SPX Study Workshop

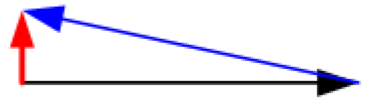
LLRF R&D

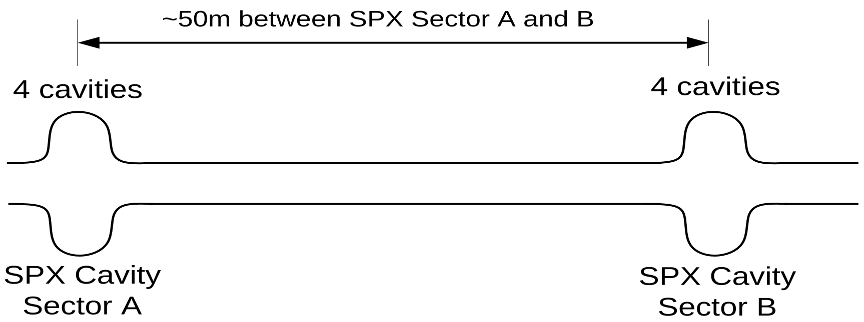
ANL: Tim Berenc, Hengjie Ma, Ned Arnold, Frank Lenkszus
LBNL: Larry Doolittle, Gang Huang, John Byrd

July 18, 2011

Performance Requirements

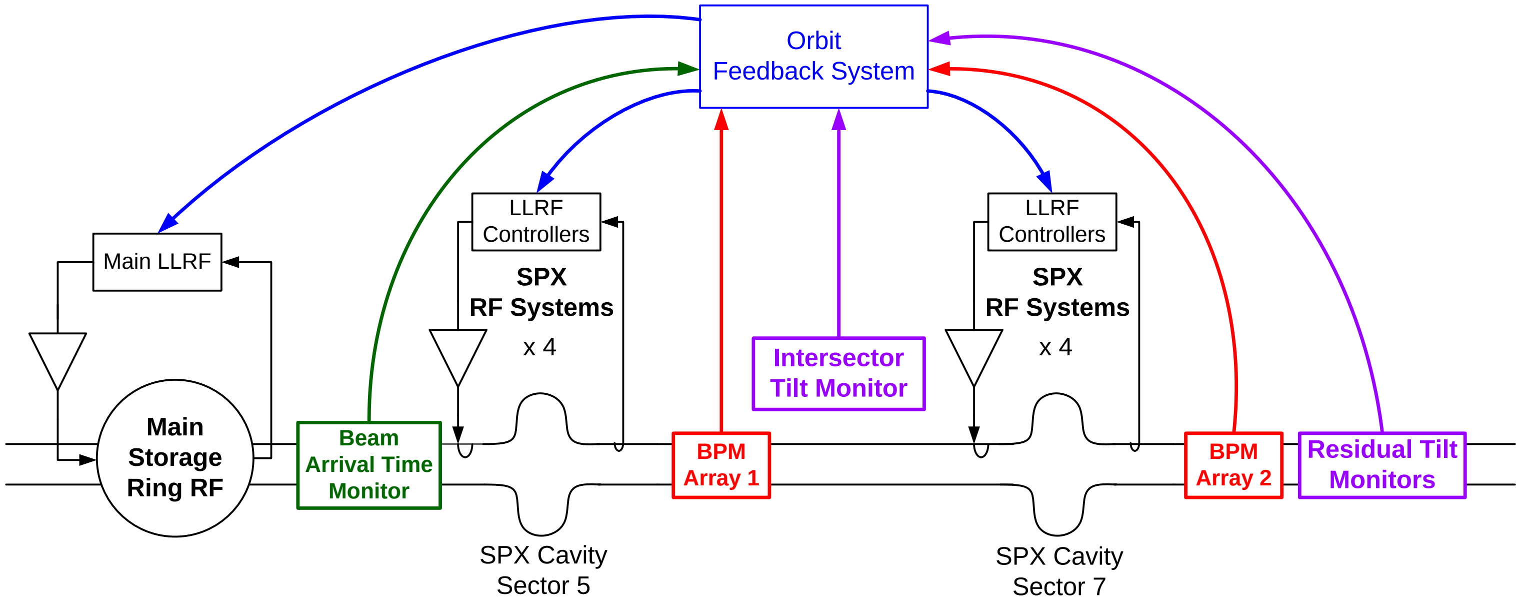
	Specification name	Rms Value	Driving requirement
Common Mode	Common-mode voltage variation	$< 1\%$	Keep intensity and pulse length variation under 1% rms
	Common-mode phase variation	$< 4.0^\circ$	Keep intensity variation under 1% rms
Differential Mode	Voltage mismatch between sectors	$< 1.1\%$	Keep rms emittance variation under 10% of nominal 40 pm
	Phase error between sectors	$< 0.18^\circ$	Keep rms beam motion under 10% of beam size/divergence





Conceptual Design Strategy

- Orbit Feedback System provides long-term stability … < 100 (200) Hz
- **LLRF System on its own > 10 Hz**
  - 10 Hz – 100(200) Hz overlap with Orbit Feedback



BPM Array 1: sets phase of Sector 5
BPM Array 2: sets phase of Sector 7

Intersector Tilt Monitor: sets amplitude of Sector 5
Residual Tilt Monitors: sets amplitude of Sector 7

Beam Arrival Time Monitor: sets phase of Main Storage Ring RF

Conceptual RF Control Architecture

- **Single Klystron per cavity with digital LLRF + Analog Front End**
  - **Want fast independent control of each cavity**
    - *Deflecting cavity beam loading is a function of offset and tilt – not expected to be the same cavity to cavity or sector to sector (i.e., electrical alignment errors)*
    - *Microphonics not expected to be common mode, especially between sectors*

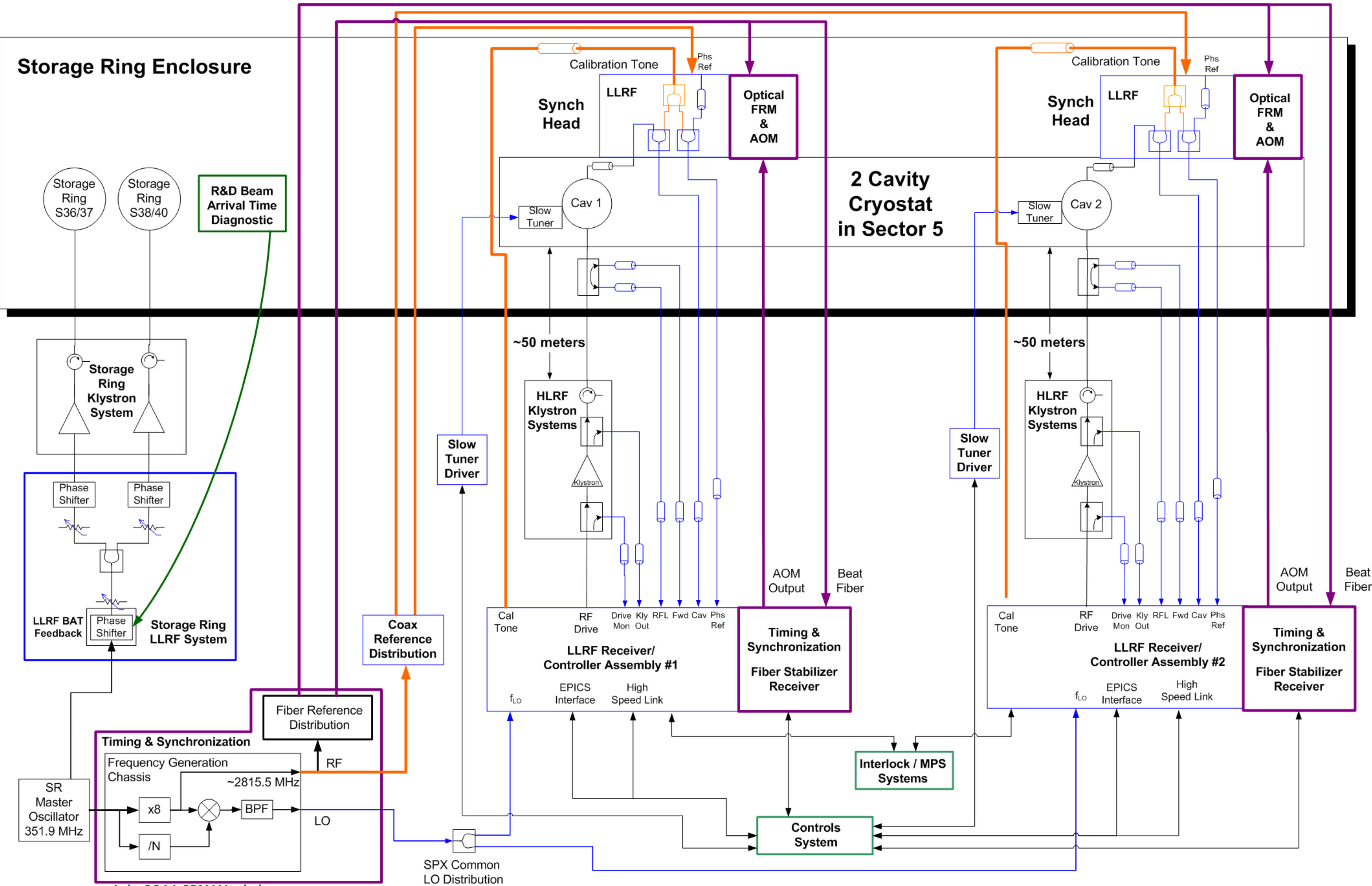
- **Phase Reference, LO (& CLK) distributed centrally to keep phase noise common mode**
  - **Provisions for both *coax-based* and *LBNL phase stabilized fiber* reference**
    - — *Orbit feedback eliminates long-term drift concerns*
    - — Coax provides superior short-term noise, fiber provides superior long-term noise to alleviate control effort of orbit feedback and is needed for synchronizing user laser
    - — Comparison of short-term noise of *fiber link* vs. *coax* needs to be measured

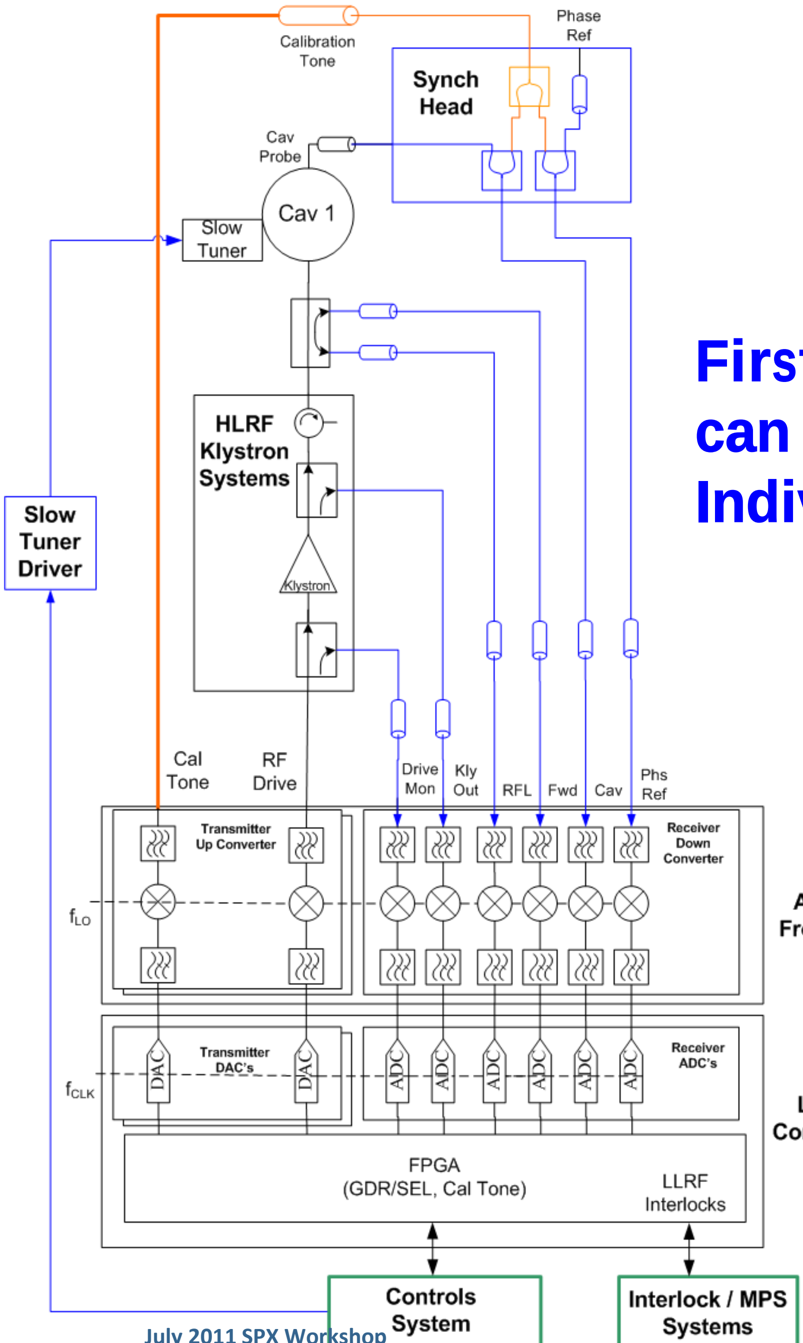
- **Receiver Chain Drift Compensation via Calibration Tone**

- **Sector to Sector Control derived from beam-based Feedback**

- **Beam Arrival Time Feedback to Main Storage Ring RF to lock beam to Master Oscillator**

R&D System Concept (1 Sector, 2 cavities)

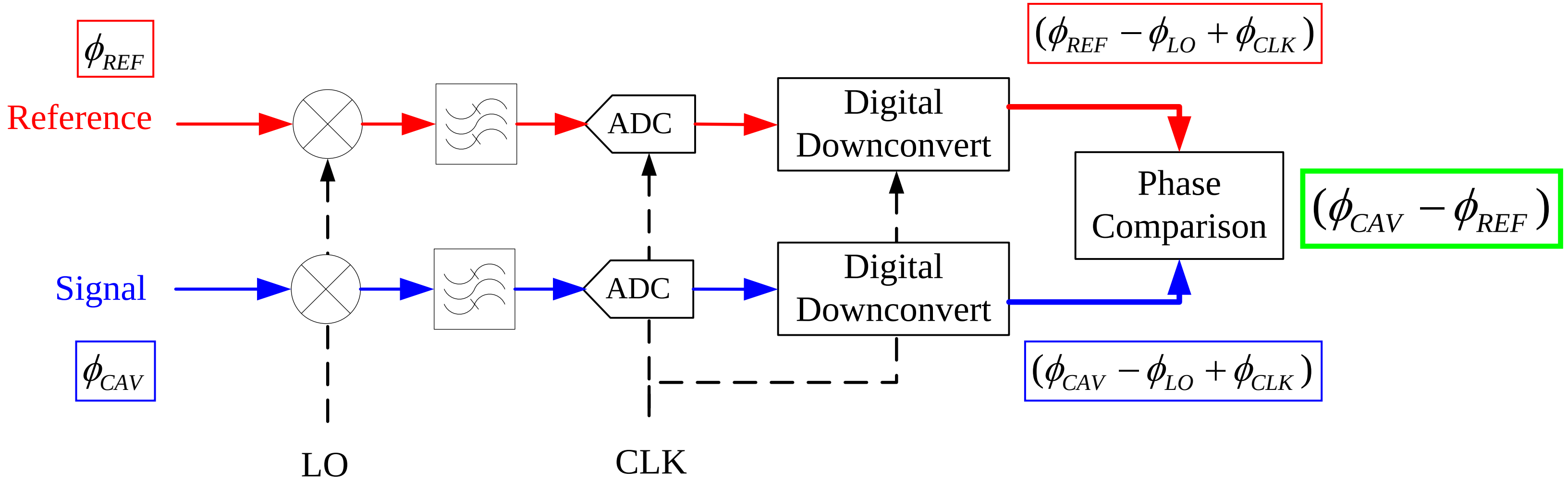




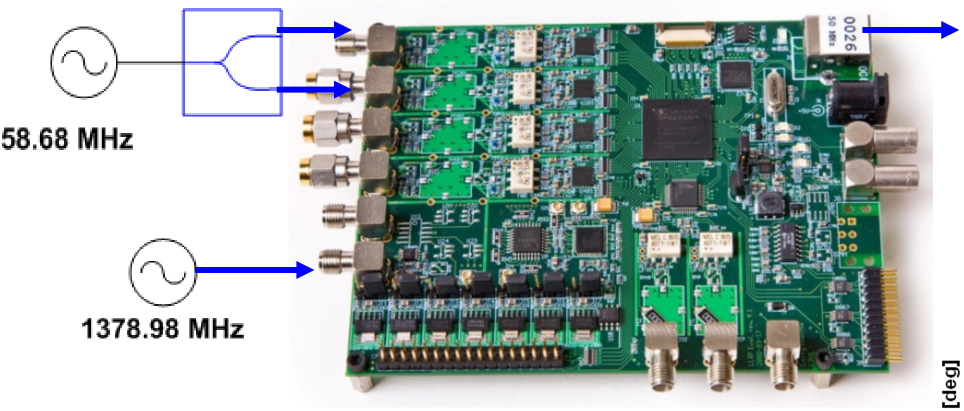
First, we will need to demonstrate that we can regulate the fields at the Individual Cavity Level ….

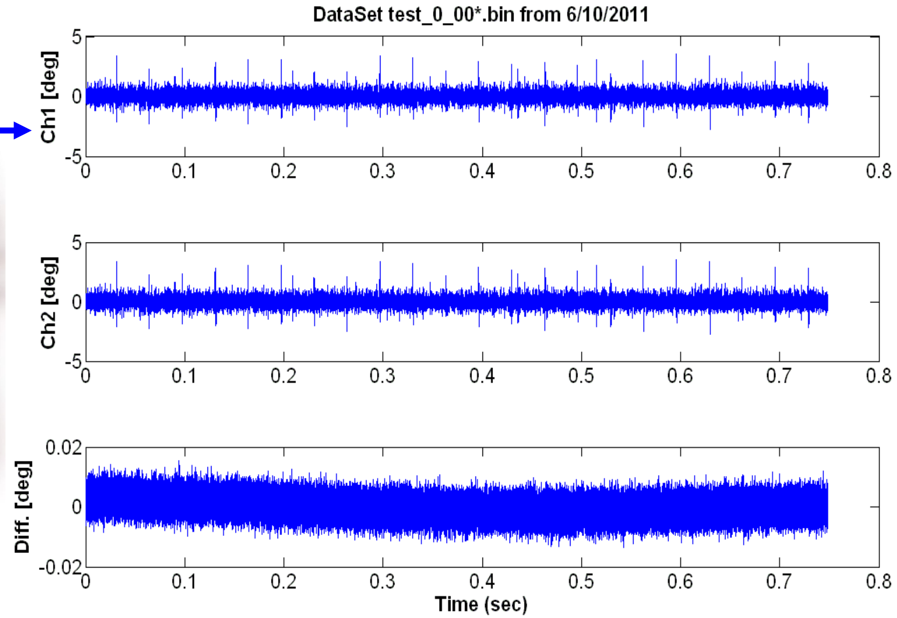
Strategy #1 – Regulate to a Designated Phase Reference

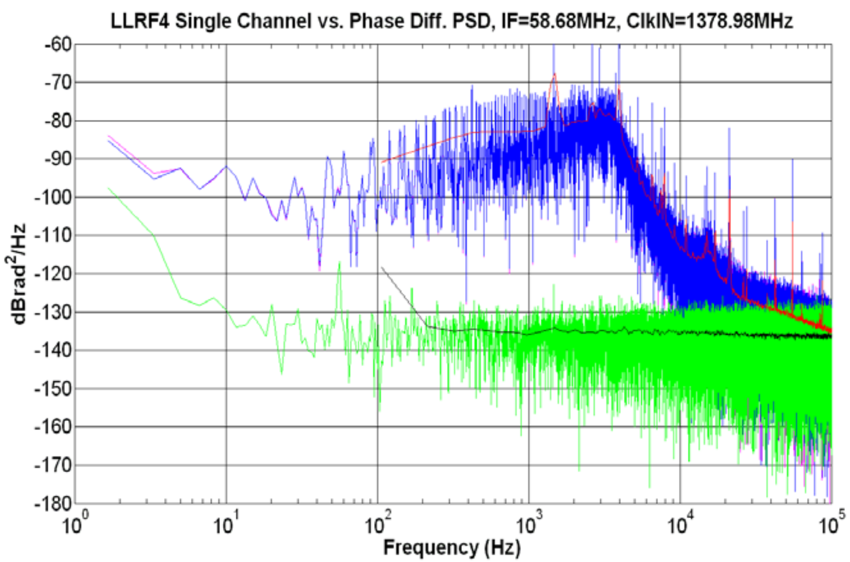
- Don’t let the LO assume the role of the phase reference
- Phase is a Differential Measurement
- Mixers preserve phase information
- In theory, common mode LO and clock noise cancels

