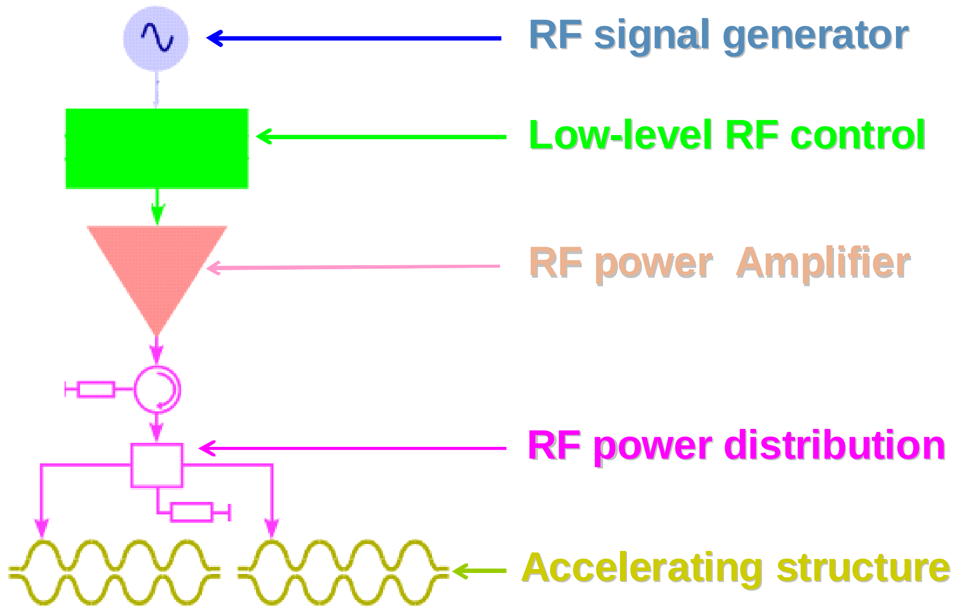
RF systems

Francis Perez

Part III:

Low Level RF



LLRF

Main Functionalities

- ✓ Control of amplitude and phase of the RF Cavity Voltage to be synchronized with the bunch beams.
- ✓ Control of resonance frequency of the cavity (Tuning)
- ✓ RF Diagnostics
- ✓ RF interlocks

Why do we need LLRF?

- ✓ Ripples of amplifiers.
- ✓ Gain and Phase of amplifiers not linear.
- ✓ Beam loading (current of beam changes voltage of the cavity).
- ✓ Cavity drifts

LLRF main loops

Three magnitudes have to be regulated in the RF system

Three main control loops:

- Amplitude

  Precision 0.05 - 1 %

- Phase

  Precision 0.01 - 0.5 °

- Frequency

  Precision 1 - 100 Hz

LLRF control loops

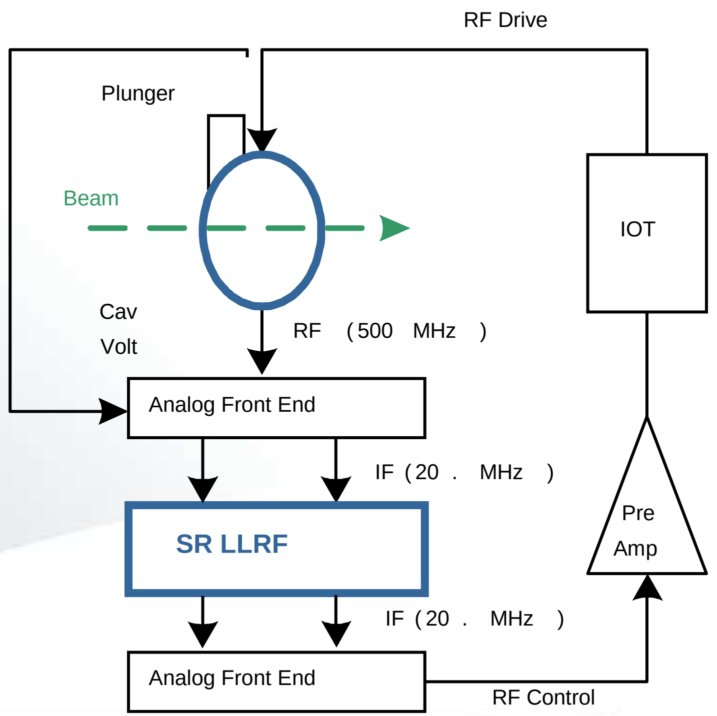
General concept:

- Measure the relevant parameter

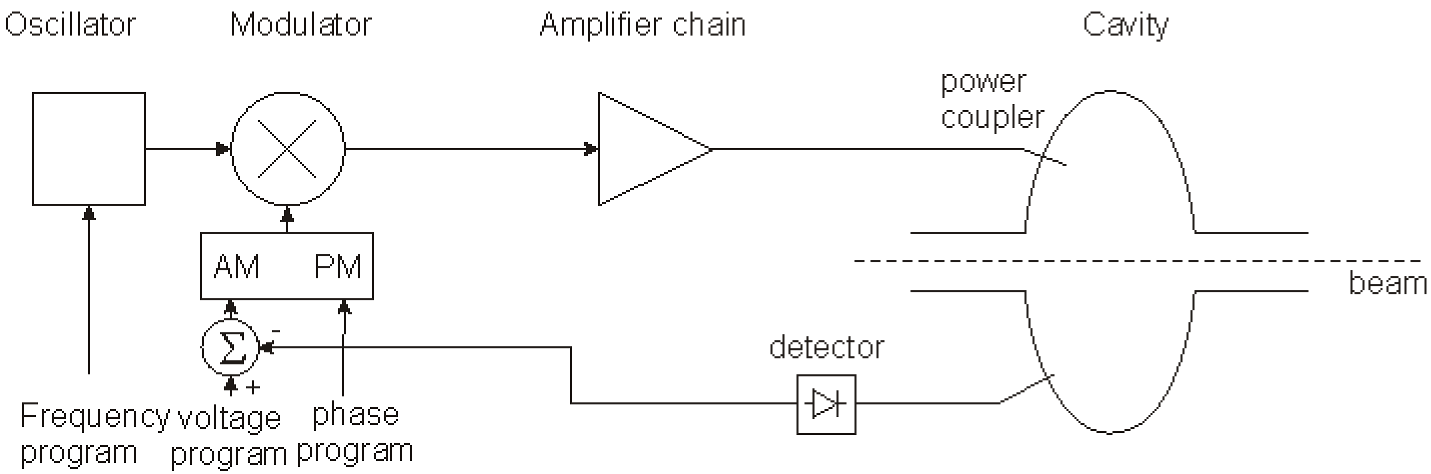
- Compare with reference

- Use the difference and PI control to define the action.

- Act in the amplifier chain



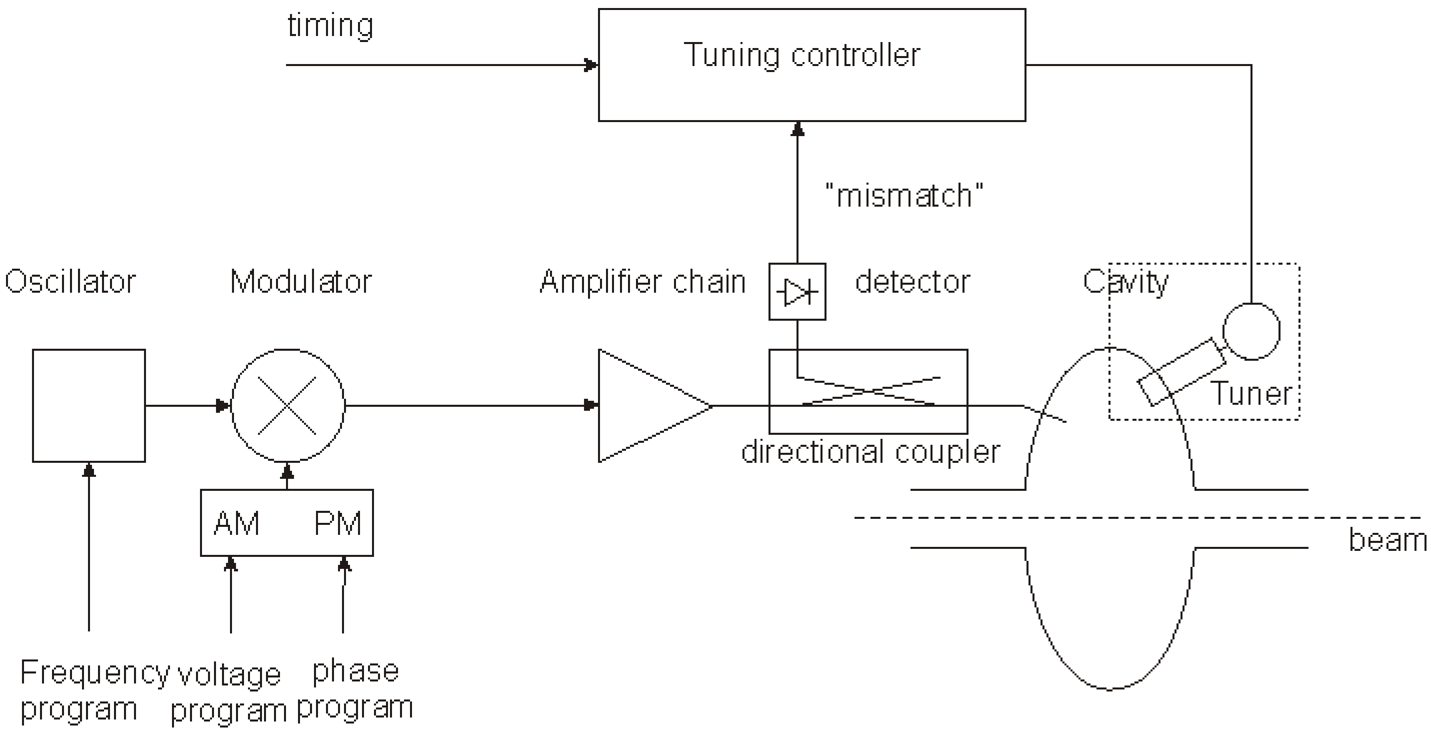
LLRF amplitude/phase loop



- Pick up a sample of the voltage inside the cavity, get amplitude and phase.
- Compute the error (difference measured respect the setting)
- Use the error signal to drive the amplifier chain


Pickup loop

LLRF tuning loop



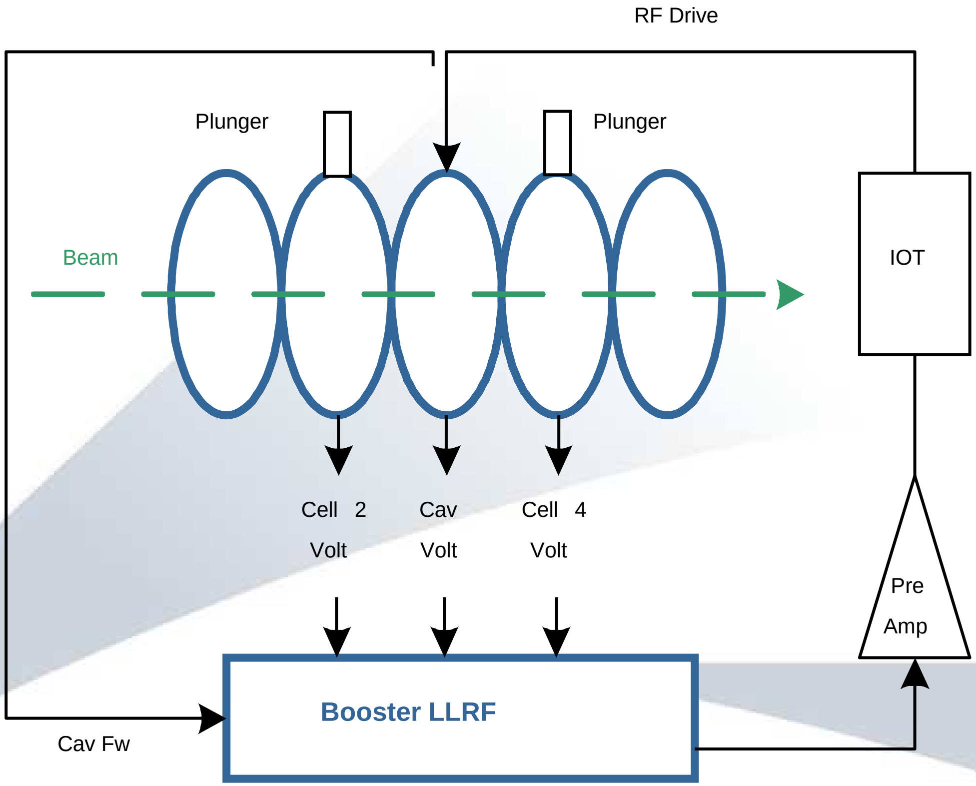
- A way to measure the mismatch of cavity with amplifier
- Compute the error (difference measured respect the setting)
- Use the error signal to drive the tuner motor

Other loops

Field flatness loop in a multicell cavity.

