C100 LLRF Controls

2017 Ops StayTreat

Trent Allison

8/3/2017

C100 Systems

Many Performance Improvements

- Field Control

  SEL-to-GDR transition, one button recovery, soft faults
- Stepper Motors

  Fast fiber link, tighter control, added protections
- Piezo (PZT) Amp

  Reduce range & strain, PI control, resonance algorithm integration
- HPA Controller

  Fault delays w/RF permit drop, filament ramping
- Interlocks

  First fault
- SRF Vacuum

  Inhibit RF when valve closed, raised limits, no PSS interlock
- Heaters

  8 channels, fast fiber link
- Cryo Diodes

  Archive as diagnostic
- DecaRad

  Install 2 heads per cryomodule

Issues for Controls

- Cavities sensitive to vibrations/microphonics
  - Valves, thunder, construction and even lawn mowers can trip cavities
  - Not enough klystron power to survive detuning
  - Mechanical coupling between cavities causes cascaded faults
- Cryo pressure instabilities detune and trip cavities
  - Small cryo vessel & heat riser choke causes boiling/pressure changes
  - 5s heater delay causes no & double heat during zone trips/recovery
  - Trip rates go down after CHL trips (due to better stability or vacuum?)
- Field emitters and bad vacuum cause higher trip rates so gradients are lowered to compensate
  - Valve movement causes microphonic trips
  - Field emitters trip at lower gradients (quench due to heating?)
  - Field emitter onsets seems to be getting worse (contamination?)

Issues for Controls

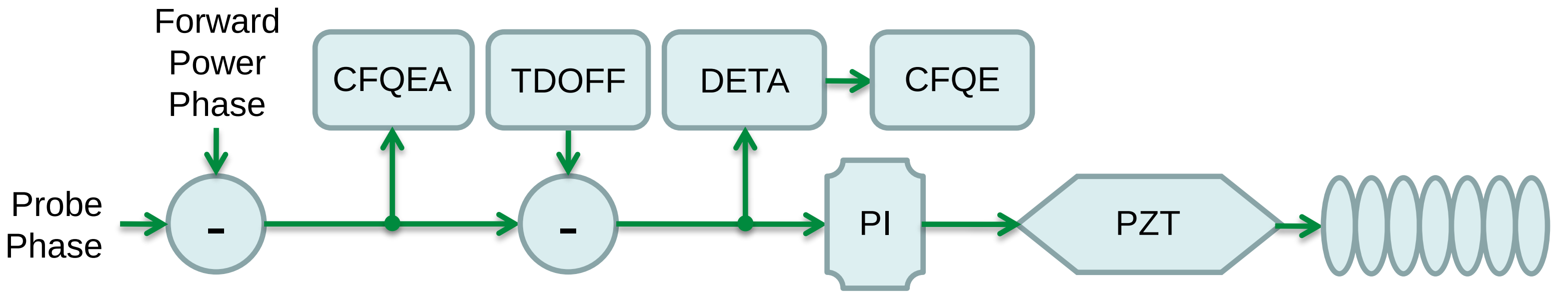
- High cavity quench rate
  - Algorithm was relaxed to avoid false trips then multiple real quenches were observed
  - Some are periodic, are we heating something or arcing?
  - Are quenches being induced during microphonics & fast detunes?
- Slow Recovery Times
  - SEL-to-GDR transition has been happening at 10MV/m to 17MV/m then slowly ramping to GSET
  - Instabilities have limited us in the past
- Cross talk within zones and between zones
  - We get GMES in cavities that are off when other cavities or zones are turned on (dark current?)
  - Cable cross talk in control system or inside cryomodule?

What Can Be Done?

There are control changes that might help but we have likely reached the point of diminishing returns

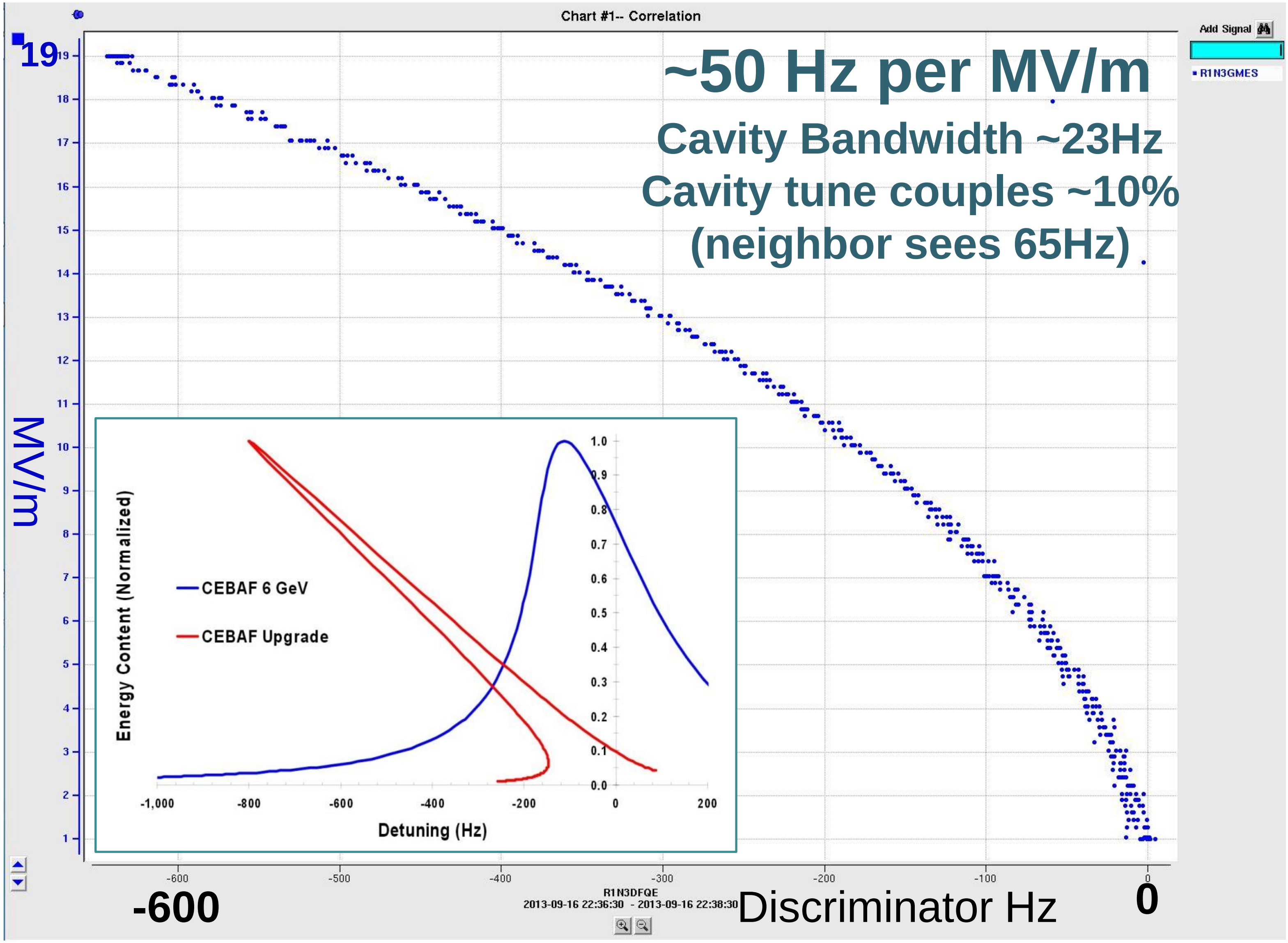
- Mechanically compensate microphonics
- Stop trips from cascading to other cavities
- Keep cryo heat load stable
- Improve recovery time
- Add diagnostics & perform tests to better understand the issues

Piezo Tuner



- PZTs have not been successfully used for microphonic compensation
  - PI control excites mechanical modes at higher bandwidths
  - Useful for tracking slow He pressure drifts
- Could try other noise canceling techniques that target the mechanical modes
- Probably need Cryomodule-wide compensation algorithm so individual cavity controls don’t fight
  - Provide 8 DETA signals to central PZT chassis

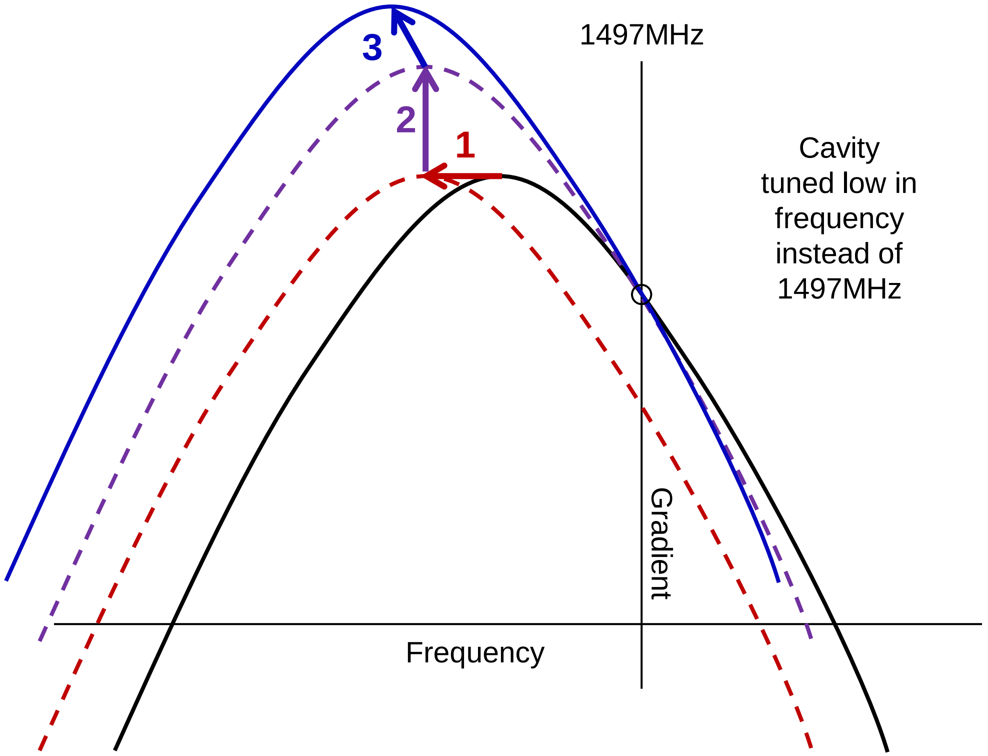
SEL Lorentz Detuning



GDR Lorentz Force Detuning

<u>Cavity tuned low</u>

1. Microphonics detunes the cavity lower
2. Loop increases drive to hold gradient
3. Increasing drive decreases cavity frequency via Lorentz Force, pushing detuning even farther

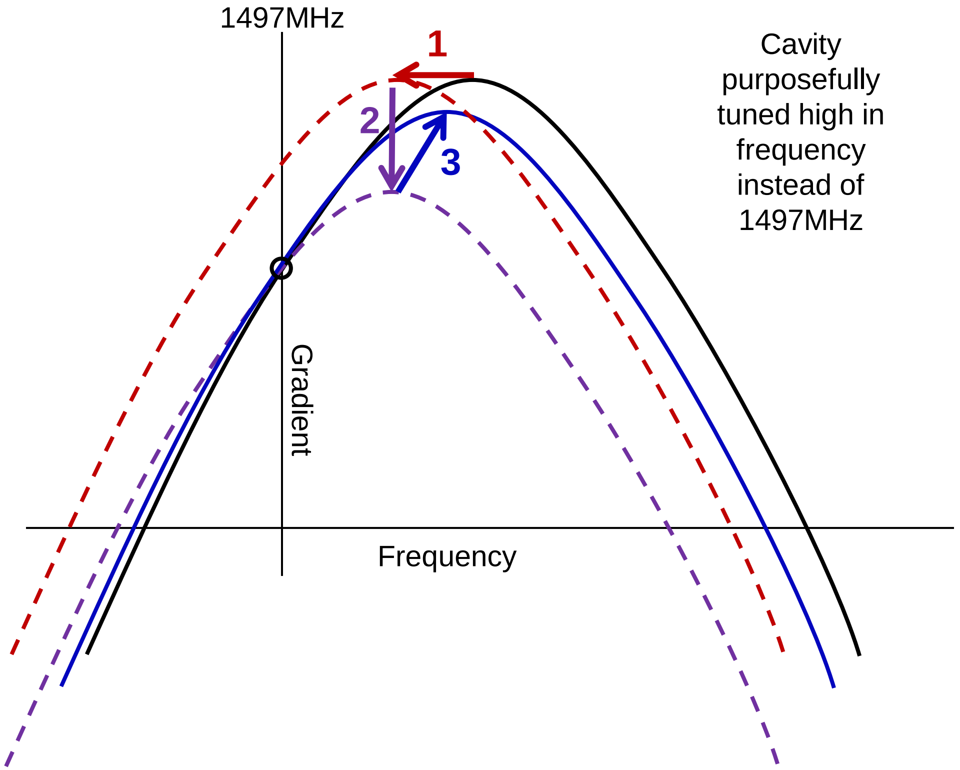


- Decreased gain in gradient control via Lorentz Force
  - Same is true if detuning forced the cavity higher in frequency

GDR Lorentz Force Tuning

<u>Cavity tuned high</u>

1. Microphonics detunes the cavity lower
2. Loop reduces drive to hold gradient
3. Reducing drive increases cavity frequency via Lorentz Force, pushing against detuning



- Increased gain in gradient control via Lorentz Force
  - Same is true if detuning forced the cavity higher in frequency
- Need to PI steppers or install PZTs to take advantage of this
- Would be wasting some klystron power being off tune

Soft Faults

Switch to SEL & pull FSD instead of opening RF switch

- Prevent 10% detune coupling from propagating through entire zone
- Keep cryo bath stable by keeping gradient (heat) in the cavities

<u>GDCL Fault</u>

Gradient Drive CLamp Fault

- Control loop rails klystron drive (13kW) for too long
- >10 msec

<u>DETA Fault</u>

DETune Angle Fault

- Detuned too far for too long
- >60º (~3x power) for >60 msec

<u>GLDE Fault</u>

Gradient Loop Drive Error

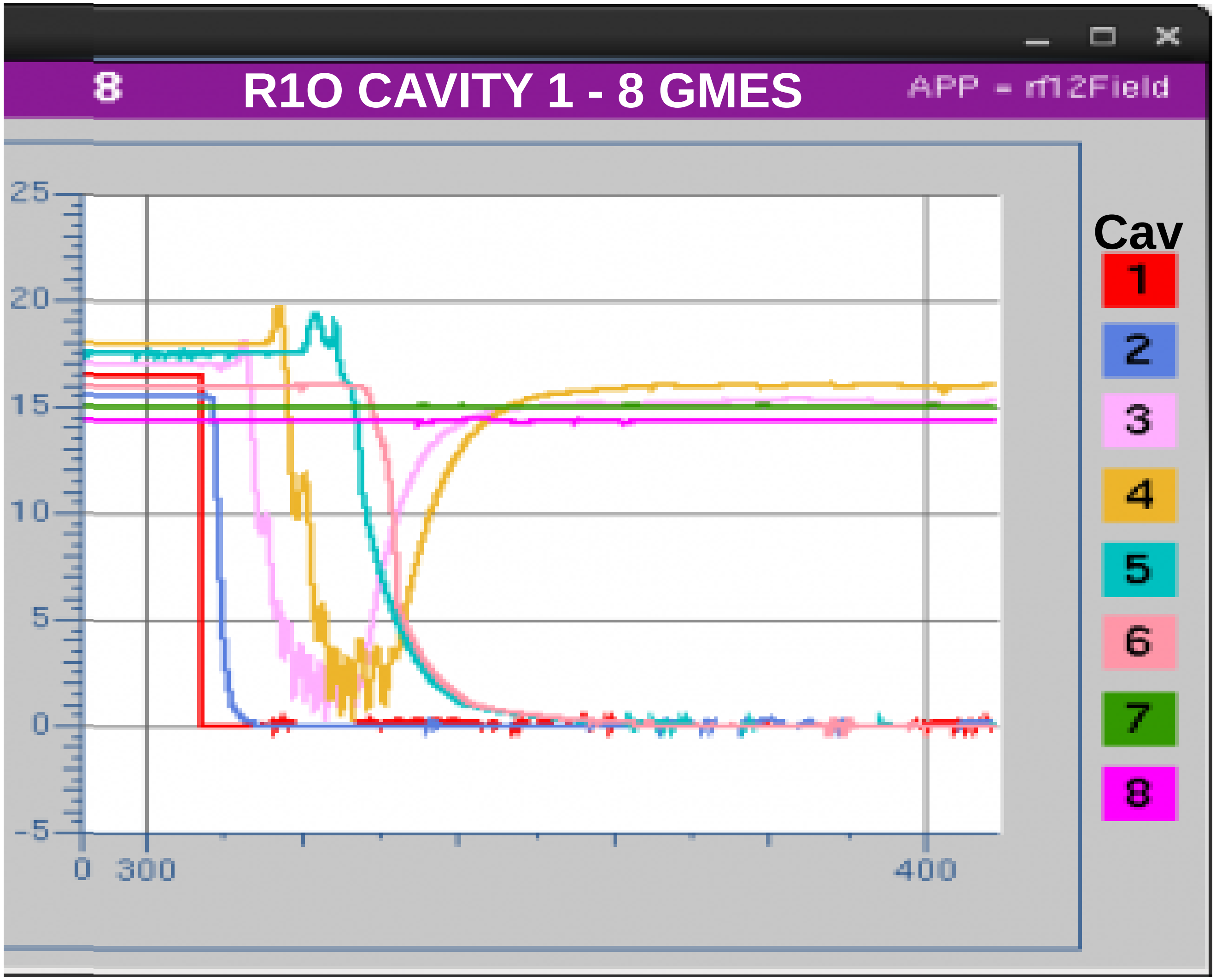
- G error too large too long
- >100 cnts for >10 msec

<u>PLDE Fault</u>

Phase Loop Drive Error

- P error too large for too long
- >1º for >10 msec

Cascaded Fault



https://logbooks.jlab.org/entry/3459286

- Cavity 1 quenched
- Cavities 2 through 6 were detuned
- Cavities 3 & 4 soft fault to SEL
- Cavities 7 & 8 barely survived, maybe due to 3 & 4 in SEL
- Goal is to stop cascade at #2

Cascaded Fault

Waveform Capture Cavity Summary

<u>Cavity 1 Quench</u>

- GMES drops to 0 very fast
- PMES bounces around w/o gradient
- Forward & reflected power also drop to 0
- Detune angle was stable at +/-10º

Cascaded Fault

(cavities 2 & 5 look similar)

<u>Cavity 6 Detuned</u>

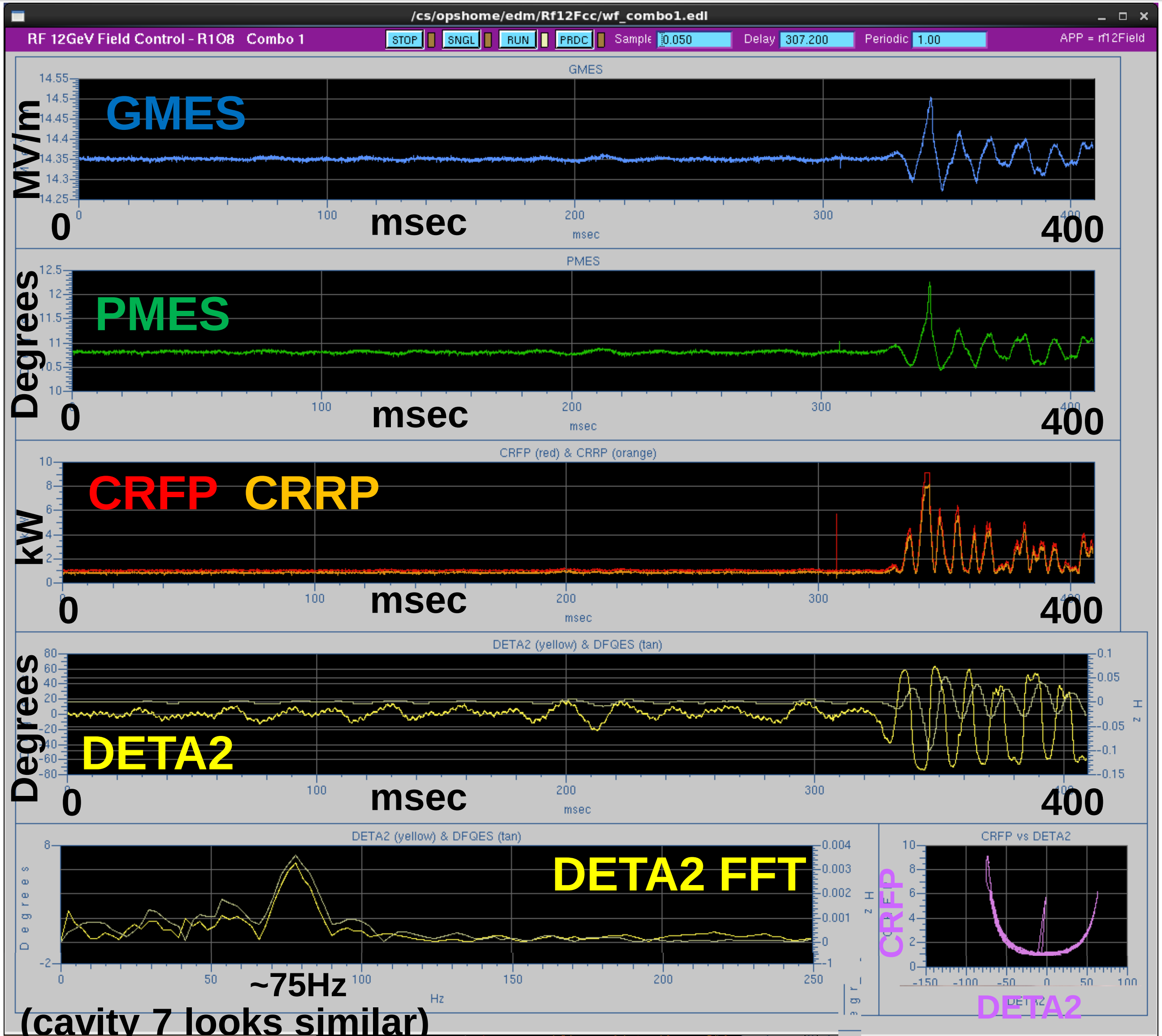
1. Large negative detune angle due to losing other cavities
2. Forward power railed until fault
3. GMES drops causing detune to go up then a quench fault opens RF switch
4. GMES decays at normal rate

Cascaded Fault

<u>Cavity 4 Detuned</u>

- DETA2 goes to zero causing GMES to go up then it drops while oscillating
- CRFP rails while CRRP oscillates
- Detune angle goes to -100º & rolls/oscillates
- Then GDCL soft fault switches cavity to SEL

Cascaded Fault

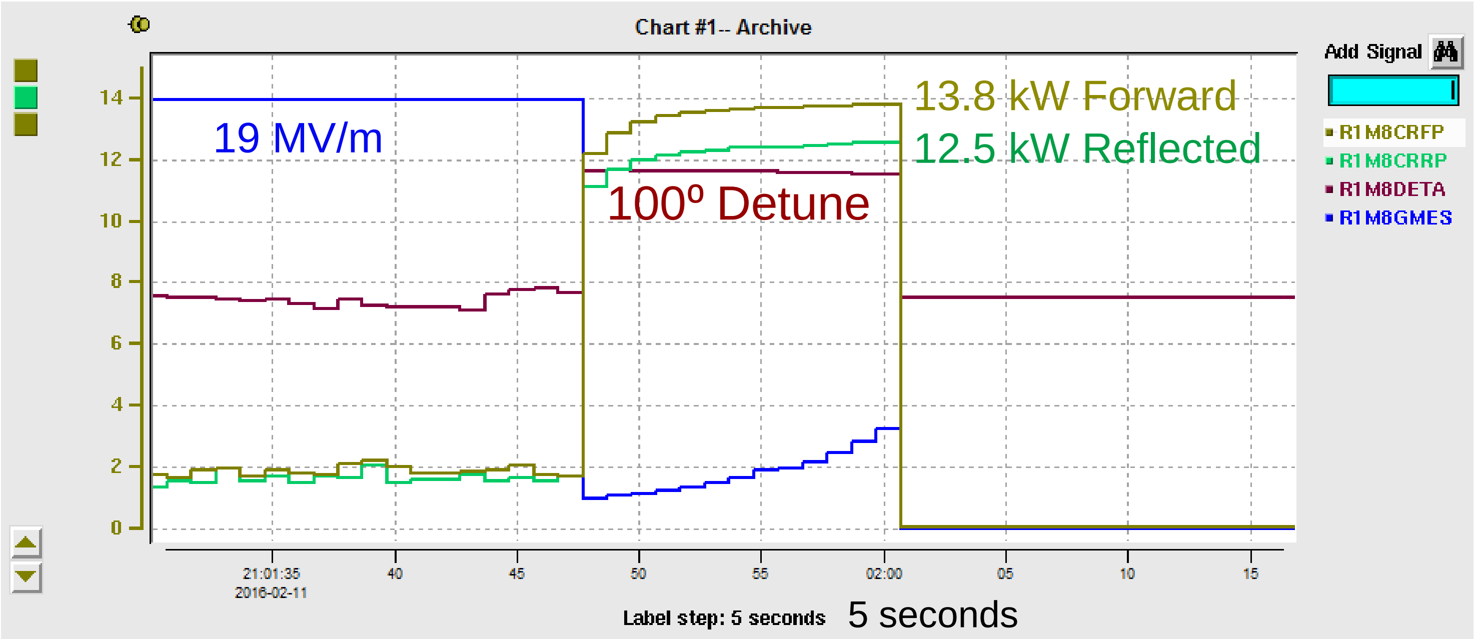


(cavity 7 looks similar)

Cavity 8 Survived

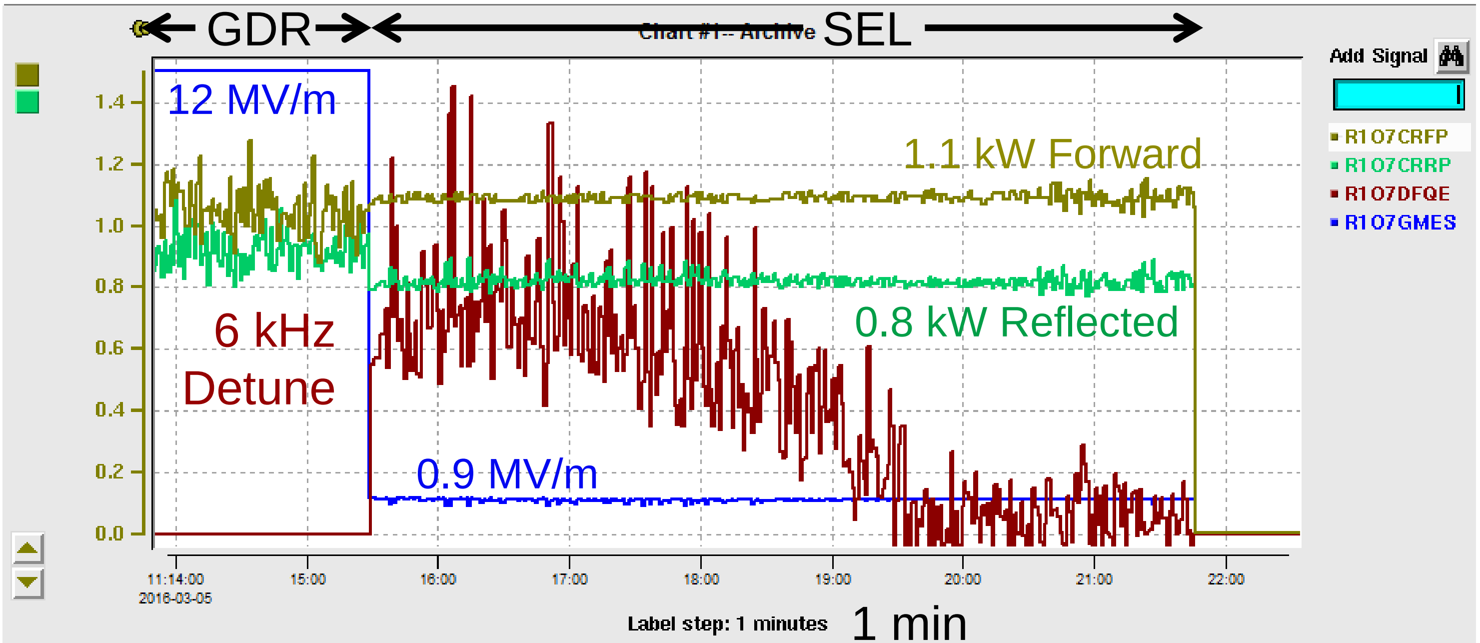
- DETA2 oscillates 135º p-p, ~75Hz
- CRFP rails once while oscillating
- CRFP vs DETA2 shows massive detune curve
- Large CRFP headroom helped
- GMES oscillates 0.25MV/m p-p
- PMES oscillates 1.8º p-p

Quench Fault



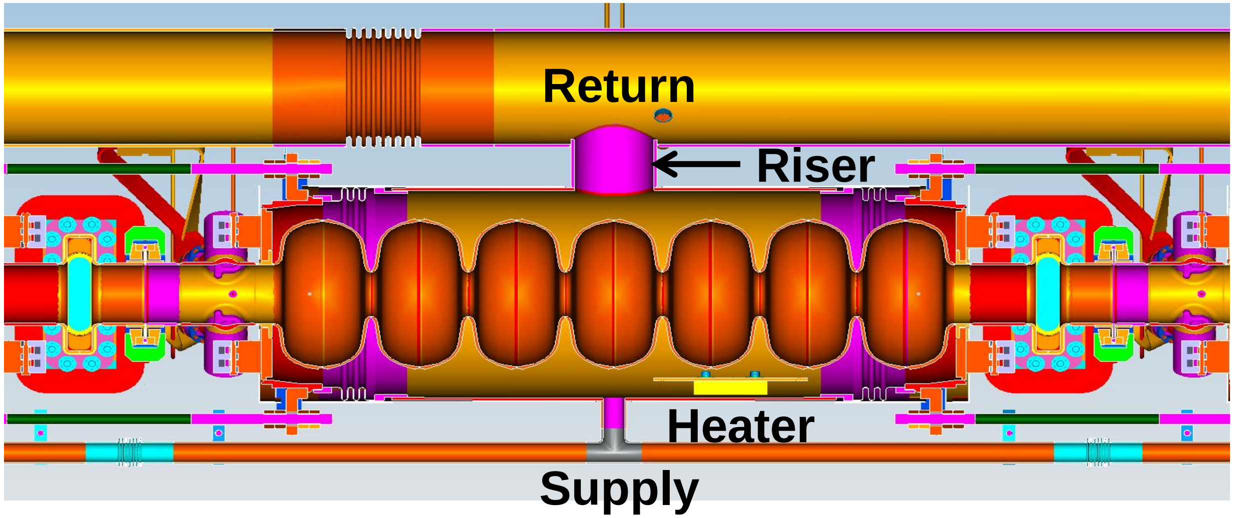
- Detects fast drop in gradient
  - Set slope 50% steeper than normal cavity decay
- Relaxed due trip rates
  - Then real quenches and fast detunes seen in archiver
- What is the cause?
  - Does this look like a quench?
- Change the algorithm?
  - Verify the quench somehow?
  - How long can I let it quench?

