Practical Aspects of SRF Cavity Testing and Operations

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SRF Workshop 2019

Tutorial Session

Note: Due to time limitations some of the slides in this presentation were not presented during the oral tutorial. They were moved from the backup slide section to the main body of the presentation for this version.

INTRODUCTION

Over the past 30 years we have done about 6500 cold cavity tests on more than 800 different cavities at Jefferson Lab. Most of these tests were done with voltage controlled oscillator based phase locked loop systems. More recently we converted most of our systems to digital low level RF based systems. In addition to doing many of these test myself, I have been involved with the development, construction and commissioning of several cavity test systems and the software used to control them.

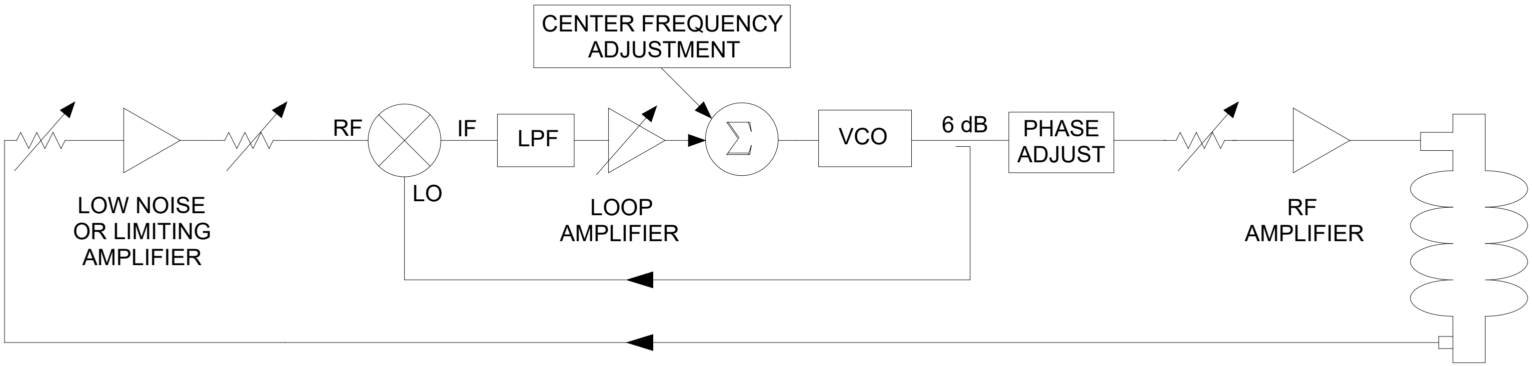
My hope today is to provide you with a basic understanding of the RF systems necessary to perform these tests. I hope you leave here with an understanding of the importance of calibration processes and the control and understanding of potential error sources. I will also provide some information relating to the practical aspects of operating SRF cavities in real machines.

Hopefully, A complete set of equations necessary for calculating the cavity parameters and can be found on the website for this conference as an addendum to this talk.

OVERVIEW

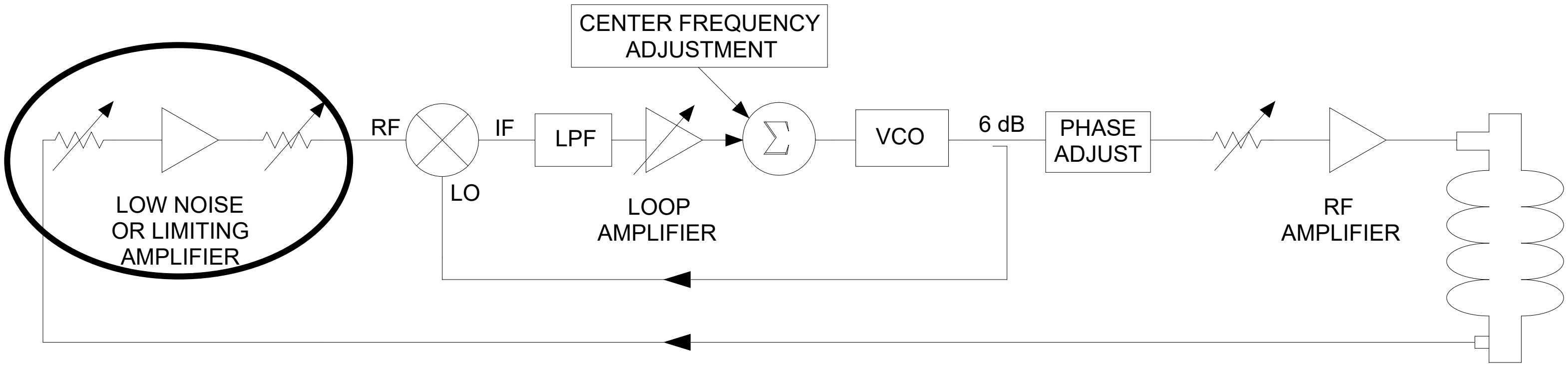
- Voltage controlled oscillator based phase locked loops
- Digital LLRF for cavity testing.
- RF system overview for cryomodule testing.
- Software for vertical and horizontal testing.
- Coupler conditioning vacuum-RF feedback loop.
- Cable calibrations
- Basic RF equations for critically coupled cavities.
- Basic RF equations for over coupled cavities.
- Qo measurements for cryomodules.
- What could go wrong? Cable breakdown, multipactors, Q-switch . . .
- Cryomodule interlocks
- Practical operational aspects of SRF cavities.

BASIC VCO-PLL



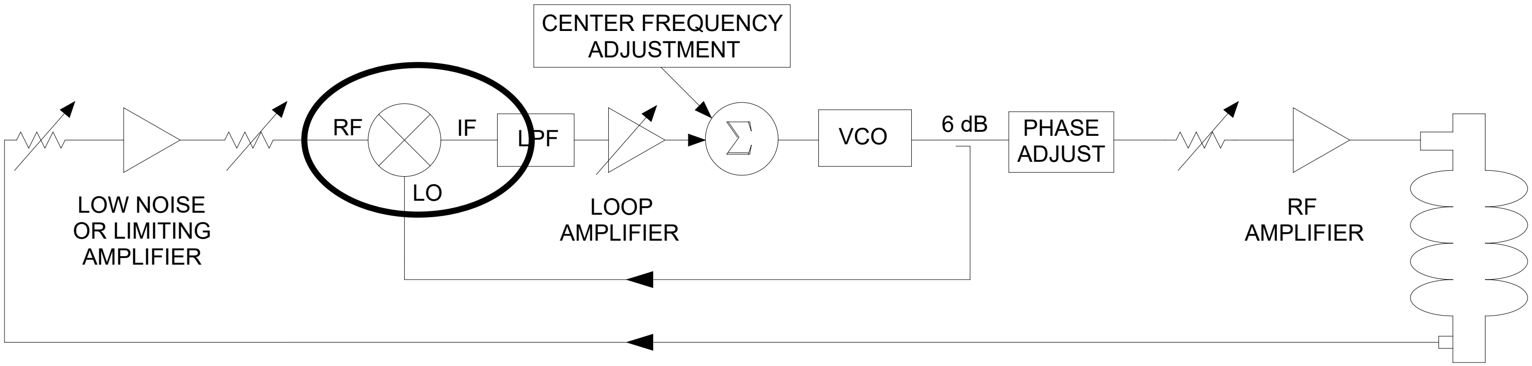
- **Two fundamental ways to drive a cavity.**
  - **Fixed frequency systems are used in conjunction with resonance controls like motorized tuners when operating fixed frequency systems in accelerators.**
  - **Variable frequency systems are used to simplify the system or to test cavities which do not have tuners attached.**
- **During vertical testing cavity bandwidths on the order of 1 Hz are not uncommon, it would be extremely difficult to maintain the cavity's frequency while testing.**
- **At Jefferson Lab we commonly use voltage controlled oscillator based phase locked loops to track the cavity frequency during the test.**

BASIC VCO-PLL



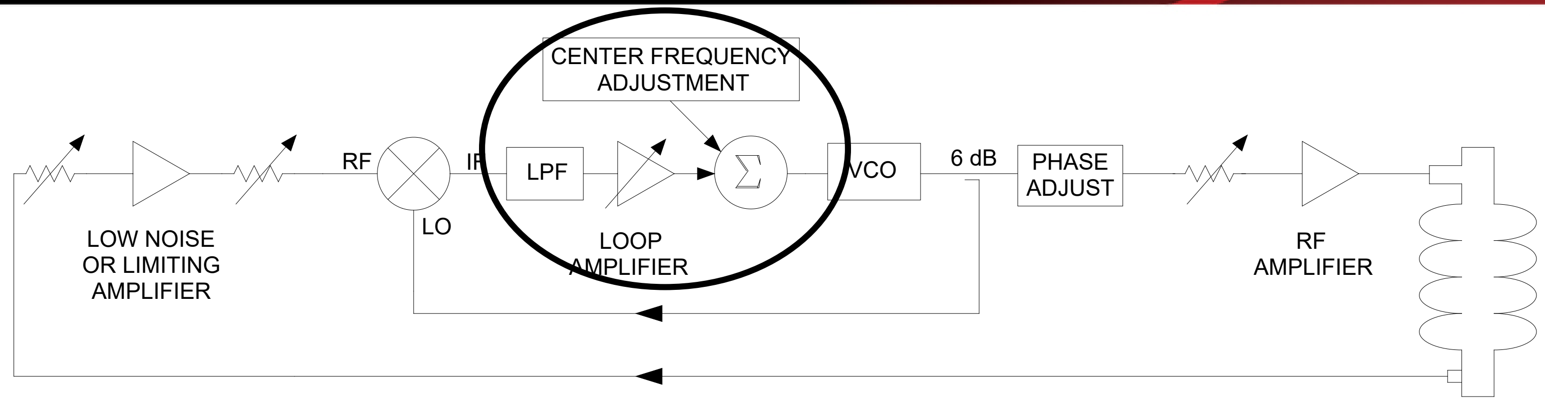
- **The front end generally makes use of a low noise amplifier and a series of variable attenuators which are used to:**
  - **Keep the mixer RF level below the maximum level, typically 6 dB below the design LO.**
  - **Ensure that the mixer and following loop amplifier, crystal detectors, etc. are not power starved.**
  - **Help to avoid loop oscillations.**
- **The loop gain is proportional to the cavity gradient. Thus a system that behaves well at 2 MV/m will very likely oscillate at 20 MV/m, unless the loop gain is reduced at higher gradient.**
- **Although difficult to find. Limiting amplifiers such as AmpliTec APT3-01000200-1515-D4-LM extend the dynamic range of the system while preventing oscillation.**

BASIC VCO-PLL



- The mixer can be a simple double balanced mixer. Devices such as a mini circuits ZFM-150 are perfectly adequate.
- The mixer IF output must go to DC.
- Typically you are limited to somewhere between 7 and 13 dBm mixers by the output level of VCO.
- Higher IP3 mixers could be used at the cost of a larger amplifier between the VCO and the LO input. This would provide a better dynamic range.
- Part of the function of the low pass filter is to reject the second harmonic component of the mixer output.

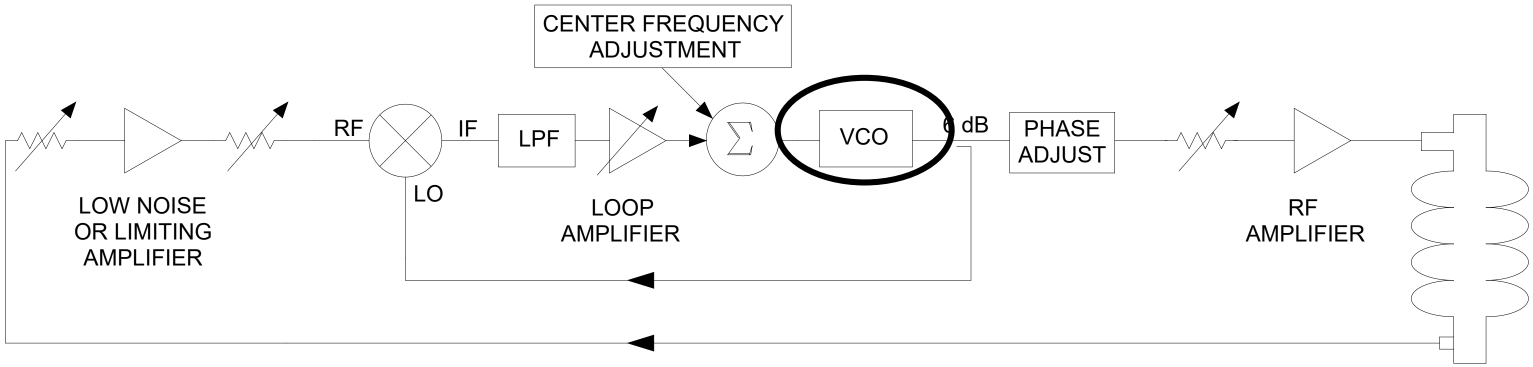
BASIC VCO-PLL



- The secondary function of the low pass filter is to reduce the noise. To that end the bandwidth of the filter is typically 20 kHz.
- The variable gain amplifier circuit is used to adjust the loop gain.
- At the summing junction a center frequency adjustment signal is summed with the output of the loop amplifier, typically we use course and fine ten-turn potentiometers.
- In addition to a custom circuit designs, a Stanford Research SR560 can be used to implement the loop amplifier and filter blocks.

NOTE: If a general purpose frequency source is used for the VCO the loop gain can be measured by manually adjusting the frequency by a fixed amount (i.e. 200 Hz) and measuring the shift in the loop frequency. The gain is the quotient of the two. Gains over 100 are considered acceptable.

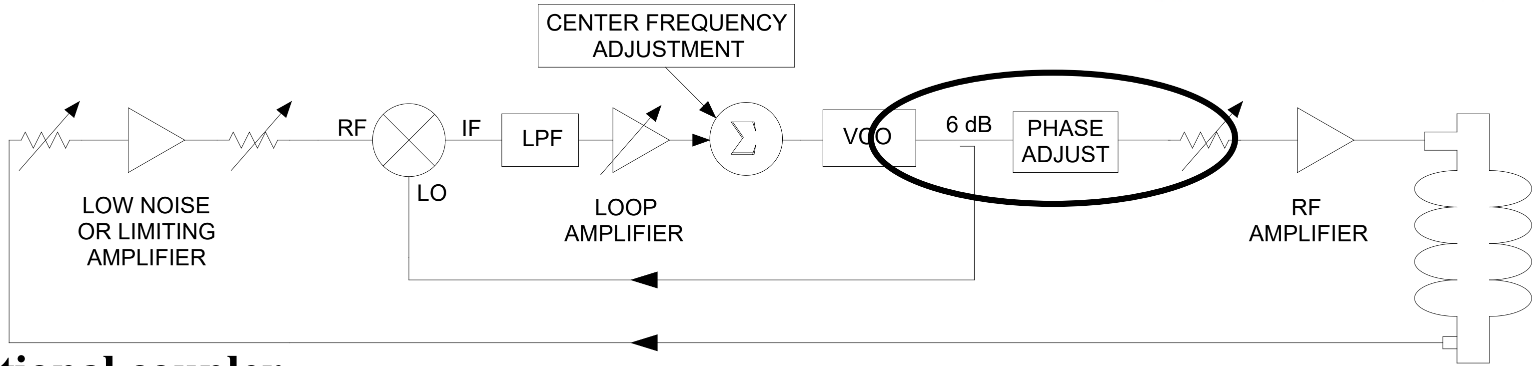
BASIC VCO-PLL



- **Inexpensive broad band devices are available from Mini Circuits for about $50.**
  - **Minus – These have very high tuning sensitivities on the order of 3 to 30 MHz/V.**
  - **Minus - With a wide frequency range they will be more susceptible to temperature induced drifts.**
  - **Plus – They can be used over a broad range without retooling.**
  - **Plus – Low cost**
- **Customized VCOs with thermal stabilization an narrow frequency ranges for about $1500**
  - **Plus – Low bandwidth crystal based devices are not sensitive to temperature drifts.**
  - **Plus – Moderate cost.**
  - **Minus – Can not be used to tune to the different pass band frequencies.**
  - **Minus – Narrow band required for different cavity frequencies.**

RF source based VCO such as an Agilent E4422B for about $12,000.
  - **Plus – Low bandwidth to reduce noise issues**
  - **Plus – Flexible and stable frequency source**
  - **Plus – Has simultaneous AM modulation capabilities which are useful for cavity conditioning, etc.**
  - **Minus – High cost device.**

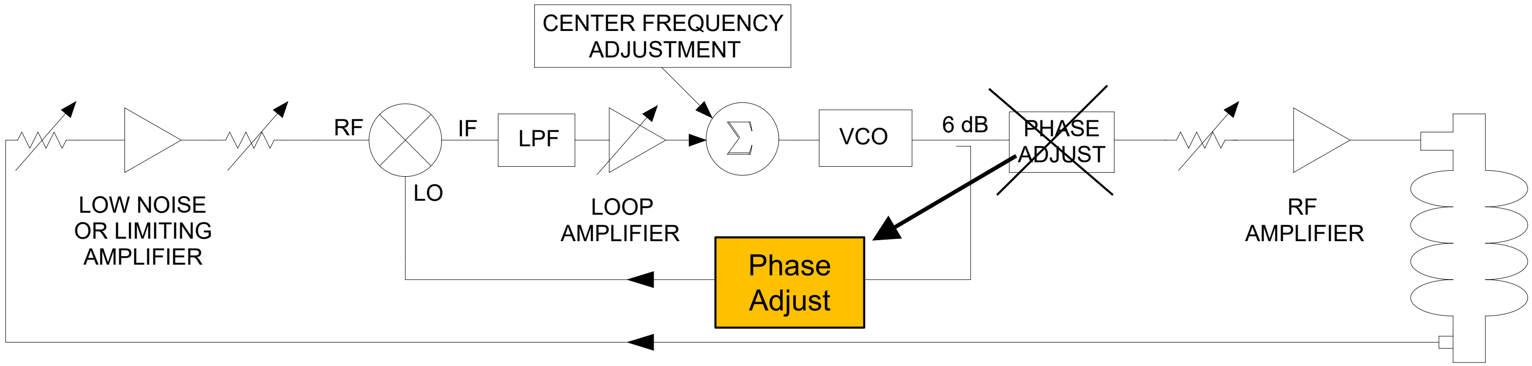
BASIC VCO-PLL



- **Directional coupler.**
  - **Coupling dictated by a combination of VCO output level and Mixer LO requirement.**
  - **LO path may require an amplifier to ensure the proper drive level for the mixer.**
- **Phase Shifter***
  - **Typically mechanical phase shifters are used such as Narda 3752 or Arra D3428B .**
  - **Ensure that they provide at least 190 degrees of phase shift at the frequency of operation.**
- **Variable Attenuator***
  - **Typically both continuous and step mechanical attenuators are used for manual systems Narda, Arra manufacture both. Caution should be used if a PIN attenuator is used as it will strongly affect the loop phase**

***Vector Modulators are frequently used to supplement the phase shifter and replace the mechanical attenuators.**
  - **Analog Devices as well as several other manufactures produce integrated circuits with analog controls**
  - **GT Microwave, and others make connectorized devices with digital controls.**

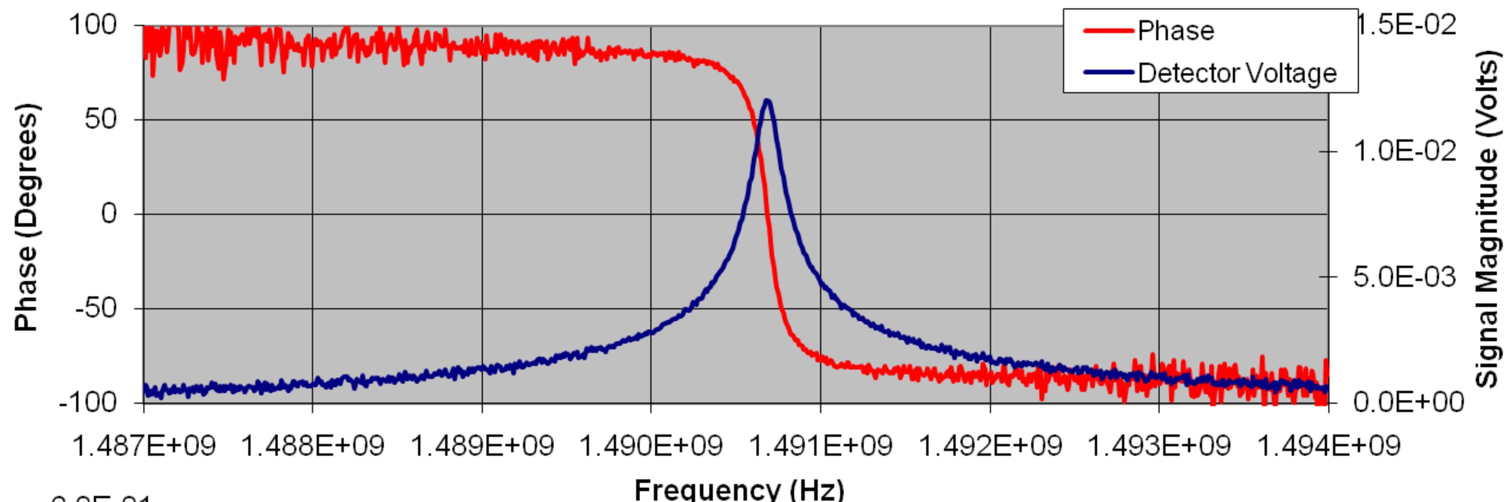
OPTIONAL TOPOLOGY



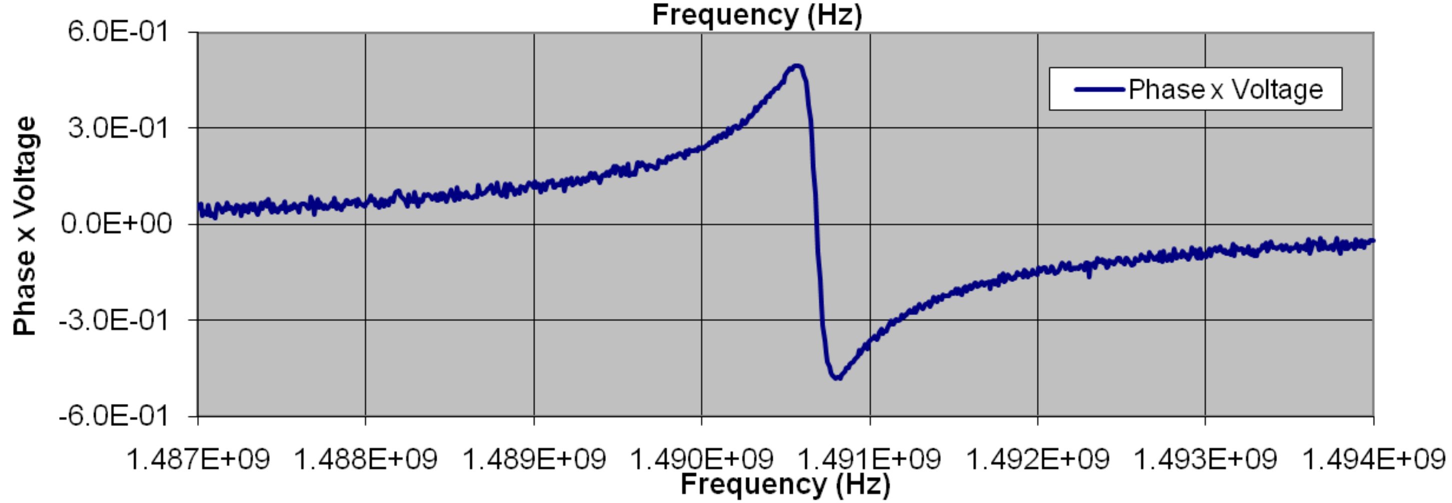
- **Problems:**
  - **Vector modulators and electronic phase shifters can introduce attenuation as a function of phase settings.**
  - **This is especially true for analog vector modulator where one can easily see changes in amplitude of 1 dB as you shift the phase a few degrees. Especially around 0º, 90º, 180º, and 270º.**
- **Solution: (Idea seen at INFN Legnaro)**
  - **Move phase shifter from the output path to the feedback loop which drives the local oscillator port on the mixer.**
  - **Insure that the nominal mixer input level is 2 dB or 3 dB higher than nominally necessary so that amplitude variations in the phase shifter do not in negatively impact operations**

PLOT OF PHASE AND AMPLITUDE NORMAL CONDUCTING CAVITY

Phase and Amplitude Transfer Function of a Cavity



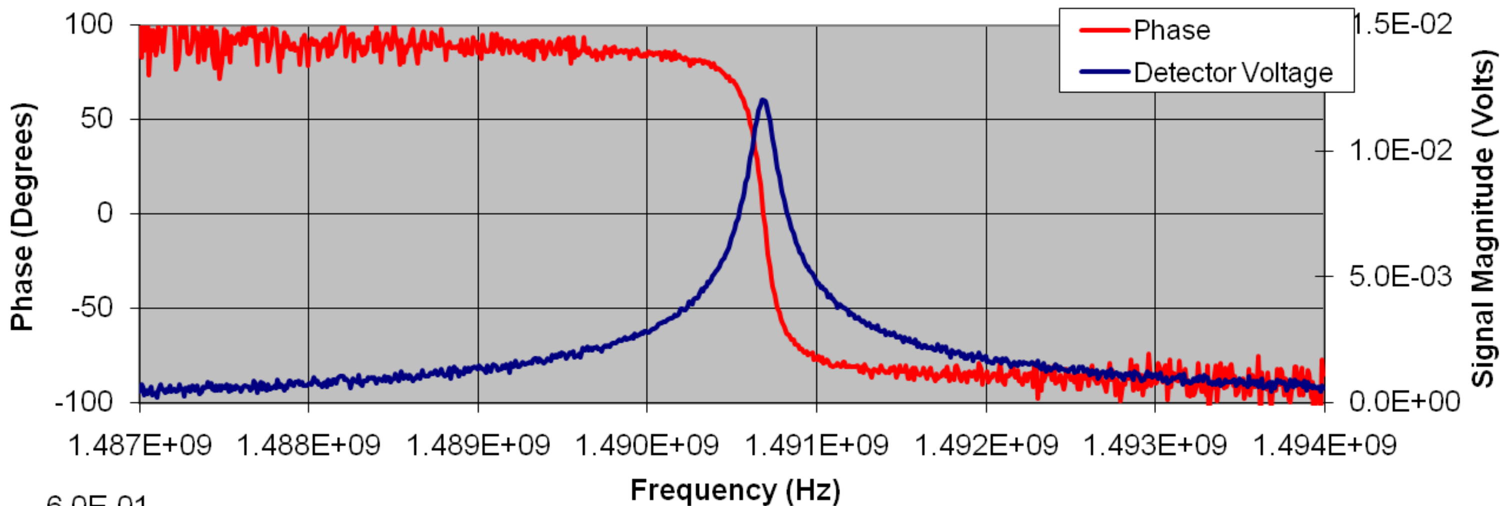
Output of Mixer (i.e. *ψ x V*)



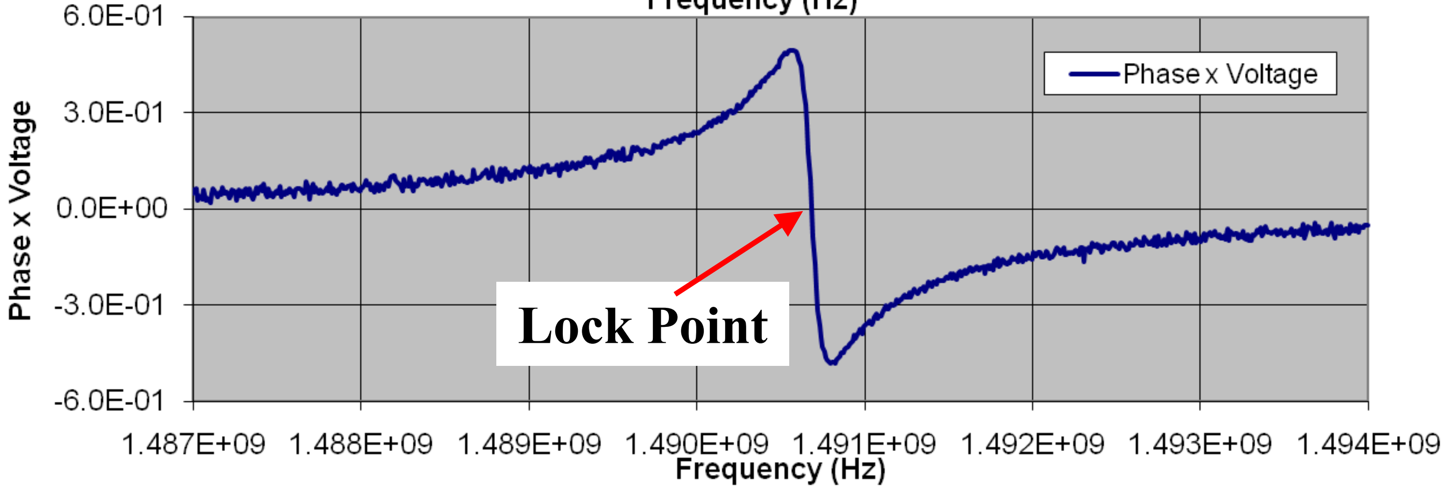
The filtered output of a mixer is the product of the signal voltage and phase.

PLOT OF PHASE AND AMPLITUDE NORMAL CONDUCTING CAVITY

Phase and Amplitude Transfer Function of a Cavity



Output of Mixer (i.e. *ψ x V*)

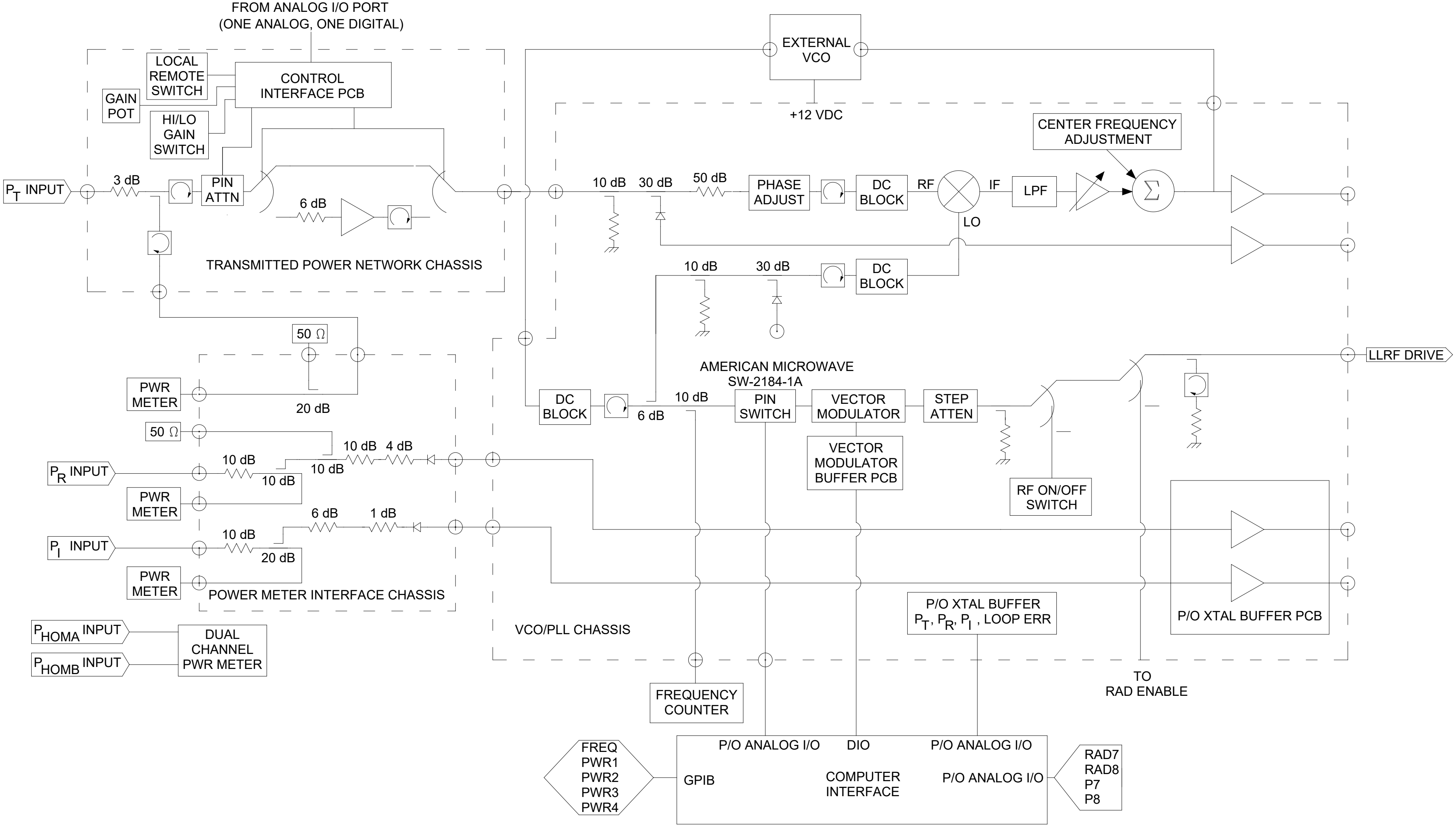


The phase lock loops locks on the zero crossing. Closing the loop switch when you are 180° out of phase will cause the system to drive away from the lock point.

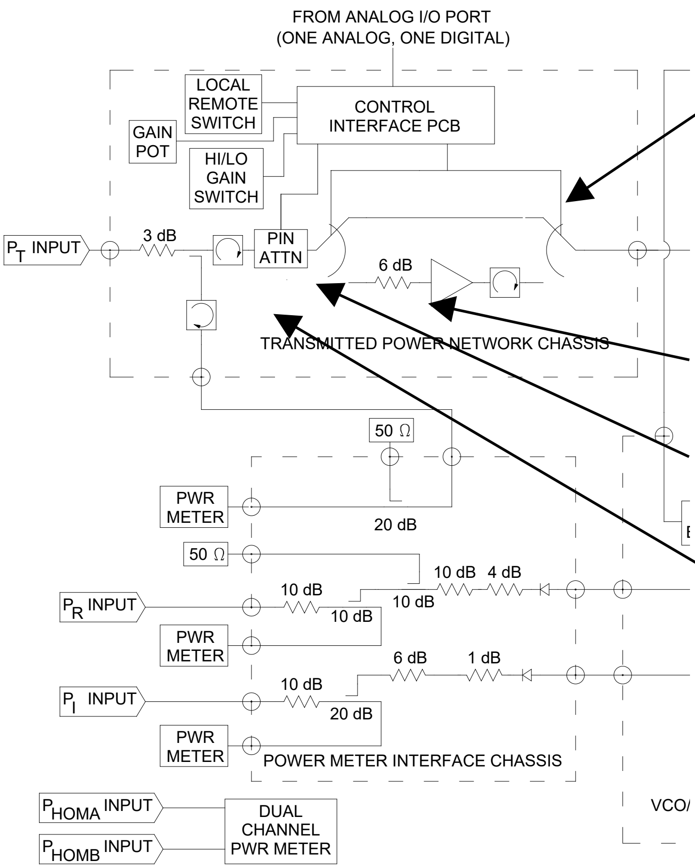
NETWORK ANALYZER MEASUREMENTS

- Use network analyzer to measure the cavity center frequency before high power tests.
- For measuring loaded-Q remember that the IF bandwidth of the network analyzer must be much less than the bandwidth that you are measuring.
- Always expand the horizontal scale out until you see the “bandwidth” of the measurement in order to insure that there are no vacuum leaks and to check for low field multipactors.
- Use the center frequency of the resonance offset by about 10 kHz for your calibration sources.
- It does not hurt to make a network analyzer measurement prior to cooldown to insure that all of the cables are connected.

Complete *VCO PLL* System Layout



Complete VCO PLL System Layout



The transmitted power network has a switchable LNA and variable attenuator, both can be controlled by the computer.

The 6 dB pad before the LNA ensures that there is a minimal gap in the continuous gain control settings. Without it there would have been a 12 dB dead band.

The phase shift associated with the PIN attenuator was measured and included as a lookup table in the program. The compensation values are factored into the vector modulator algorithm.

Circulators are used to reduce the mismatch and ensure more stable power meter calibrations. The 10 dB attenuators used in the incident and reflected power path also serve that purpose

Only low drift fixed devices are used between the power meters and the cavities.

COMPLETE VCO PLL SYSTEM LAYOUT

The VCO was moved to an external location so that it could be thermally stabilized. This also allows us to use alternate VCOs.

The 50 dB attenuator was necessary due to the excessive tuning sensitivity of the VCO, which is 5.6 MHz/V.

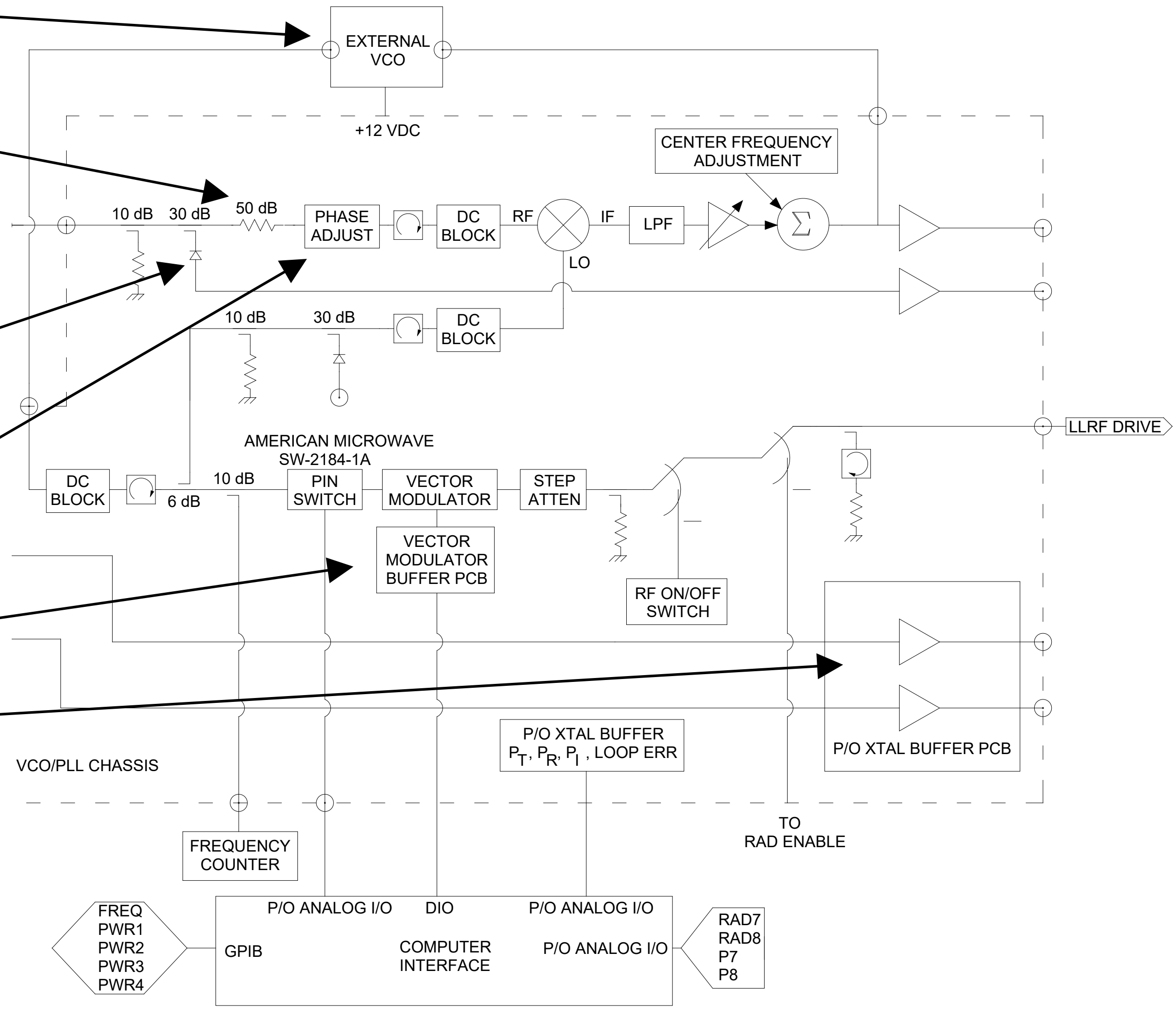
Crystal detector gain set to reduce the square law errors while maintaining a 1 V amplitude at the DAQ input.

Even though there is a vector modulator, there is a mechanical phase shifter which is used frequently.

Computer controlled vector modulator is used for amplitude and phase control.

All crystal detector signals are buffered and available for observation using an oscilloscope.

Computer controlled and automatic data acquisition ensures repeatable data and methods independent of operator.



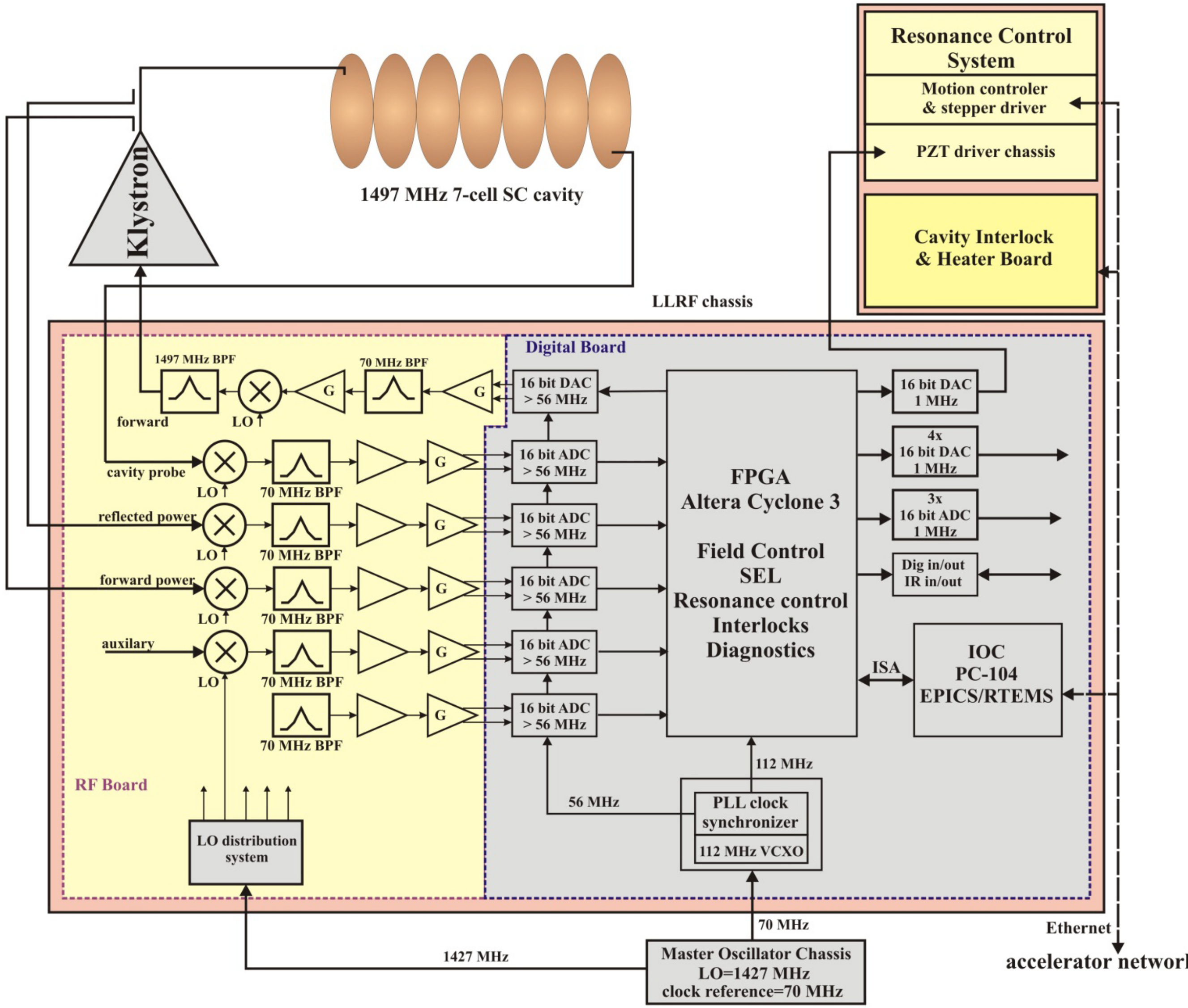
JLAB UPGRADE RF CONTROL SYSTEM

<u>Canonical LLRF</u>

- One Large FPGA
- Four Receivers
- 0ne Transmitter
- Slow Tuner

Control

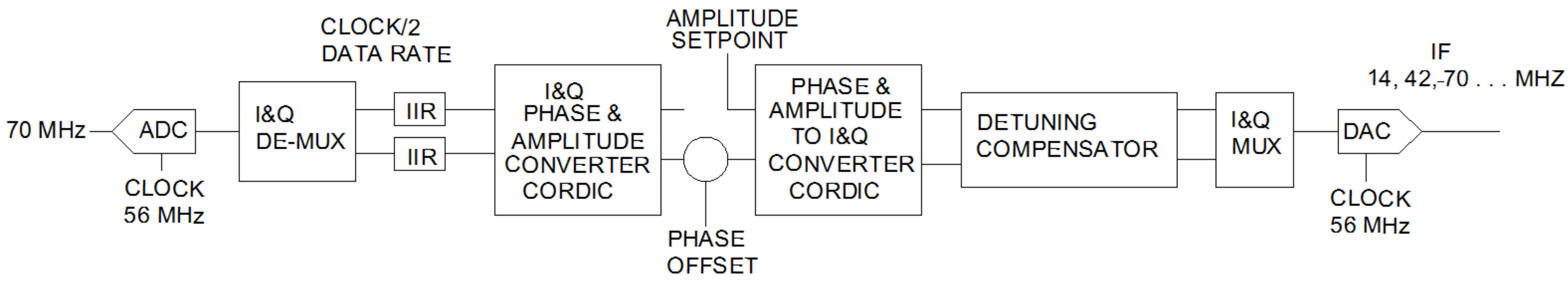
- Piezo Tuner Control
- Inexpensive PC104 interfaces to the control system



SELF EXCITED LOOP MODE

- **A self excited loop is an oscillator built around the a resonant device.**
- **In this case the resonant structure is the cavity.**
- **When the loop gain is >1 and the phase shift is about 180° the loop will oscillate at the resonant frequency.**
- **The phase setting is very forgiving when compared to a VCO-PLL system.**

SELF EXCITED LOOP ALGORITHM



- **Data acquired synchronously at 1/1.25 of IF frequency**

  $$I = V_i - V_{i+1} \qquad Q = V_{i+2} - V_{i+4}$$

- **I and Q out are sine and cosine waveforms at the difference frequency between the input and 70 MHz.**
- **Output of I/Q Mux DAC has the frequency content of a (Sin X)/X comb at 14, 42, 70, . . . (plus deltaF) MHz**
- **Choosing the 70 MHz harmonic with a filter provides the IF for the output channel.**

USING DIGITAL LLRF SYSTEMS FOR CAVITY TESTING

The JLab digital LLRF system has several modes of operation.

- Tone Mode – Output signal is fixed frequency fixed amplitude. No feedback control of cavity gradient.
- Generator Driven Resonator mode (GDR)
  - Fixed frequency output
  - Feedback control of phase and amplitude necessary to regulate the cavity gradient and phase.
- Self Excited Loop Mode (SEL)
  - For the JLAB LLRF system this mode is a constant amplitude output with a time varying phase signal which tracks the cavity frequency.
  - Optionally the cavity gradient may be regulated.
  - Optionally the cavity gradient and phase may be regulated and the system locked to a reference frequency.
- Pulse Mode
  - Actually a SEL mode with either an on/off modulation or modulation between two different RF power levels.

WORKING AROUND ISSUES LLRF SYSTEMS

- Front end bandwidths are typically 5 MHz.
  - Use frequency conversion techniques to translate the cavity frequency to that of the field control chassis (FCC).
- The system likes to lock into the wrong pi mode. Even though they have a 200 KHz filter on I and Q it can easily lock into the nearest pi mode.
- Occasionally we will get mode mixing in cavities (specifically LCLS II style) where the 7/9 pi mode is excited along with the pi mode by RF at the PI mode. This is thought to be because of loading due to a multipactor, which changes the field profile in the cavity. This accompanied by a slow rise in the reflected power.
- Designed for limited dynamic range of 20 dB.
  - Use variable gain devices in front end circuits to extend range.
  - Use a 20 dB step attenuator on the output in order to insure that output signals use plenty of bits..
  - Continue to use RF power meters for absolute measurements.
- Must insure that the front end is not overdriven which saturates the I/Q signals and causes "oscillations" to appear in the probe signal.

