Low Level RF Systems

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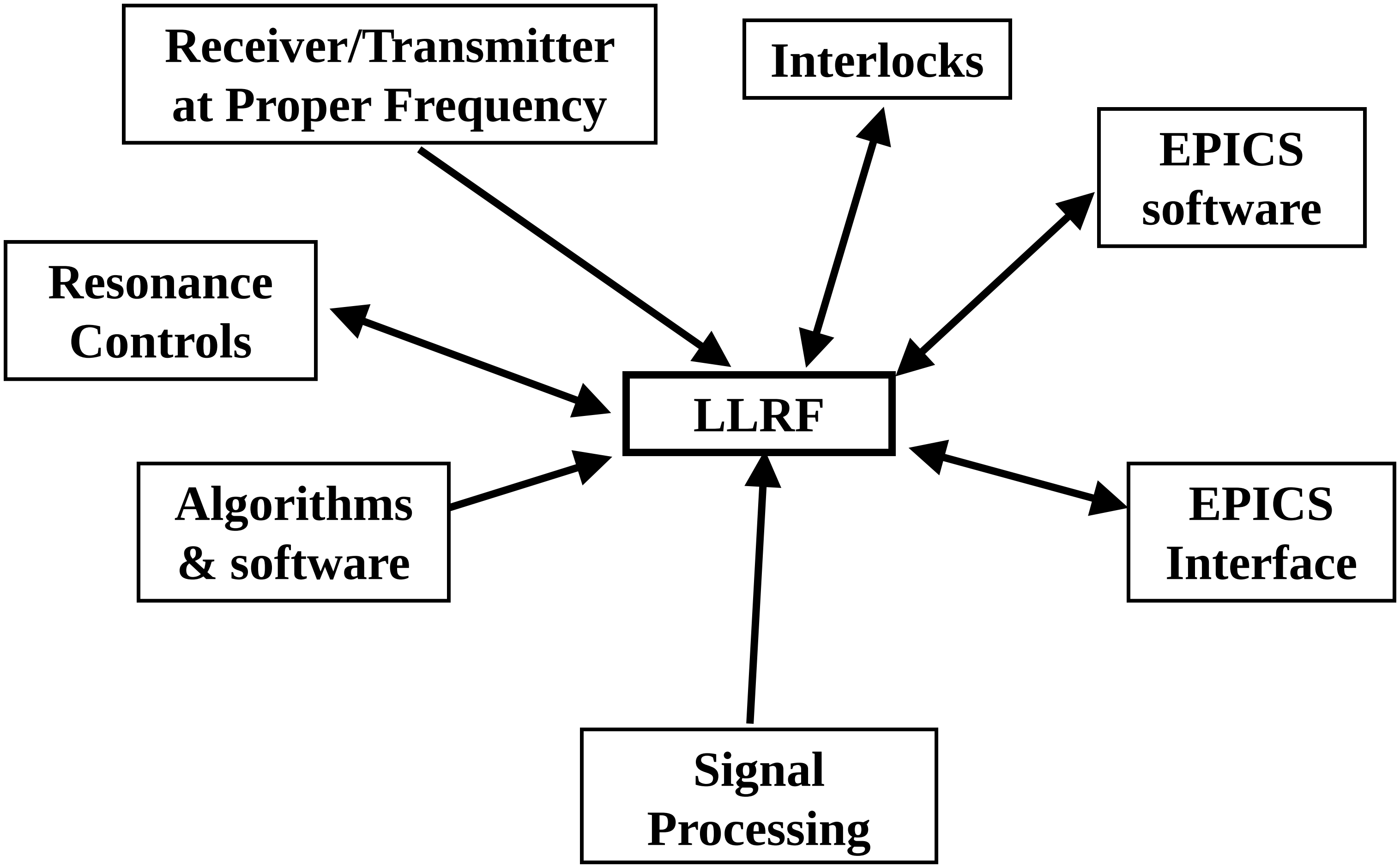
(Slides stolen from: Powers LLRF workshop 2011, Plawski LLRF workshop 2013, Power/Hovater LBL light source working group 2012, Powers, HOM workshop 2012.

LLRF the Center of the Universe ? ?



General Equation for RF Power and Phase

$$P_{RF} = \frac{(\beta+1)L}{4\beta\ R_C}\left\{\left(E + I_0 R_C \cos\psi_B\right)^2 + \left(E\tan\psi + I_0 R_C \sin\psi_B\right)^2\right\}$$

$$\psi_{Kly} = \arctan\left(\frac{2Q_L \dfrac{\delta f}{f_0} E + I_0 R_C \sin\psi_B}{E + I_0 R_C \cos\psi_B}\right)$$

where	P_{Kly}	= klystron power {W)
	V_C	= cavity accelerating voltage {V}
	R_C	= $(r/Q)Q_L$ {W/m} = Coupling impedance
	L	= Cavity accelerating length (m)
	b	= cavity coupling
	$\tan\psi$	= Tangent of cavity detuning angle $\simeq -2Q_L \frac{\delta f}{f_o}$
	ψ_{Kly}	= phase of the RF drive voltage
	I_R	= resultant beam current
	f_R	= resultant phase of beam with respect to accelerating RF field
	Q_L	= Loaded-Q of the Cavity
	δf	= frequency difference between cavity frequency, f_0, and the Generator Frequency

Cavity Gradient, RF Voltage and Phase

$$\overline{E} = \frac{1}{(1+iTan\psi)}\sqrt{\frac{4\beta\, Q_L\,(r/Q)}{Z_0(\beta+1)\,L}}\,\overline{V}_S - \frac{Q_L\,(r/Q)}{(1+iTan\psi)}\,\overline{I_0}$$

$$\overline{V_S} = \sqrt{\frac{(\beta+1)L}{Z_0 4\beta\, Q_L(r/Q)}}\left\{\left(E + I_0 Q_L(r/Q)\cos\psi_B\right) + i\left(2Q_L\frac{\delta f}{f_0}E + I_0 Q_L(r/Q)\sin\psi_B\right)\right\}$$

$$\psi_S = Tan^{-1}\left\{\frac{2Q_L\frac{\delta f}{f_0}E + I_0 Q_L(r/Q)\sin\psi_B}{E + I_0 Q_L(r/Q)\cos\psi_B}\right\} \qquad Tan\psi = 2Q_L\frac{\delta f}{f_0}$$

Where ψ is the cavity detune angle and β is the geometrical factor relating to the fundamental power coupler and is constant.

In terms of I and Q

$$\overline{V_{RF}} = (\boldsymbol{I} + \boldsymbol{iQ})$$

$$\boldsymbol{I} = \sqrt{\frac{Z_0(\beta+1)}{4\beta Q_L(r/Q)}}(E + I_0 Q_L(r/Q)cos\varphi_B)$$

$$\boldsymbol{Q} = \sqrt{\frac{Z_0(\beta+1)}{4\beta Q_L(r/Q)}}\left\{2Q_L\frac{\delta f}{f_0} + I_0 Q_L(r/Q)sin\varphi_B\right\}$$

Assumes that $\bar{E}$ is at phase equal to zero.

General Phase and Gradient Stability Requirements

- **Gradient and phase stability determined during beam physics sensitivity studies.**
- **Subject to be different from machine to machine.**
- **In general**
  - **Light Sources phase stability 0.03º to 0.01º rms (60 fs to 18 fs at 1500 MHz) (folks talk about 10 fs for synchronization of final beams to end stations.)**
  - **Other machines 0.1º to 0.5º is good enough.**
  - **Gradient stability 0.05% to 0.005% rms**
- **Temperature stabilized copper reference distributions systems good to about 100 fs to 500 fs.**
- **Fiber distributed laser based systems required for to achieve 10s of fs.**
- **For slow drifts remember one bad cable can ruin years of design and implementation.**

What is Unique About SRF Cavities

Normal Conducting

- Bandwidth of several 10s of kHz.
- Wall losses from a few kW to several hundred kW.
- Very little reflected power with no beam loading.
- Except in the highest beam loaded cases, beam loading changes forward power by about 20% or less.
- Resonance control is typically a water circuit.
- Microphonics effects minor.

Superconducting

- Bandwidth from 30 Hz to 10 kHz
- Wall losses 1 W to 300 W.
- All RF power reflected with no beam loading.
- Beam loading changes forward power by a factor of 4.
- Resonance control is typically a stepper motor and may include piezo devices.
- Microphonics can be significant especially for loaded-Qs above 5e6.

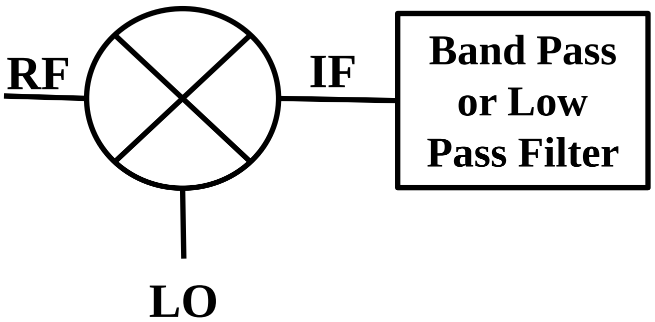
Some of the “Necessary” Features

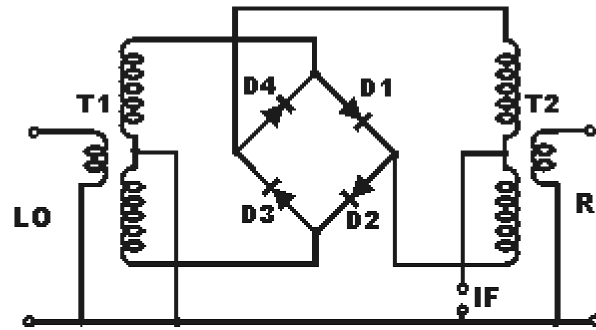
- Loop phase and amplitude control signals available in control room.
- Tuner control algorithm -- may need fast adaptive controls for pulsed machines or ERLs.
- Loop gains, bandwidths, etc. control available in the control room.
- Filter for rejection of the first π mode frequency below the fundamental frequency.
- First fault buffers.
- Interface to fast feedback control system.
- Quench detection
- Self Excited Loop for cavities with high loaded-Q
- One button turn on of cavities even if they are not properly tuned.
- Ability to monitor transients waveforms for critical control signals
- Output Clamp control which limits the drive power under all conditions

Other uses of LLRF

- **Drive and seed laser phase control.**
  - **Using optical detector along with a PZT and pico motor controls.**
  - **Lock laser fundamental frequency to sub-harmonic of cavity RF.**
  - **Switch to or augment phase feedback loop with a higher harmonic of laser frequency.**
  - **Check harmonic content, phase noise, etc. as an on line task.**
- **Receiver for beam based phase feedback.**
- **As part of a fast feedback system for energy stability.**
- **For commissioning the cryomodules and their tuners after installation into the machine.**

***Caution must be used when choosing frequency for optical and electron beam based detectors in order to avoid interference from high power RF systems.**





$$IF = \cos(w_1 t)\,\cos(w_2 t)$$

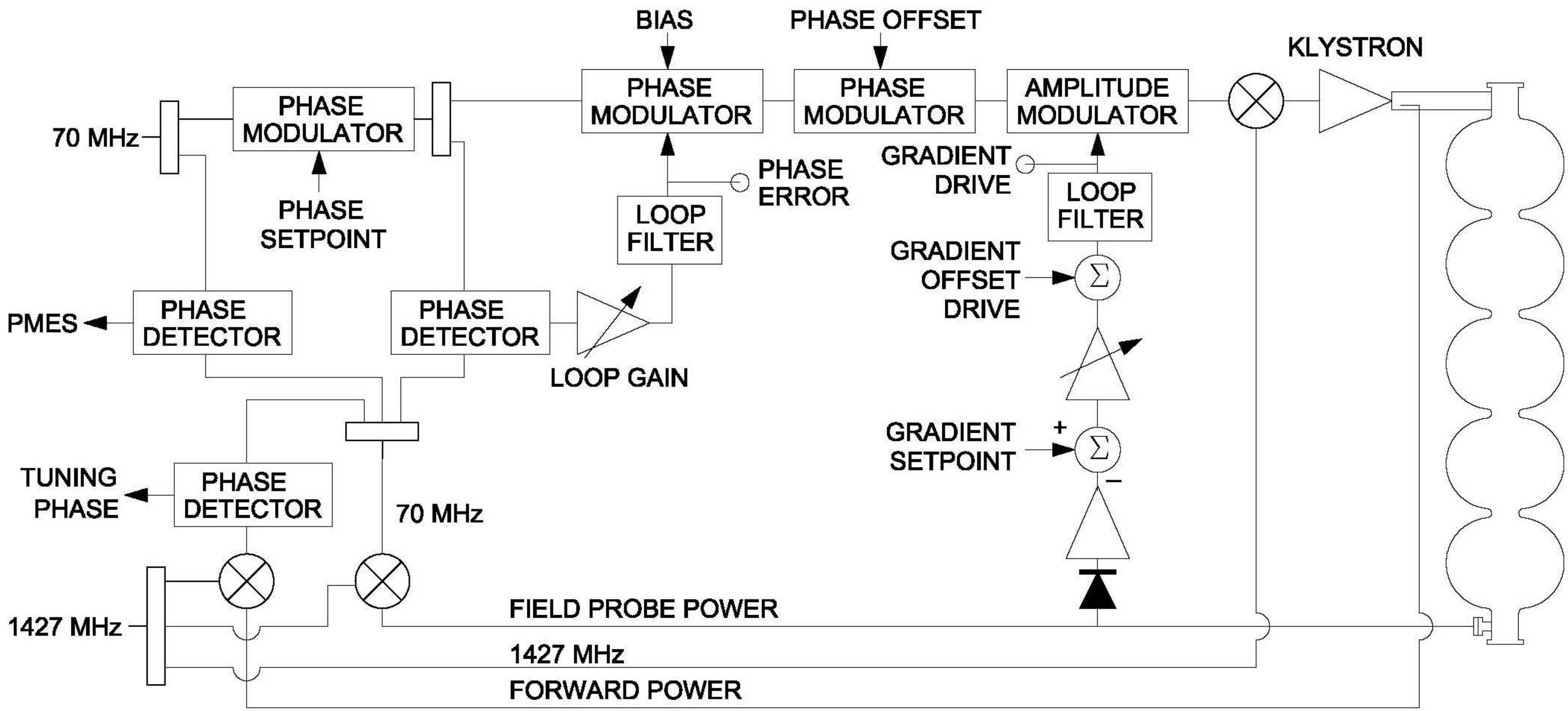
$$IF = A\cos(w_1 + w_2 t) \;+ A\cos(w_1 - w_2 t)$$

Reject with filter

$$IF = \cancel{A\cos(w_1 + w_2 t)} \;+ A\cos(w_1 - w_2 t)$$

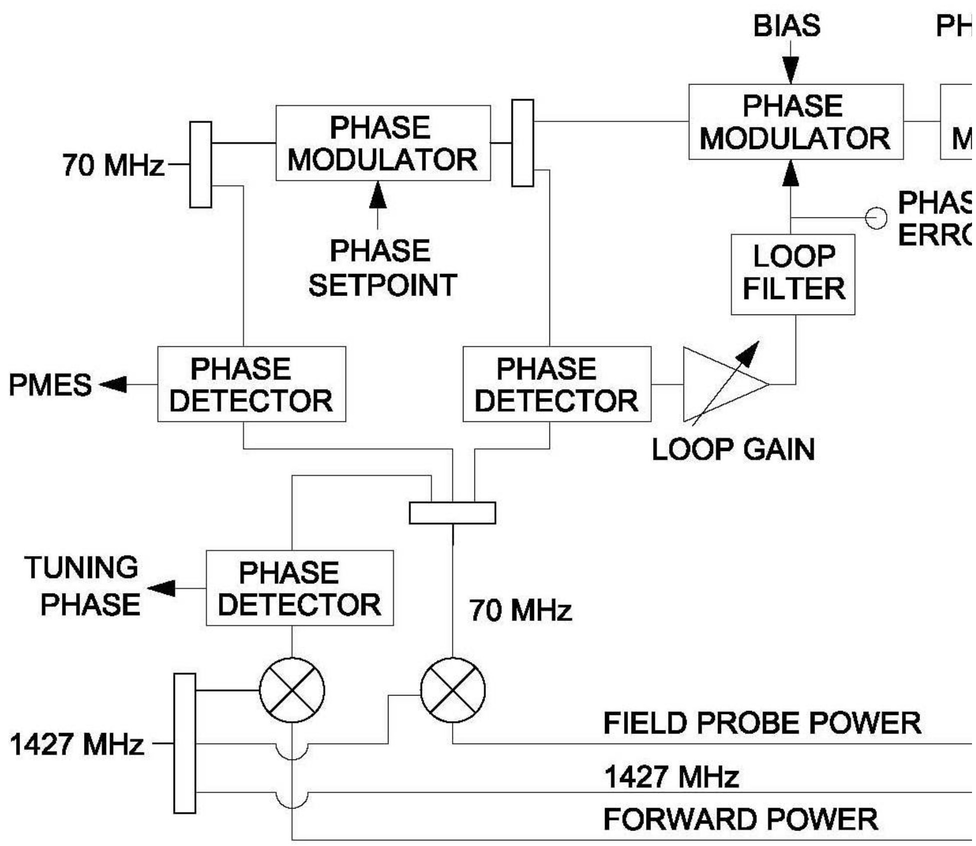
Where A is the conversion gain of the mixer

Analog Approach Phase and Amplitude



CEBAF field control chassis 1992 design

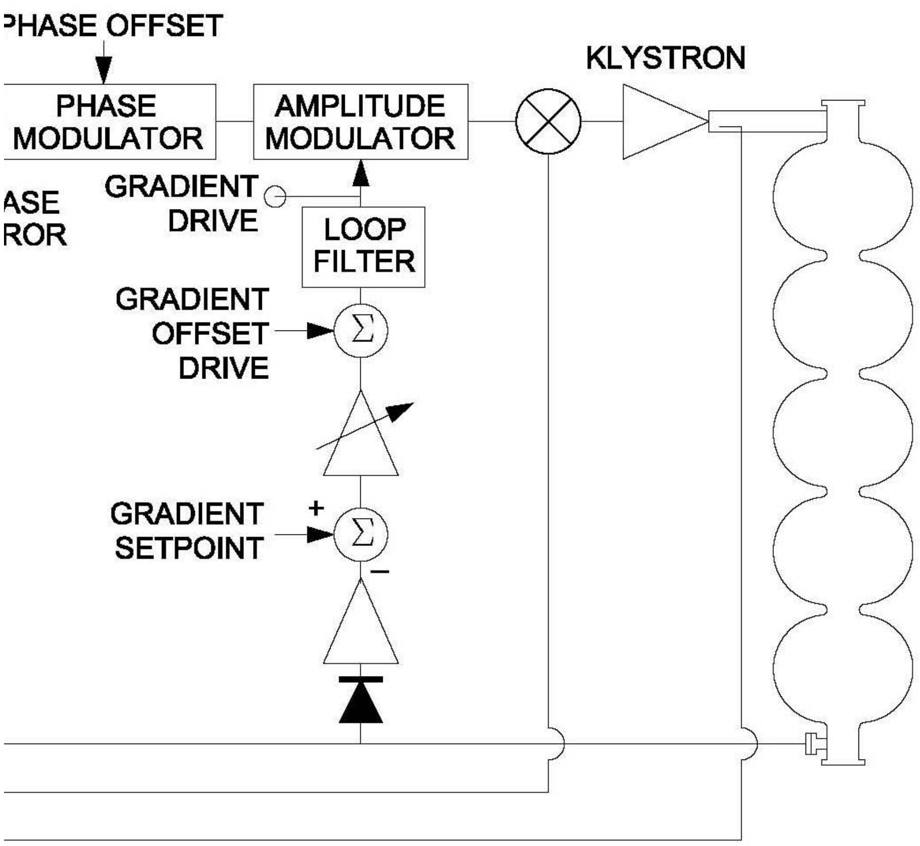
Analog Approach Phase and Amplitude



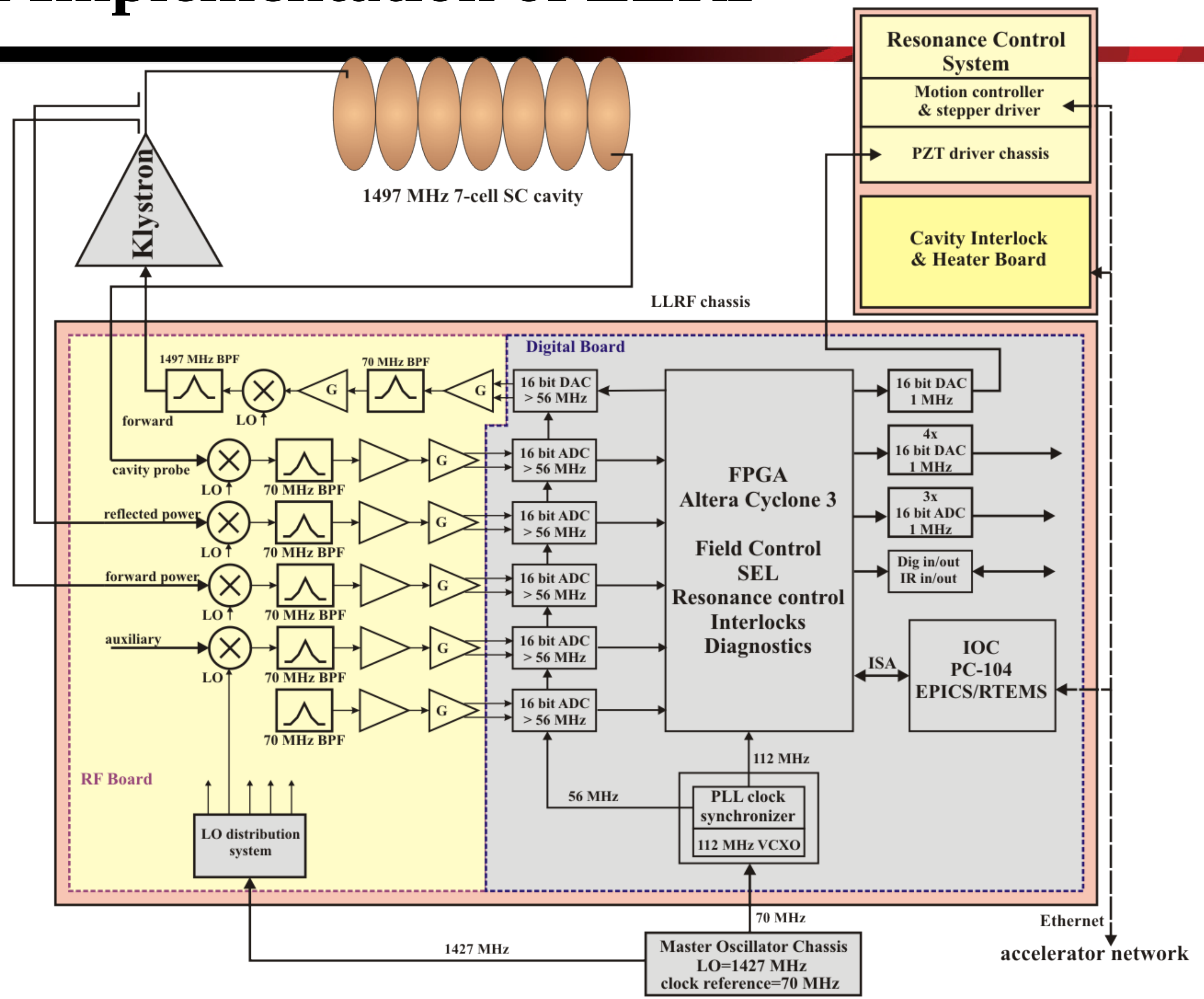
- Mixers are used to
- (a) down convert the RF signal to the IF frequency and
- (b) Generate a phase measurement between the 70 MHz reference and the cavity gradient.
- After applying an offset and gain an error signal is used to control a phase modulator.
- Note the value of the phase signal is amplitude (i.e. gradient) dependent

Analog Approach Phase and Amplitude

- The amplitude is measured with an ovenized Crystal detector.
- An error signal is used to drive the control of an amplitude modulator circuit
- The IF frequency signal which has been phase and amplitude modulated is unconverted by mixing it with a local oscillator signal.
- Note phase control does not work if the amplitude knob is set to zero.