SEL Quench Fault



- Started seeing SEL quenches after GDCL and DETA soft faults
- Quenched in GDR then continued quenching in SEL
- In SEL, if gradient is too low for forward power then open the RF switch
  – 50% low for 2 seconds
- Cut off GDR quench?

Heaters and Cryo



- Heater are used to stabilize cryogenic load on the CHL
  - RF heat gets replaced with electric heat and vice versa
- Cavities are sensitive to Helium liquid level and pressure
  - 400 Hz/Torr detuning for unstiffened cavities, 200 Hz/Torr stiffened
  - Heat riser choke causes localized boiling and instabilities
  - Liquid level from 84% to 95% should be stable but has to be kept at 88%; lower is more stable which is opposite of expected

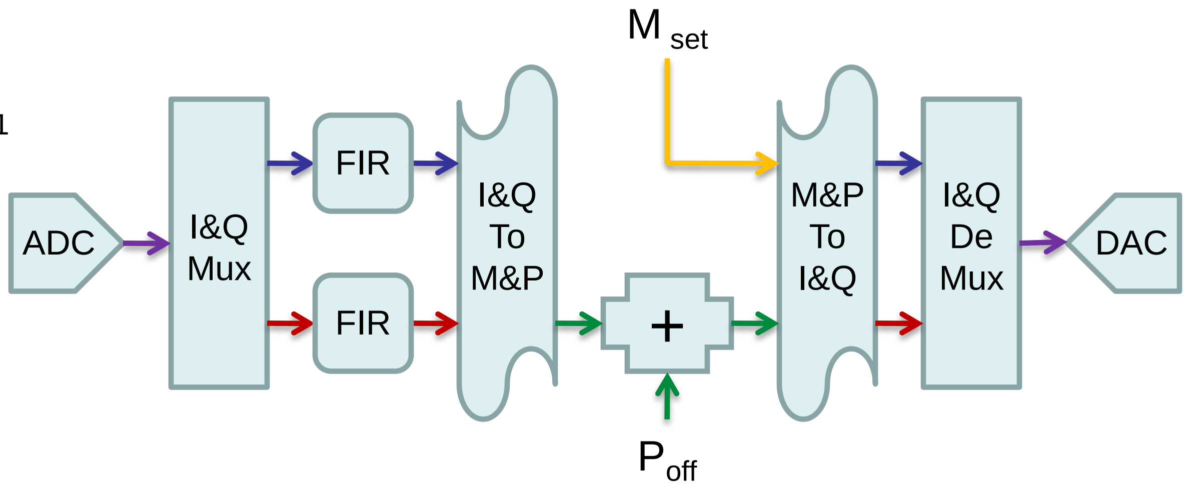
Heaters and Cryo

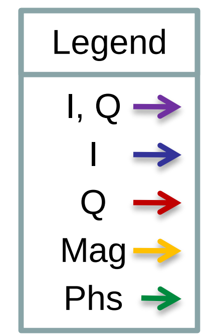
- Presently the 8 cavity heaters in a cryomodule are using one power supply
  - If a couple cavities trip then the heat goes up in all 8
  - Increased heat can cause other cavities to boil He and trip
  - Boiling Helium shakes the cryomodule and requires time to settle
- Heater control loop is slow with 5 second update
  - If a zone trips then there is no heat for 5 sec
  - Then there's double heat for 5 sec at turn on that causes boiling
- Cryo pressure is regulated at the T, far from the C100s
  - Need better C100 Helium pressure regulation and/or sensors?
- <u>Need fast 8 channel heaters (tested 0L04, coming soon)</u>
  - Field Control chassis sends heater chassis gradient at ~100ksps
  - Heater chassis calculates cavity heat and adjusts as needed

SEL vs GDR

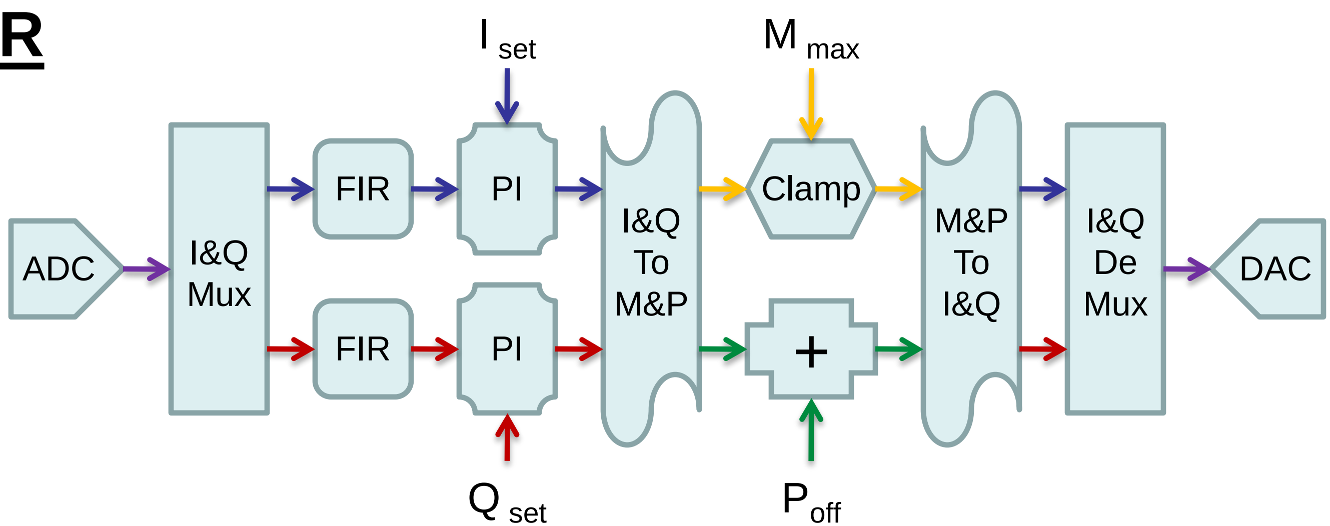
SEL

Patent Number
US 8,130,045 B1

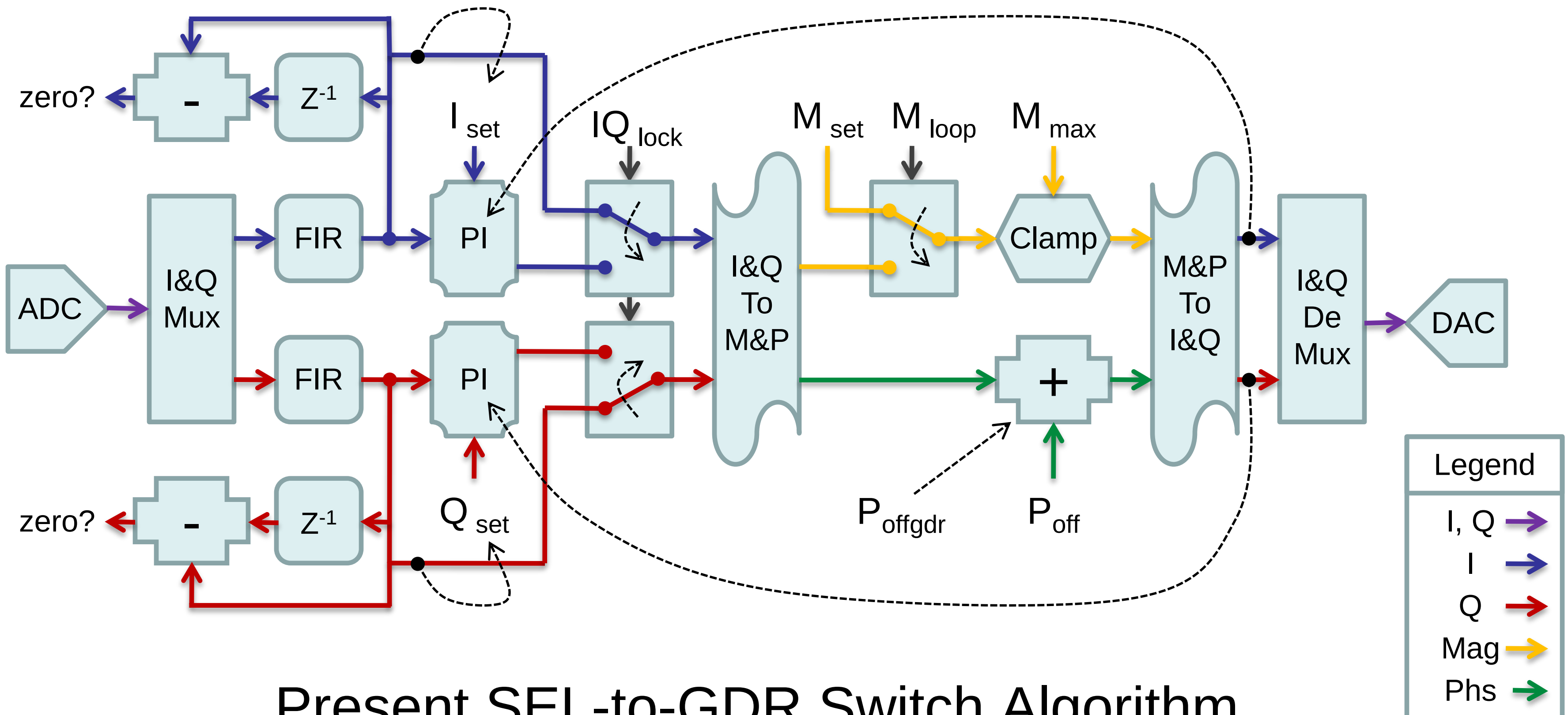




GDR



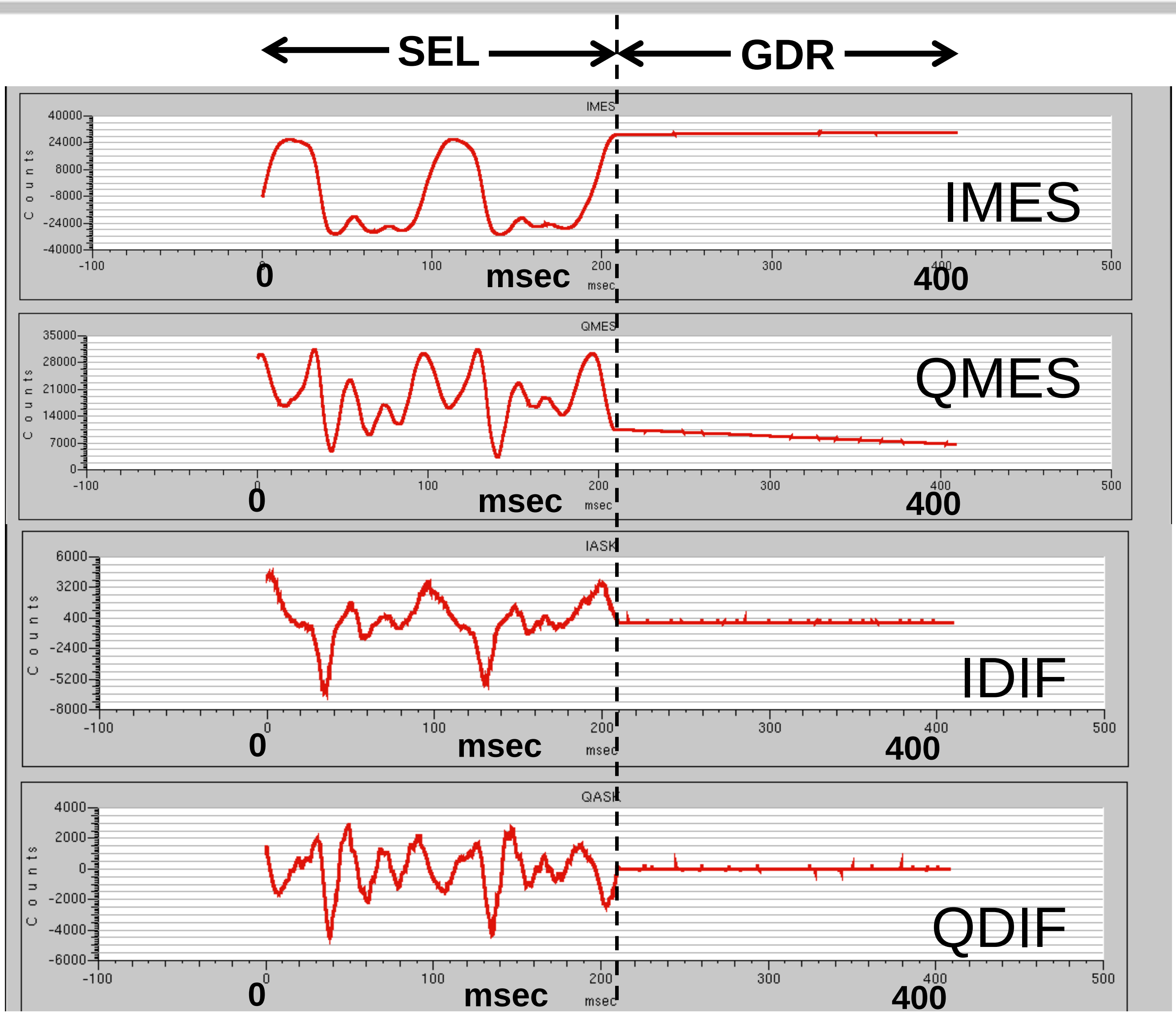
SEL to GDR Transition



Present SEL-to-GDR Switch Algorithm

- Wait for tune (steady I_{mes} & Q_{mes})
- Copy I_{mes} & Q_{mes} to I_{set} & Q_{set}
- Calc Int terms from I_{ask} & Q_{ask}
- Add P_{offgdr} to loop phase
- Switch to GDR Mode using IQ_{lock} and M_{loop}

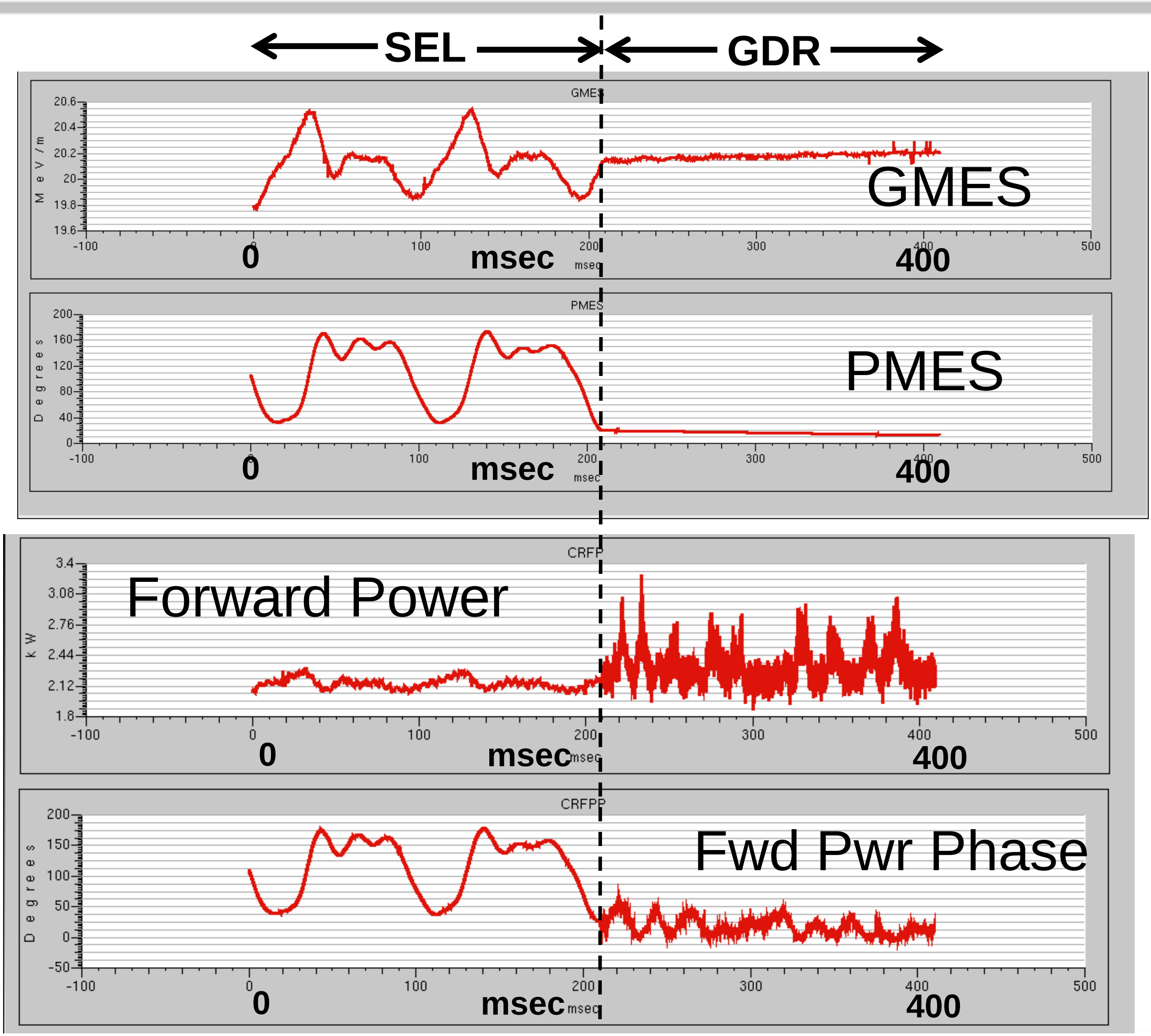
SEL to GDR Transition



SEL-to-GDR switch testing with new algorithm to wait for tune

- I_{mes} & Q_{mes} stop changing
- I_{dif} & Q_{dif} go to zero
- I_{set} & Q_{set} ramp to EPICS set points

SEL to GDR Transition

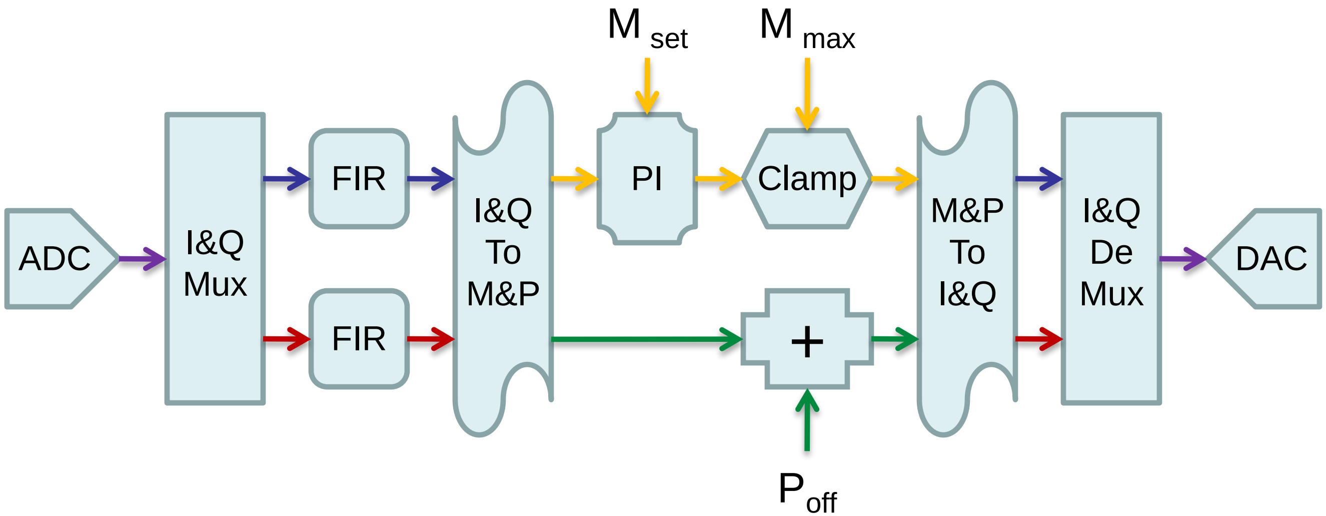


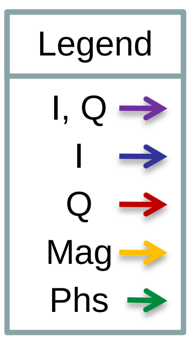
SEL-to-GDR switch testing with new algorithm to wait for tune

- No G_{mes} droop
- No Forward Power spike

Other Control Algorithms

SEL with Magnitude Lock

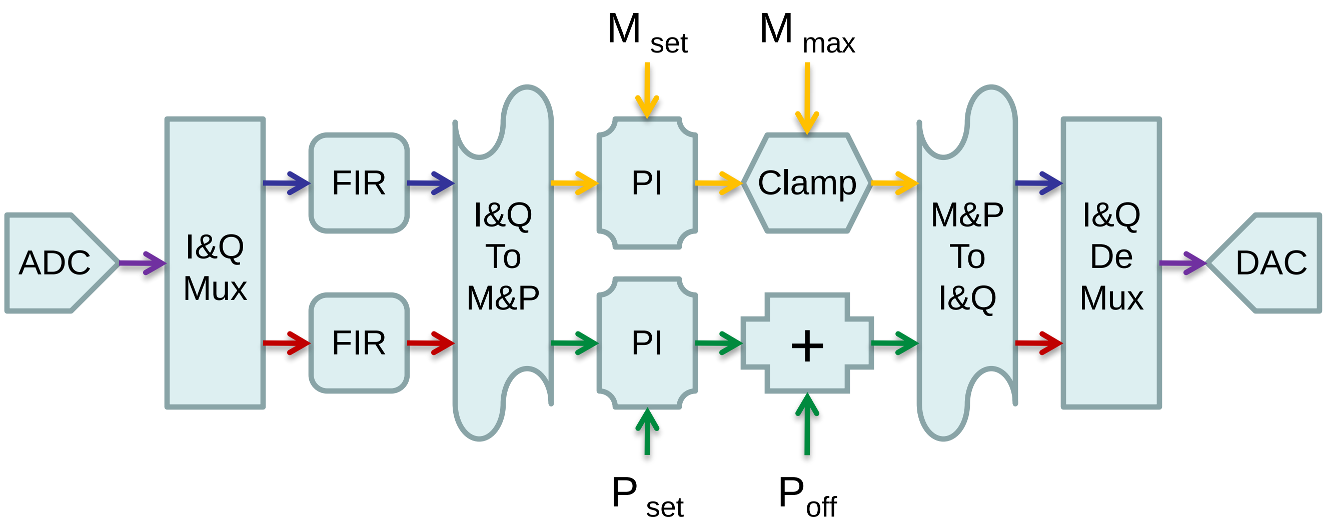


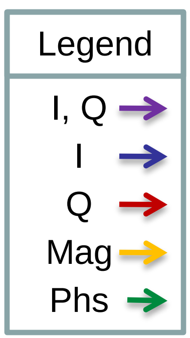


- PI control of Magnitude in SEL mode
- Constant gradient, varying output power
- Limit Lorentz force detuning & microphonics

Other Control Algorithms

GDR Gradient & Phase Lock

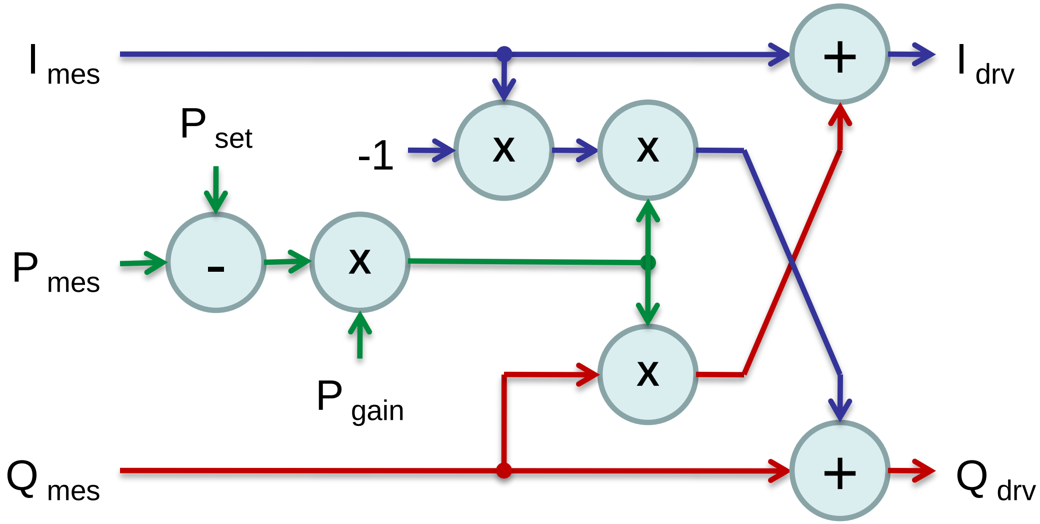


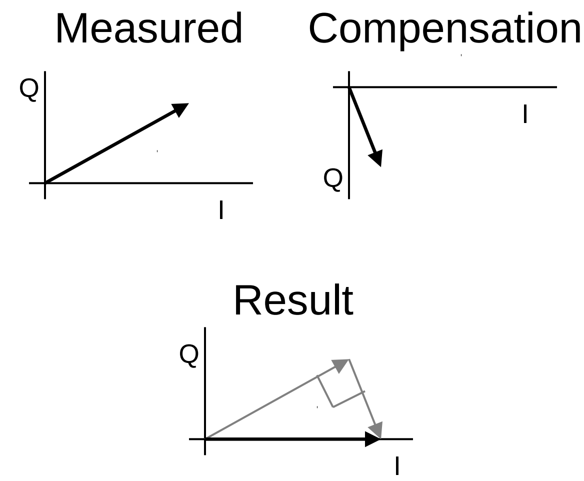


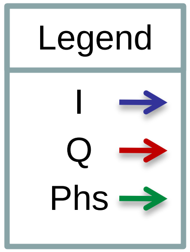
- PI control of Magnitude and Phase
- Gradient and phase loops like analog system
- Attempted early on but IQ Lock more successful