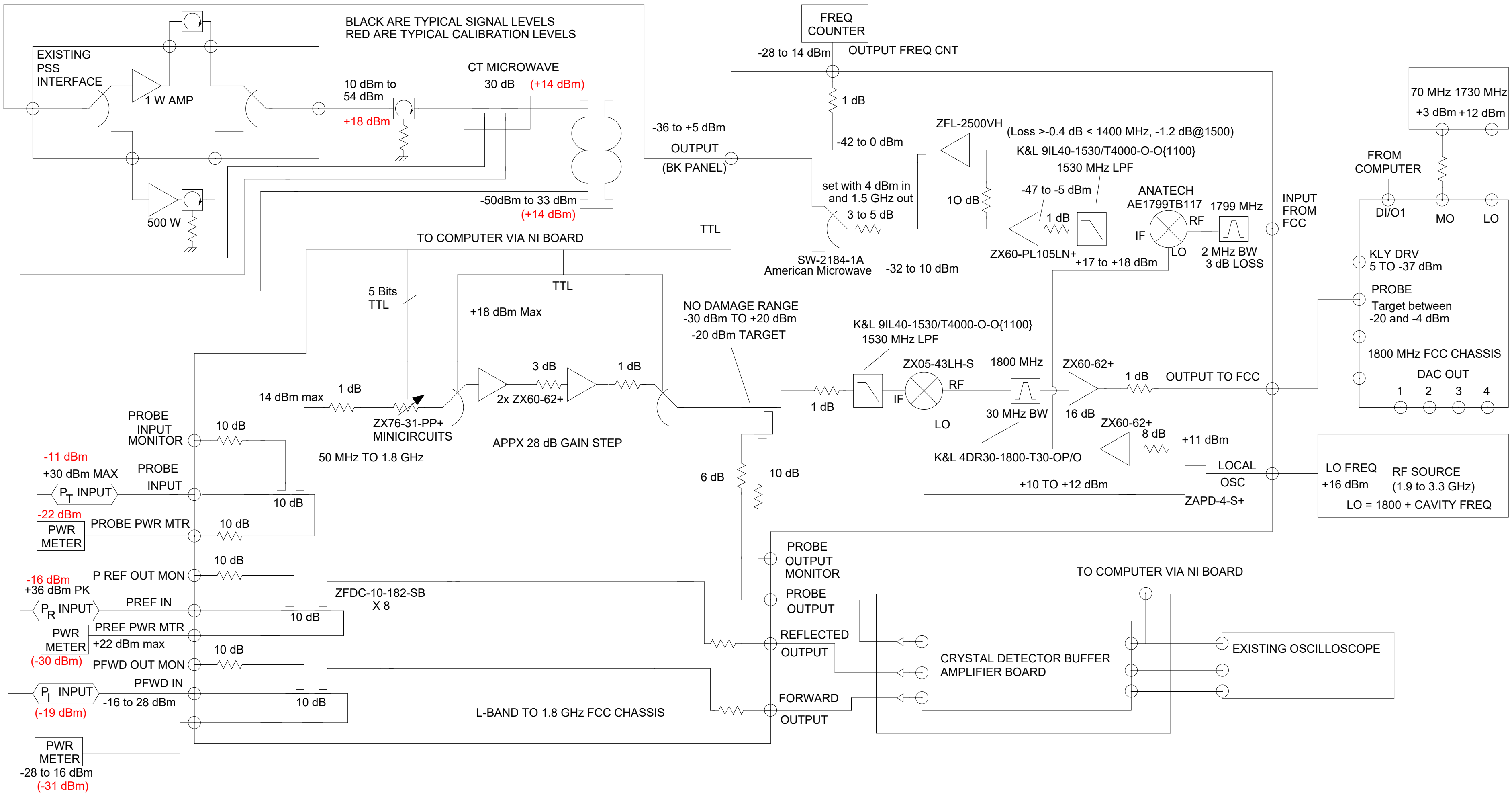
CURRENT EXPERIENCE TESTING WITH DIGITAL LLRF

- Commissioned and retested cryomodules at least 50 times in CEBAF using digital LLRF systems and pulsed power meters.
  - Pulsed and CW in self excited loop (frequency tracking) mode worked very well.
  - CW commissioning in Generator driven mode worked very well.
  - The microphonics capabilities were baselined against an analog cavity resonance monitor and a large number of microphonics measurements were taken using the systems.
- Re-comissioning of the C20 and commissioning of the C50 cryomodules was done using a modified digital LLRF system controlling the frequency of the 70 MHz IF signal used by the analog LLRF system.
- Several years of operational experience in JLab vertical test area with multiple digital LLRF systems and down/up converters. These systems have been well received by the scientists and engineers.
- Recently converted our cryomodule test facility over to digital LLRF systems for LCLS II (1.3 GHz) and CEBAF (1.497 GHz) cryomodules. See Curt Hovater's Poster THP049

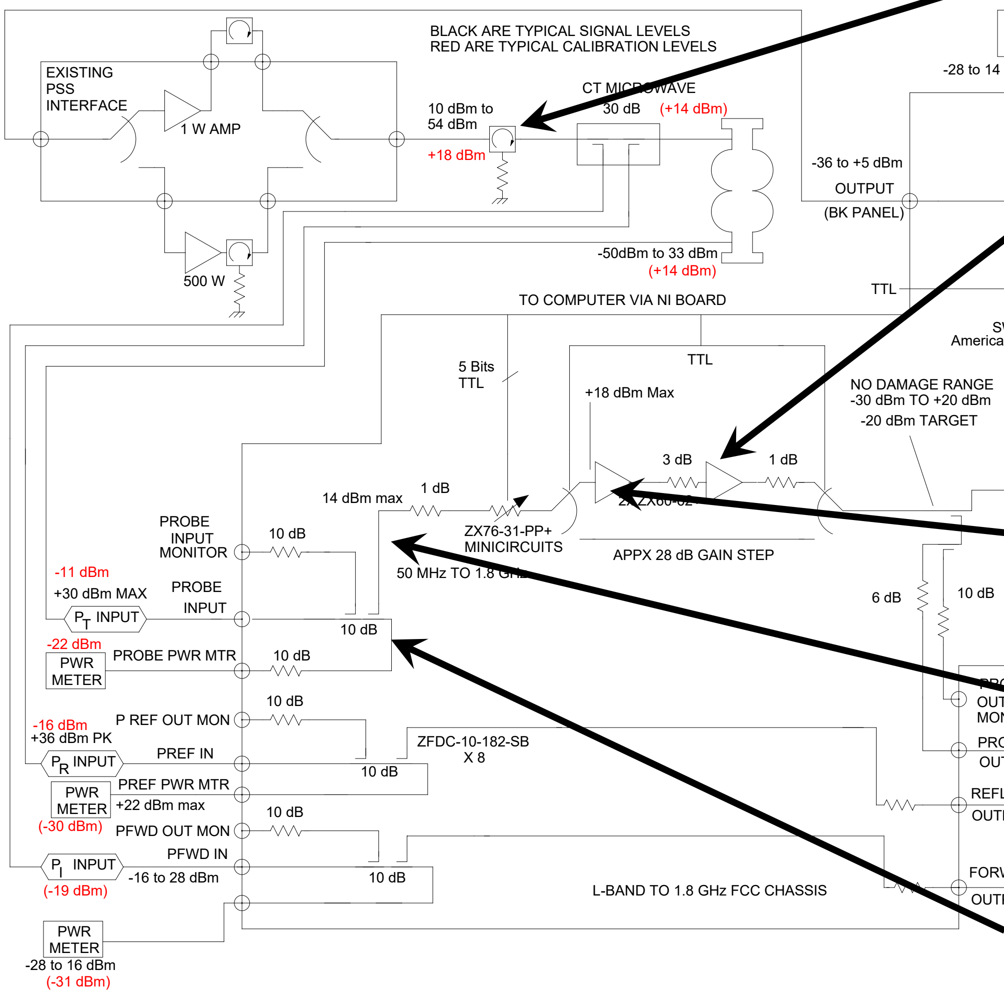
CURRENT EXPERIENCE AND THE FUTURE

- **General comments:**
  - **Easy to use once you get past the complicated user interface.**
  - **Easy to lock to the cavity frequency in SEL mode. Much easier to use than a VCO-PLL system.**
  - **BESSY developed LabView interface CALab tools make communication easy.**
  - **Systems are being integrated for full commissioning of LCLS II cryomodules at JLAB.**
- **Future:**
  - **Fully integrating commissioning software into EPICS will provide quick and efficient cryomodule commissioning tools.**
  - **Integrating triggered waveform capture, and the system described next will provide a major improvement to testing of critically coupled high-Q cavities in our vertical test area.**

BROAD BAND DIGITAL LLRF BASED SYSTEM



BROAD BAND DIGITAL LLRF BASED SYSTEM



A circulator is the last thing before the directional coupler. Target VSWR < 1.1

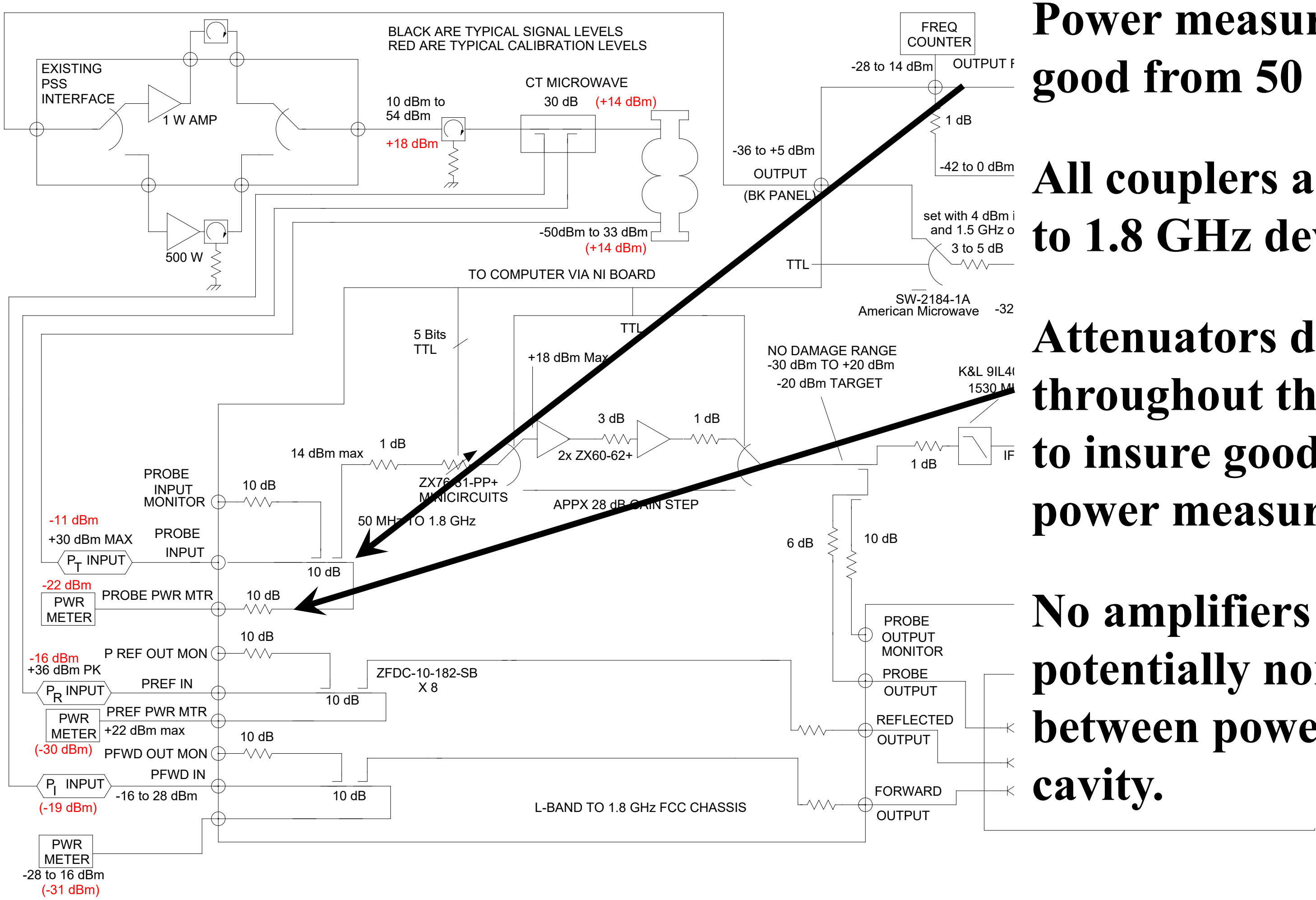
Switchable gain preamplifer on probe signal very similar to VCO System

ZX60-62 amplifiers chosen because of their 24 dBm no damage input specification.

Circulator removed in order to keep preamp circuit broad band 50 MHz to 1.8 GHz.

Coupler moved to the input circuit in order to better isolate any VSWR miss-matches present on the amplifier circuit from input circuit.

BROAD BAND DIGITAL LLRF BASED SYSTEM



Power measurement network good from 50 MHz to 1.8 GHz.

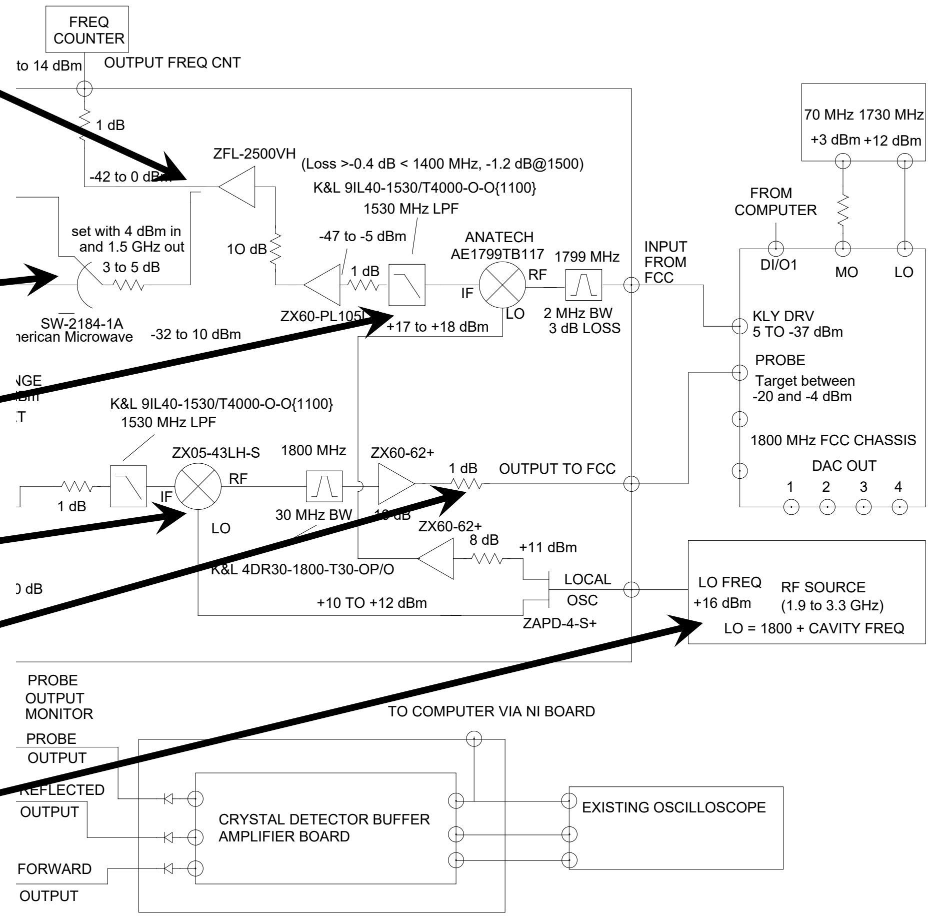
All couplers are 10 dB, 50 MHz to 1.8 GHz devices.

Attenuators distributed throughout the circuit in order to insure good VSWR values in power measurement network.

No amplifiers or other potentially non linear elements between power meters and the cavity.

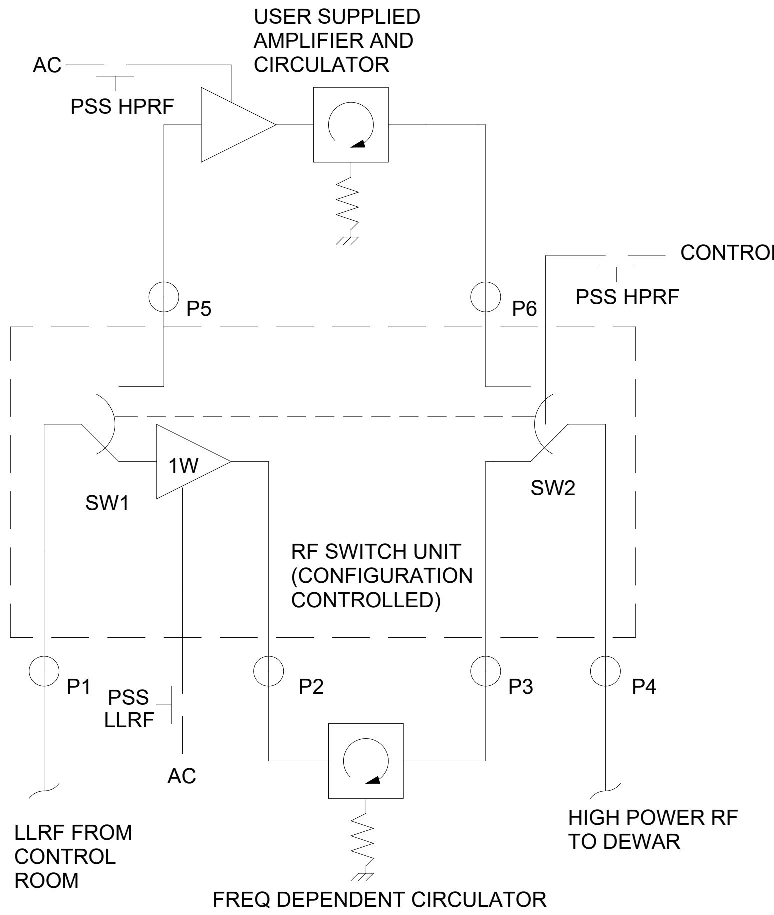
BROAD BAND DIGITAL LLRF BASED SYSTEM

- Coupled signal to output to insure that frequency counter is not starved. We do have problems with the frequency counter at low output levels due to broad band noise.
- Output On/OFF switch for pulsed mode operation.
- Low pass filter to reject higher order frequencies out of the mixer.
- Mixers used for up/down conversion.
- Attenuator on outputs to provide load in the event cables are disconnected
- High side local oscillator used to simplify the drive line filter parameters. This source is adjusted to adjusted to bring the cavity frequency to that of the LLRF chassis

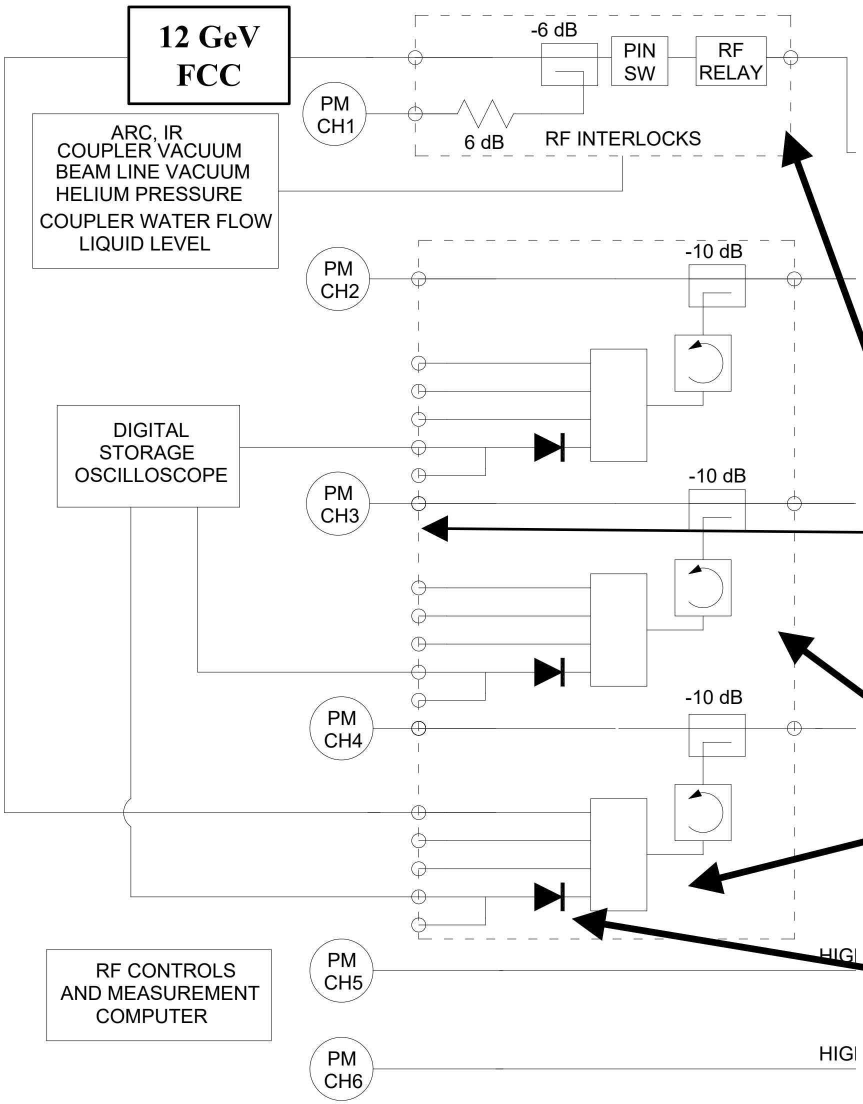


INTERLOCKS FOR VERTICAL TESTS

- **During vertical testing medium power amplifiers between 100 W and 500 W are used to drive the cavities.**
- **No cavity protection interlocks are used during these tests at Jefferson Lab. Each facility and test should be evaluated individually.**
- **Field emission radiation does present a safety hazard. This is mitigated during vertical testing at Jefferson Lab by using one of 6 shielded vertical dewars. INSURE THAT YOU USE NEUTRON AND GAMMA DETECTORS FOR CAVITIES THAT MIGHT MAKE >10 MeV.**
- **High power RF can not be applied to an accelerating structure until the PSS system confirms that the dewar shield lid is closed.**
- **Low power, less than 1 W, must be applied to the system in order to calibrate the cables.**
- **A switching system shown here was implemented to perform these functions for "R&D" testing and is currently used in our production systems.**



CRYOMODULE TEST SYSTEM LAYOUT



Due to the excessive costs to recover from a coupler failure. Full interlocks were implemented for the system, including:

- Arc
- Infrared
- Coupler and cavity Vacuums
- Helium pressure and level
- Coupler cooling water flow

Use of the interlocks was mandatory for all high power operations.

Boonton 4532 pulsed RF power meters were used to acquire waveform records of the pulsed RF power data.

A software interlock was added based on HOM coupler power levels.

Circulators added to ensure that user changes to the other outputs would not affect calibrations.

4-Way splitters added so that the RF signals could be used by other systems in parallel with the standard data acquisition process.

Crystal detectors used for operator feedback only.

Computer controlled and automatic data acquisition was necessary for calibration of the field probes using an emitted power technique.

CRYOMODULE TEST SYSTEM LAYOUT

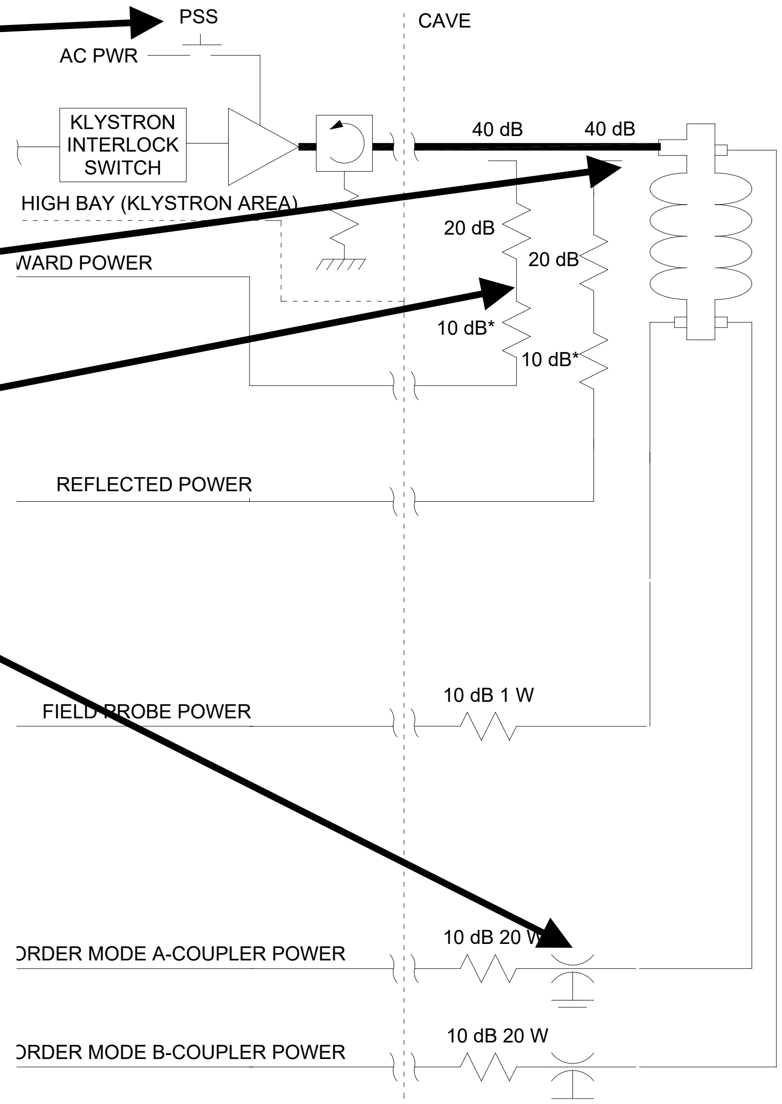
Personnel safety system provides a permit to allow high voltage operation of the klystron. Operations at less than 1 W allowed without a PSS interface.

Waveguide directional coupler placed in the middle of a 4 m run of waveguide in order to avoid errors due to evanescent modes.

Attenuators were distributed throughout the system in order to reduce the susceptibility to standing wave induced errors.

Polyphaser B50 or MR50 series lightning arrestors were added to the HOM ports after several RF power heads and medium power attenuators (20 W-CW and 500 W-PK) were destroyed. Excessive power was observed on a crystal detector when a cavity had a thermal quench.

At times during the SNS testing a 20 kW CW klystron was substituted for the 1 MW pulsed klystron. Stub tuners and iris plates were used to modify the input coupling of the system. Maximum CW power levels were limited by the coupler power capacity.



VTA TEST SYSTEMS

200 MHz to 1.5 GHz Digital LLRF based Production system

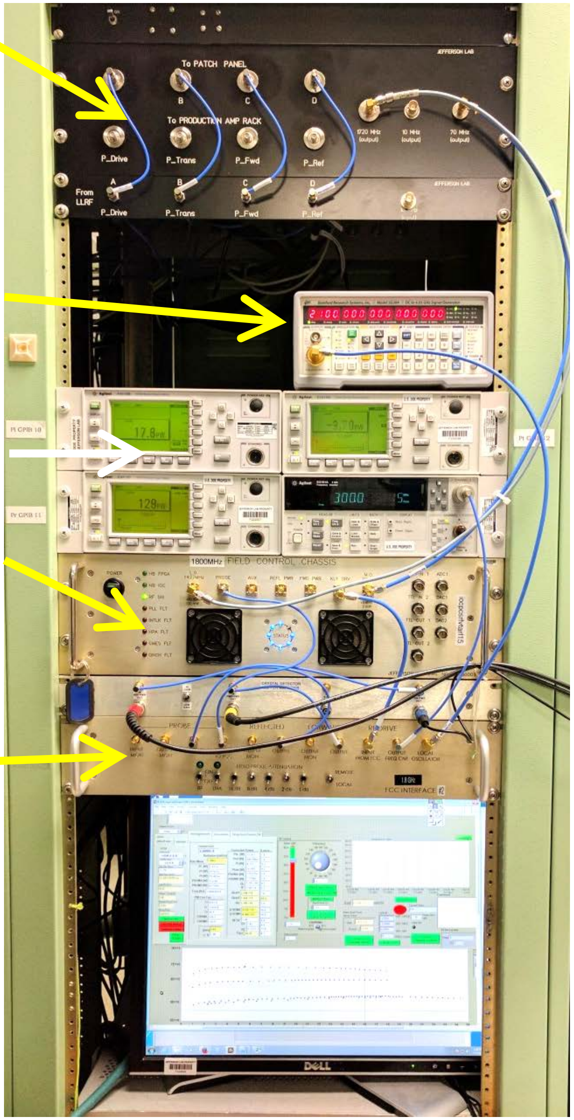
Patch Panel for R&D or production distribution system

Down converter LO RF Freq + 1800 MHz

Instrumentation

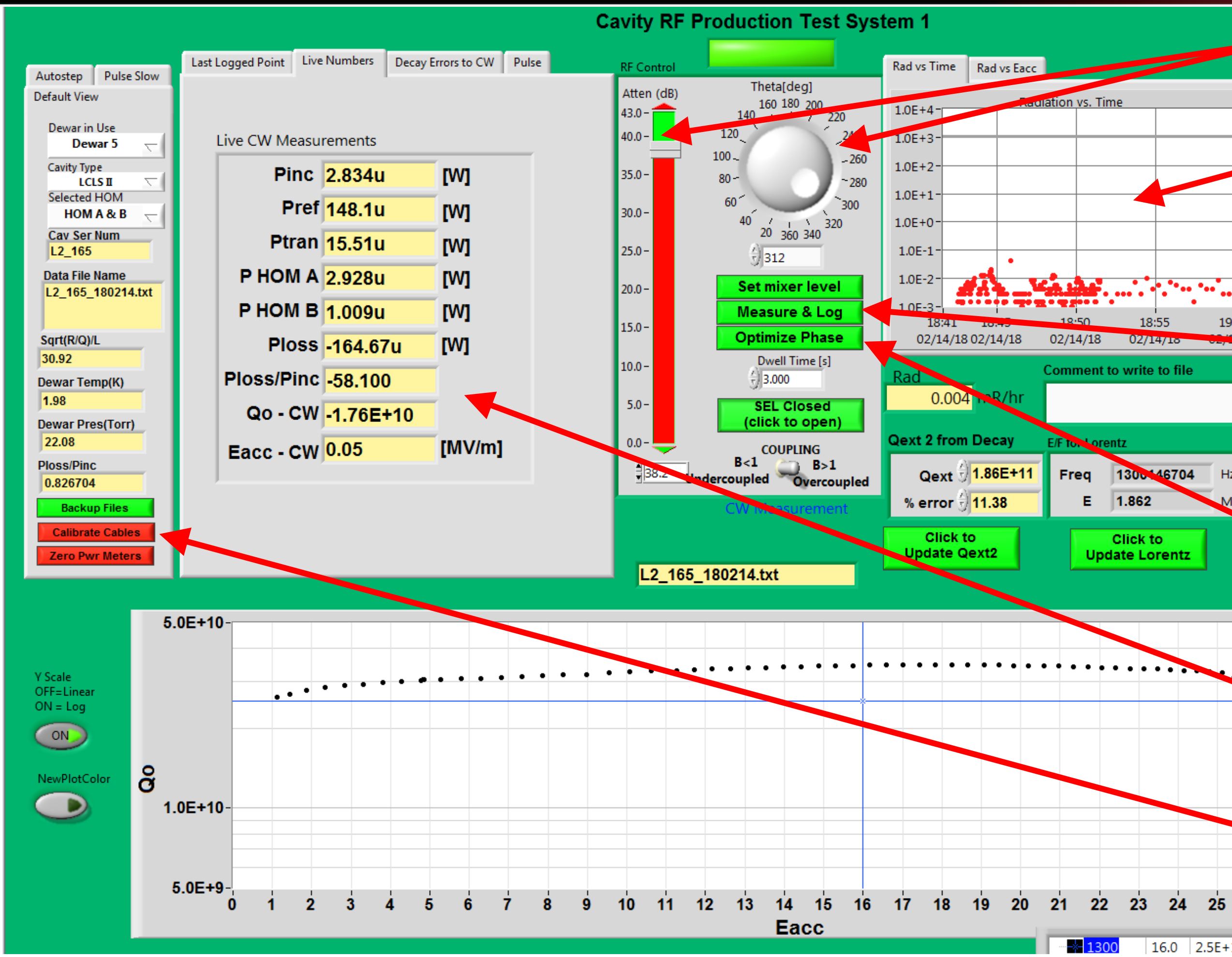
12 GeV Field Control Chassis set up for 1800 MHz

Down converter Chassis



500 to 4,000 MHz VCO-PLL system used for research and development, which was recently upgraded to include a 2 – 4 GHz digital LLRF system

VERTICAL TEST AREA TESTING SOFTWARE



Forward power and phase controlled via EPICS

Live plot of radiation with alarm for exceeding administrative limit

Measure and log button updates graph and logs data to a file.

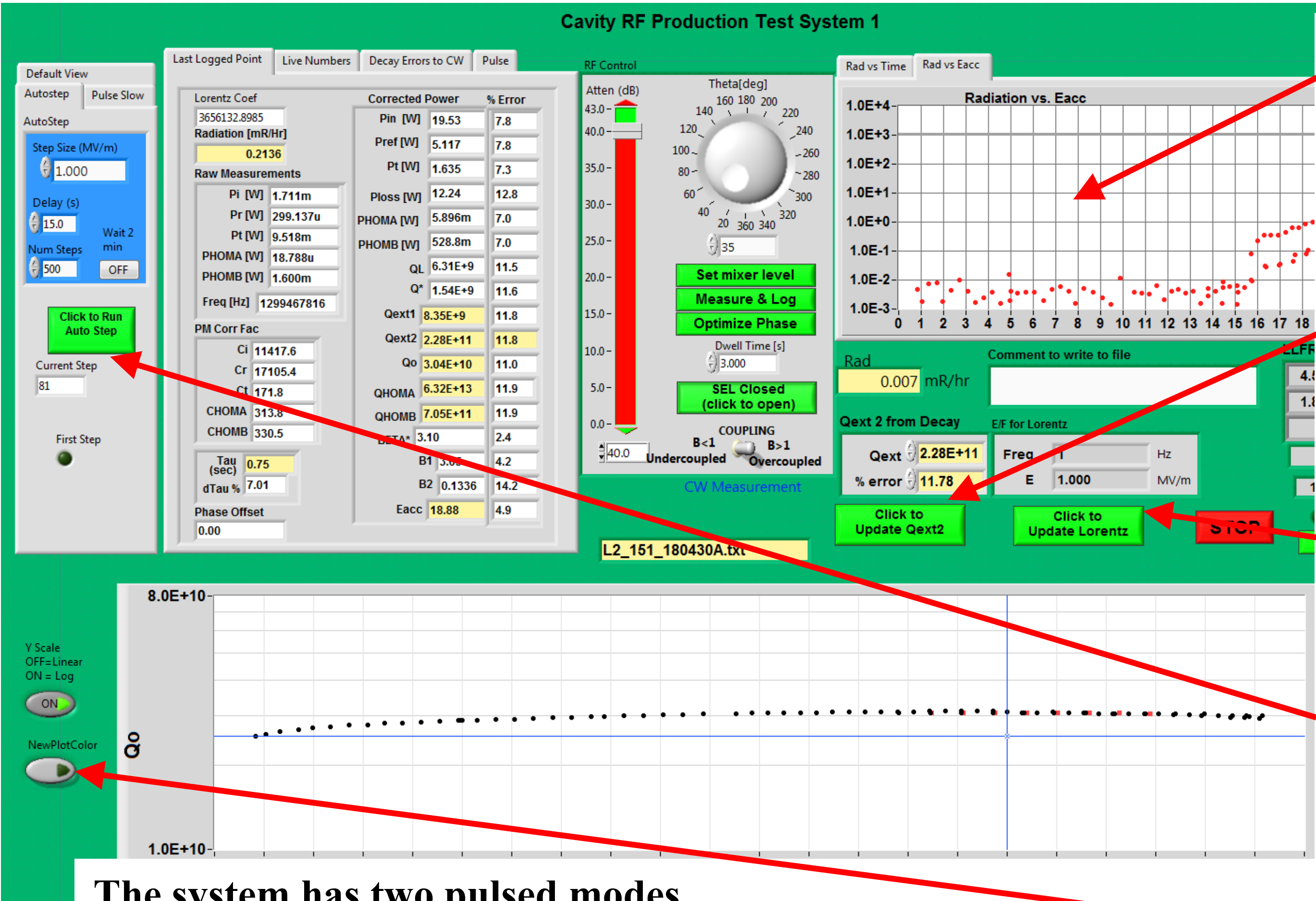
Optimize phase selector. Routine minimizes reflected power as it responds fastest.

Qo, incident power, and gradient continuously updated.

Interactive calibration routine with imbedded instructions.

- **Internal algorithm controls LNA and PIN attenuator to ensure proper signal levels for Mixer and transmitted power crystal detector.**
- **Auto step and auto phase allows for quick consistent measurements.**

VERTICAL TEST AREA TESTING SOFTWARE



Alternate plot of radiation vs gradient

Alternate view of last logged data point including errors.

Click to select which of the decay measurements and associated error numbers to use for CW measurement.

Click to select reference measurement for calculating Lorentz coefficient.

Autostep feature allows one to efficiently build up a data sets at more even gradient intervals.

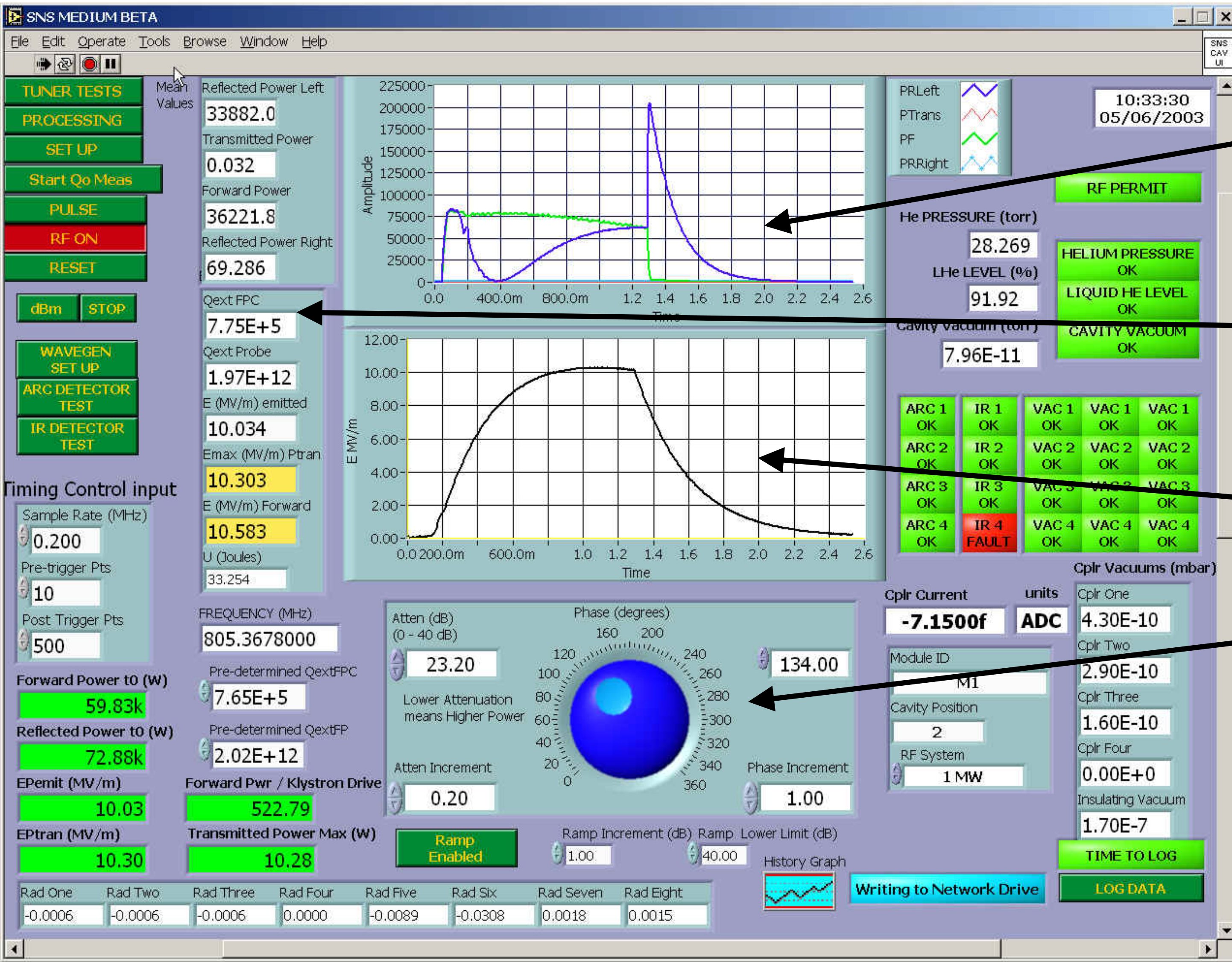
Ability to change the color on the logged data.

The system has two pulsed modes.

- Software based on/off pulsing up to about 5 Hz.
- On/off or from one level to a different level from 0.5 Hz to 100 kHz. This mode is very useful for processing multipactors

CRYOMODULE TEST FACILITY CONTROL ROOM

CRYOMODULE TESTING PROGRAM



"Real time" gradient and forward and reflected power waveforms shown (supplemented with crystal detectors and an oscilloscope)

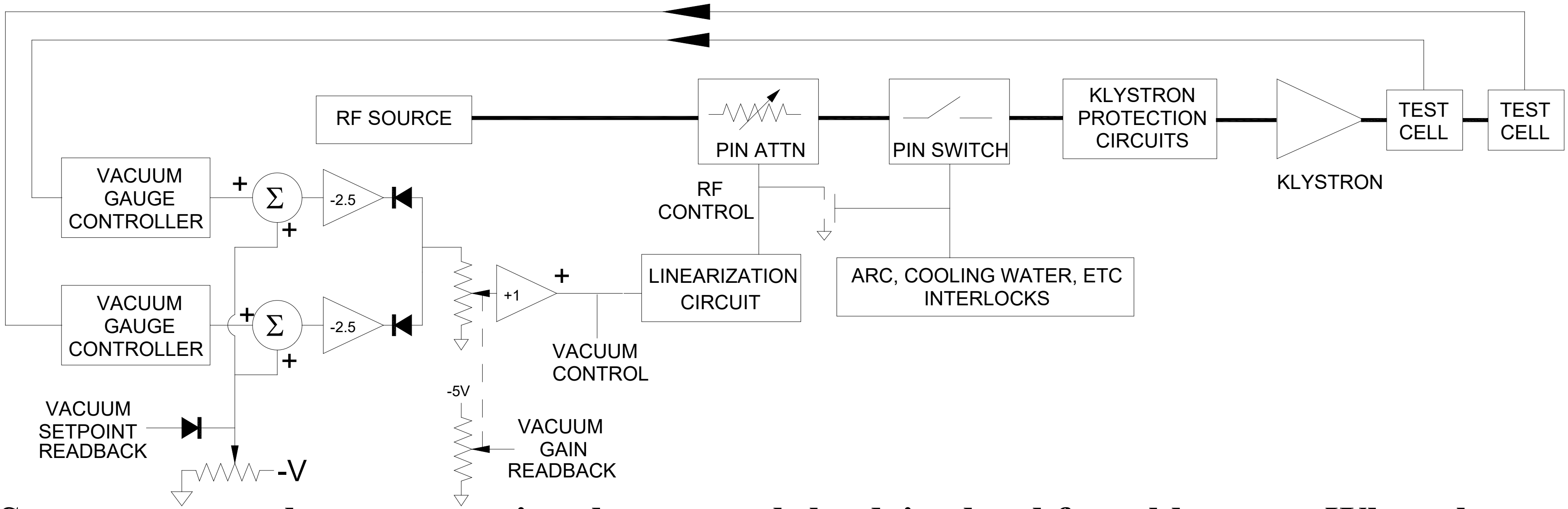
Loaded Q, Field Probe Q, gradient, and emitted power calculated on each pulse.

Gradient waveform based on an entered value of the field probe Q.

Forward power and phase controlled via an I/Q modulator.

Data continuously logged to a network drive. Waveforms recorded on request.

VACUUM CONDITIONING CONTROLLER

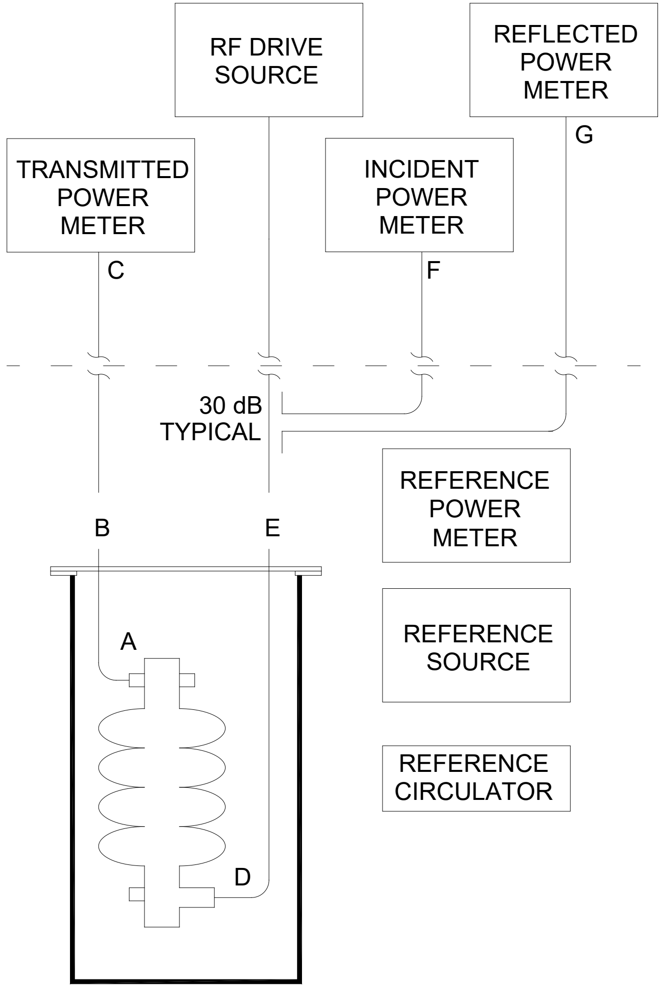


- System uses analog vacuum signal to control the drive level for a klystron. When the vacuum signal increases the PIN attenuator reduces the RF Drive signal
- Diode adder ensures that the larger of the two vacuum signals controls the feedback.
- Separate vacuum set point and gain control with analog read back
- Redundant switching of RF in the event of an interlock fault.
- Ones of millisecond response time achieved. Limited by vacuum gauge controller.
- Phase shift associated with PIN attenuator may cause problems when operating a cavity with a VCO-PLL. . The Hittite HMC473M although more difficult to bias has a very low phase shift over a 30 dB range.

CABLE CALIBRATIONS

- **Accurate consistent cable calibrations can make or break a test program.**
- VSWR mismatches in the RF circuits will cause errors to "appear" when the frequency is shifted or the load mismatch changes.
- Cable calibrations for cavity testing are complicated by the fact that one or more of the cables are only accessible from one end.
  - In a vertical test the incident power cable, the field probe cable, as well as any HOM cables all have sections that are in the helium bath.
  - In cryomodule testing the field probe cable and any HOM cables have sections of cable that are within the cryomodule.
- When possible cables should be calibrated using signal injection and measurement at the other end using either a source and power meter combination; or a network analyzer.
- Cables should be measured at or near the frequency of the test.
- The only way to measure the losses of a cable within a cryostat is to do a two way loss measurement either with a calibrated network analyzer or a source, a circulator and a power meter.

