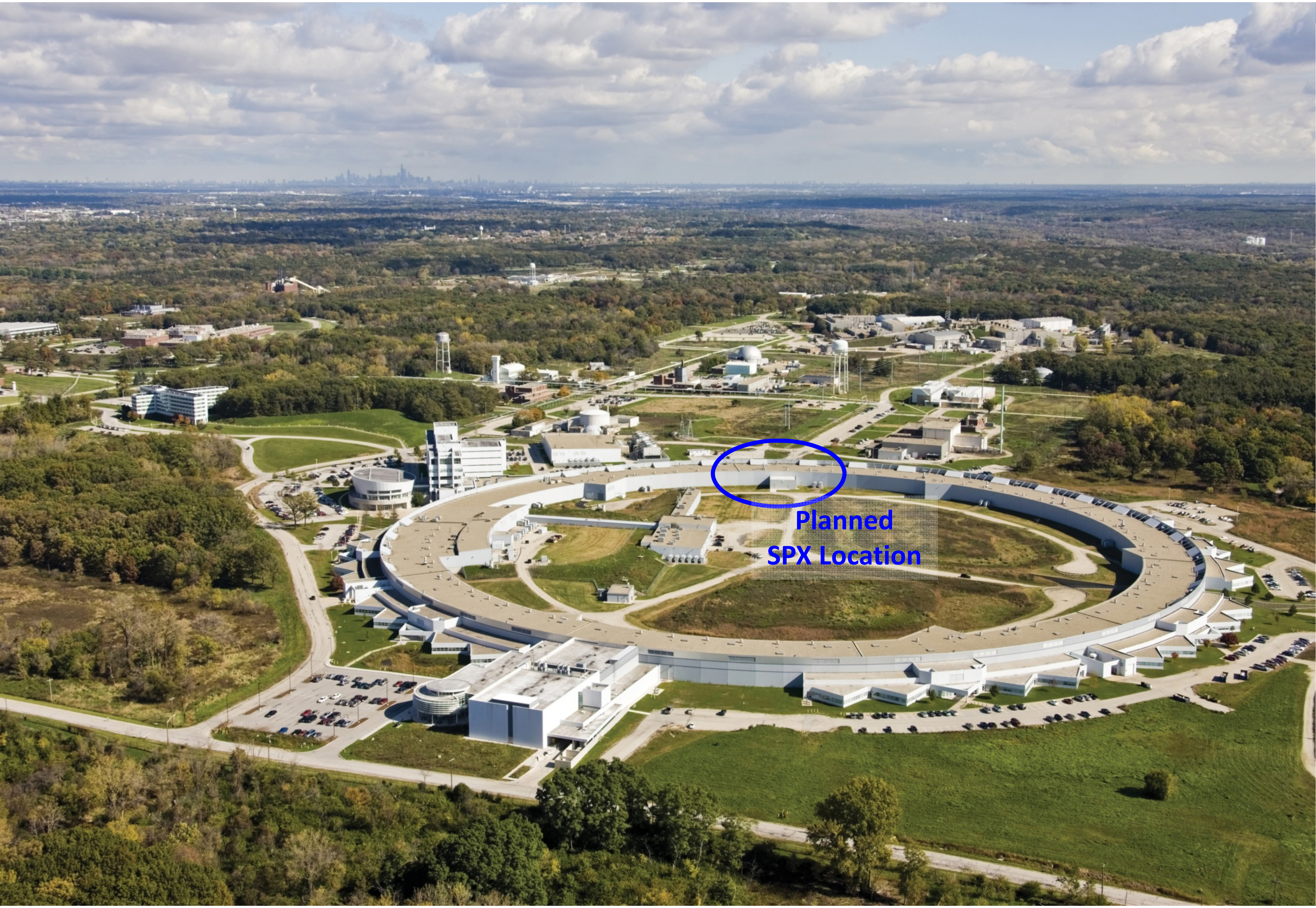
SPX LLRF R&D

ANL: Tim Berenc, Hengjie Ma, Ned Arnold, Frank Lenkszus, Tom Fors,
Bill Yoder
LBNL: Larry Doolittle, Gang Huang, John Byrd,
Jim Greer, Kerri Campbell

Feb. 6, 2012
ASD Seminar

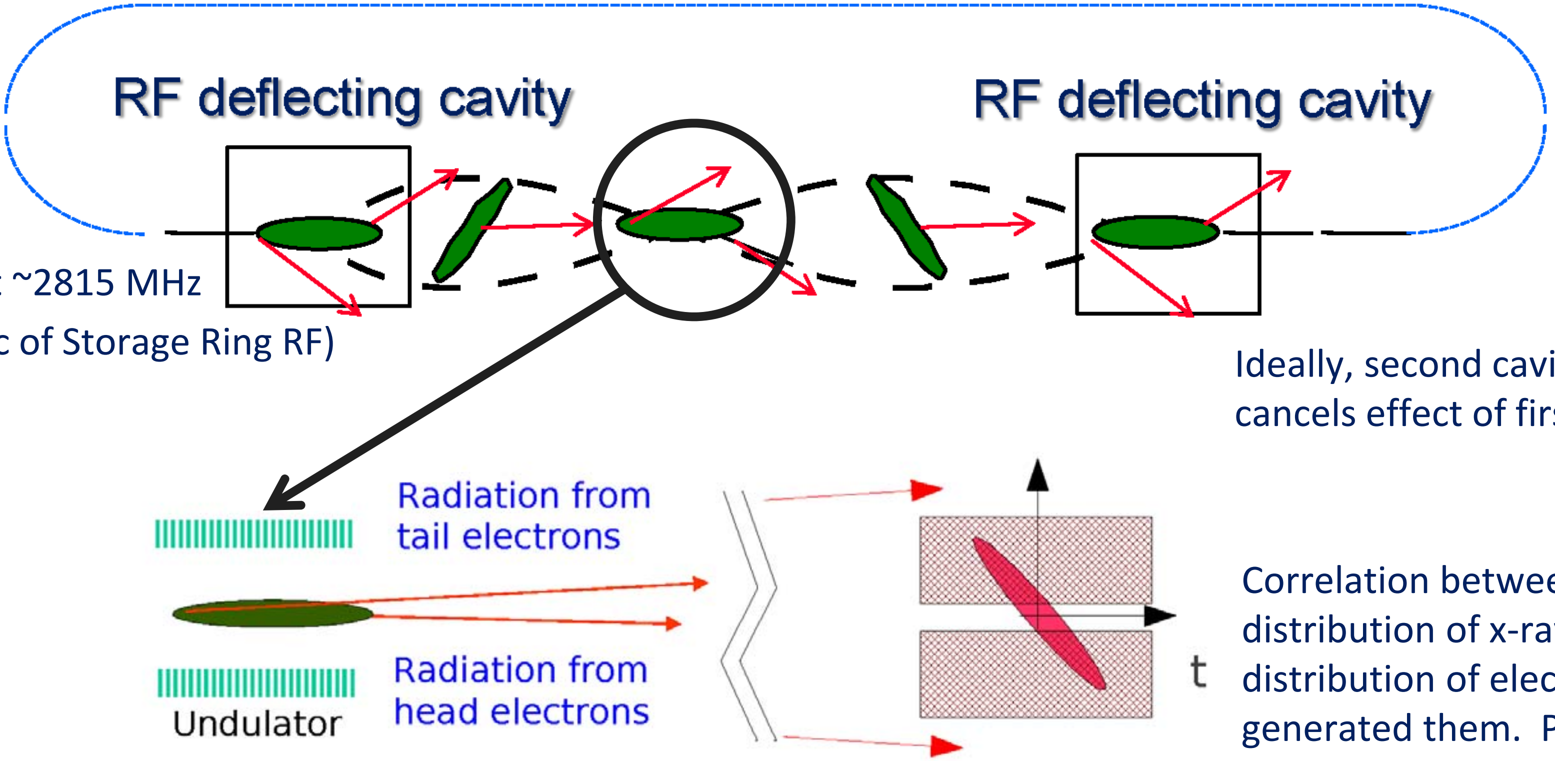
Outline

- Intro
- LLRF Receiver (prototype results)
- Deflecting Cavity Behavior (static and dynamic)
- LLRF Controller (benchtop performance tests)
- Storage Ring RF modification plans
- Summary


Planned
SPX Location

APS-U SPX System – Zholents' Transverse RF Chirp Concept[1]

Goal: provide ~2 psec (presently 50-100 psec) X-ray pulses at 6.5 MHz rep. rate for time-resolved studies

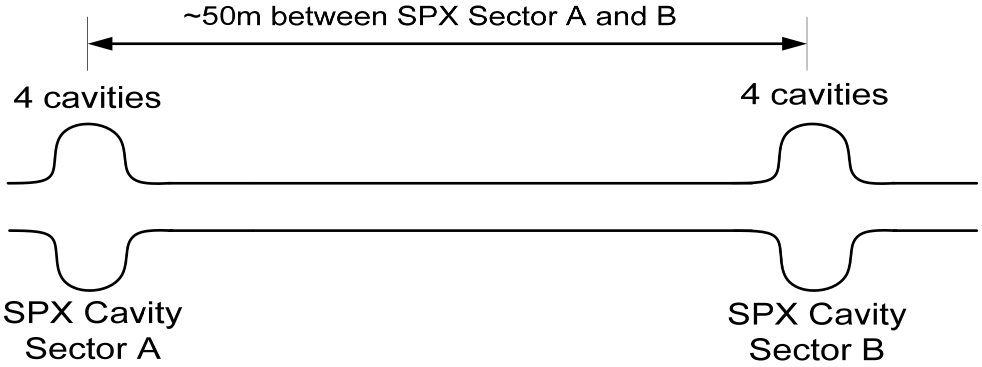


RF at ~2815 MHz

(8th harmonic of Storage Ring RF)

Ideally, second cavity exactly cancels effect of first cavity

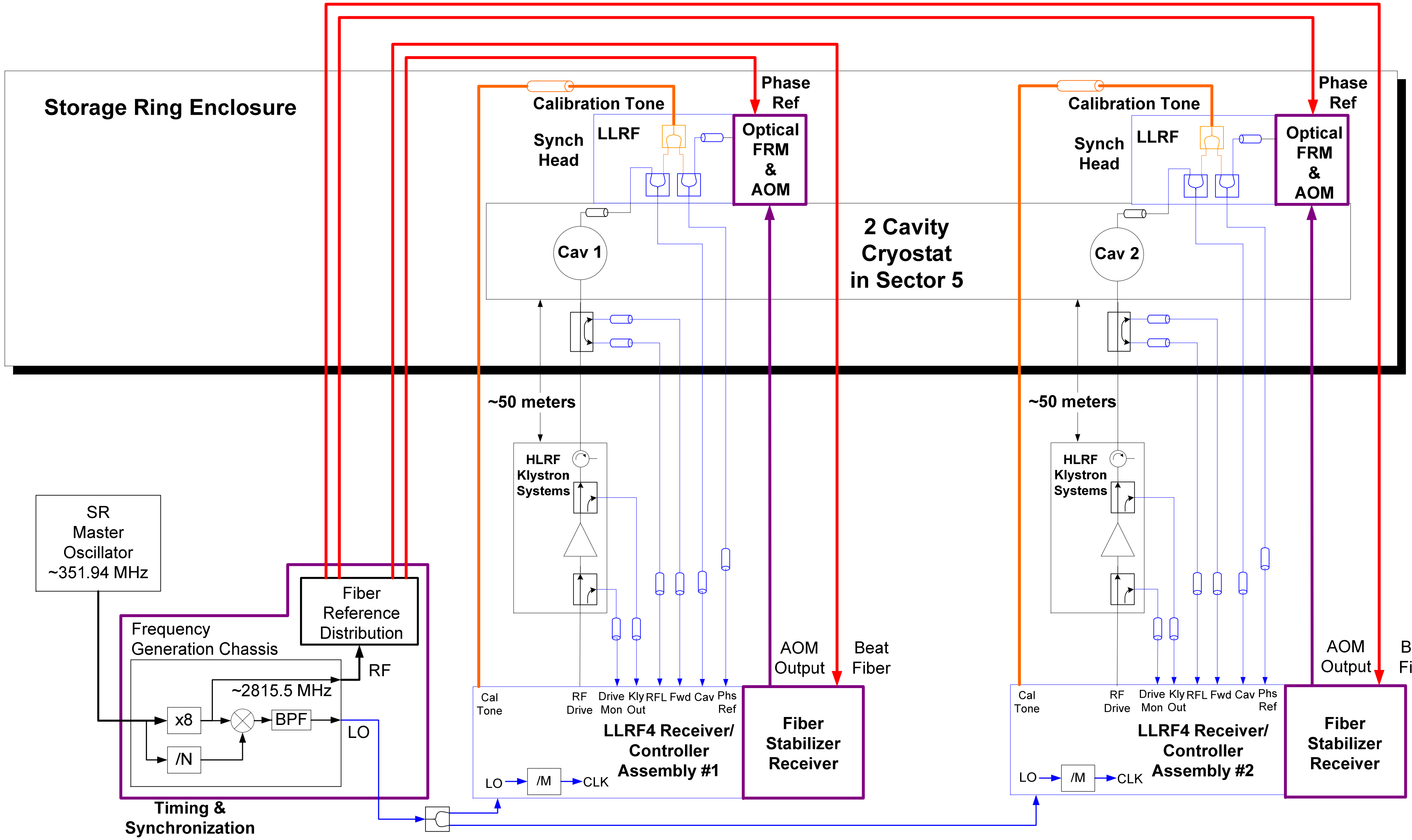
Correlation between vertical distribution of x-rays and time-distribution of electrons that generated them. Pulse can be sliced or compressed with an asymmetric cut crystal.



[1] A. Zholents *et al.*, NIM A 425, 385 (1999)

SPX0 = R&D System Proof of Principle (1 Sector, 2 cavities)

- Cavities counter-phased (180deg) to demonstrate tolerance requirements
- Cavities run in-phase to create a chirped beam around entire ring to have a look at short pulse x-rays



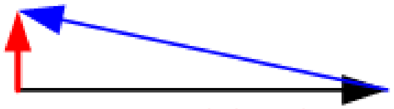
SPX0 System Performance Requirements [3]

Specification name	Rms Value	Bandwidth	Driving requirement
Common-mode voltage amplitude variation	< 7%	0.1Hz – 271kHz	Keep beam emittance variation distinguishable from the differential voltage effect for SPX0
Common-mode phase variation	< 1.0 deg	0.1Hz – 1kHz	Keep global orbit motion distinguishable from differential phase for SPX0
	< 3.6 deg	1kHz – 271kHz	Keep rms emittance variation distinguishable from differential phase for SPX0
Differential mode voltage variation	< 1%	0.1Hz – 1kHz	Keep rms emittance variation outside of SPX under 10 % of nominal 35 pm
	< 0.77%	1kHz – 271kHz	Effective emittance growth under 1.5 pm for SPX
Differential mode phase variation	< 0.077 deg	0.1Hz – 1kHz	Keep global rms orbit motion under 10% of the beam size/divergence for SPX
	< 0.28 deg	1kHz – 271kHz	Keep emittance growth outside of SPX under 10 % of nominal 35 pm

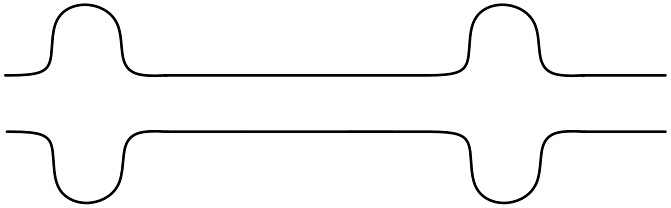
Common Mode

Differential

Residual tilt



Residual kick

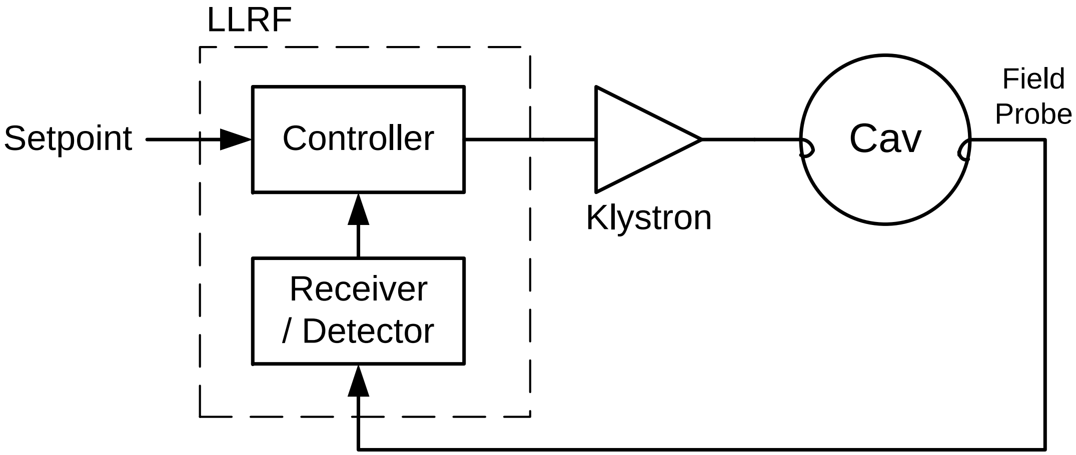


---

[3] SPX0 PRD, ICMS# APS_1423800 (1/17/12)

Low Level Radio Frequency (LLRF) System

Primary responsibility is to regulate the cavity field

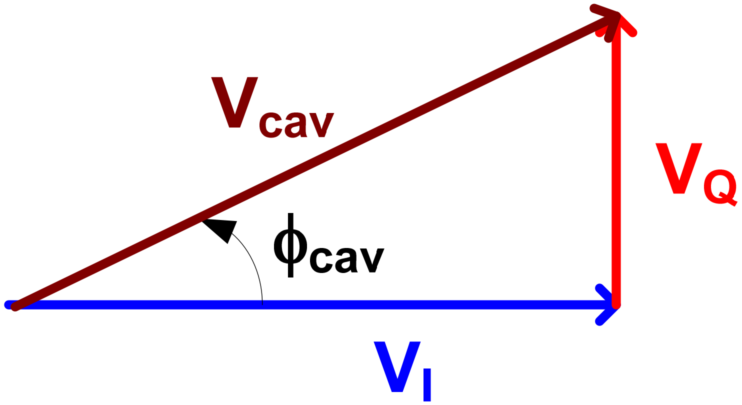


Polar Coordinates

$$V_{cav}\cos\left(\omega_{RF}t+\phi_{cav}\right)$$

Cartesian Coordinates

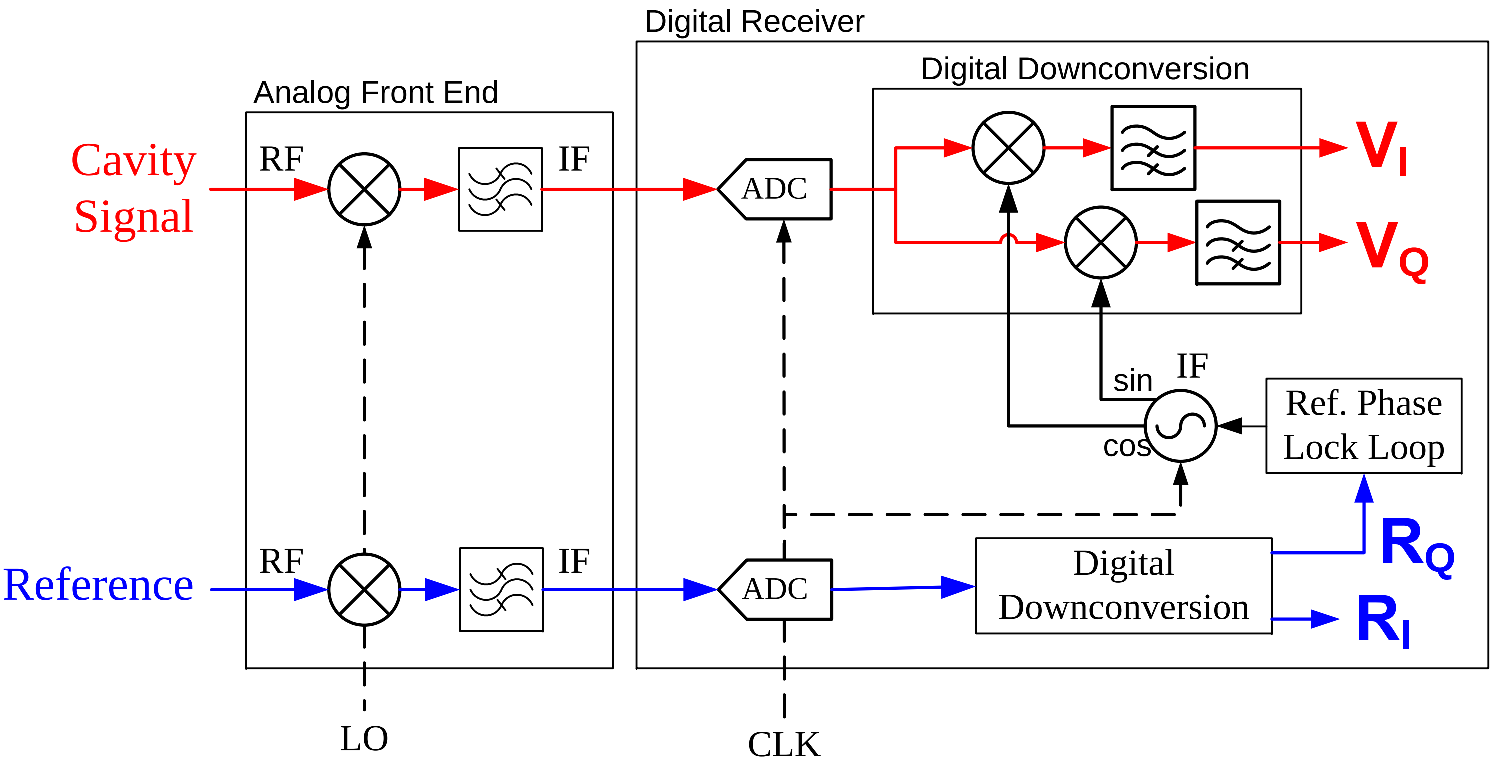
$$V_I\cos\omega_{RF}t\ -\ V_Q\sin\omega_{RF}t$$



$$V_{cav}=\sqrt{V_I^{\ 2}+V_Q^{\ 2}}$$

$$\phi_{cav}=\arg\left(V_I+jV_Q\right)$$

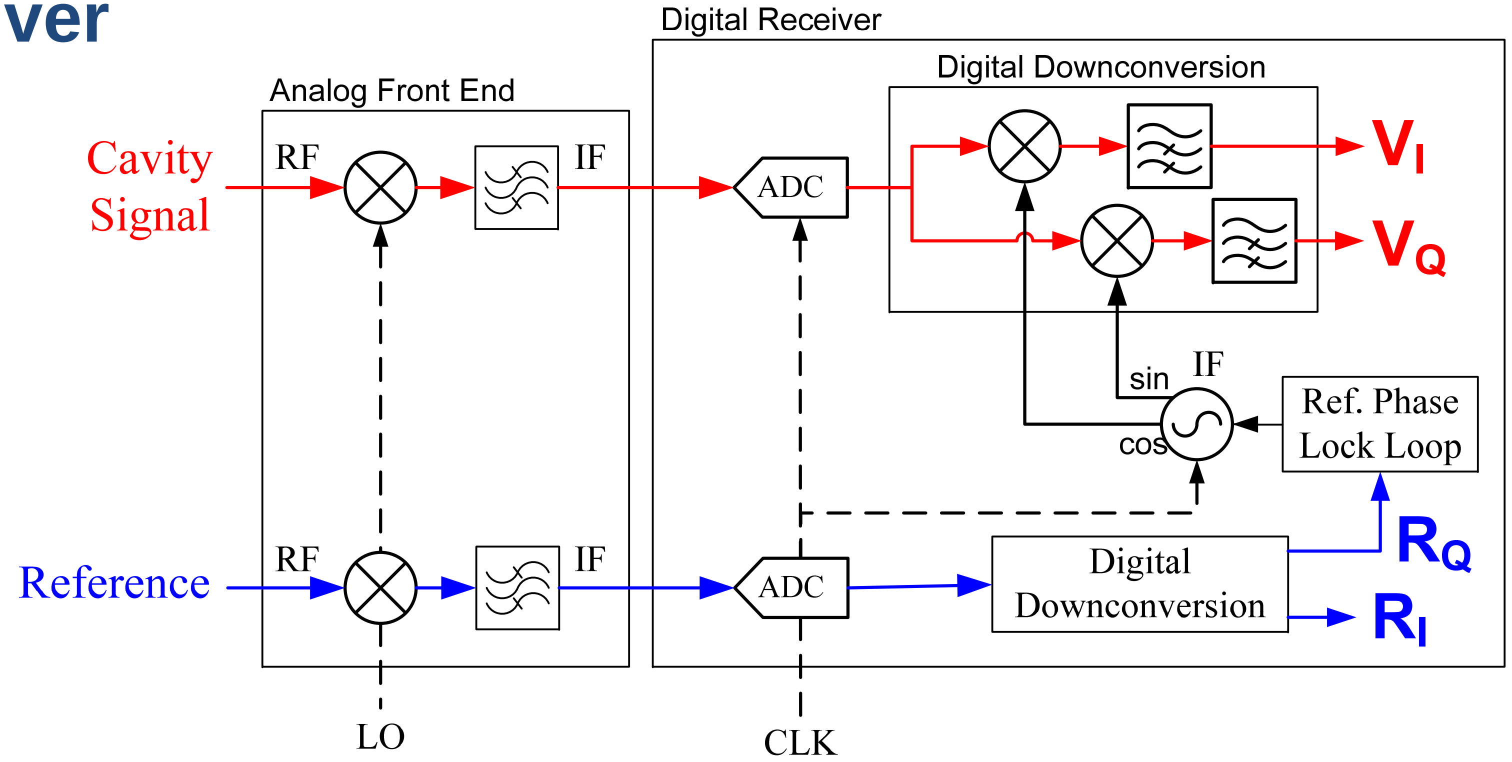
Receiver You can't regulate any better than your receiver



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**

Receiver



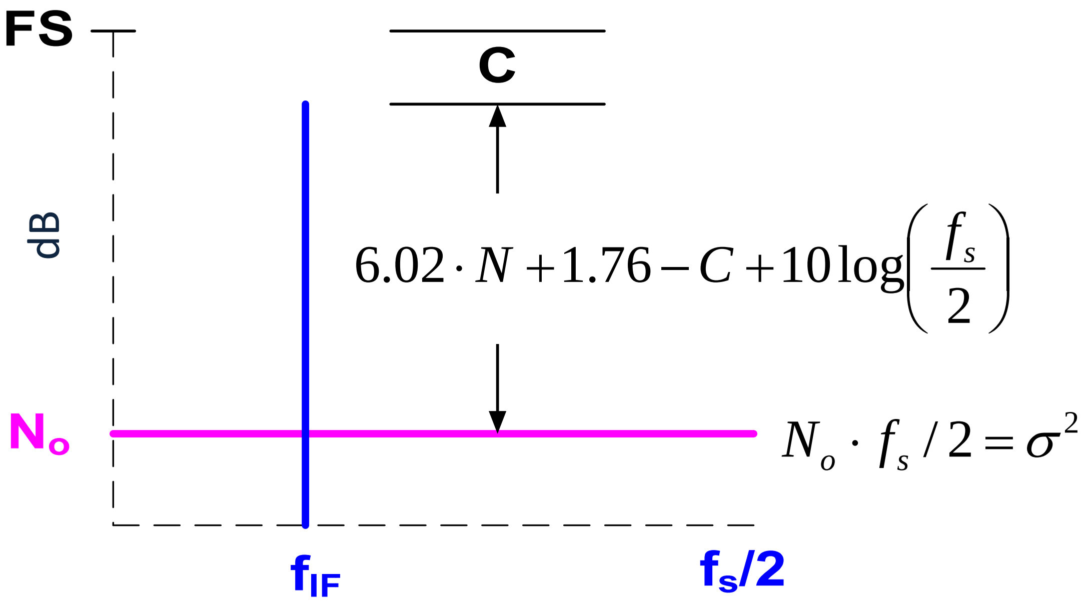
ADC Quantization Noise

Variance $\sigma^2 = \frac{q^2}{12} = \frac{1}{2^{2N} \cdot 12}$

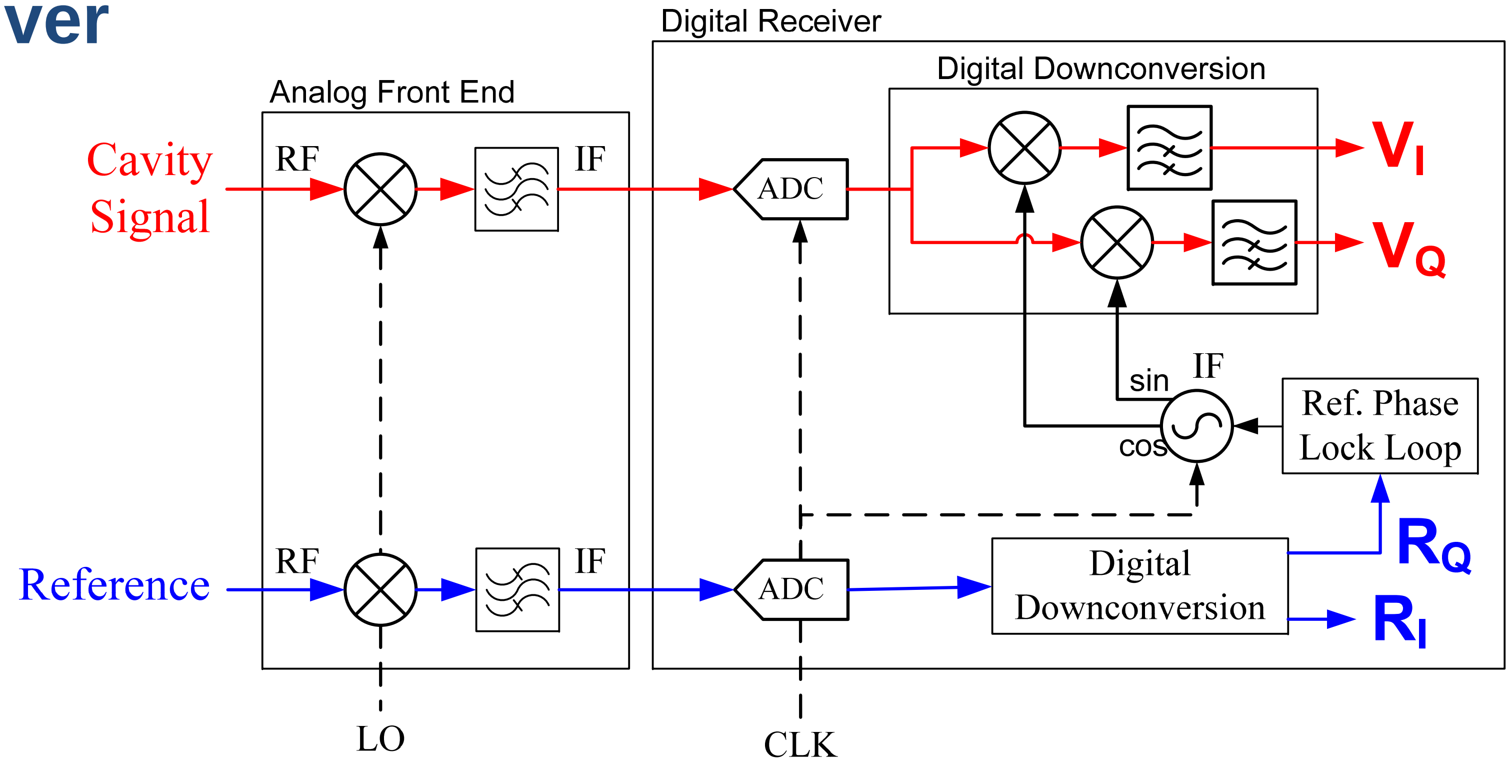
$$SNR = 6.02 \cdot N + 1.76 - C \quad [\mathrm{dB}]$$

