LLRF System for Pulsed Linacs

(modeling, simulation, design and implementation)

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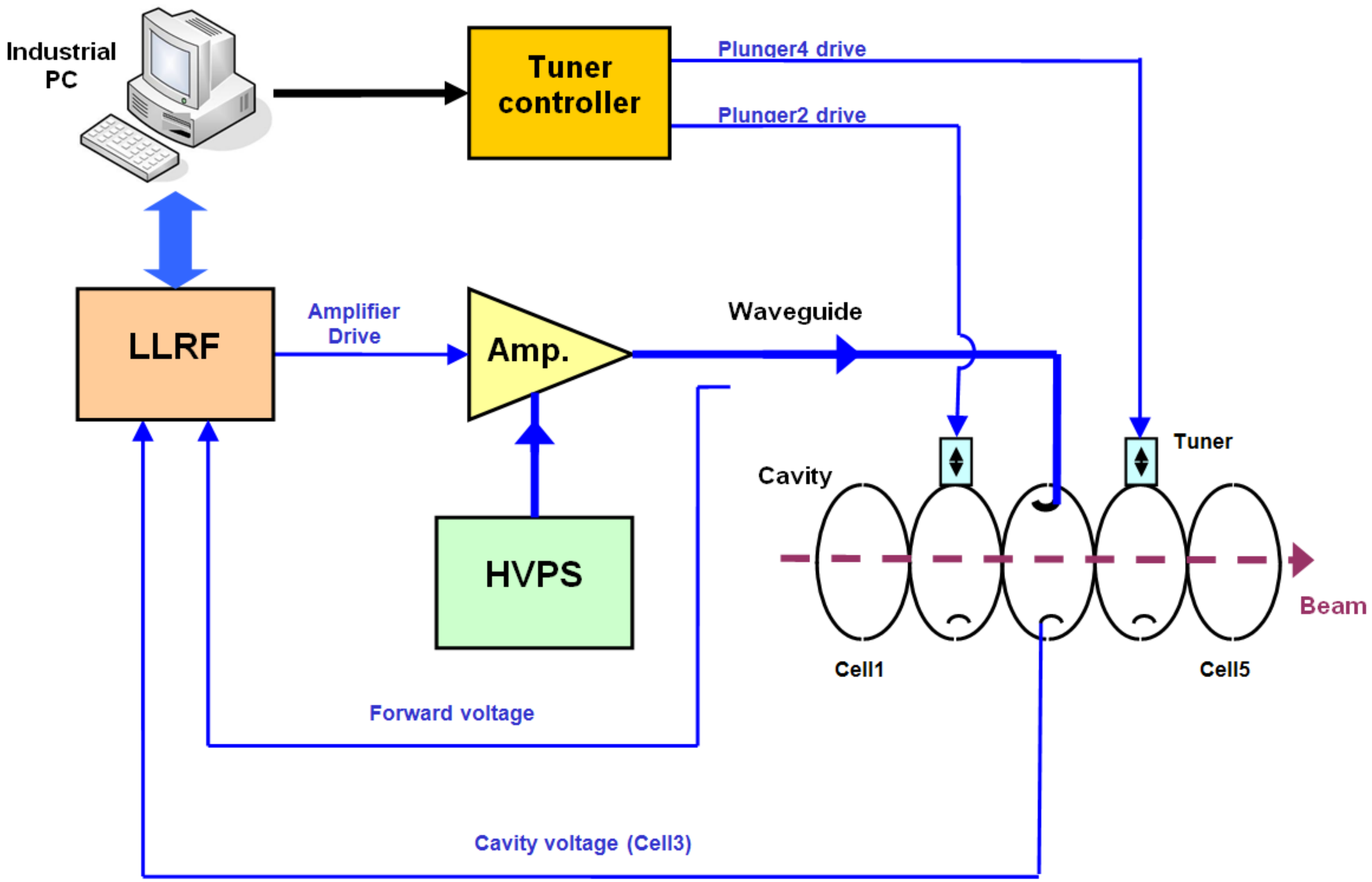
Simplified schematics of a typical RF plant and the LLRF feedback loops



Main functions of a LLRF system

1) **Amplitude regulation**

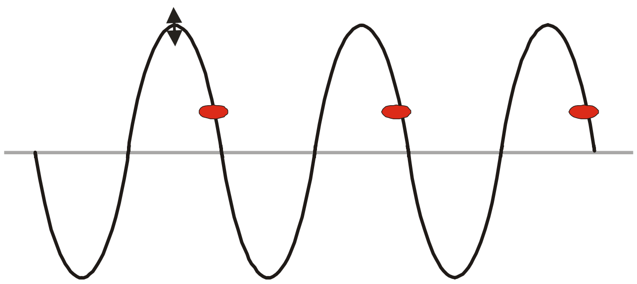
regulates the cavity voltage against disturbances such as HVPS ripples, beam loading, cavity warming, tuner movements, etc.

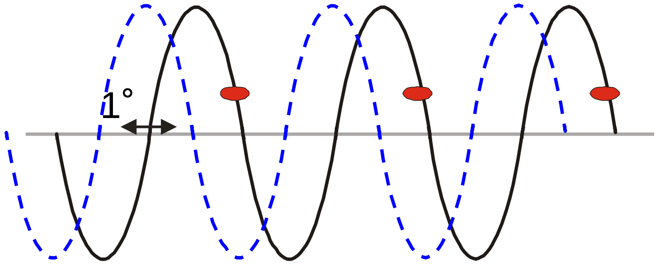
2) **Phase regulation**

regulates the cavity phase against disturbances such as HVPS ripples, beam loading, cavity warming, tuner movements, etc.