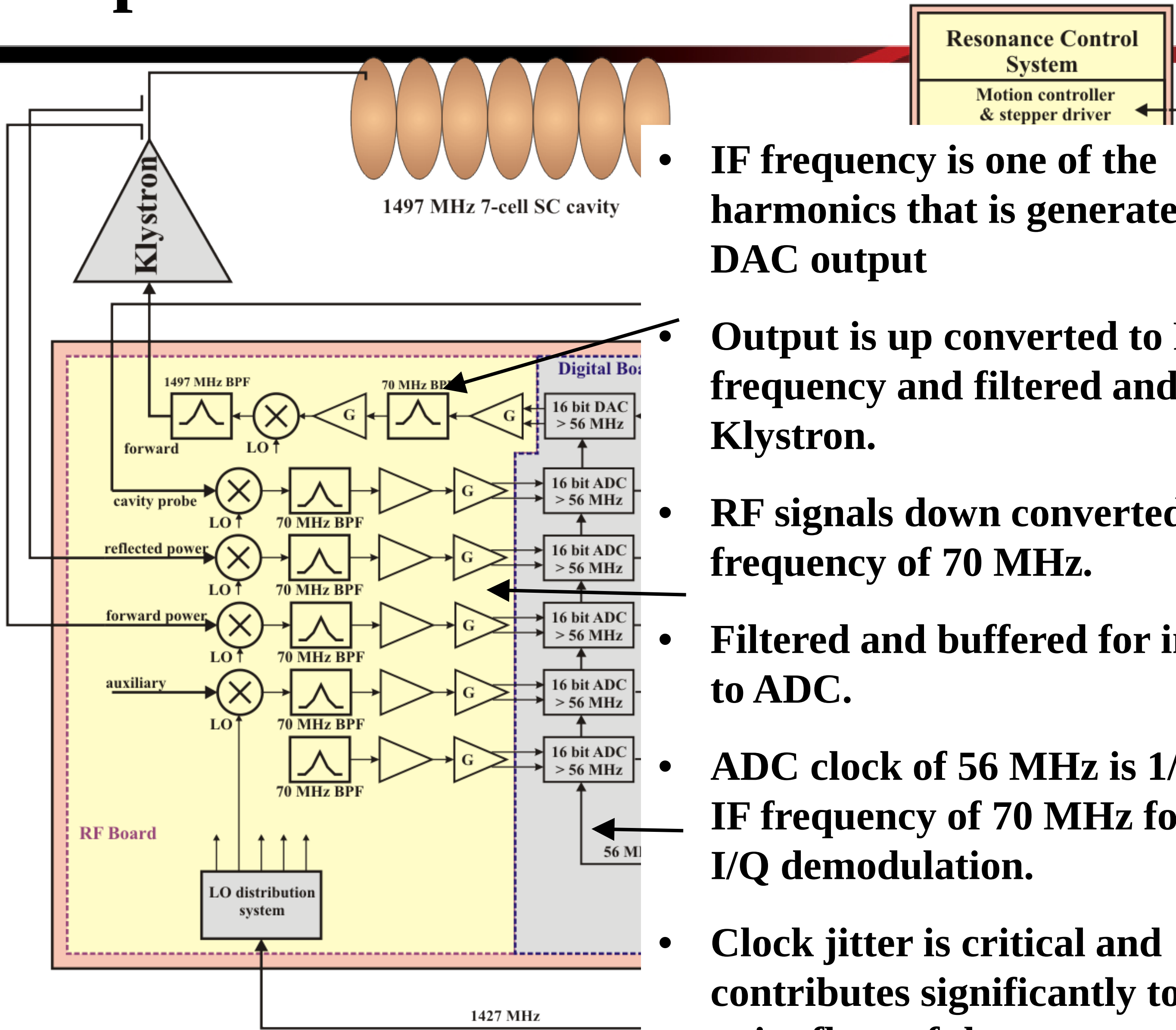


Digital Implementation of LLRF



Bachimanchi, et. al. LLRF 2011

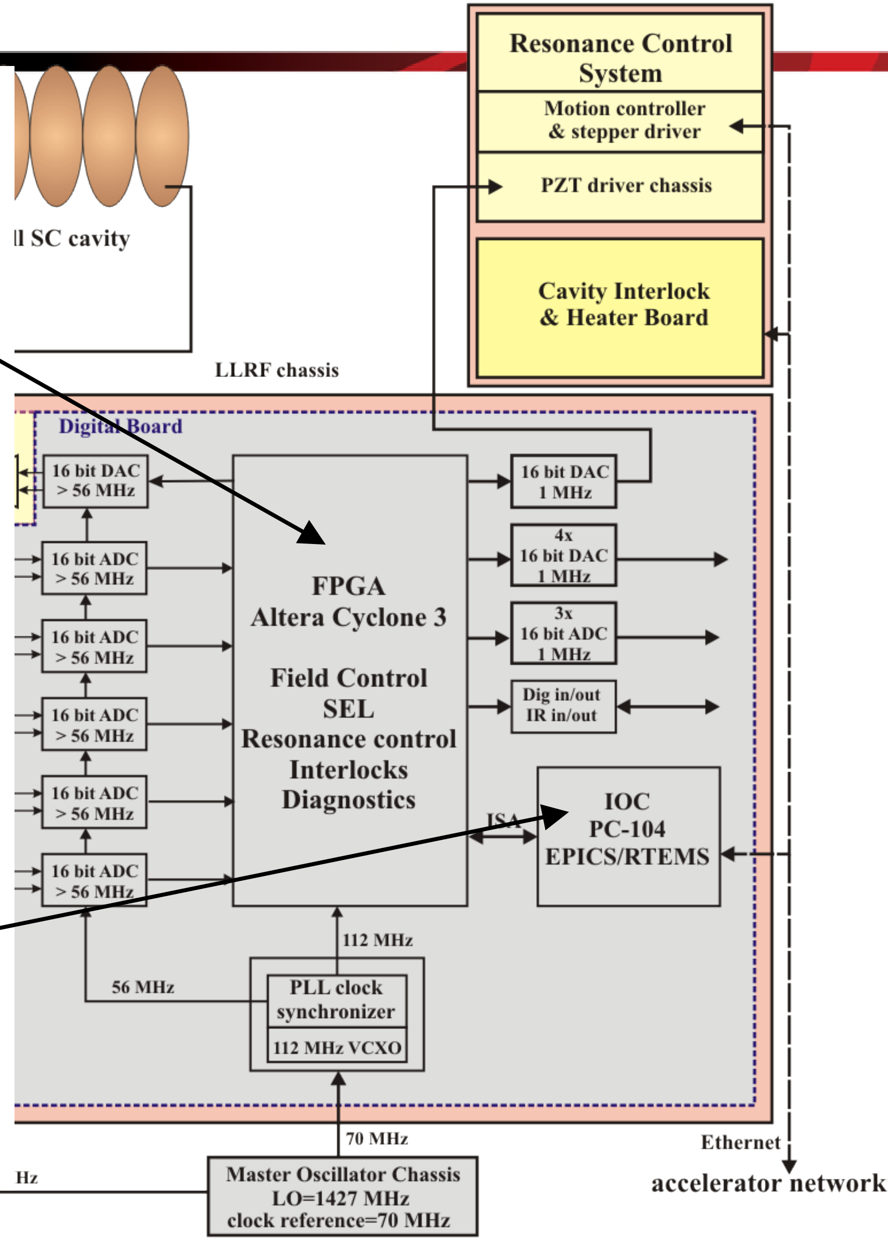
Digital Implementation of LLRF



- IF frequency is one of the harmonics that is generated by DAC output
- Output is up converted to RF frequency and filtered and sent to Klystron.
- RF signals down converted to IF frequency of 70 MHz.
- Filtered and buffered for inputs to ADC.
- ADC clock of 56 MHz is 1/1.25 of IF frequency of 70 MHz for Direct I/Q demodulation.
- Clock jitter is critical and contributes significantly to the noise floor of the system.

Digital Implementation of LLRF

- **FPGA used for signal processing. Can apply specific**
  - **Filters,**
  - **Gain control algorithms,**
  - **Feed Forward,**
  - **Adaptive feedback and**
  - **Adaptive feed forward**
  - **Waveform acquisition**
  - **First fault detection**
- **Imbedded IOC for communication to the control system and resonance control hardware**
- **Auxiliary I/O provided for interlocks and future improvements.**



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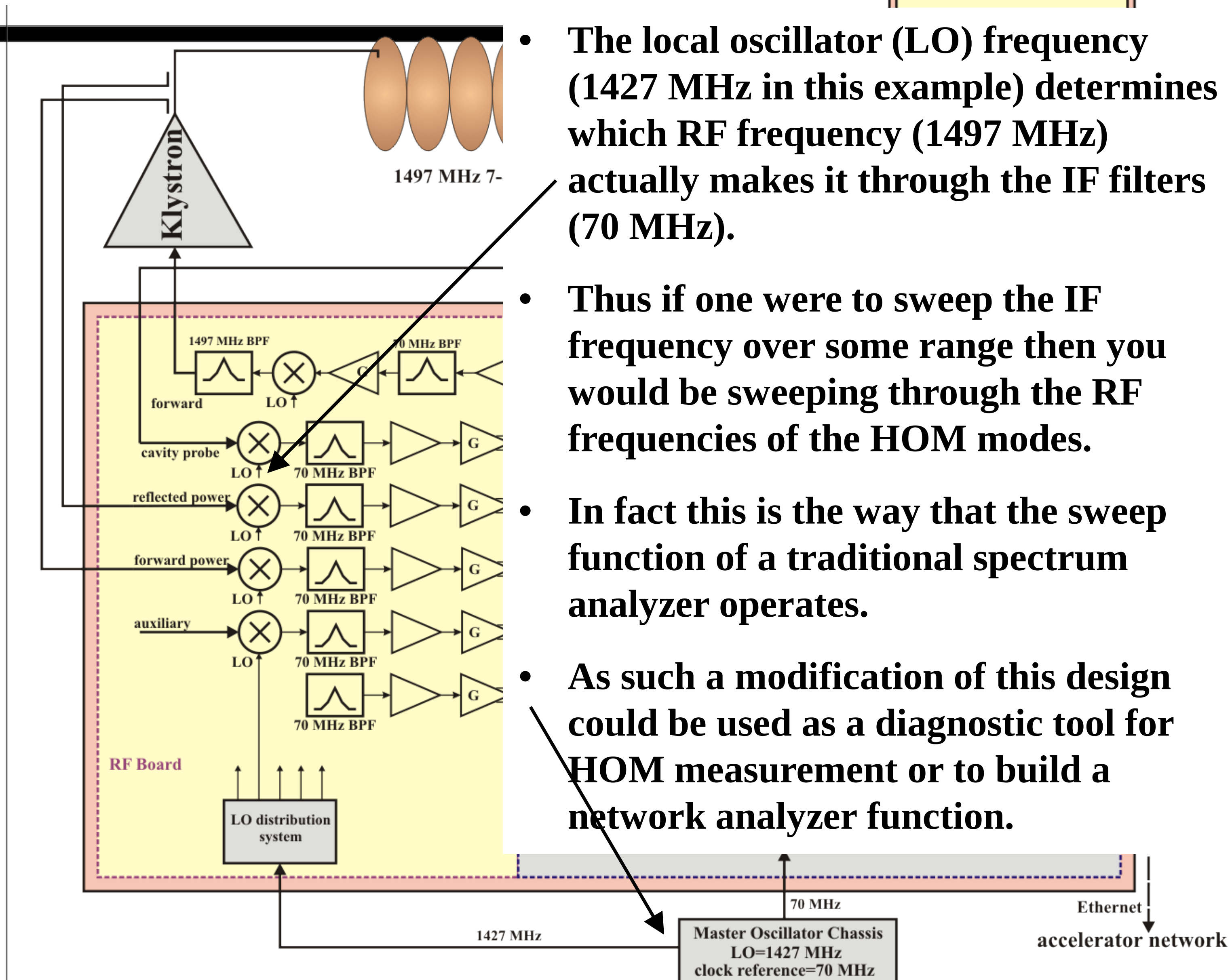
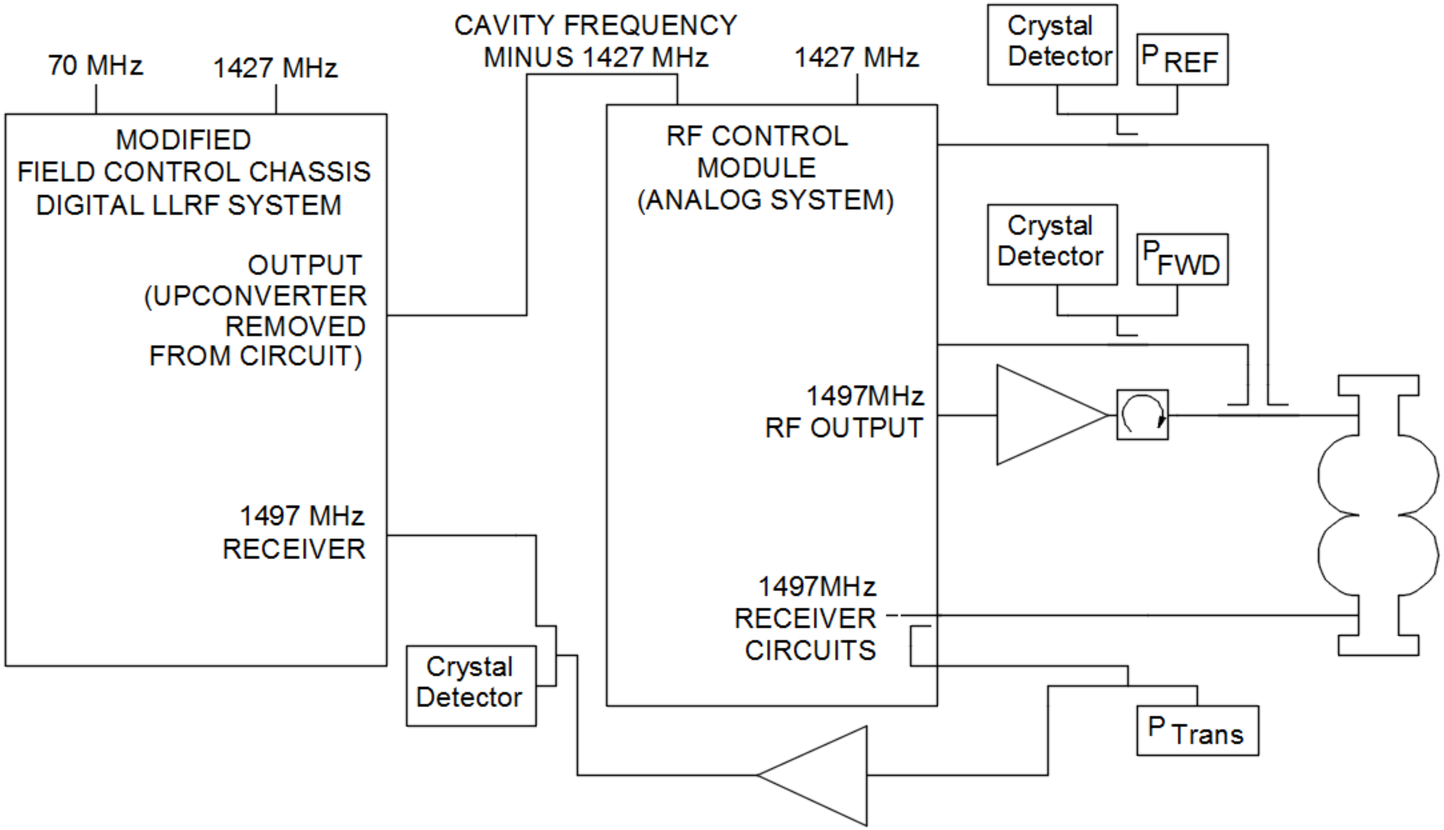


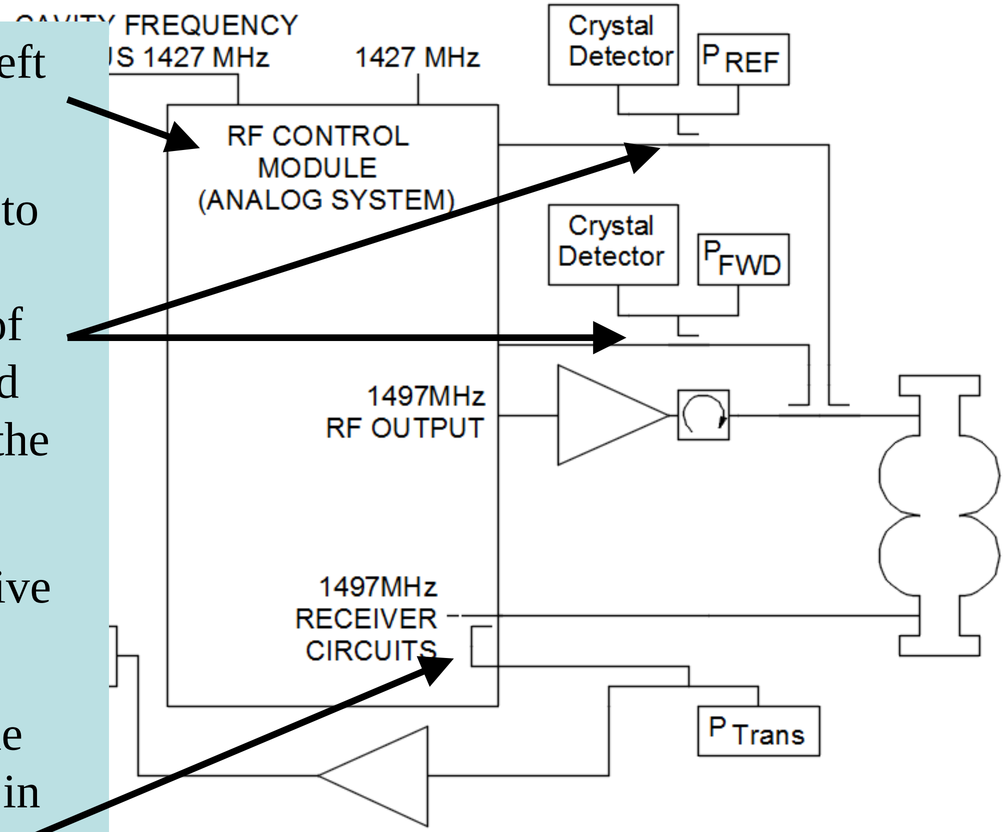
- The local oscillator (LO) frequency (1427 MHz in this example) determines which RF frequency (1497 MHz) actually makes it through the IF filters (70 MHz).
- Thus if one were to sweep the IF frequency over some range then you would be sweeping through the RF frequencies of the HOM modes.
- In fact this is the way that the sweep function of a traditional spectrum analyzer operates.
- As such a modification of this design could be used as a diagnostic tool for HOM measurement or to build a network analyzer function.