N = # of ADC bits

C = dB carrier is below full scale



Receiver



ADC Quantization Noise

phase noise variance

$$\sigma_\phi^2 = \int_0^{f_{\max}} S_\phi(f)\,df$$

14 bit ADC

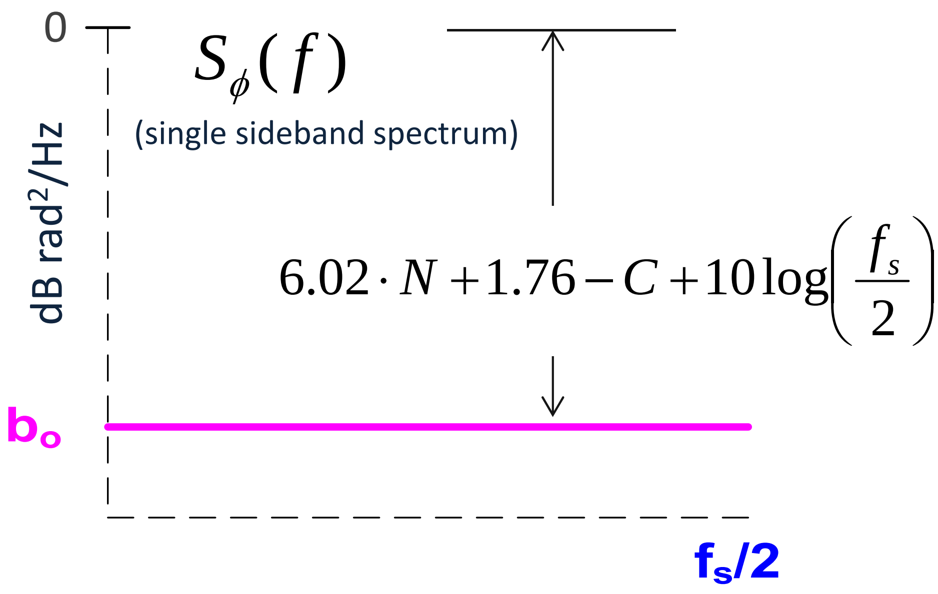
$$\sigma_\phi^2 = -85 \text{ dB rad}^2$$

$$\sigma_\phi = 0.0032 \text{ deg rms}$$

16 bit ADC

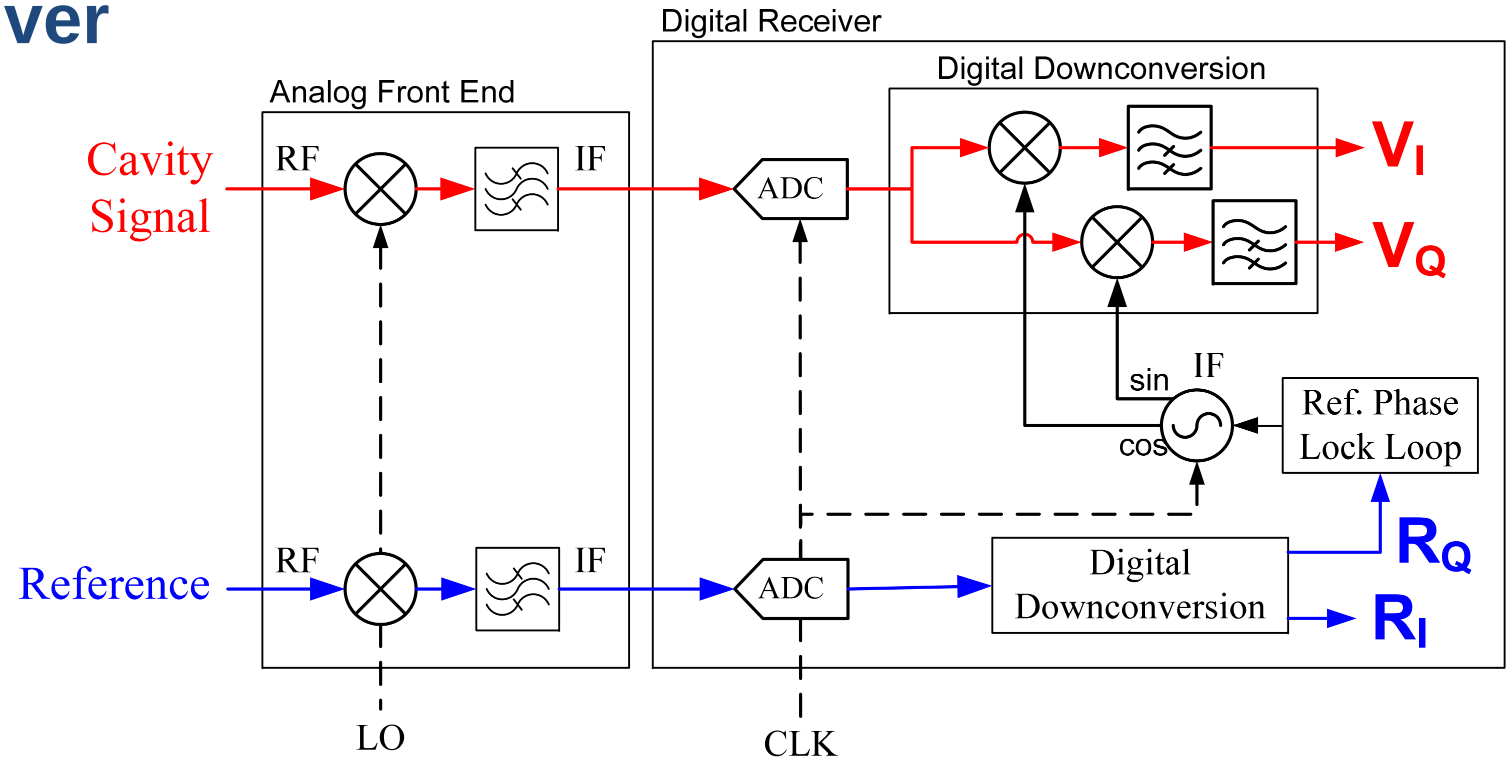
$$\sigma_\phi^2 = -97 \text{ dB rad}^2$$

$$\sigma_\phi = 0.0008 \text{ deg rms}$$



$$6.02 \cdot N + 1.76 - C + 10\log\left(\frac{f_s}{2}\right)$$

Receiver



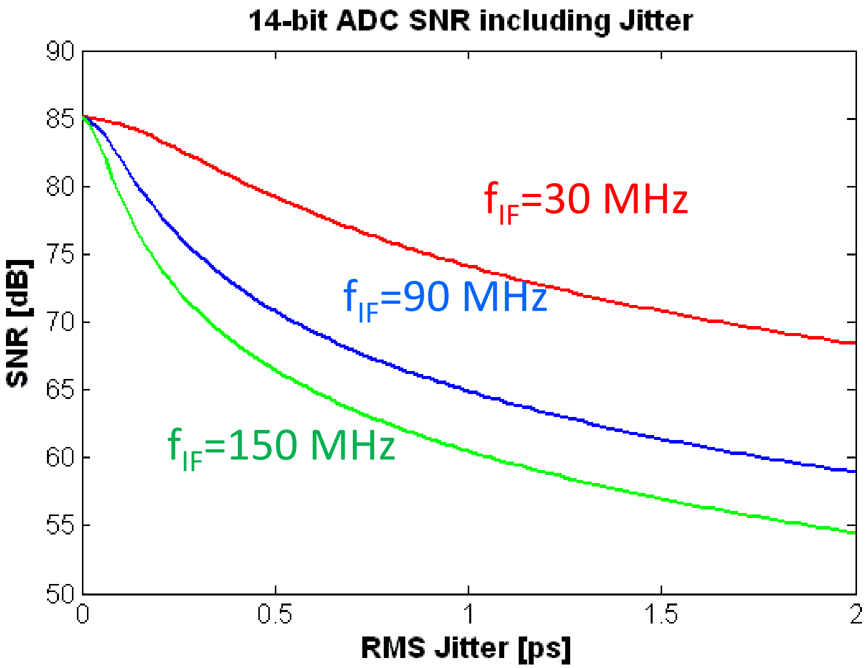
ADC Aperture Jitter

$$\cos(\omega_{IF}(t+\varepsilon)) = \cos(\omega_{IF}t + \boxed{\omega_{IF}\varepsilon})$$

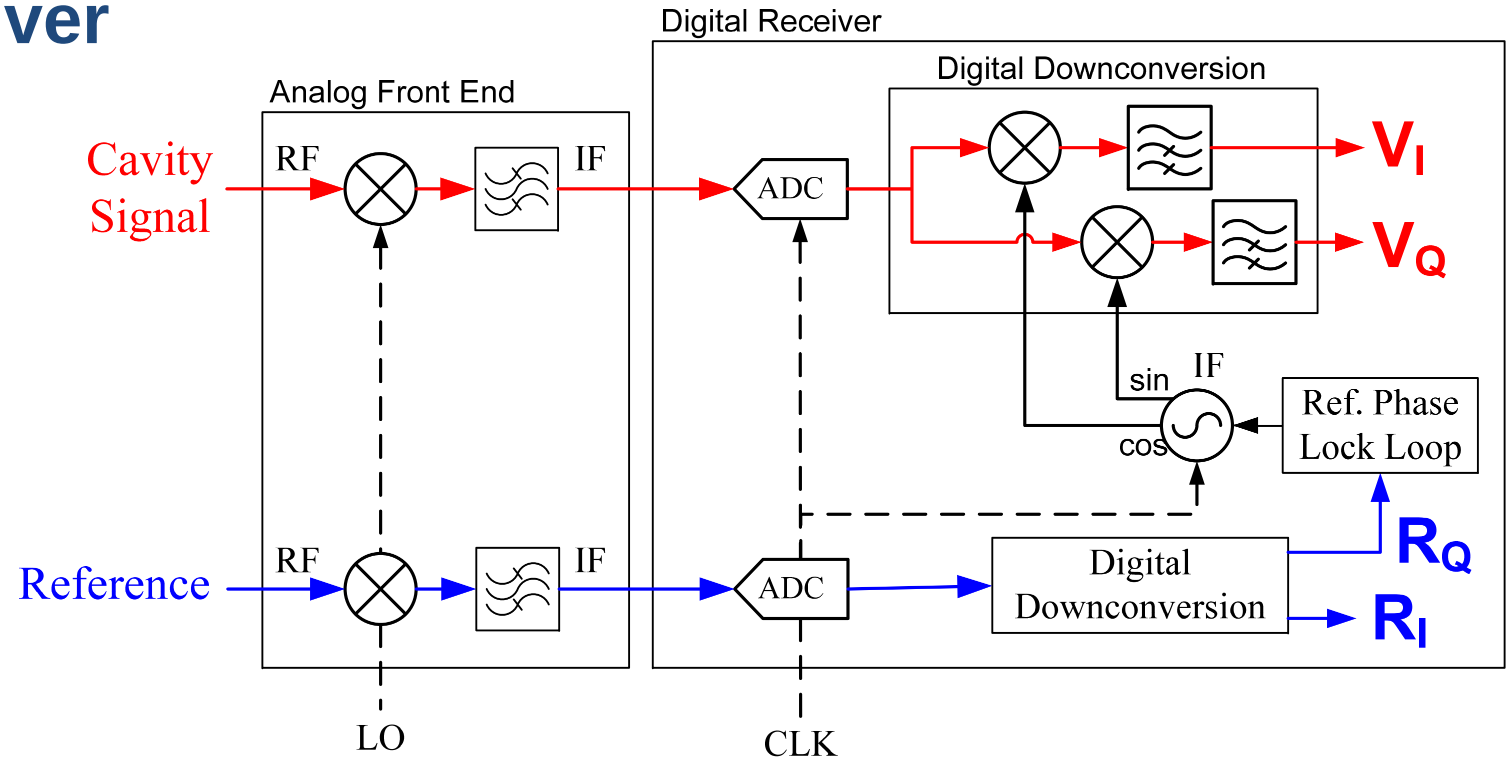
Phase noise

$$SNR_{jitter} = -20 \cdot \log(\omega_{IF} \cdot \sigma_{jitter}) \quad \text{[dB]}$$

σ_{jitter} rms aperture jitter



Receiver



ADC Aperture Jitter

phase noise variance $$\sigma_\phi^{\ 2} = \int_0^{f_{\max}} S_\phi(f)\,df$$

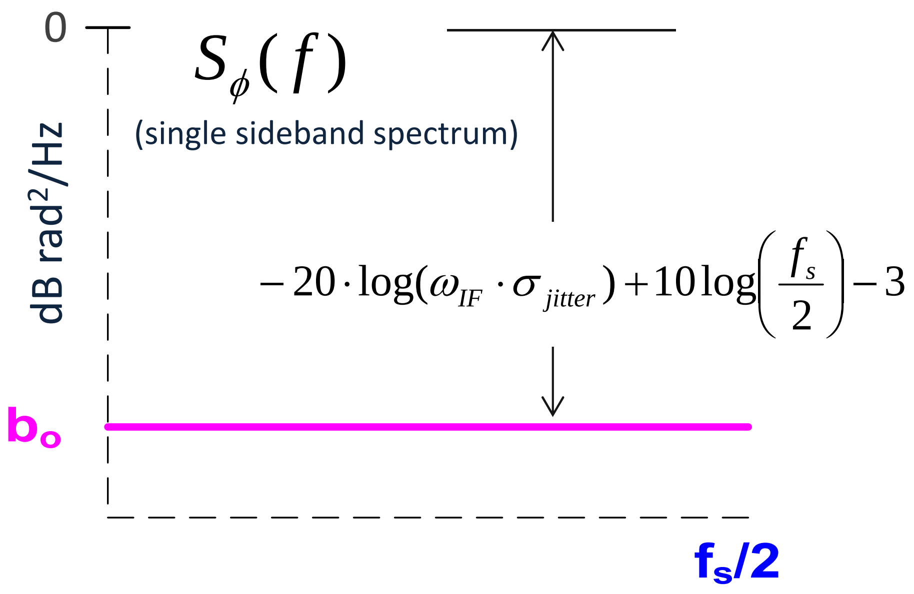
14 bit ADC, 0.5psec rms

30 MHz IF

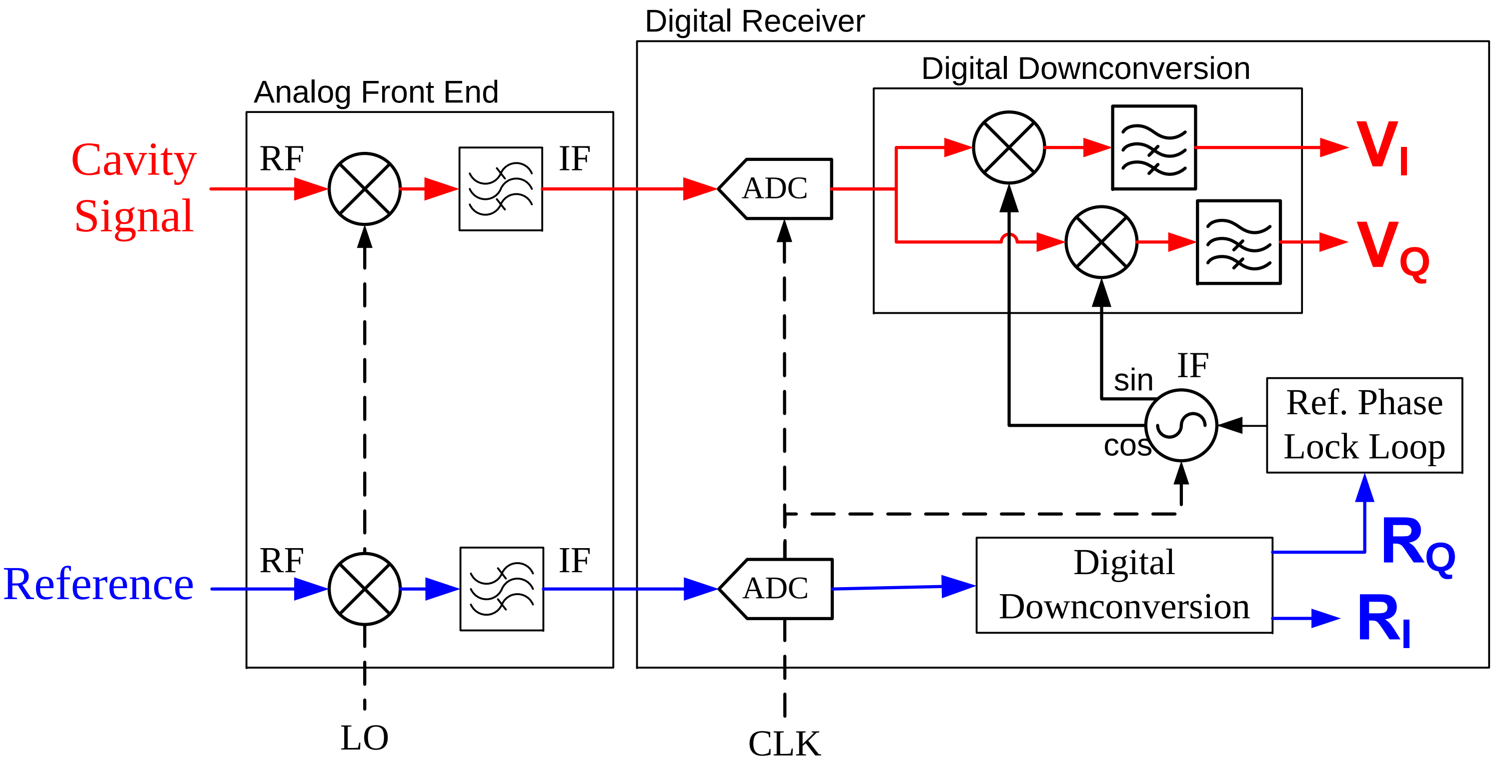
$$\sigma_\phi \approx 0.008 \text{ deg rms}$$

90 MHz IF

$$\sigma_\phi \approx 0.023 \text{ deg rms}$$



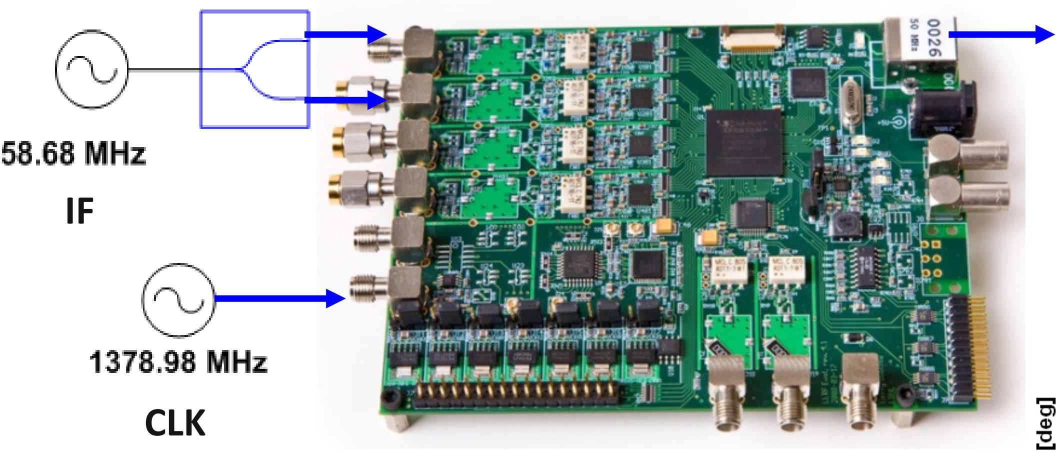
Receiver You can't regulate any better than your receiver



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**

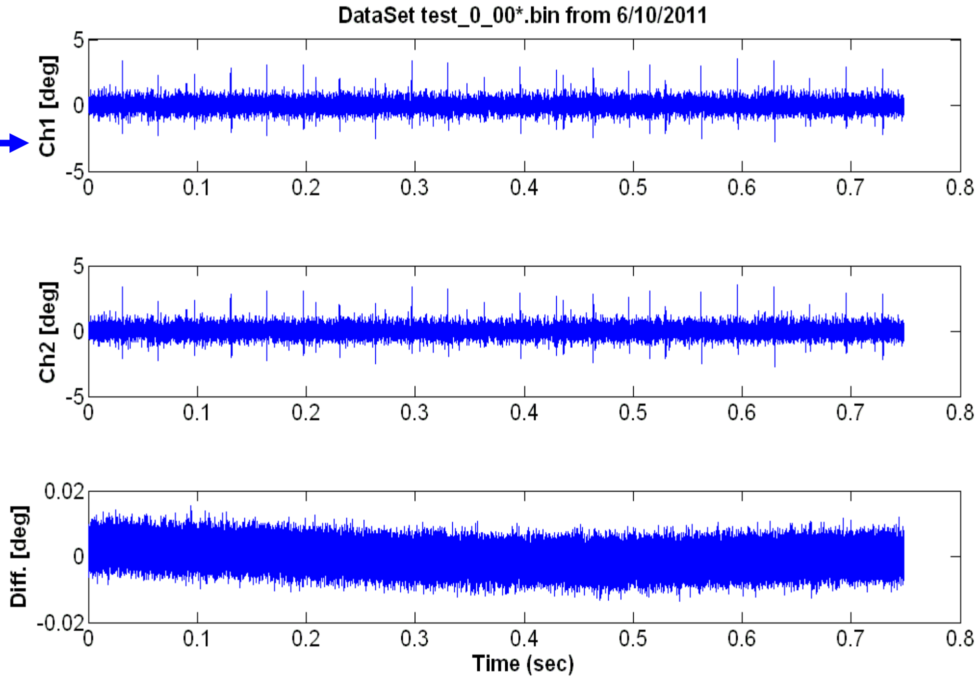
Receiver – Digital Receiver LLRF4 Board – Differential Phase Noise

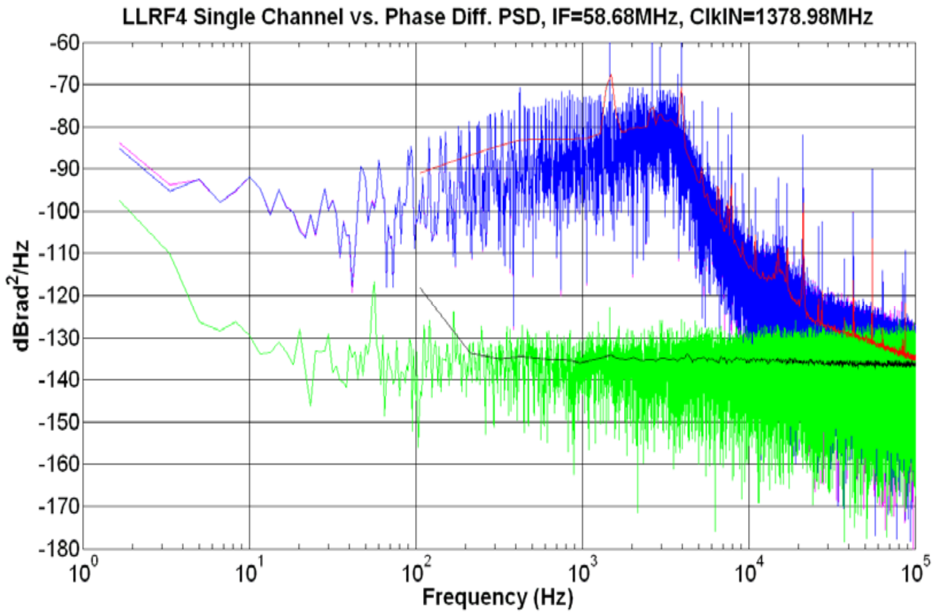

58.68 MHz

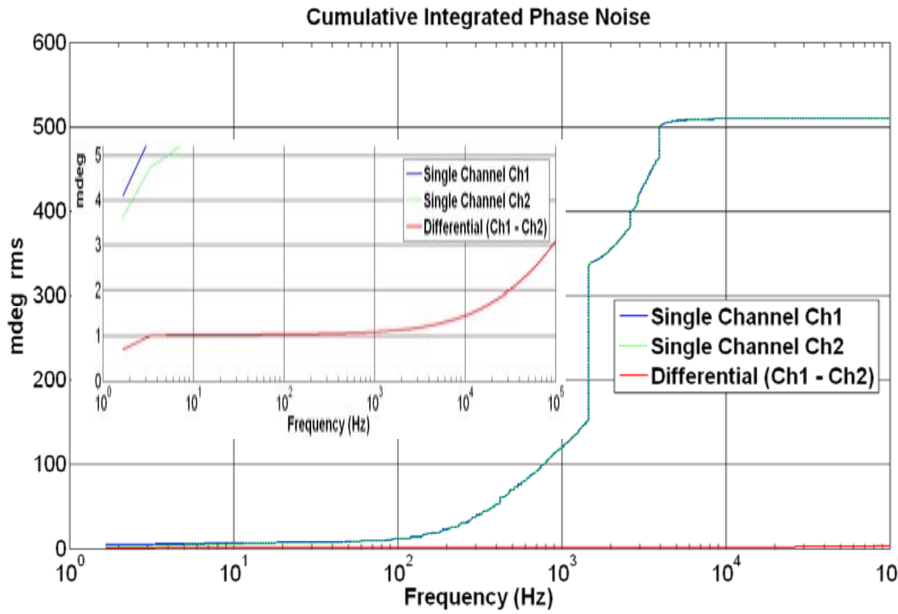
IF

1378.98 MHz

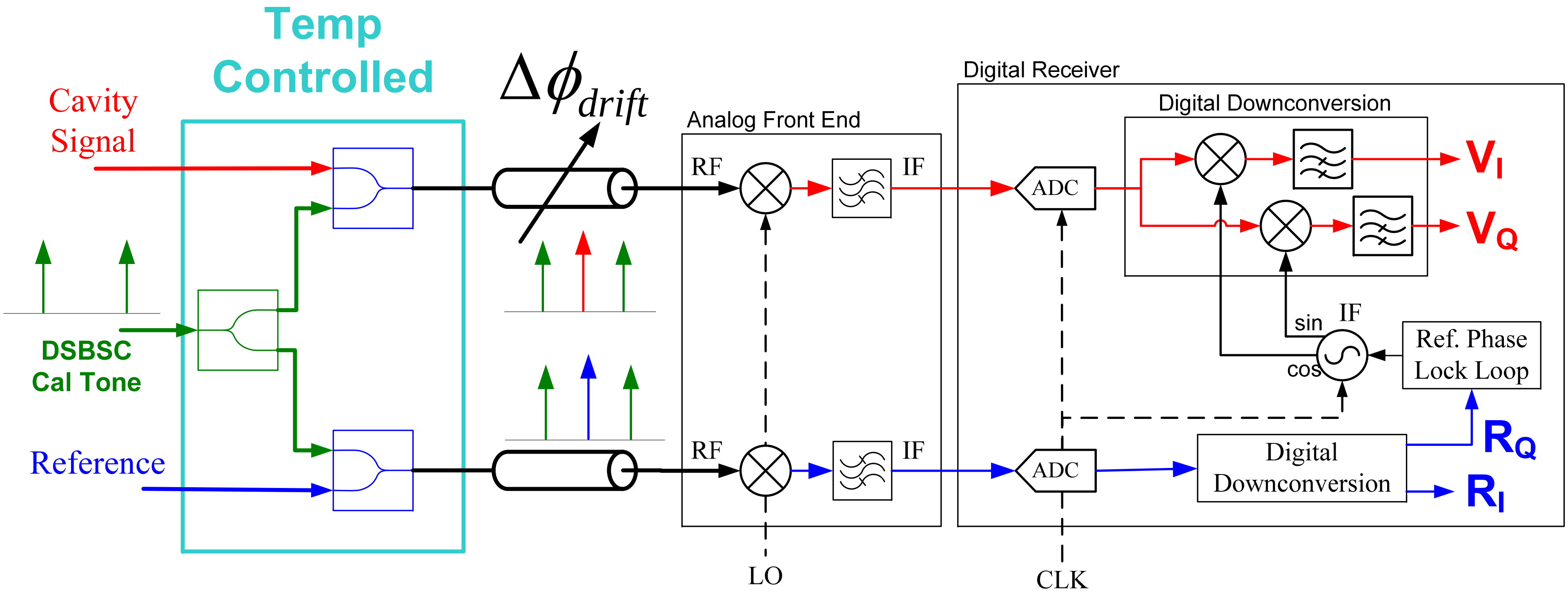
CLK







Receiver - CW Drift Compensation[4]



