Digital Self Excited Loop Implementation and Experience

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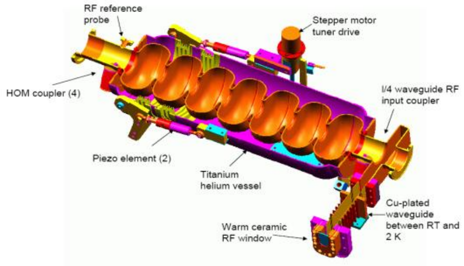
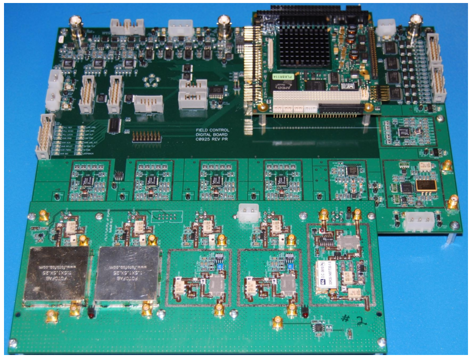
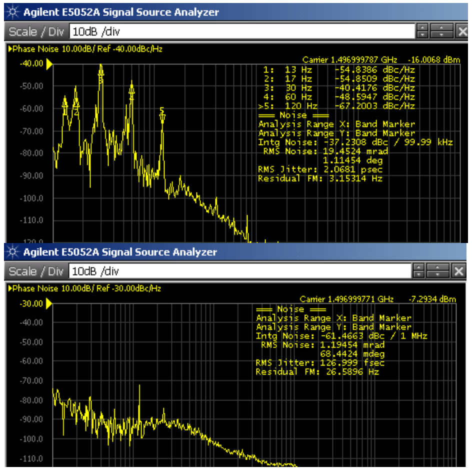
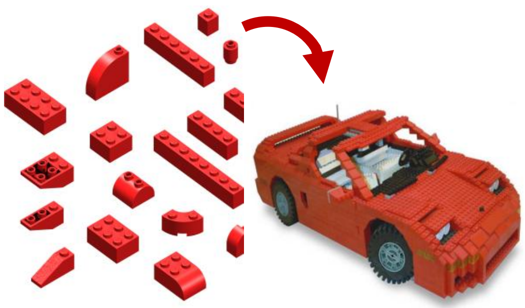
Overview



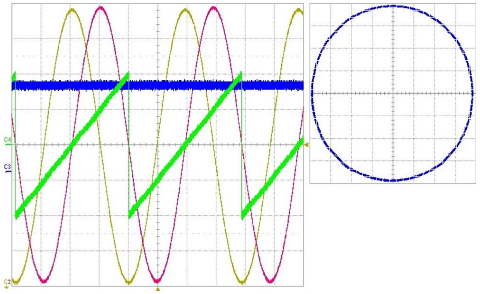




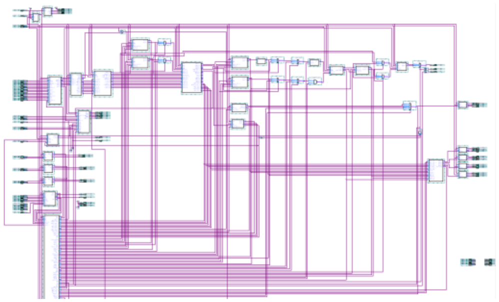
- **Why Self Excited Loop?**
- **Algorithm Building Blocks**
  - Hardware and Sampling
  - Digital Signal Processing Tools
  - Cavity Emulators



- **Digital SEL Algorithm Development & Testing**
  - Analog SEL
  - Automatic Gain Control
  - Normalizer
  - Phase Pass
  - Discriminator



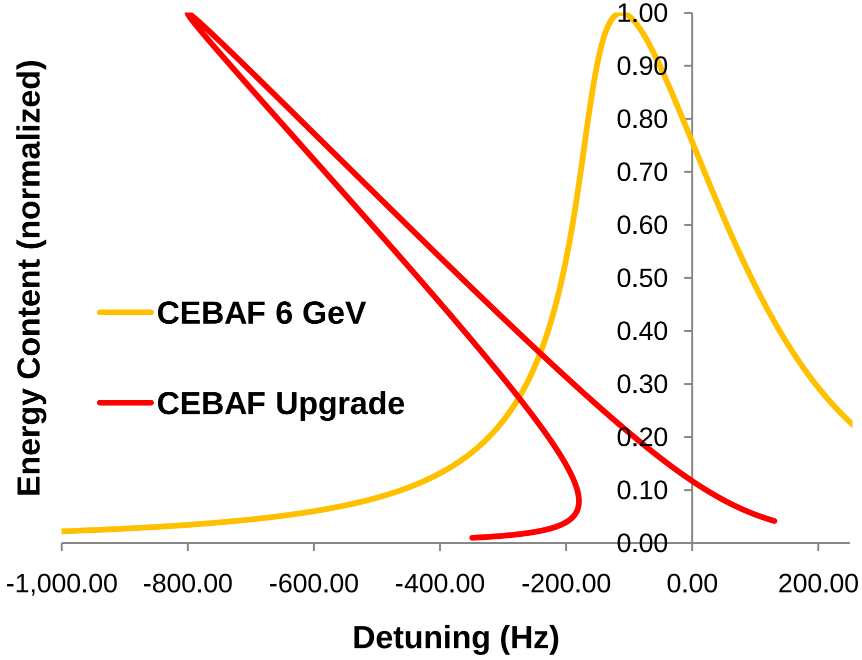
- **Control Algorithm Development & Testing**
  - Microphonic Compensator
  - Magnitude and Phase Lock
  - In-Phase and Quadrature Lock
- **Field Control Architecture**

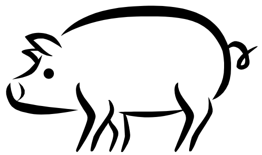


Why Self Excited Loop?

- Lorentz force detuning
  - Cavity frequency is a function of gradient
  - High Q upgrade cavities
- Generator Driven Resonator
  - Presently used in CEBAF
  - Slowly ramp gradient while mechanical tuners compensate for cavity tune
- Self Excited Loop (SEL)
  - Tolerant of cavity mistuning
  - Quickly bring up cavity gradient without running the tuners
  - Recover faulted cavities in milliseconds instead of minutes

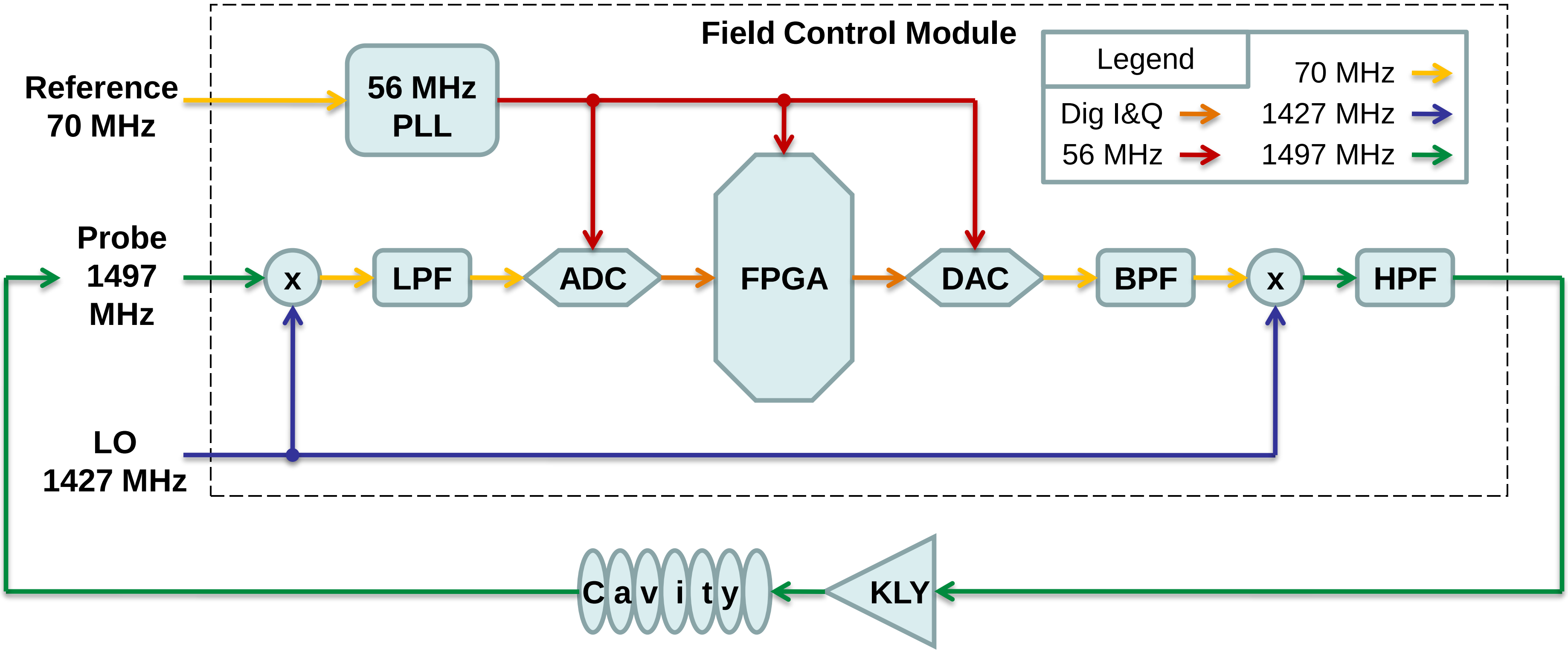
Gradient vs. Cavity Tune





It's hard to catch a greased pig

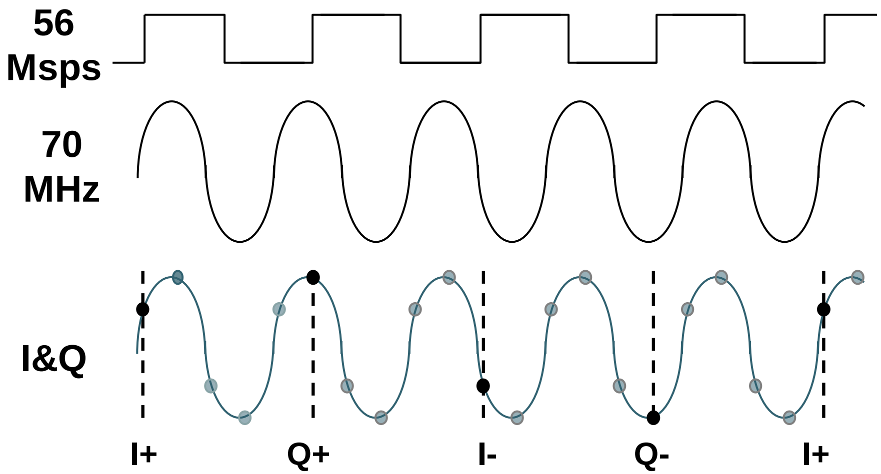
Algorithm Independent Hardware



- Down convert 1497MHz to 70MHz
- Sample 70MHz IF with 56Msps ADC to get In-Phase and Quadrature (I&Q) components
- Apply control algorithm in FPGA
- Produce 70MHz IF with DAC
- Up convert 70MHz to 1497MHz and send to klystron/cavity

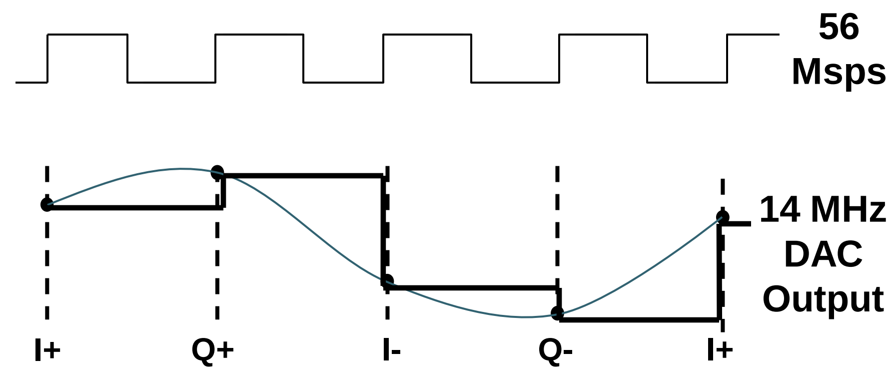
Harmonic Sampling

Sample 70 MHz IF at 56 Msps



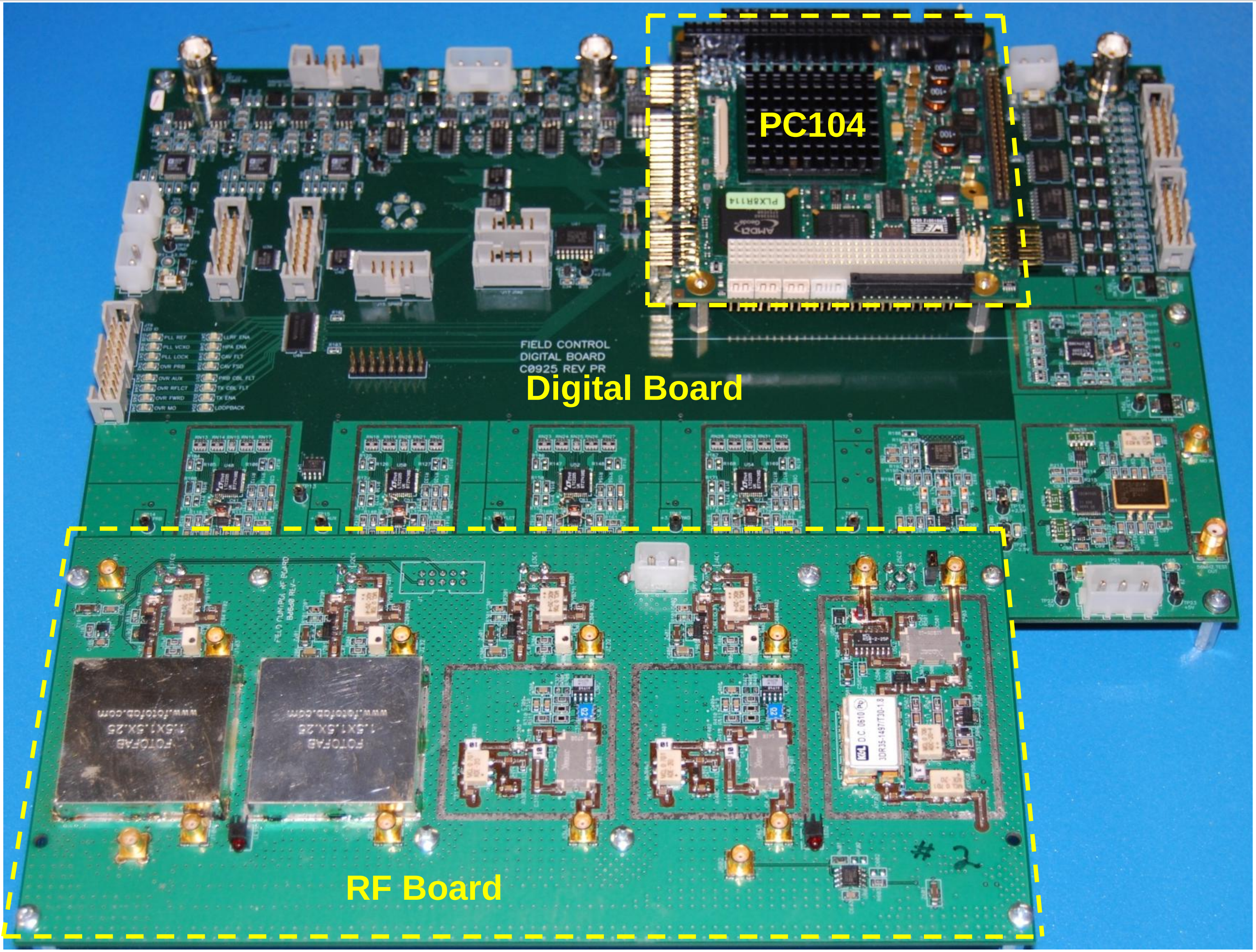
- Any odd multiple yields I&Q
  - 1 / [(2n + 1) / (4 * 70MHz)]
  - 280, 93.3, 56, 40, … Msps
- Break into 28 Msps I&Q chains
  - I+, -(I-), I+, -(I-), …
  - Q+, -(Q-), Q+, -(Q-), …