Maintain the voltage along the cells constant

Act on plunger in cells 2 and 4.

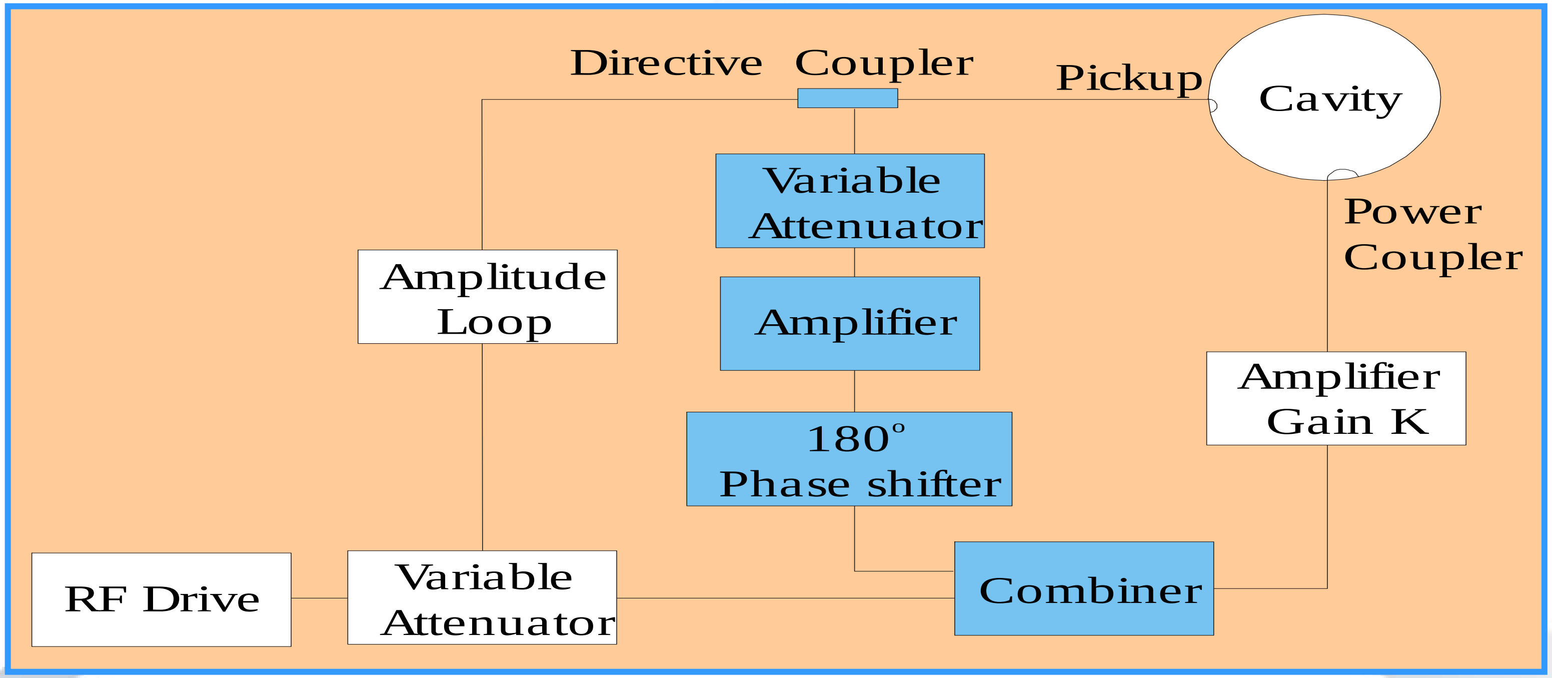


ALBA

Other loops

Fast RF feedback for beam loading compensation

The idea is to pickup a sample of the voltage in the cavity and, after proper amplification, combine it, 180° dephased, with the driving signal of the amplitude loop.



ANKA

Analogue LLRF
vs
Digital LLRF

Nowadays, digital is the chosen solution, analogue is becoming obsolete.

Only, in some specific cases, where high speed is required – low loop delay (*fast RF loops*), analogue is still competitive

Advantages of the digital system

» Higher precision, lower noise

amplitude down to 0.01% and phase 0.01 degrees

» Flexible, modifications in “software”

by reprogramming the FPGA

» Allows the parameterization of the loops

for example, change the loop gains on the flight

» Allows better diagnostics

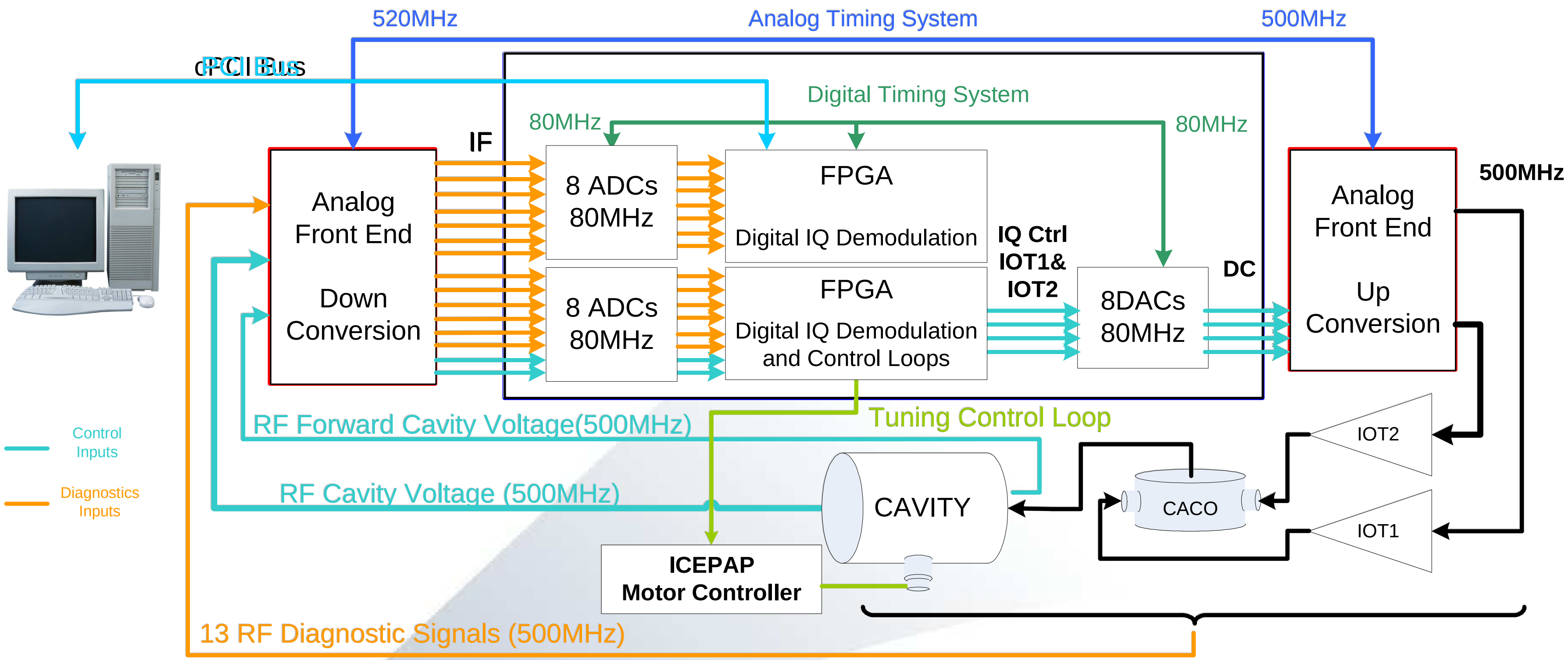
one can check how the loop is working with inside FPGA diagnostics

» Nowadays, can even be cheaper than analogue

As an example
the
ALBA Digital LLRF system

by Angela Salom

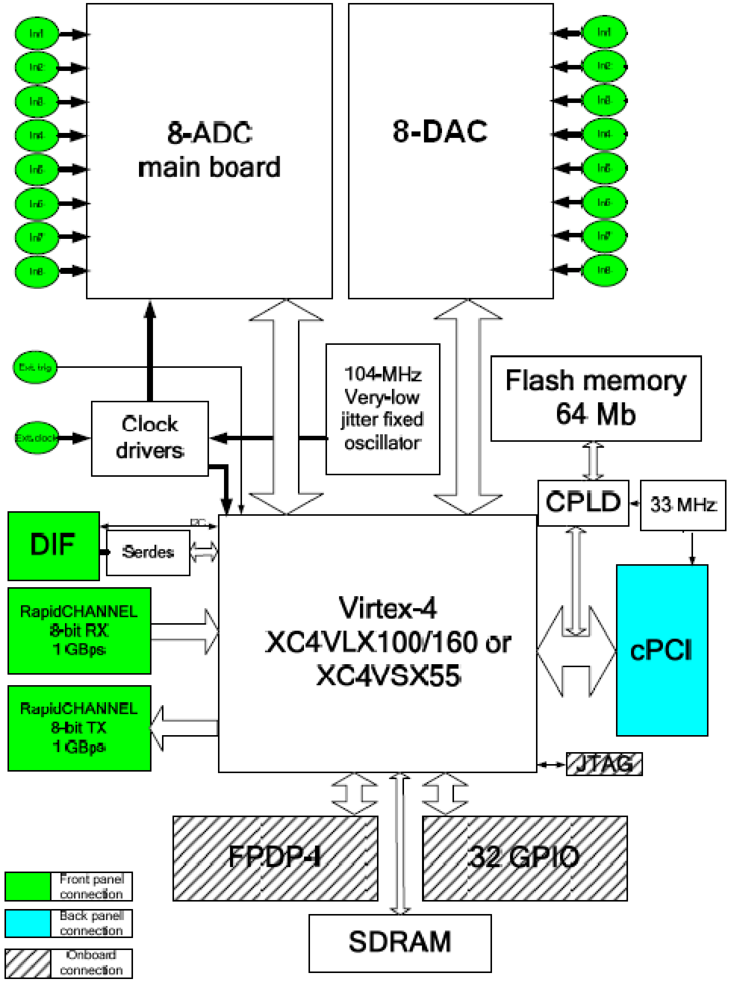
Digital LLRF Conceptual Design



- Digital Commercial Board: cPCI with 16 ADCs, 8 DACs and Virtex-4 FPGA
- Analog Front Ends for Downconversion (RF to IF) and Upconversion (DC to RF)
- Timing systems: 520MHz (500 + 20 MHz) for downconversion synchronized with digital 80MHz clock for digital acquisition

FPGA Board

✓ Lyrtech: VHS ADAC-4



cPCI format

2 x 8 ADCs 125 MHz 14 bits

8 DACs 125MHz 14 bits

2 x Virtex 4

2 x 128 Mbytes RAM

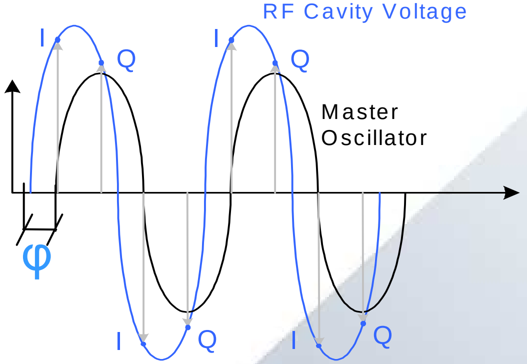
IQ Demodulation

✓ Demodulation

Removal of the periodic variation of a signal keeping its information, i.e. transform a waveform signal into baseband or DC.

