SPX Workshop

LLRF R&D

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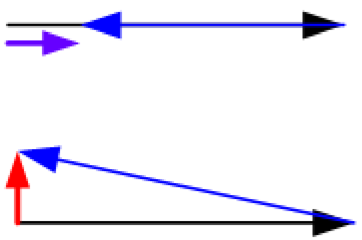
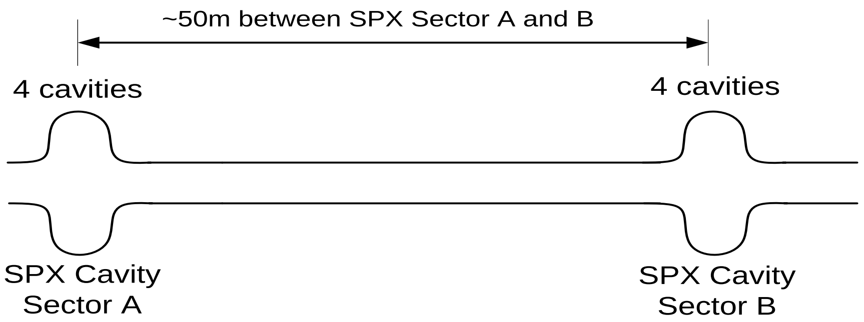
Performance Requirements

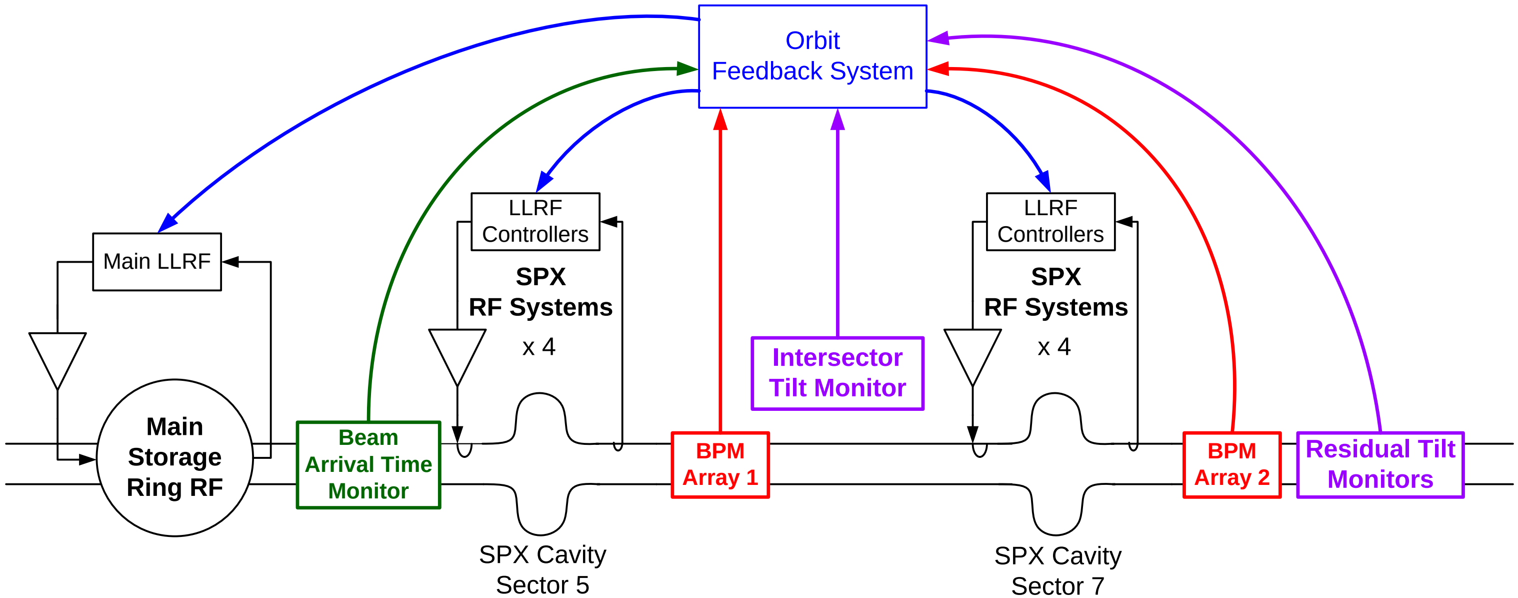
	Specification name	Rms Value	Driving requirement
Common Mode	Common-mode voltage variation	$< 1\%$	Keep intensity and pulse length variation under 1% rms
	Common-mode phase variation	$< 4.0^\circ$	Keep intensity variation under 1% rms
Differential Mode	Voltage mismatch between sectors	$< 1.1\%$	Keep 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*

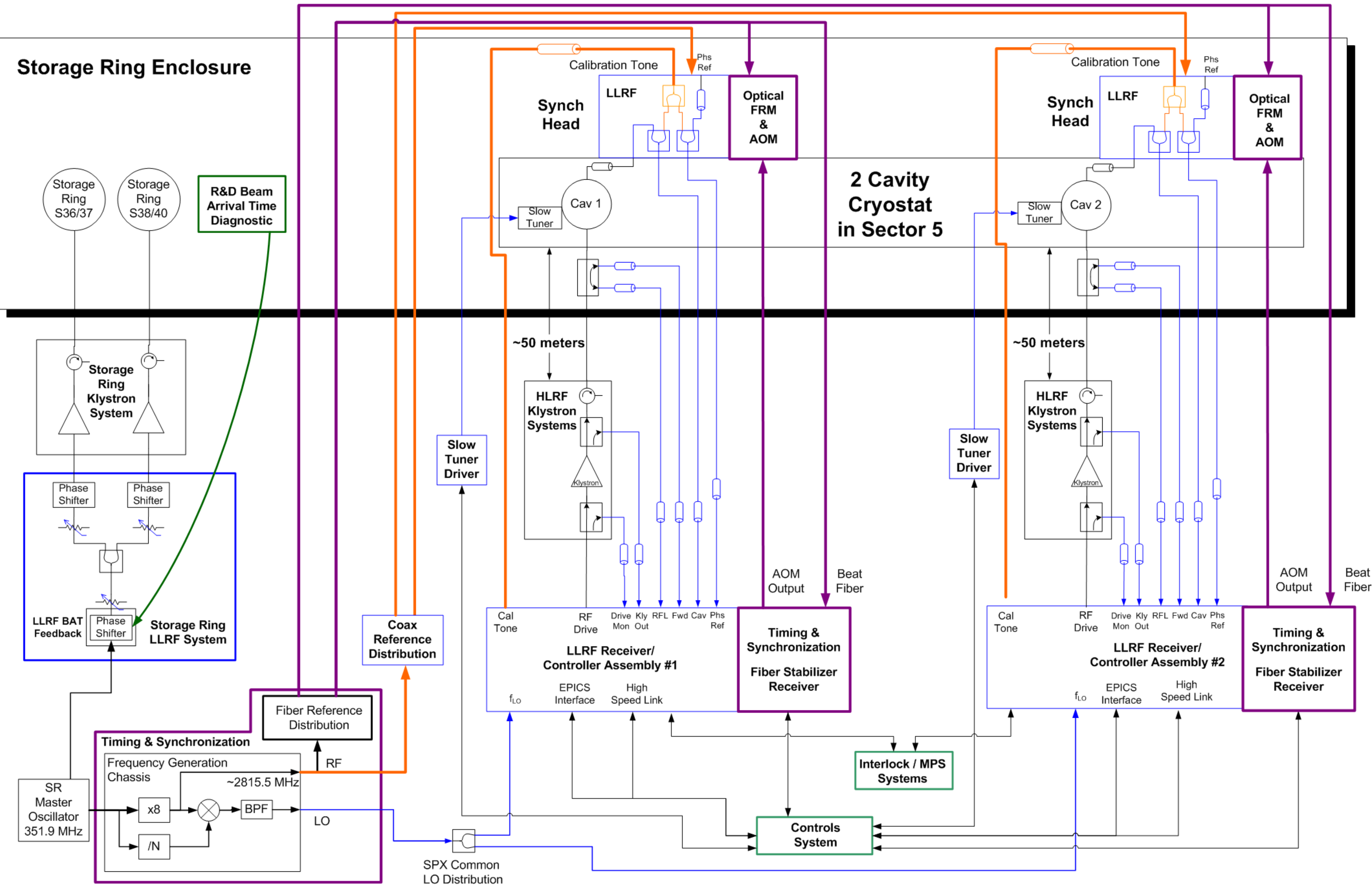
- **Phase Reference, LO (& CLK) distributed centrally to keep phase noise common mode**
  - **Provisions for both *coax-based* and *LBNL phase stabilized fiber* reference**
    - — *Orbit feedback eliminates long-term drift concerns*
    - — Coax provides superior short-term noise, fiber provides superior 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

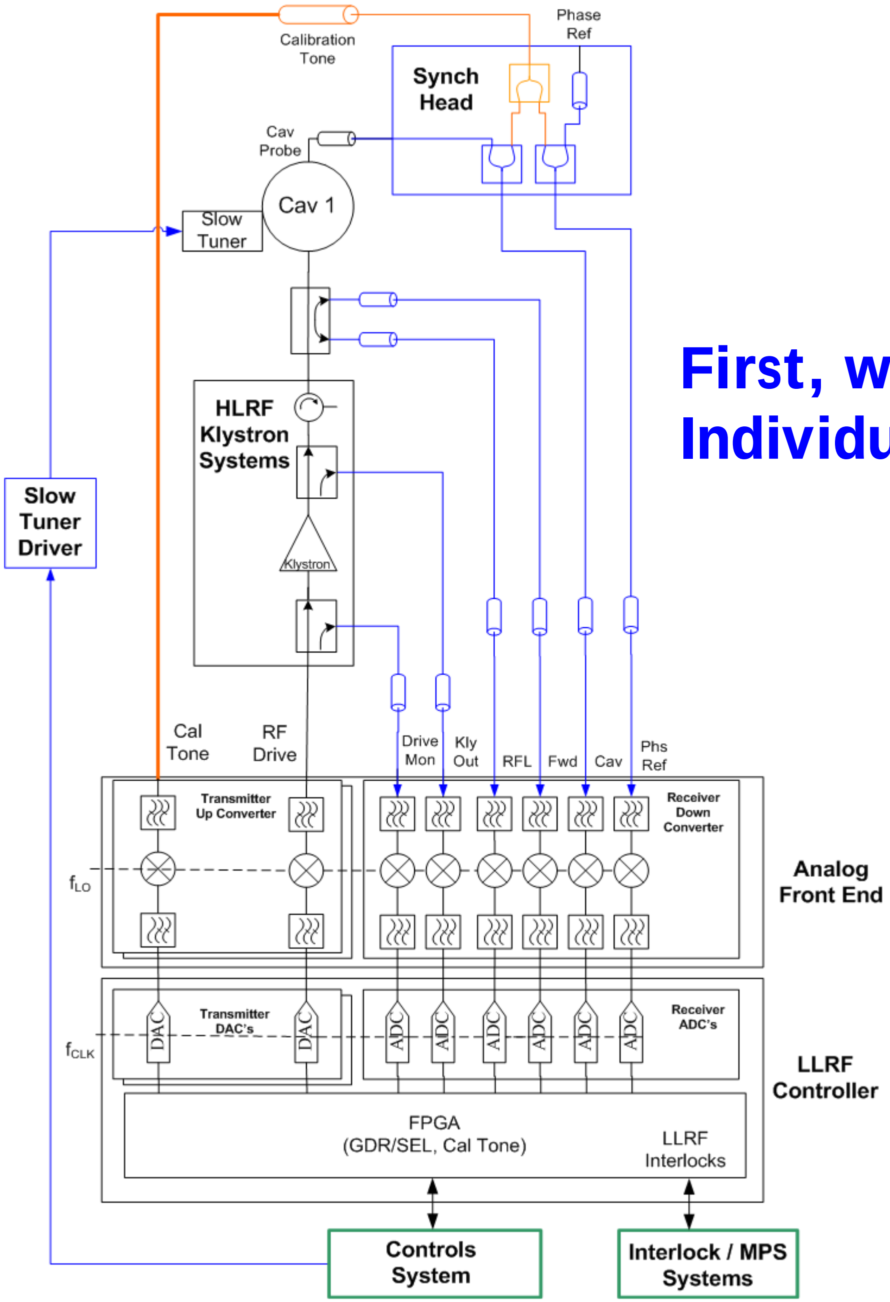
- **Receiver Chain Drift Compensation via Calibration Tone**