Create 70 MHz from 56 Msps I&Q

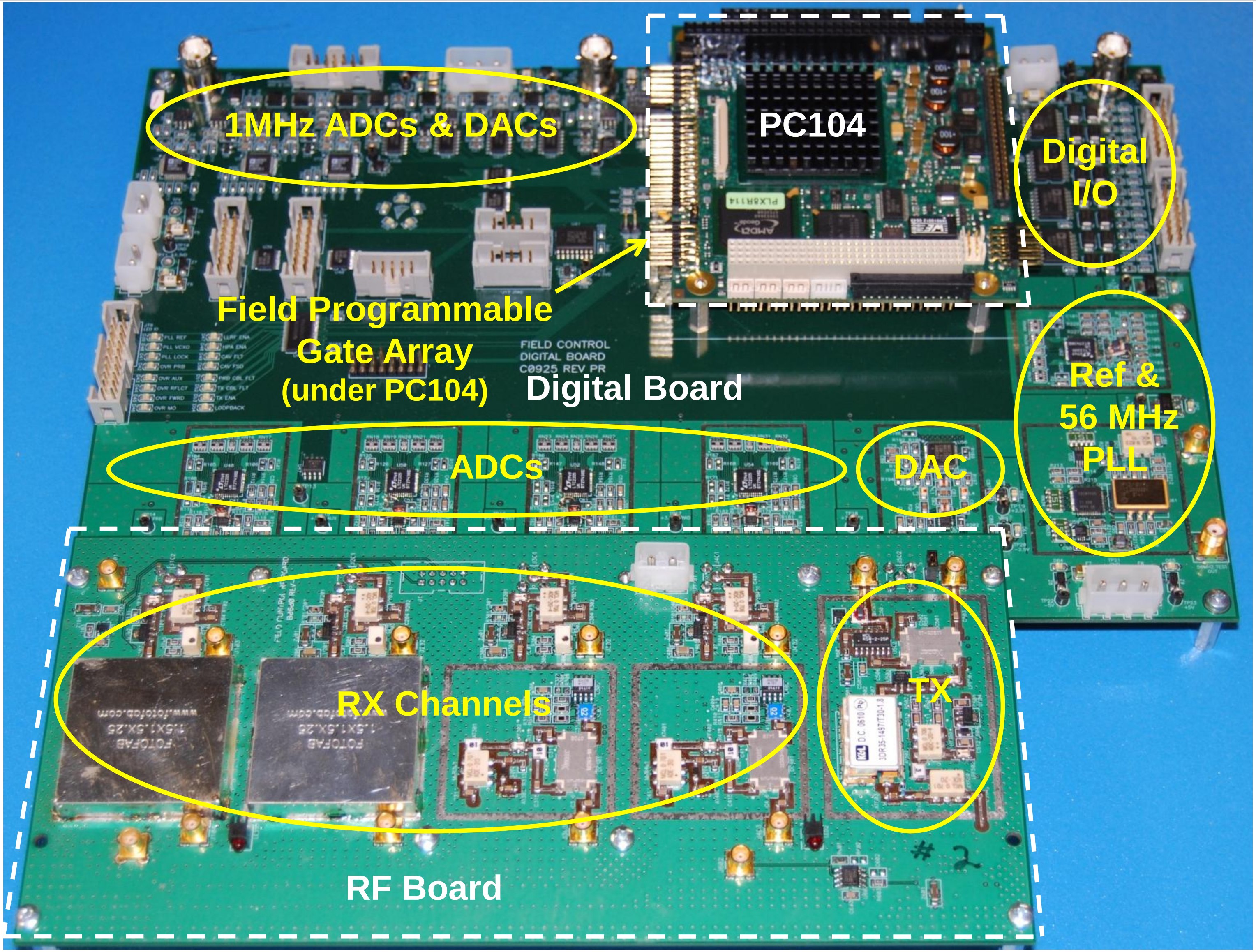


- Create 14MHz from 56Msps I&Q
  - I, Q, -(I), -(Q), I, Q, -(I), …
  - Also has the effect of mixing 14MHz with 56MHz
- Spectrum includes translation products at 42MHz and 70MHz
- Filter and amplify the 70 MHz component

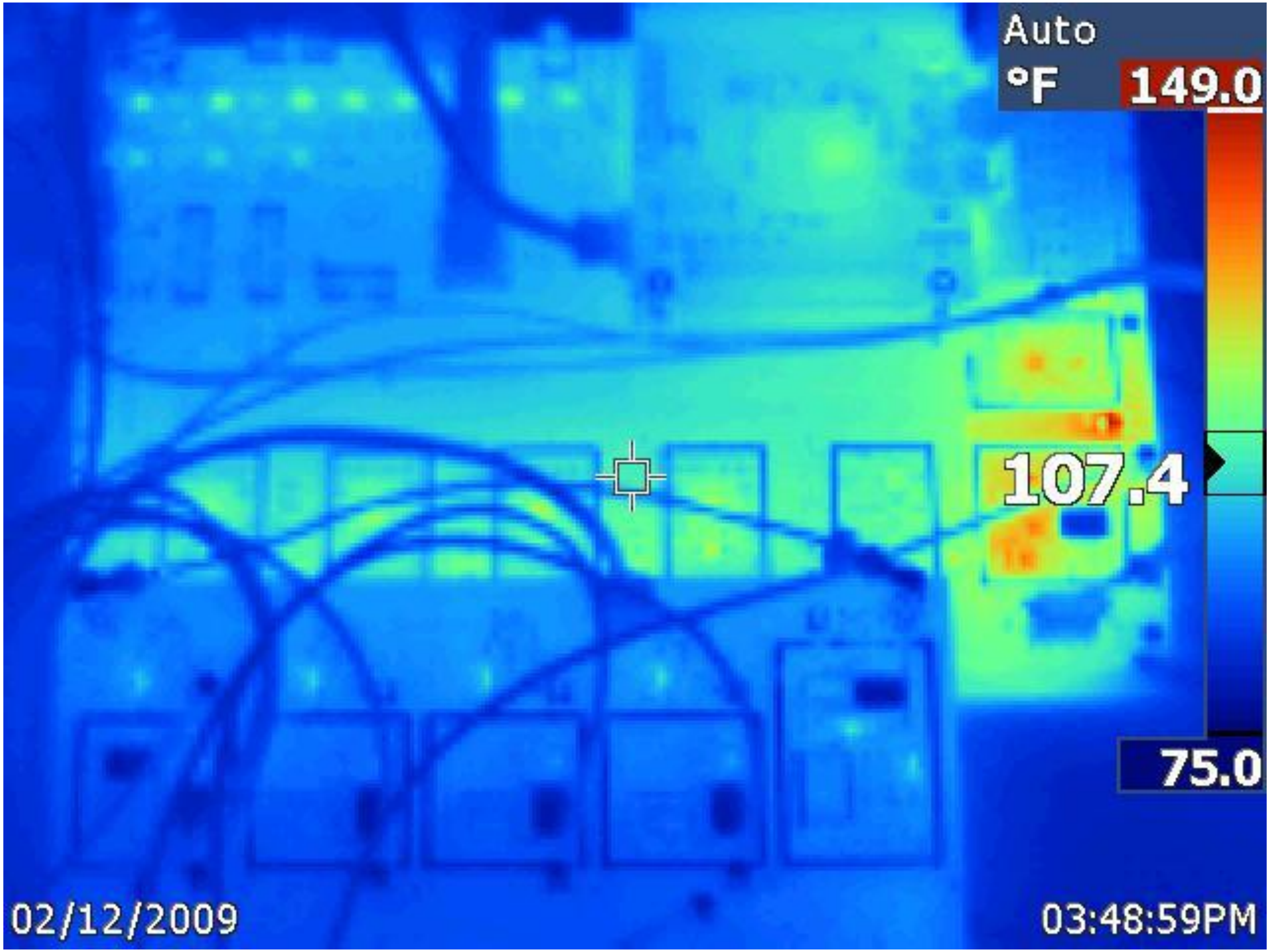
Field Control Hardware



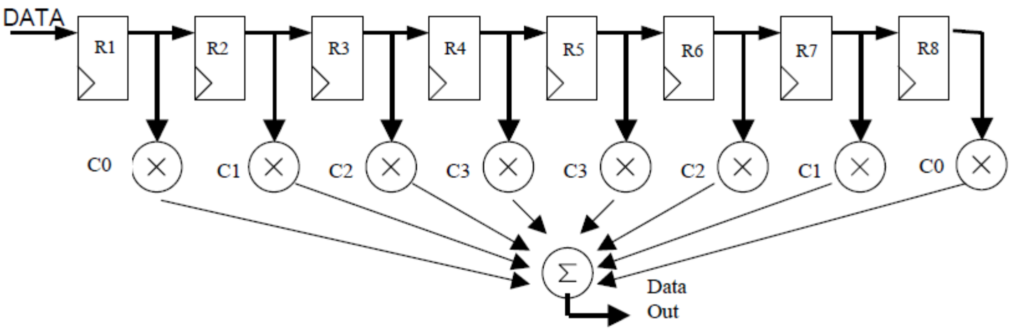
Field Control Hardware

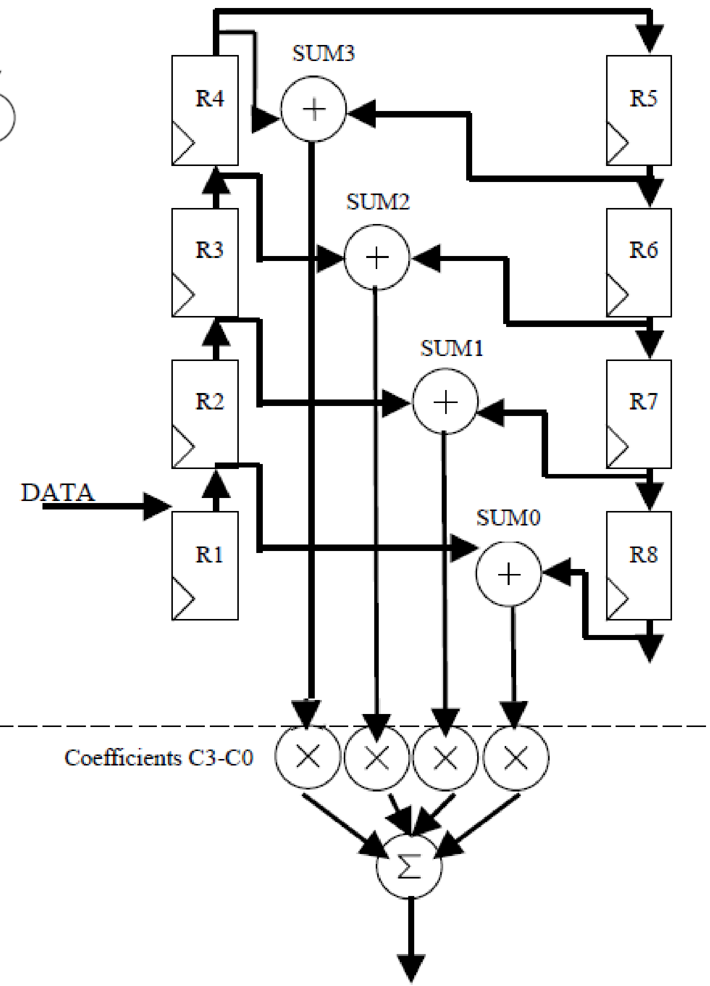


Field Control Hardware



Digital Signal Processing Tools





FIR (Finite Impulse Response)

- Stable and linear phase
- Symmetric coefficients allow for "folding"
  - Add two delayed samples together then multiply by common coefficient
  - Half as many multipliers

Digital Signal Processing Tools

IIR (Infinite Impulse Response)

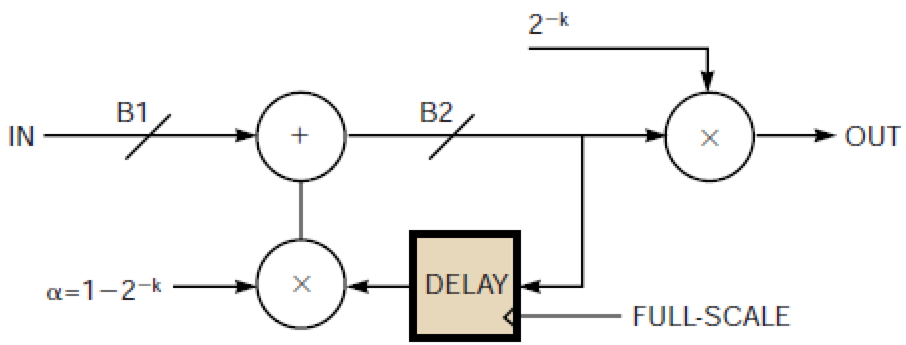
- Most like analog filter but can be unstable due to recursion
- Single pole embedded IIR
  - Uses $1-2^{-k}$ as coefficient and 2^{-k} for bit growth scaling (bit shifts)
  - Dynamically configurable k
  - Cutoff goes as ~ factors of 2

$$H(z) = \frac{N(z)}{D(z)} = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2} + \ldots + b_M z^{-M}}{1 + a_1 z^{-1} + a_2 z^{-2} + \ldots + a_N z^{-N}}$$

TABLE 1 NORMALIZED BANDWIDTH AND RISE TIME FOR VARIOUS VALUES OF k

k	Bandwidth (normalized to 1 Hz)	Rise time (samples)
1	0.1197	Three
2	0.0466	Eight
3	0.0217	16
4	0.0104	34
5	0.0051	69
6	0.0026	140
7	0.0012	280

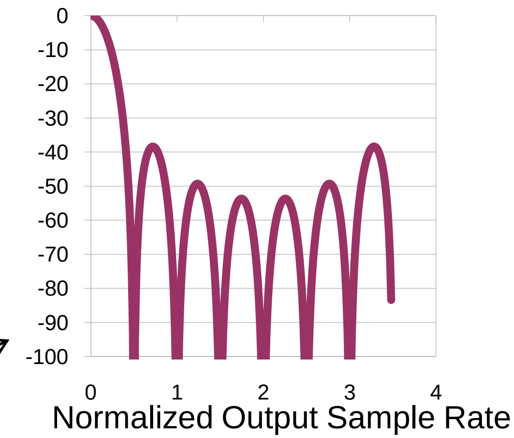
k Value	Bandwidth	k Value	Bandwidth
0 (none)	4.7 MHz	12	2.2 kHz
1	3.8 MHz	13	1.1 kHz
2	2.3 MHz	14	548 Hz
3	1.2 MHz	15	275 Hz
4	560 kHz	16	137 Hz
5	290 kHz	17	69 Hz
6	140 kHz	18	34 Hz
7	71 kHz	19	17 Hz
8	35 kHz	20	9 Hz
9	18 kHz	21	4 Hz
10	8.8 kHz	22	2 Hz
11	4.4 kHz	23	1 Hz

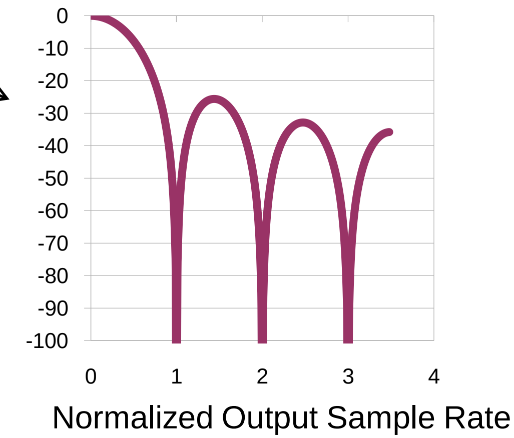


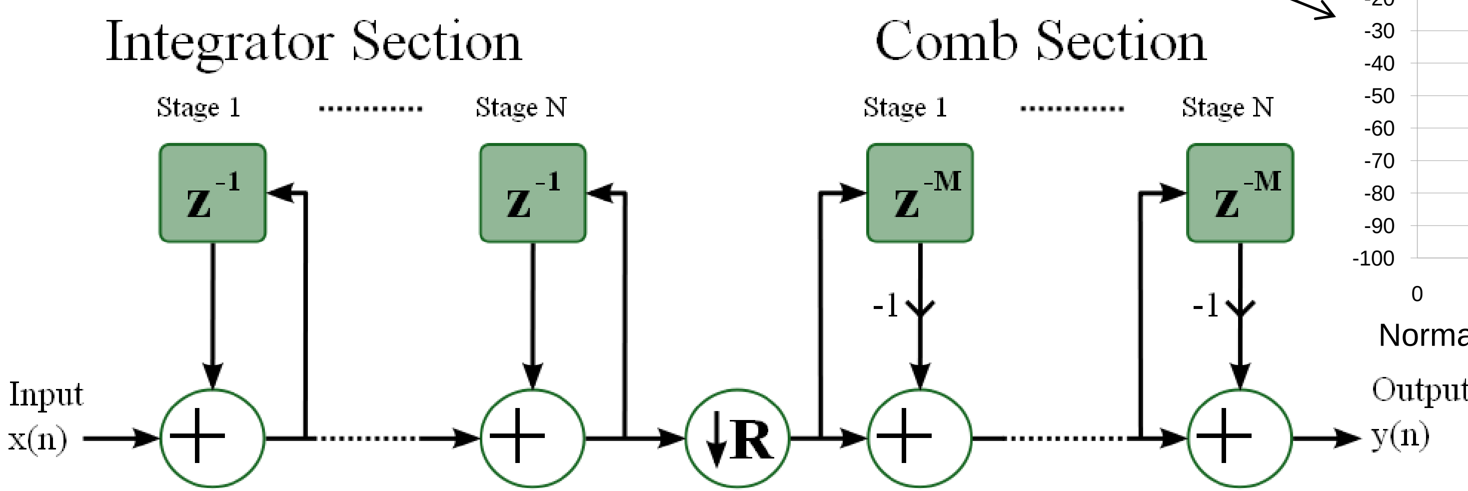
Digital Signal Processing Tools

<u>CIC (Cascaded Integrated Comb)</u>

- Good for decimation
- Sign extend for bit growth, G = (R * M) ^N
- Pick a combination that gives a factor of 2
  - R=4, M=2, N=3, G=512 (shift 9 bits)
  - R=8, M=1, N=2, G=64 (shift 6 bits)