Other Control Algorithms

GDR Microphonic Compensator



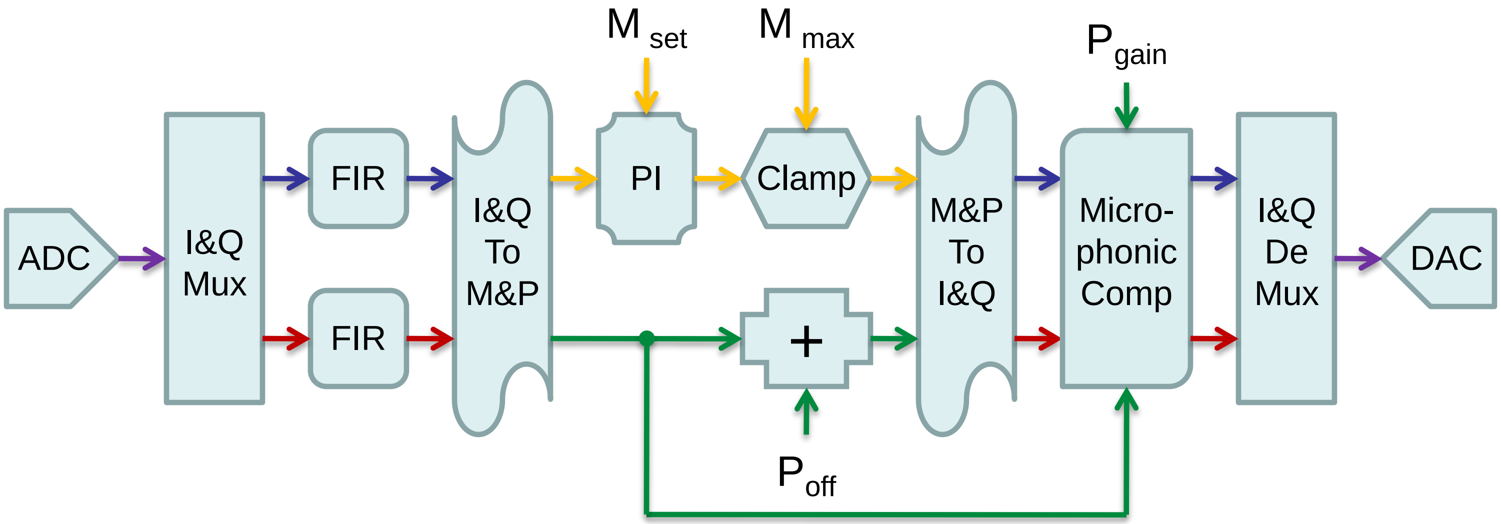


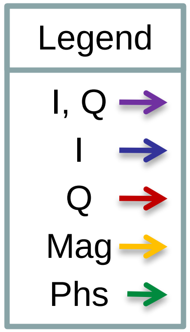


- Based on the phase error
  - Rotate the vector to compensate for detune
  - Add magnitude correction
- $I_{drv} = Q_{mes} * [P_{gain} * (P_{set} – P_{mes})]$
- $Q_{drv} = -I_{mes} * [P_{gain} * (P_{set} – P_{mes})]$

Other Control Algorithms

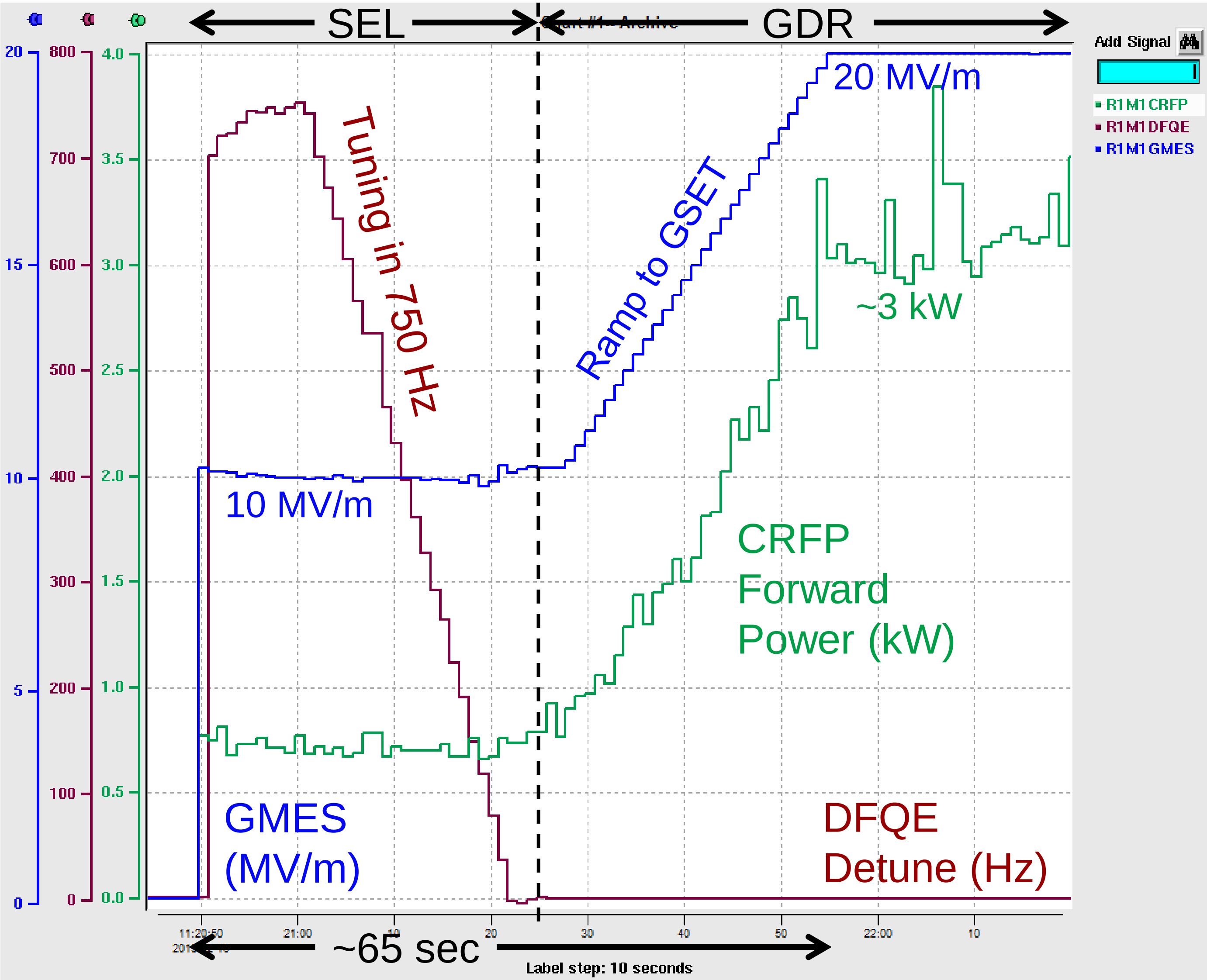
GDR Microphonic Compensation & Gradient Lock





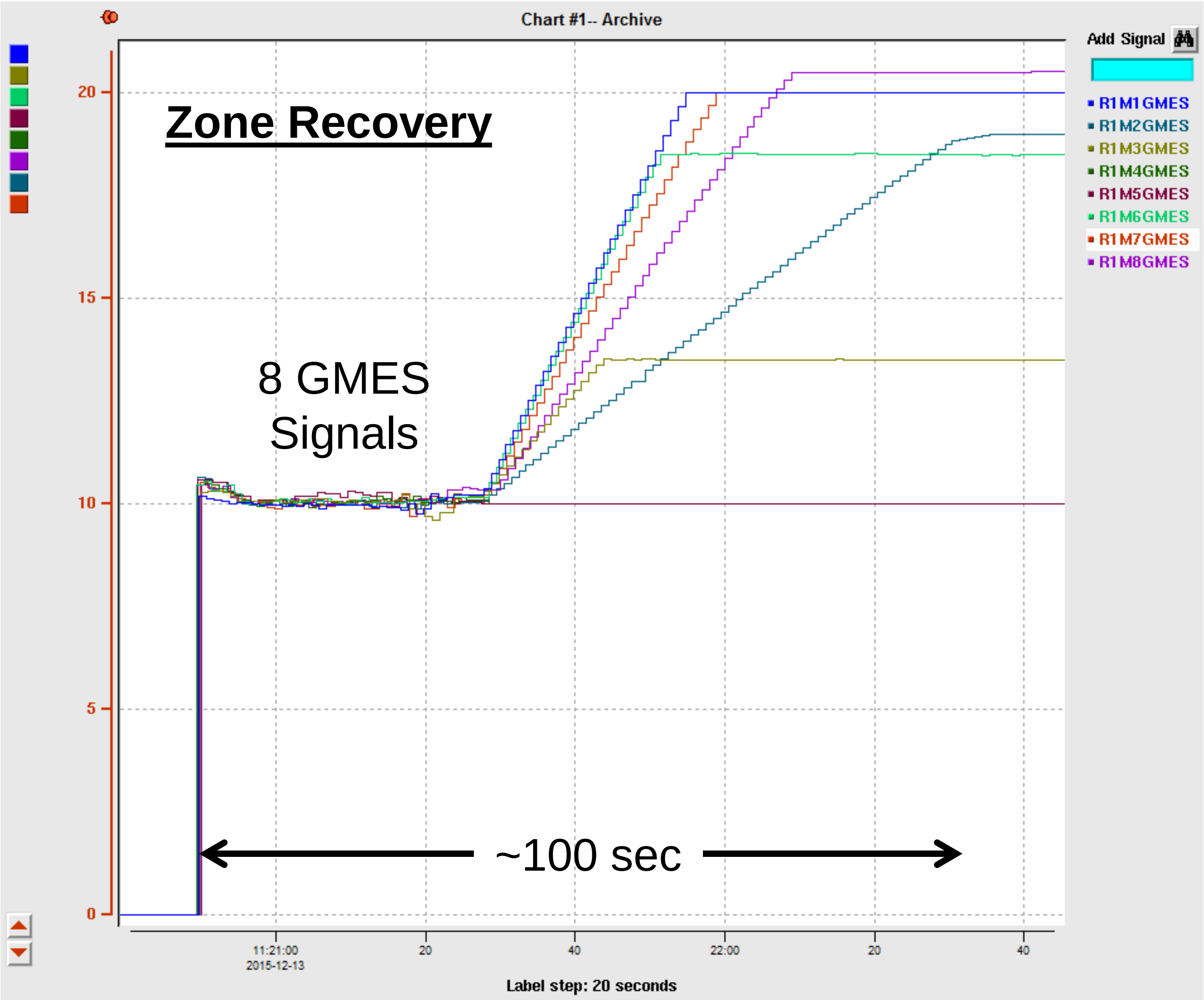
- Microphonic Compensator locks phase (~.5º)
- Can drop to SEL, lock detection FSD needed
- PI control of Magnitude needed
- Fought magnitude regulation issues (~0.1%)

One Button Recovery



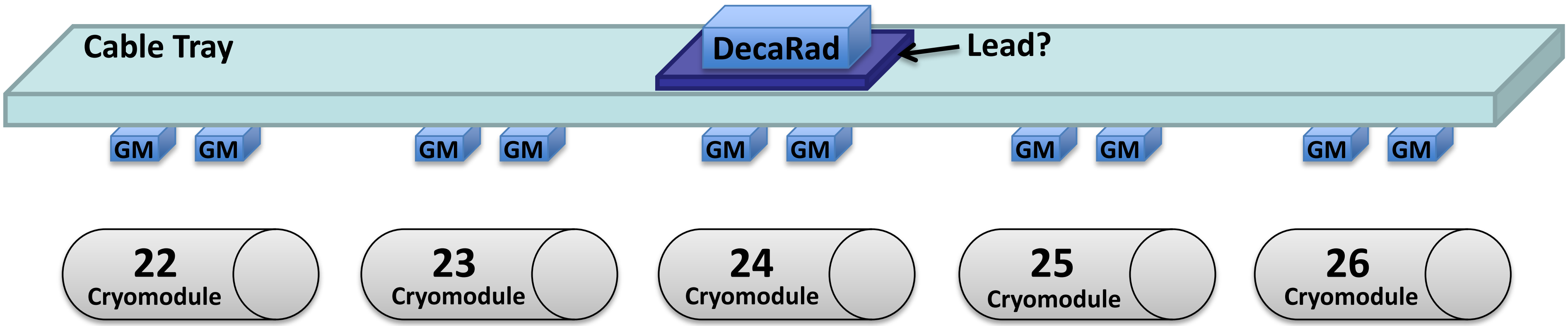
- SEL at 10 to 17MV/m
- Tune in using Discriminator and steppers
- Switch to GDR
- Ramp to 20MV/m while steppers tune

One Button Recovery



- Faster stepper settings or PZT to reduce ramp time
- 8-channel fast heaters would allow for more reliable SEL-to-GDR switch at higher gradients
- Switched at full gradient in 12 sec
- Stagger switch times?

DecaRad



- 2 heads per cryomodule to monitor radiation
  - Bottom of cable tray above cryomodule
  - Between cavities 2 & 3 and 6 & 7
  - Installed for Fall run, should survive 100 to 1,000 days
- Help find field emitters so we can turn them down
  - Reduce heating, vacuum levels and trip rates
  - Turn up non field emitters
  - Reduce radiation damage & extend equipment life

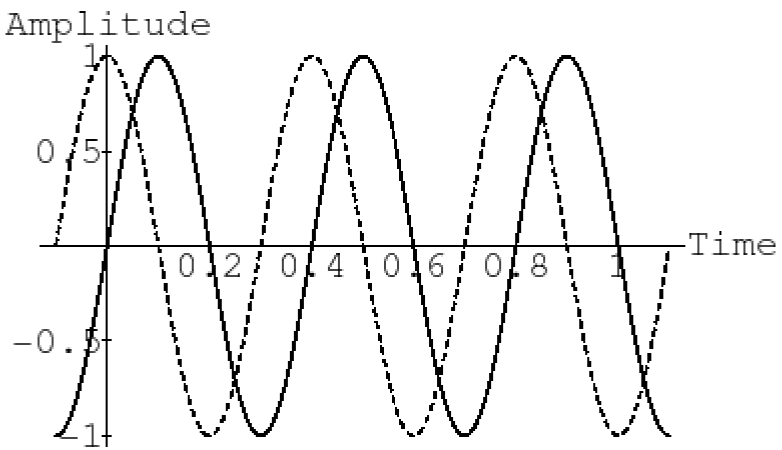
What's Next for C100 Controls?

- Tighten Soft Fault settings
- Fast 8 Channel Heaters
- Archive Cryo Diodes to investigate heating
- DecaRad to identify field emitters

- Install PZTs everywhere?
- Active zone-wide microphonics compensation?
- PI stepper controls?
- Change quench detector algorithm or turn it off?
- Try other GDR control algorithms?
- Change one button turn on algorithm?
- More diagnostics?

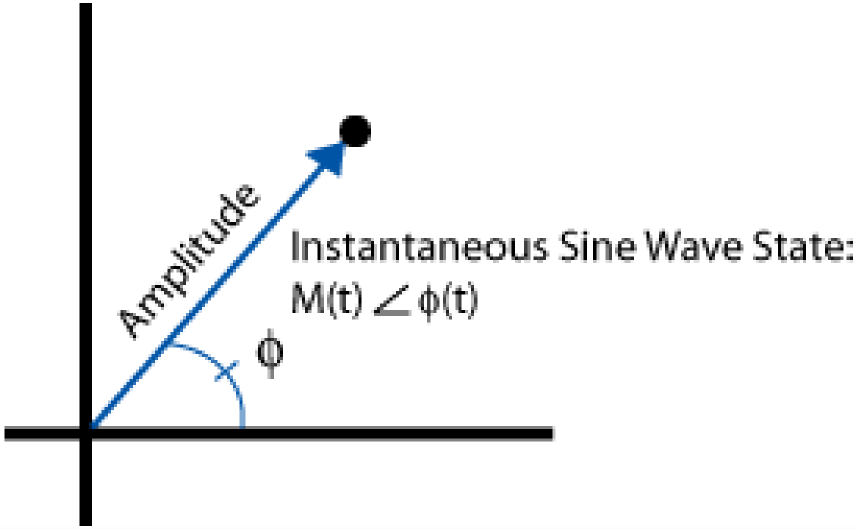
Extra Slides

Mag & Phase vs In-Phase & Quadrature

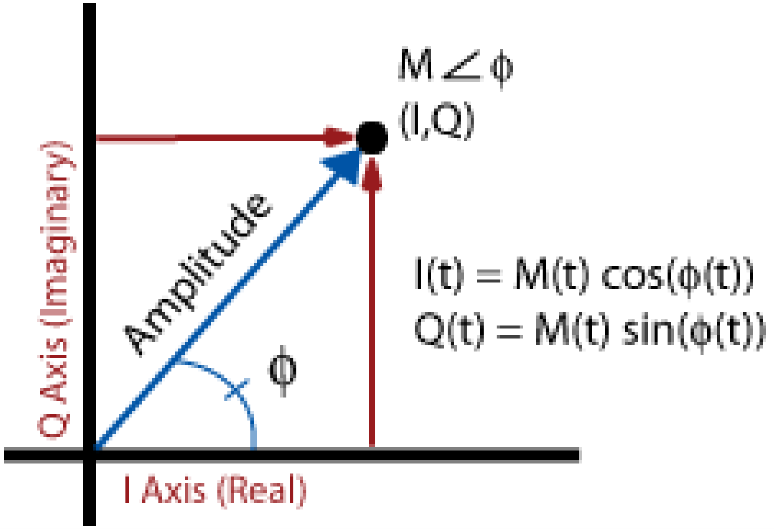


- Quadrature is shifted 90^0 from In-Phase signal
- Coordinate transformation
  - Switch between M&P and I&Q using CORDIC

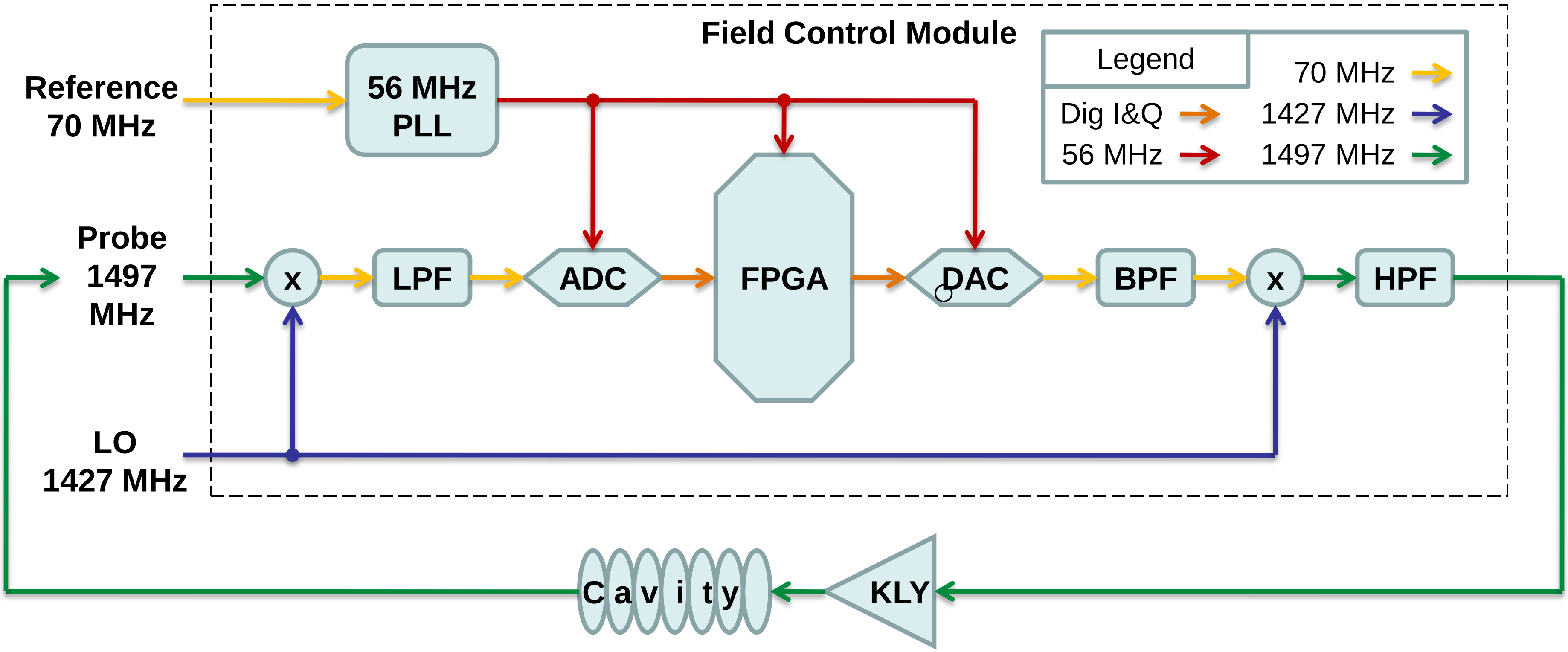
<u>Mag & Phs (Polar)</u>



<u>I & Q (Cartesian)</u>

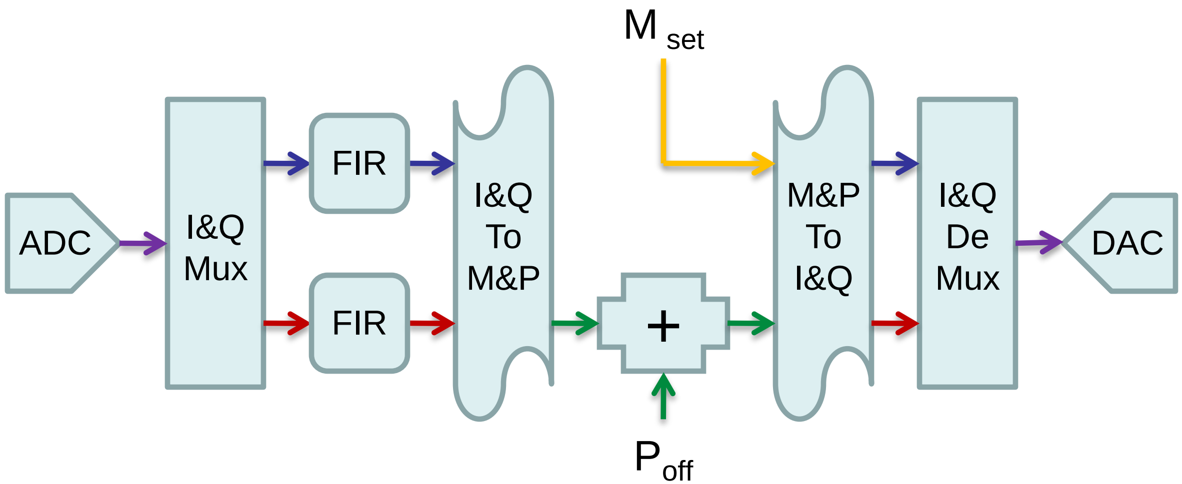


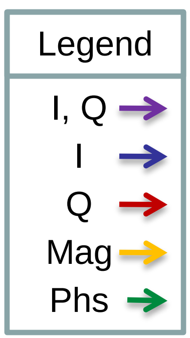
Field Control Hardware Block Diagram



- 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

Self Excited Loop

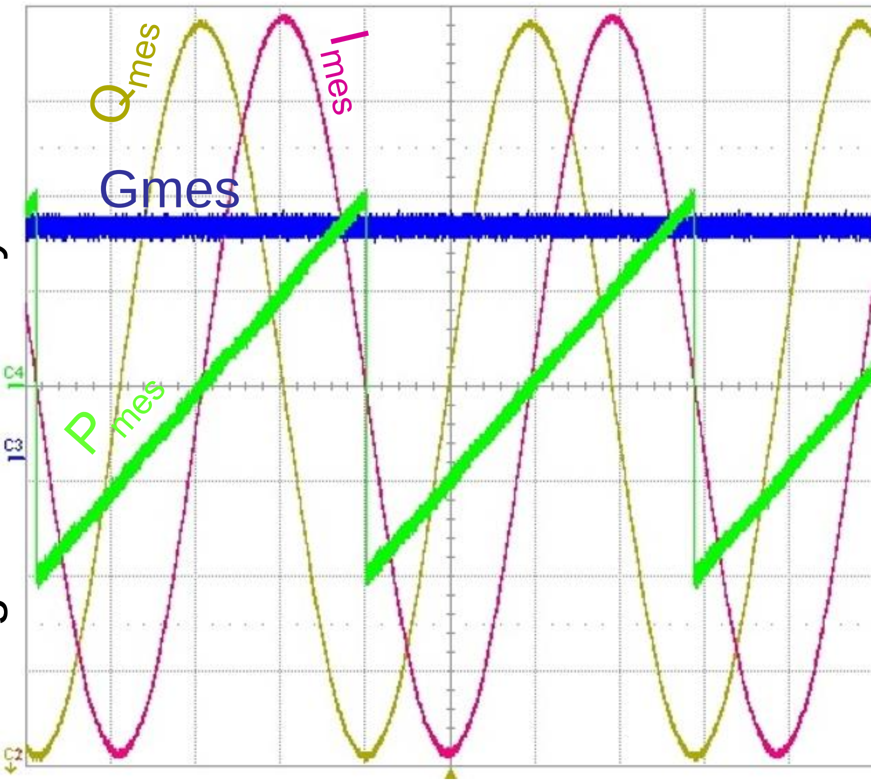


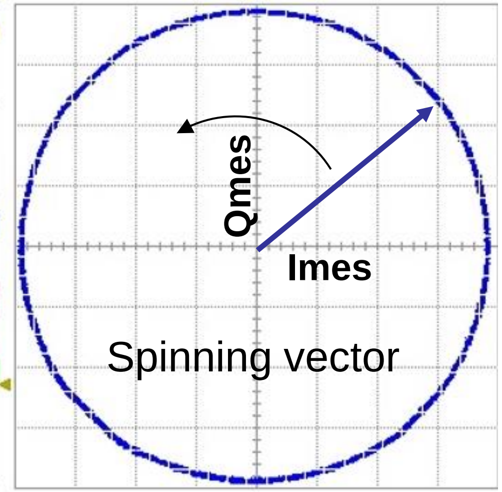


- Pass frequency info (phase) w/ loop phase offset
- Set magnitude directly
- CORDICs convert between Mag & Phs and I&Q
- Patent Number: US 8,130,045 B1

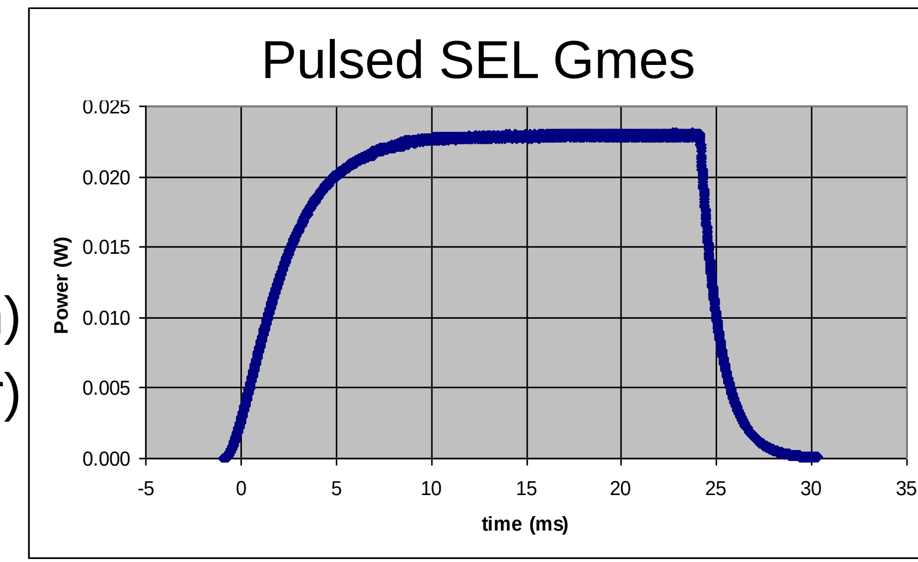
SEL Performance

Digital SEL Steady State



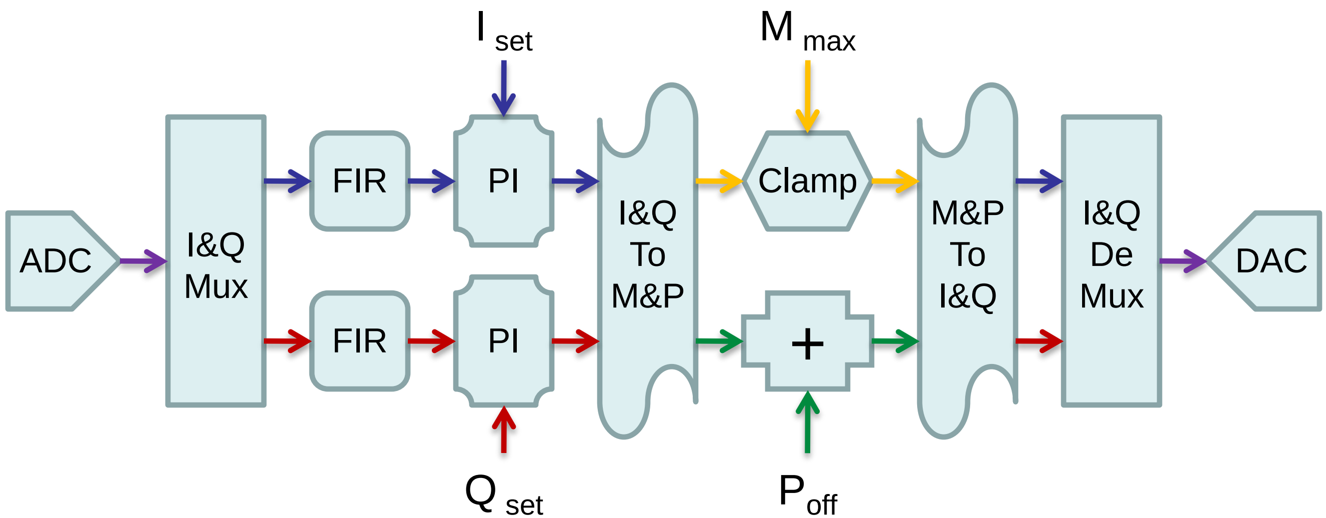


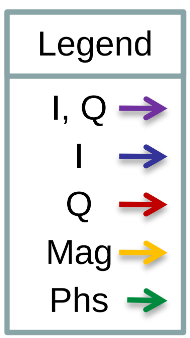
- Direction and speed of spin dependent on detuning
- Phase, I & Q all flatten out if the cavity is tuned to 1497