✓IQ Demodulation

Comparison between two signals to obtain the quadrature and in phase components of the signal demodulated in comparison to the reference signal



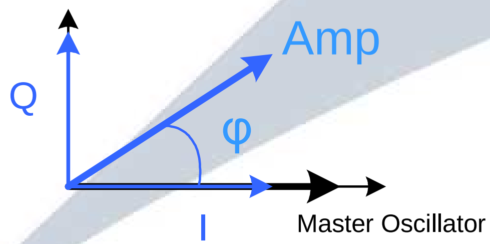
Reference: Master Oscillator Clock (500MHz)

Cavity Voltage: 500MHz

I: In Phase Component (0º)

Q: In Quadrature component (90º)

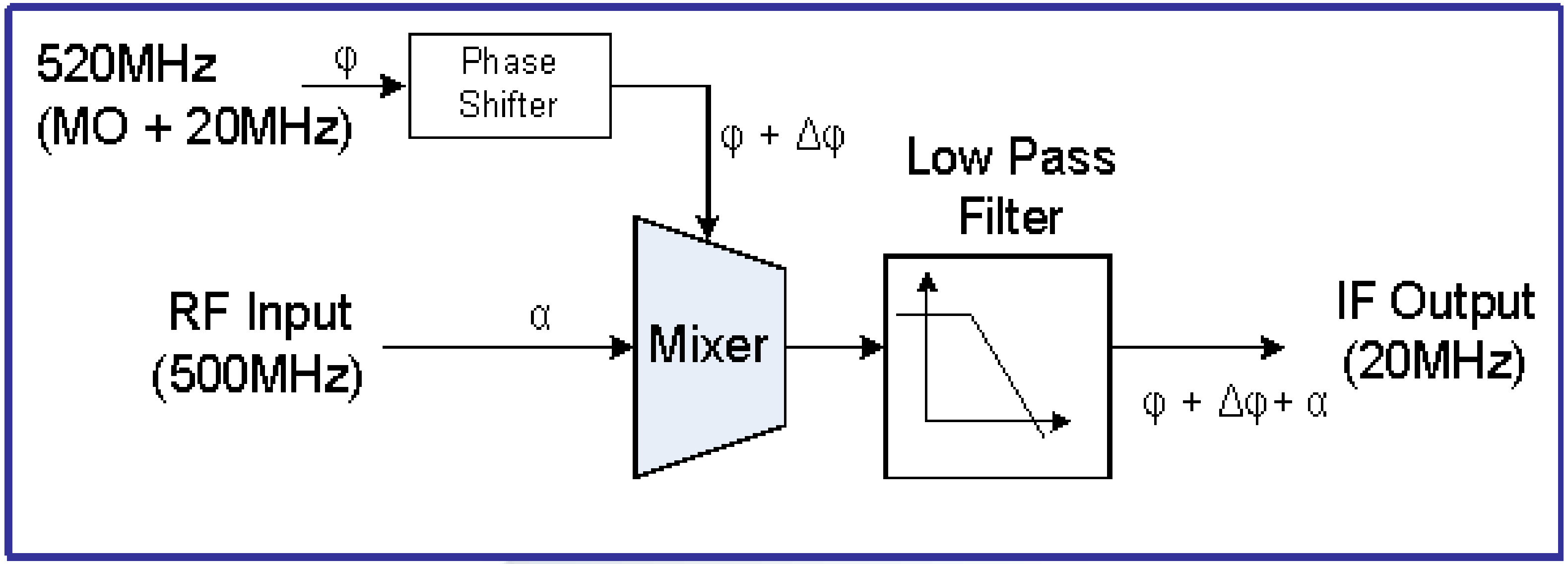
✓Phasor Diagram: I&Q



Amp: $\sqrt{I^2 + Q^2}$

Φ: $a\tan(\frac{Q}{I})$

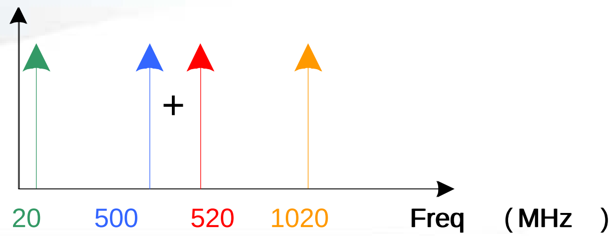
Downconversion: From RF to IF



Ref Signal (520 MHz) = MO + IF

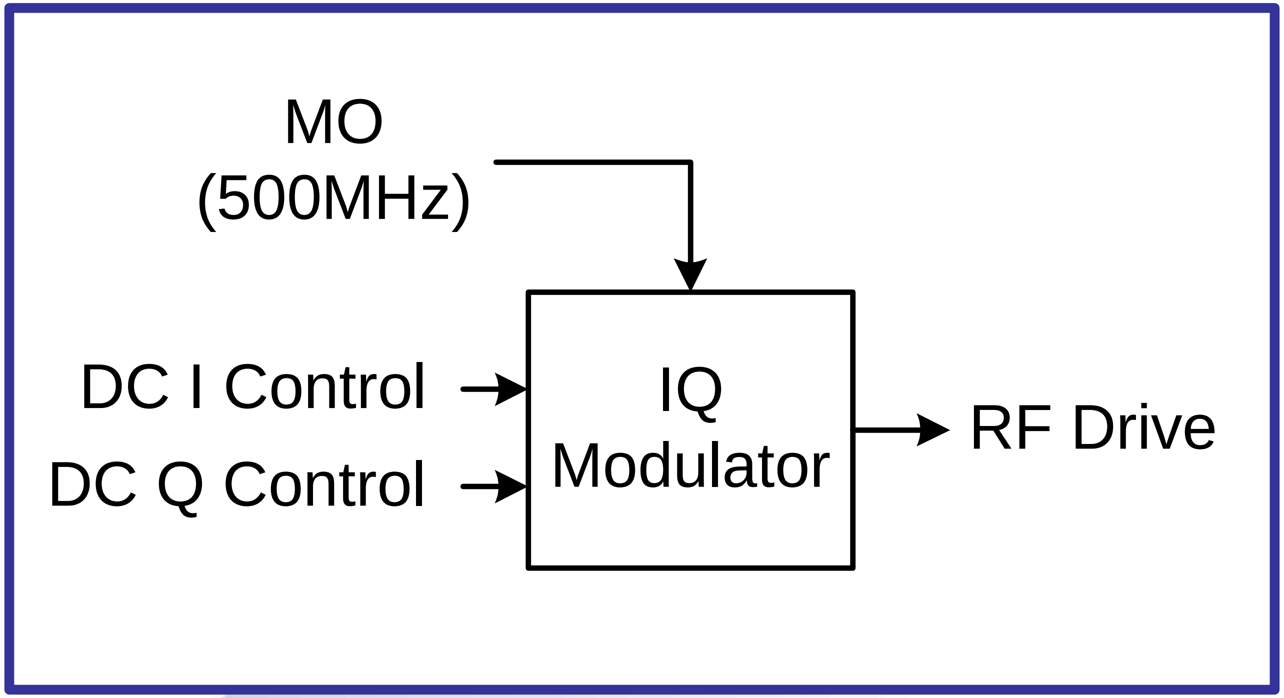
ADCs Clock = 4*IF

Phase shifter to adjust phase delay lines between RF plants



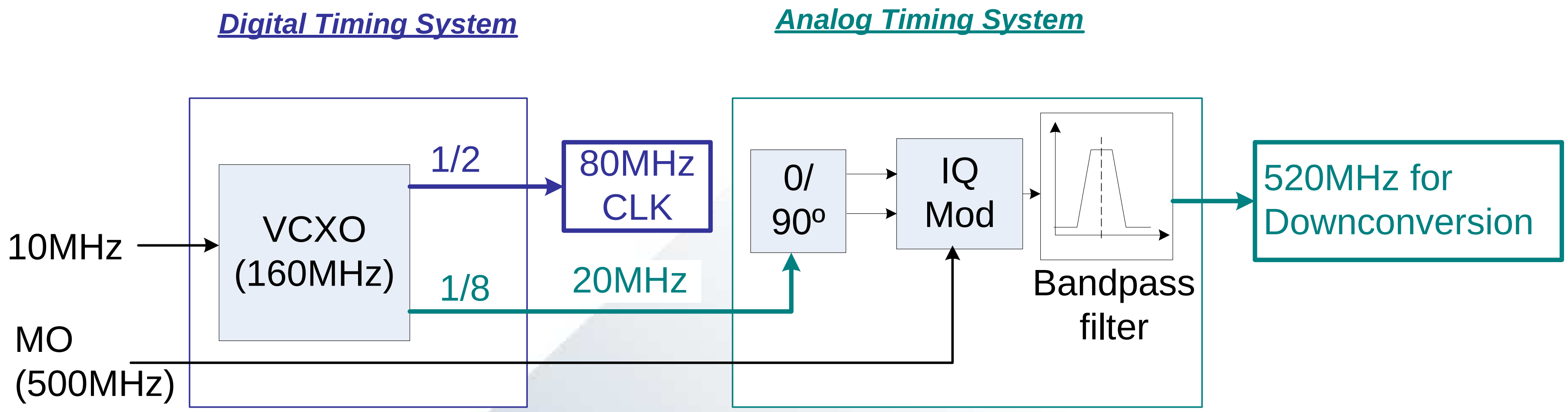
$\cos(\beta) \cdot \cos(\alpha) = \frac{1}{2} \cdot (\cos(\alpha - \beta) + \cos(\alpha + \beta))$

Upconversion: From DC to RF



The MO signal is modulated, by I & Q, in amplitude and phase

Timing System

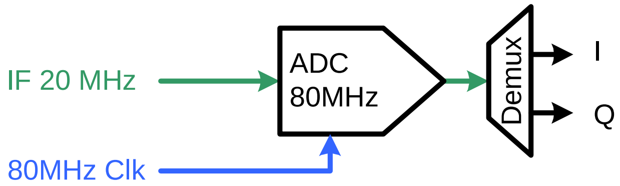


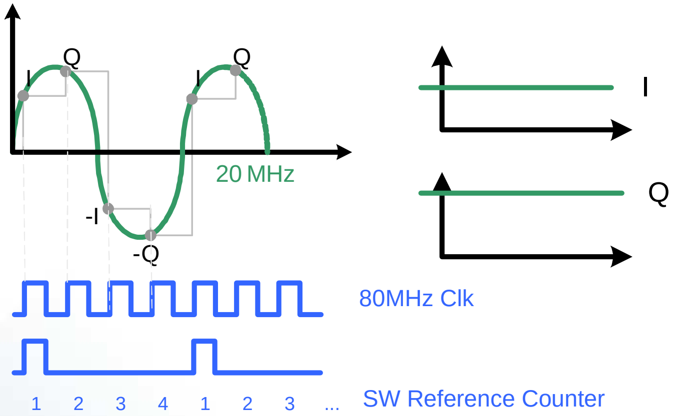
Needed for proper digitalization and synchronization

Control Loops

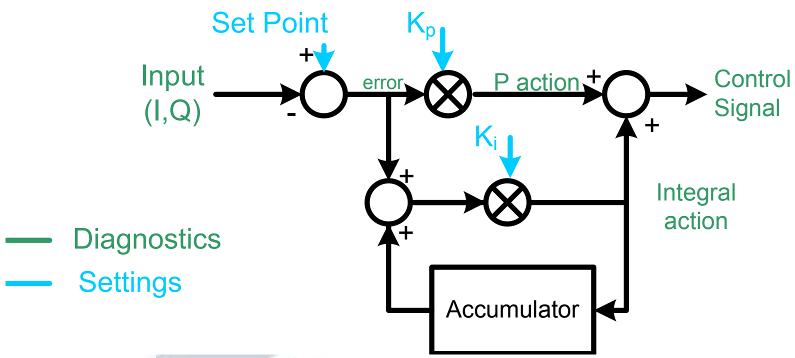
Amplitude and Phase Control Loops

✓ Digital IQ Demodulation





✓ PI Control Loop for IQ



Inputs: IQ Components of Cavity voltage

Set Point: Cav Voltage to achieve (to be set by the operator)