3) **Cavity tuning**

tunes the cavity to compensate the effect of beam loading and cavity warming thus minimizing the reflected power.





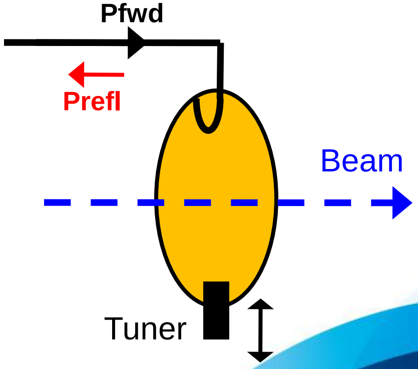


Figure of merit of a LLRF system

- The goal in the design of an amplitude/phase loop is:

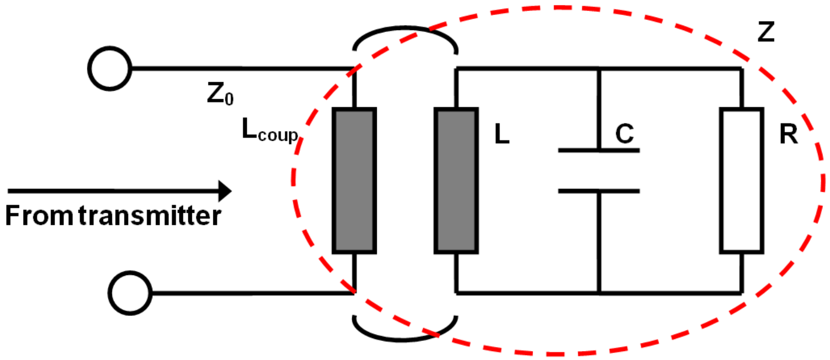
  - to give as much stability as possible to the RF field (typical values are ±1% and ±1° of amplitude and phase stability respectively).
  - to provide a large-enough bandwidth to suppress the highest frequency disturbance that may affect the RF field in the cavity.
  - to have a good stability margin (phase margins of 45° or more).
  - to have a large dynamic range (23 dB or more) if it is intended for energy ramps.

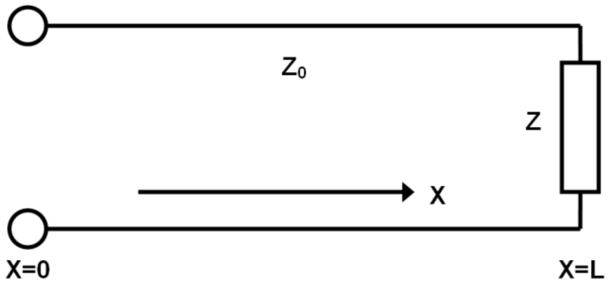
- Similarly, the tuning loop should provide enough accuracy in cavity tuning to have the least amount of reflected power although the cavity may suffer from a number of disturbances including beam loading, field ramping and temperature variations.

Conventional vs. state of the art

- **Control method / topology**
  - PID controllers vs. pole-placement feedbacks and Kalman filters
- **RF modeling and simulation**
  - Steady-state models vs. transient models
  - Simple RLC models vs. models dealing with the cavity reflected voltage
  - Mixed RF-baseband models vs. baseband-equivalent models
- **Design and implementation**
  - Analog vs. digital
  - Amp/phase loops vs. IQ loops

Cavity modeling with coupler (no beam)





$$Z = \frac{L_{coup}}{L} Z_C = \frac{L_{coup}}{L} \frac{RL.s}{RLC.s^2 + L.s + R}$$

$$\begin{aligned} V(x) &= V_{fwd}(x) + V_{refl}(x) \\ I(x) &= I_{fwd}(x) - I_{refl}(x) \end{aligned}$$

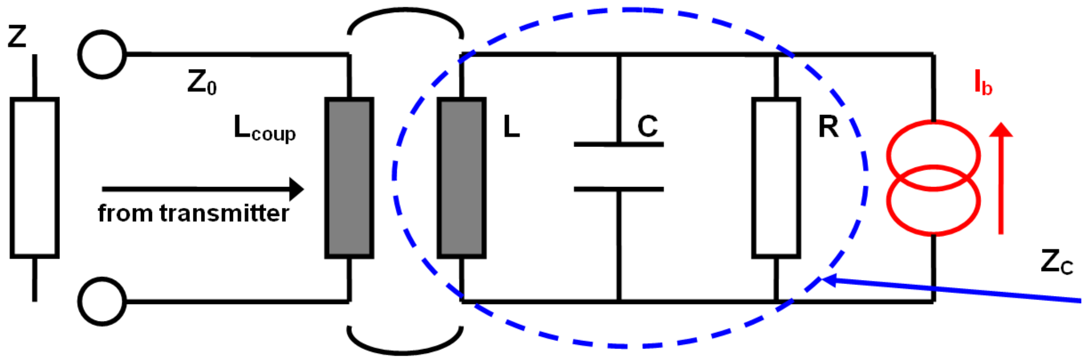
$$\beta = \frac{L_{coup}}{L} \frac{R}{Z_0}$$

$$r = \frac{\beta L.s - RLC.s^2 - L.s - R}{\beta L.s + RLC.s^2 + L.s + R}$$

$$Z = \frac{\beta Z_0 L.s}{RLC.s^2 + L.s + R}$$

$$\acute{Z}_{cav-amp} = \frac{\acute{V}_{cav-amp}}{\acute{I}_{fwd}} = \frac{2\beta Z_0}{\beta + 1 + Q_0 \left(\frac{s}{\omega_0} + \frac{\omega_0}{s} \right)}$$

