Experience with High Loaded Q cavity Operation at JLAB

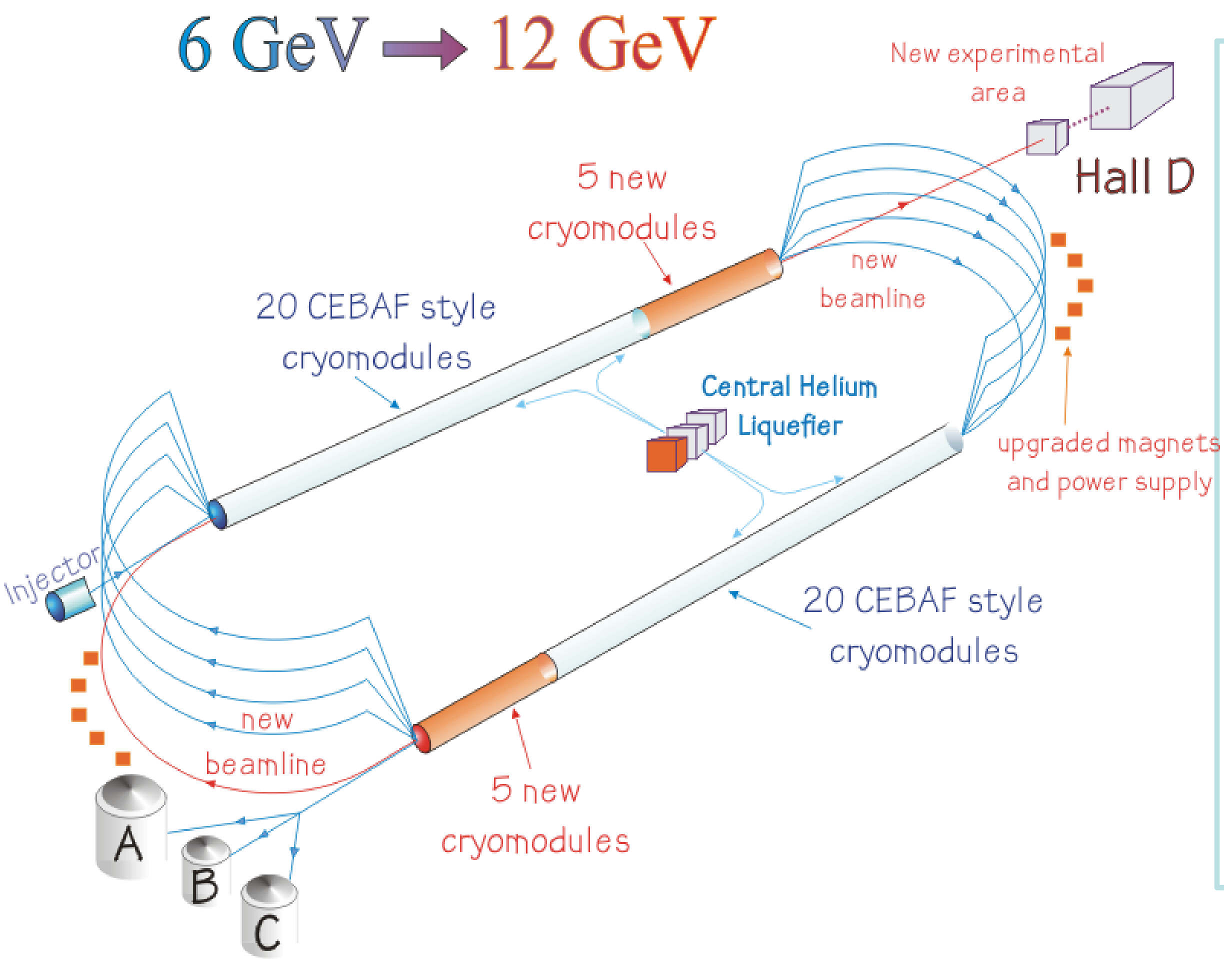
Tomasz Plawski – Jefferson Lab , Newport News, VA

On behalf of LLRF Group at JLAB

Outline

- 12 GeV Project
- High Q Cavity Operation Challenges
- C100 LLRF system
- Field Startup
- RF Field Control Results
- Operability/Improvements
- C100 One Hour Run
- C100 Commissioning
- Commissioning Summary
- LLRF - Toward the Next Generation

12 GeV Upgrade Project



- New cryomodules
- New RF power sources (13 kW)
- Refrigeration
- Magnets
- Additional arc-beamline
- Extraction system
- New experimental area Hall D

RF Control Challenges / Starting Points

- **Required Field Control to meet accelerator performance:**

    0.5^{o} rms phase and 0.045% rms gradient

- **High Q_L optimized for beam loading:**

    3.2×10^{7} / 465 uA

- **Microphonics & Lorentz Detuning:**

Determined by cavity/cryomodule design and background environment

    4 Hz rms/ 6σ=24 Hz

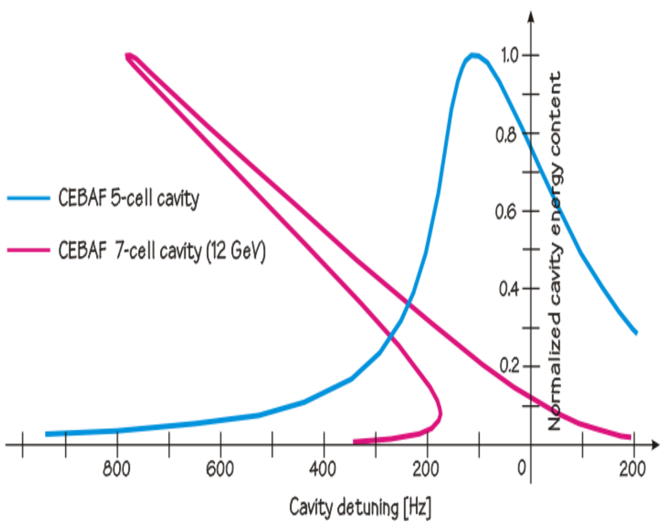
- **Master Oscillator/Timing/Synchronization**

- **Operational, Reliability/Maintainability Access etc.**

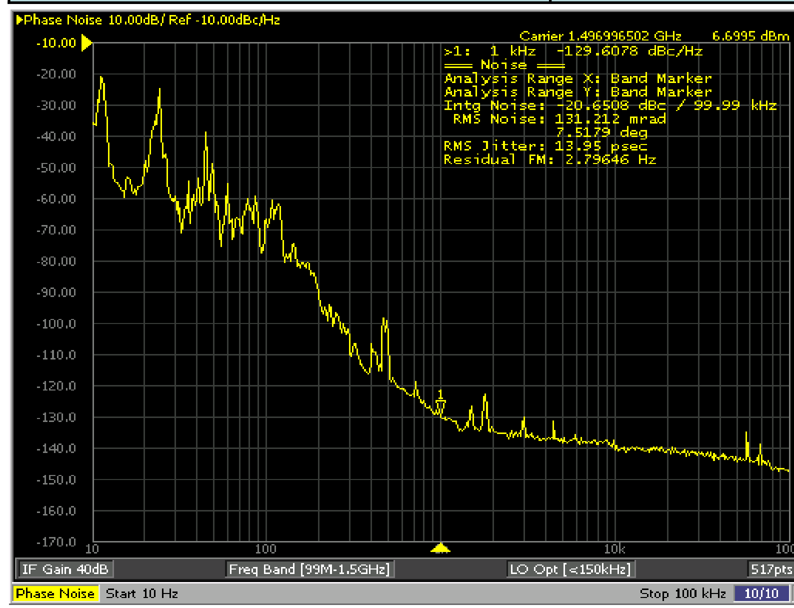
High Q_L Challenges

Fundamental frequency f_0	1497 MHz
Accelerating gradient E_{acc}	> 20 MV/m
Input coupler Q_{ext}	3.2 x 10^7
Active length	0.7 m
r/Q	1300 Ω/m
Tunning sensitivity	0.3 Hz/nm
Pressure sensitivity	420 Hz/torr
Lorenz force frequency sensitivity K_L	~2 Hz/$(MV/m)^2$

Field startup

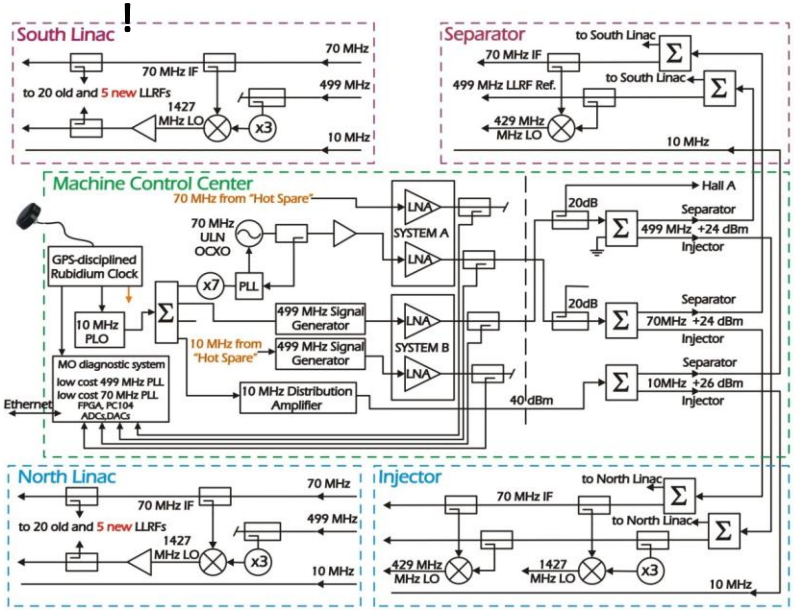


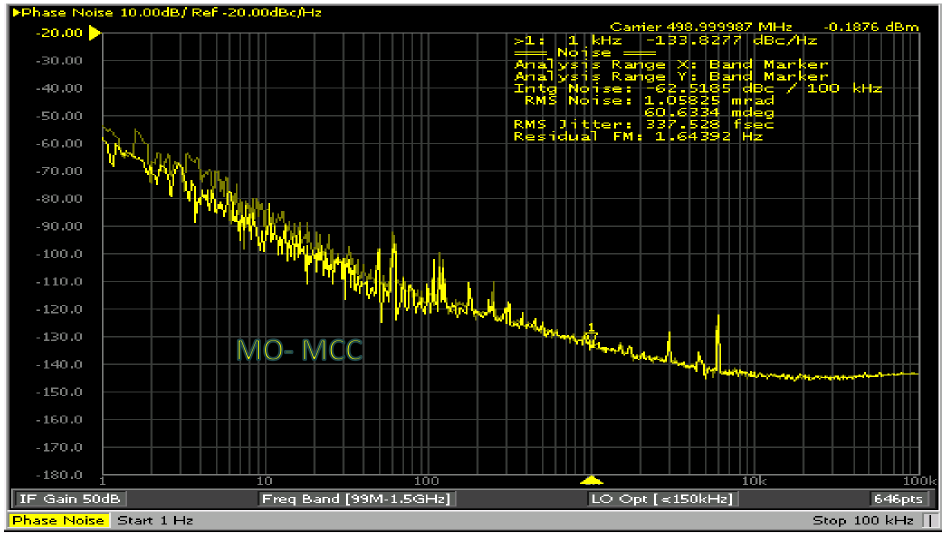
Field stability (microphonics)

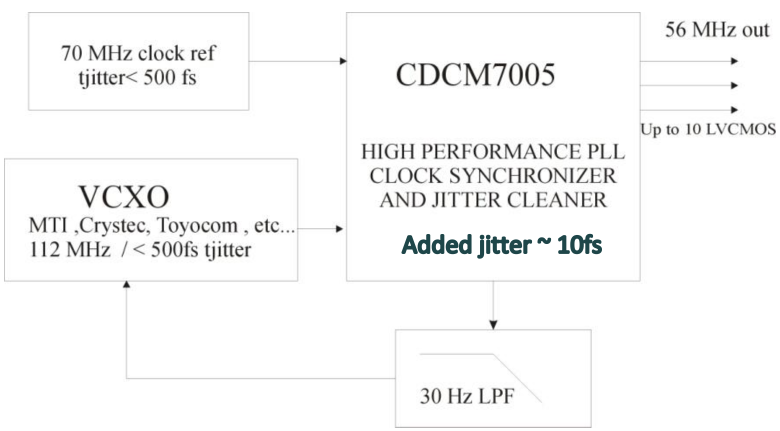


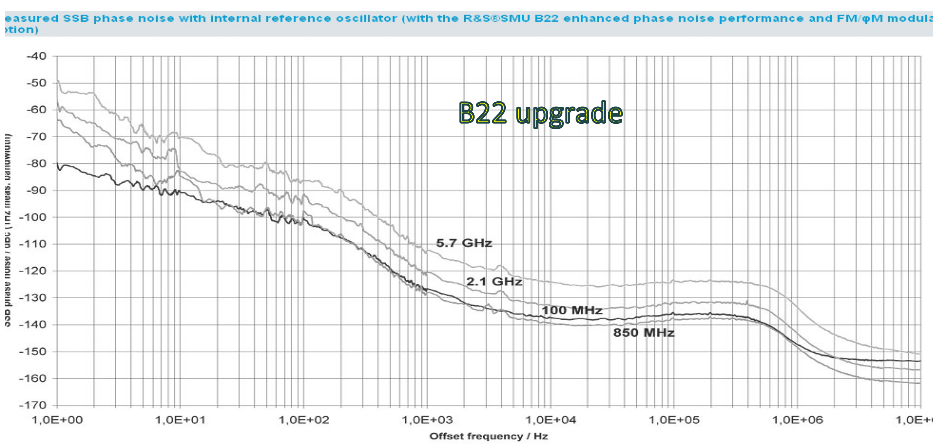
Timing/Synchronization

Local oscillator (LO) is the largest contributor of uncorrectable error in cavity accelerating field !







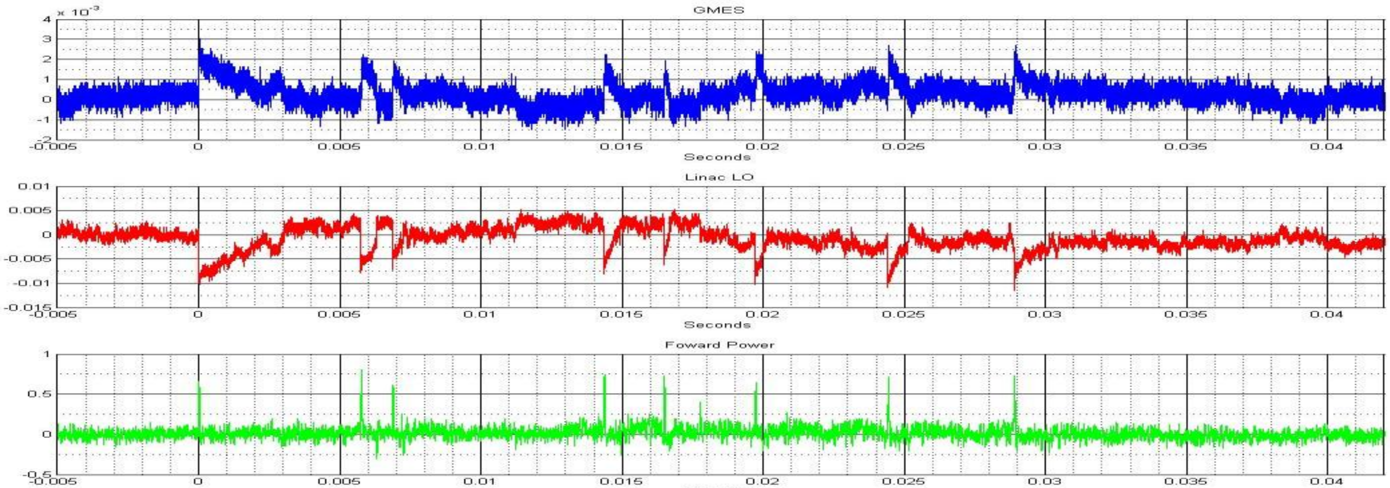


asured SSB phase noise with internal reference oscillator (with the R&S®SMU B22 enhanced phase noise performance and FM/φM modulator option)