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

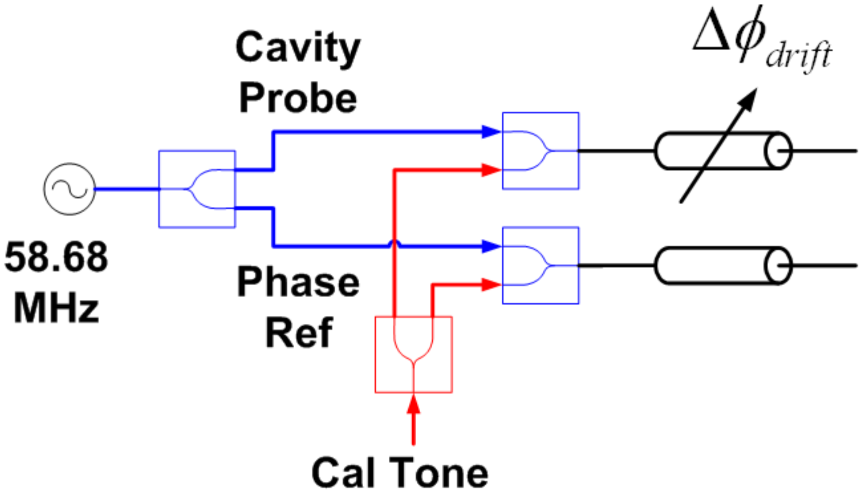
$$\Delta\phi_{calTone} = \Delta\phi_{drift}$$

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

---

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

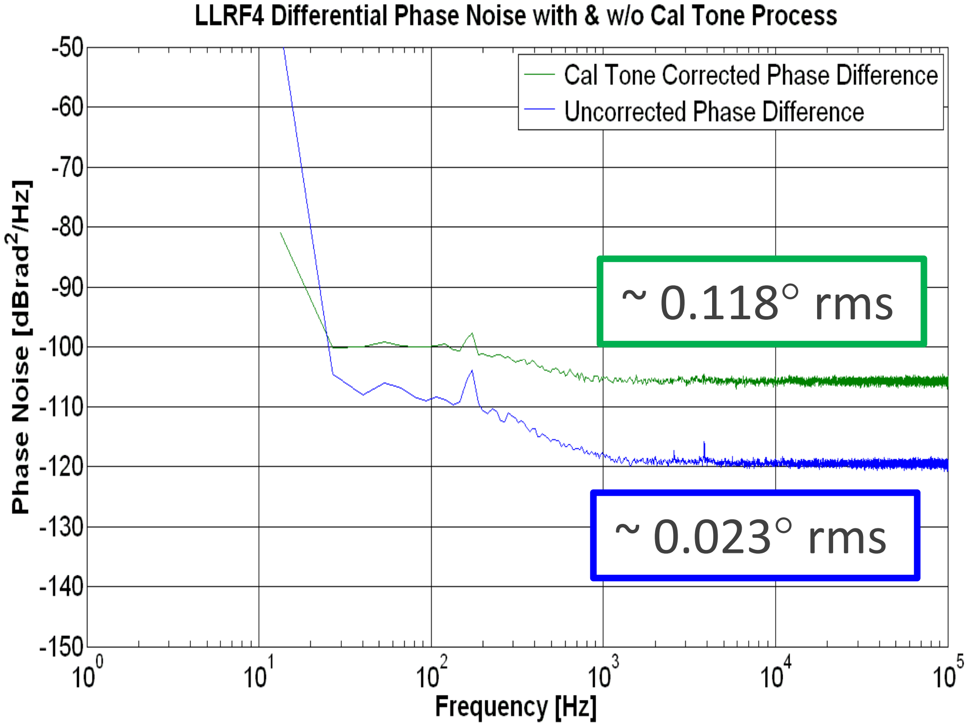
Receiver - CW Drift Compensation Demonstration



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

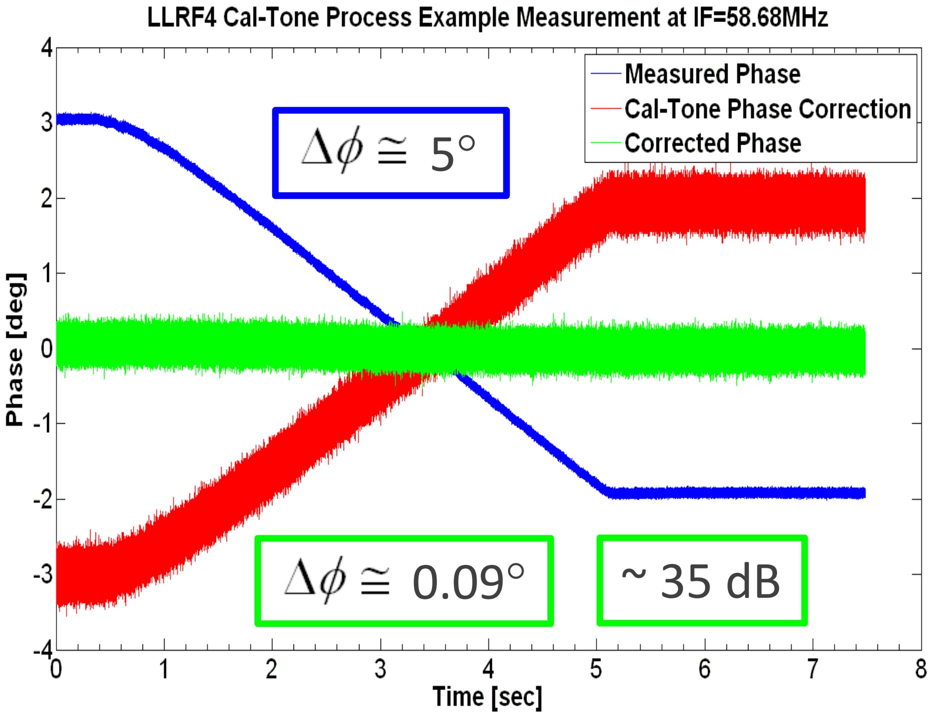
$$\Delta\phi_{calTone} = \Delta\phi_{drift}$$

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


LLRF4 Differential Phase Noise with & w/o Cal Tone Process

~ 0.118° rms

~ 0.023° rms

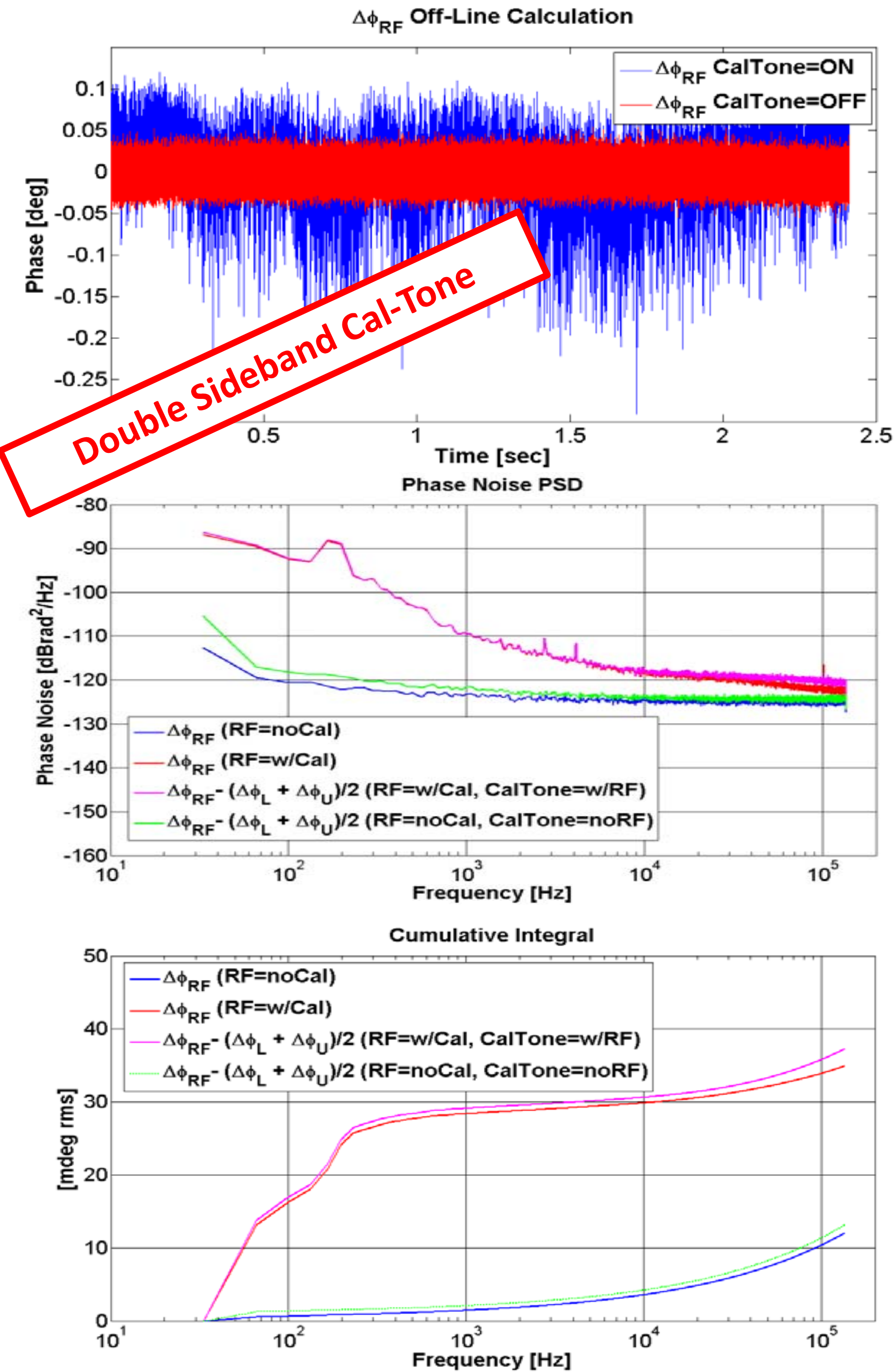

LLRF4 Cal-Tone Process Example Measurement at IF=58.68MHz

$\Delta\phi \cong 5°$

$\Delta\phi \cong 0.09°$

~ 35 dB

Receiver - Intermodulation Distortion

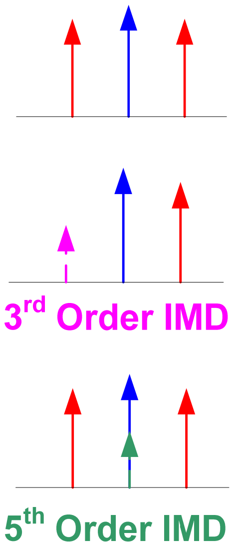


Double Sideband Cal-Tone

$\Delta\phi_{RF}$ Off-Line Calculation

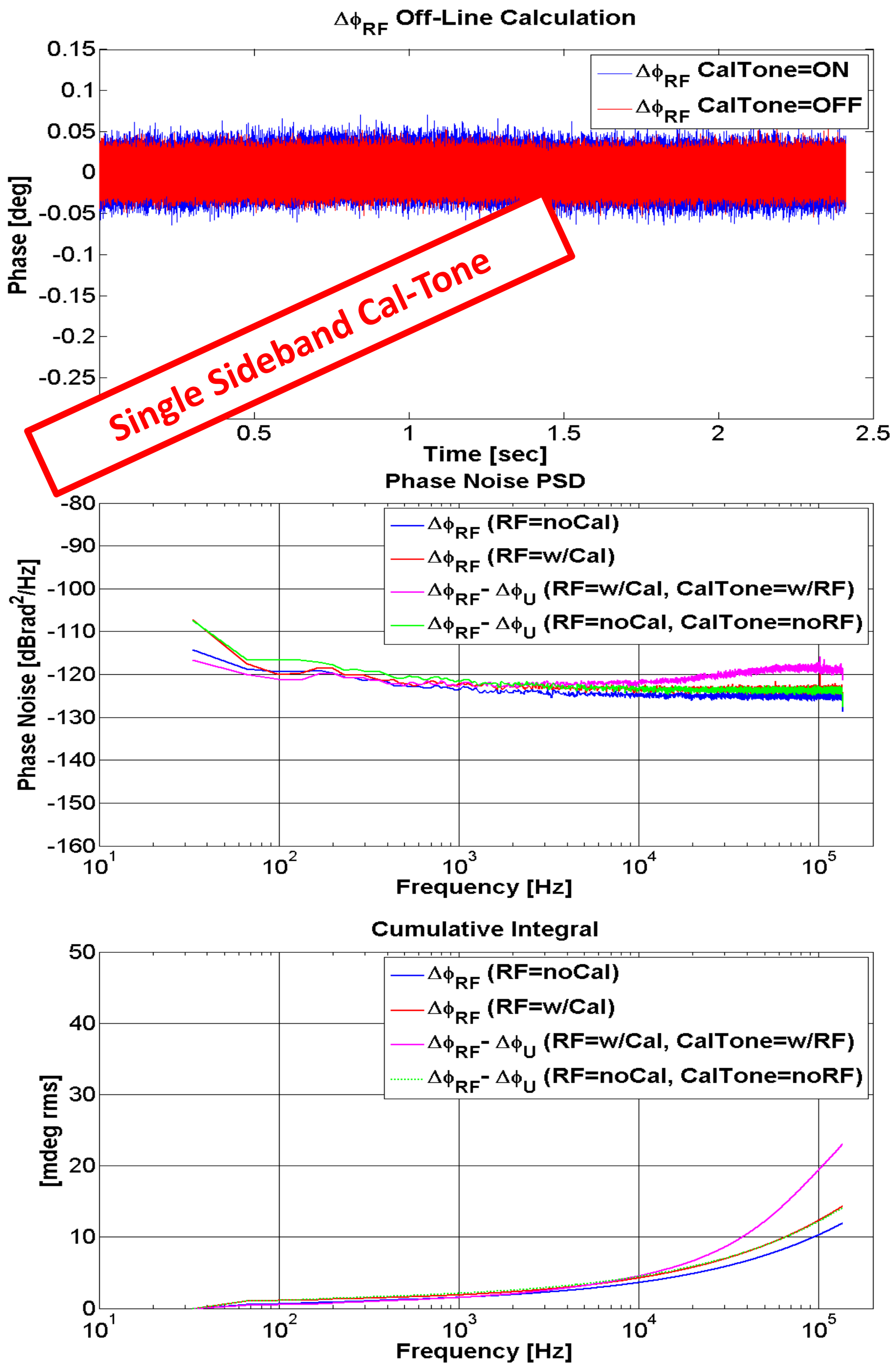
Phase Noise PSD

Cumulative Integral



3rd Order IMD

5th Order IMD



Single Sideband Cal-Tone

$\Delta\phi_{RF}$ Off-Line Calculation

Phase Noise PSD

Cumulative Integral

Receiver - Intermodulation Distortion

For simplicity assume a Taylor series approximation (in general should use Volterra series)

$$v_o \cong a_o + a_1 v_i + a_2 v_i^{\,2} + a_3 v_i^{\,3}$$

For a 3-tone input signal:

ω_o : RF carrier

ω_{LSB} : Lower side-band cal-tone

ω_{USB} : Upper side-band cal-tone

$$\Delta \equiv \omega_o - \omega_{LSB} = \omega_{USB} - \omega_o$$

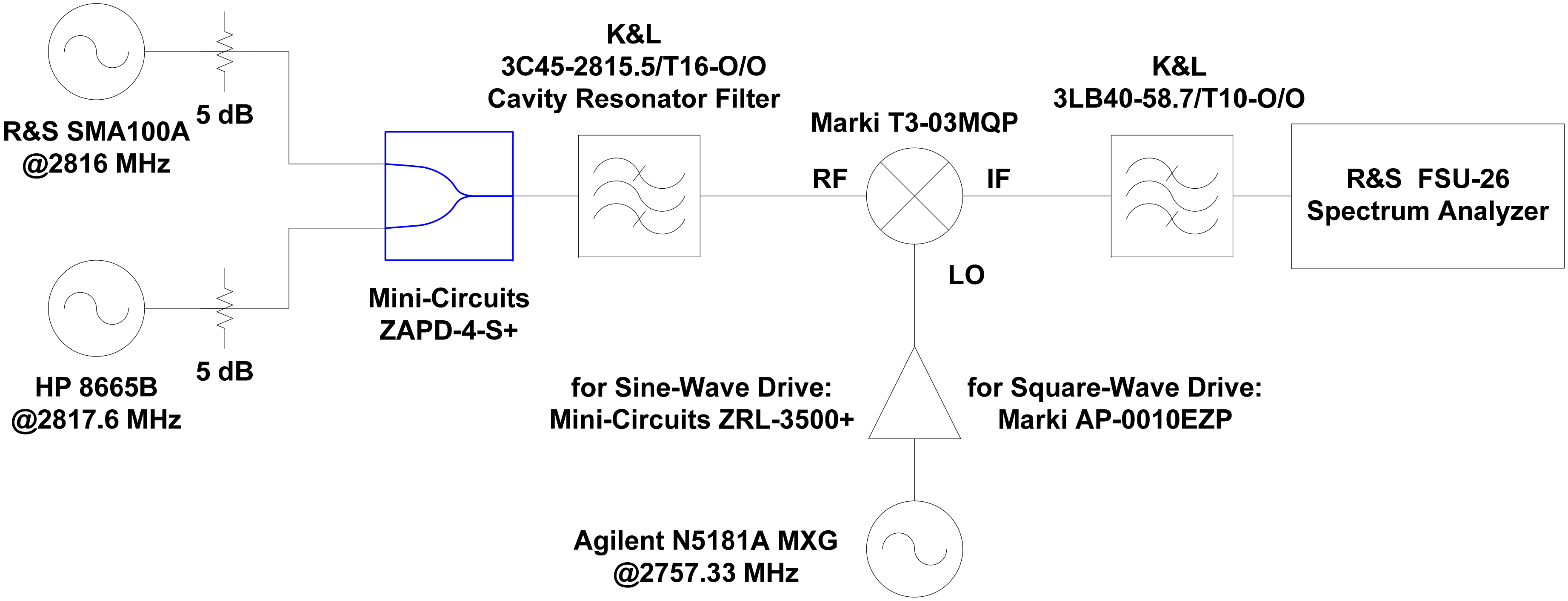
$$v_o \cong \left\{ a_1 V_{LSB} + a_3 \left[\frac{1}{2} V_{LSB} \left(V_{LSB}^{\,2} + V_o^{\,2} + V_{USB}^{\,2} \right) + \frac{1}{4} V_{LSB}^{\,3} + \frac{3}{4} V_{USB} V_o^{\,2} + V_{LSB} V_o^{\,2} + V_{LSB} V_{USB}^{\,2} \right] \right\} \cos \omega_{LSB} t$$

$$+ \quad \left\{ a_1 V_o + a_3 \left[\frac{1}{2} V_o \left(V_{LSB}^{\,2} + V_o^{\,2} + V_{USB}^{\,2} \right) + \frac{1}{4} V_o^{\,3} + \frac{3}{2} V_{LSB} V_o V_{USB} + V_o V_{LSB}^{\,2} + V_o V_{USB}^{\,2} \right] \right\} \cos \omega_o t$$

$$+ \quad \left\{ a_1 V_{USB} + a_3 \left[\frac{1}{2} V_{USB} \left(V_{LSB}^{\,2} + V_o^{\,2} + V_{USB}^{\,2} \right) + \frac{1}{4} V_{USB}^{\,3} + \frac{3}{4} V_{LSB} V_o^{\,2} + V_{USB} V_o^{\,2} + V_{USB} V_{LSB}^{\,2} \right] \right\} \cos \omega_{USB} t$$

Receiver - Intermodulation Distortion

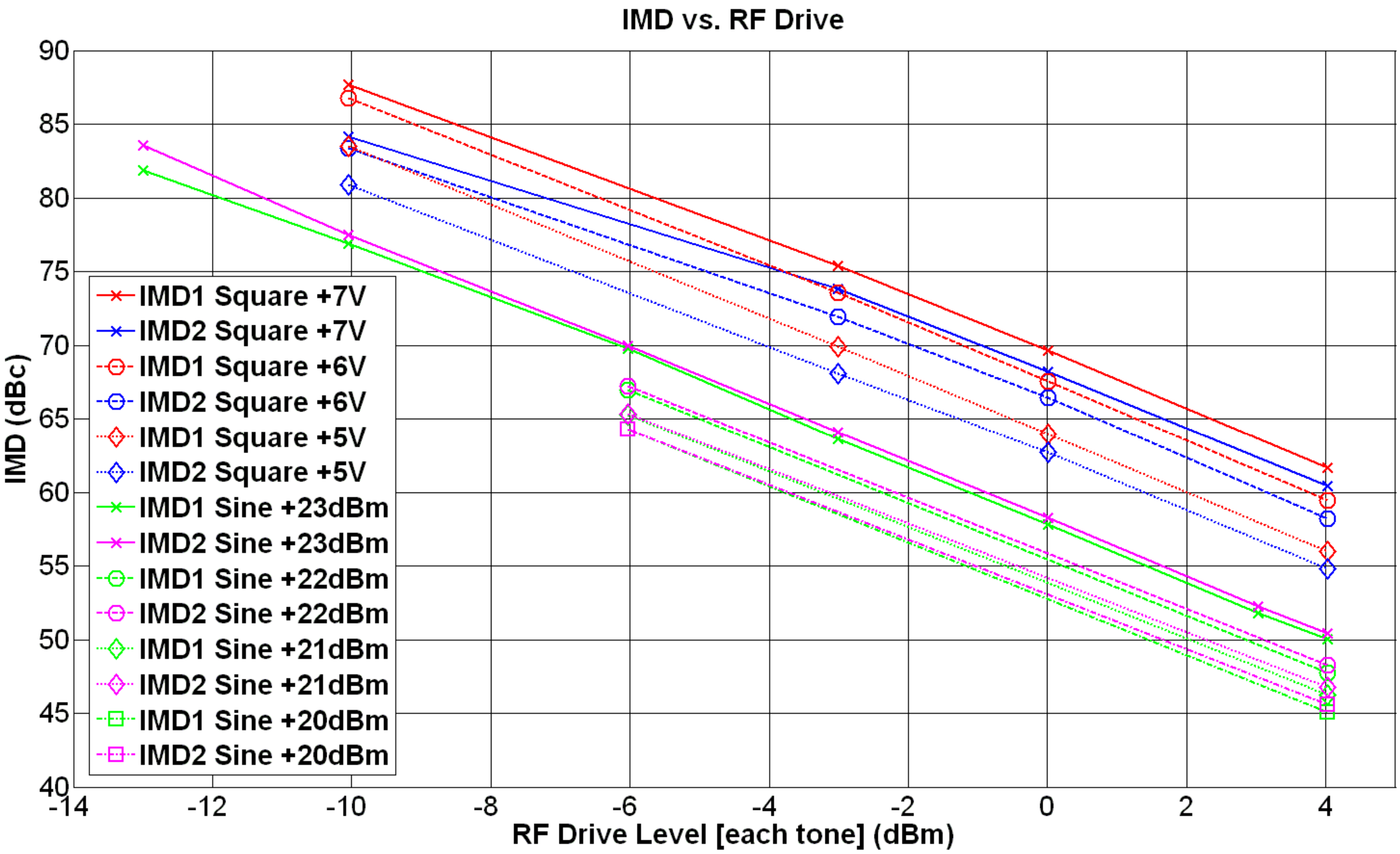
Marki T3-03MQP [5] mixer measurements, Sine vs. Square Drive



[5] "T3 Mixer Primer, A Mixer for the 21st Century", Ferenc Marki, Christopher Marki, http://www.markimicrowave.com/3436/T3_Mixer_Primer.aspx

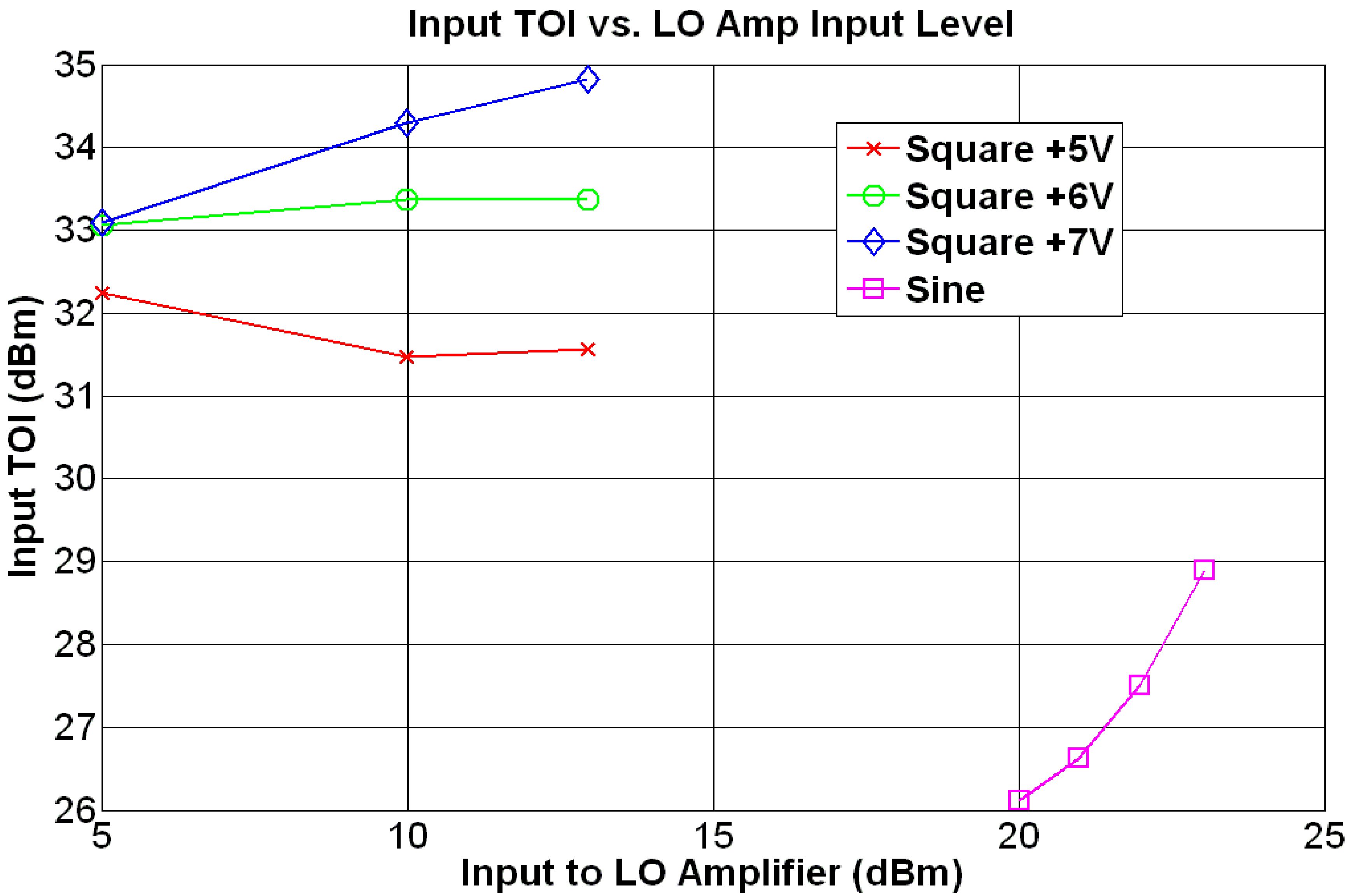
Receiver - Intermodulation Distortion

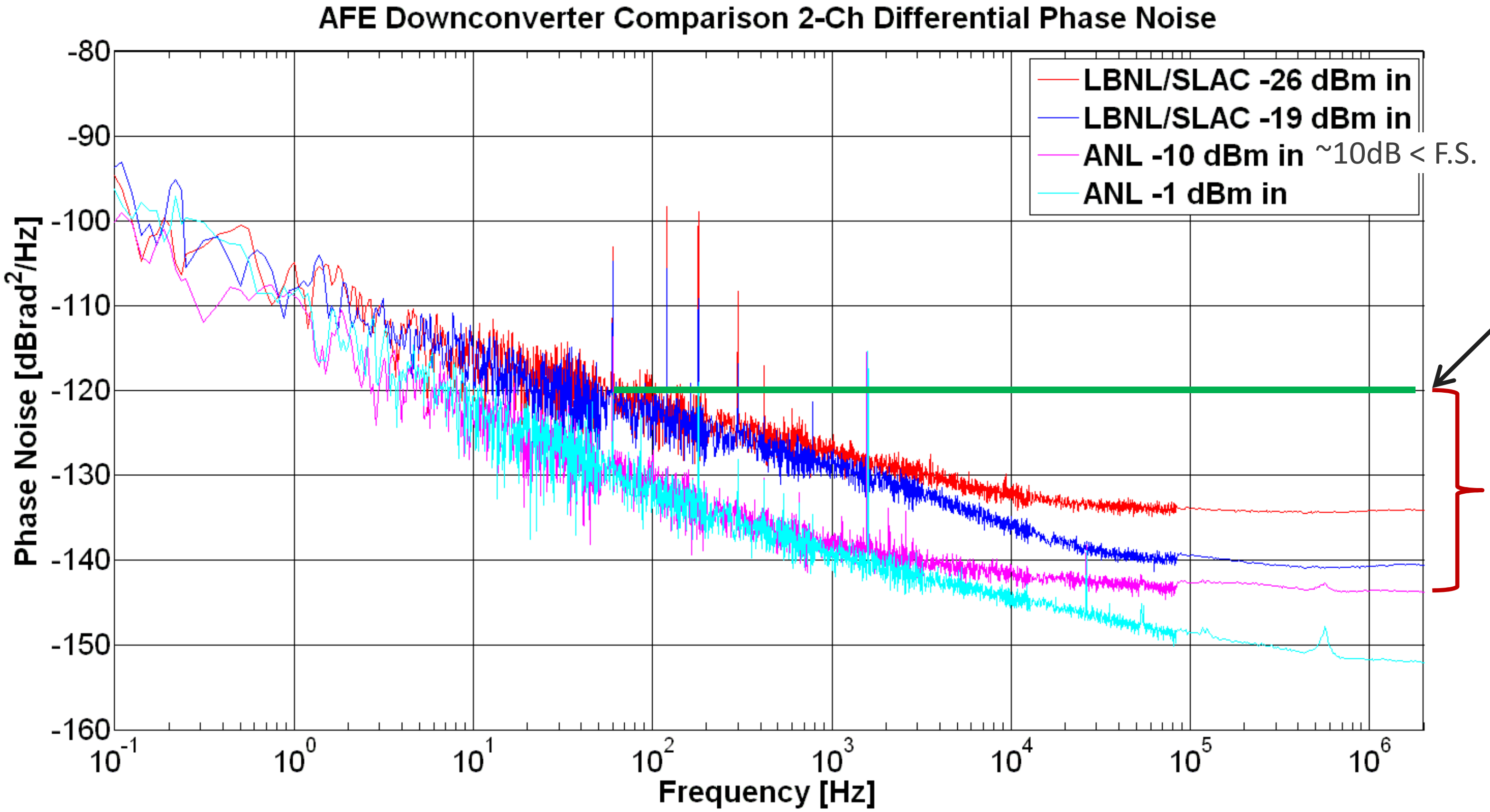
Marki T3-03MQP mixer measurements, Sine vs. Square Drive



Receiver - Intermodulation Distortion

Marki T3-03MQP mixer measurements, Sine vs. Square Drive

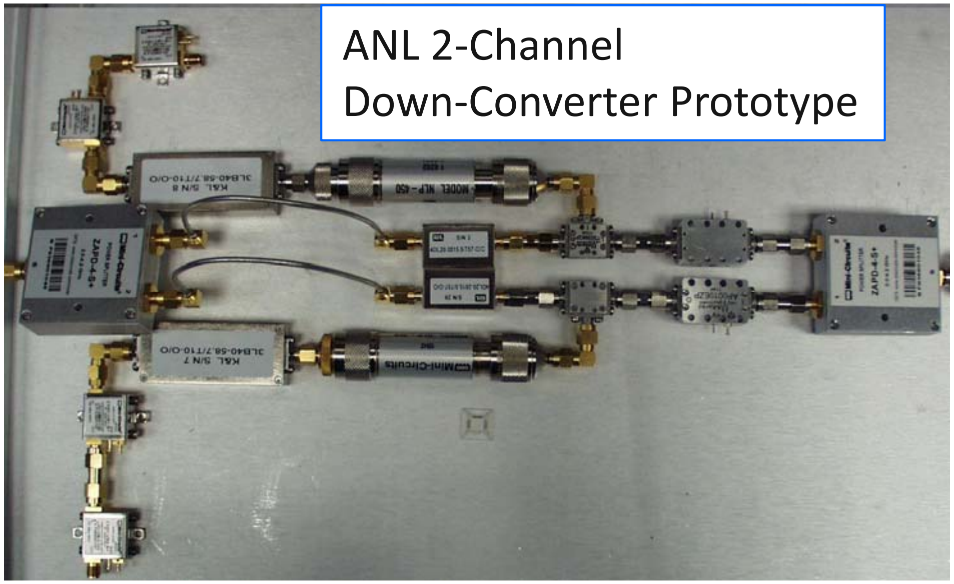




~10dB < F.S.