RF System Configuration for USPAS Cryomodule Test



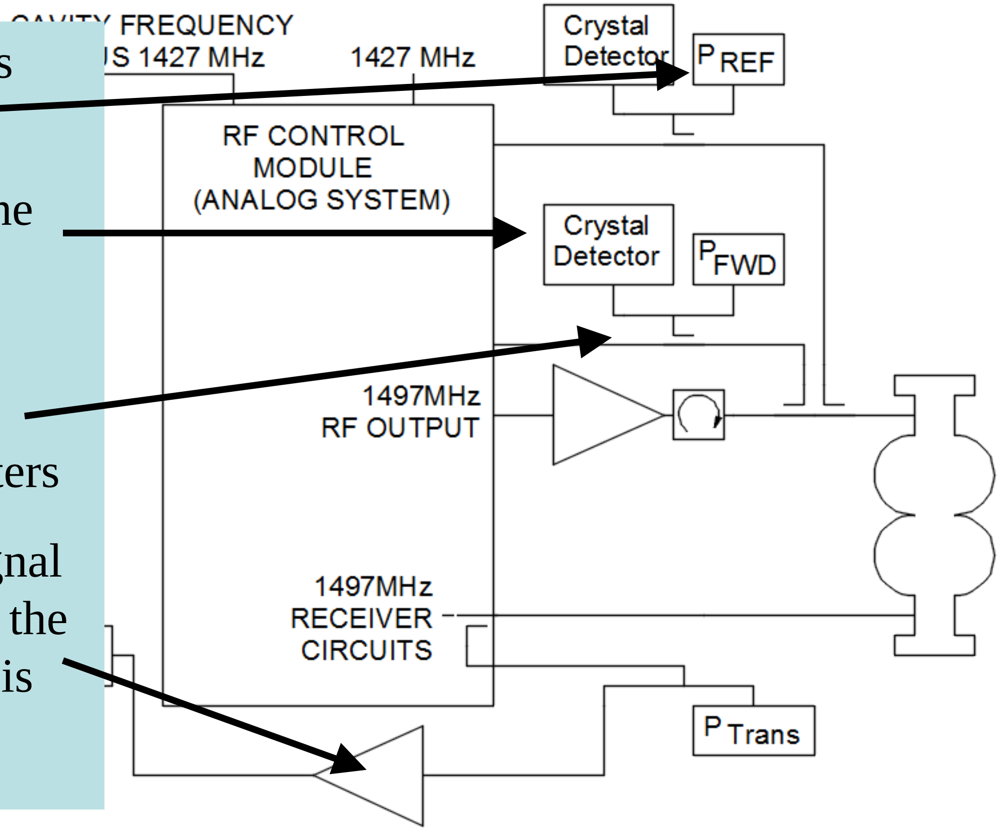
RF System Configuration for USPAS Cryomodule Test

- Installed Analog LLRF system is left in place including interlocks
- External directional couplers used to sample the forward and reflected power this introduces about 1 dB of additional losses in the forward and reflected power signals as seen in the RFCM
- Crystal detectors used to provide live waveforms of RF signals
- Transmitted coupler is built into the RFCM. Using it eliminates errors in calibration factors between the cavity probe signal and the RFCM.

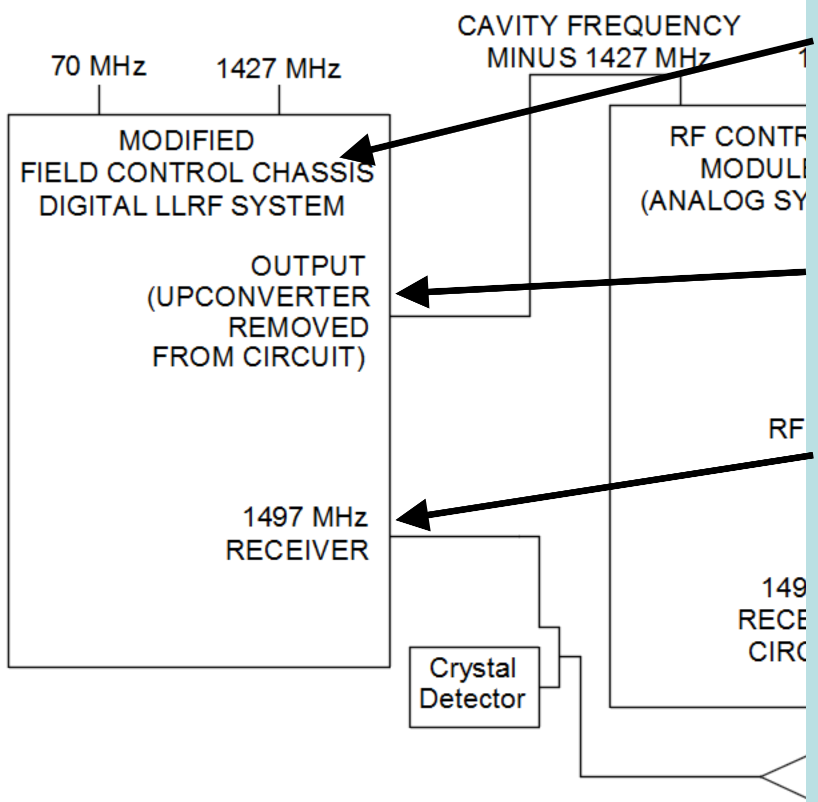


RF System Configuration for USPAS Cryomodule Test

- Boonton 4532 pulsed power meters used to capture RF waveforms.
- Crystal detectors used to provide the operator with “live” (uncalibrated) signals on an oscilloscope.
- Only passive linear circuits used between RF signals and power meters
- Amplifier used to provide extra signal to the probe crystal detector and to the receiver in the Field Control Chassis

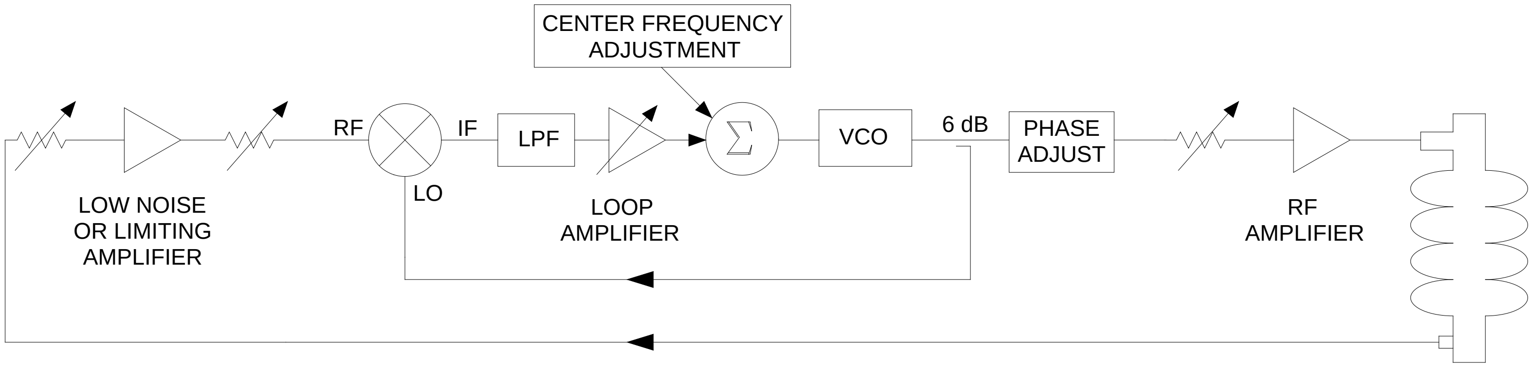


RF System Configuration for USPAS Cryomodule Test



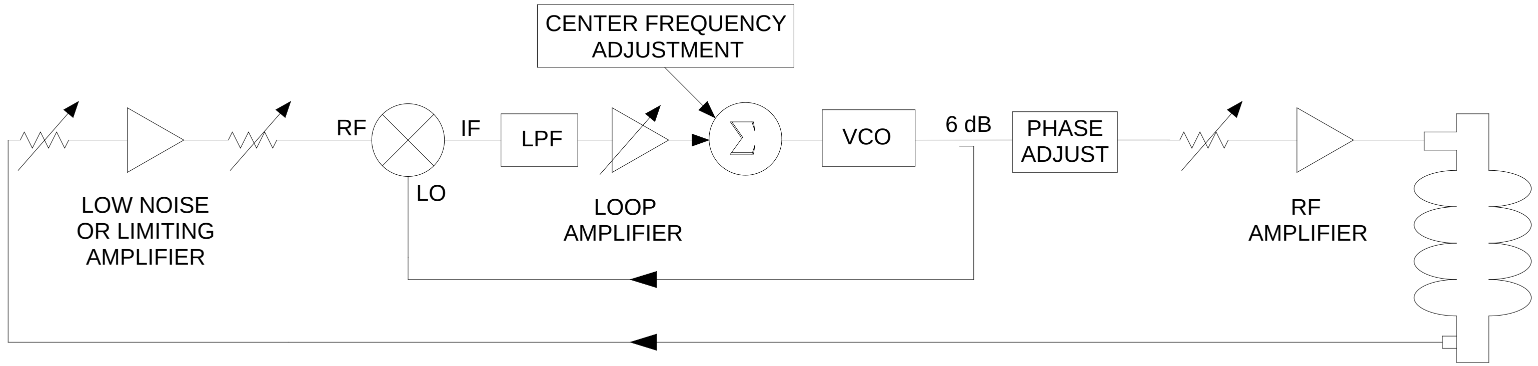
- Modified 12 GeV RF field control chassis used in order to control the RF frequency and pulsed operation.
- Normal output upconverter and drive circuit (nominal output is 1497 MHz) removed and replaced with a 70 MHz drive circuit.
- Standard input circuit at 1497 MHz retained.
- Three modes of operation uses for commissioning.
  - **Tone mode** which has an output at 1497 MHz with all control loops open.
  - **Self Excited Loop mode** (SEL) which is a frequency source that tracks the cavity.
  - **Pulsed mode** which is SEL mode with the ability to pulse the output signal.

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



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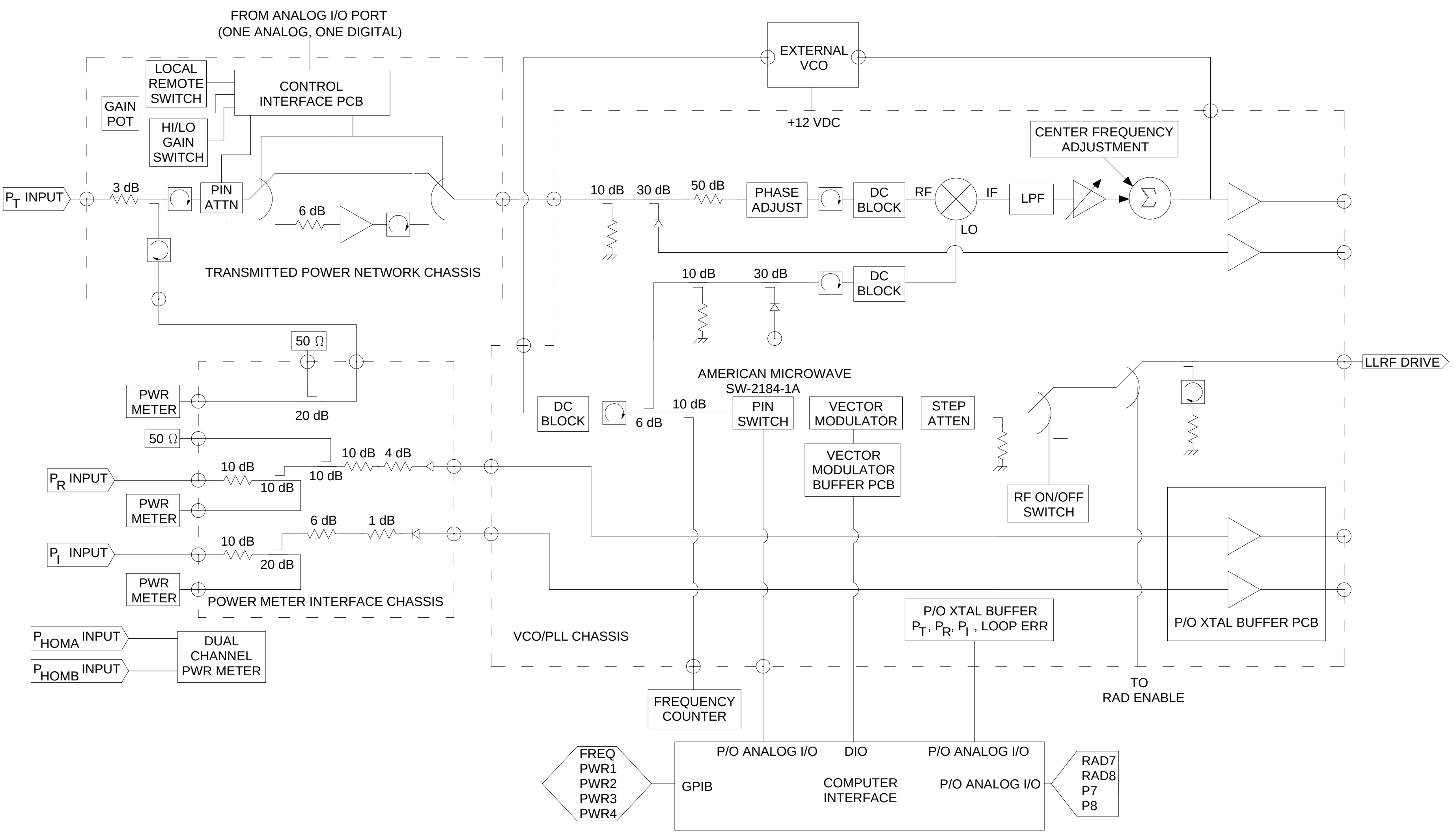
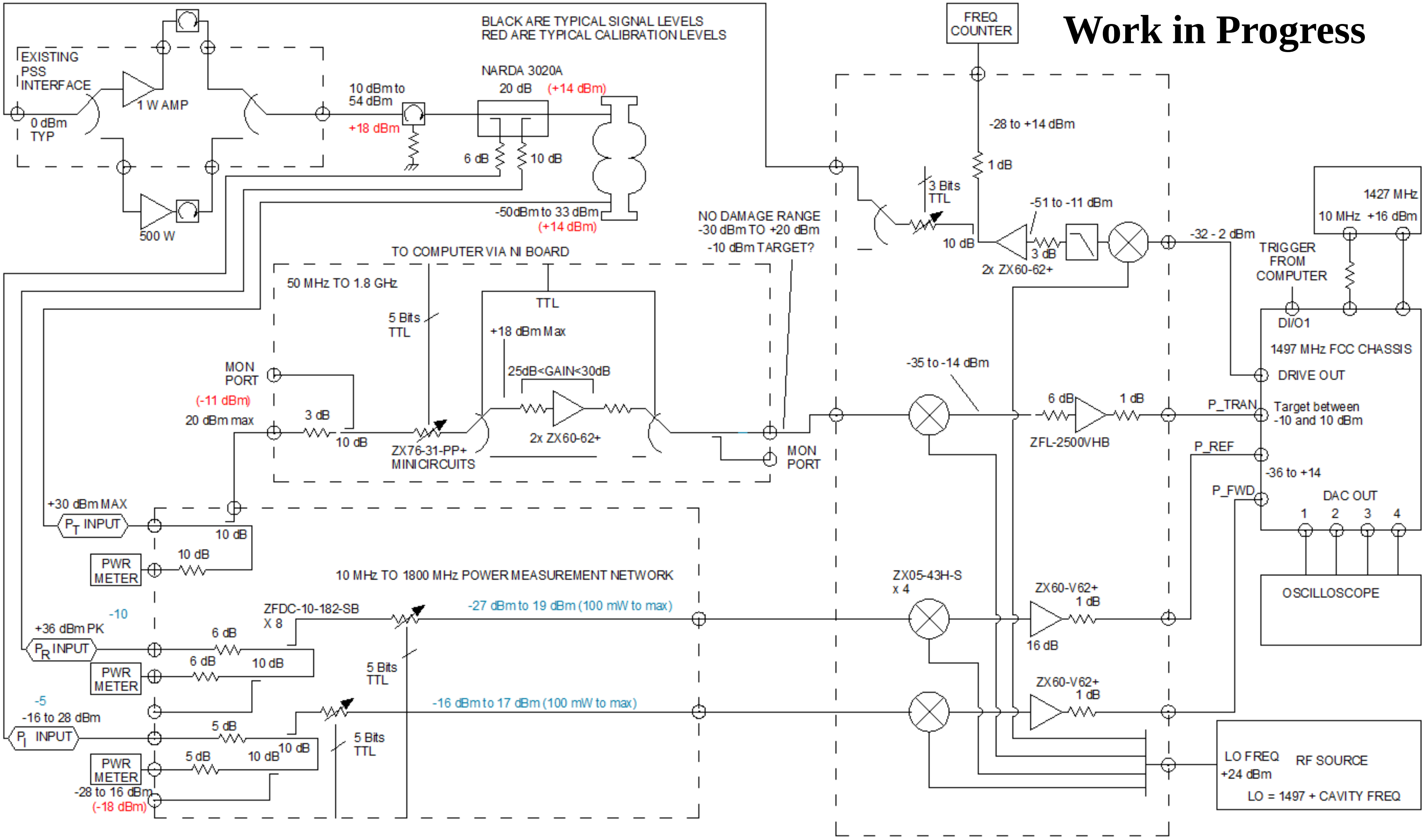
We are converting the production systems over to digital LLRF based systems.

Complete *VCO PLL* System Layout

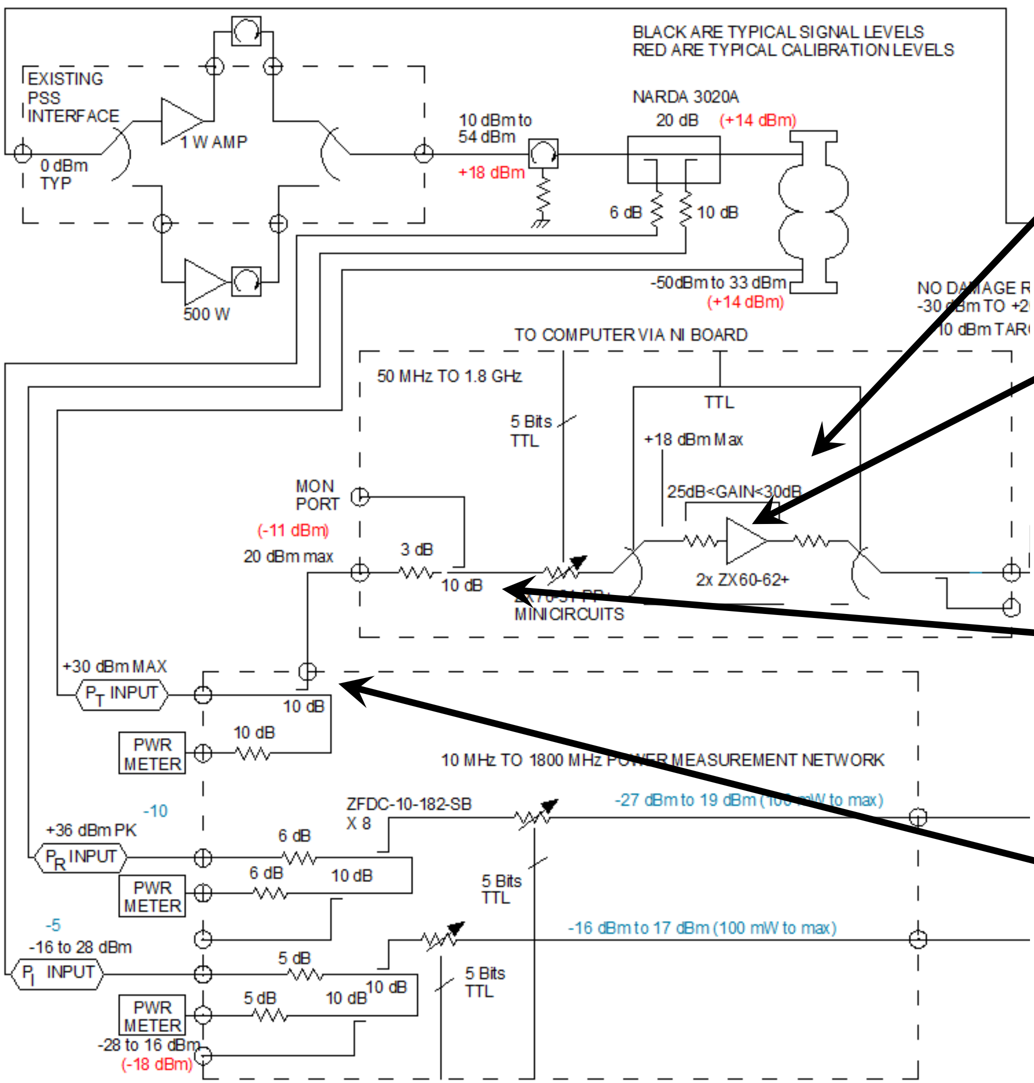


BROAD BAND DIGITAL LLRF BASED SYSTEM

Work in Progress

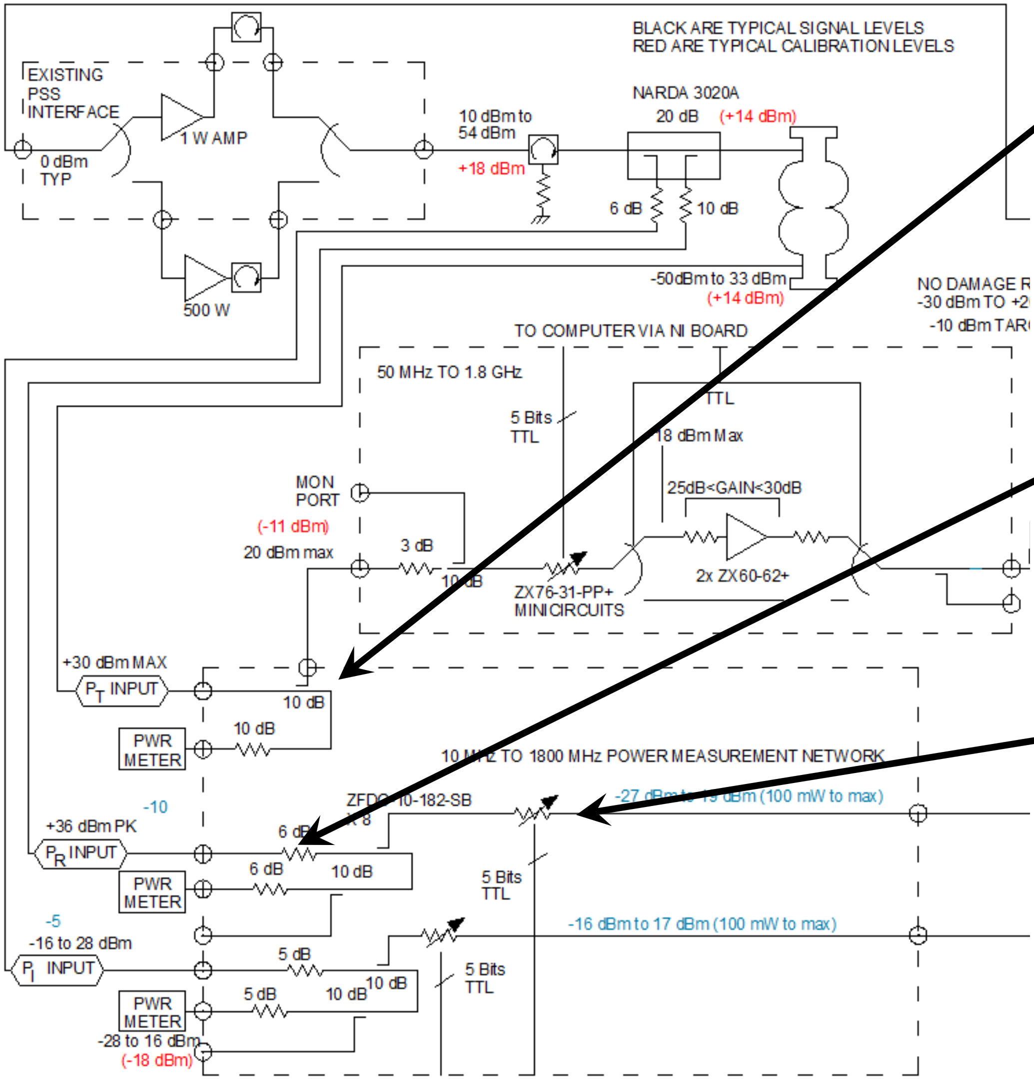


BROAD BAND DIGITAL LLRF BASED SYSTEM



- Switchable gain preamplifer on probe signal very similar to VCO system previously discussed.
- 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 missmatches present on the amplifier circuit from input circuit.