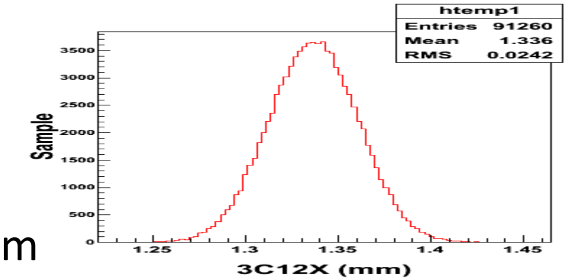
LO Induced Instabilities

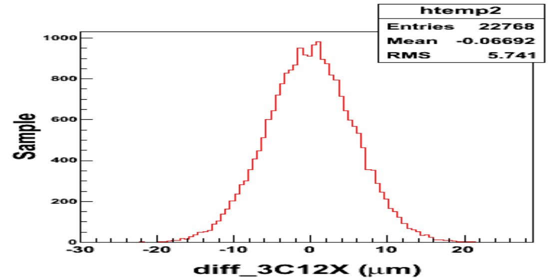
SL25/ 4 2012

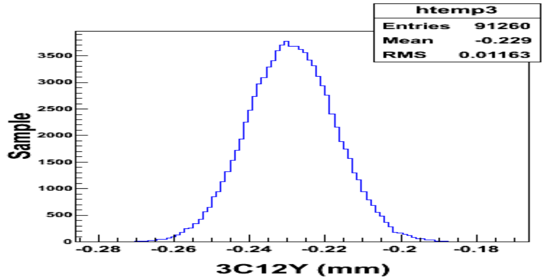
LO amplitude

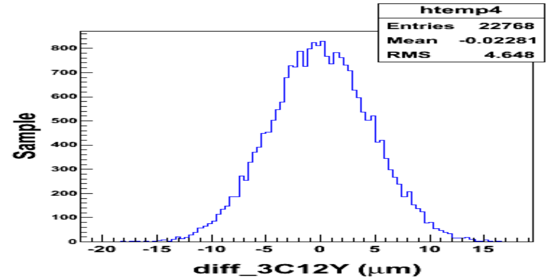


Processed data from QWeak BPM

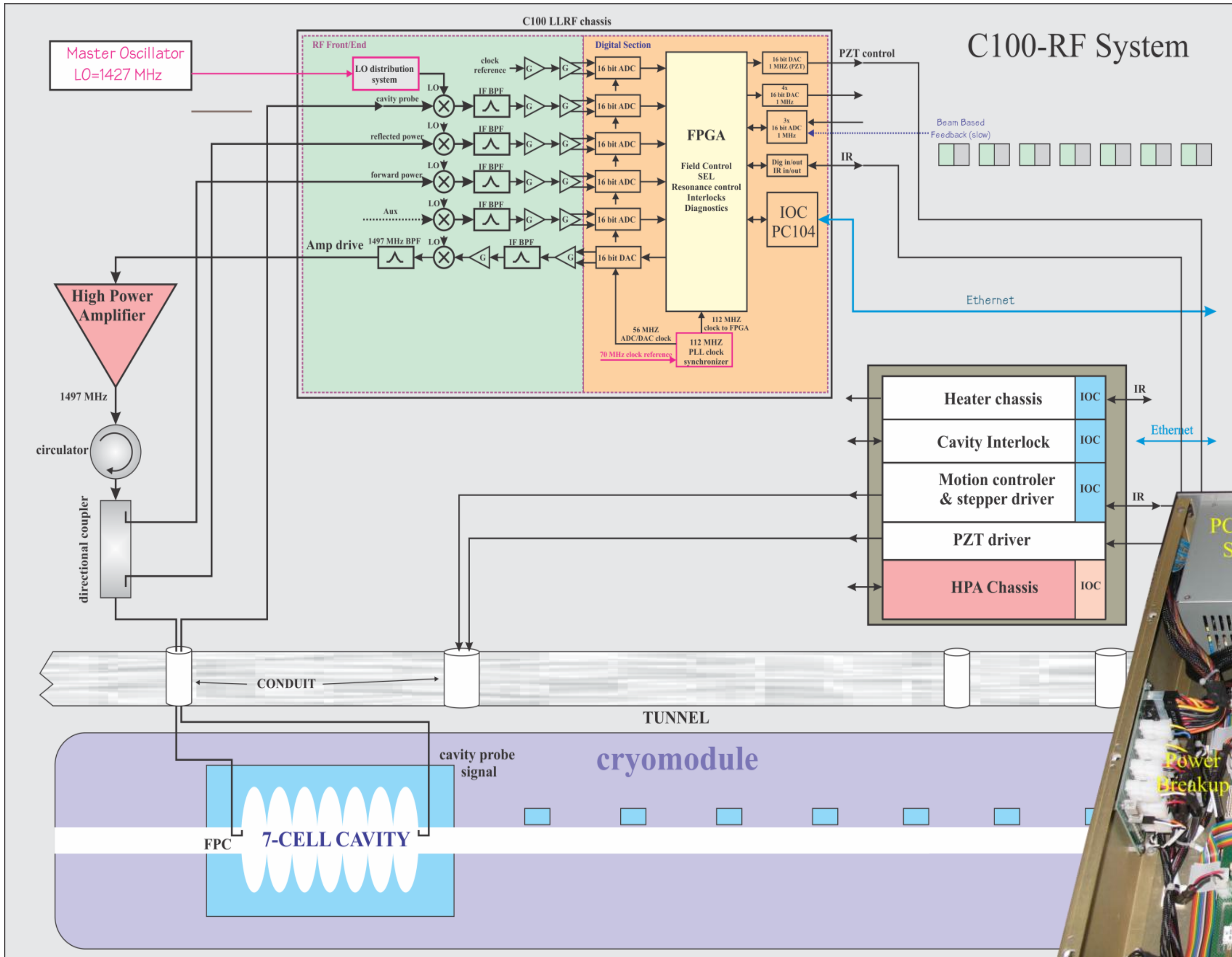




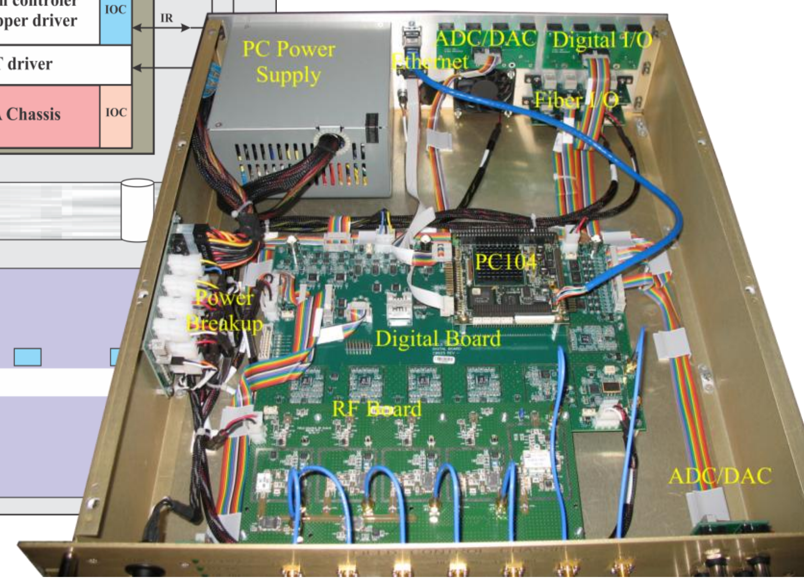




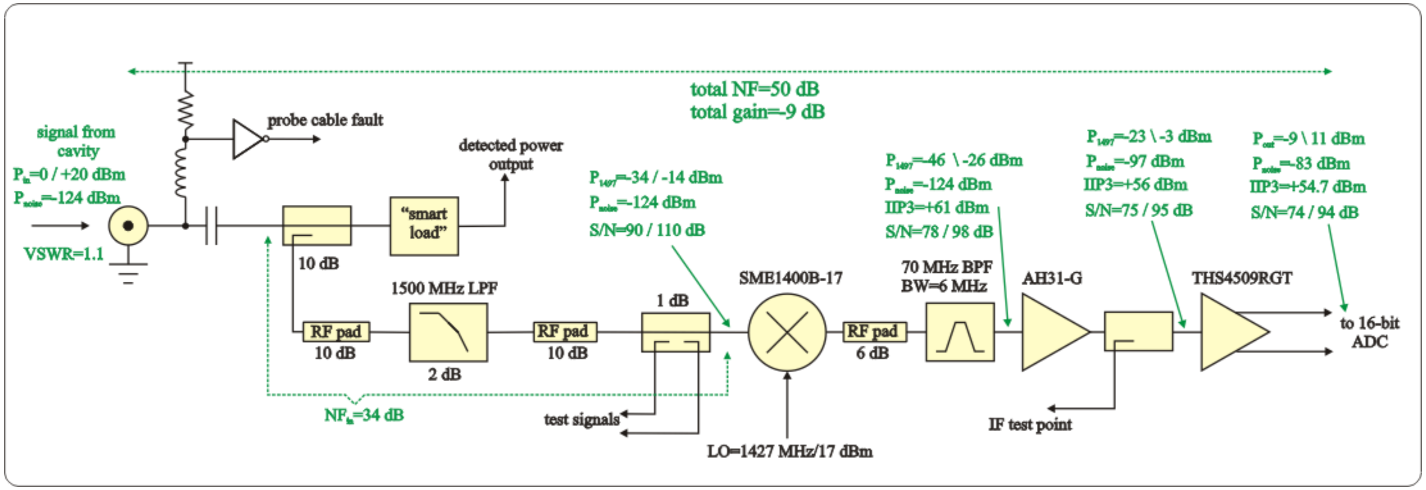
RF System for C100 Cryomodule



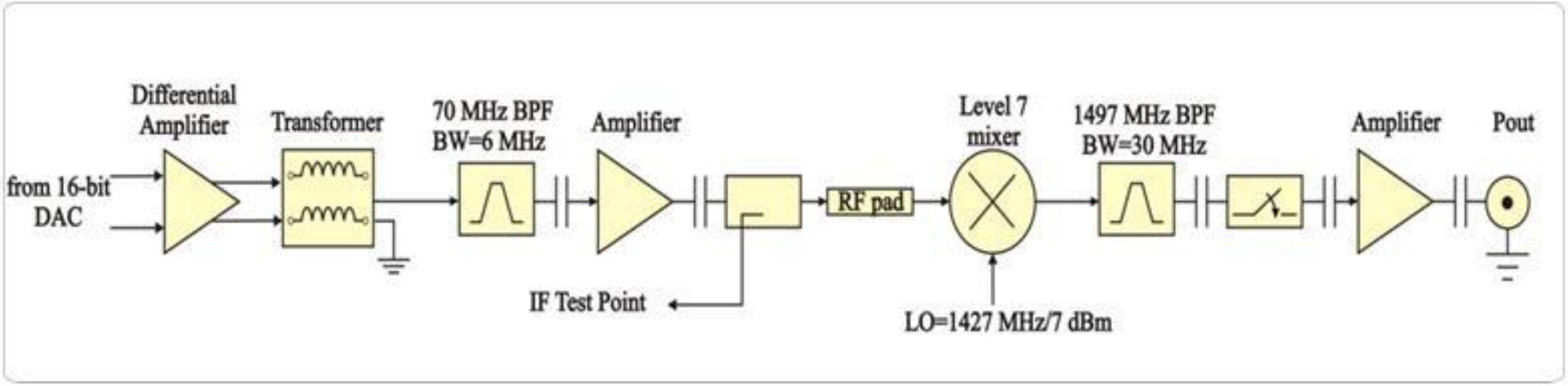
- **Heterodyning**
- **FPGA/DSP**
- **Single DAC Drive**
- **IOC – PC104**
- **EPICS**



RF Front-End



Receiver



Transmitter

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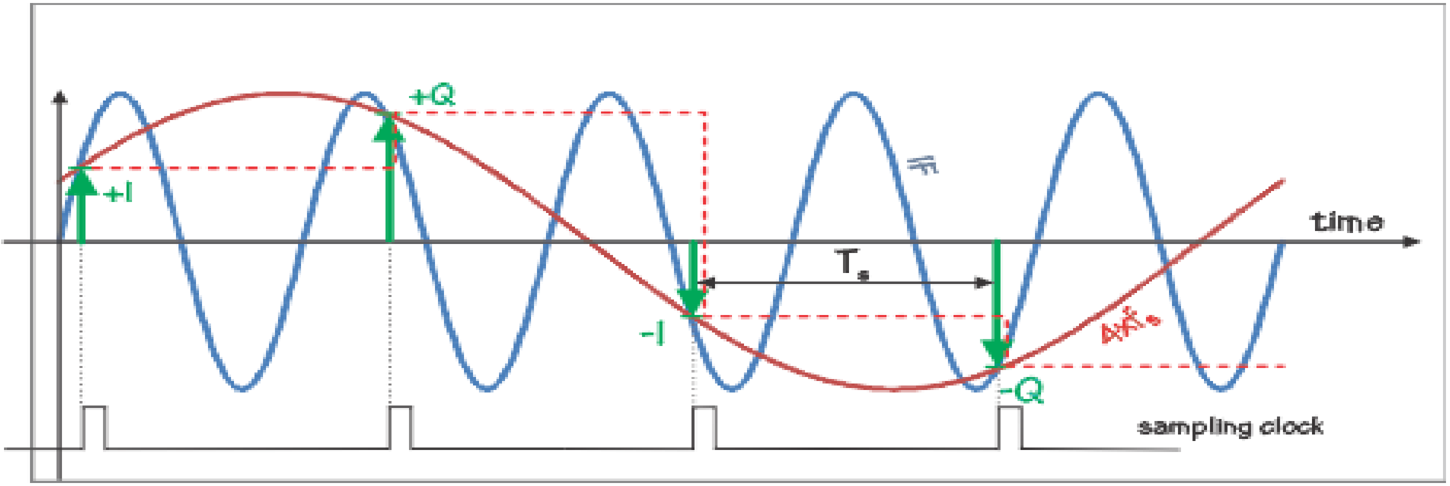
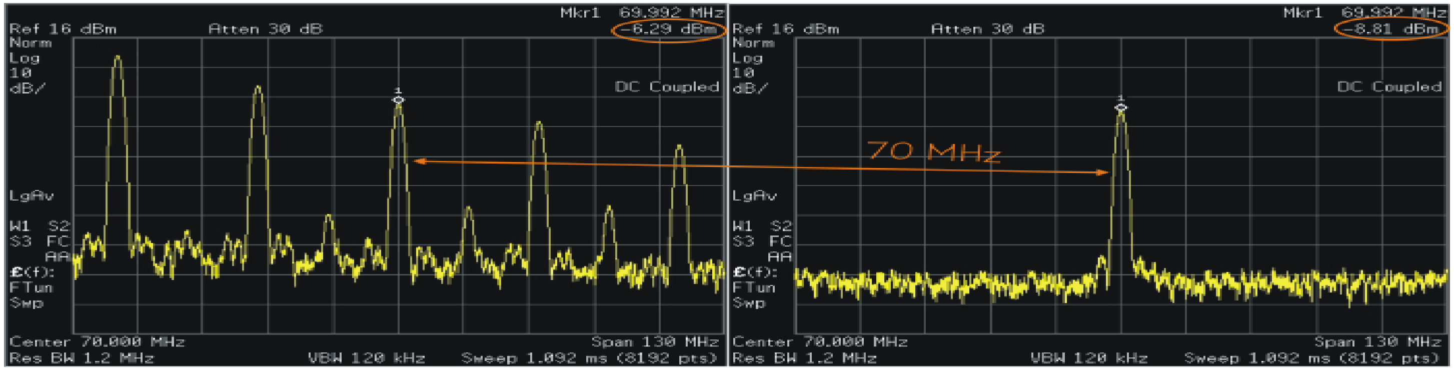
IQ Sampling

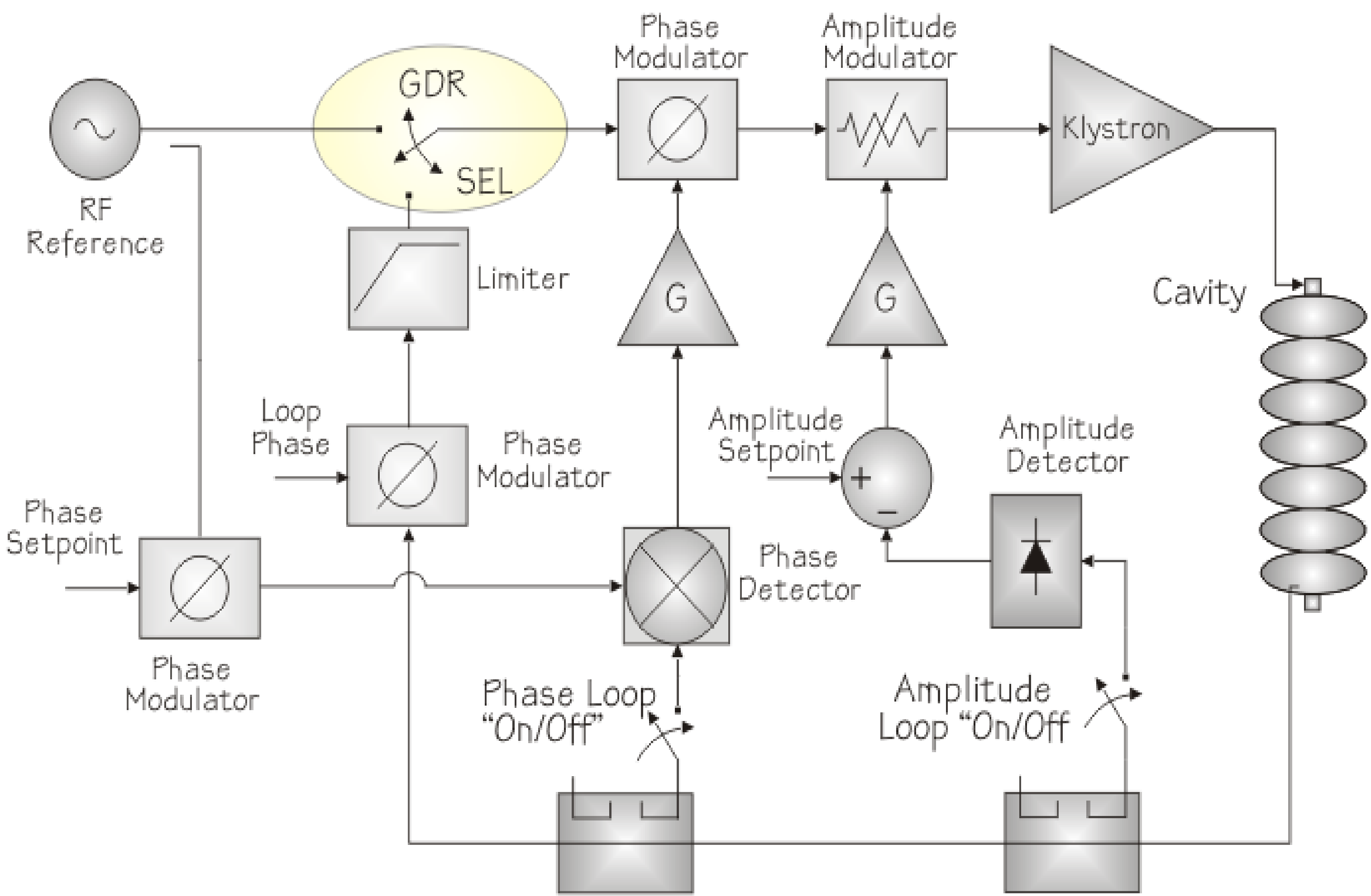


$$x(t) = I \times \sin(\omega t) + Q \times \cos(\omega t) \quad \text{where} \quad A = \sqrt{I^2 + Q^2} \quad \text{and} \quad \varphi = \arctan\frac{Q}{I}$$