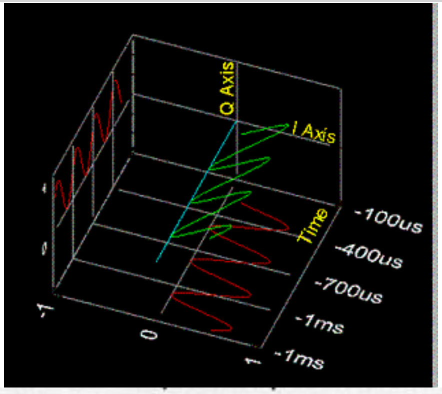




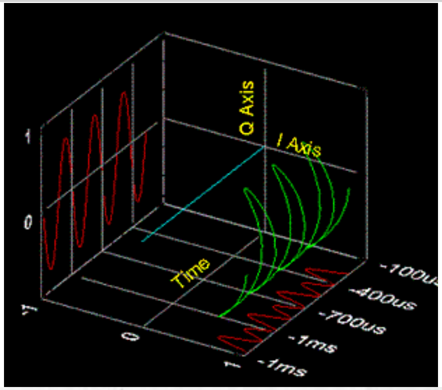


Decimating cascaded integrator-comb (CIC) filter; N stages, R decimation, M delays

Cartesian vs. Polar Coordinates



- Hard to control SEL in I&Q due to spinning phase (frequency detuning)
- Magnitude & Phase preferred
  - More intuitive
  - Simpler equations

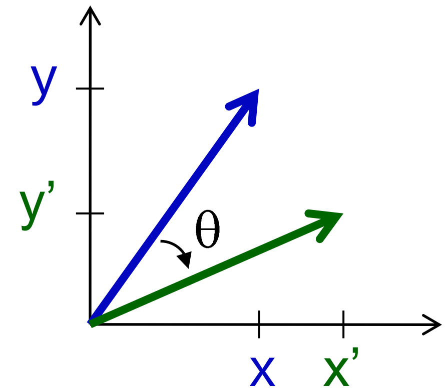


Type of Modulation	Mapping Functions $g[m]$	Corresponding Quadrature Modulation		Corresponding Amplitude and Phase Modulation		Linearity	Remarks
		$x(t)$	$y(t)$	$R(t)$	$\theta(t)$		
AM	$1 + m(t)$	$1 + m(t)$	0	$\lvert 1 + m(t)\rvert$	$\begin{cases} 0, & m(t) > -1 \\ 180°, & m(t) < -1 \end{cases}$	L[b]	$m(t) > -1$ required for envelope detection.
DSB-SC	$m(t)$	$m(t)$	0	$\lvert m(t)\rvert$	$\begin{cases} 0, & m(t) > 0 \\ 180°, & m(t) < 0 \end{cases}$	L	Coherent detection required.
PM	$e^{jD_p m(t)}$	$\cos[D_p m(t)]$	$\sin[D_p m(t)]$	1	$D_p m(t)$	NL	D_p is the phase deviation constant (radian/volts).
FM	$e^{jD_f \int_{-\infty}^{t} m(\sigma)d\sigma}$	$\cos\left[D_f \int_{-\infty}^{t} m(\sigma)d\sigma\right]$	$\sin\left[D_f \int_{-\infty}^{t} m(\sigma)d\sigma\right]$	1	$D_f \int_{-\infty}^{t} m(\sigma)d\sigma$	NL	D_f is the frequency deviation constant (radian/volt-sec).
SSB-AM-SC[a]	$m(t) \pm j\hat{m}(t)$	$m(t)$	$\pm\hat{m}(t)$	$\sqrt{[m(t)]^2 + [\hat{m}(t)]^2}$	$\tan^{-1}[\pm\hat{m}(t)/m(t)]$	L	Coherent detection required.
SSB-PM[a]	$e^{jD_p[m(t) \pm j\hat{m}(t)]}$	$e^{\mp D_p\hat{m}(t)}\cos[D_p m(t)]$	$e^{\mp D_p\hat{m}(t)}\sin[D_p m(t)]$	$e^{\mp D_p\hat{m}(t)}$	$D_p m(t)$	NL	
SSB-FM[a]	$e^{jD_f\int_{-\infty}^{t}[m(\sigma) \pm j\hat{m}(\sigma)]d\sigma}$	$e^{\mp D_f\int_{-\infty}^{t}\hat{m}(\sigma)d\sigma}\cos\left[D_f \int_{-\infty}^{t} m(\sigma)d\sigma\right]$	$e^{\mp D_f\int_{-\infty}^{t}\hat{m}(\sigma)d\sigma}\sin\left[D_f \int_{-\infty}^{t} m(\sigma)d\sigma\right]$	$e^{\mp D_f\int_{-\infty}^{t}\hat{m}(\sigma)d\sigma}$	$D_f \int_{-\infty}^{t} m(\sigma)d\sigma$	NL	
SSB-EV[a]	$e^{\{\ln[1+m(t)] \pm j\hat{\ln}[1+m(t)]\}}$	$[1 + m(t)]\cos\{\hat{\ln}[1 + m(t)]\}$	$\pm[1 + m(t)]\sin\{\hat{\ln}[1 + m(t)]\}$	$1 + m(t)$	$\pm\hat{\ln}[1 + m(t)]$	NL	$m(t) > -1$ is required so that the ln (·) will have a real value.
SSB-SQ[a]	$e^{(1/2)\{\ln[1+m(t)] \pm j\hat{\ln}[1+m(t)]\}}$	$\sqrt{1 + m(t)}\cos\{\frac{1}{2}\hat{\ln}[1 + m(t)]\}$	$\pm\sqrt{1 + m(t)}\sin\{\frac{1}{2}\hat{\ln}[1 + m(t)]\}$	$\sqrt{1 + m(t)}$	$\pm\frac{1}{2}\hat{\ln}[1 + m(t)]$	NL	$m(t) > -1$ is required so that the ln (·) will have a real value.
QM	$m_1(t) + jm_2(t)$	$m_1(t)$	$m_2(t)$	$\sqrt{m_1^2(t) + m_2^2(t)}$	$\tan^{-1}[m_2(t)/m_1(t)]$	L	Used in NTSC color television; requires coherent detection.

Digital Signal Processing Tools

<u>Rotation Matrix</u>

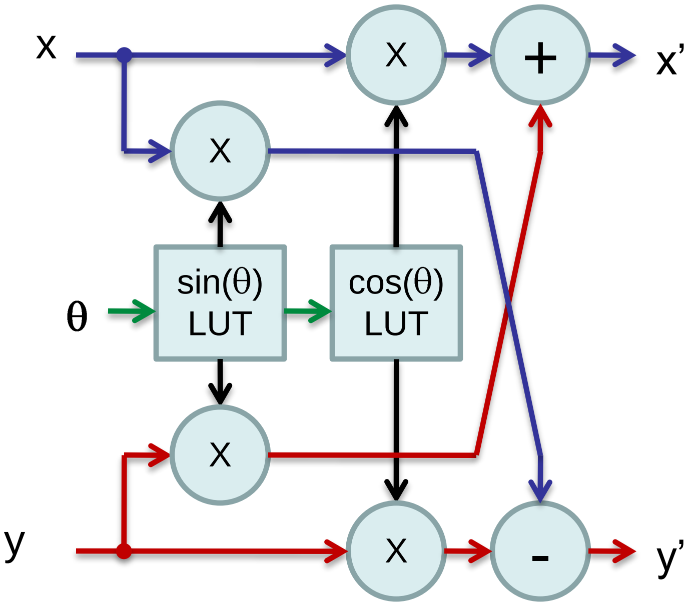
- Cartesian (I&Q) phase shifter
- Look-up-tables for sin(θ) & cos(θ)
- LUT and multipliers can be reused if multiple clock cycles are available (sin(θ) & cos(θ) are 90º apart)



$$[x', y'] = [x, y] \cdot \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

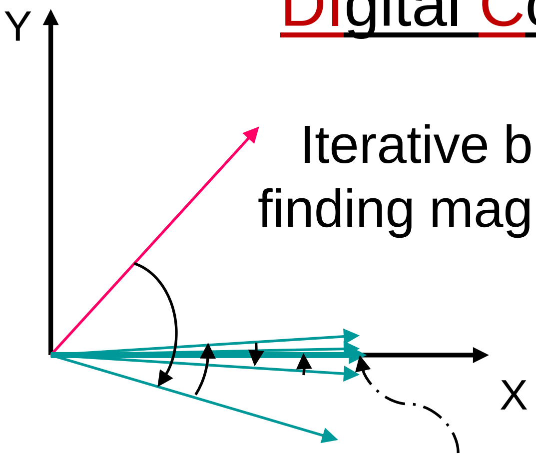
$$\rightarrow \quad x' = x\cos\theta + y\sin\theta$$

$$y' = y\cos\theta - x\sin\theta$$



Digital Signal Processing Tools

COordinate Rotation DIgital Computer



Iterative binary search for finding magnitude and phase

Angle	Tan()	Nearest 2^{-n}	Atan()
45	1.0	1	45
22.5	0.414	0.5	26.57
11.25	0.199	0.25	14.04
5.625	0.0985	0.125	7.125
2.8125	0.0491	0.0625	3.576
1.40625	0.0245	0.03125	1.790
0.703125	0.0123	0.015625	0.8952

Divide accumulated X&Y values by 2^{-i} (right shift by i) then add or subtract to/from the opposing Y&X depending if the rotated vector was positive or negative for that iteration

Resultant lies on X axis with residual gain of 1.6 due to approximations (K_i)

$$\phi = \sum_i d_i \cdot \arctan(2^{-i})$$

$$d_i = \begin{cases} +1, & if\ y_i < 0 \\ -1, & if\ y_i \geq 0 \end{cases}$$

$$[x', y'] = [x, y] \cdot \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

$$x_{i+1} = K_i\left(x_i - y_i \cdot d_i \cdot 2^{-i}\right)$$

$$y_{i+1} = K_i\left(y_i + x_i \cdot d_i \cdot 2^{-i}\right)$$

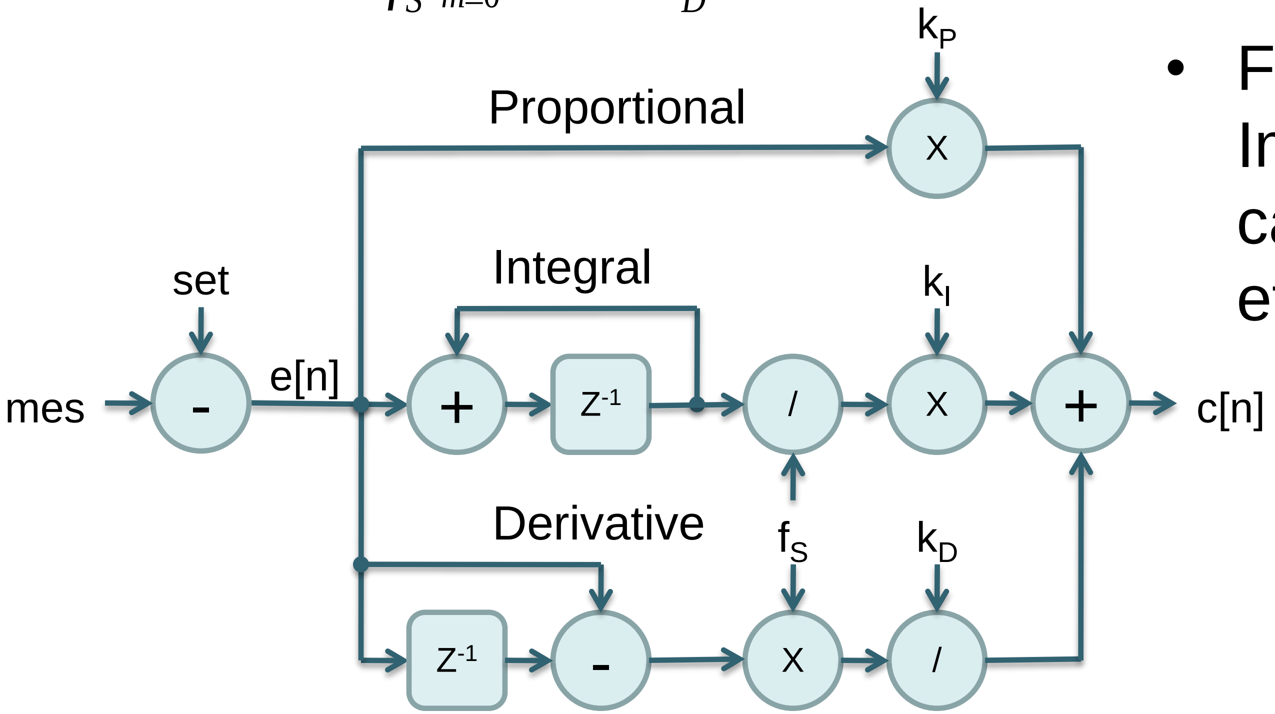
Add the positive and negative angle rotations to calculate the vector angle

Digital Signal Processing Tools

PID Controller

$$c(t) = k_P e(t) + k_I \int_0^t e(\tau)\,d\tau + k_D \frac{d}{dt} e(t)$$

$$c(n) = k_P e[n] + \frac{k_I}{f_S} \sum_{m=0}^{n} e[m] + \frac{f_S}{k_D}(e[n] - e[n-1])$$

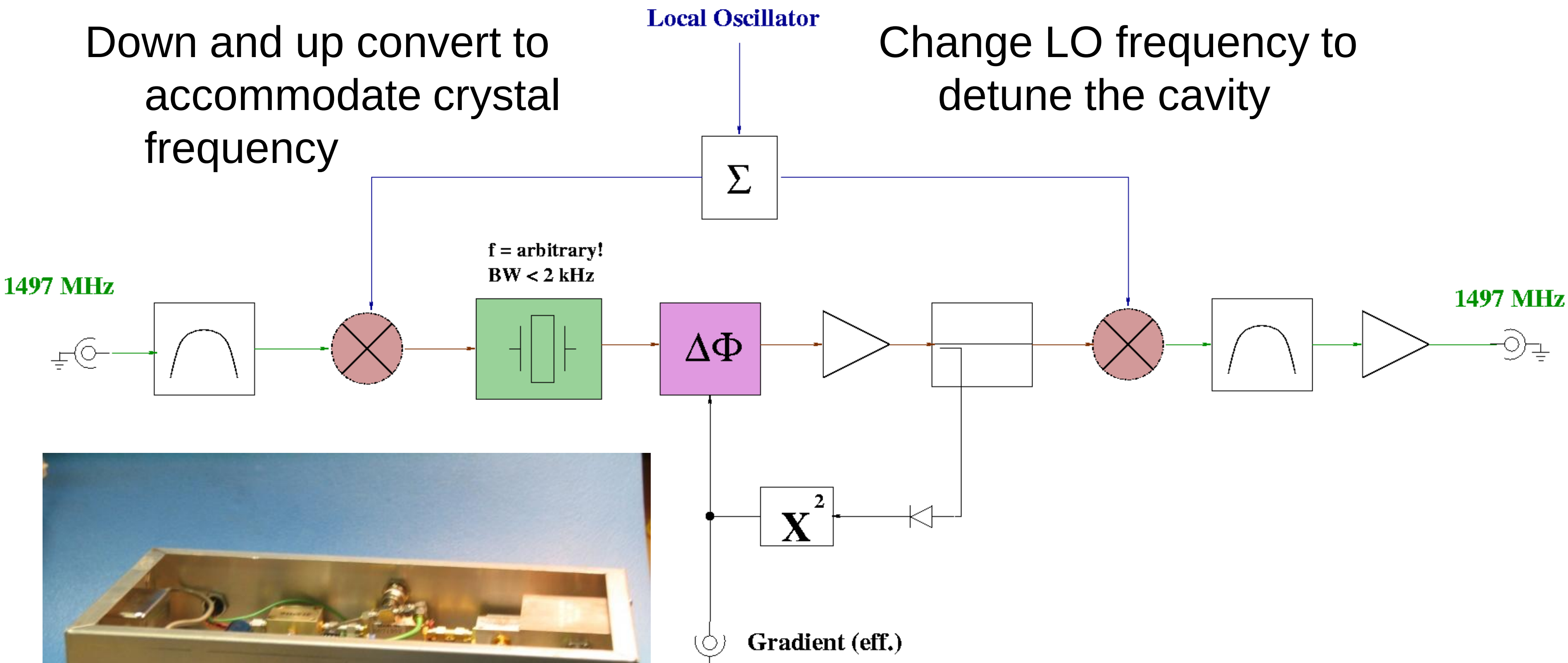


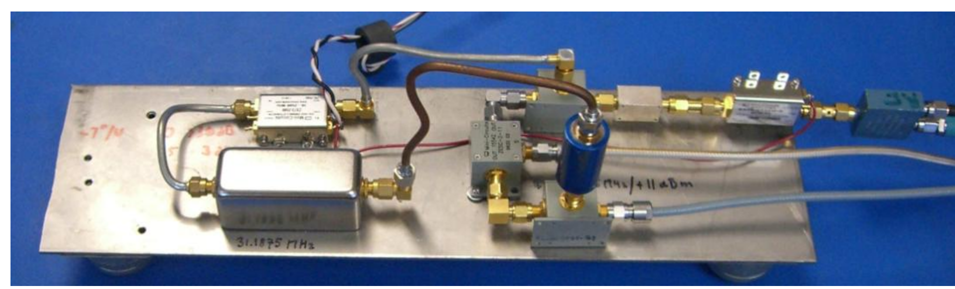
- Classic method works well
- Only P and I have been used but D is available
- Firmware Implementation can be more efficient