Error: SetPoint – Input

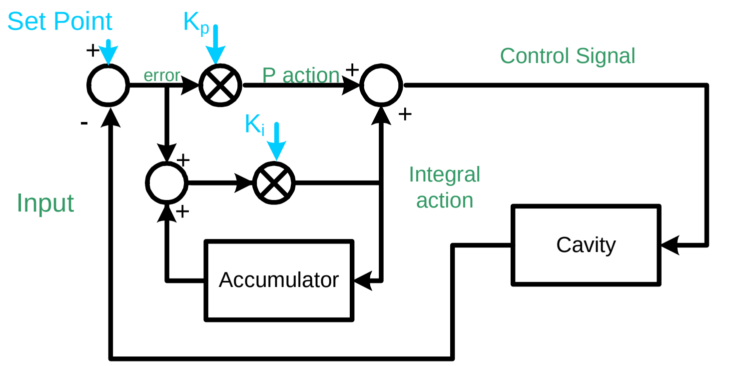
P Action: $\text{Error} \cdot k_P$

I Action: $\sum_t \text{Error} \cdot k_i$

Accum Error: $\text{Error} \cdot k_i$

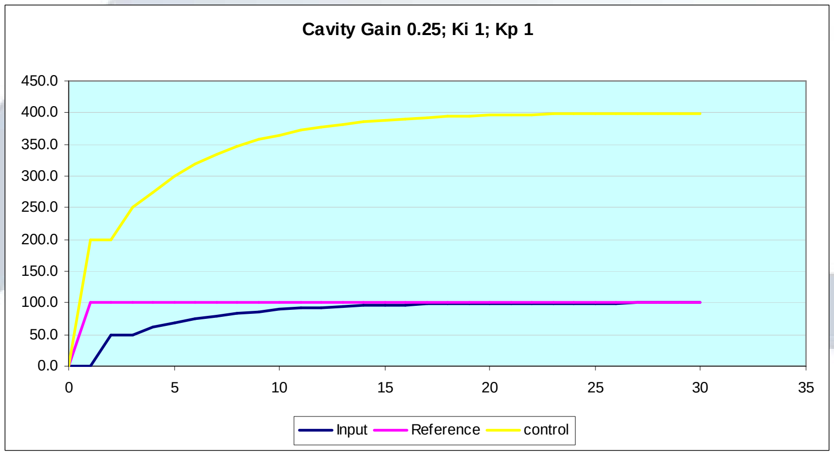
Control Signal: Proportional Action + Integral Action

Different PI Loop responses: Over-damp

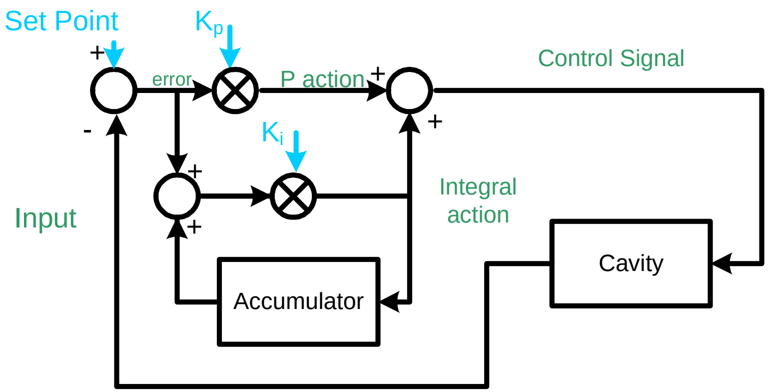


Input = Control Signal * Cavity Transfer Function

Cavity Gain: 0.25; Kp gain = 1; Ki gain = 1							
t	Input	Ref	error	Error accum	e * kp	e accum * ki	Control action
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	100	100	100	100	100	200
2	50	100	50	150	50	150	200
3	50	100	50	200	50	200	250
4	62.5	100	37.5	237.5	37.5	237.5	275
...	...	...	...	...	...	...	...
30	99.8	100.0	0.2	399.3	0.2	399.3	399.5

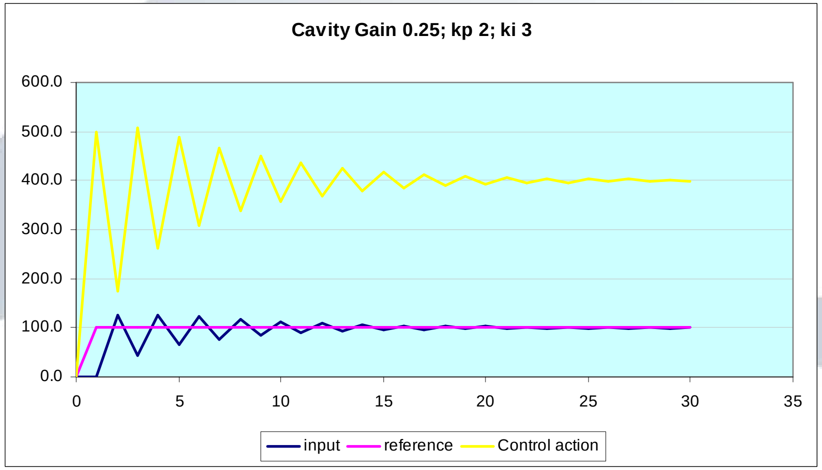


Different PI Loop responses: Under-damp



Input = Control Signal * Cavity Transfer Function

Cavity Gain: 0.25; Kp gain = 2; Ki gain = 3							
t	Input	Ref	error	Error accum	e * kp	e accum * ki	Control action
0	0.0	0	0	0	0	0	0
1	0.0	100	100	100	200	300	500
2	125	100	-25	75	-50	225	175
3	43.8	100	56.3	131.3	112.5	393.8	506.3
4	126.6	100	-26.6	104.7	-53.1	314.1	260.9
...	...	...	...	...	...	...	...
30	100.4	100	-0.4	133.1	-0.8	399.4	398.6

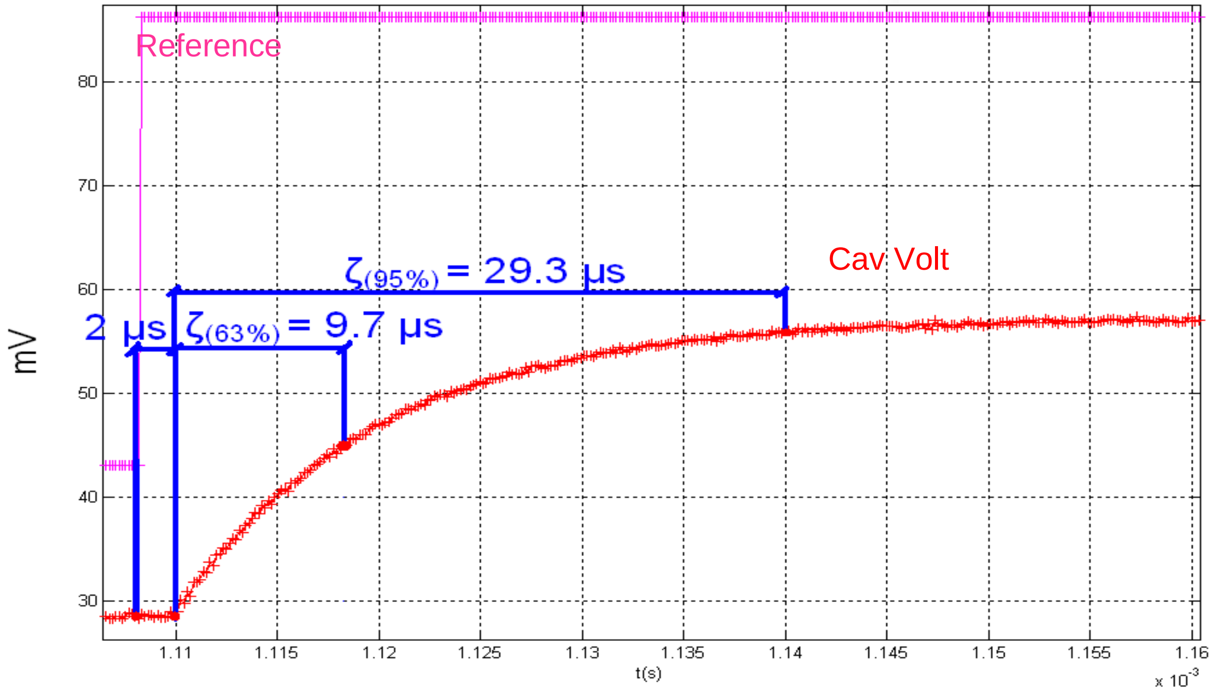


Characterization of Cavity Transfer Function

Transfer Function: Mathematical representation of a system (model)

- ✓ to be calculated analytically
- ✓ to be measured experimentally

Experimentally: Step response in Open Loop



System Characterization (1st Order)

- ✓ Group Delay = 1.93μs
- ✓ $\zeta_{(63\%)}$ = 9.7 μs
- ✓ Gain = 0.8
- ✓ Filling time = 29.3 μs

(DAMPY Cavity)

Transfer Function

$$\frac{K \cdot e^{-Ts}}{1+\tau s} = \frac{0.8 \cdot e^{-2 \cdot 10^{-6} \cdot s}}{1 + 9.7 \cdot 10^{-6} s}$$

Amplitude and Phase Control Loop

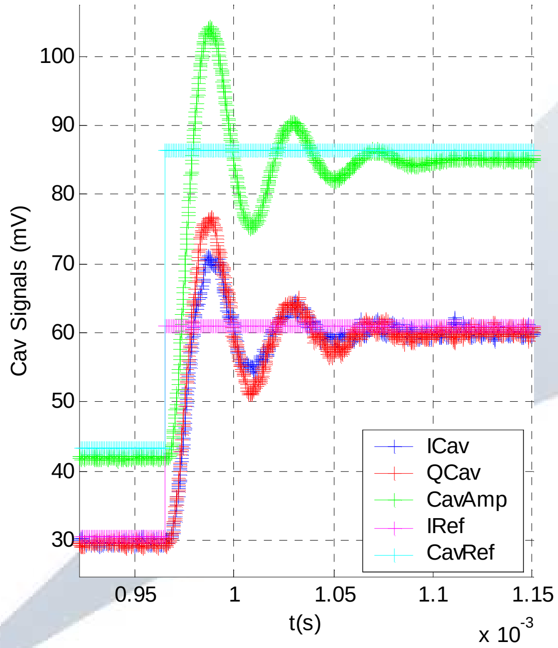
Diagnostics signals of Loops

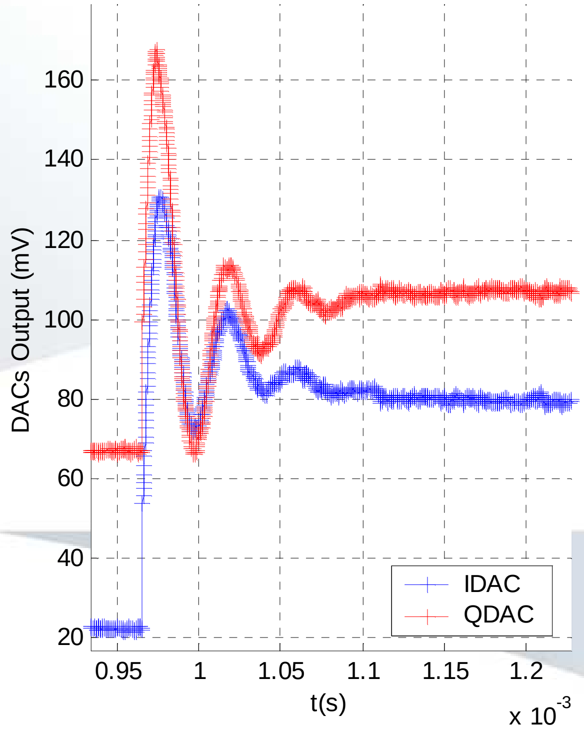
IQ Cav
Cav Amplitude
Cav Phase

IQ Error
IQ Integral Action
IQ PID Output

IQ Fw
Fw Amplitude
Fw Phase

Control Amplitude
Control Phase



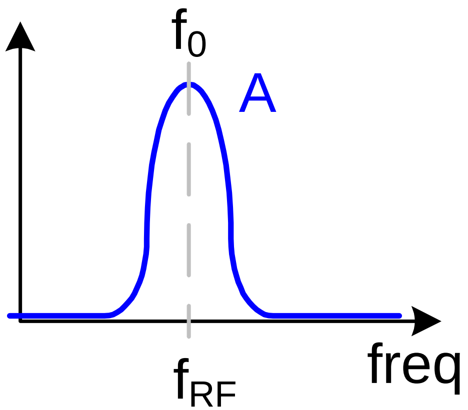


Step response in Close Loop (Cav&DACs)

Tuning Loop

✓ Loop required to adjust resonance frequency of the cavity

✓ How it works?