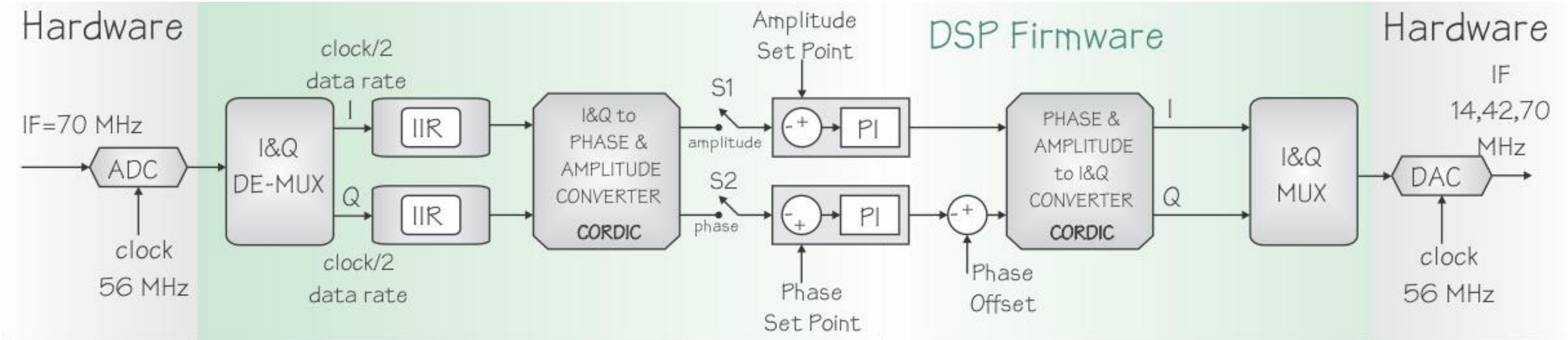
$$DAC_{IQ}(t) = \frac{4}{\pi}\left(\sin(2\pi f_{s/4} t) + \frac{1}{3}\sin(6\pi f_{s/4} t) + \frac{1}{5}\sin(10\pi f_{s/4} t) + \ldots\right)$$

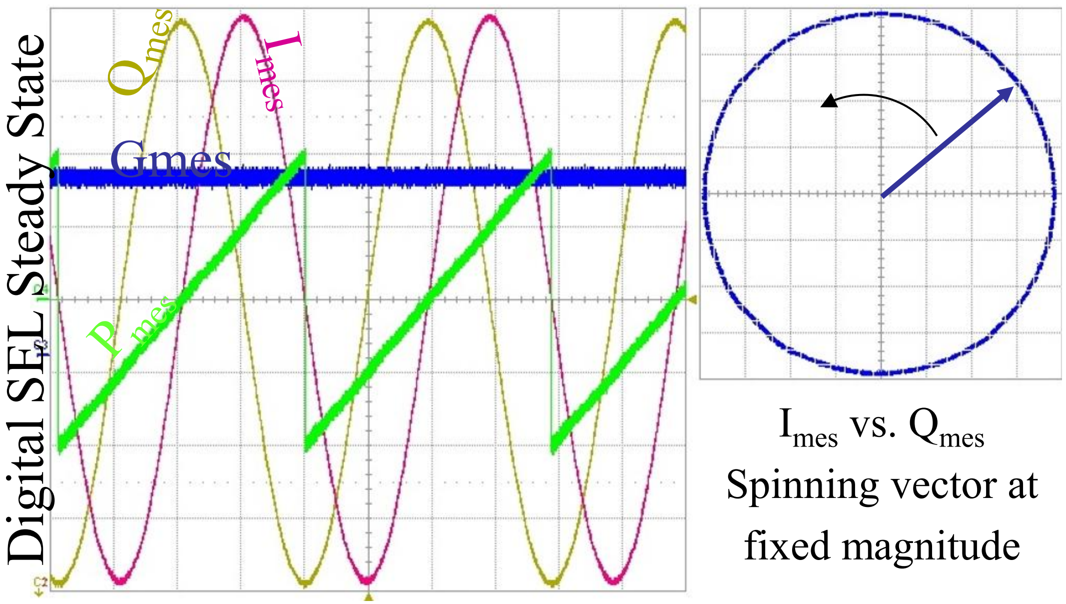
GDR/SEL



Phase
Modulator
Amplitude
Modulator
GDR
SEL
Klystron
RF
Reference
Limiter
G
G
Cavity
Loop
Phase
Phase
Modulator
Amplitude
Setpoint
+
–
Amplitude
Detector
Phase
Setpoint
Phase
Detector
Phase
Modulator
Phase Loop
"On/Off"
Amplitude
Loop "On/Off

Field Startup – DSEL (Digital Self Excited Loop)

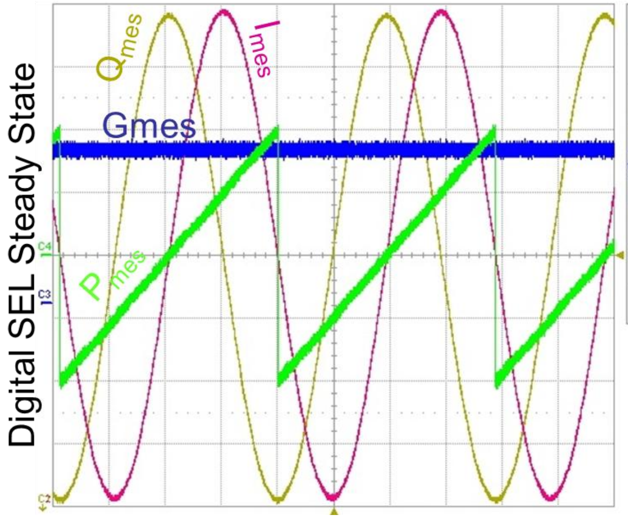


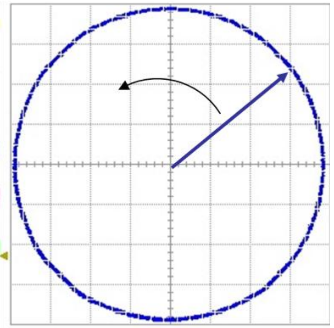


I_{mes} vs. Q_{mes}
Spinning vector at fixed magnitude

- Accept large cavity detuning (100 kHz)
- Quickly bring up cavity gradient without running the tuner(s) [ms]

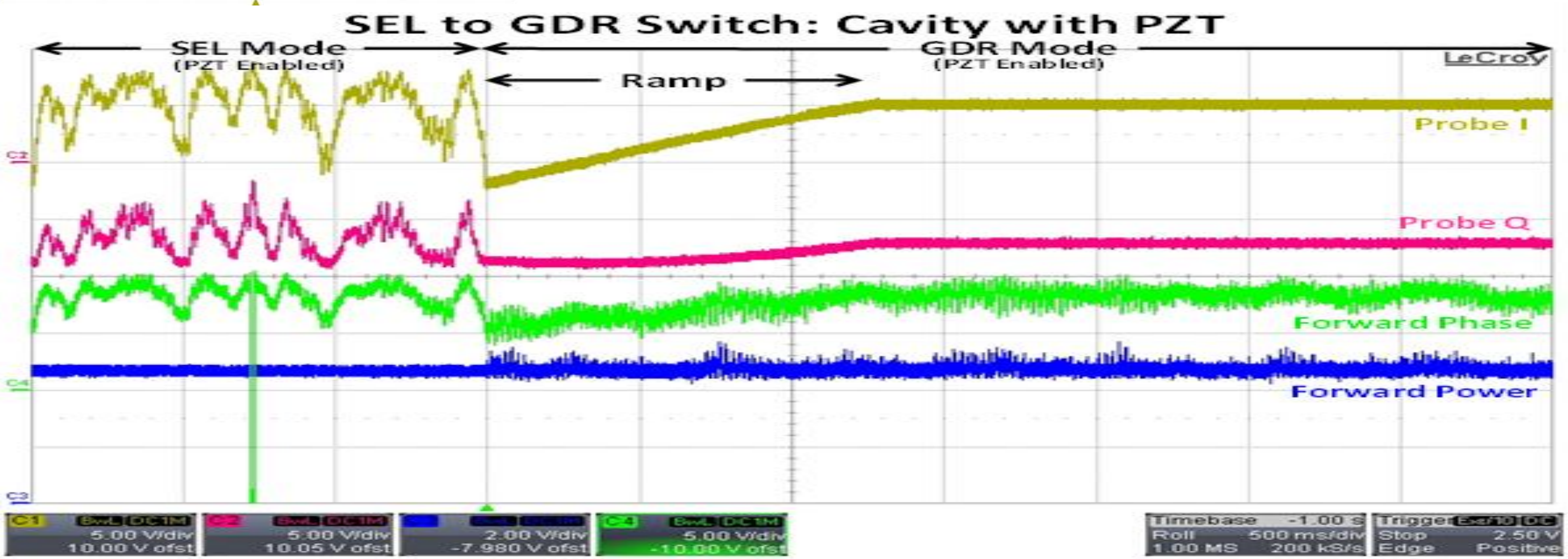
SEL To GDR



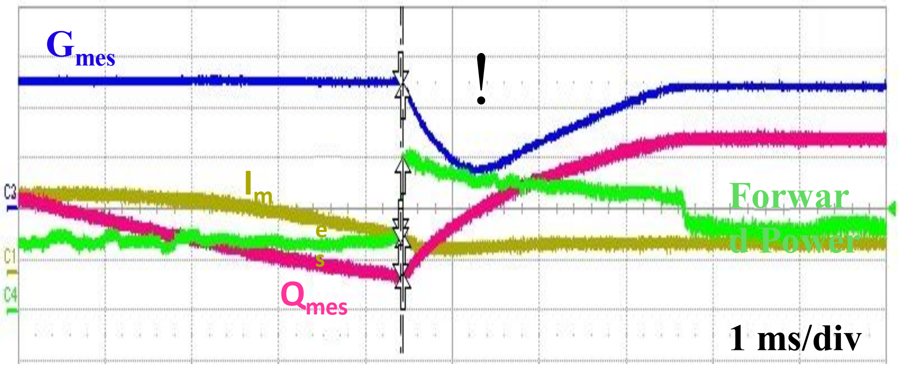


I_{mes} vs. Q_{mes}
Spinning vector at
fixed magnitude

Digital Self Exciting Loop (DSEL)



SEL to GDR



Without special procedure (firmware), transition form SEL to GDR mode will cause forward power to spike and system to trip.

Frequency Discriminator (firmware)

Four frequency ranges automatically selected

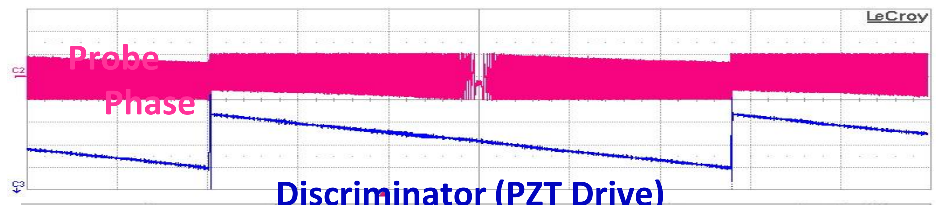
1-125 Hz (PZT, stepper)

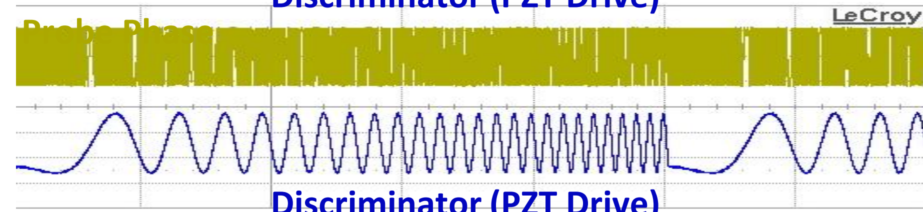
125 Hz- 1250 Hz (stepper, PZT)

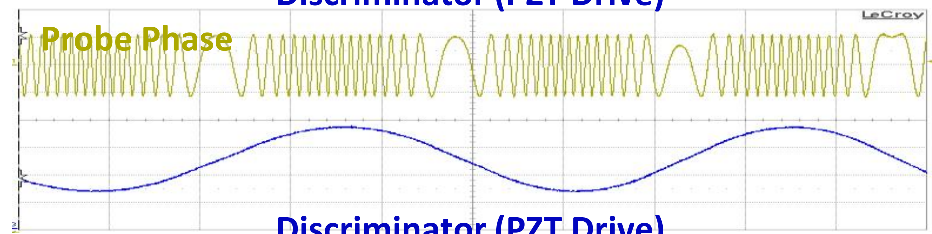
1250 Hz- 50 kHz (stepper)

50 kHz- 500 kHz (stepper)

Tuner







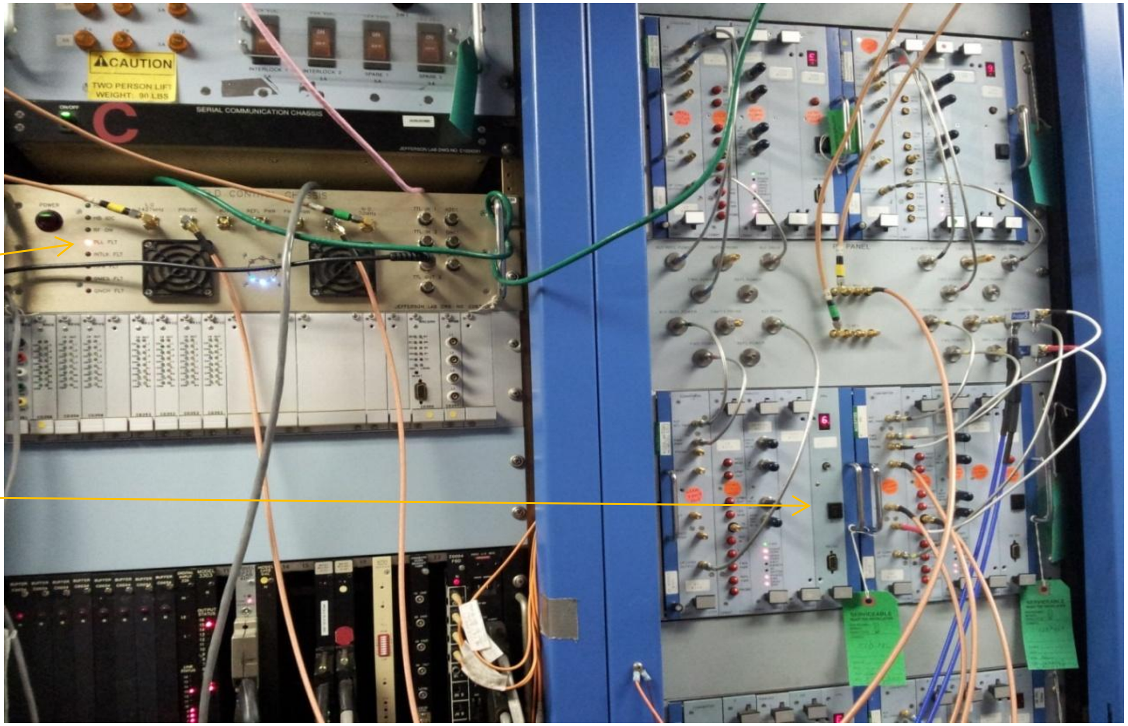
SRF Commissioning - SEL Mode

Cavity commissioning

DLLRF Chassis + CEBAF Analog LLRF

Digital LLRF System

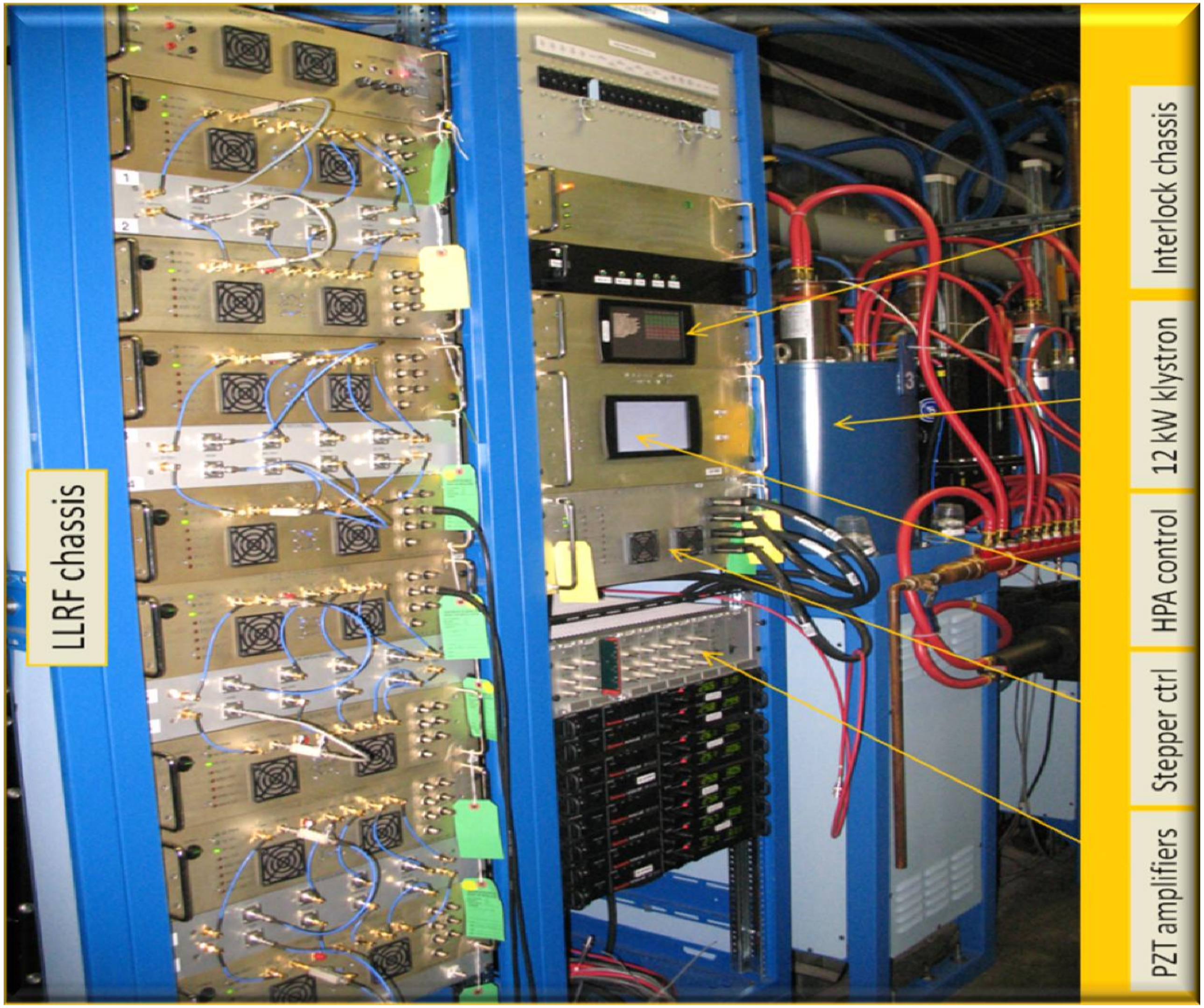
Analog LLRF Systems
for C20 and C50



Focused on determining stable operating gradients, accomplished through a combination of