Cavity modeling with beam



$$\acute{Z}_{cav-beam} = \frac{\beta Z_0 L.s}{RLC.s^2 + L(\beta+1).s + R} \qquad \left|\acute{I}_{beam}\right| = 2I_{DC}\sqrt{\frac{L}{L_{coupl}}} = 2I_{DC}\sqrt{\frac{R}{\beta Z_0}}$$

$$\begin{aligned}\acute{V}_{total}(s) &= \acute{V}_{cav-amp}(s) + \acute{V}_{cav-beam}(s)\\ &= \acute{I}_{amp}(s).\acute{Z}_{cav-amp}(s) - \acute{I}_{beam}(s).\acute{Z}_{cav-beam}(s)\end{aligned}$$

$$\acute{V}_{total}(s) = \left(2\acute{I}_{amp}(s) - \acute{I}_{beam}(s)\right)\frac{\beta Z_0 L.s}{RLC.s^2 + L(\beta+1).s + R}$$

Nucl. Inst. Meth. in Ph. Res. Section A, April (2010), vol. 615, no. 2

Compensation of steady-state beam loading

$$\acute{V}_{total} = \acute{I}_{amp}(2 - A.e^{j\omega T}).\frac{\beta Z_0}{\beta + 1 + jQ_0\zeta} \qquad (steady\ state)$$

$$A = \frac{2I_{DC}}{\left|\acute{I}_{amp}\right|}.\sqrt{\frac{R}{\beta Z_0}} \qquad T = \frac{\varphi - 90^\circ}{\omega}.\frac{\pi}{180^\circ}$$

$$\acute{Z}_{total} = \frac{\acute{V}_{total}}{\acute{I}_{amp}} = \frac{\beta(2 - A.sin\varphi_S - jA.cos\varphi_S)Z_0}{\beta + 1 + jQ_0\zeta}$$

$$\beta = \frac{1}{1 - A.sin\varphi_S} = \frac{1}{1 - \frac{2I_{DC}}{|I_{amp}|}\sqrt{\frac{R}{\beta Z_0}}sin\varphi_S}$$

$$\zeta = \frac{-A\beta.cos\varphi_S}{Q_0} = -\frac{2I_{DC}}{|I_{amp}|}.\sqrt{\frac{R}{\beta Z_0}}.\frac{\beta.cos\varphi_S}{Q_0}$$