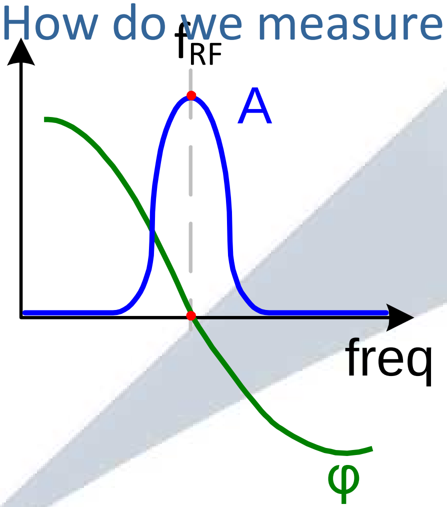


Cavity geometry defines Resonance Frequency (f_0)

Cavity should be matched to RF, without beam $f_0 = f_{RF}$

Power dissipation (heat) and beam loading requires that resonance frequency is adjusted Δf_0 → cavity geometry change → Action: modification of the geometry by a plunger in the cavity.

✓ How do we measure detuning of the cavity? (Δf_0)



Detuning effects:

- Voltage of the cavity will decrease
- Phase of the cavity will vary

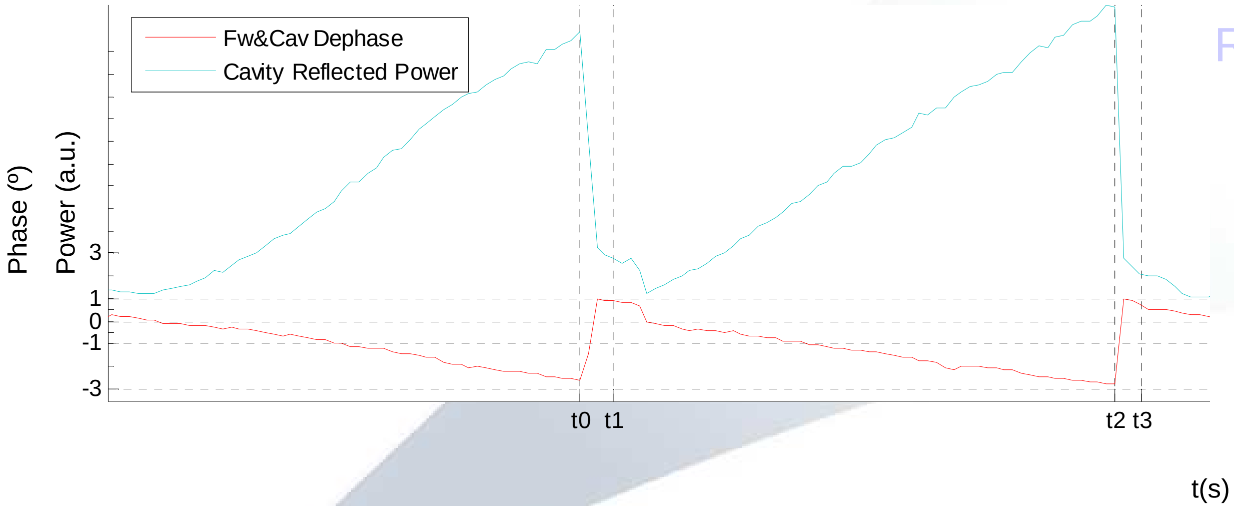
Tuning Loop Input: Phase difference between Forward Power and Cavity Voltage

Tuning Loop

✓ Cordic Algorithm to calculate Cav – Fw phase difference

Iterative process to calculate phase without employing any multipliers
Resolution better than 0.001º after 16 iterations (1/80MHz * 16 = 0.2 µs)

✓ Tuning Loop not always active to avoid plunger oscillations around 0º phase



Results on real cavity @ 20kW

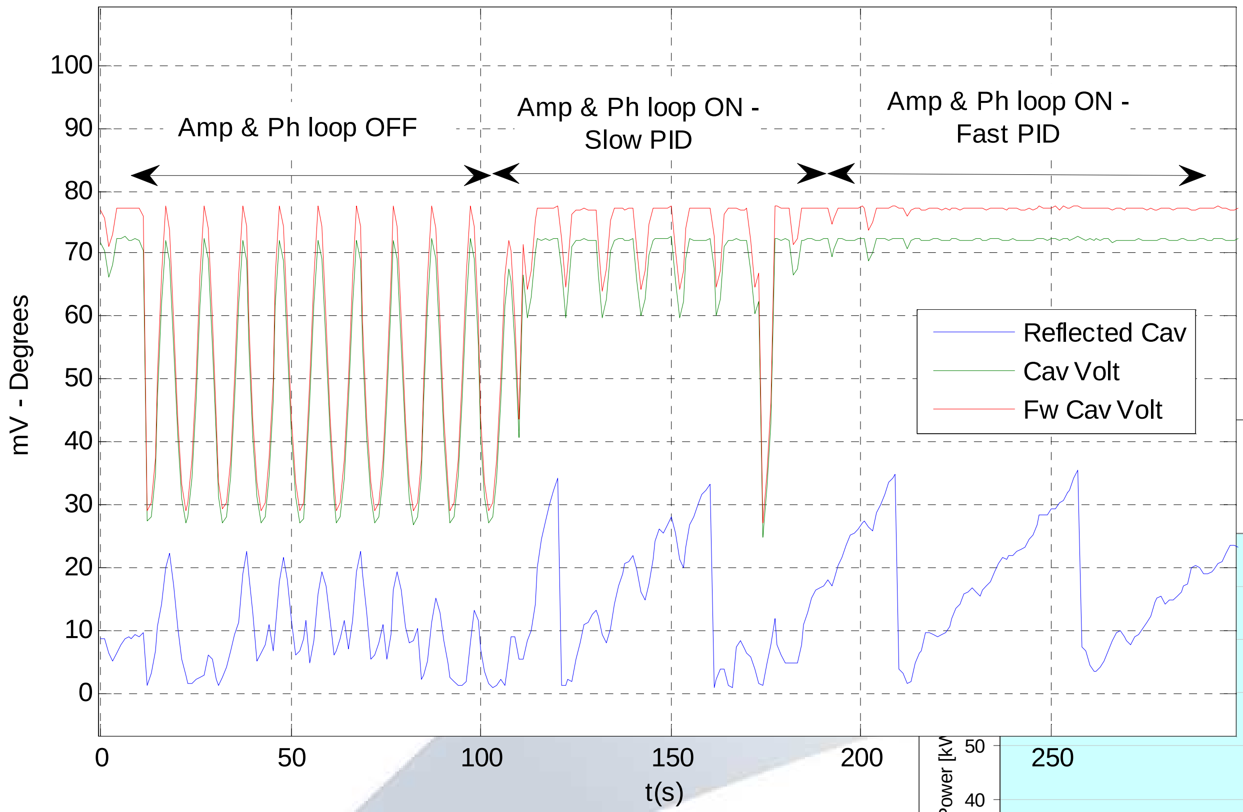
$t=t_0$	$\Delta\varphi < -3^o$	Tuning On
$t=t_1$	$\Delta\varphi = 1^o$	Tuning Off
$t=t_2$	$\Delta\varphi < -3^o$	Tuning On
$t=t_3$	$\Delta\varphi = 1^o$	Tuning Off

✓ Tuning Outputs: Two LVTTL signals (Pulse and direction)

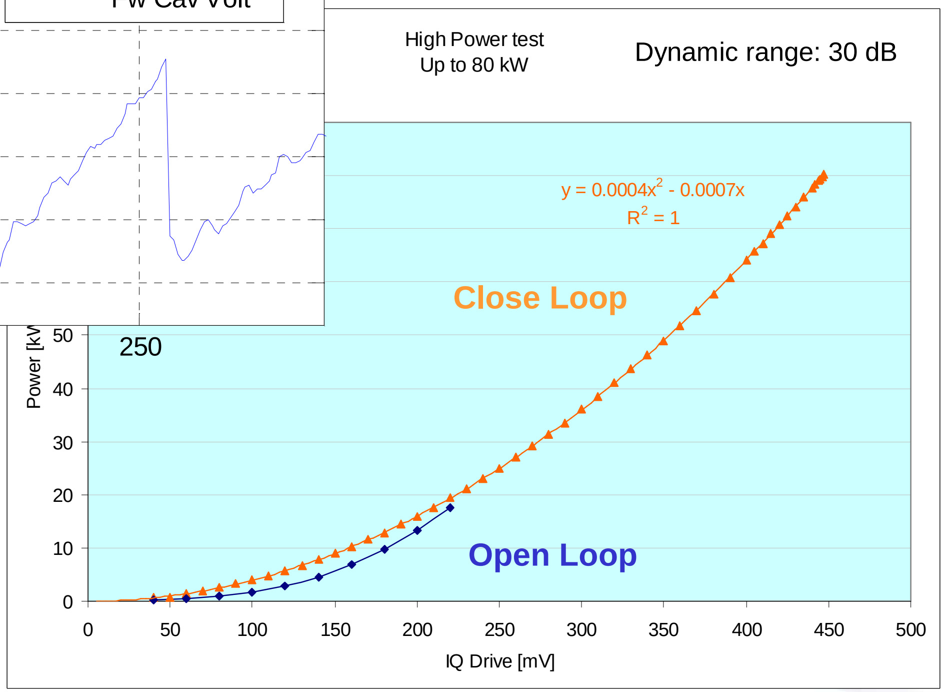
Motor Driver Control : **Icepap**
Frequency of the pulses adjustable (from 100Hz to 2kHz)

Power Tests

Loops performance:



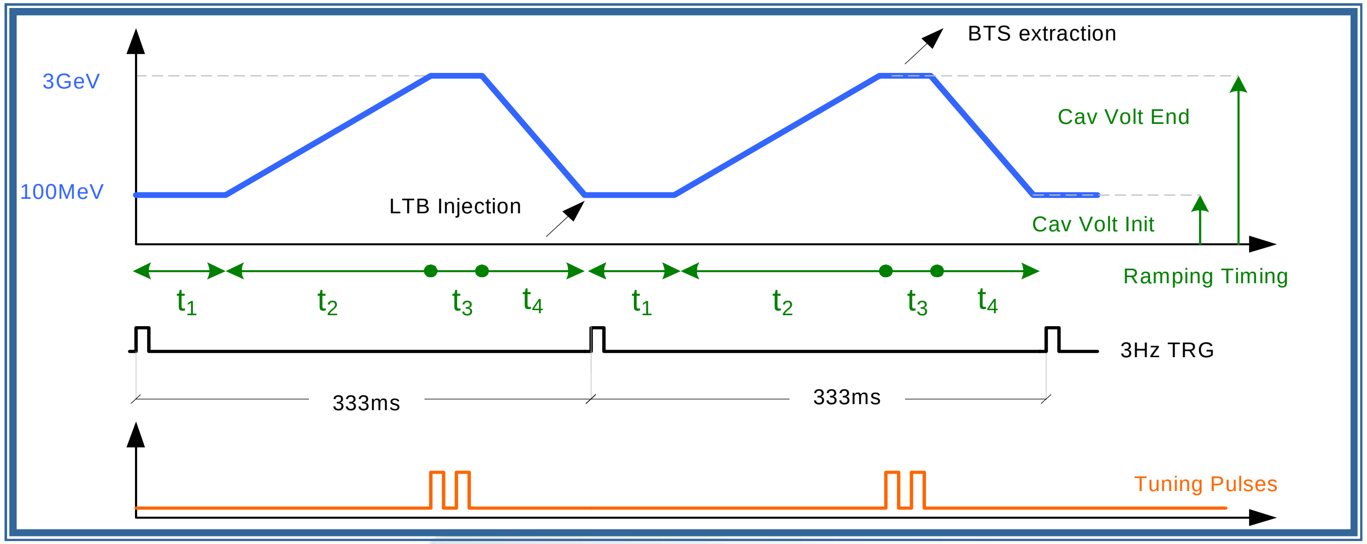
Amplitude, Phase and Tuning loops simultaneously in operation