- Maximum Gradient Determination
- Field Emission Measurements
- Q0 / RF Heat Load Measurement
  (all SEL mode)

RF system for C100 Cryomodule



8 Klystrons (12kW, CW)

8 Digital (FPGA) LLRF systems

1 Digital (FPGA) HPA system

1 Digital (FPGA) Interlock system

1 Digital (FPGA) Stepper controller

8 PZT amplifiers

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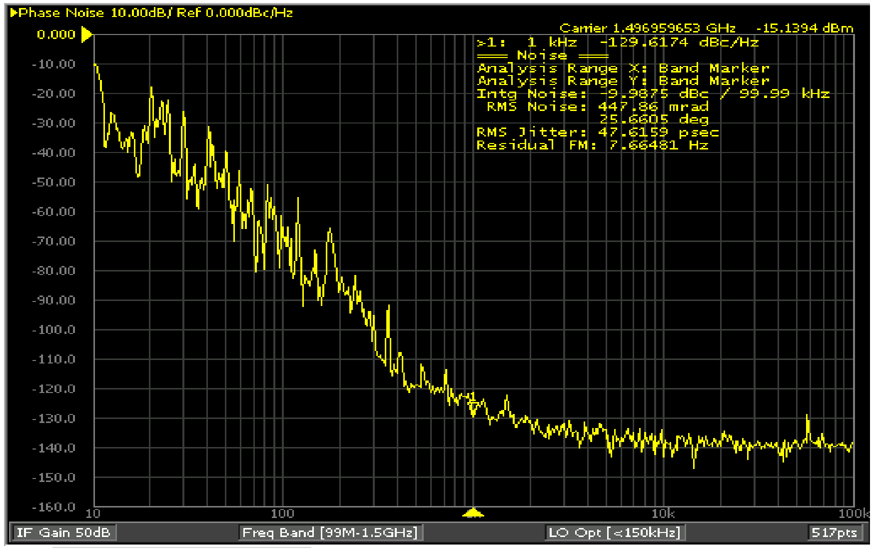
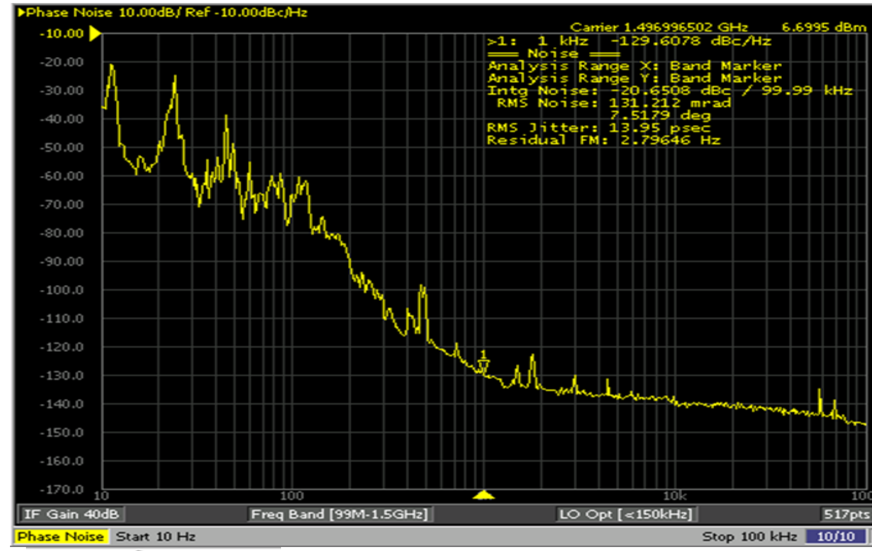
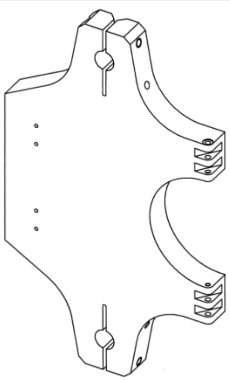
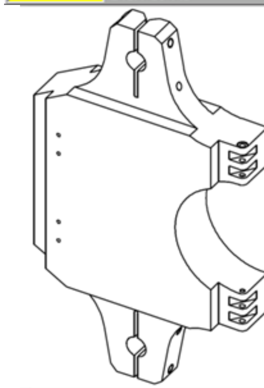
C100 GDR Mode – Original/Modified Tuner



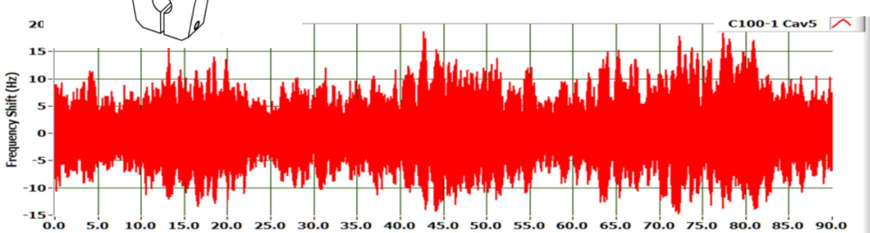


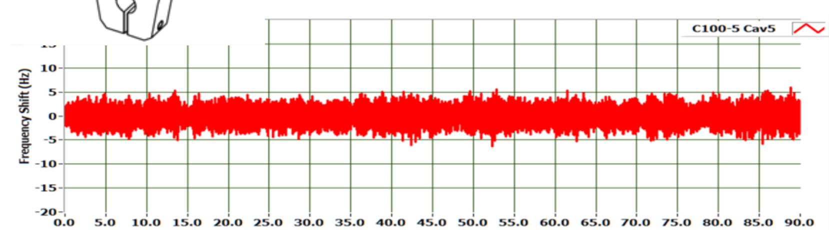


Phase noise
25.6 deg rms /14 Hz rms

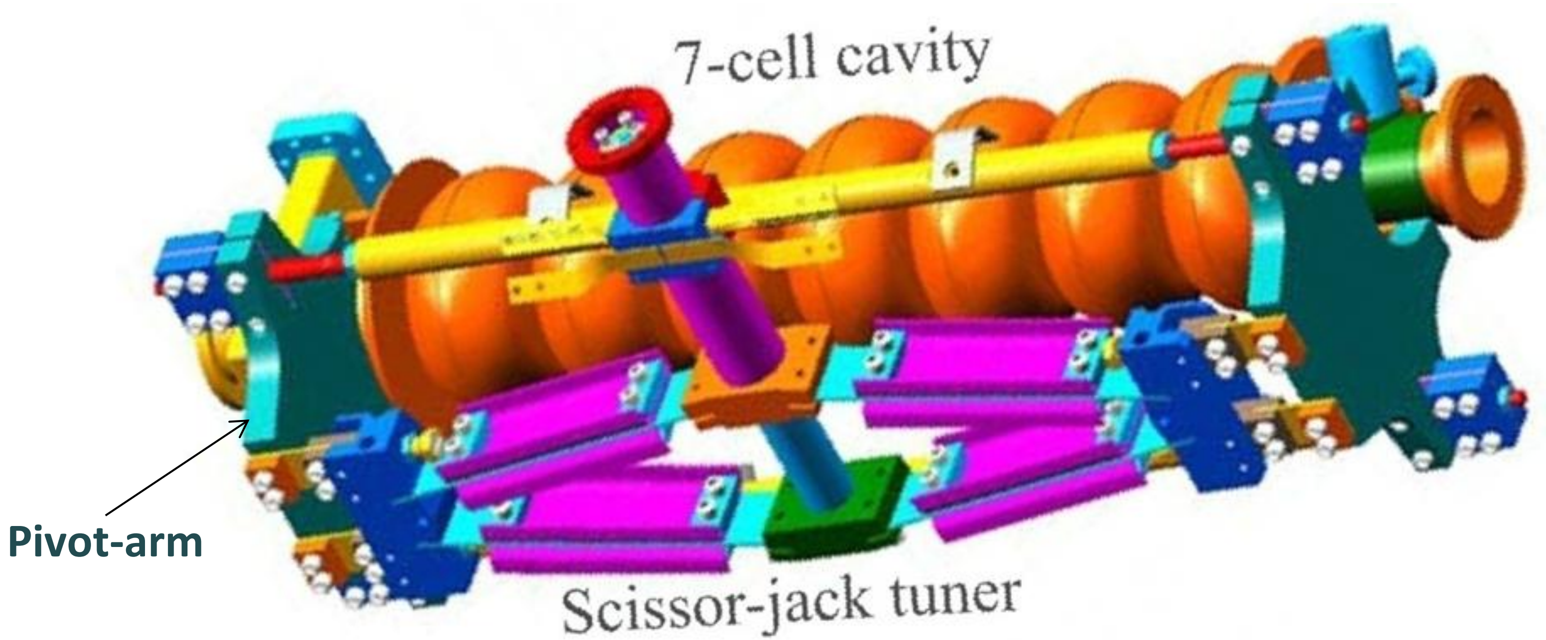


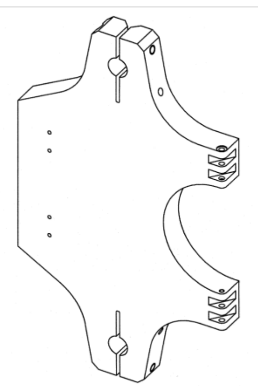
Phase noise
7.5 deg rms /4 Hz rms



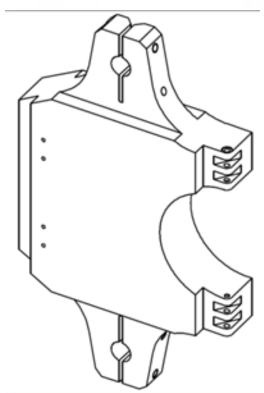


Original/Modified Tuner





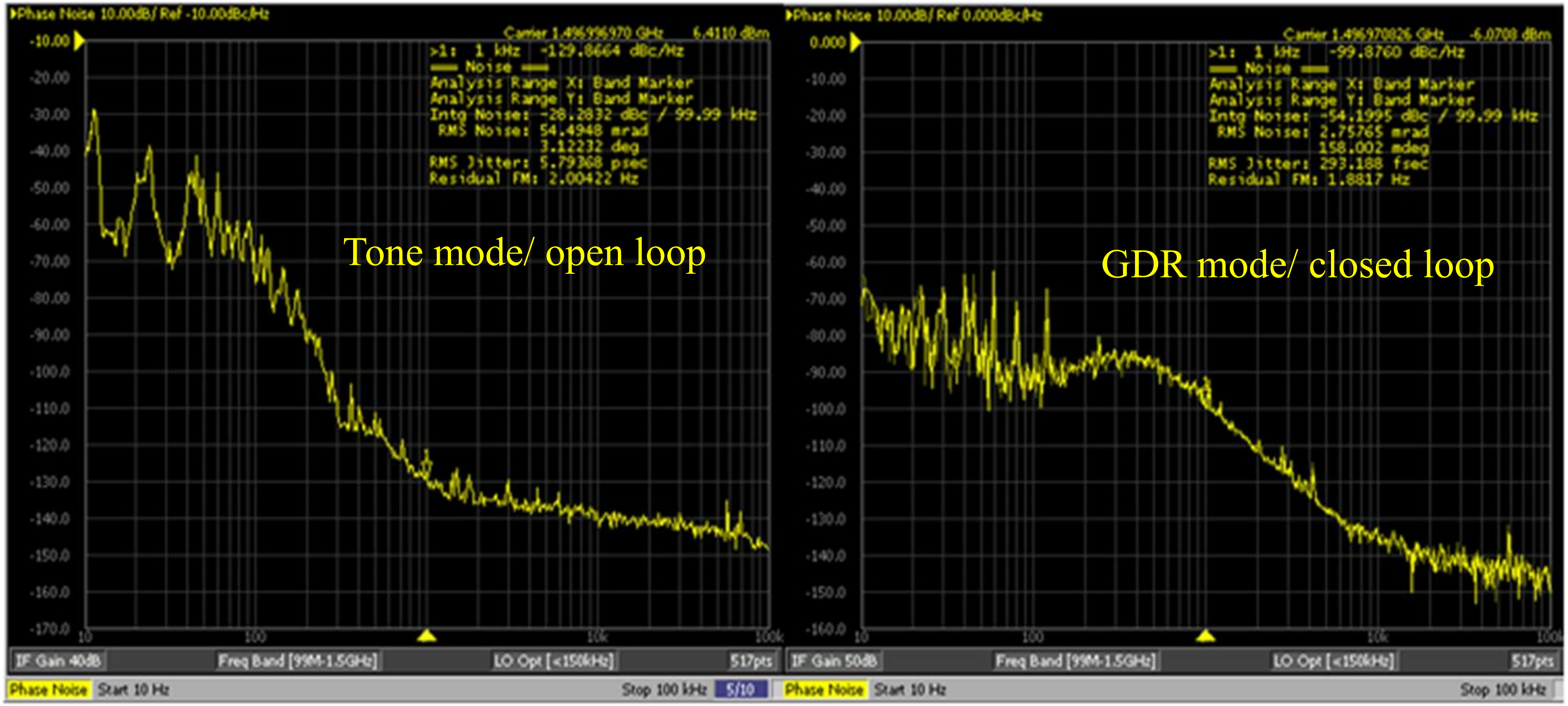
Phase noise
25.6 deg rms /14 Hz rms



Phase noise
7.5 deg rms /4 Hz rms

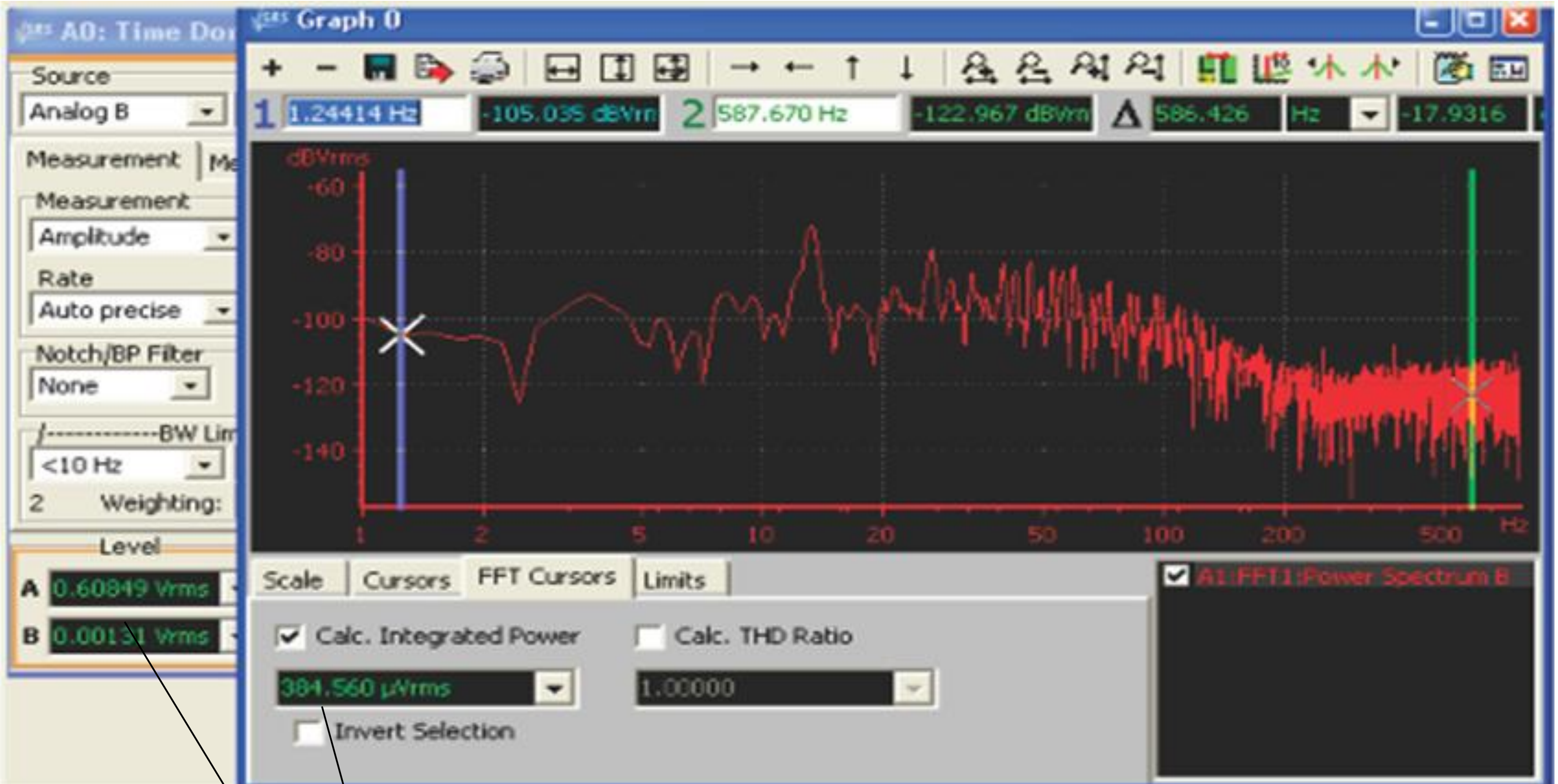
J. Matalevich – private conversation

C100 Field Stability (Phase)



