Frequency Control of an RF System

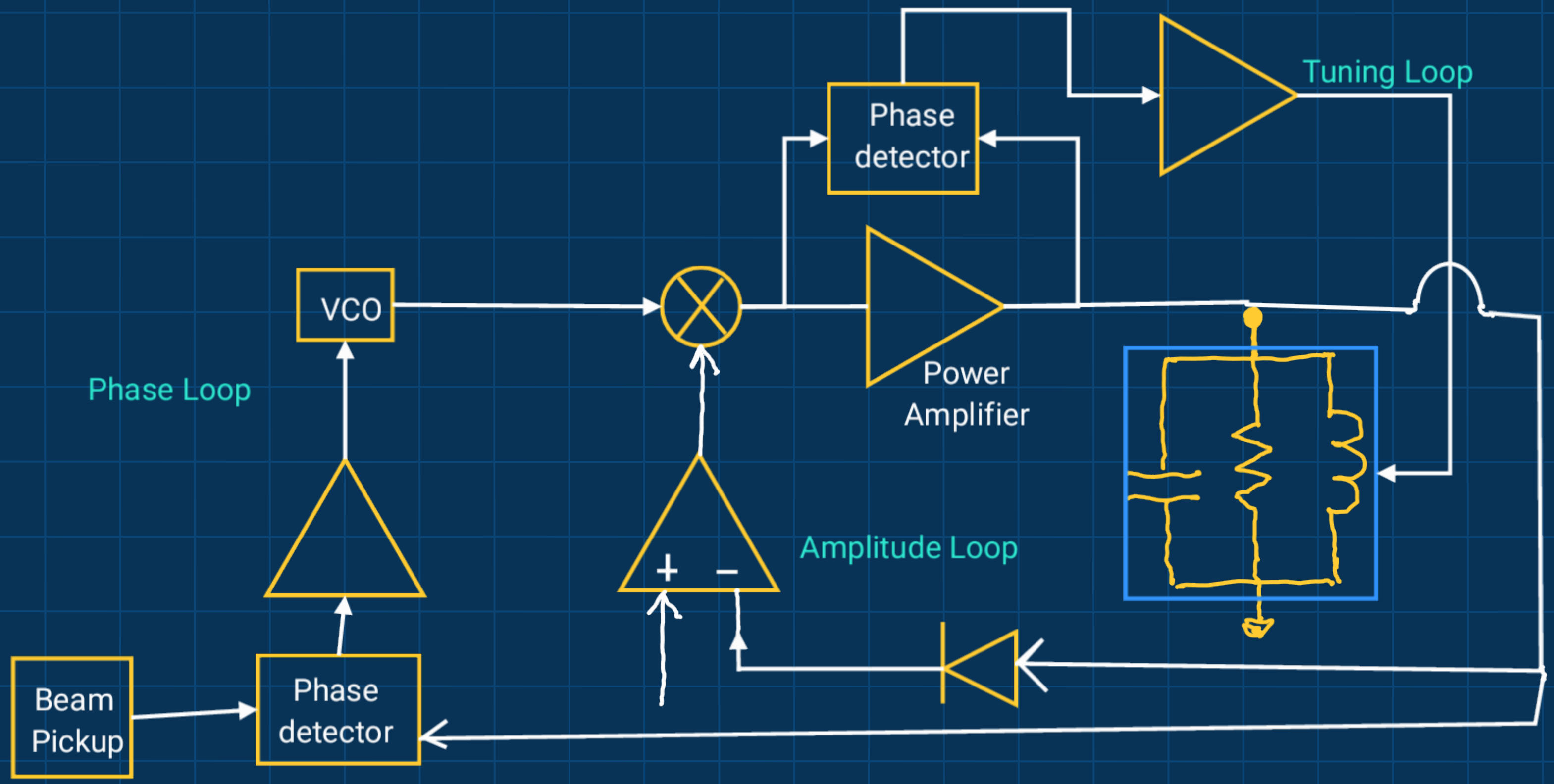
LLRF & HLRF

- Low Level RF (LLRF) is concerned with the frequency control and the amplitude control of the RF waveform that is used to accelerate charge particles.
- Some people restrict LLRF to the realm of frequency control
- and designate High Level RF (HLRF) for amplitude control.
- Before the advent of numerically controlled oscillators (NCO) or direct digital synthesizers (DDS), most RF systems used voltage controlled oscillators(VCO) for phase continuous frequency control

Frequency Sources

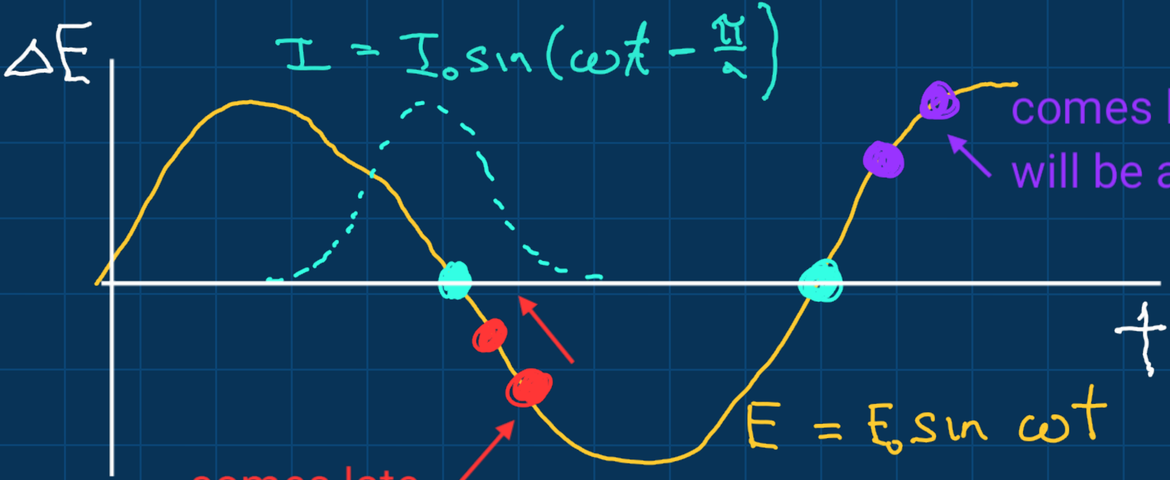
- VCOs can be very tempermental devices requiring great care in component choices, temperature stabilization, and feedback control.
- With NCOs and DDSs, the devices are so stable, the trend for many RF systems is to operate "open loop".
- However, for high intensity accelerators, LLRF systems need to incorporate feed back systems for beam stability.
- A LLRF system using DDS technology can be constructed in an FPGA but the function is still analogous to an analog VCO circuit.

