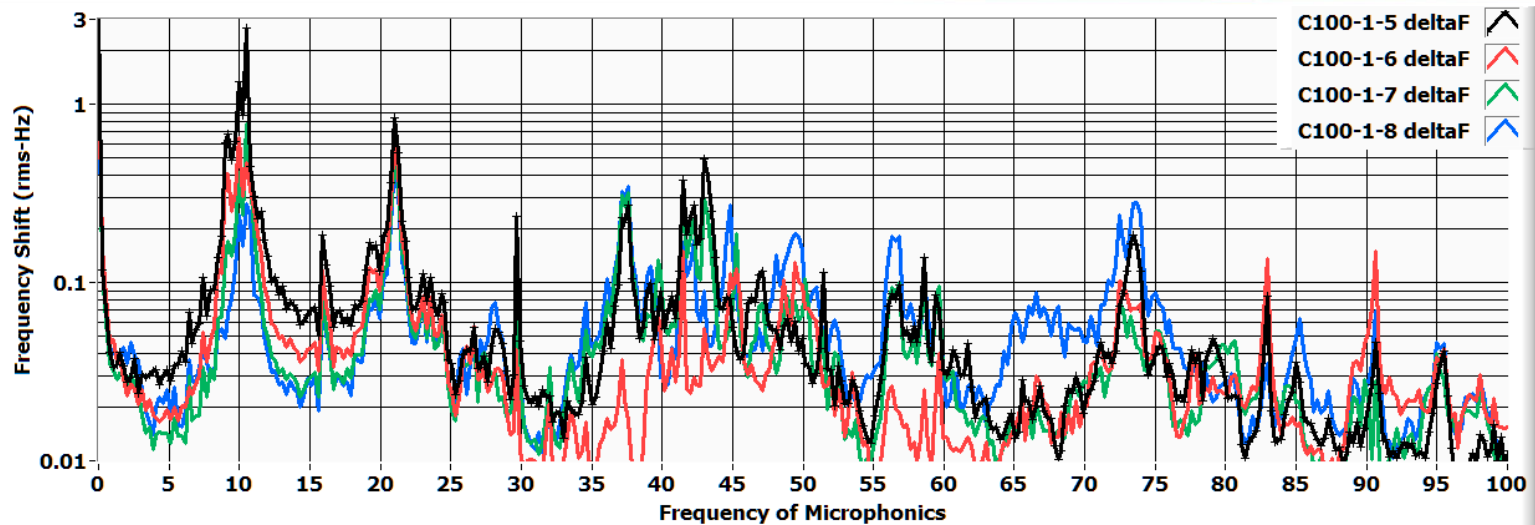
C100-5-5 deltaF



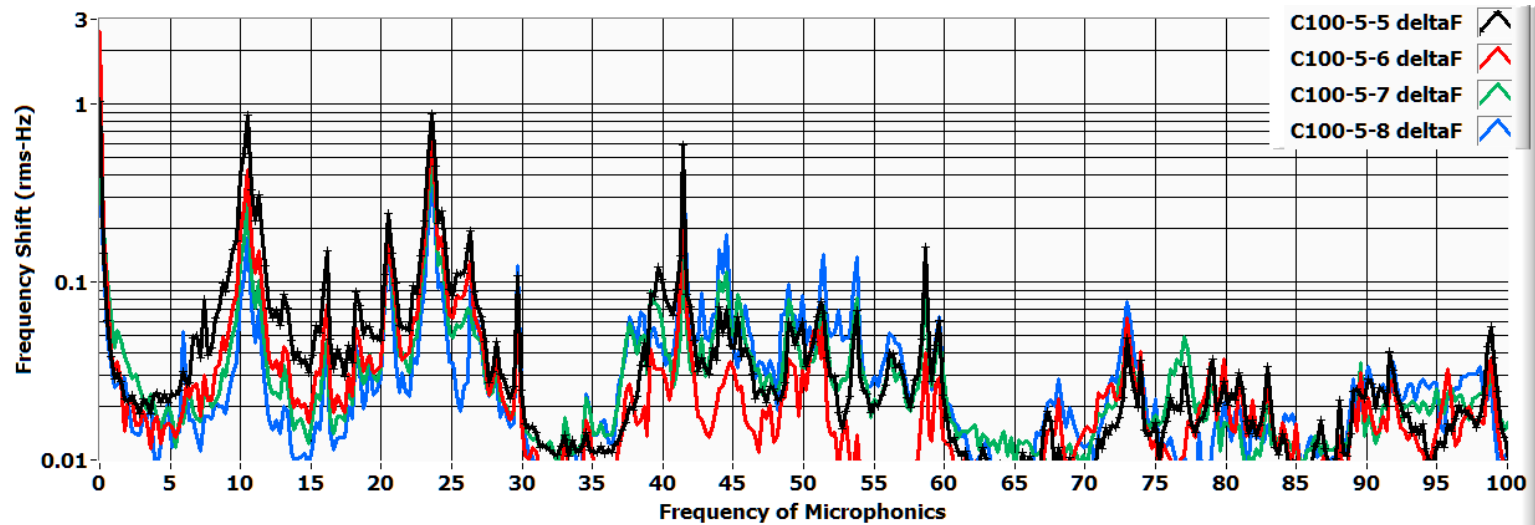
C100-5-6 deltaF



# Time Averaged Spectra

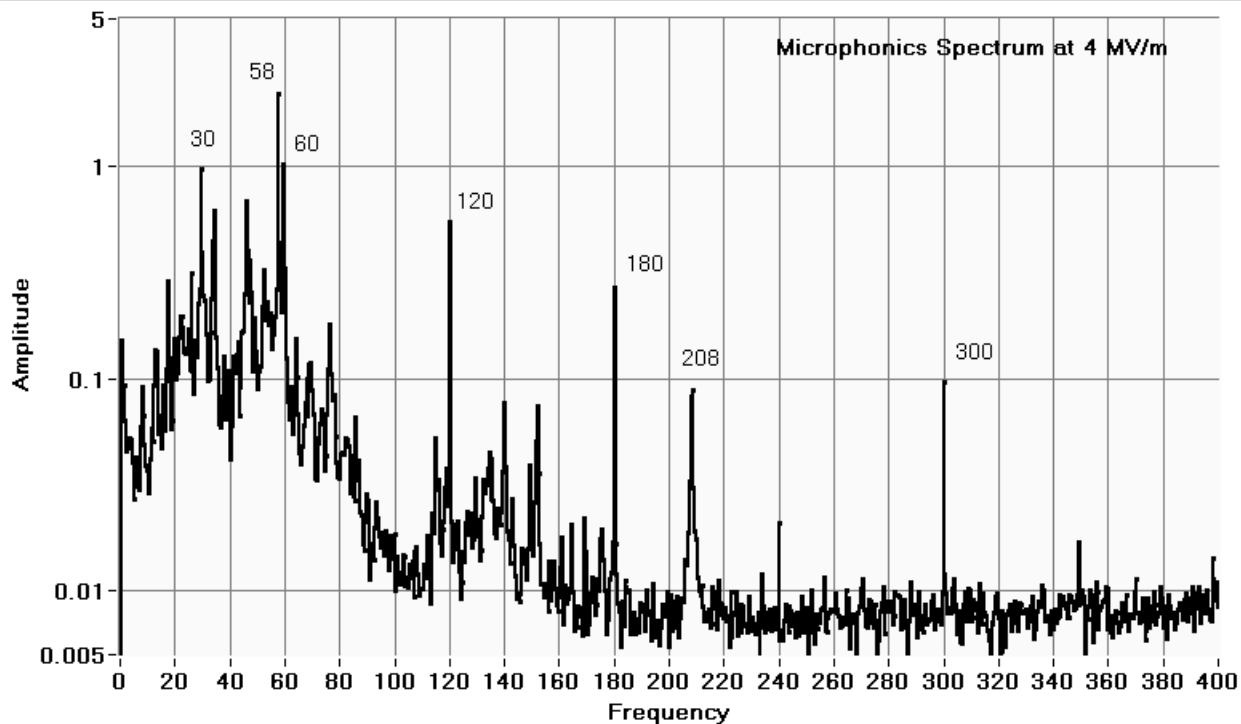
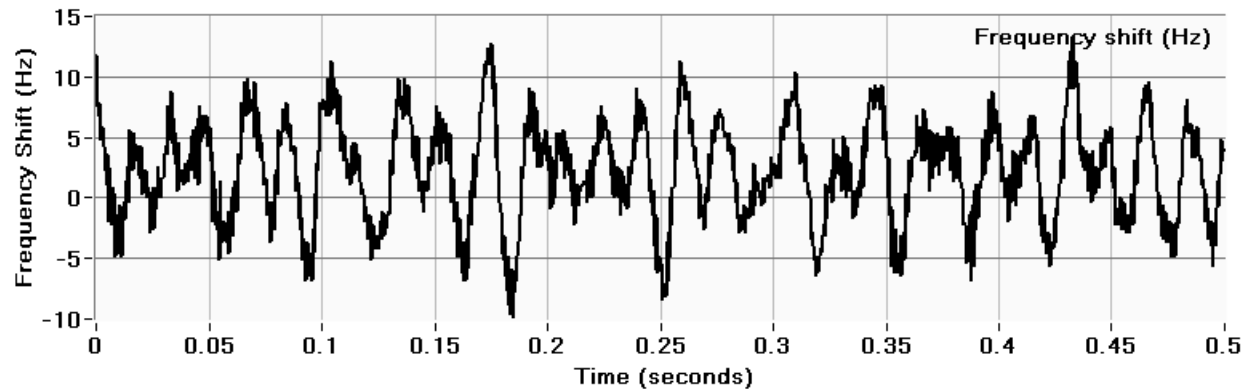