Phase noise spectral density for Tone Mode (< 3MV/m) and GDR (21 MV/m) mode

C100 Gradient Stability



$$\frac{384\times10^{-6}}{0.608}=0.6\times10^{-4}$$

measurement with Audio Analyzer

“Coupled Cavities”

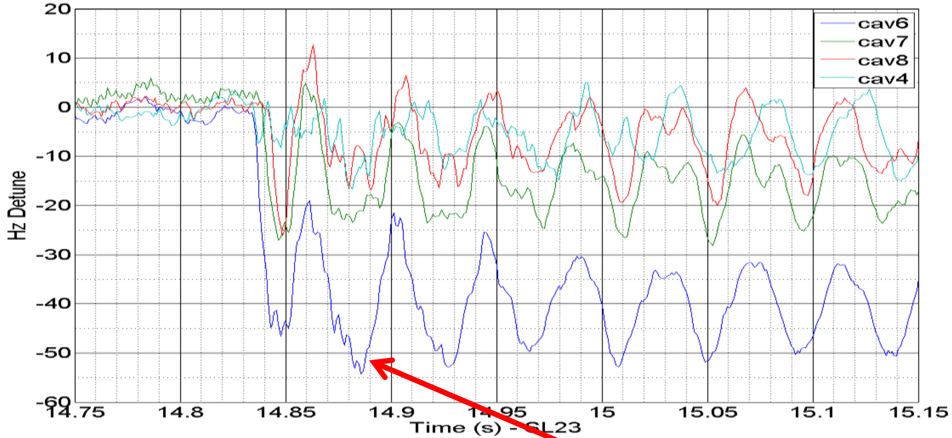
C100-4 Cavities 4, 6, 7, 8 responding to an applied PZT step voltage change from 4 to 3 volts in cavity 5

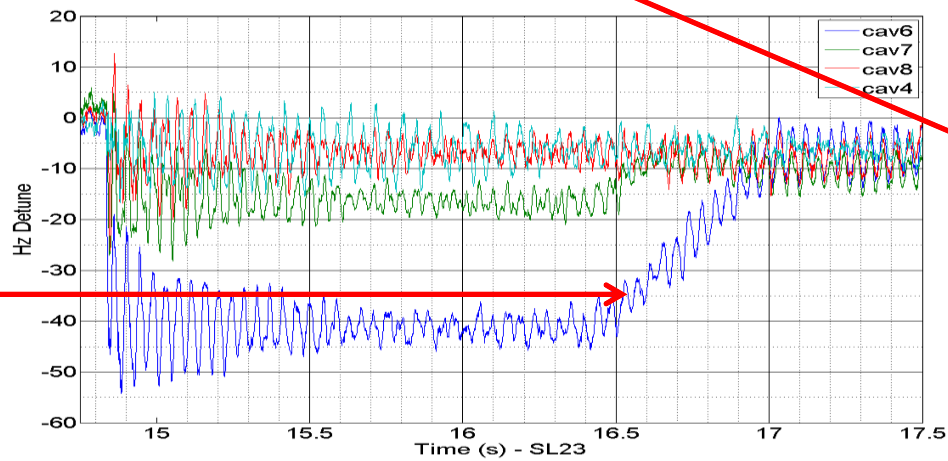
Cavity 5 PZT moved 460 Hz

Cavity Gradients 10 MV/m Locked in GDR Mode

Klystron had the overhead to keep cavities locked

Stepper Motor kicks in to tune the cavities



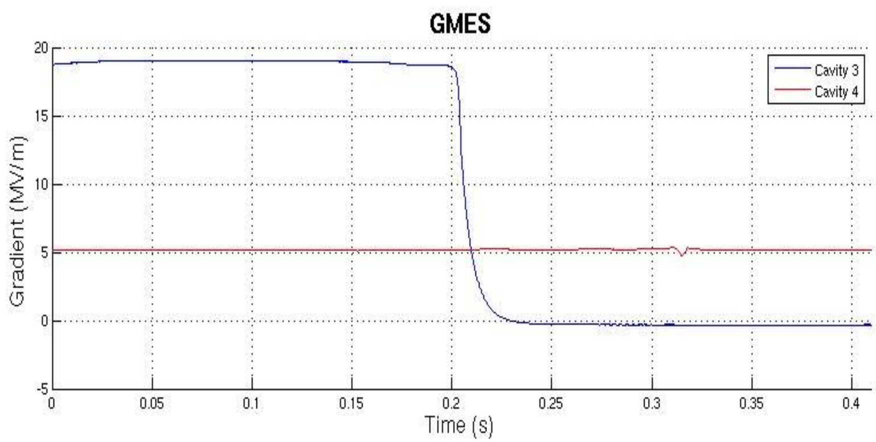


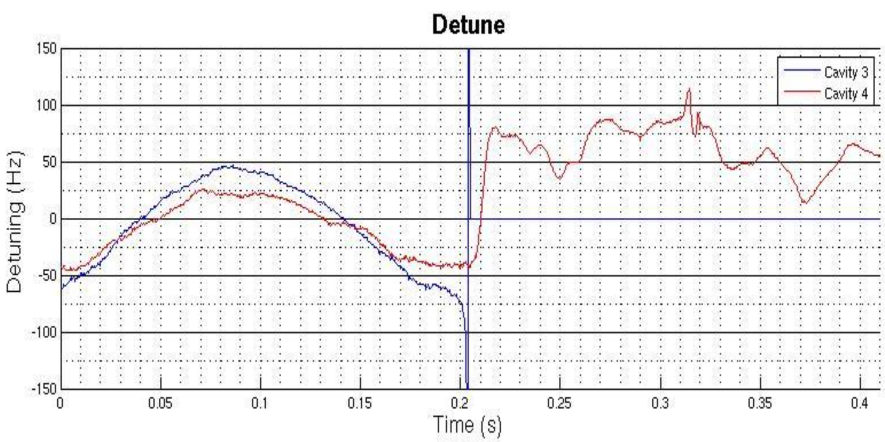
Adjacent Cavity coupling is ~ 10% between 1-4 and 5-8 cavities

Cavities 4 and 5 have a “quasi” mechanical support between them.

Ringing is the 21 Hz mechanical Mode

Cavity Fratricide





Graph of gradient and detuning (Hz) as a cavity is faulting (blue)

Cavity Fratricide occurs when one cavity faults (Arc, waveguide vacuum, quench etc.) and the Lorentz force detuning of the faulted cavity detunes the adjacent cavities resulting in the cavity faulting too.

Adjacent cavity was operating at 5 MV/m so the klystron had the overhead to absorb the detuning

6/7 π Mode

2L22 shift summary

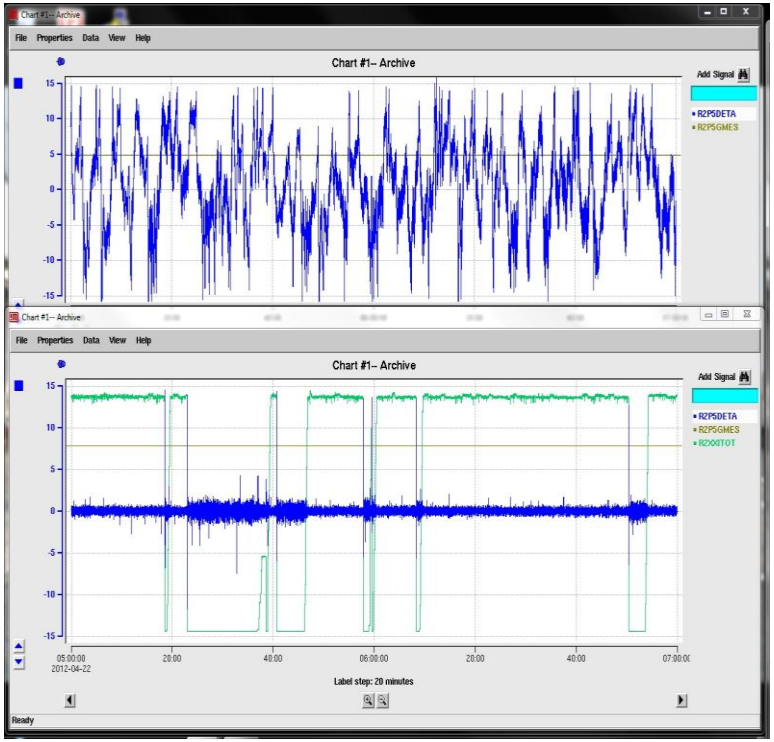
Lognumber 3254272. Submitted by xxxxxx on Sat, 09/14/2013 - 23:40.
Logbooks: ELOG LLRFLOG SADLOG
Entry Makers: xxxxxx
I spent all night measuring Emax, FE and 1 h run on Cavity 4. Towards the end of the 1 h run I noticed that the frequency measured by the frequency counter was 1495.804 MHz. The SEL excited the wrong mode (6pi/7)!
All work on Cavity 4 needs to be re-done.

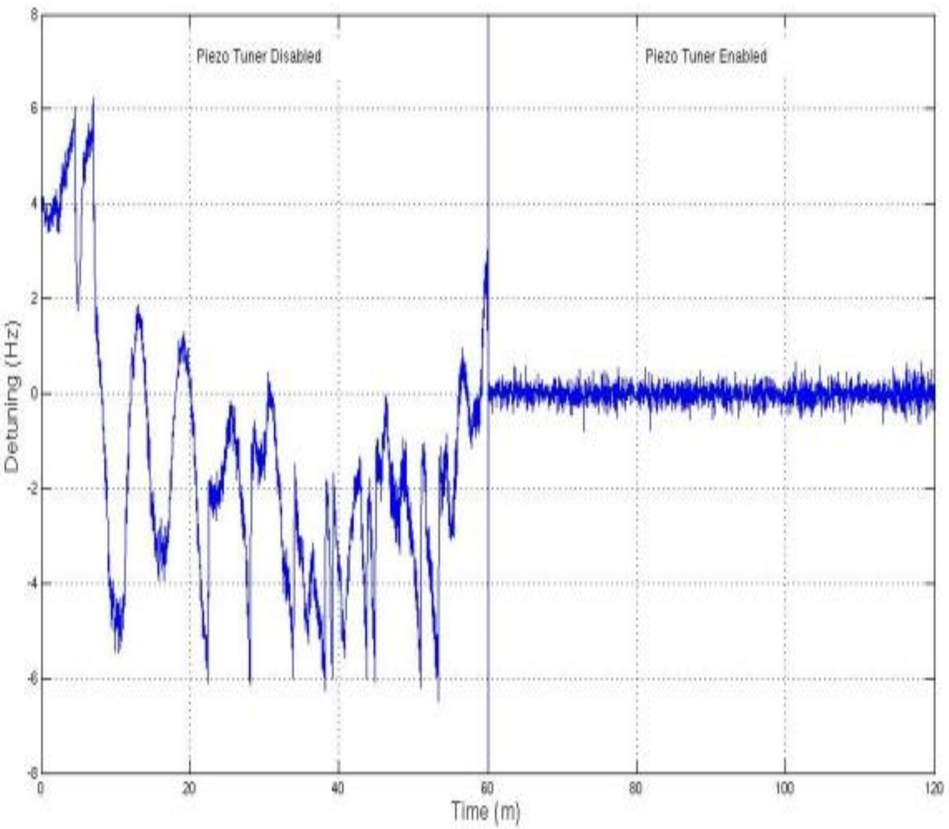
It is possible during POFF sweep excite 6/7 pi mode (SEL mode !)

Consequences:
Resonance Control System will run stepper motor till limit switch pulled !

Mitigation:
Apply narrower IIR low pas filter (17 kHz) or notch filter at 1.2 MHz . Second solution is preferable because control bandwidth remains unchanged

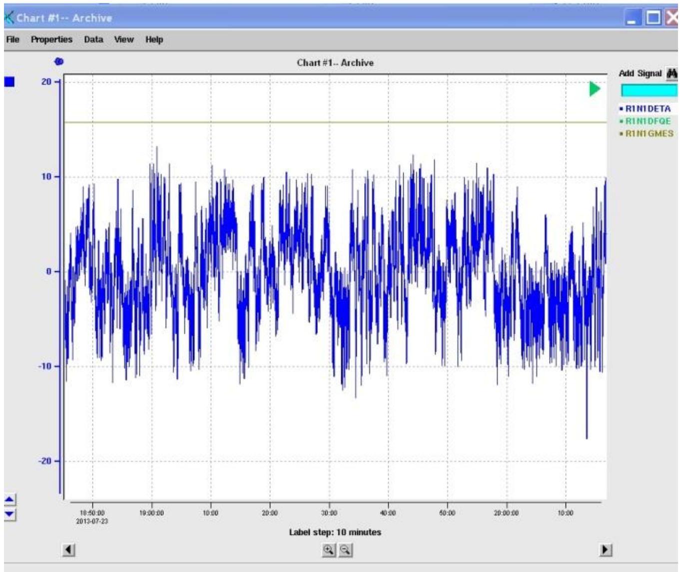
C100 PZT Control

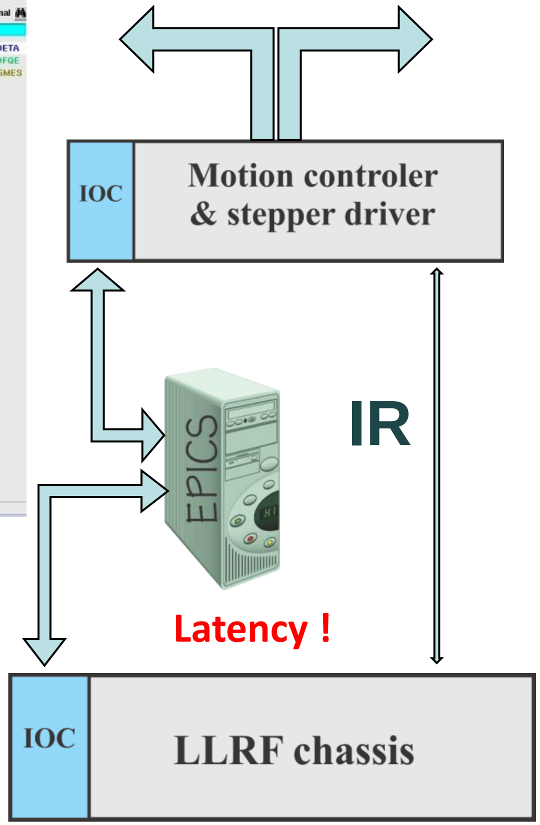


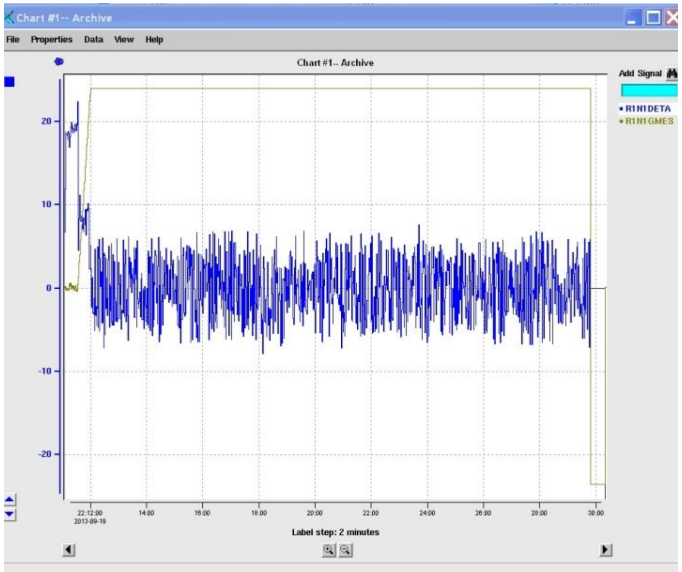


Piezo compensation bandwidth: 1 Hz
PI regulator
Wider bandwidth causes mechanical mode excitation/ instabilities
Substantial improvement for slow detuning (helium pressure drift or slow microphonics)