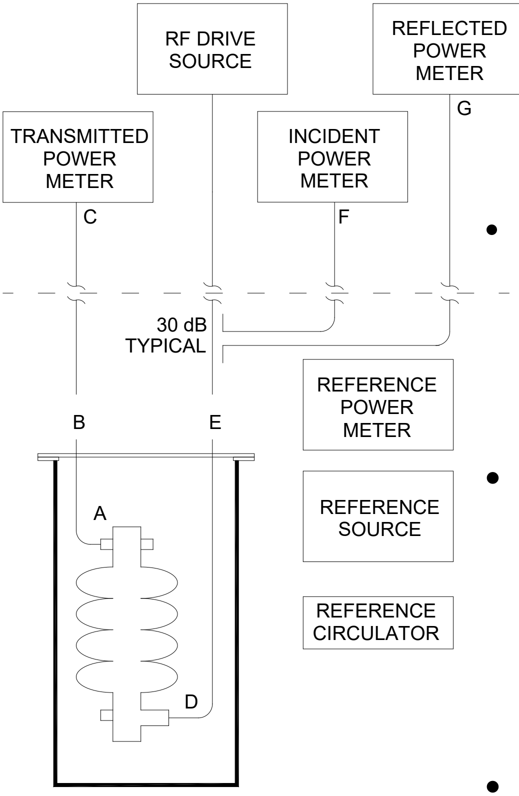
ONE WAY CABLE CALIBRATION



- **To calibrate the cable from point A to point C.**
- **Measure the one way loss of cable B-C.**
  - **Measure the reference source power level with the reference power meter. (P1)**
  - **Connect the reference source to point B of cable B-C.**
  - **Measure the power level with the transmitted power meter. (P2)**
  - **The one way loss is P1-P2 (dB)**
- **Measure the two way return loss of cable A-B**
  - **Connect the reference source to the input terminal of the circulator.**
  - **Connect the reference power meter to the load port on the circulator.**
  - **Record the reading on the reference power meter with the output port of the circulator open.* (P3)**
  - **Connect the output port of the circulator to port B of cable A-B and record the reading on the reference power meter. (P4)**
  - **The two way return loss is P3-P4 (dB)**
- **The cable calibration between for the A-C path is**

$$C_{AC} = (P1\text{-}P2) + (P3\text{-}P4)/2.$$

TWO WAY CABLE CALIBRATION



- **To calibrate the cable from point D to F and D to G**
- **Measure the forward power calibration from E to F**
  - **Connect the reference power meter to point E of the cable from the RF drive source.**
  - **Turn on the RF drive source and increase the power until the power level on the reference power meter is about 2/3 of the maximum allowed.**
  - **Record the power levels on the reference meter (P5) and the incident meter (P6)**
- **Measure the reflected power calibration from E to G**
  - **Turn off the RF source drive**
  - **Measure the reference source power level with the reference power meter. (P7)**
  - **Connect the reference source to point E of the path E-G.**
  - **Measure the power level with the reflected power meter. (P8)**
- **Measure the two way loss for the cable D-E with a detuned cavity.**
  - **Connect the RF drive source to the cavity at point E.**
  - **Turn on the RF drive source and apply power to the cavity at a frequency about 10 to 20 kHz higher or lower than the cavity's resonant frequency.**
  - **Measure the incident (P9) and reflected power (P10) with the respective meters.**
- **The cable calibration are:**

Incident $C_{D\text{-}F} = (P5 - P6 + P7 - P8 - P9 + P10)/2$ (dB)

Reflected $C_{D\text{-}G} = (P5 - P6 + P7 - P8 + P9 - P10)/2$ (dB)

CALIBRATION VERIFICATION

1. **Two ways that I use to verify calibration procedures are to:**

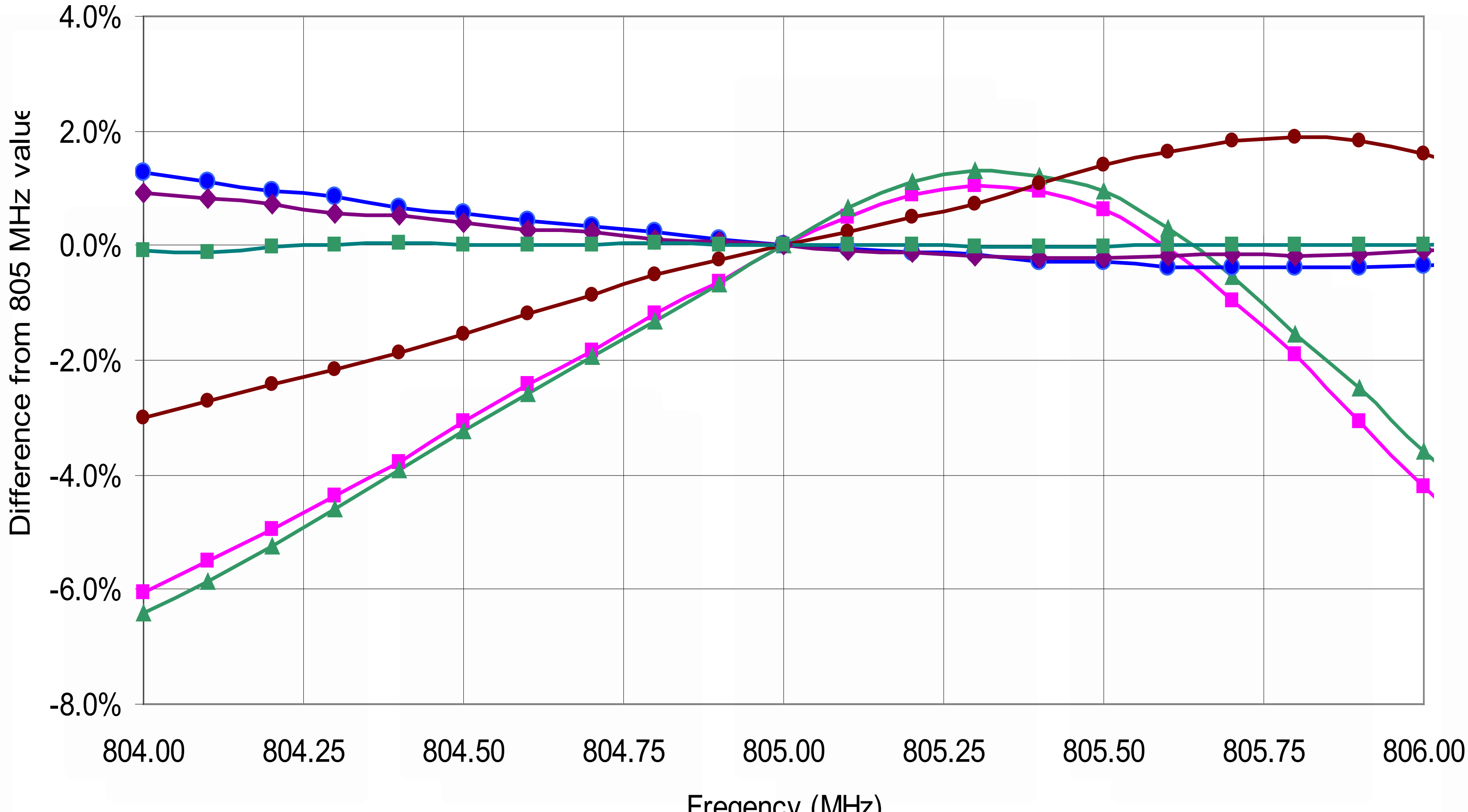
2. **Calibrate the system using an external cable rather than a cable within the dewar then:**
   - **For field probe power and reflected power inject a known signal level into the external cable and measure the power using the calibrated meter.**
   - **For the forward power connect the external cable to a remote power meter and measure the power using the remote power meter and the system power meter.**

3. **In both cases it can be a useful exercise to vary the frequency over a 1 MHz to 2 MHz range and compare the values over the range.**

CALIBRATION VERIFICATION

1. **A third way to verify the calibration and look for VSWR problems in the incident power cable is to:**
   - **Use the RF drive source to apply power to either an open test cable that has been calibrated or a detuned cavity.**
   - **Measure the calibrated forward and reflected power. They should be equal.**
   - **Vary the RF frequency by +/- 1MHz in 100 kHz increments.**
2. **Variations in the ratio of forward to reflected power indicate a VSWR problem within the cabling system.**

MEASUREMENT OF VSWR INDUCED ERRORS



Difference between RF readings calibrated at 805 MHz and those taken at nearby frequencies for several different signal paths. The paths with smaller errors had attenuators distributed throughout the signal path.

VERTICAL AND HORIZONTAL TESTING

- During production cavities are generally tested using antenna inserted into the fundamental power couplers or one of the beam pipes. The goal is to have the cavity at or near critical coupling for these tests. In this way a minimum amount of power can be used to reach design gradient. Ideally this means just enough power to overcome the heat losses in the cavity and the power coupled out of the other ports. This has the advantage that the power lost to wall heating can be calculated based on RF measurements.

- In most labs these tests are done in vertical test dewars, hence they are commonly called vertical tests.

- Cavities in a cryomodule are typically tested using the production couplers that are strongly over coupled. This presents a problem as the errors RF power dissipated in the cavity get excessive when 95% to 99.9% of the incident power is reflected back out of the fundamental power coupler.

- During cryomodule tests the RF heat load is measured calorimetrically.

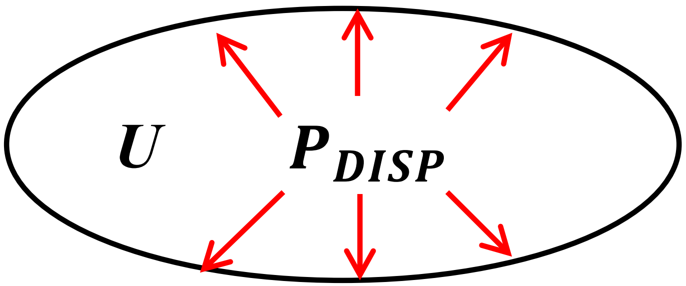
FUNDAMENTAL TERMS

r/Q	**Shunt Impedance***	**Ω/m**		T	**Operational Temperature**	**K**
G	**Geometry Factor**	**Ω**		r_{resid}	**Residual Surface Resistance**	**Ω**
E	**Electric Field**	**V/m**		Q_0	**Intrinsic Quality Factor**	
L	**Electrical Length**	**m**		Q_{FPC}	**Fundamental Power Coupler Q**	
ω_0	**Cavity Frequency**	**s^{-1}**		$Q_{FP},\ Q_2$	**Field Probe Coupler Q's**	
U	**Stored Energy**	**J**		R_C	**Coupling Impedance**	**Ω/m**
r_S	**Surface Resistance**	**Ω**		I, I_0	**Beam Current**	**A**
T_C	**Critical Temperature**	**K**		I_M	**Matching Current**	**A**
P_X	**RF Power at port X**	**W**		P_{disp}	**Dissipated Power**	**W**
P_{emit}	**Emitted Power**	**W**		τ	**Decay Time**	**s**
R	**Shunt impedance**	**Ω**		β	**Geometric Coupling Factor**	

***Beware that there are different definitions for shunt impedance in use. At Jefferson Lab we use $R = V^2/P$ that includes transit time factor for β = 1.**

DECAY MEASUREMENT DERIVATION

- Consider a system that has contains a stored energy-U and wall losses P_{DISP}
- Using the basic definition of Q_0



$$Q_0 = \frac{Stored\ Energy}{Energy\ Lost\ Per\ Cycle}$$

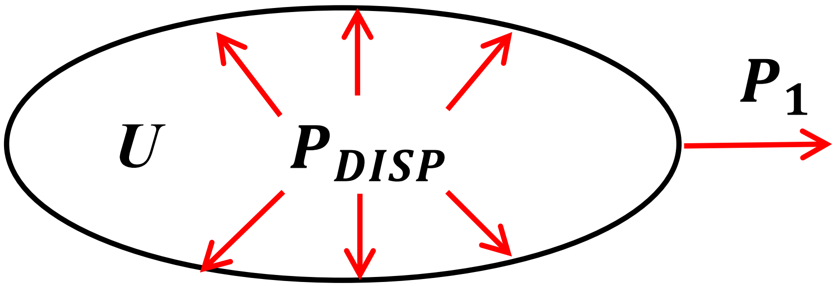
$$Q_0 = \frac{U}{P_{DISP} * T}$$

- Where U is the stored energy, P_{DISP} is the dissipated power in the walls and T is the period of the cycle.
- This can be rewritten as:

$$Q_0 = \frac{\omega U}{P_{DISP}}$$

DECAY MEASUREMENT DERIVATION

- Now add a port through which power can leave the system.



- Now you have two paths that power may leave the system. These paths are wall losses and through an RF port on the cavity. Assuming that the RF power that leaves the system is proportional to the stored energy (e.g. the electromagnetic fields within the cavity)

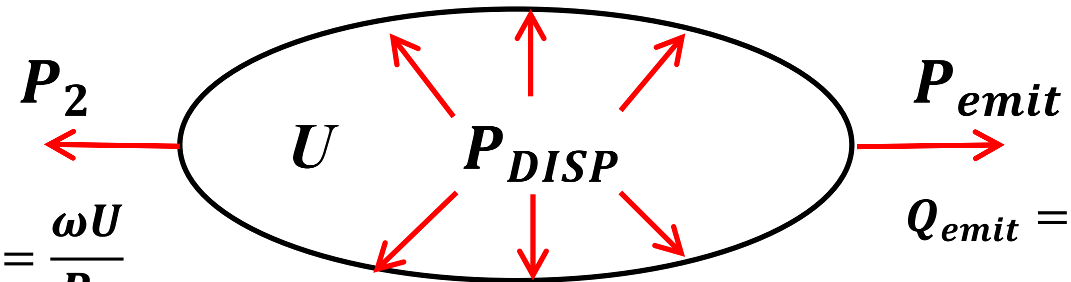
- We can DEFINE the Q for port 1 as:

$$Q_1 = \frac{\omega U}{P_1}$$

* *Note in Hassan's book P_1 is also called Pe for emitted power.*

DECAY MEASUREMENT DERIVATION

- Now add a second port through which power can leave the system.



$$Q_{emit} = \frac{\omega U}{P_2}$$

$$Q_{emit} = \frac{\omega U}{P_{emit}}$$

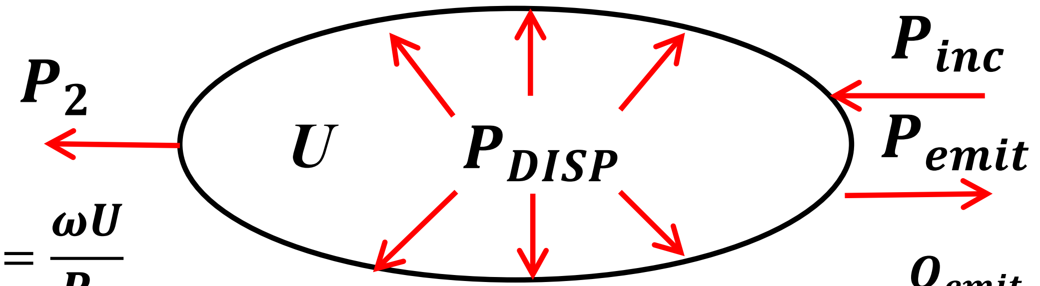
- Defining the Q-external of each port in the same way leads to and defining the total loaded-Q as seen by the stored energy in the cavity as the effective Q as determined by all of the "loss" mechanisms:

$$Q_L = \frac{\omega U}{P_{Disp} + P_{emit} + P_2}$$

$$\frac{1}{Q_L} = \frac{P_{Disp} + P_{emit} + P_2}{\omega U} = \frac{P_{Disp}}{\omega U} + \frac{P_{emit}}{\omega U} + \frac{P_2}{\omega U} = \frac{1}{Q_0} + \frac{1}{Q_{emit}} + \frac{1}{Q_2}$$

DECAY MEASUREMENT DERIVATION

- Now lets add an incident power term to port 1. This power will be just enough to balance out all of the losses in the system.



$$Q_{emit} = \frac{\omega U}{P_2} \qquad Q_{emit} = \frac{\omega U}{P_{emit}}$$

- This gets tricky because of the concept of impedance miss-match and the fact that there will be a reflected power signal. Given that:

$$P_X = \frac{V_X^2}{Z_0} \quad or \quad V_X = \sqrt{P_X Z_0}$$

- **Assuming that the cavity is perfectly tuned** and if one looks at the RF voltage at the port

$$V_R = V_{emit} - V_{inc} \rightarrow P_R = \left(\sqrt{P_{emit}} - \sqrt{P_{Inc}}\right)^2$$

DECAY MEASUREMENT DERIVATION

$$P_R = \left(\sqrt{P_{emit}} - \sqrt{P_{Inc}}\right)^2$$

- **Taking the square root of both sides of the equation, which requires that one add the +/- operator.**

$$\pm\sqrt{P_{REF}} = \sqrt{P_{emt}} - \sqrt{P_{FWD}}$$

or

$$\sqrt{P_{emt}} = \sqrt{P_{FWD}} \pm \sqrt{P_{REF}}$$

- **Next we are going to define a variable that we will call the coupling coefficient represented by the variable β_X where:**

$$\beta_X = \frac{Q_0}{Q_X} = \frac{P_X}{P_{DISP}}$$

- **Where P_X is the power leaving the port because of the stored energy in the cavity.**

DECAY MEASUREMENT DERIVATION

- Starting with:

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{emit}} + \frac{1}{Q_2} \qquad \text{and} \qquad \sqrt{P_{emit}} = \sqrt{P_{FWD}} \pm \sqrt{P_{REF}}$$

- Using the previously defined coupling coefficient represented by the variable β_X where:

$$\beta_X = \frac{Q_0}{Q_X} = \frac{P_X}{P_{DISP}}$$

$$\beta_{FPC} = \frac{Q_0}{Q_{FPC}} = \frac{P_{emt}}{P_{disp}} = \frac{\left(\sqrt{P_{FWD}} \pm \sqrt{P_{REF}}\right)^2}{P_{disp}}$$

- By convention, over coupling is when $\beta_{FPC} > 1$ and under coupling is when $\beta_{FPC} < 1$ and critically coupled when $\beta_{FPC} = 1$. Thus β_{FPC} can also be written as:

$$\beta_{FPC} = \frac{Q_0}{Q_{FPC}} = \frac{P_{emt}}{P_{disp}} = \frac{\left(\sqrt{P_{FWD}} + C_\beta\sqrt{P_{REF}}\right)^2}{P_{disp}}$$

- Using the same convention we can come up with β_{FP}.

$$\beta_{FP} = \frac{Q_0}{Q_{FP}} = \frac{P_{Trans}}{P_{disp}}$$

DECAY MEASUREMENT DERIVATION

- **Starting with.**

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{FPC}} + \frac{1}{Q_{FP}}$$

- **Multiplying both sides by Q_L/Q_0, and rewriting the equation:**

$$Q_0 = \left(1 + \frac{Q_0}{Q_{FPC}} + \frac{Q_0}{Q_{FP}}\right)Q_L = (1 + \beta_{FPC} + \beta_{FP})Q_L$$

$$Q_0 = \left(1 + \frac{\left(\sqrt{P_{FWD}} + C_\beta\sqrt{P_{REF}}\right)^2}{P_{FWD} - P_{REF} - P_{FP}} + \frac{P_{FP}}{P_{FWD} - P_{REF} - P_{FP}}\right)Q_L$$

$$Q_0 = \left(1 + \frac{\left(\sqrt{P_{FWD}} + C_\beta\sqrt{P_{REF}}\right)^2}{P_{FWD} - P_{REF} - P_{FP}} + \frac{P_{FP}}{P_{FWD} - P_{REF} - P_{FP}}\right)2\pi f_0 \tau$$

DECAY MEASUREMENT DERIVATION

- **Starting with.**

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{FPC}} + \frac{1}{Q_{FP}}$$

- **Multiplying both sides by Q_L/Q_0, and rewriting the equation:**

$$Q_0 = \left(1 + \frac{Q_0}{Q_{FPC}} + \frac{Q_0}{Q_{FP}}\right) Q_L = (1 + \beta_{FPC} + \beta_{FP}) Q_L$$

$$Q_0 = \left(1 + \frac{\left(\sqrt{P_{FWD}} + C_\beta \sqrt{P_{REF}}\right)^2}{P_{FWD} - P_{REF} - P_{FP}} + \frac{P_{FP}}{P_{FWD} - P_{REF} - P_{FP}}\right) Q_L$$

$$Q_0 = \left(1 + \frac{\left(\sqrt{P_{FWD}} + C_\beta \sqrt{P_{REF}}\right)^2}{P_{FWD} - P_{REF} - P_{FP}} + \frac{P_{FP}}{P_{FWD} - P_{REF} - P_{FP}}\right) 2\pi f_0 \tau$$

DECAY MEASUREMENT DERIVATION

- There are two ways to determine the loaded-Q of a cavity.
  - The first way is to measure the 1/e decay time constant, τ, for the reflected or transmitted power signal.
  - The second approach is to measure the bandwidth of the cavity transfer function (S21) and calculate the loaded-Q as the center frequency divided by the -3 dB full bandwidth.

$$Q_L = 2\pi f_0 \tau \qquad or \qquad Q_L = \frac{f_0}{BW}$$

- Starting with the last equation of the previous slide:

$$Q_0 = \left(1 + \frac{\left(\sqrt{P_{FWD}} + C_\beta \sqrt{P_{REF}}\right)^2}{P_{FWD} - P_{REF} - P_{FP}} + \frac{P_{FP}}{P_{FWD} - P_{REF} - P_{FP}}\right) 2\pi f_0 \tau$$

  - It can be shown that:

$$Q_0 = 4\pi f_0 \tau \frac{P_{FWD} + C_\beta \sqrt{P_{REF} P_{FWD}}}{P_{FWD} - P_{REF} - P_{FP}}$$

DECAY MEASUREMENT DERIVATION

From an earlier slide we know that:

$$Q_0 = \frac{\omega_0 U}{P_{DISIPATED}}$$

Where U is the stored energy. The stored energy is related to the accelerating gradient as:

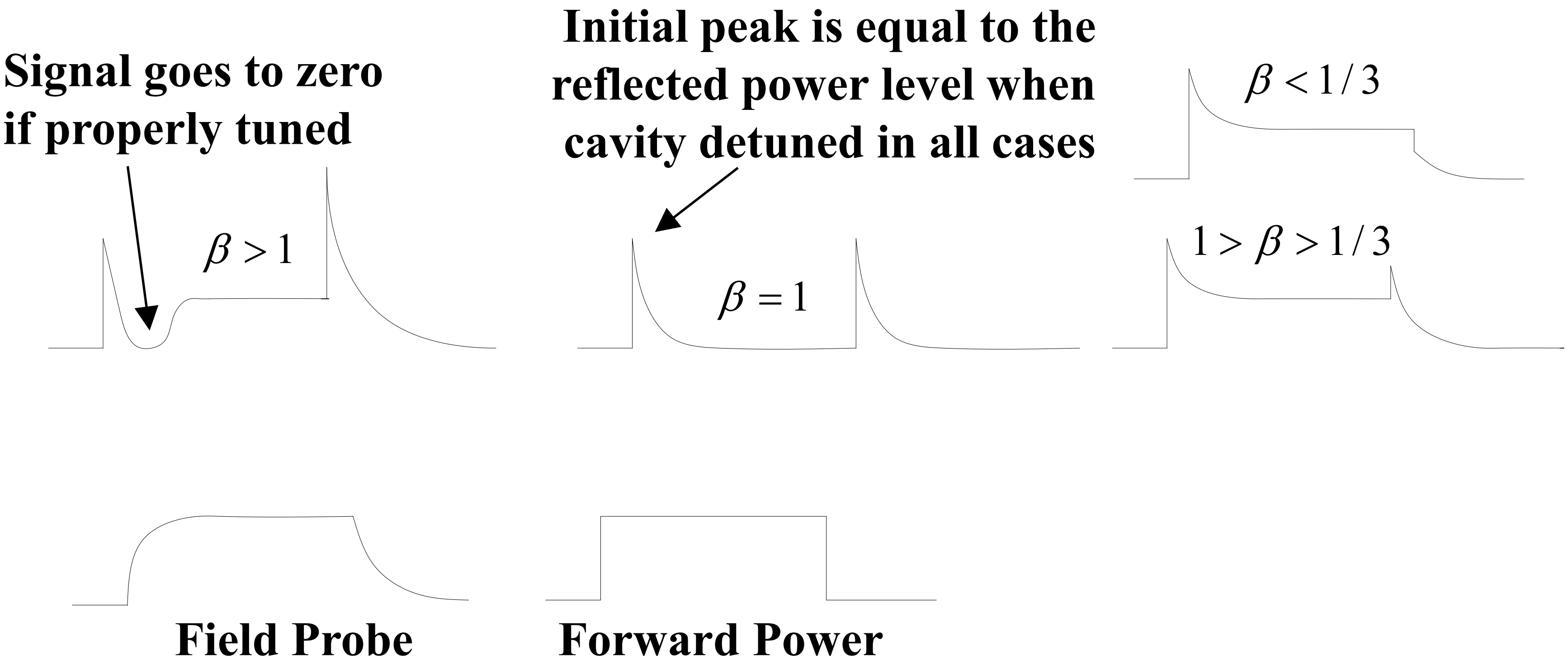
$$E^2 = \frac{\omega_0 (r/Q) U}{L} \quad or \quad E^2 = \frac{(r/Q) Q_0 P_{DISIPATED}}{L}$$

Using the equation for Q_0 from the previous slide and doing a page or two of math results in:

$$E_{acc}(V/m) = \sqrt{4\pi f_o \tau \left(P_{FWD} + C_\beta \sqrt{P_{REF} P_{FWD}}\right) \frac{(r/Q)}{L}}$$

DETERMINING IF CAVITY IS OVER OR UNDER COUPLED

When operating cavities near critical coupling and preparing to make a decay measurement, one of the items that must be determined is the cavity is over coupled or under coupled. Typically a crystal detector is placed on the reflected power signal and the waveform is observed under pulsed conditions. Alternately one can watch the reflected power meter and see if it is increasing at the end of the fill (over coupled) or decreasing (under coupled).



ERROR CALCULATIONS DECAY MEASUREMETNS

Assuming uncorrelated source terms, the error in Z(x,y) is given by:

$$\Delta Z = \sqrt{\left(\frac{\partial Z}{\partial x}\Delta x\right)^2 + \left(\frac{\partial Z}{\partial y}\Delta y\right)^2}$$

and after several pages of math, it can be shown that.

$$\Delta E = \frac{E}{2}\sqrt{\left(\frac{\left(2P_f + C_\beta\sqrt{P_f P_r}\right)}{2\left(P_f + C_\beta\sqrt{P_r P_f}\right)}\frac{\Delta P_f}{P_f}\right)^2 + \left(\frac{\sqrt{P_r}}{2\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}\frac{\Delta P_r}{P_r}\right)^2 + \left(\frac{\Delta\tau}{\tau}\right)^2}$$

$$\Delta Q_2 = Q_2\sqrt{\left(\frac{\left(2\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}{2\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}\frac{\Delta P_f}{P_f}\right)^2 + \left(\frac{\sqrt{P_r}}{2\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}\frac{\Delta P_r}{P_r}\right)^2 + \left(\frac{\Delta P_t}{P_t}\right)^2 + \left(\frac{\Delta\tau}{\tau}\right)^2}$$

ERROR CALCULATIONS DECAY MEASUREMENTS

and after several more pages:

$$\Delta Q_0 = Q_0 \sqrt{\begin{array}{l} \left(\left(\dfrac{\left(2P_f + C_\beta\sqrt{P_f P_r}\right)}{2\left(P_f + C_\beta\sqrt{P_r P_f}\right)} - \dfrac{P_f}{P_{Disp}}\right)\dfrac{\Delta P_f}{P_f}\right)^2 + \\ \left(\left(\dfrac{\left(C_\beta\sqrt{P_r P_f}\right)}{2\left(P_f + C_\beta\sqrt{P_r P_f}\right)} + \dfrac{P_r}{P_{Disp}}\right)\dfrac{\Delta P_r}{P_r}\right)^2 + \\ \left(\dfrac{\Delta\tau}{\tau}\right)^2 + \left(\dfrac{P_t}{P_{Disp}}\dfrac{\Delta P_t}{P_t}\right)^2 + \sum\left(\dfrac{P_{HOMx}}{P_{Disp}}\dfrac{\Delta P_{HOMx}}{P_{HOMx}}\right)^2 \end{array}}$$

ERROR IN DECAY TIME DUE TO VSWR MISSMATCH [1]

- **In a perfectly matched system, all of the power that leaves the fundamental power coupler is absorbed by a circulator or similar device with no reflections.**
- **If the system is not perfectly matched a fraction of the emitted power is reflected back to the cavity with a fixed but random phase. Depending on the phase this reflected wave either increases or decreased the measured decay time.**
- **A linear approximation of the error is given by:**

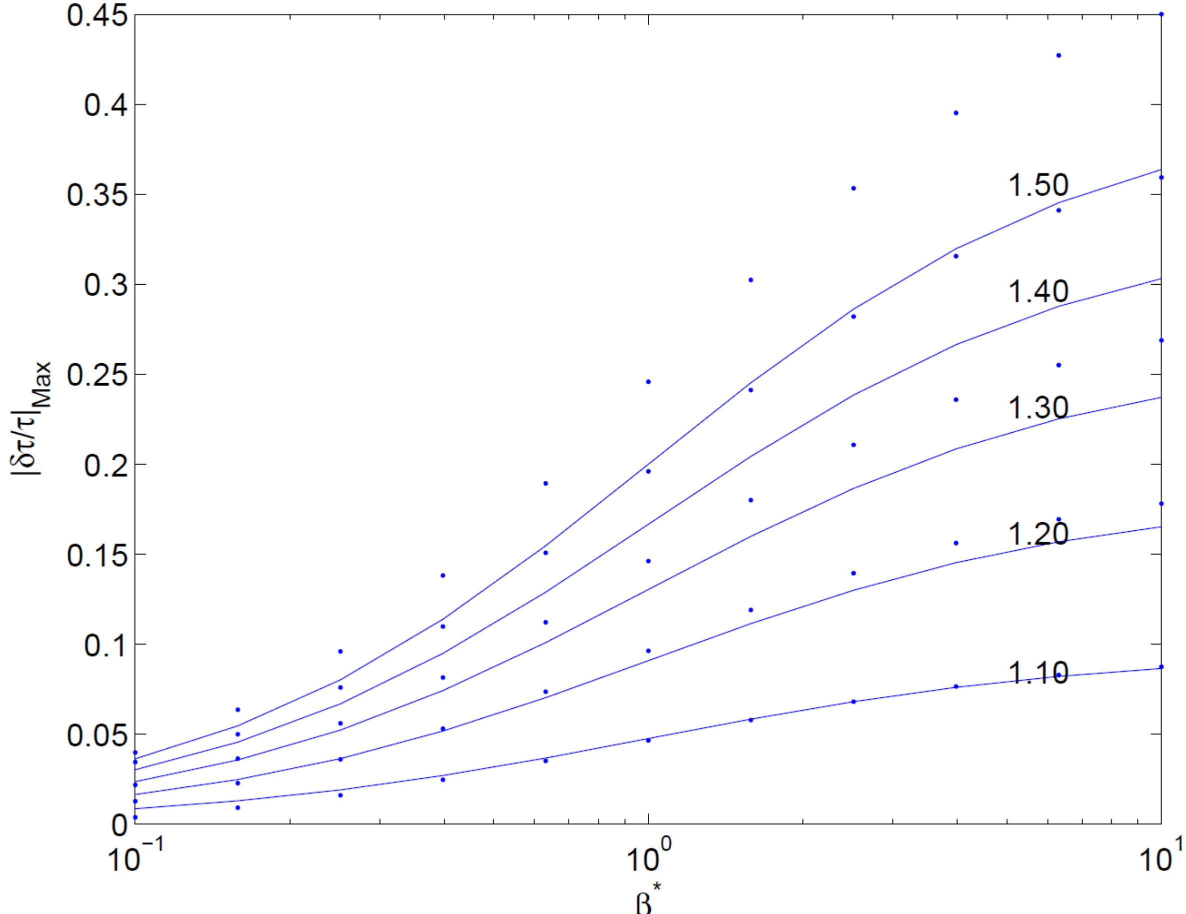
$$\left\langle \left(\frac{\Delta\tau}{\tau}\right)^2 \right\rangle^{\frac{1}{2}} \approx \frac{\sqrt{2}\beta^*(VSWR-1)}{(\beta^*+1)(VSWR+1)}$$

- **Where VSWR is the VSWR of the combination of the RF source, circulator, directional couplers, etc. and $\boldsymbol{\beta}^*$ is given by the following.**

$$\beta^* = \frac{1 \pm \sqrt{P_r/P_f}}{1 \mp \sqrt{P_r/P_f}}$$

- **Where $\boldsymbol{\beta}^*$ is greater than 1 for over coupled cavity and less than 1 for an under coupled cavity;.**

ERROR IN DECAY TIME DUE TO VSWR MISSMATCH [1]

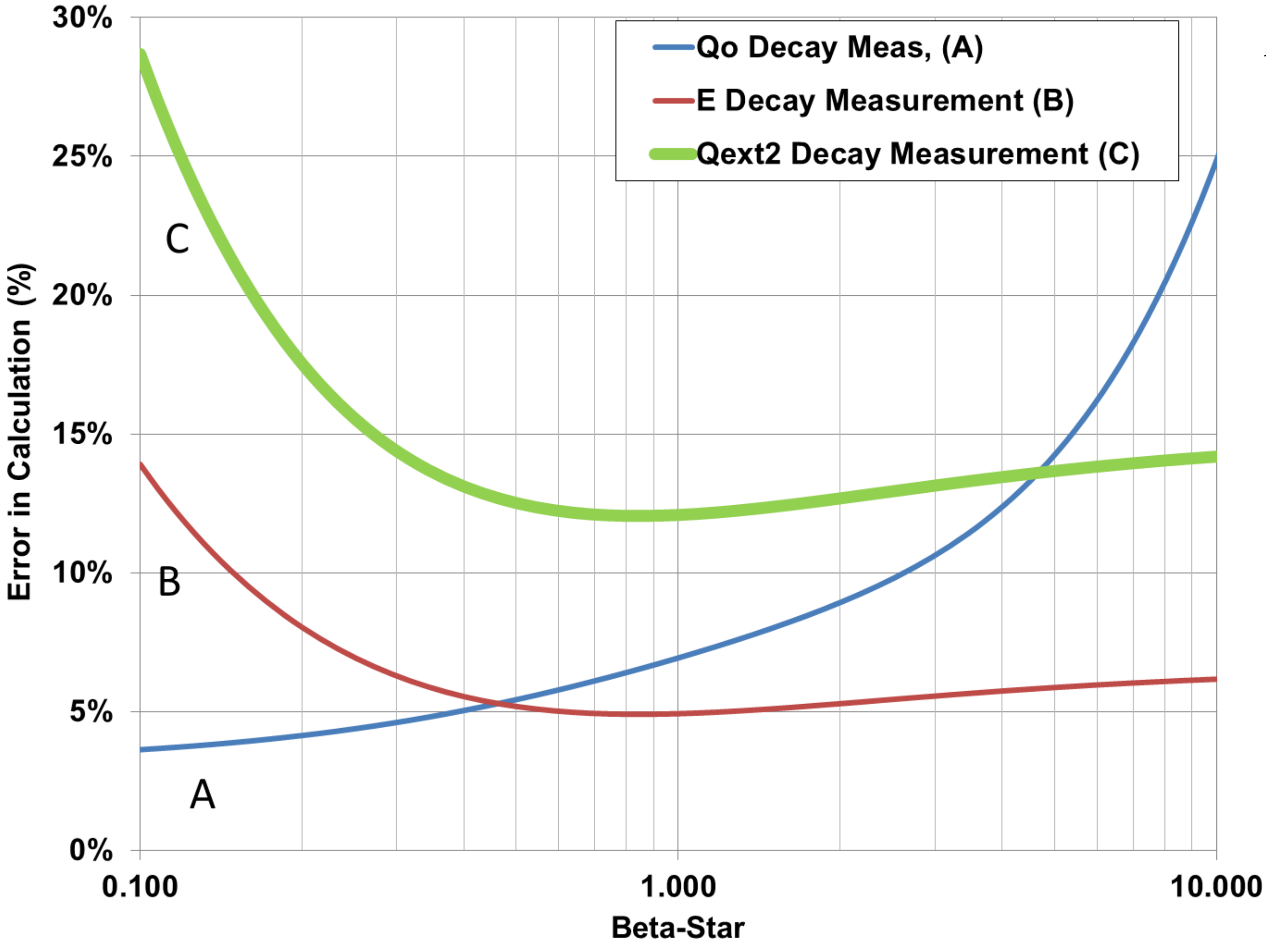


Expected systematic uncertainty in the measured decay time as a function of β^* for various values of system VSWR.

This error also applies to time constants due to loaded-Q for cryomodules where $\beta^* > 50$

[1] J.P.Holzbauer, Yu.Pischalnikov, D.A.Sergatskov, W.Schappert, S.Smith "Systematic uncertainties in RF-based measurement of superconducting cavity quality factors" NIM-A, Volume 830, 11 September 2016, Pages 22-29

DECAY MEASURMENT Qo AND E ERRORS AS A FUNCTION OF BETA*



Assumptions

- **7% power meter calibration errors**
- **2% power meter linearity errors**
- **VSWR = 1.15**
- **2% error in calculation of decay time in addition to error introduced by VSWR.**
- **As a results of VSWR and 2% error above $3\% < \Delta\tau/\tau < 11\%$**

ERROR PROPAGATION FROM DECAY TO CW MEASUREMENTS

Next we split the power measurement errors into two parts.

- **Calibration errors which are fixed between decay and CW measurements**
- **Linearity errors which can vary depending on the measured rf power.**

$$Q_0 = \left[\frac{C_t P_{tm}}{C_f P_{fm} - C_r P_{rm} - C_t P_{tm}}\right]\left[4\pi f_0 \tau' \frac{C_f P'_{fm} + C_t C'_\beta \sqrt{C_f C_r P'_{fm} P'_{rm}}}{C_t P'_{tm}}\right]$$

Where the values annotated with a prime (′) symbol are the readings taken when performing the decay, C_x are the power meter calibrations, and P_{xm} are the raw power meter measurements. Note the second term is Q2

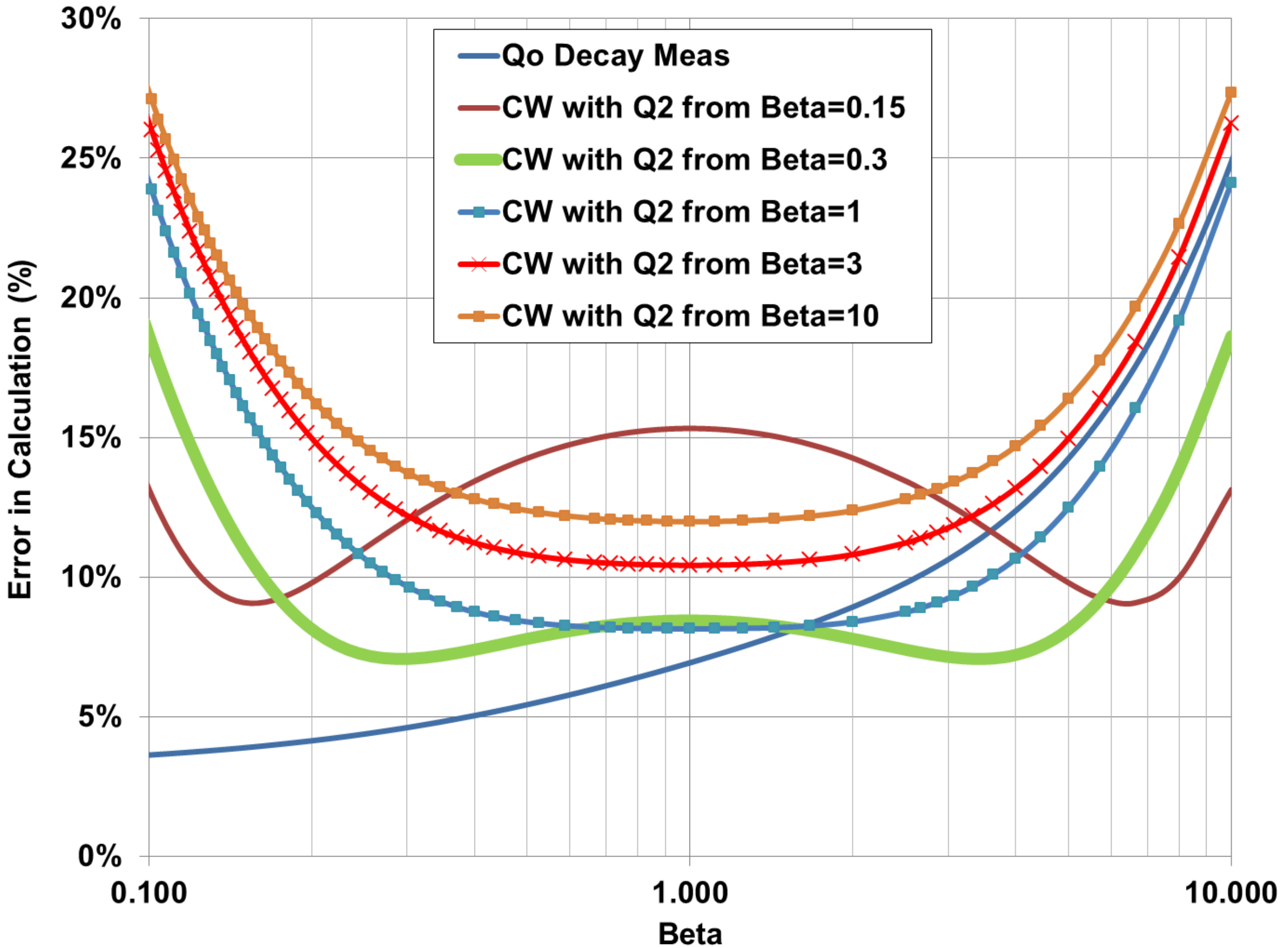
Taking the partial derivatives with respect to the calibration factors C_f, C_r, C_t, P_{fm}, P_{rm}, P_{tm} and τ and applying the results to the general error calculation leads to the results shown on the following slide. Note that during the derivation I carried through all of the calibration factors C_x, after the mathematical manipulations each P_{xm} was associated with its correction factor and the power values in the final equations are the calibrated values including the calibration factors.

Q_0 ERRORS FOR CW MEASUREMENTS

$$\Delta Q_0 = Q_0 \sqrt{\begin{aligned} &\left(\left[\frac{2P'_f + C'_\beta\sqrt{P'_f P'_r}}{2\left(P'_f + C'_\beta\sqrt{P'_f P'_r}\right)} - \frac{P_f}{P_f - P_r - P_t}\right]\frac{\Delta C_f}{C_f}\right)^2 \\ &+ \left(\left[\frac{C'_\beta\sqrt{P'_f P'_r}}{2\left(P'_f + C'_\beta\sqrt{P'_f P'_r}\right)} + \frac{P_r}{P_f - P_r - P_t}\right]\frac{\Delta C_r}{C_r}\right)^2 + \left(\frac{\Delta\tau'}{\tau'}\right)^2 \\ &+ \left(\left[\frac{P_f}{(P_f - P_r - P_t)}\right]\frac{\Delta P_f}{P_f}\right)^2 + \left(\left[\frac{P_r}{(P_f - P_r - P_t)}\right]\frac{\Delta P_r}{P_r}\right)^2 \\ &+ \left(\frac{P_t}{P_f - P_r - P_t}\frac{\Delta C_t}{C_t}\right)^2 + \left(\left[1 + \frac{P_t C_t}{(P_f - P_r - P_t)}\right]\frac{\Delta P_t}{P_t}\right)^2 \end{aligned}}$$

Where the $\frac{\Delta C_x}{C_x}$ is the error in the calibration of the respective power meter, $\frac{\Delta P_x}{P_x}$ is the linearity of the meters, $\frac{\Delta \tau'}{\tau'}$ is the error in τ, and Px is the corrected power values.

ERROR IN CW Q_0 MEASUREMENTS AS A FUNCTION OF BETA*



Assumptions

- 7% power meter calibration errors
- 2% power meter linearity errors
- VSWR = 1.15
- 2% error in calculation of decay time in addition to error introduced by VSWR.
- As a results of VSWR $3\% < \Delta\tau/\tau < 11\%$

Each plot represents the error of the measured Q_0 with a Q_2 value that was determined in a decay measurement for various values of Beta. The solid blue line is a plot of the decay based Q_0 errors.

STRONGLY OVER COUPLED CAVITIES

For strongly over coupled cavities with no beam:

$$C_\beta = 1 \text{ and}$$

$$\beta = \frac{1 + C_\beta\sqrt{P_{Reflected}/P_{Incident}}}{1 - C_\beta\sqrt{P_{Reflected}/P_{Incident}}} \gg 1$$

$$\beta = \frac{Q_0}{Q_1\left(1 + \sum_{i=2}^{N}\frac{Q_i}{Q_0}\right)} \cong \frac{Q_0}{Q_1} = \frac{Q_0}{Q_L} - 1$$

Normally $Q_1 \ll Q_0$ and $Q_0 \ll Q_2, Q_3 \;\ldots\; Q_N$

$$Q_L = 2\pi f_0 \tau$$

$$E^2 = \frac{4\beta}{(1+\beta)} P_{Incident} Q_L \frac{(r/Q)}{L} \cong 4 P_{Incident} Q_L \frac{(r/Q)}{L} \qquad \beta \gg 1$$

Although using the forward power to calculate gradient is a reasonable technique, practical experience says that there can easily be as much as 25% difference between the gradient measured using this technique as compared to the that measured using the emitted power technique or using a well calibrated field probe measurement. This difference can be reduced by properly tuning the phase locked loop, for a variable frequency system or the cavity for a fixed frequency system.

STRONGLY OVER COUPLED CAVITIES

Power levels for a strongly over coupled cavity, including on crest beam loading, where $R_C = Q_L(r/Q)$ and there is no microphonics:

delivered to beam LEI

needed from the klystron $\frac{\mathrm{L}(\mathrm{E}+\mathrm{IR_C})^2}{4\mathrm{R_C}} = \frac{1}{4}\frac{L}{Q_L(r/Q)}(E+IQ_L(r/Q))^2$

reflected to the circulator $\frac{\mathrm{L}(\mathrm{E}-\mathrm{IR_C})^2}{4\mathrm{R_C}} = \frac{1}{4}\frac{L}{Q_L(r/Q)}(E-IQ_L(r/Q))^2$

Time dependent, complex diferential equation where $\vec{K}$ is the incident wave amplitude in $\sqrt{\mathrm{Watts}}$, ω_d is the (time varying) detune angle, and $\omega_f = \omega_0/2Q_L$:

$$\left(1\text{-}j\frac{\omega_d}{\omega_f}\right)\vec{E} + \frac{1}{\omega_f}\frac{d\vec{E}}{dt} = 2\vec{K}\sqrt{\frac{R_C}{L}} - R_C\vec{I}$$

One addition to the standards is the equation for the power required for cavity center frequency $\mathrm{f_0}$ detuned by δf and beam current, I_0, off crest by ψ_B :

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

EMITTED POWER MEASUREMENT

THE REFERENCE MEASUREMENT FOR STRONGLY OVER COUPLED CAVITIES

Consider what happens when you suddenly remove the incident RF power from a cavity that has the stored energy U. This stored energy leaves the system through dissipation due to wall losses, i.e. Q_0 losses, and as RF power that is emitted from all of the RF ports in the system. Since $Q_L << Q_{FP}$ and $Q_L << Q_0$ in a strongly over coupled superconducting cavity the stored energy can be calculated as:

$$U = \int_{t_0}^{\infty} P_{emitted}(t)dt \approx \int_{t_0}^{\infty} P_{reflected}(t)dt$$

Historically value of U was measured using a gating circuit and an RMS power meter. In a sampled system, such as can be done with a Boonton 4532 pulsed power meter, the stored energy can be approximated by:

$$U \approx \sum_{m}^{N} \left(P_{reflected}\right)_i \Delta t$$

Where m is the sample point where the incident power is removed and N is the total number of sample points. In addition to the errors associated with the power measurement, there are errors in this measurement which are introduced by the sampling system that can be reduced by proper choice of system parameters.

EMITTED POWER MEASUREMENT UNCERTAINTY

The uncertainty in the stored energy is given by the following:

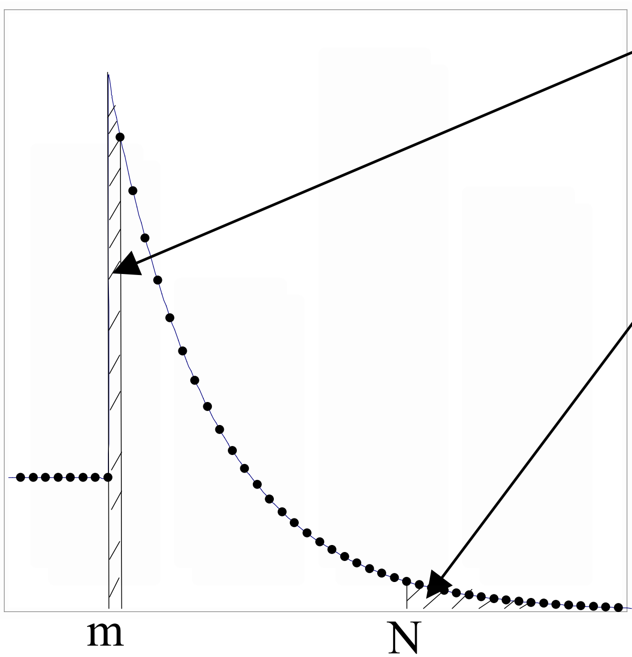
$$\Delta U = U\sqrt{\Delta C_R^2 + \Delta P_{CAL}^2} + \Delta t(N-m)C_R P_{\min} + (\Delta P_{emitted})_m \Delta t + \tau(P_{emitted})_N$$

Where :

ΔC_R is the percentage error in the power reading due to the cable calibration errors and

ΔP_{CAL} is the error in the power meter calibration.

$\Delta t(N-m)C_R P_{\min}$ is the contribution of the power meter noise floor during the integration.



$(\Delta P_{emitted})_m \Delta t$ is due to the jitter in the start of the integration and the peak of the emitted power transient

$\tau(P_{emitted})_N$ is the error introduced because you only summed the series to N and not to ∞

The last two errors can be minimized by sampling the system at a high sample rate compared to the decay time and insuring that that *(m-N)Δt* is greater than 4 decay time constants.