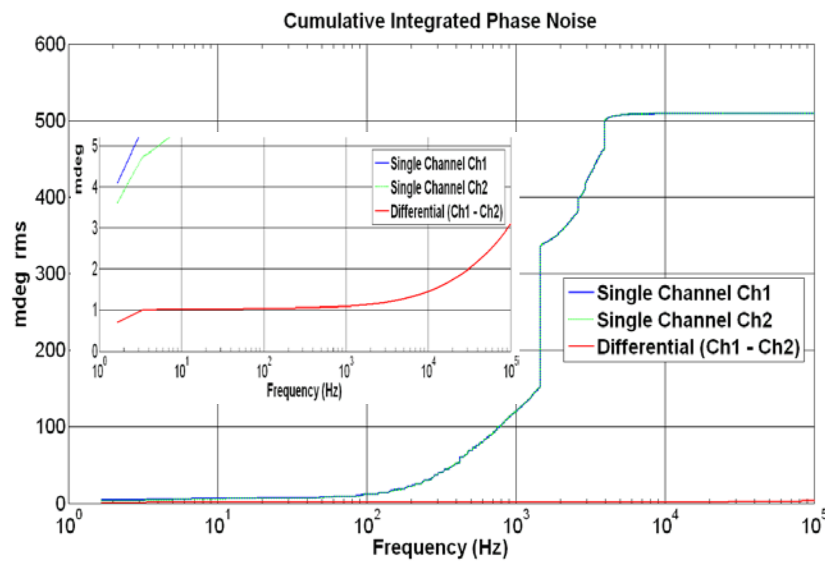


LLRF4 Board - Input Differential Phase Noise

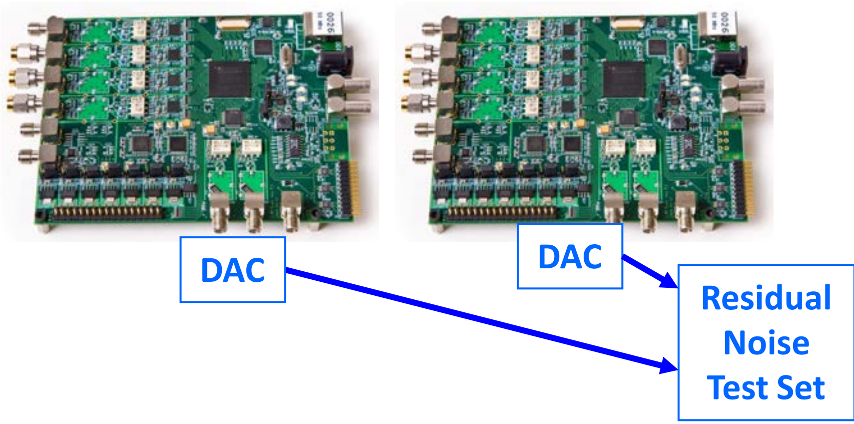


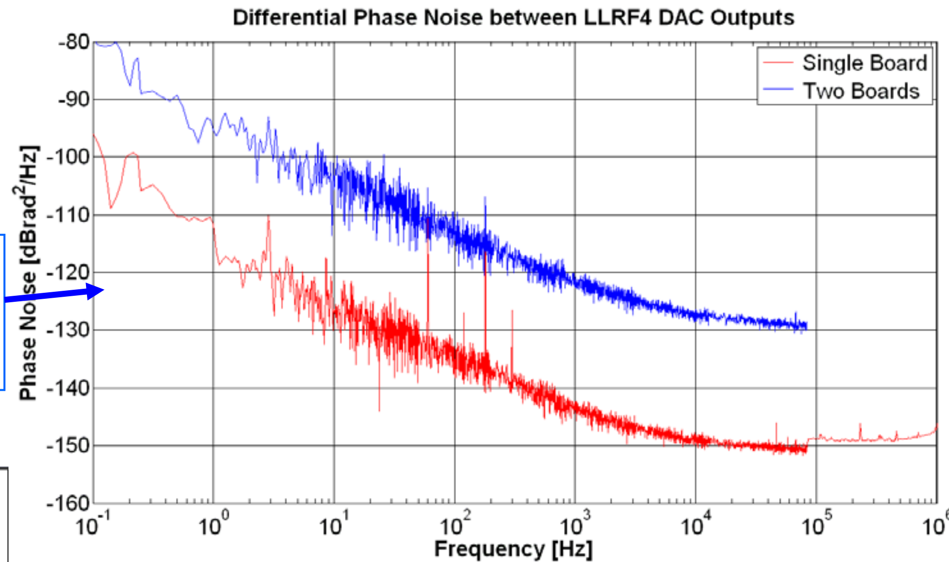


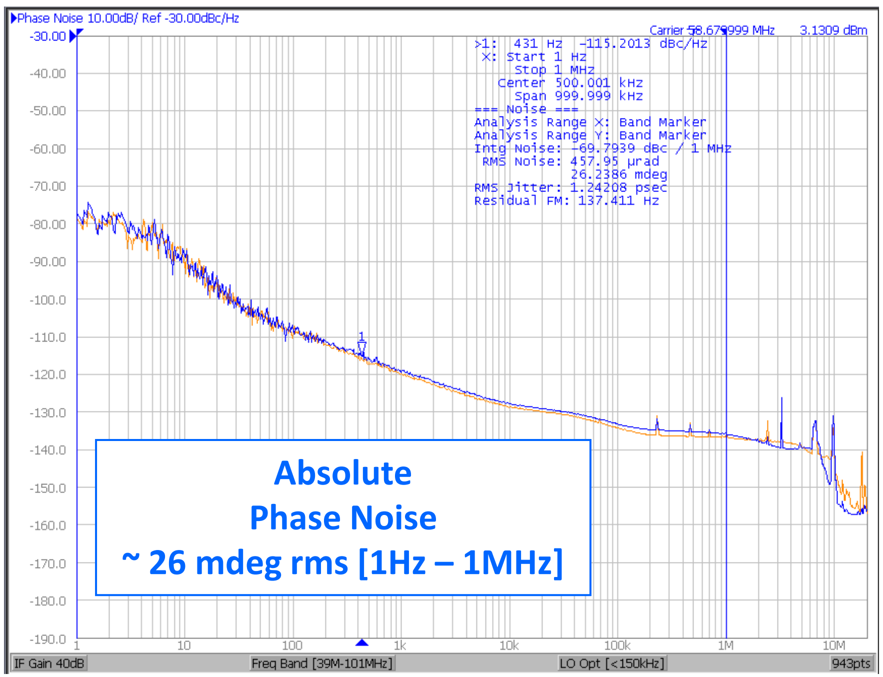


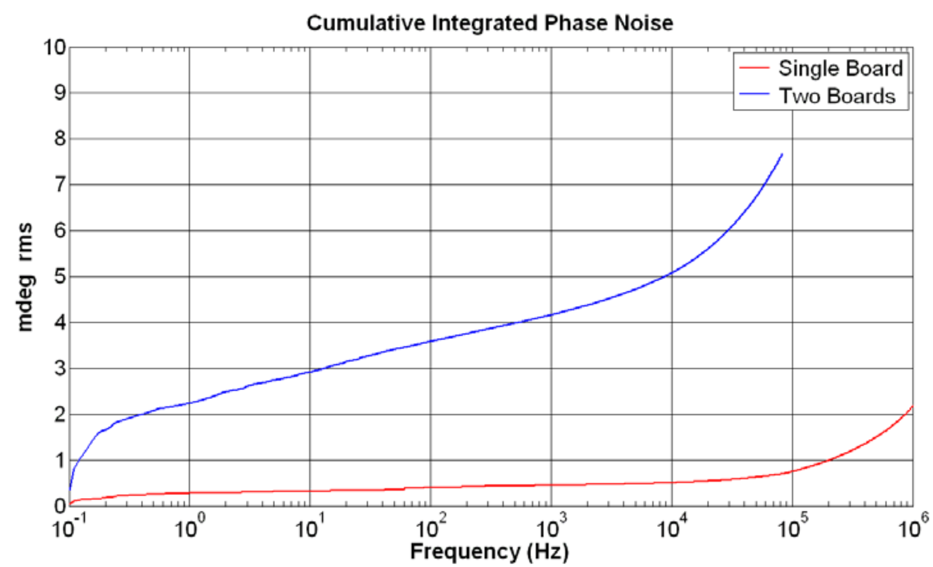


LLRF4 Board - Output Phase Noise



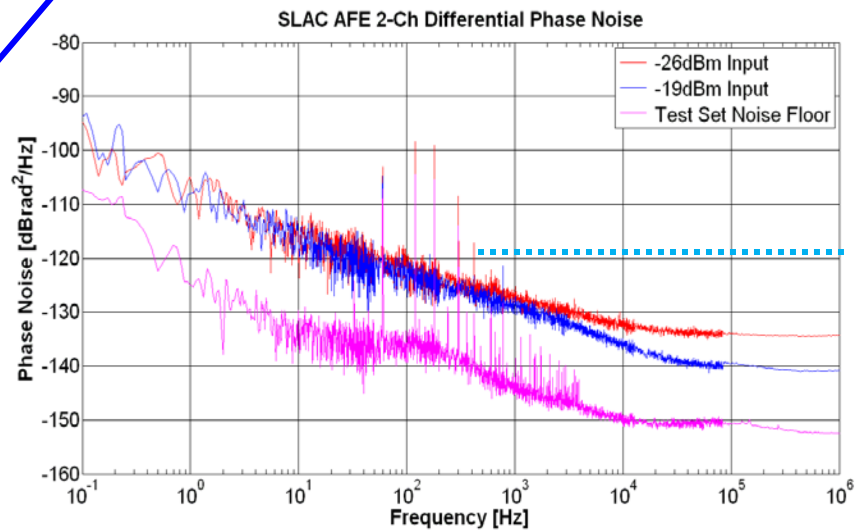


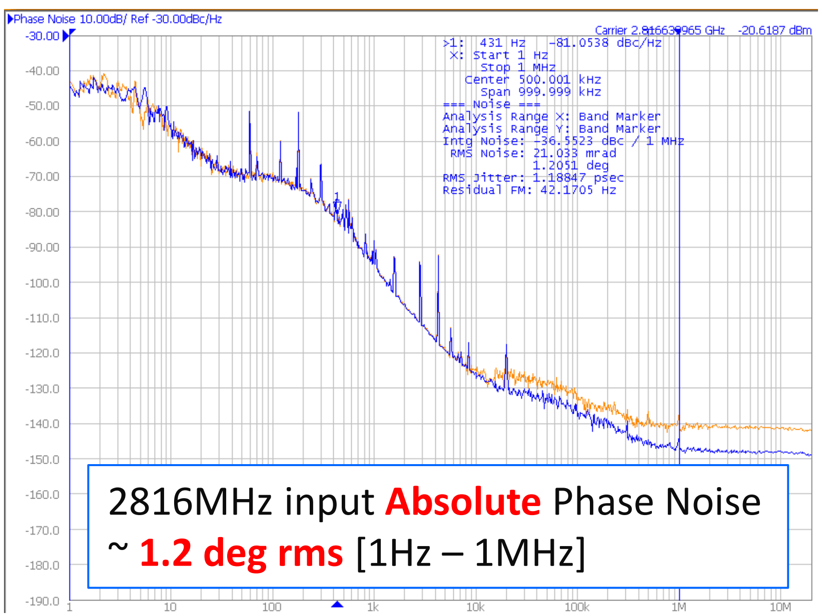




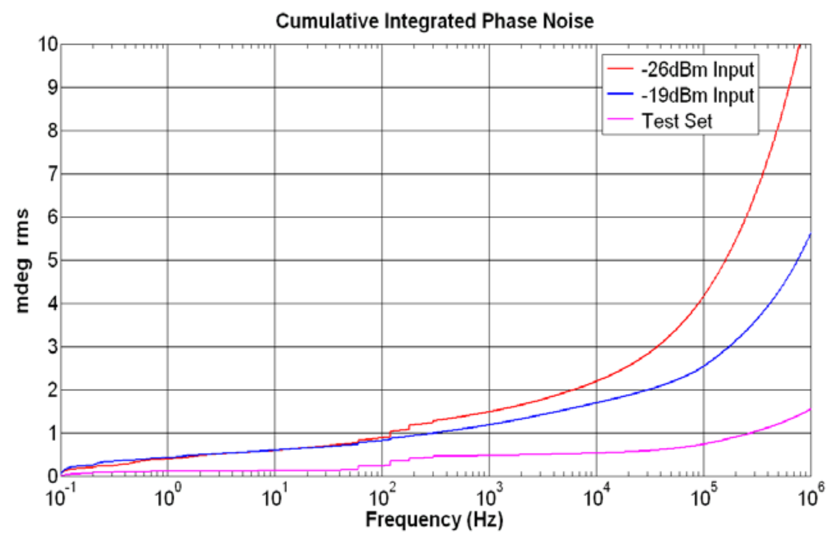
Analog Front End - Differential Phase Noise

Differential Phase Noise at IF Frequency

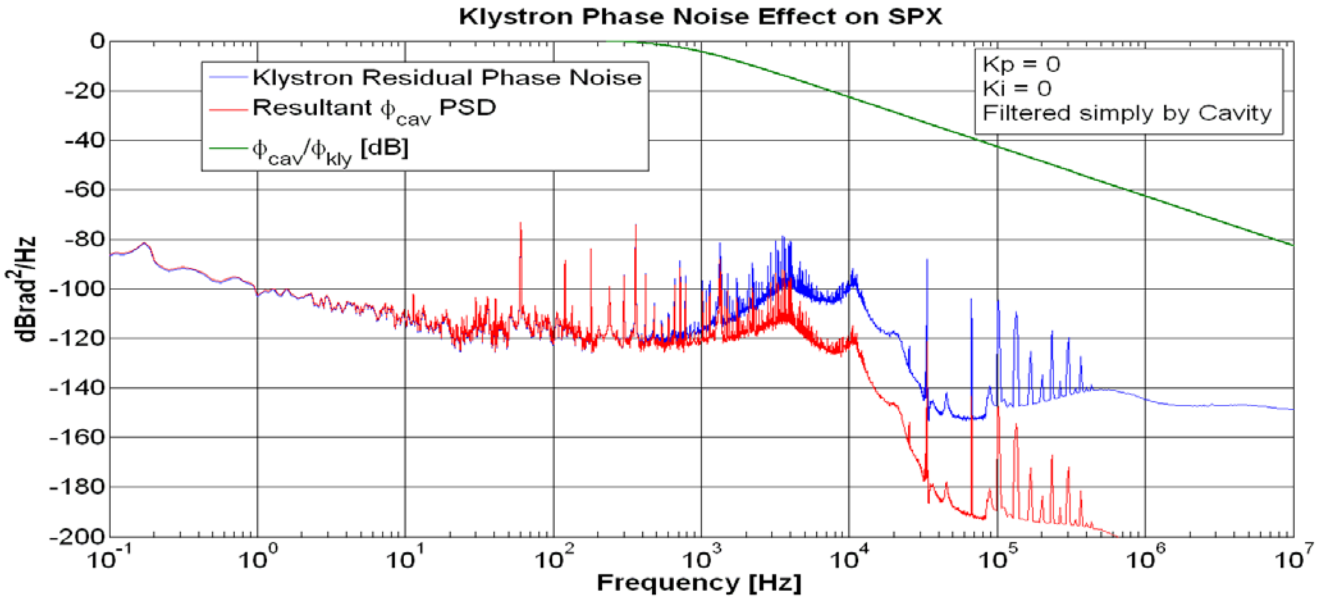


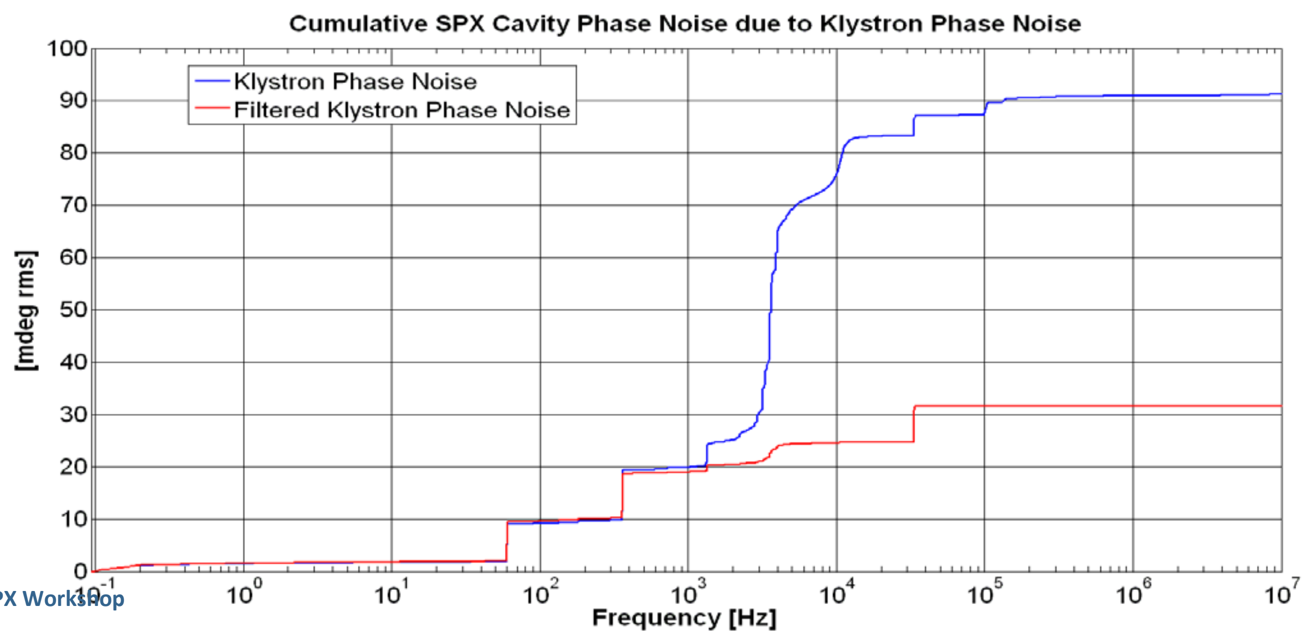


2816MHz input **Absolute** Phase Noise
~ **1.2 deg rms** [1Hz – 1MHz]

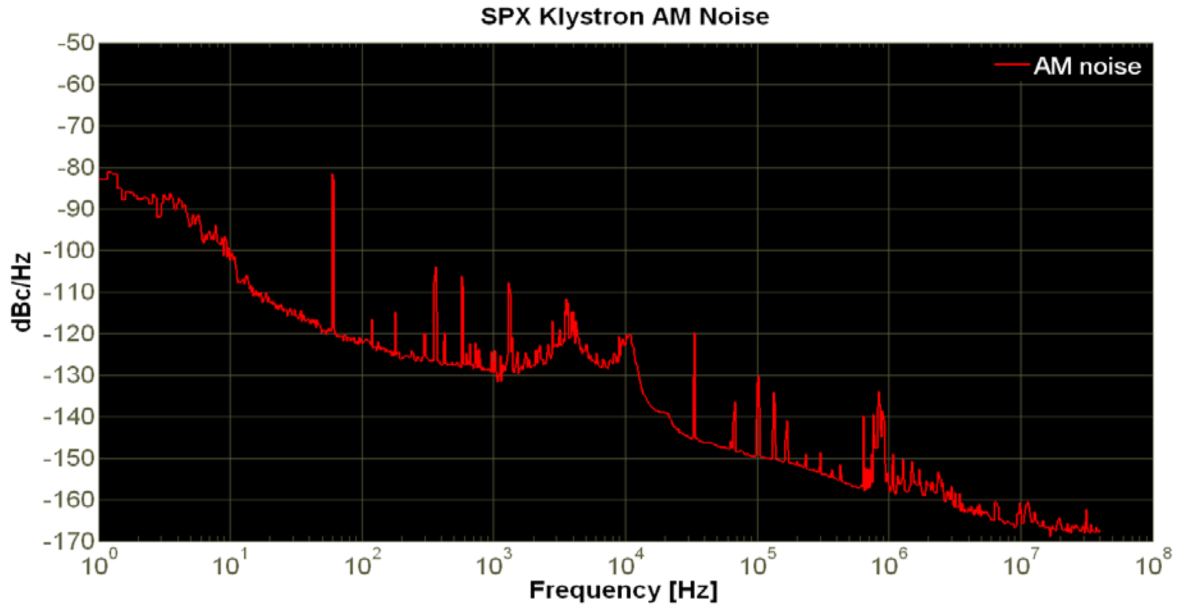


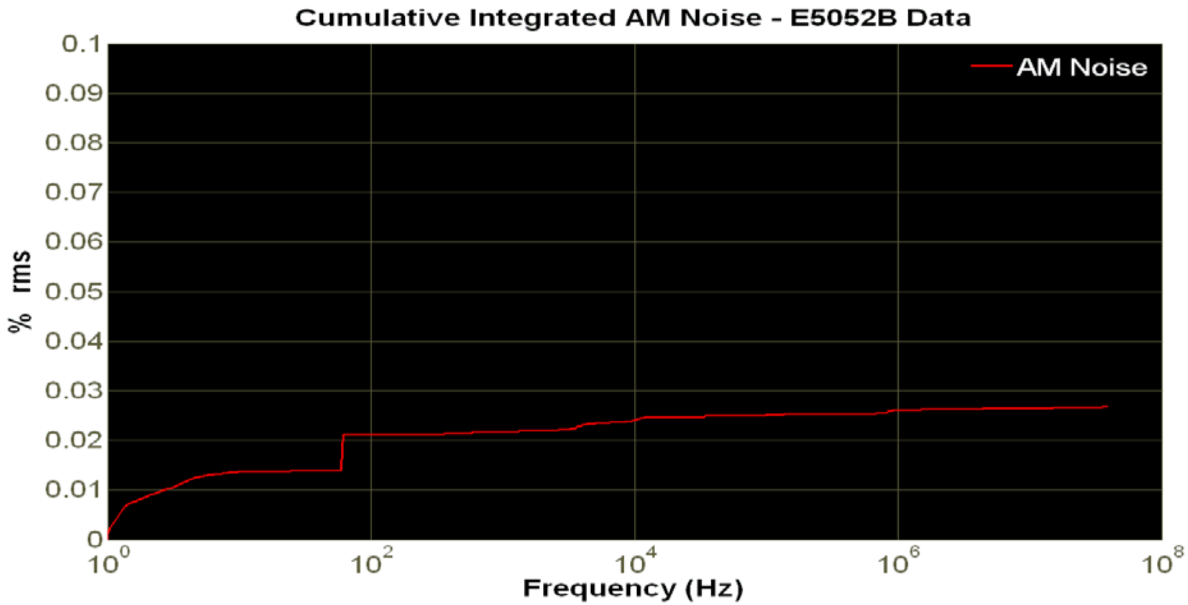
Klystron Residual Noise Measurements



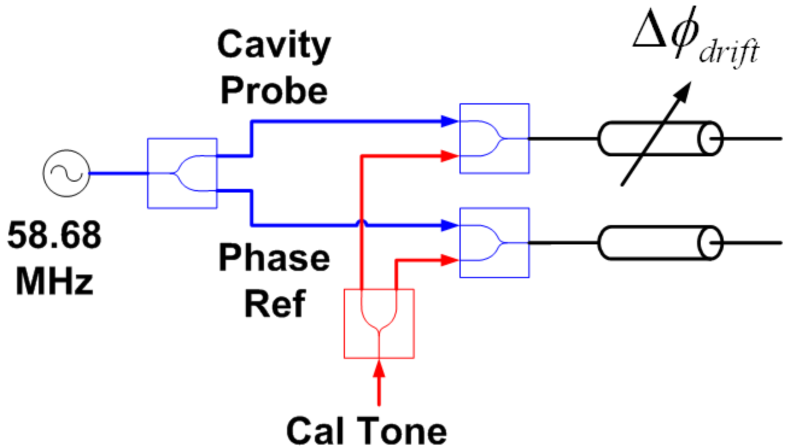


Klystron AM Noise Measurements





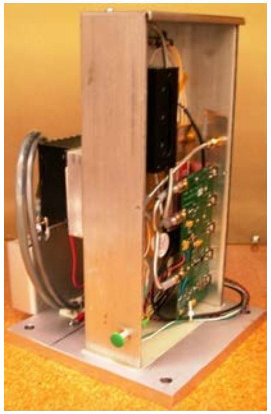
Strategy #2 - Incorporate CW Drift Compensation[1]



$$\Delta\phi_{meas} = \left(\phi_{cav} - \phi_{ref}\right) + \Delta\phi_{drift}$$

$$\Delta\phi_{calTone} = \Delta\phi_{drift}$$

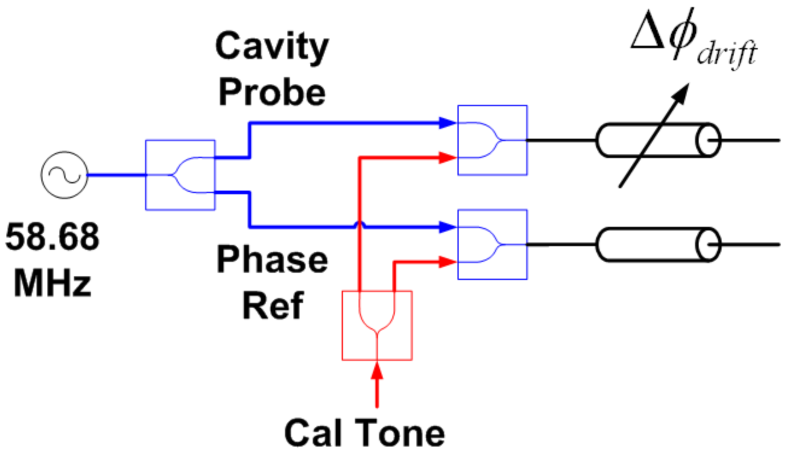
$$\Delta\phi_{correct} = \Delta\phi_{meas} - \Delta\phi_{calTone}$$



LBNL "Synch Head" example (2-channel version)

[1] "Signal Processing for High Precision Phase Measurements", G. Huang, L. Doolittle, J. Staples, R. Wilcox, J. Byrd , Proceedings of BIW10

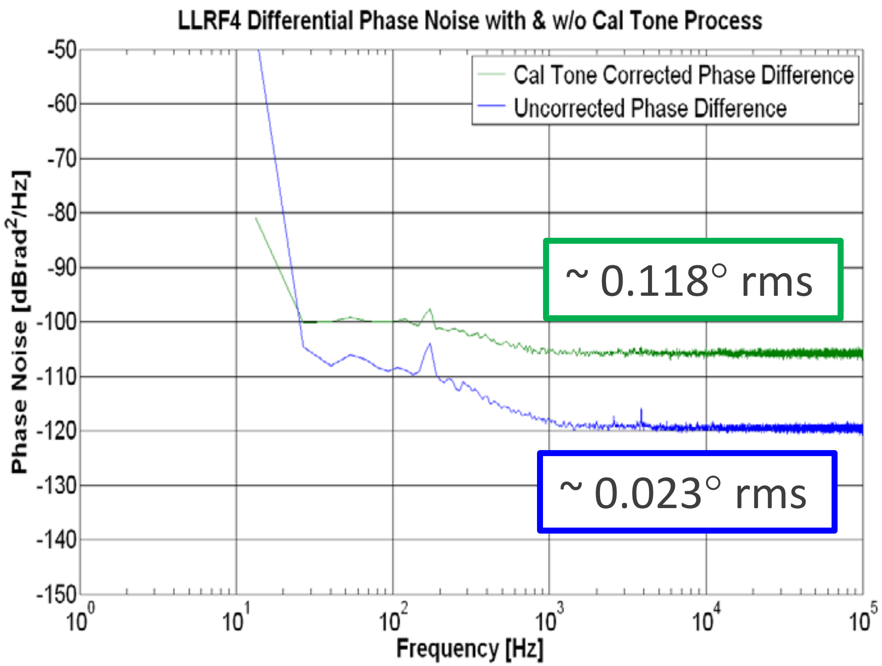
Demonstration of CW Drift Compensation

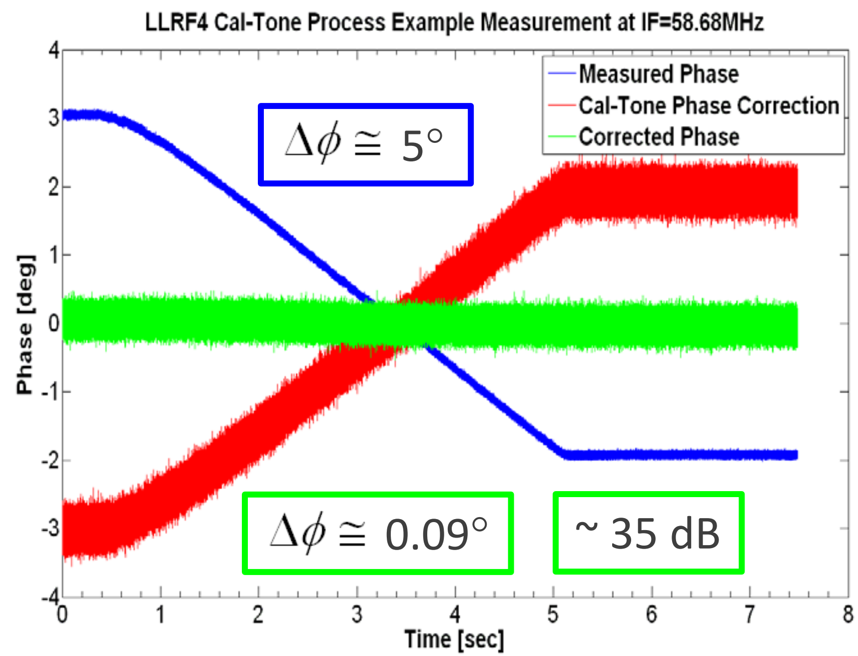


$$\Delta\phi_{meas} = \left(\phi_{cav} - \phi_{ref}\right) + \Delta\phi_{drift}$$

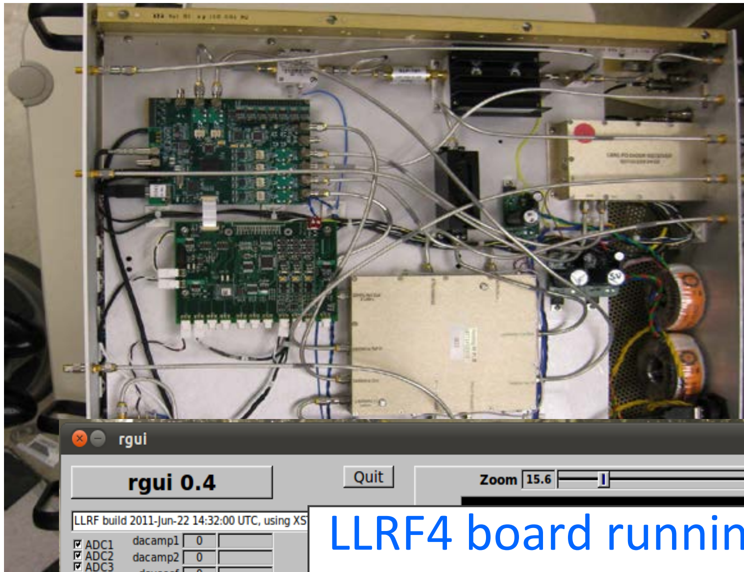
$$\Delta\phi_{calTone} = \Delta\phi_{drift}$$

$$\Delta\phi_{correct} = \Delta\phi_{meas} - \Delta\phi_{calTone}$$





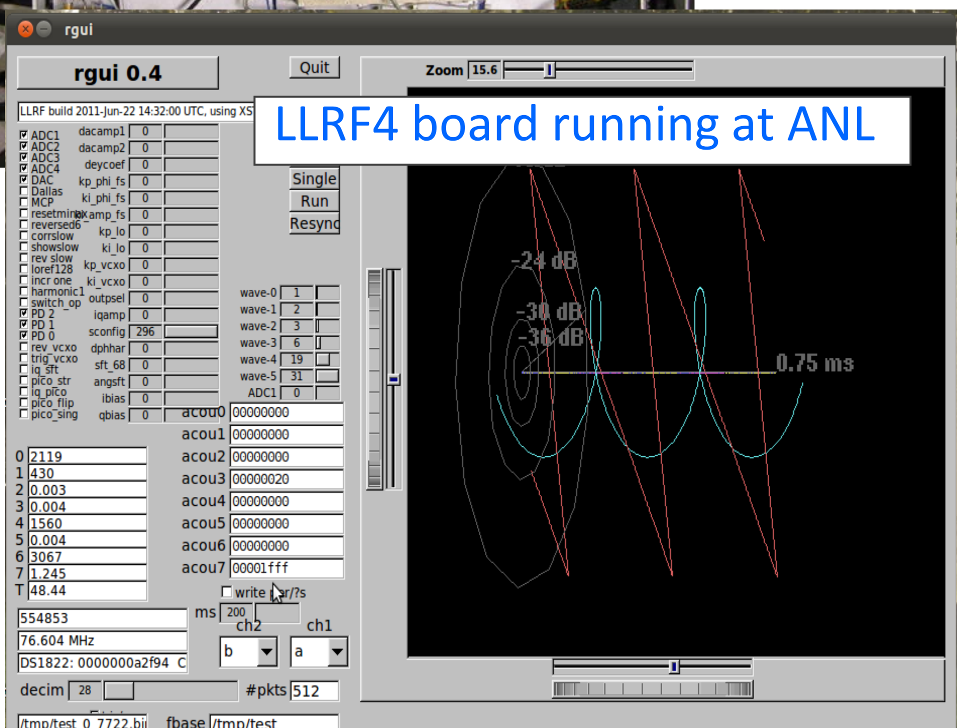
Single Cavity Testing at ANL scheduled for 2/2012