Analog Cavity Emulator

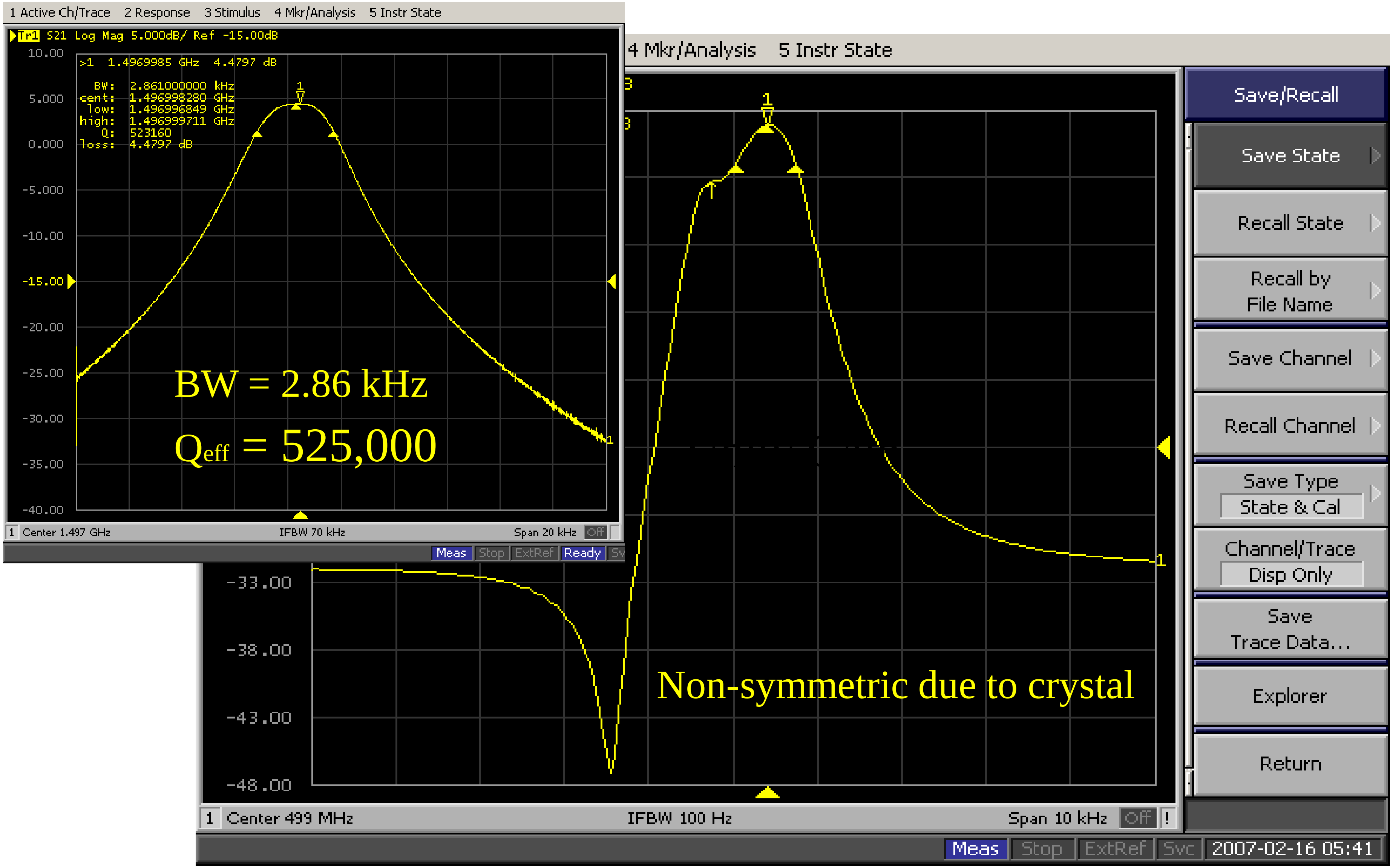
Down and up convert to accommodate crystal frequency

Change LO frequency to detune the cavity

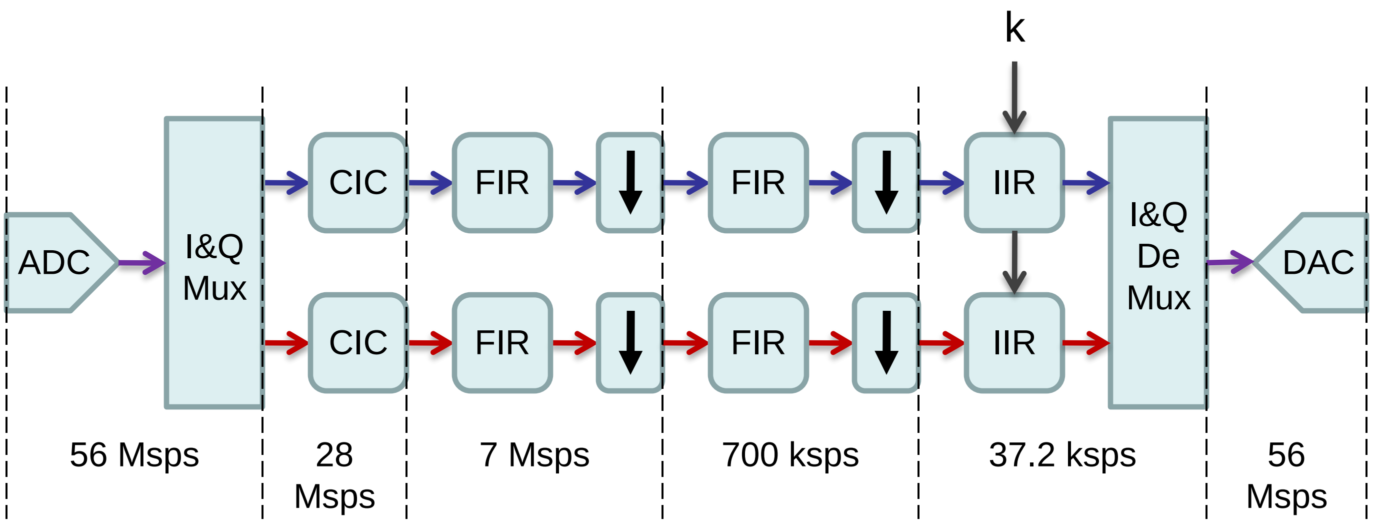


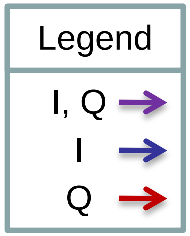


Analog Cavity Emulator



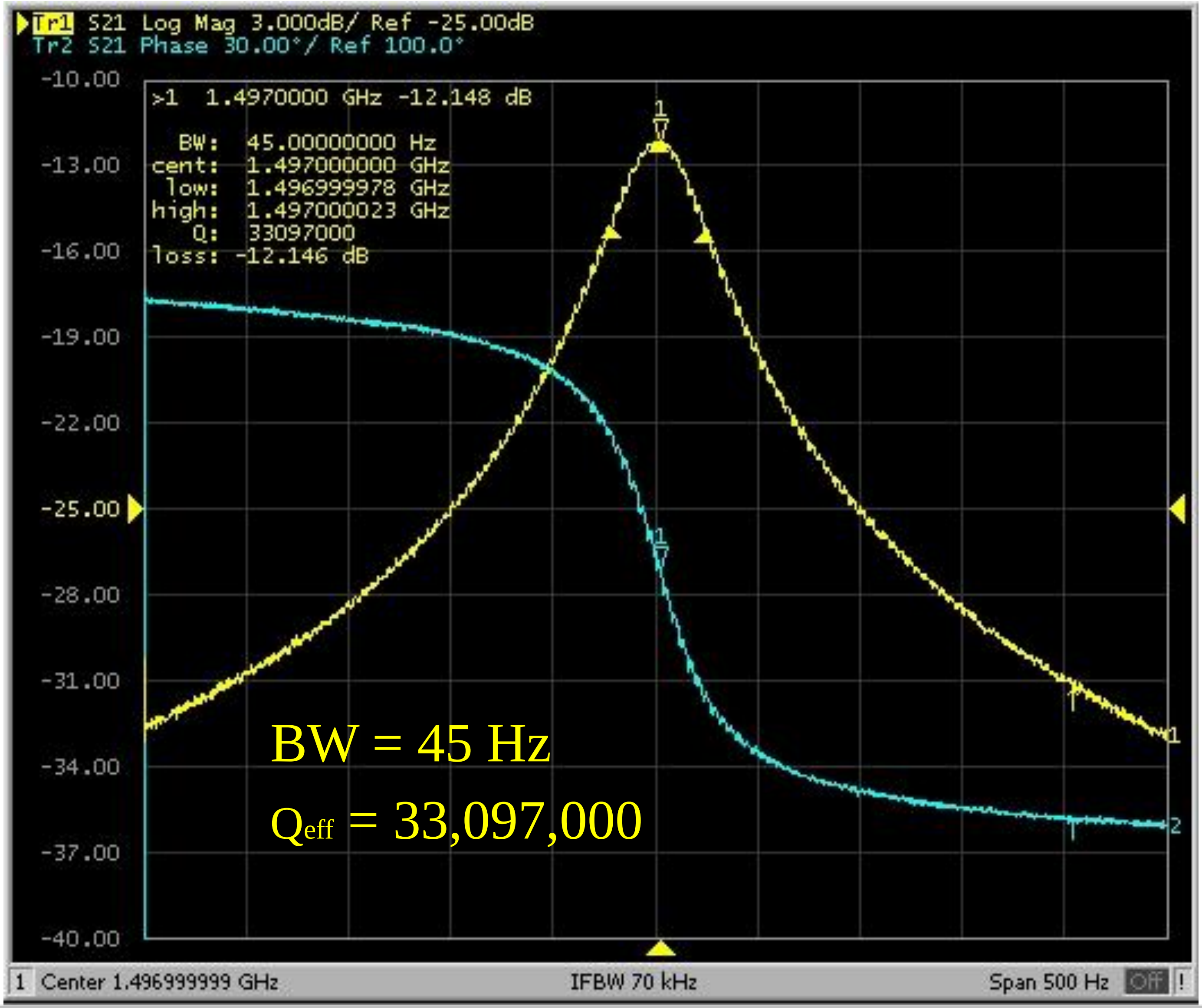
Digital Cavity Emulator





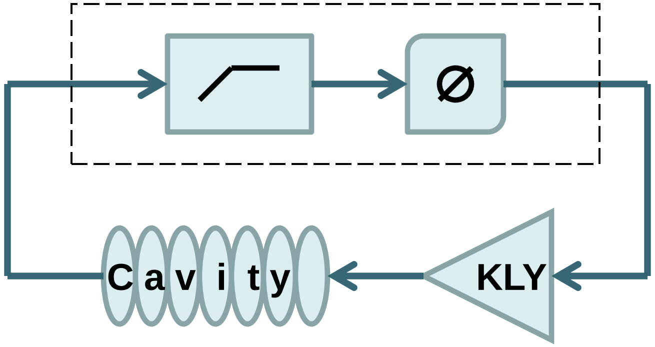
- CIC: N stages=2, R decimation =4, M delays=1
- FIR: 33 taps, ~0.05 normalized cutoff
- Sample rates are dynamically adjustable for each stage as well as IIR (k=8: 0.0007 normalized cutoff)
- Tweak the sample rate of the last section (37.2 ksps) to give exactly a 45 Hz filter (Q_{loaded}=3.3x10^7)

Digital Cavity Emulator



Digital SEL Algorithm Development

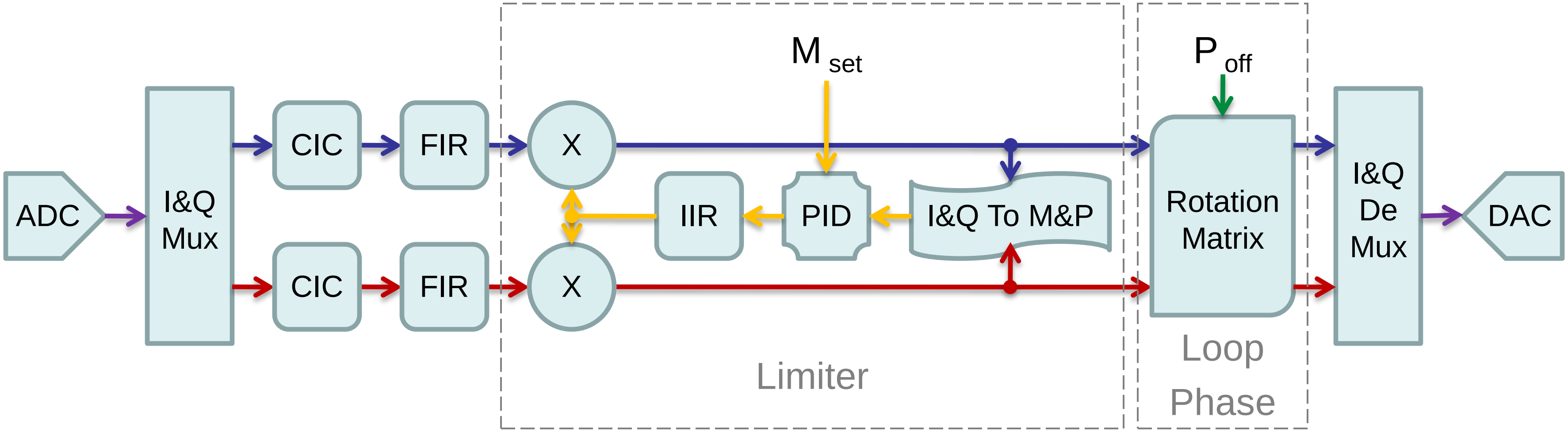
Analog Self Excited Loop

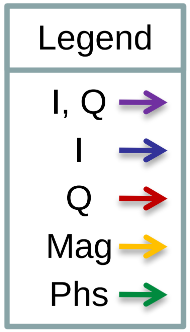


- Noise amplified by klystron then filtered by the cavity
- Limiter amplifies and clips the cavity tone
- Loop phase shifter provides positive feedback to build resonance
- Digitally implement what is in the dashed box
  - Limiter (AGC, Normalizer, or Phase Pass)
  - Loop phase shifter (Rotation Matrix or CORDICs)

Digital SEL Algorithm Development

Automatic Gain Control

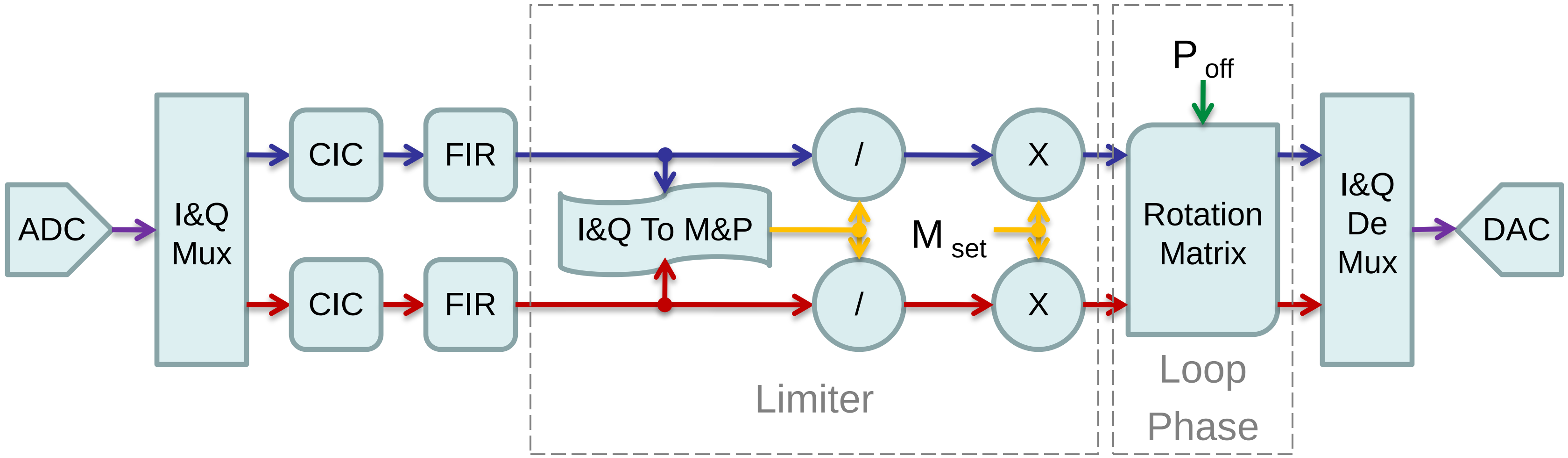


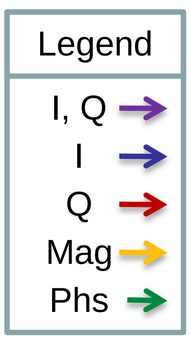


- PID Control to stabilize output magnitude
- Tuning the PID control loop was problematic
- Worked as a proof of concept
- Slow lock time