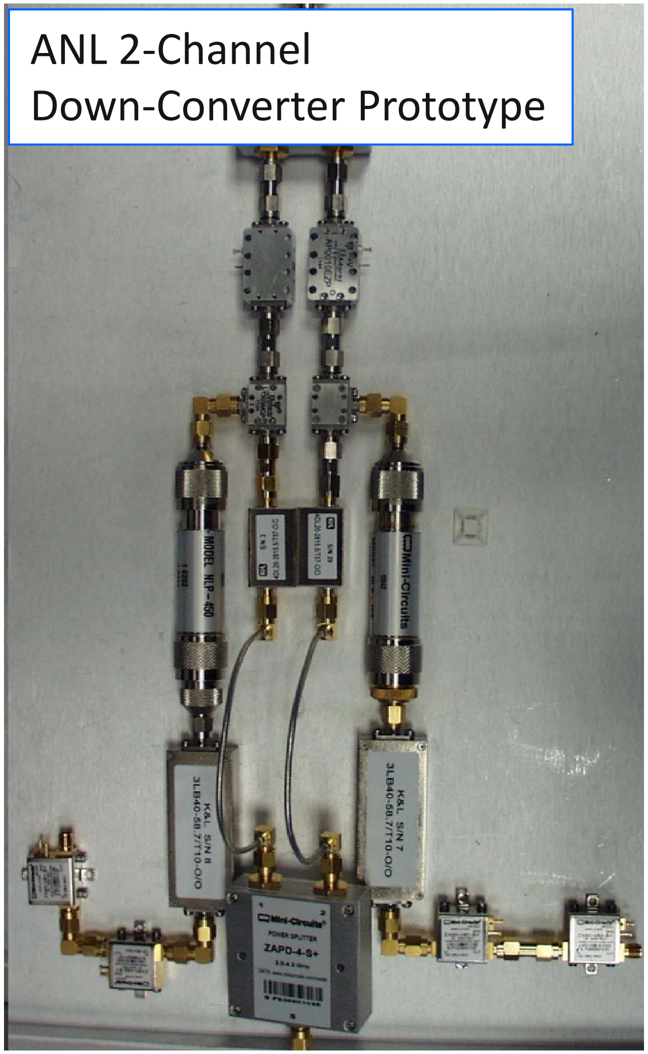
Estimated -120dBrad^2/Hz at -40dBm input (~10dB < F.S.)

> 20dB improvement



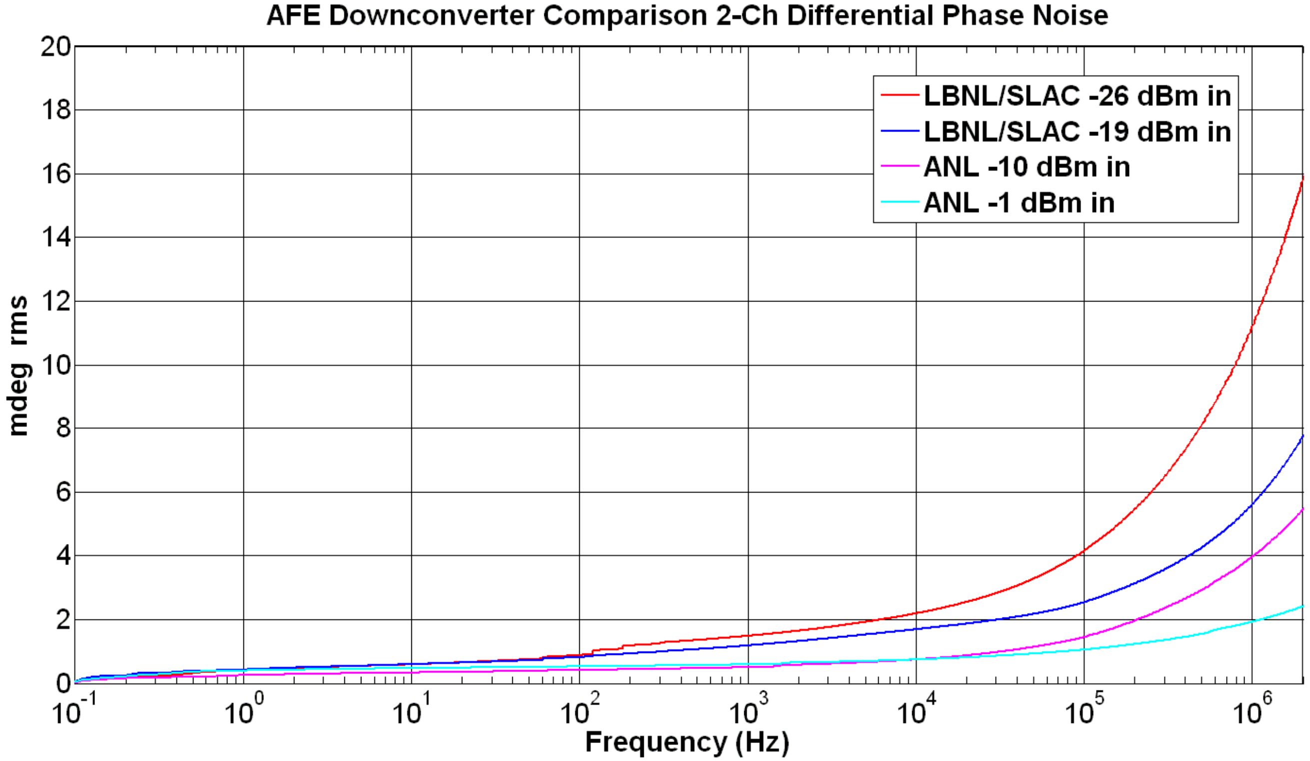
ANL 2-Channel Down-Converter Prototype

LBNL/SLAC AFE Ver.1

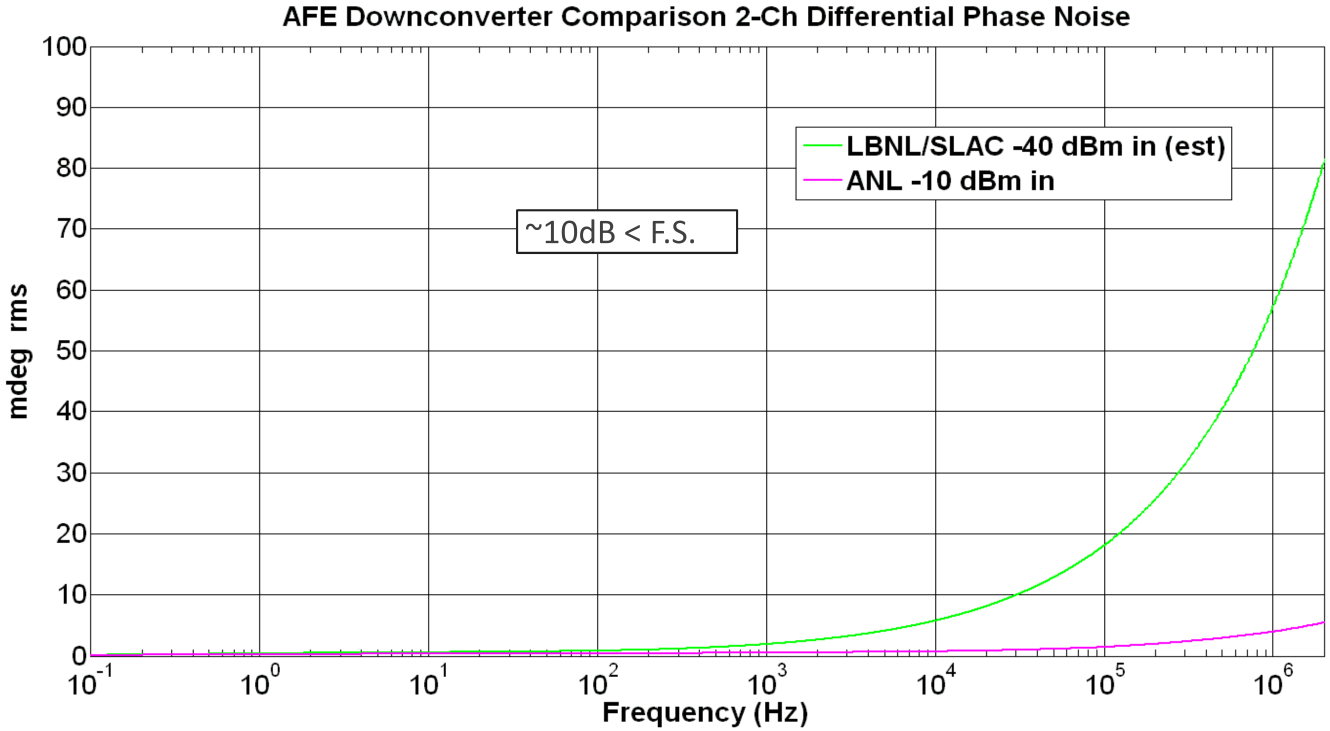


ANL 2-Channel
Down-Converter Prototype

LBNL/SLAC AFE Ver.1

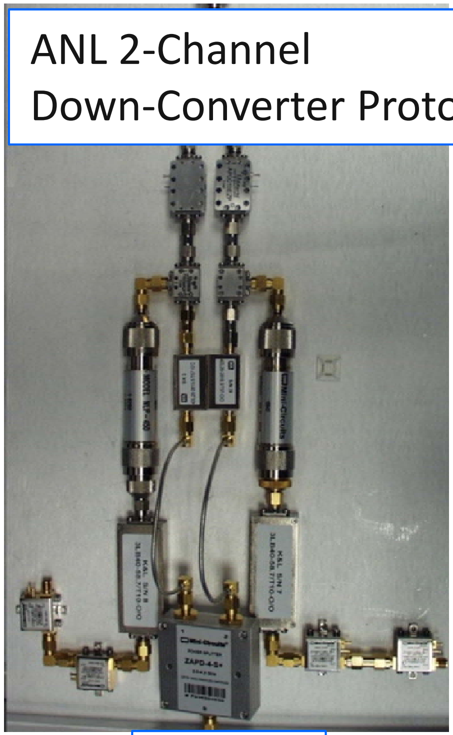


AFE Downconverter Comparison 2-Ch Differential Phase Noise



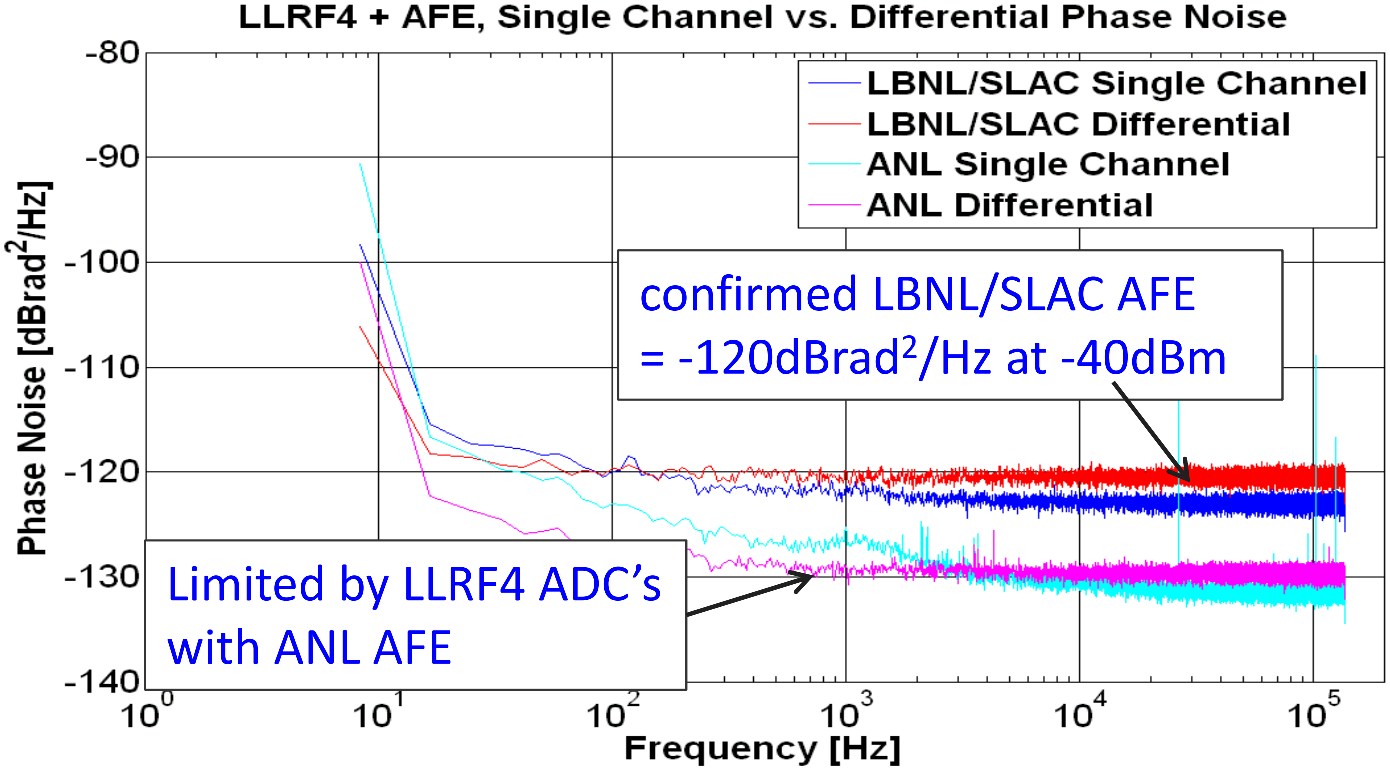
AFE Downconverter Comparison 2-Ch Differential Phase Noise

~10dB < F.S.



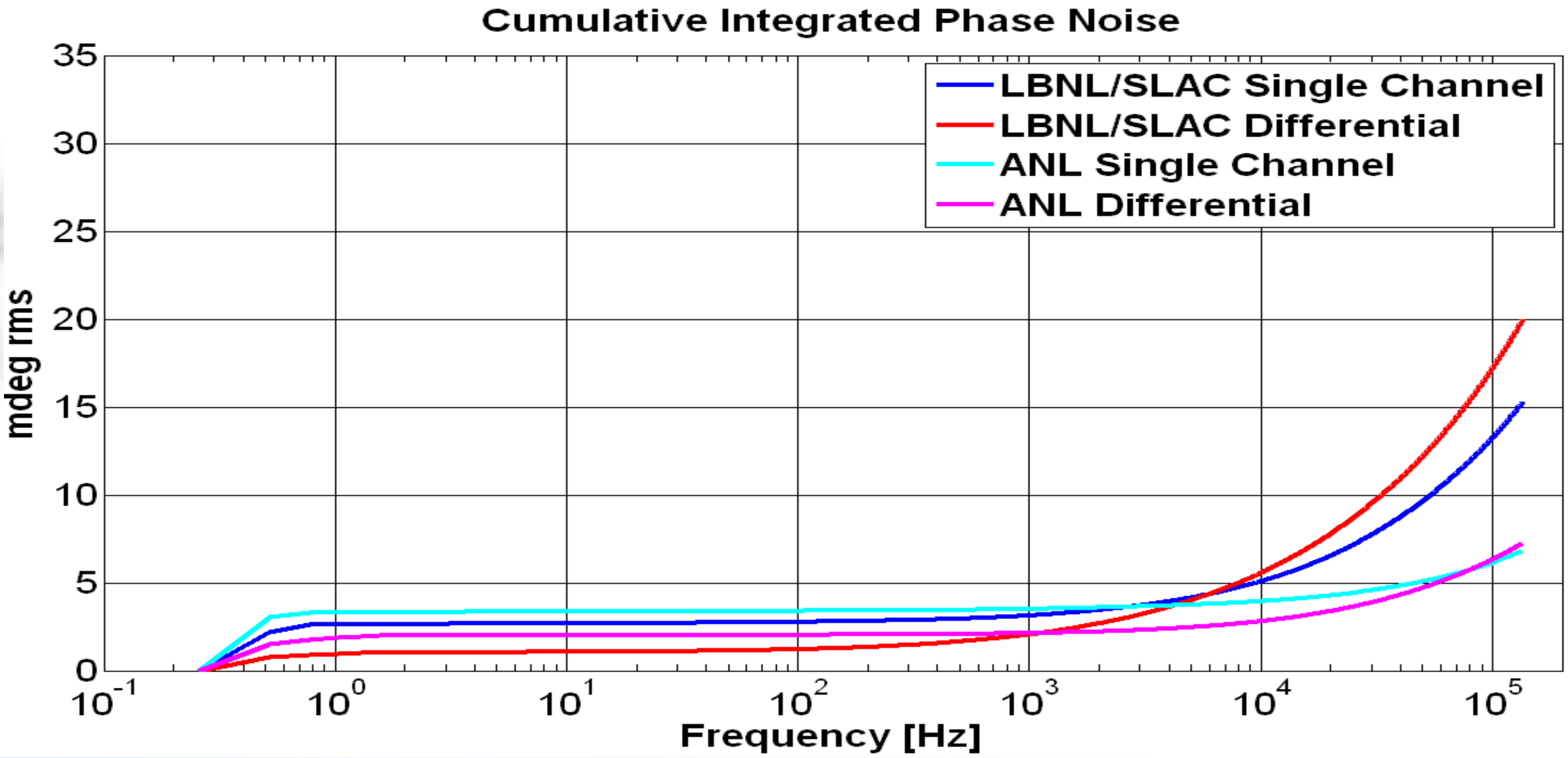
ANL 2-Channel
Down-Converter Prototype

+
LLRF4

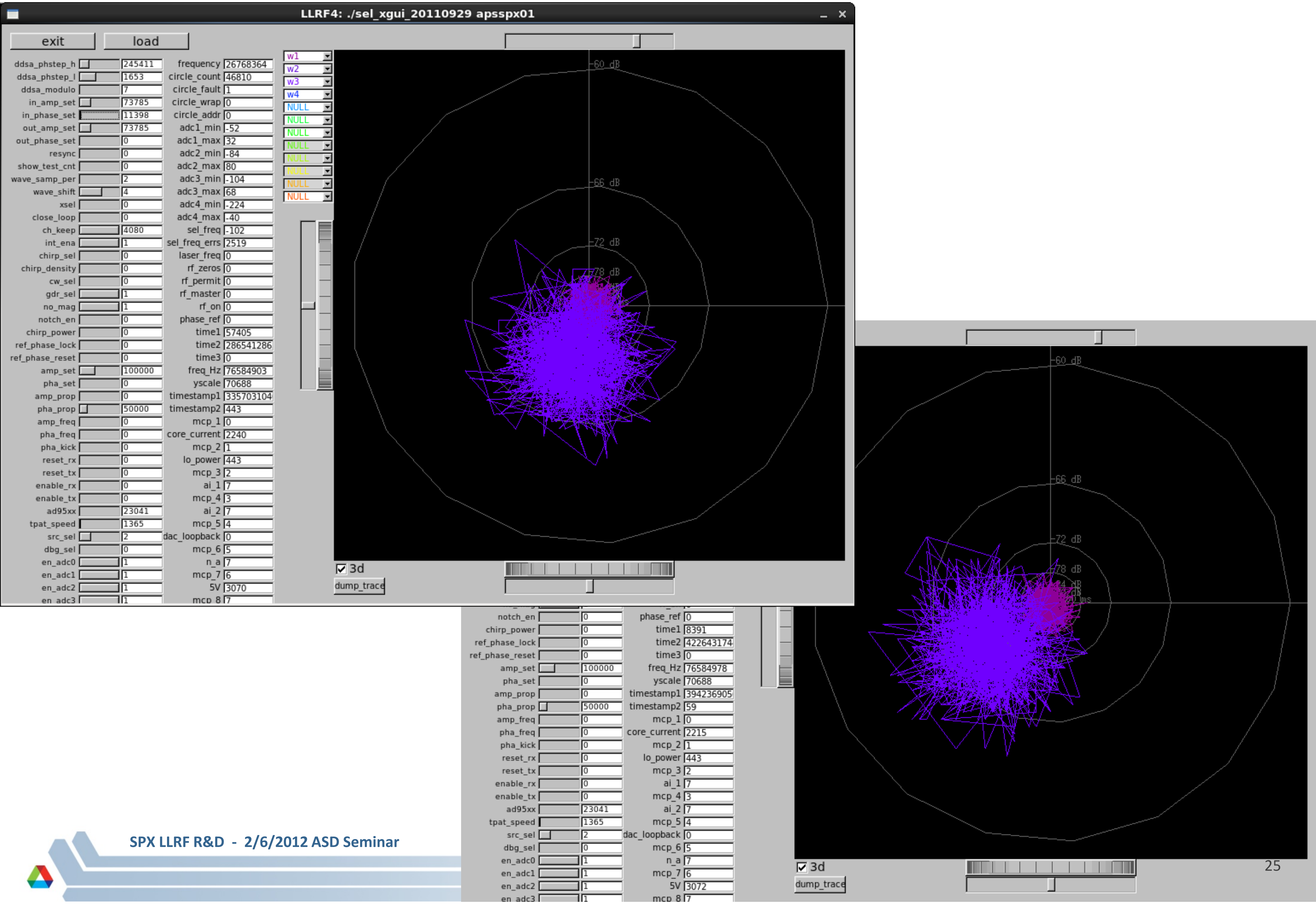


confirmed LBNL/SLAC AFE = -120dBrad^2/Hz at -40dBm

Limited by LLRF4 ADC's with ANL AFE



Receiver - comparison (Susceptibility to Interference)



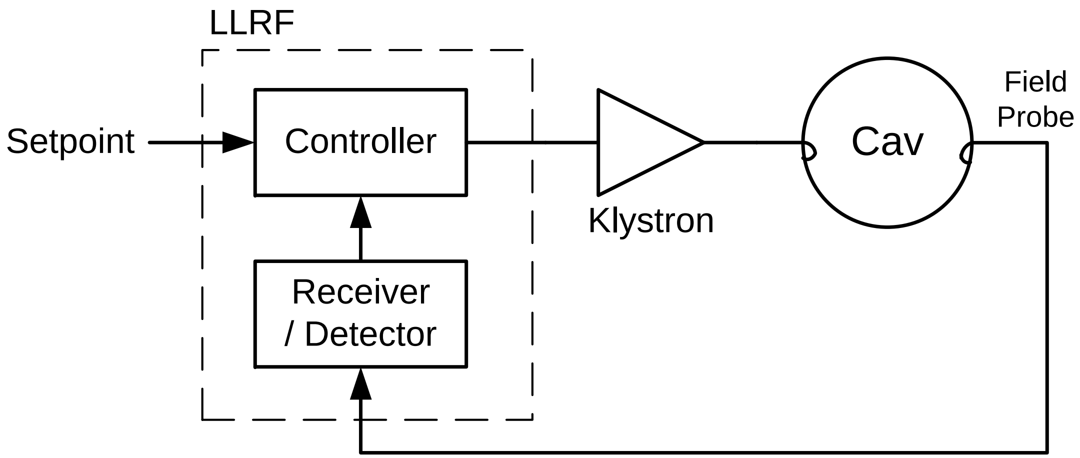
LLRF4: ./sel_xgui_20110929 apsspx01

ddsa_phstep_h	245411	frequency	26768364
ddsa_phstep_l	1653	circle_count	46810
ddsa_modulo	7	circle_fault	1
in_amp_set	73785	circle_wrap	0
in_phase_set	11398	circle_addr	0
out_amp_set	73785	adc1_min	-52
out_phase_set	0	adc1_max	32
resync	0	adc2_min	-84
show_test_cnt	0	adc2_max	80
wave_samp_per	2	adc3_min	-104
wave_shift	4	adc3_max	68
xsel	0	adc4_min	-224
close_loop	0	adc4_max	-40
ch_keep	4080	sel_freq	-102
int_ena	1	sel_freq_errs	2519
chirp_sel	0	laser_freq	0
chirp_density	0	rf_zeros	0
cw_sel	0	rf_permit	0
gdr_sel	1	rf_master	0
no_mag	1	rf_on	0
notch_en	0	phase_ref	0
chirp_power	0	time1	57405
ref_phase_lock	0	time2	286541286
ref_phase_reset	0	time3	0
amp_set	100000	freq_Hz	76584903
pha_set	0	yscale	70688
amp_prop	0	timestamp1	335703104
pha_prop	50000	timestamp2	443
amp_freq	0	mcp_1	0
pha_freq	0	core_current	2240
pha_kick	0	mcp_2	1
reset_rx	0	lo_power	443
reset_tx	0	mcp_3	2
enable_rx	0	ai_1	7
enable_tx	0	mcp_4	3
ad95xx	23041	ai_2	7
tpat_speed	1365	mcp_5	4
src_sel	2	dac_loopback	0
dbg_sel	0	mcp_6	5
en_adc0	1	n_a	7
en_adc1	1	mcp_7	6
en_adc2	1	5V	3070
en_adc3	1	mcp_8	7

notch_en	0	phase_ref	0
chirp_power	0	time1	8391
ref_phase_lock	0	time2	422643174
ref_phase_reset	0	time3	0
amp_set	100000	freq_Hz	76584978
pha_set	0	yscale	70688
amp_prop	0	timestamp1	394236905
pha_prop	50000	timestamp2	59
amp_freq	0	mcp_1	0
pha_freq	0	core_current	2215
pha_kick	0	mcp_2	1
reset_rx	0	lo_power	443
reset_tx	0	mcp_3	2
enable_rx	0	ai_1	7
enable_tx	0	mcp_4	3
ad95xx	23041	ai_2	7
tpat_speed	1365	mcp_5	4
src_sel	2	dac_loopback	0
dbg_sel	0	mcp_6	5
en_adc0	1	n_a	7
en_adc1	1	mcp_7	6
en_adc2	1	5V	3072
en_adc3	1	mcp_8	7

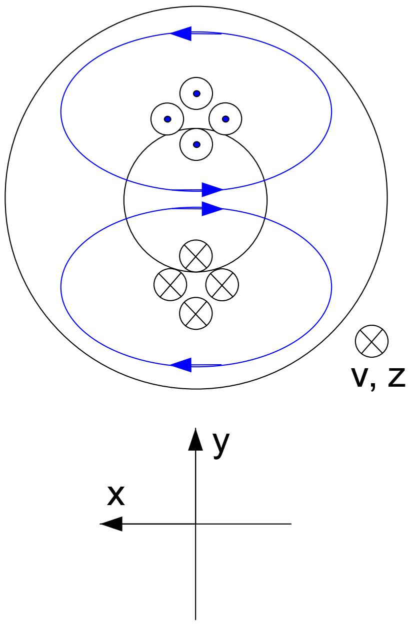
Low Level Radio Frequency (LLRF) System

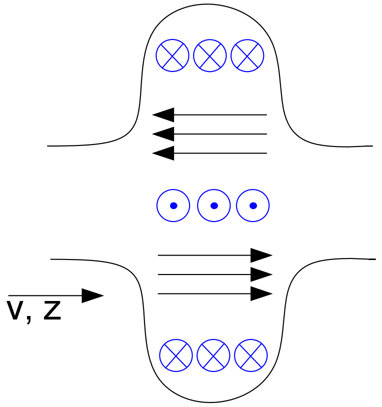
Primary responsibility is to regulate the cavity field

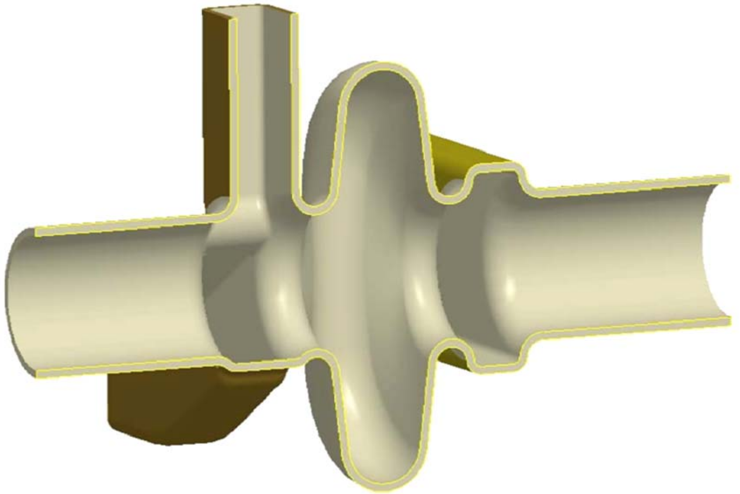


Get to know the plant you are controlling – the cavity (**deflecting not accelerating**) ….