LLRF4 based system to support LLRF & Timing R&D

10/2011

- Delivery of first LLRF4 system for LLRF control
- Report on differential stability study between 2 high Q cavity emulator systems

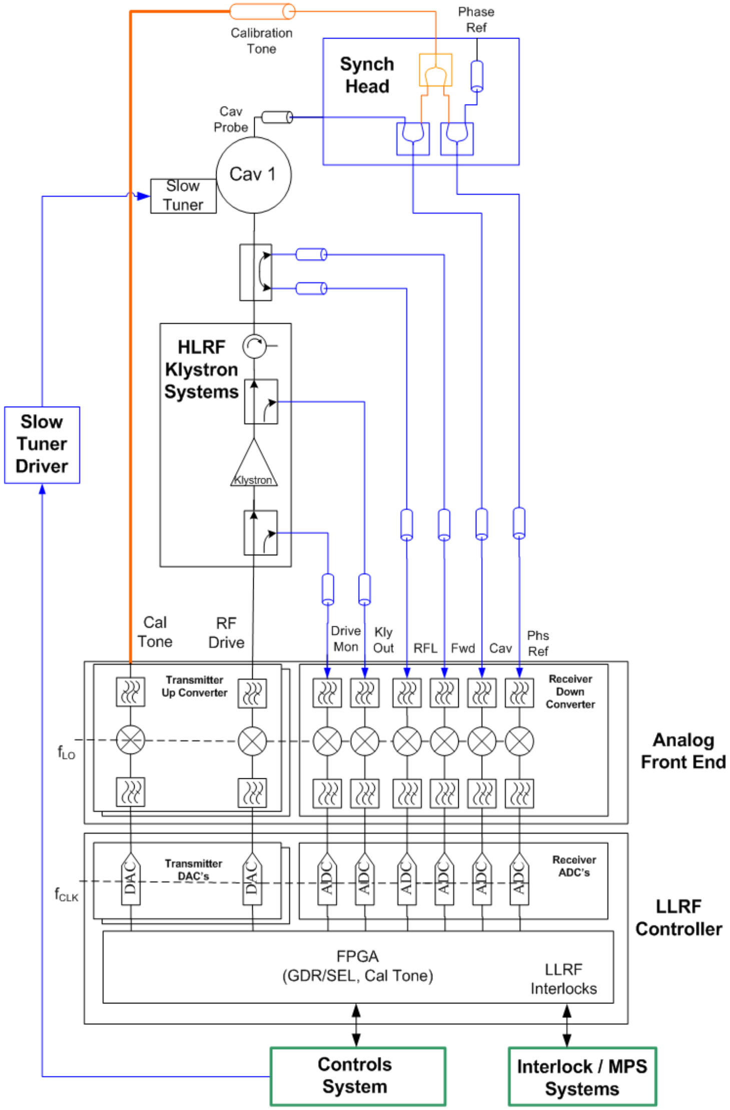


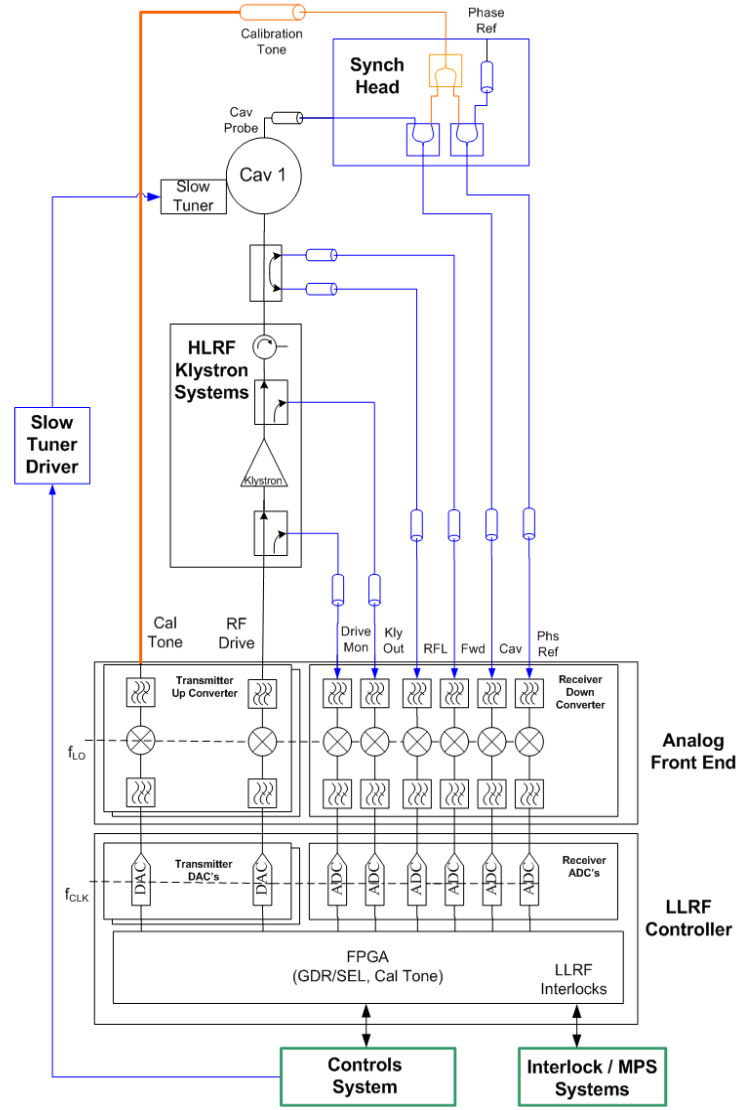
LLRF4 board running at ANL

JLab Stepper Motor Driver will be used for the Slow Tuner

- Delivery estimated 1/2012

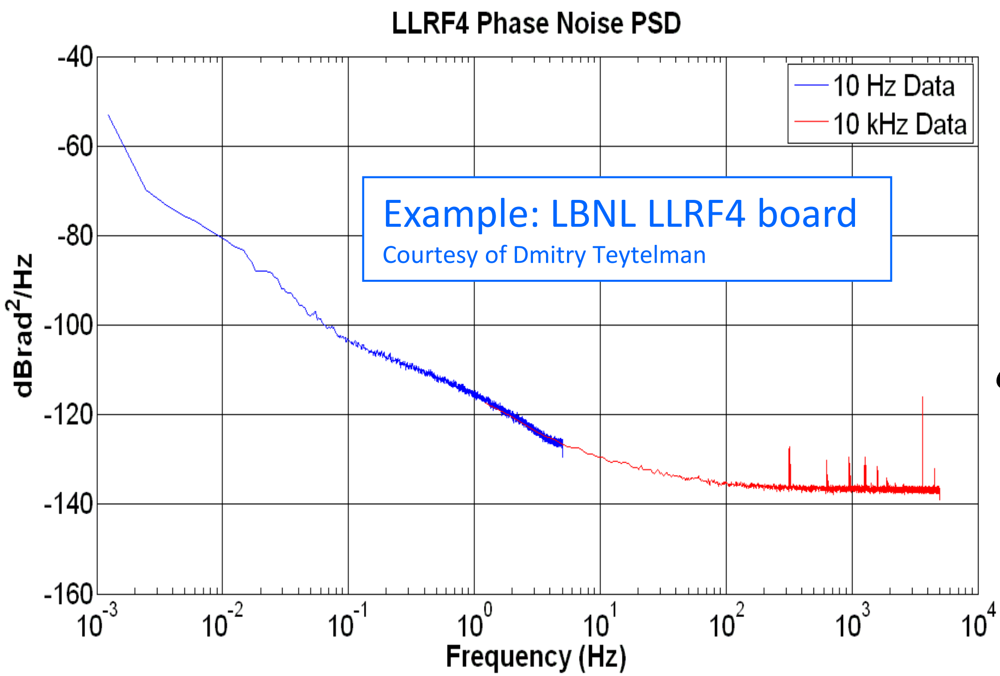
Then, we need to demonstrate that we can achieve the differential specs between 2 cavities





How to achieve 0.18° rms Differential Phase ??

- Digital LLRF receiver noise floors show capability at least > 1Hz
- Beam-based feedback strategy planned for < 100(200) Hz
- LBNL drift compensation schemes provide long term stability
- Deflecting cavity system noise performance will be measured in R&D
  - Need to explore microphonics, beam-loading & cavity alignment concepts



$$S_\phi(f) \cong b_o + \frac{b_1}{f} + \frac{b_2}{f^2}$$

$b_o = 1.585 \cdot 10^{-14}$ rad²/Hz

$b_1 = 1.585 \cdot 10^{-12}$ rad²

$b_2 = 6.31 \cdot 10^{-13}$ rad²Hz

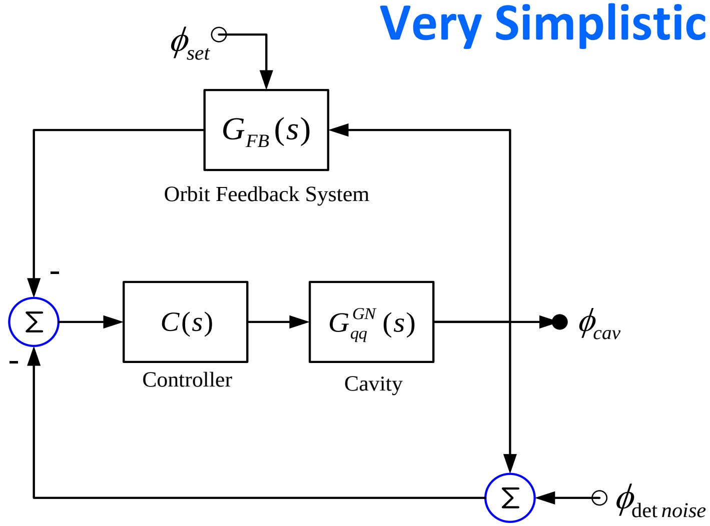
$$\sigma_\phi = \sqrt{\int_{f_{\min}}^{f_{\max}} S_\phi^{cav}(f)\,df}$$

0.0072 deg RMS

1Hz to 1MHz

How to achieve 0.18° rms Differential Phase ??

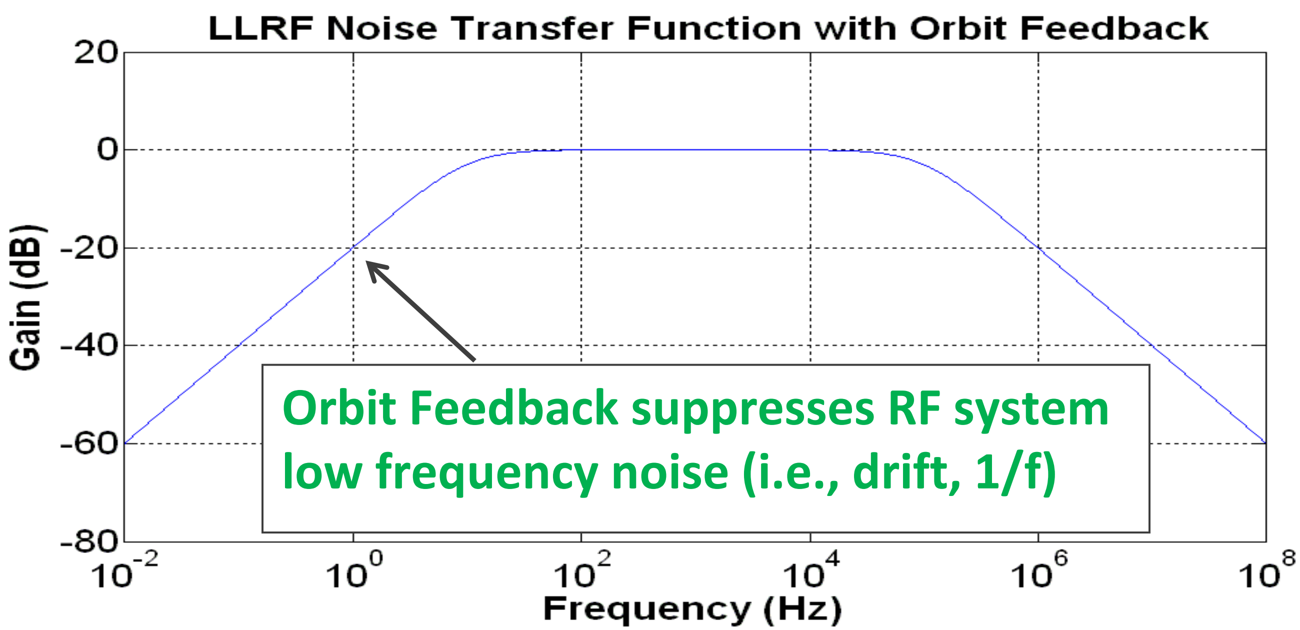
Very Simplistic First Order Orbit Feedback concept



Assume: $$G_{FB}(s) = \frac{K_p^{RTFB}\sigma_{RTFB}}{s}$$

$$N_{FB}(s) = \frac{\phi_{cav}(s)}{\phi_{det\,noise}(s)} = \frac{C(s)G_{qq}^{GN}(s)}{1+C(s)G_{qq}^{GN}(s)\left[1+G_{FB}(s)\right]}$$

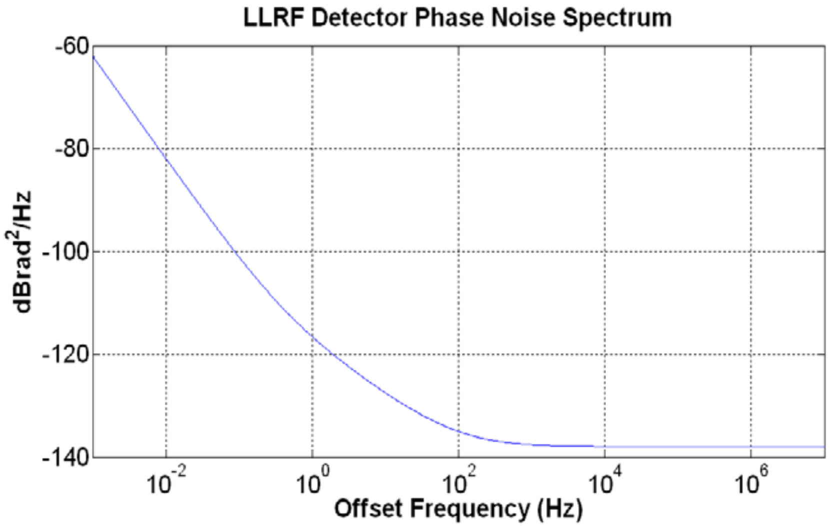
$$= \frac{K_p\sigma_{cav}\, s}{s^2 + K_p\sigma_{cav}\, s + K_p^{RTFB}K_p\sigma_{RTFB}\sigma_{cav}}$$



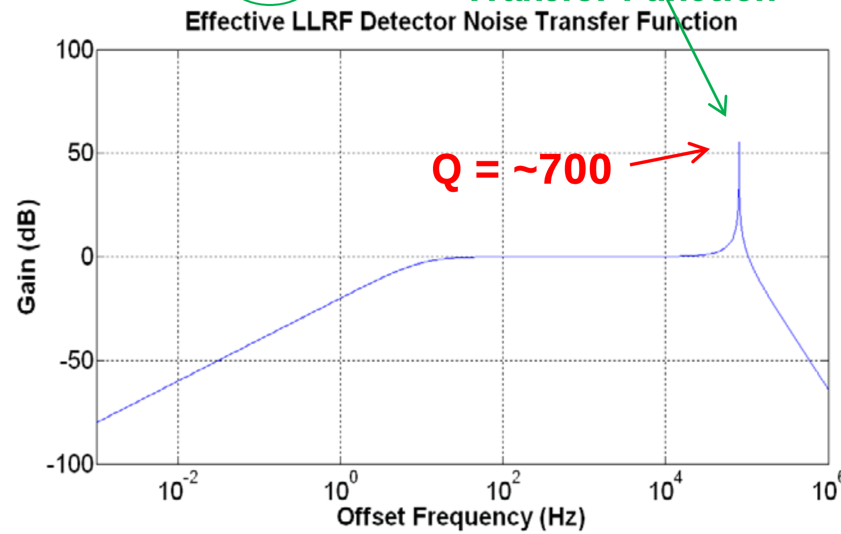
How to achieve 0.18° rms Differential Phase ??

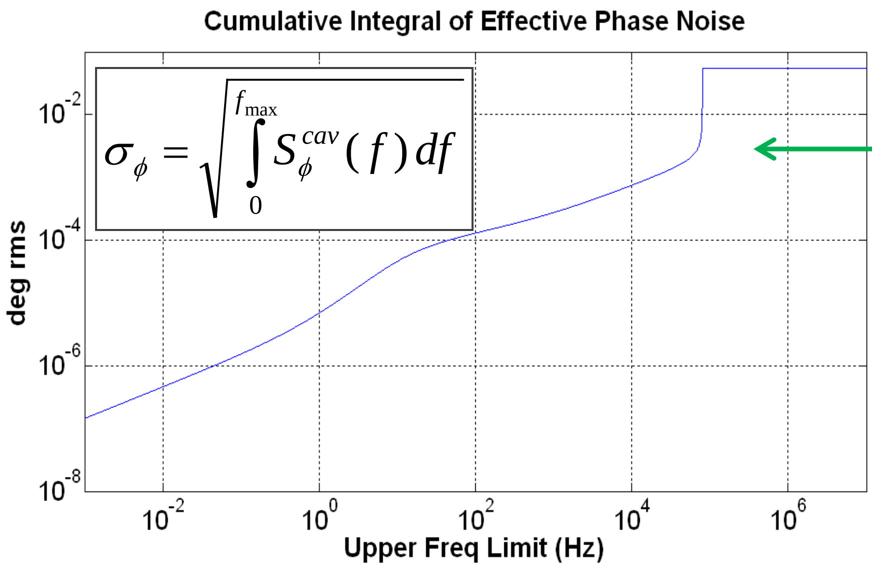
$$S_{\phi\ effective}^{cav}(f) = S_{\phi}^{LLRF} \cdot \left| N_{RTFB}(s) \cdot \beta_N(s) \right|^2$$

Beam Orbit Transfer Function



X





0.054 deg RMS w Betatron Tune

0.0034 deg RMS w/o Betatron Tune

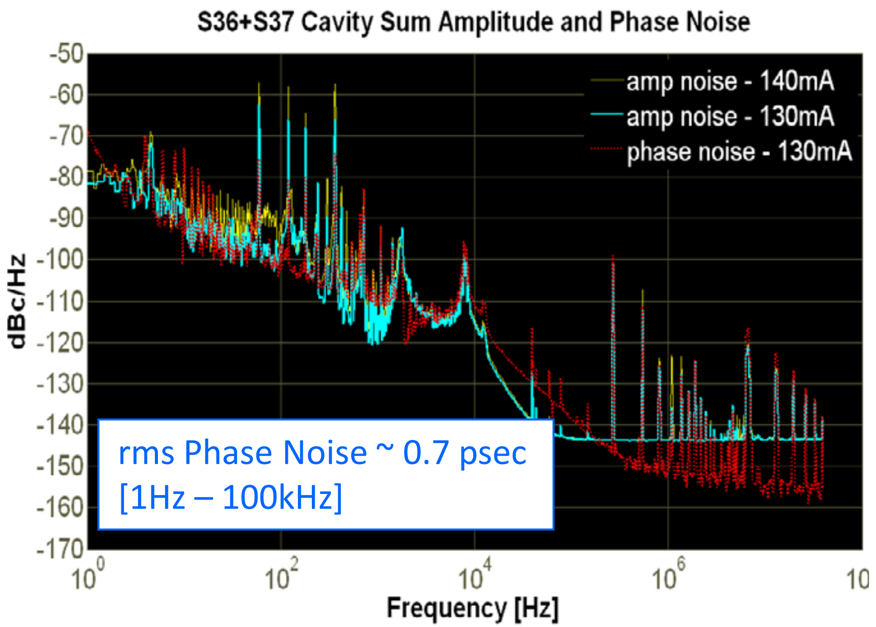
Expect lower Q when including existing transverse feedback system

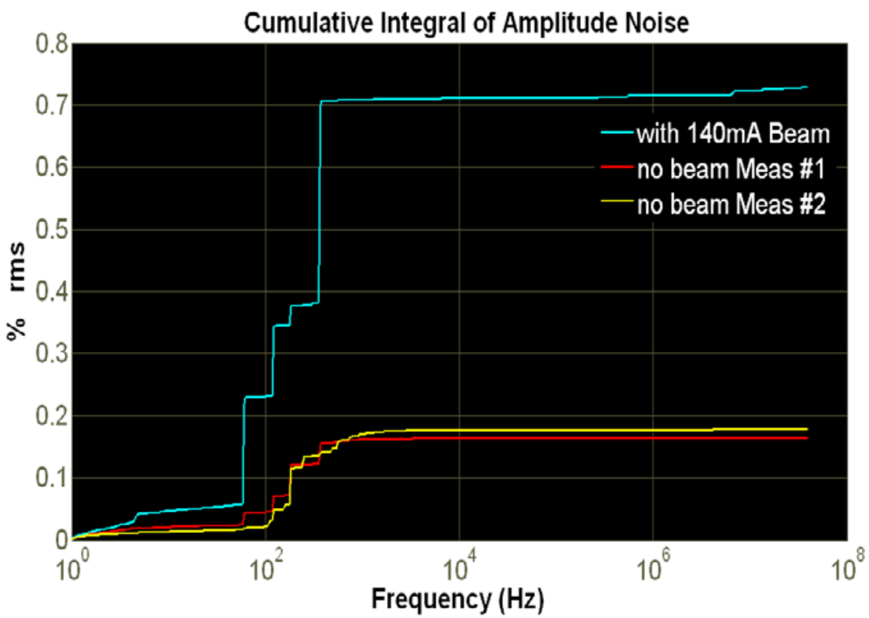
Will study the need for:

narrow-band beam-based feedback near the betatron resonance

Common Mode Phase Considerations

- 4.0° rms = ~4 psec rms common mode spec
  - Existing beam jitter
    - Initial diagnostic studies show ~2.7 psec rms beam jitter
    - Beam physics simulations based upon rf measurements of AM and PM noise resulted in 1.7 psec rms
    - Extensive studies of main 352 MHz rf system noise have been taking place (APSU_1417419, APSU_1416636, APSU_1416055, APS_1414611)
  - Planning on beam arrival time feedback to main 352 MHz

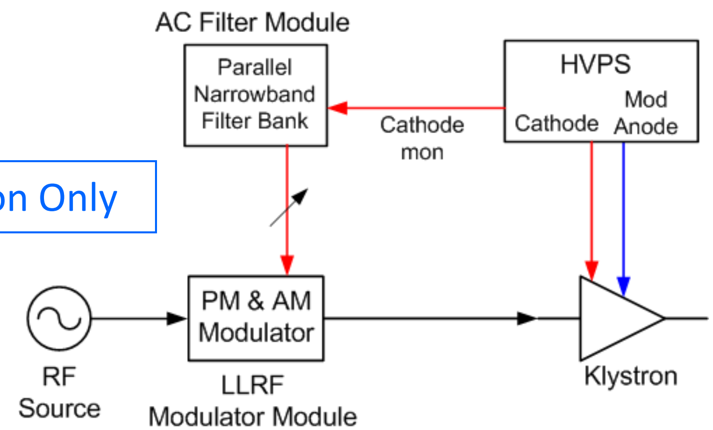


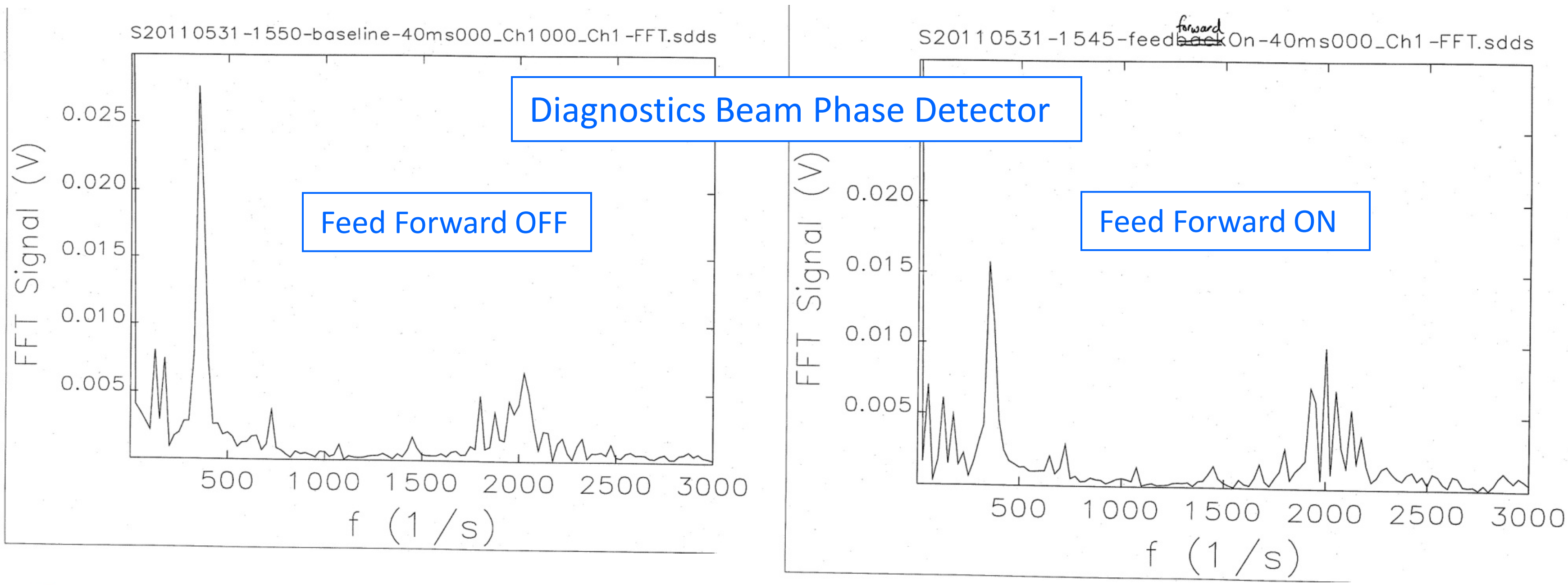


Challenges and Strategy – 4° Common Mode Phase Spec

Have recently experimented with 360Hz Feed-Forward correction of Kly HVPS induced noise