Digital SEL Algorithm Development

Normalizer

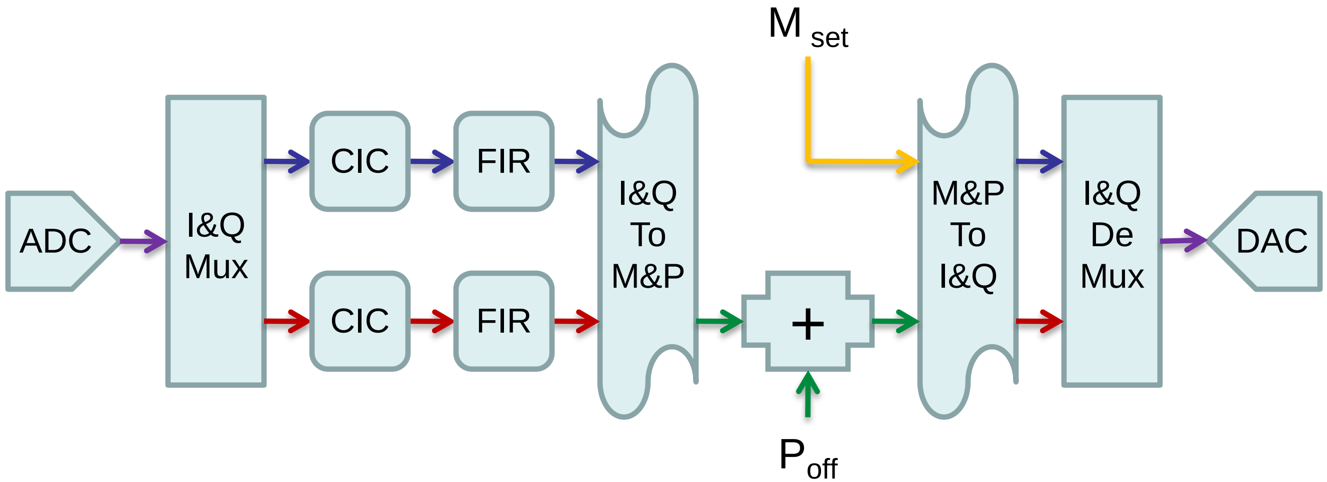


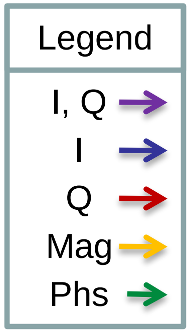


- Divide by the magnitude to normalize to 1
- Multiply I&Q by the magnitude set point
- Fixed point division causes errors and noise
- Limited operating range, setup dependent

Digital SEL Algorithm Development

☝ Phase Pass ☝

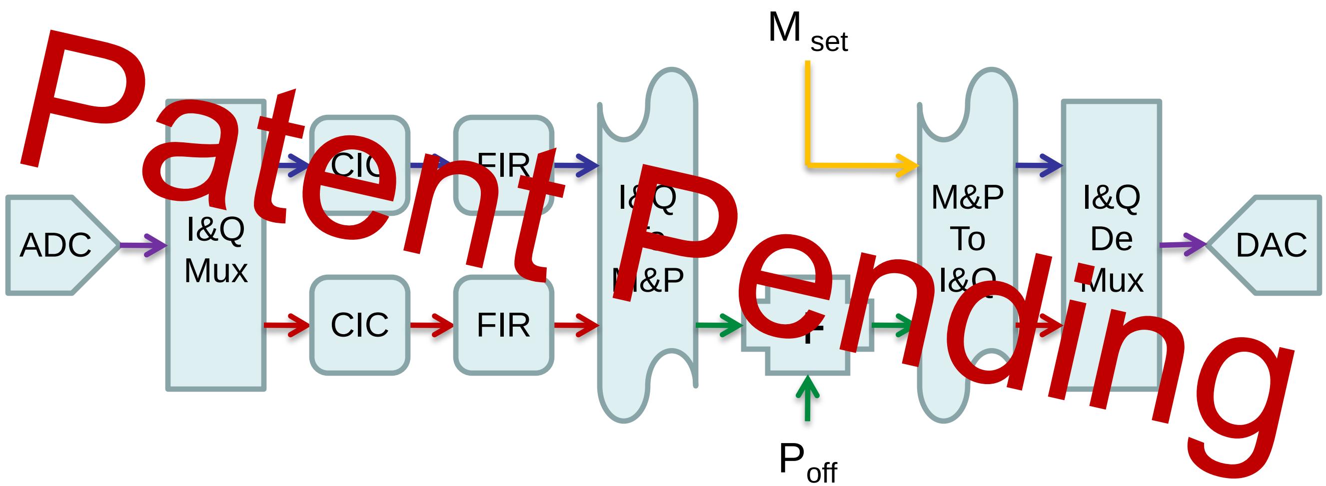


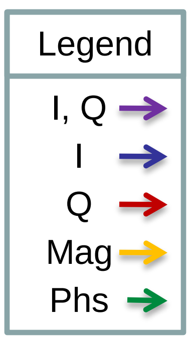


- 2nd CORDIC converts Mag & Phase to I&Q
- Set Magnitude directly
- Pass frequency info (phase) w/ loop delay
- Fast, stable, intuitive, and simple

Digital SEL Algorithm Development

Phase Pass





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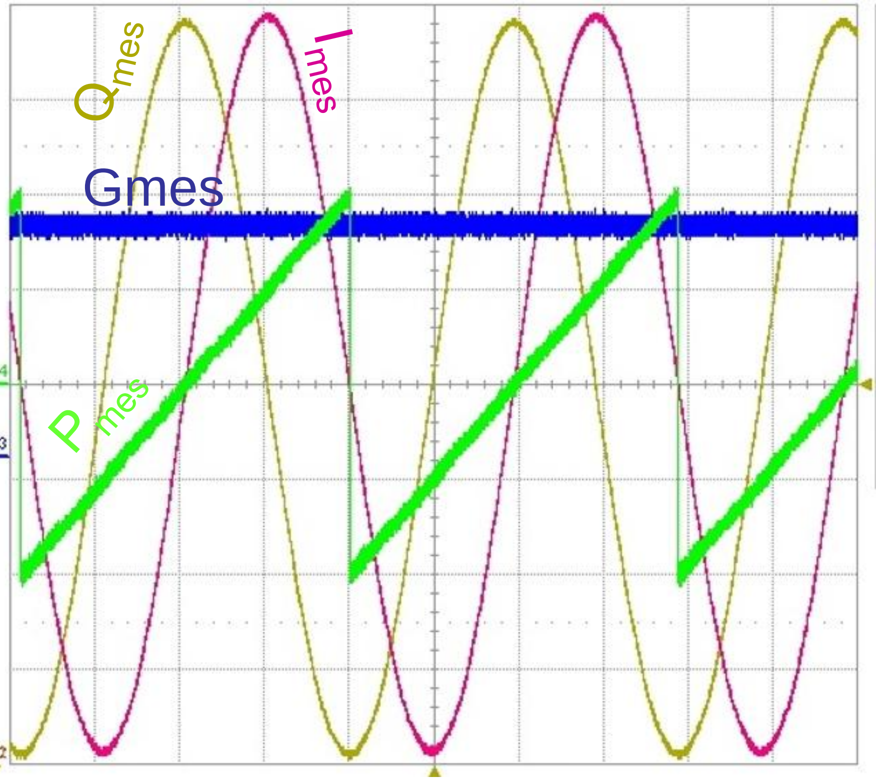
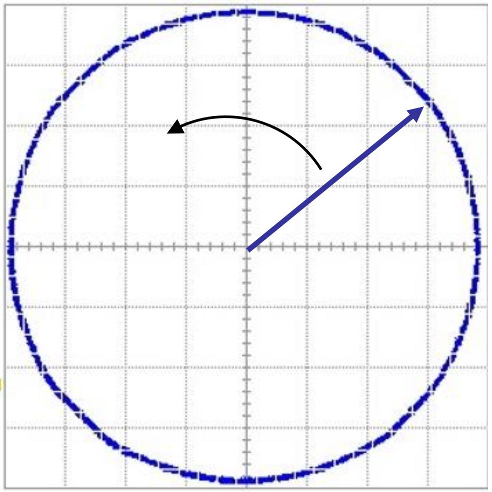
Digital SEL SRF Cavity Testing

- Measured magnitude, phase, I, and Q sent to diagnostic DACs and plotted on scope
  - When SELin', phase rolls and magnitude is constant
  - I & Q are sinusoidal with a 90º phase shift
- Detuned cavity +/-50 kHz and tracked it with the SEL

Digital SEL Steady State





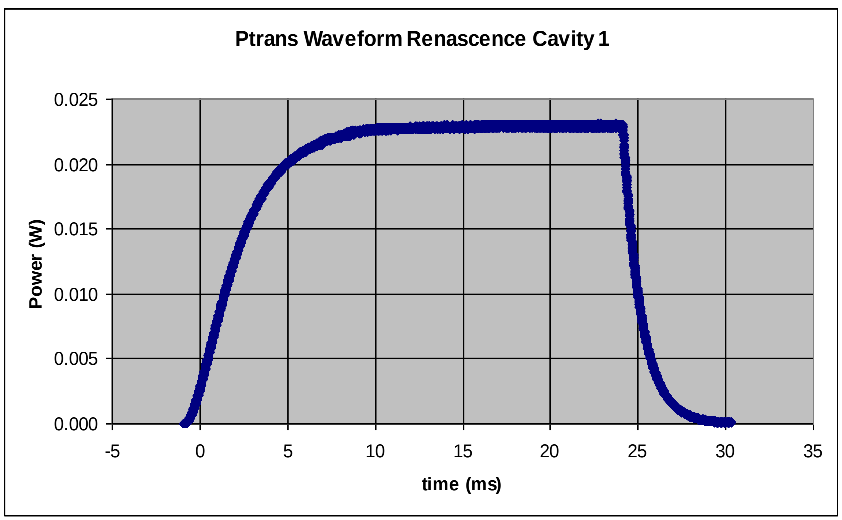
I_{mes} vs. Q_{mes}
Spinning vector at fixed magnitude

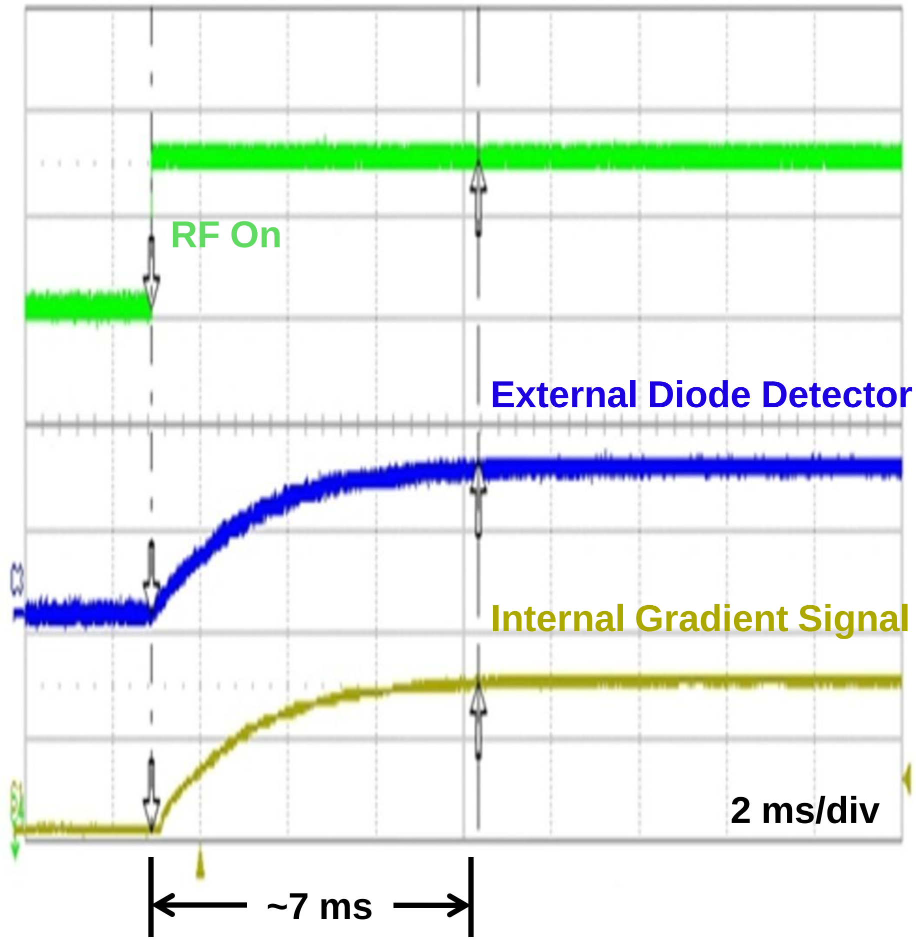
- Speed and direction of spin dependent on detuning
- Phase, I, and Q all flatten out if the cavity is tuned to 1497 MHz
- Can excite other pi modes by changing LO frequency

Digital SEL SRF Cavity Testing

- CMTF Tests on Renascence
- Turn-on of detuned cavity
  - Bringing RF up is only limited by cavity fill time
  - No excessive power needed

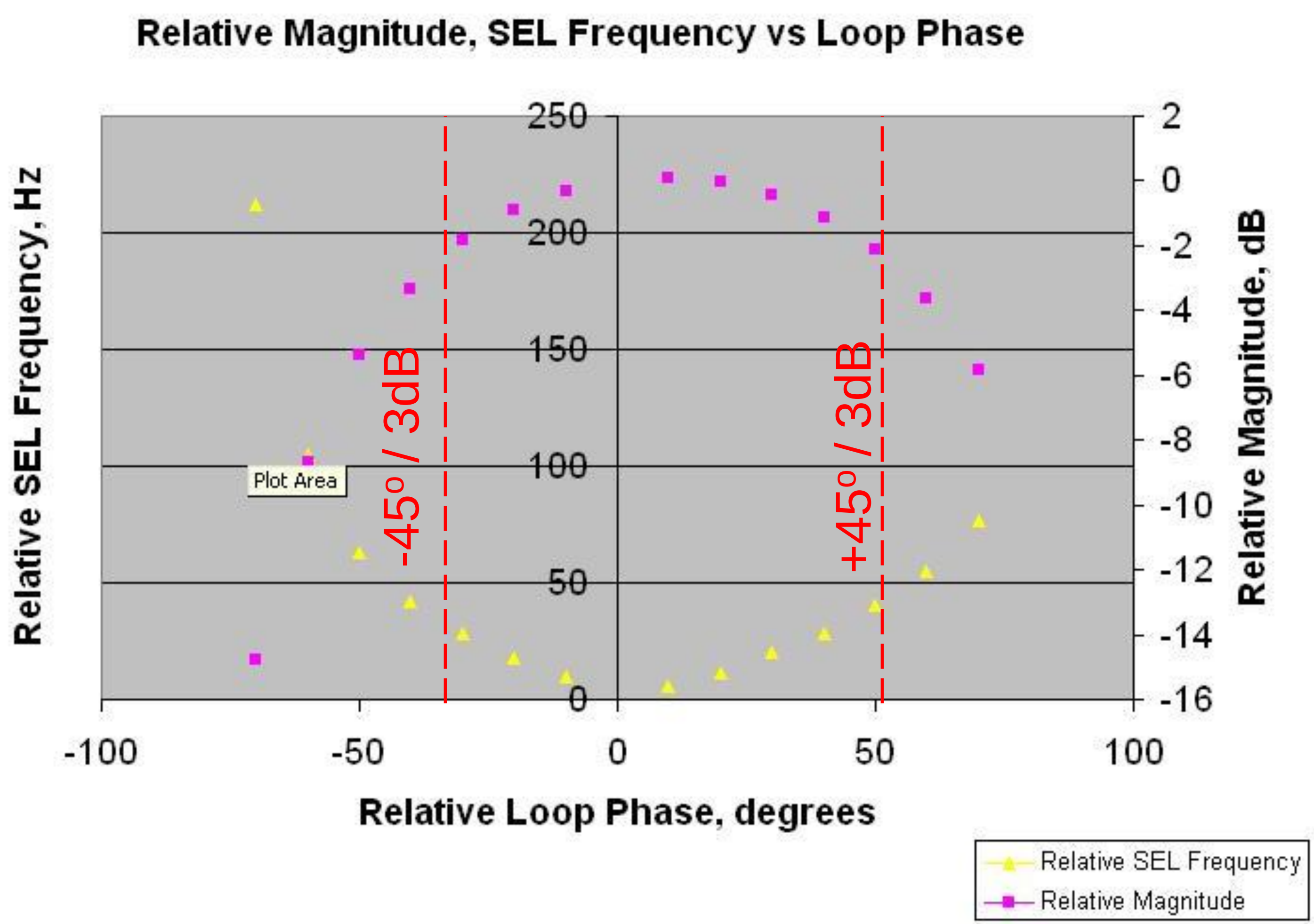
0 to 21 MV/m in 7 ms!