- **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)

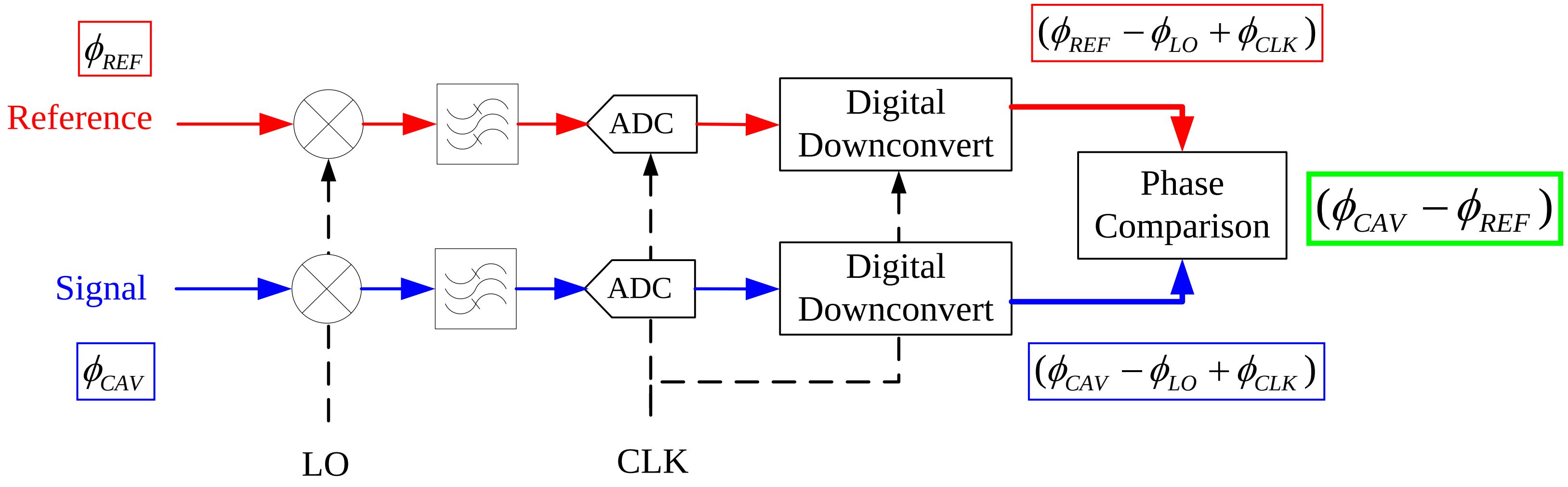




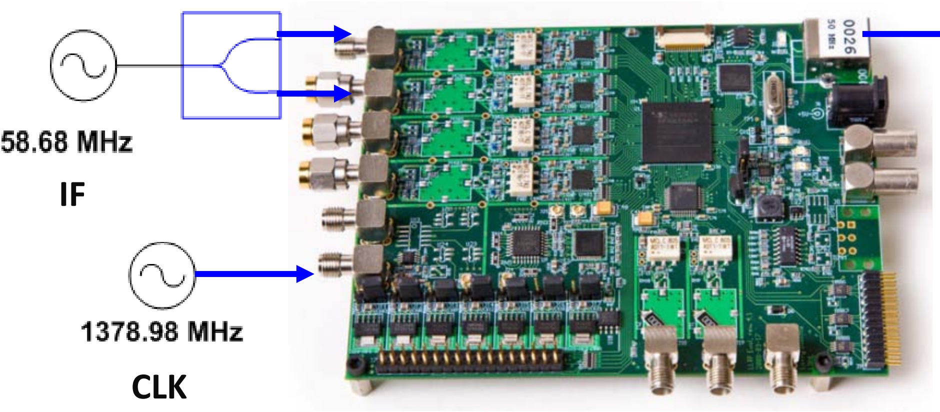
First, we need to regulate the fields at the Individual Cavity Level ....

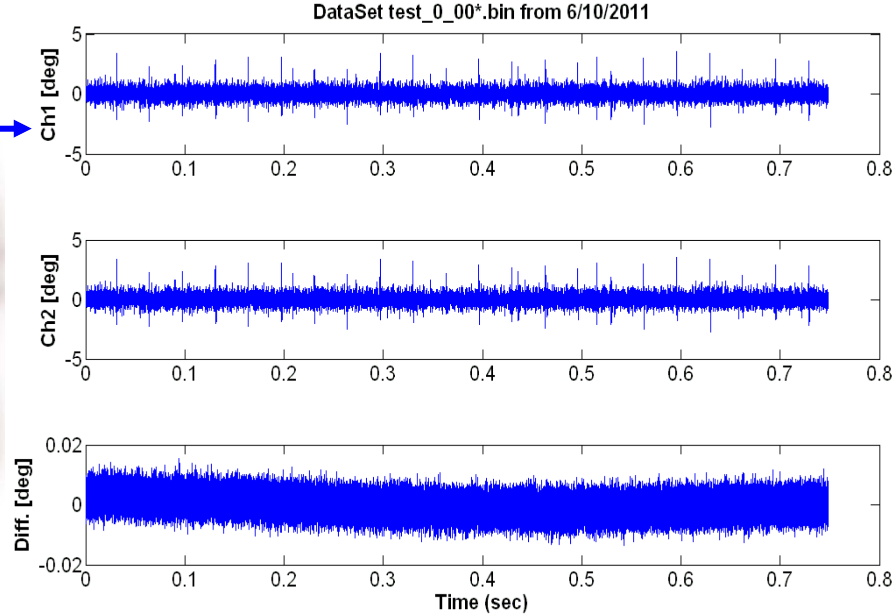
Strategy #1 – Regulate to a Designated Phase Reference

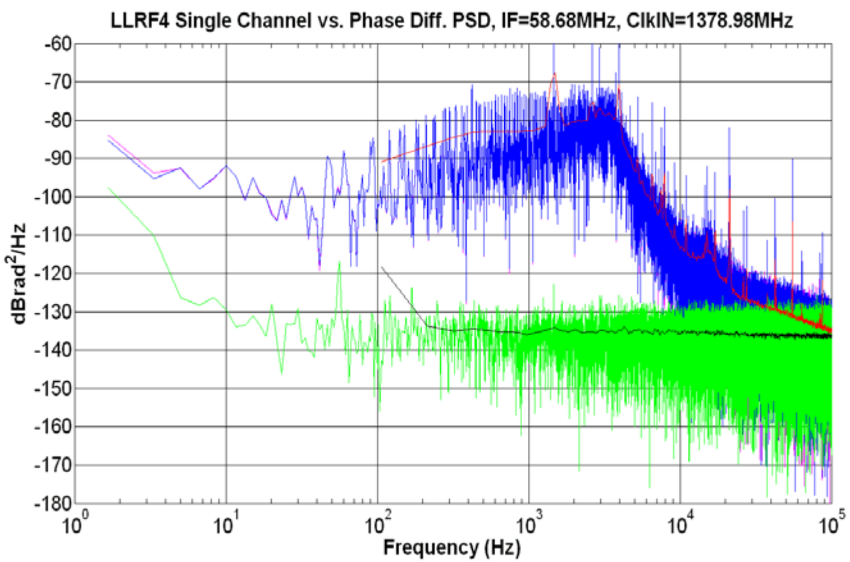
- Don’t let the LO assume the role of the phase reference
- Phase is a Differential Measurement
- Mixers preserve phase information, x’s and ÷’s preserve timing
- In theory, common mode LO and clock noise cancels