Complete RF System



Phase focusing

Above transition higher energy particles, take a longer time to go around the ring than lower energy particles.



comes late,
will be accelerated

comes late
will be decelerated

Beam Phase Transfer Function

Change in revolution frequency for a change in beam energy

$$\boxed{\frac{\Delta T_r}{T_r} = \frac{\eta}{\beta^2}\frac{\Delta E}{E_0}}$$

$$\boxed{\Delta\phi = -\frac{2\pi h}{T_r}\Delta T_r}$$

$$\boxed{\frac{\Delta\phi}{\Delta n} = -2\pi h\frac{\eta}{\beta^2}\frac{\Delta E}{E_0}}$$

$$\boxed{\frac{d\phi}{dt} = -\omega_{Rf}\frac{\eta}{\beta^2}\frac{\Delta E}{E_0}}$$

Beam Phase Transfer Function

Change in beam energy for a change in RF phase

$$\boxed{\Delta E = qV\sin\varphi \approx qV\varphi}$$

$$\boxed{\frac{d\,\Delta E}{dt} = \frac{qV\varphi}{T_r} = \frac{\omega_{Rf}}{2\pi h}\,qV\varphi}$$

$$\boxed{\frac{d^2\varphi}{dt^2} = -\omega_{Rf}\frac{\eta}{\beta^2}\,\frac{d}{dt}\,\frac{\Delta E}{E_0}}$$

Beam Phase Transfer Function

$$\frac{d^2\phi}{dt^2} + \omega_s^2 \phi = 0$$

$$\omega_s^2 = \frac{\omega_{rf}^2}{2\pi h} \frac{\eta}{\beta^2} \frac{eV}{E_0}$$