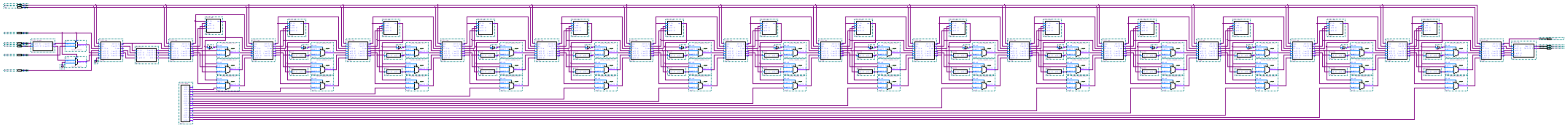


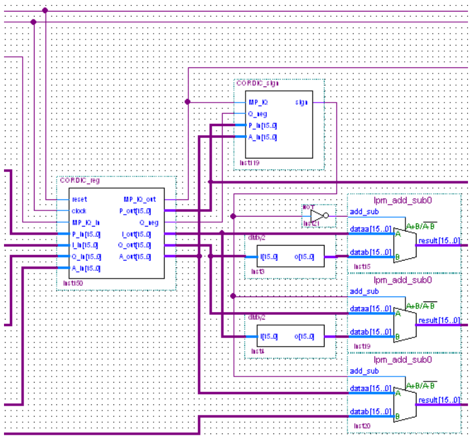
Digital SEL SRF Cavity Testing

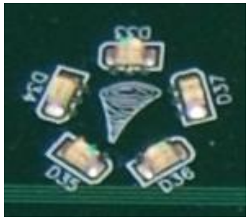
- Map cavity using loop phase
- +/-45^o shift corresponds to 3dB points
- Cavity BW ~45Hz ($Q=3.3x10^7$)
- Easy way to measure cavity Q



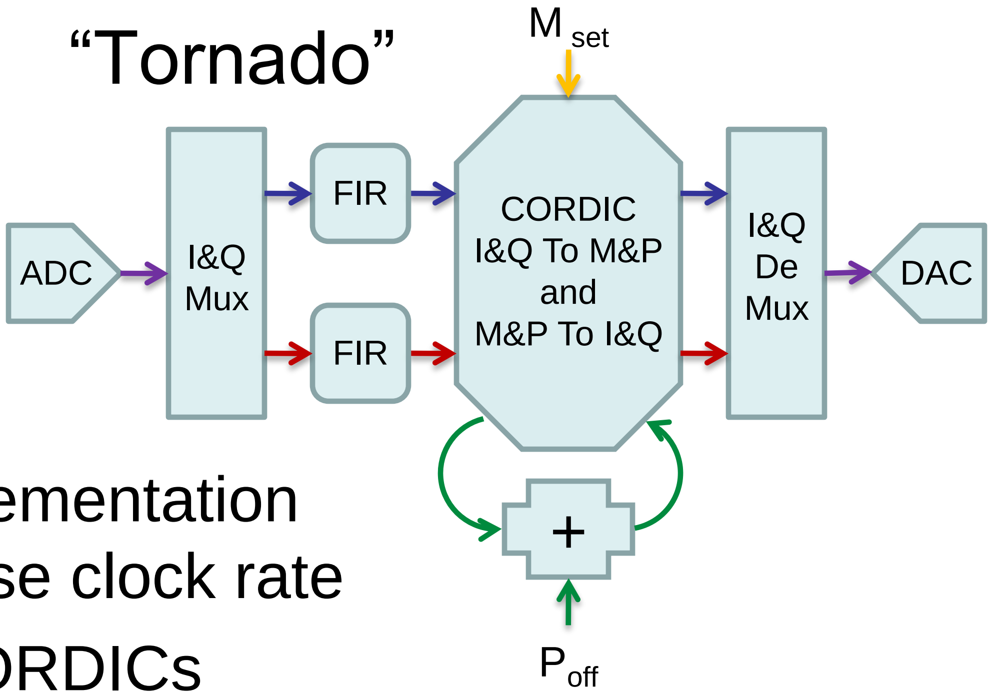
Digital SEL Firmware



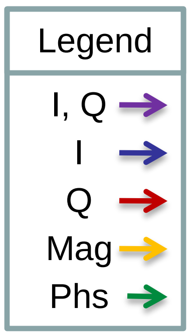




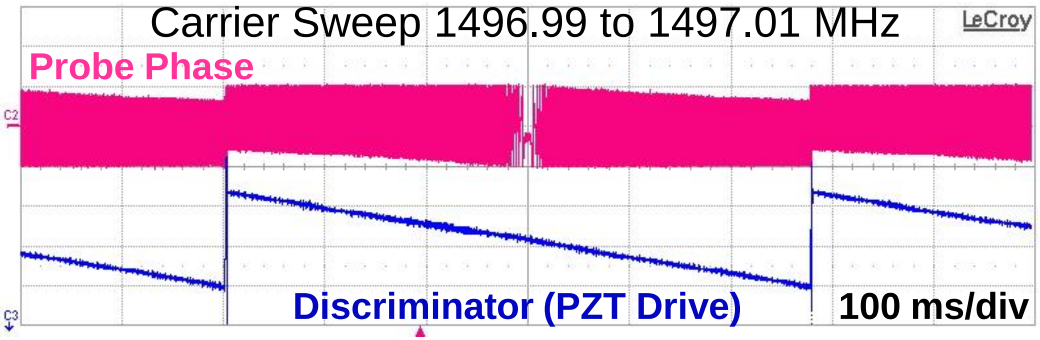
“Tornado”

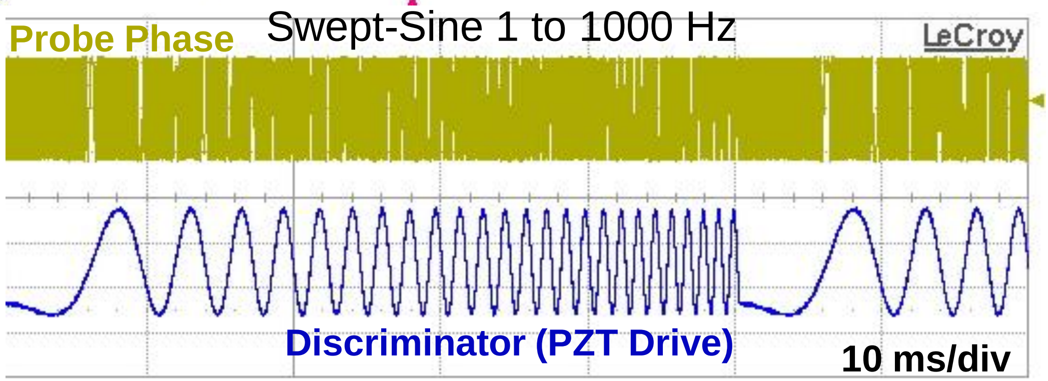


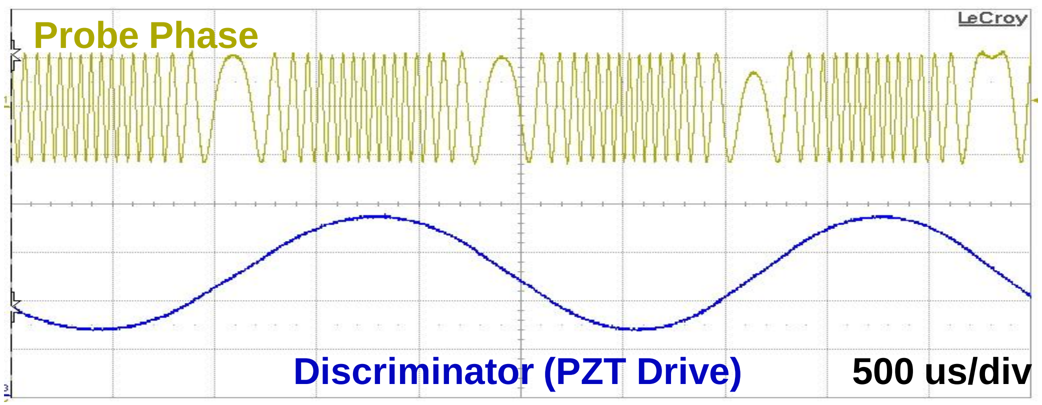
- Pipeline implementation to increase clock rate
- Interleave CORDICs
  - Reuse adds and subtracts, different decisions
  - 56 MHz clock (I&Q to M&P on even clock cycles and M&P to I&Q on odd clock cycles)

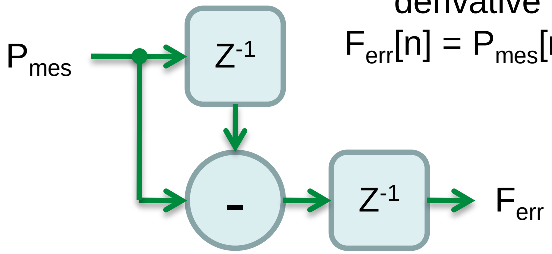


Frequency Discriminator Algorithm









Frequency is the derivative of phase

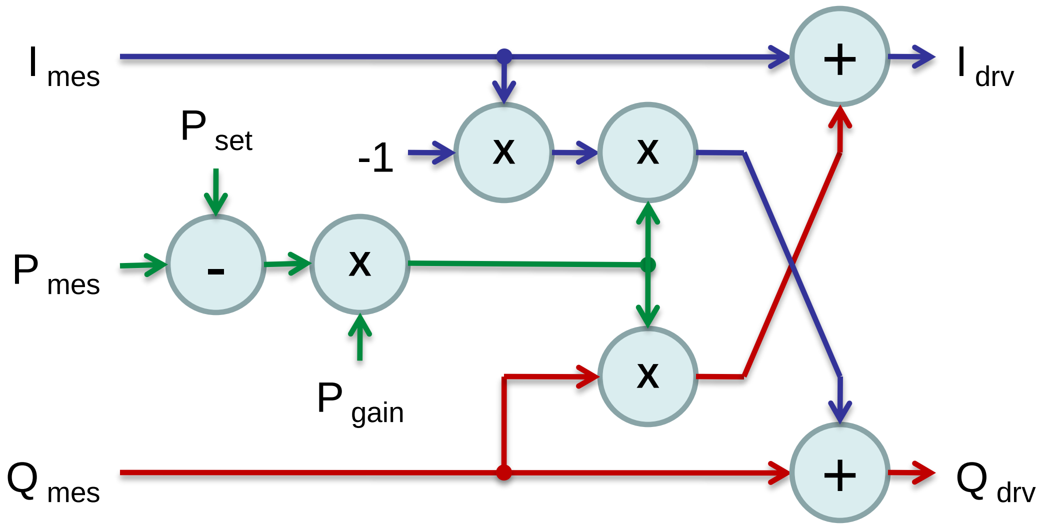
$F_{err}[n] = P_{mes}[n] - P_{mes}[n-1]$

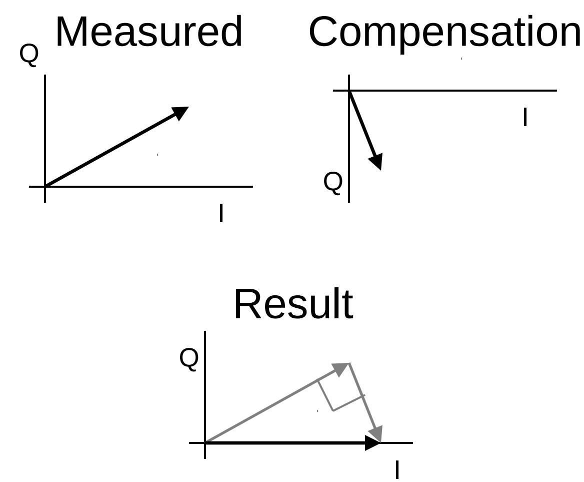
Register update rate is adjustable (dt)

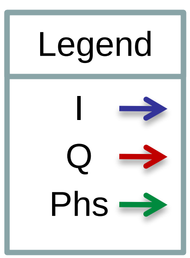
Measure the phase difference over time

- Configurable via EPICS
  - +/-40Hz to +/-2.5MHz
- Stepper Motor Channel
  - +/-150 kHz range
- PZT Channel
  - +/-1.5 kHz range

Microphonic Compensator



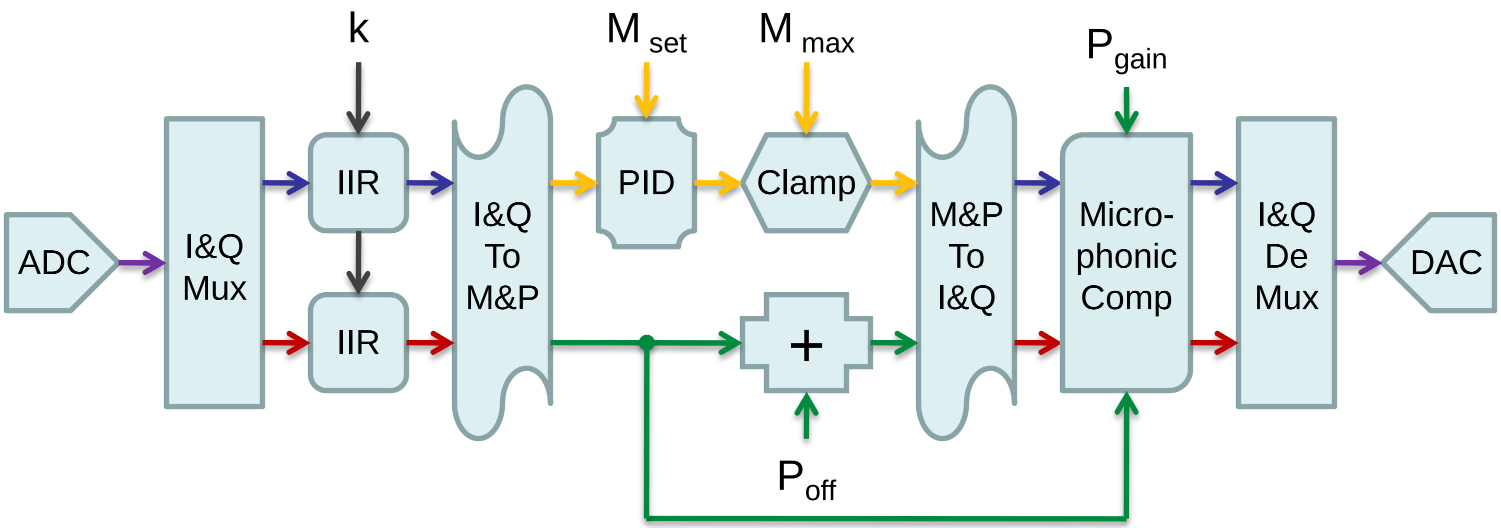


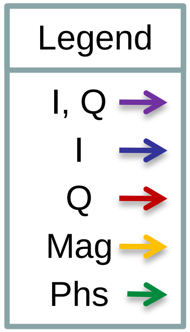


- Based on the phase error
  - Rotate the vector to compensate for detune
  - Add magnitude correction
- $I_{drv} = Q_{mes} * [P_{gain} * (P_{set} - P_{mes})]$
- $Q_{drv} = -I_{mes} * [P_{gain} * (P_{set} - P_{mes})]$

Control Algorithm Development

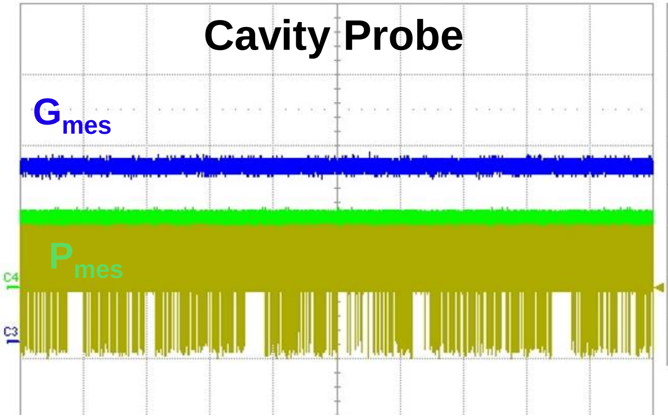
Microphonic Compensation & Magnitude Lock

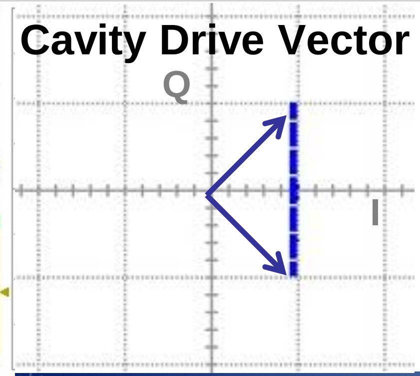




- Microphonic Compensator locks phase (~.5°)
- PID control of Magnitude needed
- Fought magnitude regulation issues (~.1%)
- Need I&Q clamp, yields up to $2^{1/2}$ magnitude