AM suppression at 1 Station Only

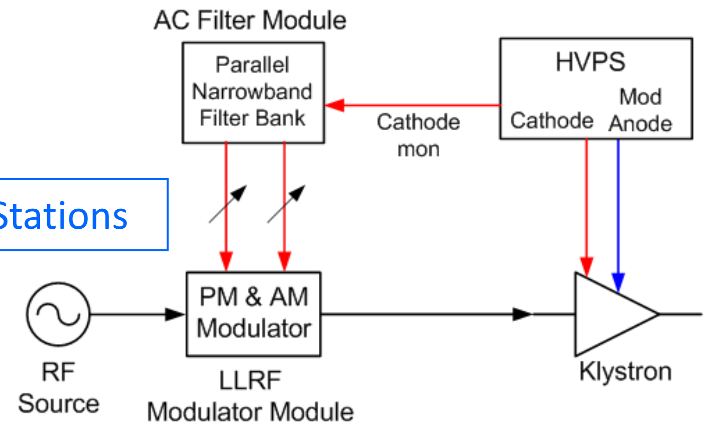


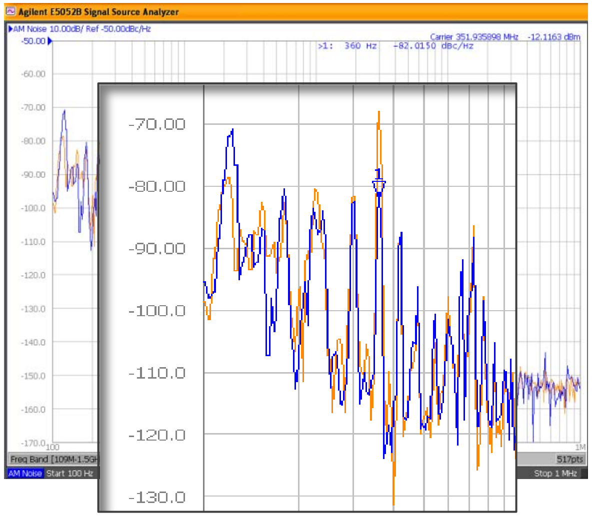


Challenges and Strategy – 4° Common Mode Phase Spec

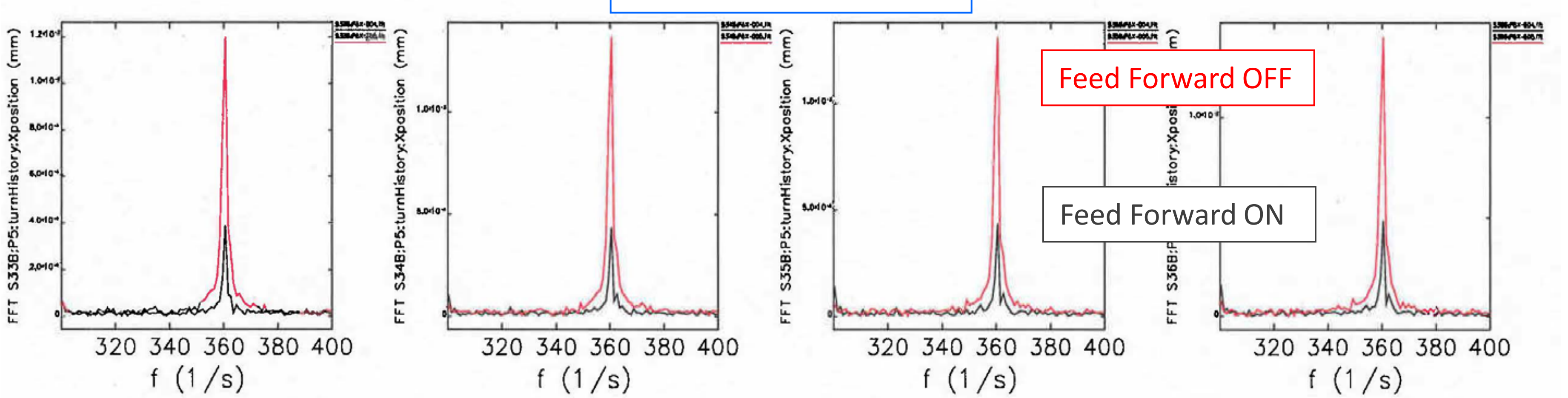
Have recently experimented with 360Hz Feed-Forward correction of Kly HVPS induced noise

AM & PM suppression at Both Stations





Horizontal BPM Data

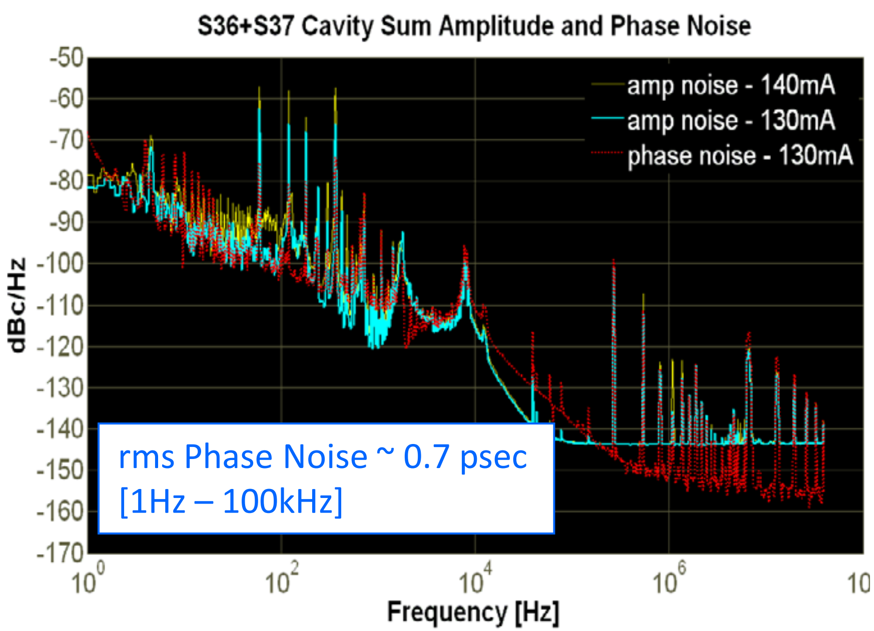


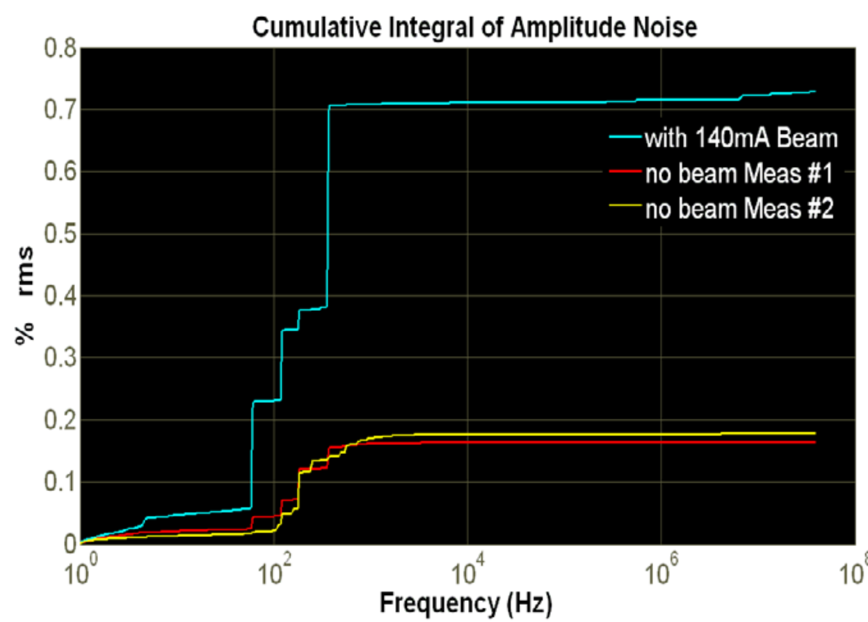
R&D Scope - Technical Description

Major Challenges

Challenges and Strategy – 4° Common Mode Phase Spec

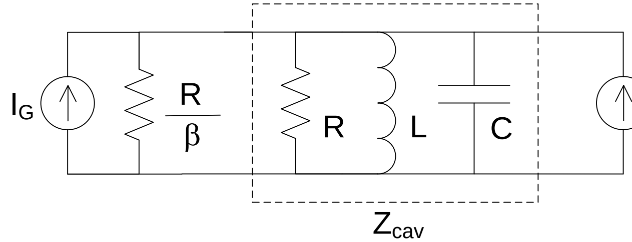
- 4.0° rms = ~4 psec rms common mode spec
  - Existing beam jitter
    - Initial diagnostic studies show only ~2.7 psec rms beam jitter
    - Beam physics simulations based upon rf measurements of AM and PM noise resulted in 1.7 psec rms
    - Extensive studies of main 352 MHz rf system noise have been taking place (APSU_1417419, APSU_1416636, APSU_1416055, APS_1414611)
  - Planning on beam arrival time feedback to main 352 MHz





Challenges and Strategy – Tools

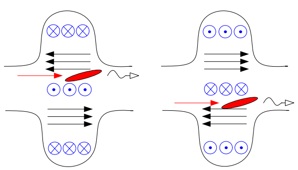
Have Beam-Loaded Deflecting Cavity Model, both static …

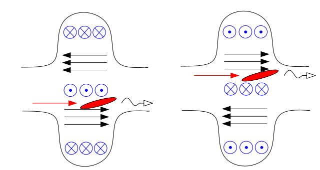


$$i_o\kappa_o\left(y + j\cdot\theta\,\omega_o c\,\sigma_t^{\,2}\right)\cdot e^{-j(\pi+\phi_s)}$$

$$i_o = 2I_{dc}\cdot e^{-\frac{1}{2}(2\pi f_o\sigma_t)^2}$$

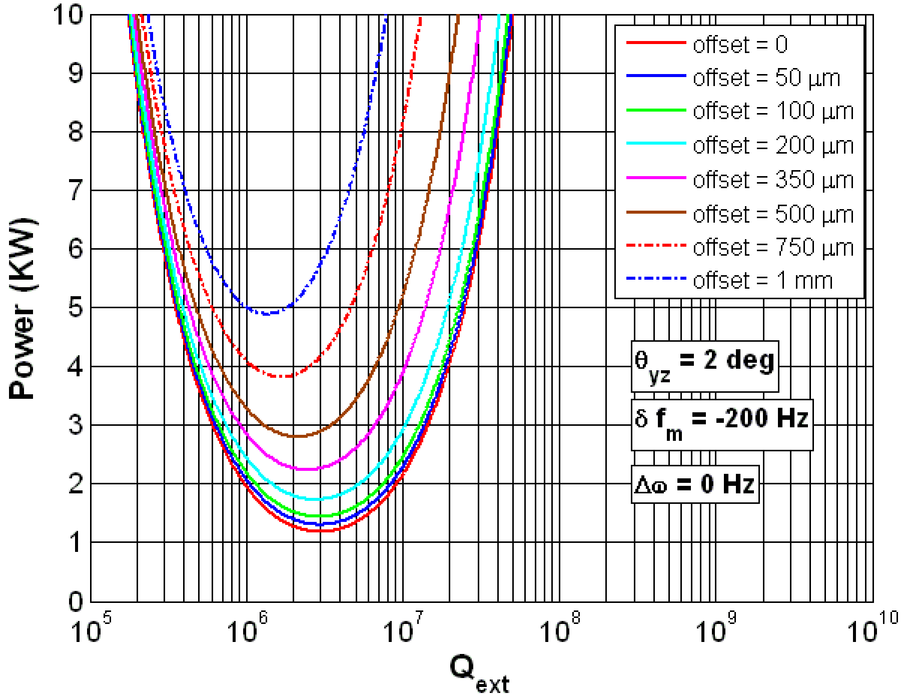
$$P_g^{\,+} = \frac{V_t^{\,2}}{8\beta\,(R/Q)'\,Q_o}\cdot\left[\left(\beta+1+\frac{P_B}{P_{cav}}\right)^2+\left(2Q_o\frac{(\Delta f+\delta f_m)}{f_r}+\frac{P_B}{P_{cav}}\tan\phi_s\right)^2\right]$$

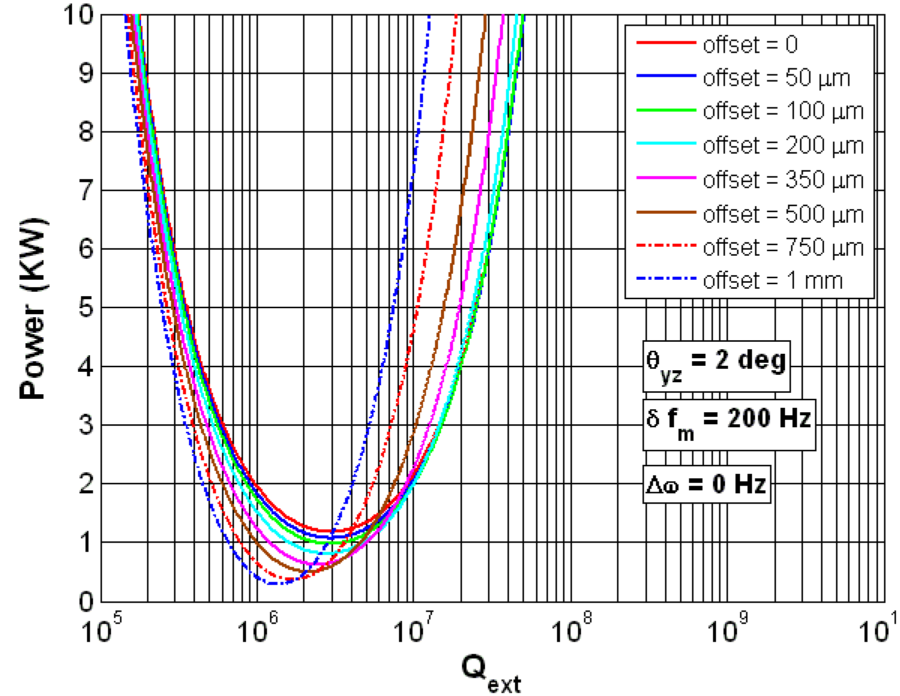




$V_t\cdot y>0$

$V_t\cdot y<0$





Summary

- Extensive studies of main 352 MHz RF system noise have been taking place
  - Simulations from rf measurements show ~1.7 psec rms beam jitter
  - Beam diagnostics measurements show ~2.7 psec rms

- Planning on beam-based feedback to relax LLRF long-term drift and $1/f^x$ noise
  - LBNL phase stable ref. & drift compensation will relax orbit control effort

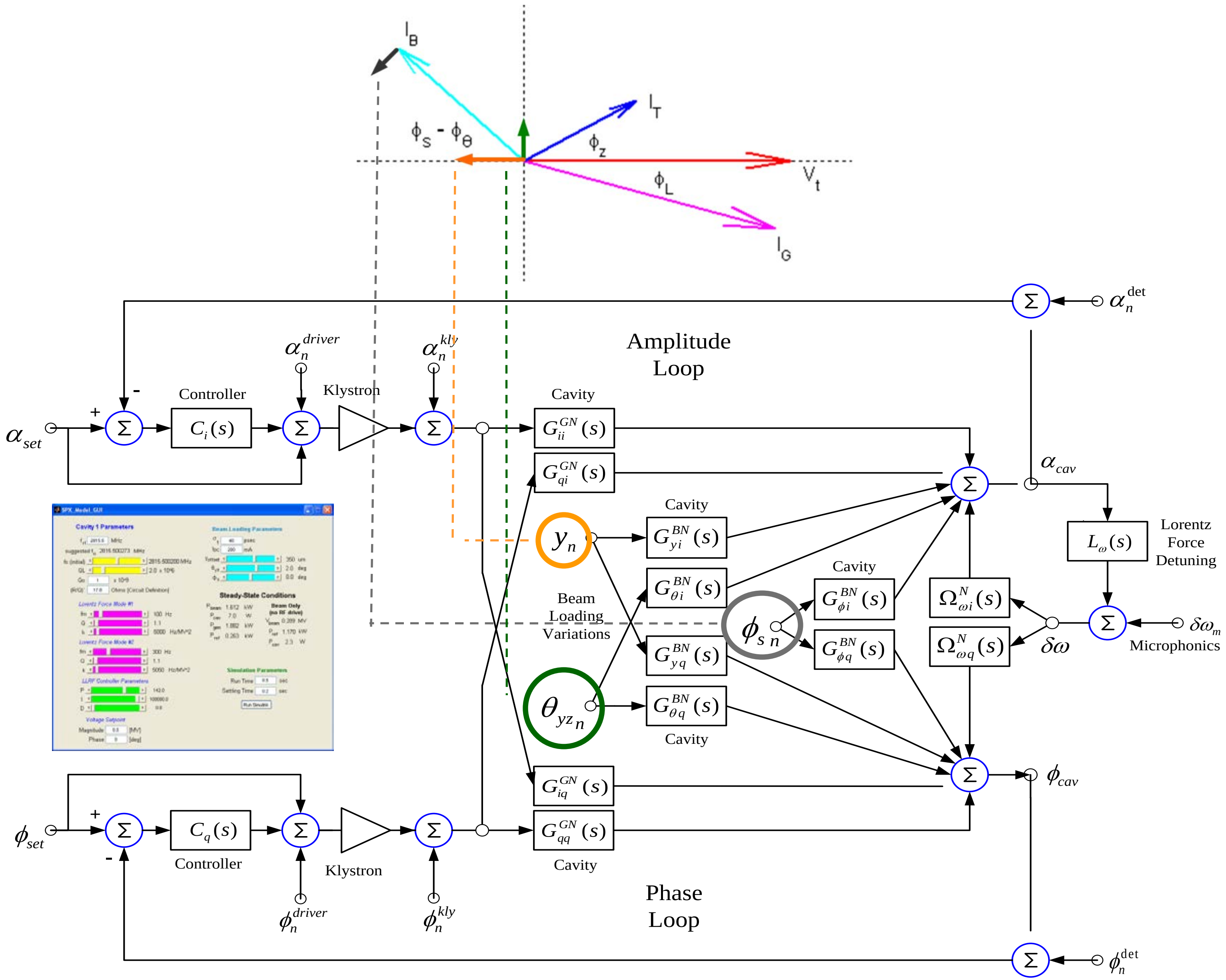
- Plan to use digital LLRF control technology
  - LLRF4 based system to support R&D 2-cavity system
  - Preliminary Engineering provisions in schedule allow for lessons learned from LLRF4 with transition into Final Engineering.

- Have excellent tools (both theoretical models and measurement equipment) to track, measure, and ensure system performance

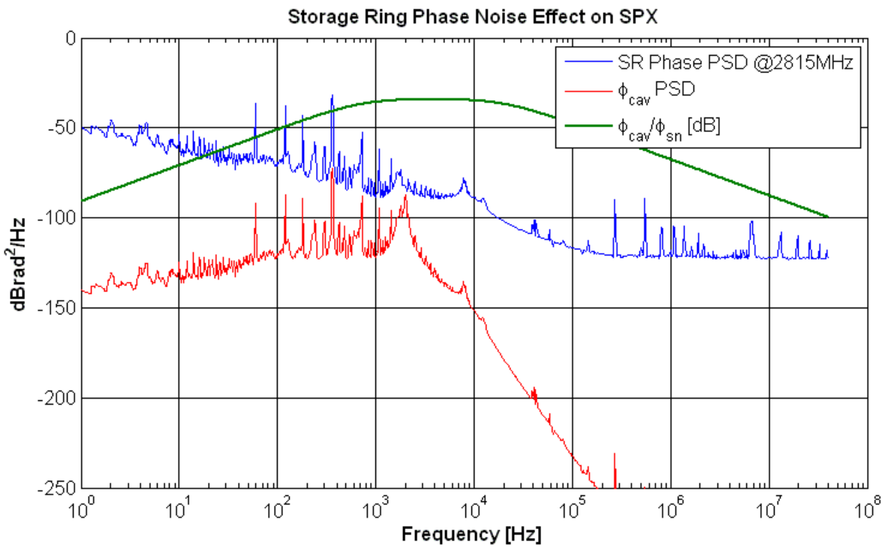
- Have an **EXCELLENT** LLRF Team capable of success
  - Collaboration with LBNL creates the synergy necessary for success

Backup Slides

Dynamic small signal model for individual crab cavity



Motivation for Cavity Electrical Alignment Adjust



Beam Loading is proportional to offset

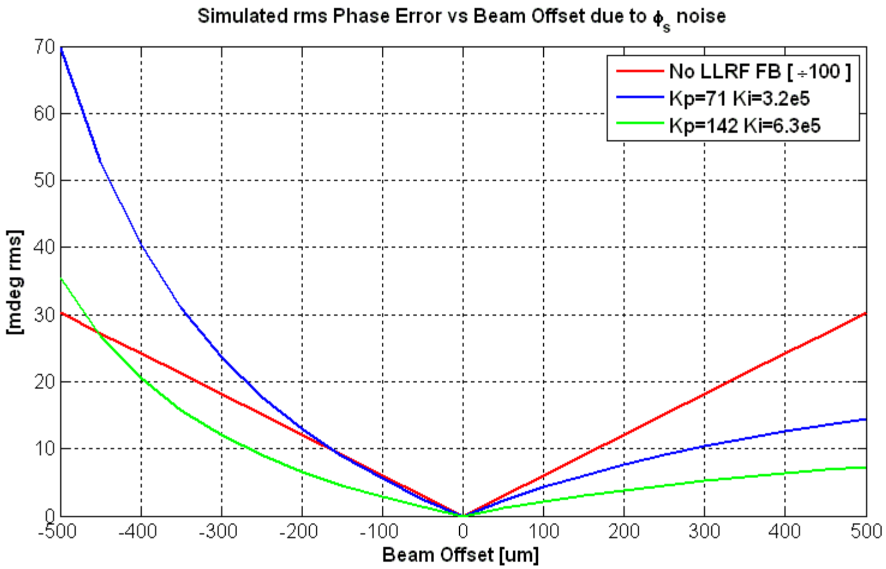
Cavity-to-cavity alignment errors cause **differential beam-loading** that will lead **to differential phase noise**

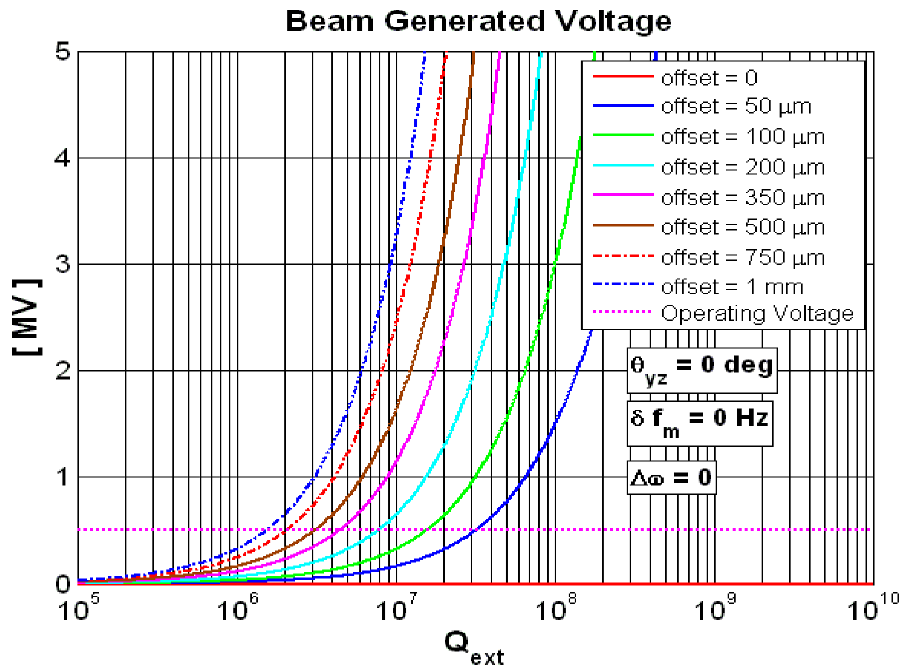
Standard cavity-to-cavity alignment = 500um

Beyond APS-U, 4MV => 0.07deg spec

Means to reduce effect:

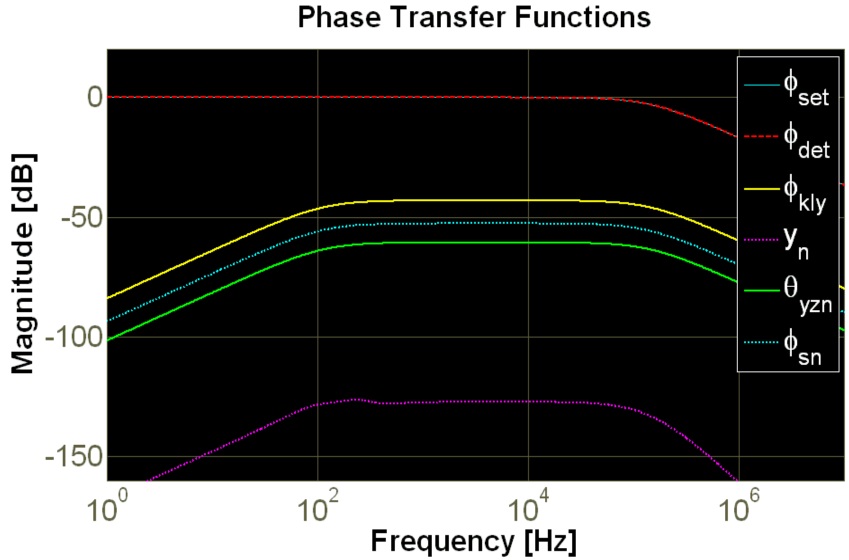
improve cavity alignment, go to lower QL, reduce Storage Ring AM & PM noise