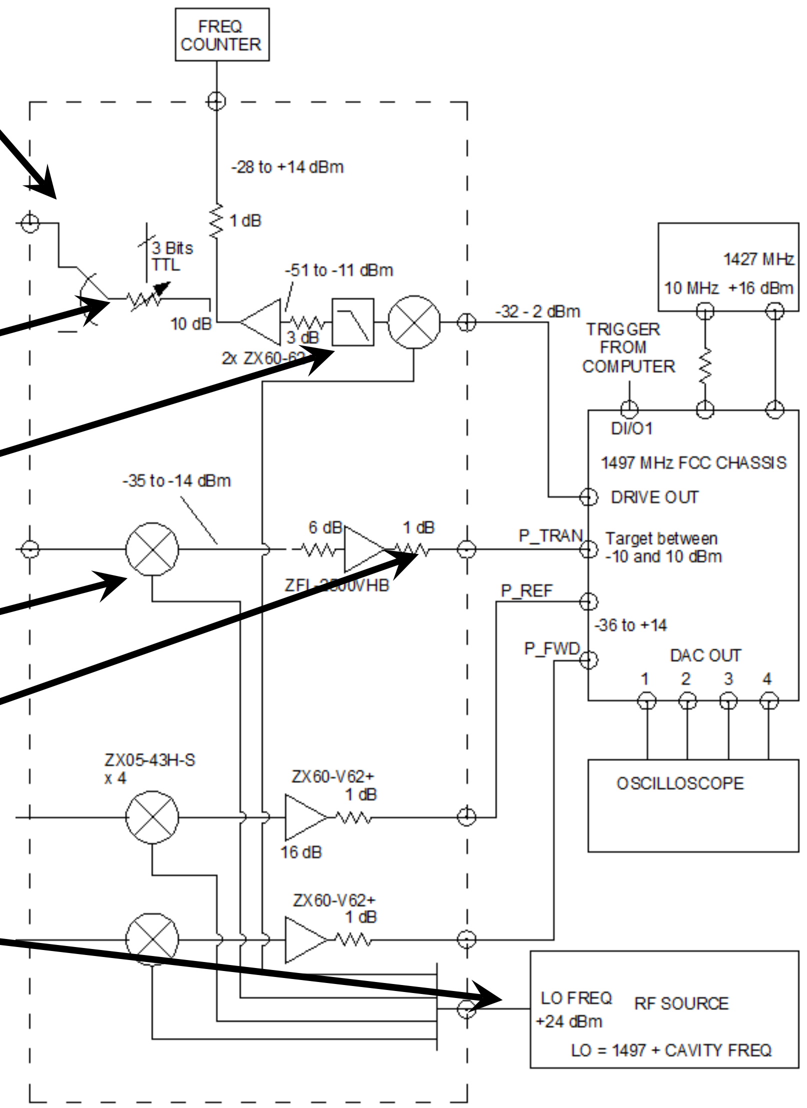
BROAD BAND DIGITAL LLRF BASED SYSTEM



- **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**
- **Variable attenuators included extend the range of linear forward and reflected power signals for observation.**

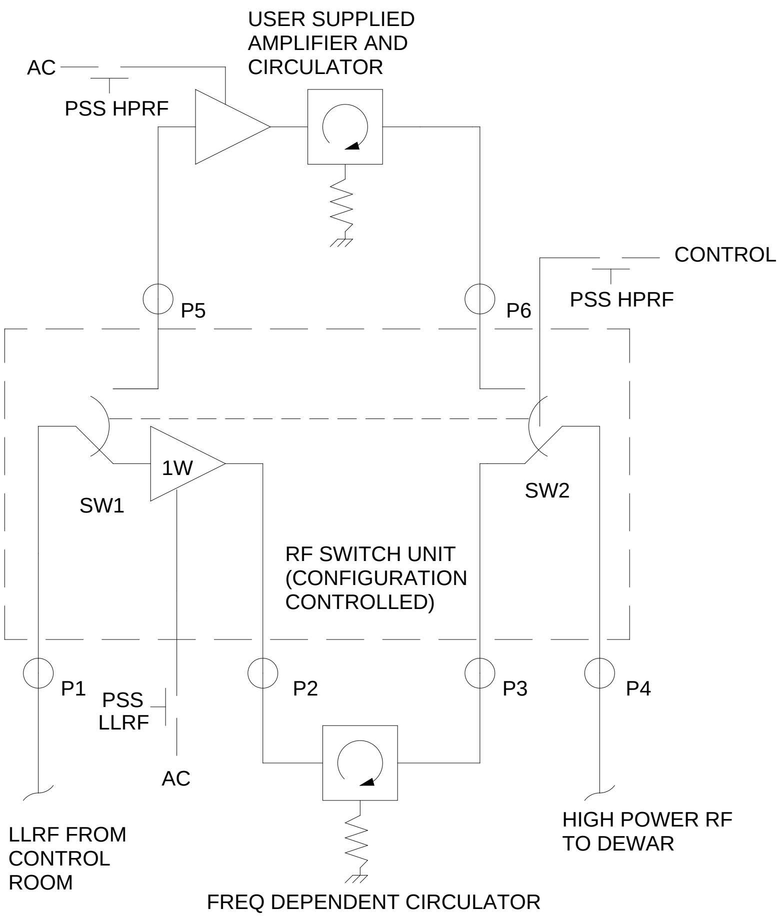
BROAD BAND DIGITAL LLRF BASED SYSTEM

- **Output On/OFF switch for pulsed mode operation.**
- **Variable attenuator necessary to insure that the frequency counter is not power starved. It will be conjunction with the LLRF output control to control the amplifier drive signal**
- **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**

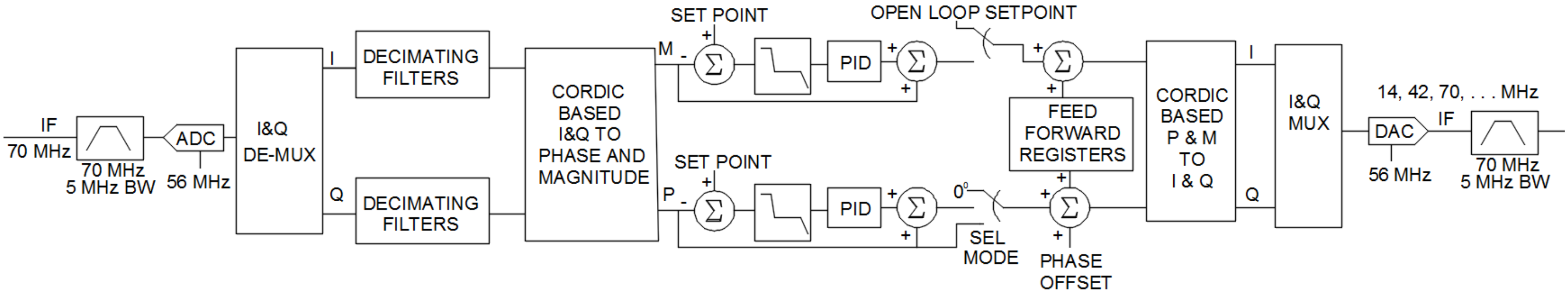


INTERLOCKS FOR VERTICAL TESTS

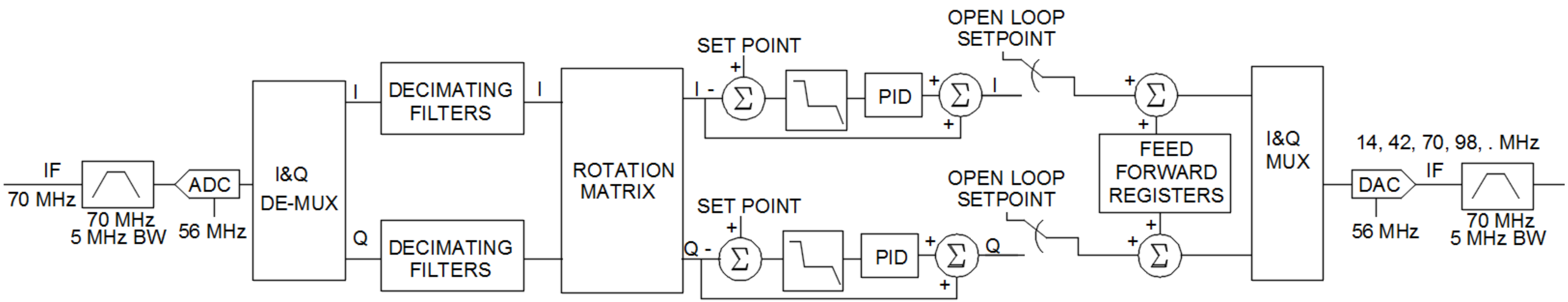
- **During vertical testing medium power amplifiers between 100 W and 500 W are used to drive the cavities.**
- **No cavity protection interlocks are used during these tests at Jefferson Lab. Each facility and test should be evaluated individually.**
- **Field emission radiation does present a safety hazard. This is mitigated during vertical testing at Jefferson Lab by using one of 6 shielded vertical dewars.**
- **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.**
- **A similar switching system, along with dewar selection switches and permanently installed cables, was implemented for the production system.**



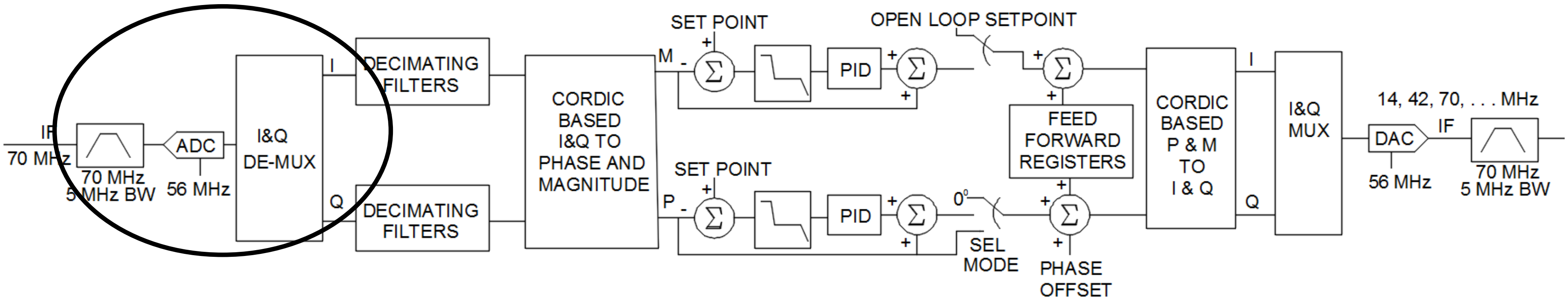
Magnitude and Phase or I/Q Control Algorithms



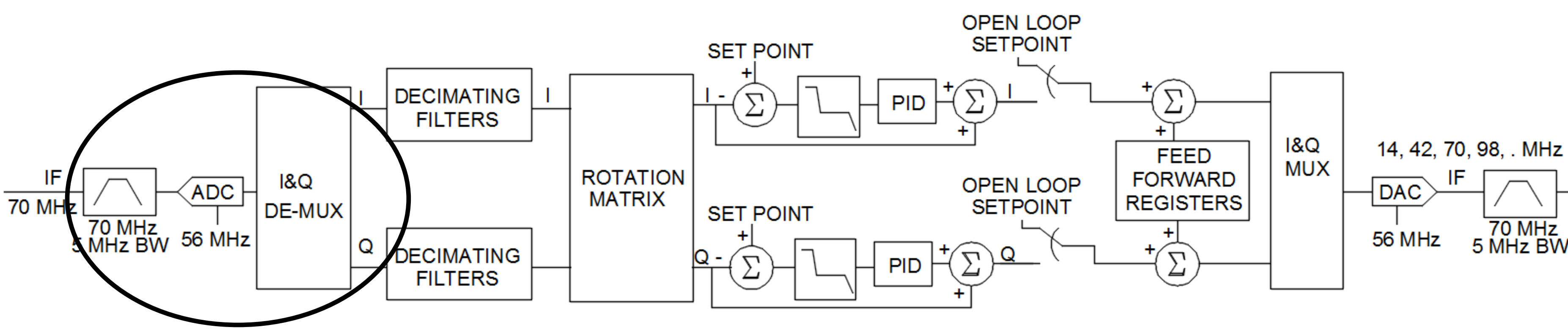
- **Similar topology for magnitude and phase control and I/Q control.**
- **Both use clocking that is effectively 4 times the IF frequency. This can also be done by having the data clock equal to the IF frequency divided by 0.25, 1.25, 2.5, 5 . .**
- **Both use I/Q de-multiplexing.**



Magnitude and Phase or I/Q Control Algorithms



Synchronous I/Q demodulation



What are I and Q?

- There are many variations on a theme for cavity field regulation. The two basic parameters that one regulates. Amplitude and Phase. This can be converted to in phase (I) and quadrature (Q).

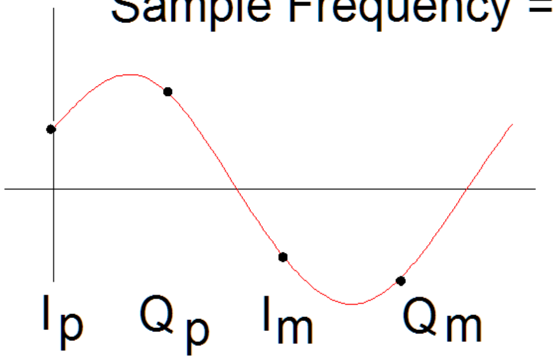
- In its simplest form.

$$V_{PEAK}\cos(\omega_o t+\varphi)=V_{PEAK}I\cos(\omega_o t)+V_{PEAK}Q\sin(\omega_o t)$$

- A system can be designed such that I an Q can be sampled directly.
- From a controls standpoint they are orthogonal and the PID loops for each are independent.
- This can be complicated by the fact that the perturbations to SRF cavity field and phase have different properties and it is desirable to control them with different loop parameters.
- For multiple cavities you can regulate the vector sum of the I's and Q's for each cavity. Generally not a good idea.

How Do You Directly Sample I and Q

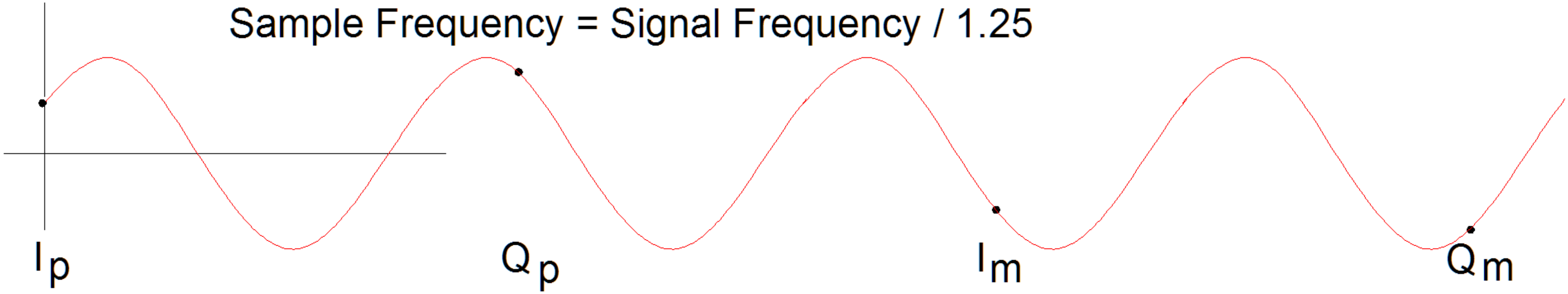
Sample Frequency = 4 x Signal Frequency



$$I = I_p - I_m \qquad Q = Q_p - Q_m$$

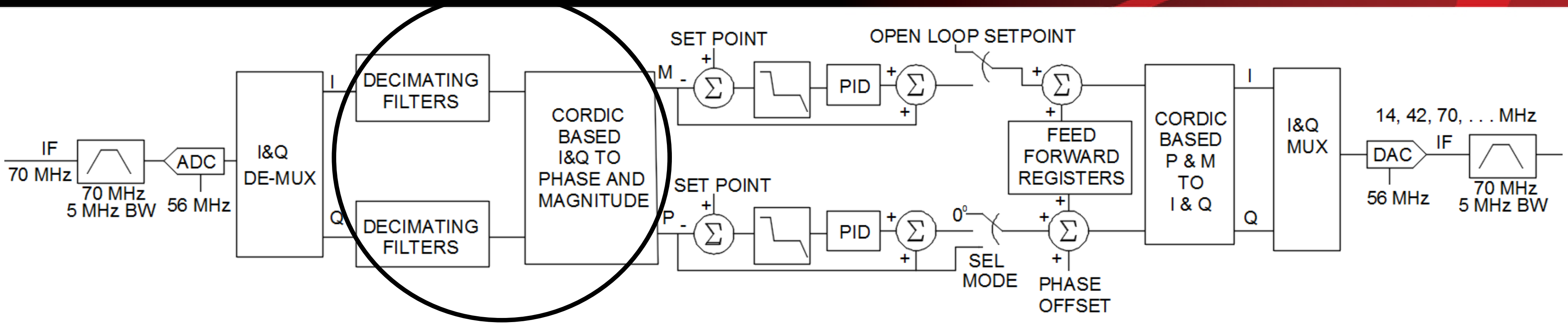
- **Simple approach**
- **Low latency**
- **Very little signal processing**

Sample Frequency = Signal Frequency / 1.25



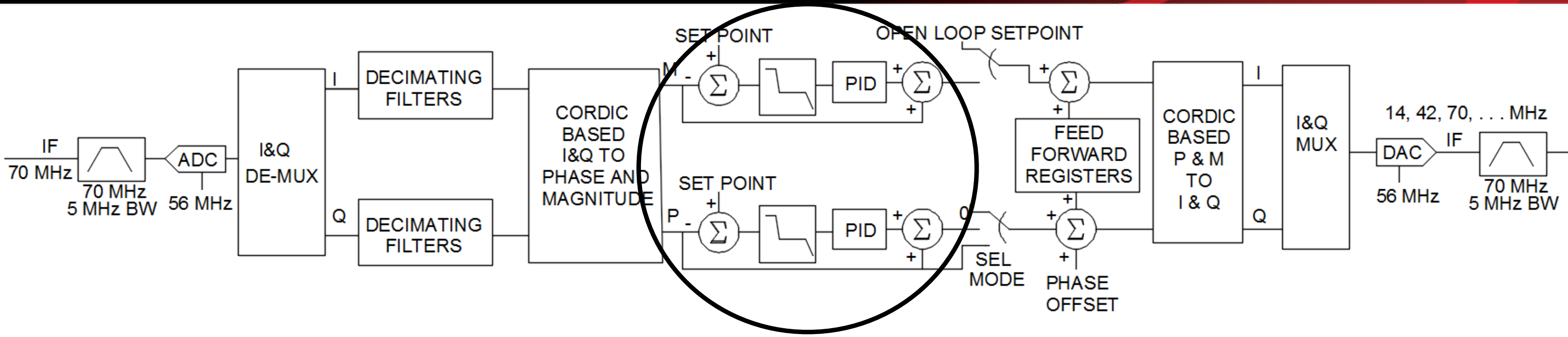
- **There are other approaches which are more complex and may be better suited depending on the application.**
  - **Direct digital down conversion**
  - **Direct sampling at RF frequency**
  - **Oversampling**

Magnitude and Phase Control Algorithm



- The amount of filtering and decimation is a debatable concept. We filter and decimate from 26 MHz to about 100 kHz.
- CORDIC -- COordinate Rotation DIgital Computer . . . also known as the digit-by-digit method and Volder's algorithm, is a simple and efficient algorithm to calculate hyperbolic and trigonometric functions. The number of clock cycles is determined by the desired accuracy. For example a 16 bit cordic takes about 17 cycles. Effectively this uses a 17 stage lookup and adder to calculate sine and cosine.
- Math is integer math, thus I, Q, M, P are in integer counts.