Original Tuner



Stiffened Tuner

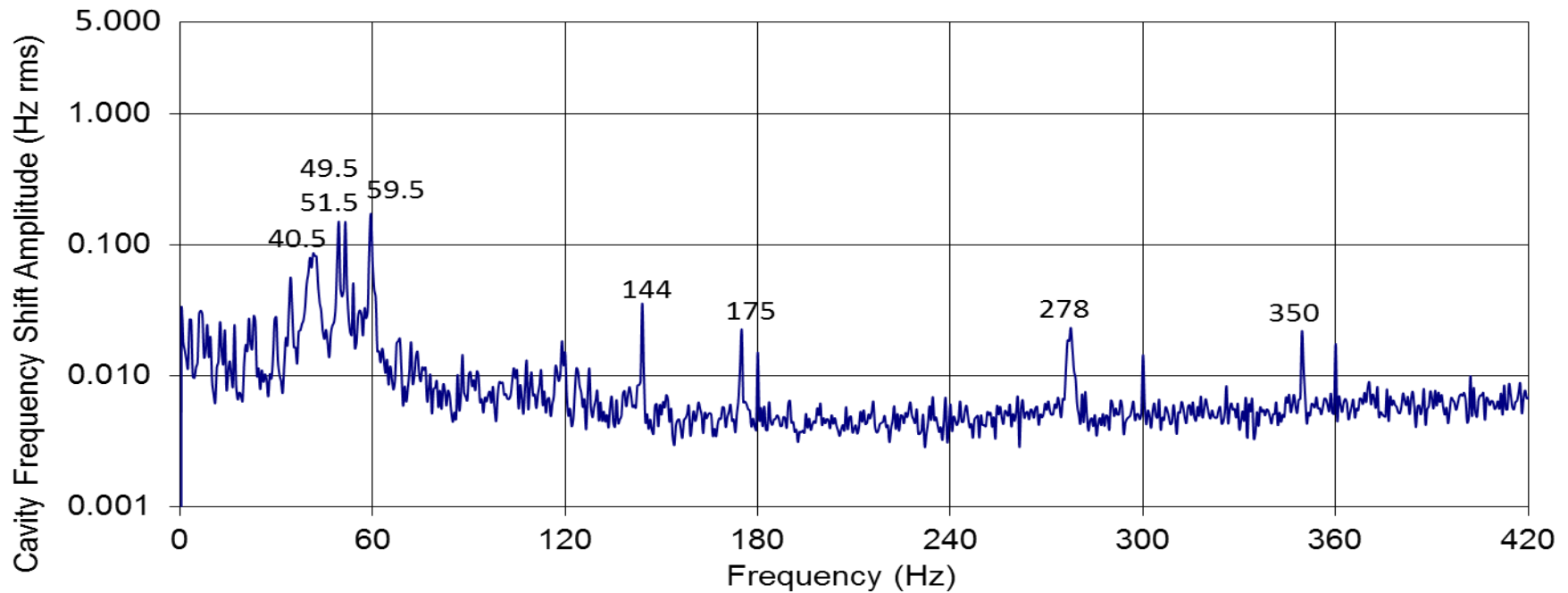
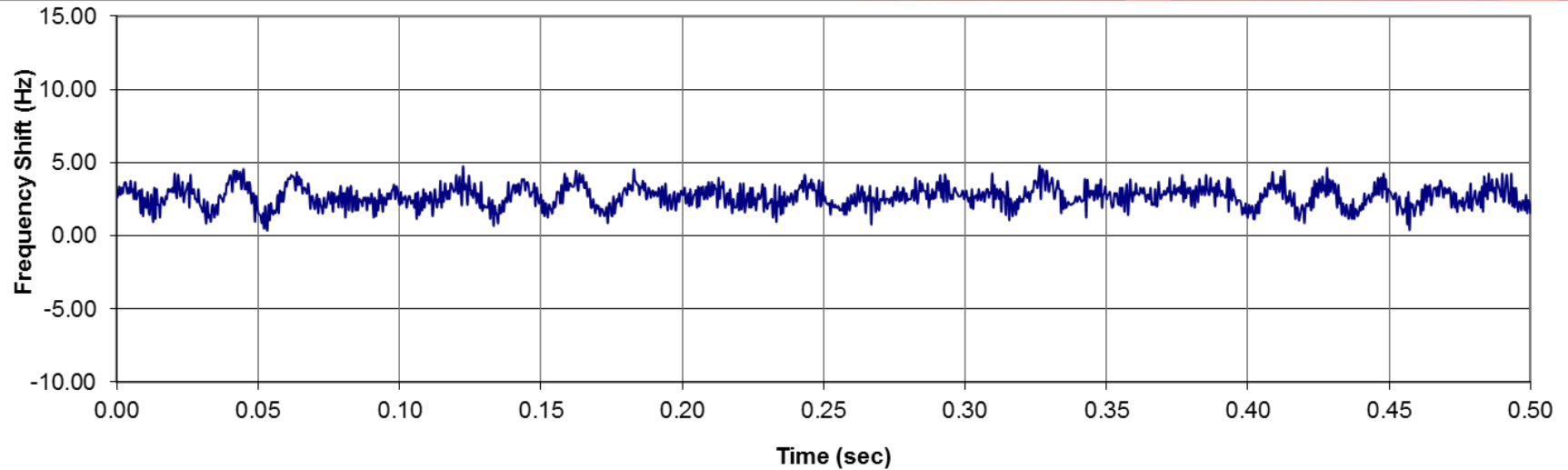
# C50 Cryomodule Microphonics



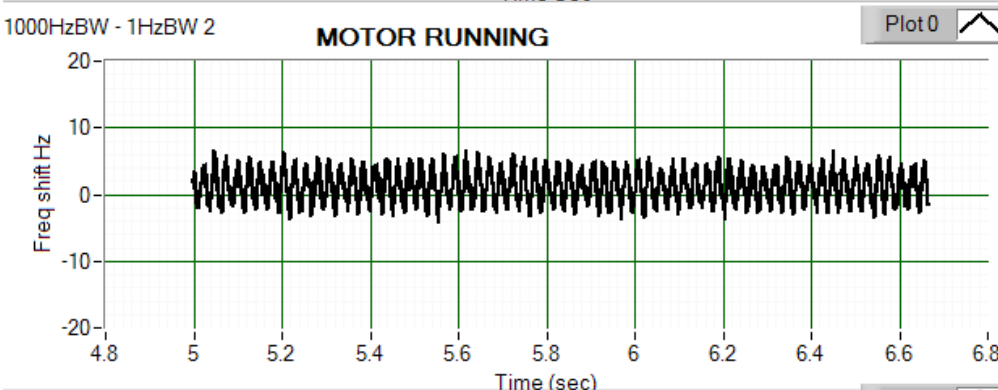
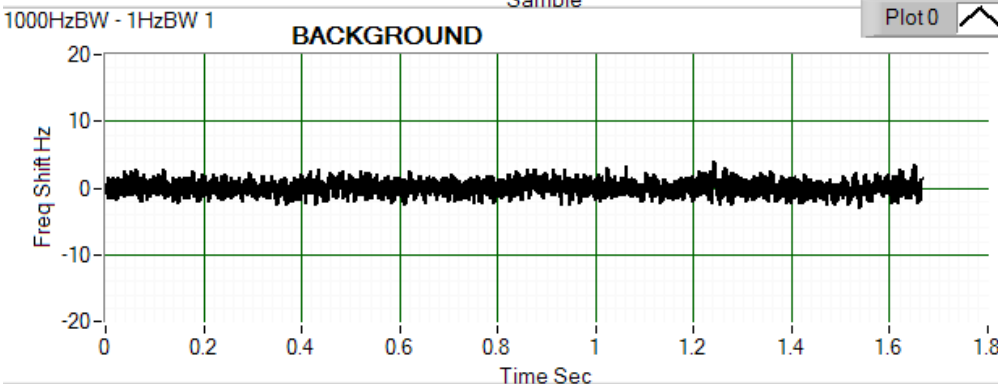
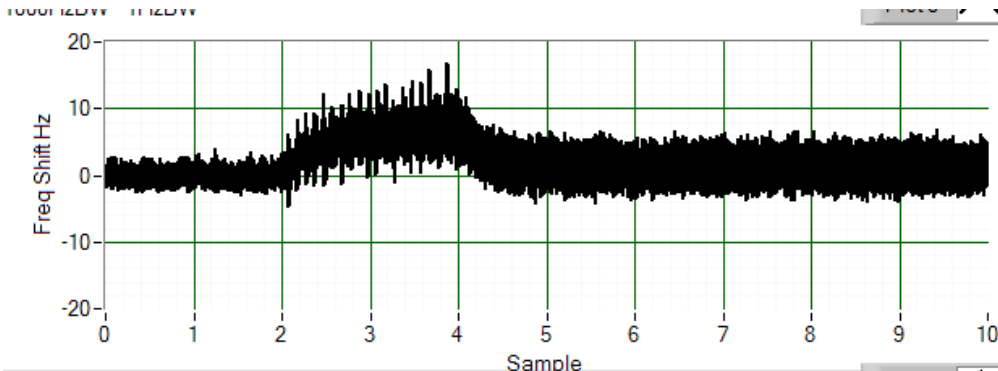
Time domain and frequency domain plots of the background microphonics for a 5-cell CEBAF cavity located in the CEBAF accelerator.

Data taken in Tunnel

# FEL3-6 Microphonics



# FEL3-5 Tuner Running 2 steps/full step



CRM IF Freq during interval 2

0.000333: STOP Get New Data

File Name H:\aatjp working files\FEL Cryomodule 3\FEL3 microphonics 06\_2007\CRM\_062207\_105455.txt

Comment String c:\Labview Data\CRM\_062207\_105455.txt Fel3-5 motor microphonics interface speed 20, half stepping again, 40 steps altogether

Channel name t(sec)

1000 HzBW

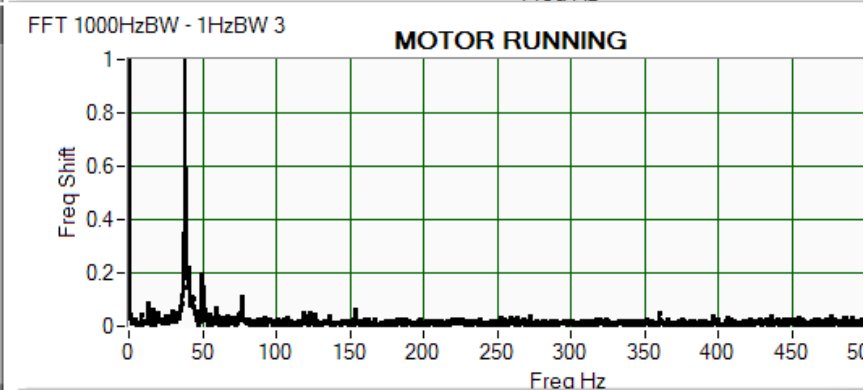
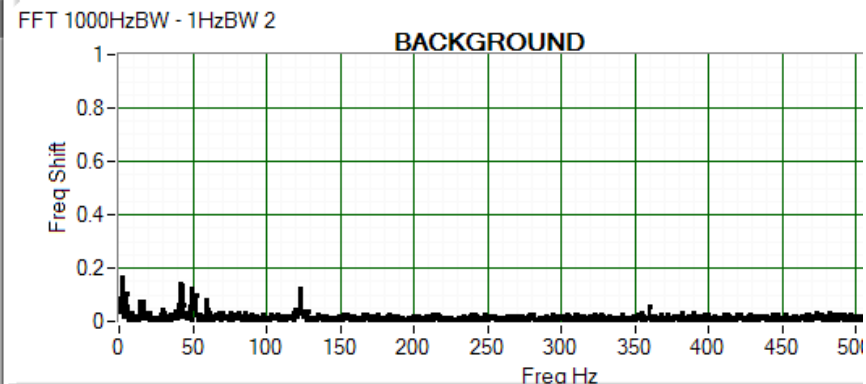
1 HzBW