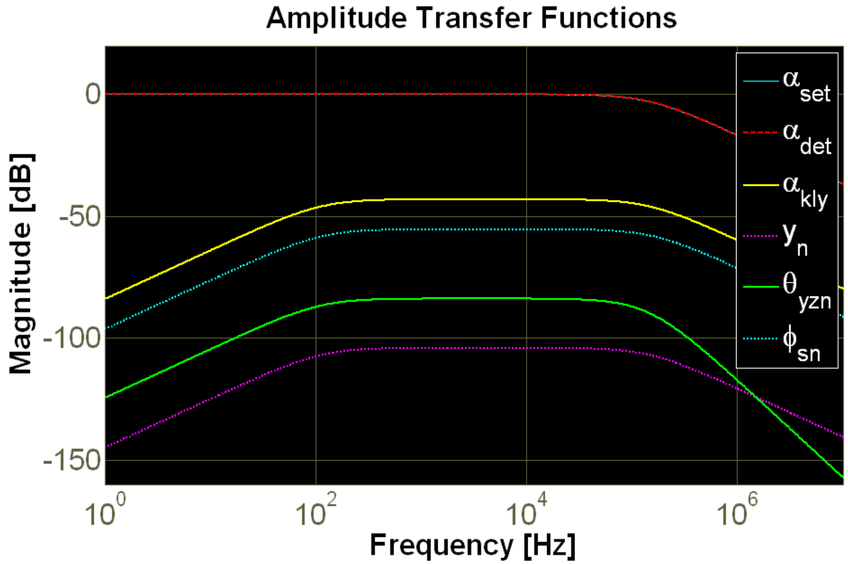


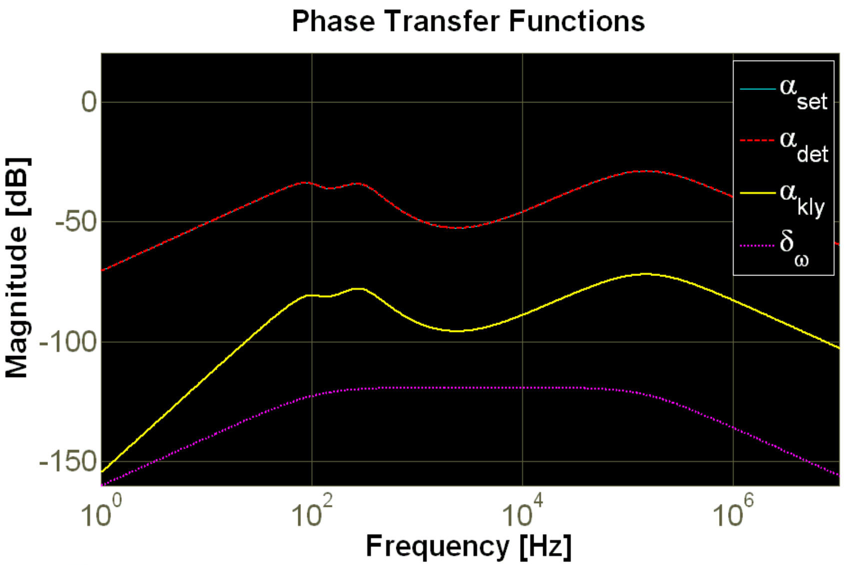


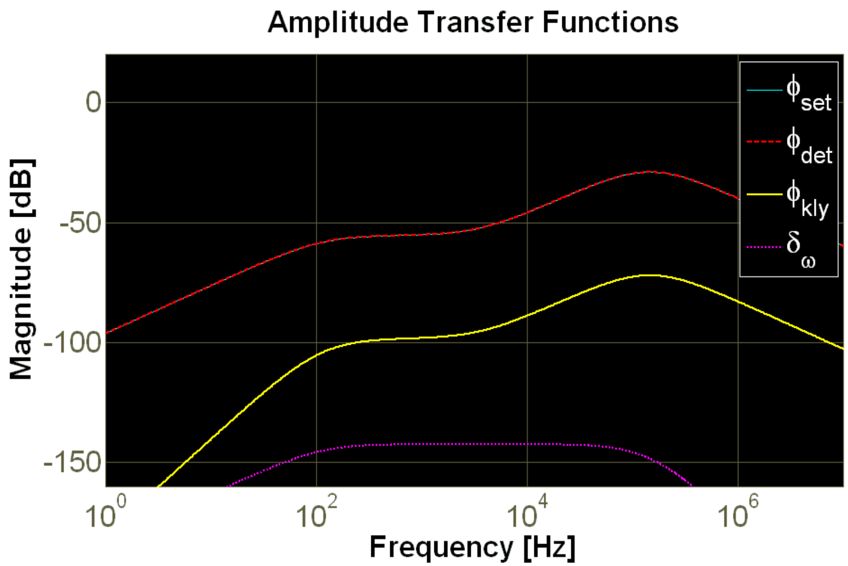
Challenges and Strategy – Tools

- … and dynamic small signal model will help track system noise & error budgets

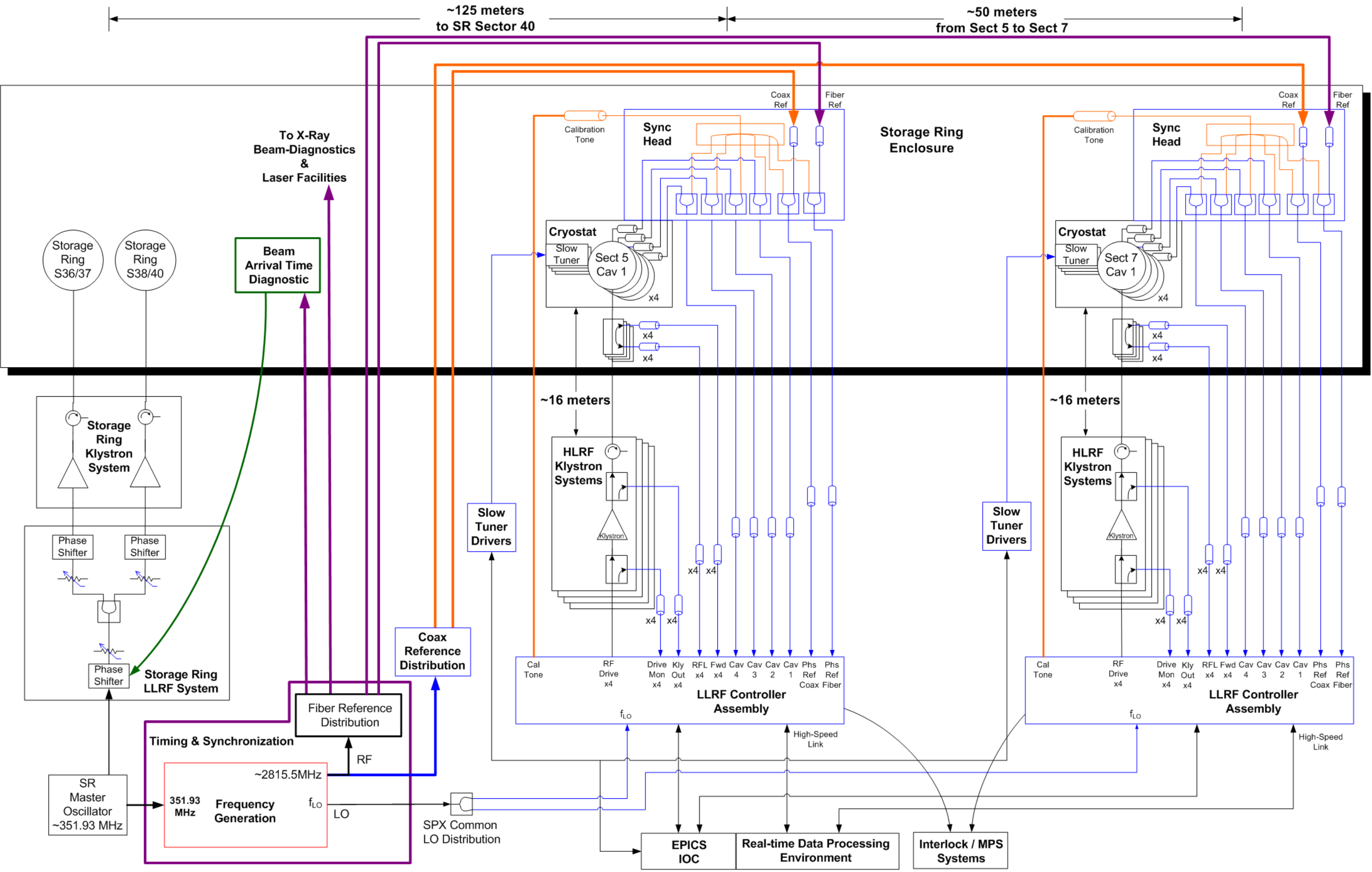




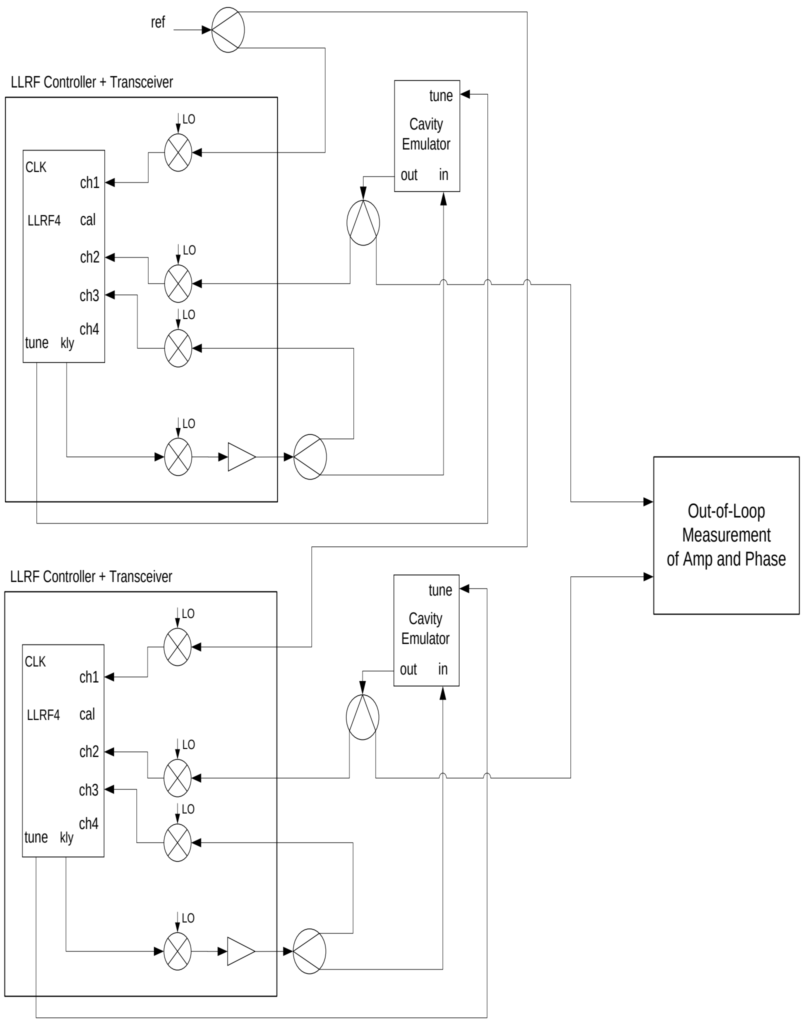




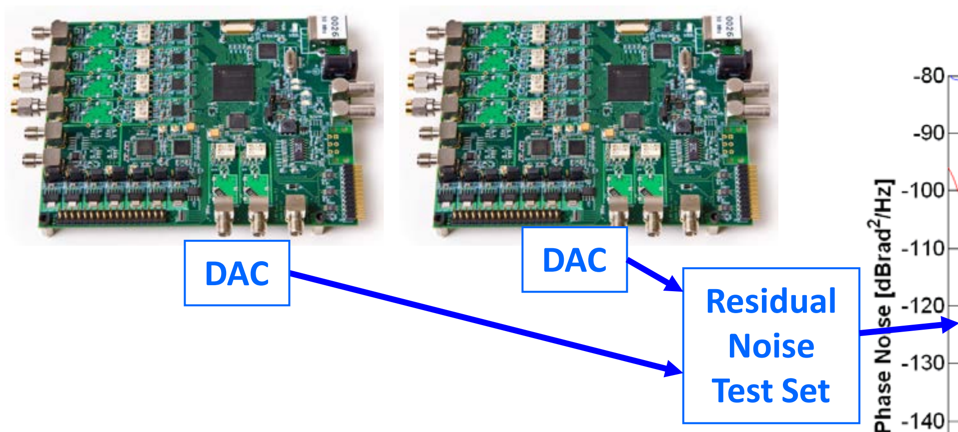
Production System Concept (2 Sectors, 4 cav/sector)

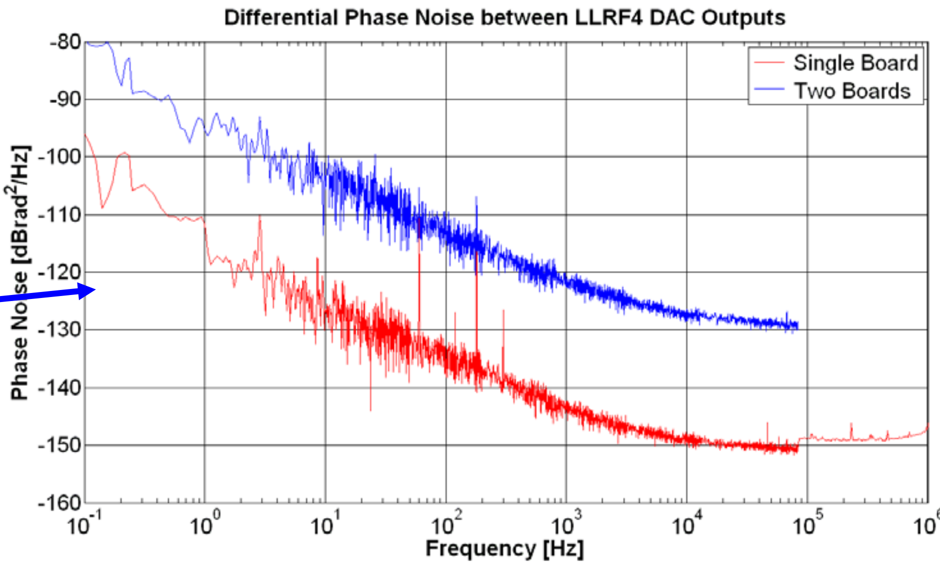


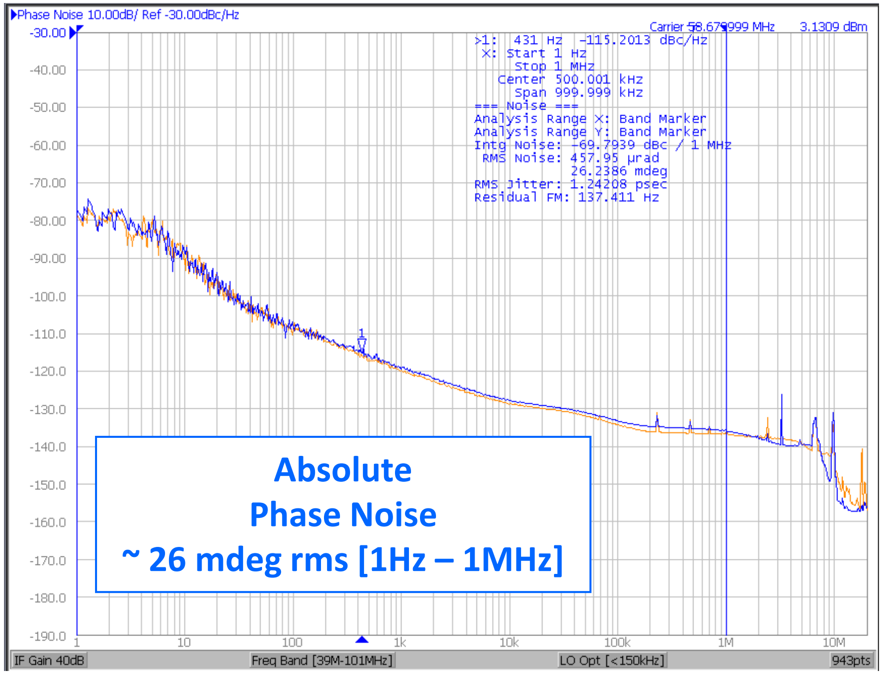
Benchtop Demonstrations until Cavities become available

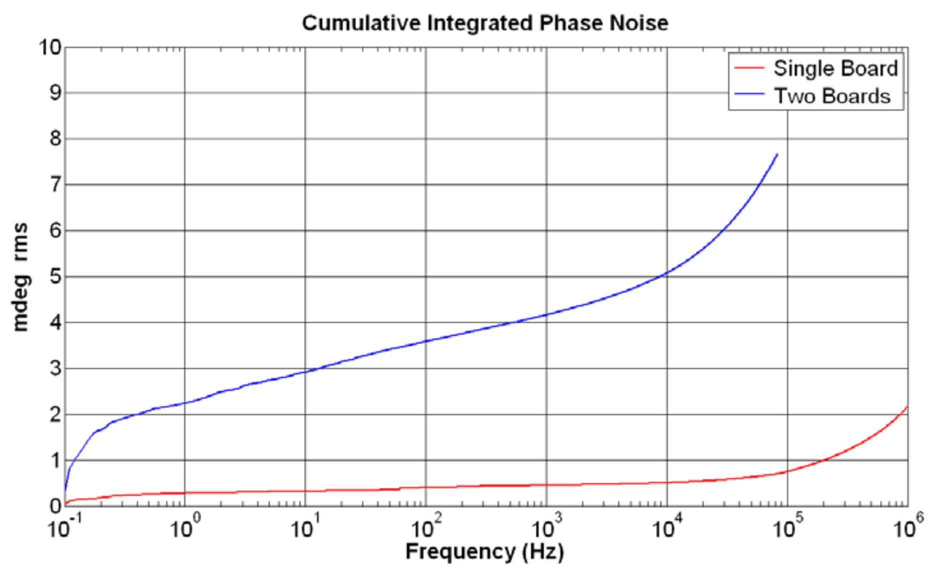


Trivial Example of Common LO/CLK source Distribution









R&D Period Highlights

- Ultimate Goal: Demonstrate required rf stability performance on a 2-cavity single cryomodule system

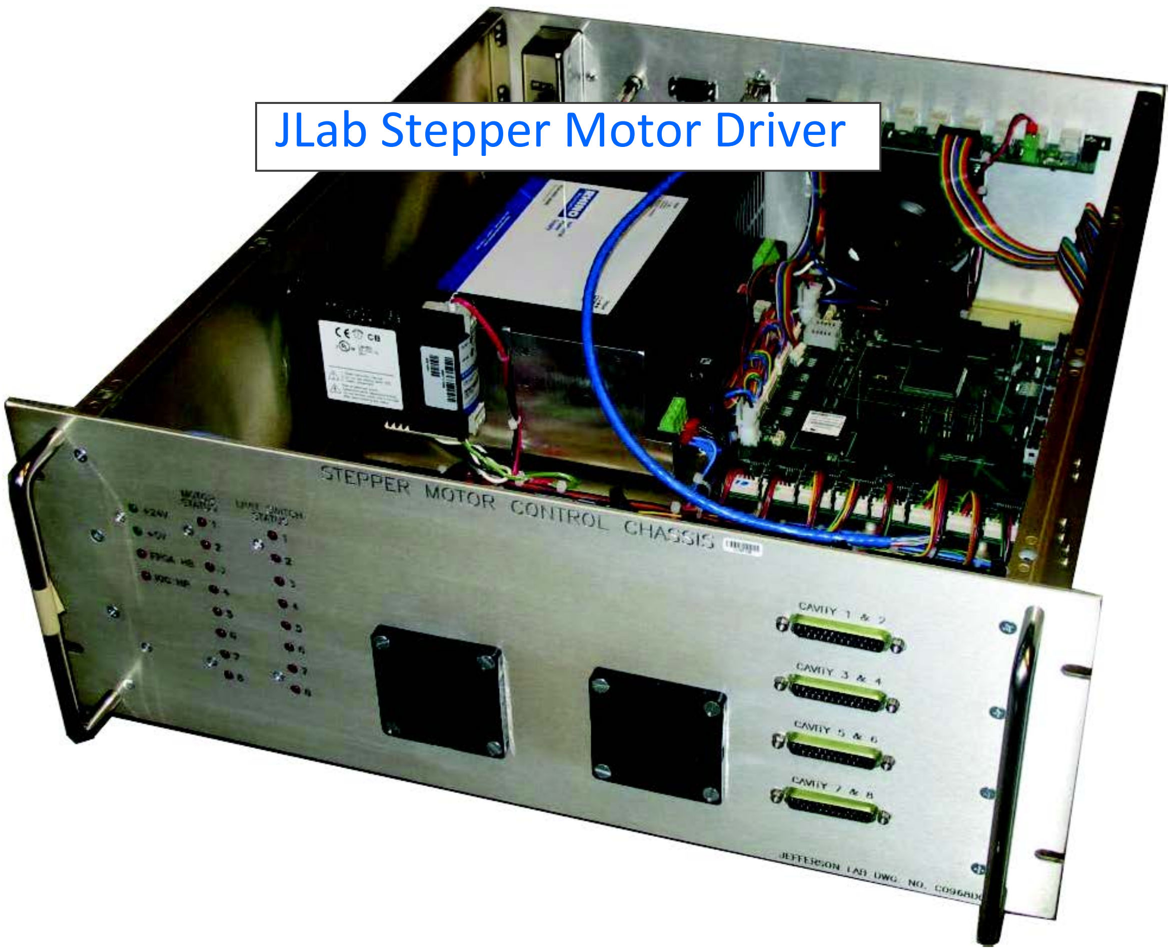
- LBNL Collaboration - Phase I [3/11 – 10/11]
  - Study & report on differential stability between two high-Q cavity emulator systems
  - Delivery of first LLRF4 Chassis and Frequency Generation Chassis
  - ANL prepares to take ownership of LLRF4 based system & prepares tests of LLRF receiver chain

- LBNL Collaboration - Phase II [10/11 – 10/12] (joint with Timing/Synchronization)
  - Completion of LLRF4 based controllers for R&D program
  - Demo of timing/synchronization concepts between RF Cavity and User Laser

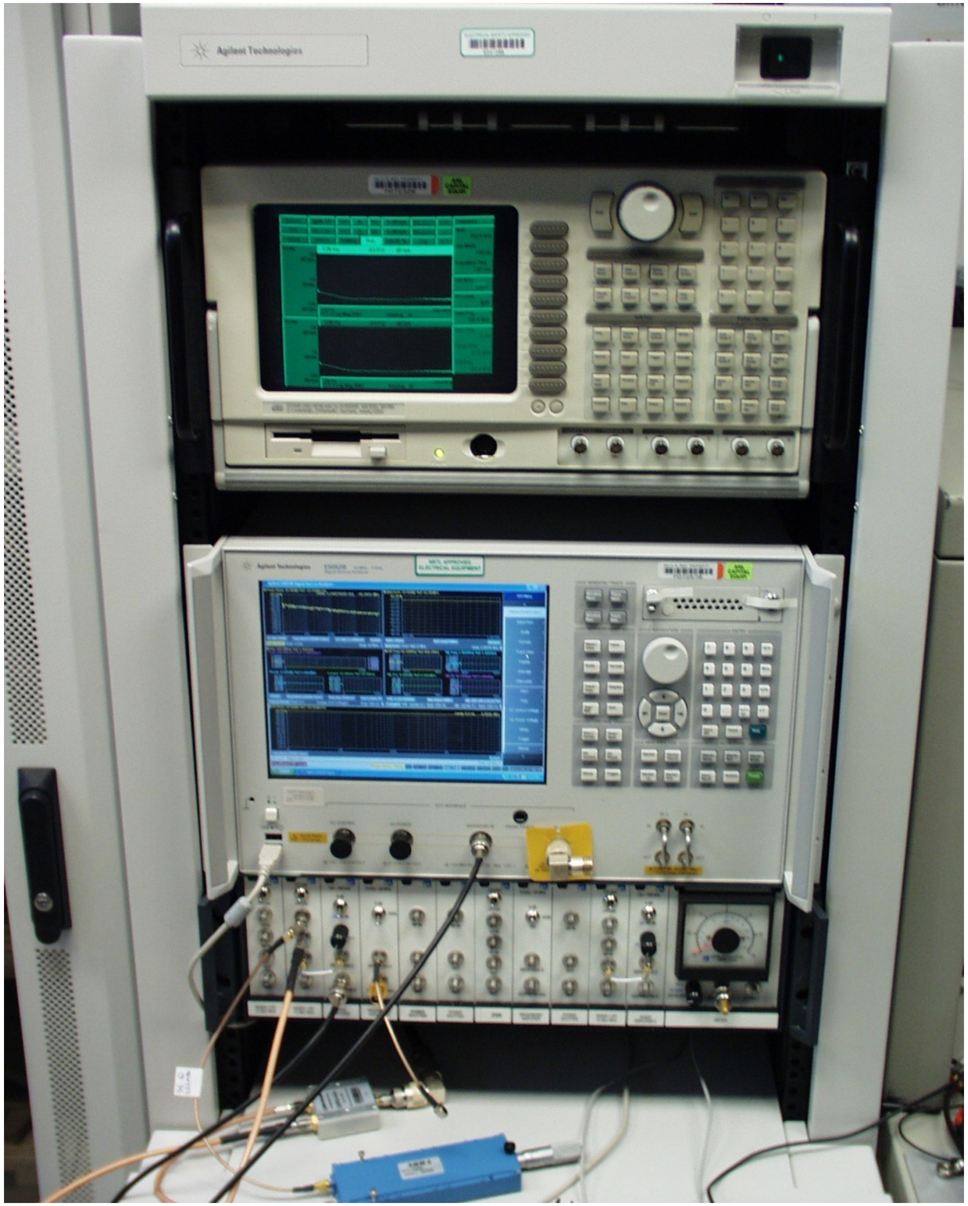
- Present LLRF R&D Timeline Overview
  - Receipt of first LLRF4 based system from LBNL [10/11]
  - Receipt of JLab slow tuner stepper motor driver [1/12]
  - Single cavity testing begins at ANL [2/12]
  - 2-cavity cryomodule testing begins at ANL [5/13]
  - 2-cavity in-ring test [begins 9/13]