- I&Q sinusoidal w/90º shift (Cartesian)
- Gradient constant, phase rolls (Polar)
- Cannot accelerate beam in SEL, must use GDR

Generator Driven Resonator (GDR)



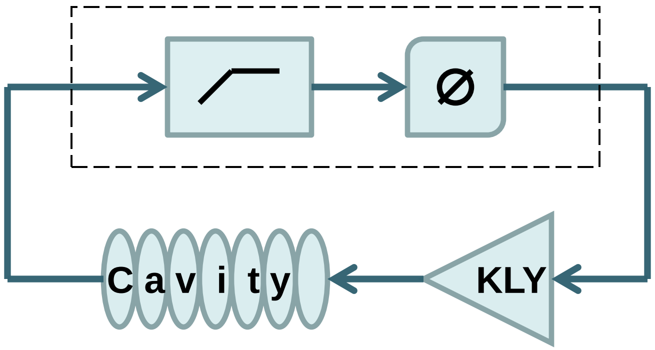


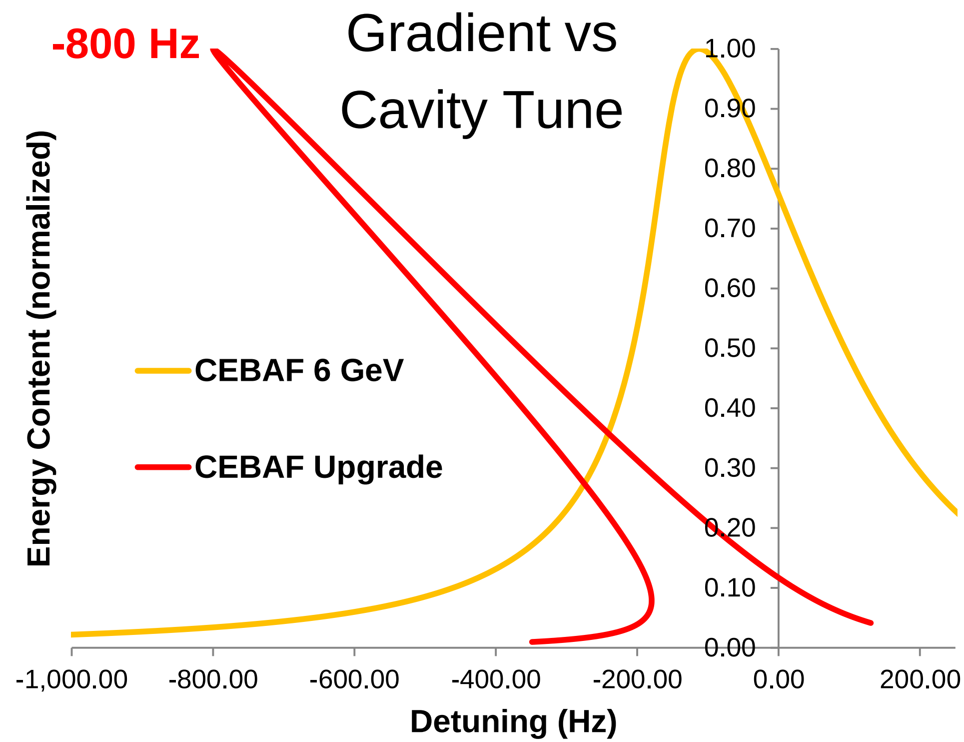
<u>GDR In-Phase & Quadrature (IQ) Lock</u>

- I&Q Proportional & Integrated controllers
- Meets requirements of 0.5^{o} and 0.044%
- 1.3 us measured latency (HW: 600 ns, FW: 700 ns)

Self Excited Loop (SEL)

Analog Implementation



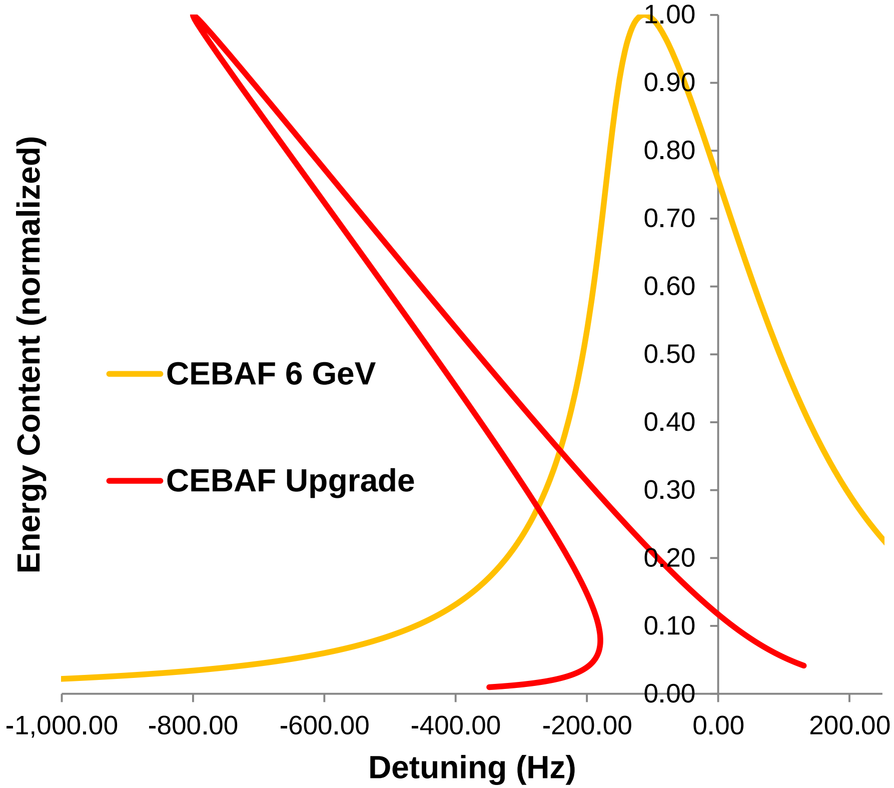


- Noise amplified by klystron then filtered by the cavity
- Limiter amplifies and clips the cavity tone
- Phase shifter provides positive feedback to build resonance
- Bring up cavity quickly without having to run tuners

Why Self Excited Loop?

- Lorentz force detuning
  - High Q C100 cavities
  - Cavity frequency is a function of gradient
- Self Excited Loop (SEL)
  - Tolerant of cavity mistuning
  - Quickly bring up cavity gradient without running the tuners
  - Recover faulted cavities in seconds instead of minutes
- Generator Driven Resonator (GDR)
  - Tune cavity at low gradient
  - Slowly ramp while mechanical tuners compensate for Lorentz

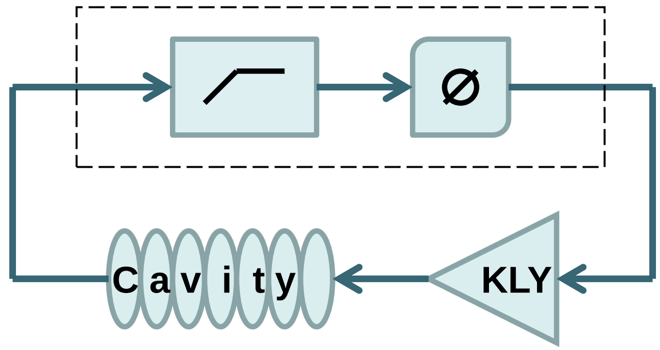
Gradient vs. Cavity Tune



-800Hz of detuning

Self Excited Loop

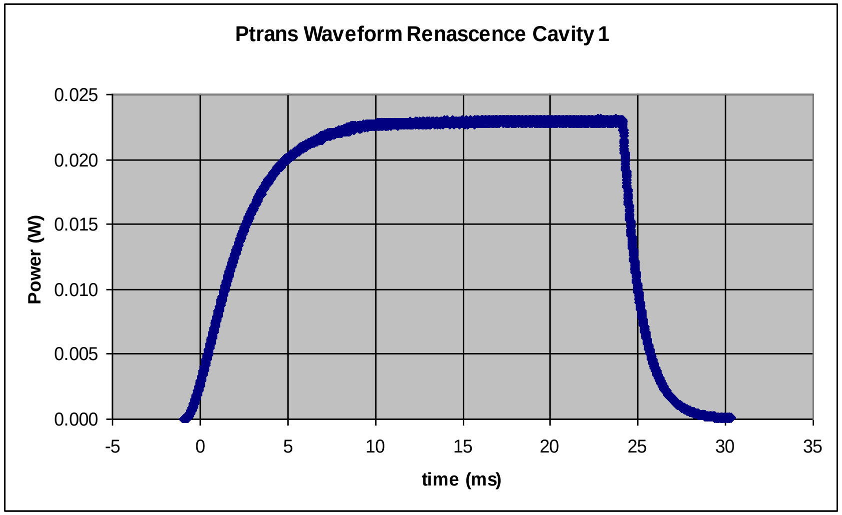
Analog Implementation



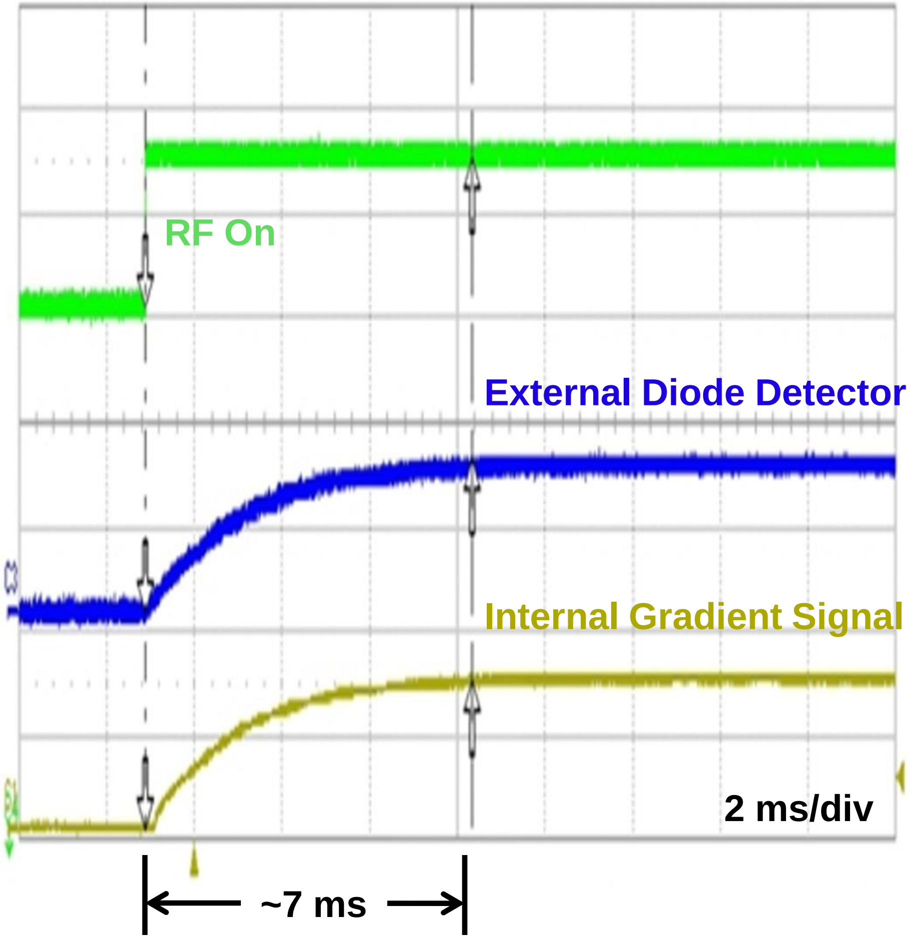
- Noise amplified by klystron then filtered by the cavity
- Limiter amplifies and clips the cavity tone
- Loop phase shifter provides positive feedback to build resonance
- Digitally implemented limiter and loop phase shifter

SEL Performance

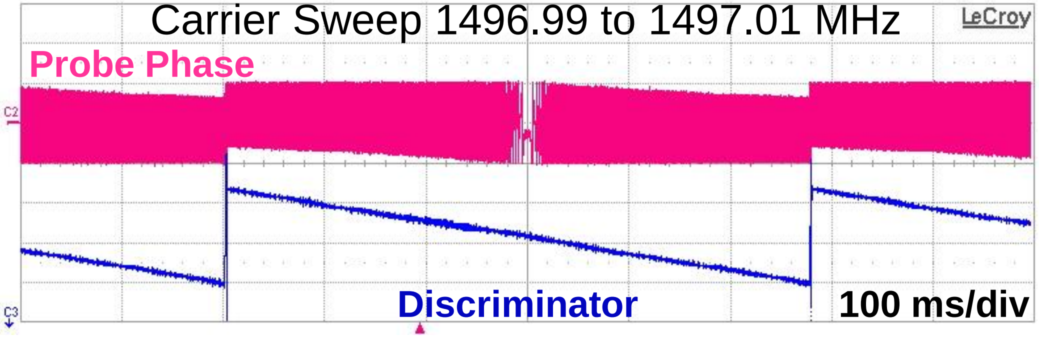
- Turn-on of detuned cavity
  - Bringing RF up is only limited by cavity fill time
  - No excessive power
  - Tracks Lorentz detuning and microphonics

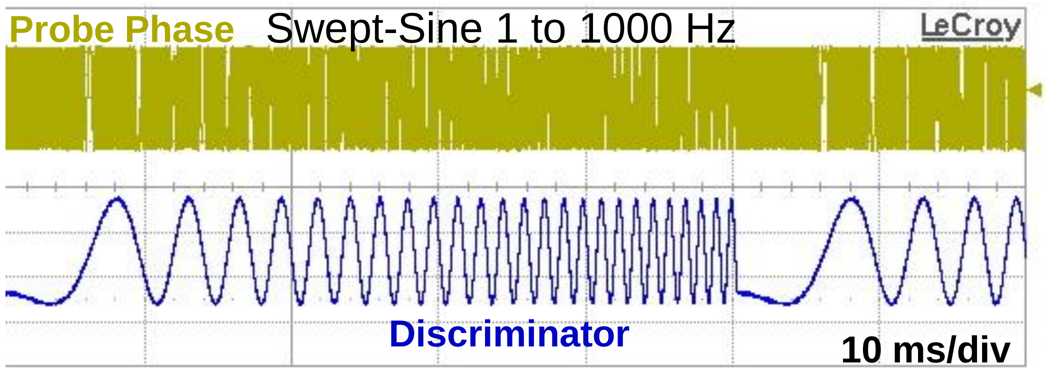


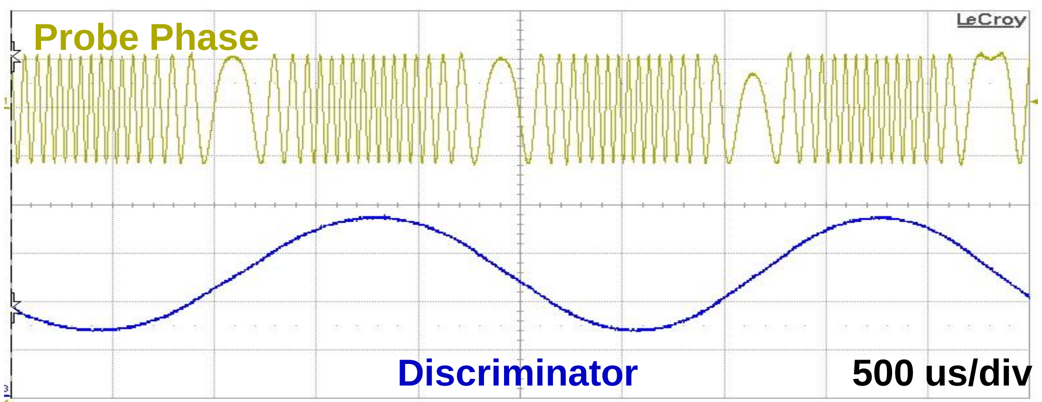
0 to 21 MV/m in 7 ms

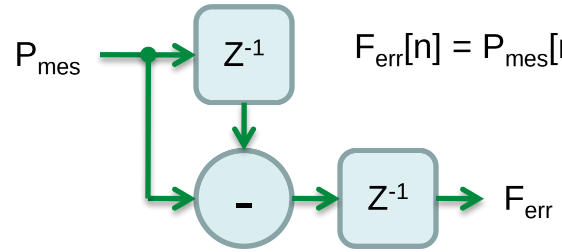


SEL Frequency Discriminator









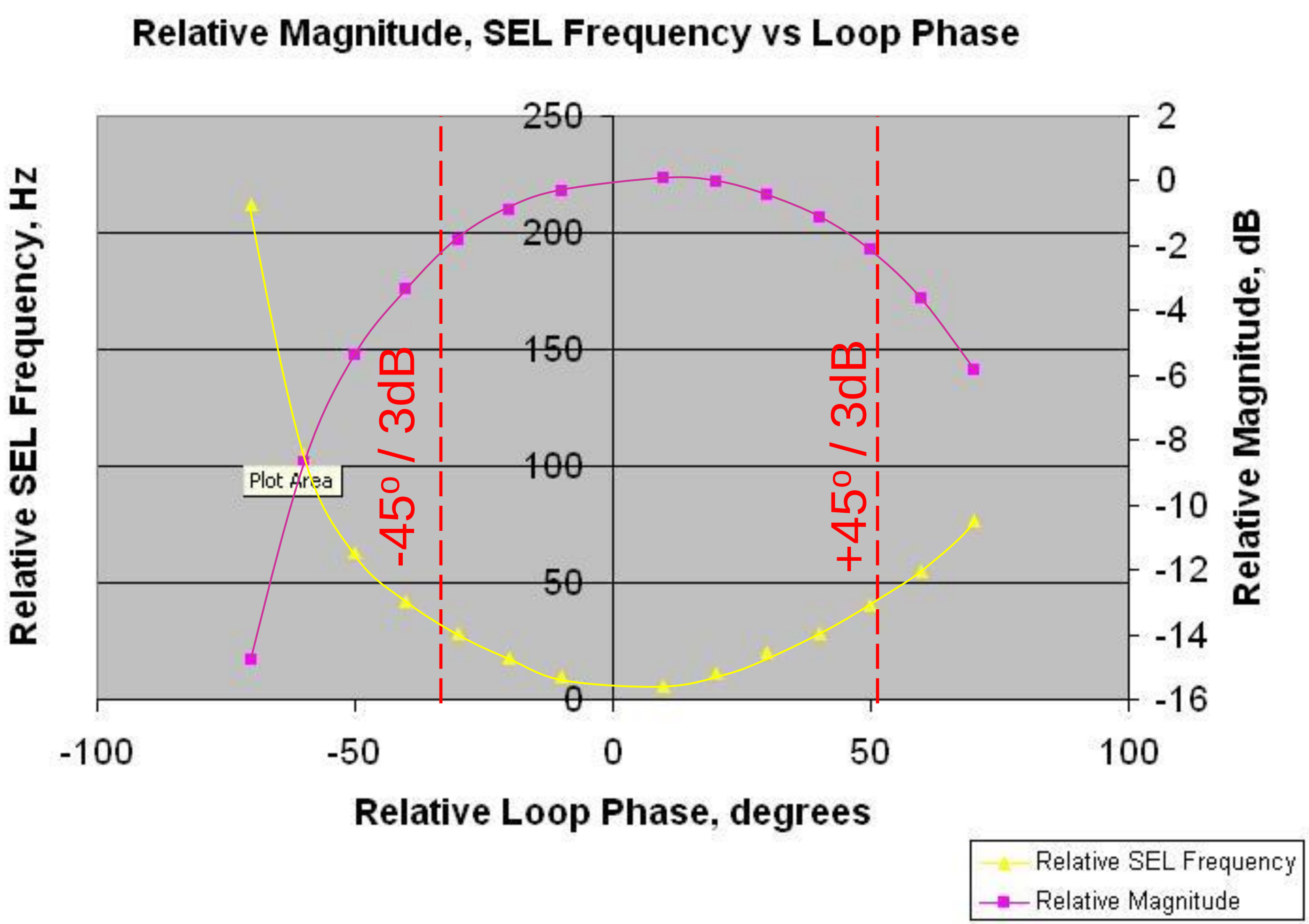
$F_{err}[n] = P_{mes}[n] - P_{mes}[n-1]$

Register update rate determines range

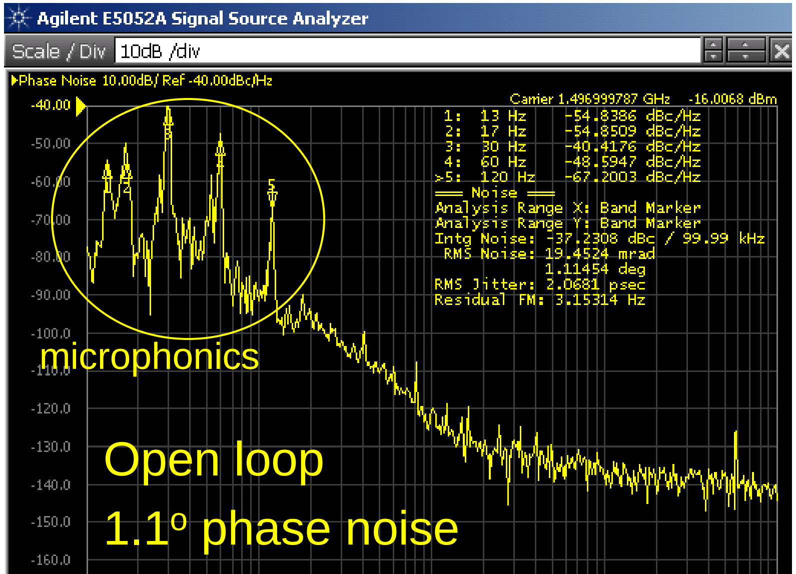
- Measure phase difference during 4 intervals
  - XL: +/- 438 kHz
  - L: +/- 27 kHz
  - M: +/- 1.71 kHz
  - S: +/- 107 Hz
  - Each represents 16-bits of a 28-bit word
- Used by Steppers or PZT to tune in SEL mode

SEL Loop Phase

- Map cavity using loop phase
- +/-45º shift corresponds to 3dB points
- Easy way to measure cavity Q



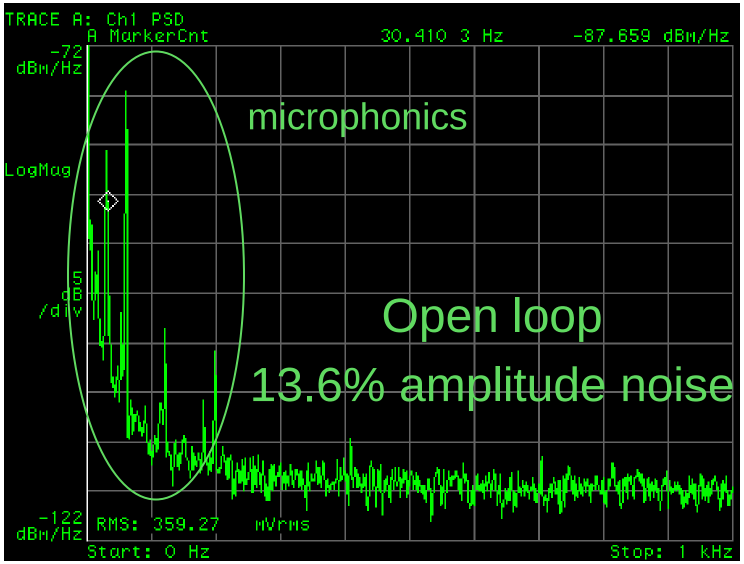
GDR I&Q Lock Performance



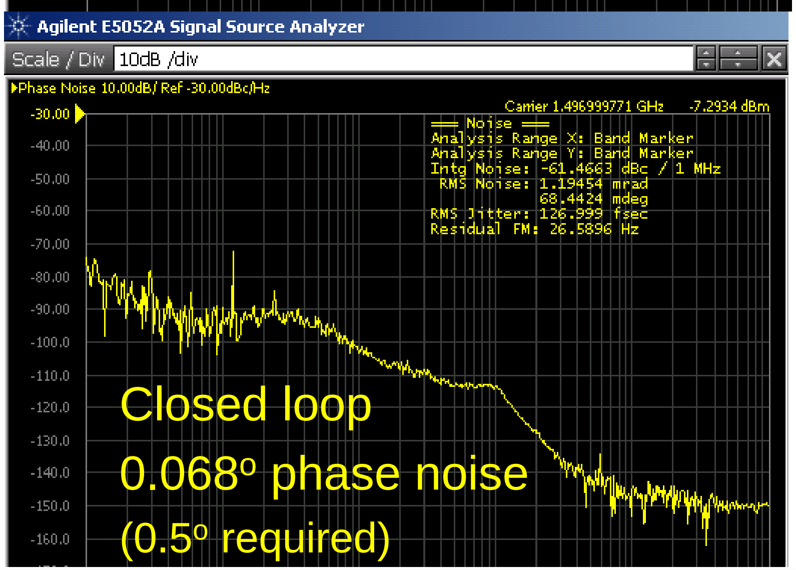
Renascence

Q_L=8.6x10^6

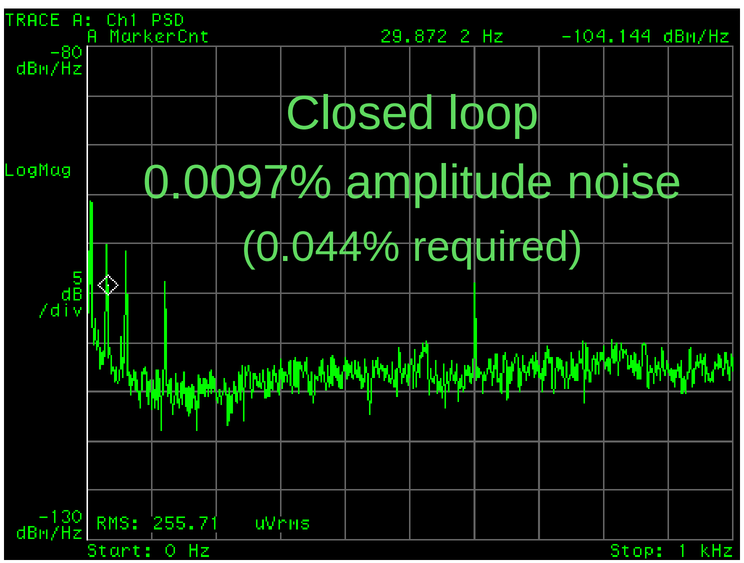
Unregulated



vs.