Resonance Control Modification



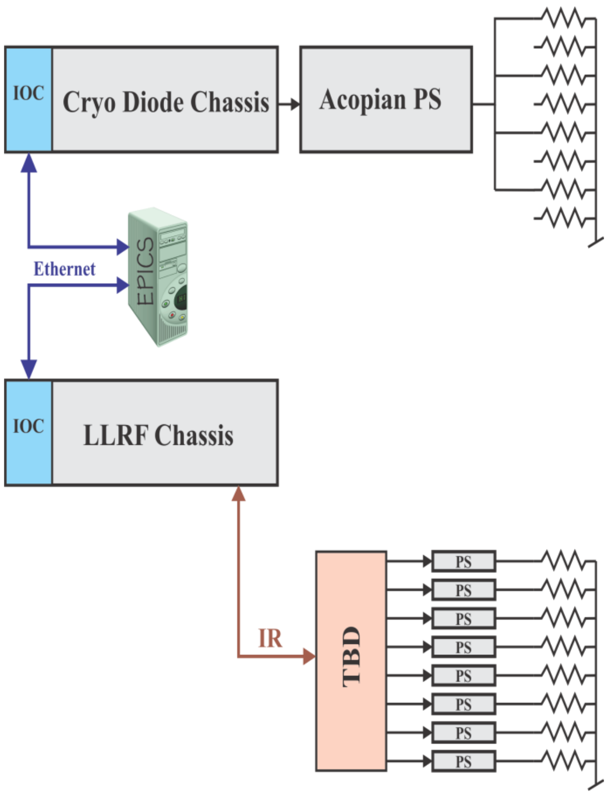


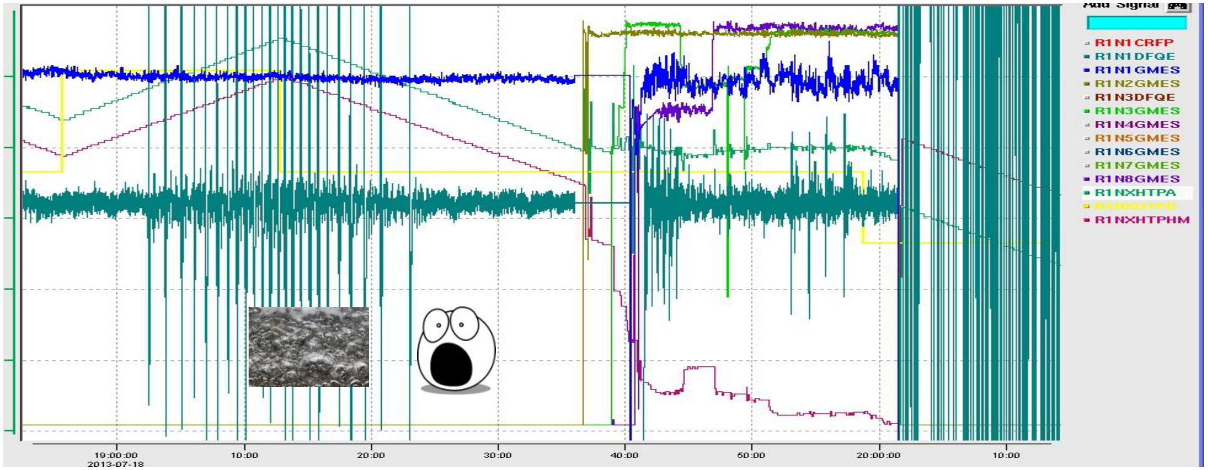


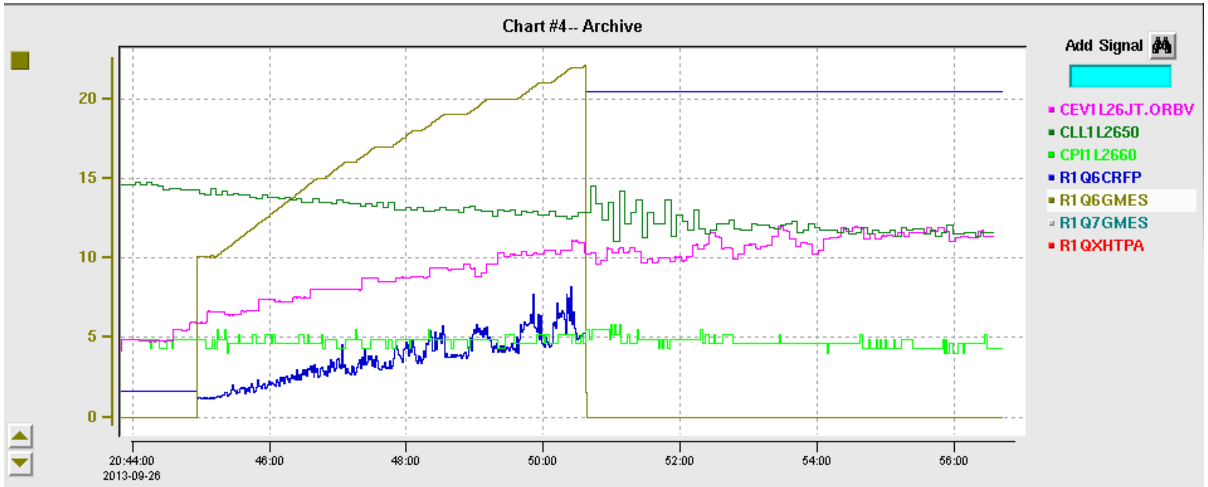
By replacing Ethernet communication between FCC and Stepper chassis with fiber optic rms detuning of the cavity dropped by factor of 2

Heater System Modification

Although C100 cryomodule is equipped with 8 heaters, only 4 of them are connected to one (!) power supply. It was expected to be sufficient to compensate dynamic heat load.







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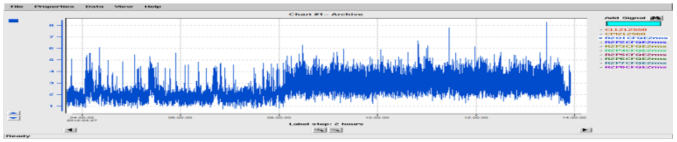
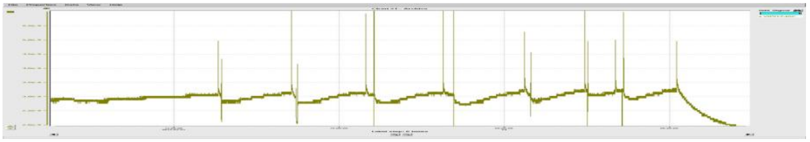
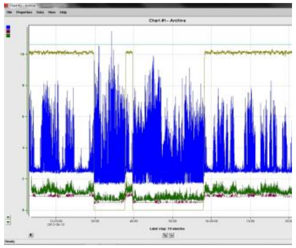
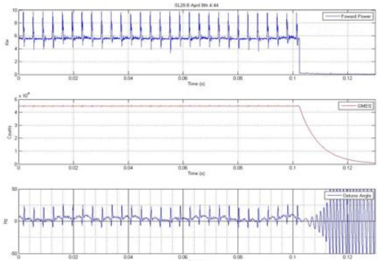
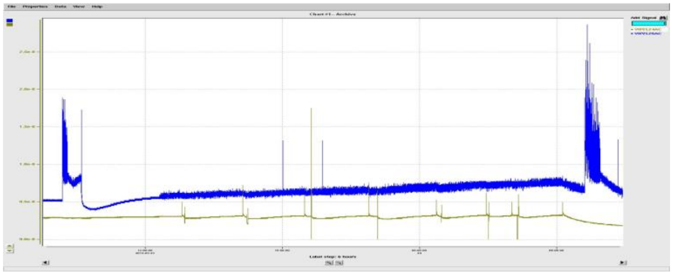
Patience

C100 Faults

Faults between March 13 and March 19										
Fault		# of Faults	Whole Zone	Cavities		Total Cavities	SL24	SL25		Reason
Arc Test Failure										Hardware
Reboot										Software
DC Overload										Hardware
Cathode Current										Hardware
Body Current		1	X	8		8	8			TBD
Quench (False)		15		1		15	15			TBD
Waveguide Vacuum		1		1		1	1			
Beam Line Vacuum										FE, vac conditioning
Cold Window		1		1		1	1			
HPA		1	X	8		8	8			power glitch
Total Cavity Faults						33	33	0		



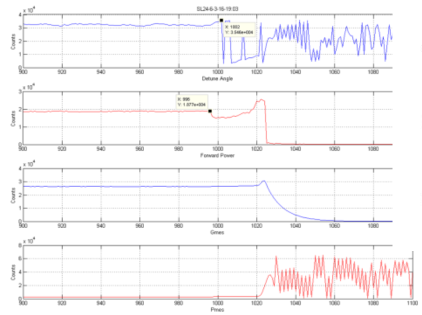
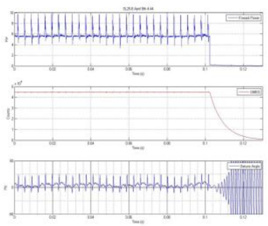
3/21 to 3/26

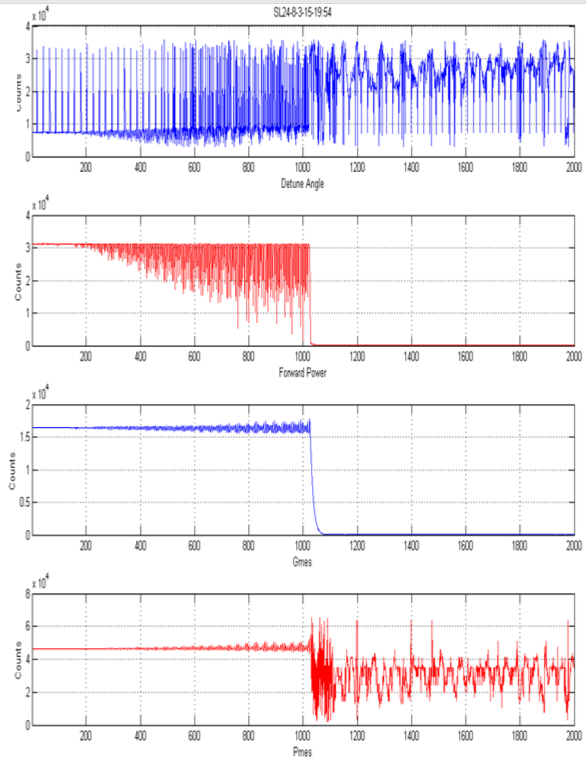
Day/Time	Cavity	Reason	Number of Trips	Gradient	# Cavities	Total Cavitiies	Recovery Time	Average Recovery Time
Total			17			115	7.24	0.4525
Total w/o SL24 Vac			9			70	3.63	0.4538

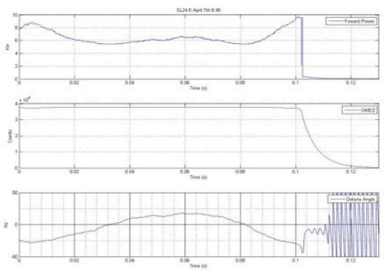
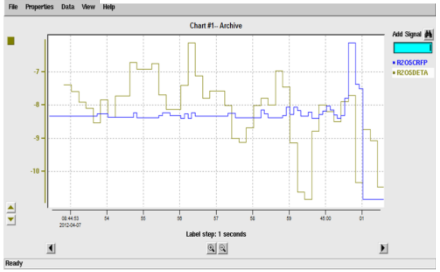
3/27 to 4/2								
Total			8			34	1.72	0.22

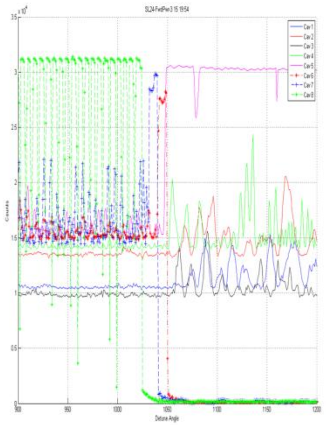
4/4 to 4/9

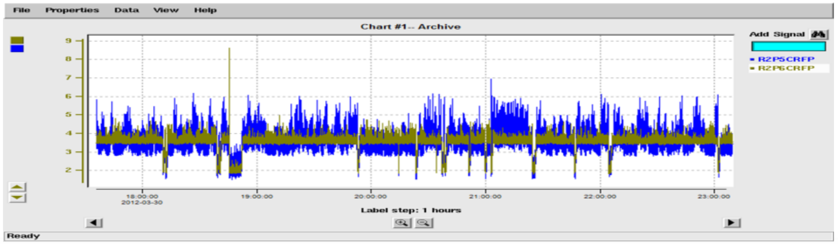
Day/Time	Cavity	Reason	Number of Trips	Gradient	# Cavities	Total Cavitiies	Recovery Time	Average Recovery Time
4/4/2012 8:29	SL24-5	Quench	1	18	1	1	0.15	
4/4/2012 9:31	SL24-5	Quench	1	18	1	1	0.13	
4/4/2012 10:22	SL24-5	Quench	1	18	1	1	0.08	
4/4/2012 13:25	SL24-5	Quench	1	18	1	1		
4/4/2012 13:25	SL25-4	Quench	1	19	1	1	0.18	
4/6/2012 8:41	SL24 & SL25	Training						
4/6/2012 12:31	SL24-7	Quench	1	19	1	1	0.02	
4/7/2012 8:45	SL24-5	Quench	1	16	1	1	0.13	
4/8/2012 4:42	Sl25-8	Quench	1	18	2(8,2)	2	0.05	
4/8/2012 8:17	SL24-5	Quench	1	16	1	1	0.18	
Total			9			10	0.92	0.12



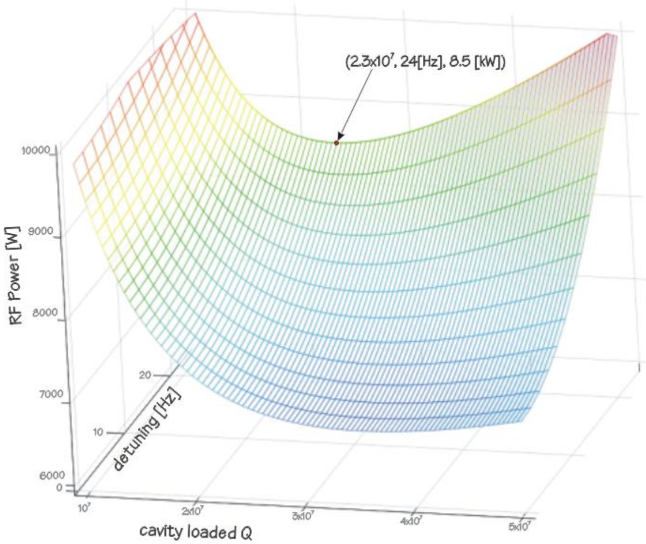


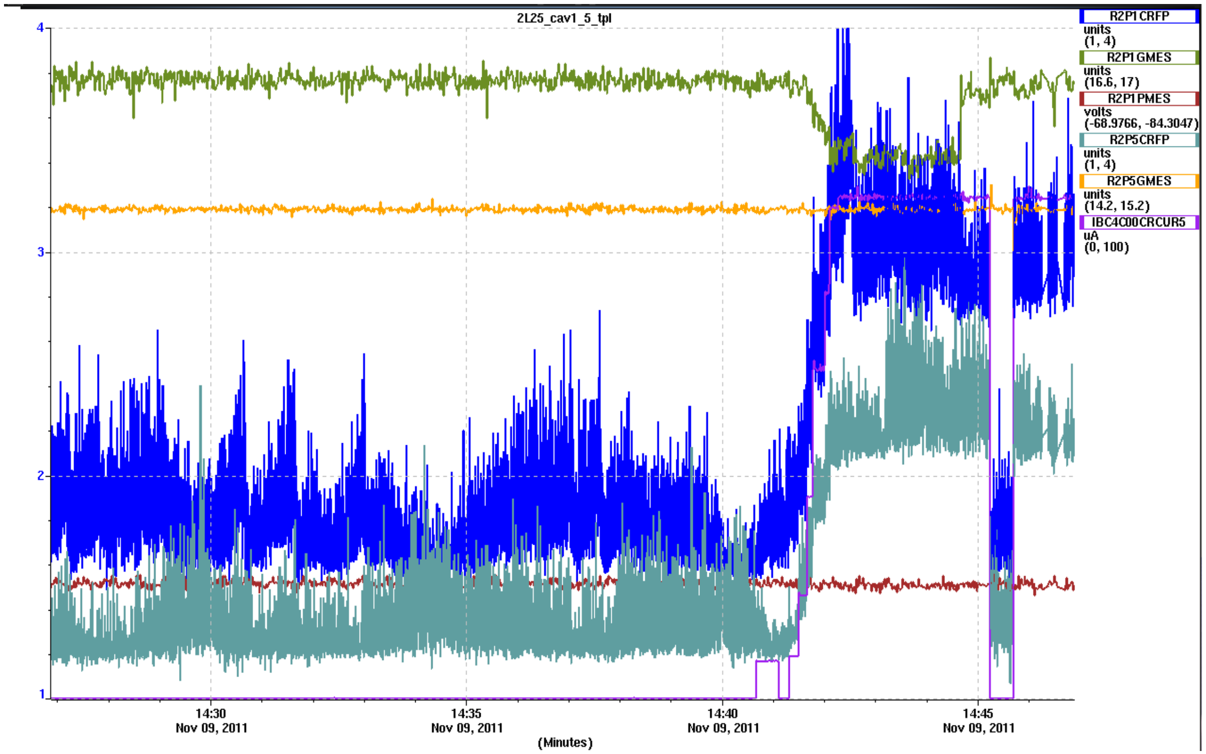


Operability: Cavity Faults

- Cavity/Cryomodule: Fault, Mitigation and Recovery
  - At 20 MV/m and K_L of 2 you are looking at a 800 Hz detuning when the cavity trips or ~ 17 bandwidths
  - Adjacent cavities will feel this and RF systems must react. Typically too fast for a PZT.
  - If we assume a cavity to cavity coupling of 10%, the RF system must have the power overhead to absorb a neighbor cavity faulting.
  - If not, it will set up a "domino" effect and you will be recovering the whole cryomodule.
  - CEBAF C100 cavities have observed this at 20 MV/m and a K_L of 2.
  - One solution is to switch the adjacent cavities to SEL mode keeping gradient in the cavities. Then switch back to GDR mode when the faulted cavity is recovered.

C100 Beam Run





21 MV/m, 460 uA beam
24 Hz detuning
8.5 kW forward power

17 MV/m, 150 uA beam
3 kW forward power
20 Hz rms detuning !

C100 One Hour Run

JEFFERSON LAB ELECTRONIC LOGBOOK

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108 MeV, 1hour with beam no C100 trips

Lognumber 1786255. Submitted by freyberg on Fri, 05/18/2012 - 02:07.

108 MeV and 465 uA

Logbooks: ELOG

Entry Makers: freyberg

One Hour at design energy gain: 108 MeV, at full beam loading, 465uA !!!!!