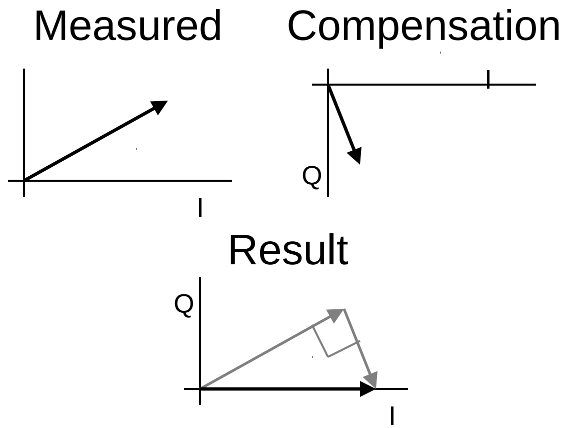
Control Algorithm Cavity Testing

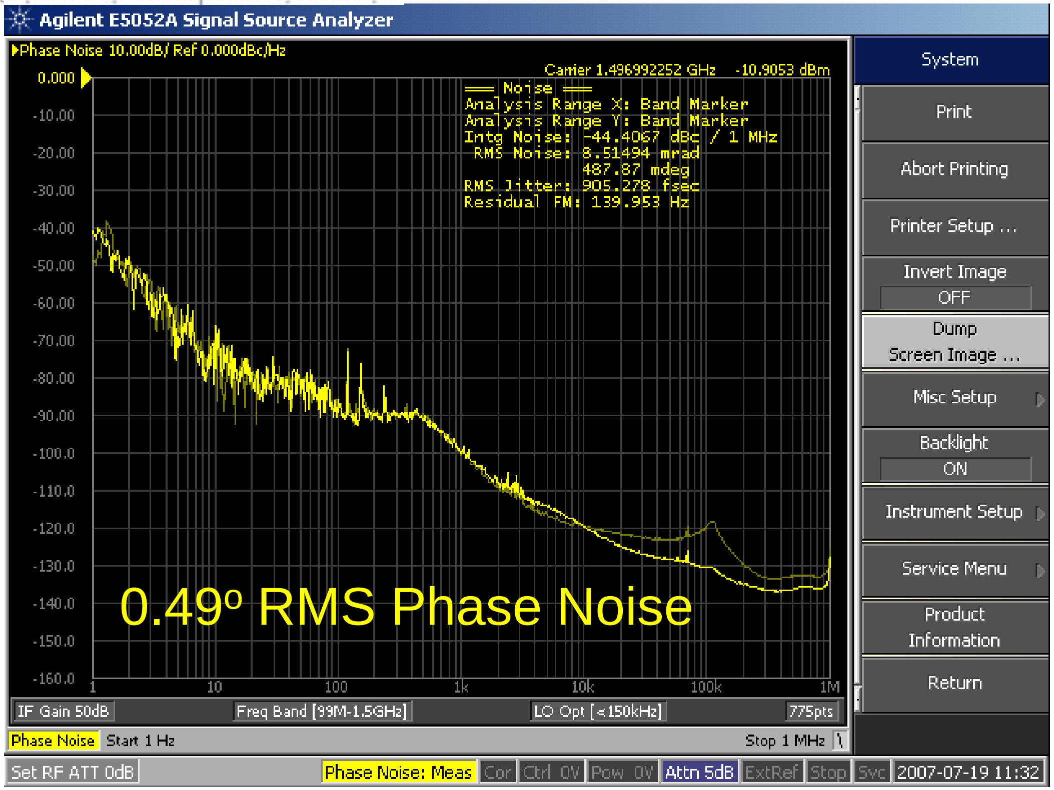




Microphonic Compensation

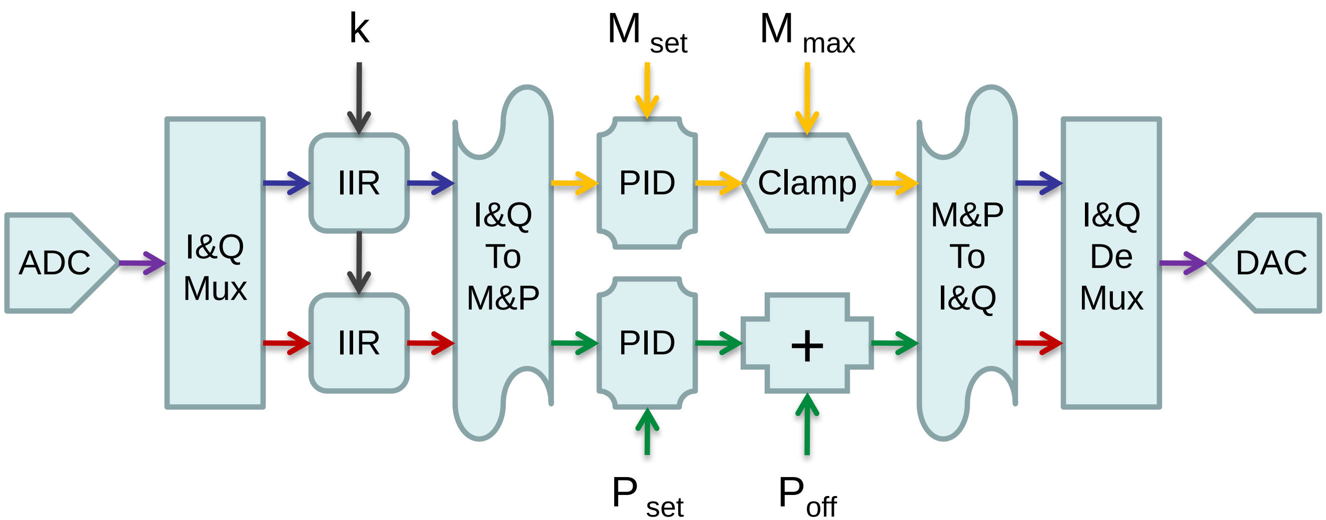
P_{mes} & G_{mes} are flat and drive is compensating for microphonics

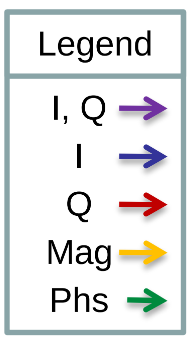




Control Algorithm Development

Magnitude & Phase Lock

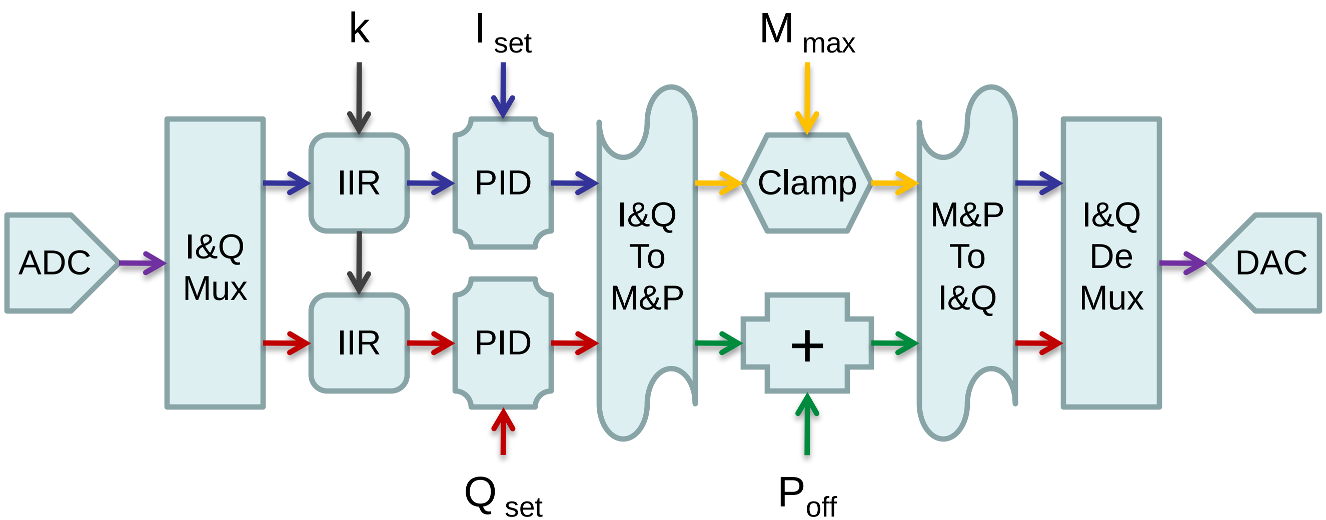


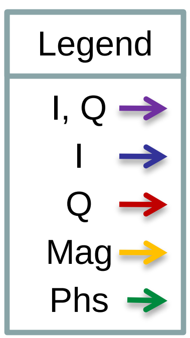


- PID control of Magnitude and Phase
- Phase rollover requires PID to be centered
- Logarithmic magnitude control needed to decouple performance from signal strength

Control Algorithm Development

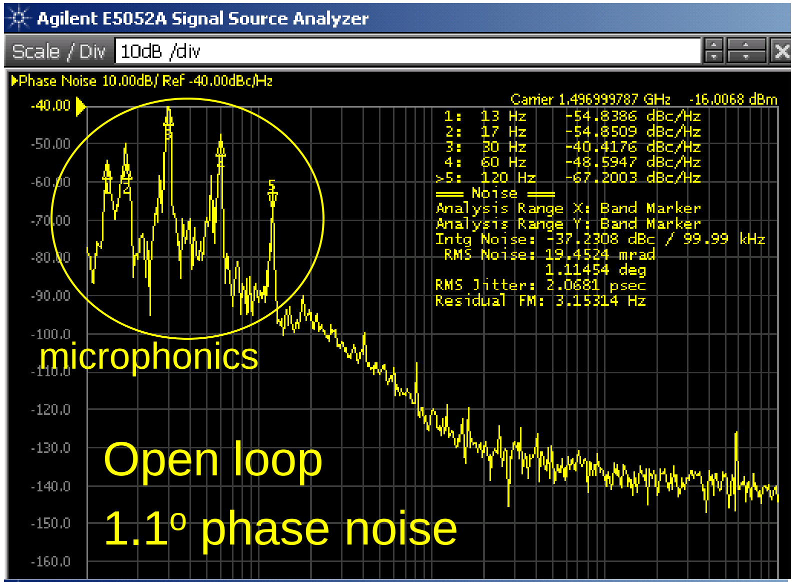
In-Phase & Quadrature Lock

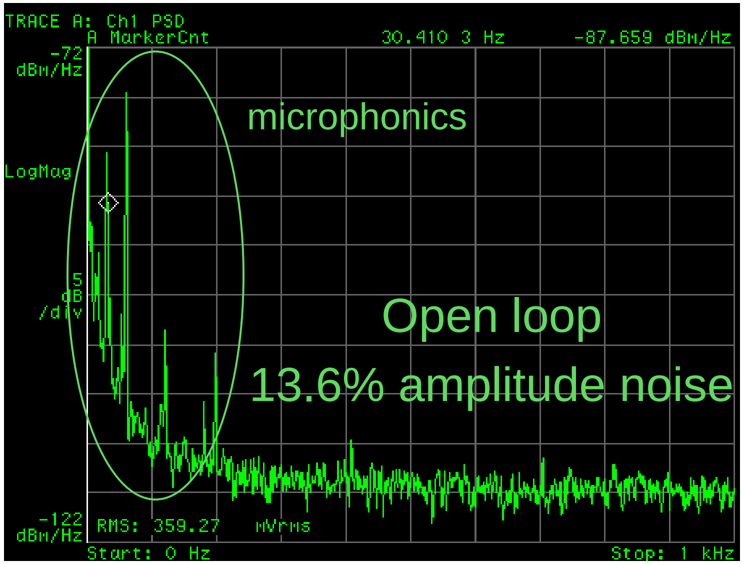




- PID control of In-Phase & Quadrature
- No phase rollover or logarithmic magnitude control issues
- Stable and meets specs (0.5º, 0.04%)

I&Q Lock Testing





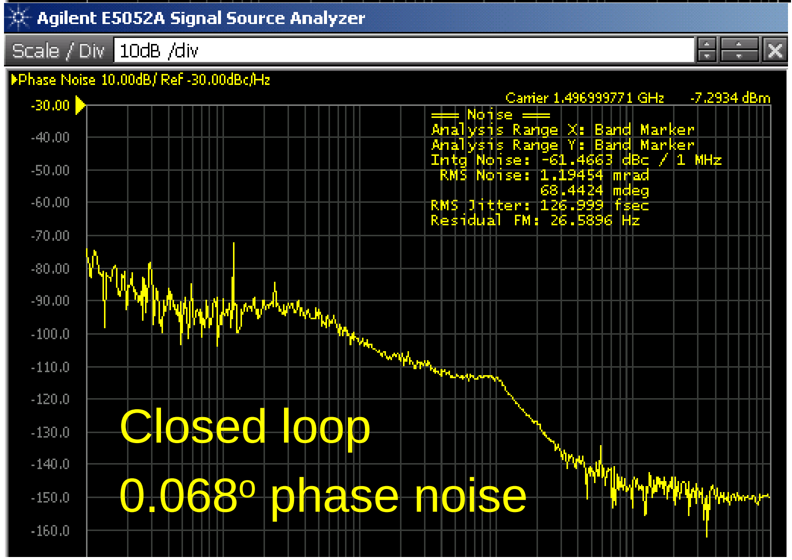
Renascence

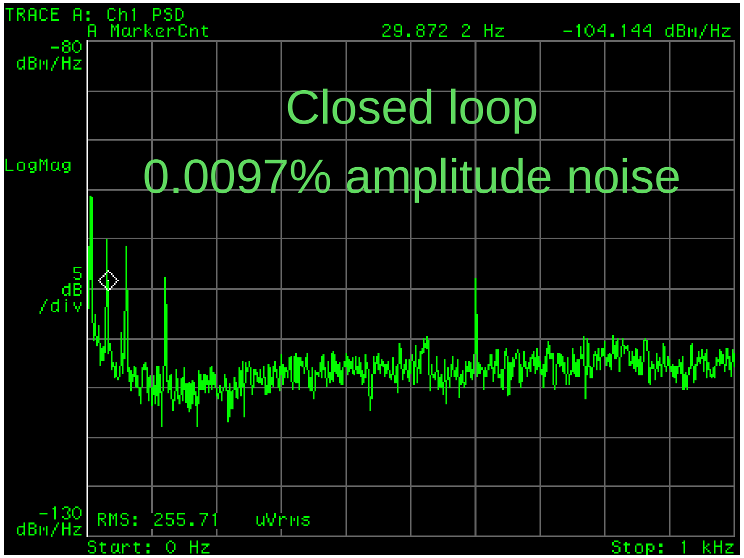
Q_L=8.6x10^6

Unregulated

vs.

Regulated

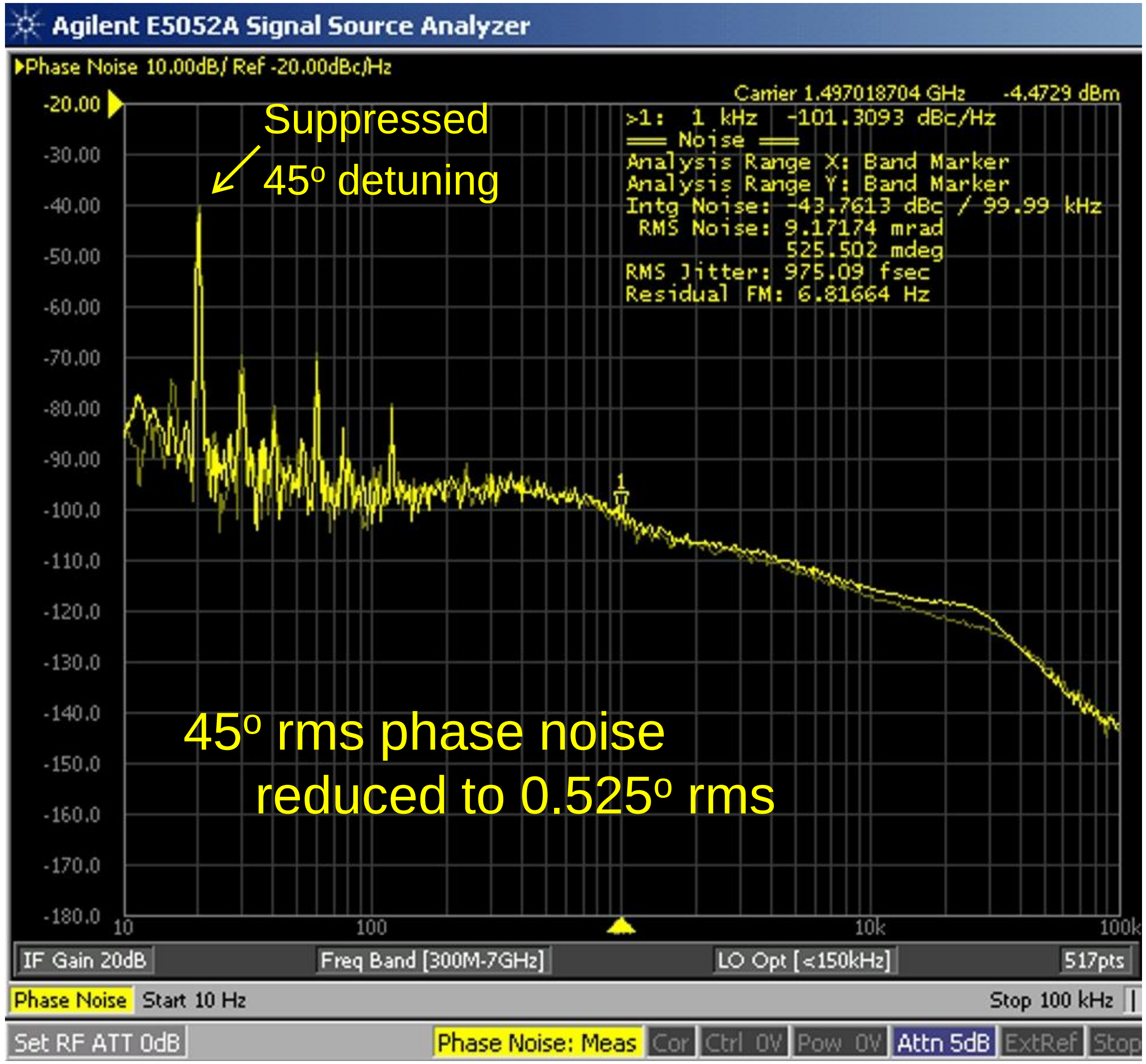




I&Q Lock Testing

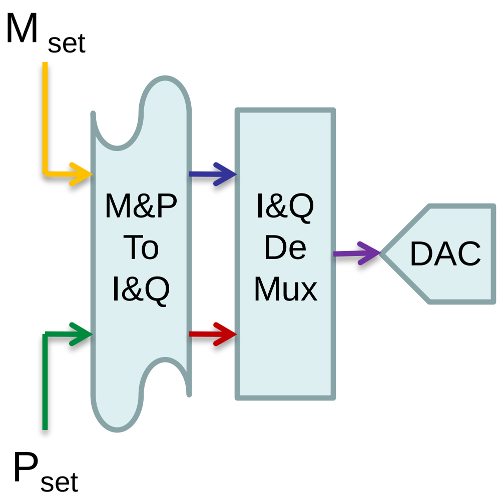
<u>Renascence Testing</u>

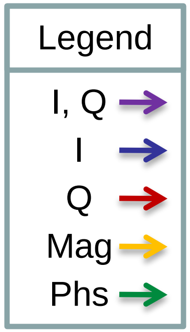
- Expect 4 Hz rms microphonics for C100 upgrade cavity
  - Worst case six sigma (24 Hz rms) corresponds to 45^{o} detuning for upgrade cavity
  - Piezo induced 45^{o} microphonics on Renascence
- System latency measured as 1.3 us
  - Hardware: 600 ns
  - Firmware: 700 ns