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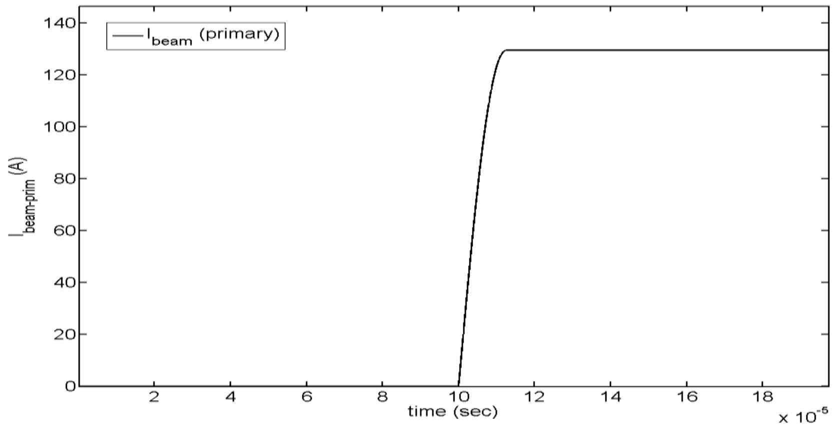
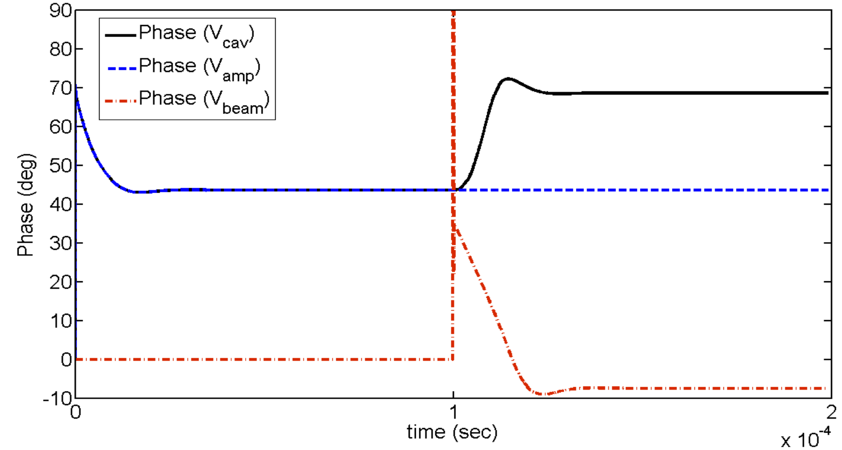
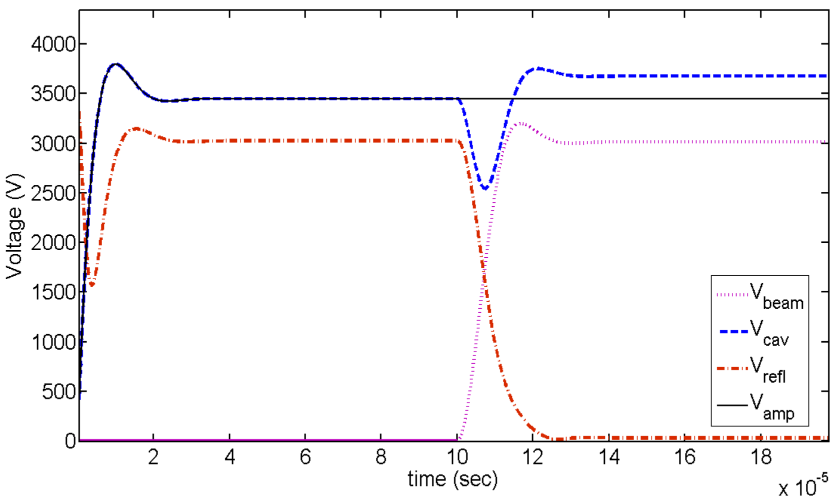
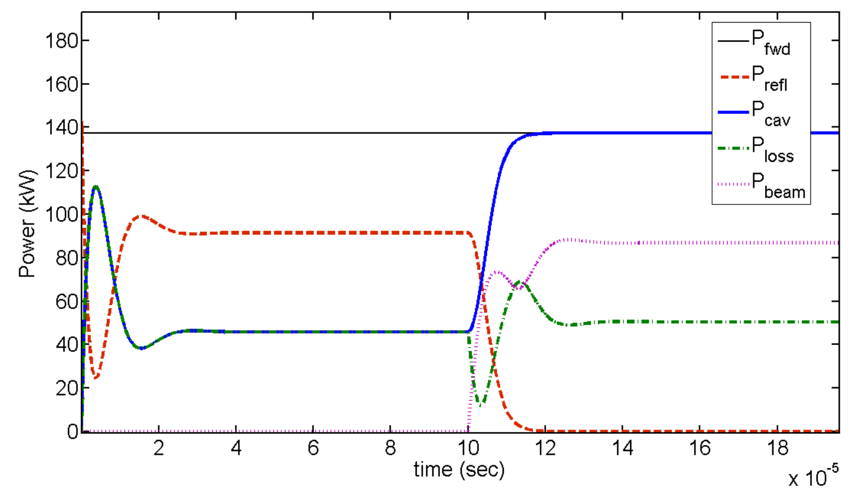
Cavity transient simulation









ESS-Bilbao RFQ / LLRF specifications

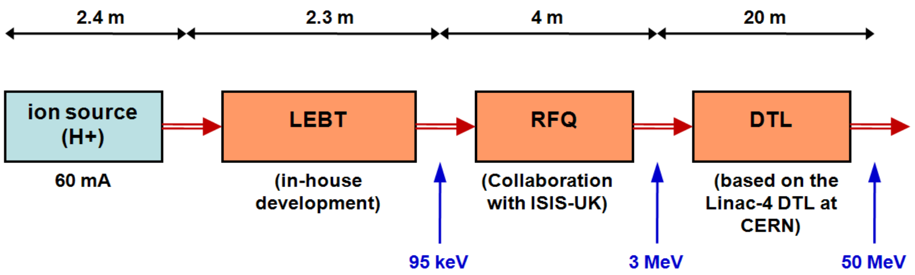
RFQ parameters

Parameter	Value	unit
RF frequency	352.209	MHz
RF pulse rate (max)	50	Hz
RF pulse width (max)	1.5	ms
Peak Klystron power	2.8	MW
Unloaded Q	9000	
Ratio of P_{Copper} to P_{beam}	5 to 1	
Emmitance	0.2π	mm. mrad
Beam energy at RFQ entrance	95	keV
Beam energy at RFQ exit	3	MeV