Magnitude and Phase Algorithm

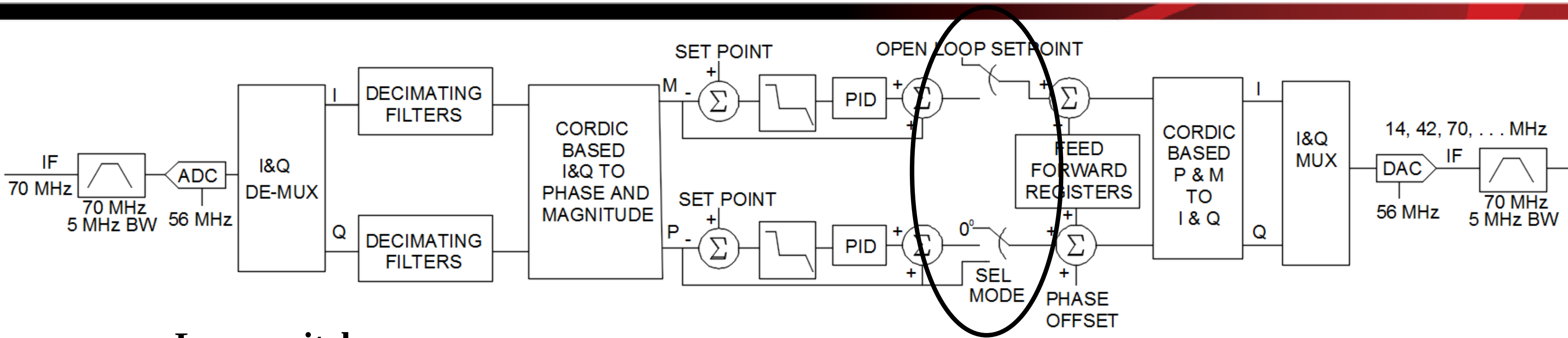


- **Standard PID controller for magnitude and phase. Because magnitude and phase are handled separately they can have different parameters.**

- **The filter shown is a gain boost filter for lower frequency. It is not clear if we actually use that in the current version of the JLAB firmware but it may prove to be useful.**

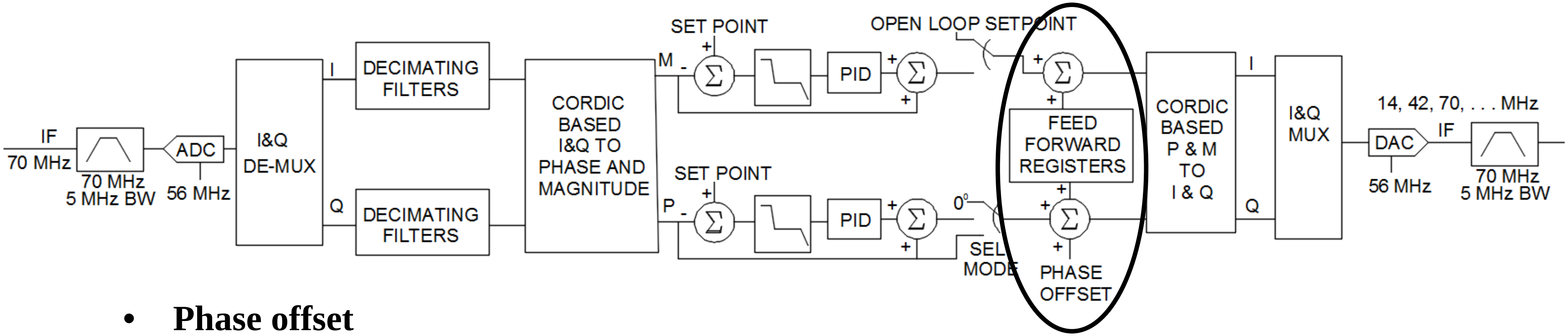
- **Since the phase signal is not scaled by the gradient (as it is in the JLAB analog system) the loop gain is independent of the gradient.**

Magnitude and Phase Algorithm



- Loop switches
- Gradient
  - Open loop with a setpoint or closed loop based on the output of the PID.
  - The gadient loop may be closed when in SEL mode. However if it is you need to make sure that the phase offset is correctly. Otherwise the RF power will increase substantially and likely cause a cavity trip.
- Phase loop.
  - Open loop where phase input is set to 0.
  - SEL mode where the phase signal rotates in a circle between 0 and 2π at a frequency which is the difference between the cavity and reference.
  - Phase offset. Used to zero out the phase error signal after the PID for GDR mode or to maximize the cavity gradient when SEL mode.

Magnitude and Phase Algorithm

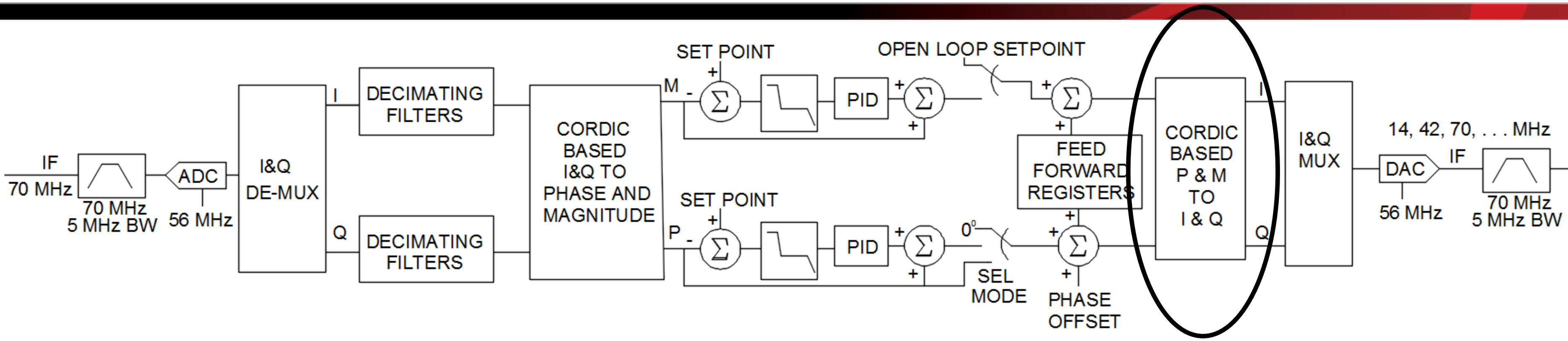


- **Phase offset**
- **Used to zero out the phase error signal after the PID for GDR mode or**
- **To maximize the cavity gradient when SEL mode.**
- **SEL mode will not track the cavity frequency unless the phase offset is within about 30d of the proper value.**

- **Feed Forward Register**
  - **Used in conjunction with a beam pulse synchronization signal to provide adaptive feed forward in order to regulate the gadient under pulsed beam loading.**

- **Other registers/inputs**
  - **One can also apply phase or amplitude offsets for purposes of beam based feedback or diagnostics.**

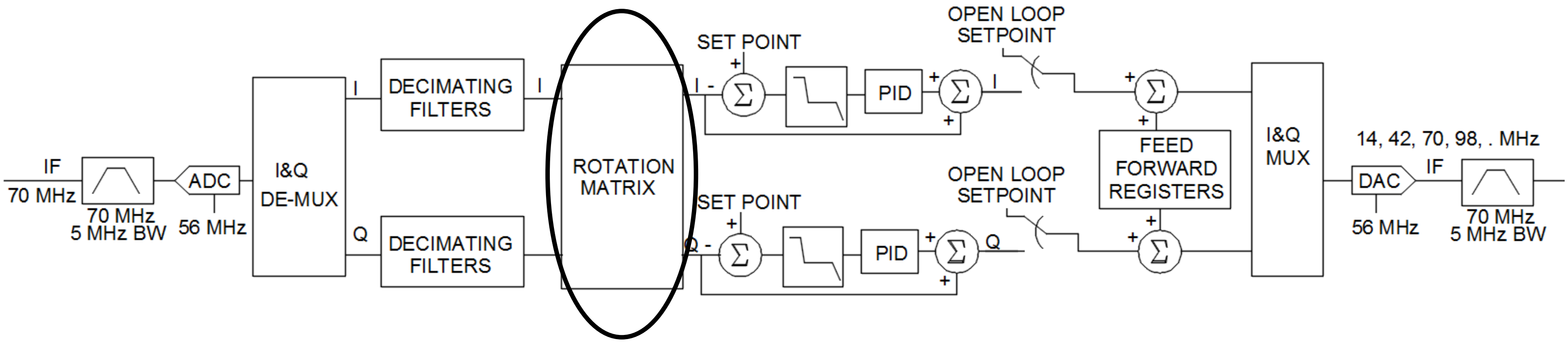
Magnitude and Phase Algorithm



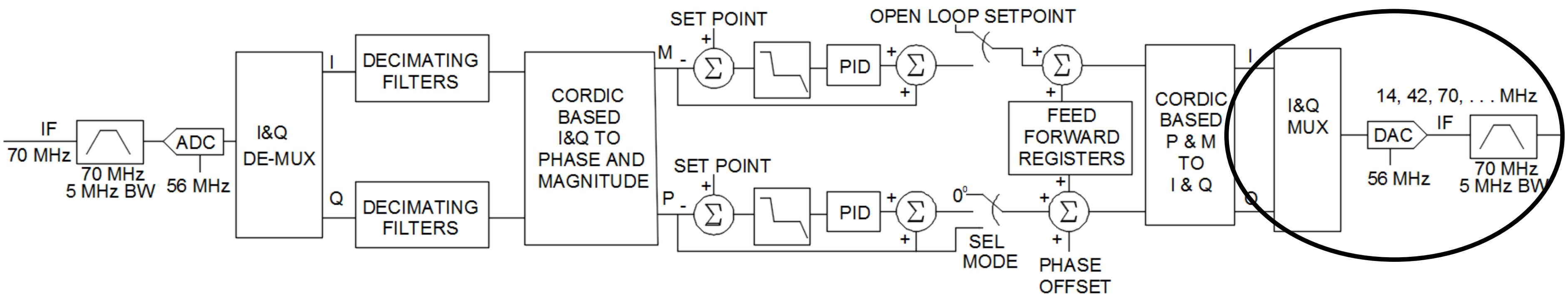
- CORDIC algorithm used to calculate Sine and Cosine of resultant phase. Not shown is the block that sets the resultant phase back to value between $-\pi$ and π.
- I = M cos(Phase), Q = M sin(Phase)

I/Q Control Algorithms

- Same front end as magnitude and phase control.
- Using the rotation matrix one can force the mean value of the Q input towards 0 which effectively makes it a phase signal.
- Note that one must use a phase and amplitude loop for SEL mode.
- Feed forward register now operates in I and Q plane.



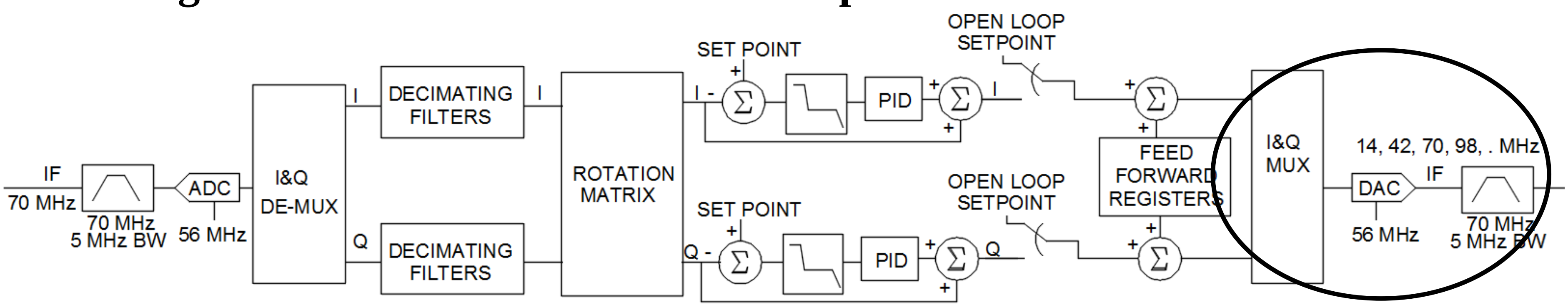
Magnitude and Phase or I/Q Control Algorithms



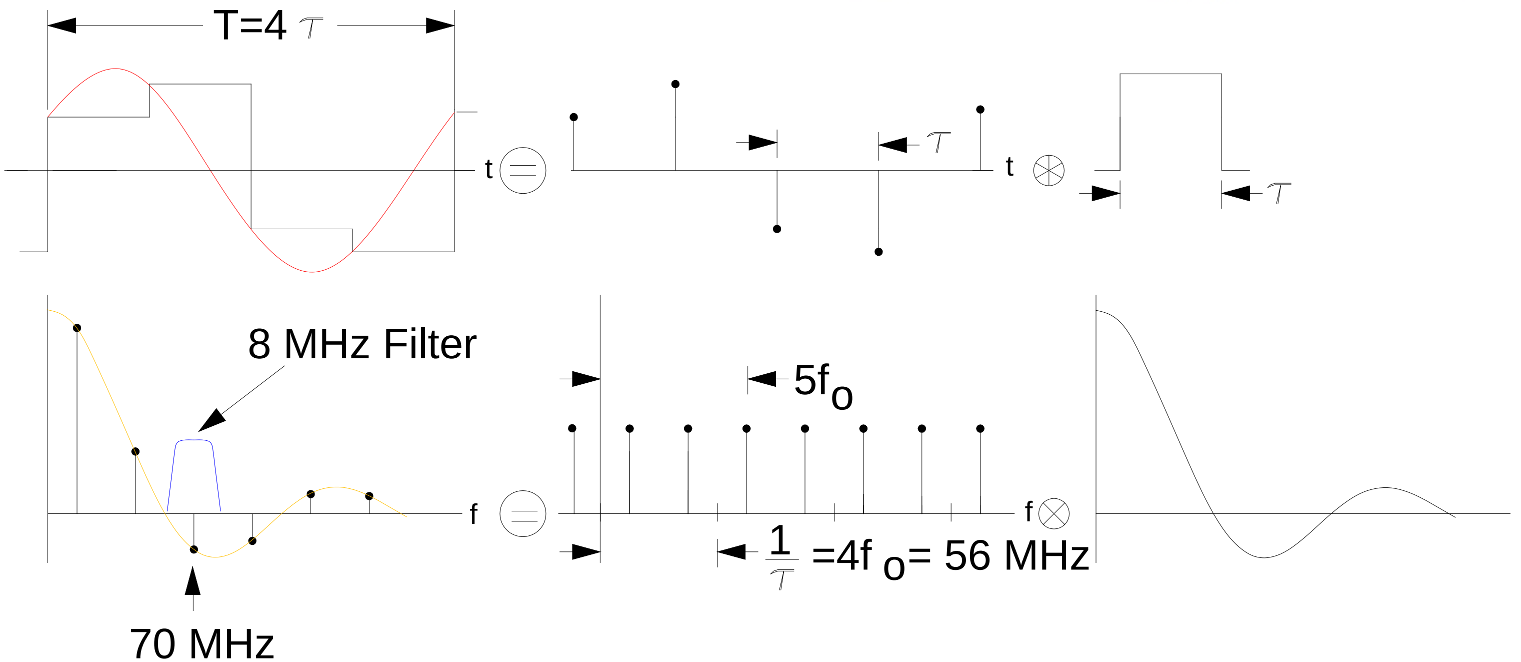
- I and Q signals are interleaved to make the data chain

$$I_i, Q_i, -I_i, -Q_i, I_{i+1}, Q_{i+1}, -I_{i+1}, -Q_{i+1}, I_{i+2}, Q_{i+2}, -I_{i+2}, -Q_{i+2}, \ldots$$

- Single DAC data clock is that of the input data stream.



Direct Sampled I/Q Output to IF

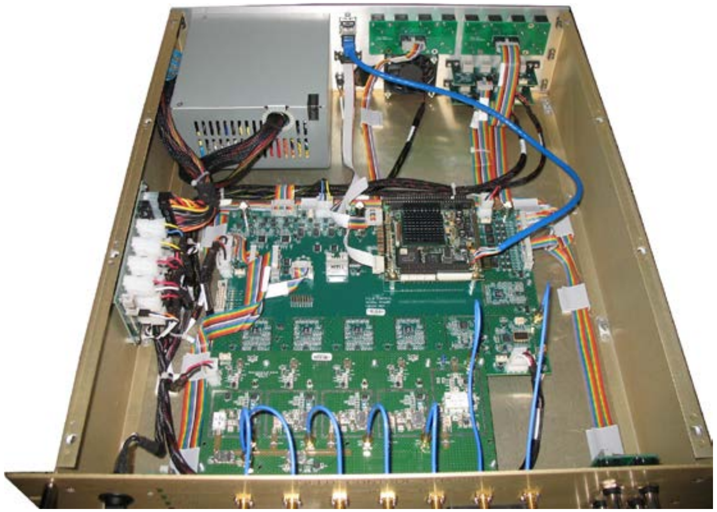


- Harmonics come out at the difference between sample rate and IF frequency or the 1, 3, 5, 7, . . . Harmonic of 14 MHz
- 70 MHz component is 28 MHz away from nearest neighbor.
- Commercial drop in 8 MHz BW filter available for $30.
- One can show that the harmonic contains the proper phase signal and is:

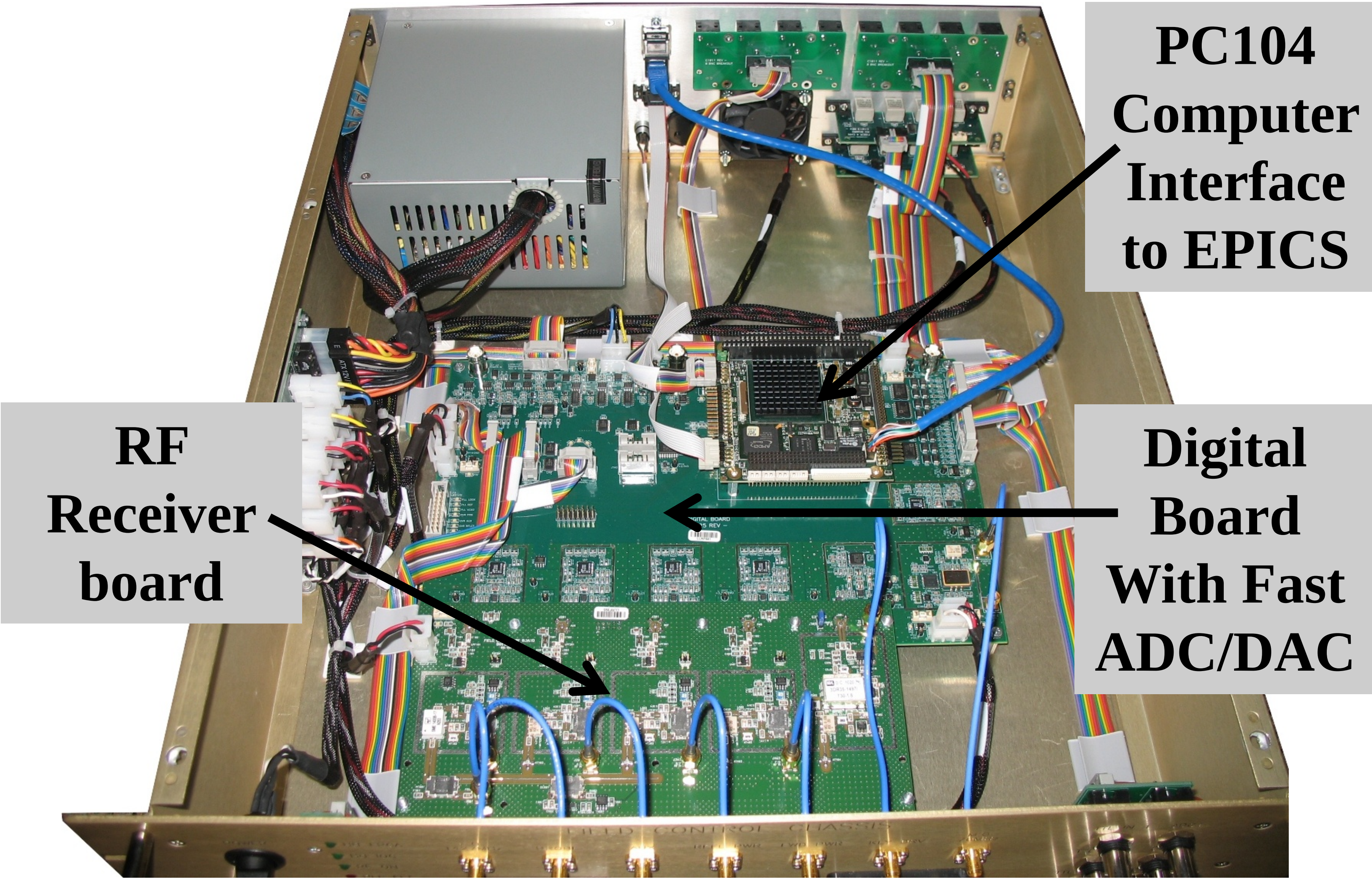
$$A\sin(2\pi f_0 + \varphi) \Rightarrow B_k A\sin\left(2\pi\left(kf_S \pm f_0\right)t + \varphi\right) \text{ where } k = 1, 3, 5, 7, \ldots$$

JLAB LLRF System Field Control Module

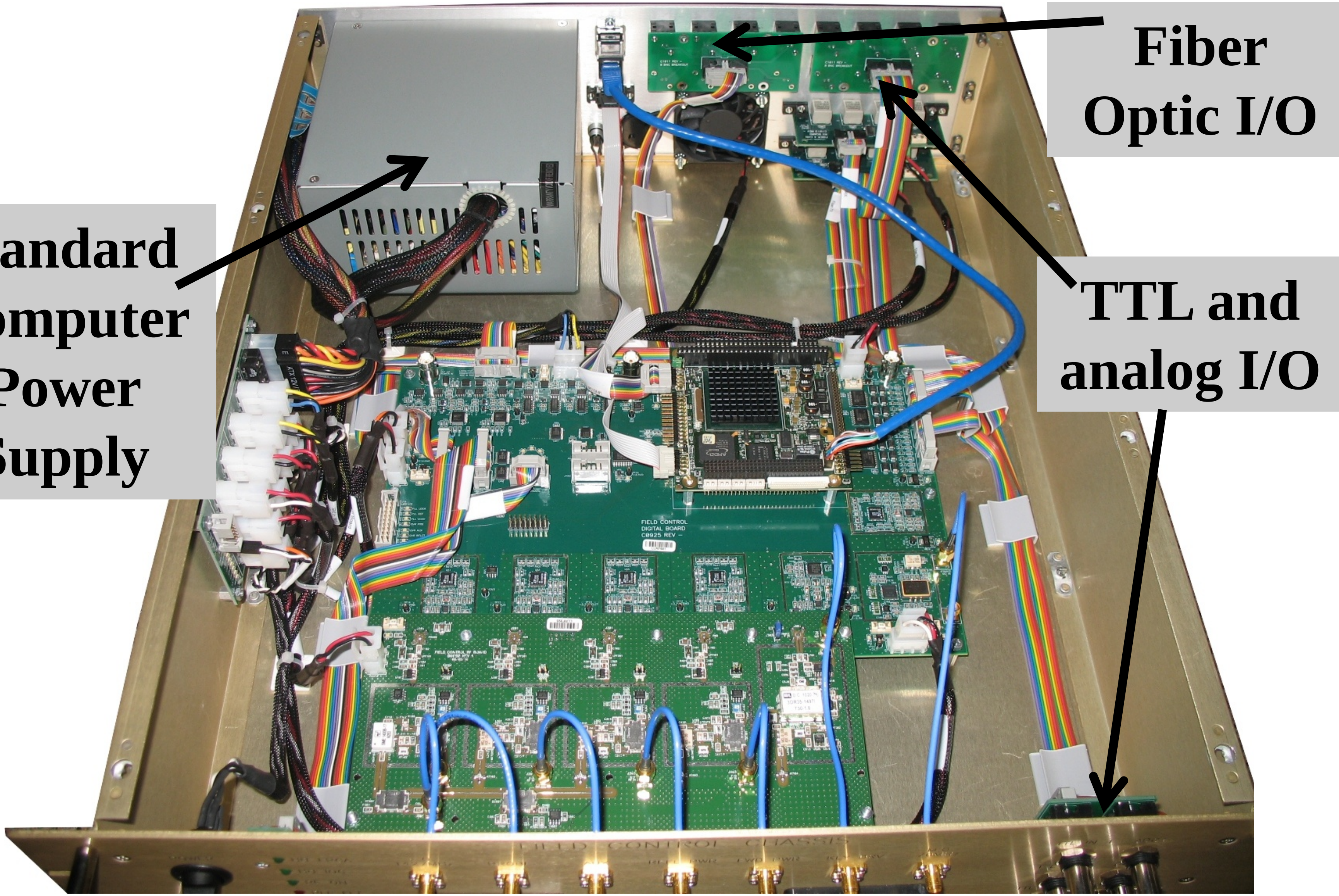
- **Typical foot print**
  - **Large Altera FPGA**
  - **Four Receivers**
  - **One transmitter**
  - **Separate RF and Digital board**
- **Features**
  - **Numerous I/O: ADC, DAC, TTL, Fiber**
  - **Ring Buffers**
  - **Hot Swappable**
- **EPICs IOC = PC104**
- **Installed and operating in Pohang, CEBAF and at University of Wisconson**



JLAB LLRF System Field Control Module



JLAB LLRF System Field Control Module



SRF Tuner Control

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

SRF Tuner Control

- Normal slow tuner operation:
- Determine the phase difference between the forward power and transmitted power (cavity field probe) where the forward power is minimized (TPOFF)
- Calculated the tuner phase error signal (TPES) as the measured tuner phase (TPMES) minus the tuner phase offset.

$$TPES = TPMES - TPOFF$$

- When the magnitude of TPES exceeds a dead band value (typically 5° to 7°) start operating the tuner motor.
- Stop the tuner motor when the magnitude of TPES is less than 3°.