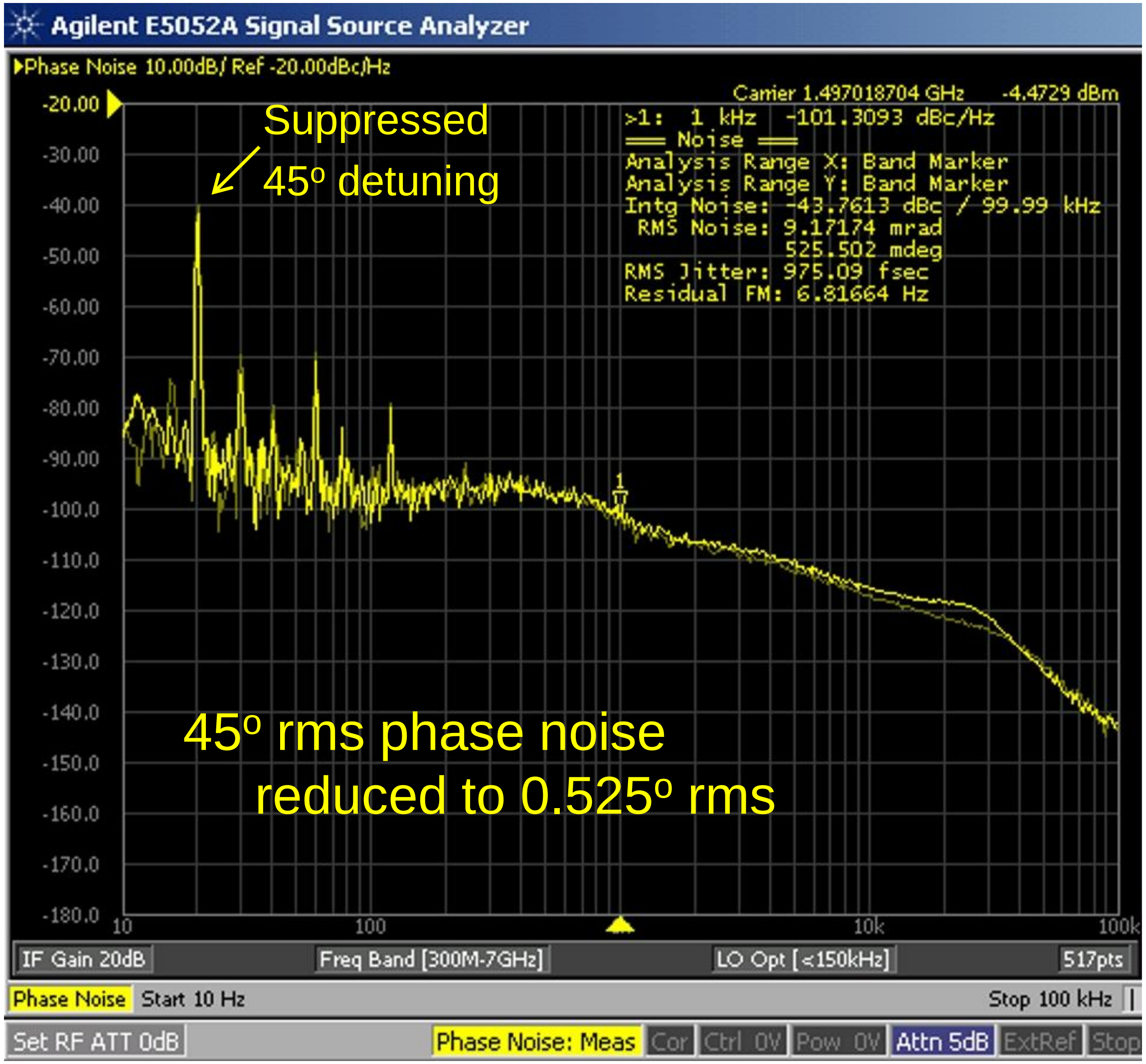
Regulated



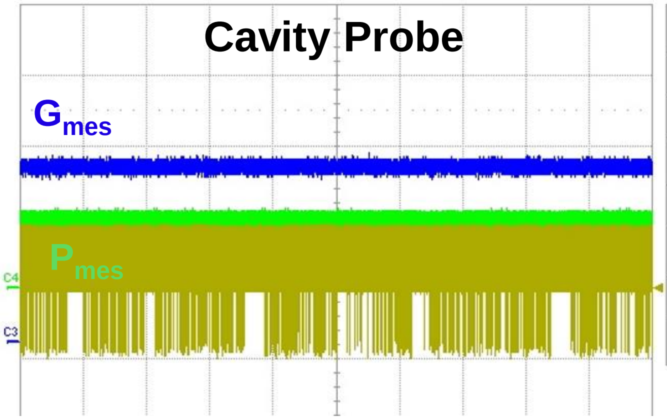
GDR I&Q Lock Performance

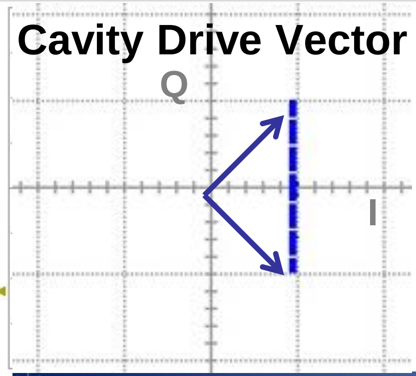
<u>Renascence Testing</u>

- Expected 4 Hz rms microphonics for C100 upgrade cavity
  - Worst case six sigma (24 Hz rms) corresponds to 45º detuning
  - Piezo induced 45º microphonics on Renascence
- C100 performance worse than expected, large microphonics



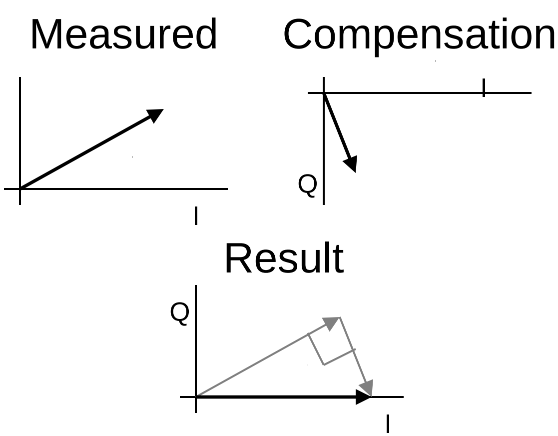
Other Control Algorithms

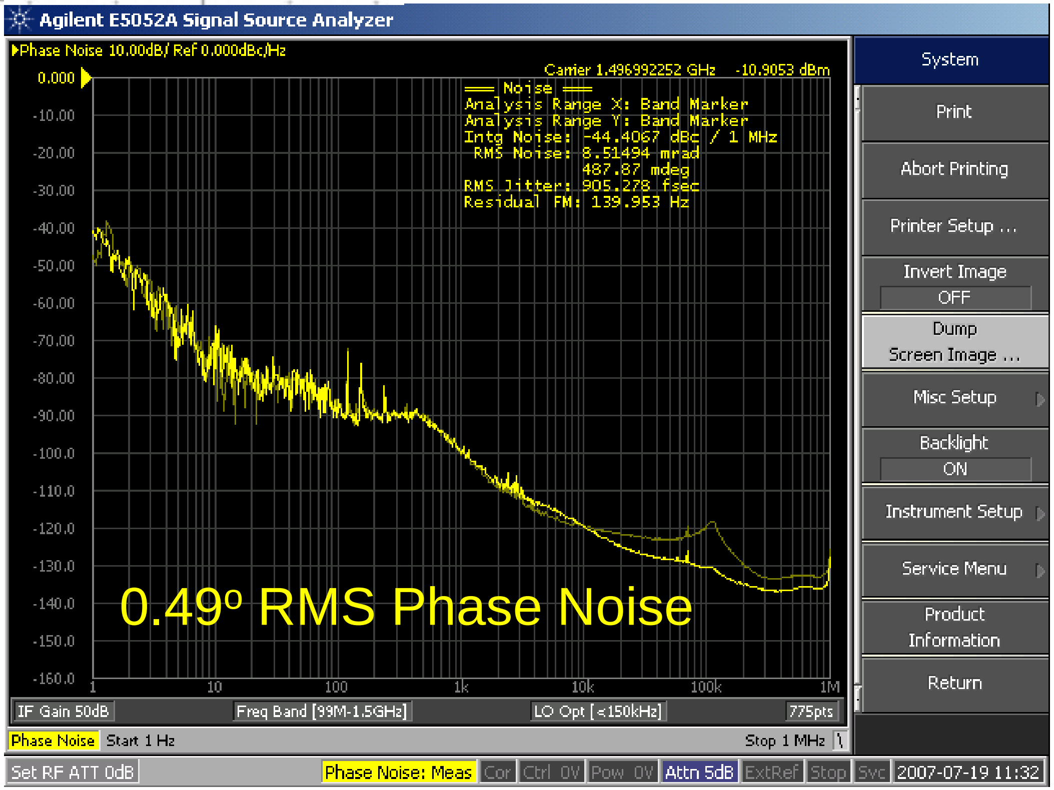




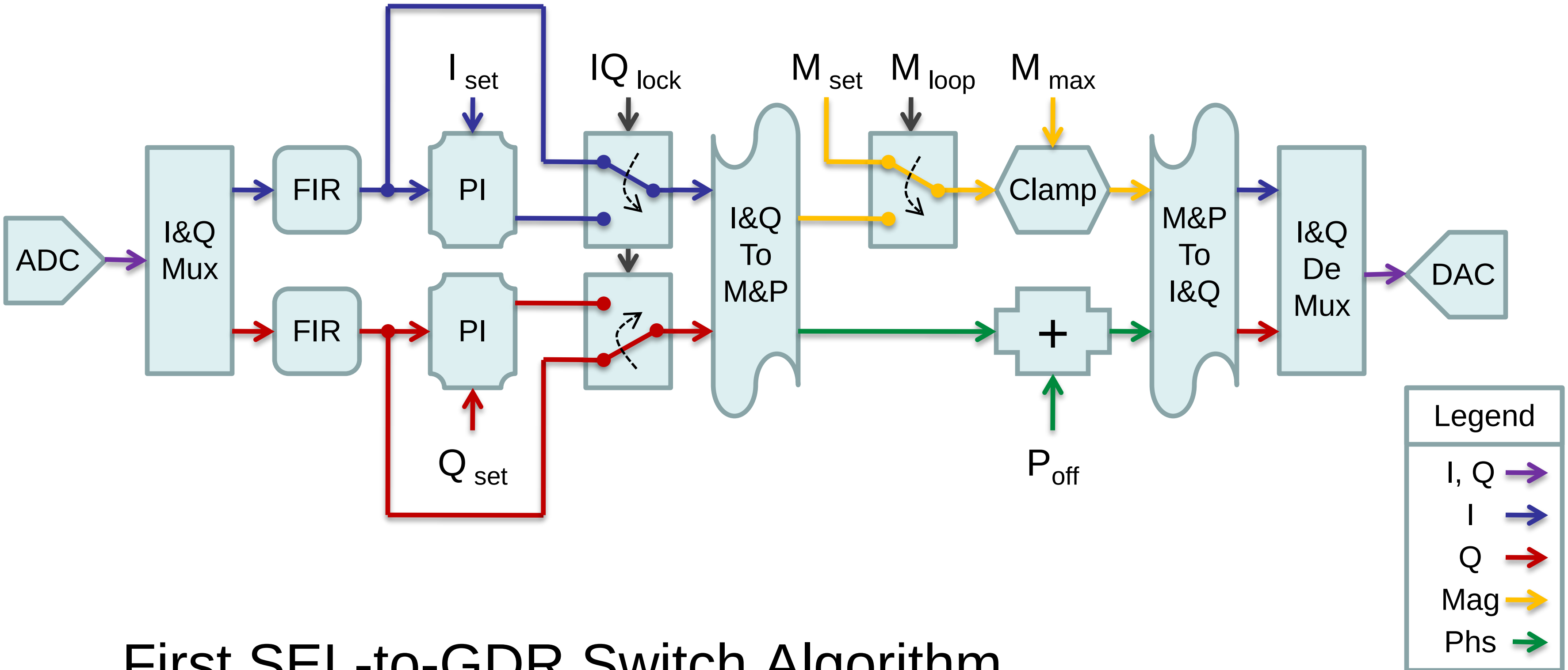
Microphonic Compensation Testing

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





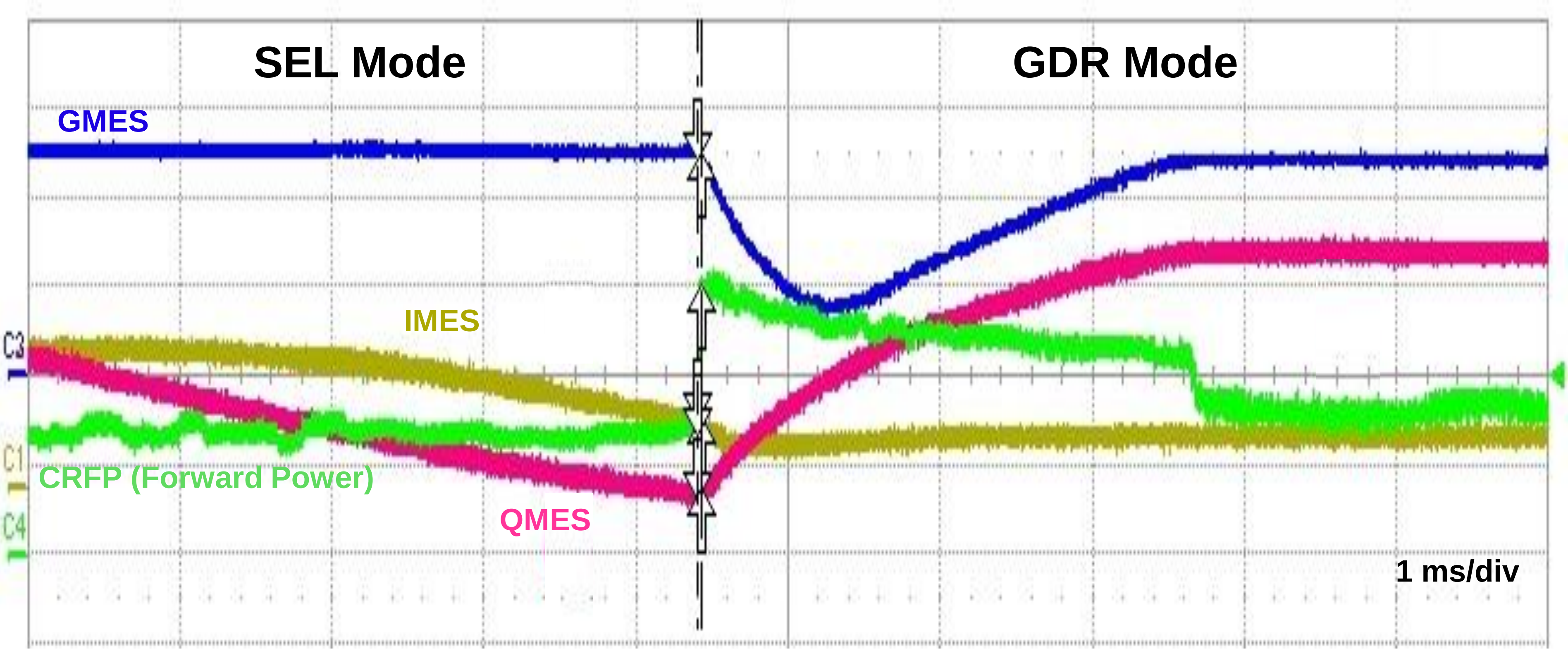
SEL to GDR Transition



First SEL-to-GDR Switch Algorithm

1. Adjust M_{set} to give desired gradient
2. Switch IQ_{lock} to PI controllers & M_{loop} loop

SEL to GDR Transition



<u>First SEL-to-GDR Switch Algorithm</u>

- Forward power spikes and Gmes droops as I&Q lock pulls the arbitrary Imes & Qmes to the set points
- Algorithm enhanced to eliminate spikes and droops

SEL to GDR Transition

Present SEL-to-GDR Switch Algorithm

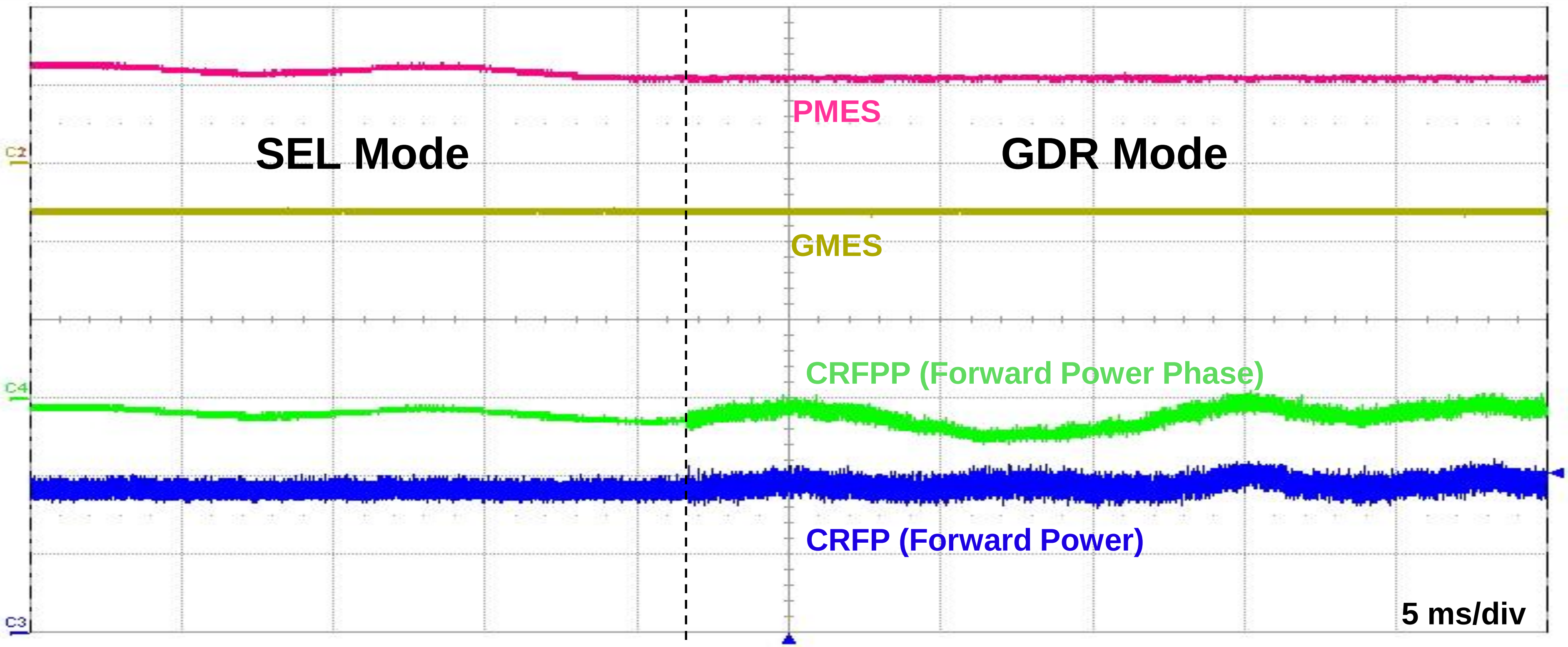
EPICS

1. Achieve desired switch gradient in SEL mode
2. Use discriminator and steppers to tune the cavity
3. Set the firmware bit to switch from SEL to GDR

Firmware

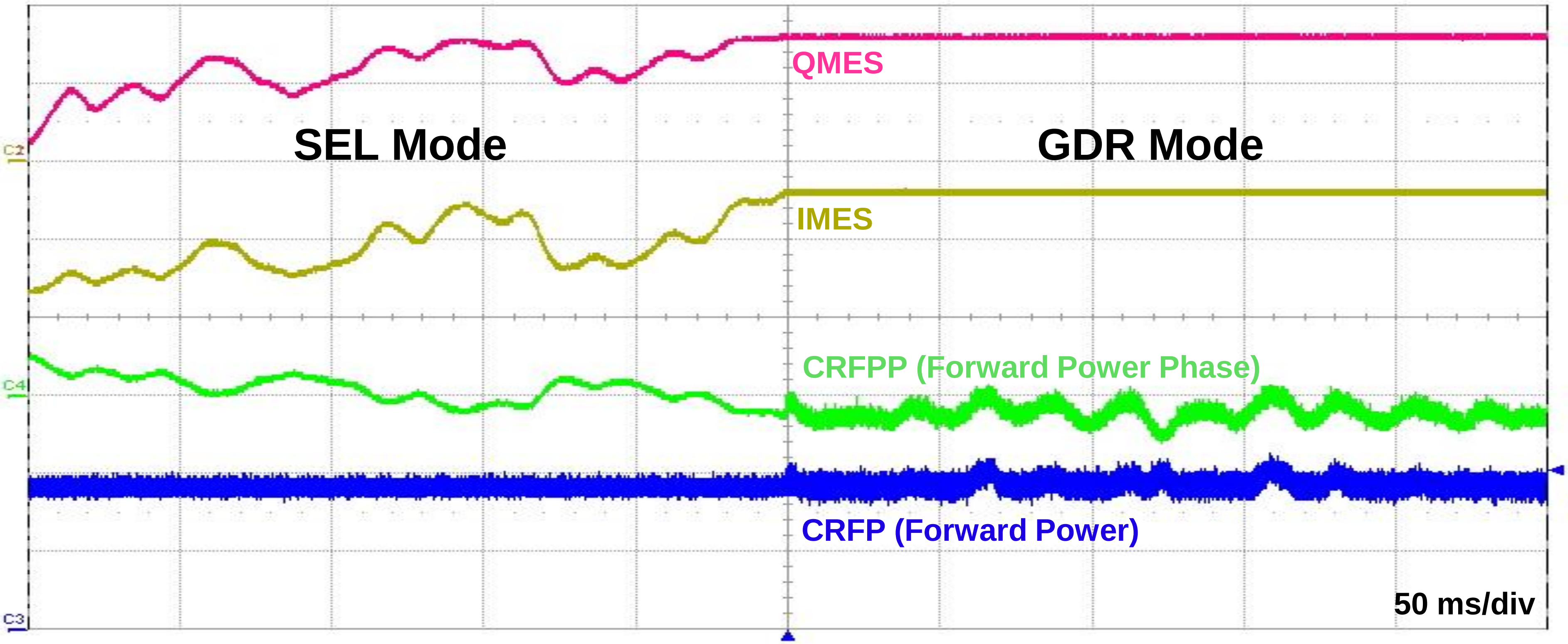
4. Wait for the cavity to be tuned exactly to 1497MHz
   - Check for I_{mes} and Q_{mes} to stop changing
   - If waiting > 500 msec then continue anyway
5. Preload the PI loop controllers with present values
   - Copy I_{mes} and Q_{mes} into I_{set} and Q_{set} (I_{err} & Q_{err} = 0)
   - Set integrators such that I_{ask} and Q_{ask} stay constant
6. Add P_{offgdr} phase offset to the loop phase
7. Send the steppers detune angle instead of discriminator
8. Switch to IQ Lock GDR mode (PI controllers and G_{loop})
9. Ramp I_{set} and Q_{set} to values requested by EPICS

SEL to GDR Transition



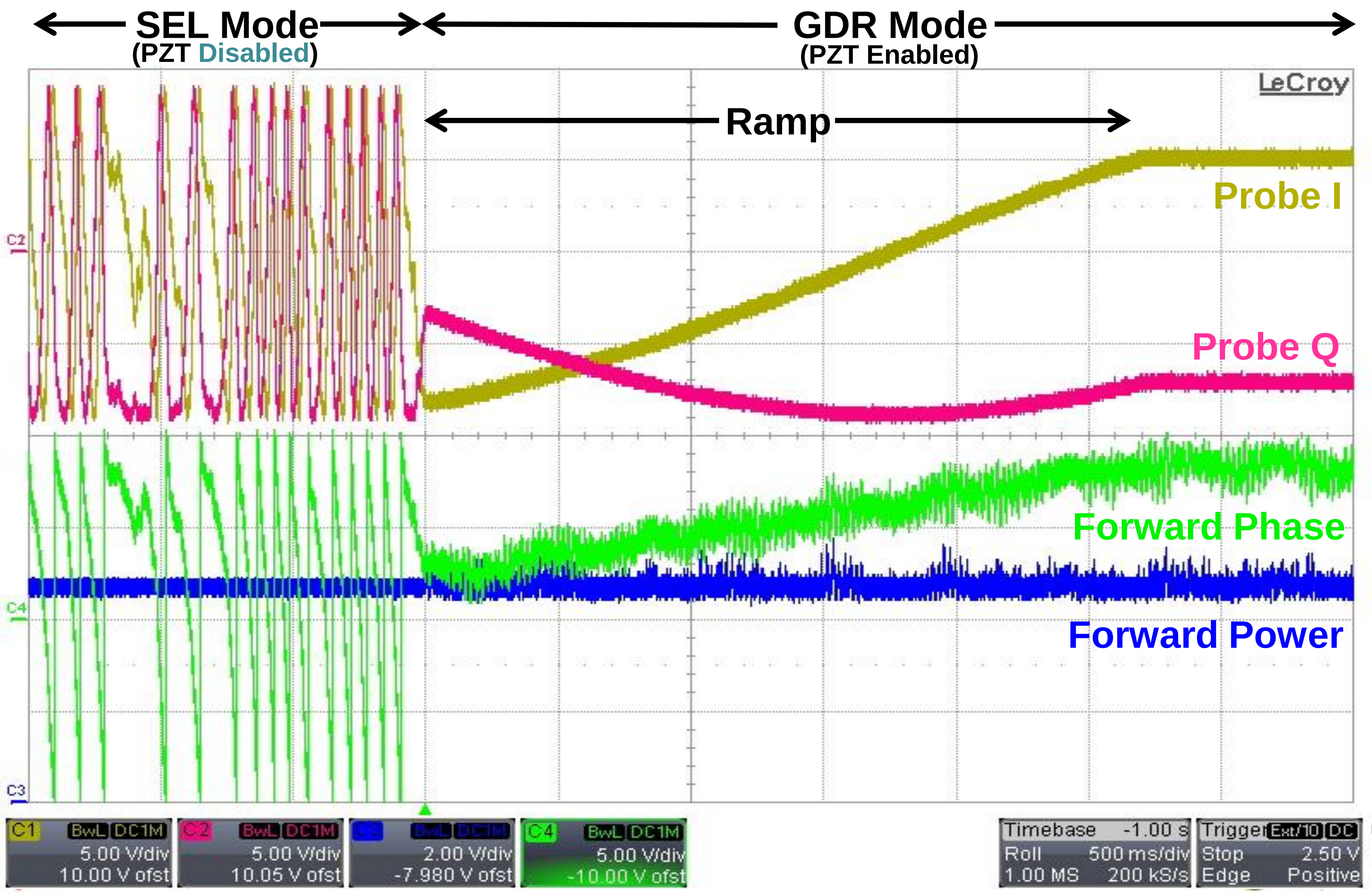
- Preload PI controllers then switch to present gradient & phase
- Eliminates forward power spike and Gmes droop
- This example did not wait for tune and did not ramp

SEL to GDR Transition

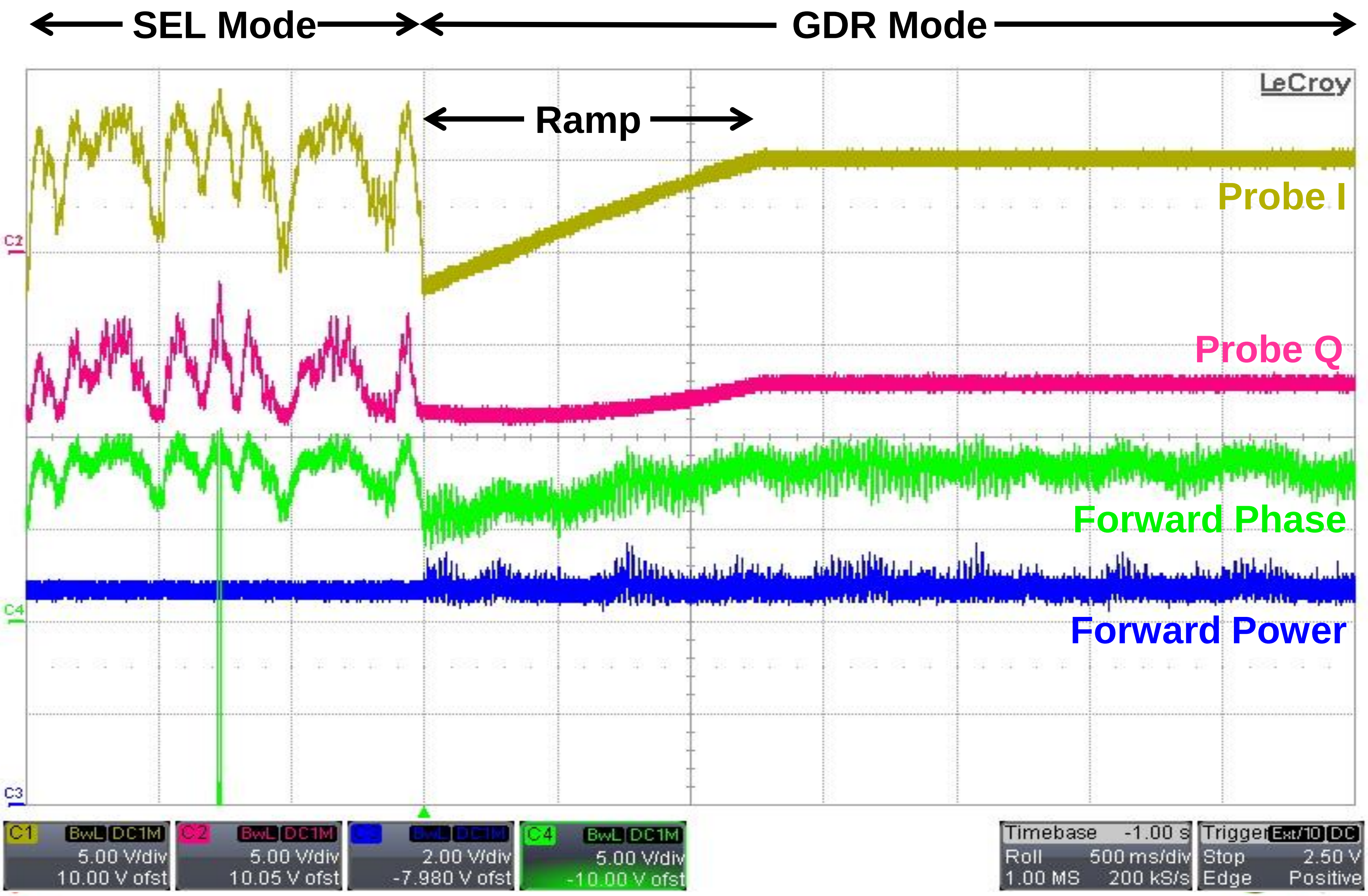


- Preload PI controllers then switch to present gradient & phase
- Eliminates forward power spike and Gmes droop
- This example did not wait for tune and did not ramp