LLRF specifications / performance

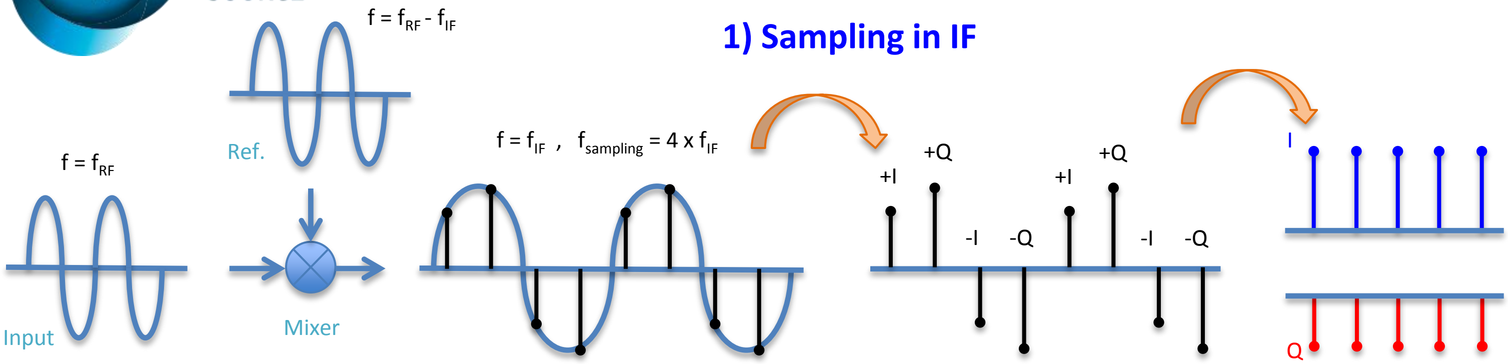
Parameter	Spec.	Actual	Unit
Operating mode	pulsed	CW/pulsed	
Settling time	≤100	<100	μs
Loop delay		800 app.	ns
Phase noise	±0.5	±0.1	°
Short-term amp. stability	±0.5	< ±0.1	%
Long-term amp. Stability (drifts)	±0.5	< ±0.5	%
Linearity		100 app.	%
Dynamic range		> 30	dB
Phase margin		±55	°
Max. reflected power		<1	%

(f_{RF} = 352 MHz, pulse rate = 50 Hz, pulse width = 1.5 ms)



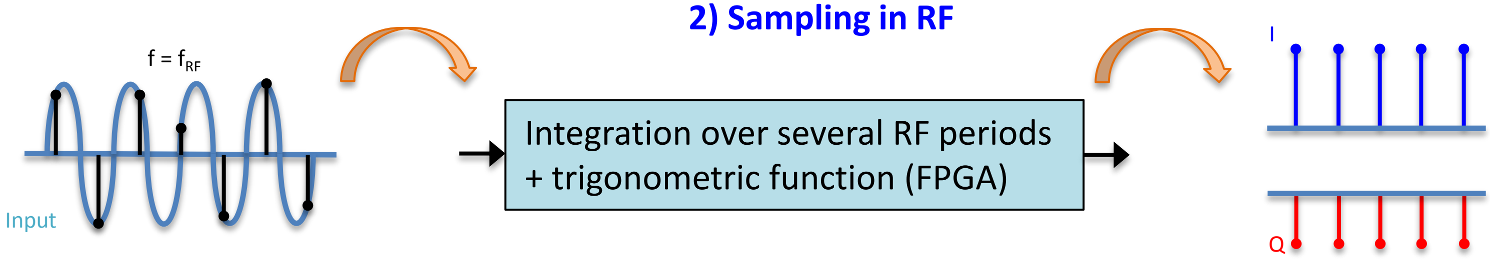
RF conversion to digital I/Q

1) Sampling in IF



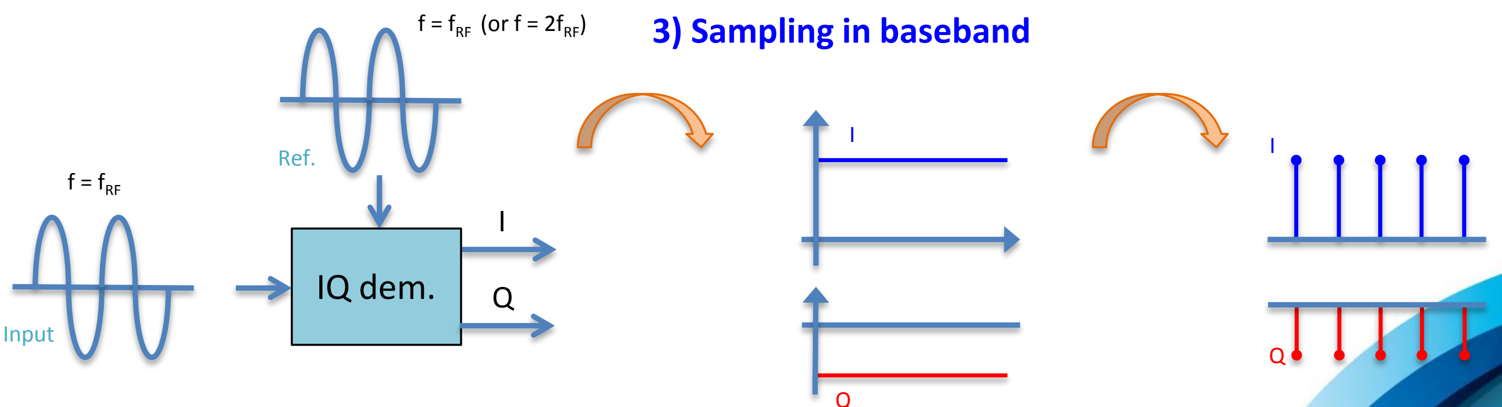
- Widely used for DLLRF
- Needs several clocks
- Clocks must be in tight synchronization (PLL or DDS)
- Not reconfigurable