Deflecting Cavity - Beam Loading





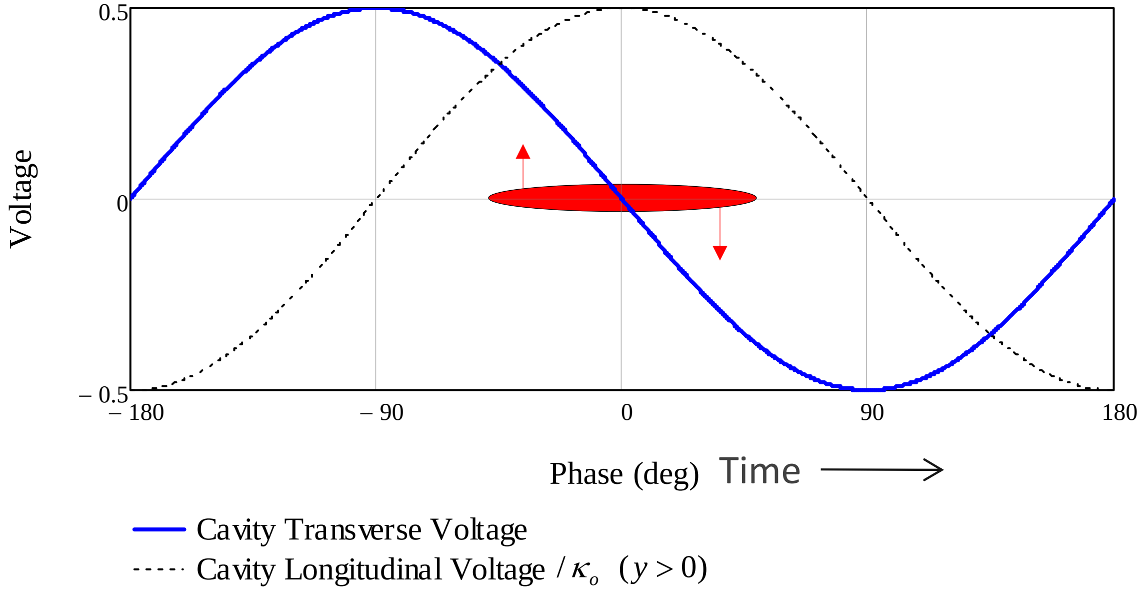


Magnetic Field

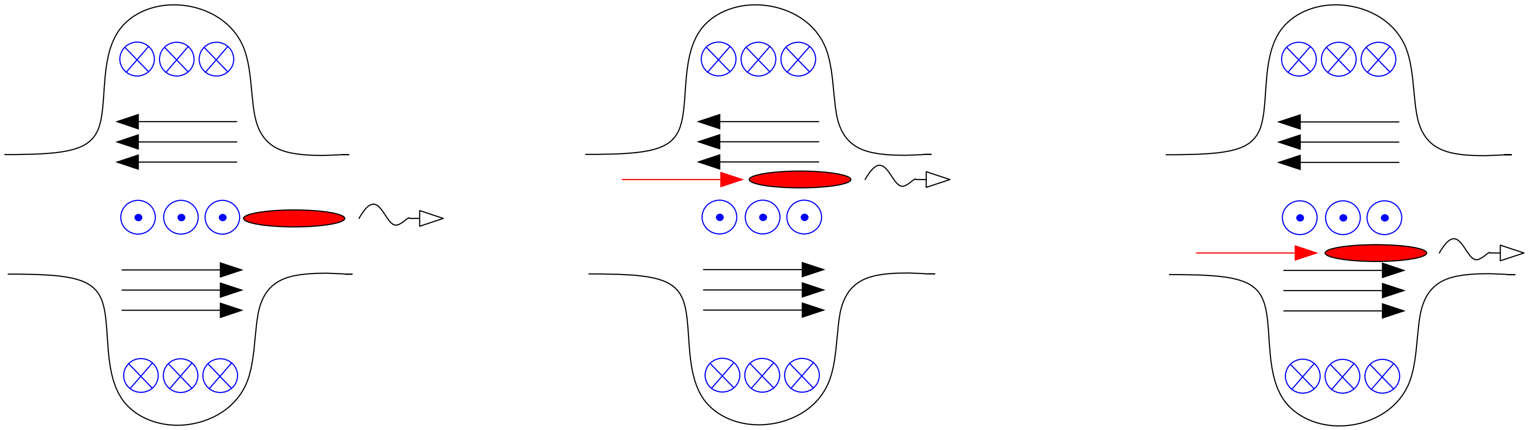
Electric Field

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

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

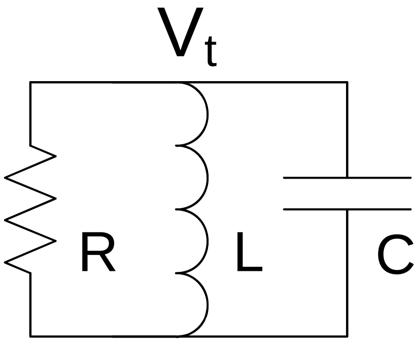


Deflecting Cavity - Beam Loading



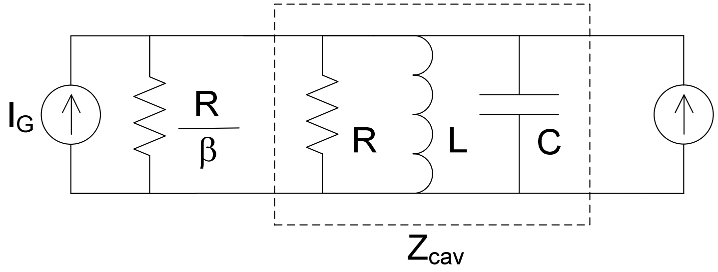
Dipole loss factor: $k_\perp \equiv \frac{U_{loss}}{q^2} = \frac{|V_Z(y)|^2}{4U} = \frac{\omega_r}{2}\left(\frac{R}{Q}\right)'(\kappa_o y)^2$

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

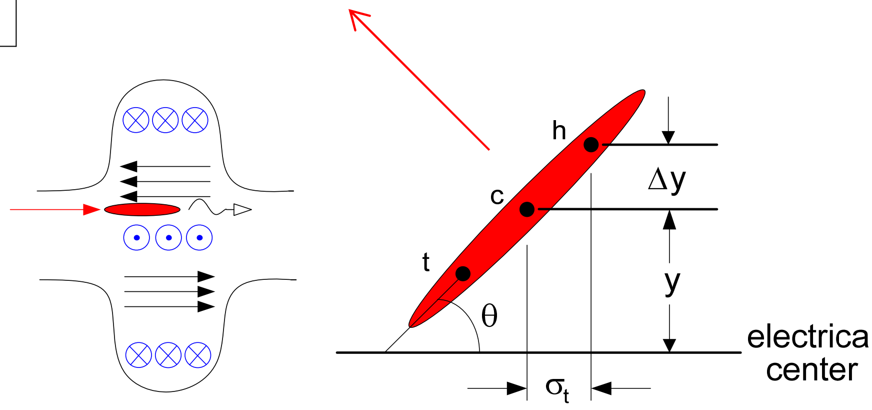


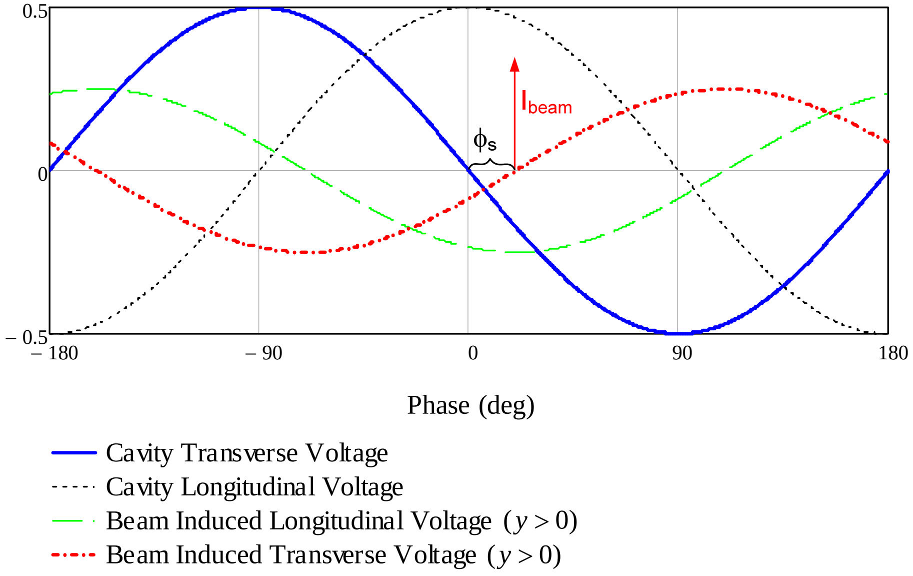
$$U_{loss} = q^2 k_\perp = \frac{1}{2} C V_t^2 \qquad \Rightarrow V_t^2 = \left(\frac{q\cdot\kappa_o y}{C}\right)^2 \qquad \Rightarrow q_{eq} = |q\cdot\kappa_o y|$$

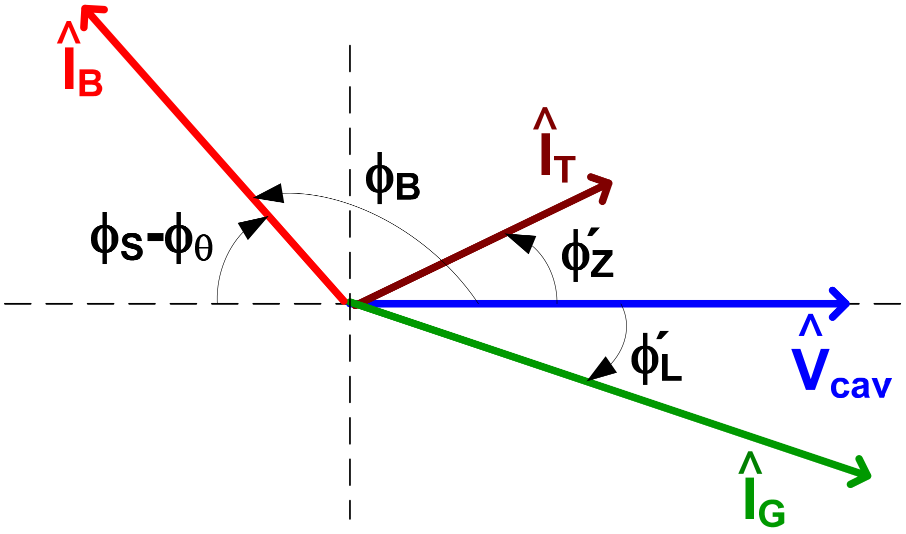
Deflecting Cavity - Beam Loading[5,6]



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





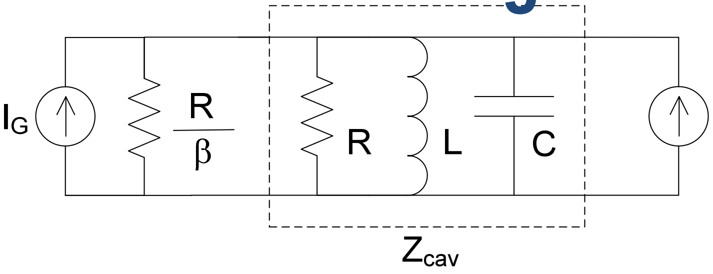


---

[5] Berenc, "An Equivalent Circuit Model ..", ICMS# APS_1405978

[6] Decker, "..Tilt Monitor", DIAG-TN-2010-10, ICMS# APS_1417048

Deflecting Cavity - Beam Loading

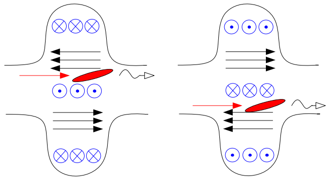


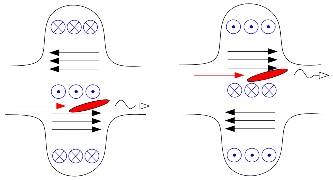
$$i_o\kappa_o\left(y + j\cdot\theta\omega_o c\sigma_t^2\right)\cdot e^{-j(\pi+\phi_s)}$$

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

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

$$P_B = -\frac{1}{2}V_t\left|\hat{I}_B\right|\cos\phi_B$$

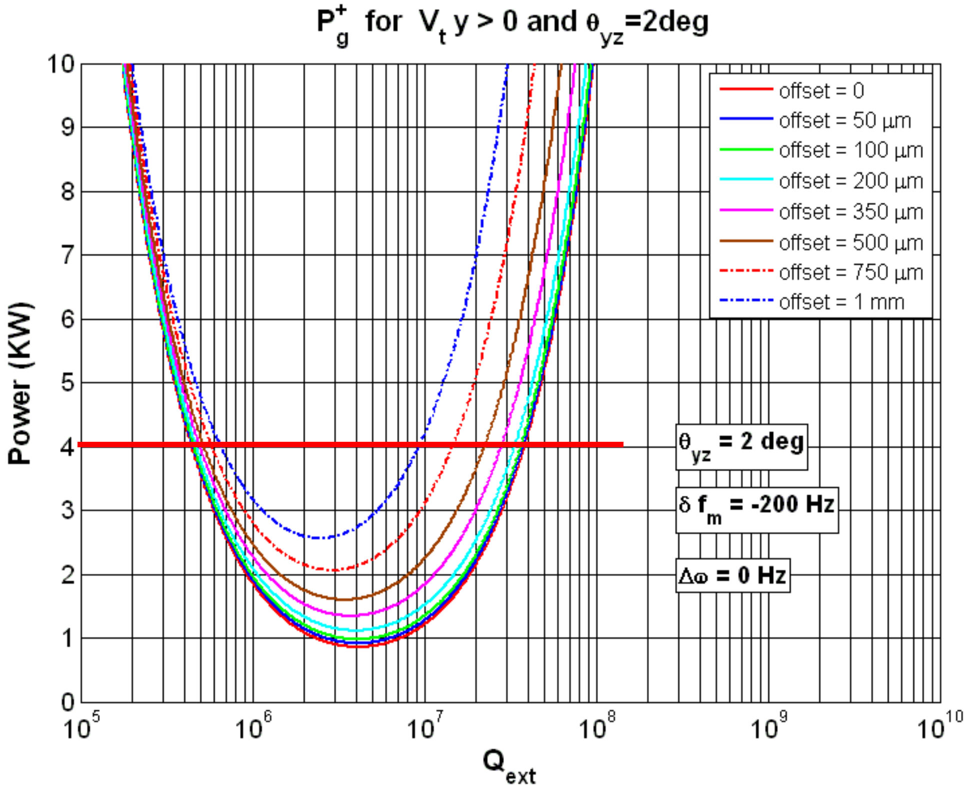


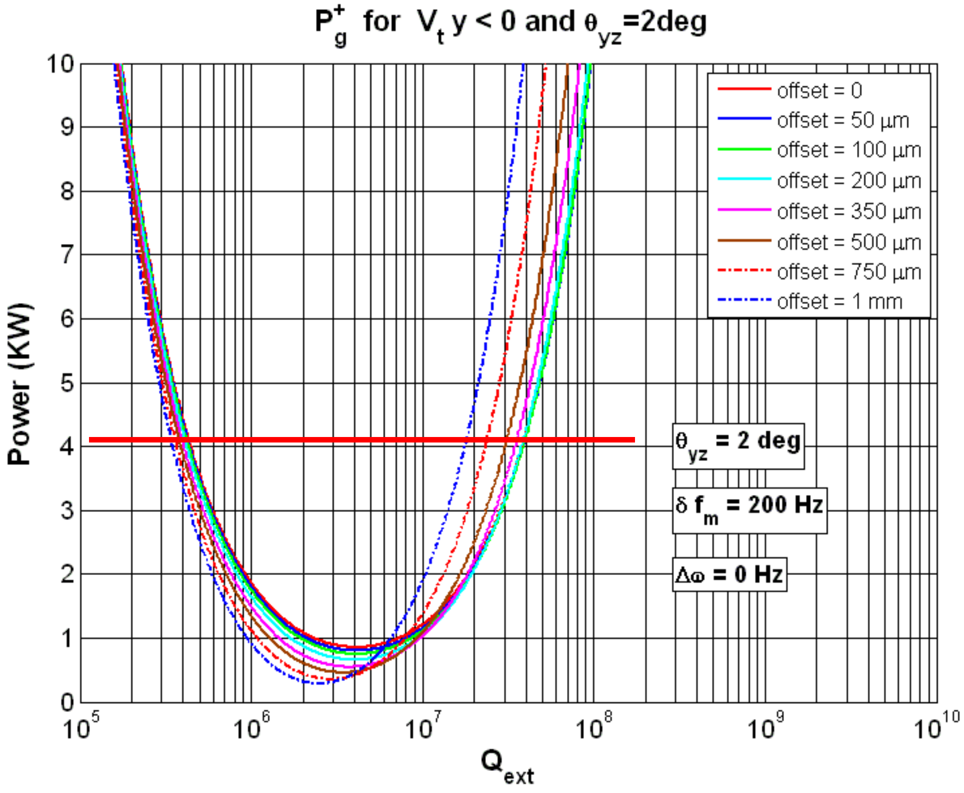


$V_t\cdot y > 0$

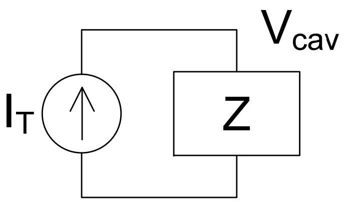
$I_{DC} = 100mA$ $V_{cav} = 0.5MV$

$V_t\cdot y < 0$





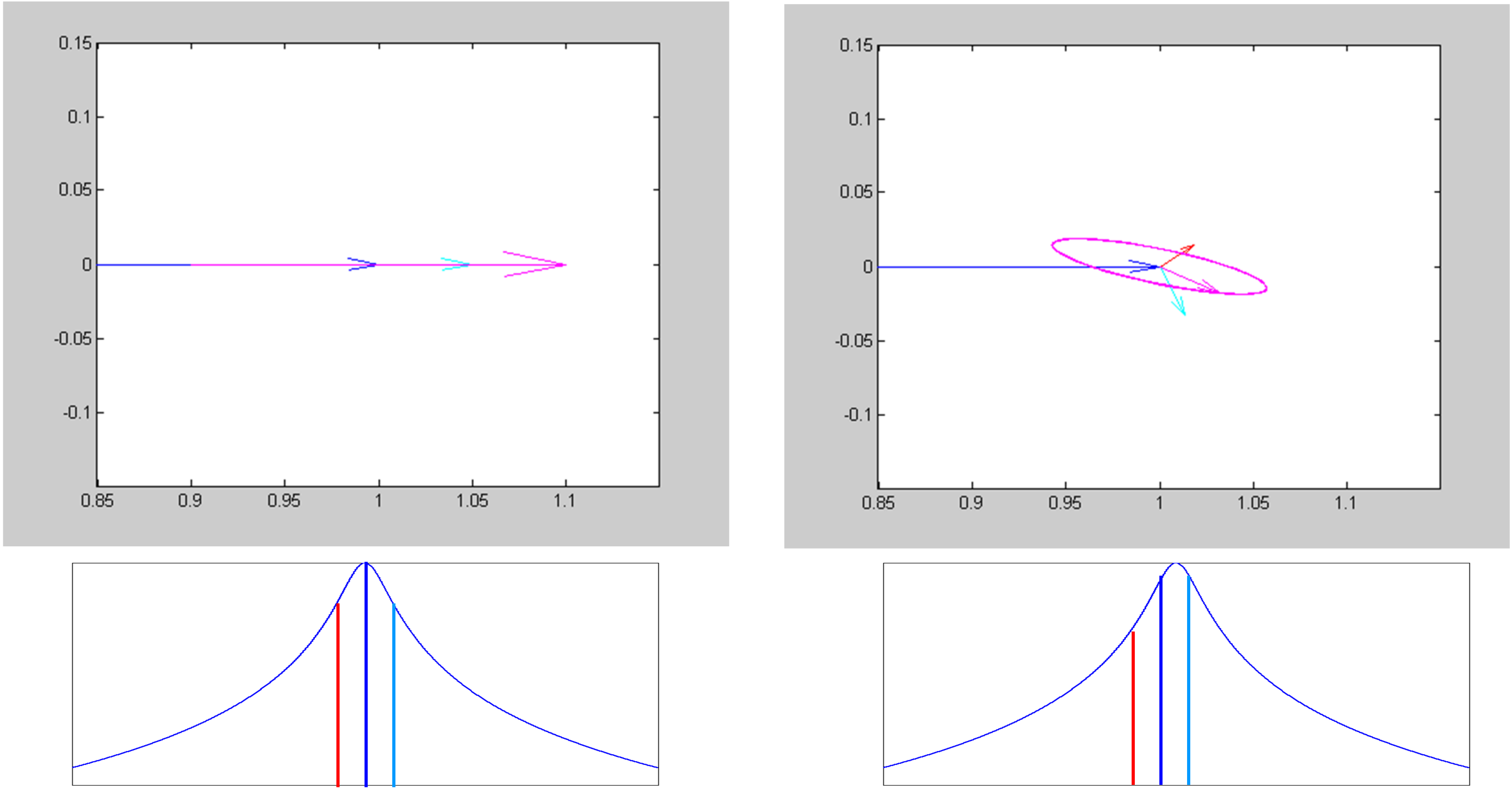
Deflecting Cavity - Dynamic Behavior



$$I_T(t) = I_r \cos\omega_{RF} t + \boxed{i_I(t)\cos\omega_{RF} t - i_Q(t)\sin\omega_{RF} t}$$

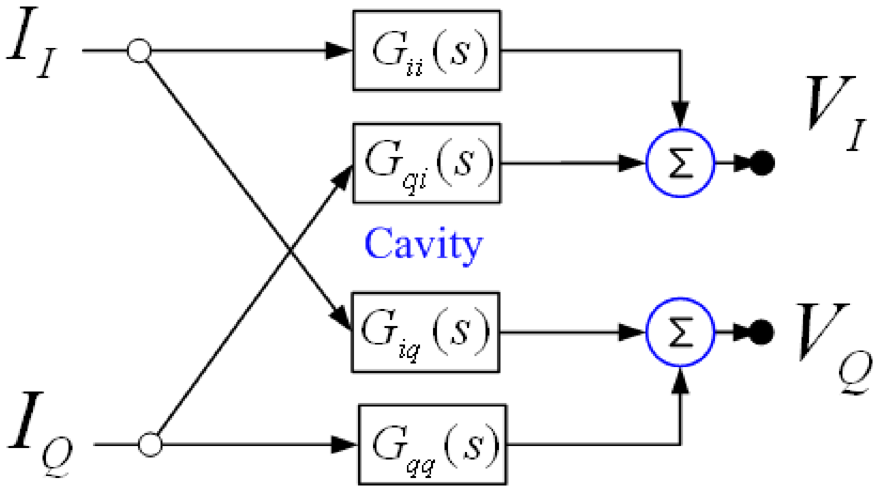
$$V_{cav}(t) = V_r \cos(\omega_{RF} t + \phi_Z) + \boxed{v_I(t)\cos(\omega_{RF} t + \phi_Z) - v_Q(t)\sin(\omega_{RF} t + \phi_Z)}$$

In-general I/Q modulations of I_T each cause both I/Q modulations of V_{cav}



For example: see P. Wilson, SLAC-PUB-2884, p. 26, prob 4.4

Deflecting Cavity - Dynamic Behavior



$$G_{ii}(s) = G_{qq}(s) = \frac{1}{2}\left[\frac{Z(j\omega_{RF}+s)}{\boxed{N}} + \frac{Z^*(j\omega_{RF}-s)}{N^*}\right]$$

$$G_{iq}(s) = -G_{qi}(s) = -\frac{j}{2}\left[\frac{Z(j\omega_{RF}+s)}{N} - \frac{Z^*(j\omega_{RF}-s)}{N^*}\right]$$

Polar Coordinates

$$I_T(t) = I_r \cos\omega_{RF}t \;+\; \alpha_I(t)\, I_r \cos\omega_{RF}t \;-\; \phi_I(t)\, I_r \sin\omega_{RF}t$$

$$\boxed{N_{polar} = \left|Z\left(j\omega_{RF}\right)\right| e^{+j\phi_Z} = Z\left(j\omega_{RF}\right)}$$

$$\boxed{G_{\alpha\alpha}(s) = G_{\phi\phi}(s) = \frac{\sigma\left(s+\sigma(1+\tan^2\phi_Z)\right)}{s^2+2\sigma s+\sigma^2(1+\tan^2\phi_Z)}}$$

$$\boxed{G_{\alpha\phi}(s) = -G_{\phi\alpha}(s) = \frac{-\sigma\tan\phi_Z\, s}{s^2+2\sigma s+\sigma^2(1+\tan^2\phi_Z)}}$$

classical “Pedersen/Boussard Equations”

Cartesian Coordinates

$$I_T(t) = I_r \cos\omega_{RF}t \;+\; i_I(t) \cos\omega_{RF}t \;-\; i_Q(t) \sin\omega_{RF}t$$

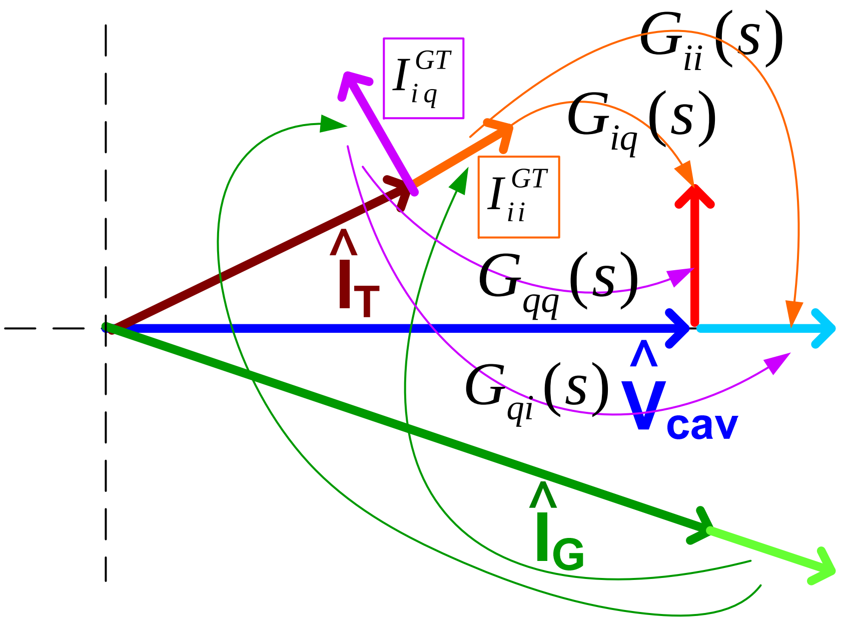
$$\boxed{N_{Cartesian} = e^{+j\phi_Z}}$$

$$\boxed{G_{ii}(s) = G_{qq}(s) = \frac{\sigma R\cos\phi_Z\left(s+\sigma\left(1+\tan^2\phi_Z\right)\right)}{s^2+2\sigma s+\sigma^2(1+\tan^2\phi_Z)}}$$

$$\boxed{G_{iq}(s) = -G_{qi}(s) = \frac{-\sigma R\sin\phi_Z}{s^2+2\sigma s+\sigma^2(1+\tan^2\phi_Z)}}$$

Modern I/Q Equations

Deflecting Cavity - Dynamic Behavior



$$\begin{bmatrix} V^G_I(s) \\ V^G_Q(s) \end{bmatrix} = \begin{bmatrix} G^G_{ii}(s) & G^G_{qi}(s) \\ G^G_{iq}(s) & G^G_{qq}(s) \end{bmatrix} \begin{bmatrix} I^G_I(s) \\ I^G_Q(s) \end{bmatrix}$$

Use vector projection techniques to find the transfer functions from generator current and beam current modulations. Generator Current in-phase modulation is shown here. **Total of 15 transfer functions describe the cavity.**