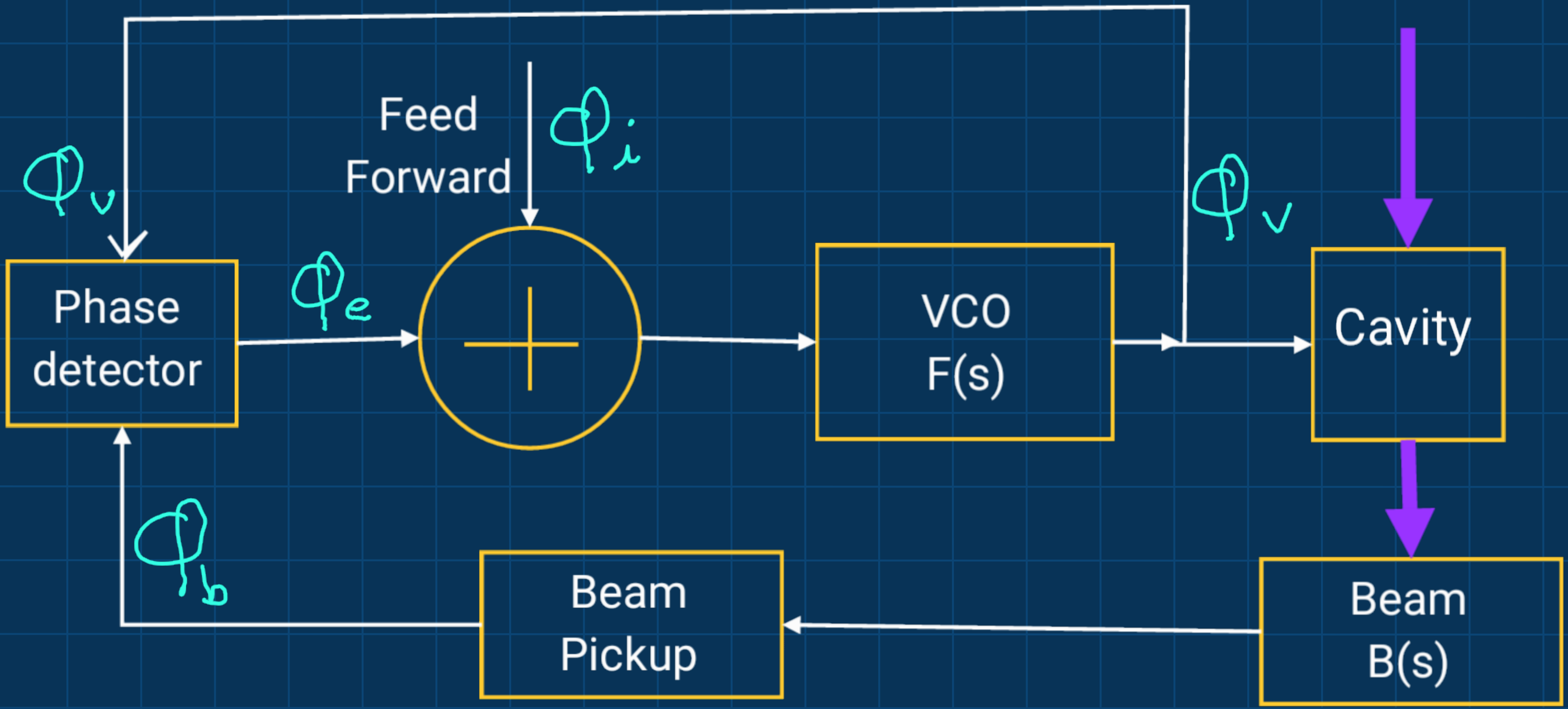
characteristic equation

$$s^2\phi + \omega_s^2 \phi = 0$$

$$B(s) = \frac{\omega_s^2}{s^2 + \omega_s^2}$$

undamped oscillator

Phase-locked RF System



Phase-locked RF System Response

$$\Phi_e = \Phi_v - B(s)\Phi_v$$

Phase detector

$$\Phi_v = F(s)(\Phi_e + \Phi_i)$$

VCO

$$\frac{\Phi_e}{\Phi_i} = \frac{F(s)s^2}{s^2 + \omega_s^2 + F(s)s^2}$$

$$F(s) = \frac{F_0}{s}$$

$$\frac{\Phi_e}{\Phi_i} = \frac{F_0 s}{s^2 + F_0 s + \omega_s^2}$$

Damped response

Cavity RLC Model

Cavity loss $\Rightarrow$ R

Stored magnetic energy $\Rightarrow$ L

Stored electric energy $\Rightarrow$ C

$$\boxed{\frac{1}{Z} = \frac{1}{R} + \frac{1}{sL} + sC}$$

Cavity RLC Model

MAX IV RF

Let

$$\boxed{\omega_0 = \frac{1}{LC}}$$

$$\boxed{\frac{R}{Q} = \sqrt{\frac{L}{C}}}$$

$$\boxed{Z = \frac{s\,\omega_0\,R/Q}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}}$$

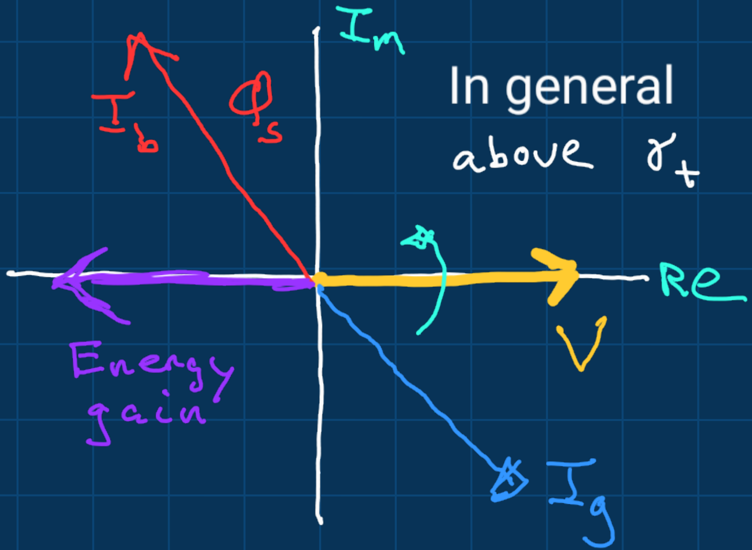
$$\boxed{Z = R\cos\varphi\, e^{j\varphi}}$$