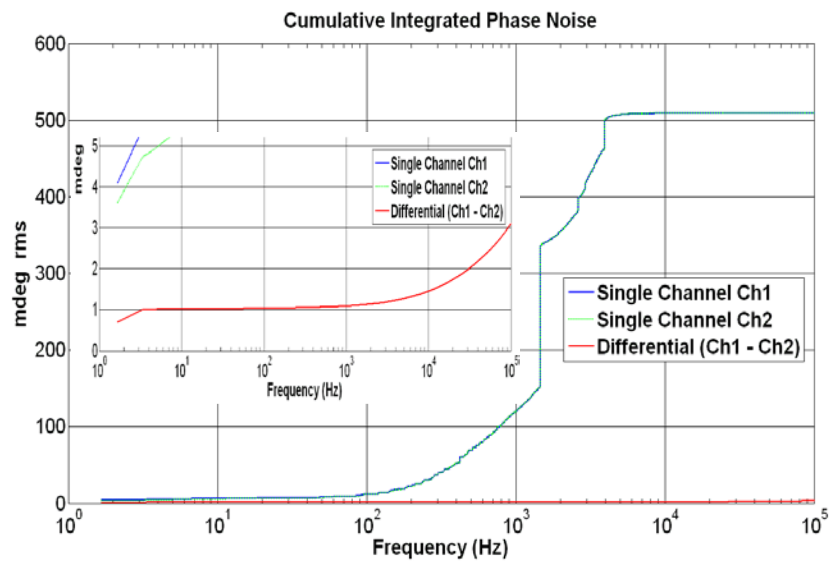


LLRF4 Board - Input Differential Phase Noise

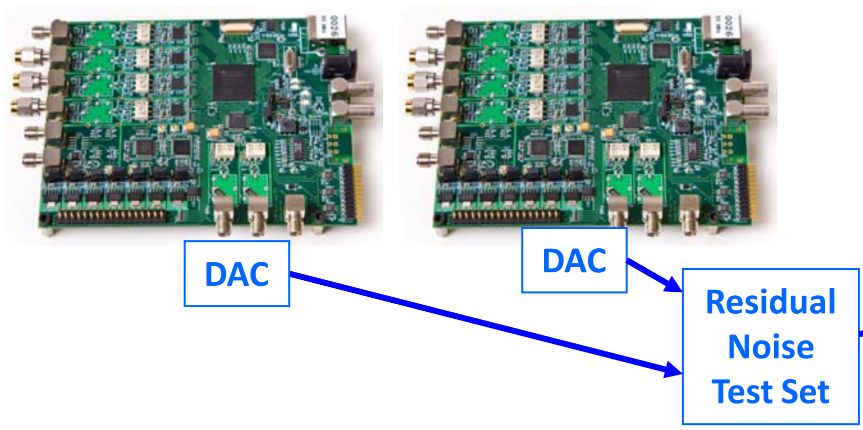


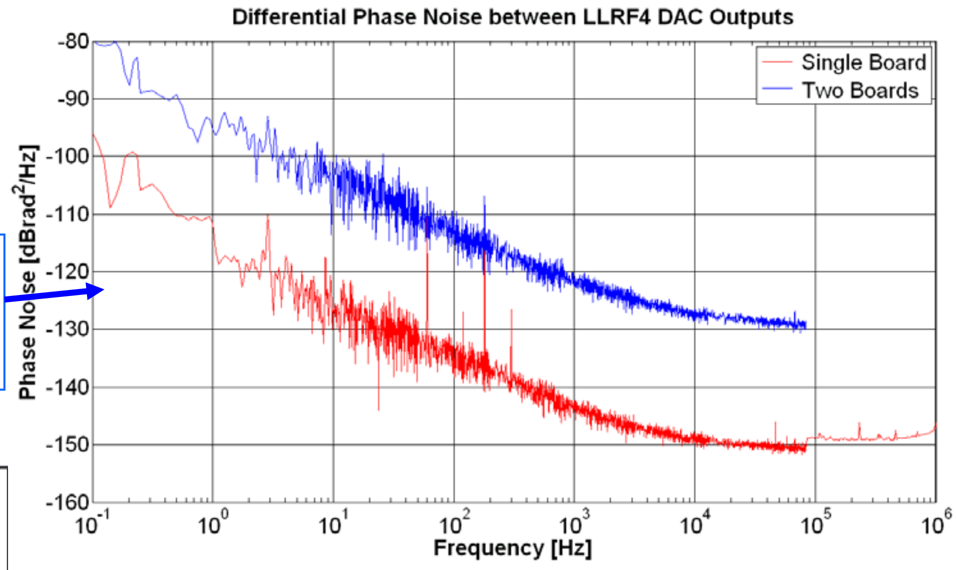


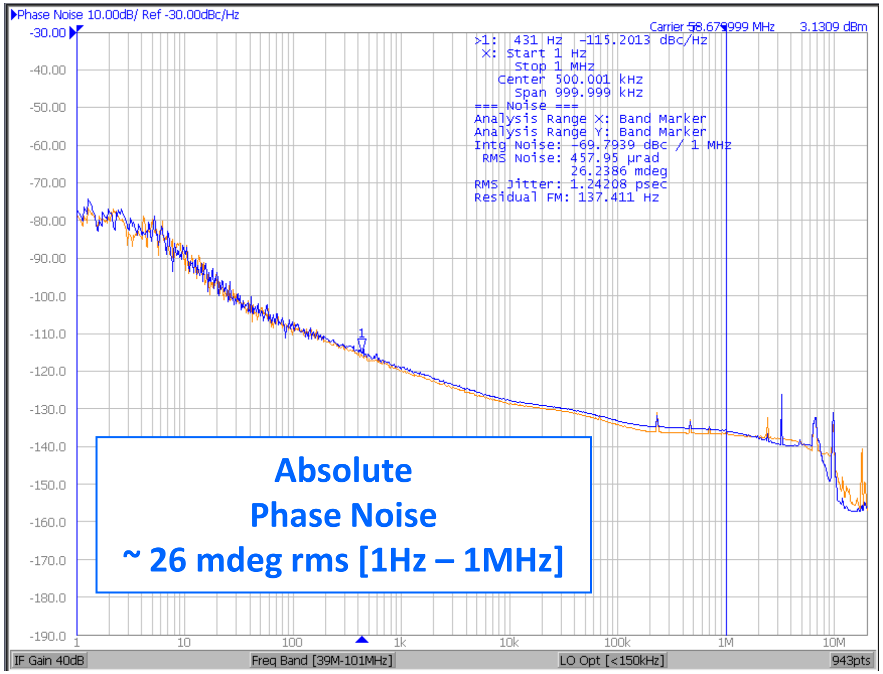


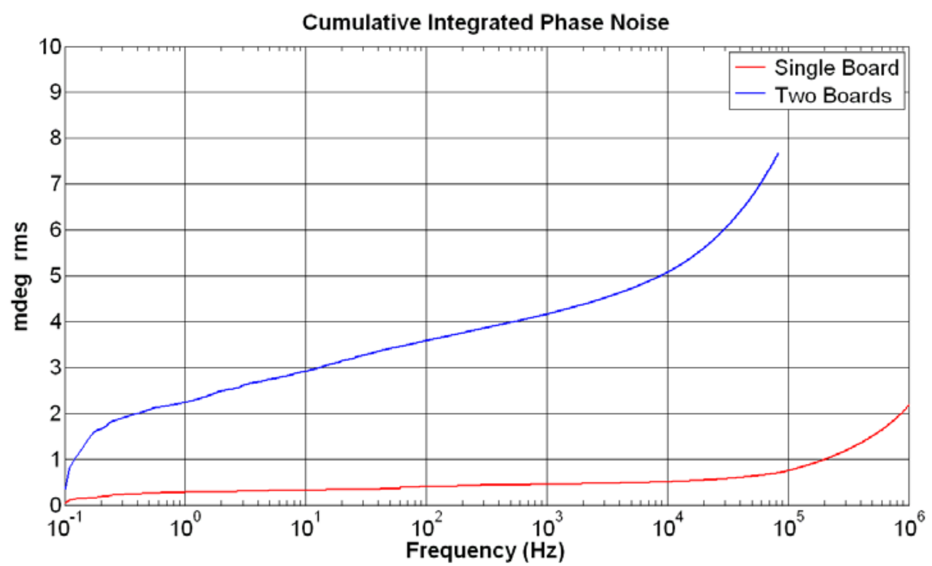


LLRF4 Board – Output Phase Noise



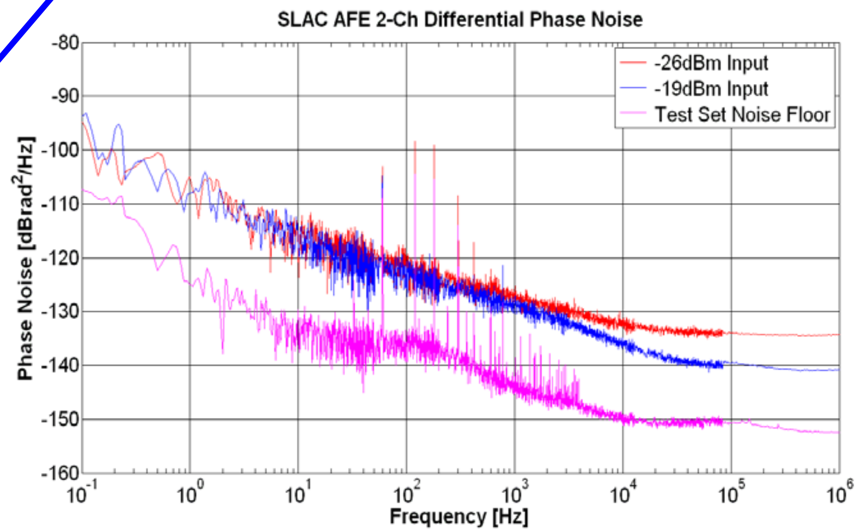


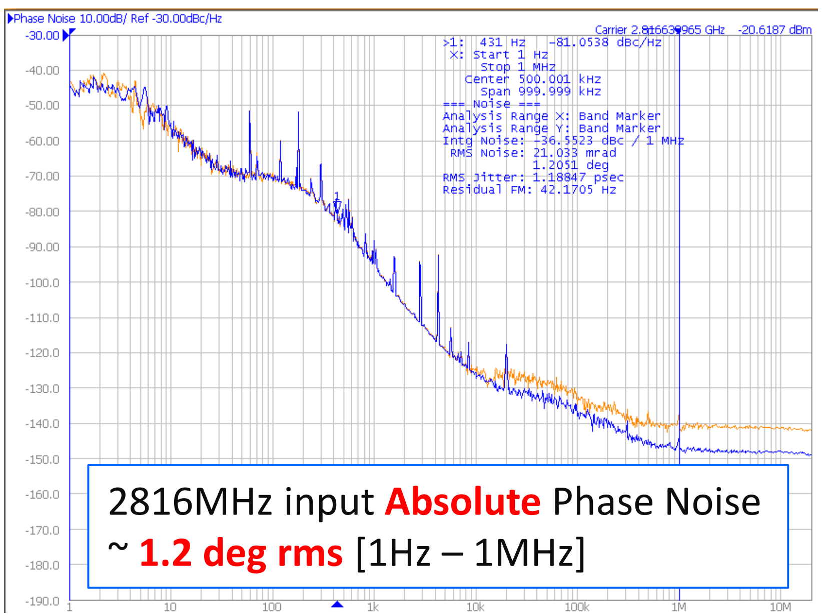




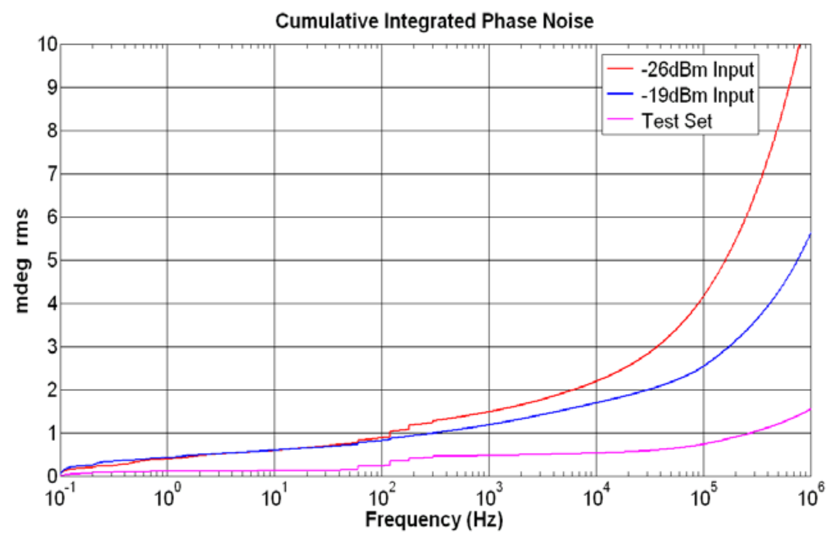
Analog Front End - Differential Phase Noise