Fig. 1 [05/18/2012 02:06:39]

Navigate

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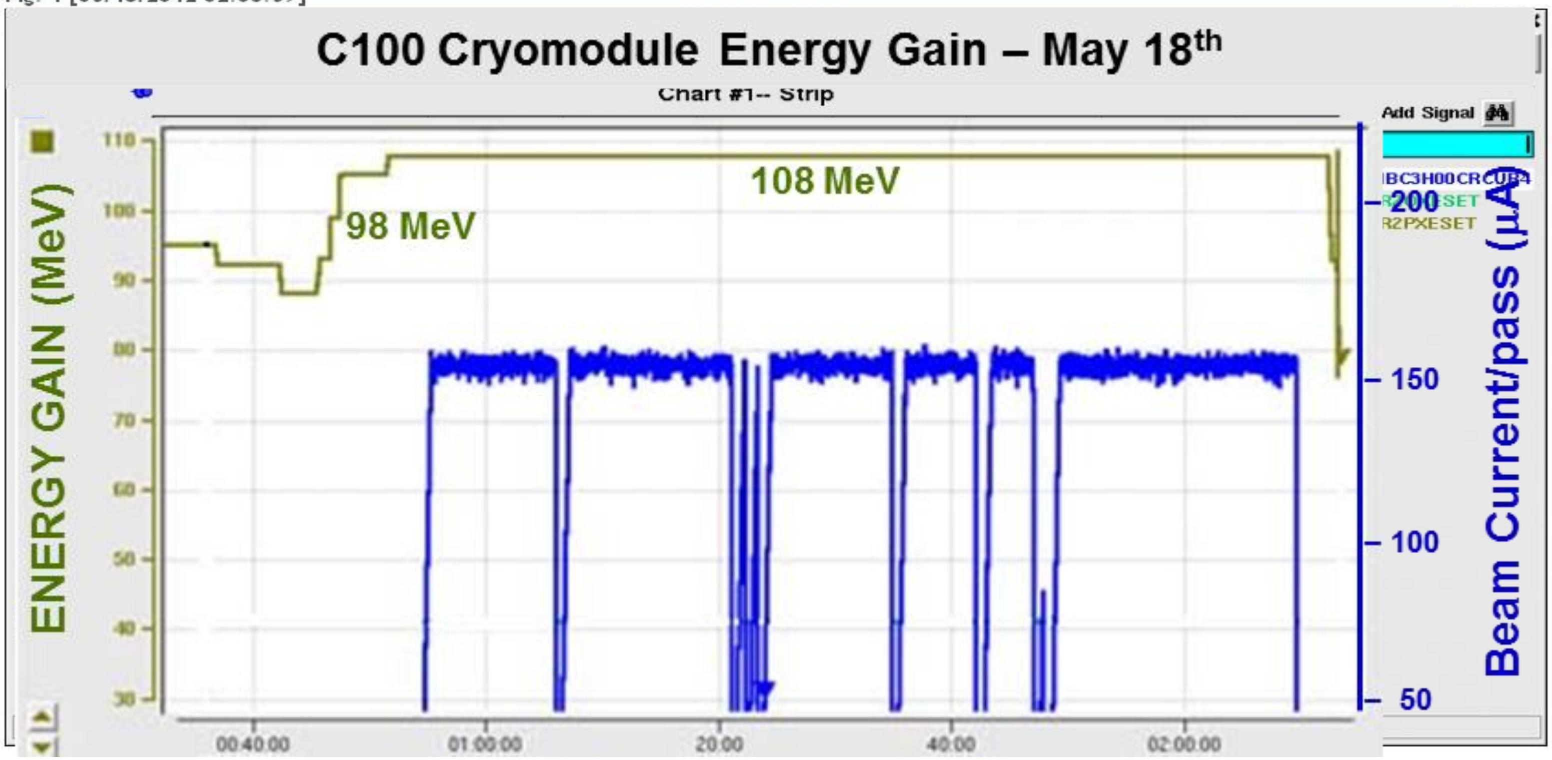
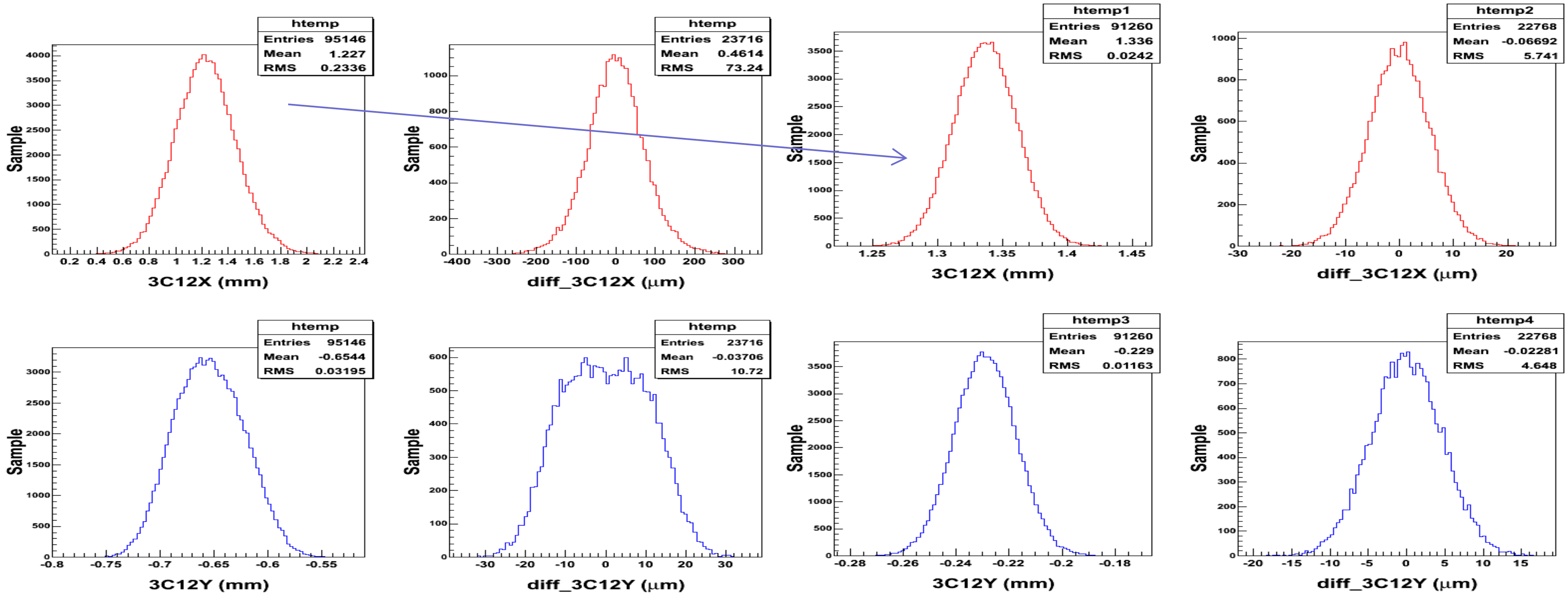
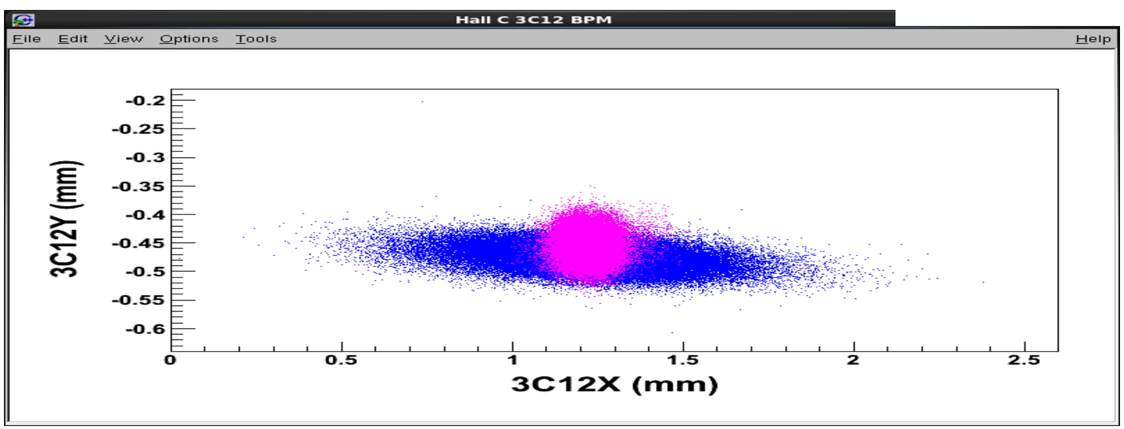
Actions

- Post Follow-up



Data from BPM during C100 Run





C100 Operation Summary

- Two C100s were operated during last years Nuclear physics run.
- Training: Operations staff were trained to operate and recover faulted C100s during this period.
- Software and Algorithms were refined and improved
  - Cavity/Cryomodule Fault recovery improved from ~ 50 mins to ~5 minutes
  - One button fault recovery is in beta testing
  - SEL to GDR crossover improved to allow switch at 20 MV/m
  - Piezo Tuning algorithm fully functional
  - Data buffers operational allowing real time fault diagnosis

- C100 Operations concluded with a successful run of SL25 at 108 MV and 465 uA for over an hour of nuclear physics beam.

Overall Jefferson Lab's technical and operations staff gained valuable experience during this time period.

C100 Commissioning

- Calibrate receiver and transmitter channels
- Klystron testing and characterization
- SRF commissioning
  - Tuning cavities to ~1497 MHz
  - Testing cavity interlocks
  - Emax for individual cavities in SEL
  - Field Emission measurements
  - Q_0 measurement
  - Operable gradient for cryomodule

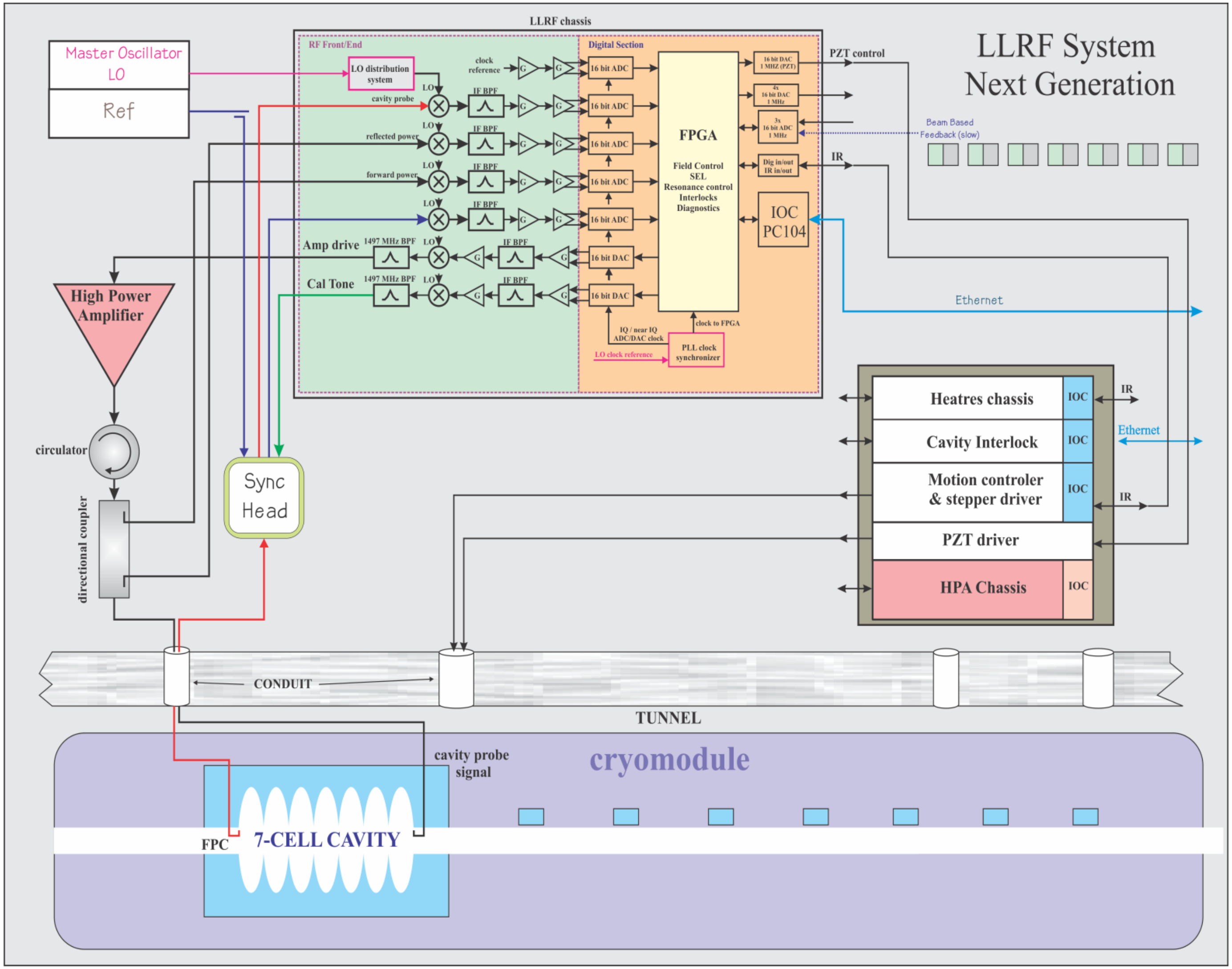
C100 Commissioning Contd.

- Optimizing for closed loop operation
  - Field Control
  - Tuner for resonance control
- One hour operation in GDR
  - Individual cavities at maximum operable gradient
  - Eight cavity operation
- Phase and Gradient stability measurements
- Ready for beam operation

Summary

- Remote FPGA update has been implemented over Network / EPICS
- Tuning algorithm has been implemented over fiber link to eliminate network latency
- New Heater System is under design/construction
- One button zone RF on/off work in progress
  - Lock the cavities at 18 MV/m and ramp to operating gradients, if higher
- High level RF apps work in progress
  - Cavity bypass
  - Fault analysis
  - RF Cavity Transient Phasing Procedure

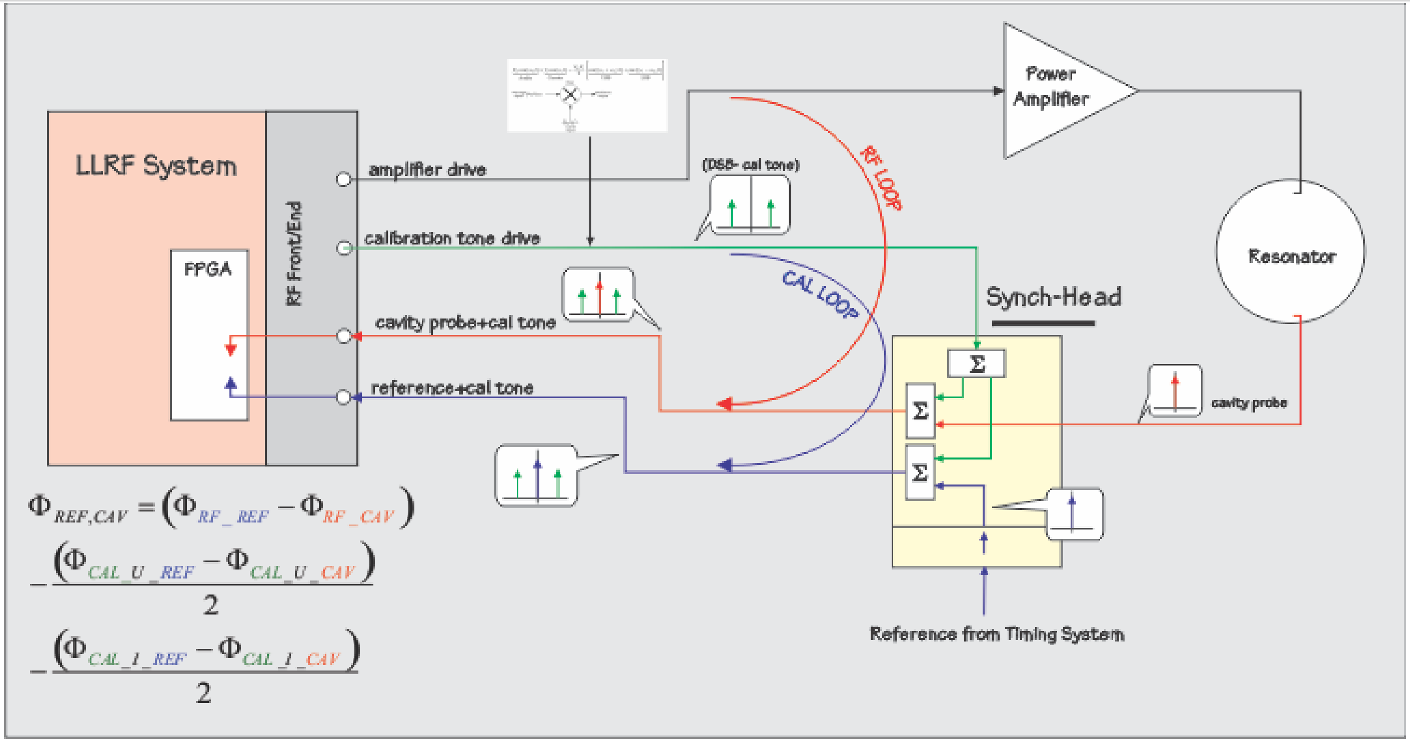
LLRF System- Toward the Next Generation



- **Drift compensation**
- **Ultra precision timing**
- **Beam Based Feedback**
- **Modeling Feedback Controller**