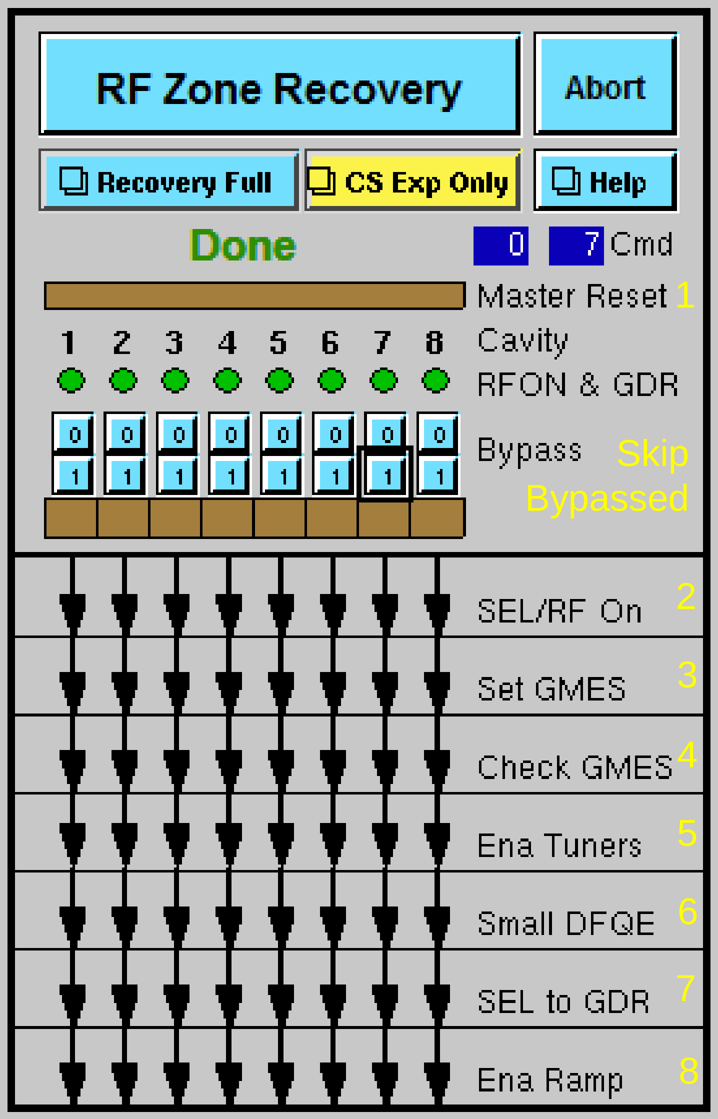
SEL to GDR Transition



SEL to GDR Transition



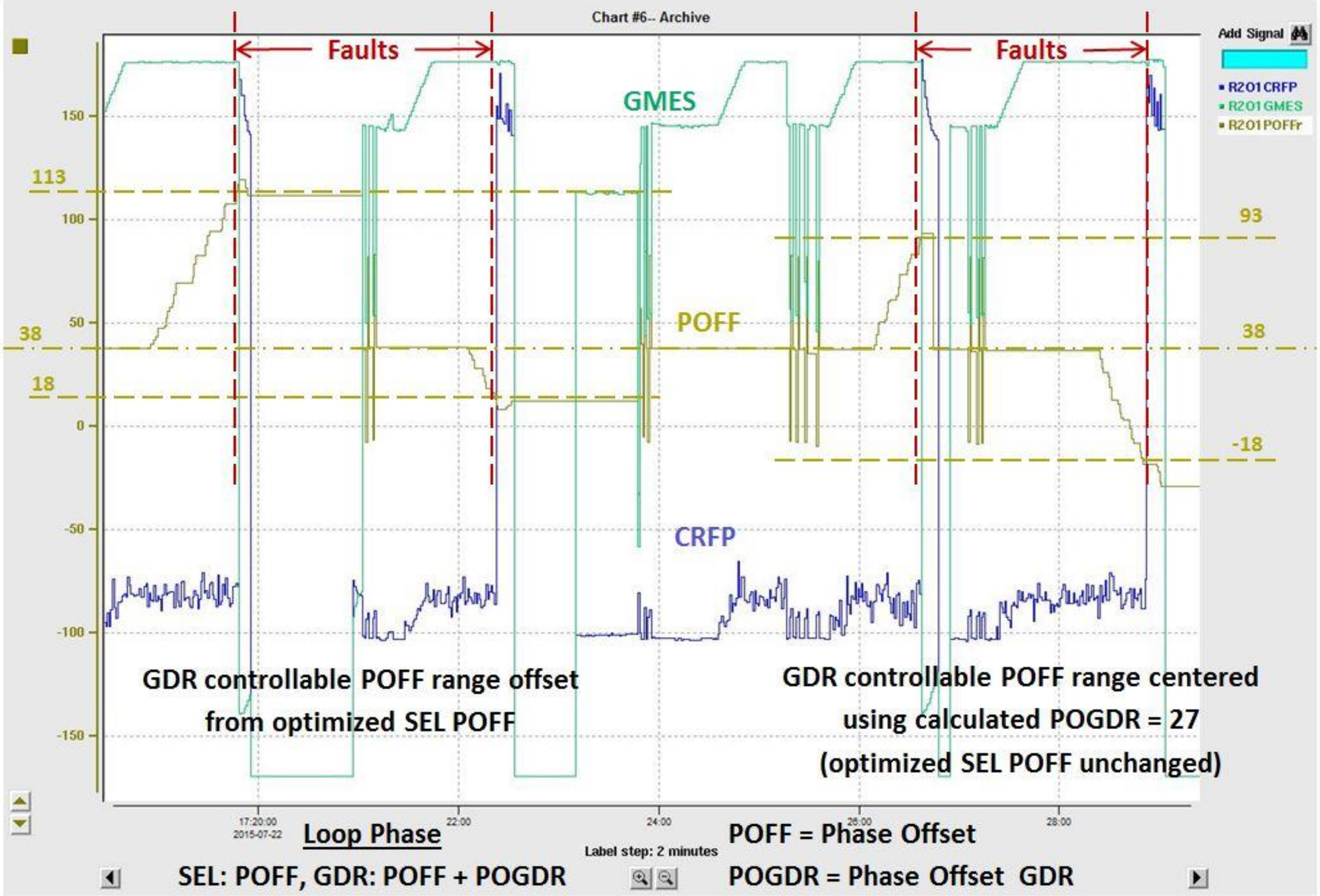
One Button Recovery



All cavities have to complete each step before any continue

1. Master Reset
2. SEL/RF On
   - Go to SEL and Clip GLOS
   - Close RF Switch
3. Set GMES
   - Adjust GLOS until GMES = GTAR
4. Check GMES (close to GTAR)
5. Enable Tuners
6. Wait for Small DFQE
7. SEL to GDR enable FW algorithm
8. Enable Ramping Grdnt & Phs

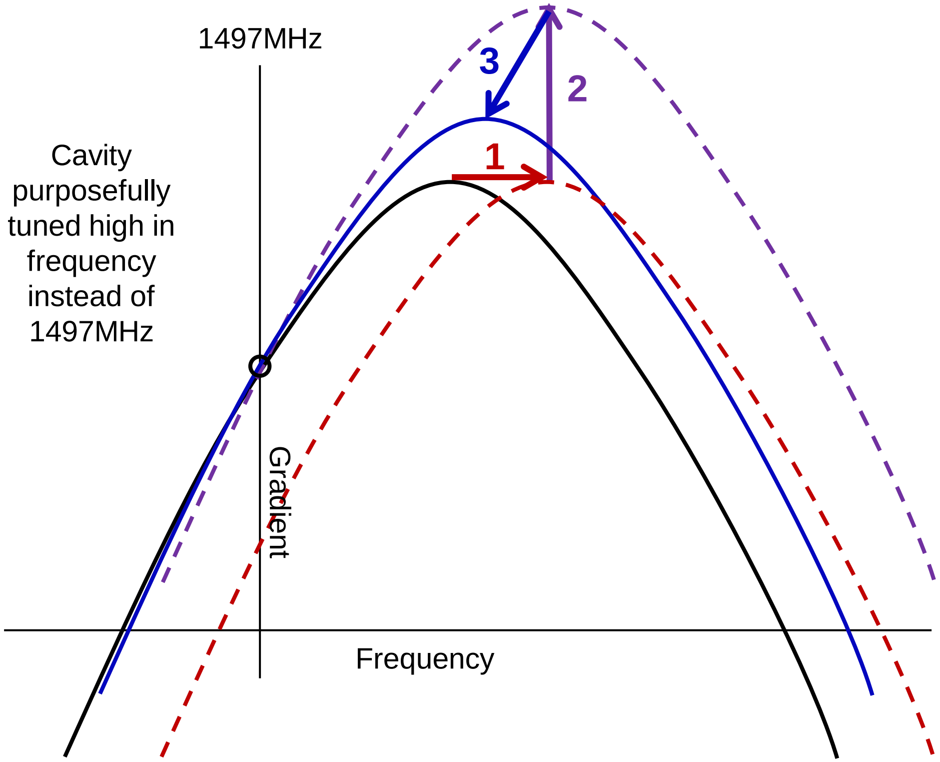
Phase Offset SEL vs. GDR



GDR Lorentz Force Tuning

<u>Cavity tuned high</u>

1. Microphonics detunes the cavity higher
2. Loop increases drive to hold gradient
3. Increasing drive decreases cavity frequency via Lorentz Force, pushing against detuning

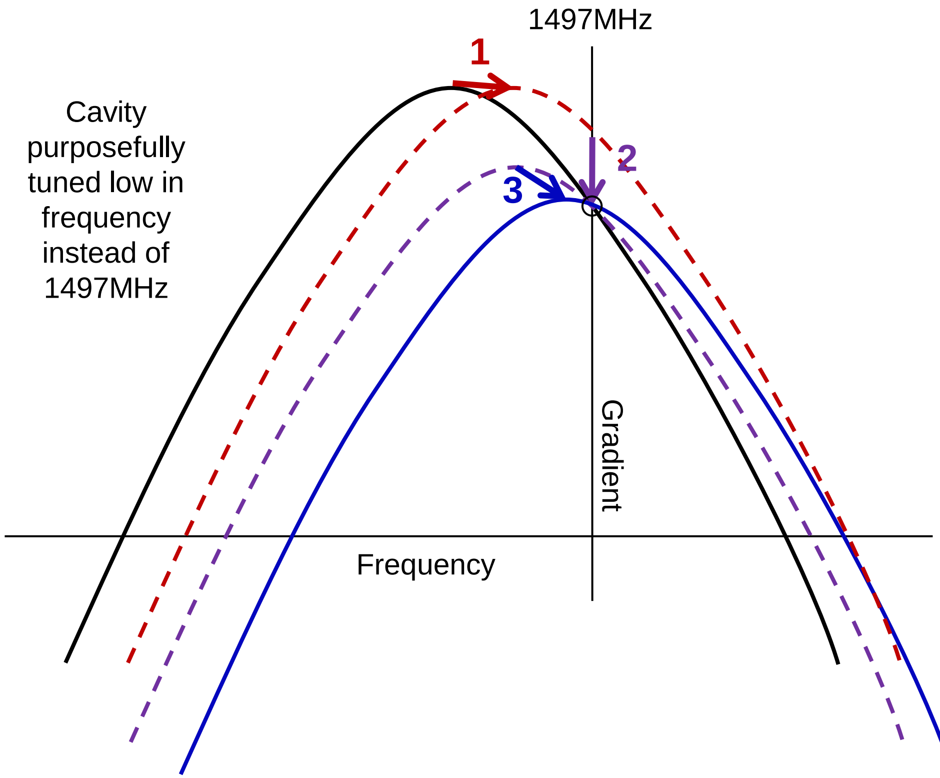


- Increased gradient control gain via Lorentz Force
  - Same is true if detuning forced the cavity lower in frequency
- Tuning the cavity lower than 1497MHz has opposite effect
- Need to PI steppers or install PZTs to take advantage of this

GDR Lorentz Force Tuning

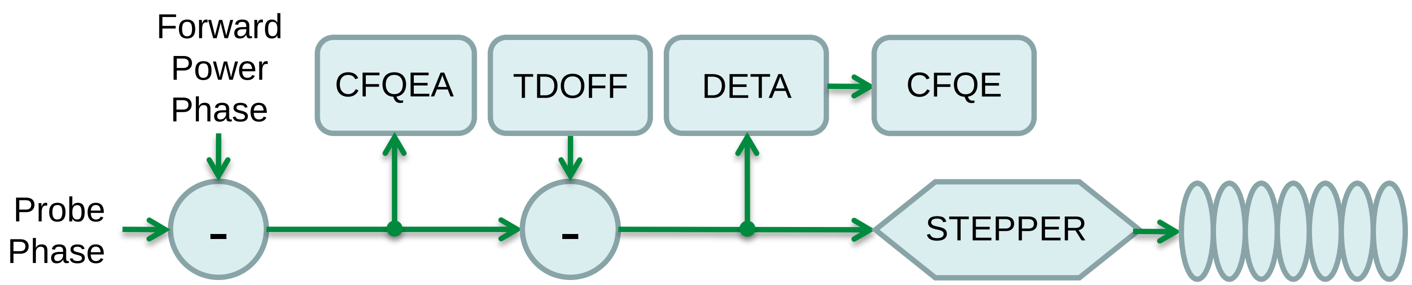
<u>Cavity tuned low</u>

1. Microphonics detunes the cavity higher
2. Loop decreases drive to hold gradient
3. Decreasing drive increases cavity frequency via Lorentz Force, pushing detuning even father



- Decreased gradient control gain via Lorentz Force
  - Same is true if detuning forced the cavity lower in frequency
- Tuning the cavity higher than 1497MHz has opposite effect

Stepper Tuner



TDOFF = Phase Offset
CFQEA = Forward Power Phase – Probe Phase
DETA = Forward Power Phase – Probe Phase – Phase Offset
CFQE = DETA converted to cavity frequency in Hz (EPICS)

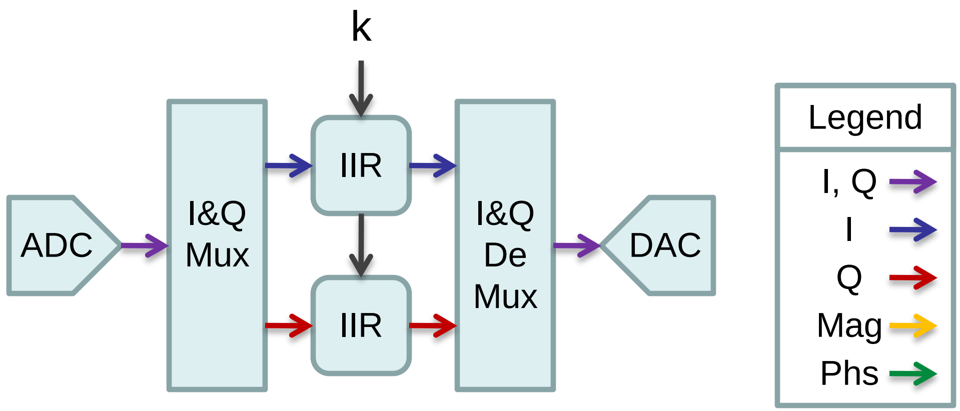
- On/Off Algorithm (adjustable)
  - If abs(DETA) >3º then tune to within +/- 1º
- Uses fiber data (~100 ksps)
  - Was slow over EPICS and caused stability issues
  - Allowed for tighter regulation
- ~28 micro steps per Hz
- Acceleration and Velocity adjustable
- Single chassis per zone
- Uses Discriminator in SEL instead of DETA

Other EPICS Algorithms

- POFF Phase Sweep
  - Sweep POFF phase +/- 180º
  - Record phase for largest gradient and set POFF
- POFF Phase Optimize
  - Adjust POFF +45º then -45º
  - Record gradients and calculate/set POFF center
  - Record Discriminator phases and calculate Q
- Drive GMES to GTAR
  - Adjust output (GLOS) to achieve target gradient in SEL
- Many more
  - Master Reset
  - SEL/RF On
  - Zero DETA
  - Tune DFQE
  - Cold Start
  - SEL-to-GDR
  - Enable Ramp after Switch
  - Etc.

Other Modes

Cavity Emulator



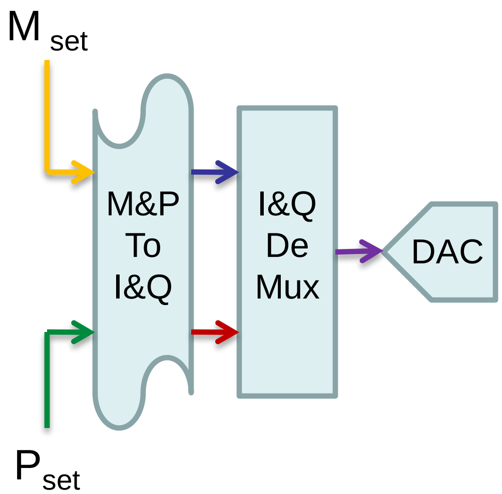
- Turn any LLRF module into a cavity for testing
- Loopback or test another module
- k = 18, BW = 34 Hz (Q = $4.4\text{x}10^7$)
- Hope to add Lorentz and microphonics

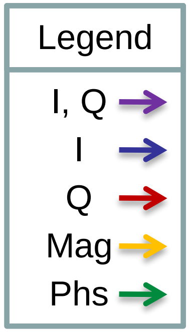
Gradient Pulse SEL

- Just like it sounds…

Other Modes

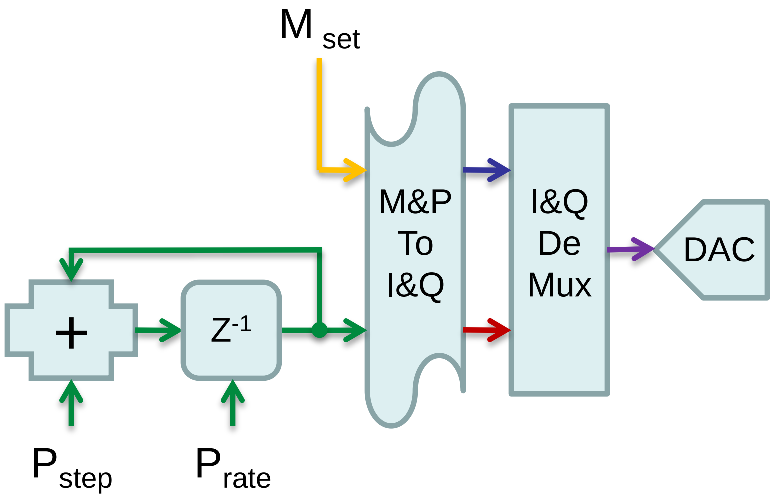
Tone





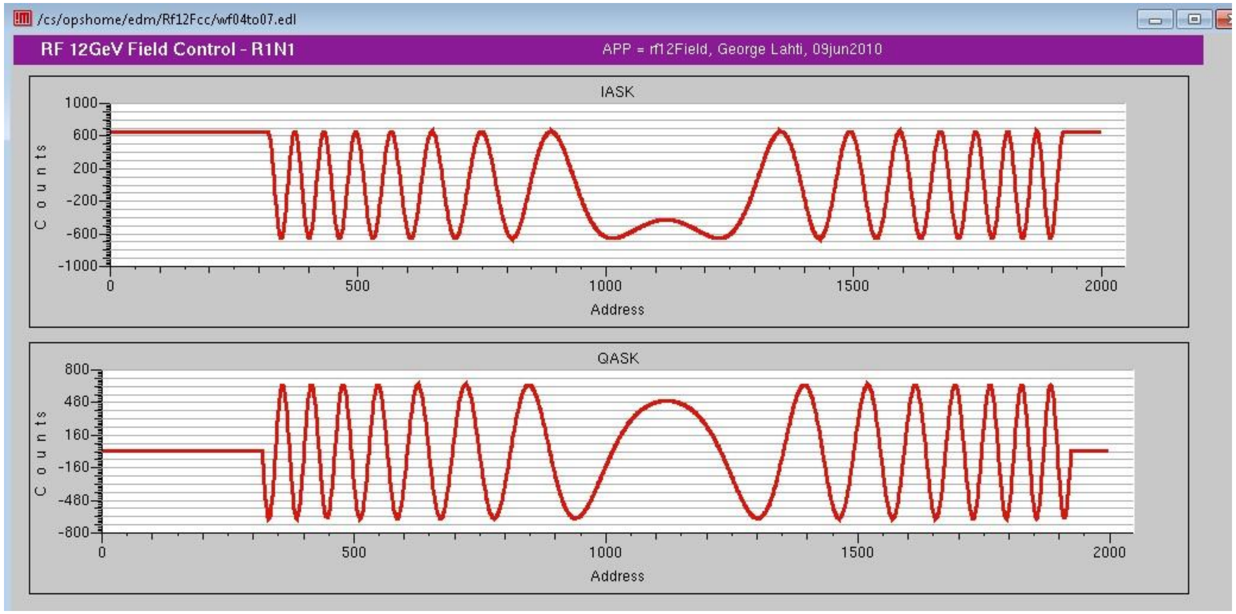
- Output 1497 MHz tone
- Magnitude and Phase set points

Phase Spin

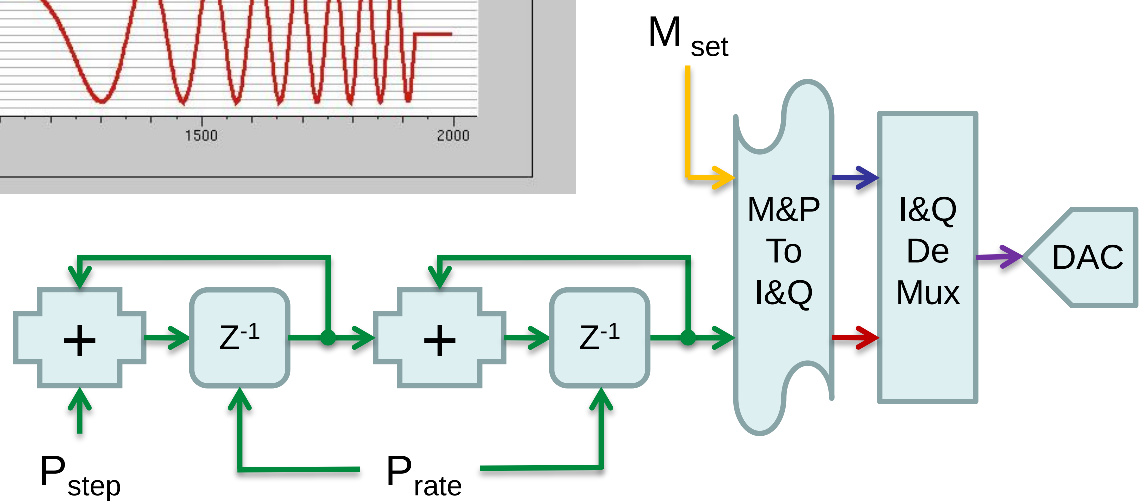


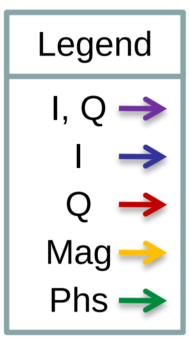
- Tone mode with spinning phase
- Output frequency can be adjusted
- 1497 MHz +/-14 MHz