Differential Phase Noise at IF Frequency

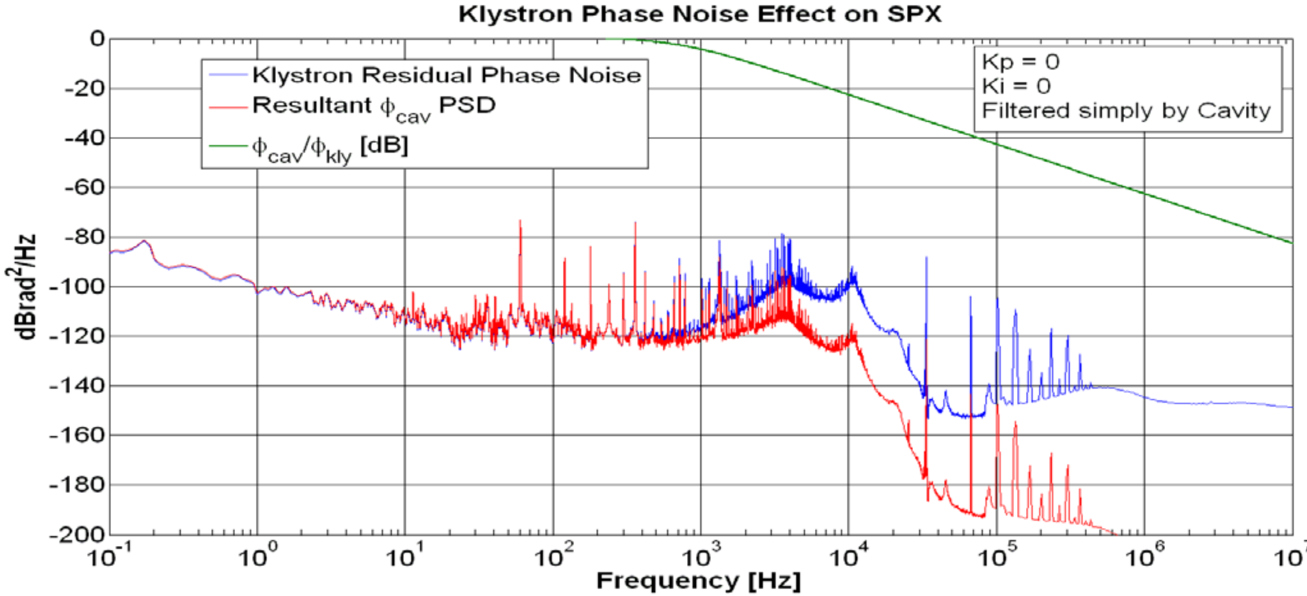


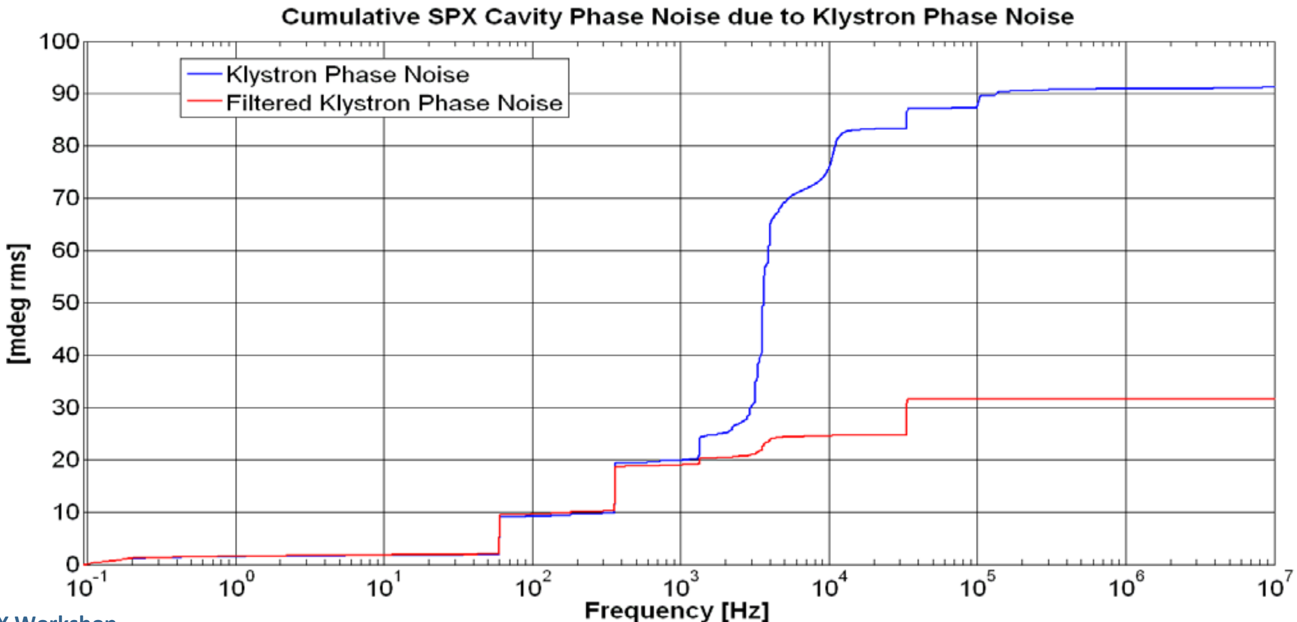


2816MHz input **Absolute** Phase Noise
~ **1.2 deg rms** [1Hz – 1MHz]

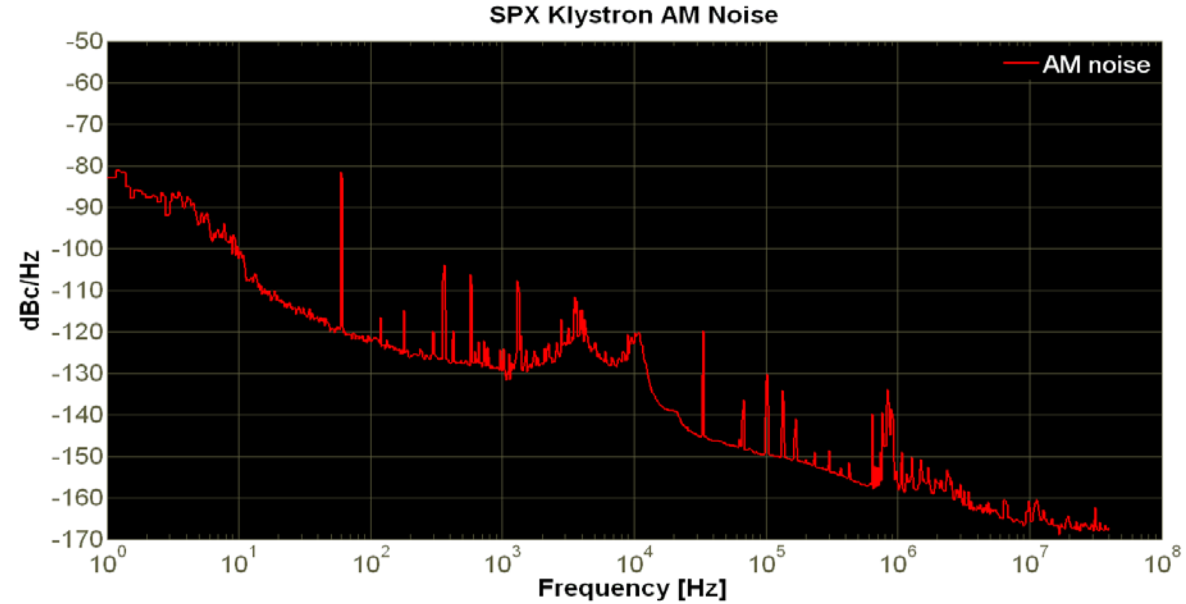


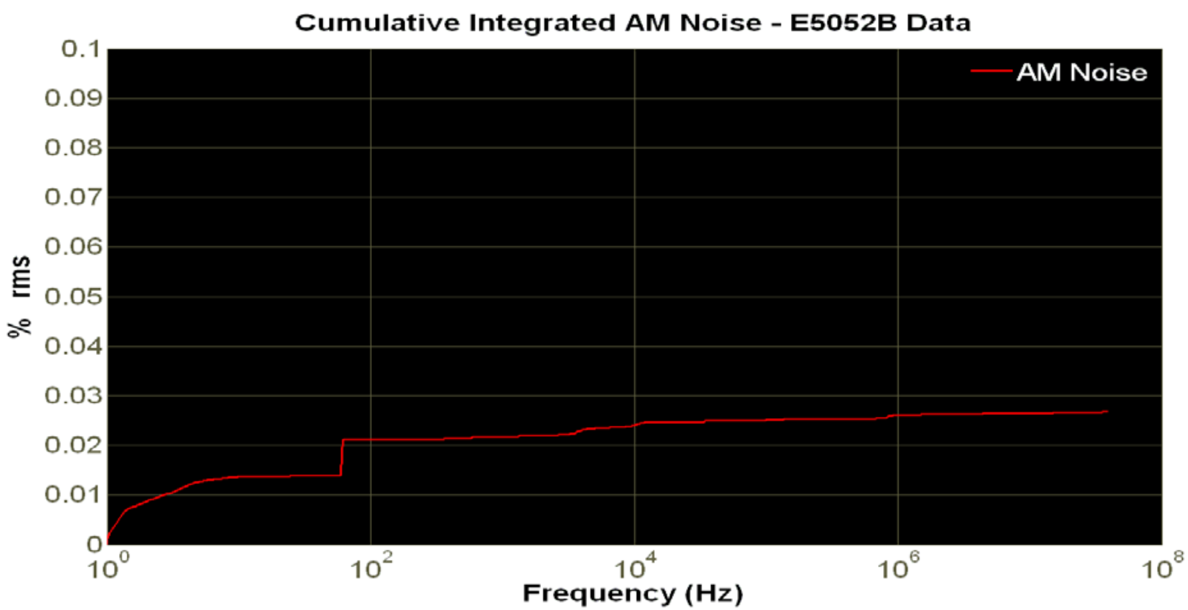
Klystron Residual Noise Measurements



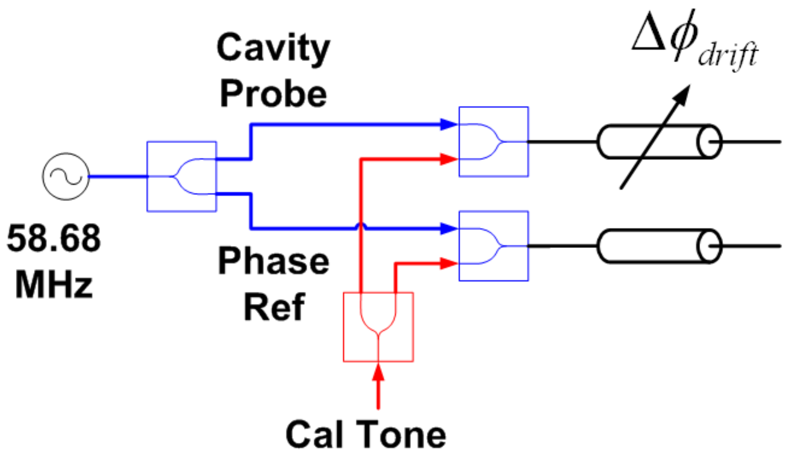


Klystron AM Noise Measurements





Strategy #2 - Incorporate CW Drift Compensation[1]



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

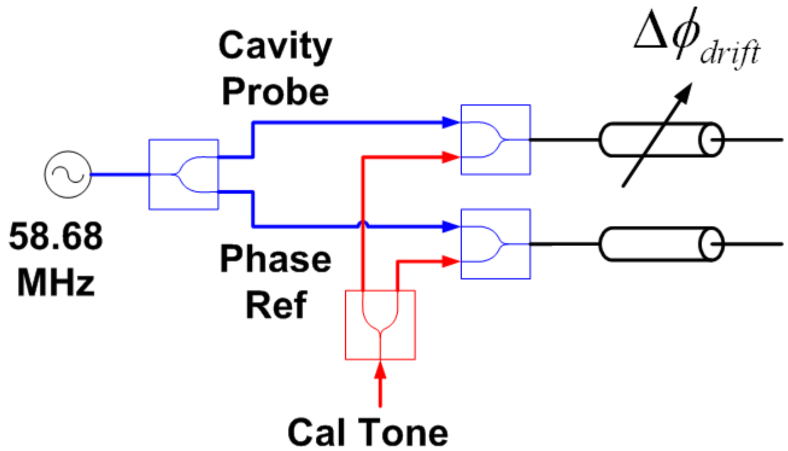
$$\Delta\phi_{calTone} = \Delta\phi_{drift}$$