Polar Coordinates

for discussion “NO DETUNING”

$$\boxed{G^G_{\alpha\phi}(s) = -G^G_{\phi\alpha}(s) \; = 0}$$

$$\boxed{G^G_{\alpha\alpha}(s) = G^G_{\phi\phi}(s) \; = \; (1+Y)\frac{\sigma}{s+\sigma}}$$

Cartesian Coordinates

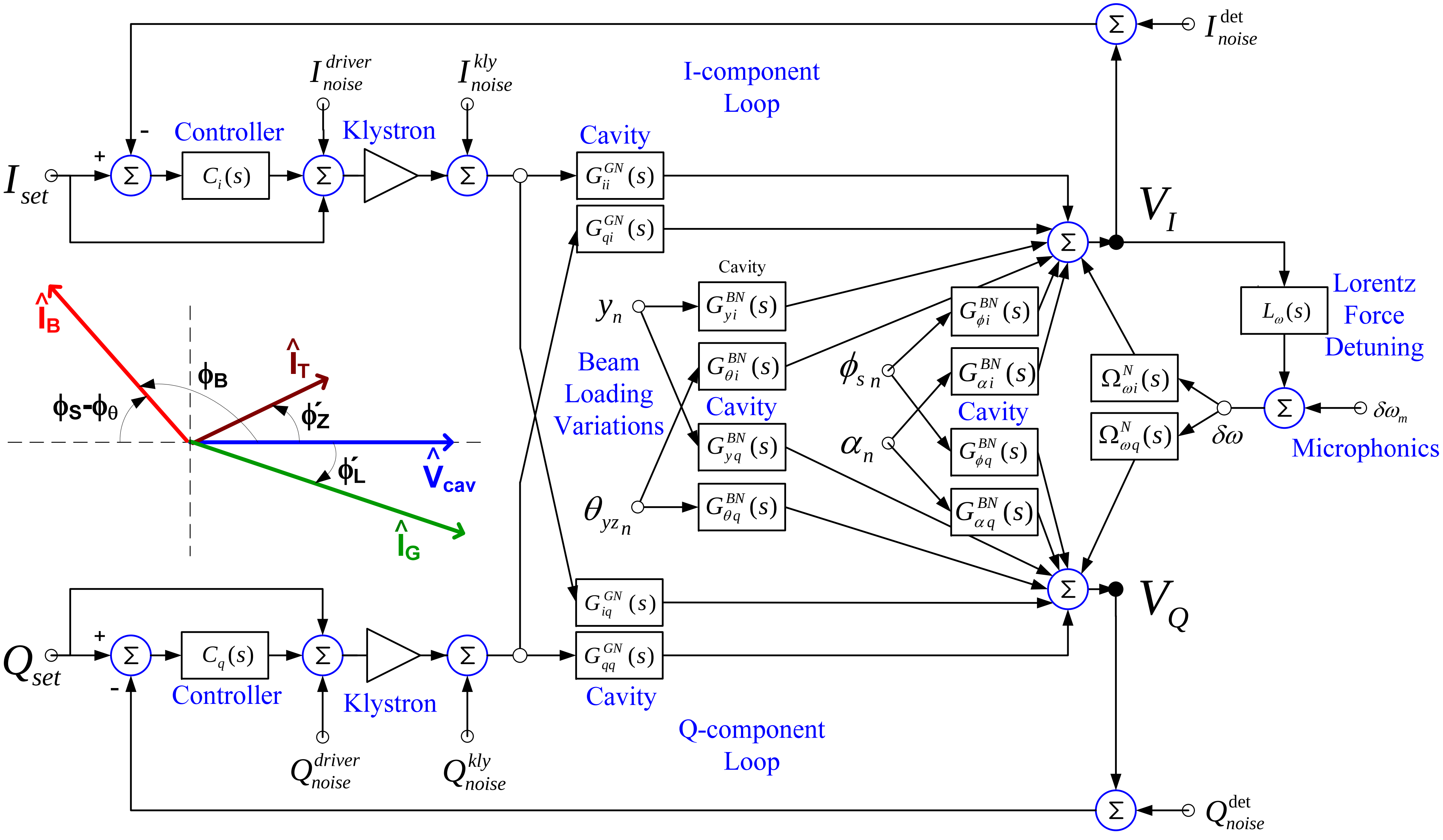
for discussion “NO DETUNING”

$$\boxed{G^G_{iq}(s) = -G^G_{qi}(s) = 0}$$

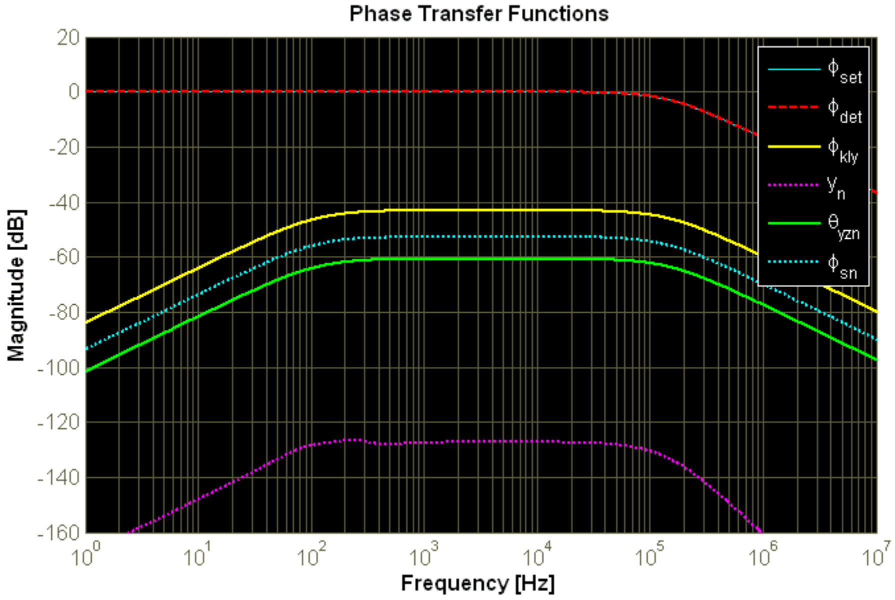
$$\boxed{G^G_{ii}(s) = G^G_{qq}(s) = \frac{\sigma R}{s+\sigma}}$$

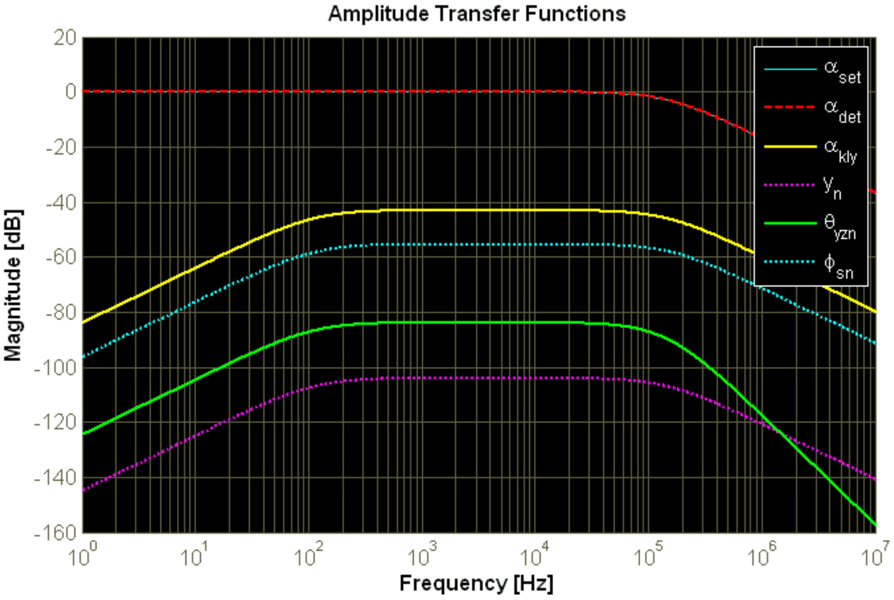
Y = Beam Loading Factor *which can be negative for deflecting cavities. Amp/Phase control can be lost when beam offset drives the cavities to full field (there is no drive carrier). This doesn’t happen for I/Q control.*

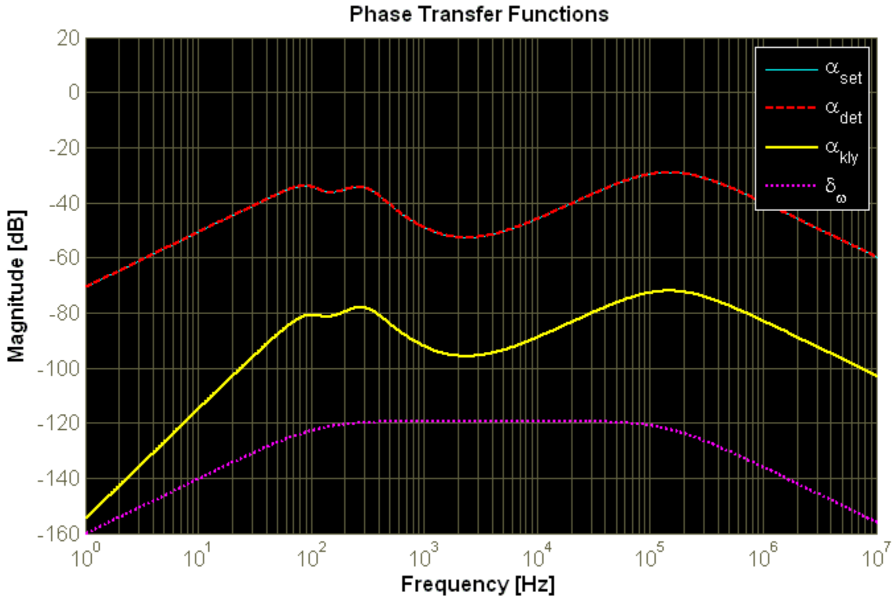
Deflecting Cavity - Dynamic Behavior

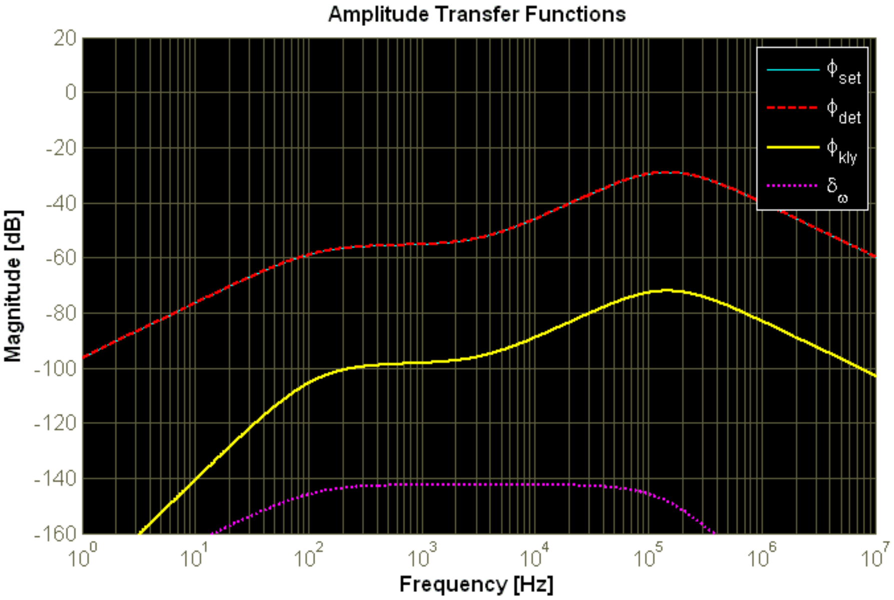


Deflecting Cavity – Dynamic Behavior

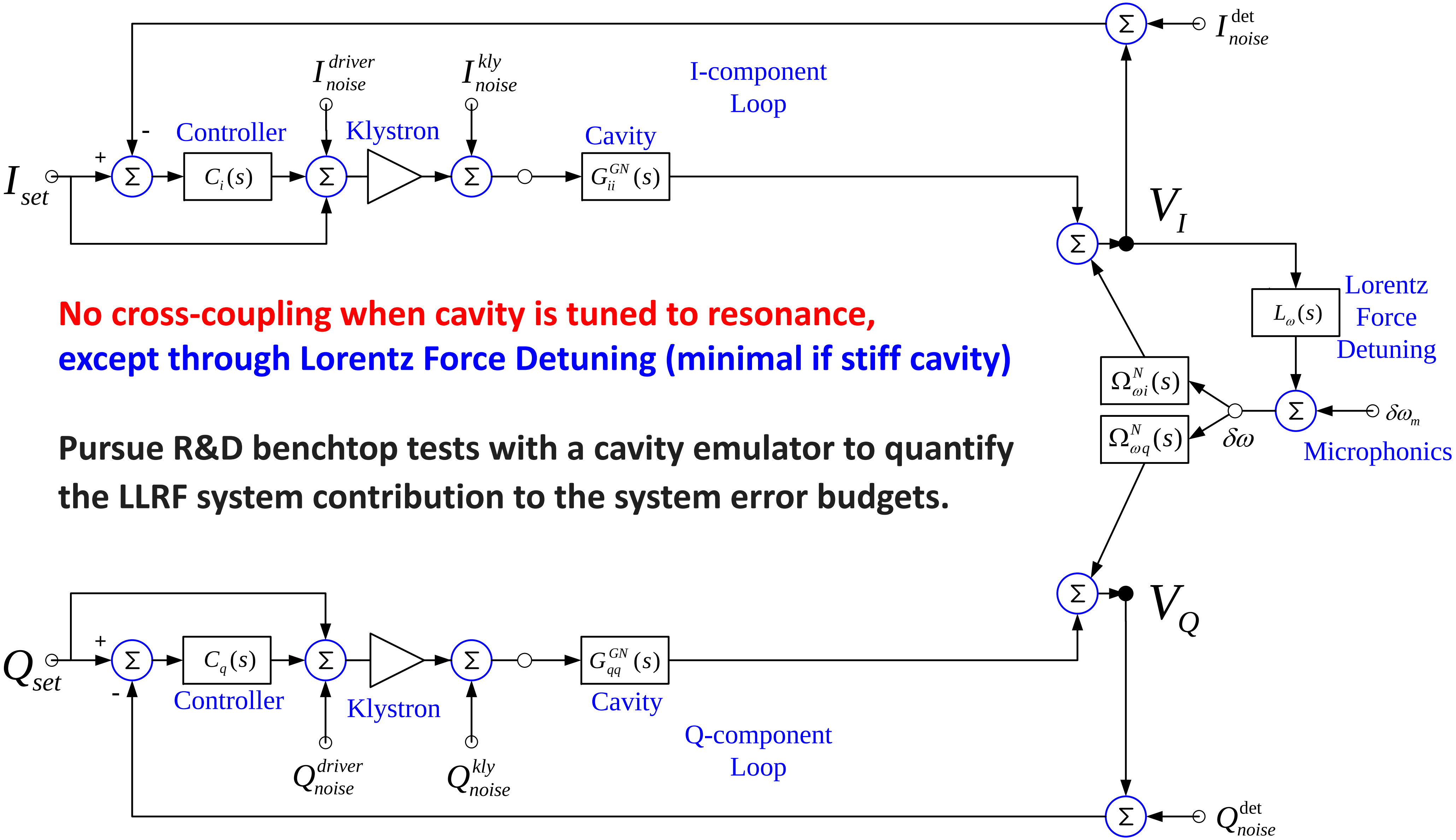

Phase Transfer Functions


Amplitude Transfer Functions


Phase Transfer Functions


Amplitude Transfer Functions

Deflecting Cavity - Dynamic Behavior

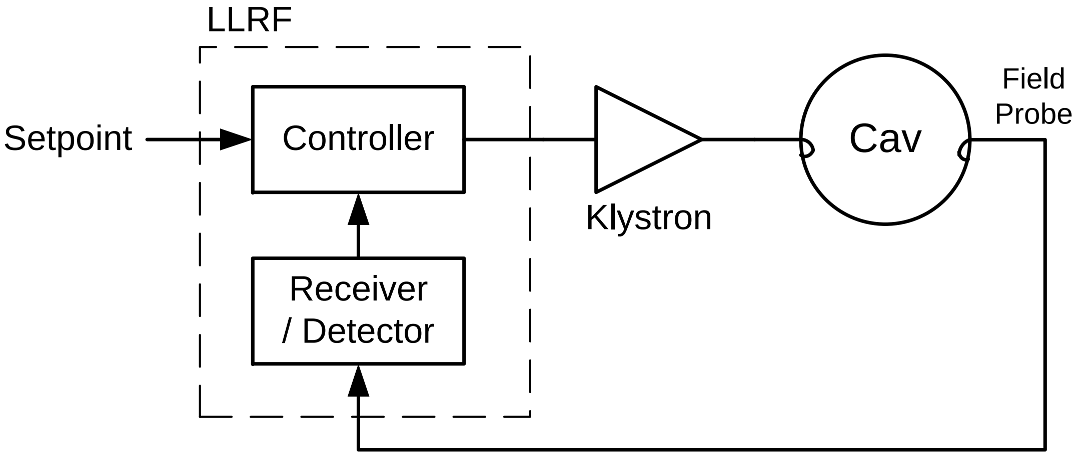


No cross-coupling when cavity is tuned to resonance,
except through Lorentz Force Detuning (minimal if stiff cavity)

Pursue R&D benchtop tests with a cavity emulator to quantify the LLRF system contribution to the system error budgets.

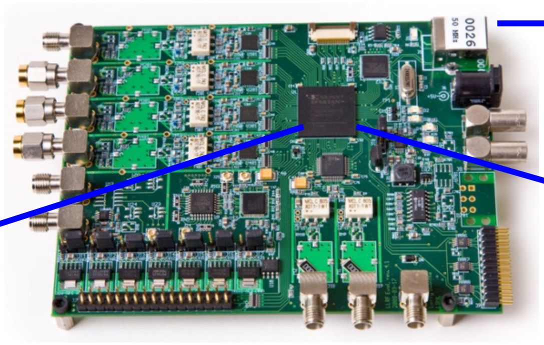
Low Level Radio Frequency (LLRF) System

Primary responsibility is to regulate the cavity field

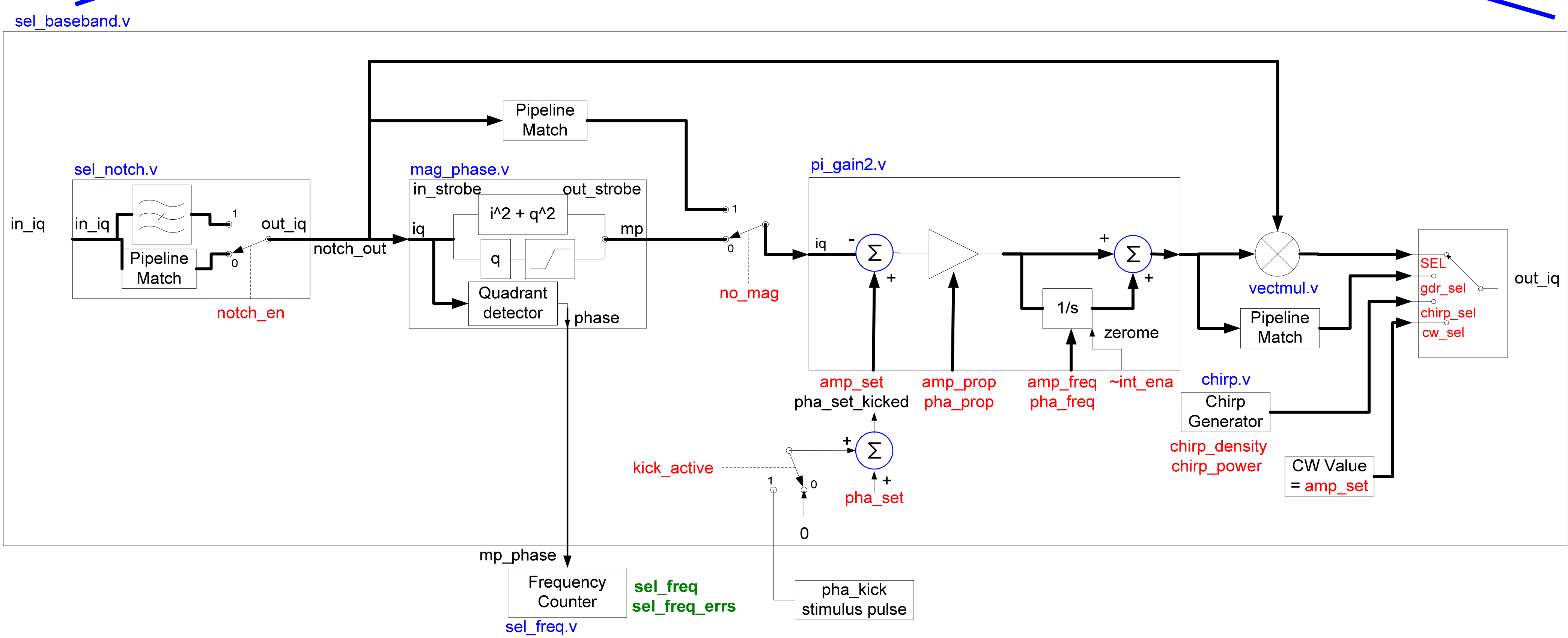


The Controller….