100HzBW

CRM 1000

CRM 1 Hz

CRM X



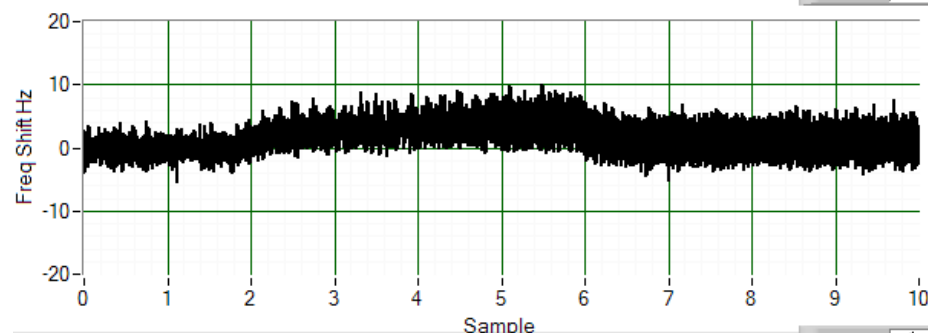
Waveform Graph





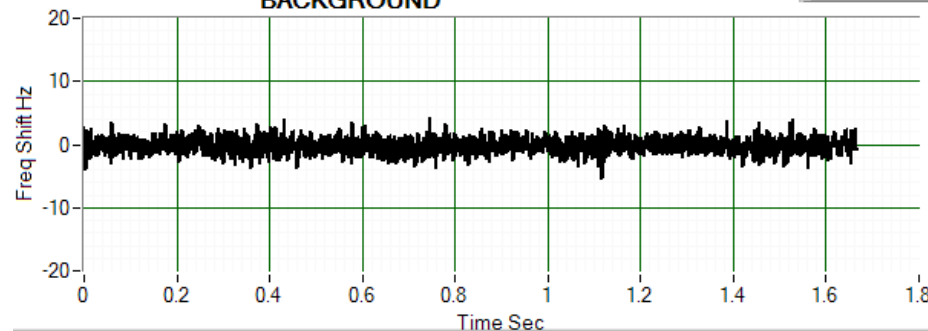
# FEL3-5 Tuner Operations 128 microsteps/step

100HzBW - 1HzBW



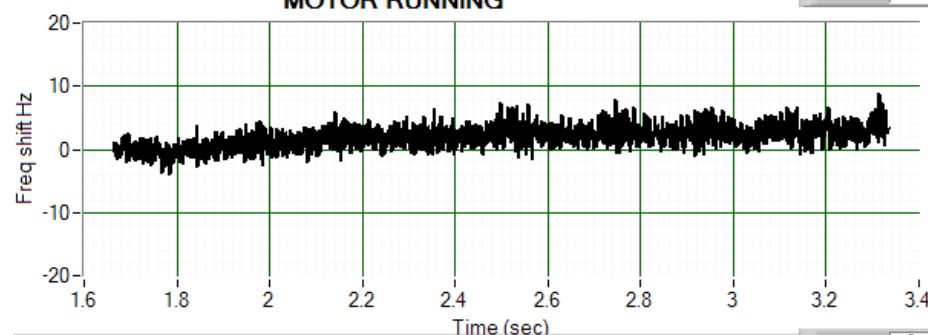
100HzBW - 1HzBW 1

BACKGROUND



100HzBW - 1HzBW 2

MOTOR RUNNING



IF Freq during interval 2

100

dt

0.000333

STOP

Get New Data

File Name

H:\aatjp working files\FEL Cryomodule 3\FEL3  
microphonics 06\_2007\CRM\_062207\_094307.txt

Comment String

c:\Labview Data\CRM\_062207\_094307.txt Fel3-5  
motor microphonics interface speed 640, 128 steps  
per full step, 2560 steps altogether

Channel names

t(sec)

1000 HzBW

1 HzBW

100HzBW-1HzBW

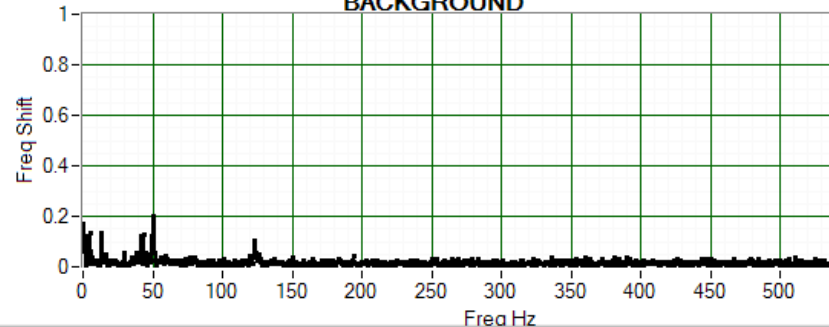
CRM 1000-1 Hz

CRM 1 Hz

CRM 1000-1 Hz

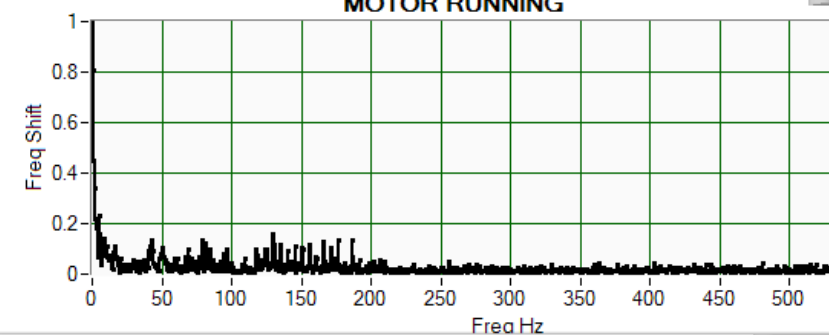
FFT 1000HzBW - 1HzBW 2

BACKGROUND



FFT 1000HzBW - 1HzBW 3

MOTOR RUNNING



Waveform Graph

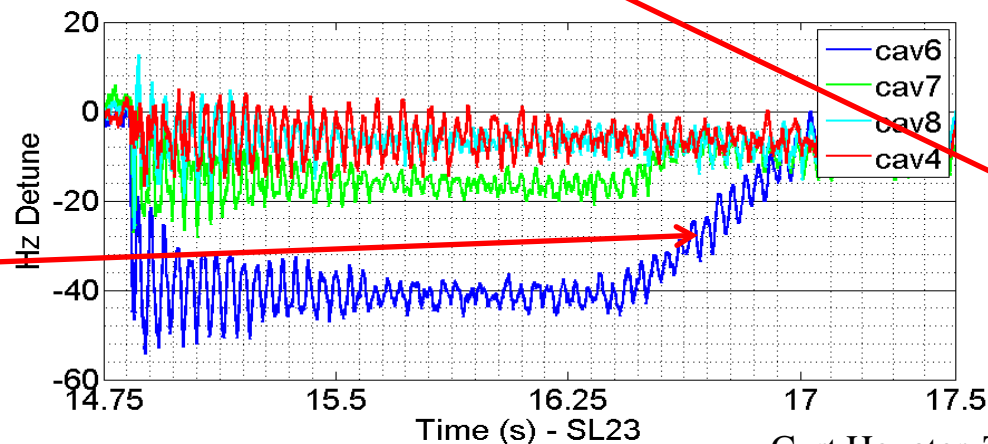
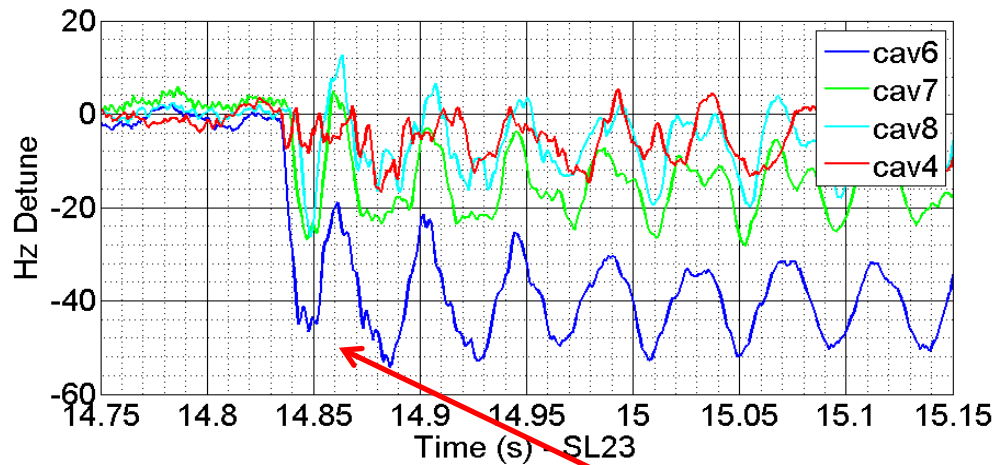
100

1000H

1000H

# DYNAMIC COUPLING BETWEEN CAVITIES

C100-4 Cavities 4, 6, 7, 8 responding to an applied PZT step control voltage change from 52 to 39 volts (130 Volt range) in cavity 5