$$\boxed{\tan\phi = \frac{\omega_0^2 - \omega^2}{\frac{\omega\,\omega_0}{Q}}}$$

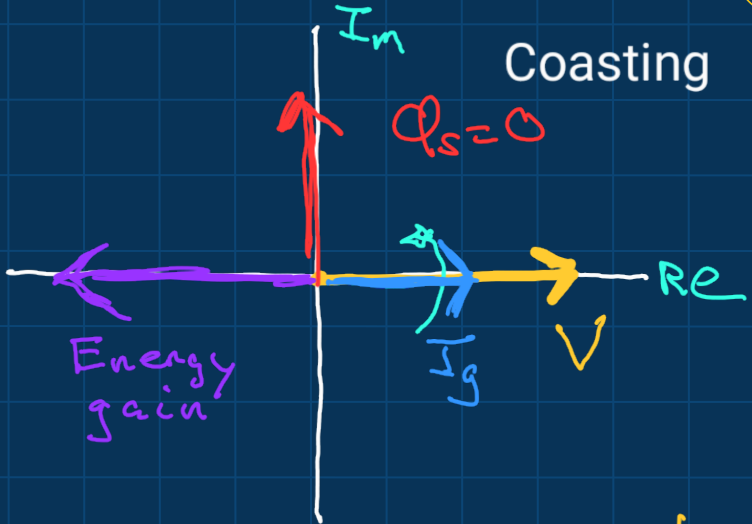
Cavity Phasors

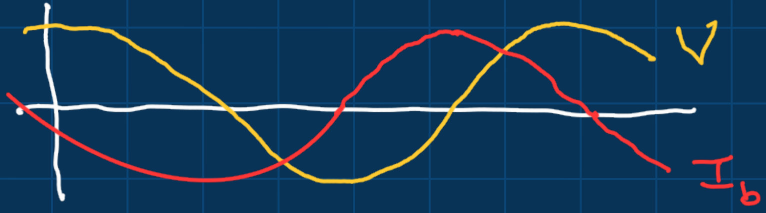
In general

above γ_t



Coasting





$$\overline{V} = V_0 e^{j\omega t}$$

$$\overline{I_g} = I_{g0} e^{j\omega t}$$

$$\overline{I_b} = j I_{b0} e^{j\omega t}$$

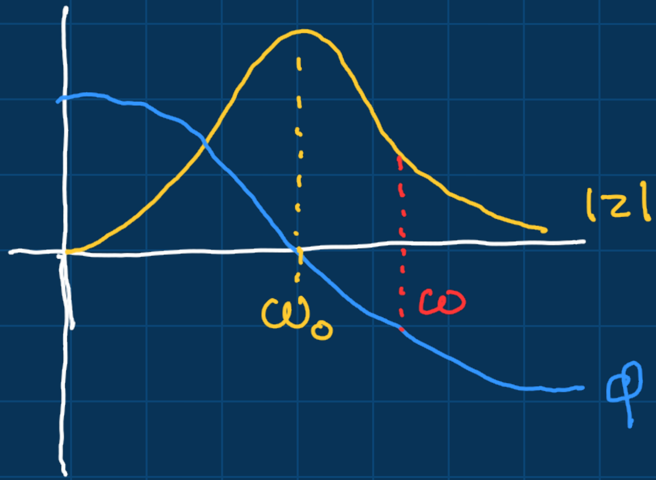
Cavity Phasors

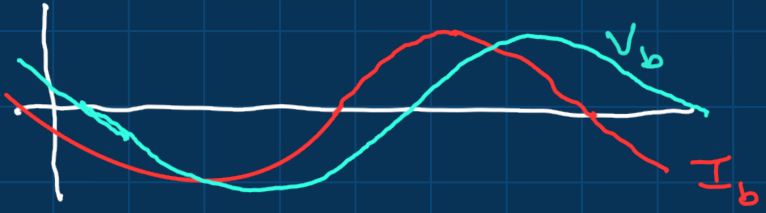
$$\boxed{\begin{aligned} \vec{V} &= \vec{Z}\left(\vec{I}_g + \vec{I}_b\right) \\ \vec{Z} &= R\cos\phi\, e^{j\phi} \end{aligned}}$$

$$\boxed{\begin{aligned} V &= R\cos\phi\left(I_g\cos\phi - I_b\sin\phi\right) \\ 0 &= I_g\sin\phi + I_b\cos\phi \end{aligned}} \quad \begin{aligned} &\text{Real Part} \\ &\text{Imag Part} \end{aligned}$$

$$\boxed{\tan\phi = -\frac{I_b}{I_g}} \qquad \boxed{V = I_g R}$$

Cavity Detuning





In the presence of beam current, the cavity must be detuned so as to present a real load to the generator. Above transition the cavity looks capacitive to the beam. i.e the voltage lags the beam current.