Stepper Motor Driver (x2   4-channel driver)

- SPX Cavity will use a scissors jack tuner similar to the JLab 12GeV Upgrade
  - Hence JLab will provide two 4-channel drivers similar to their existing design



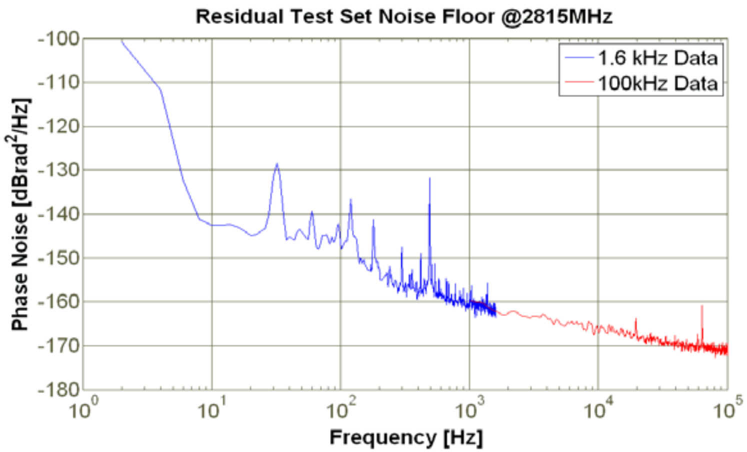
Challenges and Strategy – Tools

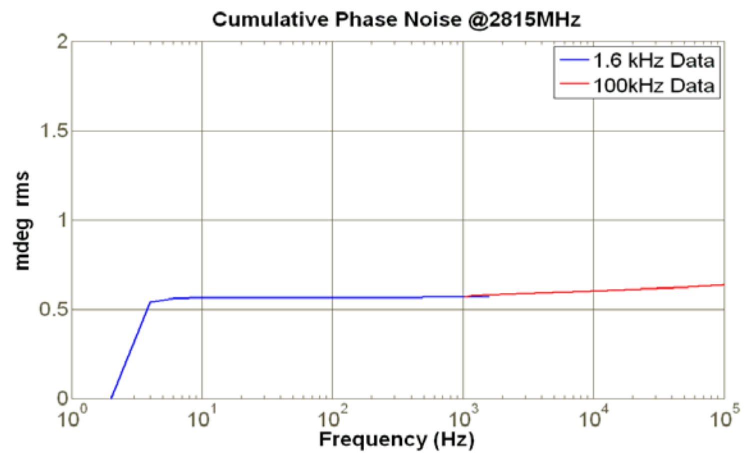


Phase Noise Measurement Equipment

- Agilent Signal Source Analyzer for absolute phase and amplitude noise

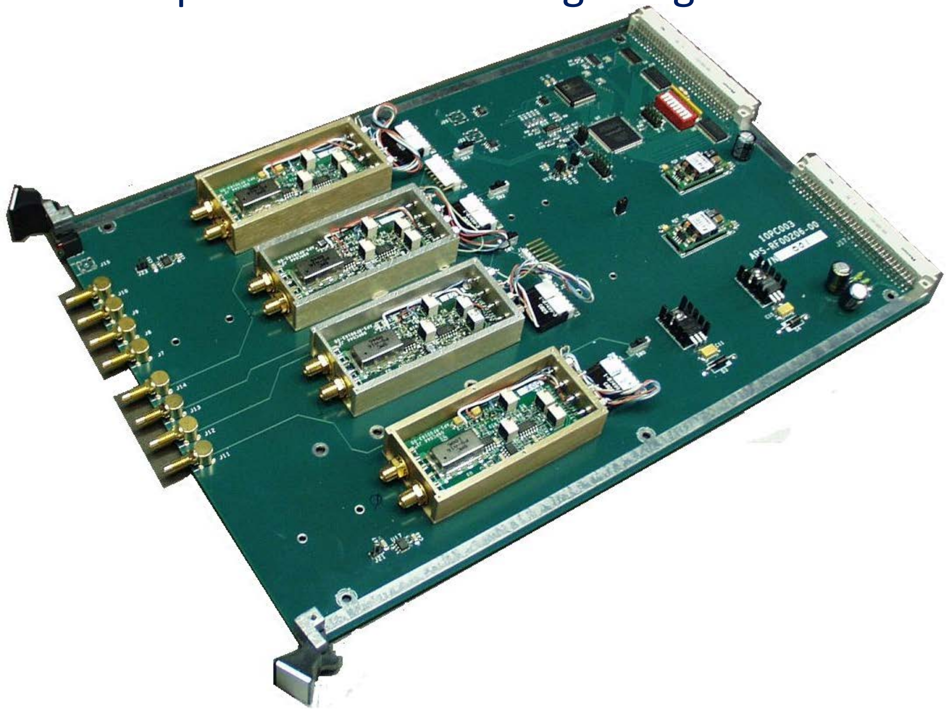
- Wenzel residual noise test set

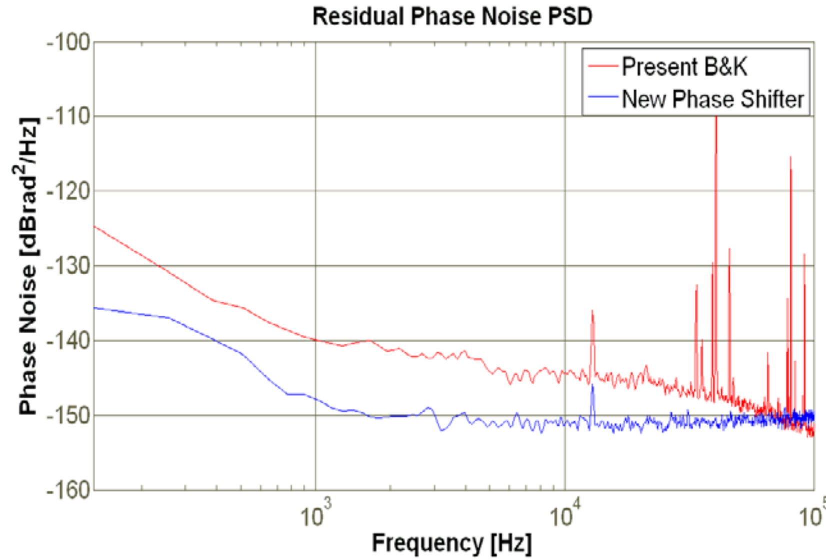


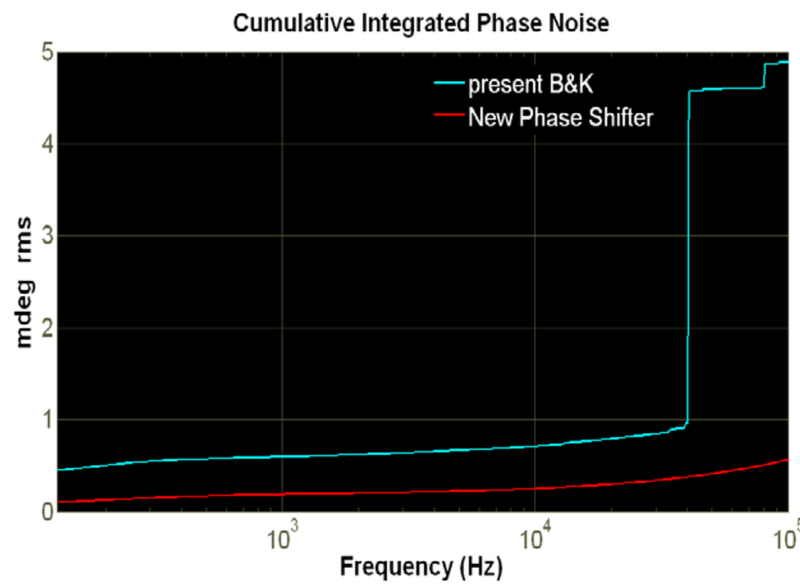


Phase Shifter candidate for BAT-based feedback to Main Storage Ring 352 MHz RF

- To address common mode phase specs, beam arrival time monitor will feedback to phase of main storage ring 352 MHz rf

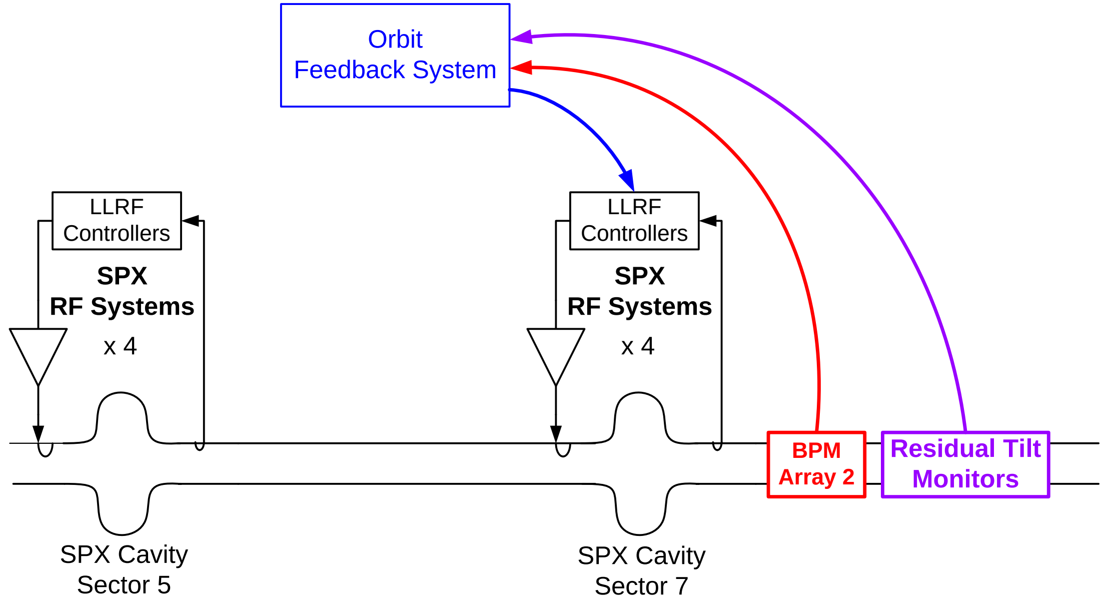






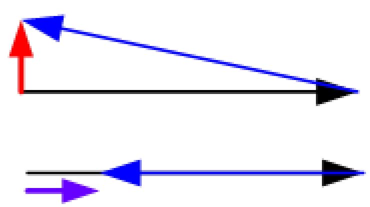
Conceptual Design Strategy: Differential Specs

- Orbit Feedback System provides long-term stability …
  - via Beam Position Monitor (BPM) Array 2 sets differential phase < 100(200) Hz
  - via Residual Tilt Monitors sets differential amplitude < 100(200) Hz
- **LLRF System on its own > 10 Hz**
  - **10 Hz – 100(200) Hz overlap with Orbit Feedback**



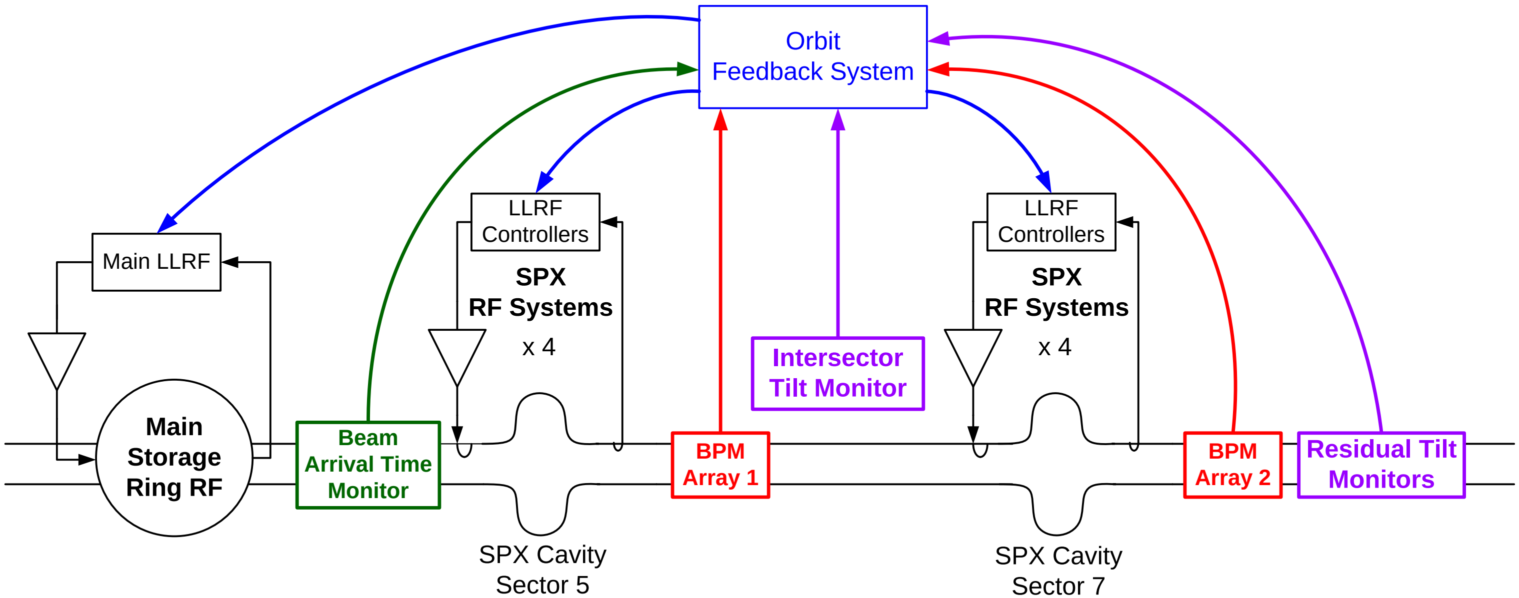
BPM Array 2: sets phase of Sector 7

Residual Tilt Monitors: sets amplitude of Sector 7



Conceptual Design Strategy: Common Mode Specs

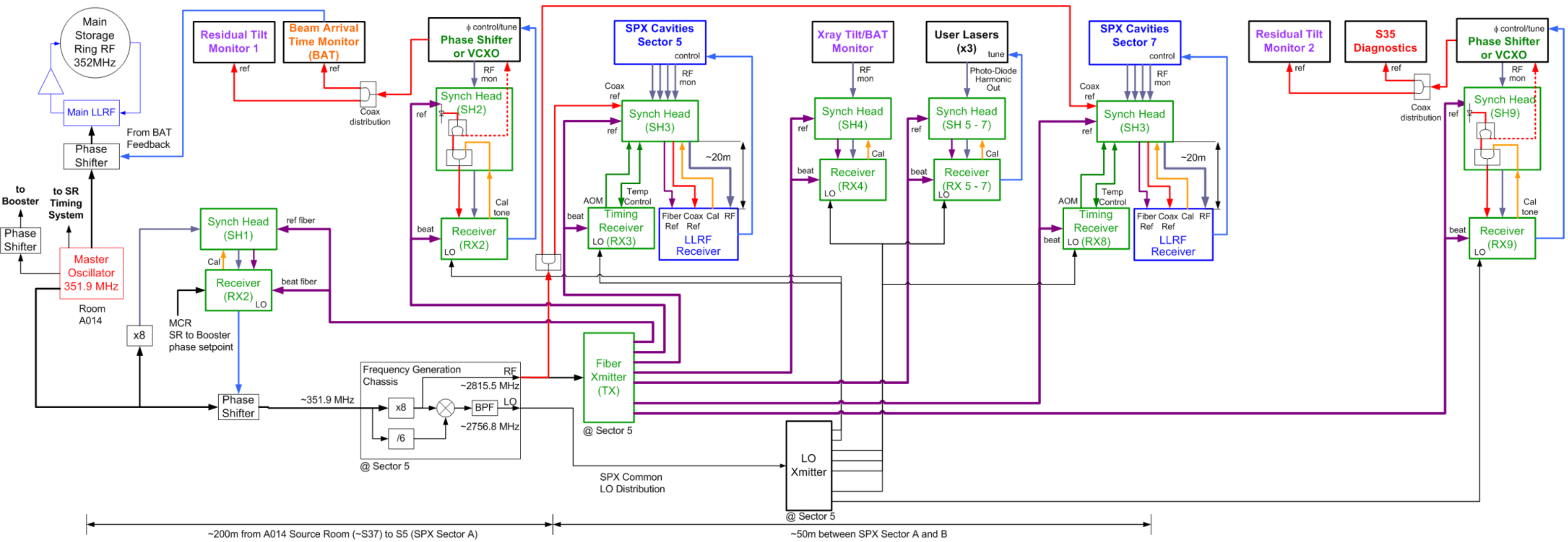
- **Main storage ring rf used to lock beam to master osc. via Beam Arrival Time diagnostic**
- SPX follows master oscillator, orbit feedback…
  - via BPM Array 1 sets common mode phase < 100(200) Hz
  - via Intersector Tilt Monitor sets common mode amp < 100(200) Hz
  - **LLRF on its own > 10 Hz**



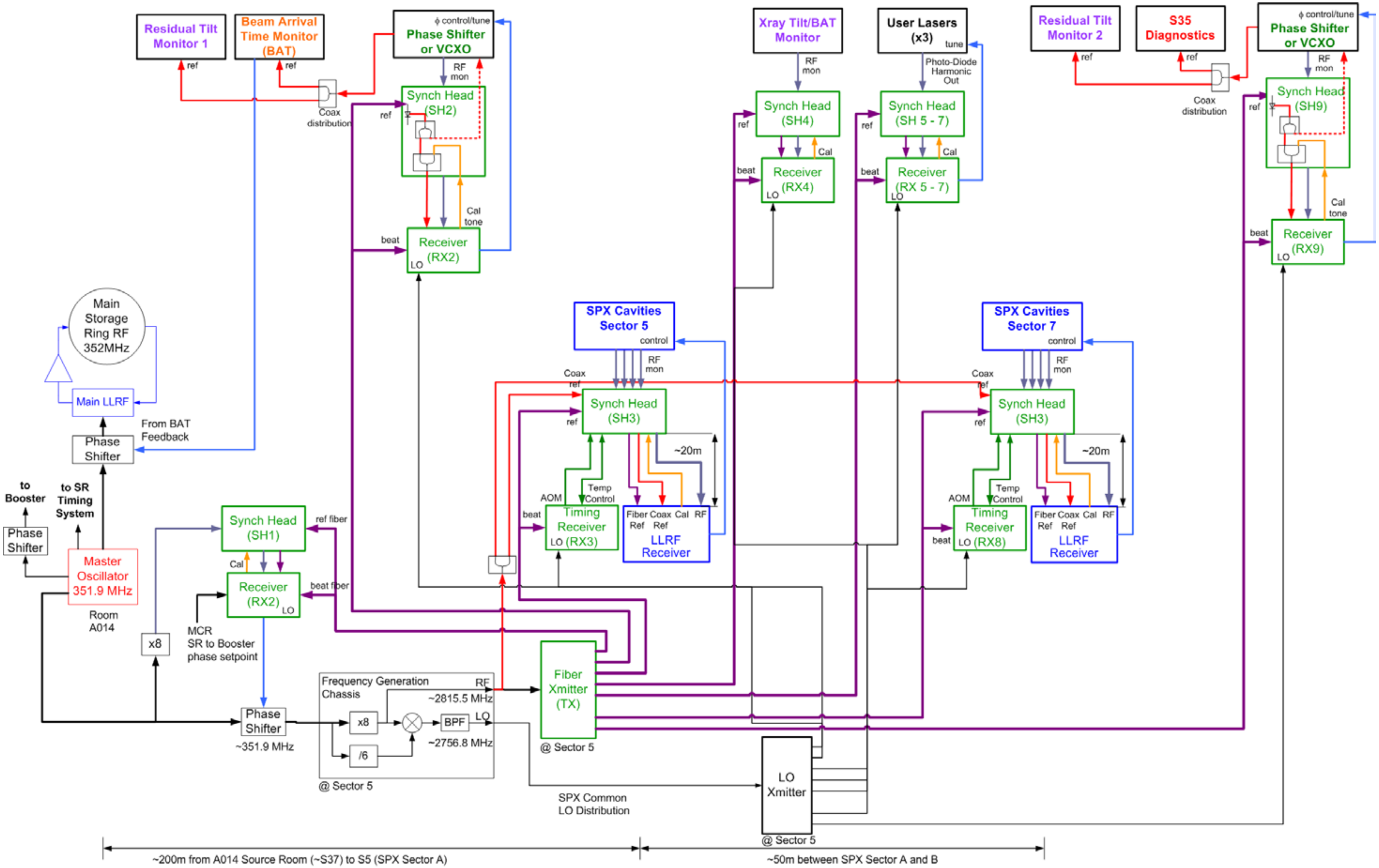
BPM Array 1: sets phase of Sector 5
BPM Array 2: sets phase of Sector 7

Intersector Tilt Monitor: sets amplitude of Sector 5
Residual Tilt Monitors: sets amplitude of Sector 7

Beam Arrival Time Monitor: sets phase of Main Storage Ring RF



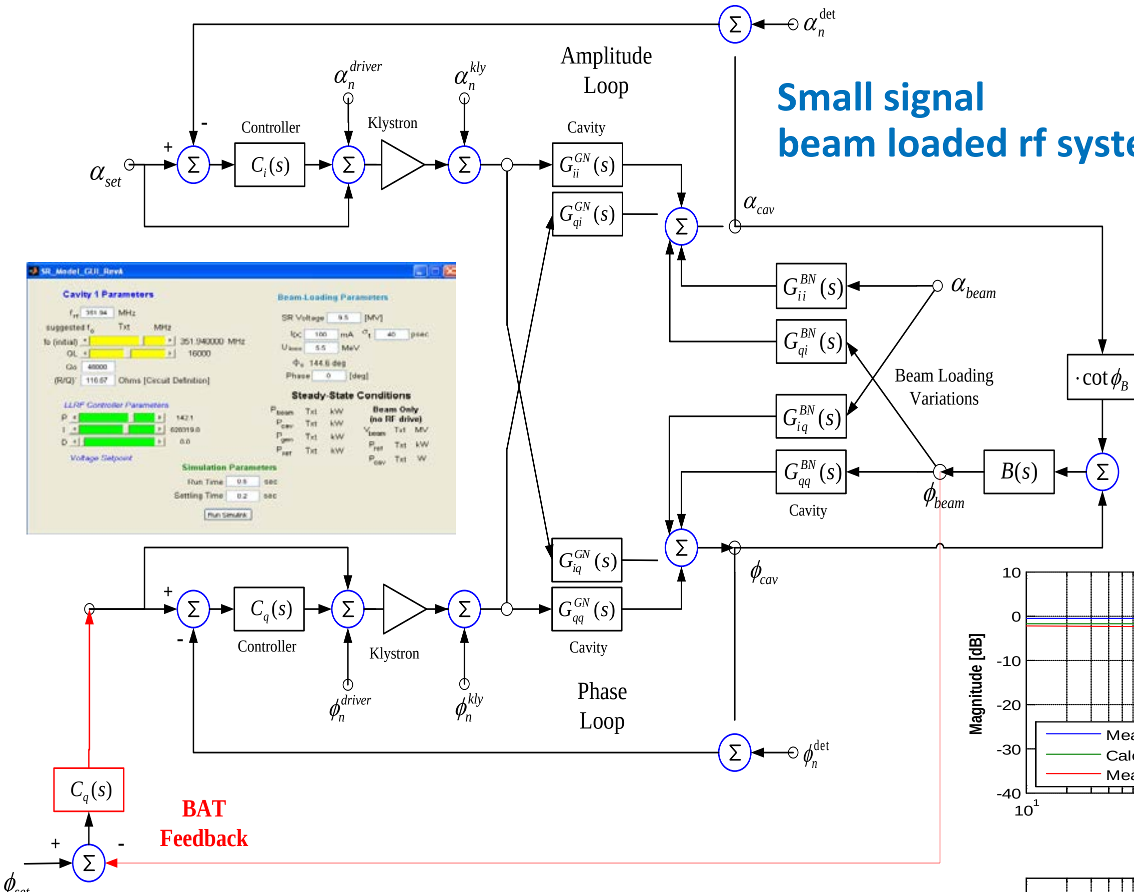
Main Storage Ring RF 352MHz
Main LLRF
Phase Shifter
From BAT Feedback
to Booster
to SR Timing System
Phase Shifter
Master Oscillator 351.9 MHz
Room A014
Residual Tilt Monitor 1
ref
Beam Arrival Time Monitor (BAT)
ref
Coax distribution
ϕ control/tune
Phase Shifter or VCXO
RF mon
Synch Head (SH2)
ref
Receiver (RX2)
beat
LO
Cal tone
Synch Head (SH1)
ref fiber
Cal
Receiver (RX2)
LO
beat fiber
MCR
SR to Booster phase setpoint
x8
Phase Shifter
~351.9 MHz
Frequency Generation Chassis
RF
~2815.5 MHz
x8
BPF
LO
/6
~2756.8 MHz
@ Sector 5
SPX Cavities Sector 5
control
Coax ref
RF mon
Synch Head (SH3)
ref
~20m
AOM
Temp Control
beat
Timing Receiver
LO (RX3)
Fiber Ref
Coax Ref
Cal
RF
LLRF Receiver
Fiber Xmitter (TX)
@ Sector 5
SPX Common LO Distribution
LO Xmitter
@ Sector 5
Xray Tilt/BAT Monitor
RF mon
Synch Head (SH4)
ref
Cal
beat
Receiver (RX4)
LO
User Lasers (x3)
tune
Photo-Diode Harmonic Out
Synch Head (SH 5 - 7)
ref
Cal
beat
Receiver (RX 5 - 7)
LO
SPX Cavities Sector 7
control
Coax ref
RF mon
Synch Head (SH3)
ref
~20m
AOM
Temp Control
Timing Receiver
beat
LO (RX8)
Fiber Ref
Coax Ref
Cal
RF
LLRF Receiver
Residual Tilt Monitor 2
ref
S35 Diagnostics
ref
Coax distribution
ϕ control/tune
Phase Shifter or VCXO
RF mon
ref
Synch Head (SH9)
Cal tone
beat
Receiver (RX9)
LO
~200m from A014 Source Room (~S37) to S5 (SPX Sector A)
~50m between SPX Sector A and B