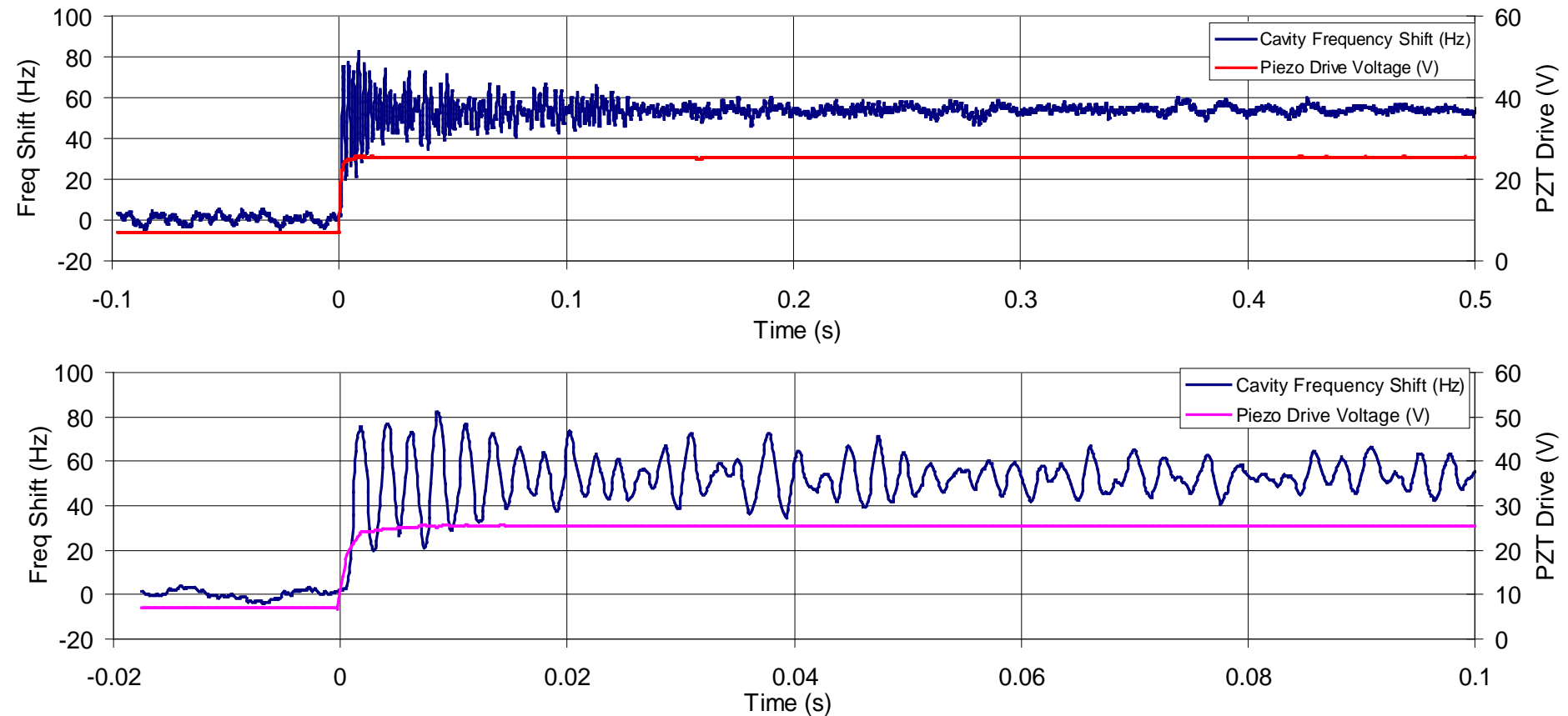


- Adjacent Cavity coupling is ~ 10% between 1-4 and 5-8 cavities
- Cavities 4 and 5 have a “quasi” mechanical support between them.
- Ringings is the 21 Hz mechanical Mode

- Cavity 5 PZT moved 460 Hz.
- Locked in GDR Mode
- Because of 10 MV/m operating point, the klystron had the overhead to keep cavities locked
- Stepper Motor operated to tune the cavities

Curt Hovater, Tomasz Plawski,, Michael Wilson, Rama Bachimanchi

# CRM EXAMPLES



Step response of a cavity excited by a by a 50 Hz step in the piezo tuner controls.  
The total range of this tuner was 550 Hz.

# Choosing Loaded-Q

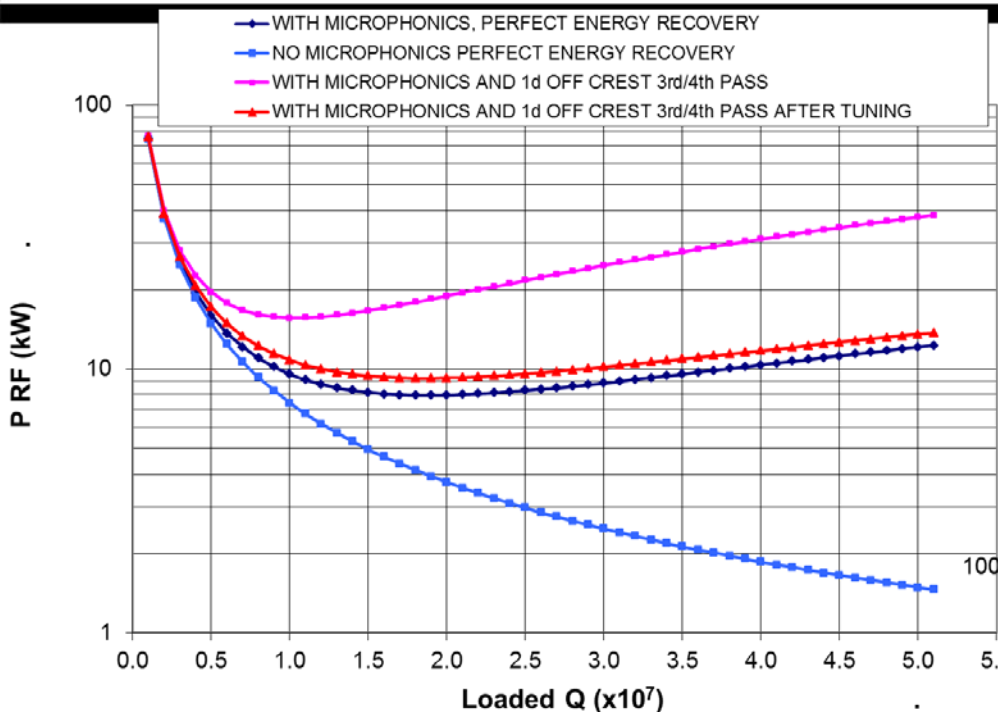
## General equation

$$Q_L|_{MinPower} = \frac{E}{\sqrt{(I_0(r/Q)\cos\psi_B)^2 + \left(2Q_L \frac{\delta f}{f_0} E + I_0(r/Q)\sin\psi_B\right)^2}}$$

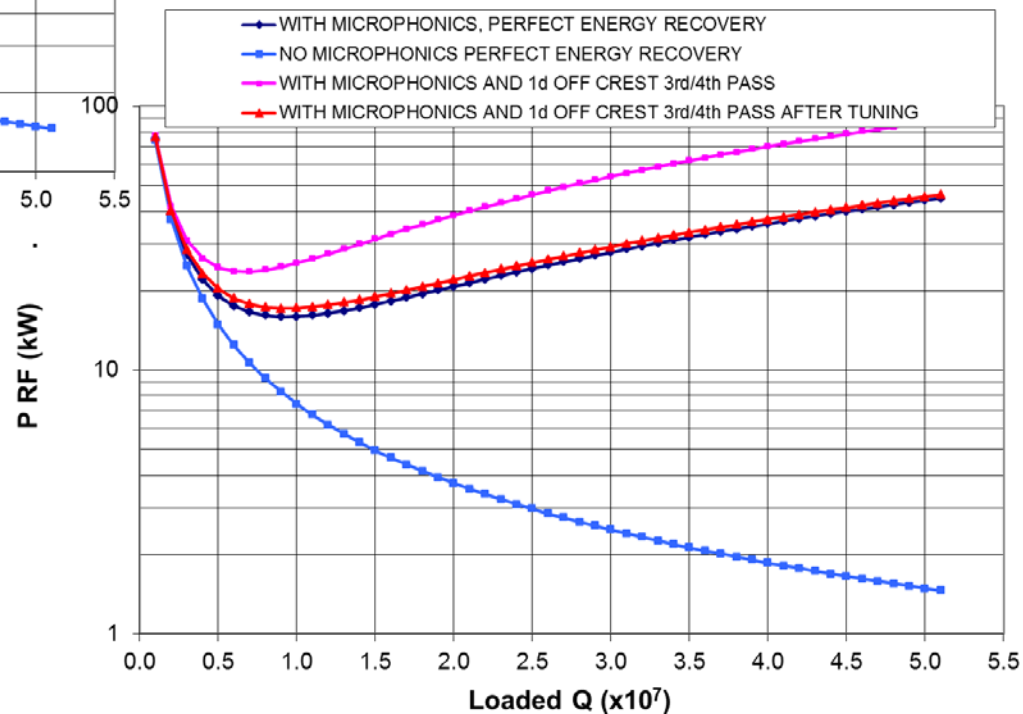
**For an ERL with perfect energy recovery.**