ASSUMES AT LEAST 20 dB RETURN LOSS ON CIRCULATOR

FIELD PROBE CALIBRATION

Once the stored energy has been determined the gradient can be calculated by using the following:

$$E_{Emitted} = \sqrt{2\pi f_0 * U * \frac{r/Q}{L}}$$

Where the emitted subscript is just an indicator of method used to determine the value. The filed probe coupling factor, Q_{FP} can the be calculated using:

$$Q_{FP} = \frac{E_{Emitted}^2}{(P_{Transmitted})_{m-1}} * \frac{L}{r/Q}$$

Where $P_{Transmitted}$ is sampled just prior to removal of the incident power signal. Normally an average of several points just prior to *m* is used for this value.

With good calibrations and proper sample rates the gradient, E, can be measured with an accuracy of 5% to 7% and Q of the field probe to about 10% to 12%.

Q_0 MEASUREMENTS STRONGLY OVER COUPLED CAVITIES

When making a Q_0 measurement on a cavity that is strongly over coupled the dissipated power must be measured calorimetrically. To do this:

- **The inlet and outlet values on the helium vessel are closed**
- **The rate of rise of the helium pressure is measured under static heat load.**
- **The rate of rise of the helium pressure is measured under a heat load of static plus known resistive power.**
- **The rate of rise of the helium pressure is measured under a heat load of static plus unknown cavity dissipated power.**
- **The following equation is used to calculate the unknown cavity dissipated power.**

$$P_{DISSIPATED} = \left(\frac{\left(\frac{dP}{dt}\right)_{RF-ON} - \left(\frac{dP}{dt}\right)_{STATIC}}{\left(\frac{dP}{dt}\right)_{HEATER-ON} - \left(\frac{dP}{dt}\right)_{STATIC}} \right) P_{HEATER}$$

where $\left(\frac{dP}{dt}\right)$ is the rate of rise of the pressure under the different conditions.

Q_0 MEASUREMENTS STRONGLY OVER COUPLED CAVITIES

There are cryomodule configurations where using the pressure measurements described previously does not work well or can not be implemented.

Some examples are:

Systems where the heaters are attached to the outside of the helium vessel rather than in the liquid. In this case the thermal mass of the helium vessel will cause a transient heat load after the heater has been turned off.

Systems where there is no return valve which can be closed.

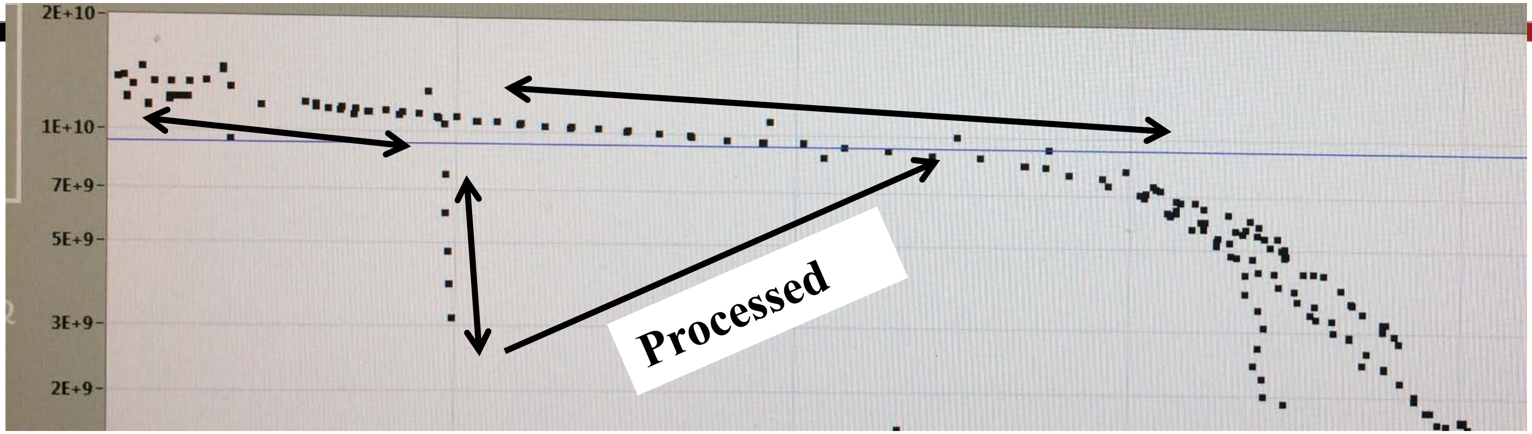
In these instances one can use liquid level or mass flow, with a constant inlet flow and temperature, as a surrogate for pressure to calculate the heat loss. When doing so:

- Use a just the heaters, rather than heaters and RF, to tune the algroithm's on/off times and confirm that one is making accurate calculations of dissipated power.
- It is best if liquid level always starts at the same point for each heater/RF/static heat run.
- As much as possible insure that the incoming helium supply is constant flow and temperature.
- Plan on long, on the order of 1 hour or more, heater/RF/static heat runs.

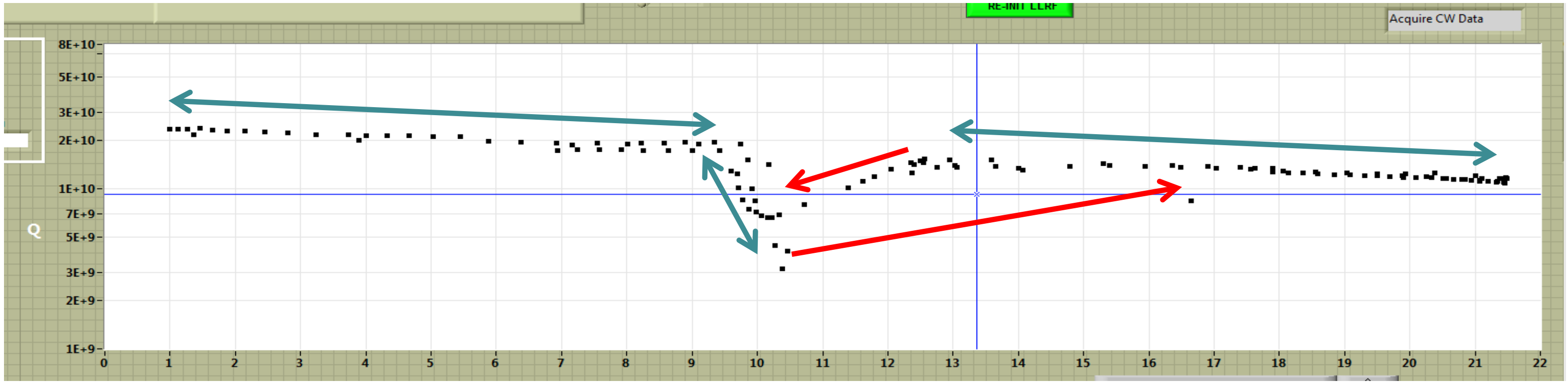
Multipactors

- A multipactor is a resonant process where an electron strikes an adjacent surface, produces more than one secondary electron which "returns" to the area where the first originated and produces one or more secondary electrons.
- The secondary emission coefficient of the surface is enhanced if there is a layer of gas or other contaminants on that surface.
- Usually multipactors can be processed, e.g. surface gas removed, by applying RF. The more power that you can put into the multipactor the faster it will process.
- Plasma processing is one way to process the surface and to remove hydrocarbons. See work by SNS folks.
- It is difficult to get power into a multipactor in a cavity with fixed coupling because the "Qo" the cavity is reduced substantially by the multipactor and most of the power is reflected back.
- A variable coupler allows you to better couple power into the multipactor.
- Because multipactors take time to build up one can use pulsed RF to move through them before it builds up. Even manually switching it on and off manually several times can work especially after you have broken through the first time.
- It can take hours to days to process a stubborn multipactor.

TYPICAL Q VS E CURVES FOR A CAVITY WITH A MULTIPACTOR

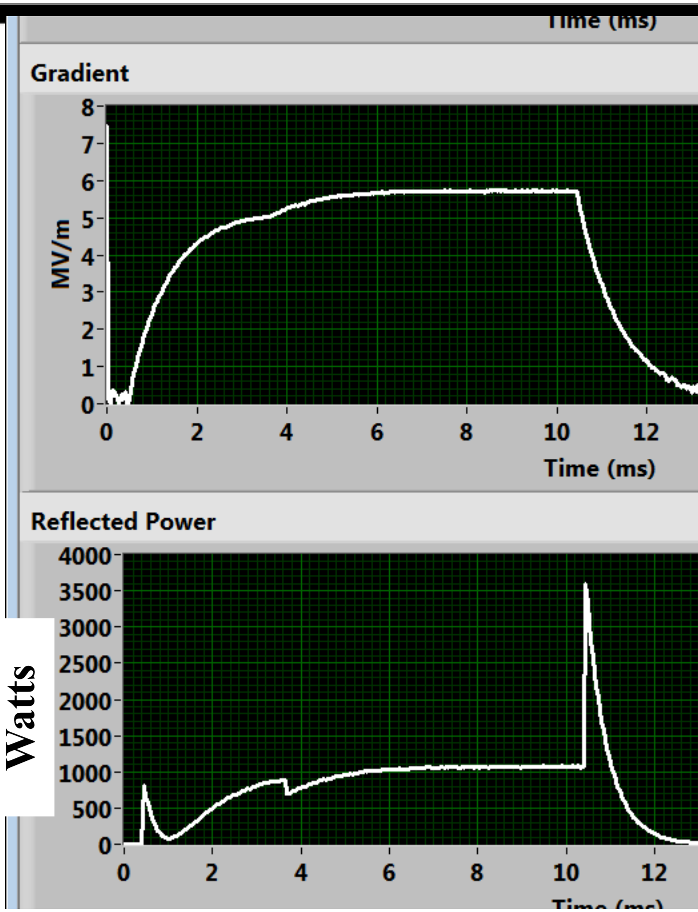


- Usually the processing jumps from multipactor to the upper curve. Often times straight to quench field levels.
- Other times it will slowly drift up over several minutes.



- Blue lines I could go in either direction.
- Red Lines I could only go in one direction.
- Once it started going down from 12.5 MV/m there was no stopping it and it took about 30 seconds to go from 12.5 MV/m to 10.2 MV/m.

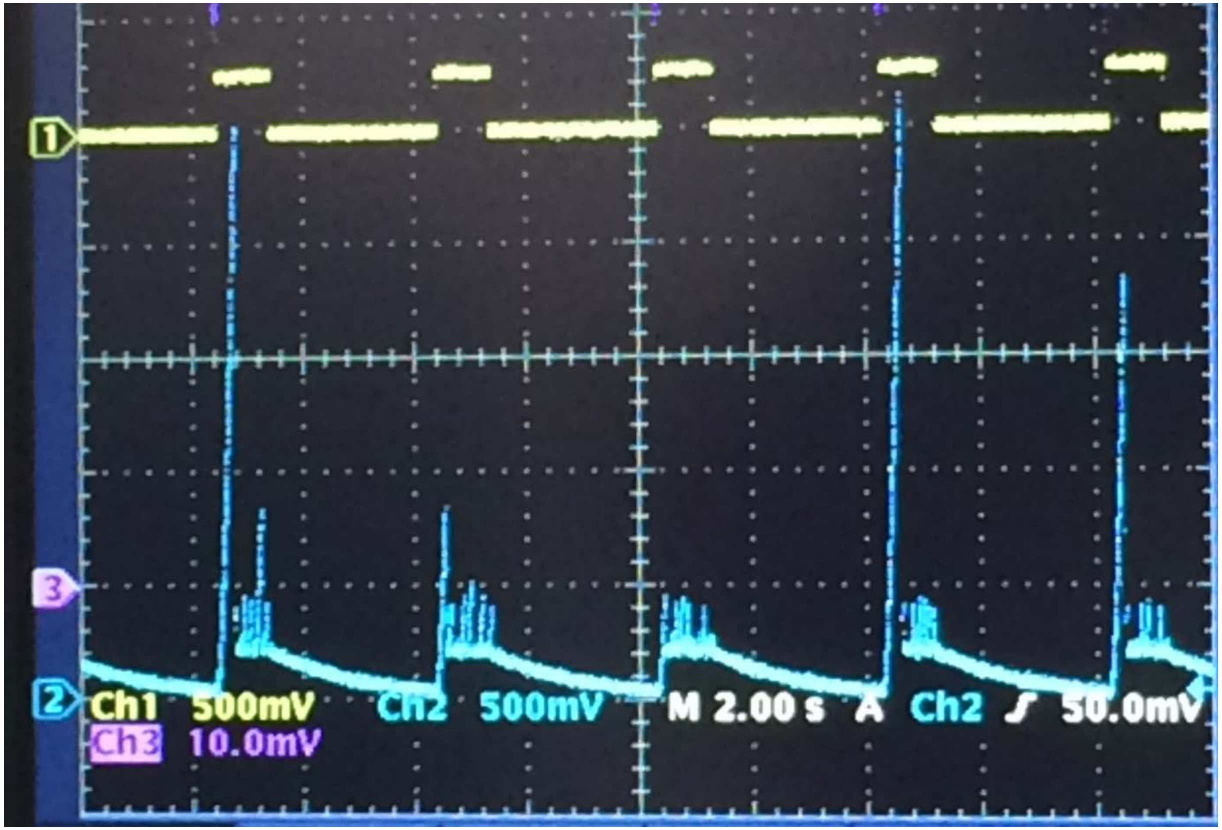
EXAMPLE OF A GLITCH WHEN GOING THROUGH A MULTIPACTOR



Overcoupled cavity with multipactor at about 5 MV/m
Upper plot is gradient lower is reflected power

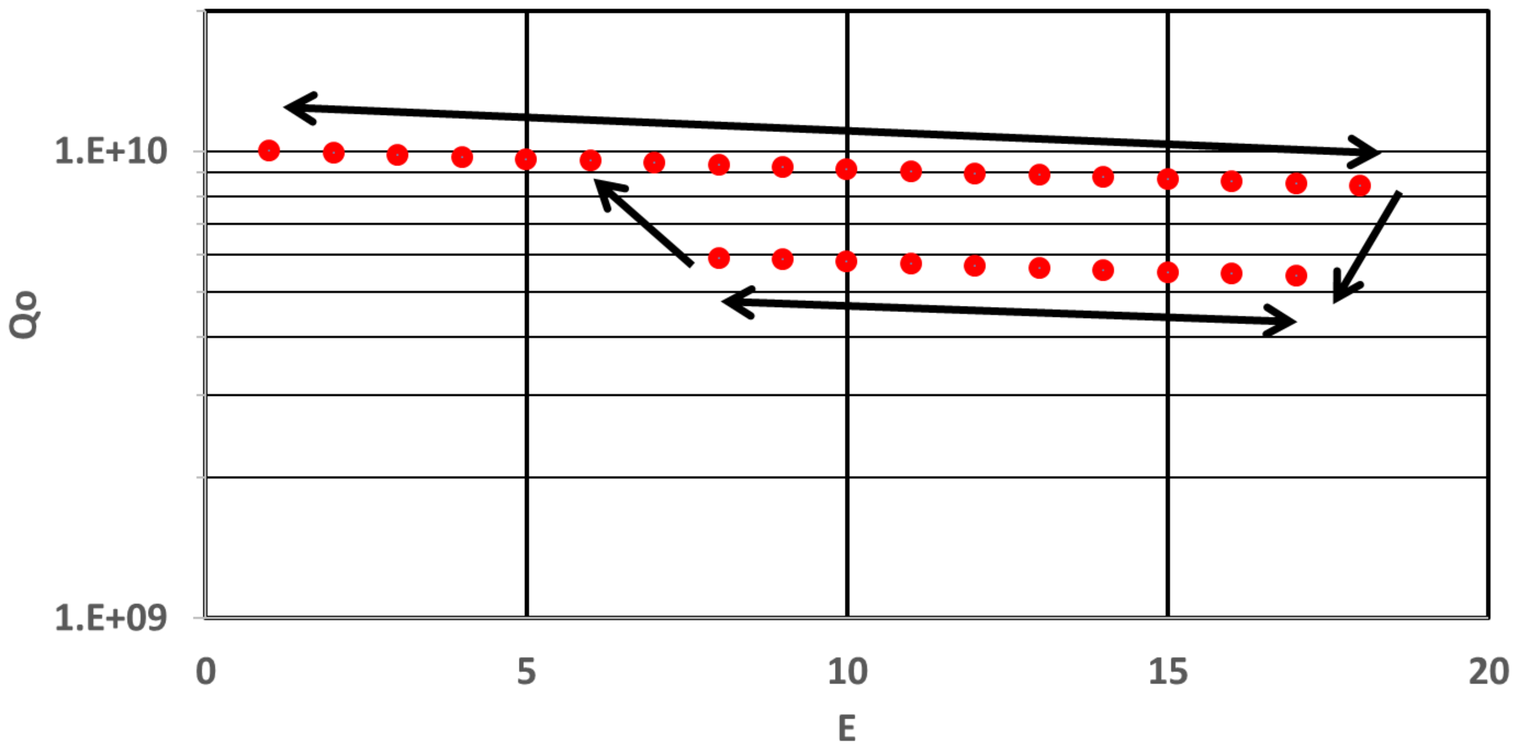
- Critically coupled cavity with multipactor notch on turn on.
- Blue is field probe signal purple is reflected power signal.

EXAMPLE OF PULSED PROCESSING A MULTIPACTOR



- Pulsed processing a multipactor.
- Blue is transmitted power, yellow is forward power, 2 seconds/division.
- Note the peaks where I breaks through the multipactor for a few hundred miliseconds.

Q-SWITCH



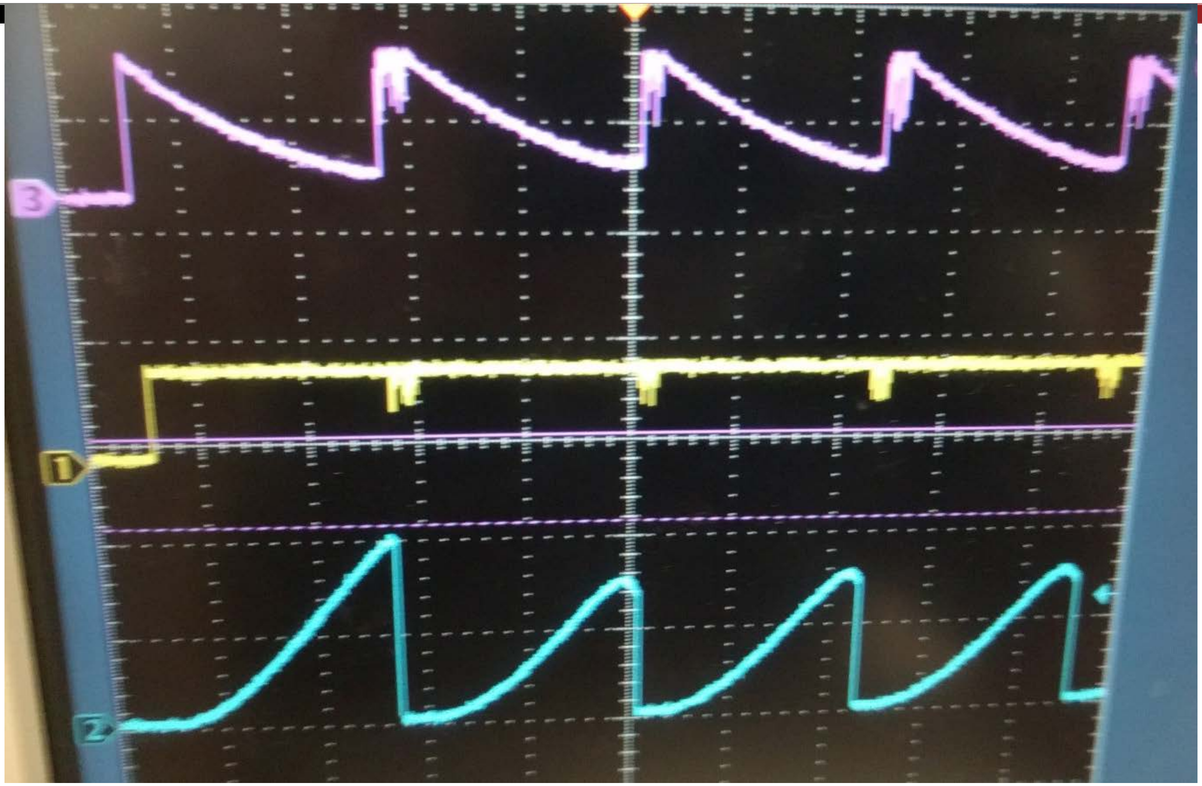
- A Q-switch occurs when a particle of superconducting material is loosely connected to the surface of the cavity.
- The particle heats up and turns normal conducting, which lowers the Qo of the cavity.
- Either of the two lines are stable and you can move in both directions.
- At a low enough field the particle will go back to superconducting and you will again be on the upper curve.

Uncovered Cavity

Reflected Power

Forward Power

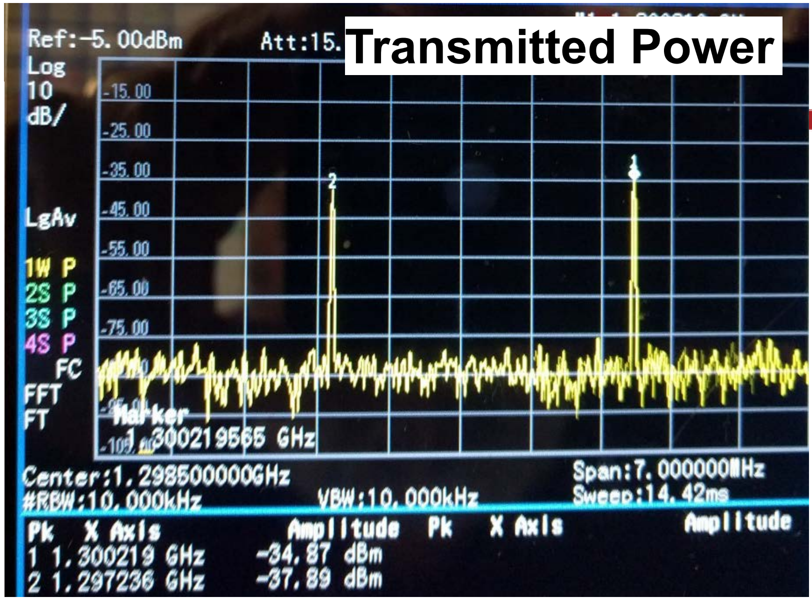
Transmitted Power



1 Sec / Division

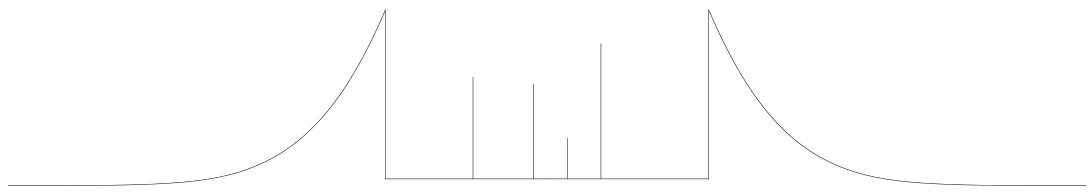
- **A cavity that is fully covered has a quench propagation time of 3 to 10 ms. The field probe signal has a sharp corner at the beginning of the falling edge.**
- **The first quench has such a rounded corner that can be seen at higher temporal resolution.**
- **The second and following pulses show very clear rounded corners.**
- **For this results just the end group was uncovered.**

Mode Mixing

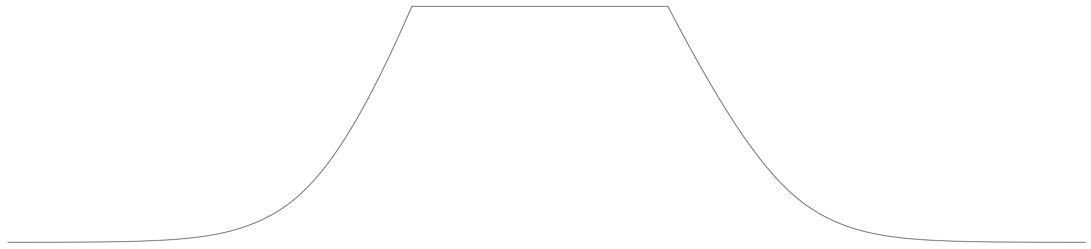


- **Excite a 9-cell cavity in the pi mode. At levels where there tends to be a multipactor (about 21 MV/m) sometimes you will get two output signals from the probe port.**
- **One at the pi mode and one at the 7/9 pi mode.**
- **This seems to like to happen in something like 10% or 30% of the ILC/XFEL/LCLS II style cavities.**
- **You will also get a substantial amount of emitted power at the 7/9 pi mode.**
- **Because there is no frequency content in the forward power a cavity with beta close to 1 will have more "reflected" power at the 7/9 pi mode than the pi mode.**
- **When mapping out a Q vs E curve this shows up as a sudden increase in Qo as the reflected power signal goes up substantially for a given gradient.**
- **Also since the field distribution is no longer flat cavities with this type of phenomena will quench earlier.**
- **Since the 7/9 pi mode is slow to build up (30 sec to 1 min) the work around is to turn the RF off wait for the mode to decay away, turn it back on and take the measurement before it builds up enough to matter.**

TWO INTERESTING NETWORK ANALYZER TRACES



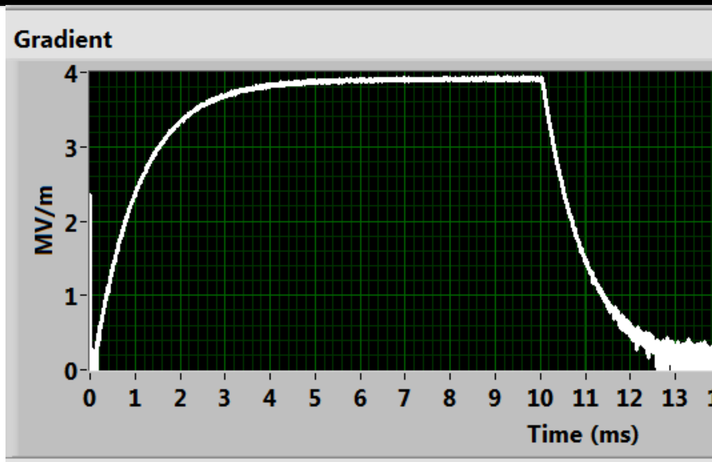
Vacuum leak in the cavity. . . The test is probably over.



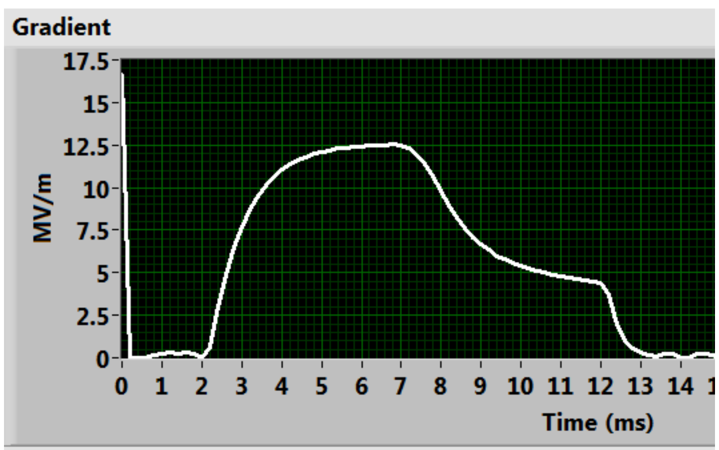
Very low field multipactor.

- **Leave the network analyzer connected and running.**
- **Go home for the evening and let it process**

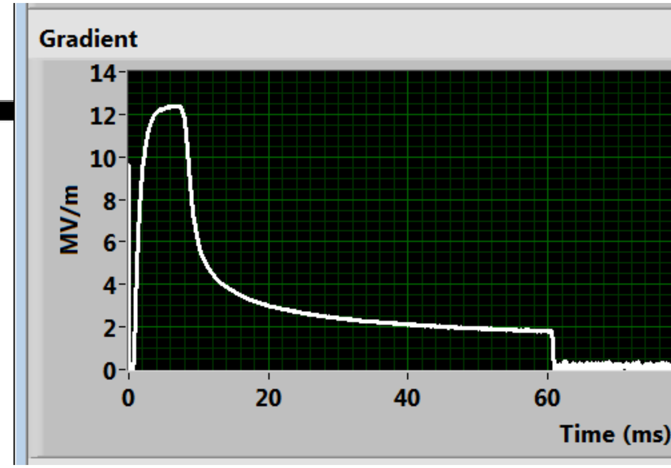
EVELOUTION OF A QUENCH



Gradient waveform, normal pulsed Operation



Gradient waveform, during quench with the same length applied RF pulse.



Gradient waveform, during quench with a 60 ms RF pulse

- CEBAF 7 cell cavity, pulsed operation self excited loop mode of operation. Loaded Q appx 2e7. No gradient regulation.
- Cavity was operated at a very low duty cycle such that it would recover between quenches.
- Note that the initial decay on the quench is much slower than that due to the nominal loaded-Q.
- Beware cavities with low loaded-Qs can put substantial power into the bath. For example SNS cavities with a QL=5e5 can dump 10 kW into the bath.

CABLE BREAKDOWN IN LOW PRESSURE HELIUM

- **When vertical testing the incident power cables must pass through the low pressure helium gas in order to get to the fundamental power coupler.**

- **Both the mating connector space as well as the cable back shell space are susceptible to this phenomena.**

- **Glow discharges have been produced in un-terminated N-connectors at 20 Torr using as little as 10 Watts.**

- **Even connectors in 2 K liquid helium have been known to break down at power levels on the order of 150 W, full reflected at the cavity.**

- **Once a breakdown is initiated it will be sustained by the forward power even at levels down to 10 W.**

CABLE BREAKDOWN IN LOW PRESSURE HELIUM

1. **Such events appear to be Q-switching within the cavity. The gradient will be reduced and the measured Qo will be reduced substantially.**
2. **These discharges destroy connectors and have the potential to cause failures in vacuum feed throughs.**
3. **To put things in perspective**
   - **The Paschen minimum is the product of the pressure and distance required for the minimum voltage breakdown in gas.**
   - **For helium this value is 4 Torr-cm.**
   - **In other words at 20 Torr the electrode spacing for a minimum voltage breakdown is 2 mm.**
4. **The theory on breakdown in liquid is that:**
   - **A few watts of heat is produced in the connector, possibly through thermal conduction down the, insulated, center conductor, from the antenna within the cavity, or in the connector pin itself.**
   - **The liquid helium flashes to gas within the connector**
   - **A breakdown occurs in the newly produced low pressure gas volume.**

CABLE BREAKDOWN IN LOW PRESSURE HELIUM

To determine if you have a cable discharge, while it is occurring:

- **Detune the frequency of the LLRF system far enough to lose lock in the cavity.**
- **Measure the forward and reflected power.**
- **Subtract the calibrated forward power from the calibrated reflected power to calculate the lost power.**
- **If any significant power is being lost you probably have a glow discharge in the connector.**

On occasion connectors damaged from mechanism this will exihibit this anomalous loss permanently at all power levels.

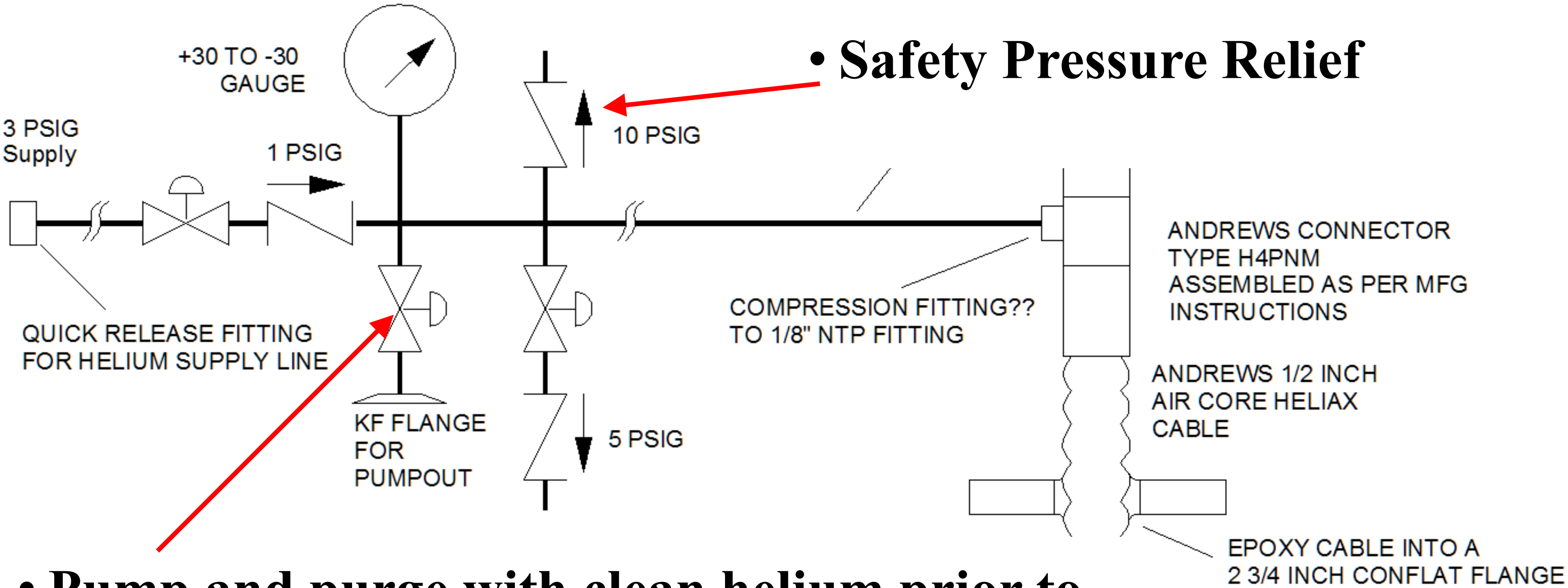
Therefore one should turn off the RF power; and repeat the steps above to ensure that the lost power is consistent with the error associated with the measurement.

CABLE BREAKDOWN IN LOW PRESSURE HELIUM

So what is an engineer to do?

1. **NEVER make a high power RF connection in low pressure helium gas.**
2. **Historically we used silicon dioxide dielectric, stainless steel jacketed, cables manufactured by Times Microwave which have the outer conductor welded into a Conflat flange. This ensures that the high power connections are only made in liquid helium. See backup material for why we are moving away from them.**
3. **We are switching over to pressurized RG?? Cable which require a clean helium supply and a few more steps when setting up a test.**
4. **Vent all connector volumes to the helium bath to improve the heat conduction out of the space, especially connector backshells.**
5. **Fill all potential spaces with insulating material. In theory this should work but we have only had limited success at 300 W.**
6. **One option that we have pursued but not fully implemented is to pressurize the cable with helium gas including the connection to the vacuum feed through at the coupler antenna.**
7. **Best of all critically couple the cavities by carefully adjusting the input antenna or by using a variable coupler so that you do not have to use more than 150 W at the cavity.**

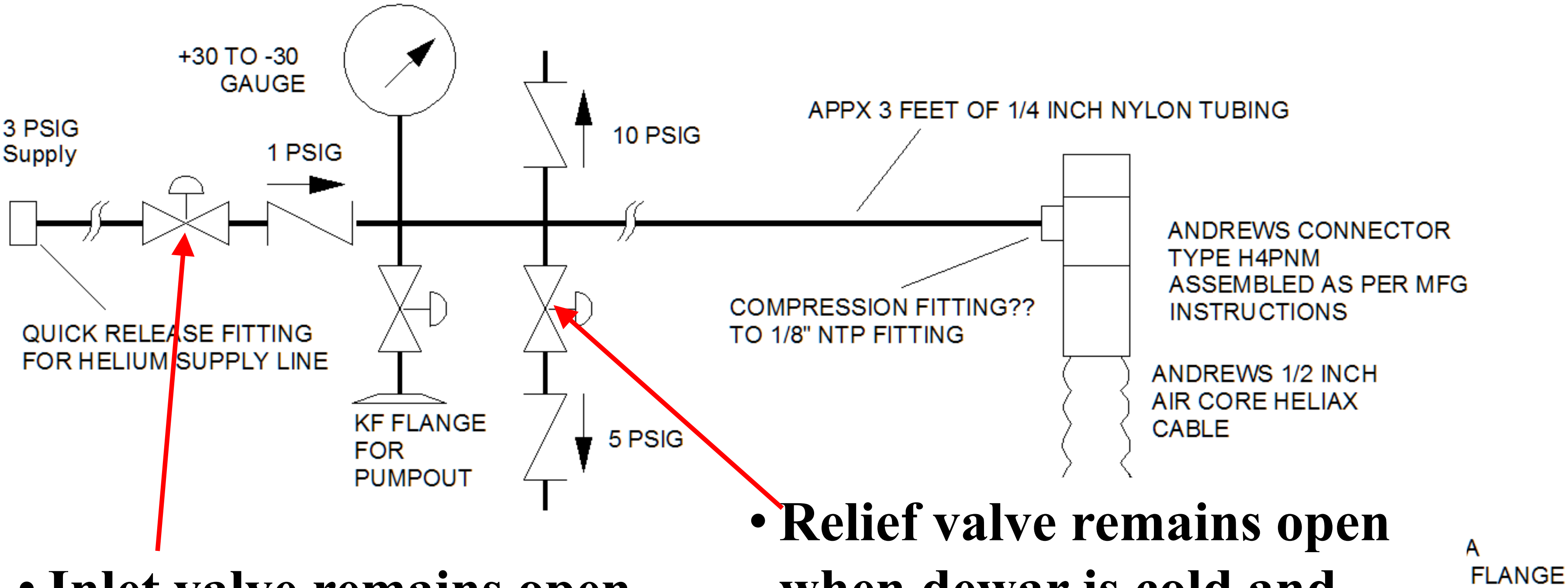
EXAMPLE OF PRESSURIZED CABLE SOLUTION



- **Safety Pressure Relief**

- **Pump and purge with clean helium prior to cooldown.**
  - **Prevents frozen air in cable**
  - **Prevents contamination within dewar if lower seals leak during operation.**

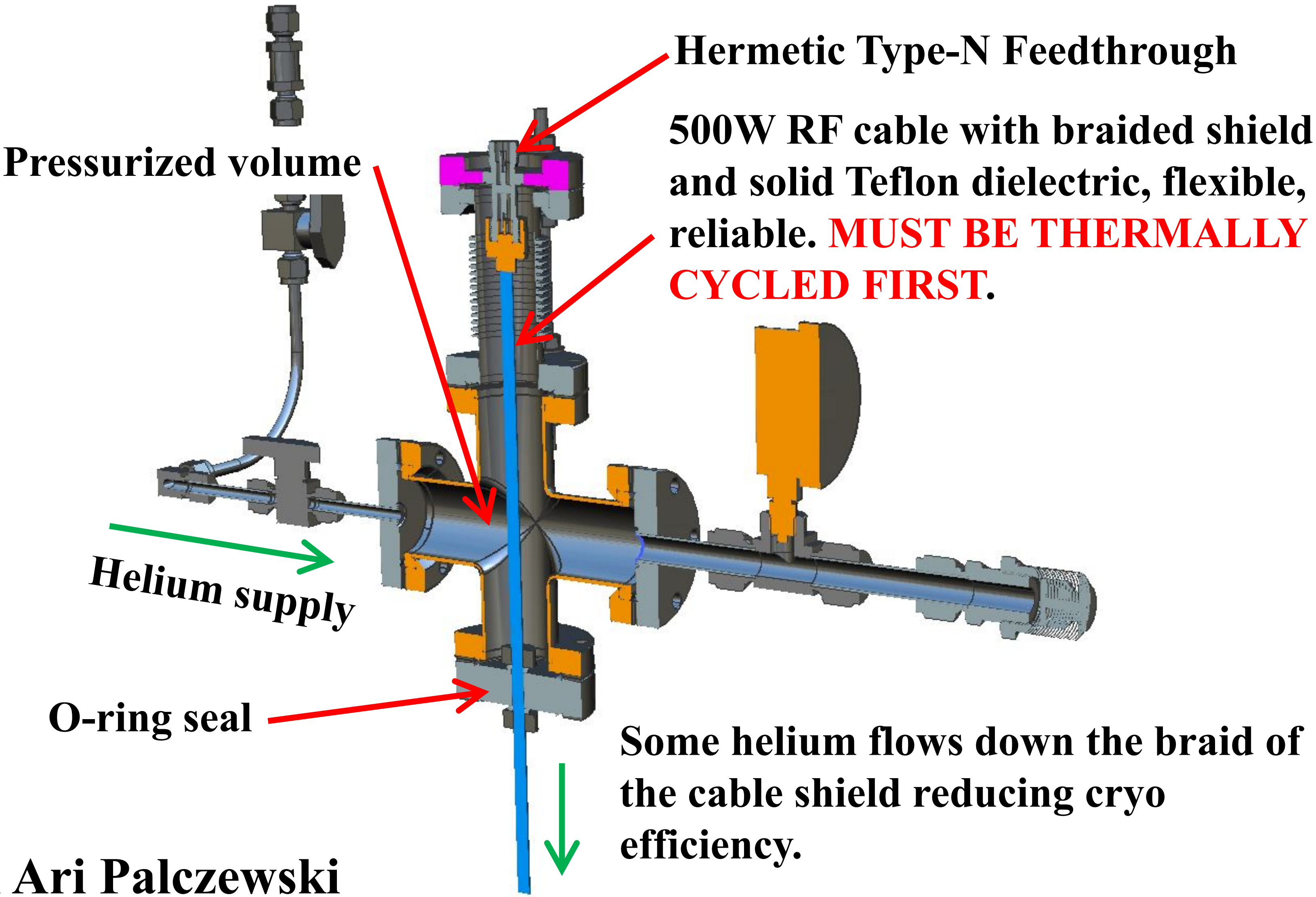
EXAMPLE OF PRESSURIZED CABLE SOLUTION



- **Inlet valve remains open when dewar is cold.**
  - **Maintains pressure in cable when helium gas gets cold or turns to liquid**
- **Relief valve remains open when dewar is cold and during warmup.**
  - **Relieves pressure when RF heat in cable causes gas to warm up or liquid to turn to gas**
  - **Relieves pressure during warmup.**

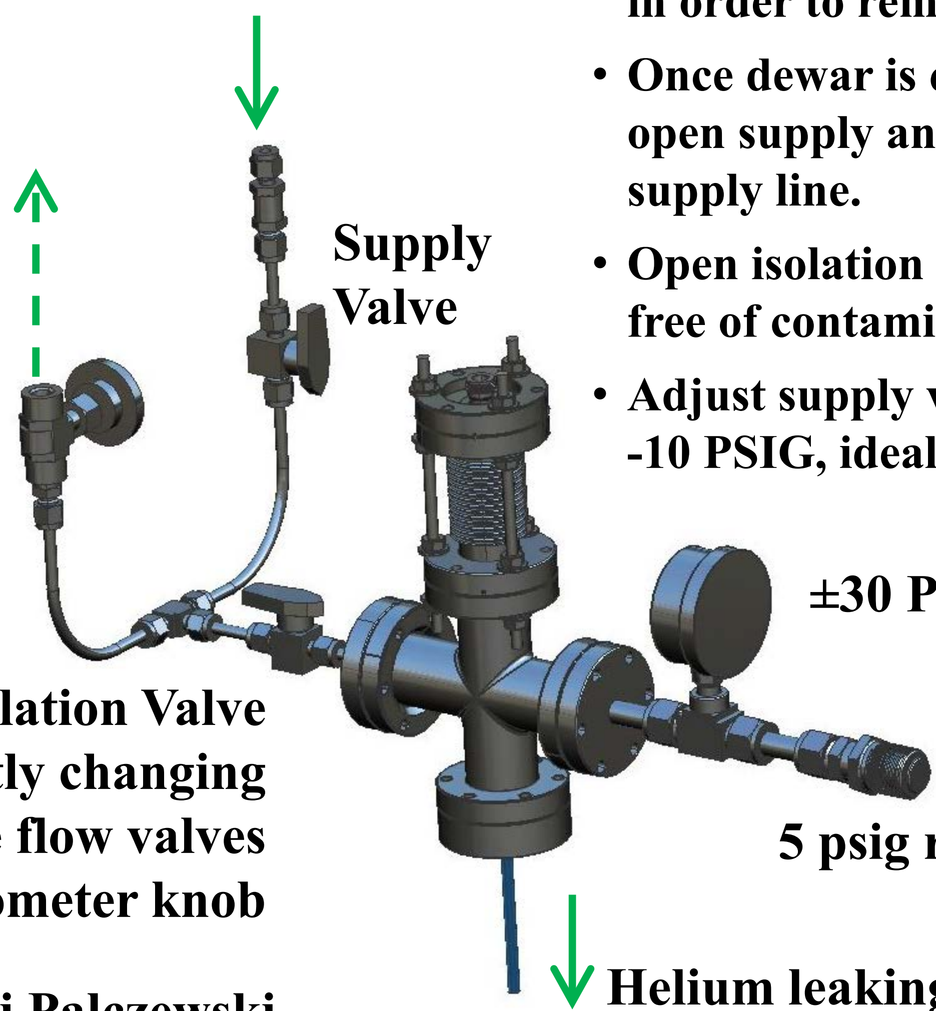
Pressurized RF Cable

Similar to what Peter Kneisel did 20 years ago with heliax cable and epoxy seals.



From Ari Palczewski

Pressurized RF Cable



- Close isolation valve when pumping out dewar in order to remove gas from the manifold.
- Once dewar is qualified as sealed and clean, open supply and supply purge valve to purge supply line.
- Open isolation valve once dewar is declared free of contamination.
- Adjust supply valve until pressure is above -10 PSIG, ideally above 1 PSIG.

From Ari Palczewski

Why did we stop using the SiO_2 cables?

We at JLAB used SiO2 cables with stainless steel jackets with hermetic seals between the inner and outer conductors art the connectors.

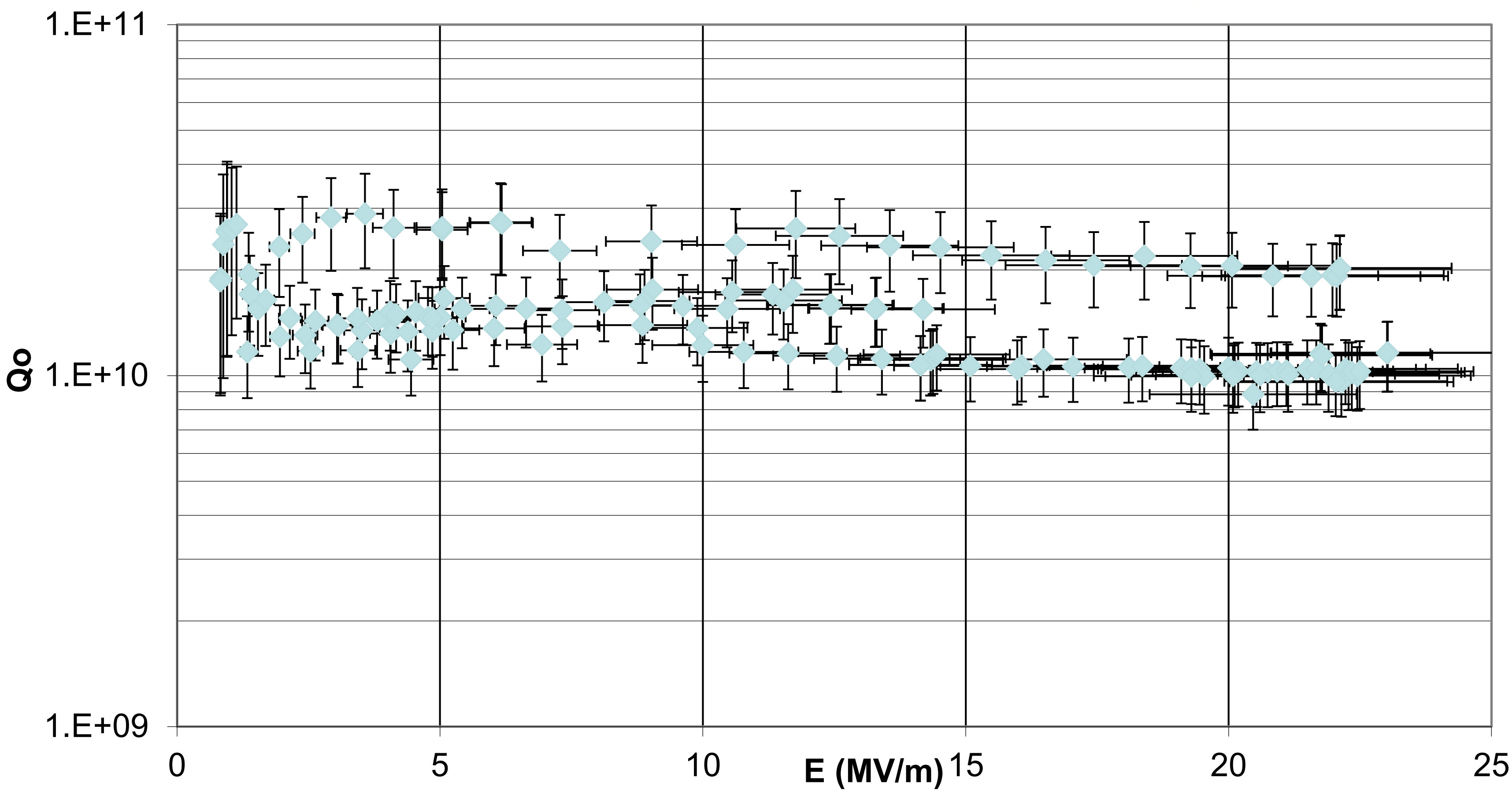
The cables were welded into a conflate flange. This provided a hermetic seal for passing the cable through the gaseous helium in the vertical test stand.