Residual Tilt Monitor 1
Beam Arrival Time Monitor (BAT)
Phase Shifter or VCXO
ϕ control/tune
RF mon
ref
Coax distribution
Synch Head (SH2)
Cal tone
beat
Receiver (RX2)
LO
Xray Tilt/BAT Monitor
User Lasers (x3)
tune
Photo-Diode Harmonic Out
Synch Head (SH4)
Synch Head (SH 5 - 7)
Cal
Receiver (RX4)
Receiver (RX 5 - 7)
Residual Tilt Monitor 2
S35 Diagnostics
Synch Head (SH9)
Receiver (RX9)
Main Storage Ring RF 352MHz
Main LLRF
Phase Shifter
From BAT Feedback
to Booster
to SR Timing System
Master Oscillator 351.9 MHz
Room A014
SPX Cavities Sector 5
SPX Cavities Sector 7
control
Coax ref
Synch Head (SH3)
~20m
AOM
Temp Control
Timing Receiver LO (RX3)
Timing Receiver LO (RX8)
Fiber Ref Coax Ref Cal RF
LLRF Receiver
Synch Head (SH1)
ref fiber
beat fiber
Receiver (RX2)
x8
MCR SR to Booster phase setpoint
Frequency Generation Chassis
RF ~2815.5 MHz
x8
BPF
LO ~2756.8 MHz
/6
~351.9 MHz
@ Sector 5
Fiber Xmitter (TX)
@ Sector 5
LO Xmitter
@ Sector 5
SPX Common LO Distribution
~200m from A014 Source Room (~S37) to S5 (SPX Sector A)
~50m between SPX Sector A and B

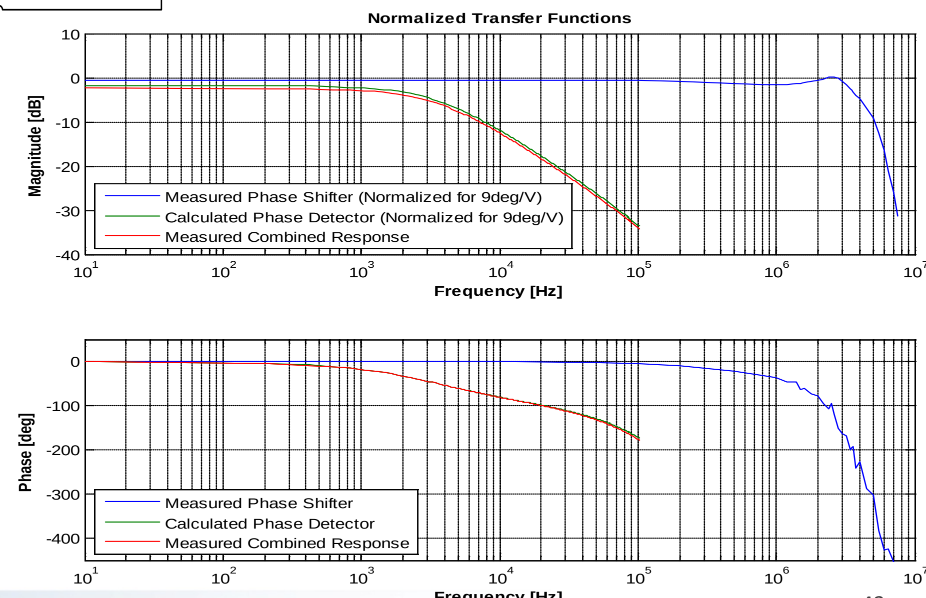
Challenges and Strategy – Tools

- Developing small signal models for main storage ring rf to aid introduction of BAT feedback loop

Small signal beam loaded rf system model



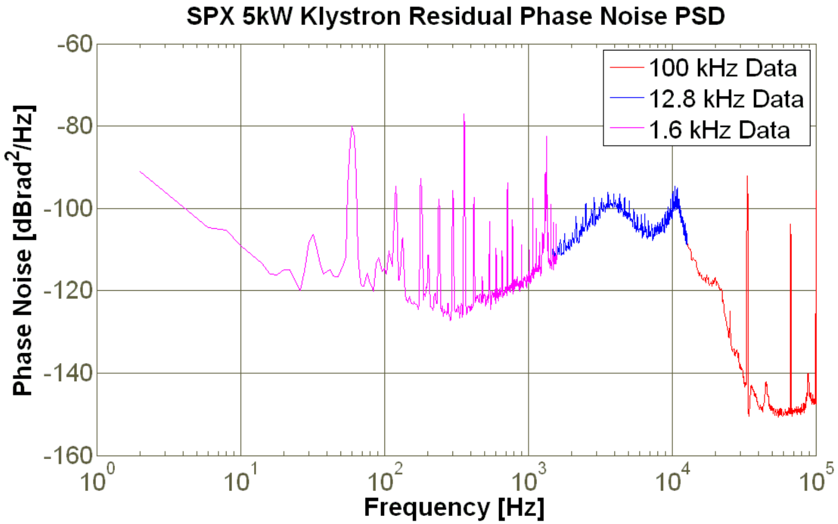
Measured Phase Shifter & Phase Detector Transfer Functions

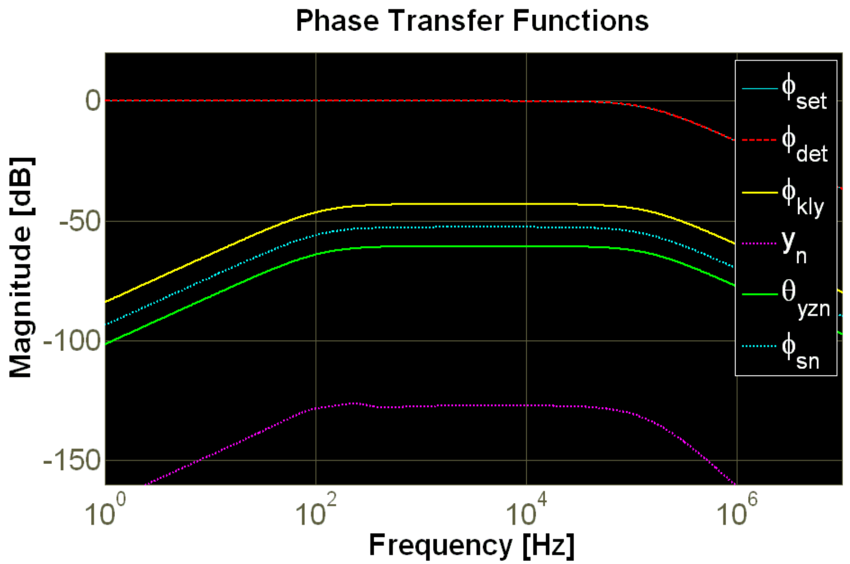


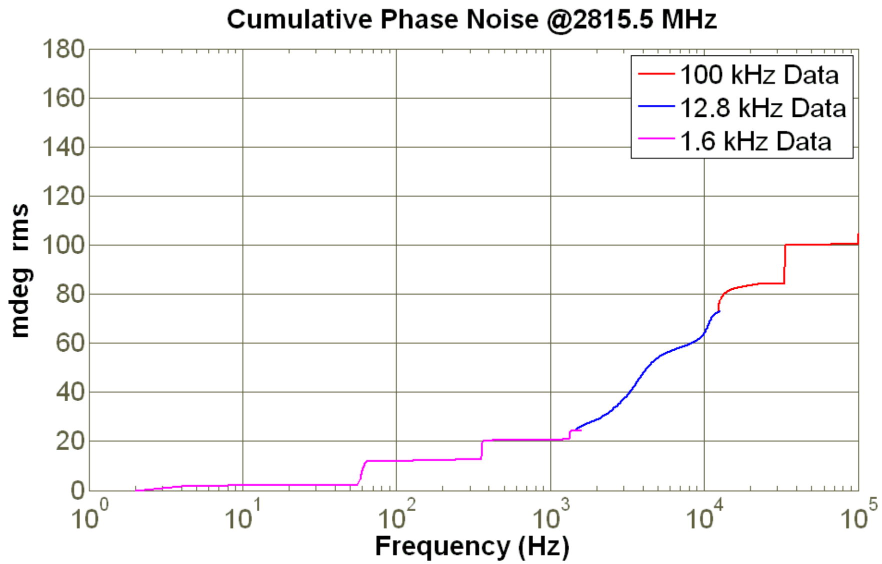
Initial Error Budgeting

	Error/Noise Source [4]	Phase Noise Common Mode [deg rms] [2]	Phase Noise Differential Mode [deg rms] [2], [3]	Amp Noise Common Mode [% rms]	Amp Noise Differential Mode [% rms]
	Total Budget	**4**	**0.18**	**1**	**1.1**
2	Frequency Generation Chassis (SPX)	0.1	N/A	N/A	N/A
3	Phase Ref. Distribution	0.1	0.016	N/A	N/A
4	LLRF Receiver Chain	0.1	0.016	0.1	0.11
5	Cavity Field Probe Cabling	0.1	0.016	0.1	0.11
6	LLRF Transmitter & Control Algorithm (up-conversion process including LO Distribution)	0.1	0.016	0.1	0.11
7	Klystron + Driver Amp	0.1	0.016	0.1	0.11
8	Microphonics	0.1	0.016	0.1	0.11
9	Beam-Loading Offset Noise	0.1	0.016	0.1	0.11
10	Beam-Loading Tilt Noise	0.1	0.016	0.1	0.11
11	Beam-Loading Synchronous Phase Noise	0.1	0.016	0.1	0.11
12	AM-to-PM Cross Modulation	0.1	0.016	N/A	N/A
13	PM-to-AM Cross Modulation	N/A	N/A	0.1	0.11
14	Orbit Feedback Process [outside SPX zone] (differential phase correction)	N/A	0.016	N/A	N/A
15	Orbit Feedback Process [inside SPX zone] (common mode phase correction)	0.1	N/A	N/A	N/A
16	Storage Ring Beam Jitter [1] with Beam Arrival Time Feedback Process (including 352MHz MO & RF system noise)	2.7	N/A	N/A	N/A
17	Residual Tilt Feedback [outside SPX zone] long-term differential amplitude correction	N/A	N/A	N/A	0.11
18	Intersector Tilt Feedback Process [inside SPX zone] common mode amplitude set-point	N/A	N/A	0.1	N/A
	# of processes competing for differential phase =	11			
	# of processes competing for common mode phase =	13			
	# of processes competing for differential amp =	10			
	# of processes competing for common mode amp =	10			
	Notes:				
	[1] existing measurements, but this is expected to be reduced by BAT feedback				
	[2] no account is taken for these processes being independent, the level to which they are independent contributes to the safety margir				
	[3] no account is taken for differential noise processes that are truly independent from cavity to cavity which will contribute an inherent sqrt(8) safety margin				
	[4] resultant contribution from each process = process noise source x transfer function				

Klystron Residual Phase Noise Measurements



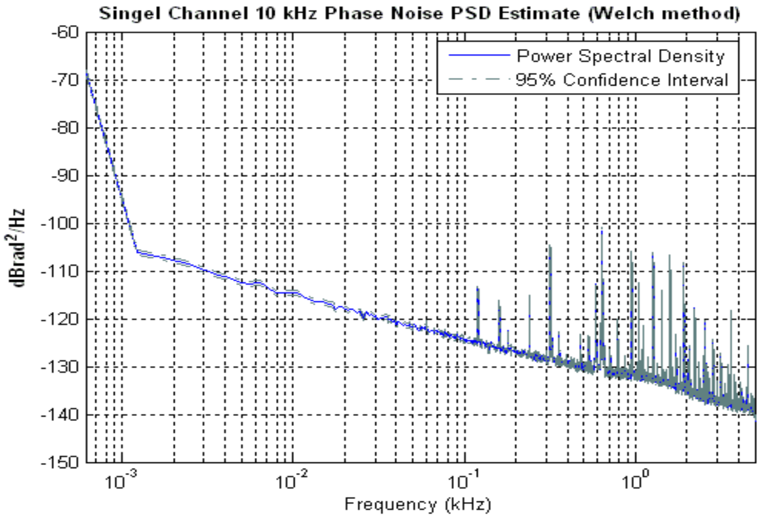


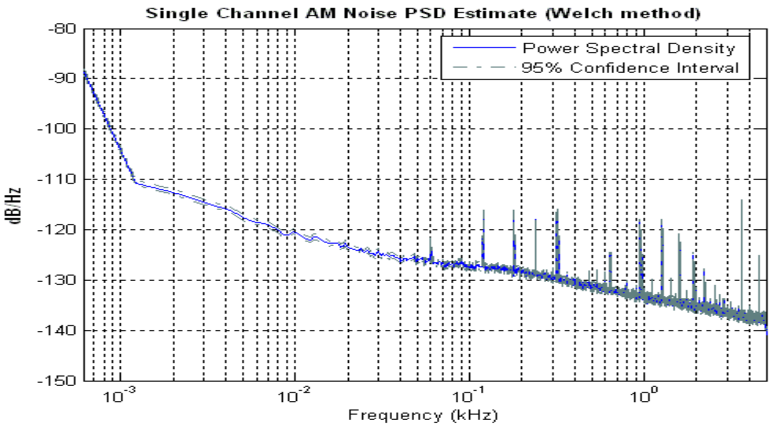


Klystron residual phase noise = 100mdeg

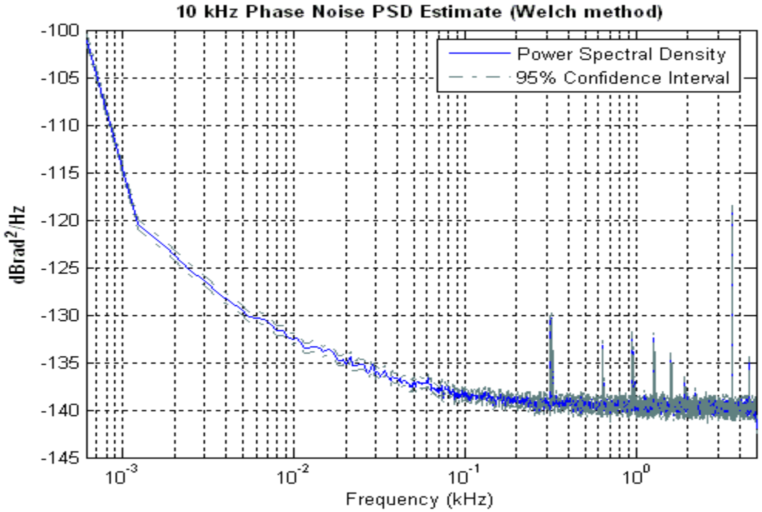
Expect this to be suppressed by at least 20dB (factor of 10) to ~10mdeg rms

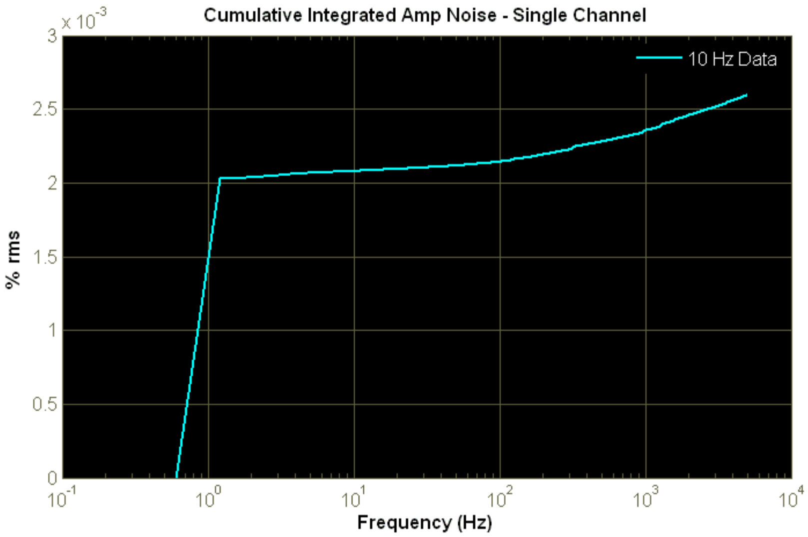
LLRF4 Noise



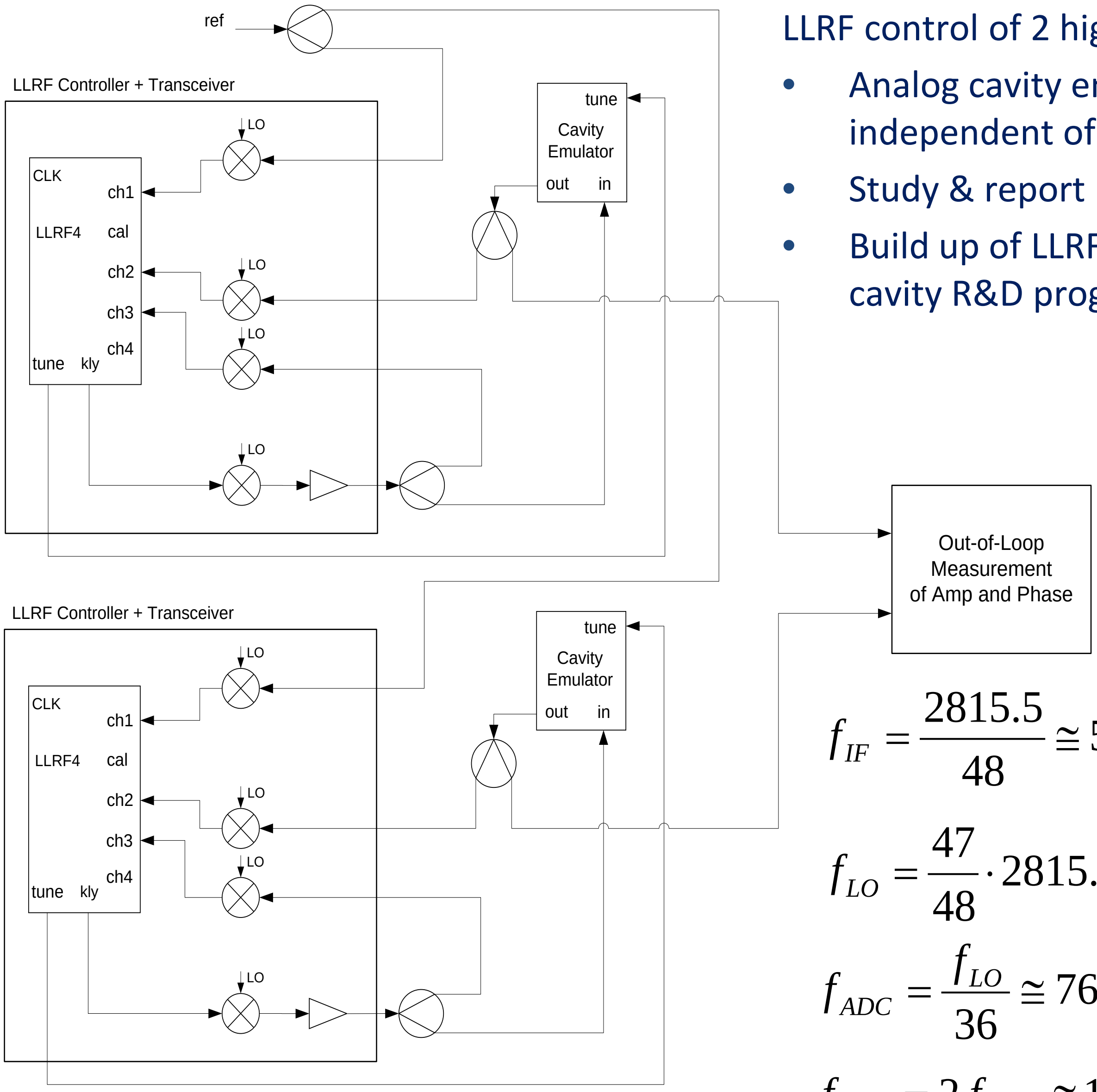


Assume -135dB/Hz over 1e6 bandwidth = ~0.02% rms





LLRF R&D Plan - LBNL Collaboration



LLRF control of 2 high-Q cavity system emulators

- Analog cavity emulators allow for LLRF development independent of cavity production schedule
- Study & report on differential stability
- Build up of LLRF4 based controllers to support 2-cavity R&D program

$$f_{IF} = \frac{2815.5}{48} \cong 58.7 \text{ MHz}$$

$$f_{LO} = \frac{47}{48} \cdot 2815.5 \cong 2756.8 \text{ MHz}$$

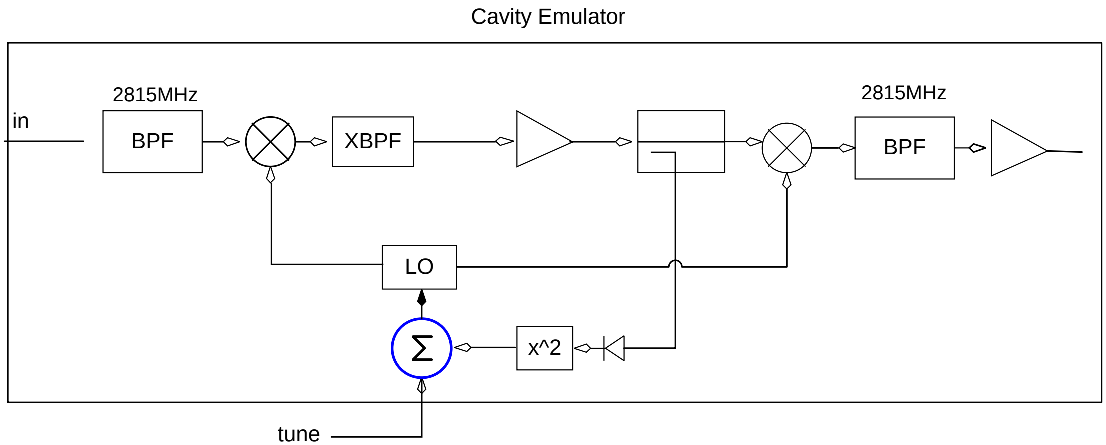
$$f_{ADC} = \frac{f_{LO}}{36} \cong 76.6 \text{ MSPS}$$

$$f_{DAC} = 2 f_{ADC} \cong 153.2 \text{ MSPS}$$

$$\frac{f_{alias}}{f_{ADC}} = \frac{11}{47}$$

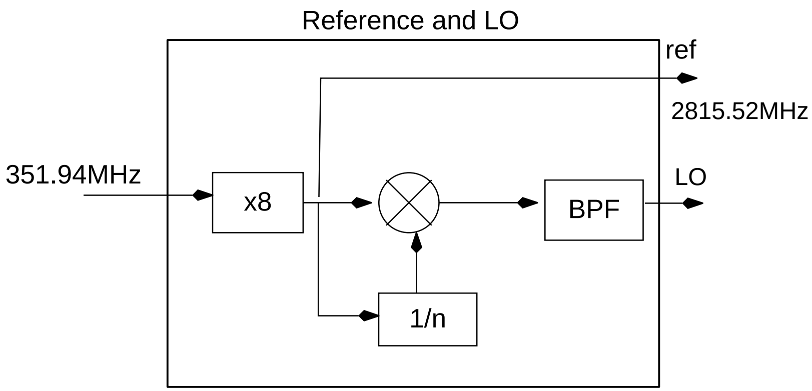
$$\frac{f_{bunch}}{f_{ADC}} = \frac{4}{47}$$

LLRF R&D Plan - BenchTop Demonstrations



Cavity Emulators

- Allow for LLRF development independent of initial cavity production schedule
- Add VCO-based LO to simulate Lorentz detuning & tuning control



$$f_{IF} = \frac{2815.5}{48} \cong 58.7 \text{ MHz}$$

$$f_{LO} = \frac{47}{48} \cdot 2815.5 \cong 2756.8 \text{ MHz}$$

$$f_{ADC} = \frac{f_{LO}}{36} \cong 76.6 \text{ MSPS}$$

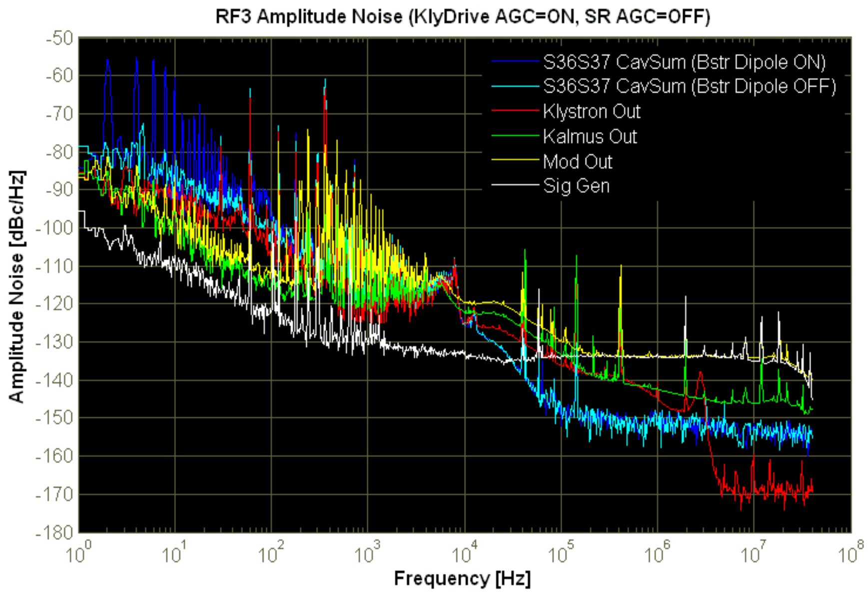
$$f_{DAC} = 2 f_{ADC} \cong 153.2 \text{ MSPS}$$

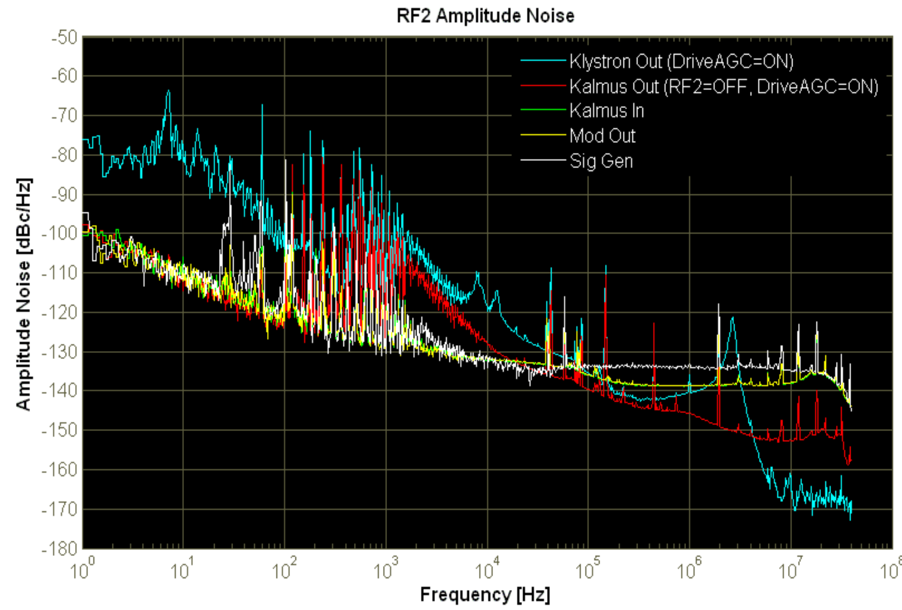
$$\frac{f_{alias}}{f_{ADC}} = \frac{11}{47}$$