Power tests at ALBA High Power RF Lab from 80W to 80kW

Booster Ramping

✓ Ramping to accelerate from 100MeV to 3GeV



✓ Amplitude and Phase loops always active

✓ Tuning Loop only active at Top of the ramp

✓ Parameters to be set by LLRF

<u>Timing</u>

t_1: Time to start ramp up after trigger

t_2: Ramp up time

t_3:Top ramping time

t_4: Ramping down time

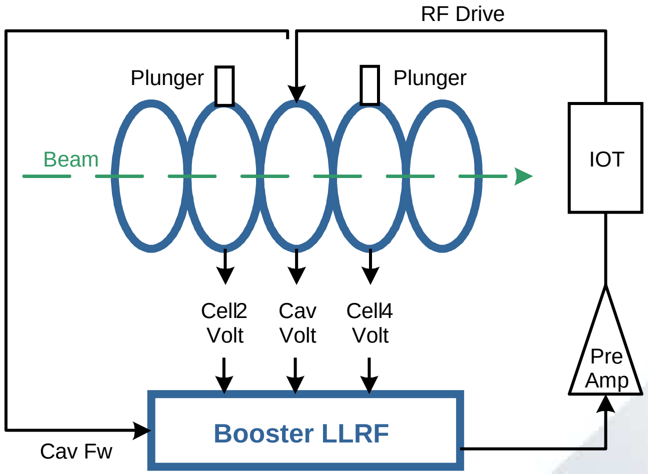
<u>Cavity Voltage</u>

Cavity voltage at Ramping start

Cavity Voltage at Top Ramp

Booster Field Flatness (FF)

- ✓ Booster Cavity: 5 cells
- ✓ Field Flatness loop: to keep the same voltage at 5 cells



Cell 3: Input of Amplitude and Phase loop (Cavity Voltage)

Cell 2 and Cell 4: Inputs of Field Flatness loop

Actuator: Two Plungers

- ✓ How does it work?

φ (CavFw)	ΔA (Cell2-Cell4)	Tuning	FF	PLG1	PLG2
φ > TM	--	ON	OFF	↑	↑
φ < -TM	--	ON	OFF	↓	↓
-TM < φ < TM	ΔA > FFM	OFF	ON	↑	↓
-TM < φ < TM	ΔA < -FFM	OFF	ON	↓	↑
-TM < φ < TM	-FFM < ΔA < FFM	OFF	OFF	Stop	Stop

TM: Tuning Margin FFM: FF Margin

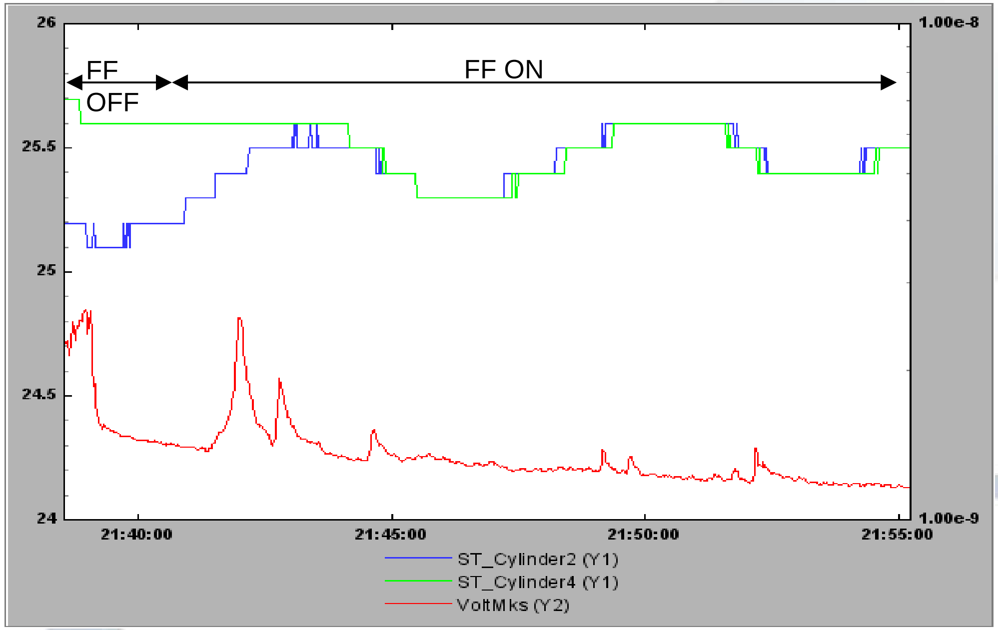
Booster Field Flatness (FF)

✓ Parameters of Booster Field Flatness (FF)

Field Flatness Margin or deadband

Gain of Amplitude of Cell 2 and Cell 4 to compensate different attenuations between channels

✓ Field Flatness Power tests



<u>FF Off</u>

Amp Cell2 > Amp Cell 4

Temp Cell2 > Temp Cell4

<u>FF On</u>

Amp Cell2 = Amp Cell 4

Temp Cell2 = Temp Cell4

RF Diagnostics

RF Diagnostics

Other RF signals Digital IQ Demodulated

✓Cavity

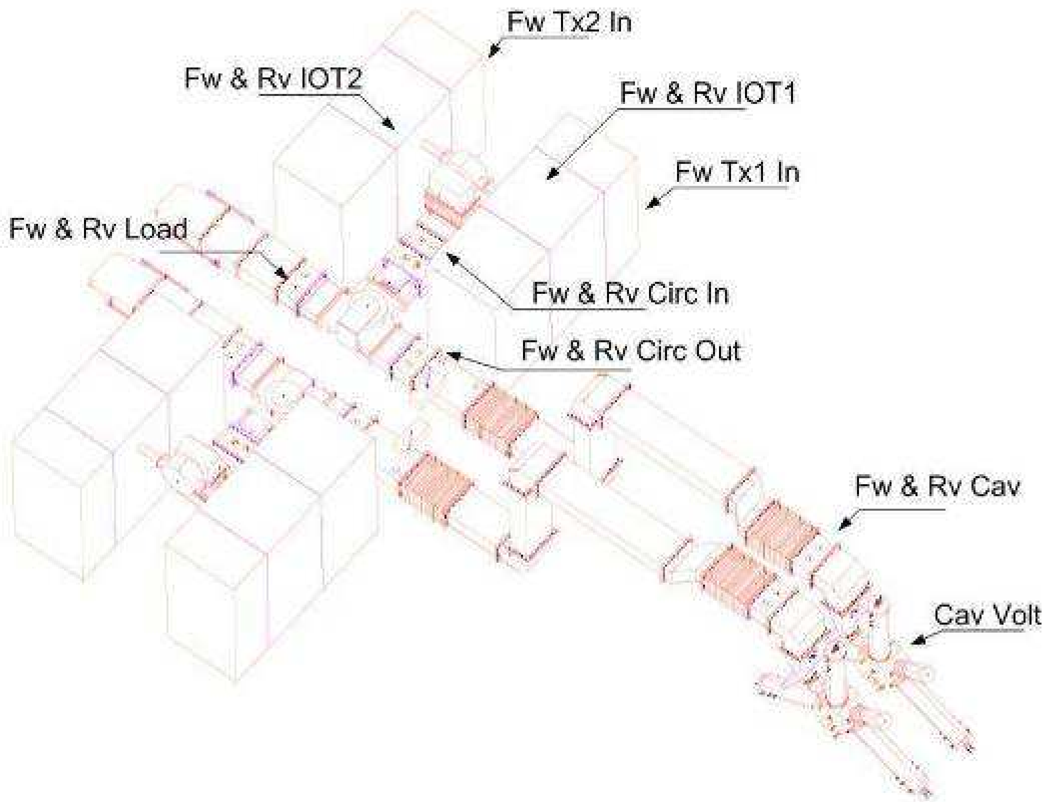
Cavity Power
Forward and Reversed Cavity Power

✓ Waveguide System

Fw and Rv Circulator Input
Fw and Rv Circulator Output
Fw and RV Load Power

✓Transmitter Signals

Fw Transmitter1 Input Power
Fw Transmitter2 Input Power
Fw and Rv IOT-01 Power
Fw and Rv IOT-02 Power



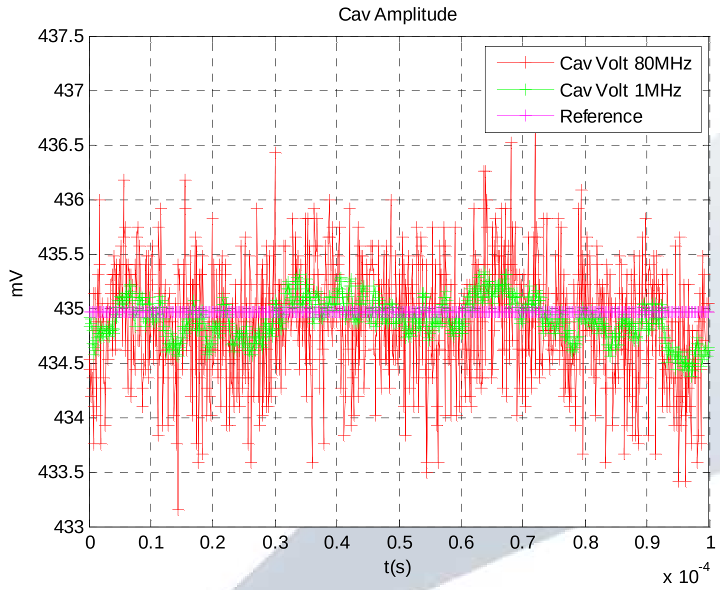
RF Diagnostics

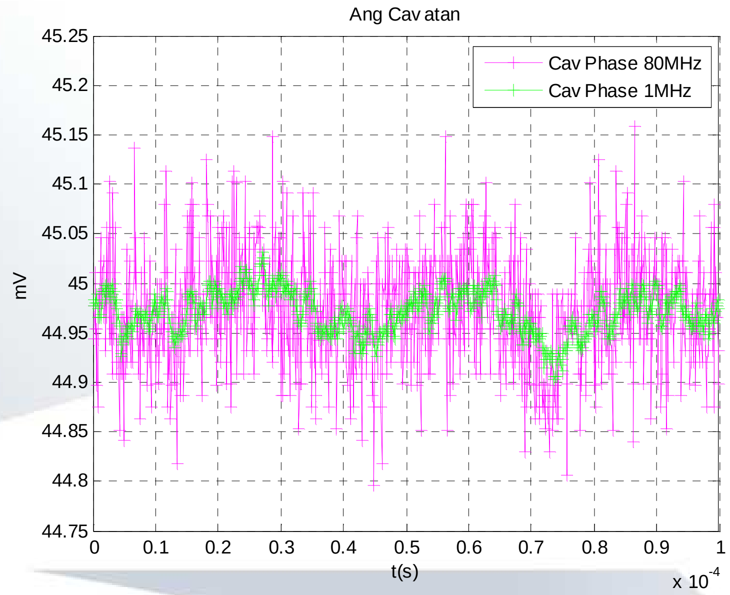
Fast Diagnostics

✓ Signals acquired at 5MHz rate

✓ Signals stored in a circular buffer of 128MBytes (equivalent to 0.5s of operation)