Other Features

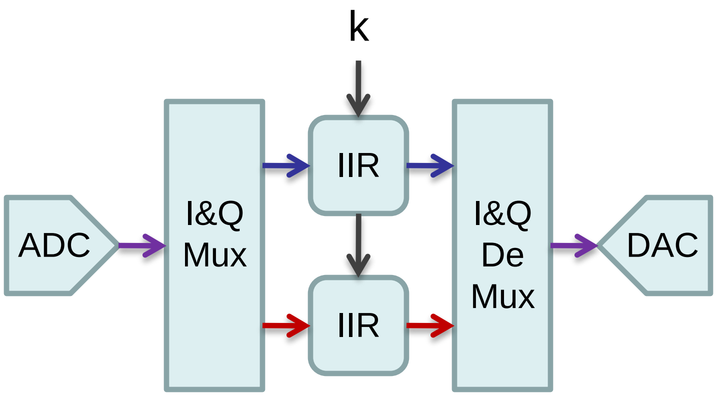
Tone Mode





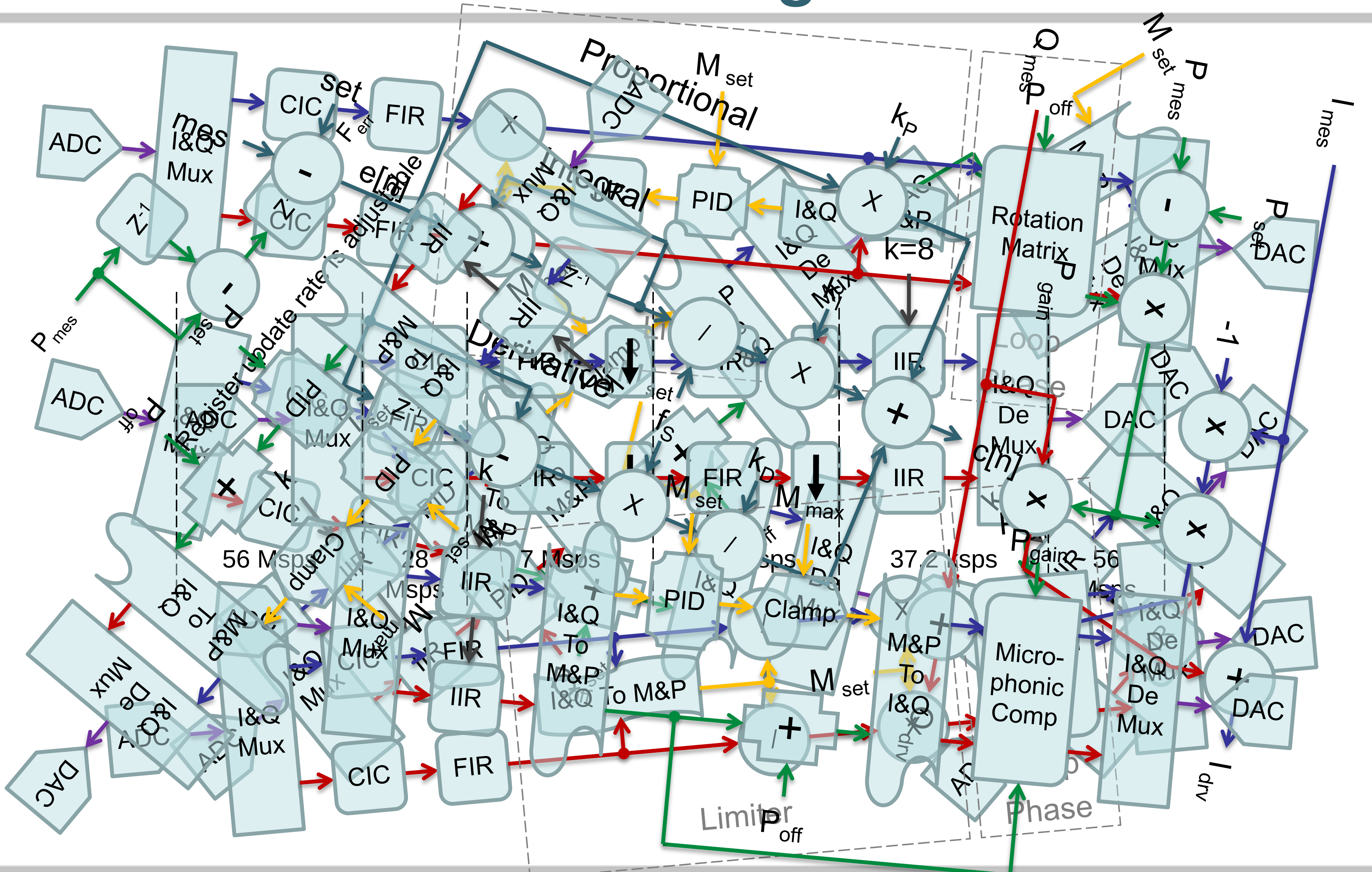
- Output 1497 MHz tone at a given magnitude and phase
- Need to add phase spin so the output frequency can be adjusted, 1497 MHz +/-14 MHz

Cavity Emulator

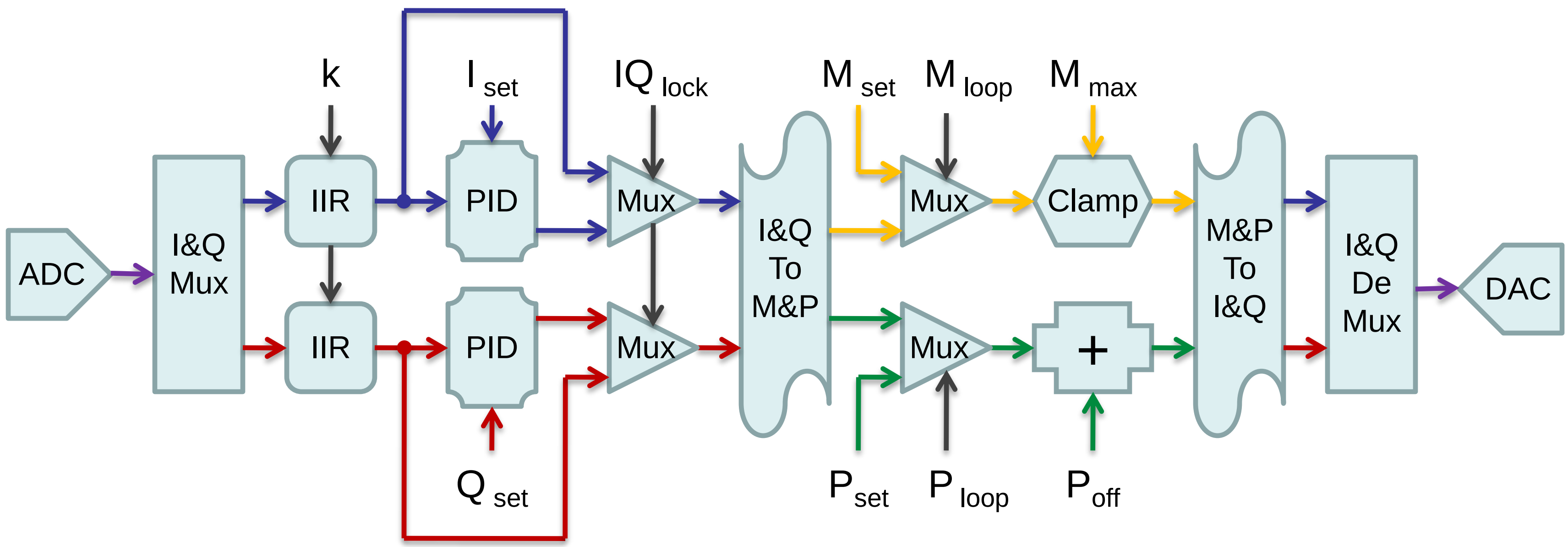


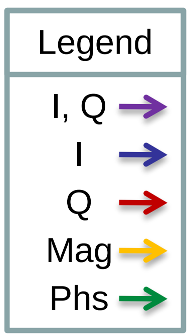
- Turn any LLRF module into a cavity for testing
- Loopback or test another module
- k = 18, BW = 34 Hz (Q = 4.4×10^{7})
- Need to add Lorentz Force detuning effects

Put It All Together



Field Control Architecture

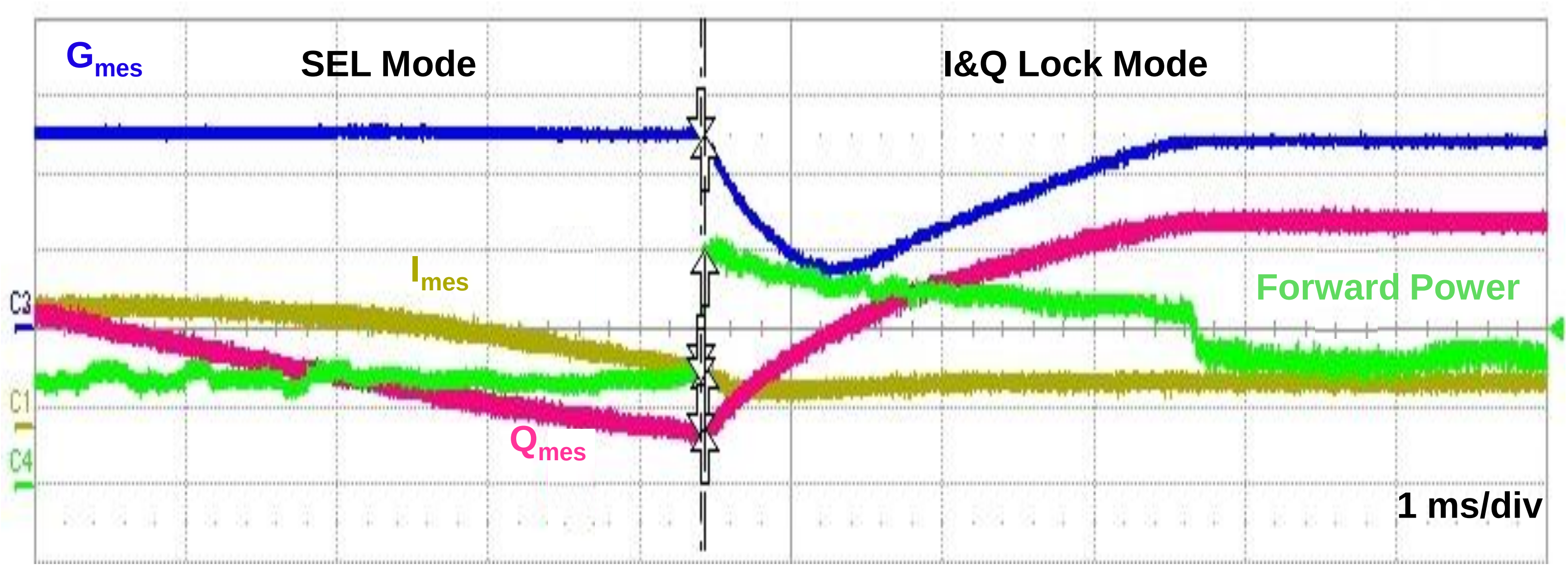




- Cavity Emulator
- I&Q Cavity Lock
- Self Excited Loop
- Tone Generator

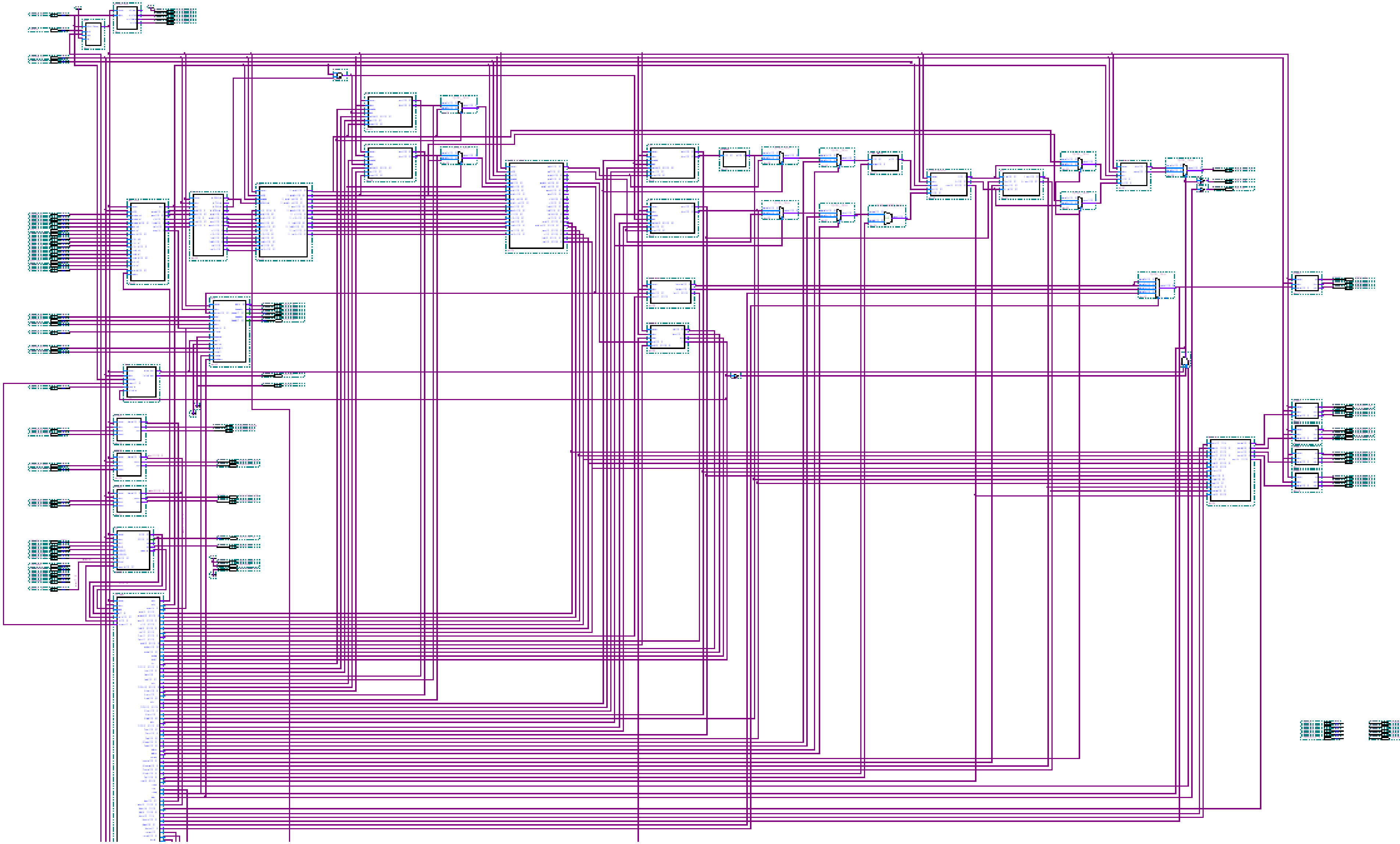
- Not shown
  - Discriminator
  - Detune Angle
  - Quench Detect
  - More…

Digital SEL to I&Q Lock Transition



- Spinning phase (sinusoidal I&Q) while in SEL mode
- Forward power spikes and G_{mes} droops as I&Q lock pulls the arbitrary I_{mes} & Q_{mes} to the set points
- Firmware SELs until the spinning phase aligns with desired I&Q set points then switches to I&Q lock
- Eliminates forward power spike and G_{mes} droop

Field Control Firmware



Any Questions?