The cables worked well for 15 years, through two different manufacturers.

Somewhere about 10 years ago we started having a problem with the cables that is described in the following slides. This problem being an unexplained change in the cable loss as a function of temperature which occurs at about 80K.

We changed back to a helium gas pressurized cable similar to the ones that Peter Kneisel used before we switched over to the SiO_2 cables. The cables that he used were foam dielectric heliax cables which had localized failures at the liquid to gas boundary.

CONFUSING DATA



- **Data varied substantially depending on:**
  - **Incident power used for incident power cable calibration**
  - **Time at higher power levels**
  - **Delay between reducing the power and making a measurement**

SiO_2 CABLE LOSS CHANGES*

1. One phenomena that was "discovered" several years ago is that the $Si0_2$ cable losses were not stable after the application of even a moderate amount of RF power, i.e. tens of Watts.

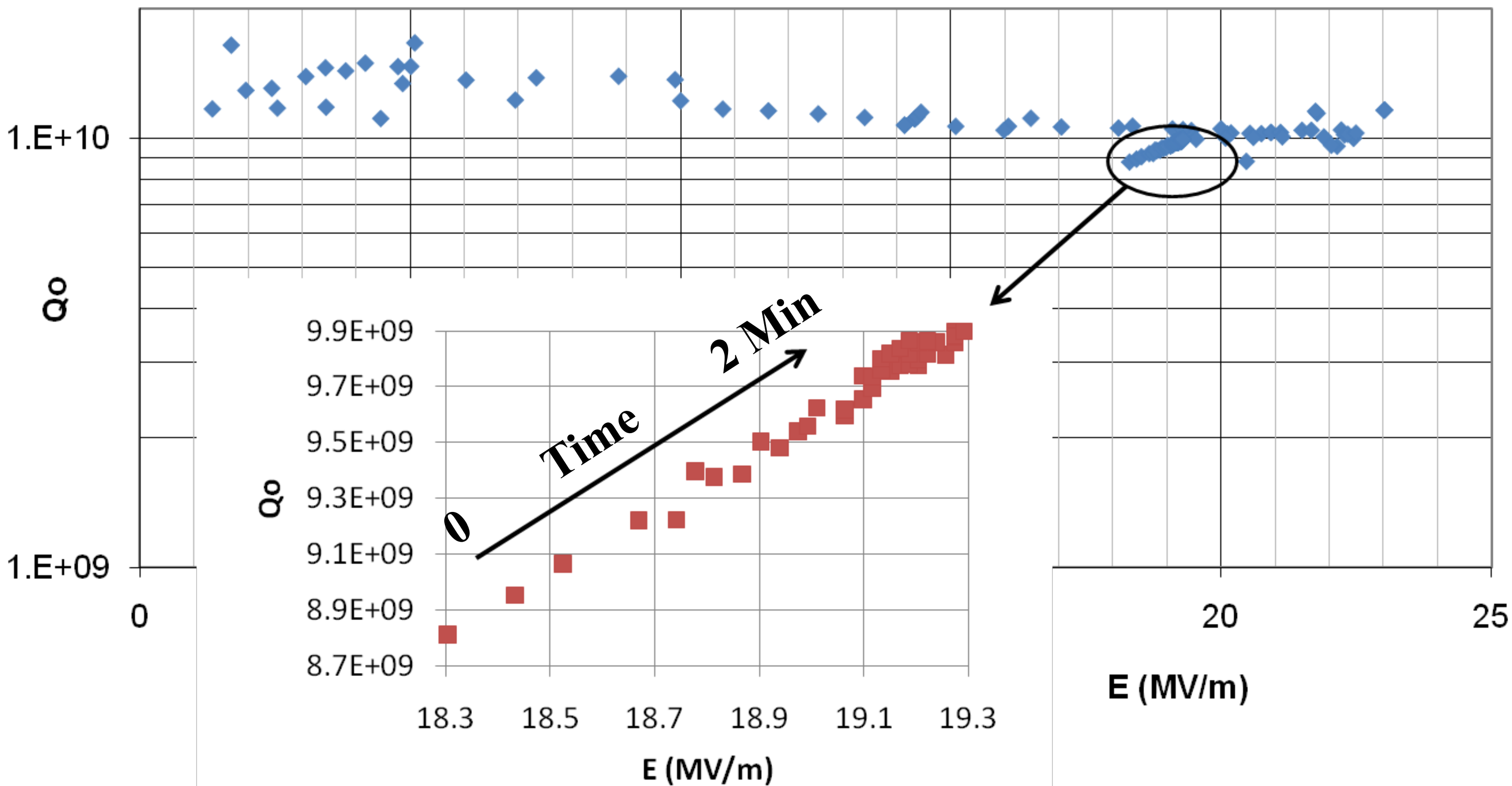
2. This shows up as a change in the forward and reflected power over time a constant RF power.

3. It introduces significant error into the measurements of gradient and Q_0 of the cavities.

4. When testing cavities changes in both Q_0 and E shortly after turning the RF on at higher power levels may be an indicator of the problem.

5. When using these cables we check for errors in the disipated power by opening up the self excited loop at power and if necessary we preform the forward power to detuned cavity at power step of the calibration procedure at that power level.

INITIAL SYMPTOMS Q VS E DATA



- **Data more consistent if incident power cable calibrated at multiple power levels**
- **Data shown in inset graph taken by**
  - **Calibrating the incident power cable at high power**
  - **Turning off the RF for 3 minutes**
  - **Turning the power back on at about 37 W**
  - **Recording the data continuously for 2 minutes**

SiO_2 CABLE LOSS CHANGES

1. It can easily be observed by
   1. Detuning the cavity
   2. Turing the RF power off for several minutes
   3. Turning the RF Power on and observing the forward, reflected and "lost" power over a 1 to 5 minute time frame.

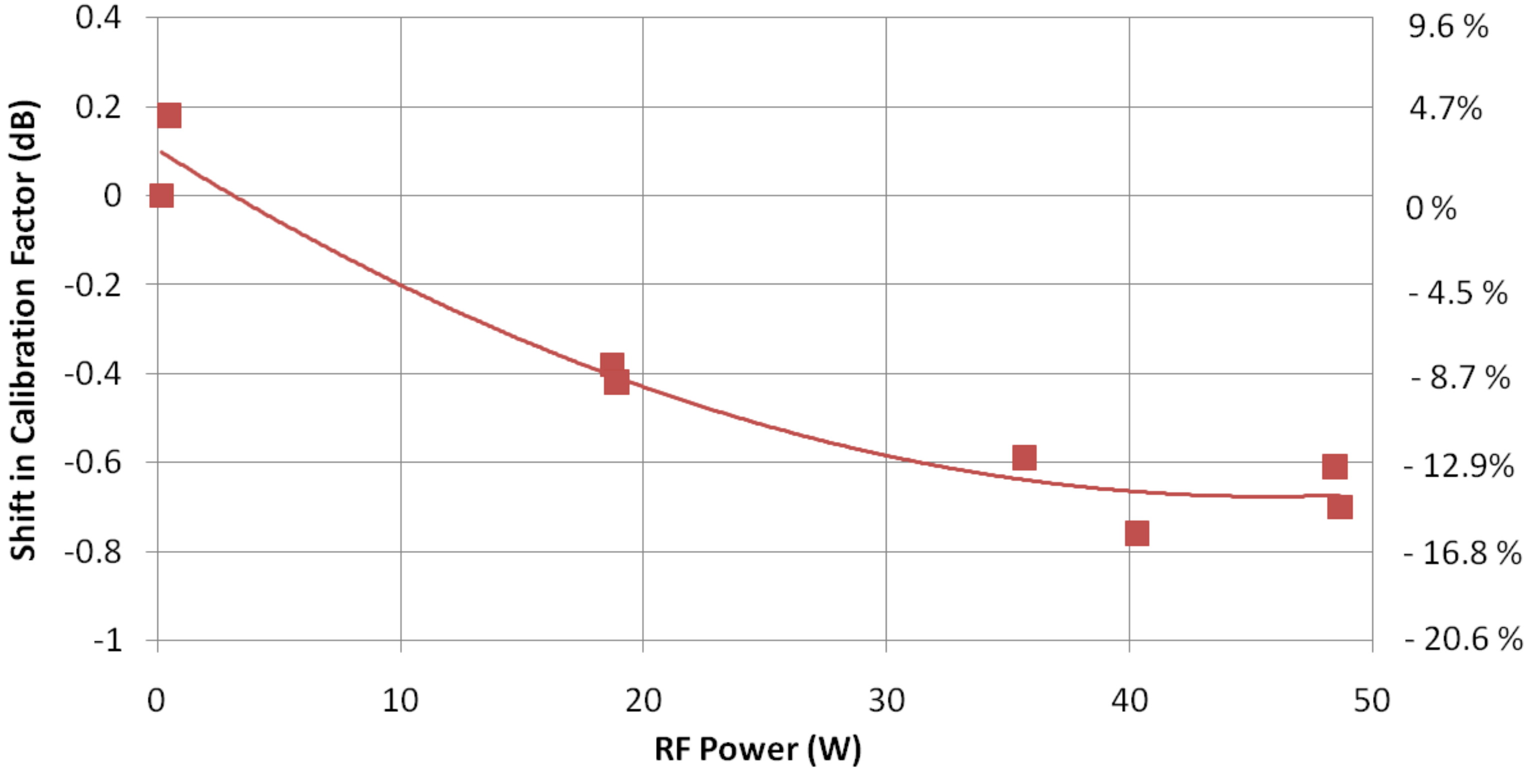
2. Some variation in the Incident and Reflected power is expected as the amplifiers may have a transient in their gain due to thermal issues.

3. The "lost" power should remain constant as it is the calibrated difference between the Incident and Reflected Power.

4. The amount of change in the "lost" power indicates the magnitude of the introduced error.

5. If the "lost" power is more than a few percent we recalibrate the cable in the dewar by doing the forward power into detune cavity step of the calibration at power.

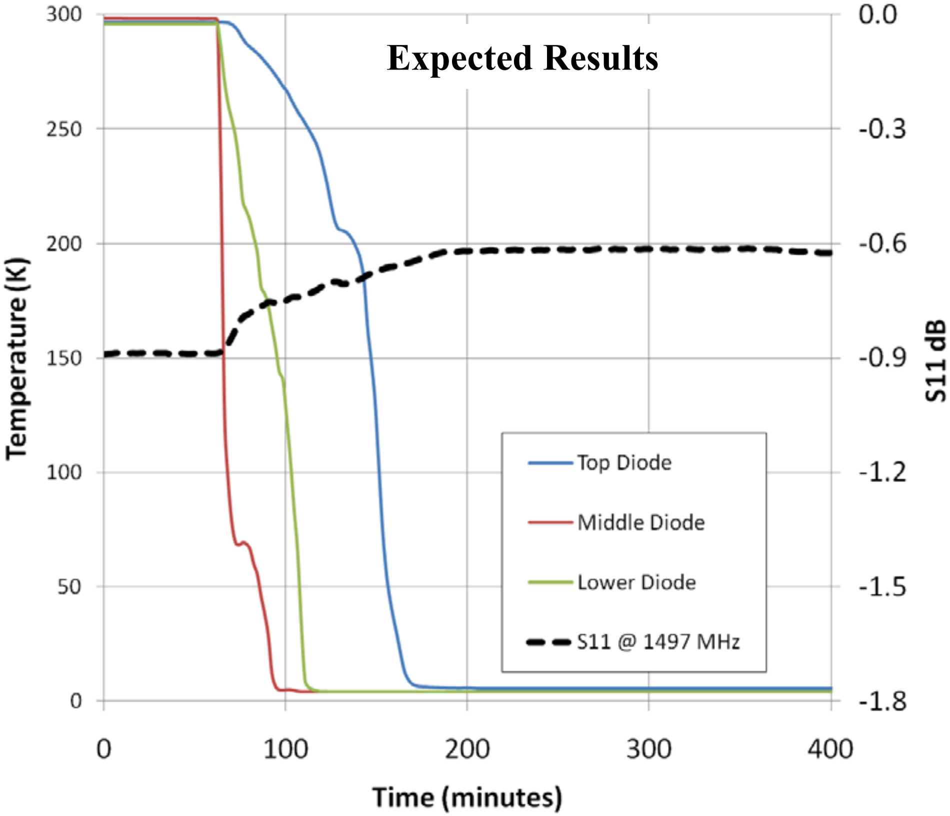
SiO_2 CABLE LOSS CHANGES

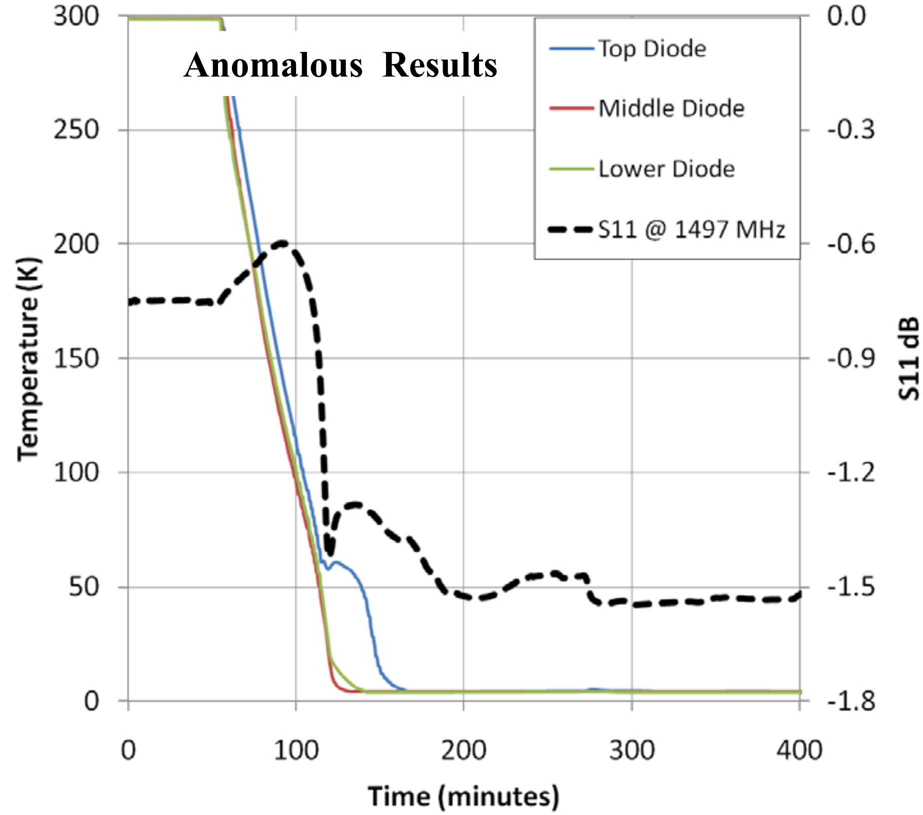


Change in SiO2 Cable calibration as a function of forward Power

1. **Data taken with dewar at 2K**
2. **Power applied and allowed to stabilize for a few minutes prior to taking the calibration data.**

GRAPHS OF GOOD AND ANOMALOUS CABLE COOL DOWNS





- **S11 of unterminated cable measured during "standard" cool down process**
- **Thermometry was installed in a channel mounted on the wall of the dewar, thus the actual temperature of the cable is only loosely correlated to the temperature readings.**
- **Swept S11 data was recorded periodically during the cool down process**

DIRECTIONAL COUPLERS ARE NOT CREATED EQUAL

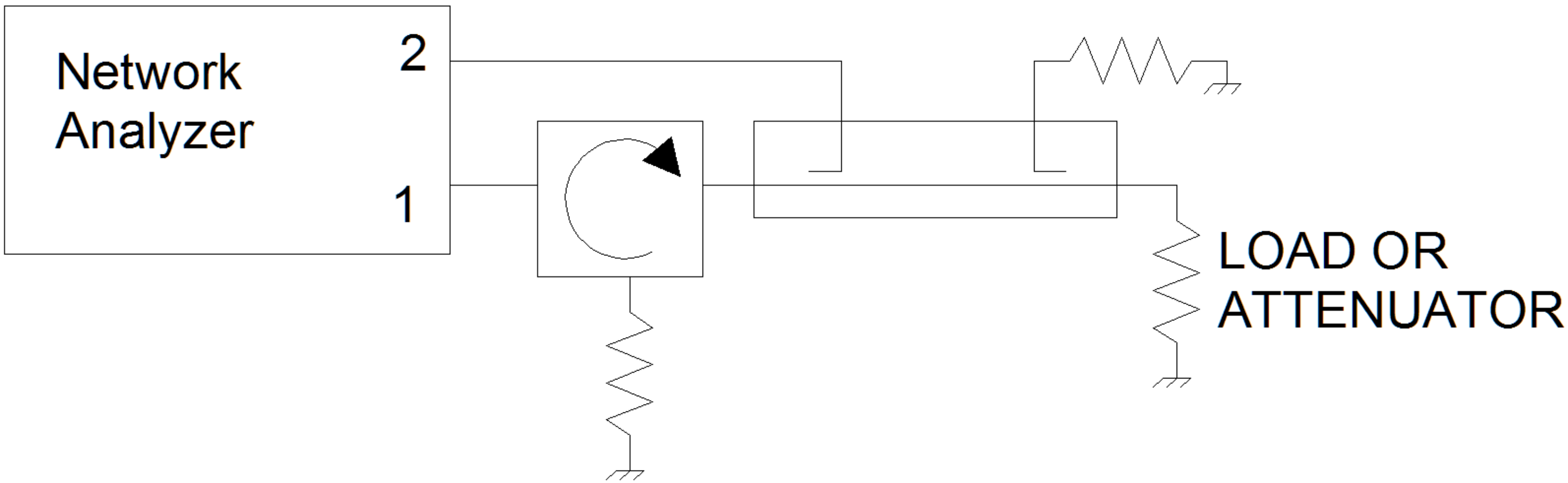
1. **Directional couplers are used to make measurements for which the load is not matched at 50 Ohms**
2. **One example is the final step on the incident and reflected power calibrations where the reflected power is some 3 to 6 dB below the forward power**
3. **Another example is when measuring a cavity that is not quite matched, i.e. $\beta \neq 1$.**

MEASUREMENT TECHNIQUES

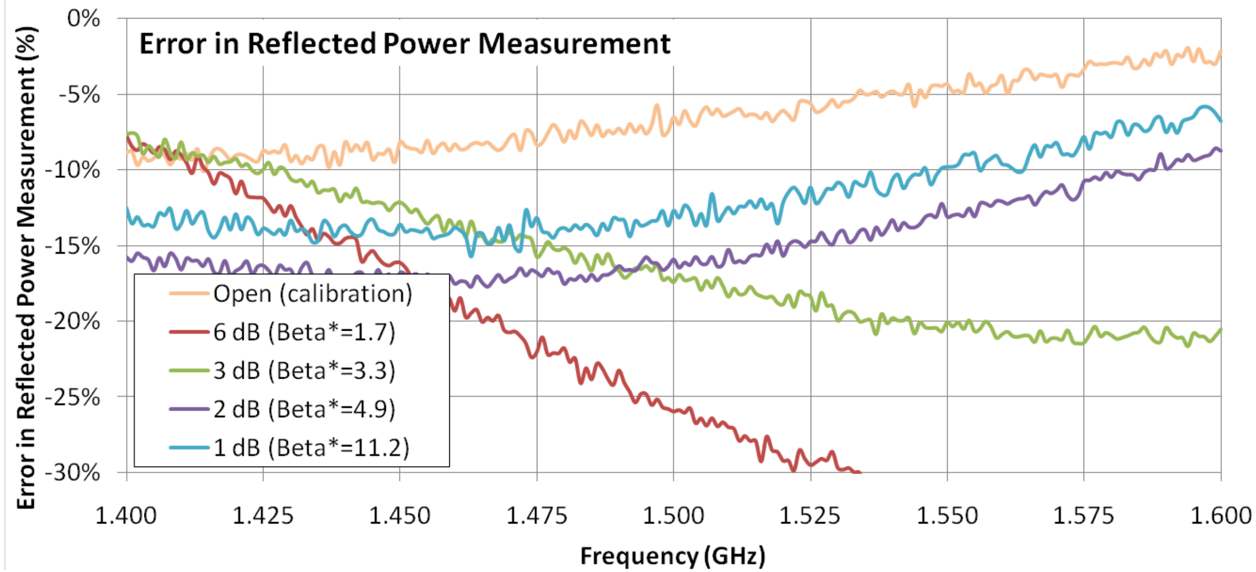
1. Perform S21 measurements of different ports with all of the other ports terminated at 50 Ohms or with a broad band miss-matched load.

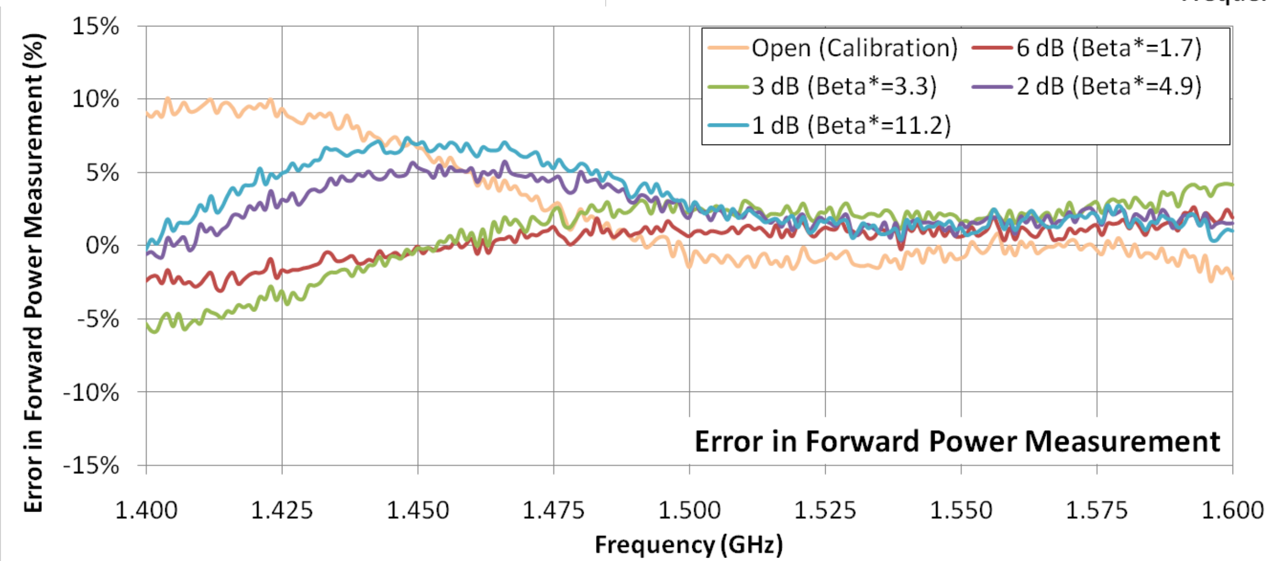
2. One critical item is that there is a significant error introduced due to S11 of the output port on the network analyzer. To remedy this one must insert a circulator between port 1 and the unit under test.

3. A good broad band miss match is an unterminated attenuator.



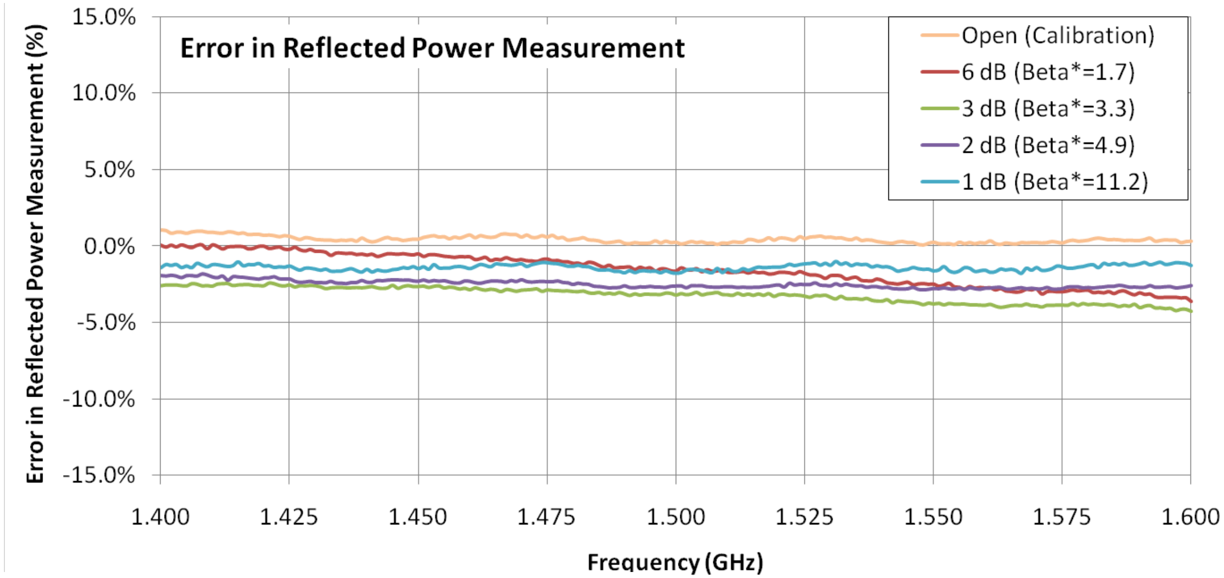
NARDA 20 dB COUPLER

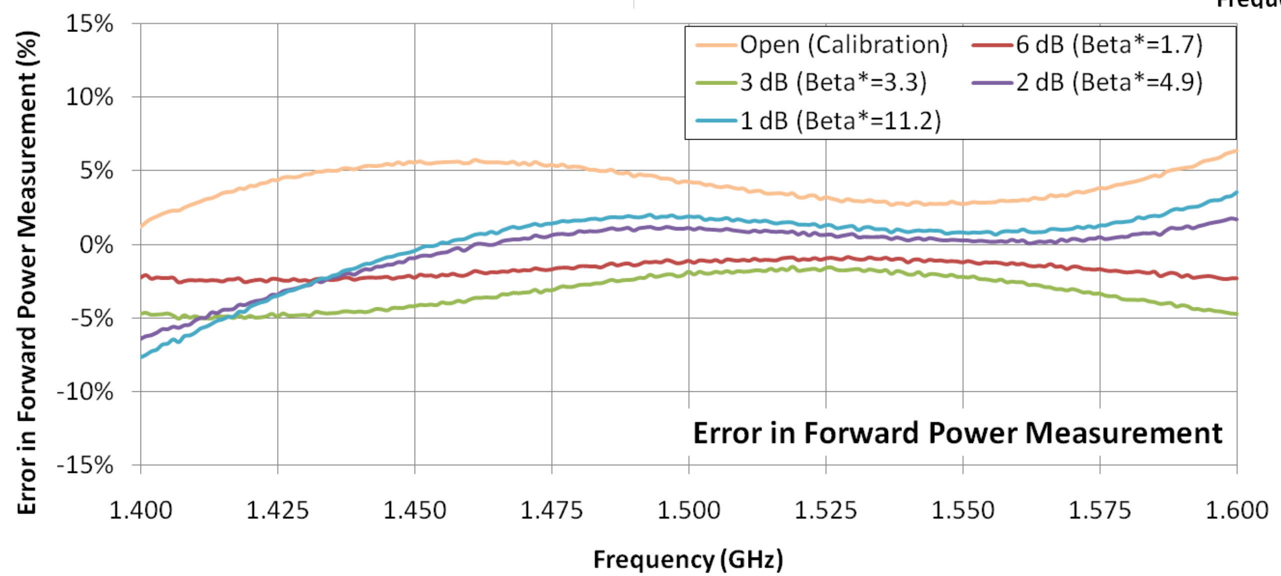




Error in power measurement with different loads on the output of the directional coupler (i.e. different beta*) Narda 3320 Serial 73091

CT MICROWAVE 30 dB COUPLER





Error in power measurement with different loads on the output of the directional coupler (i.e. different beta*) CT Microwave 441433, serial 73091

MEASUREMENT CONCLUSIONS

1. **Quality measurements necessary to qualify superconducting cavities require quality equipment designs, careful measurement techniques and well characterized calibrations processes.**
2. **Errors for the standard measurements are calculable. However, the are a function of the measurement equipment, the quality of the calibration and the specific conditions of each data point. As such they should be included in the measurement system not as an afterthought.**
3. **In addition to the slides presented, I have included a handout of the equations for both the cavity measurements and the associated errors.**
4. **I want to thank all of the folks in the SRF Institute at Jefferson Lab for their constant patience in helping me put this presentation together.**

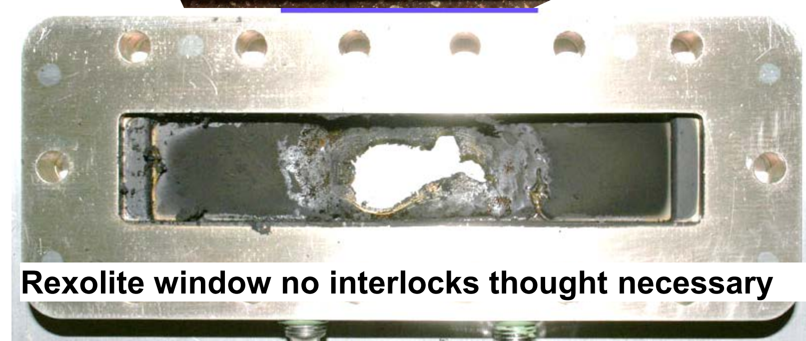
CRYOMODULE INTERLOCKS

NEVER OPERATE A CRYOMODULE WITH HIGH POWER RF AND THE COUPLER INTERLOCKS BYPASSED ! ! ! !

1. Coupler Interlocks
    1. Arc detector(s)
    2. Coupler vacuum
    3. Window temperature
    4. Water flow (If water cooled)
    5. Electron probe (Useful but not required)
    6. Water temperature (Useful but not required)
2. Cryomodule
    1. Cavity vacuum
    2. Helium level
    3. Helium pressure (Useful but not required depending on cryo plant)
    1. Insulating vacuum (Useful but not required)
3. RF Driven Interlocks
    1. Quench detection
    2. E^2/P_{FWD} ratio
    3. Gradient Present with RF off

What you can not see is the cracks in the ceramic!

Polyethylene window interlocks bypassed
Network analyzer connected to klystron.



Rexolite window no interlocks thought necessary

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 ω_m with a modulation depth (or frequency shift) of ω_D and an RF frequency of ω_m is given by:

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

In this method one uses the concept that an RF signal at a frequency of ω_0 can be written in the form:

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

Applying this to the above equation leads to:

$$\mathrm{V}(t) = V_{Peak} Cos\big(\omega_0 t + \varphi(t)\big)$$

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

MICROPHONICS MEASUREMENTS WHEN USING A FREQUENCY TRACKING SOURCE

It can be shown that.

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

or

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

Nominally V_{Peak} is ½ 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:

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

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

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

Which can be reduced to:

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

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

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

Solving for $\boldsymbol{\varphi(t)}$

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

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 $\boldsymbol{\varphi(t)}$. If this is done then one can calculate the frequency shift as.

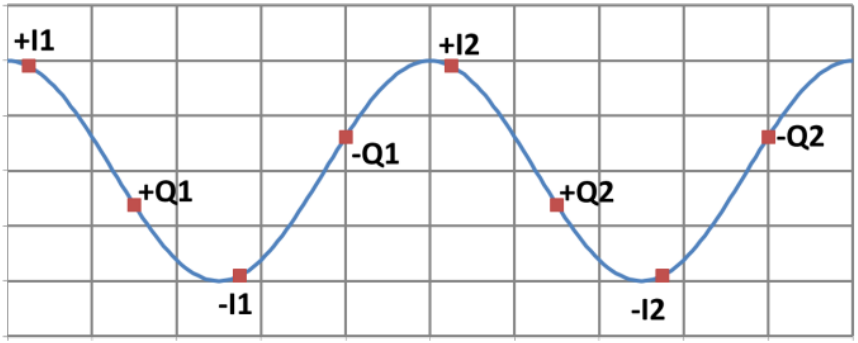
$$\Delta f = \frac{\varphi_{i+1} - \varphi_i}{2\pi\Delta t}$$

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

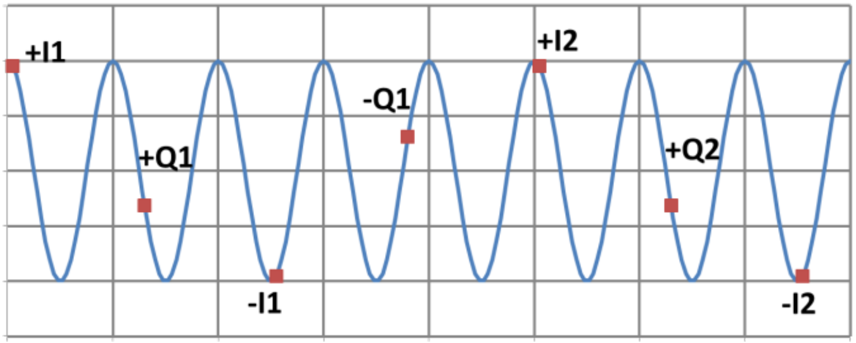
$$f_{i+1} = \frac{(Q_i I_{i+1} - I_i Q_{i+1})}{2\pi\Delta t\left(Q_i^2 + I_i^2\right)}$$

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, . . . and I and Q are given by:

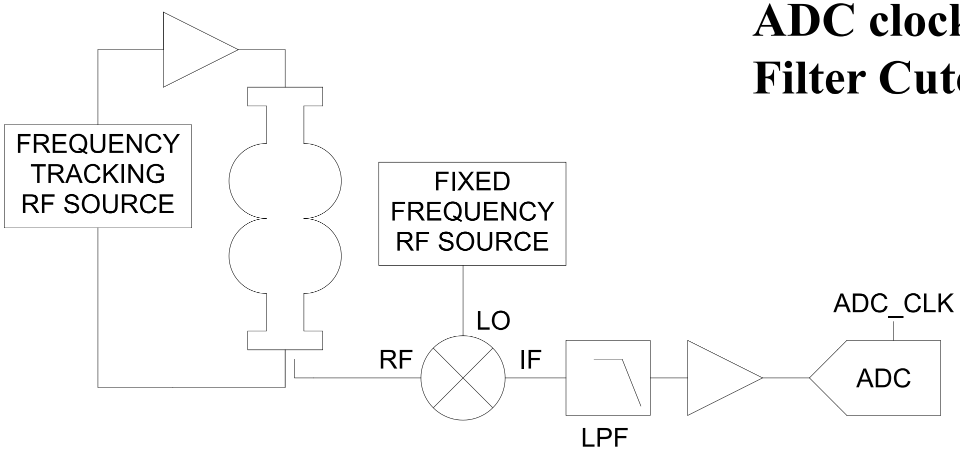
$$I_k = v_{4k} - v_{4k+2} \quad and \quad Q_k = v_{4k+1} - v_{4k+3}$$

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:

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

Where $\boldsymbol{\omega_1}$ 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 low pass fitler:
IF = 25 kHz,
ADC clock = 100 kHz
Filter Cutoff = 30 kHz

Example parameters, band pass filter CEBAF 12 GeV Field Control Chassis:
IF = 70 MHz,
ADC clock = 56 MHz
Filter BW = 5 MHz
DSP filter bandwidths ≈ 30 kHz variable

METHOD FOR CALCULATING MICROPHONICS FREQUENCY GENERATOR DRIVEN RESONATOR MODE

For a regulated steady state GDR system and no beam loading the relative phase of RF Drive siganl is given by*

$$\mathrm{Tan}\,\varphi = 2Q_{\mathrm{L}}\frac{\delta f}{f_0}$$

$$OR$$

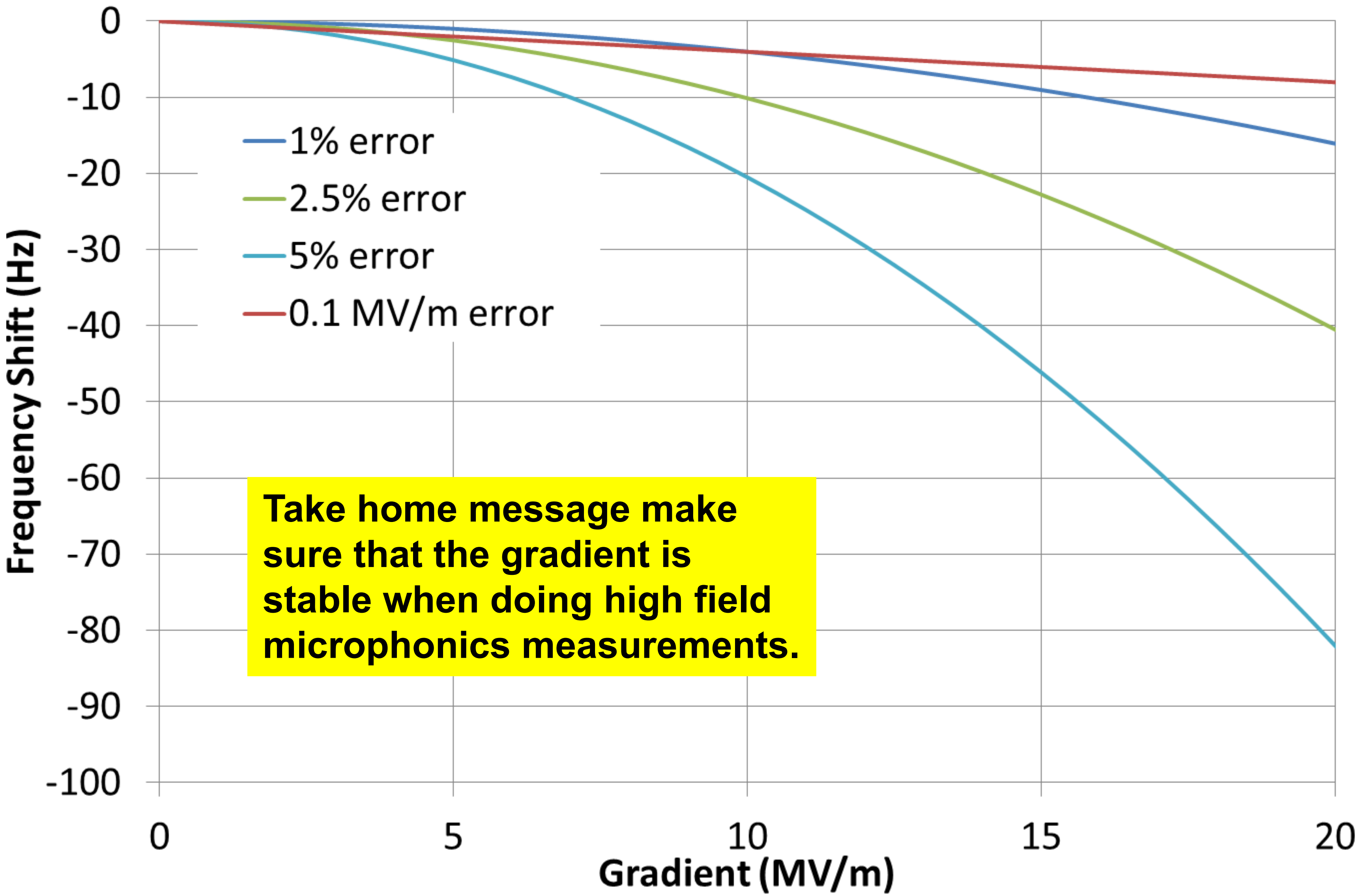
$$\delta f = \frac{f_0 \tan\varphi}{2Q_L}$$

- **Where φ is the phase angle between the incident and transmitted (cavity probe) signals, Q_L is the loaded-Q of the cavity and f_0 is the center frequency of the cavity.**

- **Thus the LLRF determines the point by point phase difference and does a simple calculation either directly or using a CORDIC technique.**

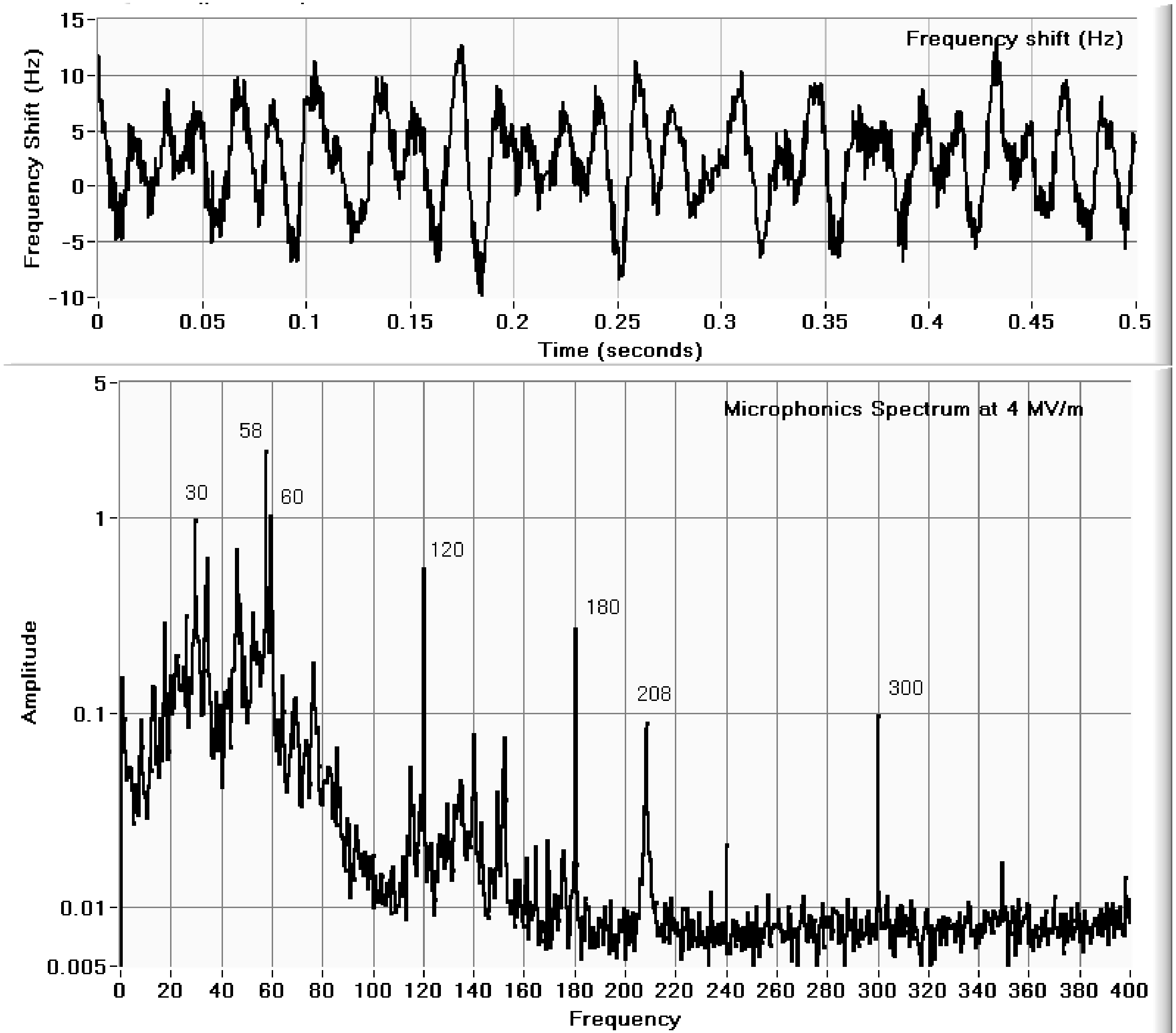
***This is a first order and does not take the effect of the control bandwidth effects of the fundamental power coupler**

LORENTZ FORCE EFFECT ON CAVITY FREQUENCY AS A FUNCTION OF GRADIENT AND FOR DIFFERENT INSTABILITIES IN THE GRADIENT WITH M=2



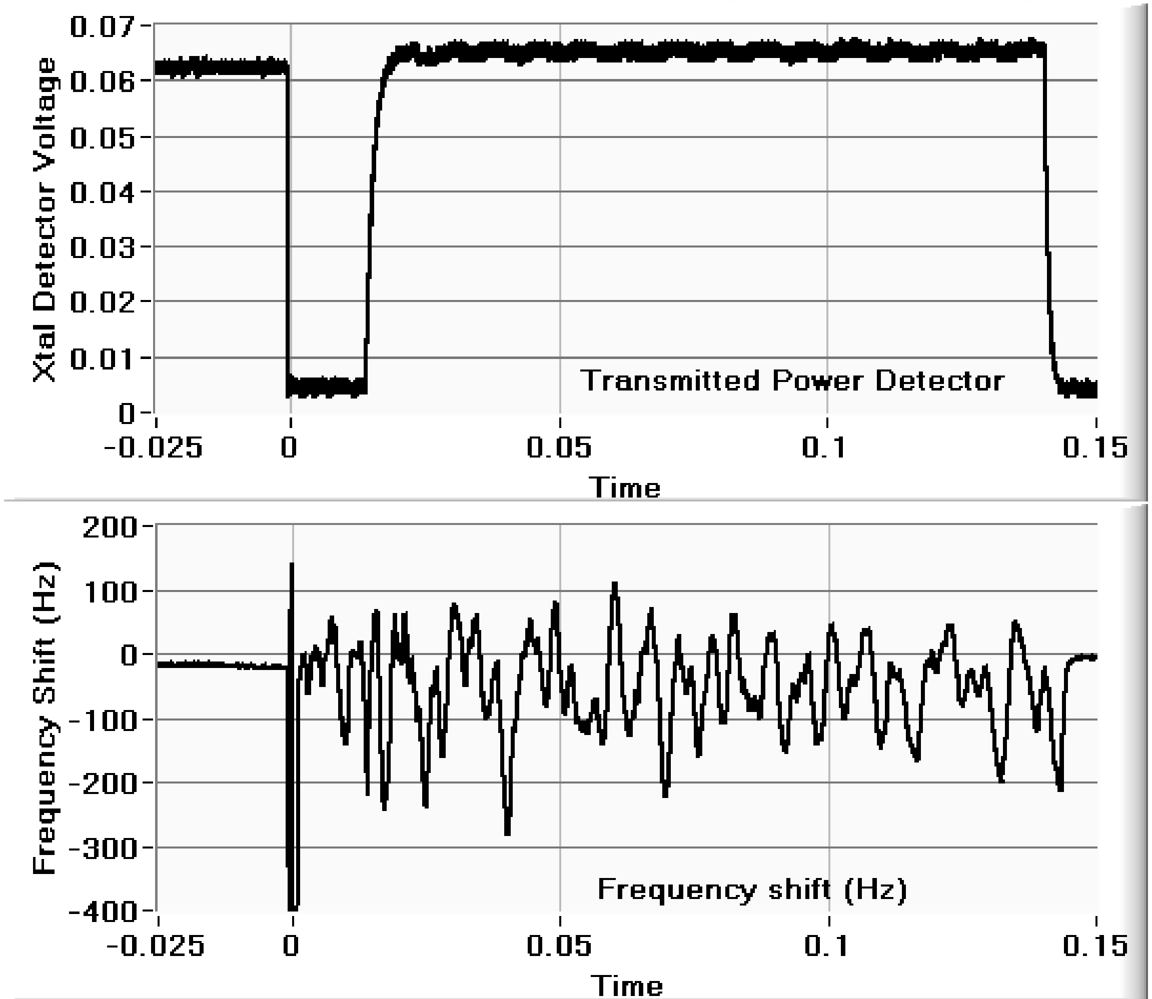
Take home message make sure that the gradient is stable when doing high field microphonics measurements.