✓ Used for post mortem analysis and transient studies





Amplitude RMS Errors:

δV_{rms} = 0.50mV/435mV = 0.11% @ 80MHz

δV_{rms} = 0.18mV/435mV = **0.03% @ 1MHz**

Phase RMS Errors:

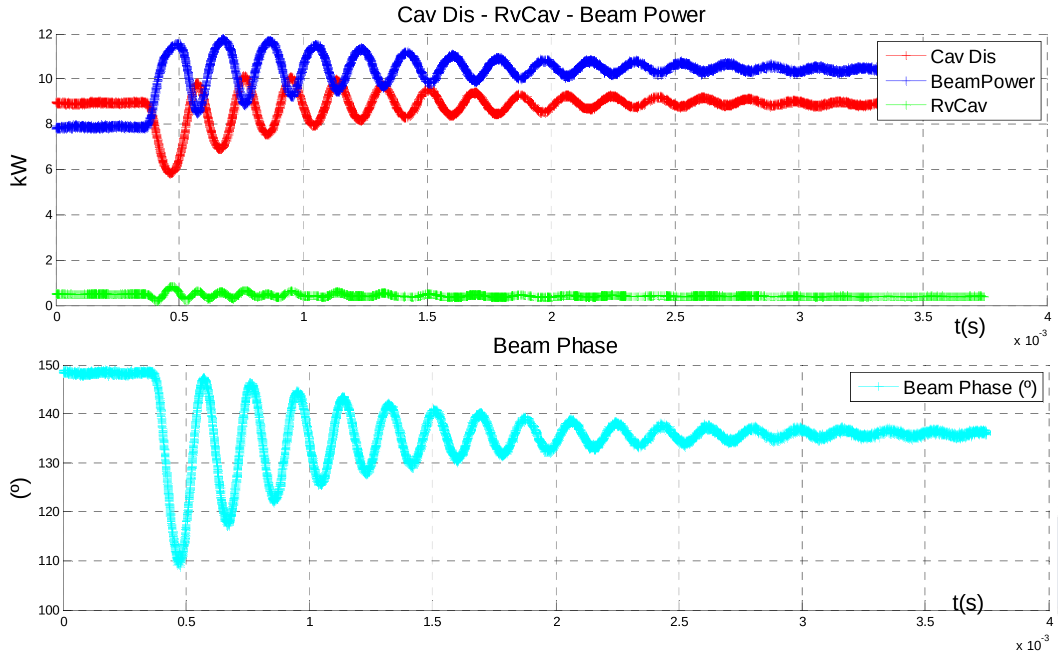
δPh_{rms} = 0.05º @ 80MHz

δPh_{rms} = **0.02º @ 1MHz**

RF Diagnostics

Post Mortem Analysis Example

- ✓Power to beam increases
- ✓Beam phsae gets reduced
- ✓Frequency oscillations ~ 6kHz (synchrotron freq)
- ✓Stabilization time ~ 3ms (longitudinal damping time)

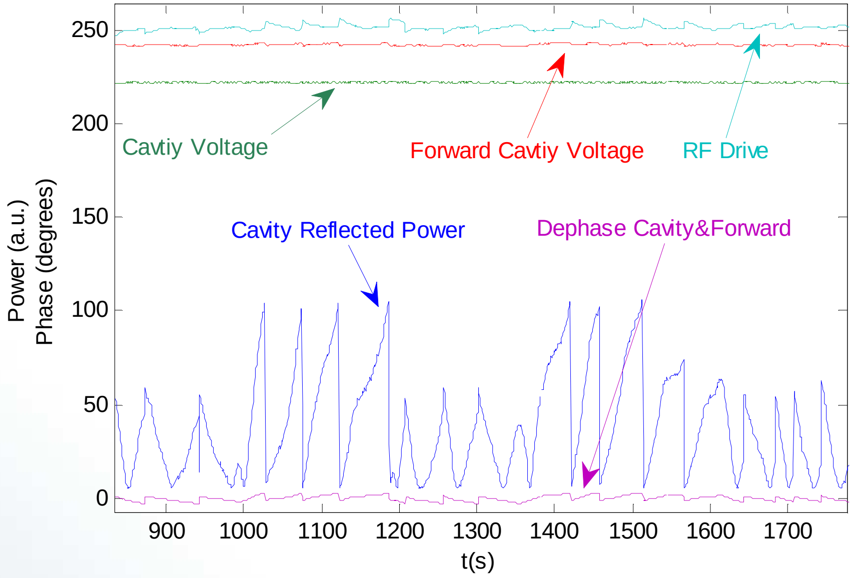


Behavior of 06B after a trip in 10B and no beam dump (61mA)

RF Diagnostics

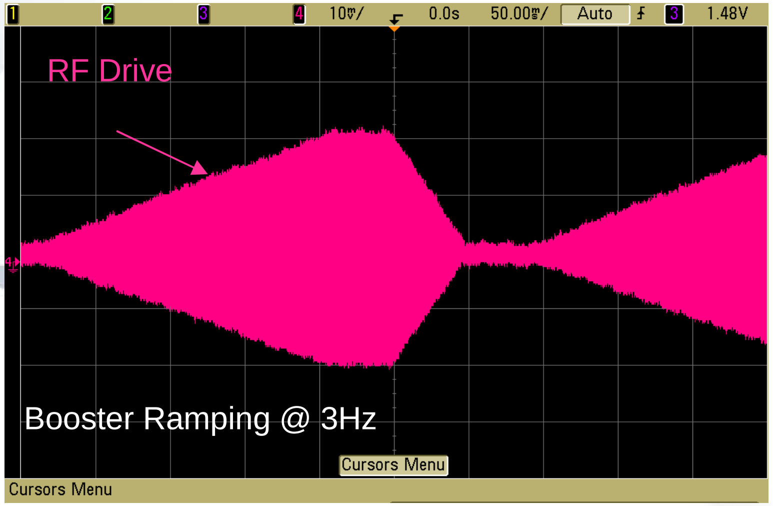
Slow diagnostics

- ✓ Archiving and Taurus Trend
- ✓ Signals acquired at 1Hz rate
- ✓ Historical purposes
- ✓ Slow trend analysis



Test Points

- ✓ BNC Test points of main RF signals



Conditioning

Conditioning

Cavity conditioning

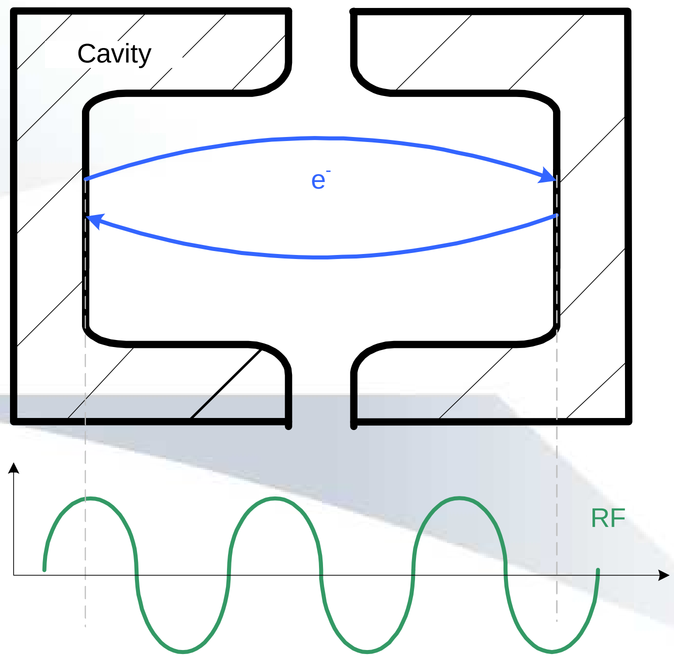
- ✓ Process to “clean” the cavity before putting full power

Multipacting

- ✓Secondary electron emission in resonance with RF
- ✓Depending on geometry of cavity components
- ✓Depending on RF power level
- ✓Depending on RF frequency
- ✓Depending on surface roughness

Effects

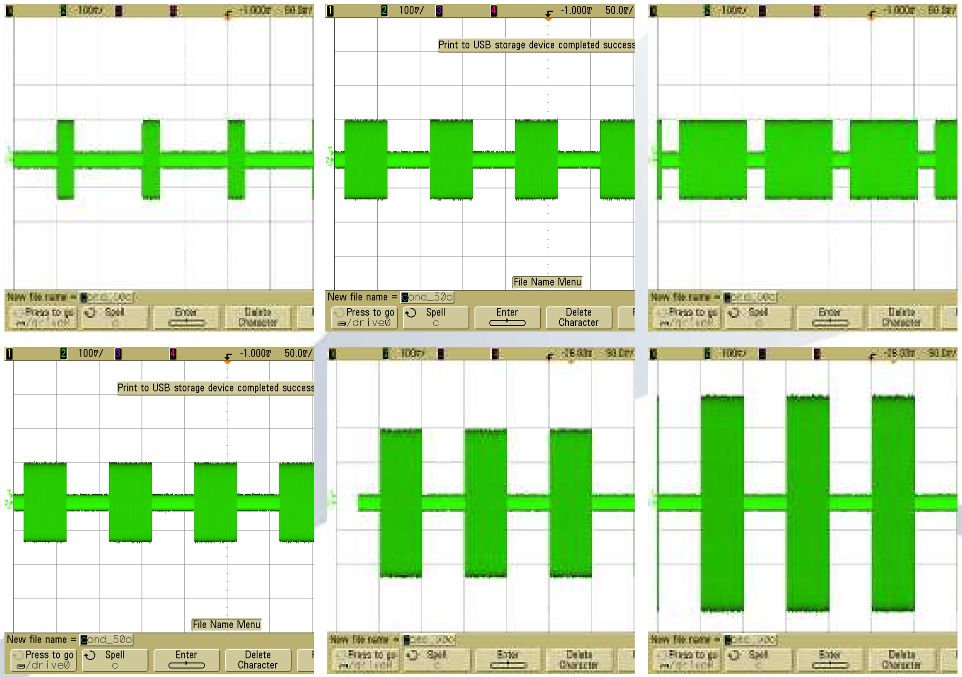
- ✓Vacuum pressure increase
- ✓Reflected power
- ✓Arcs



Manual Conditioning

RF Drive square modulated

- ✓Duty Cycle of pulses adjustable (1-100%)
- ✓Amplitude adjustable
- ✓Time between pulses = 100ms (10Hz)
- ✓ Tuning Loop only enable at top of the pulses