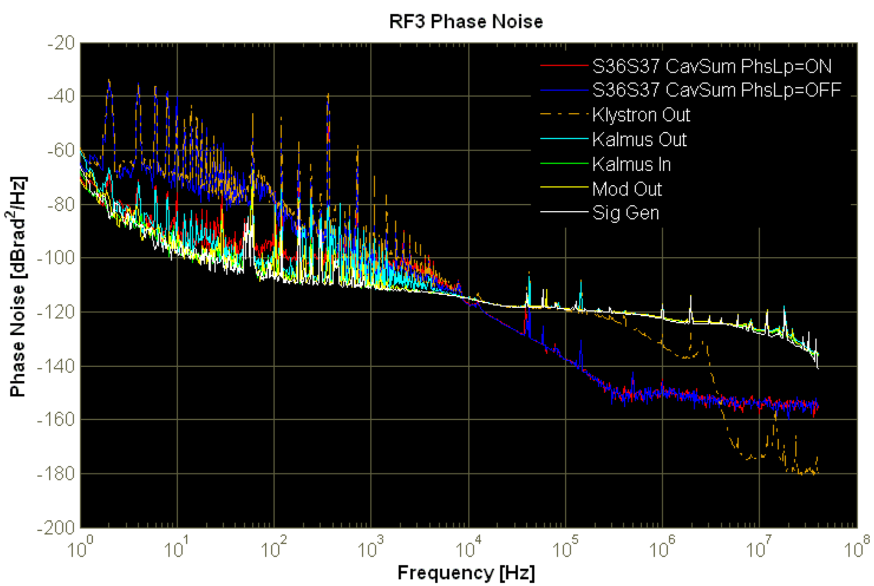
$$\frac{f_{bunch}}{f_{ADC}} = \frac{4}{47}$$

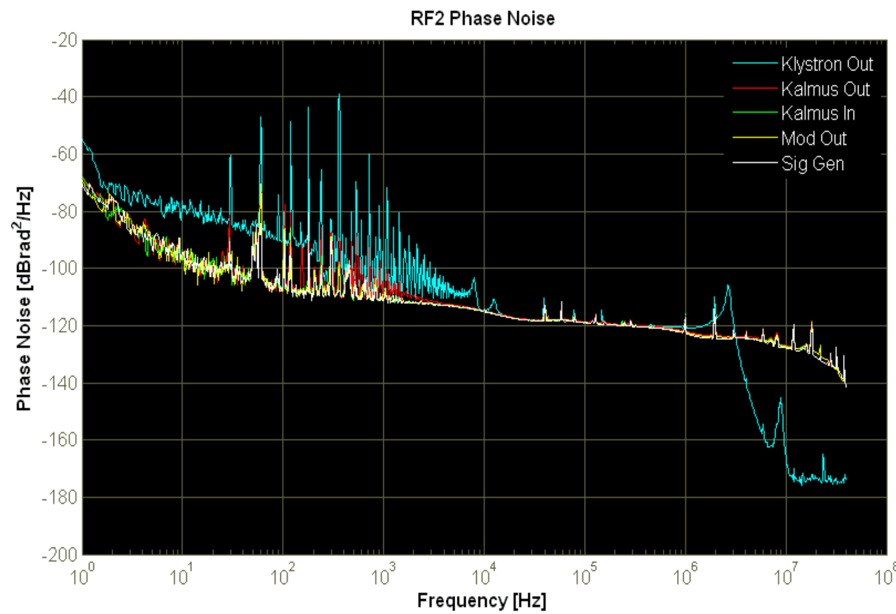
Frequency Plan has considered the following:

- **Direct synthesis, clock generation input frequencies, ADC & DAC clock needs, SNR degradation concerns for 2-point processing, separating harmonics due to non-linearities, clock jitter vs. sensible S-band filters in choice of IF frequency, bunch spacing considerations**

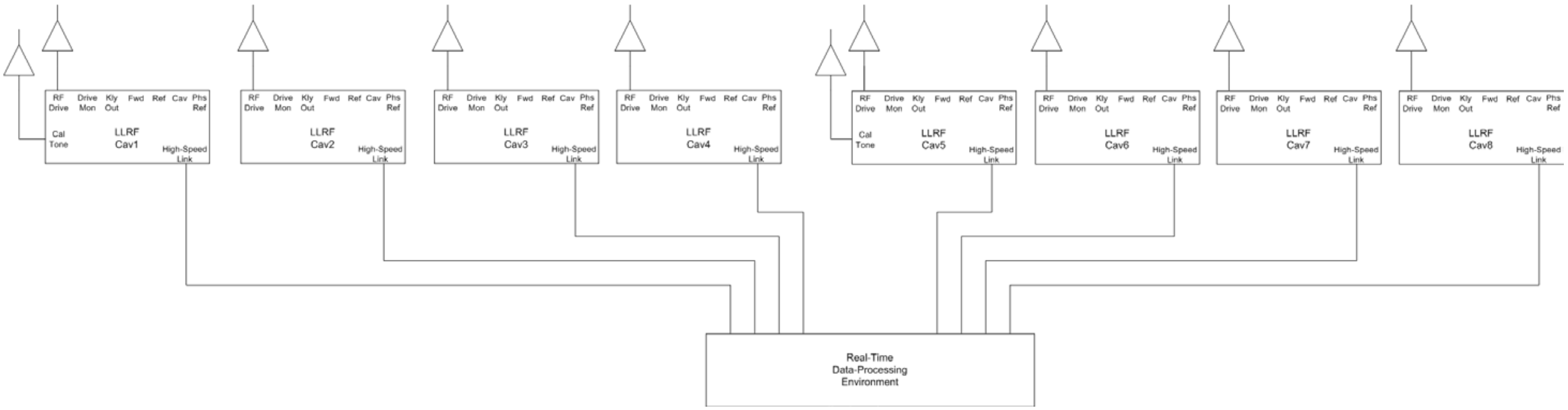

RF3 Amplitude Noise (KlyDrive AGC=ON, SR AGC=OFF)
S36S37 CavSum (Bstr Dipole ON)
S36S37 CavSum (Bstr Dipole OFF)
Klystron Out
Kalmus Out
Mod Out
Sig Gen
Amplitude Noise [dBc/Hz]
Frequency [Hz]


RF2 Amplitude Noise
Klystron Out (DriveAGC=ON)
Kalmus Out (RF2=OFF, DriveAGC=ON)
Kalmus In
Mod Out
Sig Gen
Amplitude Noise [dBc/Hz]
Frequency [Hz]

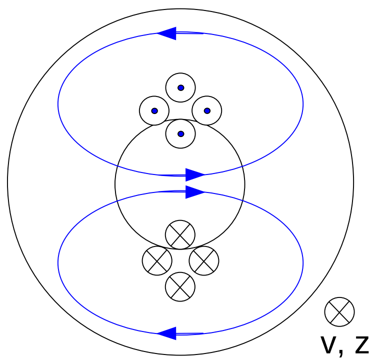

RF3 Phase Noise
S36S37 CavSum PhsLp=ON
S36S37 CavSum PhsLp=OFF
Klystron Out
Kalmus Out
Kalmus In
Mod Out
Sig Gen
Phase Noise [dBrad²/Hz]
Frequency [Hz]

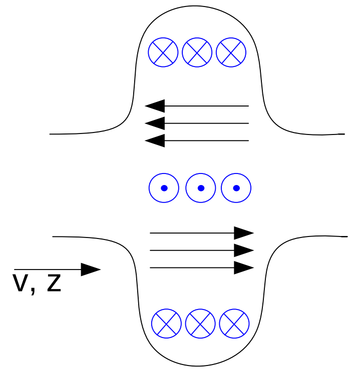

RF2 Phase Noise
Klystron Out
Kalmus Out
Kalmus In
Mod Out
Sig Gen
Phase Noise [dBrad²/Hz]
Frequency [Hz]

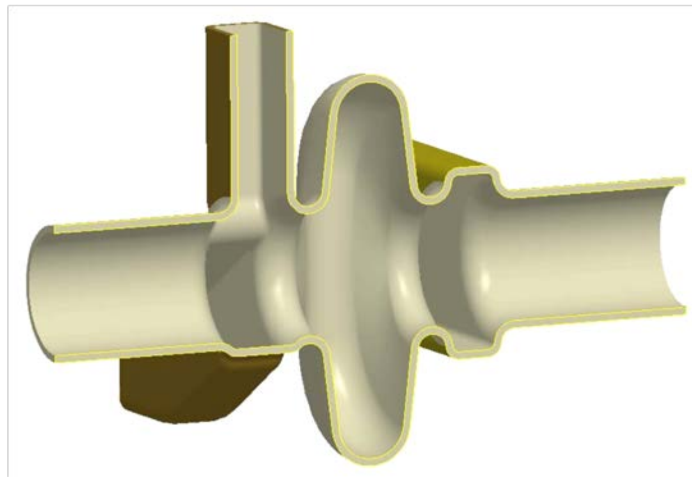
Signal	Condition	Integrated Jitter / Phase Noise [1 Hz - 100 kHz] Bandwidth	
		Jitter (psec RMS)	Phase Noise @352MHz (deg RMS)
352 MHz Source	N/A	0.280	0.036
S36+S37 Cav Sum (3)	Both Phase Loops OPEN	19.219	2.435
	Both Phase Loops CLOSED	2.726	0.345
S38+S40 Cav Sum (4)	Both Phase Loops OPEN	16.047	2.033
	Both Phase Loops CLOSED	0.952	0.121

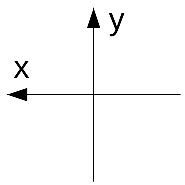

RF Drive
Drive Mon
Kly Out
Fwd
Ref
Cav
Phs Ref
Cal Tone
LLRF Cav1
High-Speed Link
LLRF Cav2
LLRF Cav3
LLRF Cav4
LLRF Cav5
LLRF Cav6
LLRF Cav7
LLRF Cav8
Real-Time Data-Processing Environment

Beam Loading







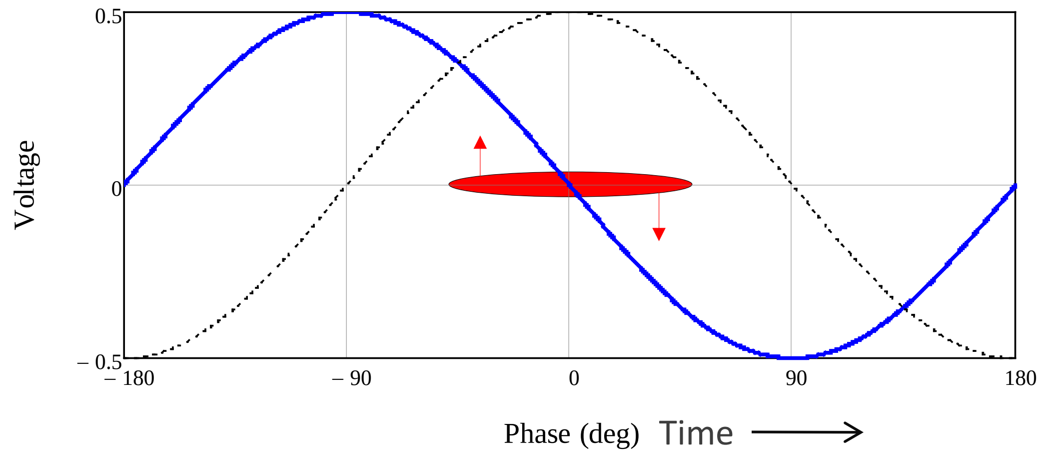


Magnetic Field

Electric Field

$$V_Z(y) = V_m \cdot y$$ Longitudinal voltage

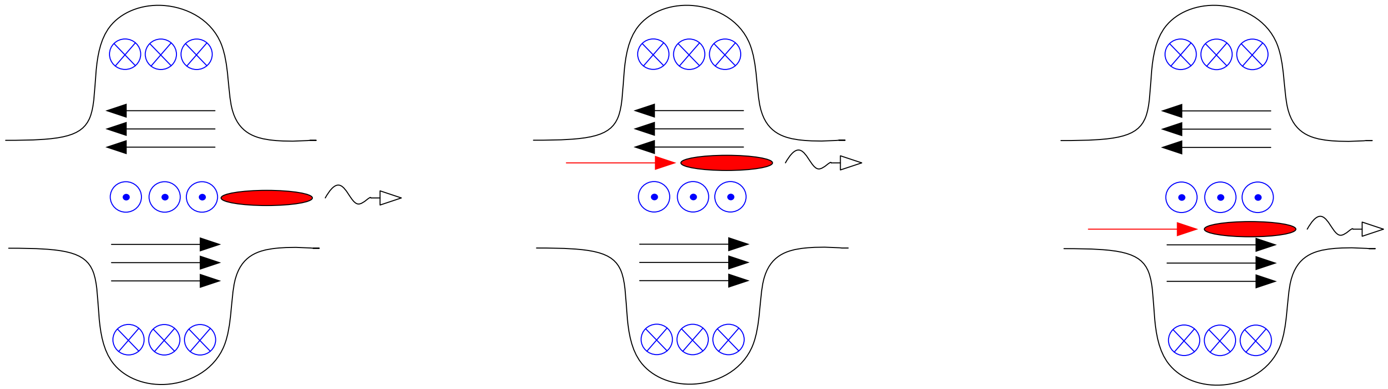
$$V_t = j\frac{V_m}{\kappa_o}$$ Vertical deflecting voltage



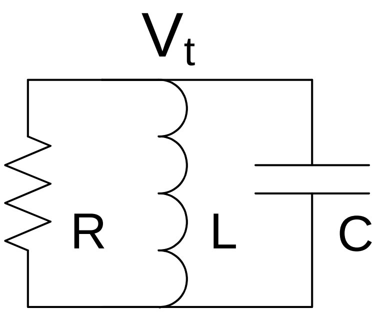
Cavity Transverse Voltage

Cavity Longitudinal Voltage / κ_o $(y > 0)$

Beam Loading



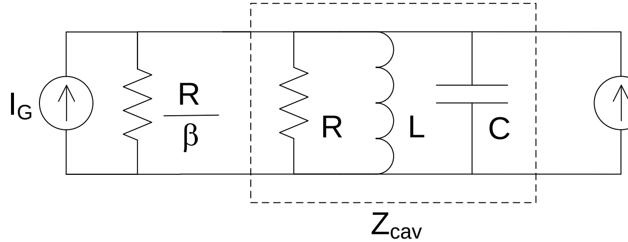
Dipole loss factor: $k_{\perp} \equiv \frac{U_{loss}}{q^2} = \frac{|V_Z(y)|^2}{4U} = \frac{\omega_r}{2}\left(\frac{R}{Q}\right)'(\kappa_o y)^2$



Circuit definition R/Q: $\left(\frac{R}{Q}\right)' = \frac{V_t^2}{2\omega_r U} = 17.8\Omega$

$$U_{loss} = q^2 k_{\perp} = \frac{1}{2} C V_t^2 \qquad \Rightarrow V_t^2 = \left(\frac{q \cdot \kappa_o y}{C}\right)^2 \qquad \Rightarrow q_{eq} = |q \cdot \kappa_o y|$$

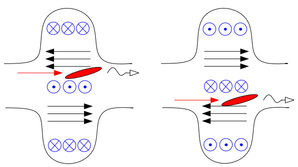
Deflecting Cavity Beam Loading



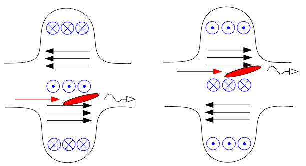
$$i_o\kappa_o\left(y + j\cdot\theta\,\omega_o c\,\sigma_t^{\,2}\right)\cdot e^{-j(\pi+\phi_s)}$$

$$i_o = 2I_{dc}\cdot e^{-\frac{1}{2}(2\pi f_o\sigma_t)^2}$$

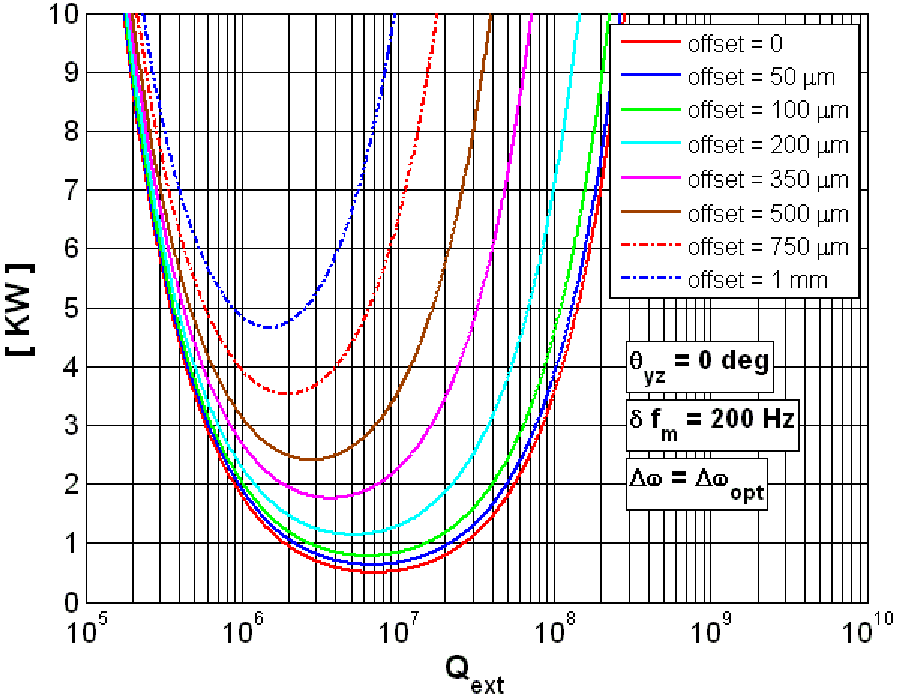
$$P_g^{\,+} = \frac{V_t^{\,2}}{8\beta\,(R/Q)'\,Q_o}\cdot\left[\left(\beta+1+\frac{P_B}{P_{cav}}\right)^2+\left(2Q_o\cancel{\frac{(\Delta f+\delta f_m)}{f_r}}+\cancel{\frac{P_B}{P_{cav}}\tan\phi_s}\right)^2\right]$$

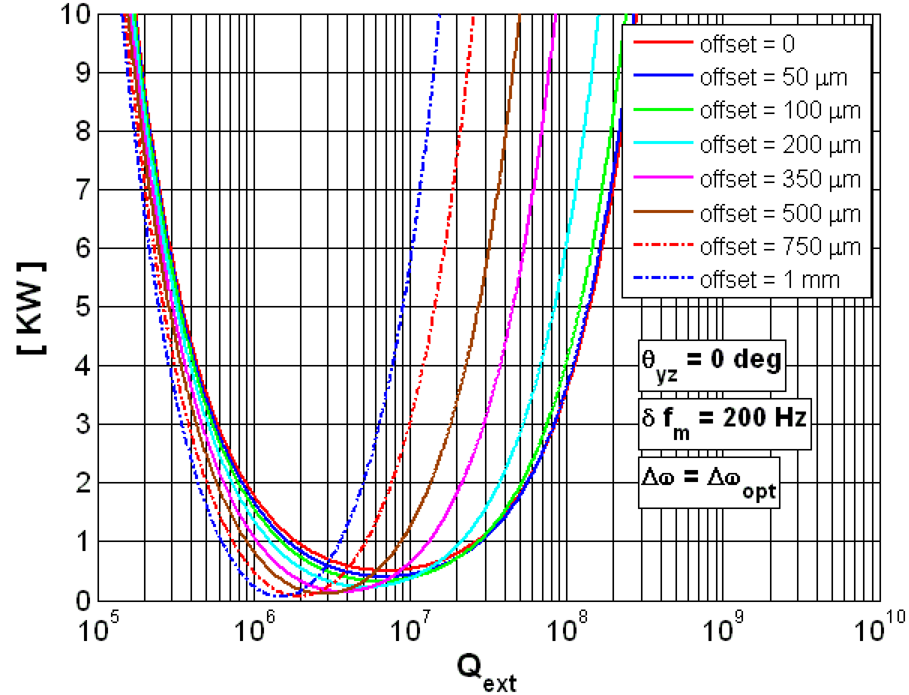


$V_t\cdot y>0$

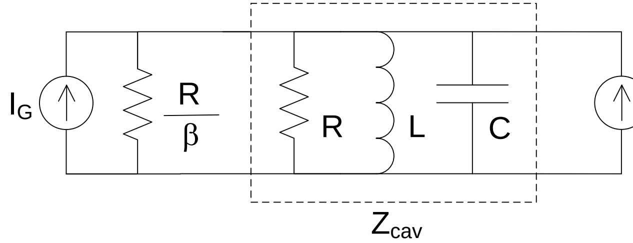


$V_t\cdot y<0$





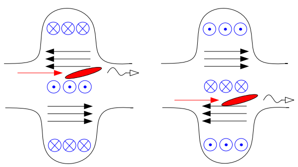
Deflecting Cavity Beam Loading



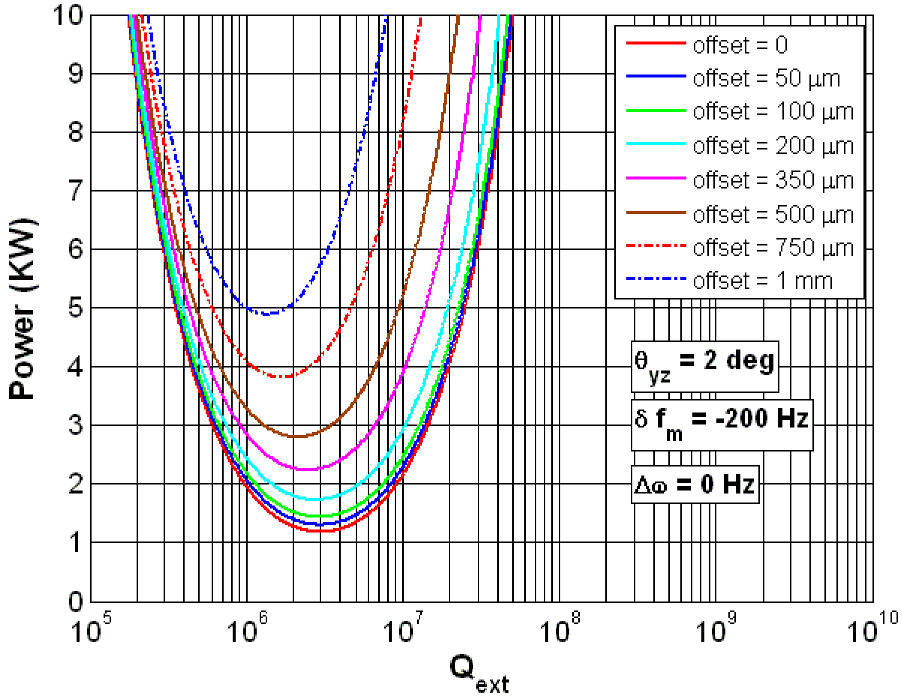
$$i_o \kappa_o \left(y + j\cdot\theta\,\omega_o c\,\sigma_t^{2}\right)\cdot e^{-j(\pi+\phi_s)}$$

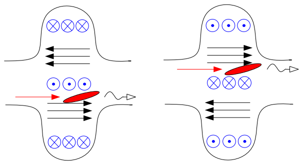
$$i_o = 2 I_{dc}\cdot e^{-\frac{1}{2}(2\pi f_o \sigma_t)^2}$$

$$P_g^{+} = \frac{V_t^{2}}{8\beta\,(R/Q)'\,Q_o}\cdot\left[\left(\beta+1+\frac{P_B}{P_{cav}}\right)^2+\left(2Q_o\frac{(\cancel{\Delta f}+\delta f_m)}{f_r}+\frac{P_B}{P_{cav}}\tan\phi_s\right)^2\right]$$

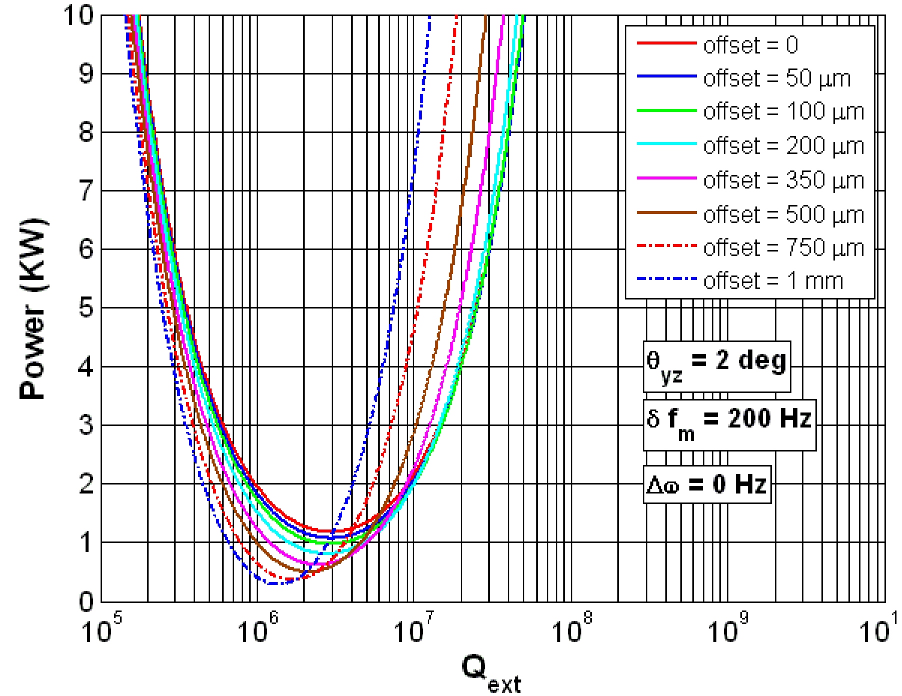


$V_t \cdot y > 0$





$V_t \cdot y < 0$



LLRF Timeline