This also "assists" phase focusing which keeps the beam Robinson stable

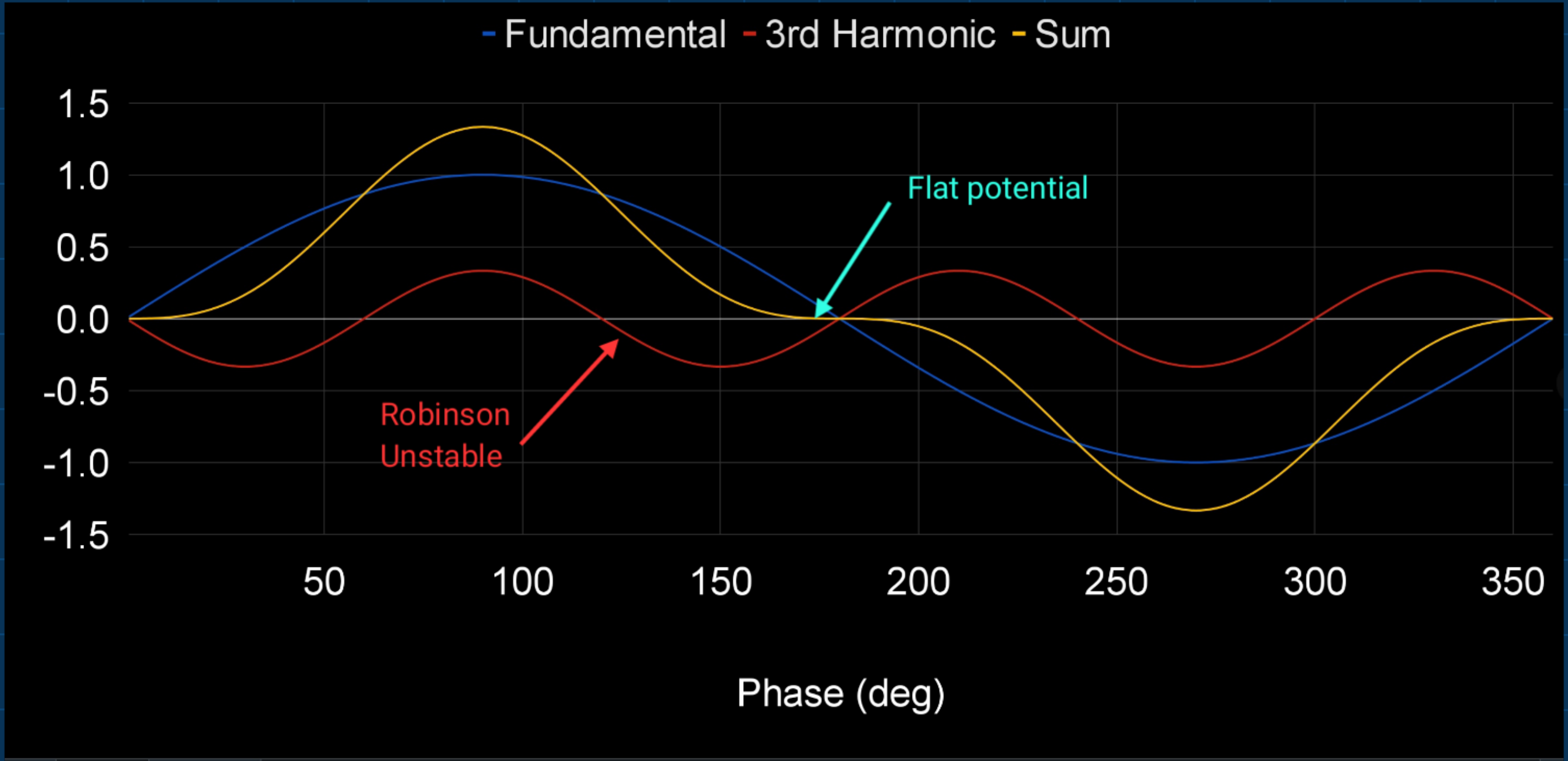
3rd Harmonic Bunch Lengthening

- For light sources, synchrotron radiation will provide a natural damping term.
- If all the cavities are detuned for power match and hence, are Robinson stable, there is no need for a phase loop.
- However, for light sources, low energy spread in the beam is very desireable
- For high frequency single harmonic RF systems, electrons in a bunch will clump together at the synchronous phase resulting in short bunches with large energy spread

3rd Harmonic RF

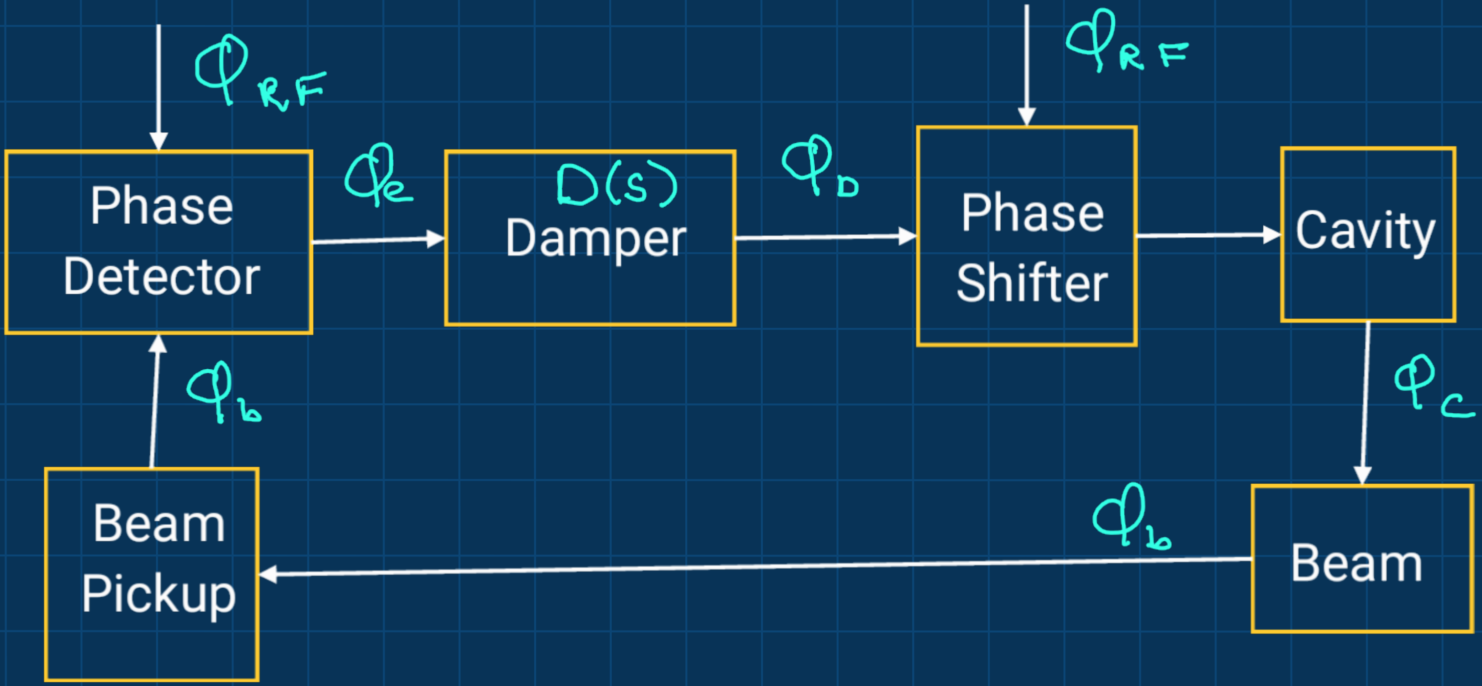
- At Max IV, a relatively low RF frequency (100 MHz) was chosen.
- The bunches are lengthened by the additon of 3rd harmonic cavities (300MHz) providing a flat potential for the electrons.
- The 3rd harmonic cavities are passive and are detuned so that the beam wake provides the field in the cavities. However, this results in the 3rd harmonic cavites being tuned to Robinson unstable!