$$Q_L|_{MinPower} \approx \frac{f_0}{2Q_L \delta f}$$

# Power Requirements As a Function of Loaded-Q

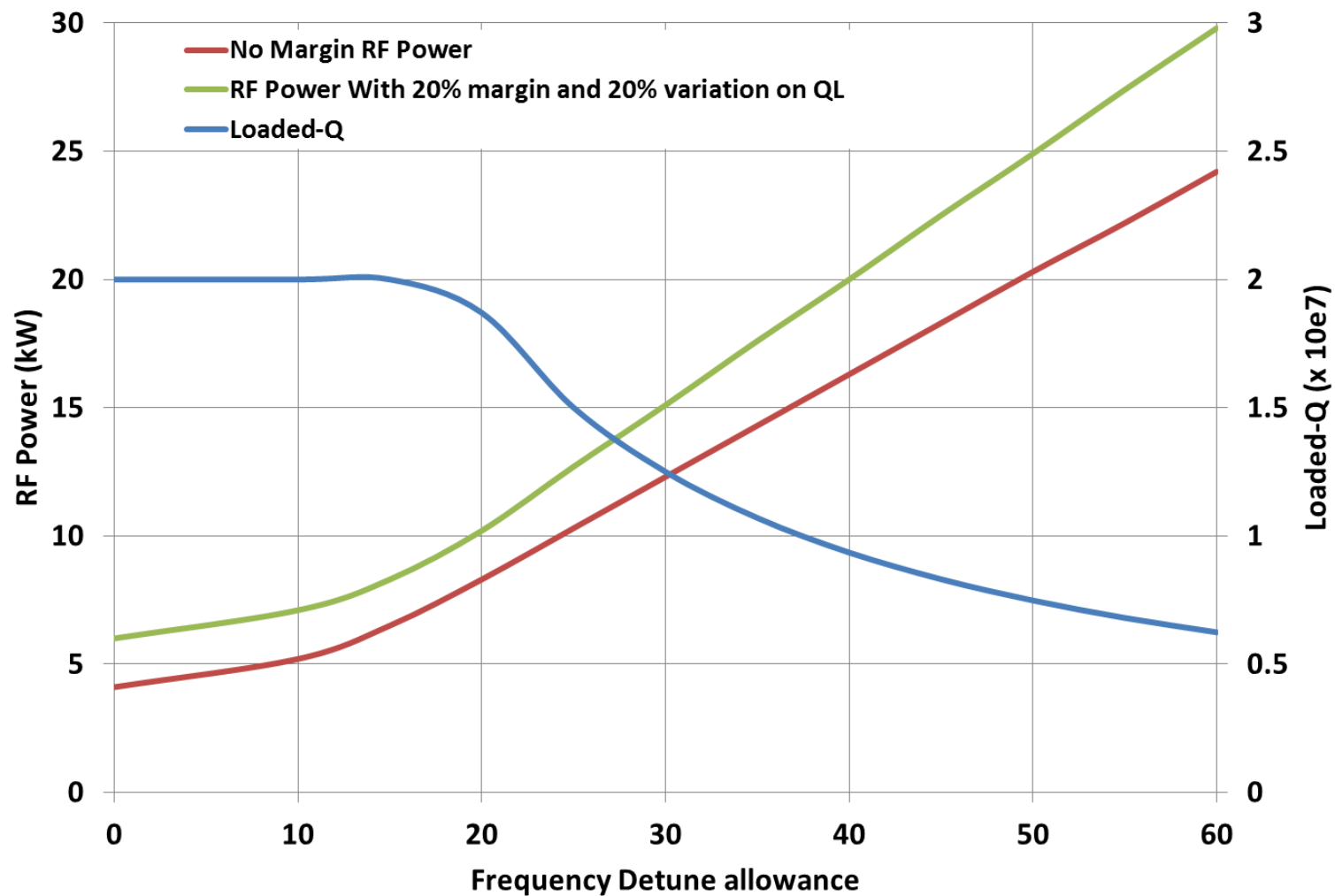


## 40 Hz detune allowance



# Required RF Power Including Margins

## As a function of Detune Allowance





# The Math of Measuring Microphonics

- Neglecting coupler and control system bandwidths, etc. the RF power or voltage necessary to sustain steady state operation are given by the following equations.

$$P_{RF} = \frac{(\beta + 1)}{4\beta Q_L(R/Q)} \left\{ (V_C + I_o Q_L(R/Q) \cos \varphi_B)^2 + \left( 2Q_L \frac{\delta f}{f_0} V_C + I_o Q_L(R/Q) \sin \varphi_B \right)^2 \right\}$$

$$\overrightarrow{V_{RF}} = \sqrt{\frac{Z_0(\beta + 1)}{4\beta Q_L(R/Q)}} \left\{ \overrightarrow{V_C} (1 + iTan \varphi_{RF}) + I_o Q_L(R/Q) (\cos \varphi_B + i \sin \varphi_B) \right\}$$

Where  $\varphi_{RF}$  is the relative phase between the RF drive signal a signal (e.g. field probe signal) which is in phase and proportional to the cavity voltage. Thus as will be discussed later one can use the relative phase between the RF drive signal and the cavity field probe signal to calculate a relative value of  $\delta f$ . Assuming that the beam current is zero this reduces to:

$$\overrightarrow{V_{RF}} = \sqrt{\frac{Z_0(\beta + 1)}{4\beta Q_L(R/Q)}} \left\{ \overrightarrow{V_C} \left( 1 + i2Q_L \frac{\delta f}{f_0} \right) \right\}$$

# Closed Loop RF Drive Requirements

- The bandwidth of the fundamental power coupler is given by the follow:

$$BW = \frac{f_0}{Q_L}$$

- Equation (1) is the steady state equation that does not take into account the time domain nature of the beam loading or microphonics as well as the stored energy within the cavity.
- Ignoring the beam loading and stored energy effects and including the time domain microphonics effects this equation can be written as:

$$\overrightarrow{V_{RF}} = \sqrt{\frac{Z_0(\beta + 1)}{4\beta Q_L(R/Q)}} \left\{ \overrightarrow{V_C} \left( 1 + i2Q_L \frac{\delta f(t)}{f_0} \right) \right\}$$

It can be shown that any frequency dependence of  $\delta f(t)$  is maintained through the phase rotation and that both  $I$  and  $Q$  must be processed as part of the fundamental power coupler compensation.

# Closed Loop Drive Requirements

- If one assumes that:

$$\delta f(t) = \omega_D \sin(\omega_m t)$$

- And that the relative phase shift between the source and the cavity is zero then:

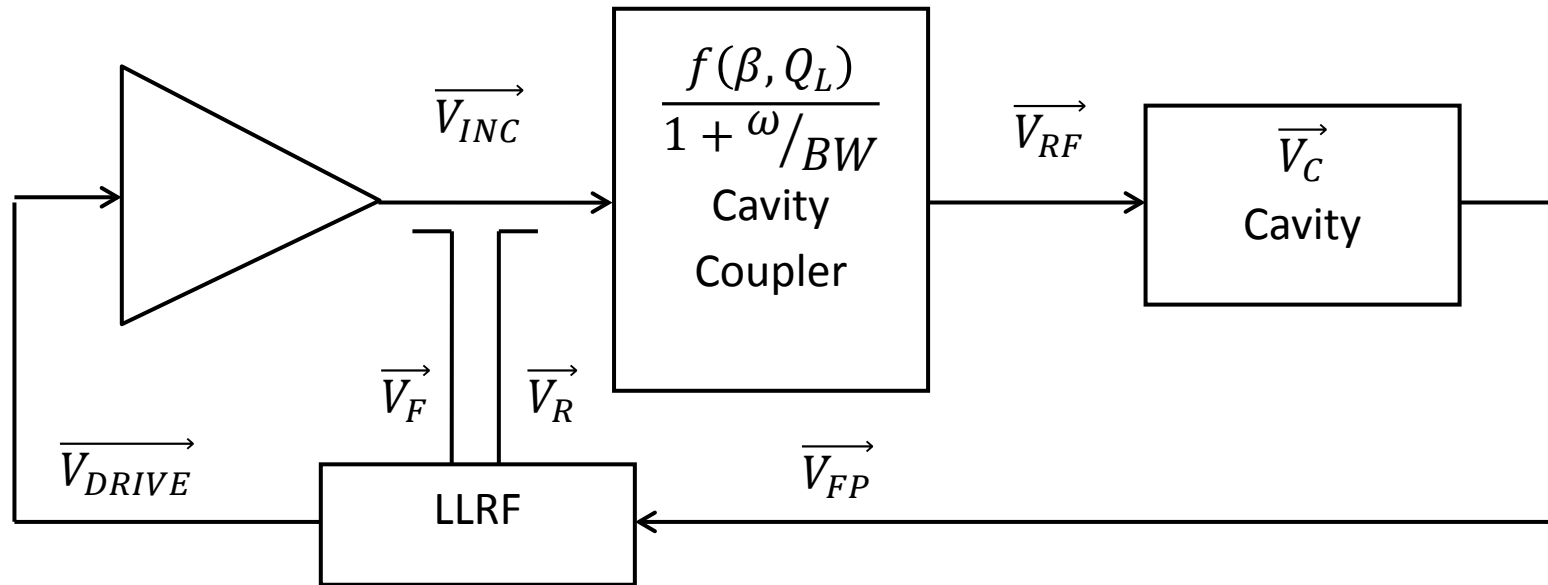
$$\overrightarrow{V_{RF}} = \sqrt{\frac{Z_0(\beta + 1)}{4\beta Q_L(R/Q)}} \left\{ \overrightarrow{V_C} \left( \cos(\omega_0 t) + 2Q_L \frac{\omega_D \sin(\omega_m t)}{f_0} \sin(\omega_0 t) \right) \right\}$$

- Rewriting this in complex form:

$$\overrightarrow{V_{RF}} = \sqrt{\frac{Z_0(\beta + 1)}{4\beta Q_L(R/Q)}} \left\{ \overrightarrow{V_C} \left( 1 + j2Q_L \frac{\omega_D \sin(\omega_m t)}{f_0} \right) \right\}$$

# Closed Loop Drive Requirements

- Looking at the closed loop control system block diagram:



- What you are really measuring is  $\vec{V}_{INC}$ . To understand what the cavity is actually doing you must apply a low pass filter to the I/Q data prior to processing.
- Conversely if one wants to understand the real RF power requirements one must model the system with the predicted microphonics and a cavity model that includes the coupler bandwidth.

# Microphonics Measurements when using a frequency tracking source

The goal is to come up with a way to calculate microphonics frequency from some basic RF measurement that is insensitive to magnitude.