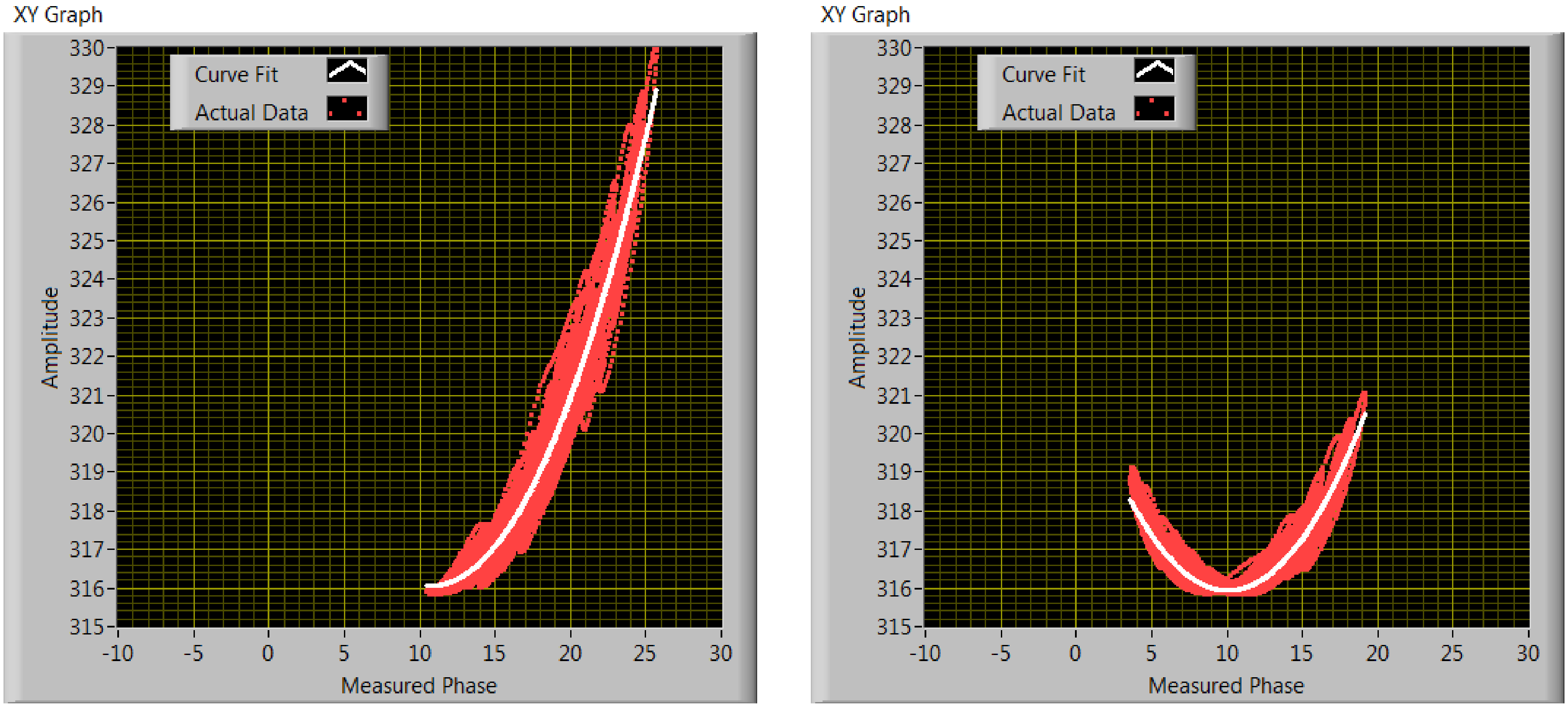
Turning On a Detuned Cavity

- **Initial Turn on cavity frequency >> SEL range.**
  1. **Open the phase and magnitude loops and apply a moderate amount of power.**
  2. **Start running the stepper motor tuner until one observes some gradient in the cavity.**
  3. **Close the SEL mode switch.**
  4. **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.**
  5. **Operate the tuner until the frequency error is close to zero.**
  6. **Increase the RF power until you are near the desired cavity gradient.**
  7. **Adjust the phase offset until the cavity gradient is maximized.**
  8. **Switch over from SEL to GDR mode.**
  9. **Close the tuner loop and allow the computer to control the tuner motor.**
  10. **Apply the closed loop tuner algorithm from the next slides.**
- **Normal turn on after a trip or if the cavity was recently operated.**
  1. **Skip step 2 above.**

Automatically Determining TPOFF

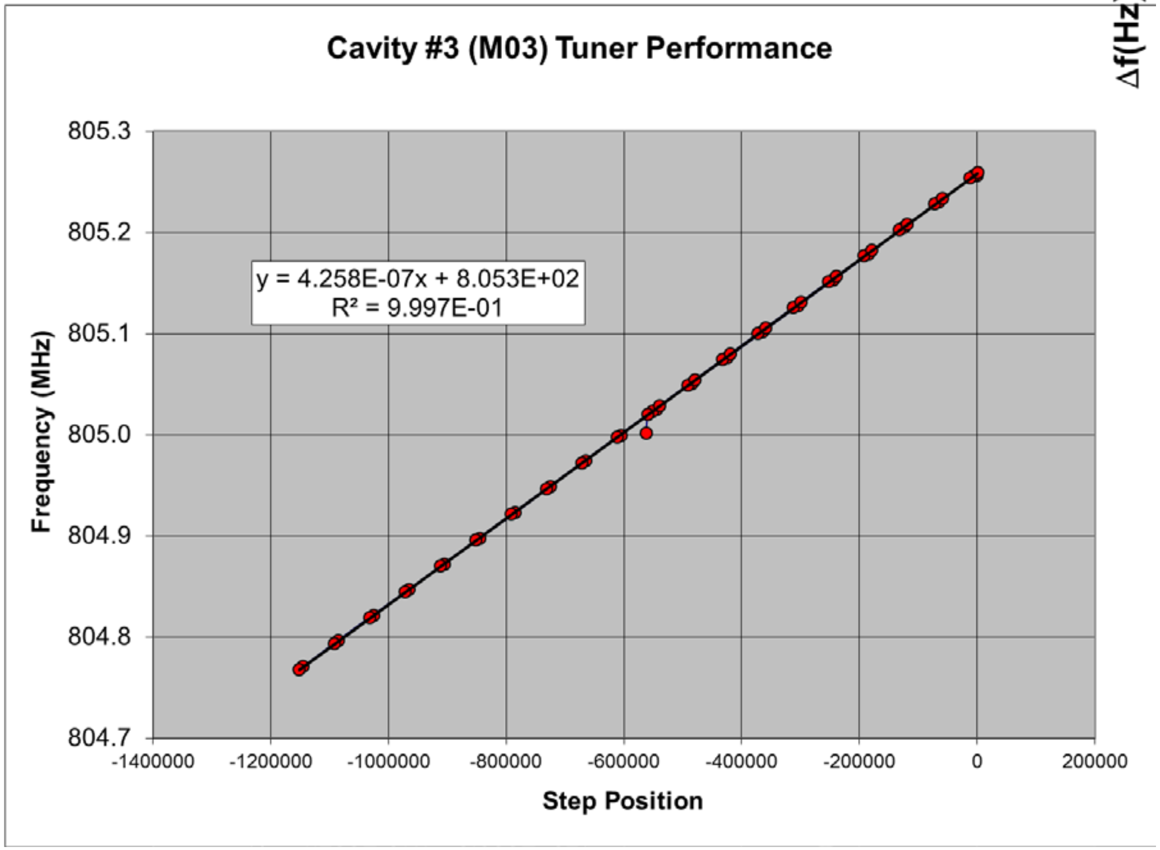
- Using a digital LLRF system one can record the forward RF voltage (magnitude of the I/Q signal) and the difference between the transmitted power phase and the forward power phase for several seconds.
- The microphonics noise in the system will introduce spread in the data.
- If a second order fit (X value is the phase difference and the Y value is the RF voltage) is applied to the data the minimum will occur when TPES = TPOFF.
- This process is valid in GDR mode both with and without CW beam.
- It not valid during pulsed beam operation.

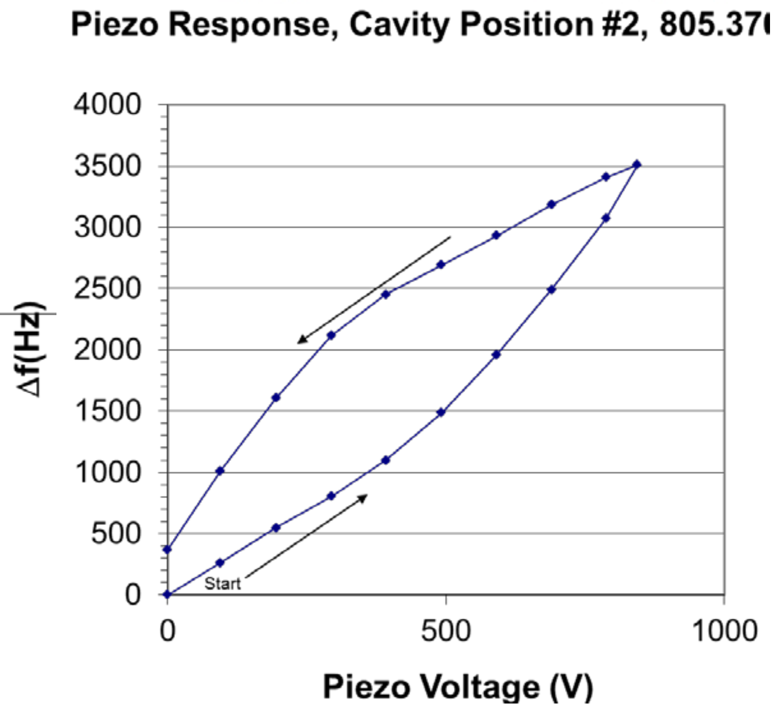
Maintaining Proper Value of TPOFF



Curve fitting for measured microphonics data 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°.

SNS Style Tuner

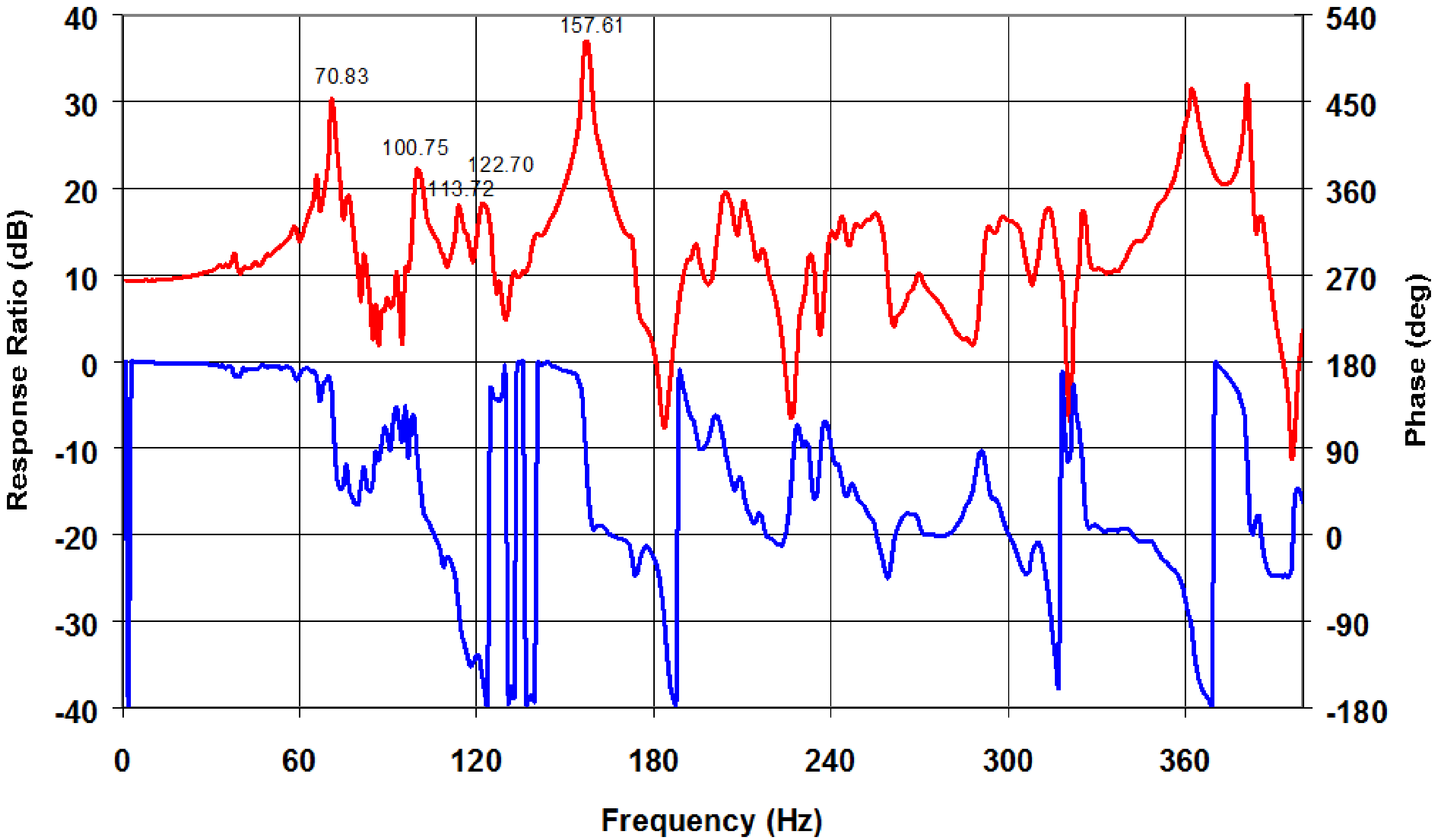




SNS Style Tuner

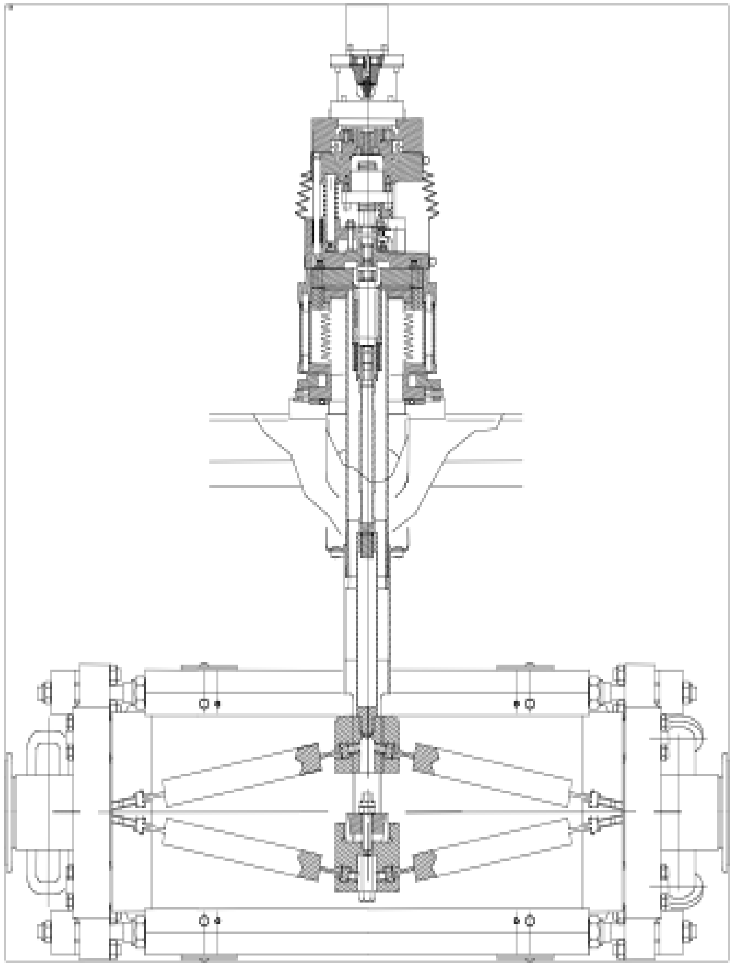
Cavity Pos 1, Piezo Transfer Function

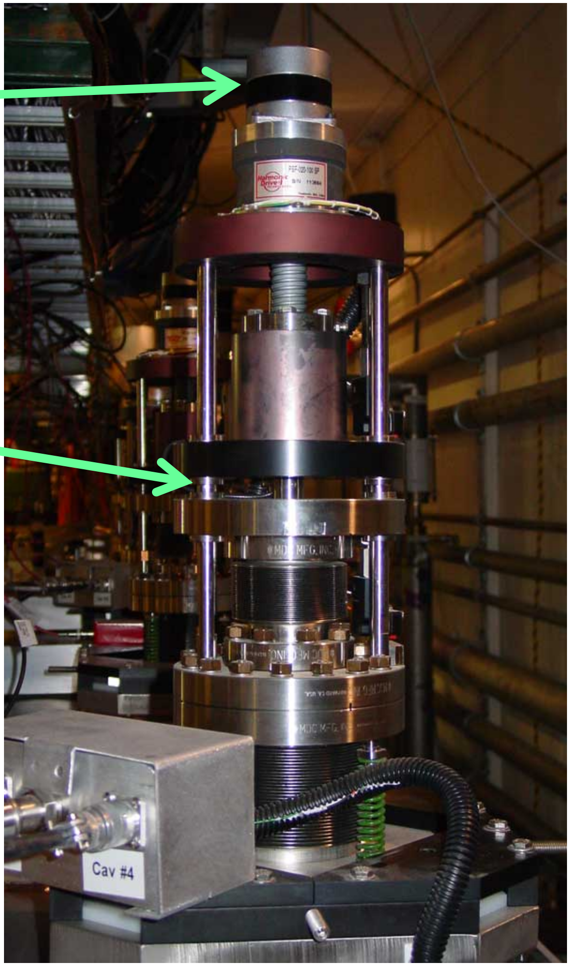
22 October 2002



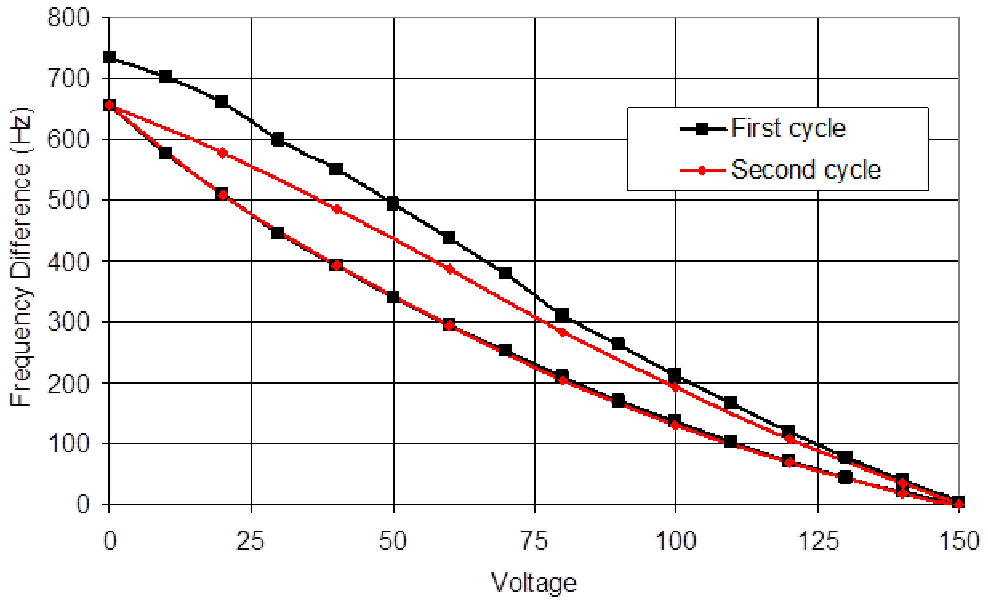
Cavity Response to Piezo, Swept Sinudoid, Drive Amplitude = 26Vpp
Med B Cryomodule Prototype, Cavity Position 2, 804.612MHz, 3.5 MV/m CW