Other Modes



Chirp





- Spinning the phase twice generates a chirp
- Output frequency ramps

Other Modes

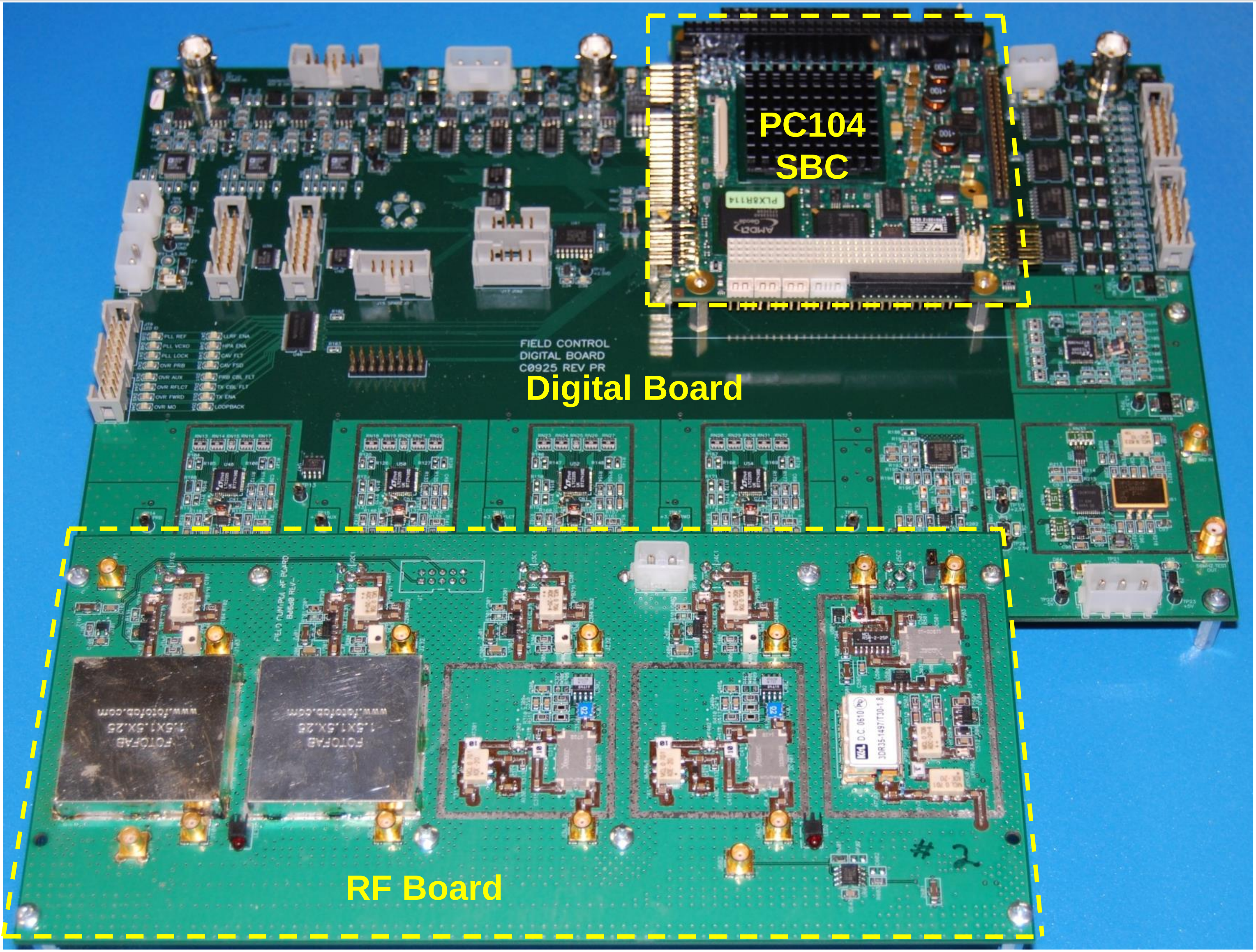
Lorentz Lock

Legend

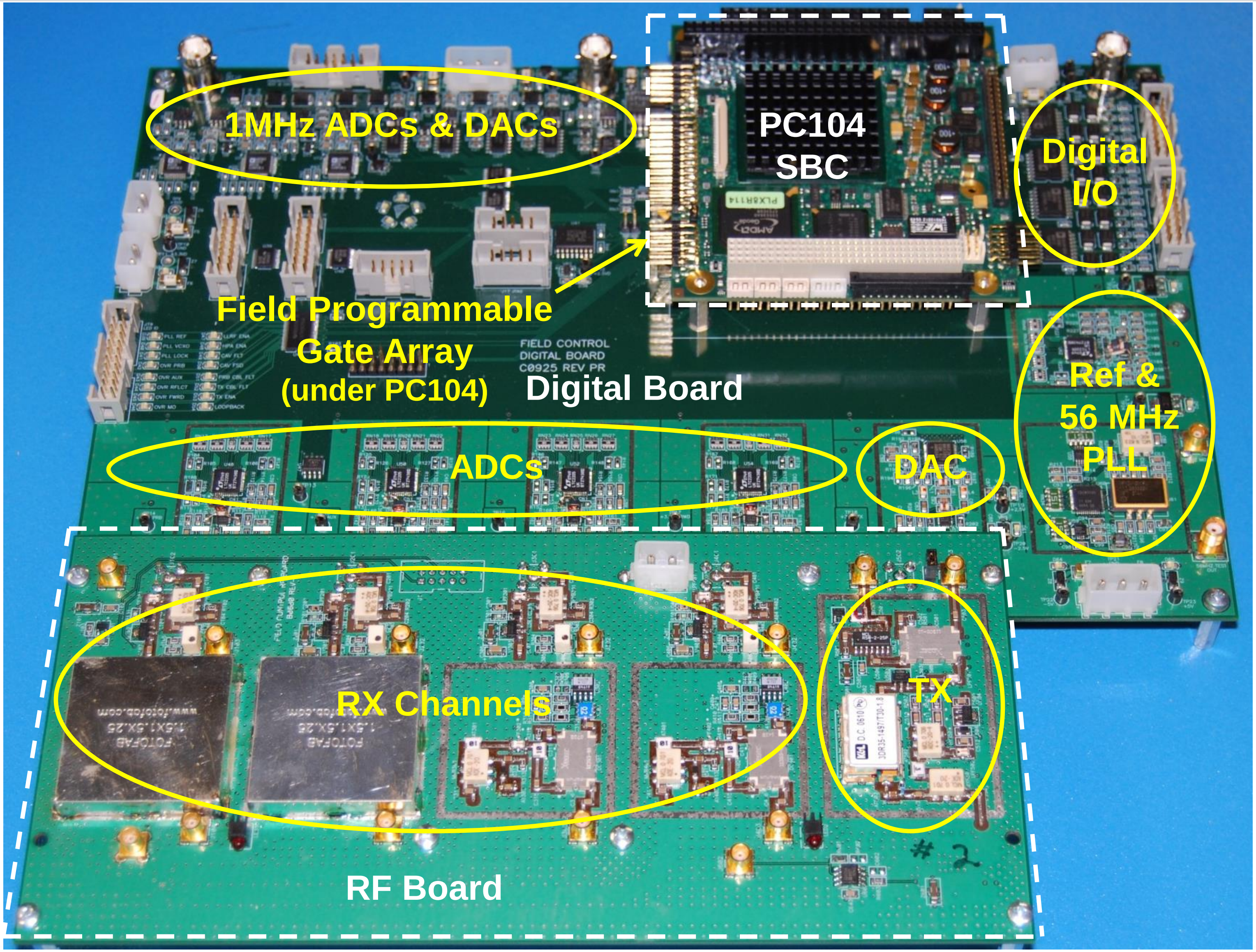
- I, Q →
- I →
- Q →
- Mag →
- Phs →

- Use Lorentz Force to lock phase via gradient control

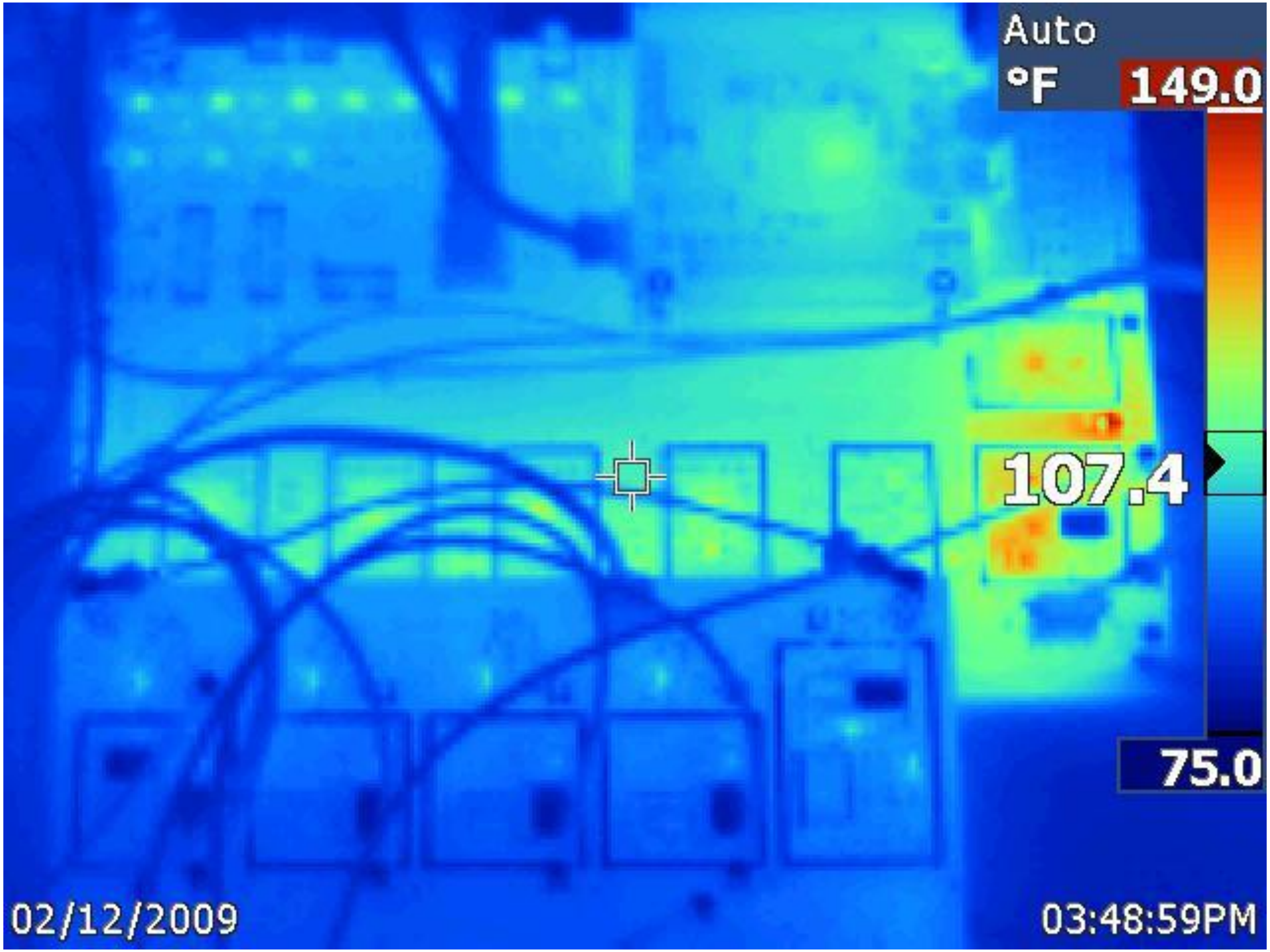
Field Control Hardware



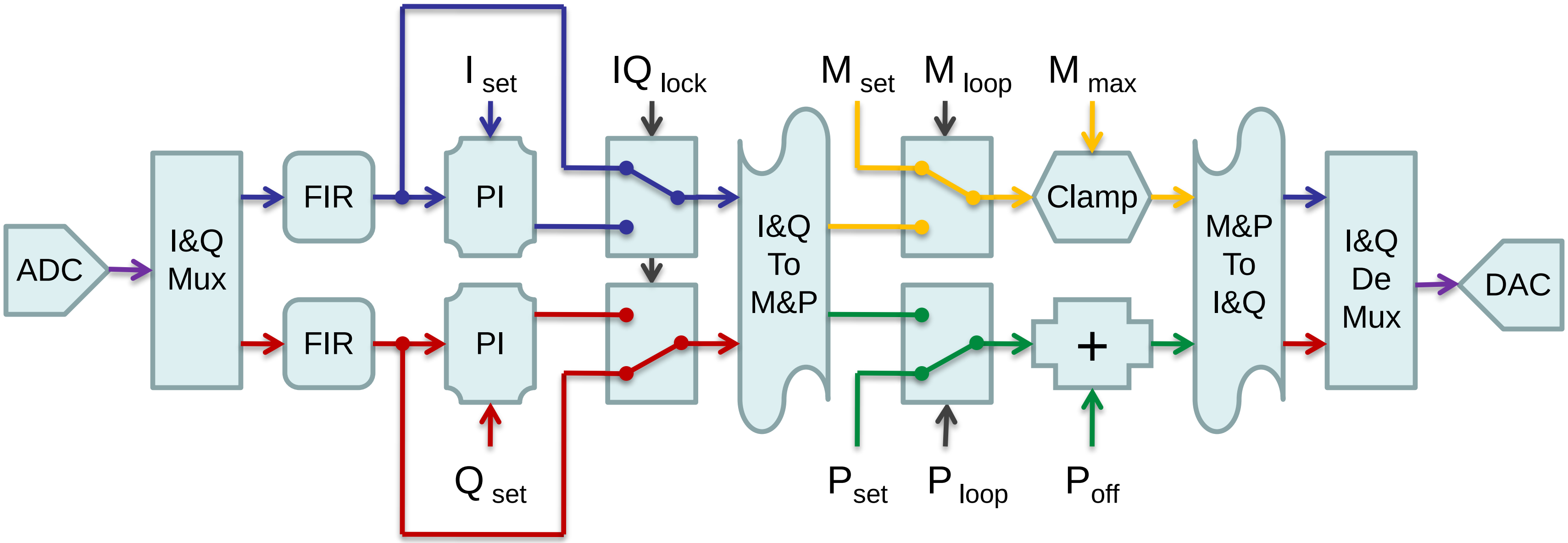
Field Control Hardware

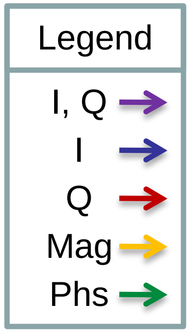


Field Control Hardware



Firmware Block Diagram

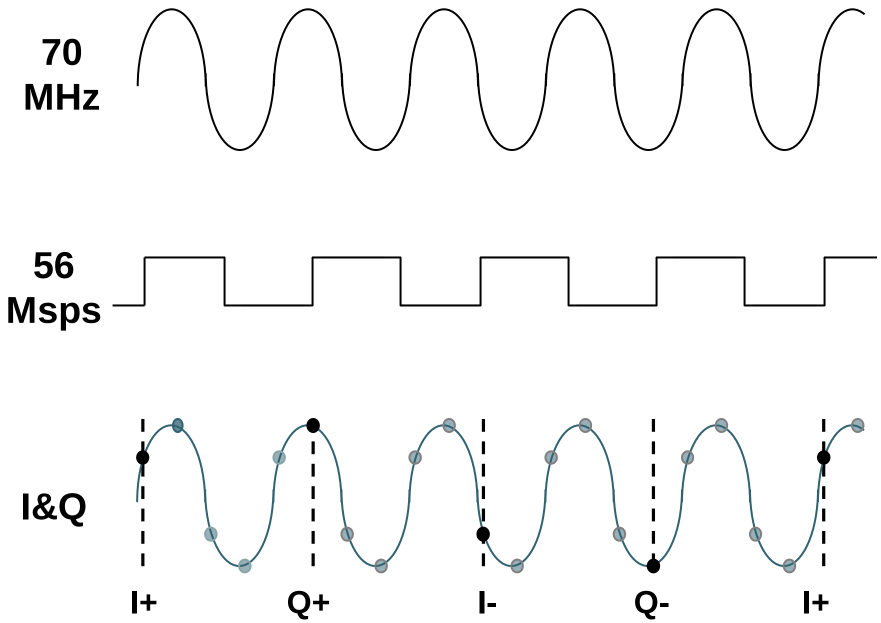




- Self Excited Loop (SEL)
- Generator Driven Resonator (GDR)
  - I&Q Lock
- Many other modes and algorithms not shown…

ADC Sampling & IQ Multiplexer

Sample 70 MHz IF at 56 Msps

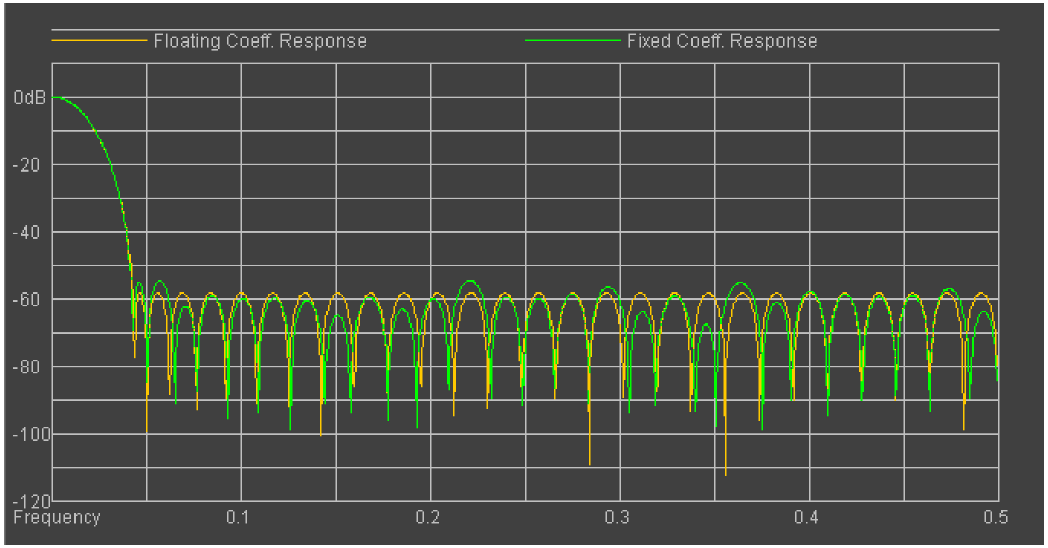


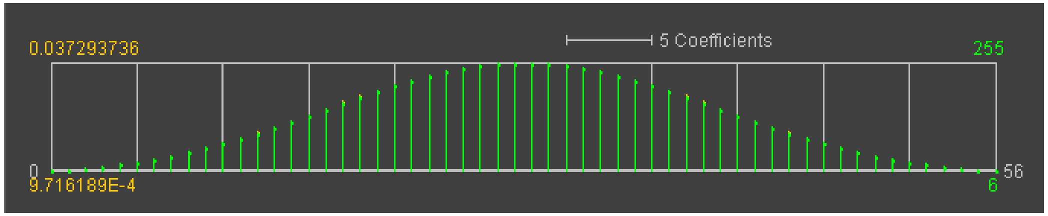
- Any odd multiple yields I&Q
  - 1 / [(2n + 1) / (4 * 70MHz)]
  - 280, 93.3, **56**, 40, … Msps
- Firmware breaks serial chain into parallel 28 Msps I&Q chains
  - I+, -(I-), I+, -(I-), …
  - Q+, -(Q-), Q+, -(Q-), …
  - 28 Msps load also generated

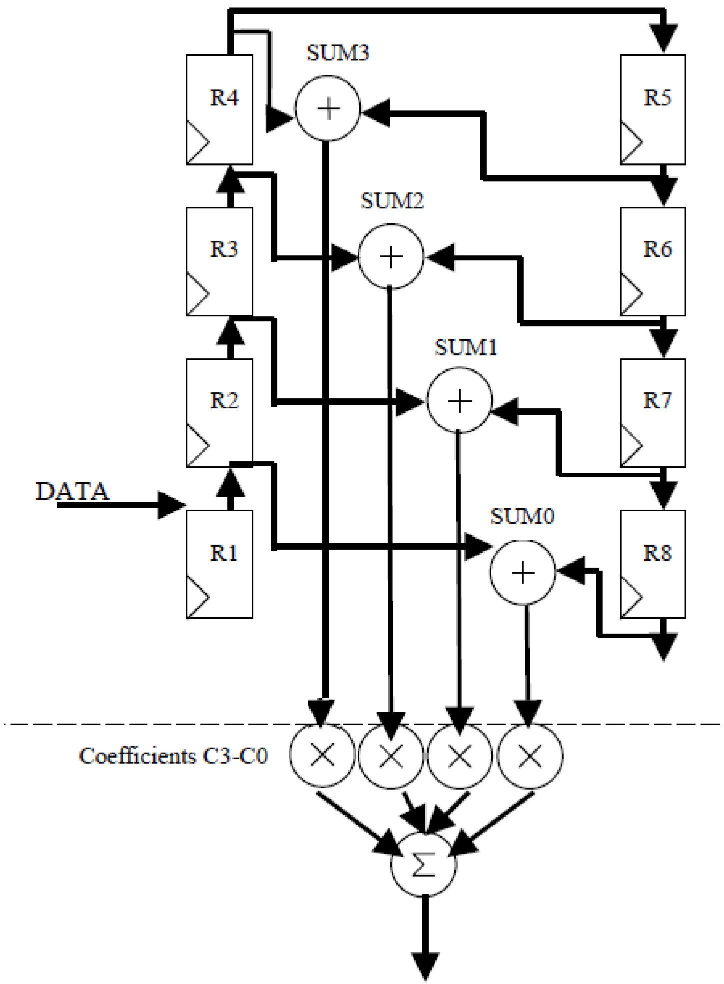
FIR Input Filter

Finite Impulse Response (FIR)

- 200kHz low pass, 56 taps
- 1.2MHz notch to avoid exciting the π/6 cavity mode

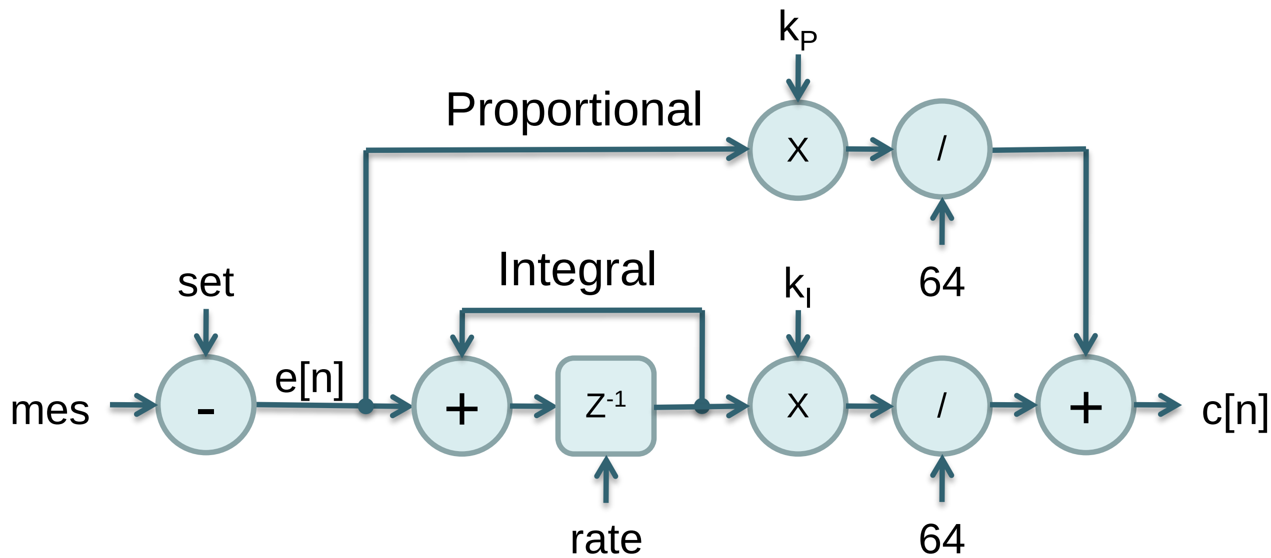






Proportional Integrator Controller

PID Controller (minus D)



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

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

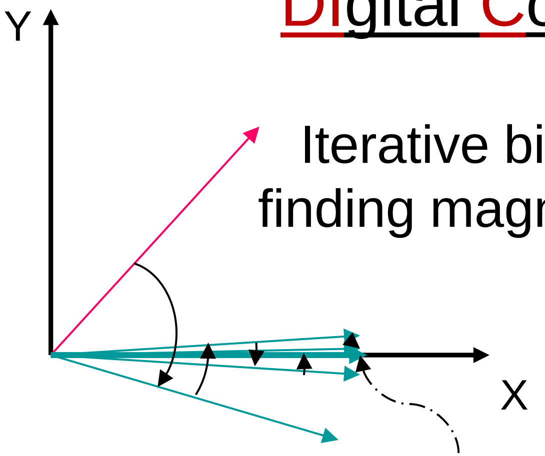
- IQ Lock Mode
- 64 gives a digital gain of 1
- Loop gain measured experimentally
  - Include attenuators, klystron, …
  - With no Int term, gain is 1 when G_{mes} is ½ G_{set}

CORDIC

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



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

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

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

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

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

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

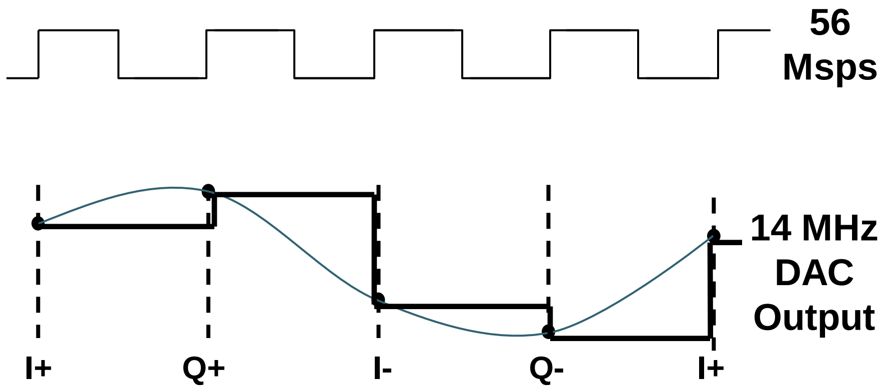
$$y_{i+1} = K_i \left[y_i + x_i \cdot d_i \cdot 2^{-i} \right]$$

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

IQ De-Multiplexer & DAC Output

- 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

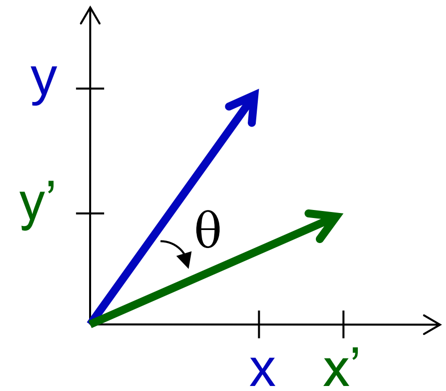
Create 70 MHz from 56 Msps I&Q



Digital Signal Processing Tools

<u>Rotation Matrix</u>

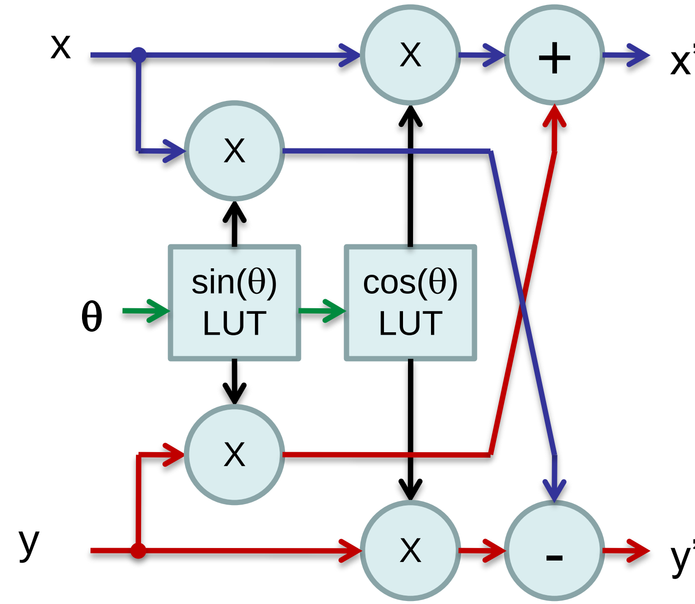
- Cartesian (I&Q) phase shifter
- Look-up-tables for sin(θ) & cos(θ)
- LUT and multipliers can be reused if multiple clock cycles are available (sin(θ) & cos(θ) are 90º apart)



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

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

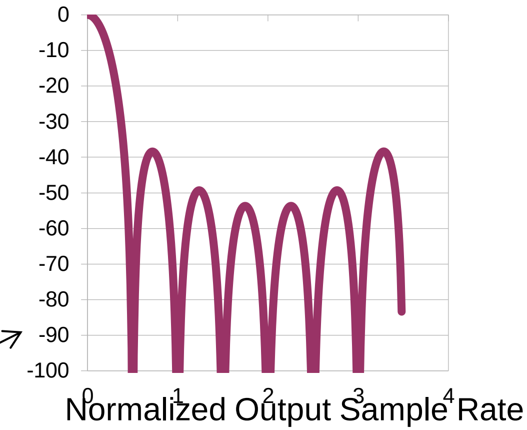
$$y' = y\cos\theta - x\sin\theta$$

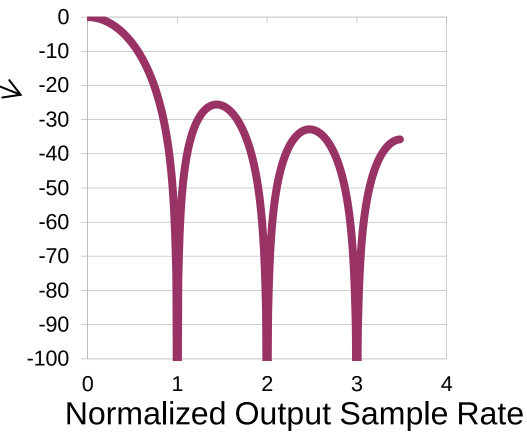


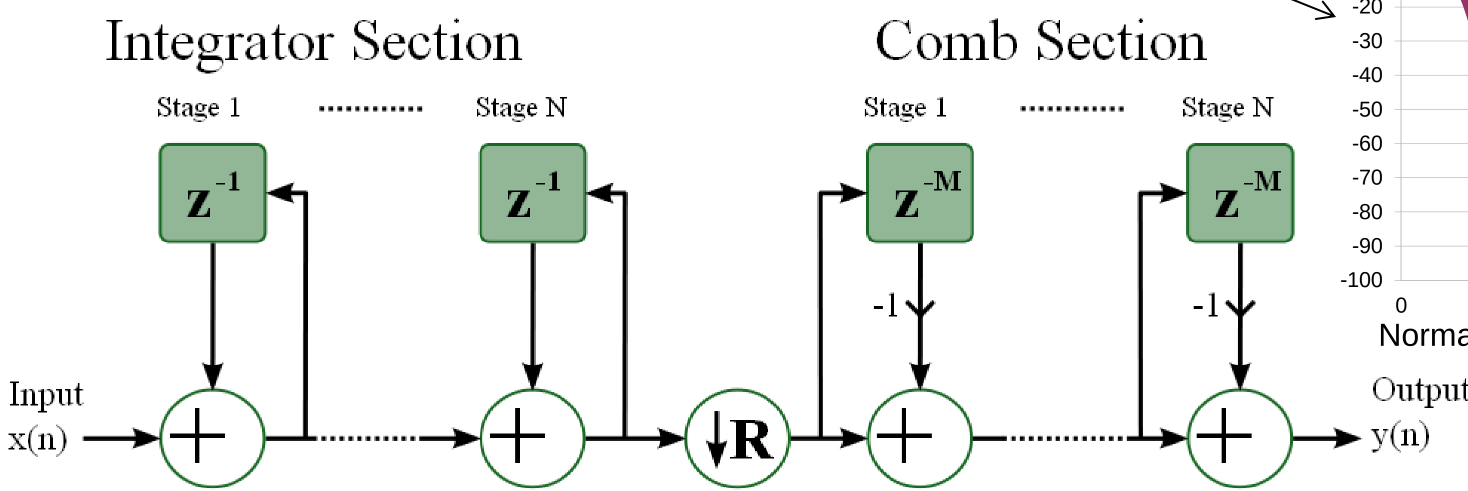
Digital Signal Processing Tools

CIC (Cascaded Integrated Comb)

- 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)

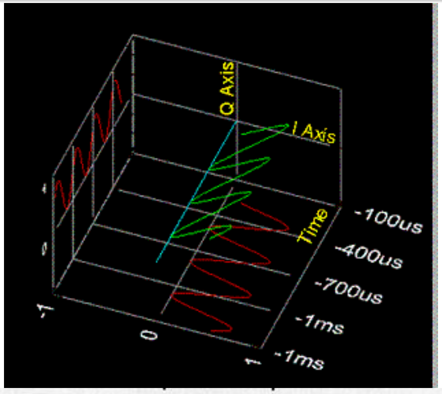




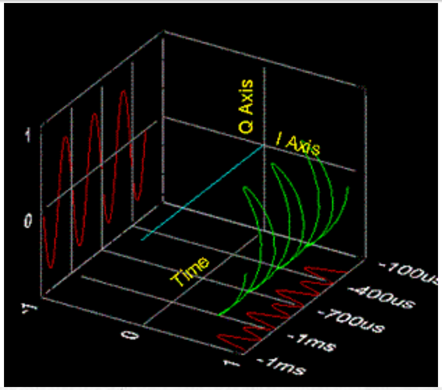


Decimating cascaded integrator-comb (CIC) filter; N stages, R decimation, M delays

Cartesian vs. Polar Coordinates



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

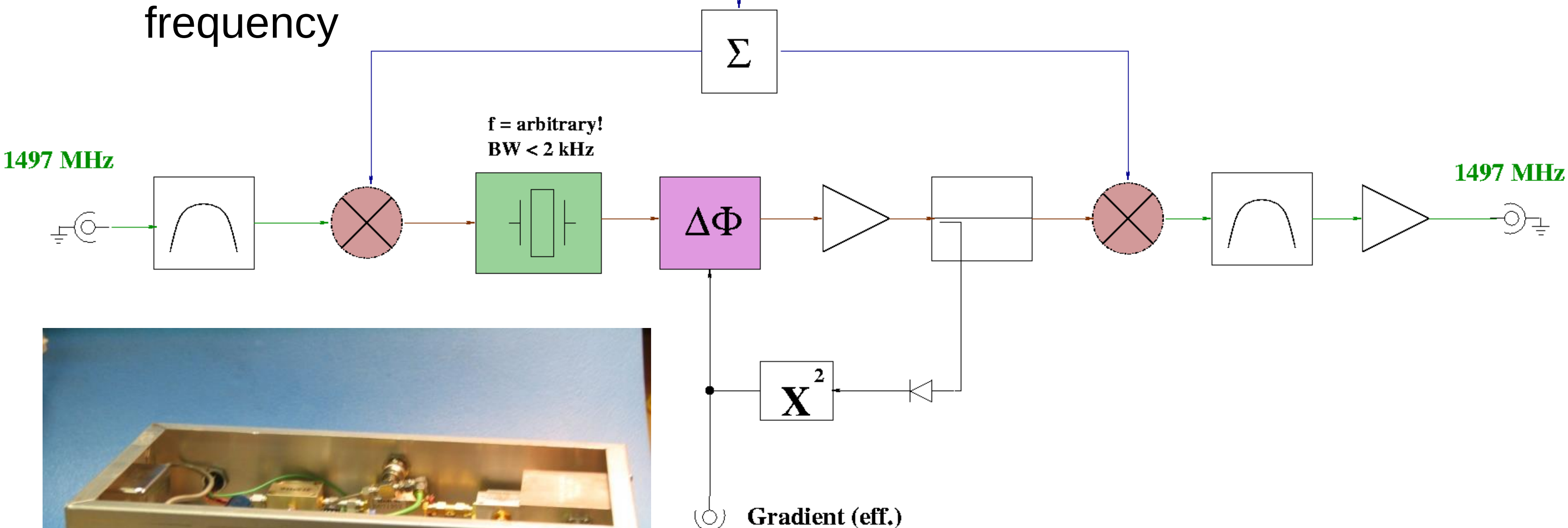


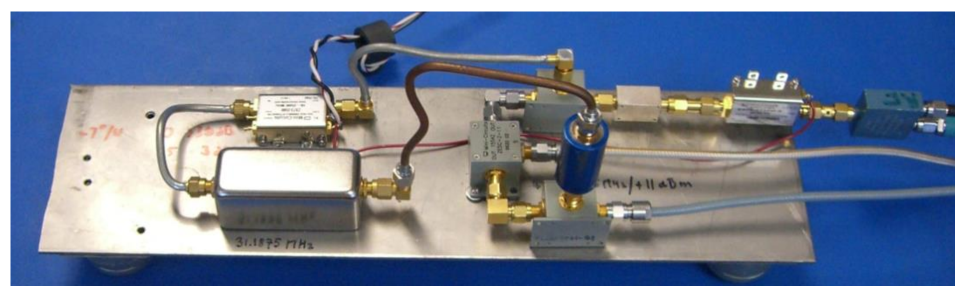
Type of Modulation	Mapping Functions $g[m]$	Corresponding Quadrature Modulation $x(t)$	Corresponding Quadrature Modulation $y(t)$	Corresponding Amplitude and Phase Modulation $R(t)$	Corresponding Amplitude and Phase Modulation $\theta(t)$	Linearity	Remarks
AM	$1 + m(t)$	$1 + m(t)$	0	$\lvert 1 + m(t)\rvert$	$\begin{cases} 0, & m(t) > -1 \\ 180°, & m(t) < -1 \end{cases}$	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.