T.Plawski, Accelerator Seminar, Jefferson Lab, October 31 , 2013

Calibration Loop Concept

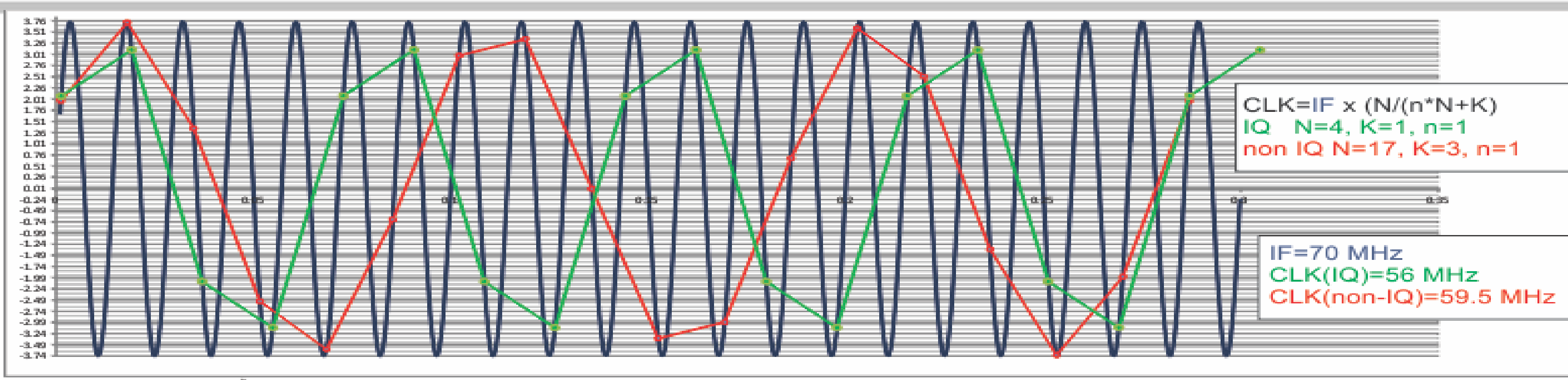


$$\Phi_{REF,CAV} = \left(\Phi_{RF\_REF} - \Phi_{RF\_CAV}\right) - \frac{\left(\Phi_{CAL\_U\_REF} - \Phi_{CAL\_U\_CAV}\right)}{2} - \frac{\left(\Phi_{CAL\_l\_REF} - \Phi_{CAL\_l\_CAV}\right)}{2}$$

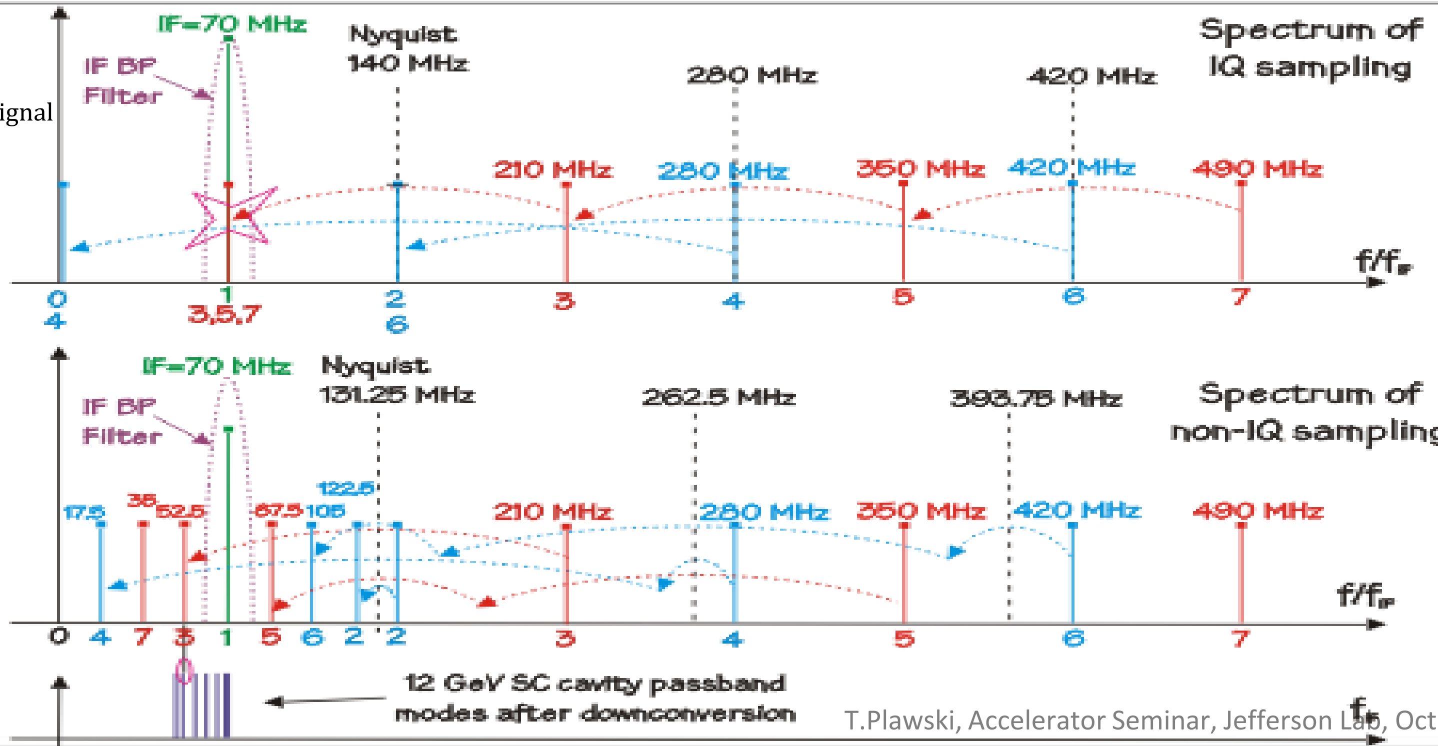
- **Problem**: coaxial cables and optical fiber have a temperature dependence of propagation delay of about 45 fsec/m/deg-C. An unacceptable number for single millidegree stability requirement
- **Solution**: use optical interferometry over fiber links to measure length change and actively feedback to stabilize signal propagation delay in order to obtain very good phase reference
- Add **Sync Head**
- Inject **Calibration Tone** in RF signal transmission channels for phase drift detection
- **Apply** measured correction to phase set point in FPGA

Reference:
L. Doolittle at all , SPX LLRF R&D, ASD Seminar Feb 6, 2012

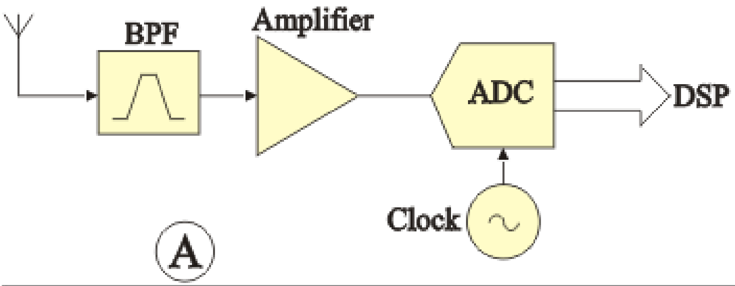
Non-IQ Sampling

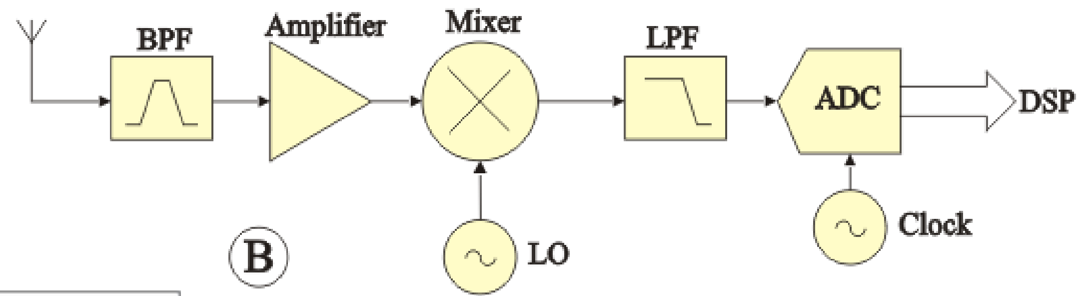


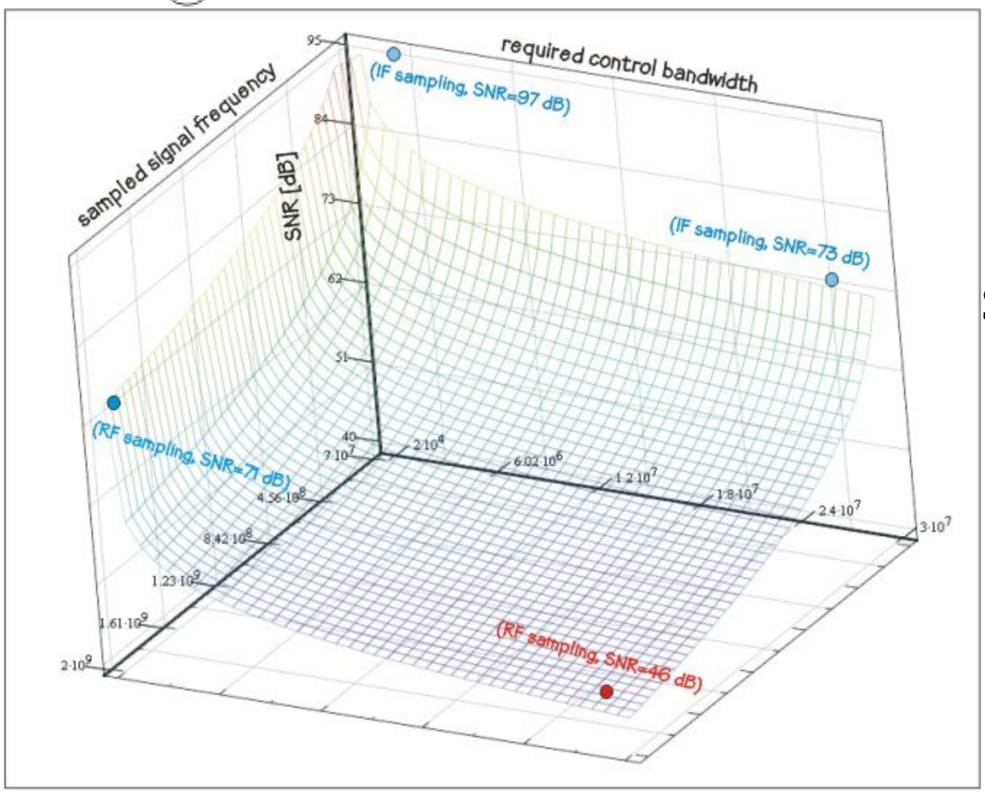
$$f_s = \frac{N}{n \times N + K} \times f_{signal}$$



Direct RF Sampling







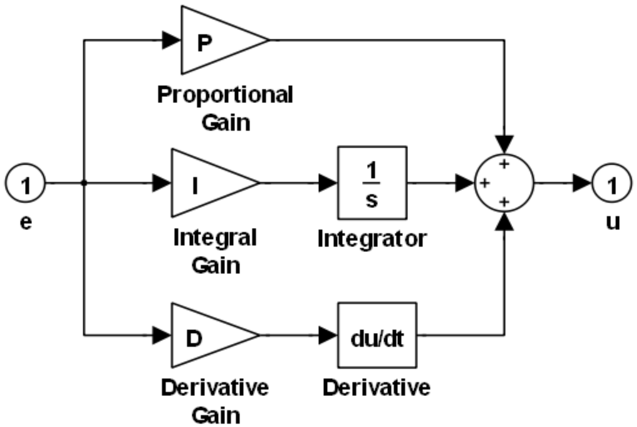
$$SNR_{jitter} = -20\log(\omega\sigma_{jitter}) = -20\log(2\pi f\sigma_{jitter})$$

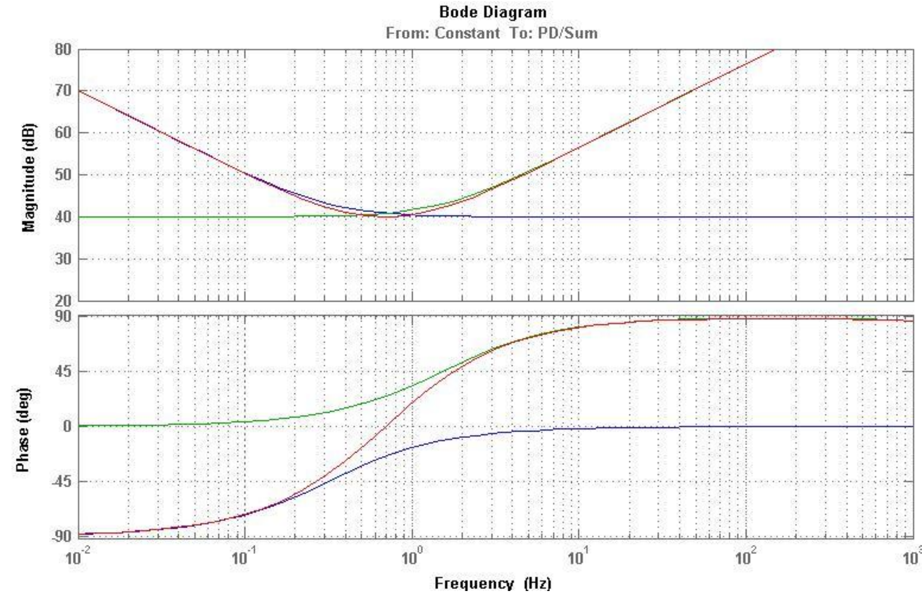
$$10\times\log\left(\frac{BW_{sampled}}{BW_{control}}\right) = 10\times\log\left(\frac{28\times10^6}{10^5}\right) = 24.5 \quad [dB]$$

SNR improvement for
28 MHz measuring bandwidth / 100 KHz regulation bandwidth

PID Controller

Proportional-integral-derivative controller

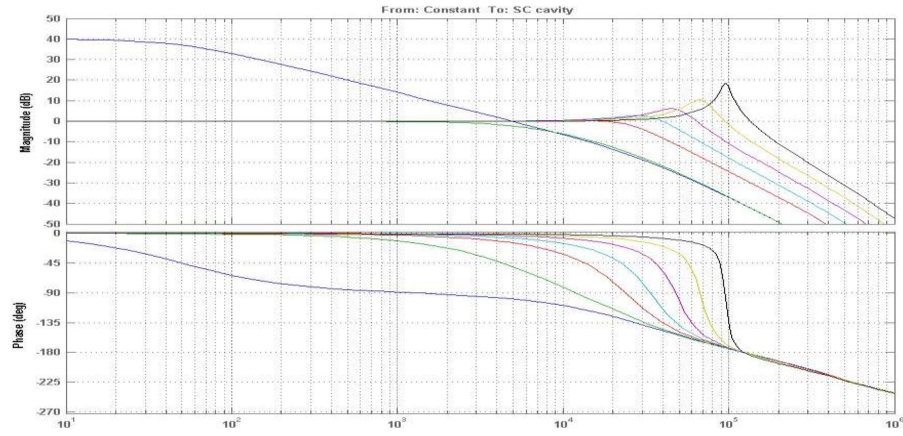




$$K\left(1+\frac{1}{T_i s}\right) \qquad K\left(1+T_D s\right) \qquad K\left(1+\frac{1}{T_i s}+T_D\right.$$

PID tuning – Ziegler-Nichols method

Controller	P	Ti	Td
P	0.5 G_{osc}	inf	0
PI	0.45 G_{osc}	$T_{osc}/1.2$	0
PID	0.6 G_{osc}	$T_{osc}/2$	$T_{osc}/8$



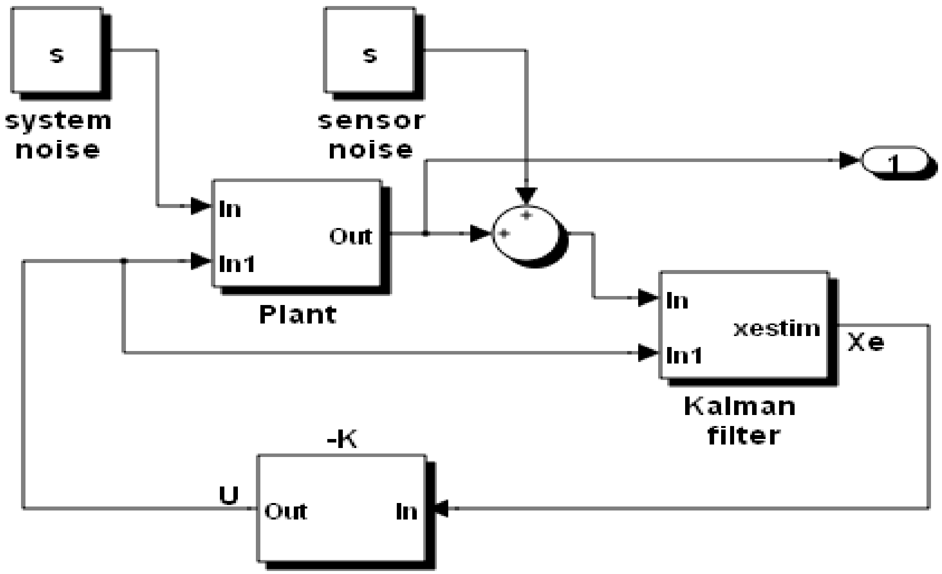
This method requires a plants that can be rendered unstable under proportional control

Optimal Control

Linear quadratic Gaussian (LQG) problem - analyzes linear dynamic system and produces a feedback control law (LQG controller)

$$\dot{x}(t) = Ax(t) + Bu(t) + system_{noise}(t)$$
$$y(t) = Cx(t) + Du(t) + sensor_{noise}(t)$$

LQG Problem – find u(t) based on the past measurements y(t) to minimize quadratic cost function (not shown) . Large controls and state deviations are penalized.



$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + K_{gain}\left(y(t) - C\hat{x}(t) - Du(t)\right)$$
$$u(t) = -K_{feedback}\hat{x}(t)$$

LQG controller consists of Kalman filter (state estimator) and feedback controller - linear quadratic regulator (LQR), solves above problem

Kalman filter – provides best state estimate

K - minimizes the quadratic cost function / integral for cont. and sum for discrete system)

LLRF Summary

- Basic functionality of RF field control (SEL, GDR, Resonance Control, PI regulator) has been successfully implemented
- We would like to address some enhancements related to field stability
  - Calibration Loop
  - LO based clock
  - PZT feedback
  - Beam-feedback modulations of RF field set-points
  - Smoother transition between SEL and GDR mode (IQ feedback vs Detuning Compensator)
  - Adoptive Control
  - Electronic damping of microphonics

Thank You !

C100 LLRF Team

Curt Hovater
Trent Allison
Rama Bachimanchi
George Lahti
Clyde Mounts
Tomasz Plawski
Mike Wilson
and many others