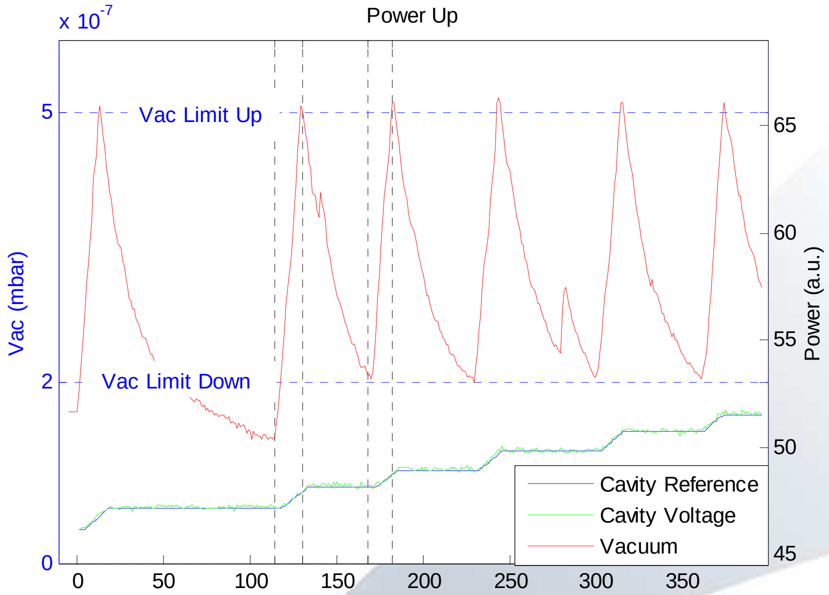


Drawbacks

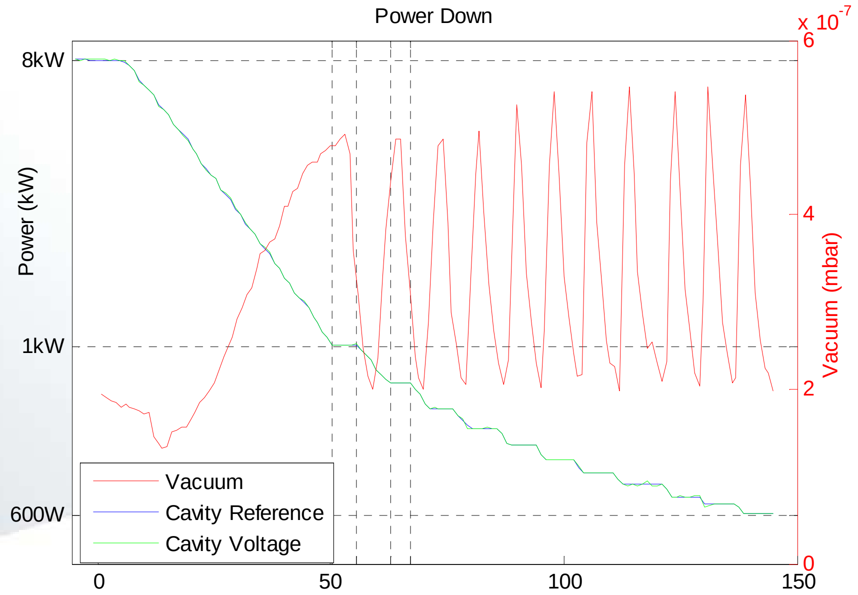
- ✓Operator needed to adjust amplitude and duty cycle
- ✓Vacuum levels not considered by LLRF → frequent interlocks

Automated Conditioning

- ✓Amplitude and duty cycle increase depending on vacuum levels
- ✓Amplitude increase rate (slope): adjusted by operator
- ✓Vacuum signal connected to LLRF



Voltage Increase rate set to 0.03mV/s



Voltage Decrease rate set to 1mV/s

- Vacuum < Limit Down → Voltage Amplitude Increases/Decreases
- Vacuum > Limit Up → Voltage Amplitude remains constant until vacuum is below limit down

Automatic Startup

Automatic Startup without beam

After an RF trip, LLRF goes to Standby State:

- ✓Low RF Drive
- ✓Tuning Disable
- ✓Amplitude and Phase loops opened

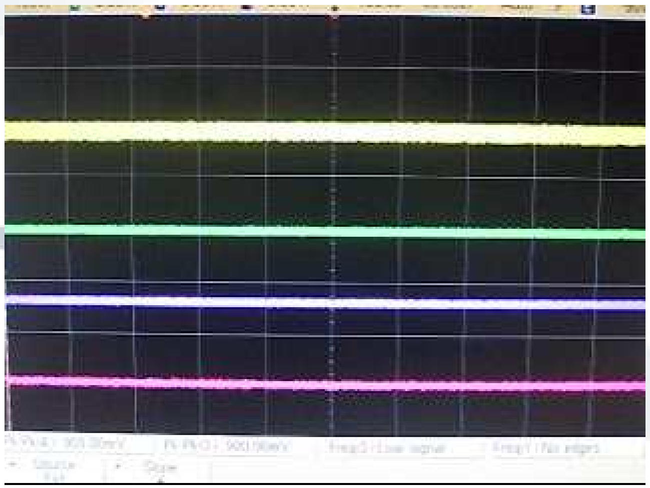
After resetting the interlock and switching on transmitter

- ✓ Detection of RF presence in cavity
- ✓ Cavity tuning before increasing power
- ✓ Amplitude and Phase Loops closed at low power
- ✓ Smooth power increase
- ✓ Message: Ready for beam operation

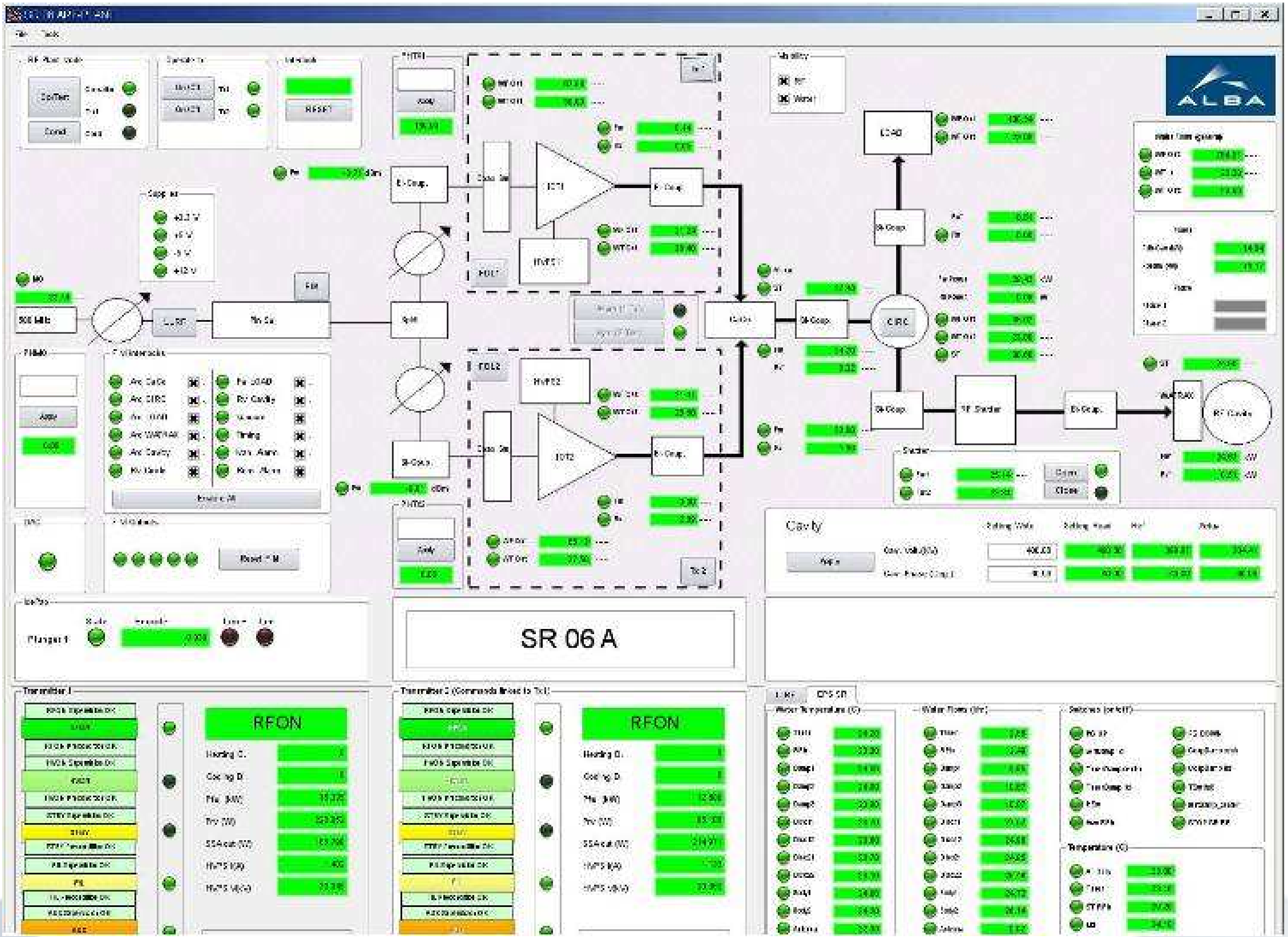
RF Power

Tuning pulses

Plungers direction



RF Plant GUI

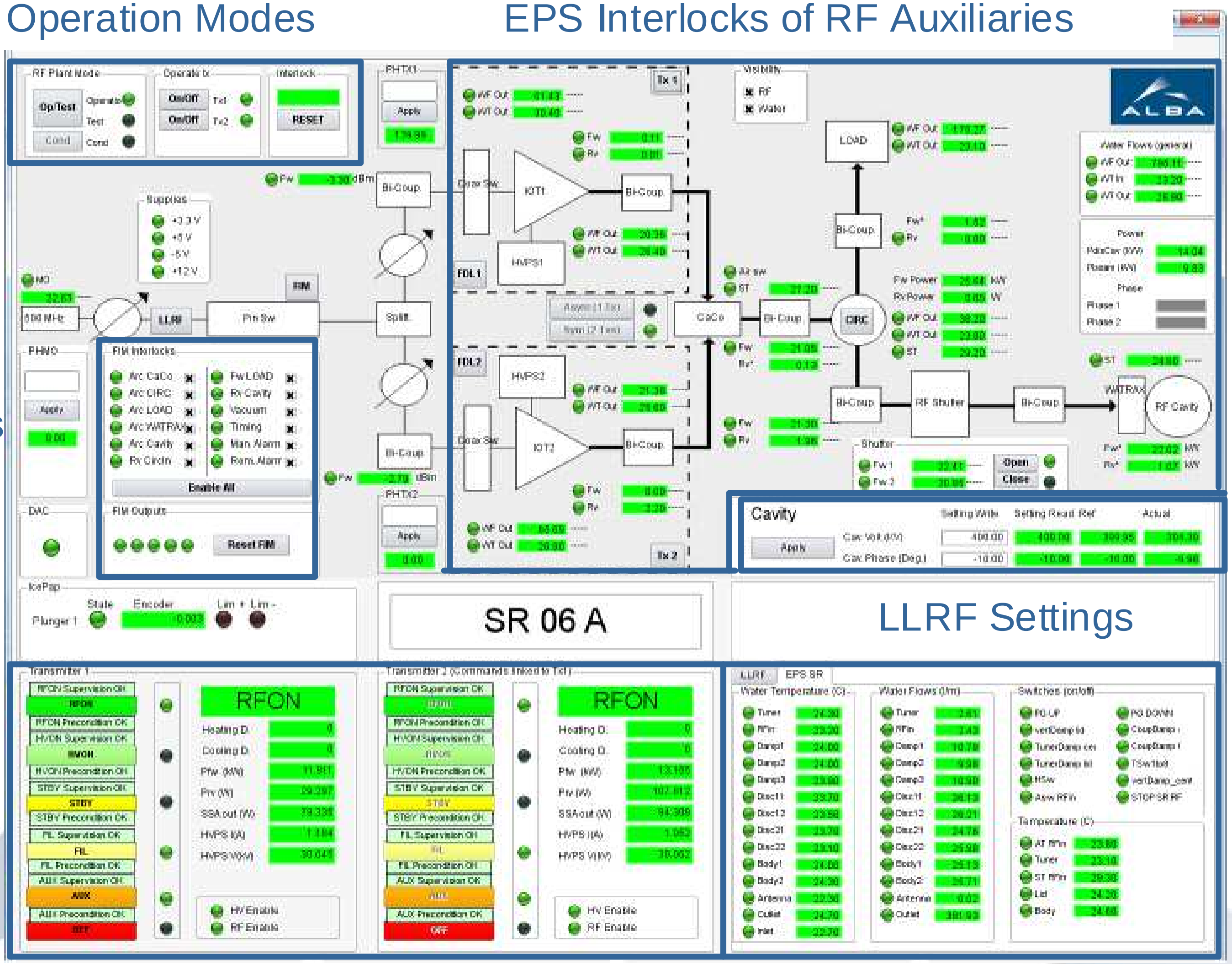


RF Plant GUI

Operation Modes

EPS Interlocks of RF Auxiliaries

Fast Interlocks (FIM)



Transmitters Information

Cavity Interlocks from EPS

Thank you

Francis Perez