Controller

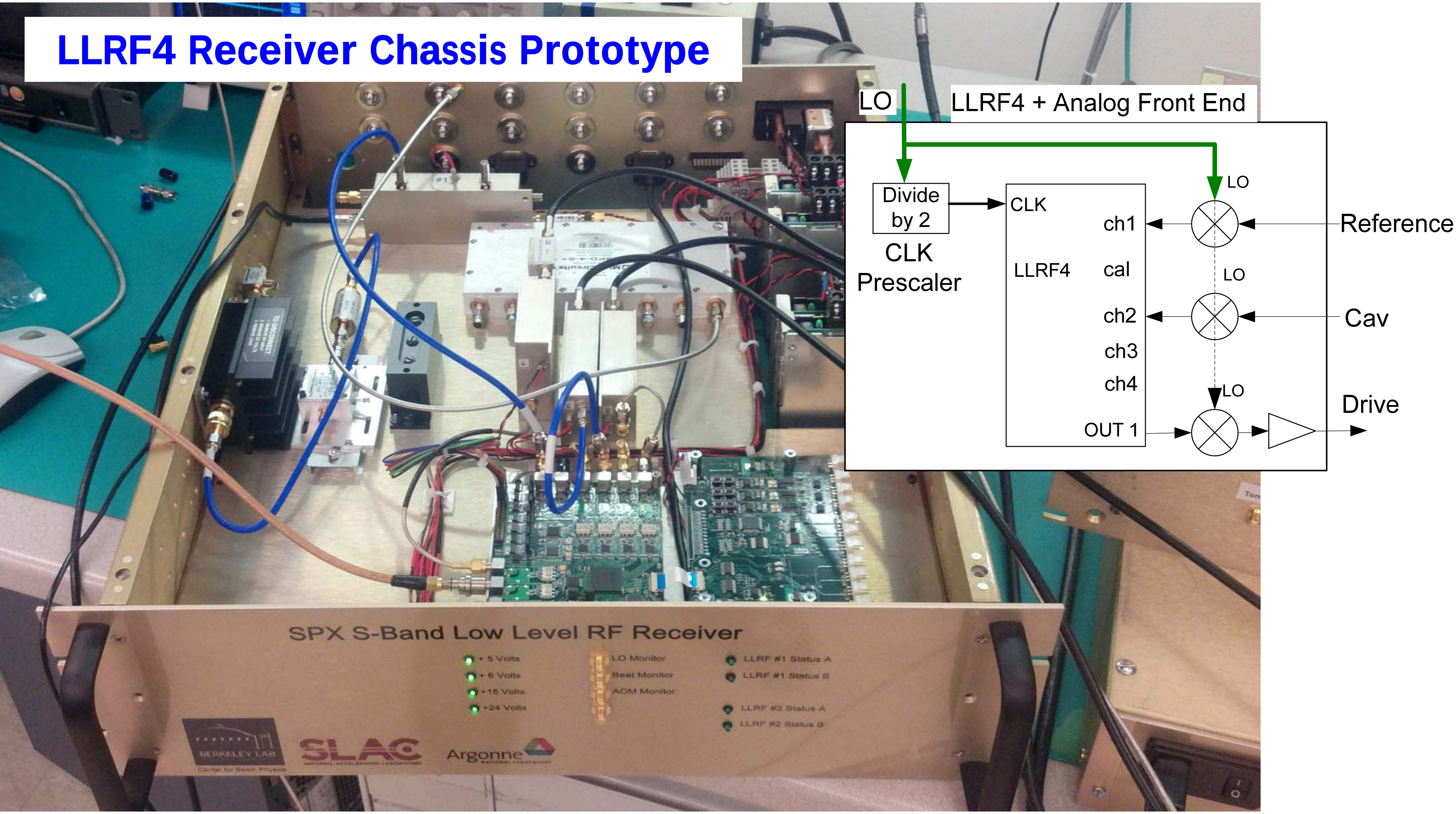


USB interface to host computer

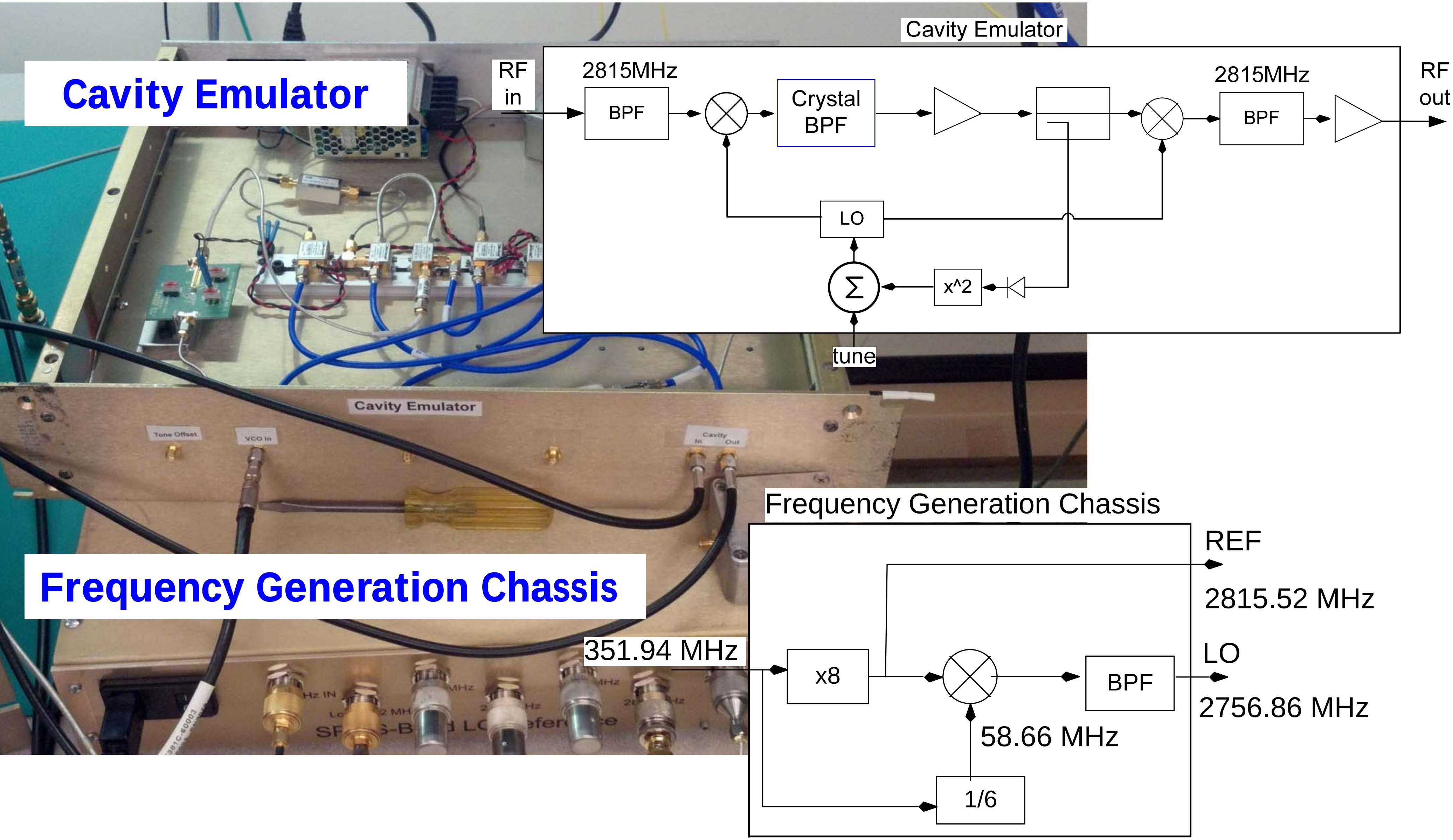


Controller – Benchtop Tests

LLRF4 Receiver Chassis Prototype

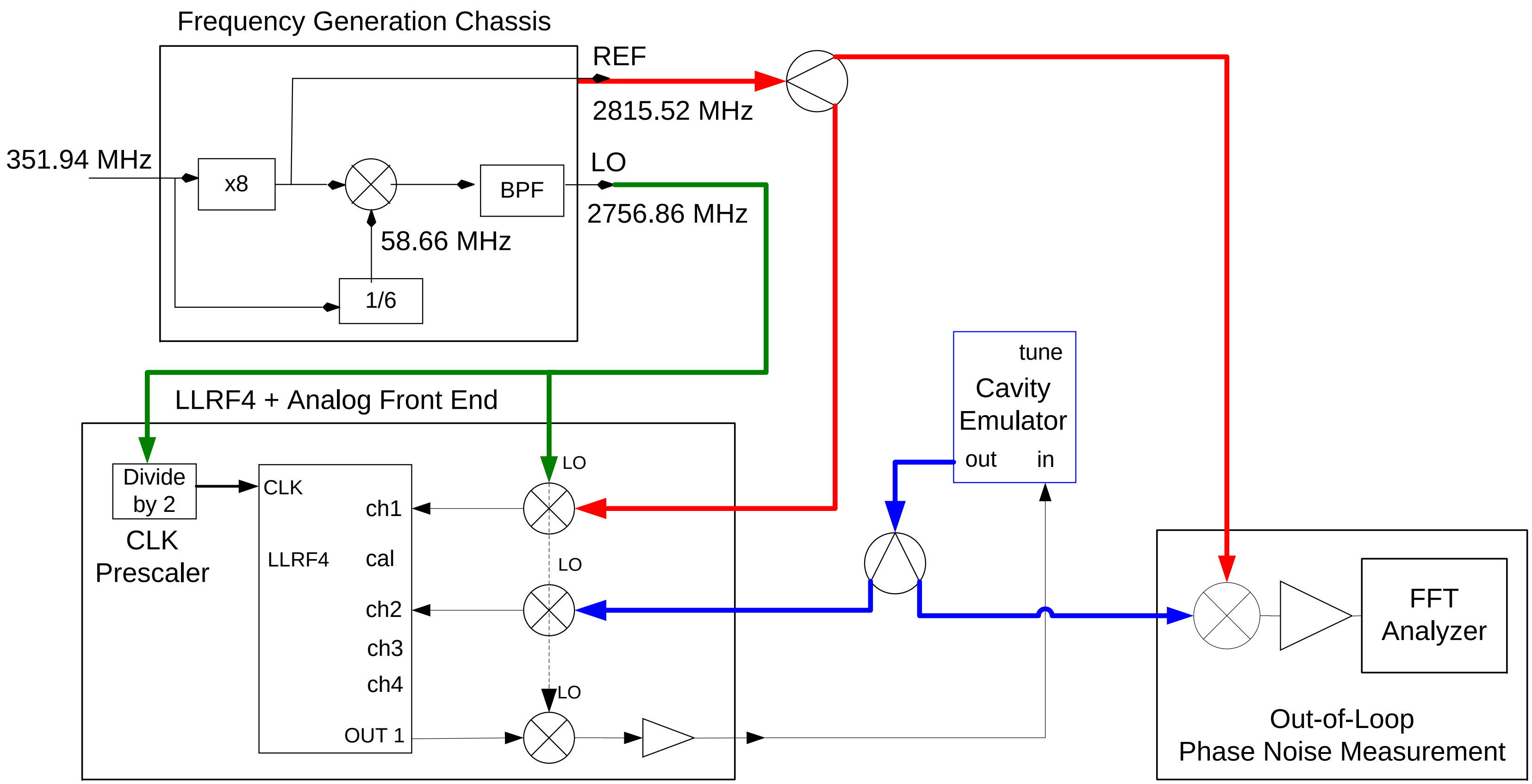


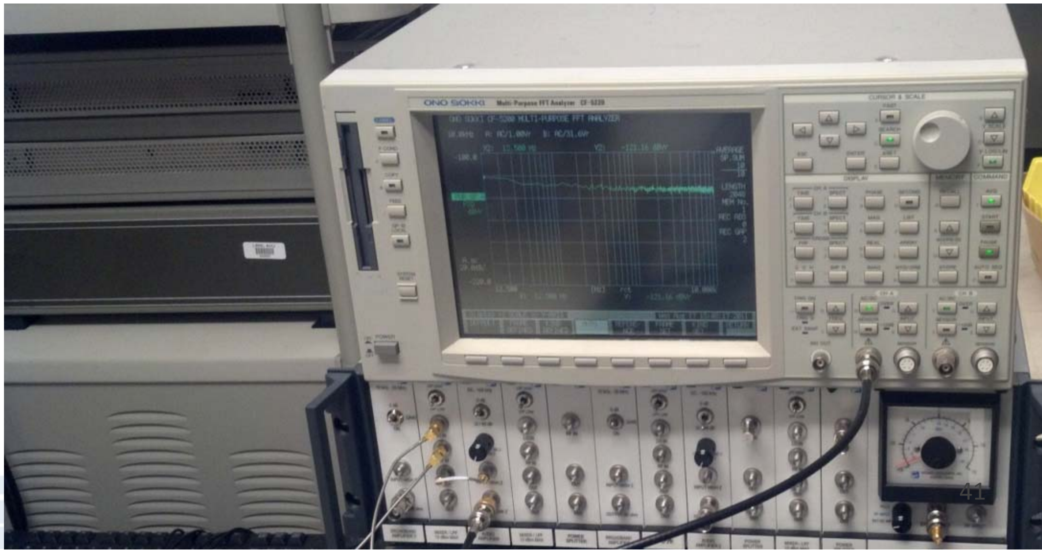
Controller – Benchtop Tests

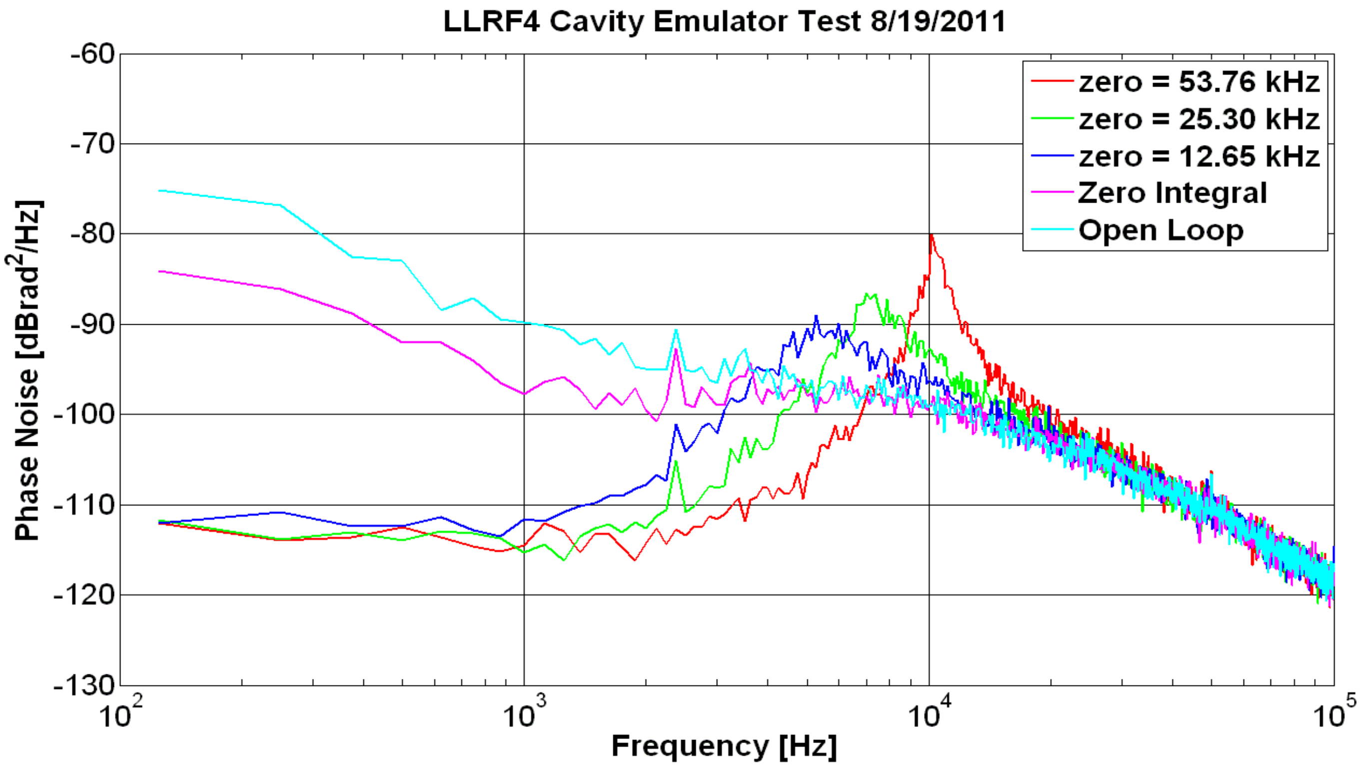

Cavity Emulator

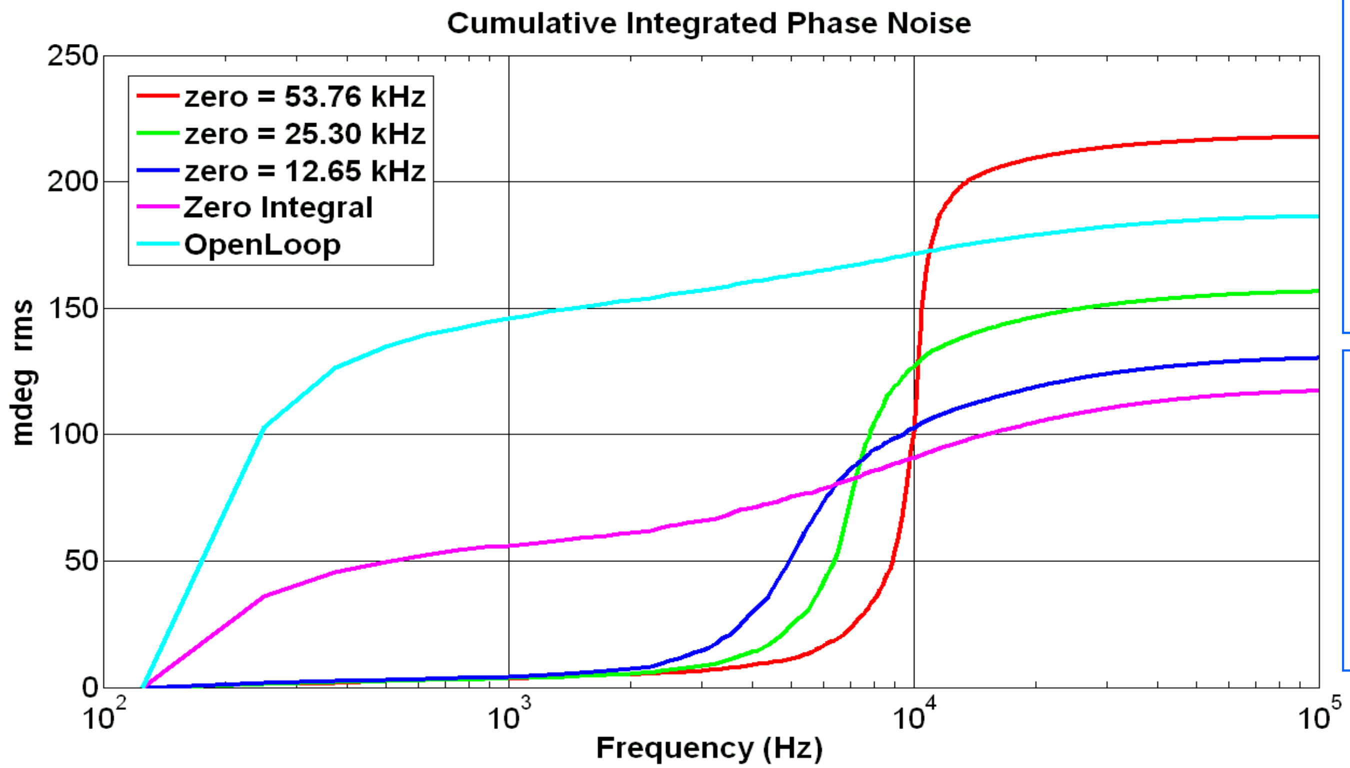
Frequency Generation Chassis

Controller – Single System Benchtop Test



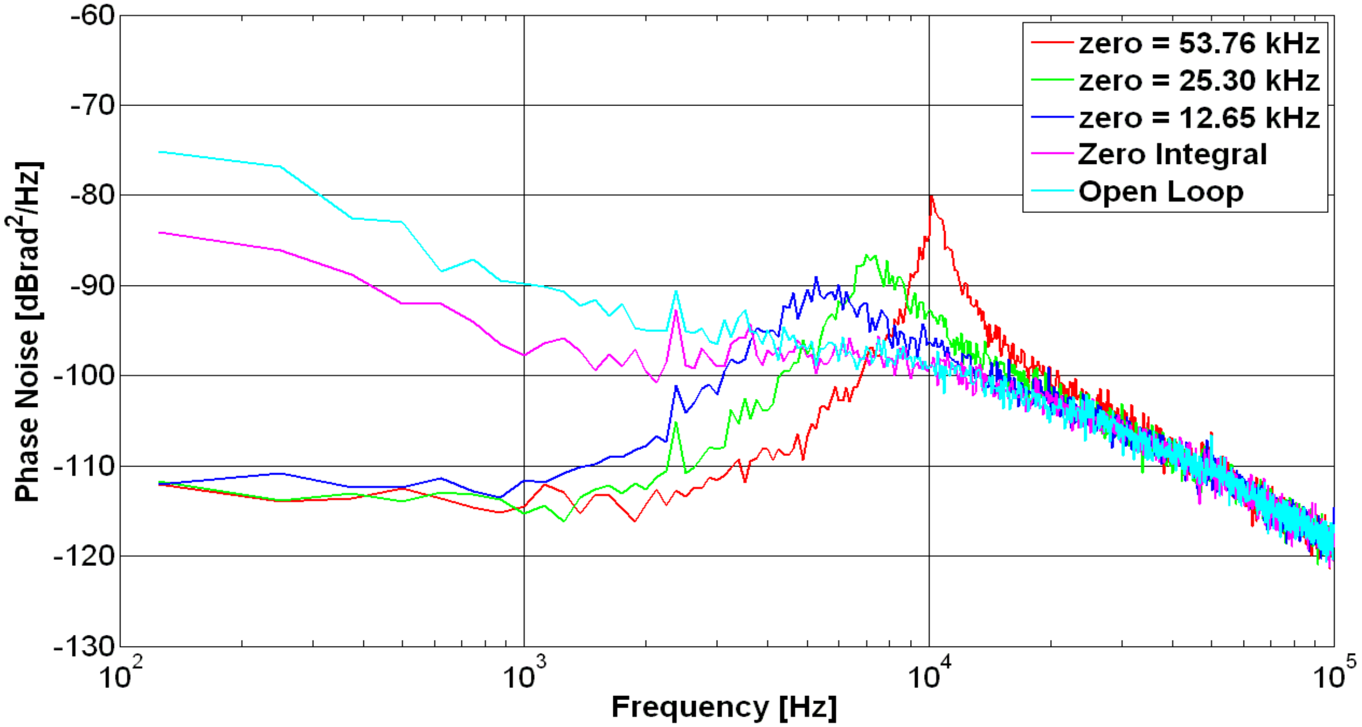


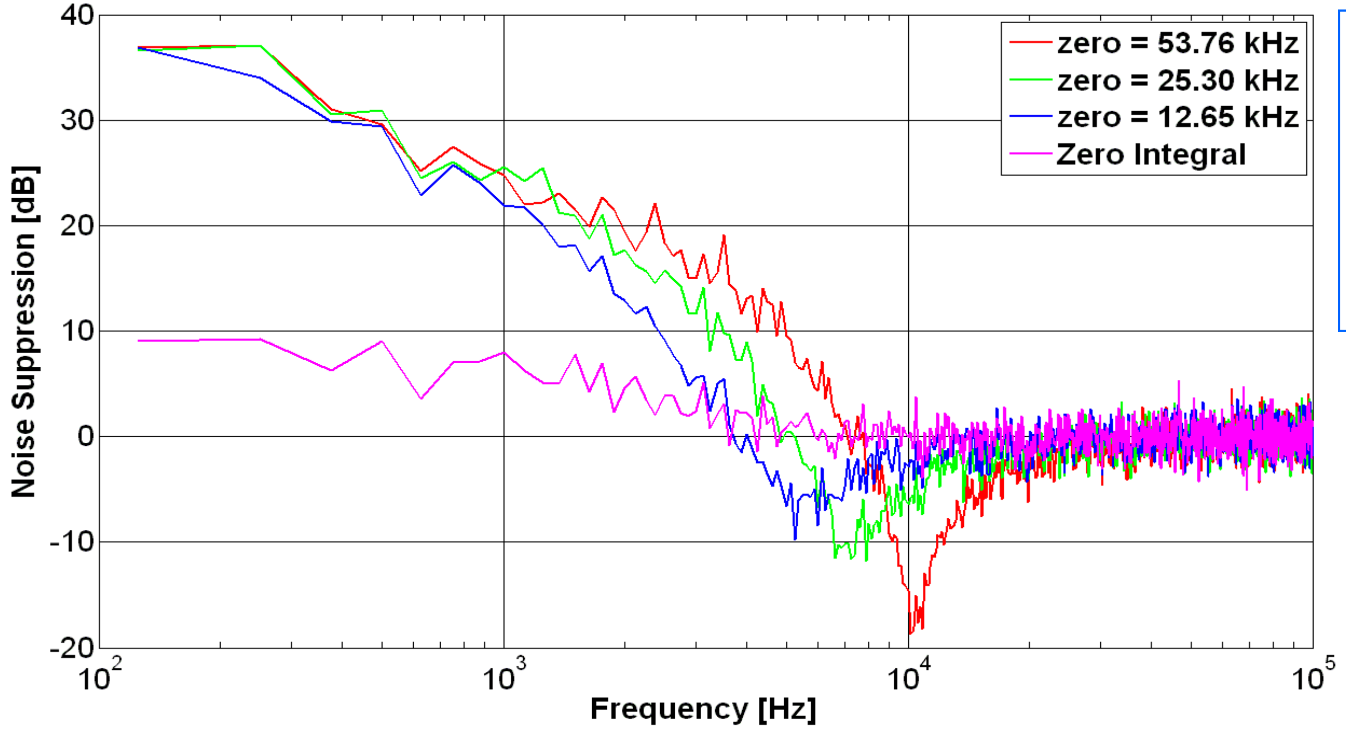




Noise sources include an independent LO generator used for cavity emulator. This is not something that exists in the 'real' system.

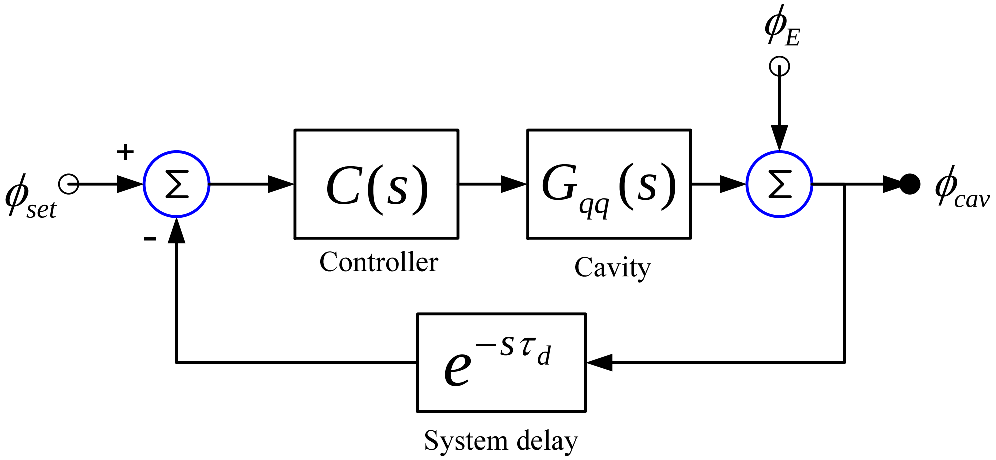
What matters is the noise suppression capability in combination with our expected noise sources.


LLRF4 Cavity Emulator Test 8/19/2011


Noise Suppression - LLRF4 Cavity Emulator Test 8/19/2011

What matters is the noise suppression capability in combination with our expected noise sources.

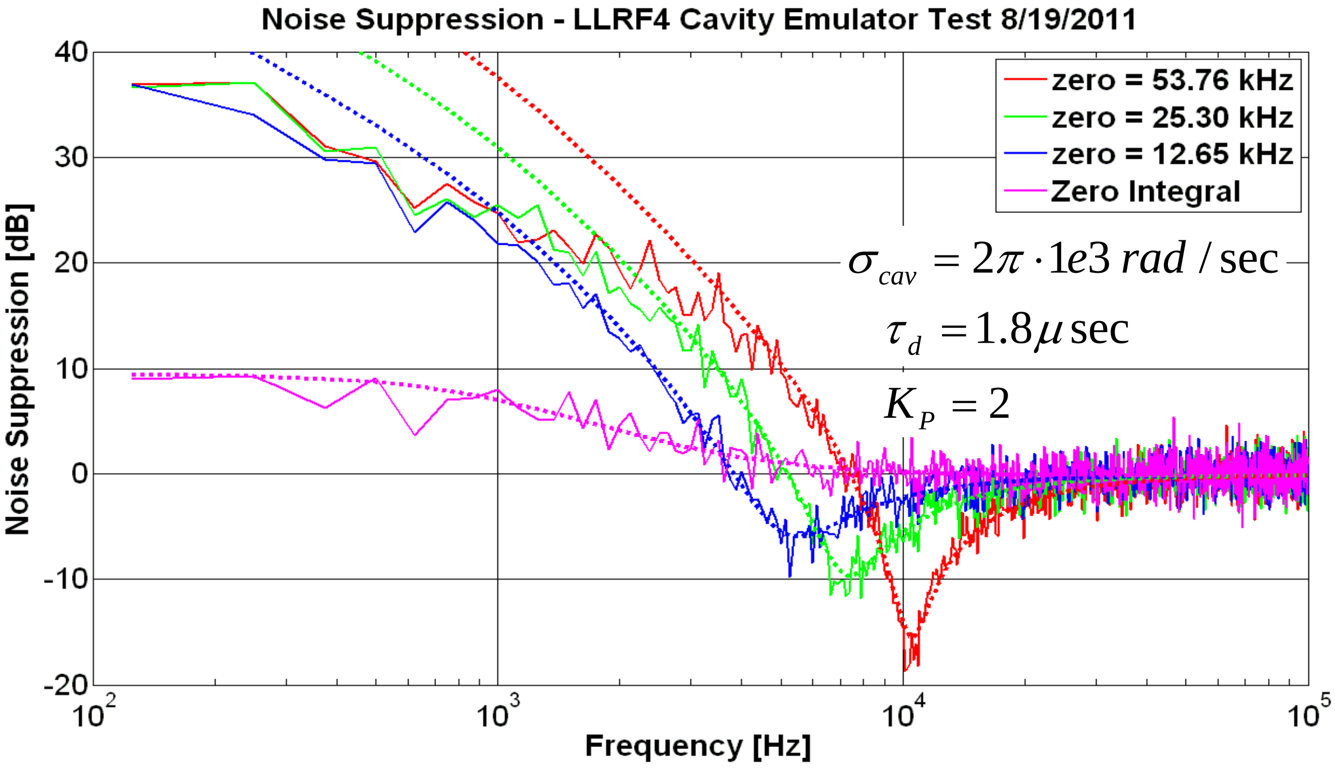
Controller – Noise Suppression Model



$$C(s) = K_P\left(1+\frac{\sigma_Z}{s}\right) = K_P\left(\frac{s+\sigma_Z}{s}\right)$$

$$G_{qq}(s) = \frac{\sigma_{cav}}{s+\sigma_{cav}}$$

$$\frac{\phi_{cav}}{\phi_E} = \frac{1}{1+C(s)\,G_{qq}(s)\,e^{-s\tau_d}}$$

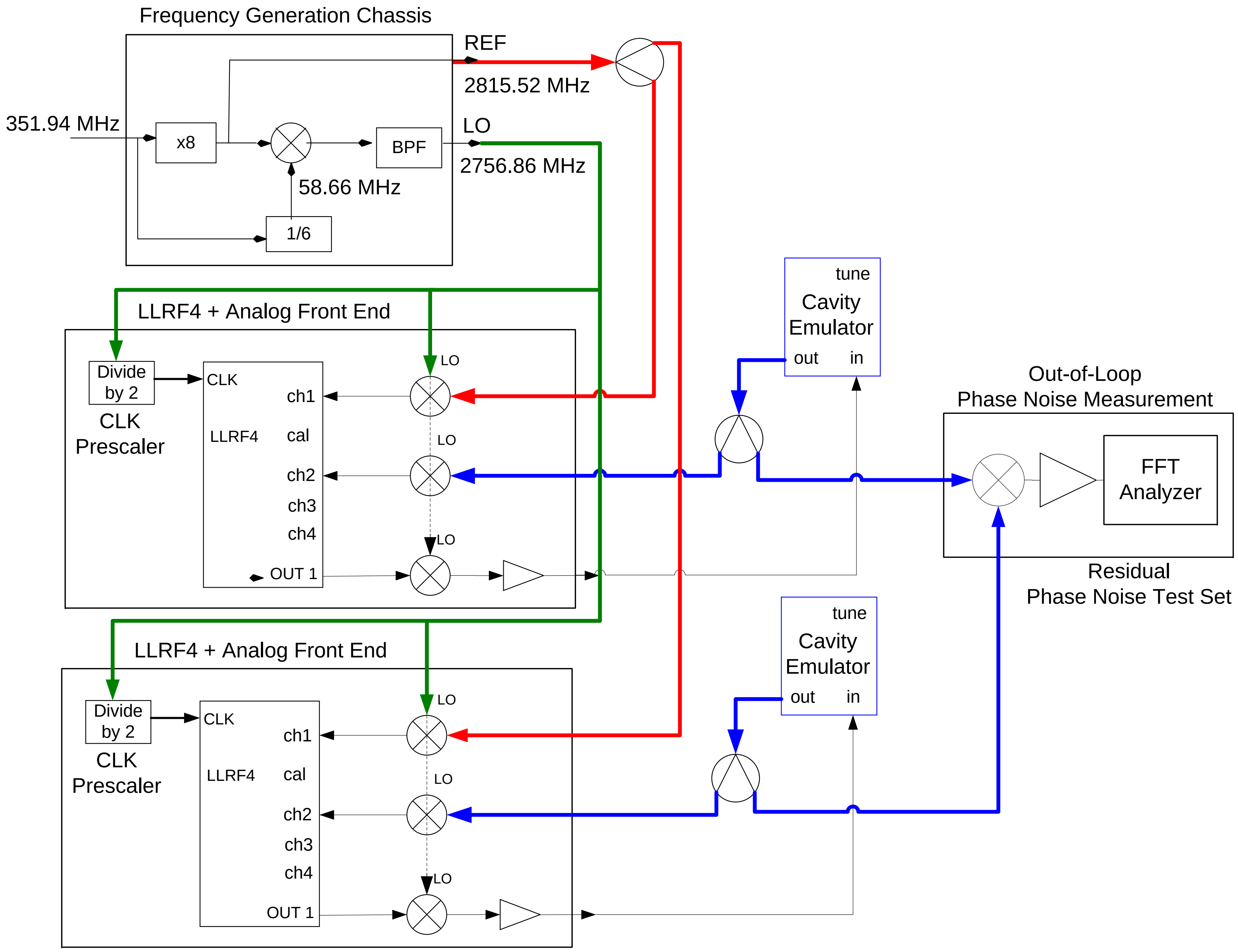


$$\sigma_{cav} = 2\pi\cdot 1e3\ rad/\sec$$

$$\tau_d = 1.8\mu\sec$$

$$K_P = 2$$

Controller – 2 System Benchtop Test



Controller – 2 System Benchtop Test

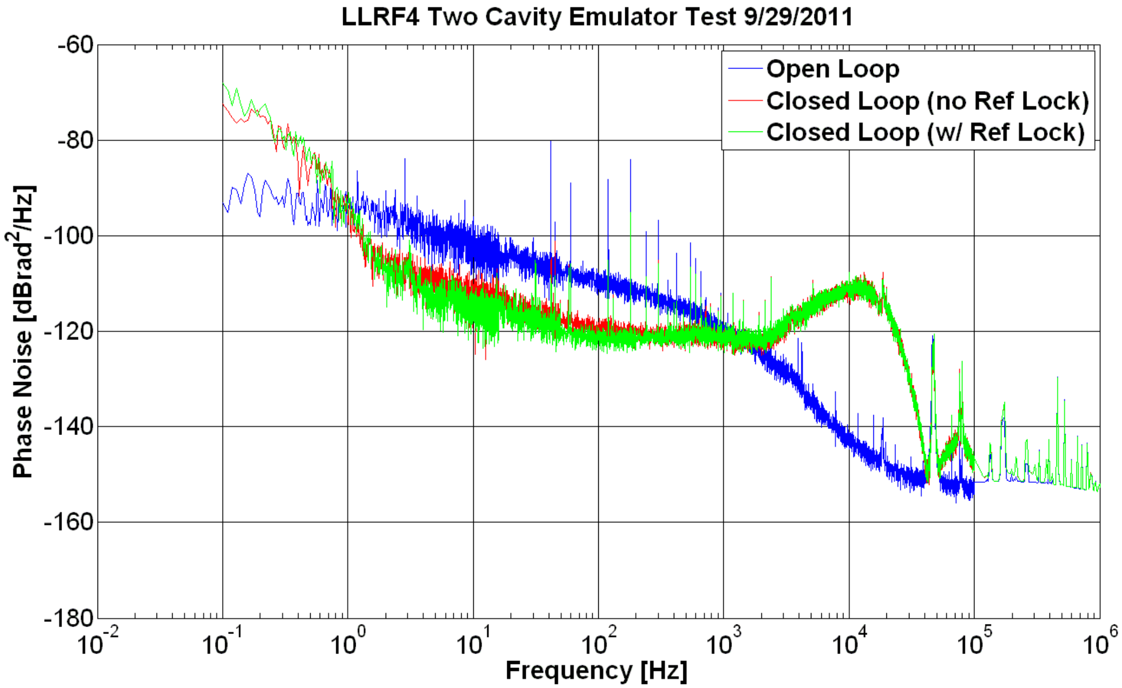
Residual Phase Noise Test Set
(measure noise between cavity emulators)