3rd Harmonic RF



AC Coupled Phase Loop

An AC coupled phase loop can be easily added to an existing RF system


Phase Detector

Damper

Phase Shifter

Cavity

Beam

Beam Pickup

AC Coupled Phase Loop

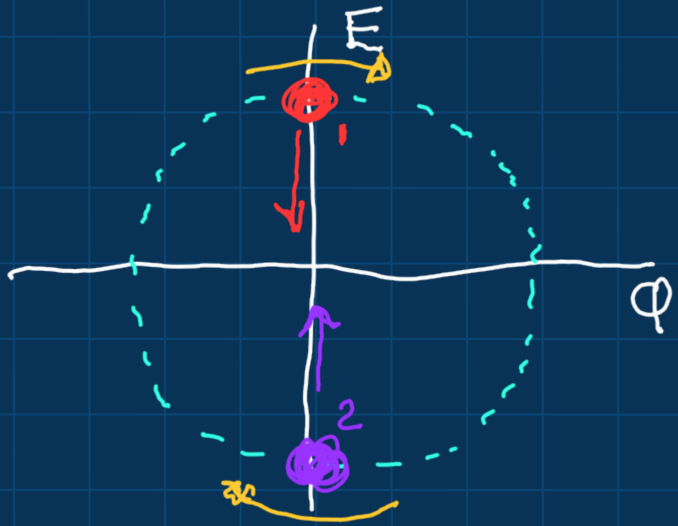
$$\boxed{\varphi_e = \frac{1-B}{1+BD}\varphi_{RF} = \frac{s^2}{s^2+\omega_s^2+D\omega_s^2}\varphi_{RF}}$$

Let $D(s) = D_0 s$ (derivative)

$$\boxed{\varphi_e = \frac{s^2}{s^2 + D_0\omega_s^2 s + \omega_0^2}}$$

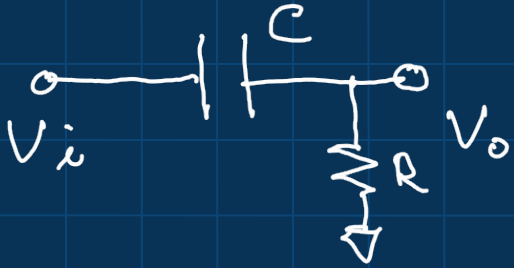
Critically damped for $\boxed{D_0 = 2/\omega_s}$

Practical AC Coupled Phase Loop



- Situation 1 and situation 2 have the same phase but require different energy corrections.
- However for Situation 1, the phase is increasing. For Situation 2, the phase is decreasing.
- Taking the time derivative of phase distinguishes the different situations.

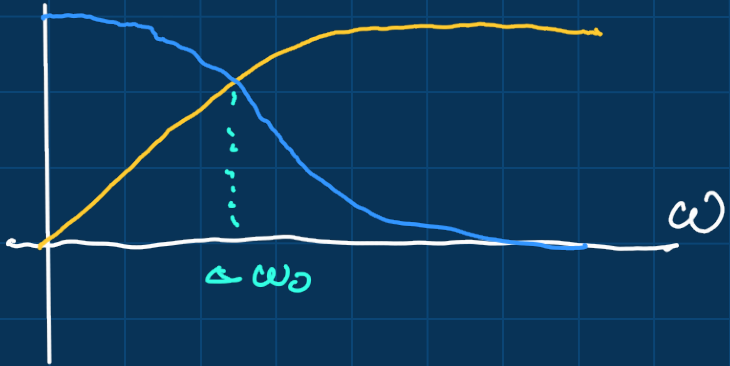
Analog High Pass Filter Derivative



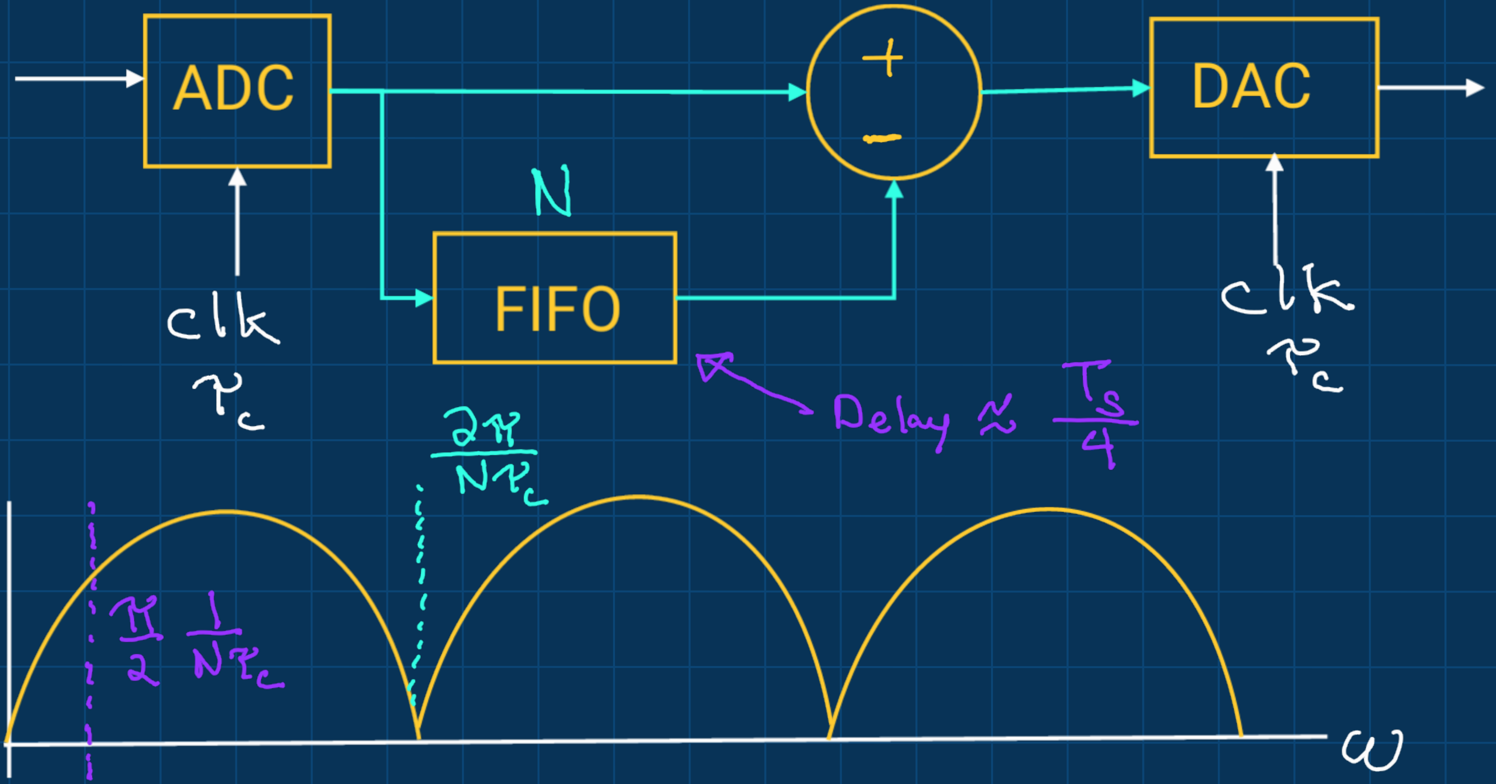
$$\frac{V_o}{V_i} = \frac{s/\Delta\omega_0}{1+ s/\Delta\omega_0}$$