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

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

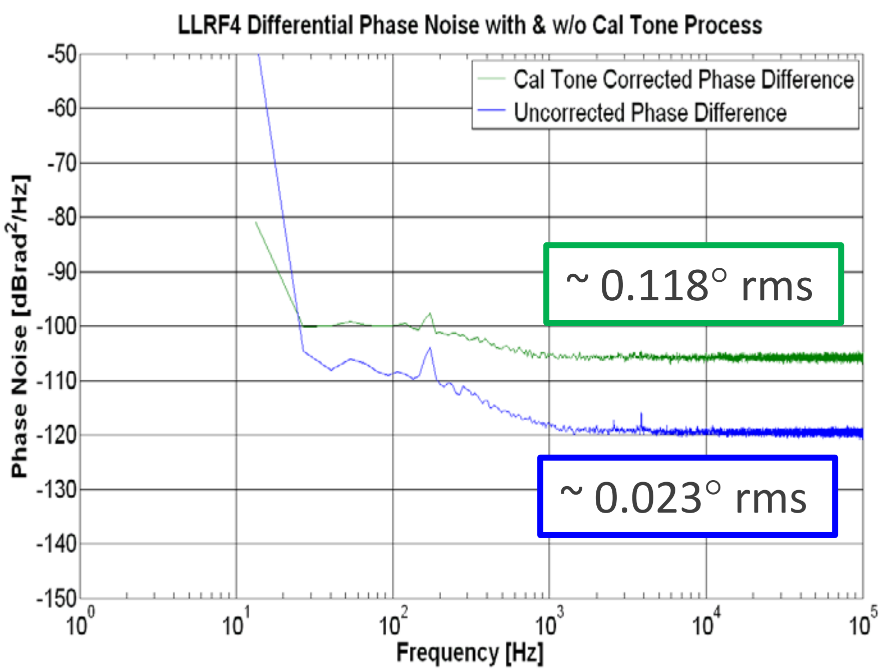
Demonstration of CW Drift Compensation

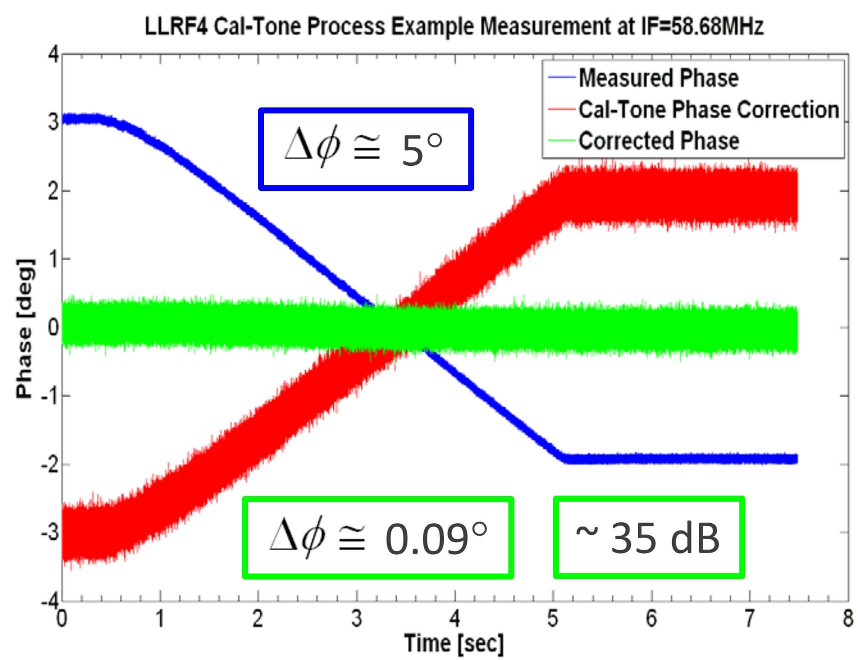


$$\Delta\phi_{meas} = (\phi_{cav} - \phi_{ref}) + \Delta\phi_{drift}$$

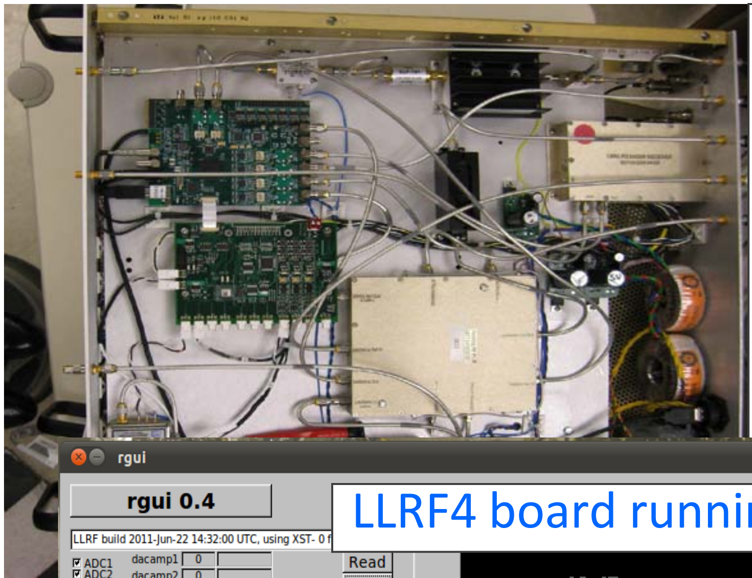
$$\Delta\phi_{calTone} = \Delta\phi_{drift}$$

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





Single Cavity Testing at ANL scheduled for 2/2012

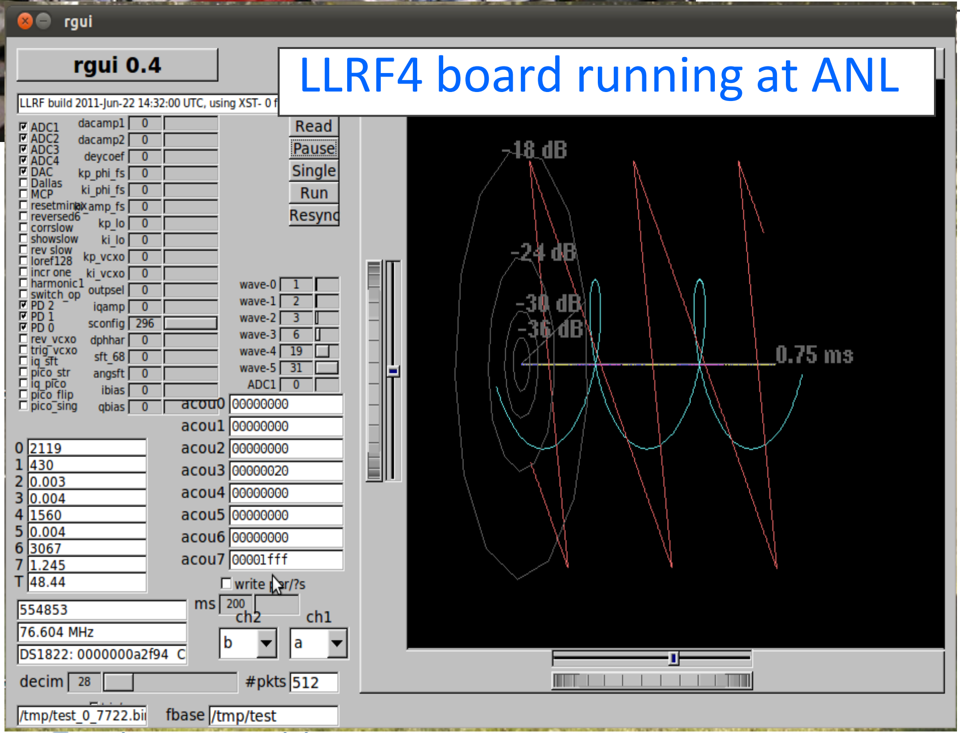


LLRF4 based system to support LLRF & Timing R&D

2 LLRF4 boards presently at ANL

10/2011:

- LBNL delivery of 1st LLRF4 system for LLRF
- Report on differential stability study between 2 high Q cavity emulator systems