The equation for an RF signal that is frequency modulated at a frequency of  $\omega_m$  with a modulation depth (or frequency shift) of  $\omega_D$  and an RF frequency of  $\omega_0$  is given by:

$$V(t) = V_{Peak} \cos\left(\omega_0 t + \omega_1 t + \frac{\omega_D}{\omega_m} \sin(\omega_m t)\right) = V_{Peak} \cos(\omega_0 t + \varphi(t))$$

In this method one uses the concept that an RF signal at a frequency of  $\omega_0$  can be written in the form:

$$V = V_{Peak} (I(t) \cos(\omega_0 t) + Q(t) \sin(\omega_0 t))$$

Applying this to the above equation leads to:

$$V(t) = V_{Peak} \cos(\omega_0 t + \varphi(t))$$

$$V(t) = V_{Peak} \cos(\varphi(t)) \cos(\omega_0(t)) - V_{Peak} \sin(\varphi(t)) \sin(\omega_0(t))$$

# Microphonics Measurements when using a frequency tracking source

It can be shown that.

$$Q \frac{dI}{dt} - I \frac{dQ}{dt} = V_{Peak}^2 \frac{d\phi(t)}{dt}$$

OR

$$\frac{1}{2\pi V_{Peak}^2} \left( Q \frac{dI}{dt} - I \frac{dQ}{dt} \right) = f(t)$$

Nominally  $V_{Peak}$  is  $\frac{1}{2}$  the peak-to-peak value of the sine waveforms that are collected in the  $I$  and  $Q$  data stream, that is achieved when acquiring the data using a  $I/Q$  based receiver system. However, if the  $I/Q$  receiver happens to be very close ( $\omega_0 + \omega_1$ ) then  $I$  and  $Q$  will be DC or close to DC values (i.e. a full sine or cosine waveform is not collected in the data set. In this case one needs to calculate the magnitude of  $V_{Peak}$  on a point by point basis as:

$$V_{Peak}^2(t) = I^2(t) + Q^2(t)$$



# Microphonics Measurements when using a frequency tracking source

If one has a discrete data stream the general form of the frequency shift is given by:

$$f_{i+1} = \frac{1}{2\pi(Q_i^2 + I_i^2)} \left( Q_i \frac{I_{i+1} - I_i}{\Delta t} - I_i \frac{Q_{i+1} - Q_i}{\Delta t} \right)$$

Which can be reduced to:

$$f_{i+1} = \frac{(Q_i I_{i+1} - I_i Q_{i+1})}{2\pi \Delta t (Q_i^2 + I_i^2)}$$

Another way to approach the problem is to look at just the  $I$  term in equation from two slides ago which is:

# Microphonics Measurements when using a frequency tracking source

Another way to approach the problem is to look at just the  $I$  term in equation from two slides ago which is:

$$I(t) = V_{Peak} \cos(\varphi(t)) = \sqrt{I^2(t) + Q^2(t)} \cos(\varphi(t))$$

Solving for  $\varphi(t)$

$$\varphi(t) = \cos^{-1} \left( \frac{I(t)}{\sqrt{I^2(t) + Q^2(t)}} \right)$$

There is digital signal processing techniques known as a CORDIC algorithm [Lang, Antelo] which allows one to calculate the inverse cosine function efficiently. This would provide you with a sampled signal set of  $\varphi(t)$ . If this is done then one can calculate the frequency shift as.

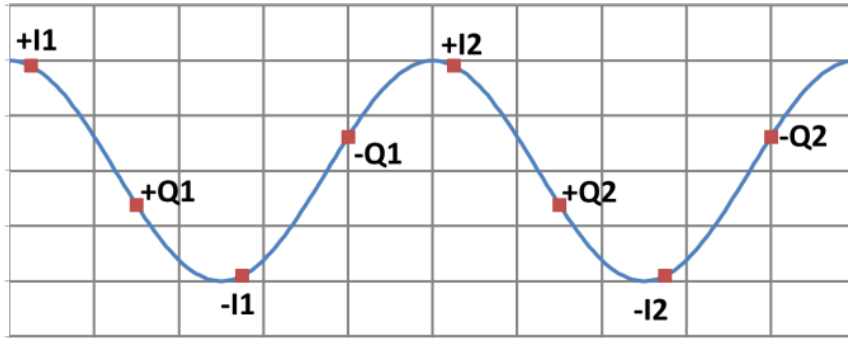
$$\Delta f = \frac{\varphi_{i+1} - \varphi_i}{2\pi\Delta t}$$

One can also take the derivative of the inverse cosine function above and show that:

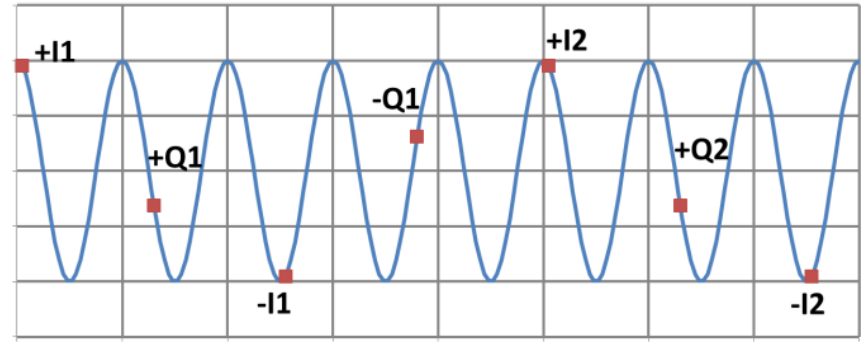
$$f_{i+1} = \frac{(Q_i I_{i+1} - I_i Q_{i+1})}{2\pi\Delta t (Q_i^2 + I_i^2)}$$

# Approaches to Acquiring I/Q Data Stream

There are two basic approaches to acquiring a digital I/Q data stream. In the first, called synchronous acquisition, the RF signal is down converted to an intermediate frequency and sampled at a frequency that is either 4, 1/1.25, 1/2.5, 1/5 . . . times the nominal IF frequency. When this is done and the actual IF frequency the sampled points are as shown below:



Sampled at 4 times the IF frequency



Sampled at 1/1.25 times the IF frequency.

Using this approach provides a data stream  $v_1, v_2, v_3, \dots$  and I and Q are given by:

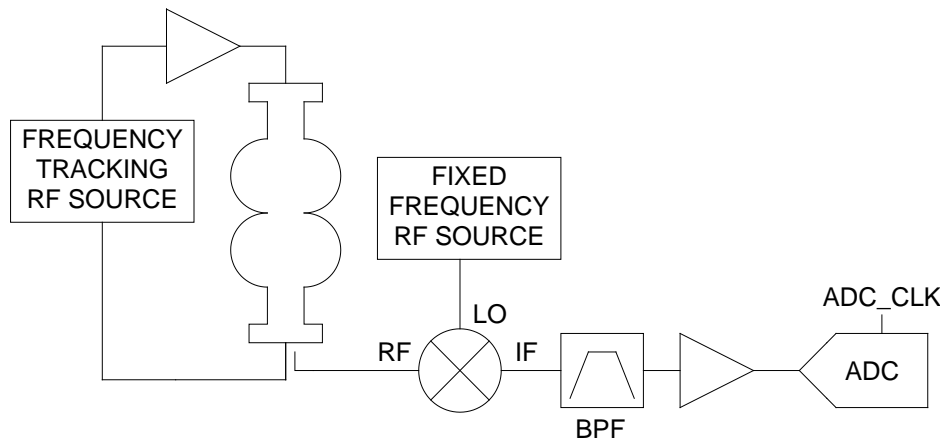
$$I_k = v_{4k} - v_{4k+2} \quad \text{and} \quad Q_k = v_{4k+1} - v_{4k+3}$$

# Approaches to Acquiring I/Q Data Stream

If the RF IF frequency is not precisely related to the sample frequency by the ratio 4, 1/1.25, 1/2.5, 1/5 . . . the I and Q signals will have the form:

$$I(t) = V_{Peak} \cos(\omega_1 t + \varphi(t)) \quad Q(t) = -V_{Peak} \sin(\omega_1 t + \varphi(t))$$

Where  $\omega_1$  is the difference frequency between the ideal IF frequency and the actual IF frequency. One can implement such a system using a simple mixer to down convert the RF signal to an IF frequency as shown below to collect the data.



Example Parameters:

IF = 400 kHz,

ADC clock = 320 kHz

Filter BW = 200 kHz

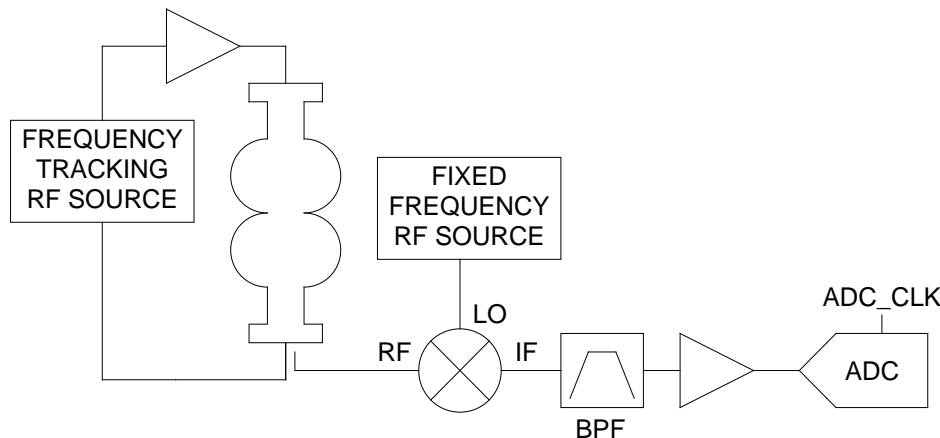
We will try this next week.

# Approaches to Acquiring I/Q Data Stream

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Where  $\omega_1$  is the difference frequency between the ideal IF frequency and the actual IF frequency. One can implement such a system using a simple mixer to down convert the RF signal to an IF frequency as shown below to collect the data.