Acts as a derivative for c

$$\omega < \Delta\omega_0$$

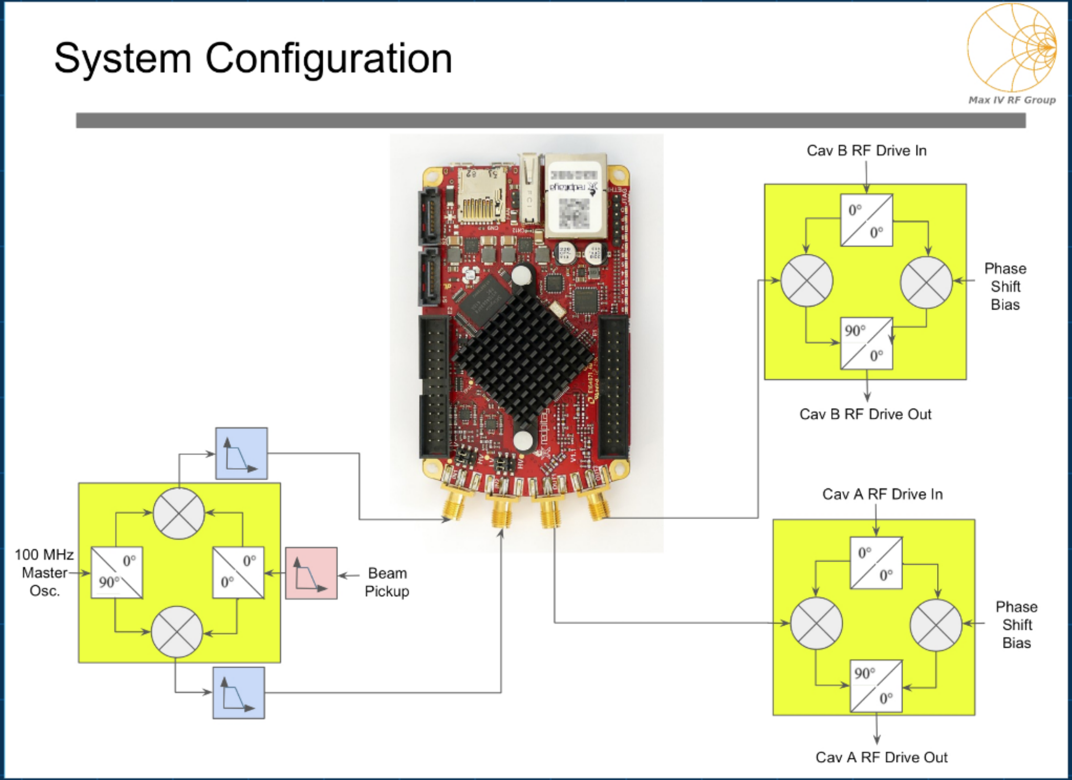


Digital Notch Filter Derivative



Delay $\approx \frac{T_s}{4}$

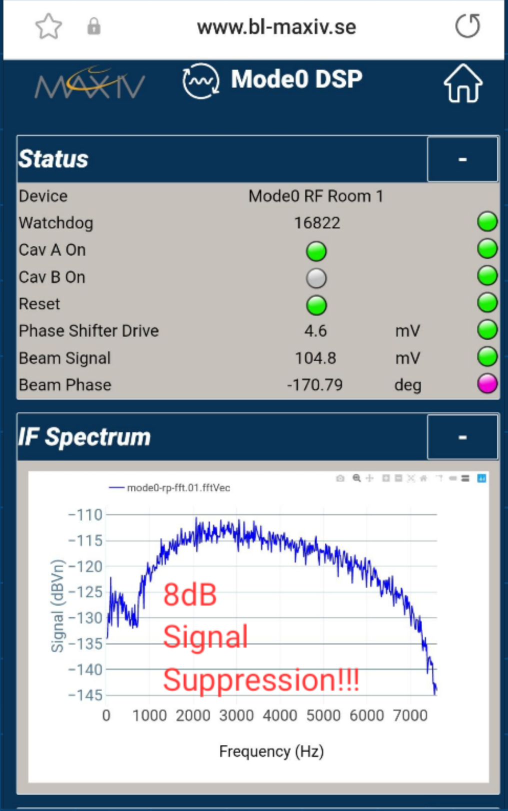
AC Phase Loop Implementation



System Configuration

Max IV RF Group

AC Phase Loop Control

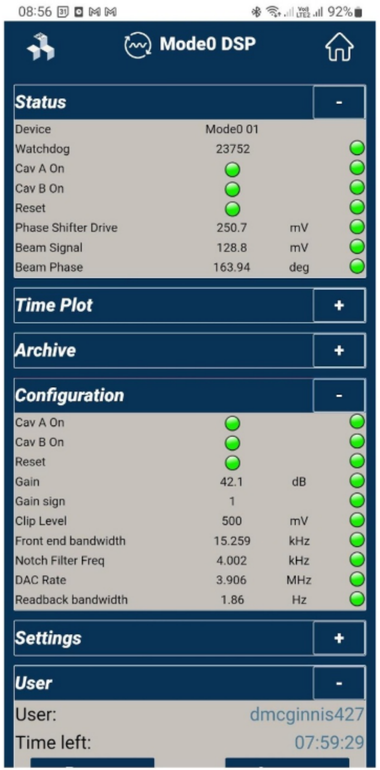


Status

Device	Mode0 RF Room 1		
Watchdog	16822		●
Cav A On	●		●
Cav B On	○		●
Reset	●		●
Phase Shifter Drive	4.6	mV	●
Beam Signal	104.8	mV	●
Beam Phase	-170.79	deg	●

IF Spectrum

8dB Signal Suppression!!!



Status

Device	Mode0 01		
Watchdog	23752		●
Cav A On	●		●
Cav B On	●		●
Reset	●		●
Phase Shifter Drive	250.7	mV	●
Beam Signal	128.8	mV	●
Beam Phase	163.94	deg	●

Time Plot +

Archive +

Configuration -

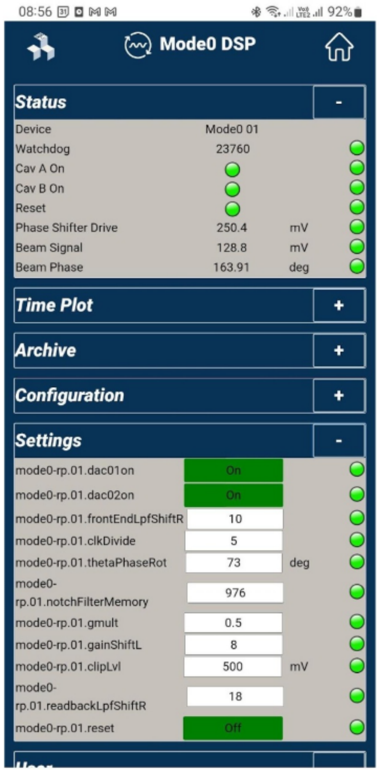
Cav A On	●		●
Cav B On	●		●
Reset	●		●
Gain	42.1	dB	●
Gain sign	1		●
Clip Level	500	mV	●
Front end bandwidth	15.259	kHz	●