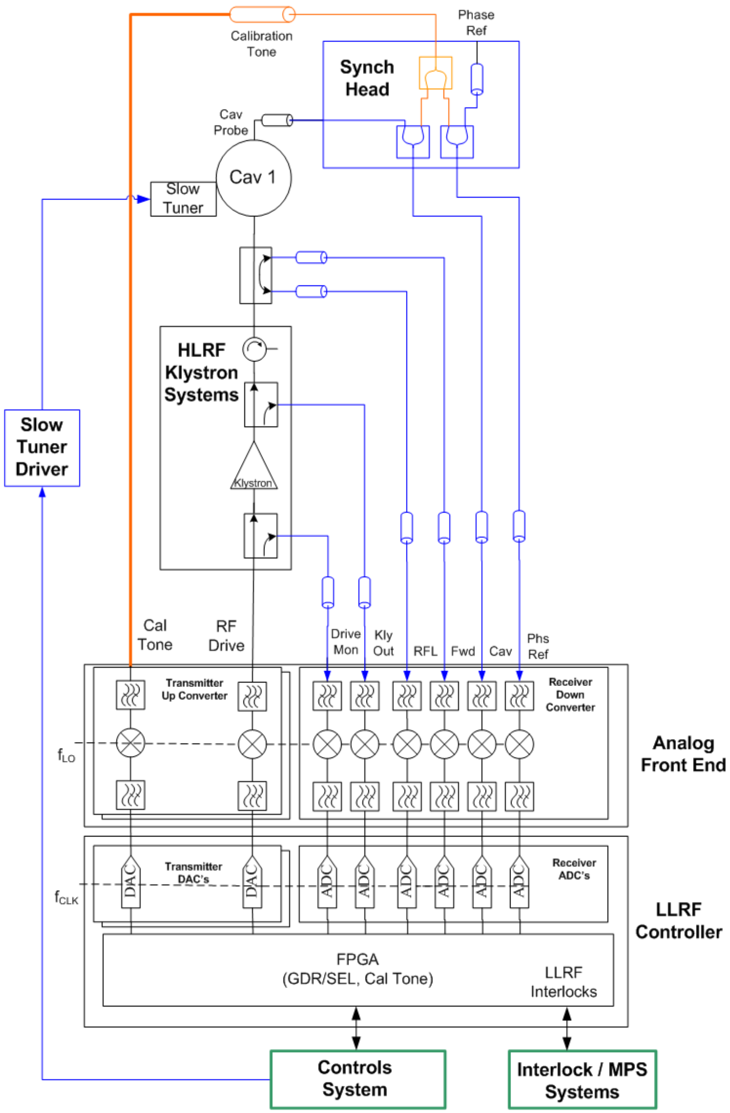


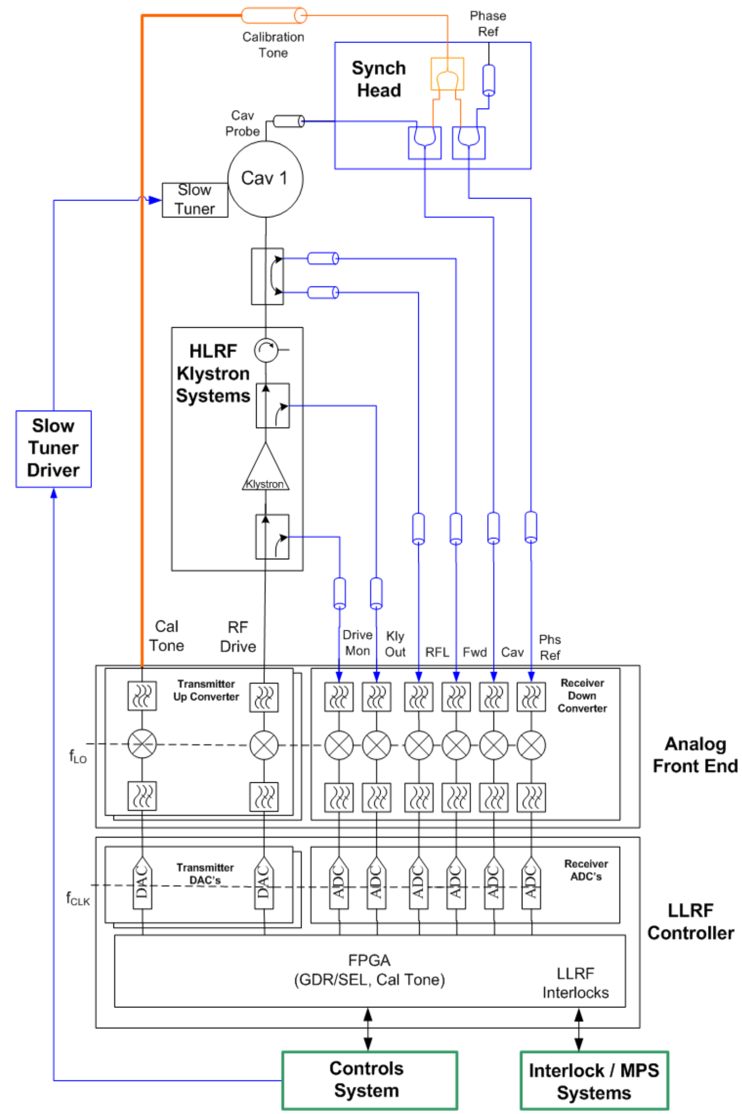
LLRF4 board running at ANL

JLab Stepper Motor Driver will be used for the Slow Tuner

- Delivery anticipated 1/2012

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

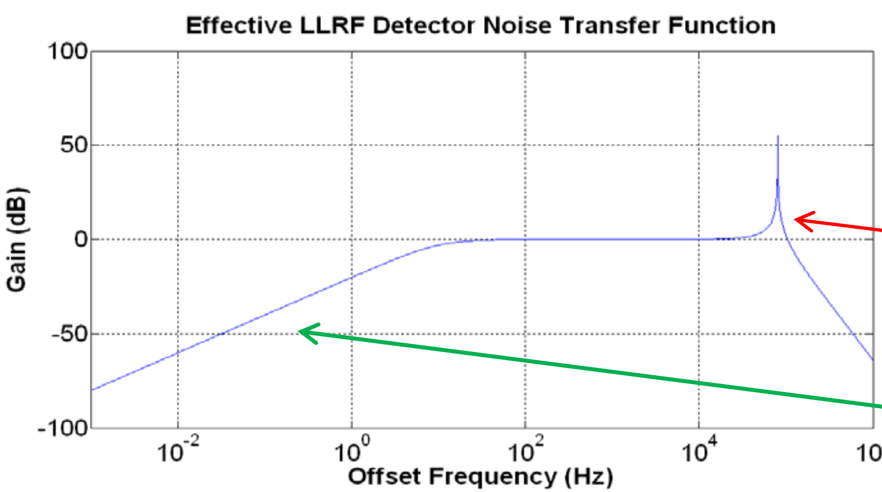




How to achieve 0.18° rms Differential Phase ??

- 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
- We need to explore cavity system noise performance through R&D
  - microphonics, beam-loading disturbances & cavity alignment, sources of common mode to differential mode conversion, AM-to-PM conversion
- We also need to study anticipated interaction with orbit feedback and influence of bunch by bunch feedback on betatron tune Q

Very Simplistic First Order Orbit Feedback concept



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

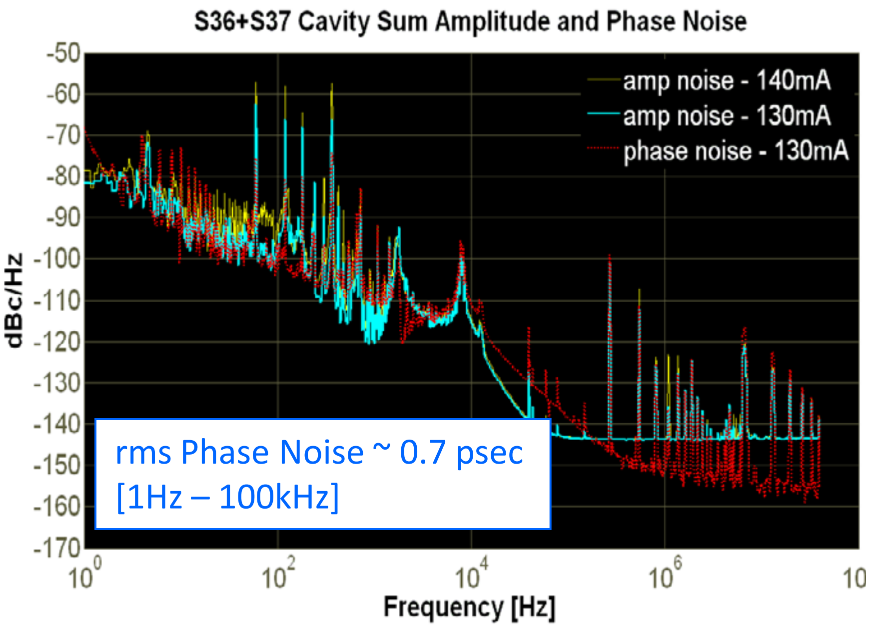
Betatron Tune Transfer Function

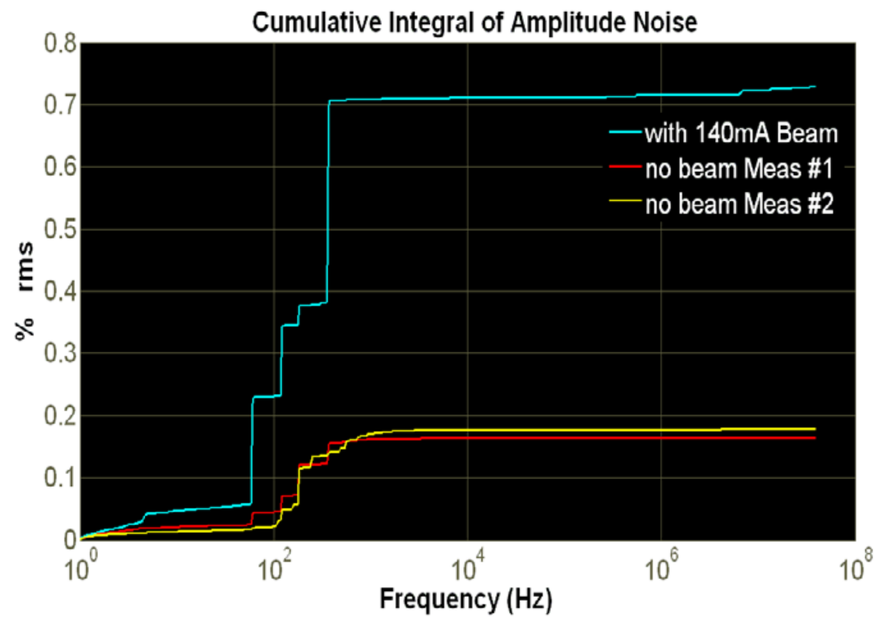
Q = ~700

Orbit FB suppresses RF system low freq. noise (i.e., drift, 1/f)

Update on Common Mode Phase Considerations

- 4.0° rms = ~4 psec rms common mode spec
  - Storage Ring 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 to lock beam to M.O.

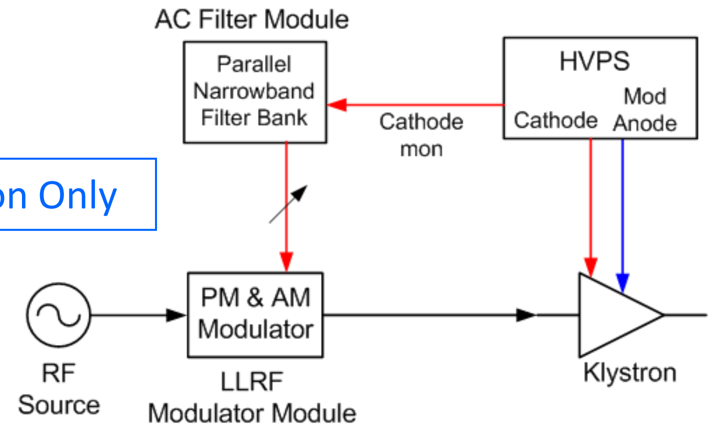




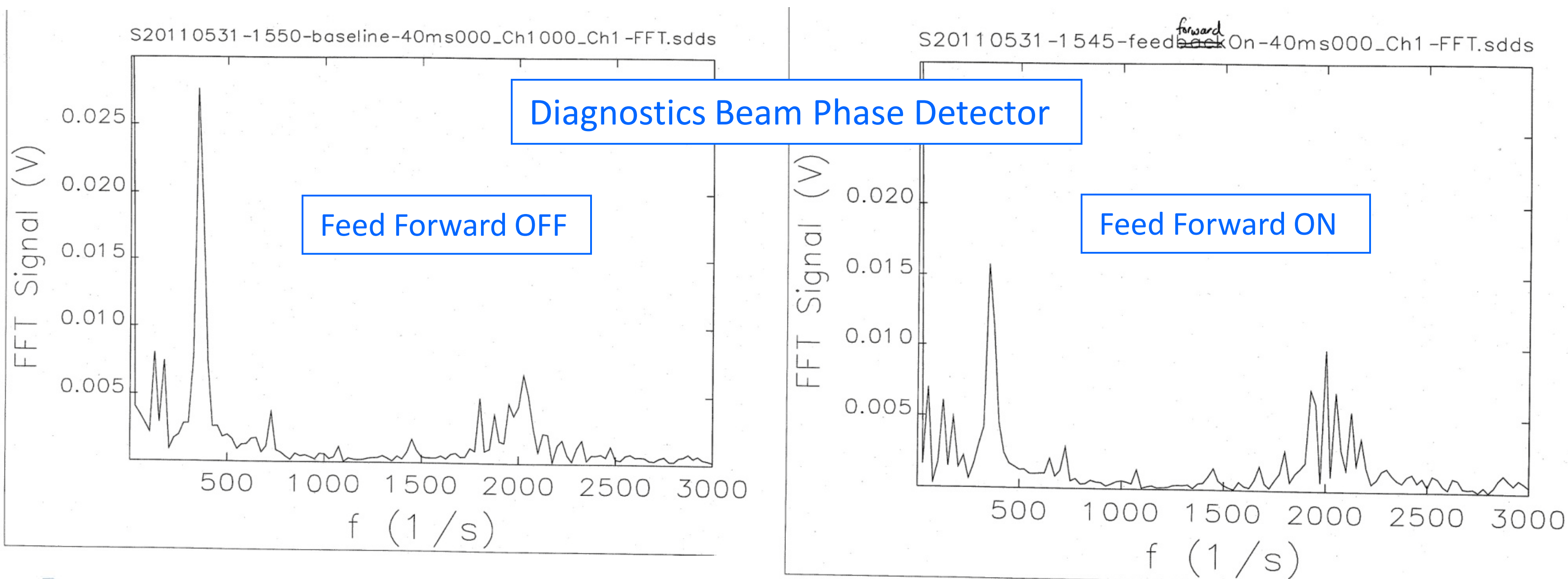
Update on Common Mode Phase Considerations

Have recently experimented with 360Hz Feed-Forward correction of Storage Ring Klystron High-Voltage Power Supply (HVPS) induced noise