MICROPHONICS EXAMPLES



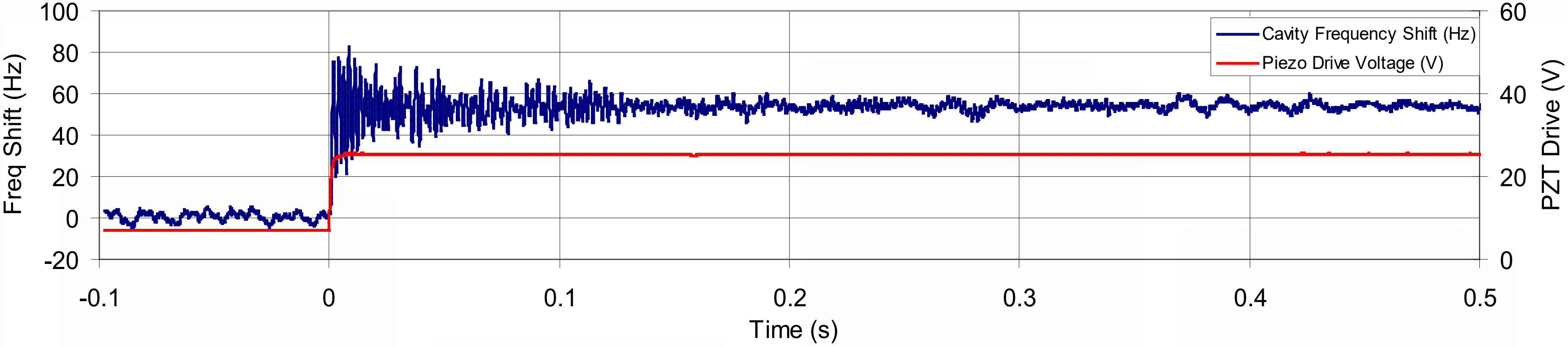
Time domain and frequency domain plots of the background microphonics for a 5-cell CEBAF cavity located in the CEBAF accelerator.

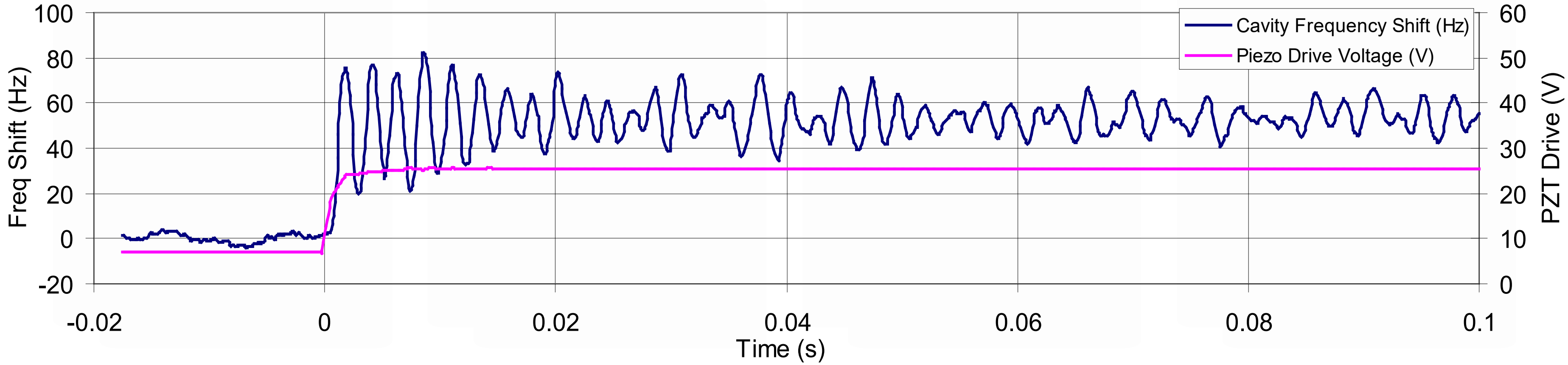
CAVITY TRIP DRIVEN Microphonics



Vibrational modes excited by the sudden loss of cavity gradient due to a window discharge on the cavity side of a cold window in the same cavity as the previous slide.

PIEZEO STEP RESPONSE



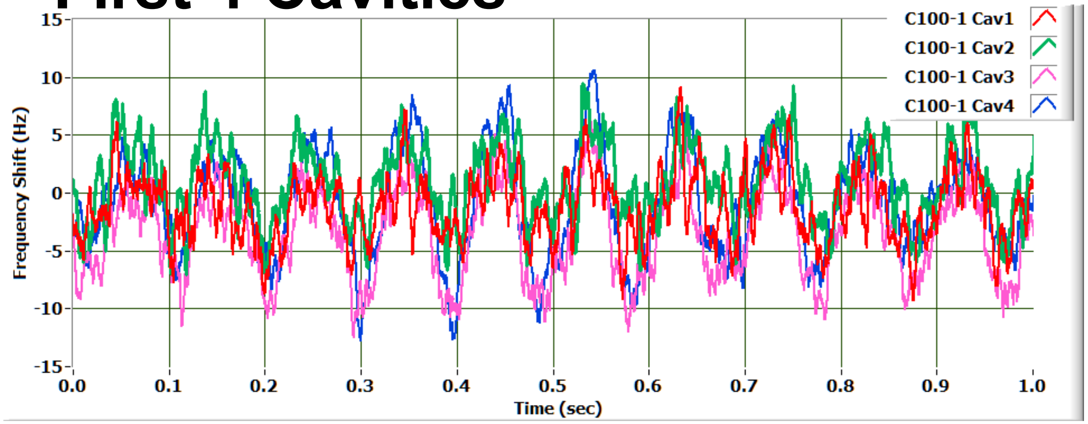


Step response of a cavity excited by a by a 50 Hz step in the piezo tuner controls. The total range of this tuner was 550 Hz.

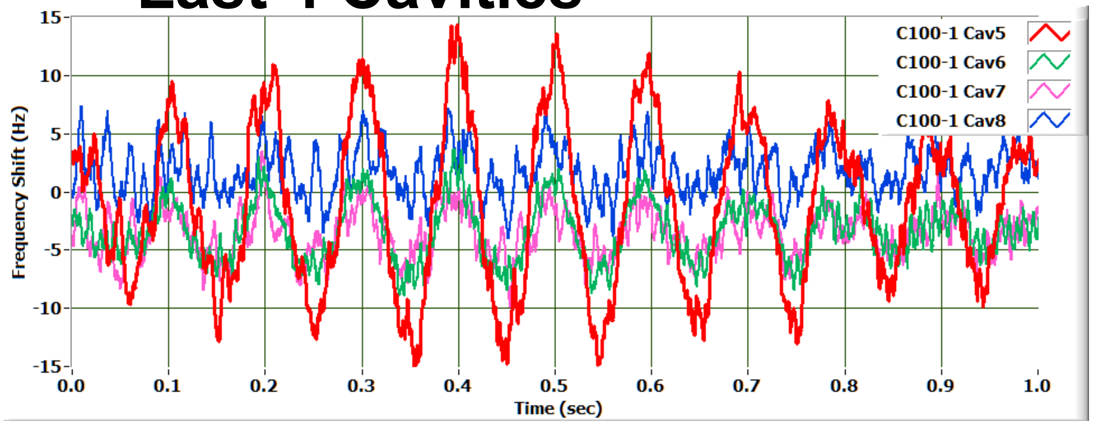
MULTIPLE CAVITIES SYNCHRONOUSLY

- Used analog outputs from digital LLRF with a commercial DAQ module to capture 8 channels synchronously.
- This allowed us to better understand coupling within a cryomodule.
- Capturing signals from two adjacent cryomodules synchronously was used to insure that they were not driven modes

First 4 Cavities

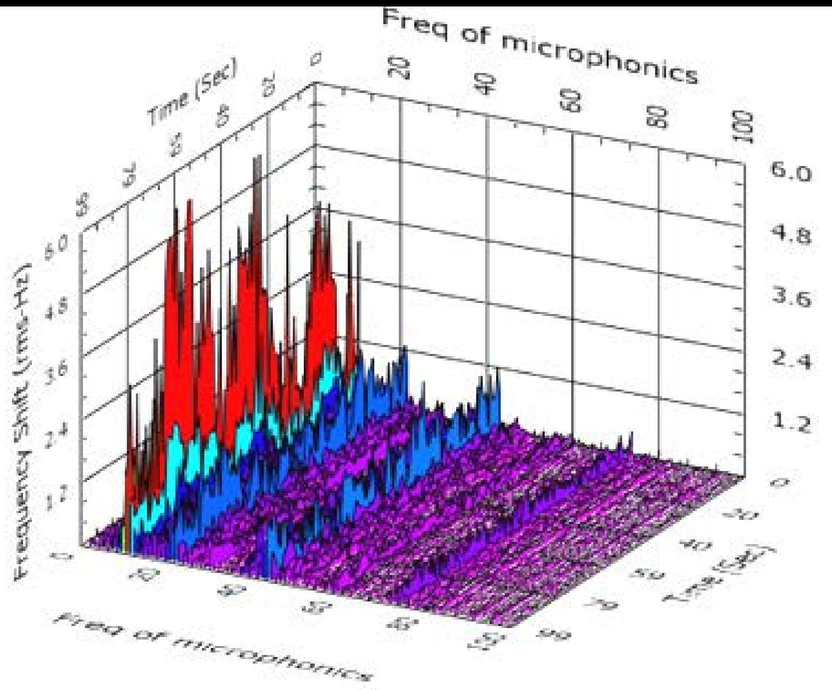


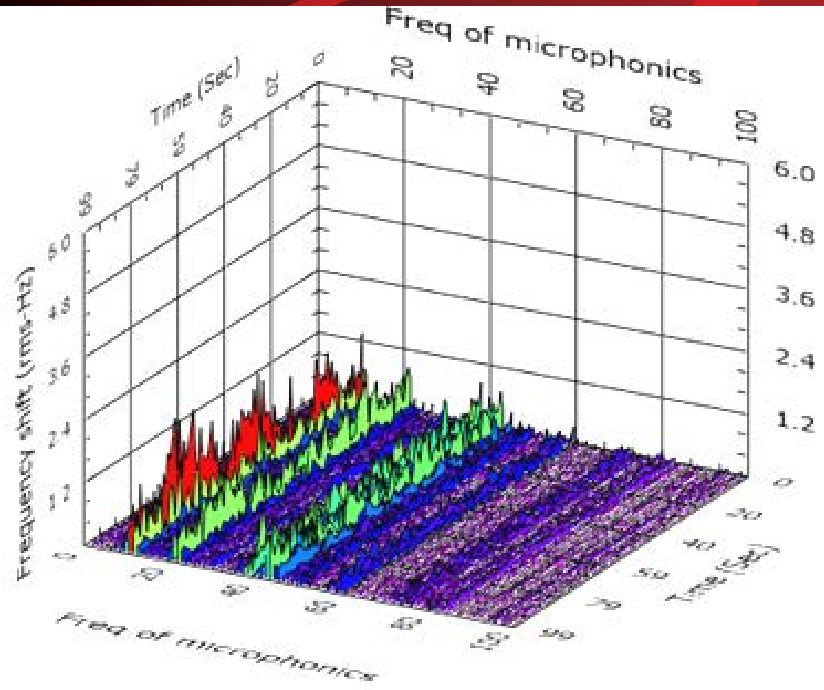
Last 4 Cavities

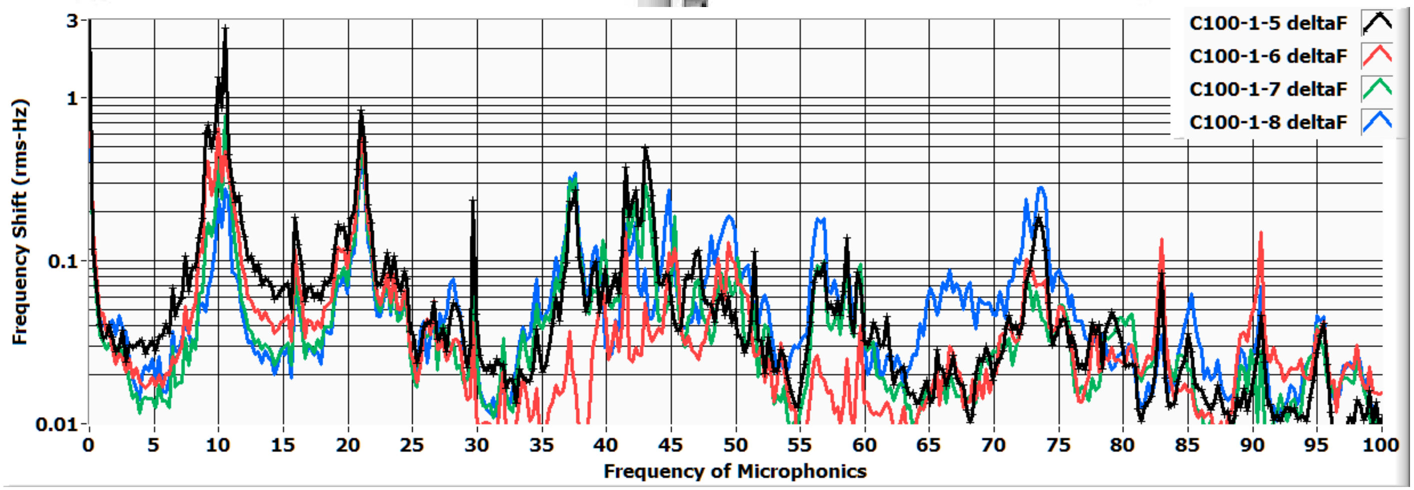


CEBAF C100 CRYOMODULE

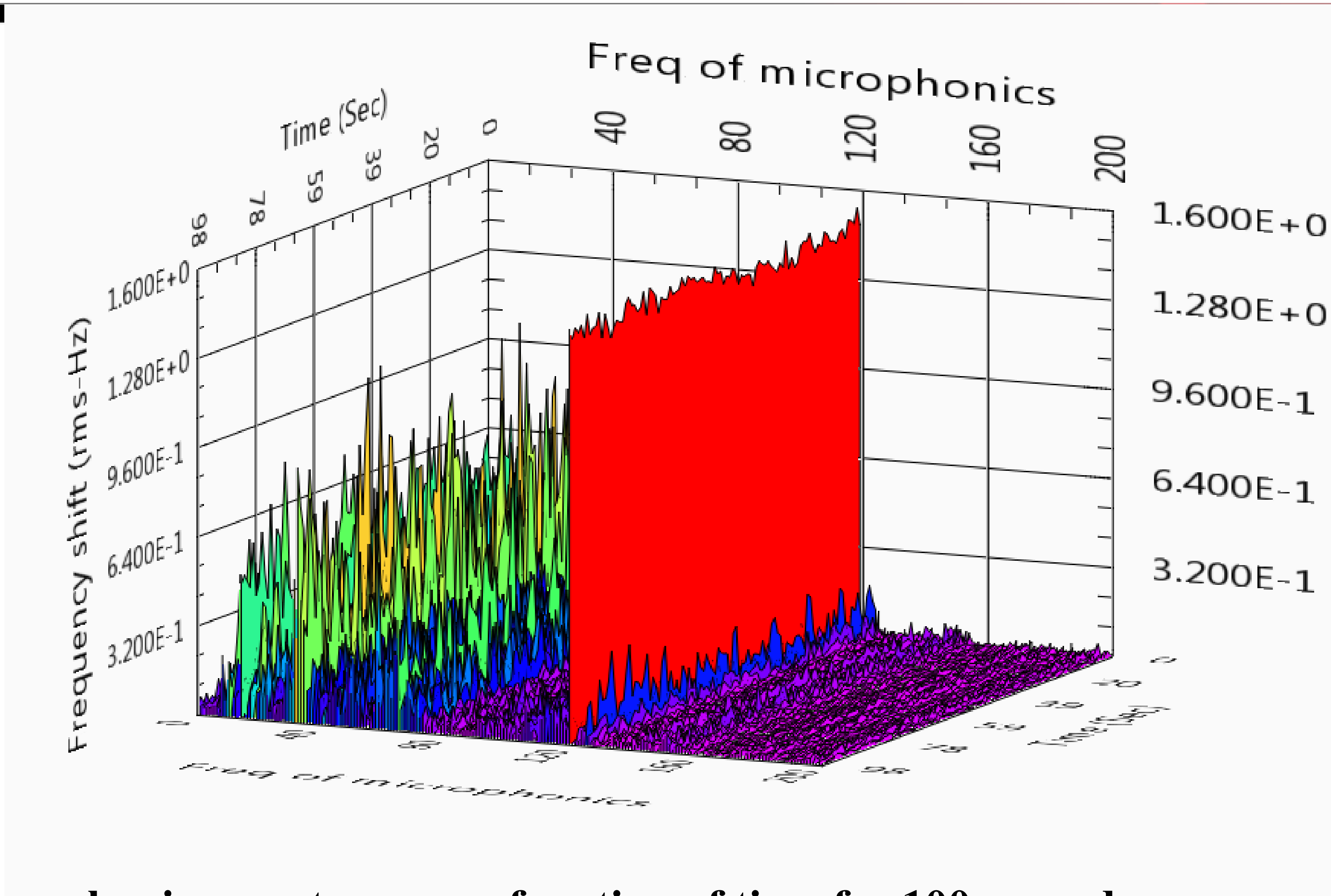
FREQUENCY DOMAIN MEASUREMENTS







MICROPHONICS EXAMPLE OF A DRIVEN MODE



- **Microphonics spectrum as a function of time for 100 seconds.**
- **The red plane is a 120 Hz mode driven by the roughing pump which is part of a turbo pump that is attached to the insulating vacuum.**
- **The remainder of the microphonics seems to be driven by random noise.**

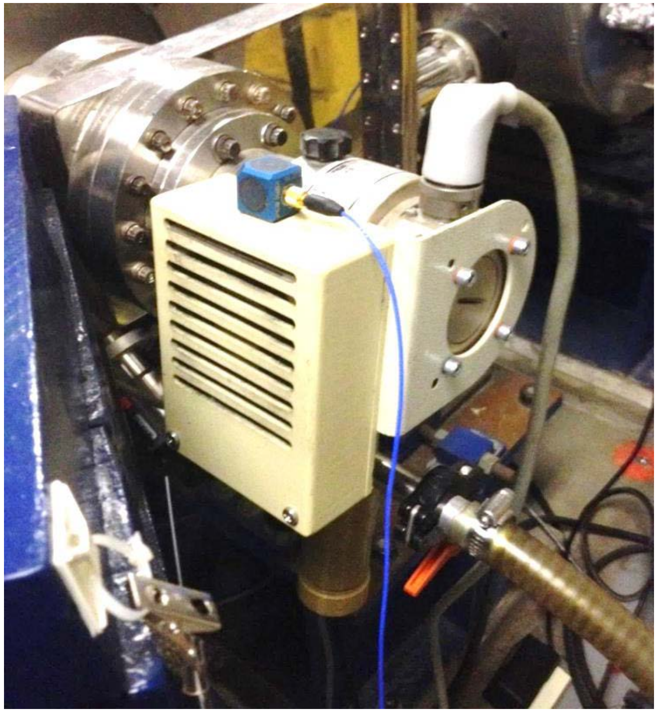
MICROPHONICS PROBLEMS AND MITIGATION

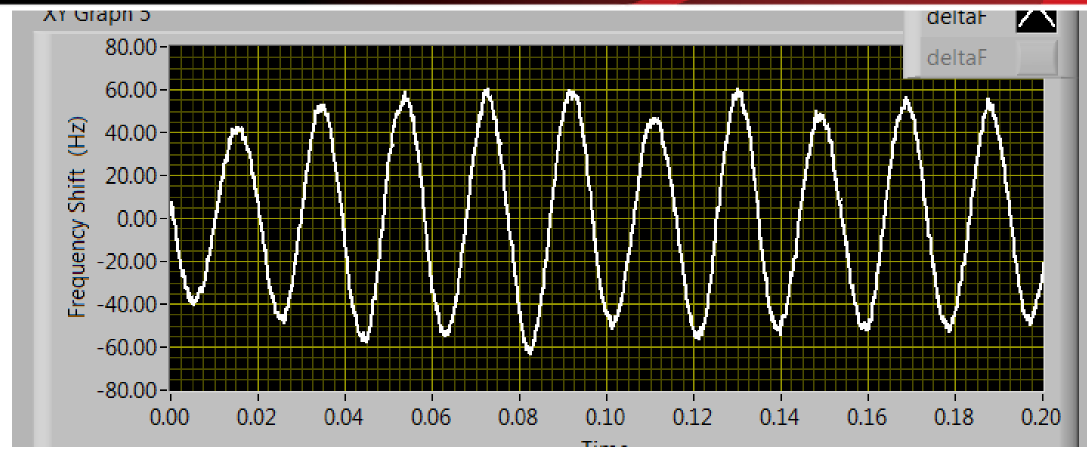
- **Microphonics is becoming more important as cavity control bandwidths become smaller and smaller.**
- **Remember at 1.5 GHz, and a 1 meter long structure 10 nm of change in length is about a 15 Hz change in frequency. The control BW of an LCLS II cavity is 16 Hz.**
- **A driving sources and mechanical resonances near the same frequency will effectively amplify the effect of the sources terms. If a narrow band source lands near a modal resonance you will have problems. Often time these types of microphonics will have constant amplitude as a function of time.**
- **Modes driven by random noise or weak narrow band sources will vary substantially as over time as the driver randomly goes from in phase to out of phase with the vibrational mode.**
- **There are times when you can have a source term that is not capable of exciting a mode within the structure.**
- **When we measured the floor vibrations in CEBAF we found about 30 spectral lines between 1 Hz and 50 Hz. Only a small number drove modes that caused microphonics. In most cases they were different modes in different cryomodules.**

MICROPHONICS PROBLEMS AND MITIGATION

- **Typical narrow band sources are:**
  - **Roughing pumps, etc. that are attached to the cryomodule. Braided hoses or rubber are better than bellows type hoses.**
  - **Large motors in cryogenic plants and cooling water systems which generally show up as narrow harmonics.**
  - **Motor vehicle traffic especially close in where they create differential motion between the RF gallery and the tunnel floor.**
- **On a few occasions we saw precisely the same frequency (and phase) of microphonics in two or more adjacent cryomodules two examples are:**
  - **10.75 Hz causing excessive microphonics on 4 zones (32 cavities) in the north linac. The source was a failing motor in a cooling tower that was about 50 m from the linac.**
  - **21 Hz in the first half of three cryomodules in the south linac where the suspected source path is the cryogenic piping.**
- **Pay attention to coupling paths. Not much is transmitted to a 5,000 pound cryomodule through air. RF transmission lines, vacuum pumping lines and cryogenic piping as well as the floor are all important.**
- **Cryogenic thermo-acoustic oscillations will cause excessive microphonics.**

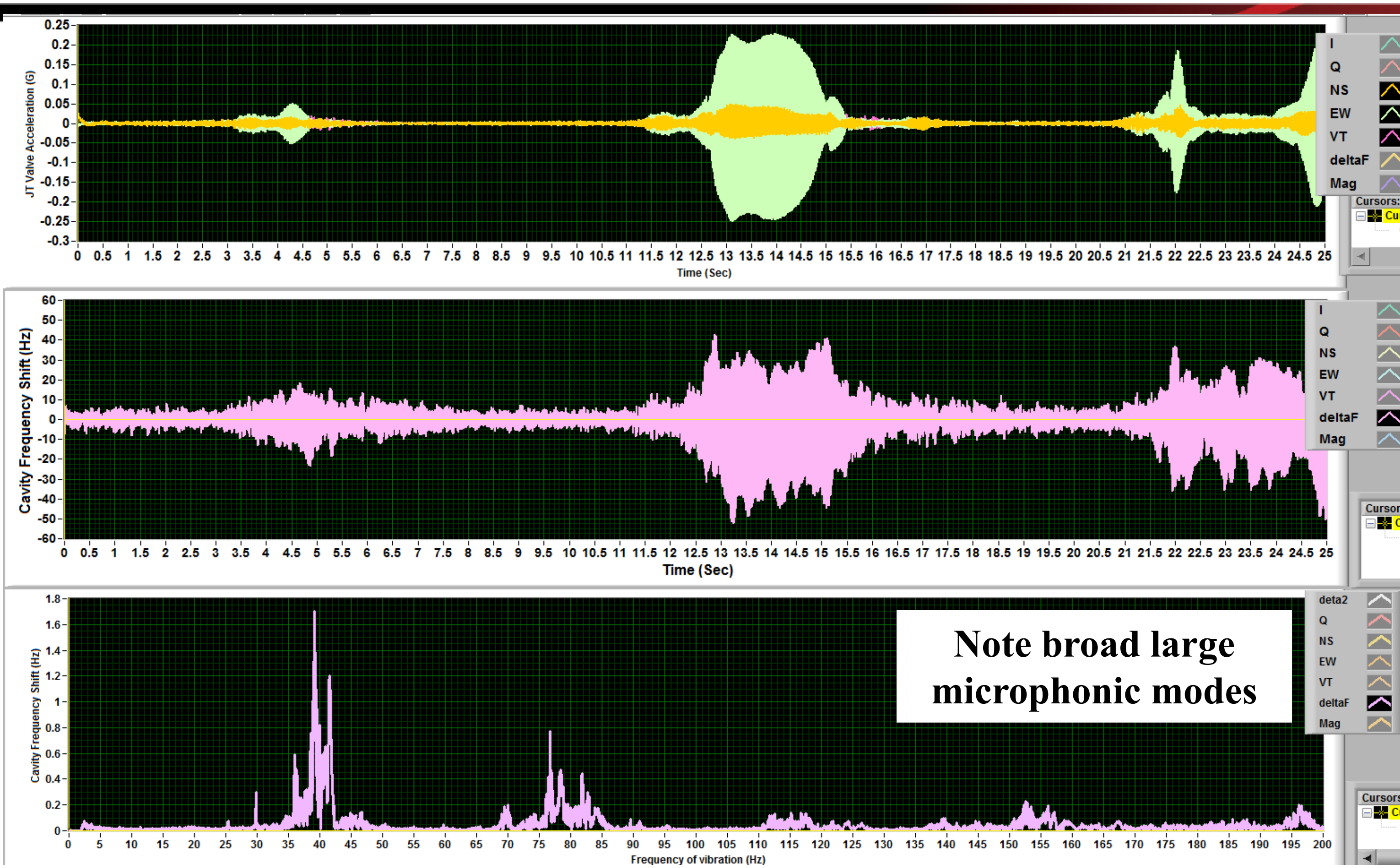
EXAMPLE OF LOCALLY DRIVEN MICROPHONICS





- **52 Hz microphonic observed in CEBAF injector.**
- **Peak to peak microphonics was 120 Hz.**
- **Although the RF system was able to maintain reasonable gradient regulation phase was not properly regulated.**
- **The source was a 10 cm x 15 cm cooling fan on a turbo pump. After 20-plus years of operation the rubber standoff grommets failed.**
- **The fan was attached to a turbo pump which was on the insulating vacuum vessel. Even this minor amount of mass and force was enough to cause excessive microphonics.**
- **The fan was removed from the turbo pump and mounted on a separate stand.**
- **Note the hose exiting the lower left side of the pump it is connected to a roughing pump about 1 meter from the cryomodule. The rubber hose provided sufficient isolation that we did not observe the 120 Hz microphonics normally associated with a roughing pump.**

LCLS II MICROPHONICS AND JT VALVE VIBRATIONS, DUE TO THERMO-ACOUSTIC OSCILLATIONS



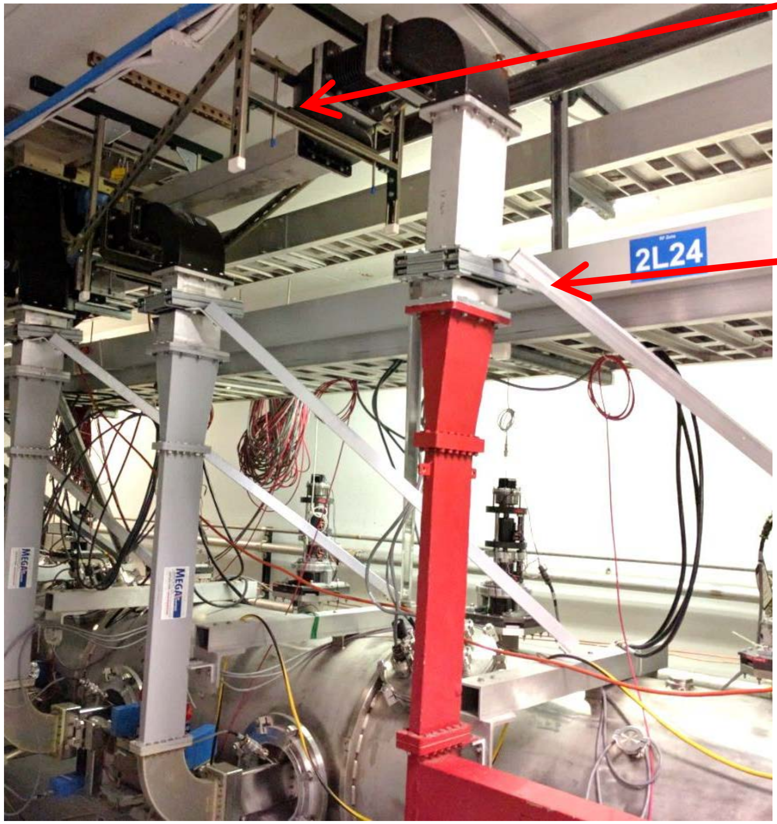
Accelerometer on JT Valve +/- 0.2 G

Microphonics +/-60 Hz full scale.

Spectrum Peak harmonic 1.8 Hz-rms

- Time scale 25 seconds, Microphonic cavity frequency shift scale 60 Hz.
- Clear correlation.
- Modifications to the JT Valve stem and flow parameters were implemented to address the problem.

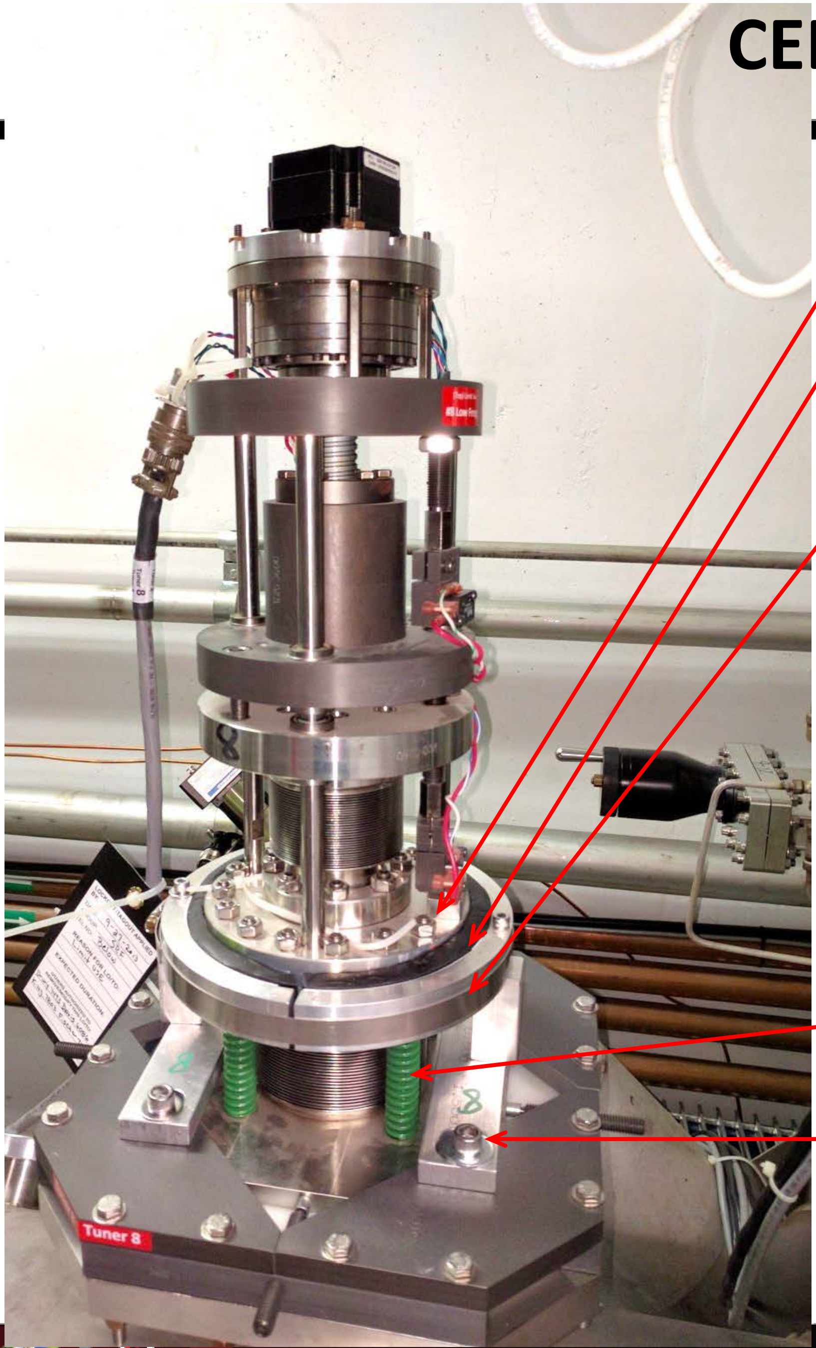
C100 CRYOMODULE HARDENING AGAINST TRANSIENT EXCITATION



- Waveguide ceiling mounts 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.
  - Has 1/8" 50 durometer Sorbothane® to damp vertical motion and to a lesser extent EW/NS motion.
- Not all rubber or foam materials actually damp vibrations. Good damping materials have a relatively high loss tangent.
- We also installed dampers on the tuner stacks to help reduce the Q of the resonant modes of the structure.

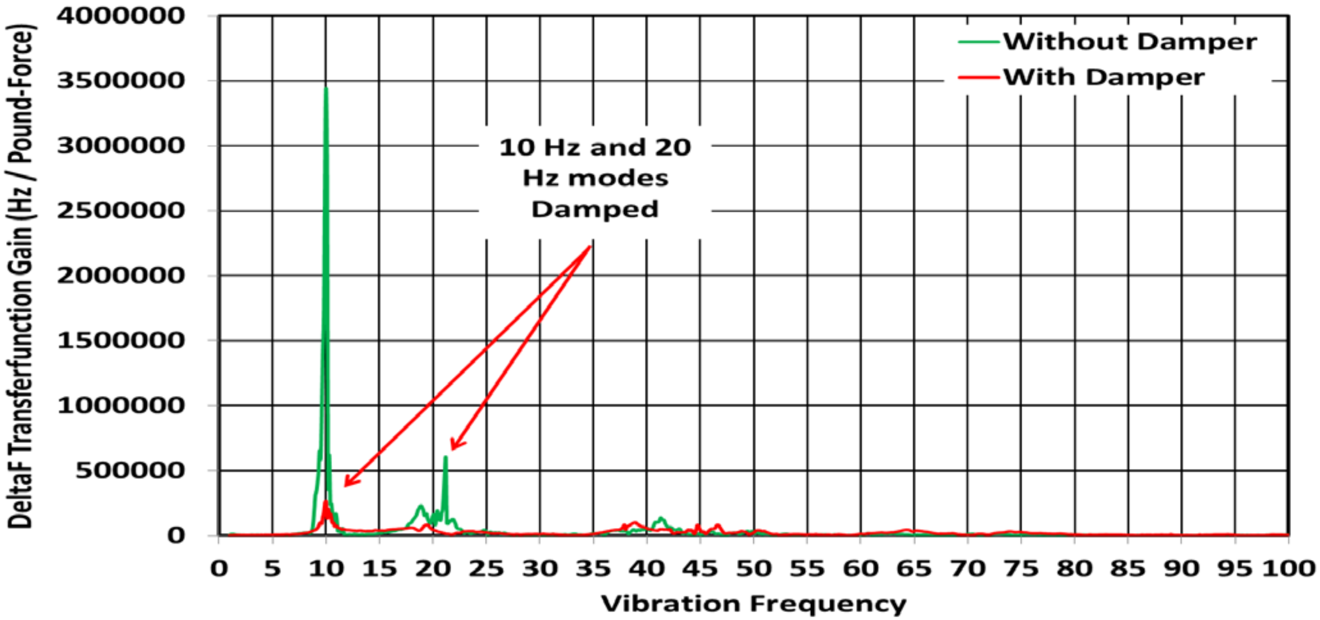
- The vibrational modes of the cryomodule where measured several years ago as part of an microphonics improvement program.
- Knowledge of the modes along with impulse hammer testing from structure to cavity microphonics was used as a metric to quantify effectiveness of different approaches.

CEBAF C100 Tuner Damper Ring



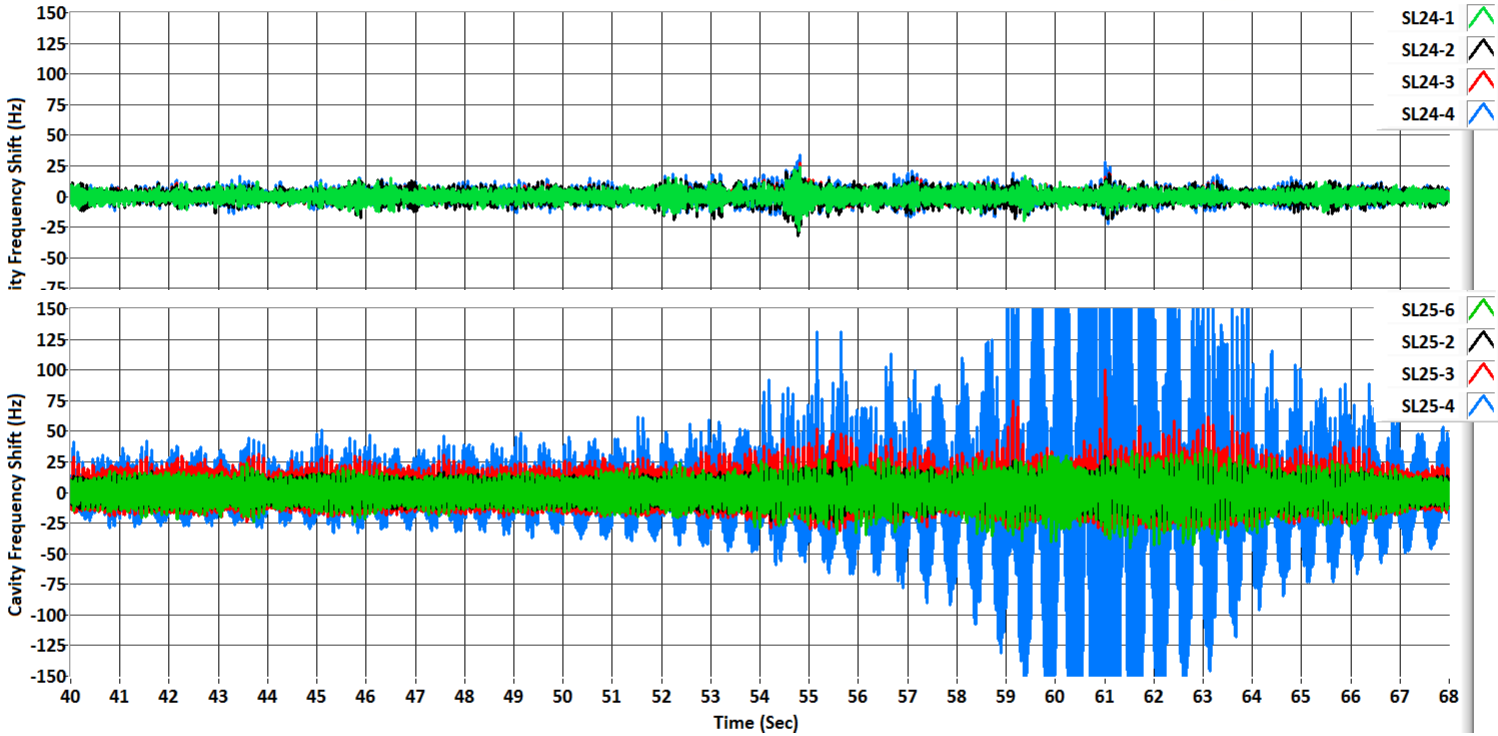
1. Lower tuner flange 6” OD, 1.5” thick.
2. 30 durometer, 1/2” x 1” sorbothane with polyethylene tape on the inner surface in order to allow vertical motion.
3. Split ring with a nominal ID of 7” and with two 3/8” gaps for adjustment.
    1. Compression adjustment made by tightening the hose clamp while measuring the OD of the short axis of the split ring.
    2. 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.
4. Green springs adjusted to relaxed state after cavity is cold and tuned.
5. Mounting plates fixed in place after compression adjustment insuring minimum lateral forces on tuner.

IMPULSE RESPONSE TRANSFER FUNCTION WITH AND WITHOUT TUNER DAMPERS



- In both data sets, an instrumented impulse hammer with a relatively soft tip was used to strike the wavguide at the bottom of the half height to full height transition.
- The measured response was the microphonic frequency shifts of the cavity.
- One set of data (red) was taken with the tuner dampers in place and the other (green) is without.
- The dominant modes without the damper were the 10 Hz full string mode and the 21 Hz half string mode.
- Two metrics which indicate an improvement are a reduction in the quality factor, Q, of the modes and a reduction in the peak value of the transfer function for each mode.

ADJACENT CRYOMODULES WITH AND WITHOUT HARDENING DURING A TRUCK DRIVE-BY

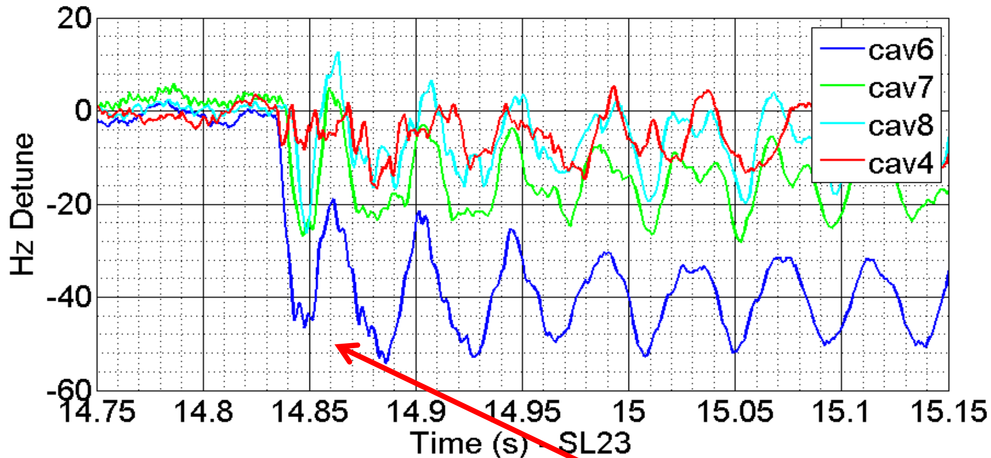


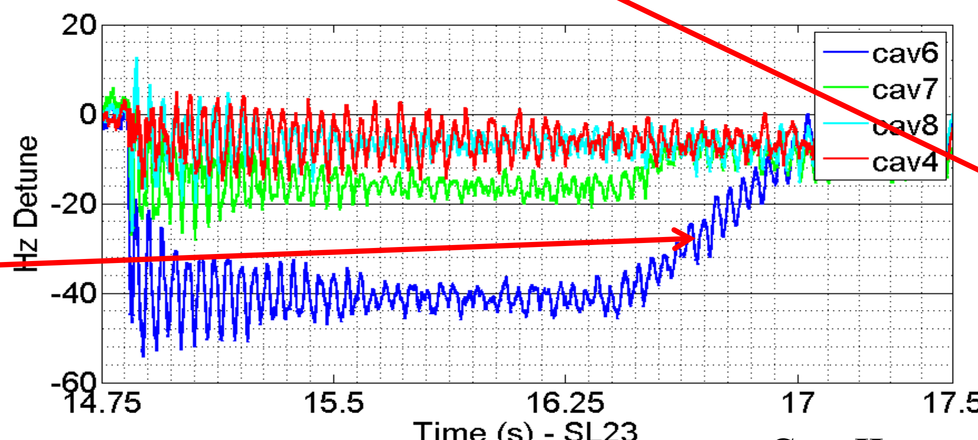
- At about 52 seconds a nitrogen truck drove based the linac service building adjacent to the two zones.
- Upper data is microphonics in cryomodule with improved waveguide mounting and tuner damper.
- Lower data is adjacent cryomodule of the same type.
- There was a moderate improvement to the background microphonics and a substantial improvement to the sensitivity to the truck drive-by which caused a differential motion between the klystron gallery and the tunnel floor.

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

- 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





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

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

OPTIMIZING LOADED-Q

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

Assuming that $\beta >> 1$ this reduces to

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

- **Where**
  - δf **is the frequency shift of the cavity from the generator frequency**
  - ψ_B **is the phase of the resultant* beam relative to cavity gradient and**
- **You need to take the derivative of this equation with respect to Q_L in order to calculate the minimum klystron power necessary.**

$$\beta = \frac{Q_0}{Q_1\left(1 + \sum_{i=2}^{N} \frac{Q_i}{Q_0}\right)}$$

Normally $Q_1 \ll Q_0$ and $Q_2, Q_3 \ldots Q_N \gg Q_0$ Thus:

$$\beta \cong \frac{Q_0}{Q_1} \quad \textbf{or} \quad \beta \cong \frac{Q_0}{Q_L} - 1$$

*** Note: For an multiple beams at once, i.e. an energy recovered linac (ERL), the resultant beam current is the vector sum of the beams**

MODERATE AMOUNT OF MATH

$$P_{Kly} = \frac{L}{4Q_L\,(r/Q)}\left\{\left(E + I_0 Q_L\,(r/Q)\cos\psi_B\right)^2 + \left(2Q_L\frac{\delta f}{f_0}E + I_0 Q_L\,(r/Q)\sin\psi_B\right)^2\right\}$$

$$\text{Let } A = \left(2\frac{\delta f}{f_0}E + I_0\,(r/Q)\sin\psi_B\right)^2 \text{ and } B = I_0(r/Q)\cos\psi_B$$

$$P_{Kly} = \frac{L}{4Q_L\,(r/Q)}\left\{(E + Q_L B)^2 + Q_L^2 A\right\}$$

For minimum P_{Kly} as a function of Q_L :

$$\frac{dP_{Kly}}{dQ_L} = 0 = \frac{L}{4(r/Q)}\frac{d}{dQ_L}\left(\frac{1}{Q_L}\left\{(E + Q_L B)^2 + Q_L^2 A\right\}\right)$$

$$0 = \frac{-1}{Q_L^2}\left\{(E + Q_L B)^2 + Q_L^2 A\right\} + \frac{1}{Q_L}\left\{2B\left(E + Q_L B\right) + 2Q_L A\right\}$$

$$0 = Q_L^2(B^2 + A) - E^2 = Q_L^2 - \frac{E^2}{B^2 + A}$$

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

REDUCED SOLUTION FOR SRF CAVITIES OPERATED ON CREST

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

A typical linac operated on crest, with no microphonics

$$Q_L\Big|_{MinPower} \cong \frac{E}{I_0(r/Q)}$$

For an perfect energy recoverd linac with microphonics

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

But life is never perfect

THE EFFECTS OF TUNING ON OFF CREST CW BEAM LOADING

- **On beam turn on the forward power increases the phase shifts and microphonics effects are multiplied**

- **The tuner operates with a goal of making ψ_{Kly} *equal to zero by* shifting the frequency by δf_S which compensates for the $I_0 R_C \sin\psi_B$ term.**

- **Thus $\psi_{Kly} \rightarrow 0$ and P_{Kly} is minimized to:**

$$P_{Kly} = \frac{(\beta+1)L}{4\beta\, R_C}\left\{ \left(E + I_0 R_C \cos\psi_B\right)^2 + \left(2Q_L \frac{\delta f_M}{f_0} E + \cancelto{0}{2Q_L \frac{\delta f_S}{f_0} E + I_0 R_C \sin\psi_B} \right)^2 \right\}$$

- **Where δf_M is the frequency shifts due to microphonics**

- **Thus in this case:**

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

SEE Backup slides for more details on topic.