Notch Filter Freq	4.002	kHz	●
DAC Rate	3.906	MHz	●
Readback bandwidth	1.86	Hz	●

Settings +

User -

User: dmcginnis427

Time left: 07:59:29



Status

Device	Mode0 01		
Watchdog	23760		●
Cav A On	●		●
Cav B On	●		●
Reset	●		●
Phase Shifter Drive	250.4	mV	●
Beam Signal	128.8	mV	●
Beam Phase	163.91	deg	●

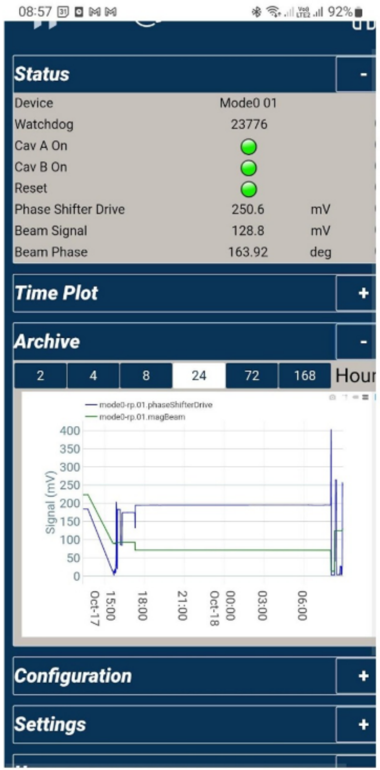
Time Plot +

Archive +

Configuration +

Settings -

mode0-rp.01.dac01on	On		●
mode0-rp.01.dac02on	On		●
mode0-rp.01.frontEndLpfShiftR	10		●
mode0-rp.01.clkDivide	5		●
mode0-rp.01.thetaPhaseRot	73	deg	●
mode0-rp.01.notchFilterMemory	976		●
mode0-rp.01.gmult	0.5		●
mode0-rp.01.gainShiftL	8		●
mode0-rp.01.clipLvl	500	mV	●
mode0-rp.01.readbackLpfShiftR	18		●
mode0-rp.01.reset	Off		●



Status

Device	Mode0 01	
Watchdog	23776	
Cav A On	●	
Cav B On	●	
Reset	●	
Phase Shifter Drive	250.6	mV
Beam Signal	128.8	mV
Beam Phase	163.92	deg

Time Plot +

Archive -

Configuration +

Settings +