## Example Parameters

**CEBAF 12 GeV Field Control Chassis:**

IF = 70 MHz,

ADC clock = 56 MHz

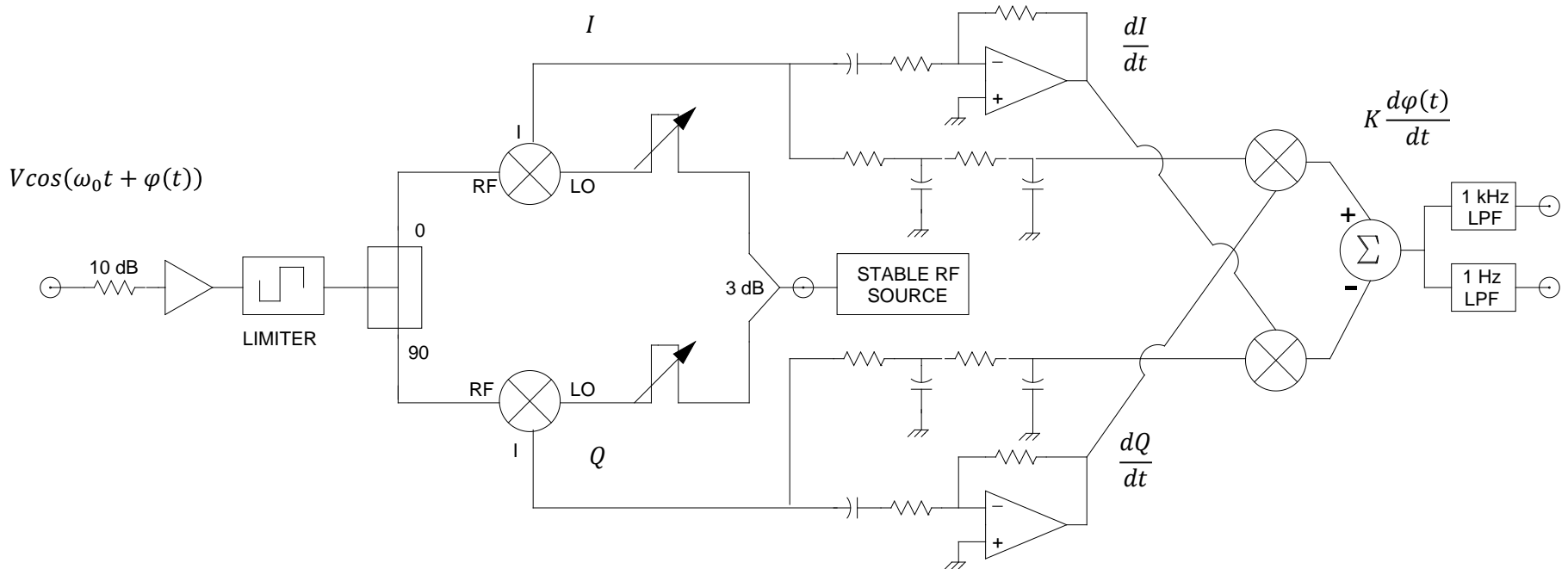
Filter BW = 5 MHz

DSP filter bandwidths  $\approx$  30 kHz variable

We will also use one of these next week.

# Approaches to Acquiring I/Q Data Stream

Alternately one can use an analog cavity resonance monitor.



- The front end circuitry requires careful tuning to ensure precise I/Q demodulation.
- The limiting amplifier is used to stabilize the gain in the system. Without it a separate power measurement would have to be made in order to calibrate the output signals.
- The analog baseband electronics provides the mathematical function of:  $\left( Q \frac{dI}{dt} - I \frac{dQ}{dt} \right)$



# Application of Filters

$$V_{Baseband}(t) = V_{Peak} \cos \left( \omega_1 t + \frac{\omega_D}{\omega_m} \sin(\omega_m t) \right)$$

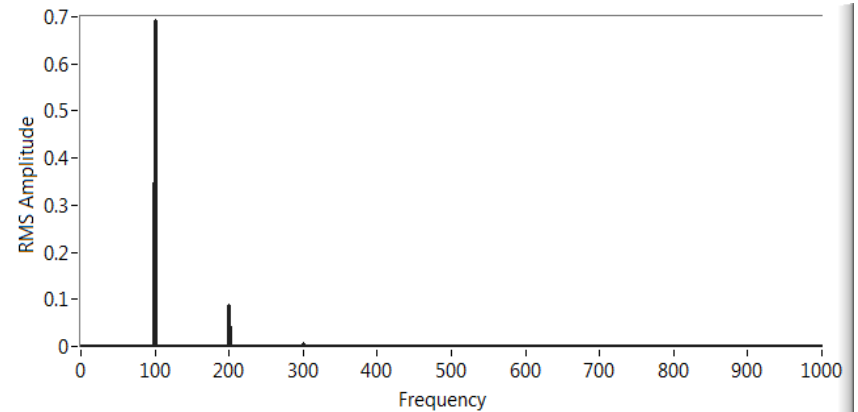
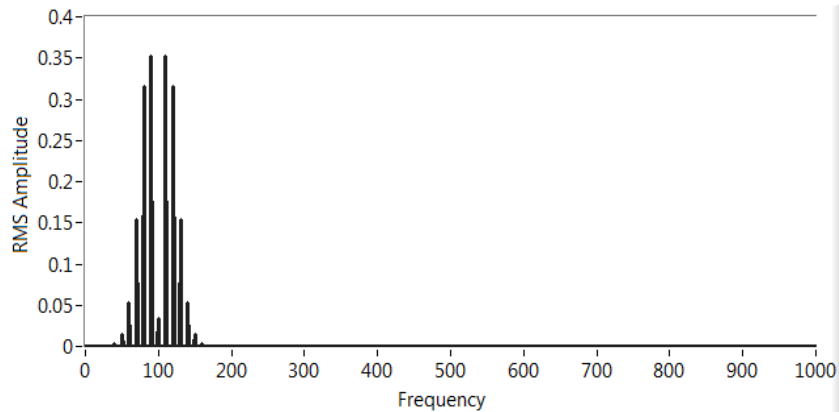
This is the formula for an FM modulated signal. The solution has the form of Bessel functions.

$$\frac{V(t)}{V_{Peak}} = \cos(\omega_1 t) \left[ J_0(m) + 2 \sum_{k=1}^{\infty} (-1)^k J_{2k}(m) \cos(2k\omega_m t) \right] \\ + \sin(\omega_1 t) \left[ 2 \sum_{k=0}^{\infty} (-1)^k J_{2k+1}(m) \cos((2k+1)\omega_m t) \right]$$

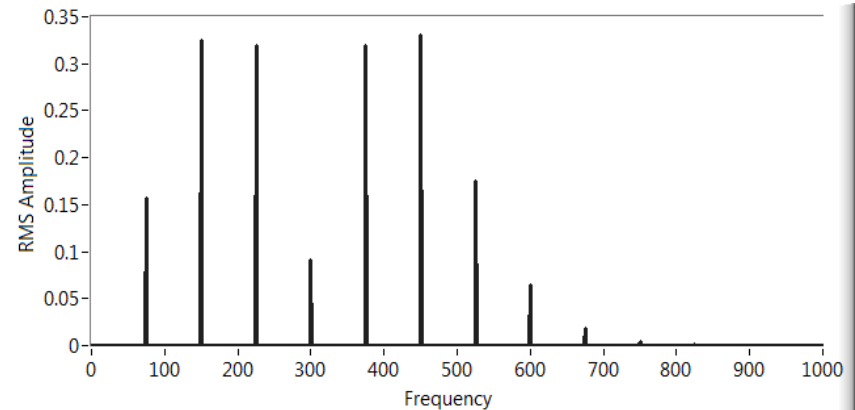
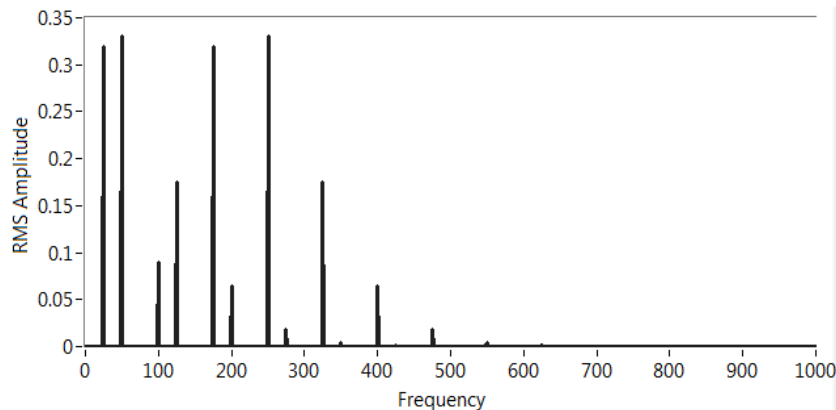
Where:

$$m = \frac{\omega_D}{\omega_m}$$

# Example Spectra for FM Modulation

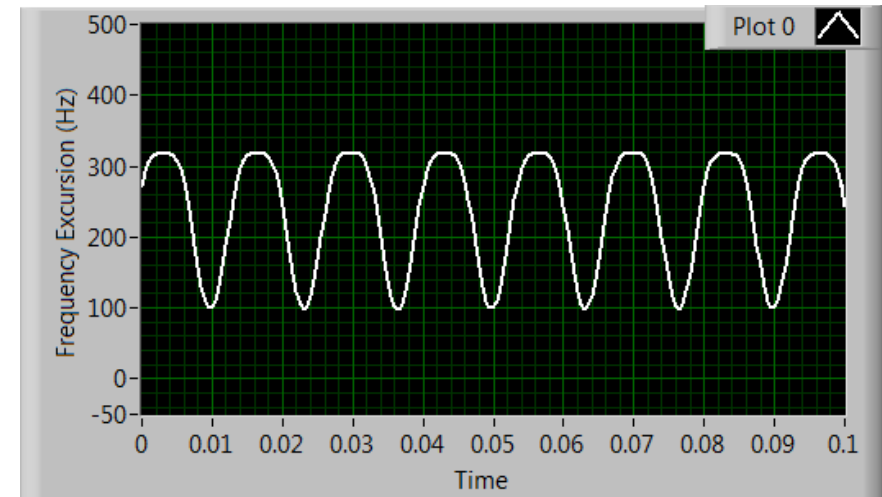
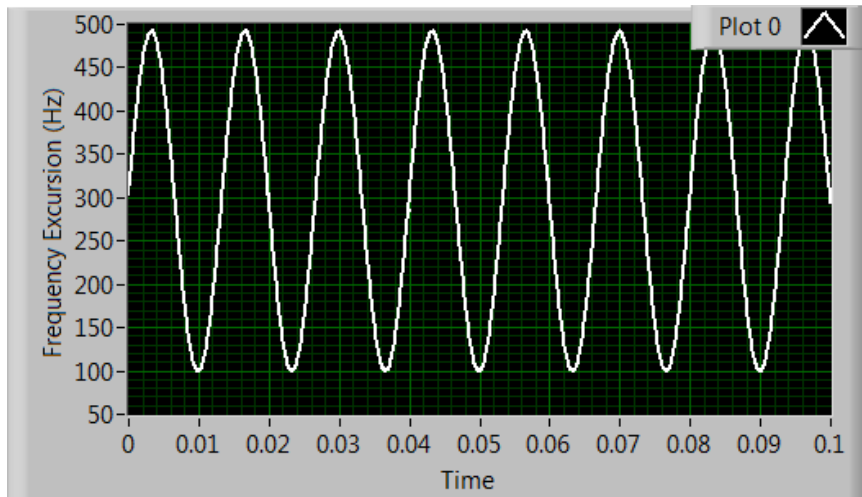
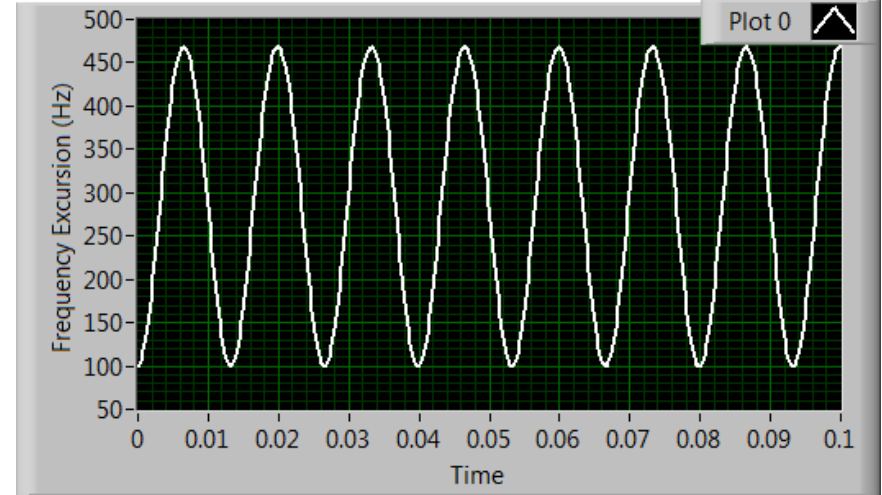
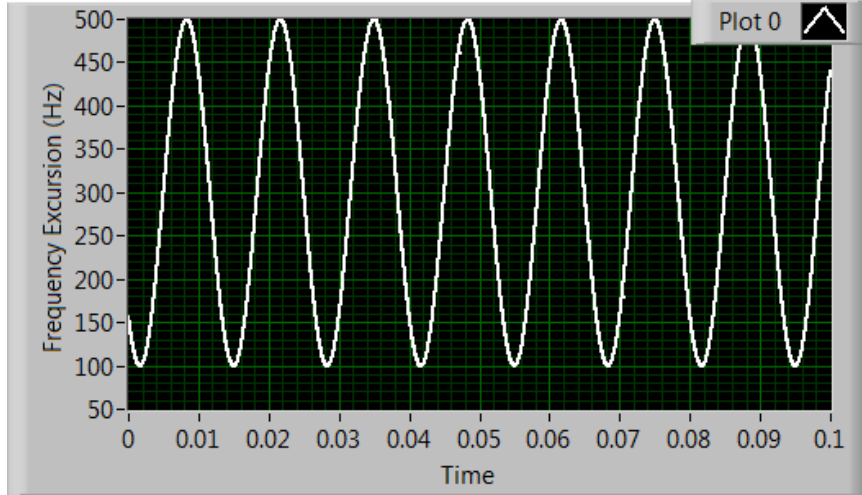