2) Sampling in RF



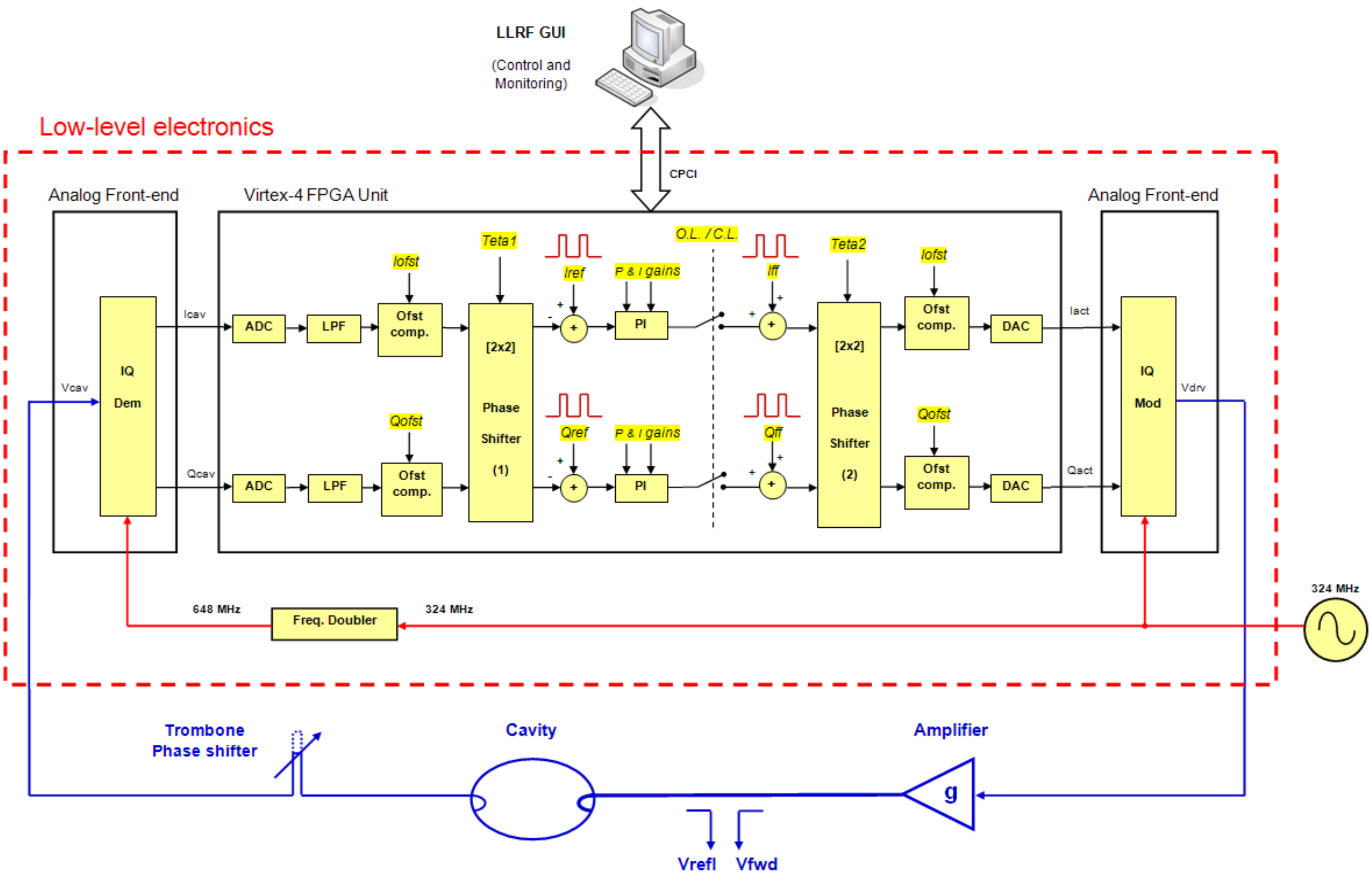
- Recently tested for the ILC
- Improves measurement bandwidth and eliminates errors of RF-IF conversion
- Needs precise clock generation
- Needs very fast ADC and FPGA with extremely low clock jitter