Analog Cavity Emulator

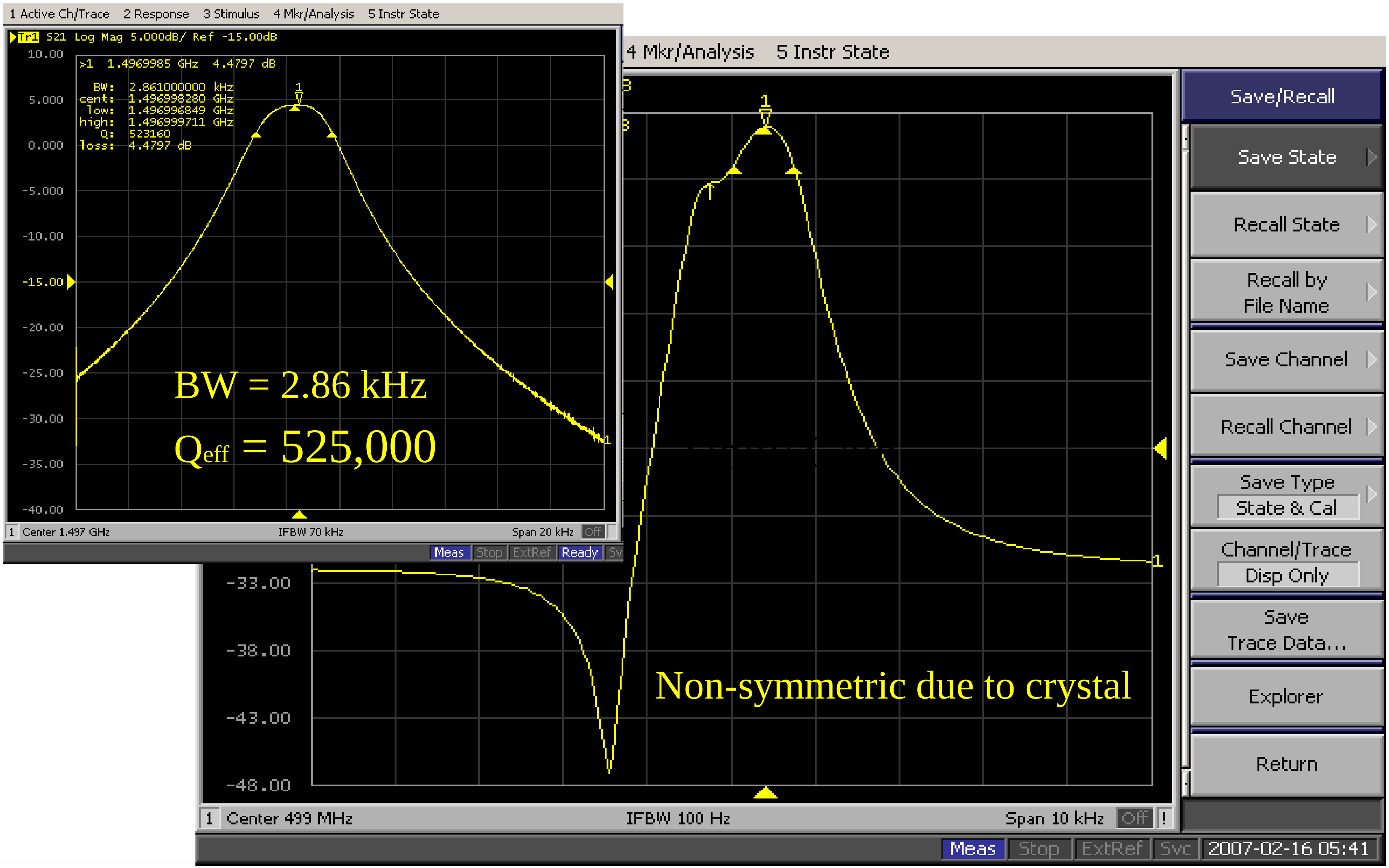
Down and up convert to accommodate crystal frequency

Change LO frequency to detune the cavity

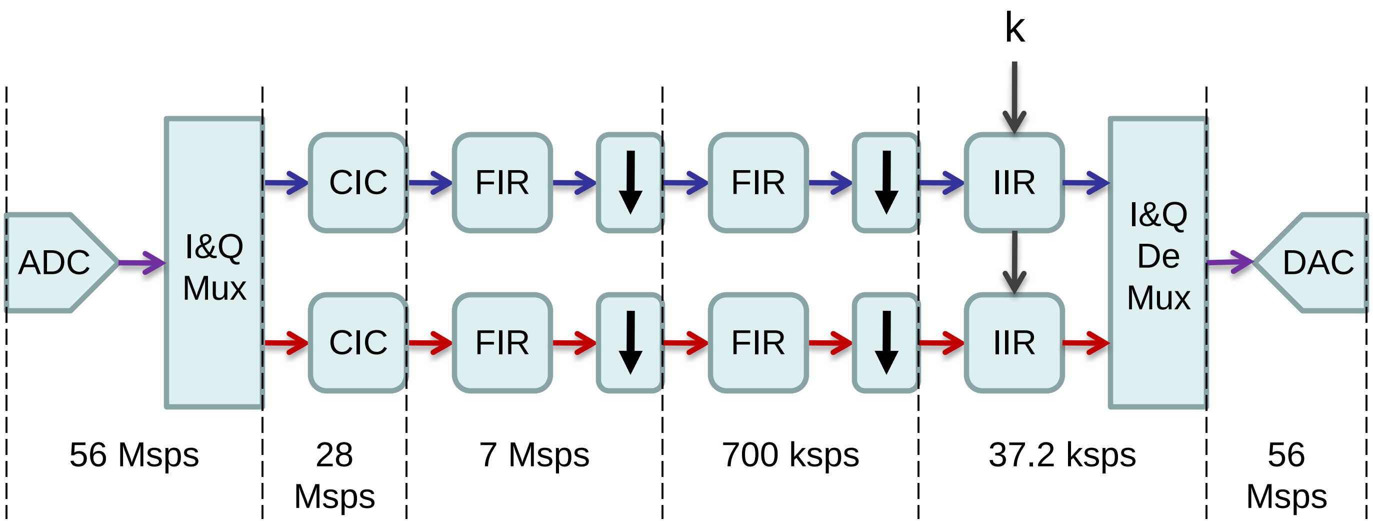


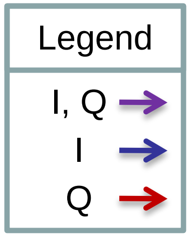


Analog Cavity Emulator



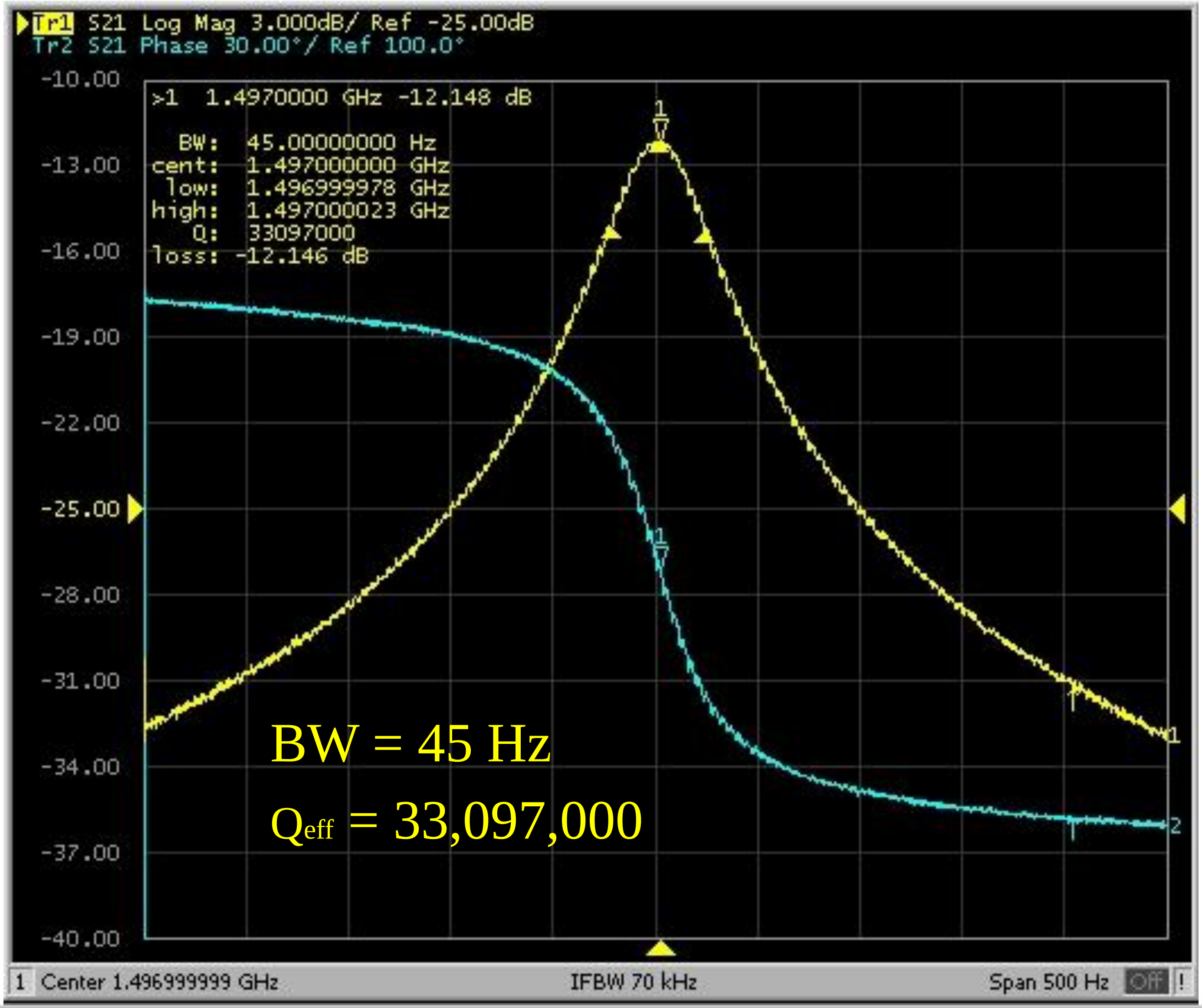
Digital Cavity Emulator





- 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 ($Q_{loaded}=3.3\times10^7$)

Cavity Emulator



Digital Signal Processing Tools

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

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

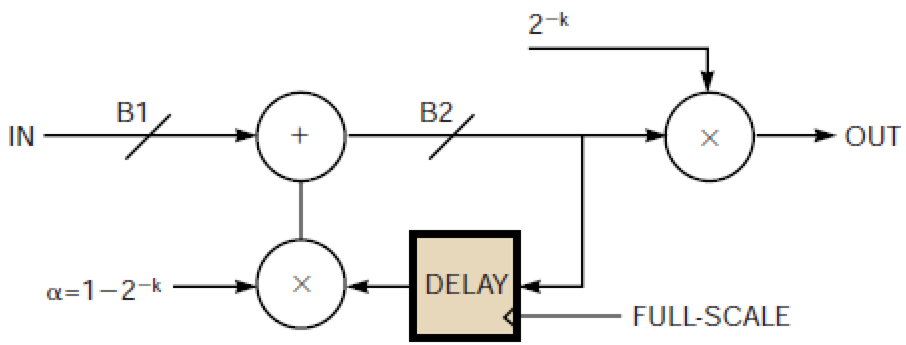


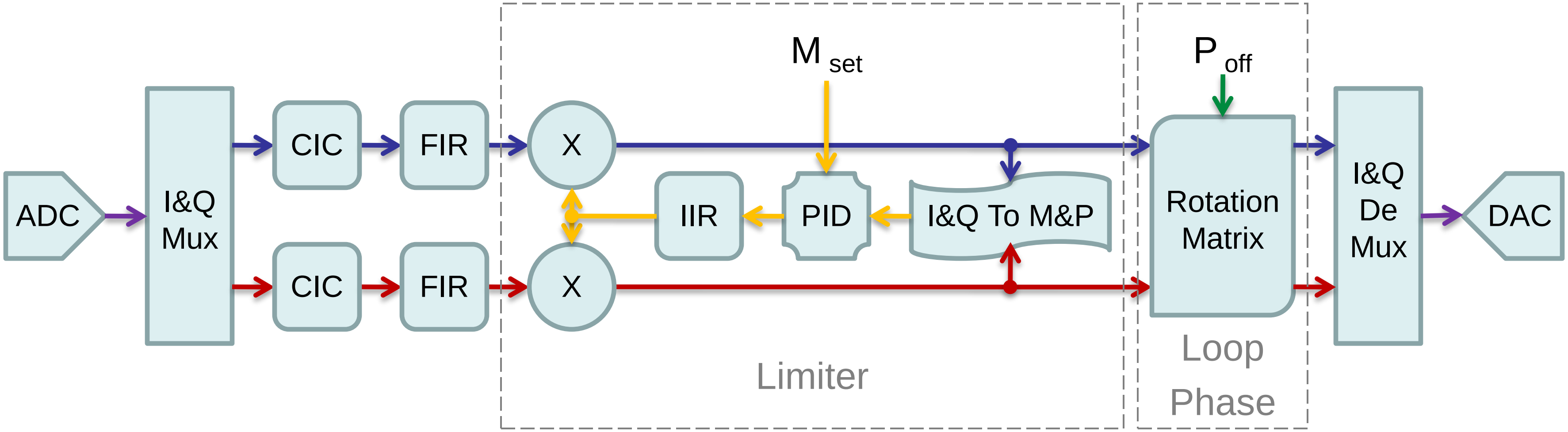
TABLE 1 NORMALIZED BANDWIDTH AND RISE TIME FOR VARIOUS VALUES OF k

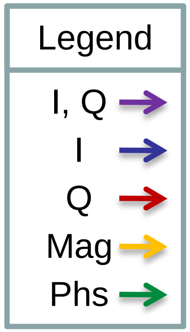
k	Bandwidth (normalized to 1 Hz)	Rise time (samples)
1	0.1197	Three
2	0.0466	Eight
3	0.0217	16
4	0.0104	34
5	0.0051	69
6	0.0026	140
7	0.0012	280

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 SEL Algorithm Development

Automatic Gain Control

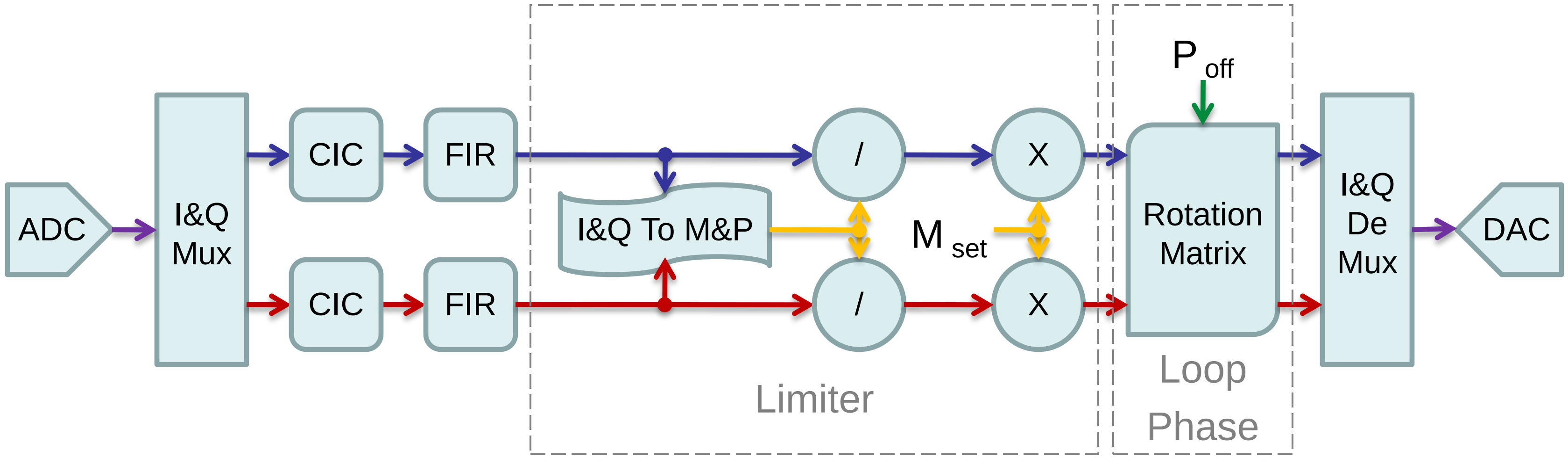


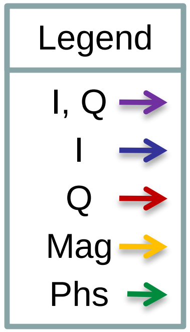


- PID Control to stabilize output magnitude
- Tuning the PID control loop was problematic
- Worked as a proof of concept
- Slow lock time

Digital SEL Algorithm Development

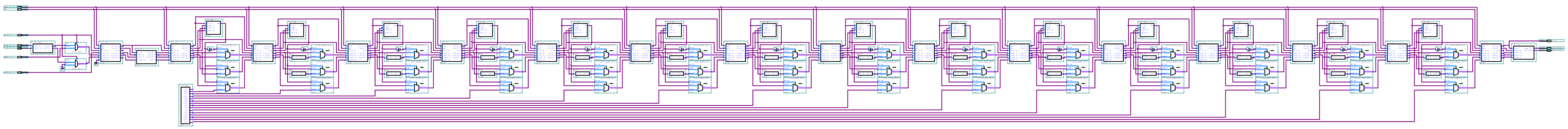
Normalizer

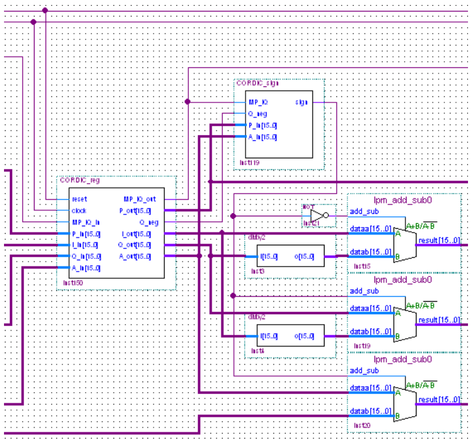


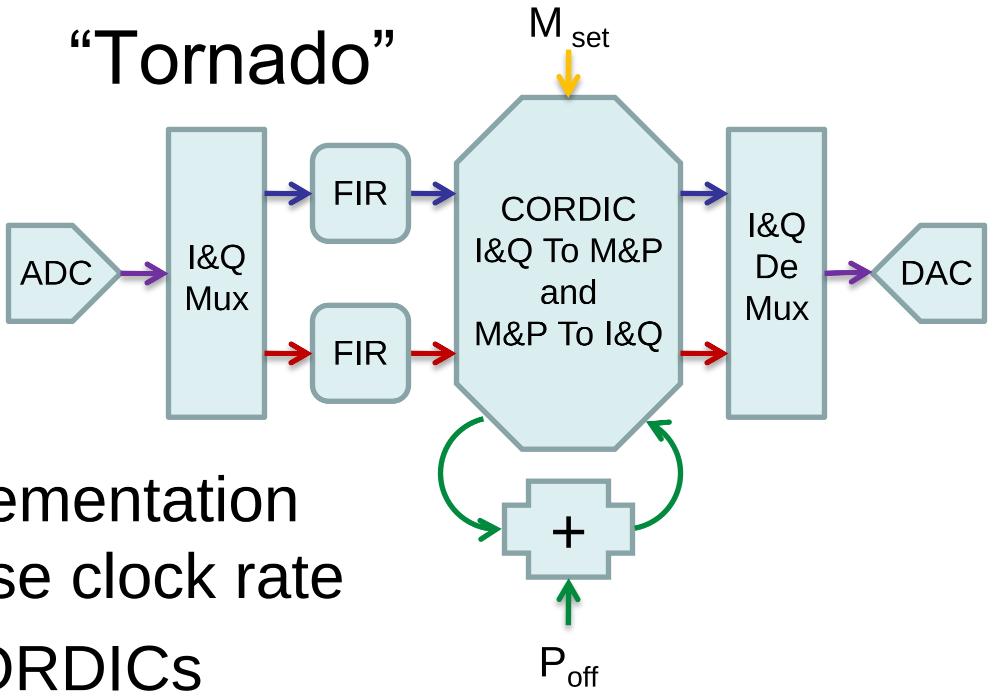


- Divide by the magnitude to normalize to 1
- Multiply I&Q by the magnitude set point
- Fixed point division causes errors and noise
- Limited operating range, setup dependent

Digital SEL Firmware





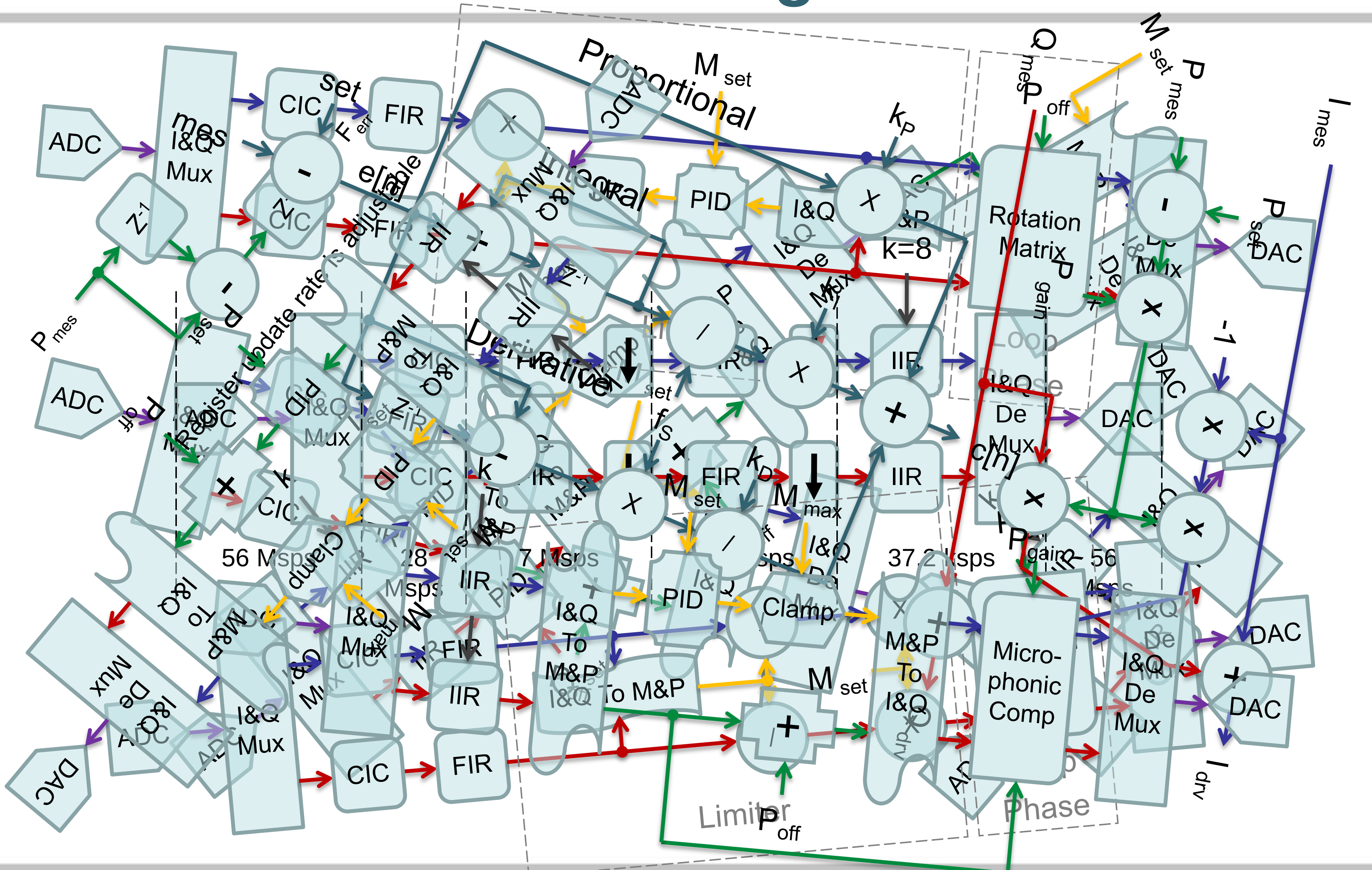


- Pipeline implementation to increase clock rate
- Interleave CORDICs
  - Reuse adds and subtracts, different decisions
  - 56 MHz clock (I&Q to M&P on even clock cycles and M&P to I&Q on odd clock cycles)

Legend

- I, Q →
- I →
- Q →
- Mag →
- Phs →

Put It All Together



Any Questions?