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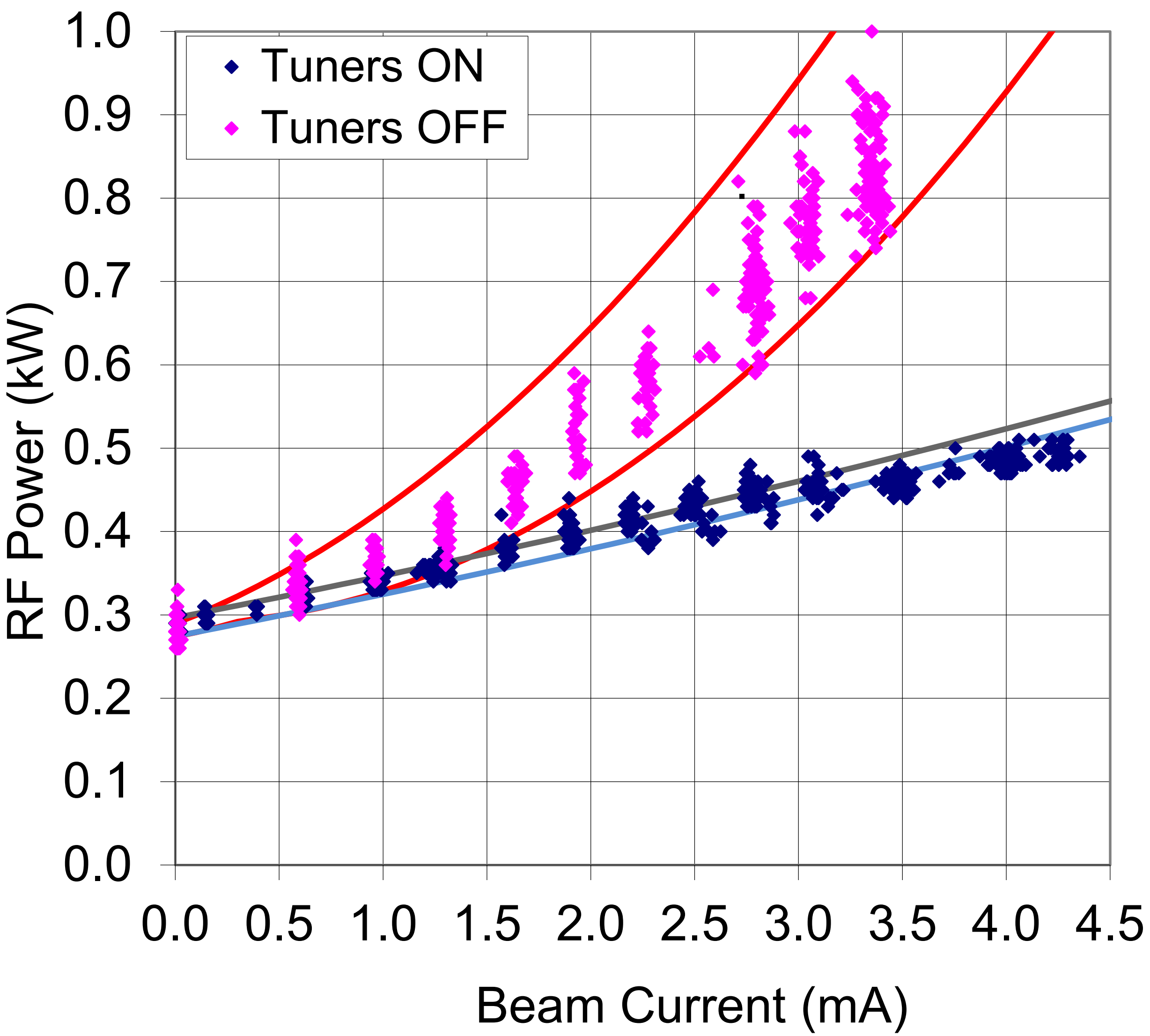
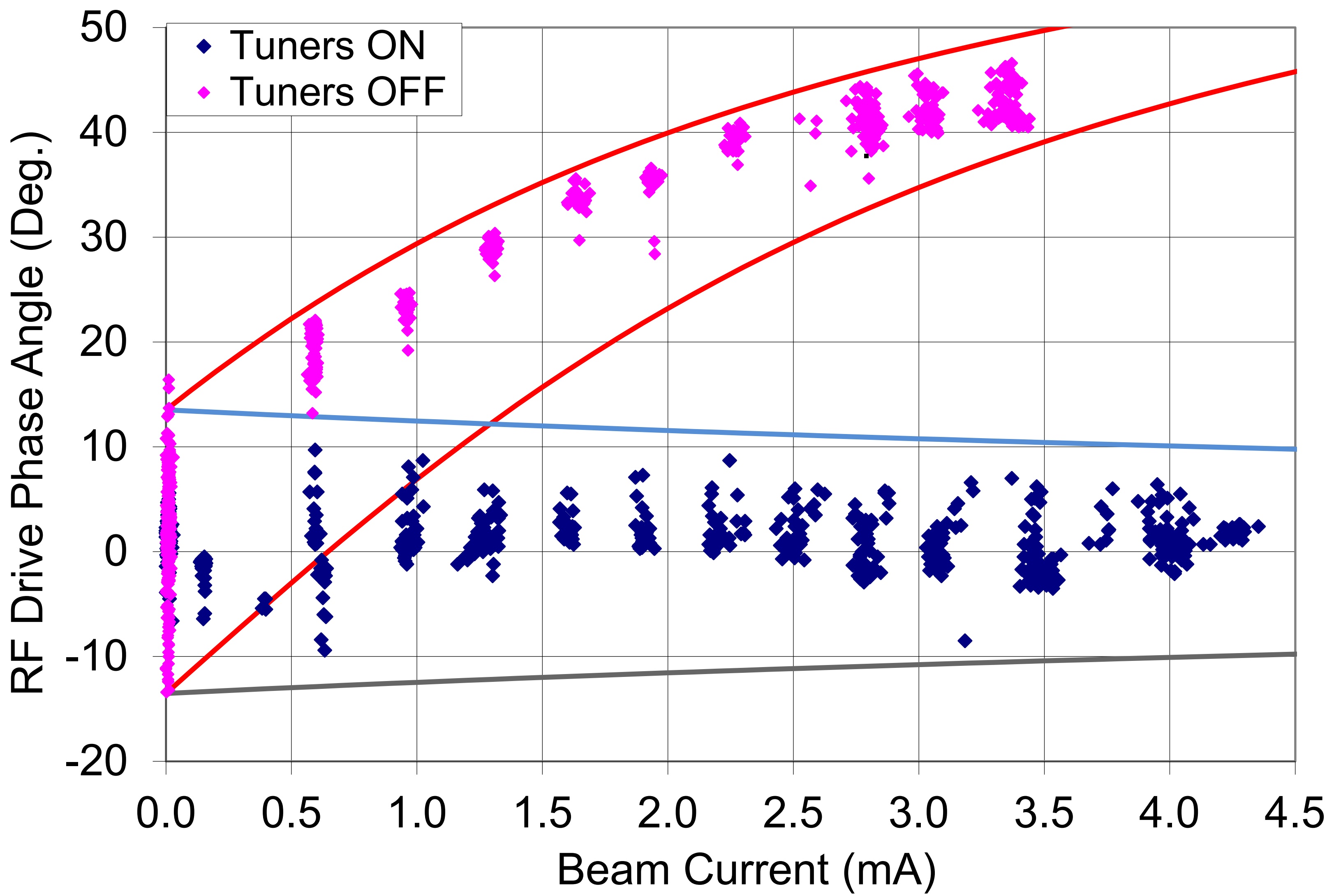
SEE Backup slides for more details on topic.

PREDICTED AND MEASURED FORWARD POWER IN AN ERL

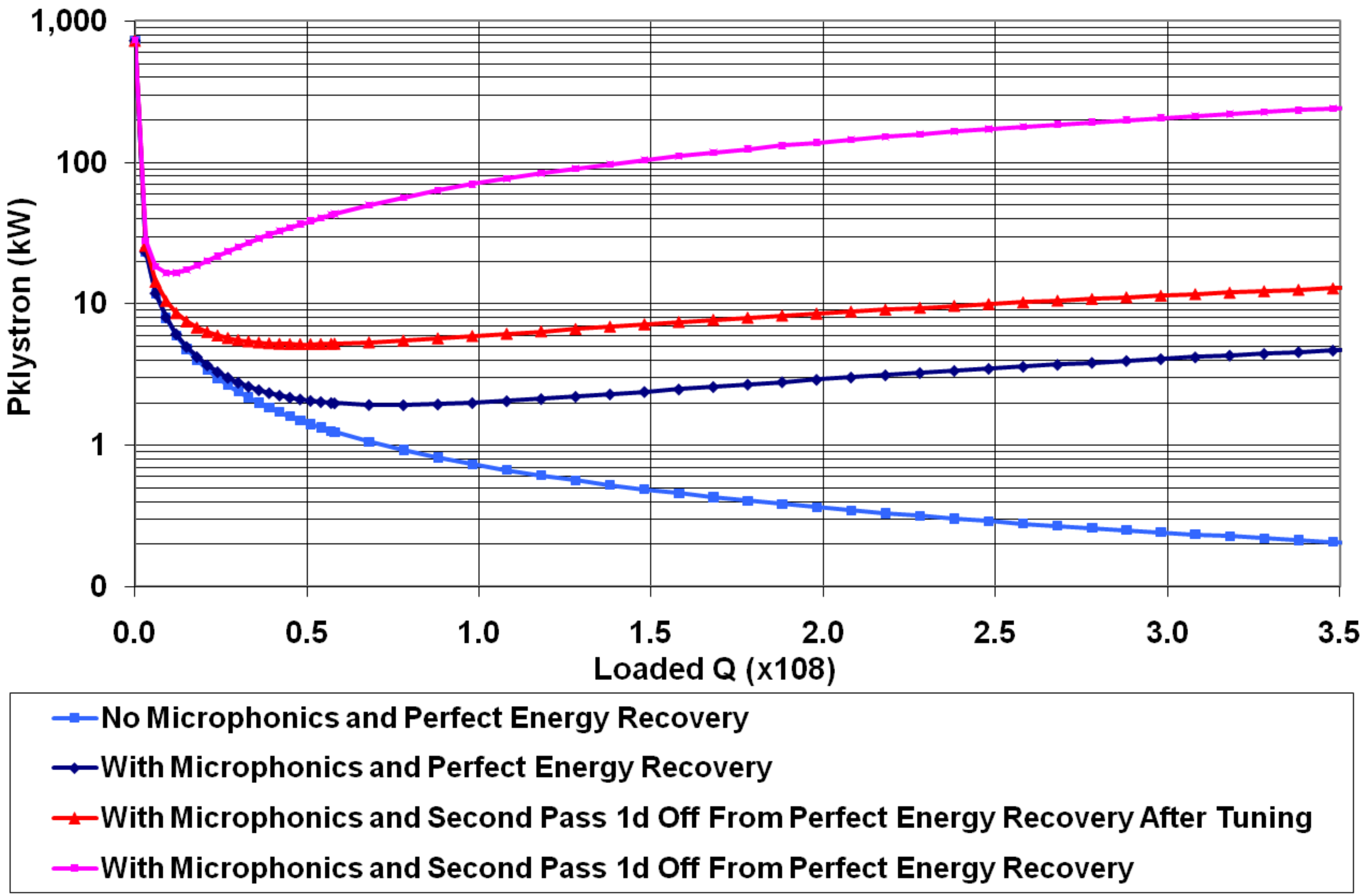


- **The solid lines indicate the predicted values based on:**
  - **$Q_L = 2 \times 10^7$**
  - **E = 5.6 MV/m.**
  - ***Δf = 10 Hz***
- **Test Process:**
  - **Tune the cavity with no current.**
  - **Disable the mechanical tuners.**
  - **Ramp the current up and record the forward power and phase.**
  - **Repeat with Tuners enabled.**

Predicted and Measured RF Drive Phase In an ERL



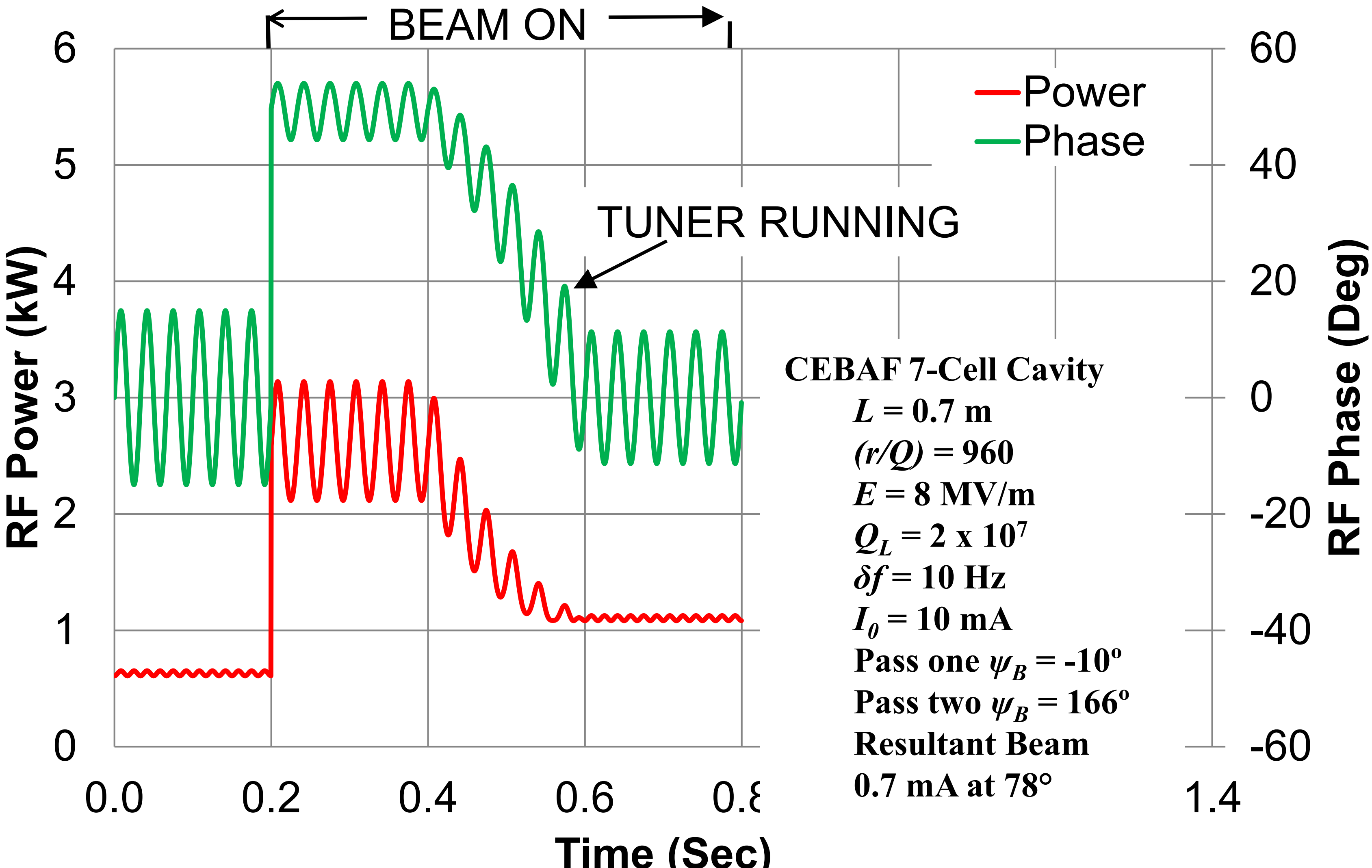
EFFECTS OF MICROPHONICS AND IMPERFECT ENERGY RECOVERY IN AN ERL CAVITY E = 20 MV/m, I_0 = 100 mA, 10 Hz DETUNE



SELECTING LOADED-Q FOR OFF CREST BEAM

1. Selection of loaded-Q has implications on RF power requirements.
2. When the beam is operated on crest the process is straight forward and margins only have to be added for
    1. Microphonics,
    2. Uncertainties in cavity parameters such as Q_L and operating gradient.
    3. Overall Margin
    4. Detuning effects.
3. When the beam is not operated on crest operational modes must be considered. Often this can substantially reduce the RF power requirements.
    1. Ramping current simultaneous with operating tuners.
    2. Allowed levels of pulsed operation
    3. Uncertainty of the relative beam phases in an ERL

THEORETICAL EXAMPLE OF TUNERS COMPENSATING FOR OFF CREST BEAM LOADING



CEBAF 7-Cell Cavity

L = 0.7 m

(r/Q) = 960

E = 8 MV/m

Q_L = 2 x 10^7

δf = 10 Hz

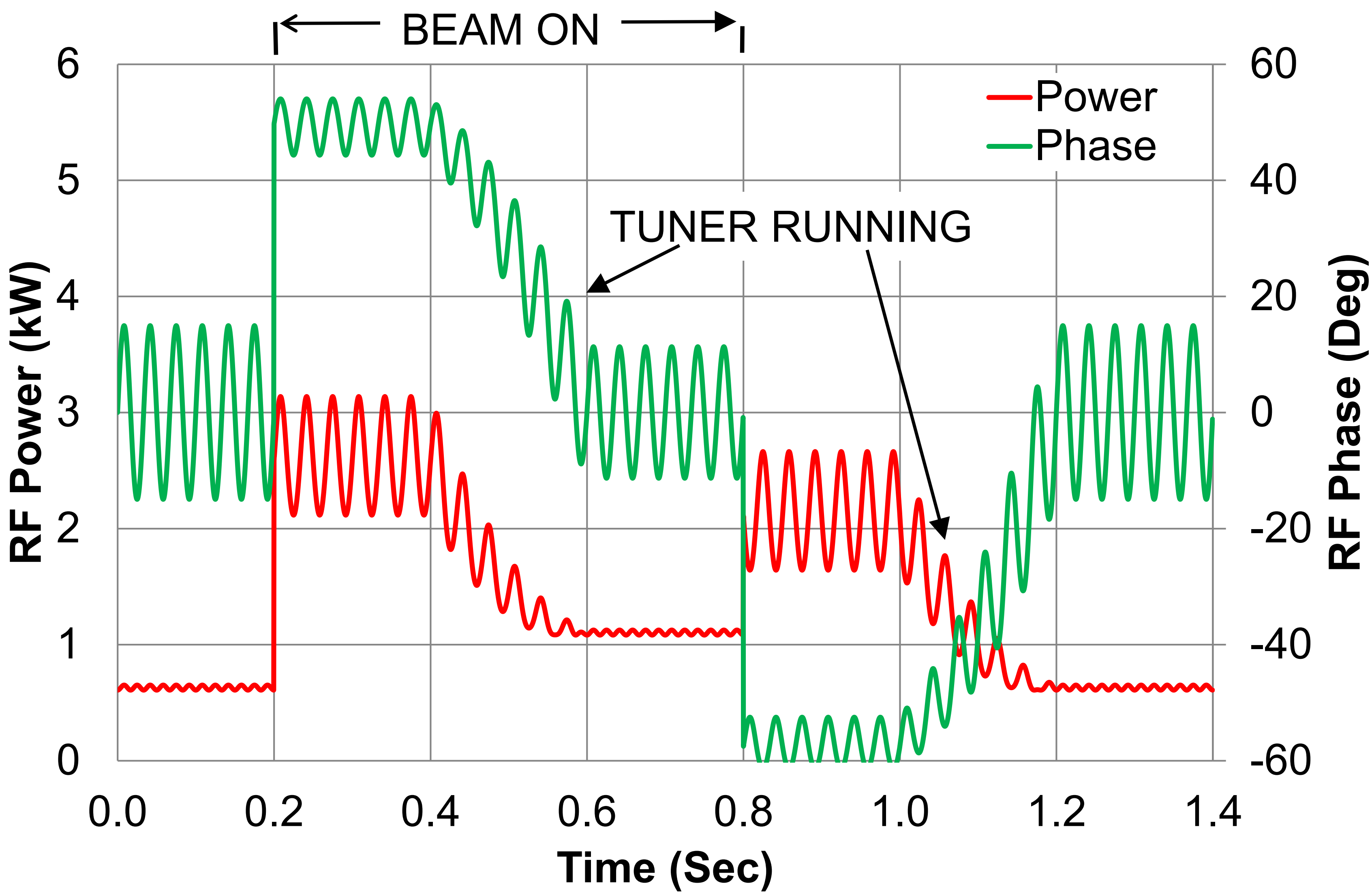
I_0 = 10 mA

Pass one ψ_B = -10°

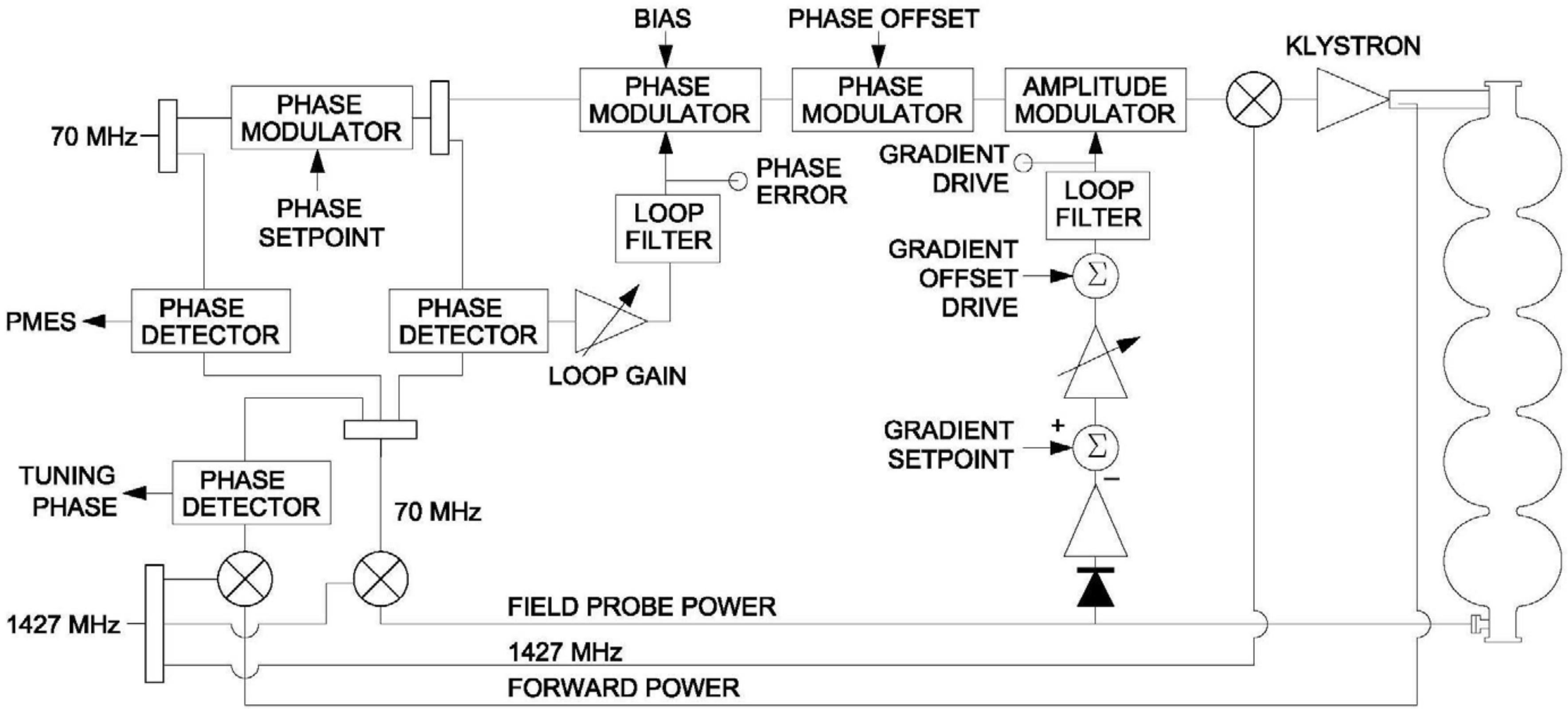
Pass two ψ_B = 166°

Resultant Beam 0.7 mA at 78°

THEORETICAL EXAMPLE OF TUNERS COMPENSATING FOR OFF CREST BEAM LOADING



"SIMPLE" BLOCK DIAGRAM OF ANALOG CONTROL SYSTEM*



*System used for the next 8 slides

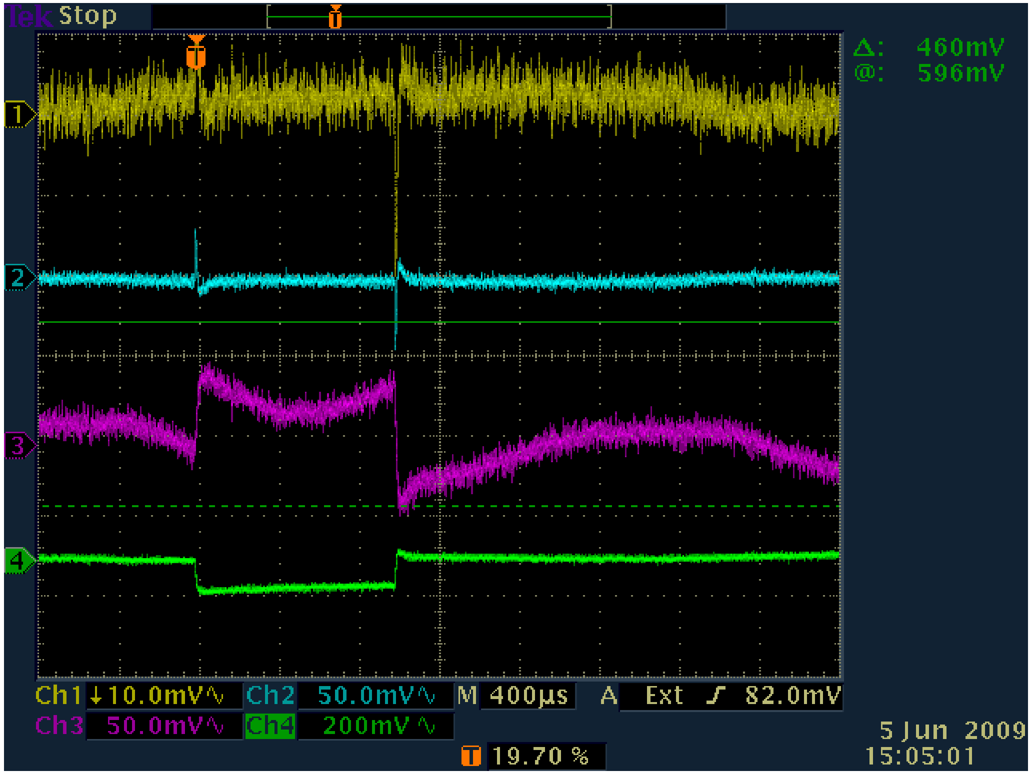
CONTROL SYSTEM OVERVIEW

1. **System down converts to 70 MHz**
2. **Phase and amplitude control are done at 70 MHz.**
3. **Software control of loop gains allows for on the fly changes during operations.**
4. **Analog monitor ports, coupled with the FEL's analog monitoring system allows us to monitor the health of the control loops during CW and pulsed operations**
5. **Bias control on phase shifter allows increased range at the price of loop gain.**
6. **The design has 20 years of history and successful use at CEBAF.**

JLAB FEL RF CONTROL SYSTEM “FEATURES”

1. System designed in the early 90s for a CW machine.
2. Proportional control, no integral term, no derivative term.
3. No flexibility in control loop to increase the speed when driving the low bandwidth fundamental power couplers
4. Nominal phase loop control range +/-45º
5. 6/7 or 4/5 Pi mode filter hard wired on analog board.
6. Designed for CW operations, which meant problems during high current pulsed operations.

TYPICAL CONTROL TRANSIENTS LOADED Q = 1x10^5

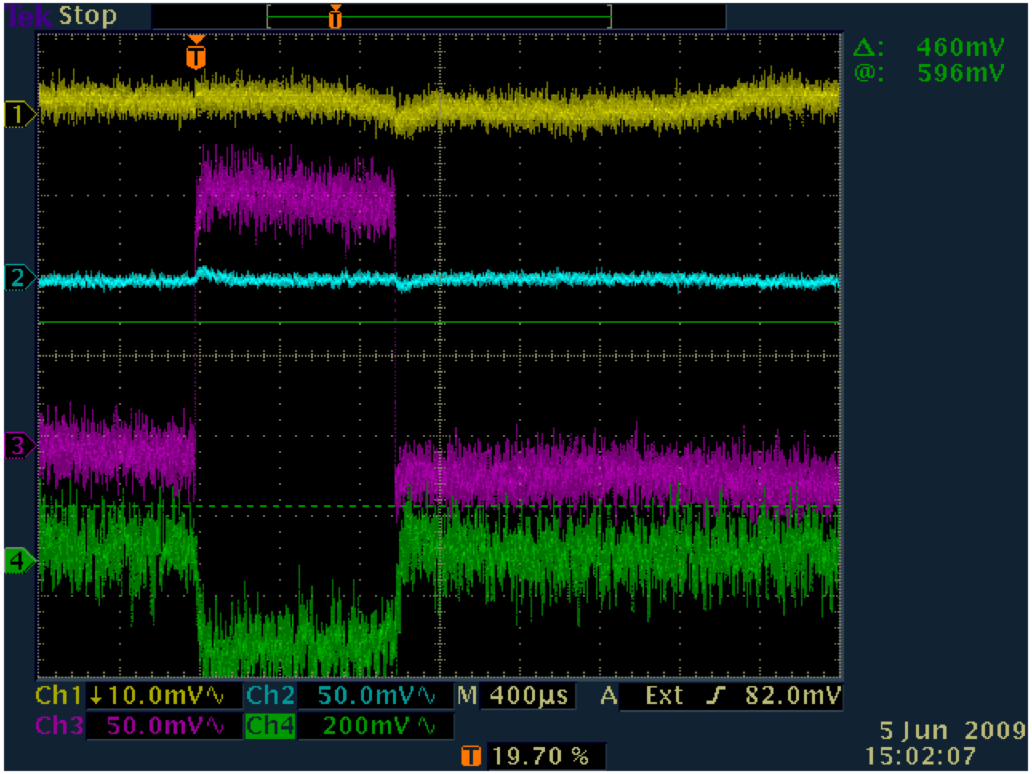


1 Measured gradient
2 Measured phase
3 Gradient drive
4 Phase drive

I_{BEAM} = 600 uA
Phase ≅ 90°

- "Normal" beam loading in the buncher cavity where the beam is at the zero crossing.
- Note the fast rise time of the signals and the short transients on the measured phase signal

TYPICAL CONTROL TRANSIENTS LOADED Q = $2x10^6$

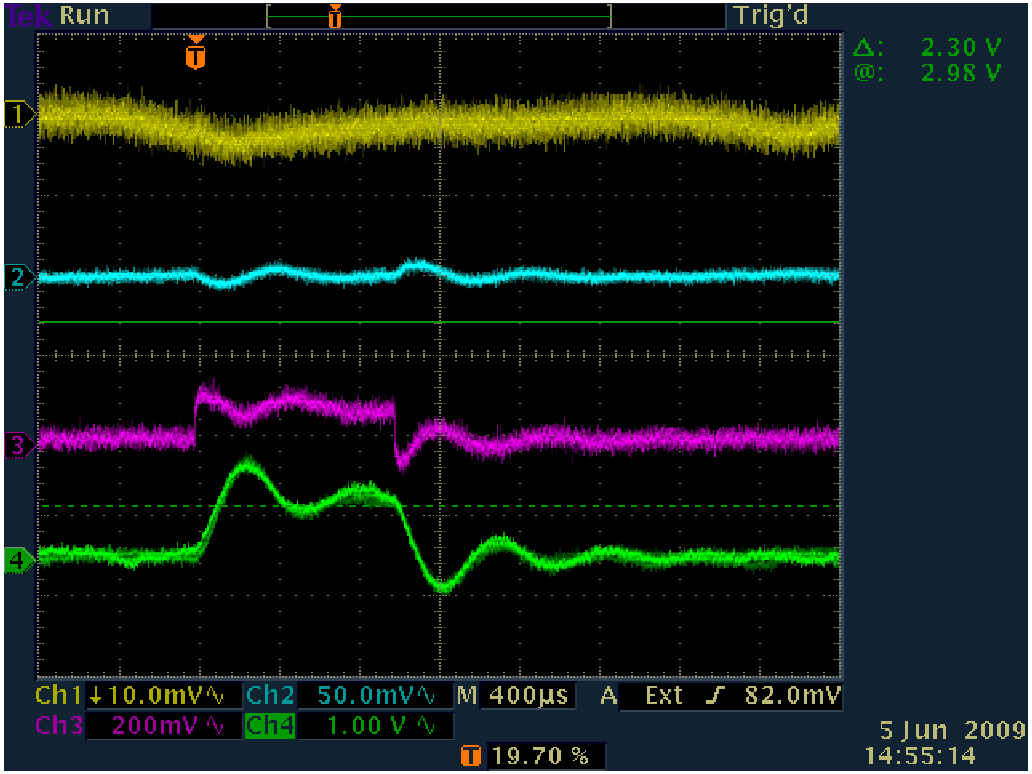


1 Measured gradient
2 Measured phase
3 Gradient drive
4 Phase drive

I_{BEAM} = 600 uA
Phase ≅ 90°

- "Normal" beam loading in the injector where the beam is near crest.
- Note the rise time of the signals and the fact that Gradient drive signal has a moderate transient.

TYPICAL CONTROL TRANSIENTS LOADED Q = $2\text{x}10^7$

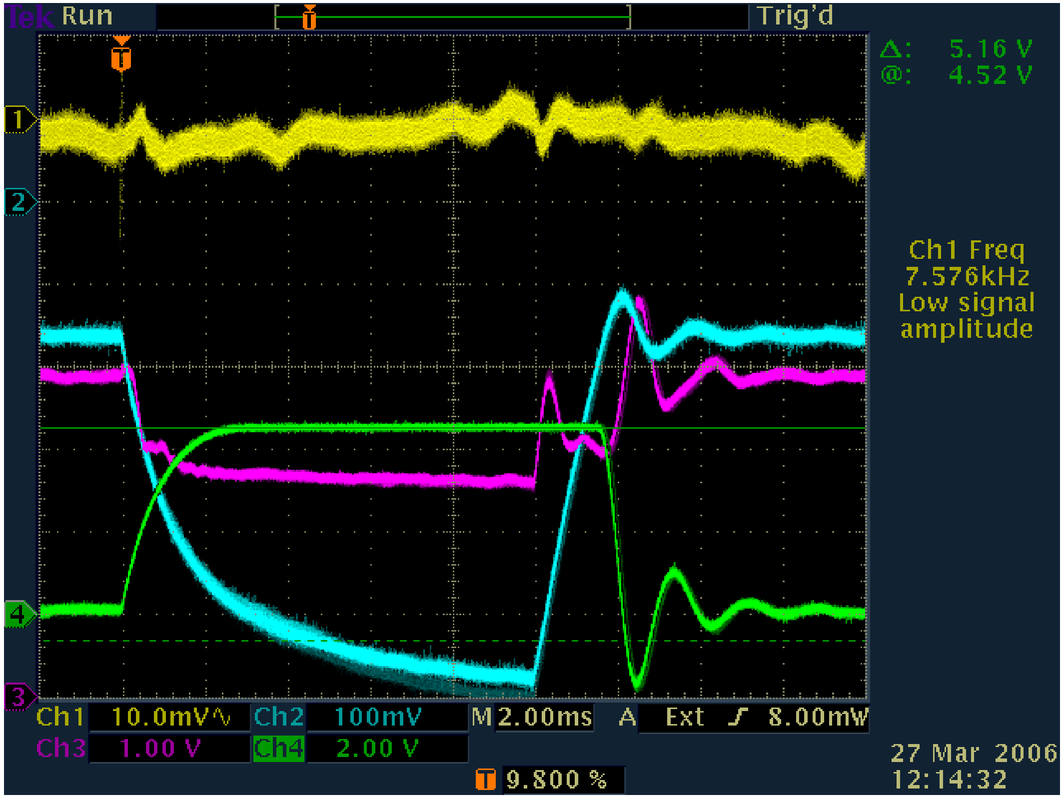


1 Measured gradient
2 Measured phase
3 Gradient drive
4 Phase drive

I_{BEAM} = 600 uA
Phase ≅ 90°

- Beam loading on a high Loaded-Q cavity.
- Note the rise time of the signals and the fact that Phase drive signal has a fairly large transient.

TYPICAL CONTROL TRANSIENTS LOADED Q = $1x10^5$



1 Measured gradient
2 Measured phase
3 Gradient drive
4 Phase drive

I_{BEAM} = 600 uA
Phase ≅ 90°

- Note the measured phase has a large transient.
- Note that the phase drive signal is saturated
- This was "fixed" by adjusting the phase modulator bias signal thus providing more range.

Pass Band Mode Filters

1. Multicell cavities support a number of frequencies that are close to the fundamental frequency of the pi-mode.

2. For the JLAB 5-cell cavity the closest mode is about 4 Mhz lower than the fundamental frequency.

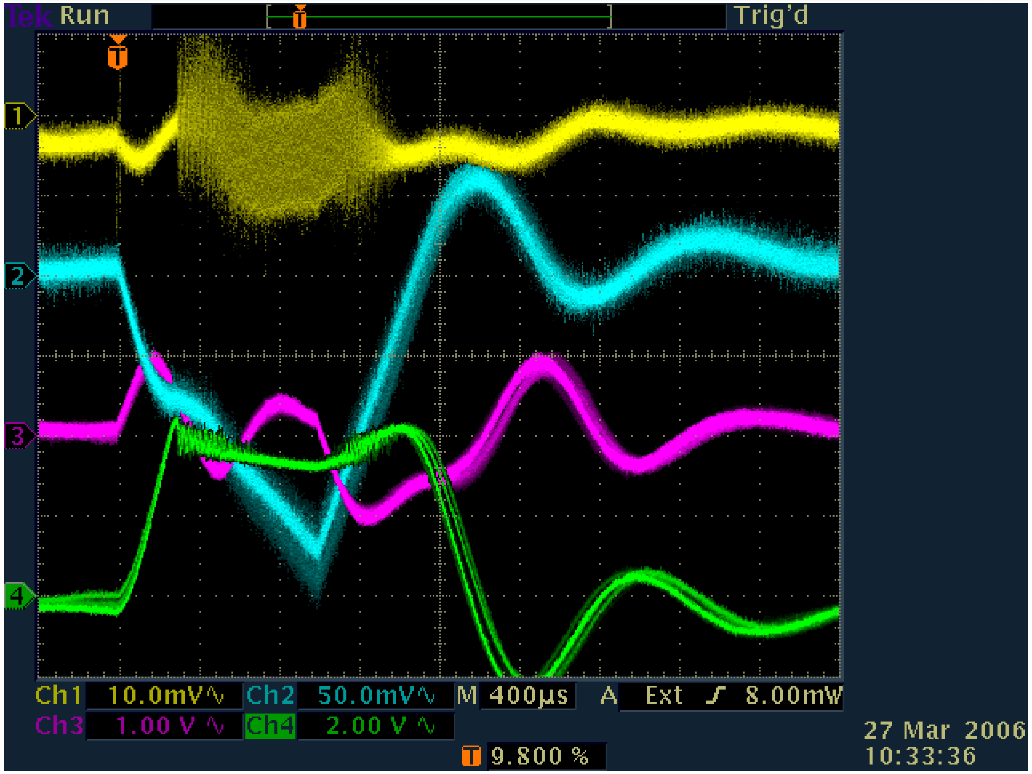
3. For the JLAB 7-cell cavity the closest mode is between 2 and 2.7 MHz lower than the fundamental.

4. If the control system is not designed correctly this mode can be excited and an energy modulation is introduced on the beam.

5. Although special filters were added to the low level RF system they were not always adequate to suppress these modes.

6. Typically the 8/9 Pi mode on ILC cavities is 800 kHz below the Pi mode. Thus, it presents even more of a concern.

TYPICAL CONTROL TRANSIENTS LOADED Q = $1x10^5$



1 Measured gradient
2 Measured phase
3 Gradient drive
4 Phase drive

I_{BEAM} = 600 uA
Phase ≅ 90°

- Beam loading on a high Loaded-Q cavity.
- In addition to poor phase regulation the 6/7-Pi mode is causing an oscillation in the system, which was remedied by lowering the broad band gain in the phase loop.

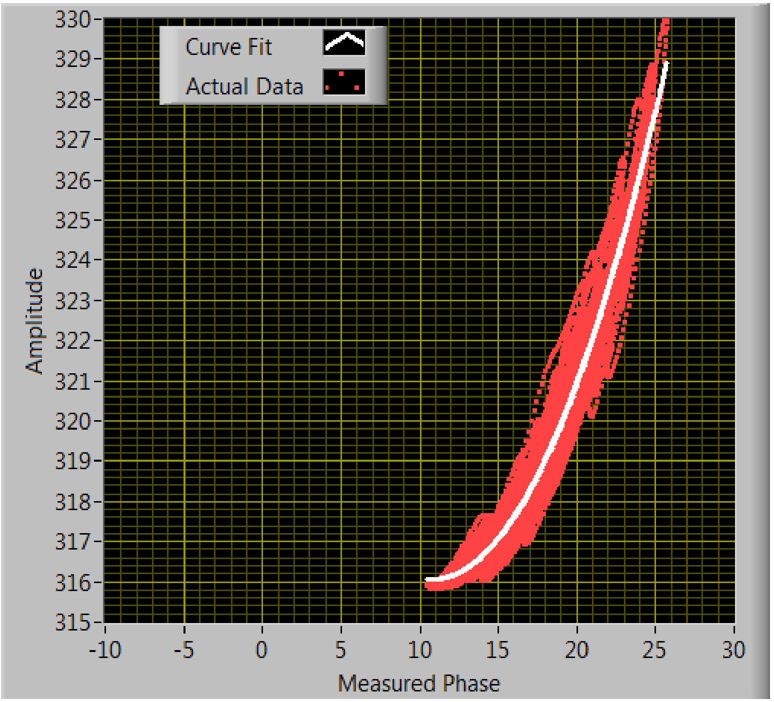
SRF TUNER CONTROLS

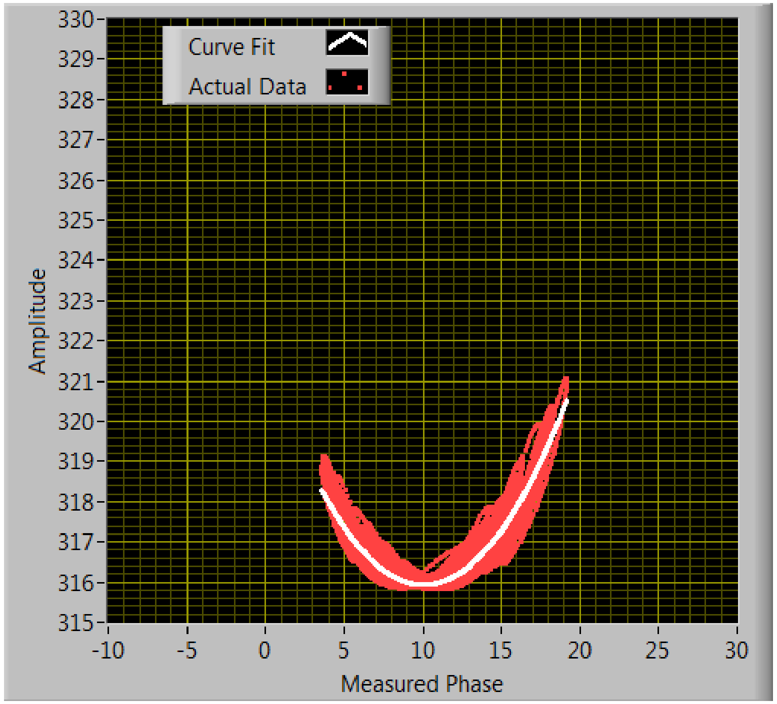
- **“Slow” stepper motor tuner.**
  - **Typically CW SRF systems make use of stepper motor tuners to track the helium pressure driven frequency shifts. These shifts typically have time constants on the order of minutes to hours.**
  - **Typical range of a stepper tuner is +/- 200 kHz.**
  - **Typical resolution of a stepper tuner is a few tenths of Hz per full step.**
  - **If done correctly the tuner will have very little close in hysteresis.**
  - **Actuating the motor can introduce minor microphonics noise.**
  - **Unlike a warm cavity tuning system, the system should “remember” where it was at the last turn off in order to insure a quick turn on of the cavity.**

- **“Fast” Piezo tuner**
  - **Typically 1 kHz full range.**
  - **Has a 1 kHz bandwidth.**
  - **Can be difficult to control because of complex transfer function which is dependent on the modal characteristics of the structure.**
  - **Is invaluable for pulsed gradient operations.**
  - **A number of projects are coming to rely on PZT tuners for day to day operations.**

- **At JLAB we have 25 years of successful operations using just the stepper motor tuners.**

MAINTAINING PROPER TUNER PHASE OFFSET

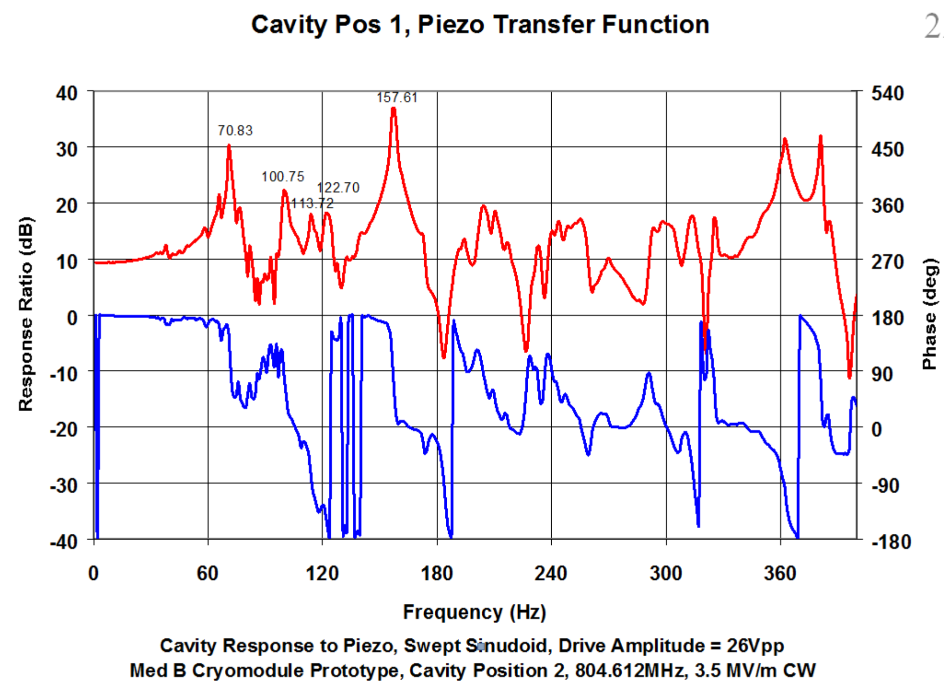




Curve fitting for measured RF drive phase perturbations due to microphonics with a peak to peak value of 15 Hz and a cavity that off resonance with a detune offset of 10° and (right) curve fitting for measured microphonics data with a peak to peak value of 15 Hz and a cavity that is close to on resonance. In both cases the data indicates that the proper detune offset is approximately 10°.

DYNAMIC FEEDBACK WITH PZT TUNERS

- PZT tuners can be used to compensate for pulsed Lorentz detuning effects as well as background microphonics.
- Systems must be characterized with a concern for having nodes (no control) in frequency bands that need to be controlled and resonances such as found in the SNS cavities.



- DESY has excellent results of dynamic feedback control of the pulsed Lorentz effects using an algorithm that adaptively builds up a correction waveform on a point by point basis.
- Cornell, DESY, Fermi, HZB and others have demonstrated the ability to reduce the RF power requirements due to microphonics using PZT tuners.

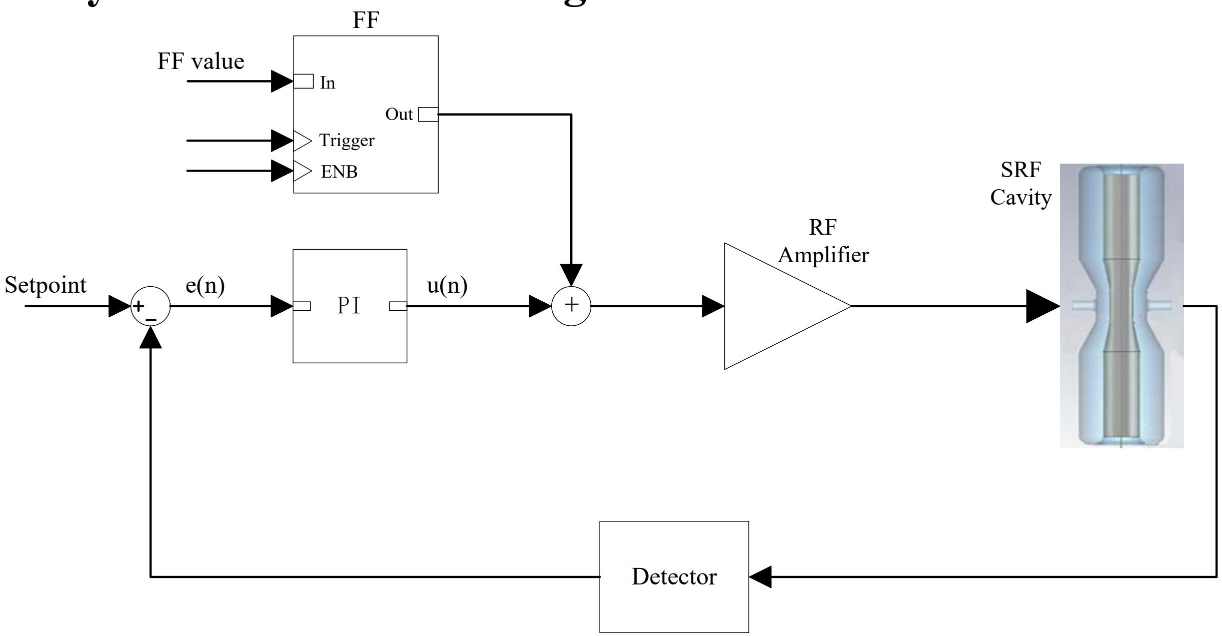
Turning On a Detuned Cavity

- **Initial Turn on cavity frequency*.**
  1. Close the SEL mode switch.
  2. Move the phase offset variable in 15° increments until one establishes maximum gradient. Continue to decrease the cavity phase increment until you are within 5° of the maximum gradient.
  3. Operate the tuner until the frequency error is close to zero.
  4. Increase the RF power until you are near the desired cavity gradient.
  5. Adjust the phase offset until the cavity gradient is maximized.
  6. Switch over from SEL to GDR mode. Note you will likely have to apply a phase offset due to processing latency differences.
  7. Close the tuner loop and allow the computer to control the tuner motor.
  8. Apply the closed loop tuner algorithm.
- **Normal turn on after a trip or if the cavity was recently operated.**
  1. Skip step 2 above.