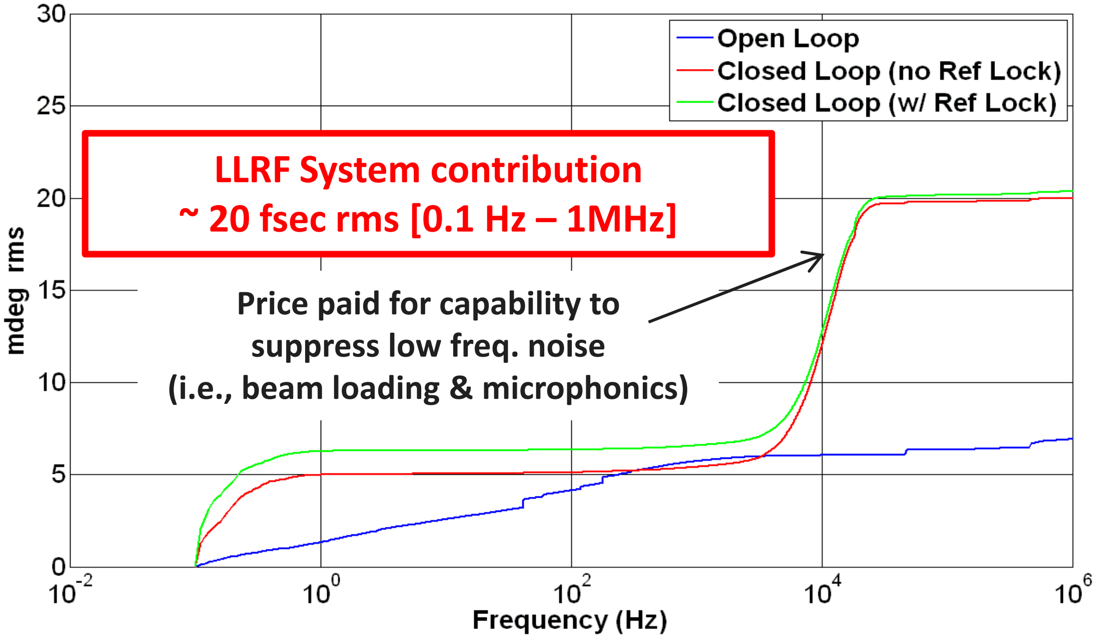
Cavity Emulators #1 and #2

LLRF Receiver #1

Freq. Generation Chassis

LLRF Receiver #2





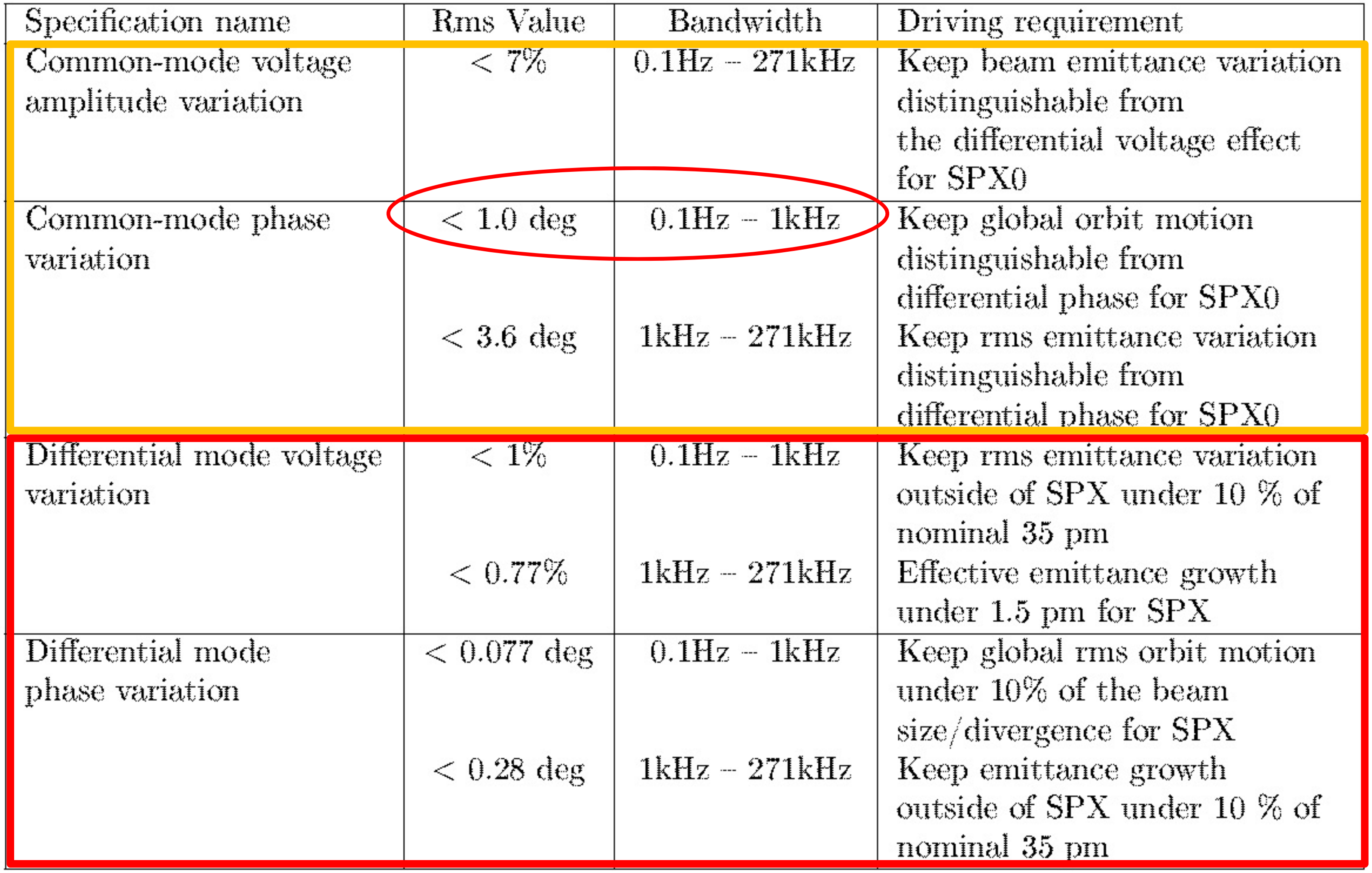
LLRF System contribution
~ 20 fsec rms [0.1 Hz – 1MHz]

Price paid for capability to suppress low freq. noise (i.e., beam loading & microphonics)

LLRF R&D Outlook (overly simplified)

- Adding the calibration tone scheme into the cavity control gateware. Currently these are 2 separate code bases, parts need to be merged.
- Preparing for real single cavity testing to begin ~ June 2012
- Modifications to Storage Ring RF System …

SPX0 System Performance Requirements [7]

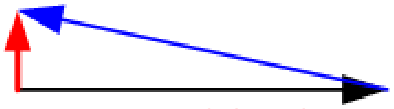


Specification name	Rms Value	Bandwidth	Driving requirement
Common-mode voltage amplitude variation	$< 7\%$	0.1Hz – 271kHz	Keep beam emittance variation distinguishable from the differential voltage effect for SPX0
Common-mode phase variation	< 1.0 deg	0.1Hz – 1kHz	Keep global orbit motion distinguishable from differential phase for SPX0
	< 3.6 deg	1kHz – 271kHz	Keep rms emittance variation distinguishable from differential phase for SPX0
Differential mode voltage variation	$< 1\%$	0.1Hz – 1kHz	Keep rms emittance variation outside of SPX under 10 % of nominal 35 pm
	$< 0.77\%$	1kHz – 271kHz	Effective emittance growth under 1.5 pm for SPX
Differential mode phase variation	< 0.077 deg	0.1Hz – 1kHz	Keep global rms orbit motion under 10% of the beam size/divergence for SPX
	< 0.28 deg	1kHz – 271kHz	Keep emittance growth outside of SPX under 10 % of nominal 35 pm

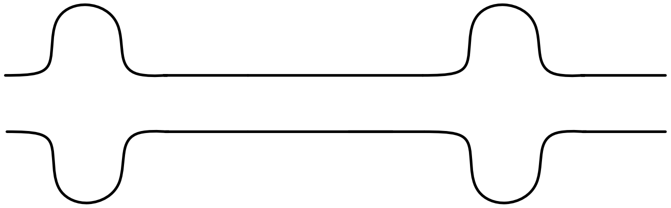
Common Mode

Differential

Residual tilt



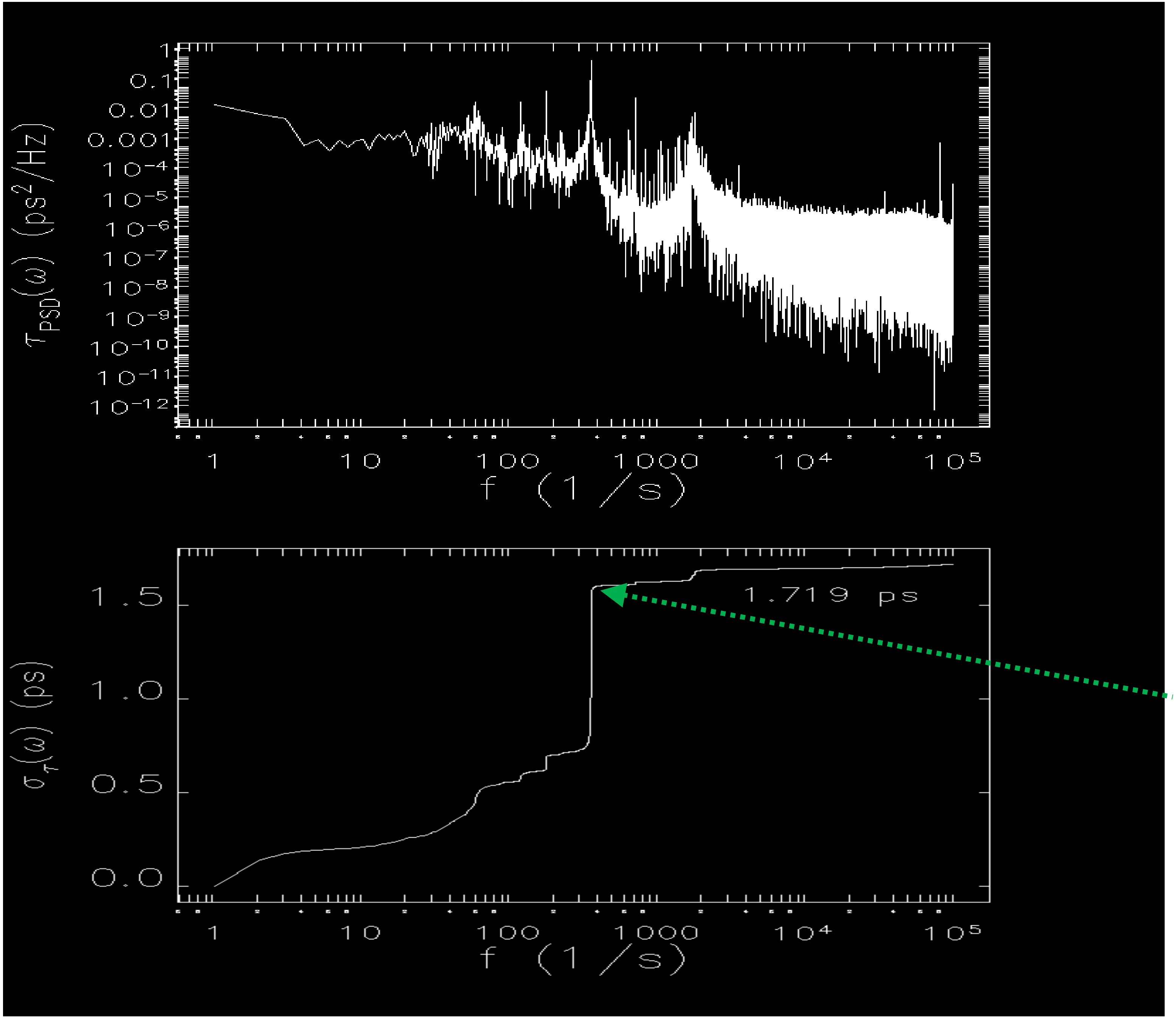
Residual kick



---

[7] SPX0 PRD, ICMS# APS_1423800 (1/17/12)

Present Storage Ring Beam Jitter [8]



$$\sim 1.65 = \sqrt{0.7^2 + 1.5^2}$$

$$0.86 = \sqrt{0.7^2 + 0.5^2}$$

$$0.72 = \sqrt{0.7^2 + 0.15^2}$$

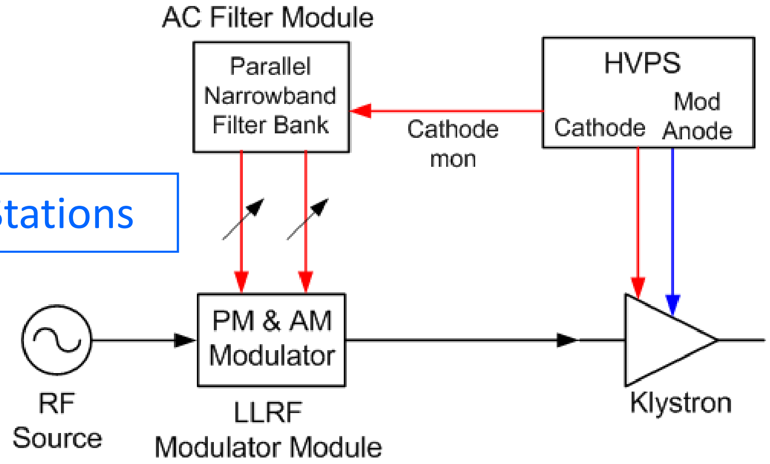
---

[8] Sereno et. al, “Storage Ring Phase Noise Studies …” AOP-TN-2012-001

Proof of Principle Feed Forward Experiment

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

AM & PM suppression at Both Stations



AC Filter Module

Parallel Narrowband Filter Bank

HVPS

Cathode

Mod Anode

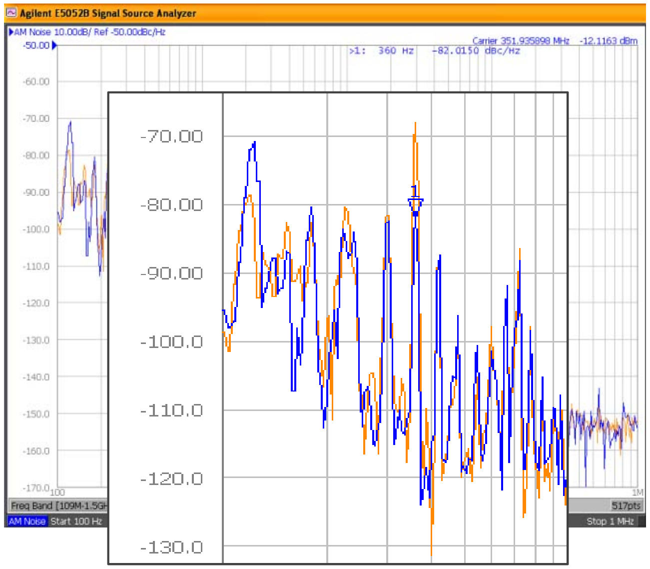
Cathode mon

PM & AM Modulator

RF Source

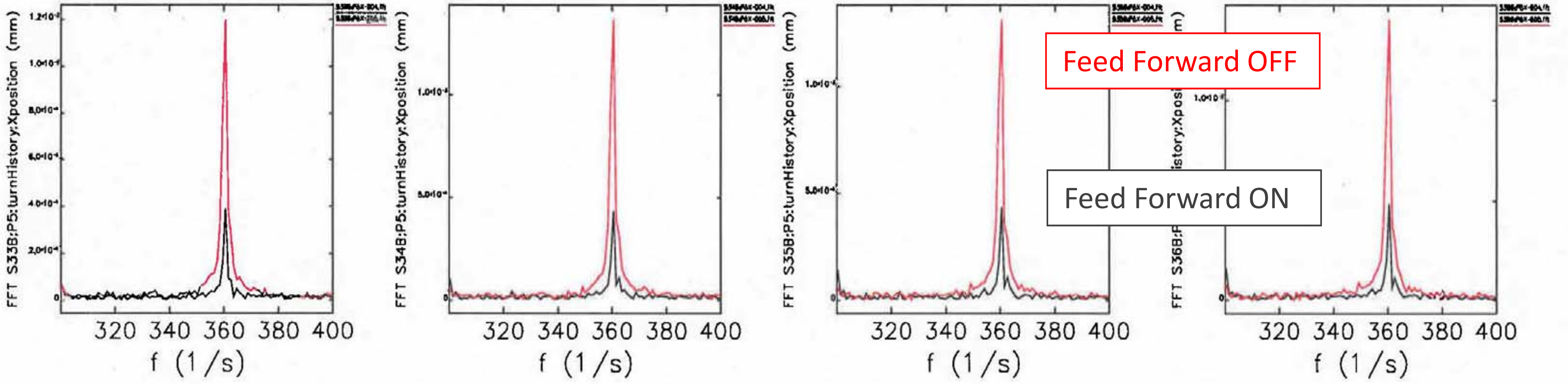
LLRF Modulator Module

Klystron



Agilent E5052B Signal Source Analyzer

Horizontal BPM Data



Feed Forward OFF

Feed Forward ON

Adaptive Noise Cancellation Concept [9]

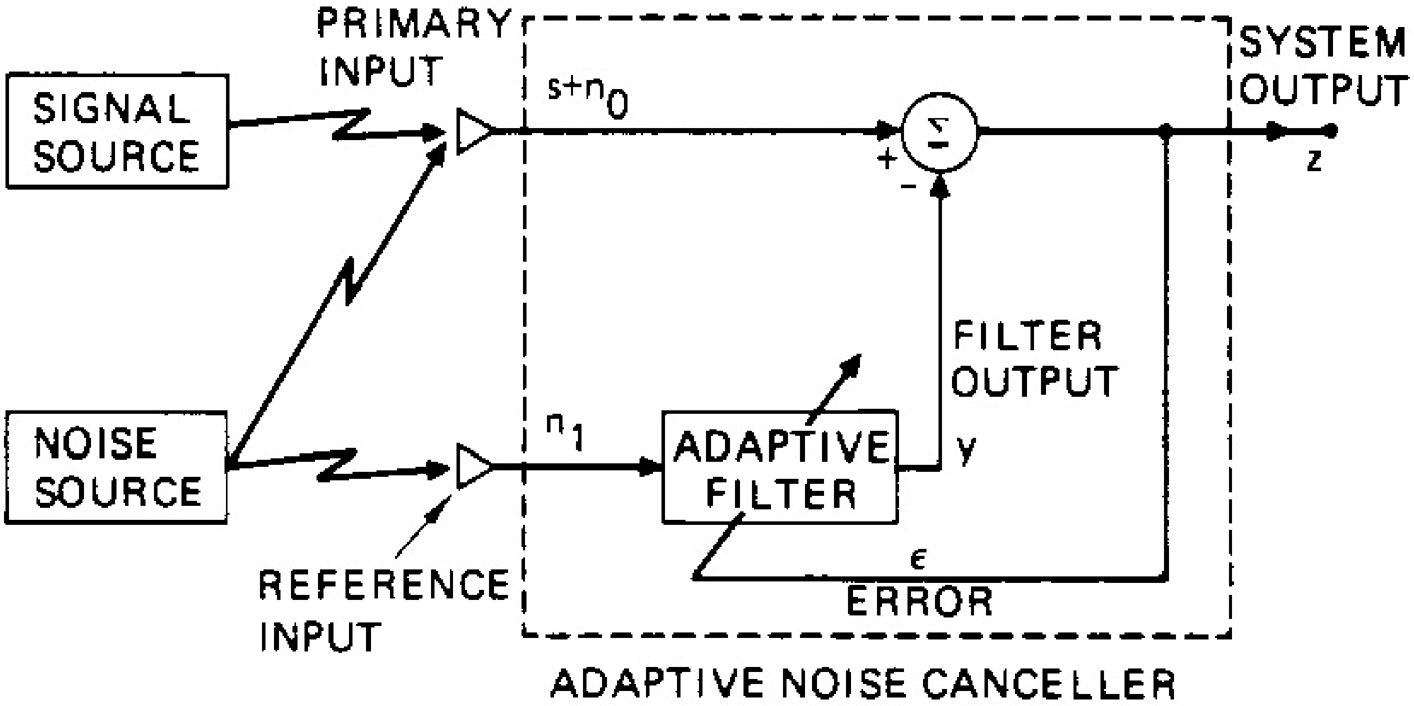


Fig. 1. The adaptive noise cancelling concept.

From [9]

---

[9] Widrow et. al, “Adaptive Noise Cancelling: Principles & Applications” IEEE Vol. 63, No. 12, Dec. 1975

Adaptive Noise Cancellation Concept [9]

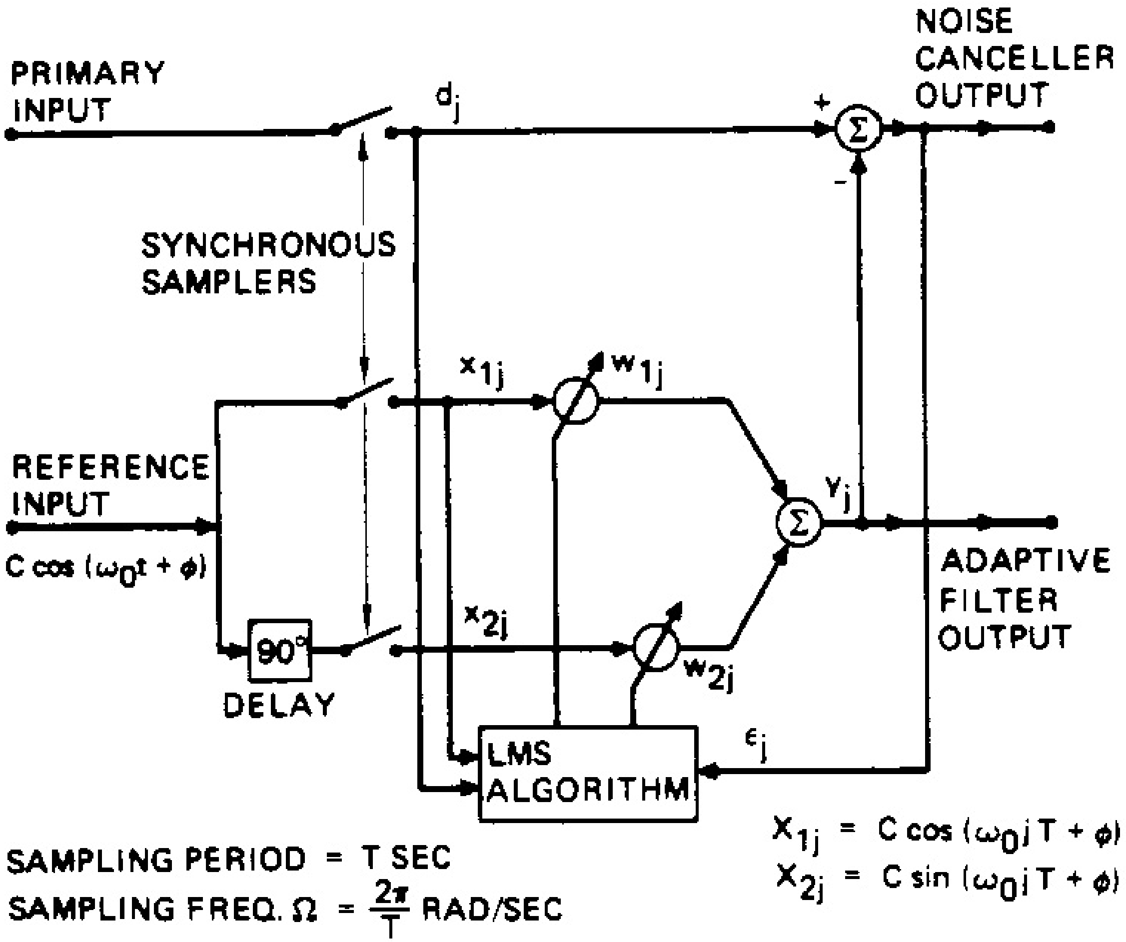
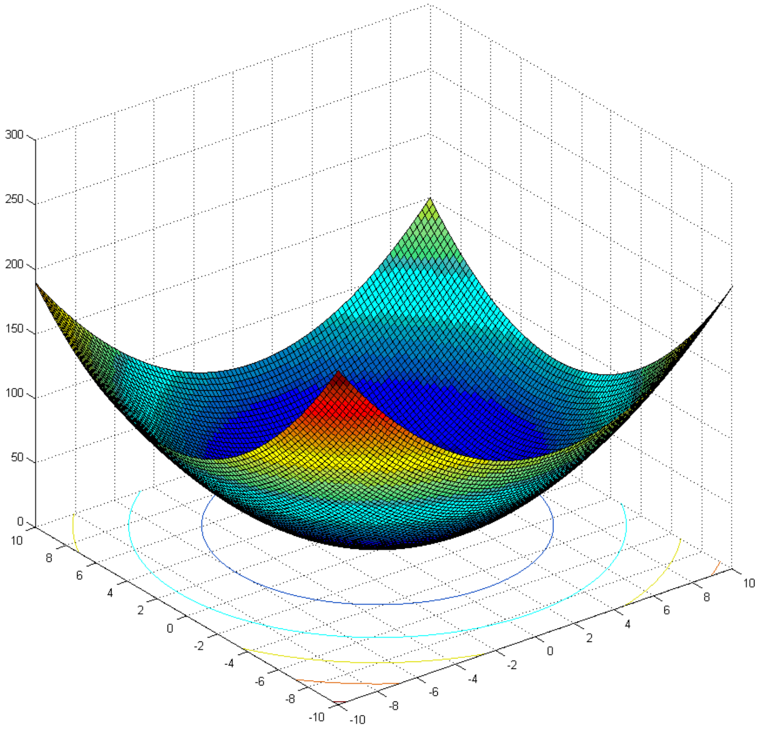


Fig. 6. Single-frequency adaptive noise canceller.

From [9]

$$N_I \cos \omega_N t \;-\; N_Q \sin \omega_N t$$

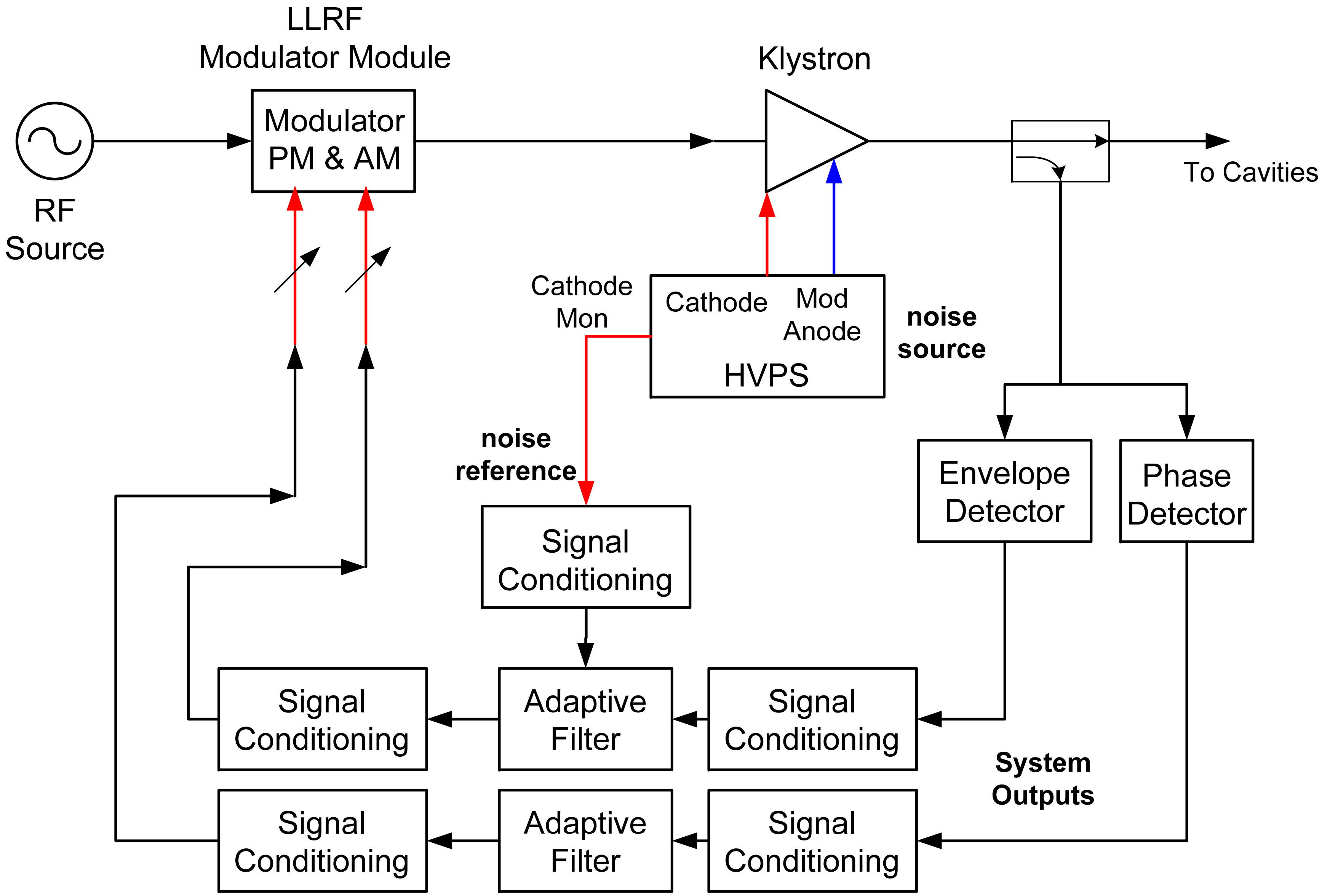
$$(Y_I - N_I)^2 + (Y_Q - N_Q)^2$$



---

[9] Widrow et. al, “Adaptive Noise Cancelling: Principles & Applications” IEEE Vol. 63, No. 12, Dec. 1975

Storage Ring RF AM/PM Noise Suppression Concept



Summary

- Digital LLRF system shows promise of femto-second level synchronization [0.1 Hz – 1MHz] with proper attention to common source distribution

- Great design improvement demonstrated for Analog Front End with T3 mixers

- New I/Q small-signal baseband model developed for SRF Deflecting Cavities

- Adaptive noise cancellation of Storage Ring main 352MHz RF system AM/PM noise is being pursued to reduce present beam jitter