Spectrum of I for (Left)  $f_D = 25$  Hz,  $f_M = 10$ ,  $f_I = 100$  and  $M = 2.5$ , (Right)  $f_D = 25$  Hz,  $f_M = 100$ ,  $f_I = 100$  and  $M = 0.25$ .



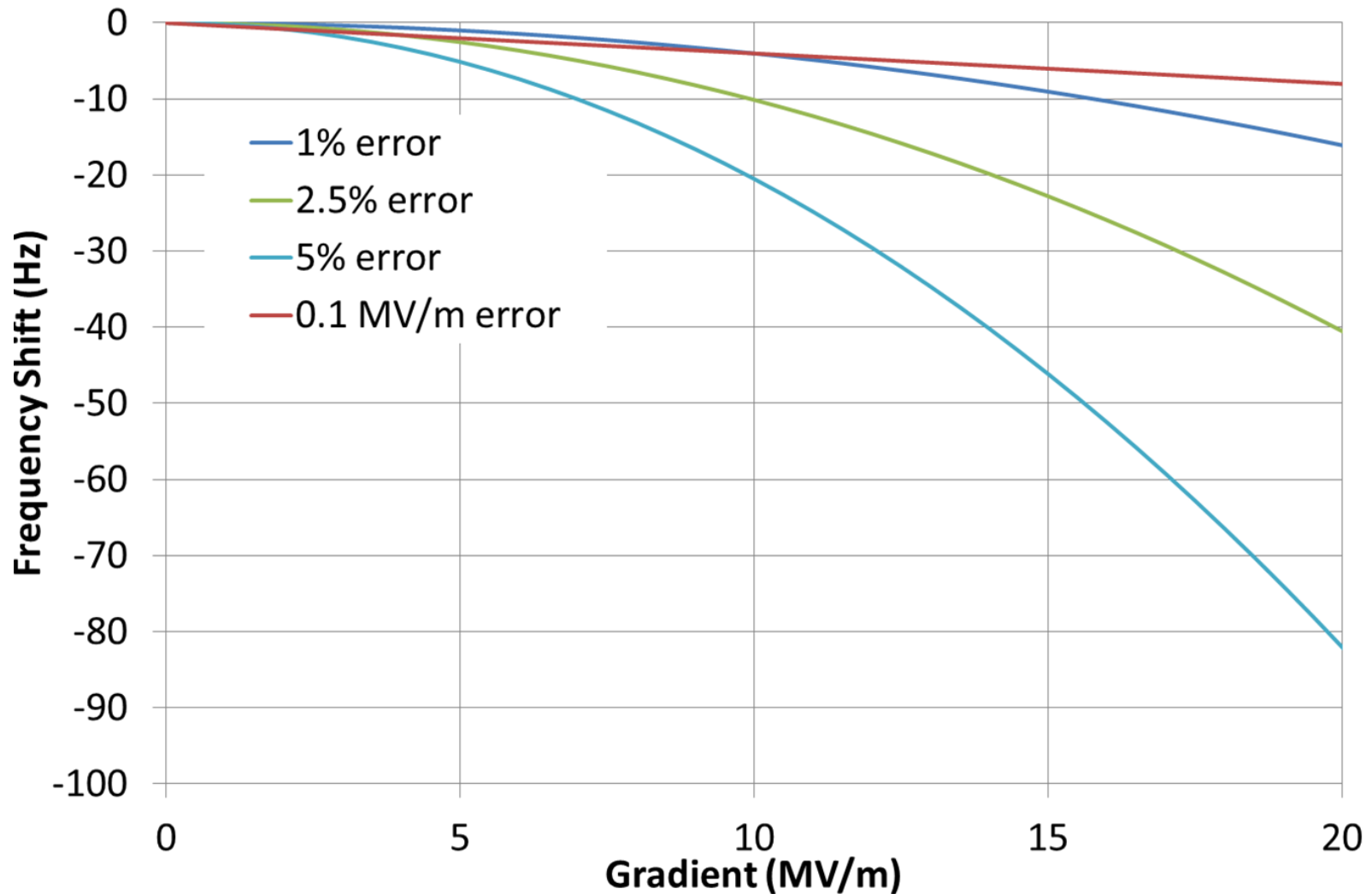
Spectrum of I for (Left)  $f_D = 200$  Hz,  $f_M = 75$ ,  $f_I = 100$  and  $M = 2.66$ , (Right)  $f_D = 200$  Hz,  $f_M = 75$ ,  $f_I = 300$  and  $M = 2.66$

# Effect of Sample Rate in Digitized System

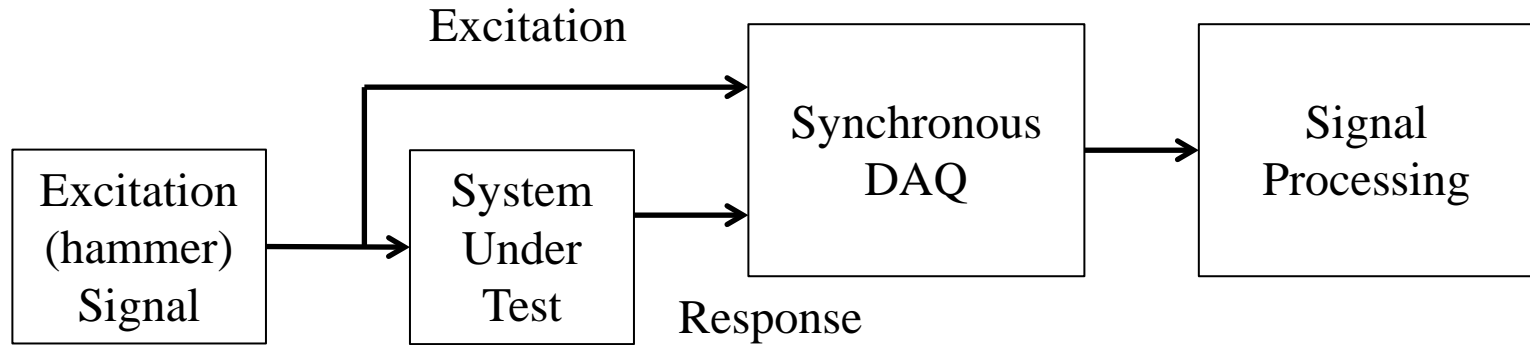


Time domain plot of the data from figure 3 sampled at (Top Left) 100 kS/s, (Top Right) 10 kS/s, (Lower Left) 5 kS/s and (Lower Right) 2 kS/s

# Lorentz Force Effect on Cavity Frequency as a Function of Gradient and for Different Instabilities in the Gradient with $M=2$



# Impulse Response Test Math



$$\text{Transfer Function. } \vec{H}(\omega) = \frac{\text{avg}(\vec{Y}(\omega))}{\text{avg}(\vec{X}(\omega))}$$

$$\text{Coherence. } C(\omega) = \frac{\text{avg}(\vec{X}^*(\omega)\vec{Y}(\omega))^2}{\text{avg}(\vec{X}(\omega)\vec{X}^*(\omega)) \text{avg}(\vec{Y}(\omega)\vec{Y}^*(\omega))}$$

# Math

## **Transfer Function.**

Complex FFT is performed of the excitation and response signals. Because both real and imaginary information is included the transformed data contains all of the information in the original signal.

The transfer function is calculated in the frequency domain and both phase and amplitude are plotted.

## **Coherence**

- Coherence is an indication that the system response is caused by the excitation.
- Coherence is calculated on a point by point basis in the frequency domain.
- Coherence is used to distinguish between responses that are driven by the excitation and the system response. If the system has vibrational characteristics that are driven by outside sources the coherence value will be less than one.
- Coherence **REQUIRES** averaging.