3) Sampling in baseband

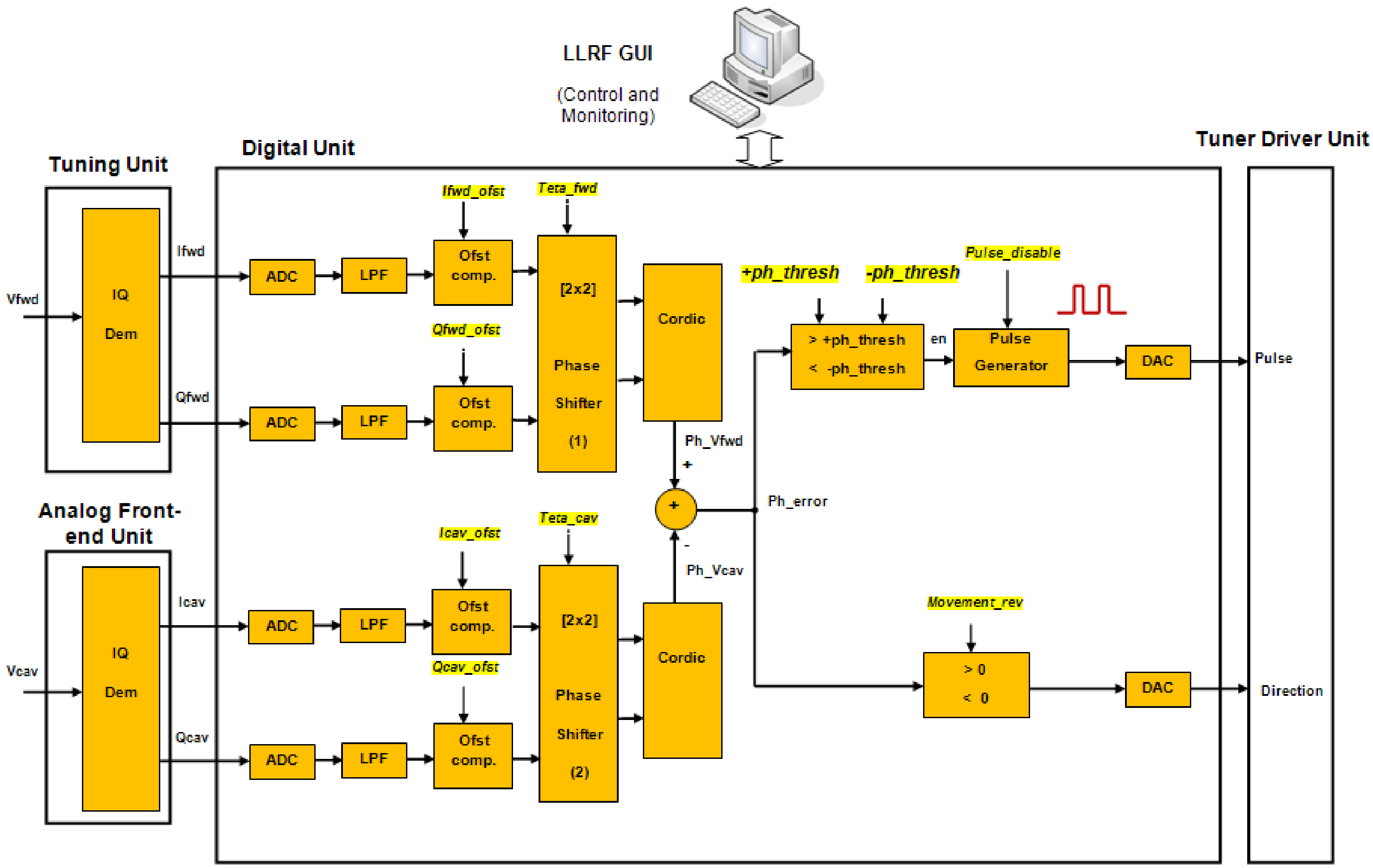


- Easy to implement
- Reconfigurable
- Very simple timing
- Needs 2 ADCs per RF measurement
- IQ dem. errors should be compensated to improve accuracy

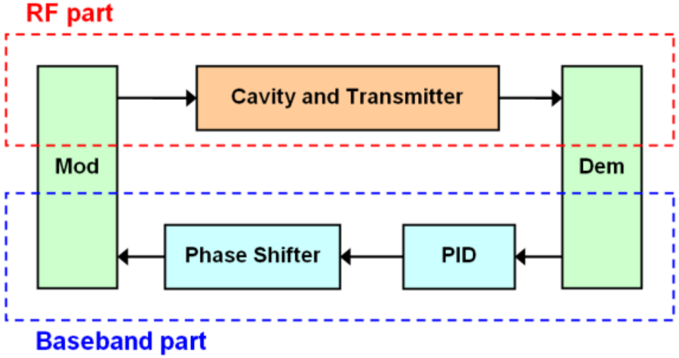
DLLRF design (amp/ph loops)



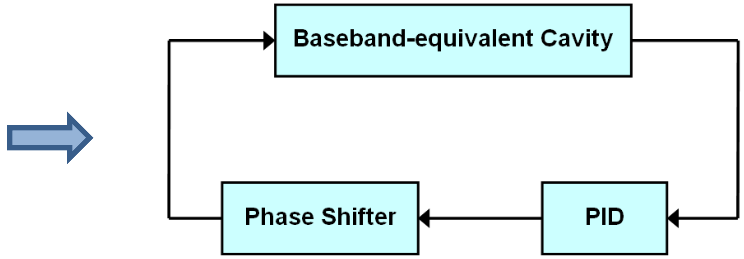
DLLRF design (tuning loop)



Baseband-eq. model of the RF cavity



Conventional model of the LLRF Feedback loop



Baseband-eq. model of the LLRF Feedback loop

- A conventional time-domain simulation of the LLRF feedback loop is usually very slow.
- The simulation speed is low because a very small sample time is normally needed for the simulation of the RF signals. On the other hand, the baseband signals have a relatively slow variation with time because of the high cavity quality factor.
- This drawback is resolved in the ADS software from Agilent which only simulates the envelope of RF signals (without RF carrier), hence significantly improves the simulation speed.
- A similar method is presented here for translating the cavity resonant frequency to baseband, leading to a baseband-equivalent model for the LLRF feedback loop with a much higher simulation speed compared to the conventional methods.