JLAB Scissor Jack Tuner



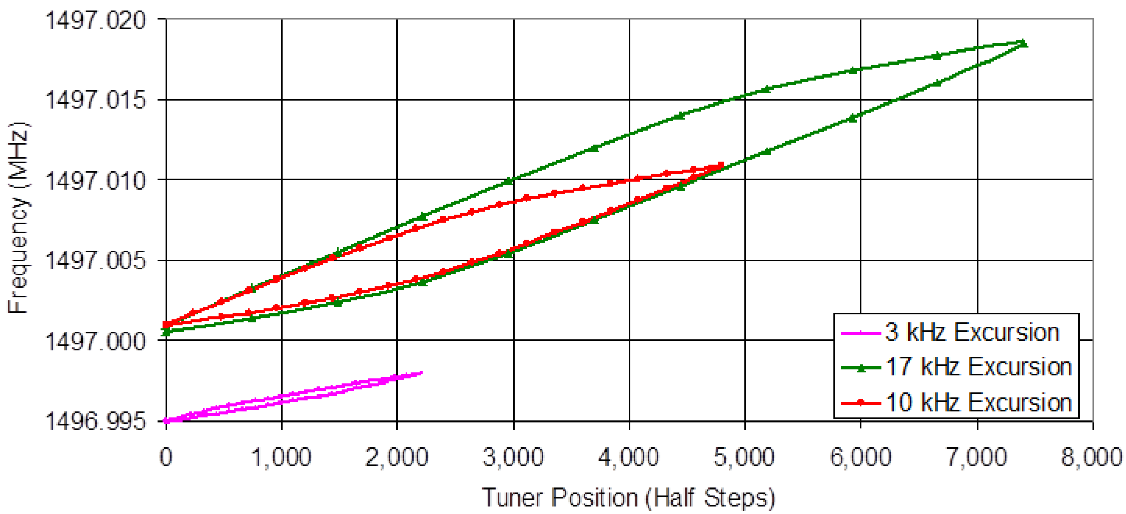


JLAB Scissor Jack Tuner

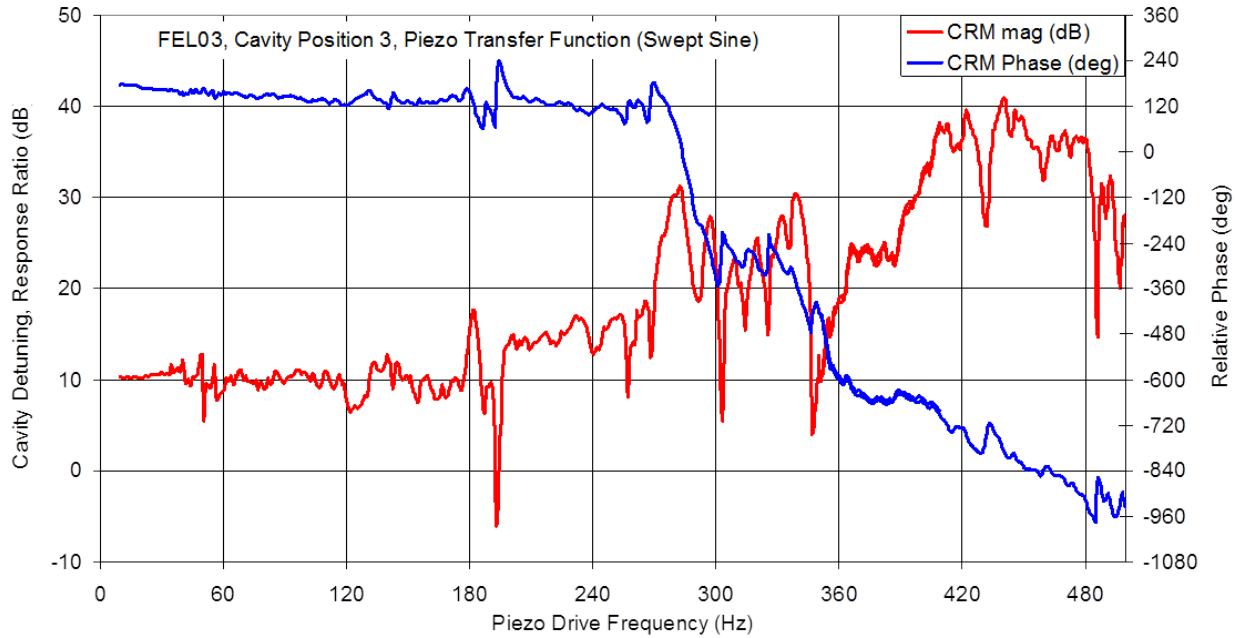


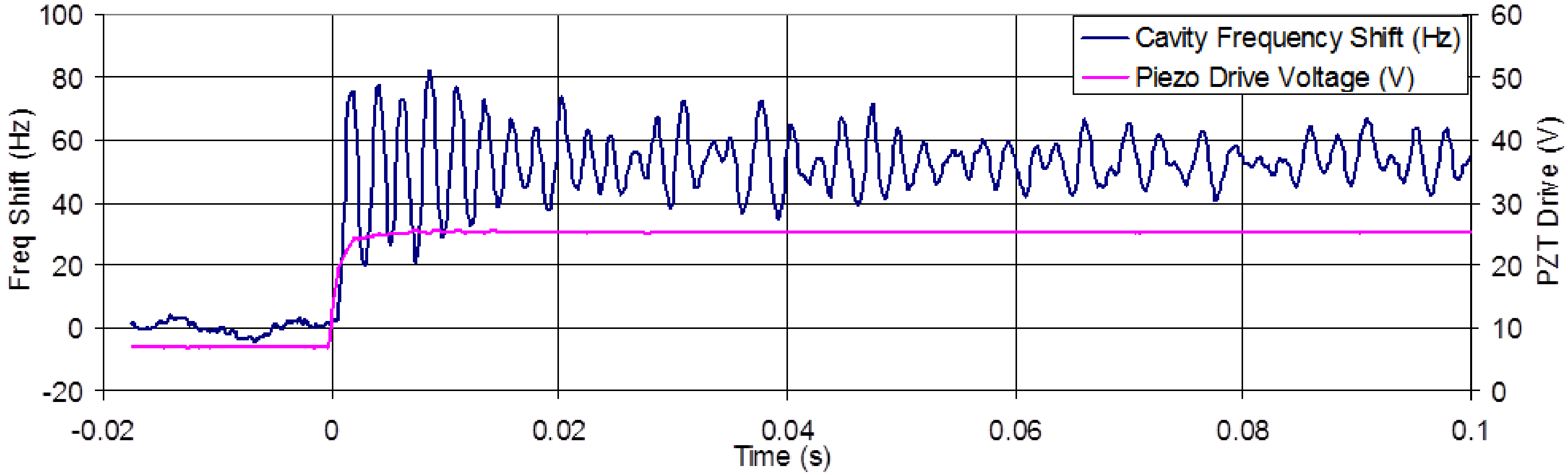
PZT Operations

Stepper Motor Operations



Piezo Transfer Function

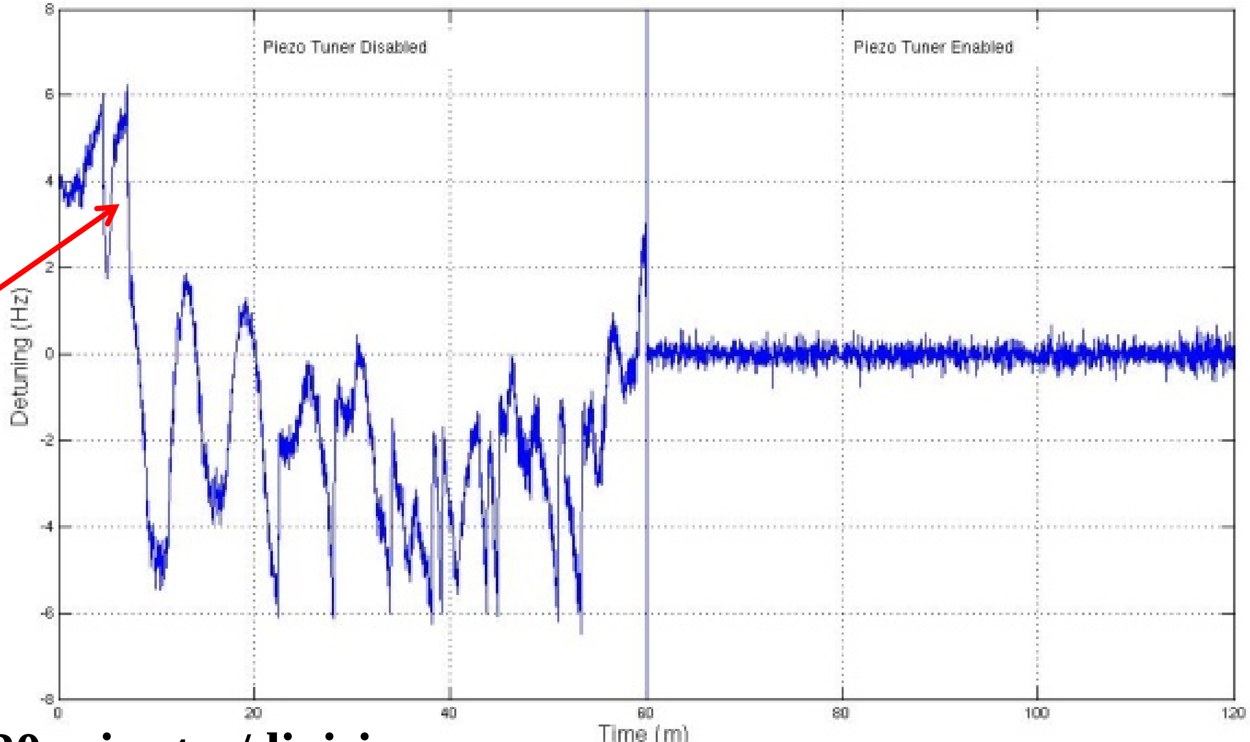




Impact of PZT On/Off

- **C100-2 cavity operating at ~ 15 MV/m with the PZT off and then on (2 Hz BW). Slow tuner was on in the background.**
  - Th

Slow tuner turns On to re-center The cavity



Note 20 minutes/division
Thus this is addressing slow pressure drifts

PZT bandwidth was limited to 2 Hz

Summary

Where we are

- Field control requirements of 0.1^{o} and 0.1%, phase and amplitude control can be met with modern electronics.
- Reconfigurable Digital Hardware has made development and operations easier.

Challenges - Thoughts

- Even with moderate specifications of 0.1^{o} and 0.1%, one has to be careful about mundane issues that affect accuracy and drifts.
- The assumptions on field control are fast control . . . not drifts.
  - Drift control . . . one needs a phase drift budget.
  - Drift control will probably drive hardware configuration and thermal stability issues.
- PZT active control has room to grow, but cavity to cavity coupling adds to the complexity for frequencies above a few Hertz.

Backup Slides

Cavity Resonance Control

Slow Tuner

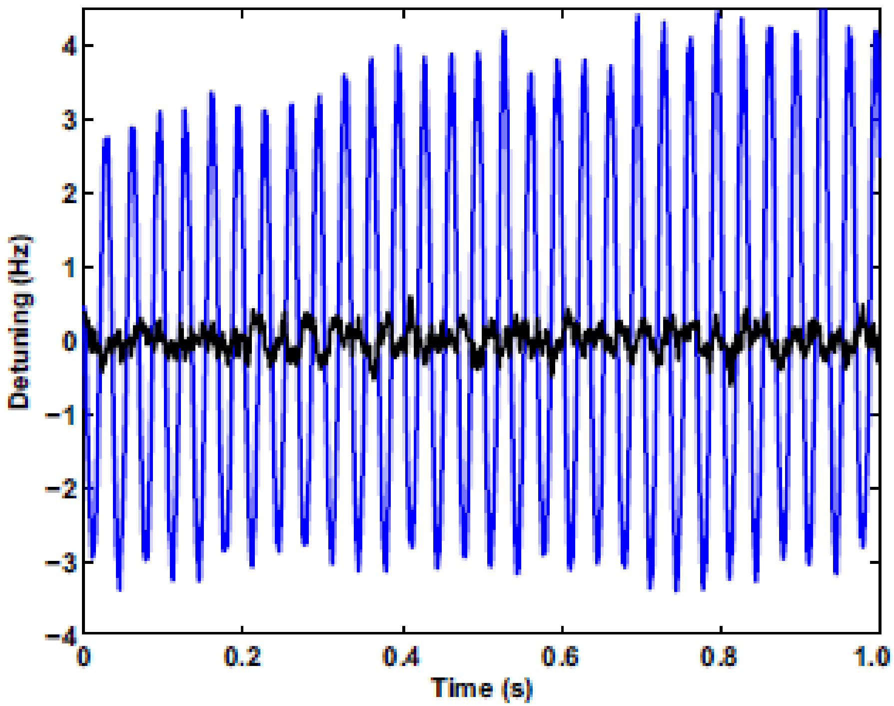
Stepper Motor:

- Recover cavity from large excursions associated with down time activities quenches or CHL trips.
- Keep Fast Tuner centered
- Control can be slow < 1 sec

Fast Tuner

Piezo-Electric Tuner (PZT):

- Large Industrial Base for Piezo and electronics
- Recover or compensate for Lorentz Detuning (Feed Forward or Feedback)
- Minimizes small changes in resonance do to He pressure.
- Control logic embedded in FPGA or fast DSP
- Concern regarding aging effects.



Time domain detuning for the open loop case (blue curve) and a combined feedback and feedforward controller (black curve) at a *QL of 6.4e7*

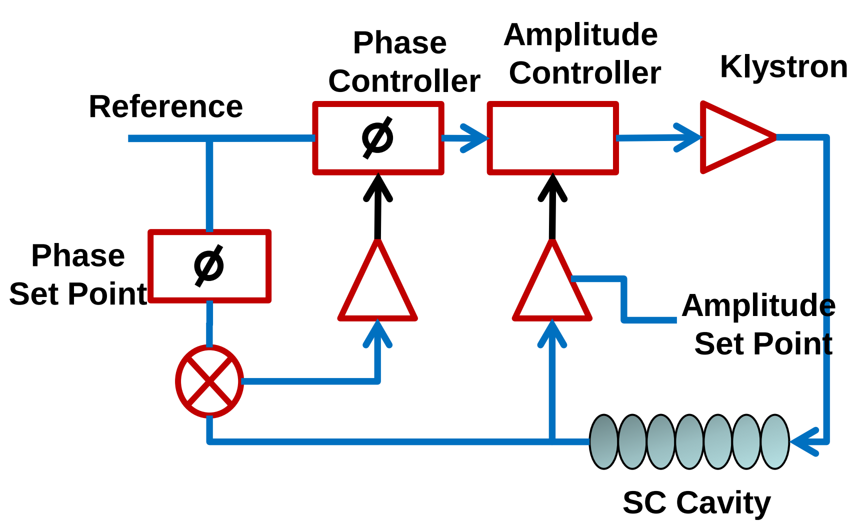
Single cavity test in HOBiCAT

A. Neumann SRF2007, data taken on sc cavities at HZB

Generator Driven Resonator vs. Self Excited Loop Analog Implementation

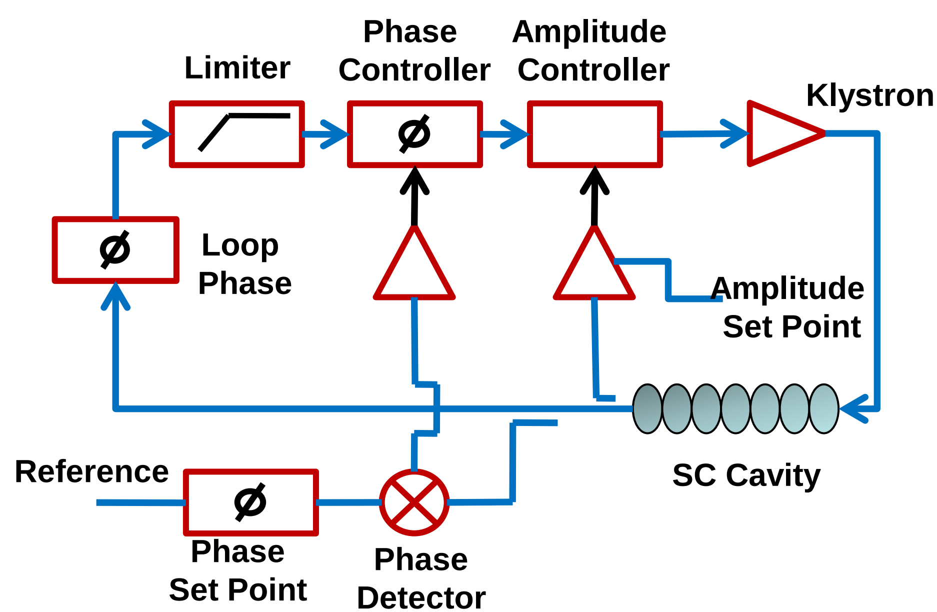
GDR

- **Advantages**
  - Where fast/deterministic lock up times are critical
- **Disadvantages**
  - High Q machines with high microphonic content and large Lorentz detuning could go unstable

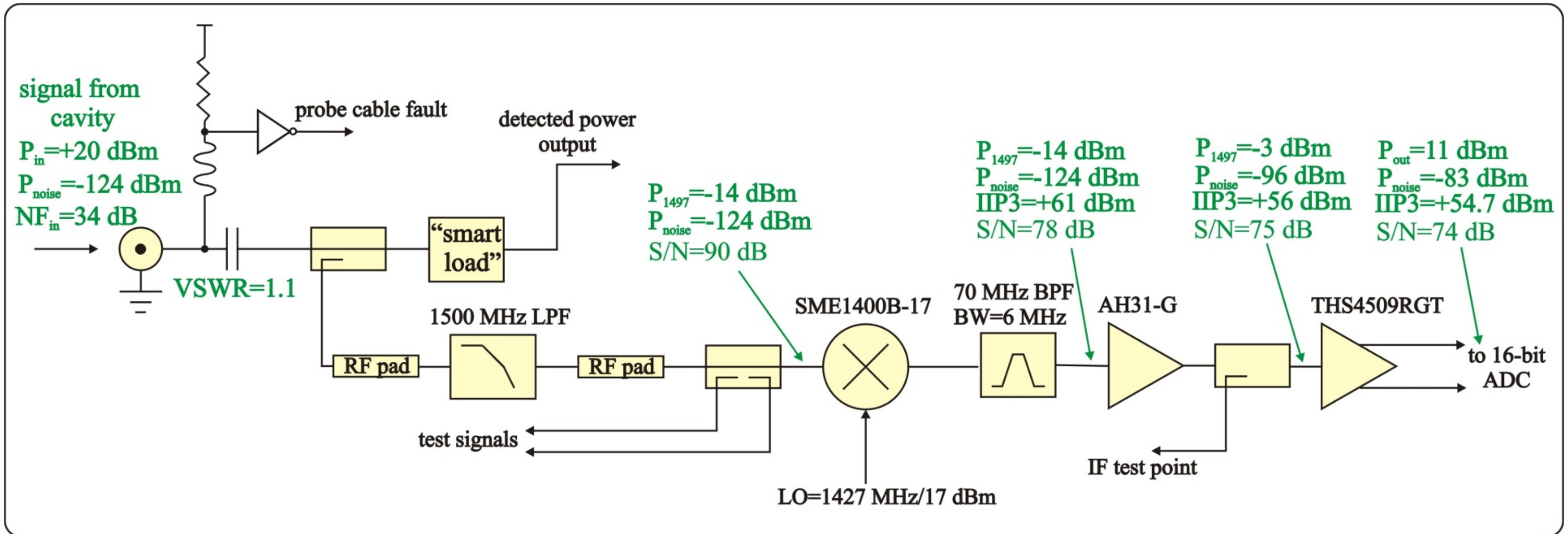


SEL

- **Advantages**
  - High Q_L Cavities
  - Systems with large Lorentz detuning
- **Disadvantages**
  - Slow lock up time



JLAB Upgrade RF Receiver



Parameter	Specification Value	Imposing Quantities
S/N	72 dB	0.1 degree resolution, 0.01% gradient accuracy
Receiver Bandwidth	8 MHz	Latency, S/N, temperature stability
Latency	100 ns	Control BW
Noise Figure (NF)	52 dB, BW = 100 kHz	S/N for phase resolution
Linearity	0.01% F.S.	Stability, accuracy
Dynamic Range	+54 dBm IIP3	Gradient range
Channel Isolation	67 dB	Phase, gradient resolution/accuracy
In-band intermodulation distortion (IMD)	67 dBc	THD

Field Control: Amplitude

- **Receiver S/N determines minimum residual amplitude control.**

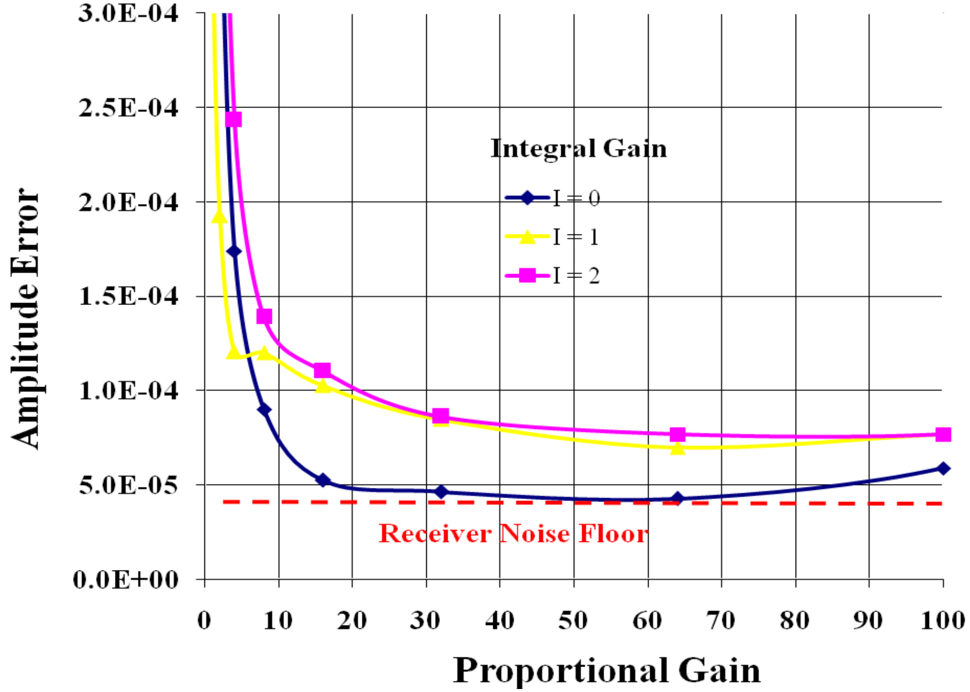
  Amplifiers

  Mixer

  ADC

- **Linear components needed for stability and accuracy over large dynamic range.**

It is possible to improve S/N, through process gain, but at the expense of control bandwidth and ultimately stability (latency).