AM suppression at 1 Station Only



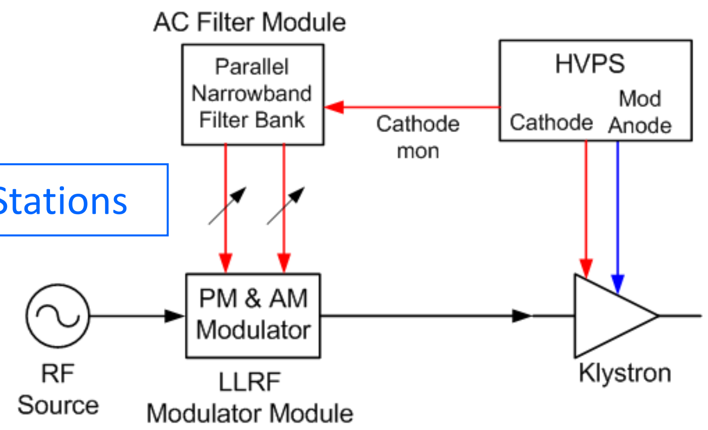
Diagnostics Beam Phase Detector

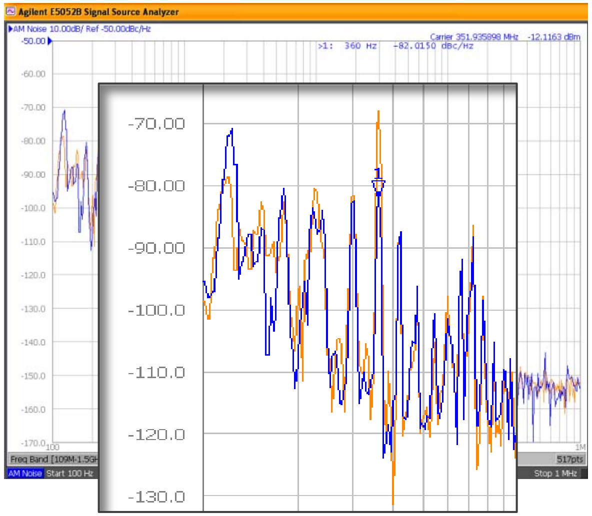


Update on Common Mode Phase Considerations

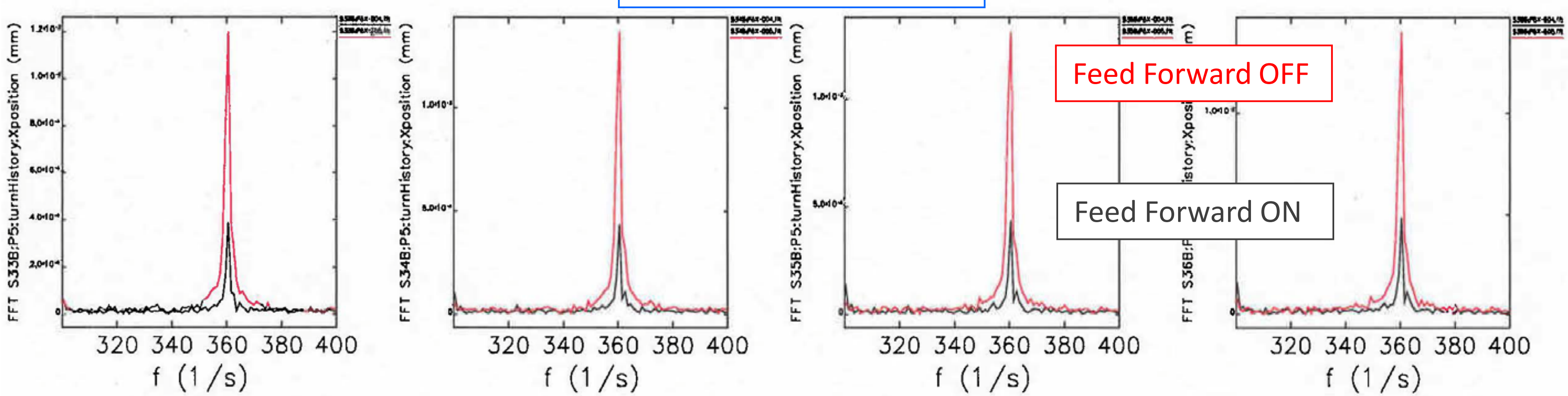
Have recently experimented with 360Hz Feed-Forward correction of Storage Ring Klystron High-Voltage Power Supply (HVPS) induced noise

AM & PM suppression at Both Stations





Horizontal BPM Data



Summary

- LLRF4 2-Channel measured phase noise floor ~ -135 $dBrad^2/Hz$

- Calibration Tone scheme provides phase drift compensation
  - Need to be careful with signal levels in order not to reduce SNR
  - Anticipated ability to capture phase noise of Analog Front End, more to explore

- LBNL delivery of first LLRF4 receiver to ANL and differential noise study: 10/11

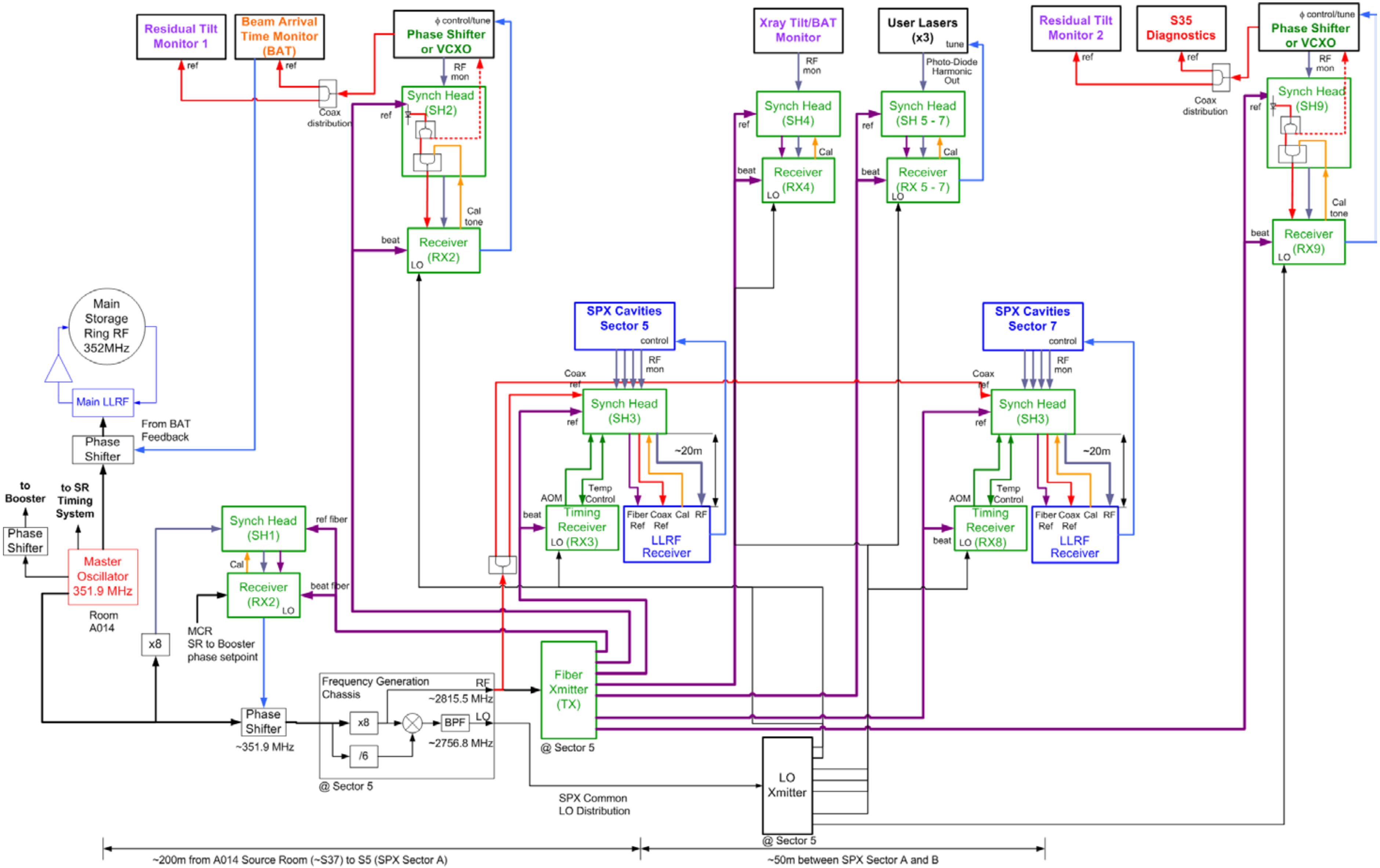
- Single cavity testing at ANL scheduled to begin 2/2012
- Two cavity system to be explored through SPX-0 R&D program

- Storage Ring performance studies well underway

Possible topics to discuss

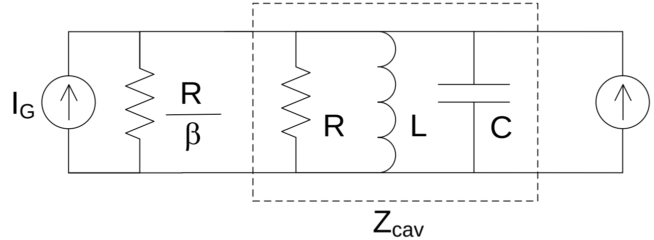
  - beam-loading disturbances & cavity alignment, potential sources of common mode to differential mode conversion, microphonics, Lorentz force detuning
  - interaction with orbit feedback and influence of bunch by bunch feedback on betatron tune Q

Backup Slides



Residual Tilt Monitor 1
Beam Arrival Time Monitor (BAT)
ϕ control/tune
Phase Shifter or VCXO
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
From BAT Feedback
Phase Shifter
to Booster
to SR Timing System
Master Oscillator 351.9 MHz
Room A014
x8
Synch Head (SH1)
ref fiber
Receiver (RX2)
beat fiber
MCR SR to Booster phase setpoint
SPX Cavities Sector 5
control
Coax ref
Synch Head (SH3)
~20m
AOM
Temp Control
Timing Receiver LO (RX3)
Fiber Ref
Coax Ref
LLRF Receiver
SPX Cavities Sector 7
Timing Receiver LO (RX8)
Frequency Generation Chassis
~2815.5 MHz
x8
/6
BPF
~2756.8 MHz
~351.9 MHz
@ Sector 5
Fiber Xmitter (TX)
LO Xmitter
SPX Common LO Distribution
~200m from A014 Source Room (~S37) to S5 (SPX Sector A)
~50m between SPX Sector A and B

Deflecting Cavity Beam Loading

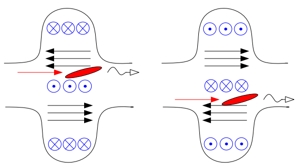


$$i_o \kappa_o \left(y + j \cdot \theta \, \omega_o c \, \sigma_t^{\,2} \right) \cdot e^{-j(\pi + \phi_s)}$$

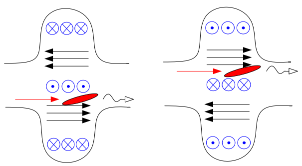
$$i_o = 2 I_{dc} \cdot e^{-\frac{1}{2}(2\pi f_o \sigma_t)^2}$$

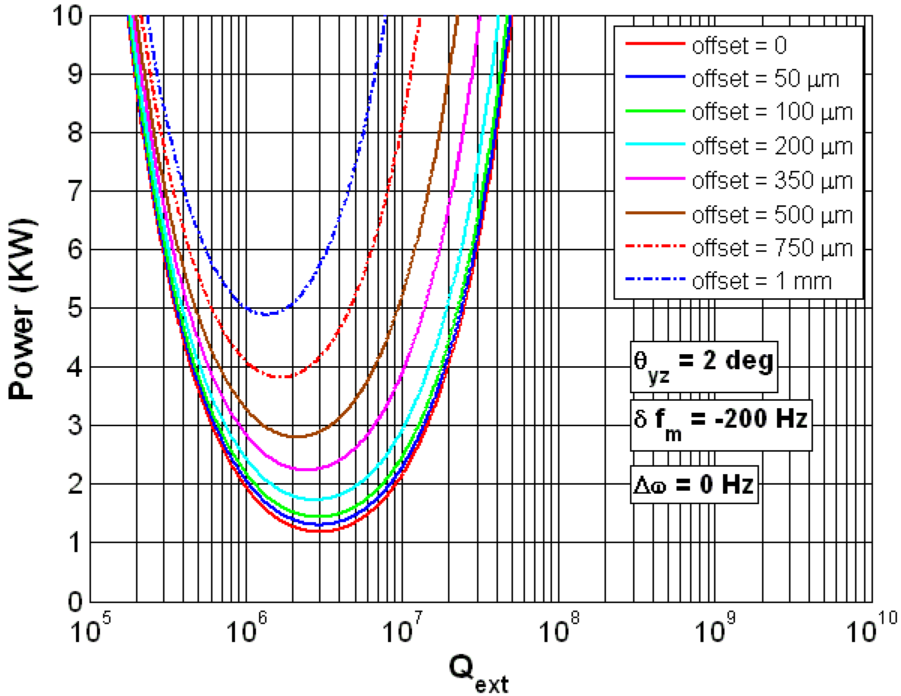
$$P_g^{\,+} = \frac{V_t^{\,2}}{8\beta \left(R/Q\right)' Q_o} \cdot \left[\left(\beta + 1 + \frac{P_B}{P_{cav}} \right)^2 + \left(2Q_o \frac{(\Delta f + \delta f_m)}{f_r} + \frac{P_B}{P_{cav}} \tan \phi_s \right)^2 \right]$$