*This assumes that the SEL mode has a very wide capture range. For the JLAB FCC it is in excess of 200 kHz.

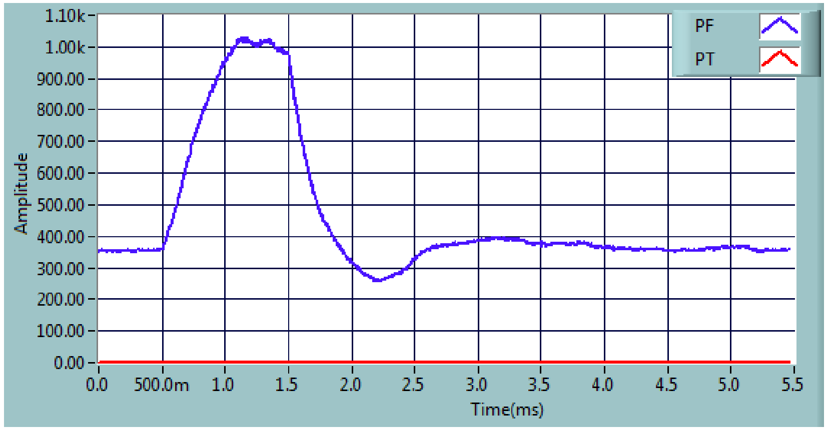
FEED FORWARD FOR PULSED BEAM OPERATION

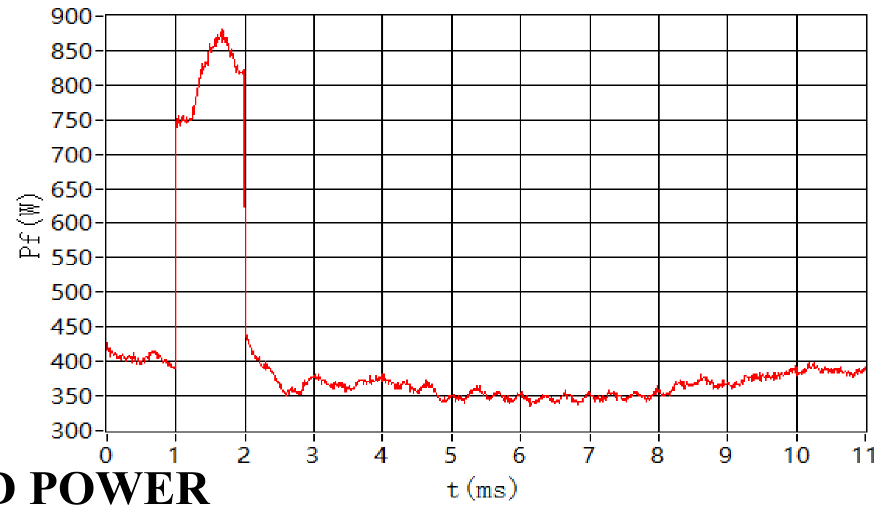
- If one looks at the standard RLC circuit model of a cavity, you would notice that the beam current has the same effects on the cavity gradient as current from the RF source.
- The implication is that one can compensate for pulsed beam loading effects by predictively applying feed forward signal of the proper phase and amplitude in order to compensate for the beam loading.
- This can be done as a simple predictive algorithm or for more accuracy as a dynamic feed forward algorithm



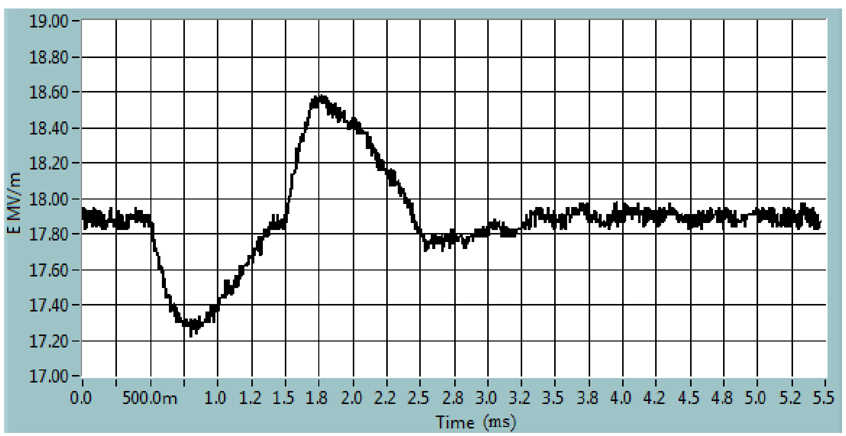
- Block diagram of IMPs feed forward algorithm.

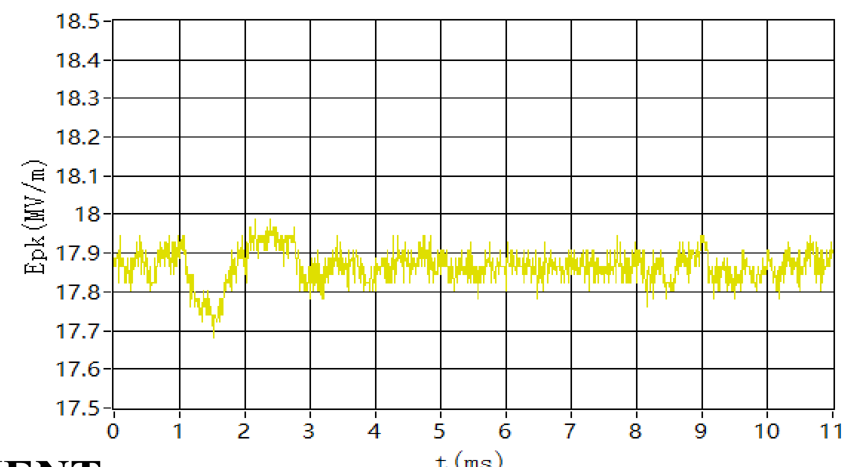
EXAMPLE WAVEFORMS SIMPLE PREDICTIVE FEED FORWARD SYSTEM 20 mA PULSED BEAM LOADING





FORWARD POWER





GRADIENT

FEED FORWARD OFF

SIMPLE FEED FORWARD ON

CONCLUSIONS

Thank you for your attention. I hope what I have presented will be useful.

Selected References.

Padamsee, Knobloch, and Hays, RF Superconductivity for Accelerators, John Wiley & Sons 1998.

T. Powers, “RF Controls Experience with the JLAB IR Upgrade FEL”, 2009 ERL Workshop.

J. Delayen, et. al., “Development of a Digital Self Excited Loop for Field Control in High-Q Superconducting Cavities, SRF 2007.

L. Merminga, “RF Cavity Equations Steady State”, JLAB Technical note TN-95-019.

K. Davis “Microphonics Testing of the CEBAF Upgrade 7-Cell Cavity”. PAC 2001.

J.P.Holzbauer, Yu.Pischalnikov, D.A.Sergatskov, W.Schappert, S.Smith "Systematic uncertainties in RF-based measurement of superconducting cavity quality factors" NIM-A, Volume 830, 11 September 2016, Pages 22-29

Basic cavity formulas

r/Q	Geometric Shunt Impedance	Ω/m		T	Operational Temperature	K
G	Geometry Factor	Ω		R_{resid}	Residual Surface Resistance	Ω
E	Electric Field	V/m		$Q0$	Intrinsic Quality Factor	
L	Electrical Length	M		Q_{FPC}	FPC coupling Factor	
ω_0	Cavity Frequency	S^{-1}		Q_{FP}, Q_2	Field Probe Coupling Factor	
U	Stored Energy	J		R_C	Coupling Impedance	Ω
r_S	Surface Resistance	Ω		I	Beam Current	A
T_C	Critical Temperature	K		I_M	Matching Current	A
P_X	RF Power at Port X	W		P_{disp}	Dissipated Power	W
P_{emit}	Emitted Power	W		τ	Decay Time	s
R	Shunt Impedance	Ω		r	Shunt Impedance per Unit L	Ω/m

Power levels for strongly overcoupled cavites.

delivered to beam LEI

needed from the klystron $\frac{\mathrm{L}(\mathrm{E}+\mathrm{IR_C})^2}{4\mathrm{R_C}} = \frac{1}{4Q_L}\frac{L}{(r/Q)}(E+IQ_L(r/Q))^2$

reflected to the circulator $\frac{\mathrm{L}(\mathrm{E}-\mathrm{IR_C})^2}{4\mathrm{R_C}} = \frac{1}{4Q_L}\frac{L}{(r/Q)}(E-IQ_L(r/Q))^2$ $\qquad U = \frac{E^2 L}{(r/Q)\omega_0}$

Time dependent, complex diferential equation where $\vec{K}$ is the incident wave amplitude in $\sqrt{\text{Watts}}$, ω_d is the (time varying) detune angle, and $\omega_f = \omega_0 / 2Q_L$:

$$\left(1\text{-}j\frac{\omega_d}{\omega_f}\right)\vec{E} + \frac{1}{\omega_f}\frac{d\vec{E}}{dt} = 2\vec{K}\sqrt{\frac{R_C}{L}} - R_C\vec{I}$$

$$U = \frac{E^2 L}{(r/Q)\omega_0}$$

$$P = \frac{U\omega_0}{Q_0} = \frac{E^2 L}{Q_0(r/Q)}$$

$$Q_0 = G/r_S \,||\, Q_{ElectronLoading}$$

$$r_S \approx 10 - 4(\Omega K/GHz^2)\frac{f^2}{T}e^{-1.95T_c/T} + r_{resid}$$

$$Q_L = Q_0 \,||\, Q_{FPC} \,||\, Q_{FP} \approx Q_{FPC}$$

$$R_C = Q_L(r/Q)$$

$$I_M = E/R_C \quad \text{and} \quad \beta = \frac{Q0}{QL} - 1$$

RF Power Requirements

The equation for the power required for cavity center frequency f_0 detuned by δf and beam current, I_0, off crest by ψ_B :

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

where

$$\beta = \frac{Q_0}{Q_1\left(1+\sum_{i=2}^{N}\frac{Q_0}{Q_i}\right)} = \frac{Q_0}{Q_1(1+\sum_{i=2}^{N}\beta_i)}$$

Normally for all of the other ports except for port 1, $Q_i \gg Q_o$ which leads to:

$$\beta \cong \frac{Q_0}{Q_1}$$

Because and

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_1} + \frac{1}{Q_2} + \frac{1}{Q_3} \rightarrow \frac{Q_0}{Q_L} = 1 + \frac{Q_0}{Q_1} + \frac{Q_0}{Q_2} + \frac{Q_0}{Q_3}$$

Again all except for port 1, $Q_i \gg Q_o$ and this reduces to:

$$\frac{Q_0}{Q_L} \cong 1 + \frac{Q_0}{Q_1}$$

Or

$$\beta \cong \frac{Q_0}{Q_L} - 1$$

Note that the above equations do not include the effects of the controls gain and the controls "bandwidth" of the fundamental power coupler which is given by

$$BW_{Controls} = \frac{f_0}{2Q_L}$$

This is not the same as the bandwidth of the controls which is typically in the hundreds of kilo-Hertz range.

The klystron phase no beam is given by.

$$Tan\varphi = 2Q_L\frac{\delta f}{f_0}$$

Or to calculate δf

$$\delta f = \frac{f_0 Tan\varphi}{2Q_L}$$

Klystron phase with beam and a DC detune frequency.

$$\varphi_{RF} = arcTan\left(\frac{2Q_L\frac{\delta f}{f_0}E + I_0Q_L(r/Q)sin\varphi_B}{E + I_0Q_L(r/Q)cos\varphi_B}\right) + \varphi_{Offset}$$

On crest beam

$$\varphi_{RF} = arcTan\left(\frac{2Q_L\frac{\delta f}{f_0}E}{E + I_0Q_L(r/Q)}\right) + \varphi_{Offset}$$

Optimized Loaded Q

To determine the following start with.

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

And solve the following:

$$\frac{\partial P_{FWD}}{\partial Q_L} = 0$$

Matched loaded Q under all conditions.

$$Q_L|_{Minimum\ Power} = \frac{E}{\sqrt{(I_0(r/Q)cos\varphi_B)^2 + \left(2\frac{\delta f}{f_o}E + I_0(r/Q)sin\varphi_B\right)^2}}$$

Where

Matched Loaded-Q for accelerator operated on crest.

$$Q_L|_{Minimum\ Power} = \frac{E}{\sqrt{\left(I_0(r/Q)\right)^2 + \left(2\frac{\delta f}{f_o}E\right)^2}}$$

Matched Loaded-Q for accelerator operating off crest after transient loading.

$$Q_L|_{Minimum\ Power} = \frac{E}{\sqrt{(I_0(r/Q)cos\varphi_B)^2 + \left(2\frac{\delta f}{f_o}E\right)^2}}$$

It can be shown that:

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

Using capacitance rather than shunt impedance

Sergey Stark (formally at INFN later at RIB FRIB) set up his software at INFN with a Capacitance rather than shunt impedance or normalized shunt impedance.

$$E = \frac{\sqrt{\frac{U}{C}}}{L} \rightarrow \; E^2 = \frac{U}{CL^2} = \frac{(r/Q)U\omega_0}{L}$$

$$\frac{1}{CL^2} = \frac{(r/Q)\omega_0}{L}$$

$$\frac{1}{\omega_0 CL} = (r/Q)$$

$$Q_0 = \frac{\omega_0 E^2 L^2 C}{P_{DISP}}$$

Microphonics Measurements

For a SEL or PLL system, e.g. frequency tracking with some type of analog or digital I/Q receiver on the probe signal. Define the RF signal as.

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

Let:

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

Where

$$I(t) = V_{Peak}cos\big(\varphi(t)\big) \qquad Q(t) = -V_{Peak}sin\big(\varphi(t)\big)$$

It can be shown that

$$f_1 = \frac{1}{2\pi V_{Peak}^2}\left(Q(t)\frac{dI(t)}{dt} - I(t)\frac{dQ(t)}{dt}\right)$$

or

$$f_1 = \frac{1}{2\pi\big(I^2(t) + Q^2(t)\big)}\left(Q(t)\frac{dI(t)}{dt} - I(t)\frac{dQ(t)}{dt}\right)$$

For a sampled system.

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

Which can be reduced to:

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

CEBAF Cryomodule testing RF Performance Characterization

Emitted Power Based Measurements

Starting Parameters:

$P_{im}, P_{rm}, P_{tm}, P_{ha}, P_{hb}$ – Actual Measured Power (Watts)

C_i, C_r, C_t, C_a, C_b – Cable Cal Factors relating measured Power to Associated Power at the Cavity

P_{emit} – Sampled Emitted Power - Value of the Reflected Power with no Applied Incident Power.

$P_{disipated}$ – Disipated Power Measured Calimetrically.

τ – Decay fit Parameter for the $P_{\text{Reflected}}$ Signal Fit Starting at index point m

r/Q (Ω/m) – Cavity Shunt Impedance

L (m) – Cavity Active Length

U (J) – Cavity Stored Energy

f_0 (Hz) – Cavity Resonant Frequency

N - Data set sample size for pulsed measurement

m - Data Sample Set Index When the Incident Power is Removed From the Cavity

k - Data Sample Set Index When the Incident Power is Applied to the Cavity

Δt - Data sample interval.

T - Period of the pulsed waveform (Typically 60 Hz or less)

E (V/m) - Cavity Gradient

$E_{(emit),(trans),(fpwr)}$ (V/m) - Cavity accelerating gradient as indicated by subscript

Ports - number of RFports on the cavity, includes beam pipes, HOM couplers, etc.

Derivation of Performance Parameters:

$$P_{incident} = P_{im} C_i$$

$$P_{reflected} = P_{rm} C_r$$

$$P_{transmitted} = P_{tm} C_t$$

$$P_{\text{hom}\,a} = P_{ha} C_a$$

$$P_{\text{hom}\,b} = P_{hb} C_b$$

$$|\Gamma| = \sqrt{P_{reflected} / P_{incident}}$$

$$\beta = \frac{1+|\Gamma|}{1-|\Gamma|} \quad \text{(Overcoupled Cavity)}$$

$$Q_L = 2\pi f_0 \tau$$

CEBAF Cryomodule testing RF Performance Characterization

Emitted Power Based Measurements

$$U = \sum_{j=1}^{Ports}\left(\sum_{i=m}^{N}\left(\left(P_{emit}\right)_j\right)_i * \Delta t\right)$$

Where $\left(\mathrm{P_{emit}}\right)_j$ is the power emitted from the j^{th} port on the cavity.

Assuming that $\{Q_0,\ Q_{extX}, \text{etc.}\} >> Q_L$ or $\mathrm{P_{LOSS}}, \mathrm{P_{tranX}} << P_{emit}$

$$U \cong \sum_{i=m}^{N}(P_{emit})_i * \Delta t$$

$$E_{(emit)} = \sqrt{2\pi F * U * \frac{r/Q}{L}}$$

$$\Gamma = C_\beta \sqrt{P_{reflected} / P_{incident}}$$

$$\beta = \frac{1+\Gamma}{1-\Gamma} \quad \text{Note: } \beta >> 1 \text{ for strongly over coupled cavities}$$

For a perfectly tuned cavity:

$$E = \sqrt{\frac{4\beta}{(1+\beta)} * P_{incident} * Q_L * \frac{r/Q}{L}}$$

Assuming that $\beta >> 1$ and that the cavity is perfectly tuned.

$$E_{(fpwr)} \cong \sqrt{4P_{incident} * Q_L * \frac{r/Q}{L}}$$

$$Q_{tran} = \frac{2\pi f_0 * U}{P_{transmitted}}$$

$$Q_{\mathrm{hom}a} = \frac{2\pi f_0 * U}{P_{\mathrm{hom}a}}$$

$$Q_{\mathrm{hom}b} = \frac{2\pi f_0 * U}{P_{\mathrm{hom}b}}$$

$$E_{(trans)} = \sqrt{Q_{ext2} * P_{transmitted} * \frac{(r/Q)}{L}}$$

Assumes known value of Q_{ext2} which is typically based on an emitted power measurement.

CEBAF Cryomodule testing RF Performance Characterization

Q0 Measurements

CW measurements where $P_{dissipated}$ is the average dissipated power measured calimetricly.

$$Q_0 = \frac{E^2}{P_{dissipated}} * \frac{L}{r/Q} = \frac{2\pi f_0 * U}{P_{dissipated}}$$

For pulsed operation the gradient is not constant throughout the measurement. In this case the field probe transmitted power is recorded as a function of time with at a sample interval Δt; the gradient can be calculated using the transmitted power method; and Q0 is calculated as:

$$Qo = \frac{\frac{1}{T}\sum_{i=k}^{N} E_{(trans)i}^2 * \Delta t}{P_{disapated}} * \frac{L}{r/Q}$$

Where $P_{dissipated}$ is the average dissipated power measured calimetrically, and T is the period of the pulses. It should be noted that the numerator in the above equation is used to account for the non-square pulse shape. Values of Q_0 calculated using this method will be different for different gradient pulse shapes or CW operations. If CW values are desired, it is best to make such measurements with pulse widths that are much greater than the cavity fill times.

To measure the dissipated power calimetrically one isolates the cryomodule from the helium supply and return lines and records the rate of rise of the pressure under three conditions. These are static heat load with RF and resistive heaters on; static plus a known resistive heat load applied to the bath; and static plus a unknown RF heat load due to the cavity losses. The dissipated power is then calculated using the following.

$$P_{DISSIPATED} = \left(\frac{\left(\frac{dP}{dt}\right)_{RF-ON} - \left(\frac{dP}{dt}\right)_{STATIC}}{\left(\frac{dP}{dt}\right)_{HEATER-ON} - \left(\frac{dP}{dt}\right)_{STATIC}} \right) P_{HEATER}$$

where $\left(\frac{dP}{dt}\right)$ is the rate of rise of the pressure under the different conditions.

Measurement Errors - Cryomodule:

Starting Parameters:

$P_{\min}$ – Sensitivity limit of power sensors used

δP_{cal} – Fractional uncertainty in absolute power measured

δC – Fractional uncertainty in cable calibrations

δP_{Lin} – Fractional uncertainty of the linearity of the power meter measurement

Δ – Error of a variable. The units are the same as the variable, i.e. ΔP_{tran} is the error in P_{tran} in Watts.

Parameter Uncertainties:

$$\Delta P_{im} = P_{im} \times \delta P_{cal} + P_{\min}$$

$$\Delta P_{rm} = P_{rm} \times \delta P_{cal} + P_{\min}$$

$$\Delta P_{tm} = P_{tm} \times \delta P_{cal} + P_{\min}$$

$$\Delta P_{ham} = P_{ham} \times \delta P_{cal} + P_{\min}$$

$$\Delta P_{hbm} = P_{hbm} \times \delta P_{cal} + P_{\min}$$

$$(\Delta P_{rm})_i = (P_{rm})_i \times \delta P_{cal} + mean(P_{\min}\Big|_{over\ 500\,pts}^{zero\ RF\ pwr})$$

$$\Delta P_{incident} = P_{incident}\sqrt{(\delta C)^2 + \left(\frac{\Delta P_{im}}{P_{im}}\right)^2}$$

$$\Delta P_{reflected} = P_{reflected}\sqrt{(\delta C)^2 + \left(\frac{\Delta P_{rm}}{P_{rm}}\right)^2}$$

$$\Delta P_{transmitted} = P_{transmitted}\sqrt{(\delta C)^2 + \left(\frac{\Delta P_{tm}}{P_{tm}}\right)^2}$$

$$\Delta P_{\text{hom}\,a} = P_{\text{hom}\,a}\sqrt{(\delta C)^2 + \left(\frac{\Delta P_{ham}}{P_{ham}}\right)^2}$$

$$\Delta P_{\text{hom}\,b} = P_{\text{hom}\,b}\sqrt{(\delta C)^2 + \left(\frac{\Delta P_{hbm}}{P_{hbm}}\right)^2}$$

$$(\Delta P_{emit})_i = (P_{reflected})_i\sqrt{(\delta C)^2 + \left(\frac{(\Delta P_{rm})_i}{(P_{rm})_i}\right)^2}$$

$$\Delta|\Gamma| = \frac{|\Gamma|}{2}\sqrt{\left(\frac{\Delta P_{reflected}}{P_{reflected}}\right)^2 + \left(\frac{\Delta P_{incident}}{P_{incident}}\right)^2}$$

Measurement Errors - Cryomodule Continued

$$\Delta U = U\sqrt{\Delta C_r^2 + \Delta P_{cal}^2} + (\Delta P_{emit})_m \Delta t + \tau \times P_N + \Delta t(N-m)C_r P_{\min}$$

$\tau \times P_N$ term from not integrating to ∞

$((P_{emit})_m \Delta t)$ Term is due to jitter for starting the integration

$\Delta t(N-m)C_r P_{\min}$ Term is due to power meter noise floor

$$\Delta E_{emit} = \frac{E_{emit}}{2}\frac{\Delta U}{U}$$

$$\Delta E_{fpwr} = \frac{E_{fpwr}}{2}\sqrt{\left(\frac{\Delta Q_L}{Q_L}\right)^2 + \left(\frac{\Delta P_{incident}}{P_{incident}}\right)^2}$$

$$\Delta Q_{extX} = Q_{extX}\sqrt{4 * \left(\frac{\Delta E_{emit}}{E_{emit}}\right)^2 + \left(\frac{\Delta P_{transX}}{P_{transX}}\right)^2}$$

$$\Delta E_{transX} = \frac{E_{trans}}{2}\sqrt{\left(\frac{\Delta Q_{transX}}{Q_{transX}}\right)^2 + \left(\frac{\Delta P_{transX}}{P_{transX}}\right)^2}$$

Where Q_{trans} and ΔQ_{trans} were entered values that were determined under different operating conditions and calibrations than the current measurement.

$$\Delta E_{trans} = \frac{E_{trans}}{2}\sqrt{\left(\frac{\Delta Q_{trans}}{Q_{trans}}\right)^2 + \left(\frac{\Delta P_{Lin} * P_{transX} + C_X * P_{\min}}{P_{trans}}\right)^2}$$

Where Q_{trans} and ΔQ_{trans} were determined under same operating conditions and calibrations than the current measurement.

$$\Delta Q_{0(fpwr)} = Q_{0(fpwr)}\sqrt{\left(\frac{2\Delta E_{fpwr}}{E_{fpwr}}\right)^2 + \left(\frac{\Delta P_{dissipated}}{P_{dissipated}}\right)^2}$$

$$\Delta Q_{0(trans)} = Q_{0(trans)}\sqrt{\left(\frac{2\Delta E_{trans}}{E_{trans}}\right)^2 + \left(\frac{\Delta P_{dissipated}}{P_{dissipated}}\right)^2}$$

$$\Delta \beta = \beta\sqrt{\left(\frac{\Delta|\Gamma|}{1+|\Gamma|}\right)^2 + \left(\frac{\Delta|\Gamma|}{1-|\Gamma|}\right)^2}$$

$$\Delta Q_L = Q_L \times \frac{\Delta \tau}{\tau} = Q_L \times \Delta P_{Lin}$$

CEBAF Vertical Pair Testing RF Performance Characterization

Decay Measurement Formulas

Starting Parameters:

$P_{fm}, P_{rm}, P_{tm}, P_{HOMAm}, P_{HOMBm}$ – Actual measured CW RF power (Watts), just prior to turning the RF OFF for the decay measurement

C_f, C_r, C_t, C_a, C_b – Cable calibration factors relating measured RF power to associated RF power at the cavity.

C_β – Over/under coupling factor -1 for under coupled, $+1$ for over coupled.

τ – Decay fit darameter (seconds) for the emitted (as measured at the reflected power signal) or the transmitted power signal as measured when the incident RFpower has been turned OFF.

f_0(Hz) – Cavity resonant frequency

Performance Parameters:

$$P_f = P_{fm}C_f$$
$$P_r = P_{rm}C_r$$
$$P_t = P_{tm}C_t$$
$$P_{HOMA} = P_{HOMAm}C_a$$
$$P_{HOMB} = P_{HOMBm}C_b$$
$$\Gamma = \sqrt{\frac{P_r}{P_f}}$$
$$\beta^* = \frac{1 + C_\beta \Gamma}{1 - C_\beta \Gamma} = \frac{\sqrt{P_f} + C_\beta \sqrt{P_r}}{\sqrt{P_f} - C_\beta \sqrt{P_r}}$$
$$Q_L = 2\pi f_0 \tau$$
$$P_{Disp} = P_f - P_r - P_t - P_{HOMA} - P_{HOMB}$$

Or in the general form

$$P_{Disp} = P_f - P_r - P_t - P_X$$

Where P_X is the power exiting all of the other ports.

Decay Measurement Formulas Continued

The following implicitly assumes that *Q0* and the external-*Q* of all of the RF ports are independent of the stored energy, i.e. linear, flat *Q0* , and constant coupling factor for gradients at or below that of the starting point of the decay measurement; that the RF frequency is exactly that of the cavity resonance; and for error purposes that all devices within the power measurement path are linear and constant with respect to frequency and amplitude, e.g. no VSWR mismatch.

$$\beta_2 = \frac{Q_0}{Q_2} = \frac{P_2}{P_{Disp}} = \frac{P_t}{P_{Disp}}$$

$$\beta_3 = \frac{Q_0}{Q_3} = \frac{P_3}{P_{Disp}} = \frac{P_{HOMA}}{P_{Disp}}$$

$$\beta_4 = \frac{Q_0}{Q_4} = \frac{P_4}{P_{Disp}} = \frac{P_{HOMB}}{P_{Disp}}$$

It can be shown that:

$$\beta_1 = \beta^*(1 + \beta_2 + \beta_3 + \beta_4) = \frac{\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)^2}{P_{Disp}}$$

$$Q_L = 2\pi f_0 \tau$$

$$Q_0 = (1 + \beta_1 + \beta_2 + \beta_4 + \beta_4)Q_L$$

Which one can show is equivalent to ($C_\beta = +1$ for over coupled):

$$Q_0 = 4\pi f_0 \tau \frac{P_f + C_\beta\sqrt{P_r P_f}}{P_f - P_r - P_t - P_{HOMA} - P_{HOMB}} = 4\pi f_0 \tau \frac{P_f + C_\beta\sqrt{P_r P_f}}{P_{Disp}}$$

$$E_{acc}(V/m) = \sqrt{Q_0 P_{Disp} \frac{(r/Q)}{L}} = \sqrt{4\pi f_o \tau\left(P_f + C_\beta\sqrt{P_r P_f}\right)\frac{(r/Q)}{L}}$$

$$U(Joules) = \frac{Q_0 P_{Disp}}{2\pi f_0} = 2\tau\left(P_f + C_\beta\sqrt{P_r P_f}\right)$$

$$Q^* = \frac{Q_L}{1 + \beta^*} = \pi f_0 \tau\left(1 - \frac{C_\beta\sqrt{P_r}}{\sqrt{P_f}}\right)$$

$$Q_1 = \frac{Q_0}{\beta_1} = 4\pi f_0 \tau \frac{\sqrt{P_f}}{\sqrt{P_f} + C_\beta\sqrt{P_r}}$$

$$Q_2 = \frac{Q_0}{\beta_2} = \frac{Q_0 P_{Disp}}{P_2} = 4\pi f_0 \tau \frac{P_f + C_\beta\sqrt{P_r P_f}}{P_t}$$

$$Q_3 = \frac{Q_0}{\beta_3} = \frac{Q_0 P_{Disp}}{P_3} = 4\pi f_0 \tau \frac{P_f + C_\beta\sqrt{P_r P_f}}{P_{HOMA}}$$

$$Q_4 = \frac{Q_0}{\beta_4} = \frac{Q_0 P_{Disp}}{P_4} = 4\pi f_0 \tau \frac{P_f + C_\beta\sqrt{P_r P_f}}{P_{HOMB}}$$

CW Formulas

Starting Parameters:

$P_{fm}, P_{rm}, P_{tm}, P_{ha}, P_{hb}$ – Actual Measured CW RF Power (Watts), just prior to turning the RF OFF for the decay measurement

C_f, C_r, C_t, C_a, C_b – Cable Calibration Factors relating measured RF power to associated RF power at the cavity.

C_β – Over/Under coupling factor -1 for under coupled, $+1$ for over coupled.

τ – Decay fit darameter (seconds) for the emitted (as measured at the reflected power signal) or the transmitted power signal as measured when the incident RFpower has been turned OFF.

Q_2 – Transmission Probe External Q as determined from a previous Decay measurement

f_0(Hz) – Cavity Resonant Frequency

Derivation of Performance Parameters:

$$P_f = P_{fm} C_f$$

$$P_r = P_{rm} C_r$$

$$P_t = P_{tm} C_t$$

$$P_{HOMA} = P_{HOMAm} C_a$$

$$P_{HOMB} = P_{HOMBm} C_b$$

$$\Gamma = \sqrt{\frac{P_r}{P_f}}$$

$$Define\ C_\beta = -1\ for\ under\ coupled\ and + 1\ for\ over\ coupled$$

$$\beta^* = \frac{1 + C_\beta \Gamma}{1 - C_\beta \Gamma} = \frac{1 + C_\beta \sqrt{\frac{P_r}{P_f}}}{1 - C_\beta \sqrt{\frac{P_r}{P_f}}} = \frac{\sqrt{P_f} + C_\beta \sqrt{P_r}}{\sqrt{P_f} - C_\beta \sqrt{P_r}}$$

$$Q_L = 2\pi f_0 \tau$$

$$P_{Disp} = P_f - P_r - P_t - P_{HOMA} - P_{HOMB}$$

or in the general form:

$$P_{Disp} = P_f - P_r - P_t - P_X$$

Where P_X is the power exiting all of the other ports.

CW Measurement Formulas Continued

$$E = \sqrt{Q_2 P_t \frac{(r/Q)}{L}}$$

$$Q_0 = \frac{E^2}{P_{Disp}} \frac{L}{(r/Q)} = \frac{Q_2 P_t}{P_{Disp}}$$

$$\beta_2 = \frac{Q_0}{Q_2} = \frac{P_2}{P_{Disp}} = \frac{P_t}{P_{Disp}}$$

$$\beta_3 = \frac{Q_0}{Q_3} = \frac{P_3}{P_{Disp}} = \frac{P_{HOMA}}{P_{Disp}}$$

$$\beta_4 = \frac{Q_0}{Q_4} = \frac{P_4}{P_{Disp}} = \frac{P_{HOMB}}{P_{Disp}}$$

$$\beta_1 = \beta^*(1 + \beta_2 + \beta_4 + \beta_4) = \frac{\left(\sqrt{P_f} + C_\beta \sqrt{P_r}\right)^2}{P_{Disp}}$$

$$Q^* = \frac{Q_2 P_t \left(P_f\right)}{\left(2P_f + 2C_\beta \sqrt{P_f P_r} + P_r\right)^2}$$

$$Q_L = \frac{Q_2 P_T}{2\left(P_f + C_\beta \sqrt{P_f P_r}\right)}$$

$$Q_1 = \frac{Q_0}{\beta_1} = \frac{Q_2 P_t}{\left(\sqrt{P_f} + C_\beta \sqrt{P_r}\right)^2}$$

$$Q_3 = \frac{Q_0}{\beta_3} = \frac{Q_2 P_t}{P_{HOMA}}$$

$$Q_4 = \frac{Q_0}{\beta_4} = \frac{Q_2 P_t}{P_{HOMB}}$$

$$U(Joules) = \frac{Q_2 P_t}{2\pi f_0}$$

Measurement Errors - Decay Measurement:

Starting Parameters:

$P_{fm}, P_{rm}, P_{tm}, P_{ha}, P_{hb}$ - Actual Measured CW RF power meter reading (Watts), just prior to turning the RF off for the decay measurement.

$P_{\min}$ - Sensitivity limit of power sensor used.

δP_{cal} - Factional uncertainty in absolute power measured. This includes uncertainties such as power meter absolute error of the reference power meter, non-linearity of the individual power meters during the calibration process as well as during the measurement process, errors introduced due to standing waves in the measurement circuit. Also included are errors introduced due to the frequency dependent directional coupler errors because to varying load impedances on the output of the high power directional coupler.

δP_{Lin} Fractional uncertainty in the linearity of the power meter calibration

δC - Fractional uncertainty in cable calibrations.

Δ - Error of a variable. The units are the same as the variable, i.e. ΔP_{tran} is the error in P_{tran} in Watts.

Parameter Uncertainties:

$$\Delta P_{fm} = P_{fm} \times \delta P_{cal} + P_{min}$$
$$\Delta P_{rm} = P_{rm} \times \delta P_{cal} + P_{min}$$
$$\Delta P_{tm} = P_{tm} \times \delta P_{cal} + P_{min}$$
$$\Delta P_{tLinm} = P_{tm} \times \delta P_{Lin} + P_{min}$$
$$\Delta P_{ham} = P_{ham} \times \delta P_{cal} + P_{min}$$
$$\Delta P_{hbm} = P_{hbm} \times \delta P_{cal} + P_{min}$$

$$\Delta P_f = \Delta P_{fm} C_f$$
$$\Delta P_r = \Delta P_{rm} C_r$$
$$\Delta P_t = \Delta P_{tm} C_t$$
$$\Delta P_{HOMA} = \Delta P_{ham} C_a$$
$$\Delta P_{HOMB} = \Delta P_{hbm} C_b$$

$$\Delta P_{Disp} = \sqrt{\left(\Delta P_f^2 + \Delta P_r^2 + \Delta P_t^2 + \Delta P_{HOMA}^2 + \Delta P_{HOMB}^2\right)}$$

$$\Delta E = \frac{E}{2}\sqrt{\left(\frac{\left(2P_f + C_\beta\sqrt{P_f P_r}\right)}{2\left(P_f + C_\beta\sqrt{P_r P_f}\right)}\frac{\Delta P_f}{P_f}\right)^2 + \left(\frac{\sqrt{P_r}}{2\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}\frac{\Delta P_r}{P_r}\right)^2 + \left(\frac{\Delta\tau}{\tau}\right)^2}$$

Measurement Errors Continued - Decay Measurement:

Error in Tau due to mismatch looking back at the source. [1]

$$\frac{d\tau}{\tau} \cong \frac{\sqrt{2}\beta^*(VSWR-1)}{(\beta^*+1)(VSWR+1)}$$

Where VSWR is the VSWR of the system looking from the cavity back to the source. Note that this value is also used in the CW measurements.

[1] J.P.Holzbauer, Yu.Pischalnikov, D.A.Sergatskov, W.Schappert, S.Smith "Systematic uncertainties in RF-based measurement of superconducting cavity quality factors" NIM-A, Volume 830, 11 September 2016, Pages 22-29

$$\Delta Q_0 = Q_0\sqrt{\begin{gathered}\left(\left(\frac{\left(2P_f + C_\beta\sqrt{P_f P_r}\right)}{2\left(P_f + C_\beta\sqrt{P_r P_f}\right)} - \frac{P_f}{P_{Disp}}\right)\frac{\Delta P_f}{P_f}\right)^2 + \left(\left(\frac{\left(C_\beta\sqrt{P_r P_f}\right)}{2\left(P_f + C_\beta\sqrt{P_r P_f}\right)} + \frac{P_r}{P_{Disp}}\right)\frac{\Delta P_r}{P_r}\right)^2 + \\ \left(\frac{\Delta\tau}{\tau}\right)^2 + \left(\frac{P_t}{P_{Disp}}\frac{\Delta P_t}{P_t}\right)^2 + \sum\left(\frac{P_{HOMx}}{P_{Disp}}\frac{\Delta P_{HOMx}}{P_{HOMx}}\right)^2\end{gathered}}$$

$$\Delta\beta^* = \beta^*\sqrt{2}\frac{\sqrt{P_f P_r}}{\left(P_f - P_r\right)}\frac{\Delta P_{r,f}}{P_{r,f}}$$

$$\Delta Q^* = Q^*\sqrt{\left(\frac{\sqrt{P_r}}{2\left(\sqrt{P_f} - C_\beta\sqrt{P_r}\right)}\frac{\Delta P_f}{P_f}\right)^2 + \left(\frac{P_r}{2\left(\sqrt{P_f P_r} - C_\beta P_r\right)}\frac{\Delta P_r}{P_r}\right)^2 + \left(\frac{\Delta\tau}{\tau}\right)^2}$$

$$\Delta Q_1 = Q_1\sqrt{\left(\frac{\Delta P_f}{2P_f}\right)^2 + \left(\frac{\sqrt{P_r}}{2\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}\frac{\Delta P_r}{P_r}\right)^2 + \left(\frac{\Delta\tau}{\tau}\right)^2}$$

$$\Delta Q_2 = Q_2\sqrt{\left(\frac{\left(2\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}{2\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}\frac{\Delta P_f}{P_f}\right)^2 + \left(\frac{\sqrt{P_r}}{2\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}\frac{\Delta P_r}{P_r}\right)^2 + \left(\frac{\Delta P_t}{P_t}\right)^2 + \left(\frac{\Delta\tau}{\tau}\right)^2}$$

$$\Delta Q_3 = Q_3\sqrt{\left(\frac{\left(2\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}{2\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}\frac{\Delta P_f}{P_f}\right)^2 + \left(\frac{\sqrt{P_r}}{2\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}\frac{\Delta P_r}{P_r}\right)^2 + \left(\frac{\Delta P_{HOMA}}{P_{tHOMA}}\right)^2 + \left(\frac{\Delta\tau}{\tau}\right)^2}$$

$$\Delta Q_4 = Q_4 \sqrt{\left(\frac{\left(2\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}{2\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}\frac{\Delta P_f}{P_f}\right)^2 + \left(\frac{\sqrt{P_r}}{2\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)}\frac{\Delta P_r}{P_r}\right)^2 + \left(\frac{\Delta P_{HOMB}}{P_{tHOMB}}\right)^2 + \left(\frac{\Delta\tau}{\tau}\right)^2}$$

$$\Delta\beta_1 = \beta_1 \sqrt{\left(\left(\frac{\sqrt{P_f}}{\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)} - \frac{\left(P_f + C_\beta\sqrt{P_r P_f}\right)}{P_{Disp}}\right)\frac{\Delta P_f}{P_f}\right)^2 + \left(\left(\frac{C_\beta\sqrt{P_r}}{\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)} + \frac{P_r}{P_{Disp}}\right)\frac{\Delta P_r}{P_r}\right)^2 + \sum\left(\frac{P_{t,HOMx}}{P_{Disp}}\frac{\Delta P_{t,HOMx}}{P_{t,HOMx}}\right)^2}$$

Measurement Errors - CW Measurement:

$P_{fm}, P_{rm}, P_{tm}, P_{ha}, P_{hb}$ Actual Measured CW RF power meter reading (Watts).

$P_{\min}$ Sensitivity limit of power sensor used.

$P_L = C_f P_{fm} - C_r P_{rm} - C_t P_{tm} - \sum C_{HOMx} P_{HOMxm}$ is the power dissipated in the cavity walls.

$\frac{\Delta C_f}{C_f}$ Factional uncertainty in absolute power measured.

$\frac{\Delta P_{fm}}{P_{fm}}$ Fractional uncertainty in the linearity of the power meter calibration

Δ Error of a variable. The units are the same as the variable, i.e. ΔP_{tran} is the error in P_{tran} in Watts.

ΔQ_2 Uncertainty in Q_2 as determined from a decay measurement.

C'_β Coupling factor used for decay measurement

P'_f, P'_f Measured incident and reflected power at the cavity input that was used for the decay measurement which was used to calculate Q_2

Parameter Uncertainties:

$$\Delta P_{fm} = P_{fm} \times \delta P_{cal} + P_{min}$$
$$\Delta P_{rm} = P_{rm} \times \delta P_{cal} + P_{min}$$
$$\Delta P_{tm} = P_{tm} \times \delta P_{cal} + P_{min}$$
$$\Delta P_{tLinm} = P_{tm} \times \delta P_{Lin} + P_{min}$$
$$\Delta P_{ham} = P_{ham} \times \delta P_{cal} + P_{min}$$
$$\Delta P_{hbm} = P_{hbm} \times \delta P_{cal} + P_{min}$$

$$\Delta P_f = \Delta P_{fm} C_f$$
$$\Delta P_r = \Delta P_{rm} C_r$$
$$\Delta P_t = \Delta P_{tm} C_t$$
$$\Delta P_{tLin} = \Delta P_{tLinm} C_t$$
$$\Delta P_{HOMA} = \Delta P_{ham} C_a$$
$$\Delta P_{HOMB} = \Delta P_{hbm} C_b$$

$$\Delta P_{Disp} = \sqrt{\left(\Delta P_f^2 + \Delta P_r^2 + \Delta P_t^2 + \Delta P_{HOMA}^2 + \Delta P_{HOMB}^2\right)}$$

$$\Delta E = \frac{E}{2}\sqrt{\left(\frac{\Delta Q_2}{Q_2}\right)^2 - \left(\frac{\Delta C_t}{C_t}\right)^2 + \left(\frac{\Delta P_{tm}}{P_{tm}}\right)^2}$$

$$\Delta Q_0 = Q_0 \sqrt{\begin{array}{l}\left(\left[\frac{2P_f' + C_\beta'\sqrt{P_f'P_r'}}{2\left(P_f' + C_\beta'\sqrt{P_f'P_r'}\right)} - \frac{P_f}{P_L}\right]\frac{\Delta C_f}{C_f}\right)^2 + \left(\left[\frac{C_\beta'\sqrt{P_f'P_r'}}{2\left(P_f' + C_\beta'\sqrt{P_f'P_r'}\right)} + \frac{P_r}{P_L}\right]\frac{\Delta C_r}{C_r}\right)^2 + \\ \left(\frac{P_t'}{P_L'}\frac{\Delta C_t}{C_t}\right)^2 + \sum\left(\frac{P_{HOMx}'}{P_L'}\frac{\Delta C_{HOMx}}{C_{HOMx}}\right)^2 + \left(\frac{\Delta\tau'}{\tau'}\right)^2 + \left(\left[\frac{P_f}{(P_L)}\right]\frac{\Delta P_{fm}}{P_{fm}}\right)^2 + \\ \left(\left[\frac{P_r}{(P_L)}\right]\frac{\Delta P_{rm}}{P_{rm}}\right)^2 + \left(\left[1 + \frac{P_t}{(P_L)}\right]\frac{\Delta P_{tm}}{P_{tm}}\right)^2 + \sum\left(\frac{P_{HOMx}}{P_L}\frac{\Delta P_{HOMxm}}{P_{HOMxm}}\right)^2\end{array}}$$

Where the primed values are those used to determine Q_{FP} (Q_2), $\frac{\Delta P_{tm}}{P_{tm}}, \frac{\Delta P_{rm}}{P_{rm}}, and\ \frac{\Delta P_{fm}}{P_{fm}}$ are the linearity errors associated with the instruments (typically 2%), and $\frac{\Delta C_f}{C_f}, \frac{\Delta C_r}{C_r}, and\ \frac{\Delta C_t}{C_t}$ are the absolute calibration errors for the power measurements, (typically 7%).

Measurement Errors - CW Measurement Cont.:

$$\Delta U = U\sqrt{\left(\frac{\Delta Q_2}{Q_2}\right)^2 - \left(\frac{\Delta C_t}{C_t}\right)^2 + \left(\frac{\Delta P_{tLin}}{P_t}\right)^2}$$

$$\Delta Q_3 = Q_3\sqrt{\left(\frac{\Delta Q_2}{Q_2}\right)^2 - \left(\frac{\Delta C_t}{C_t}\right)^2 + \left(\frac{\Delta P_{tLin}}{P_t}\right)^2 + \left(\frac{\Delta P_{HOMA}}{P_{HOMA}}\right)^2}$$

$$\Delta Q_4 = Q_4\sqrt{\left(\frac{\Delta Q_2}{Q_2}\right)^2 - \left(\frac{\Delta C_t}{C_t}\right)^2 + \left(\frac{\Delta P_{tLin}}{P_t}\right)^2 + \left(\frac{\Delta P_{HOMB}}{P_{HOMB}}\right)^2}$$

$$\Delta U = U\sqrt{\left(\frac{\Delta Q_2}{Q_2}\right)^2 - \left(\frac{\Delta C_t}{C_t}\right)^2 + \left(\frac{\Delta P_{tLin}}{P_t}\right)^2}$$

$$\Delta Q^* = Q^*\sqrt{\begin{gathered}\left(\left[1 - \frac{\left(2P_f + C_\beta\sqrt{P_f P_r}\right)}{\left(P_f + C_\beta\sqrt{P_f P_r} + P_r\right)}\right]\frac{\Delta P_f}{P_f}\right)^2 + \\ \left(\frac{\left(P_r + C_\beta\sqrt{P_f P_r}\right)}{\left(P_f + C_\beta\sqrt{P_f P_r} + P_r\right)}\frac{\Delta P_r}{P_r}\right)^2 + \left(\frac{\Delta Q_2}{Q_2}\right)^2 - \left(\frac{\Delta C_t}{C_t}\right)^2 + \left(\frac{\Delta P_{tLin}}{P_t}\right)^2\end{gathered}}$$

$$\Delta\beta^* = \beta^*\sqrt{2}\frac{\sqrt{P_f P_r}}{\left(P_f - P_r\right)}\frac{\Delta P_{r,f}}{P_{r,f}}$$

$$\Delta\beta_1 = \beta_1\sqrt{\begin{gathered}\left(\left(\frac{\sqrt{P_f}}{\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)} - \frac{\left(P_f + C_\beta\sqrt{P_r P_f}\right)}{P_{Disp}}\right)\frac{\Delta P_f}{P_f}\right)^2 + \left(\left(\frac{C_\beta\sqrt{P_r}}{\left(\sqrt{P_f} + C_\beta\sqrt{P_r}\right)} + \frac{P_r}{P_{Disp}}\right)\frac{\Delta P_r}{P_r}\right)^2 + \\ \sum\left(\frac{P_{t,HOMx}}{P_{Disp}}\frac{\Delta P_{t,HOMx}}{P_{t,HOMx}}\right)^2\end{gathered}}$$

$$\Delta\beta_2 = \beta_2\sqrt{\frac{\left(\Delta P_f^2 + \Delta P_r^2 + \Delta P_{HOMA}^2 + \Delta P_{HOMB}^2\right)}{P_{Disp}^2} + \left(\frac{\left(P_{Disp} - P_t\right)}{P_{Disp}}\frac{\Delta P_t}{P_t}\right)^2}$$

$$\Delta\beta_3 = \beta_3\sqrt{\frac{\left(\Delta P_f^2 + \Delta P_r^2 + \Delta P_t^2 + \Delta P_{HOMB}^2\right)}{P_{Disp}^2} + \left(\frac{\left(P_{Disp} - P_{HOMA}\right)}{P_{Disp}}\frac{\Delta P_{HOMA}}{P_{HOMA}}\right)^2}$$

$$\Delta\beta_4 = \beta_4\sqrt{\frac{\left(\Delta P_f^2 + \Delta P_r^2 + \Delta P_t^2 + \Delta P_{HOMA}^2\right)}{P_{Disp}^2} + \left(\frac{\left(P_{Disp} - P_{HOMB}\right)}{P_{Disp}}\frac{\Delta P_{HOMB}}{P_{HOMB}}\right)^2}$$