Measured amplitude error vs. proportional gain for a digital receiver (14 bit).
Over sampling improved S/N from 74 dB to ~ 85 dB.

Measurements done on 14 bit system packaged in VME format.

Analog or Digital System

- Both analog and digital systems can be made to work.
- With an analog system the design effort is in the analog circuitry and once it is built changes are limited or expensive.
- Digital systems provide better opportunities for incremental improvements of algorithms and functionality by reprogramming the FPGA and real time computing software.
- My experience is that analog systems are more prone to drifts and calibration errors.
- Pulsed feed forward systems will require some type of adaptive digital controls with an analog system one would have to create analog signals to feed into the LLRF controls. These analog signals would be susceptible to issues like ground loop noise.

The Vector Sum

- There are cost optimization reasons to consider using one large RF source for multiple cavities.
- When using such a system the common approach is to sacrifice the gradient and phase regulation in one cavity while maintaining the gradient and phase regulation in the aggregate of the cavities.
- Variable waveguide couplers and phase shifters are used in order to set the relative phase and gradient of each cavity. Normally these are slow devices rather than dynamic control.
- Multiple receivers are used to monitor all of the cavity field signals.
- The I signals and the Q signals are summed in the FPGA and the sum of each is controlled using a PID loop.
- A single drive channel is used to provide RF to the input of the klystron.
- There are applications where such a system is less than ideal. One example his injectors where cavities are operated at different gradients and phases due to space charge effects and cavity focusing effects.
- There are operating regimes where there is a strong potential for Lorentz force driven instabilities.

The Vector Sum

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- When using suc[illegible]e common approach is to sacrifice the gradient and phase regulation in [illegible]aintaining the gradient and phase regulation in the aggregate of the [illegible]
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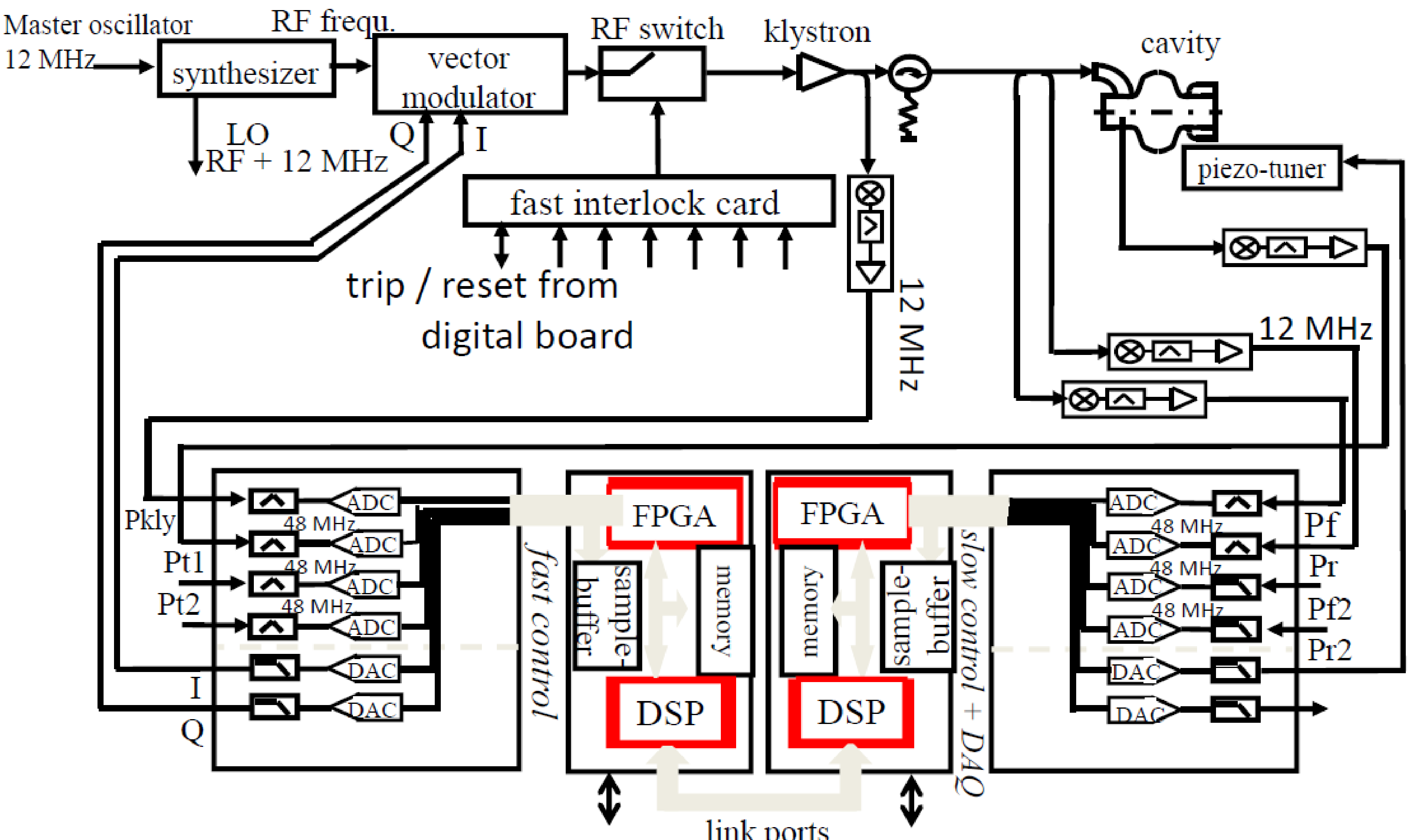
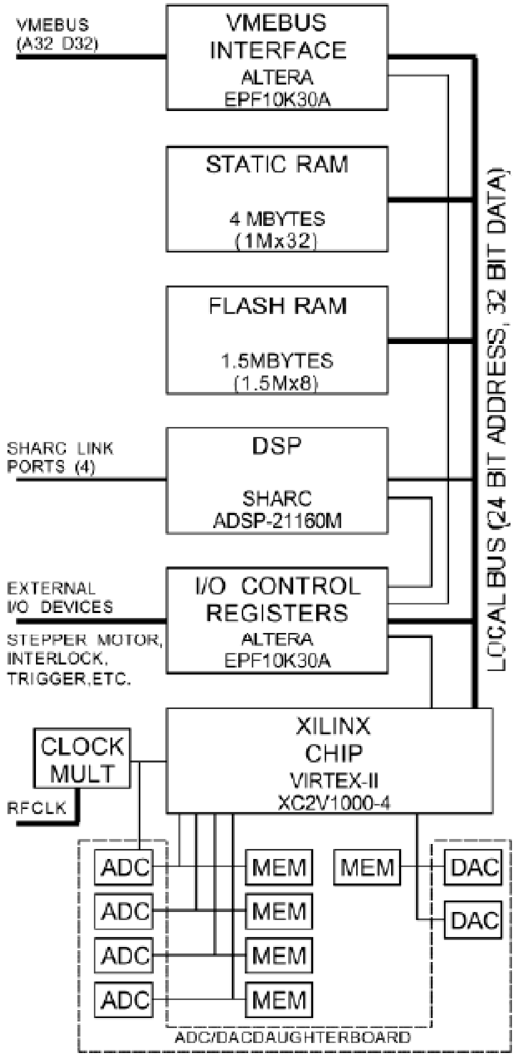
In my opinion BAD IDEA for CW SRF Operations

Gen 1: CESR LLRF Control System



Vivian Ho - LLRF Workshop 2011 5

Gen 1: CESR LLRF Control System



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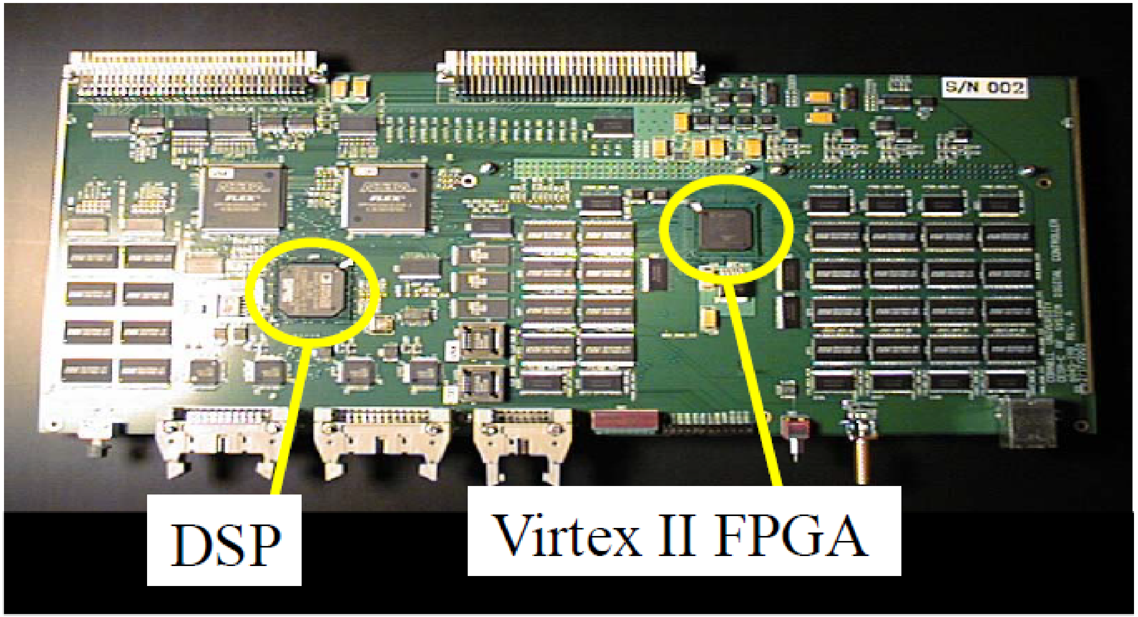
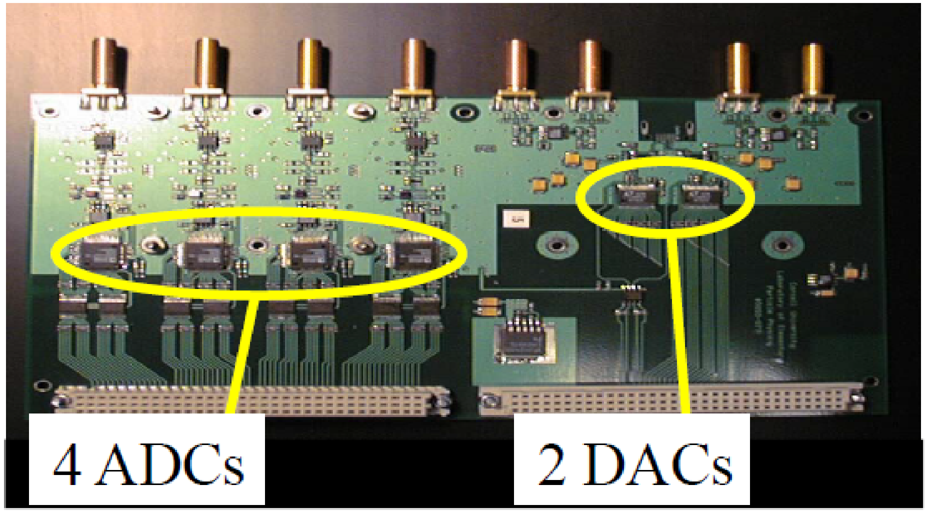
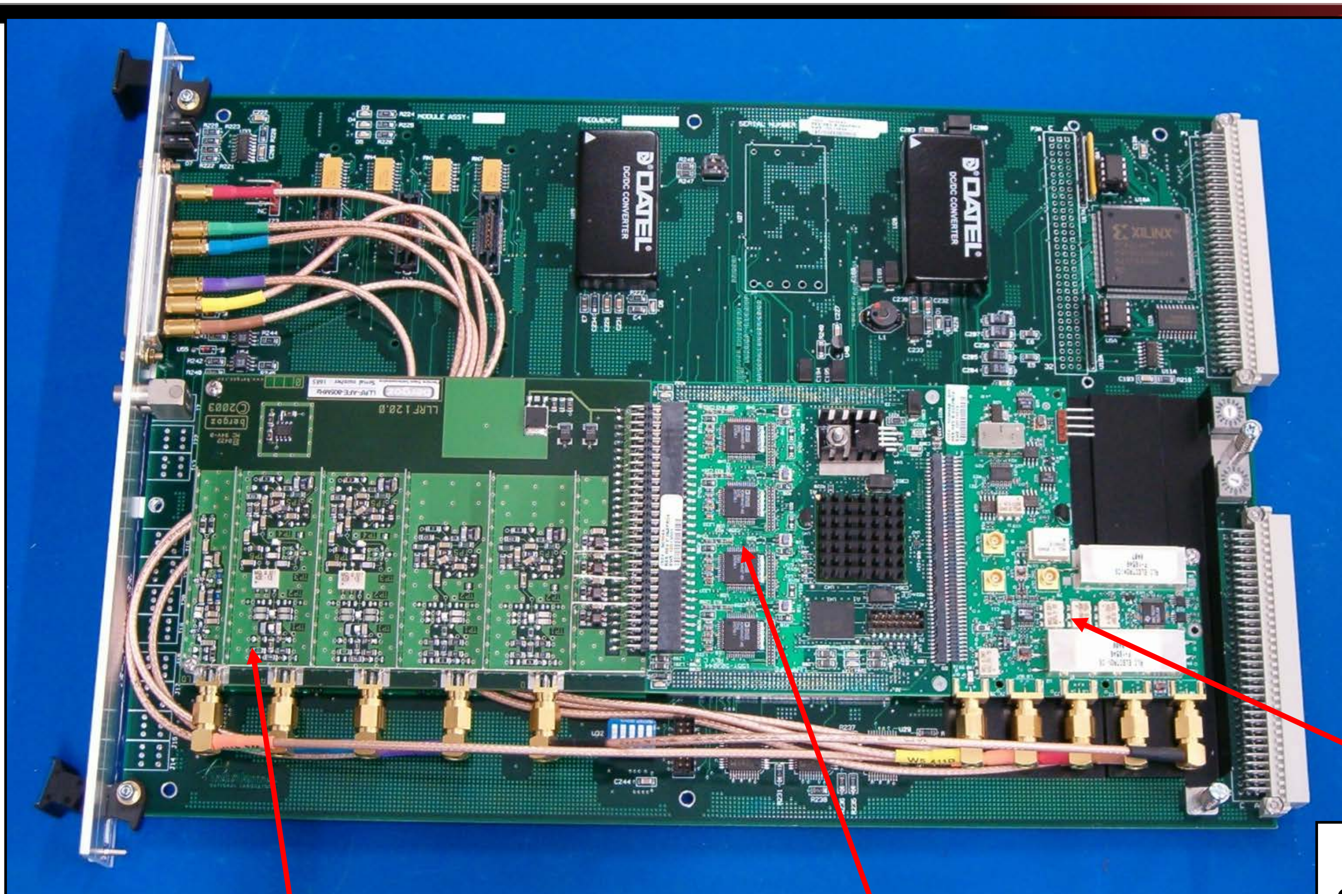




SNS



- **VXI format**
- **Single Cavity single RF amplifier.**
- **Secondary module to monitor the amplitude of the signals generated at the HOM ports.**

RF Output (RFO)
Clock & PLL circuitry
One 14 bit, 80 MHz DAC
Up-Conversion to 402.5/805 MHz
Filtering

Analog Front End (AFE)
Down-converting channels:
Incident and Reflected RF
(402.5 or 805 MHz)
IF channels:
Cavity and Reference (50 MHz)

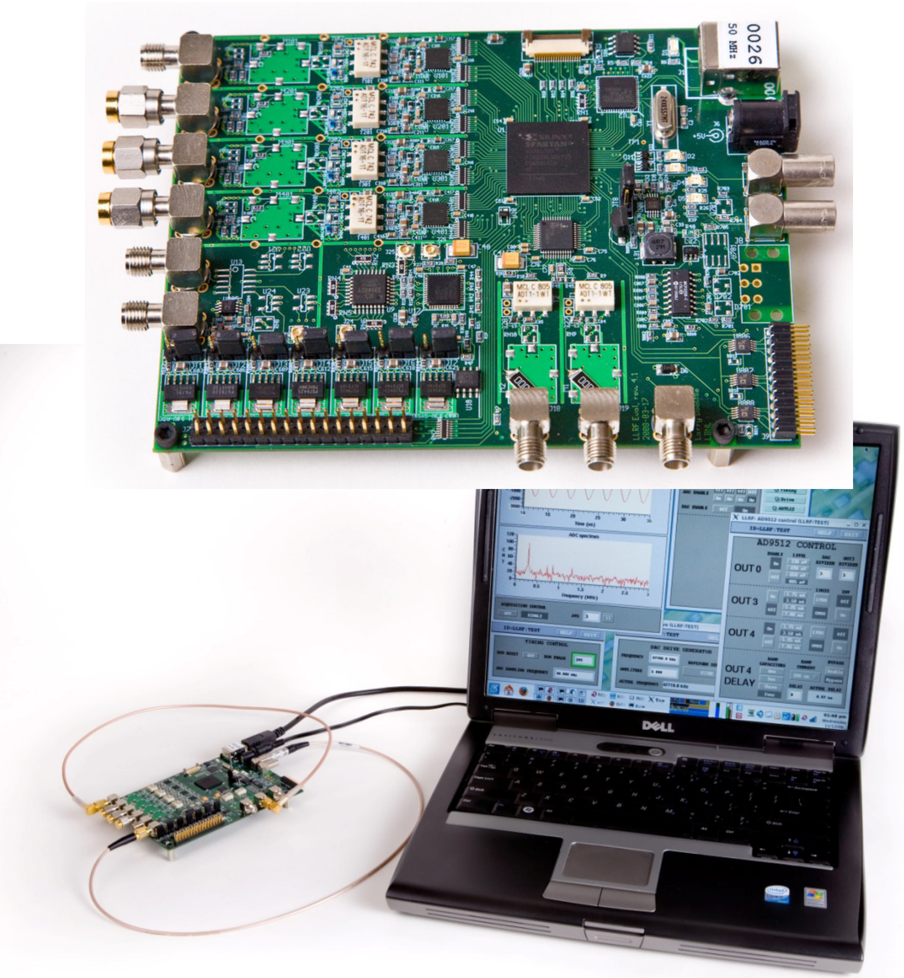
Digital Front End (DFE)
Four 14 bit, 40 MHz ADC channels
One Virtex II FPGA
(XC2V1500 – 1.5M gates)

Champion, M. LLRF 2005

Dimtel, Inc

- Bunch-by-bunch feedback processors;
- RF front and back ends for bunch-by-bunch feedback;
- Bunch-by-bunch current monitors;
- Bunch-by-bunch data recorders;
- General-purpose gigasample digital signal processing channels;
- Low-level RF processors.

- Located in San Jose, CA, USA



LLRF-4 Evaluation board

Instrumentation Technologies

- **Digital LLRF systems**
- **Beam Position Monitros**
- **Clock Distribution Systems**
- **Bunch by Bunch Feedback systems**
- **Photon Beam Processor**

Libera Digital LLRF System

- **Located in Solkan, Slovenia**

Microphonics and Frequency Drifts

- SRF cavity frequency shifts can come from multiple sources.
- Slow Helium fluctuations
- Vibrations can be driven by external narrow band sources such as HVAC motors, cooling water systems, cryogenic systems.
- They can also driven by broad band noise which, in general, will excite the resonant modes of the structure.
- In my opinion slow sub-Hertz frequency drifts, such as due to slow pressure fluctuations, are **frequency drifts** while frequency shifts which have higher frequency content are considered **microphonics effects**.

Microphonics Measurement

- SEL mode use I and Q and the following equation:

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

- Where Δt Is the sample rate of I and Q.
- In some cases individuals use:

$$\varphi_i = cos^{-1}\left(\frac{I_i}{\sqrt{I_i^2 + Q_i^2}}\right)$$

and

$$\Delta f_i = \frac{\varphi_i - \varphi_{i-1}}{\Delta t}$$

- Which after enough math is the same as the equation at the top of the page.

Microphonics Measurement

- GDR mode, use the phase difference between the forward and transmitted power (φ) and the following equation (no beam)

$$\Delta f = \frac{f_0}{2Q_L} Tan^{-1}(\varphi)$$

More on microphonics yesterday