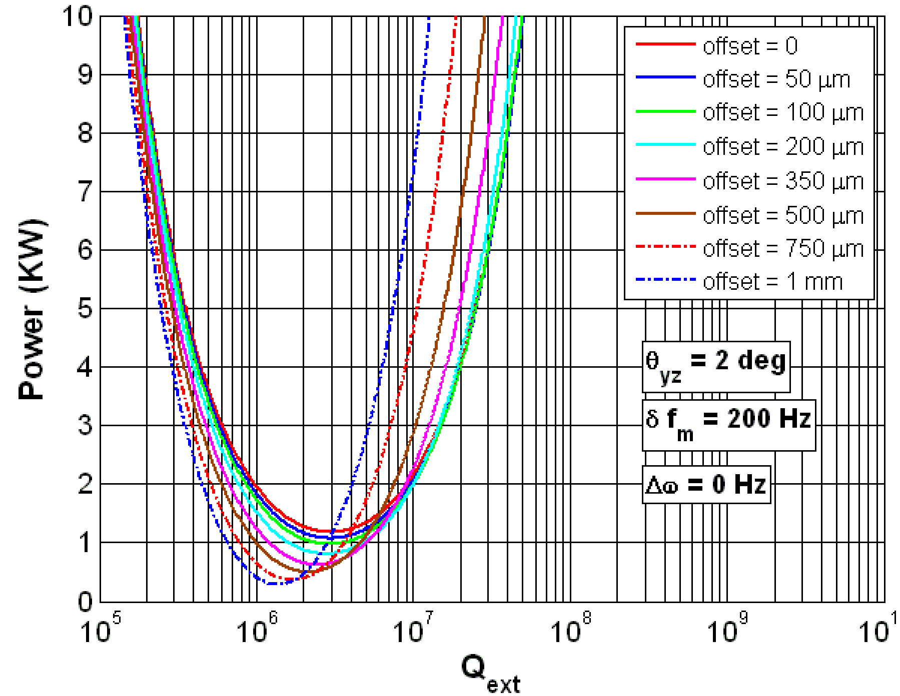
$V_t \cdot y > 0$



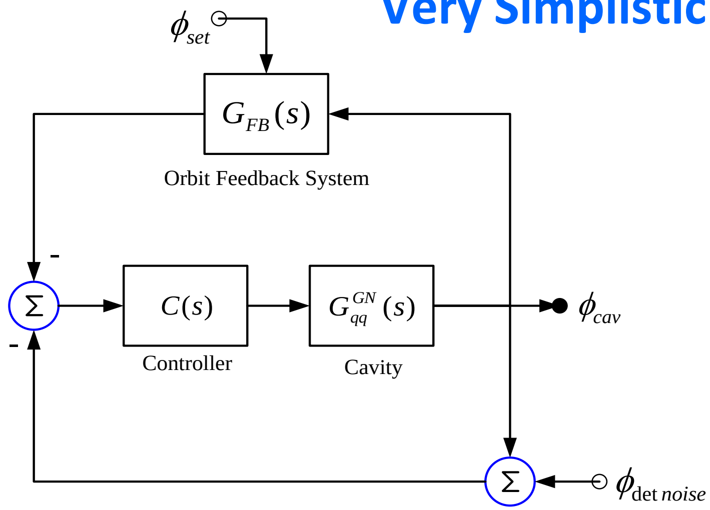
$V_t \cdot y < 0$







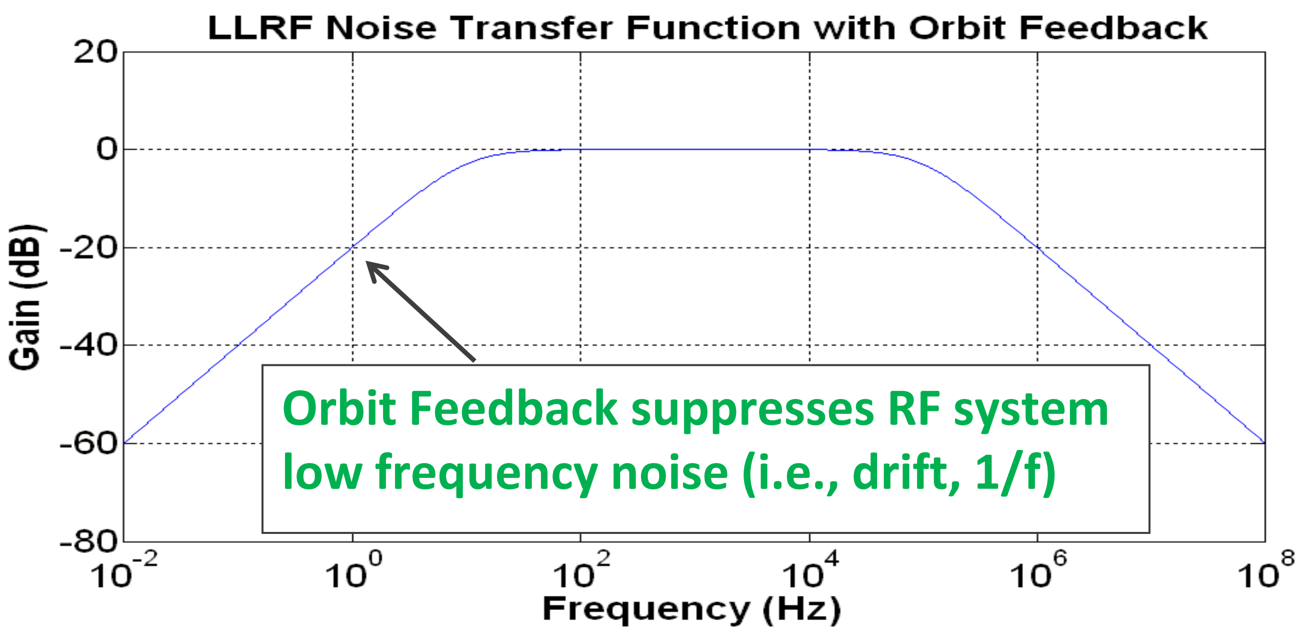
Very Simplistic First Order Orbit Feedback concept



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

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

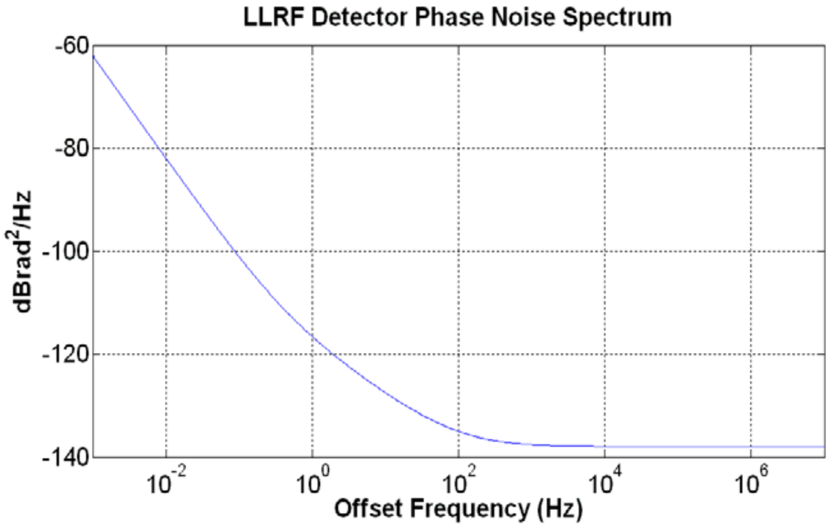
$$= \frac{K_p\sigma_{cav}\, s}{s^2 + K_p\sigma_{cav}\, s + K_p^{RTFB}K_p\sigma_{RTFB}\sigma_{cav}}$$



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



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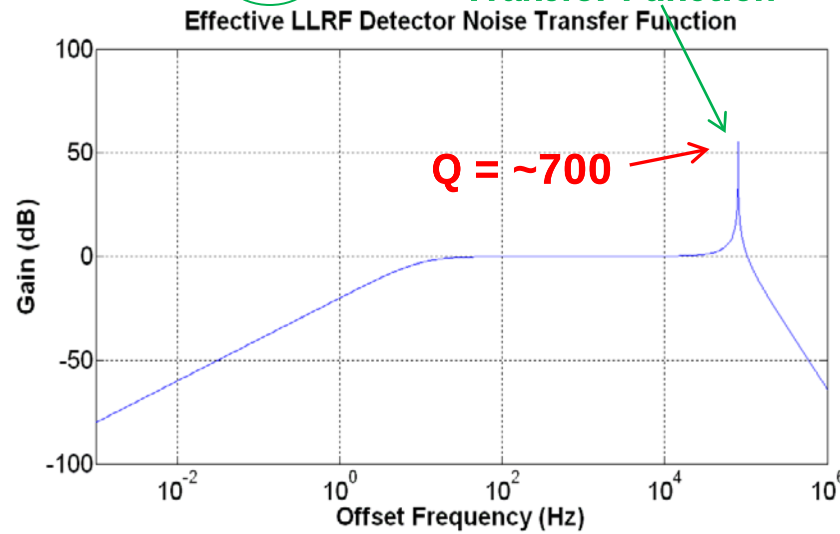

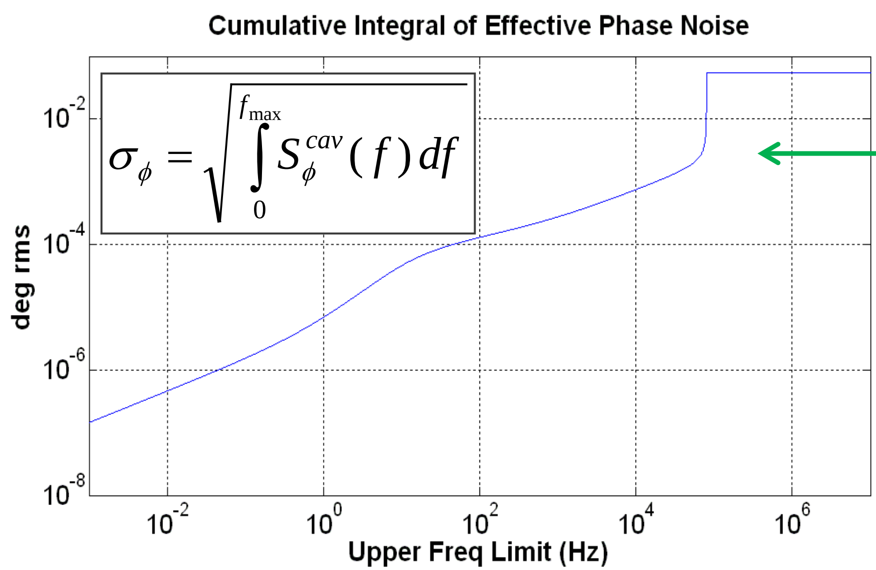

0.054 deg RMS w Betatron Tune

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