Baseband-eq. modeling of the RF cavity (cont.)

$$\acute{V}_{total}(s) = \left(2\acute{I}_{amp}(s) - \acute{I}_{beam}(s)\right) \frac{\beta Z_0 L.s}{RLC.s^2 + L(\beta+1).s + R}$$

$$\begin{aligned} \acute{V}_{total}(t) &= \left[\acute{V}_r(t) + j\acute{V}_i(t)\right].e^{j\omega_{RF}t} \\ \acute{I}_{total}(t) &= \left[\acute{I}_r(t) + j\acute{I}_i(t)\right].e^{j\omega_{RF}t} \end{aligned}$$

$$\frac{d^2\left[(\acute{V}_r + j\acute{V}_i).e^{j\omega_{RF}t}\right]}{dt^2} + \frac{(\beta+1)\omega_0}{Q_0}\frac{d\left[(\acute{V}_r + j\acute{V}_i).e^{j\omega_{RF}t}\right]}{dt}$$

$$+ \quad {\omega_0}^2(\acute{V}_r + j\acute{V}_i).e^{j\omega_{RF}t} = \frac{\beta Z_0 \omega_0}{Q_0}\frac{d\left[(\acute{I}_r + j\acute{I}_i).e^{j\omega_{RF}t}\right]}{dt}$$

$$\acute{V}_r(s) = \acute{I}_r(s)\frac{\beta Z_0 \omega_{RF}}{2Q_0.s + (\beta+1)\omega_{RF}} - \acute{V}_i(s)\frac{(\beta+1).s + 2Q_0(\omega_0 - \omega_{RF})}{2Q_0.s + (\beta+1)\omega_{RF}}$$

$$\acute{V}_i(s) = \acute{I}_i(s)\frac{\beta Z_0 \omega_{RF}}{2Q_0.s + (\beta+1)\omega_{RF}} + \acute{V}_r(s)\frac{(\beta+1).s + 2Q_0(\omega_0 - \omega_{RF})}{2Q_0.s + (\beta+1)\omega_{RF}}$$

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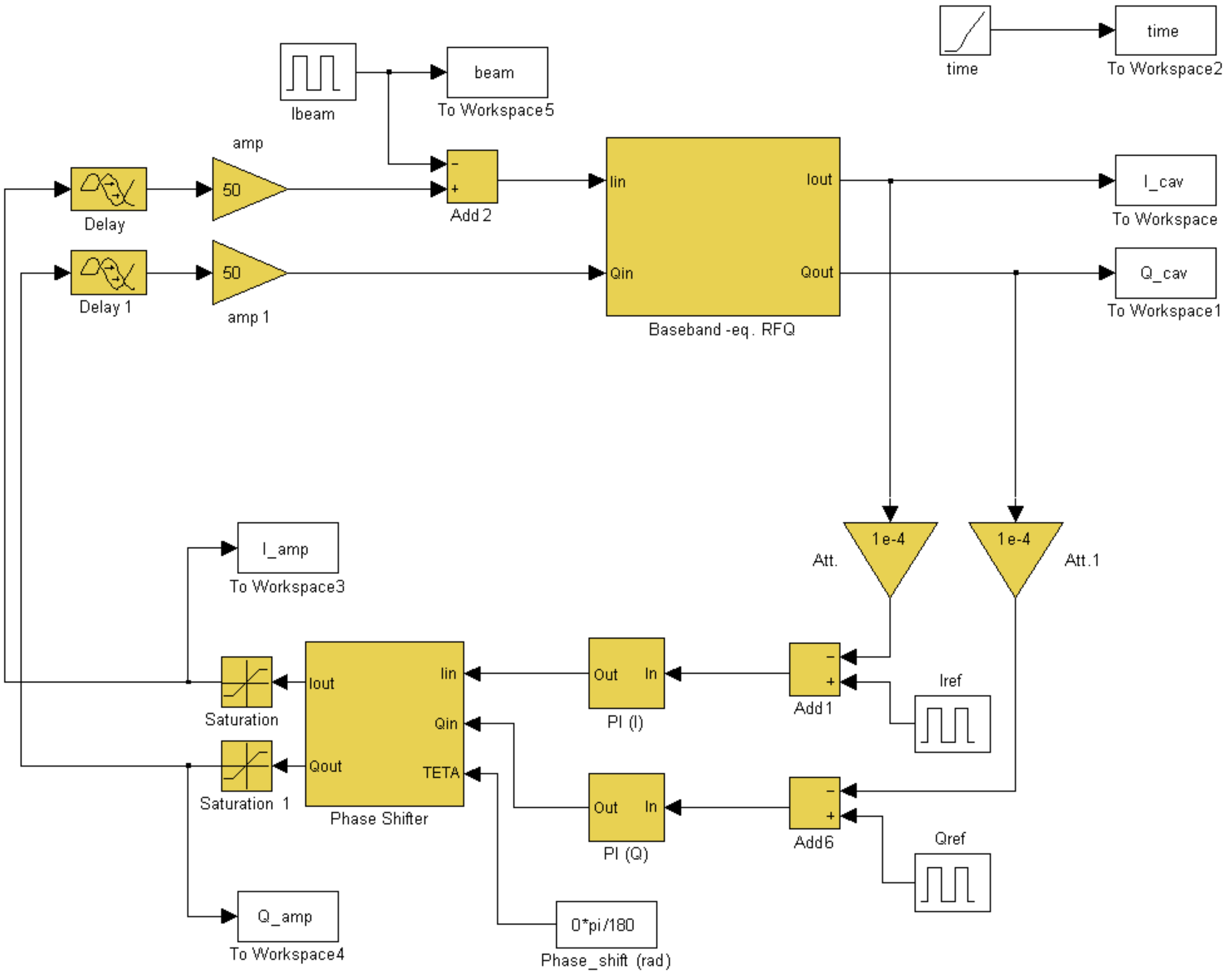
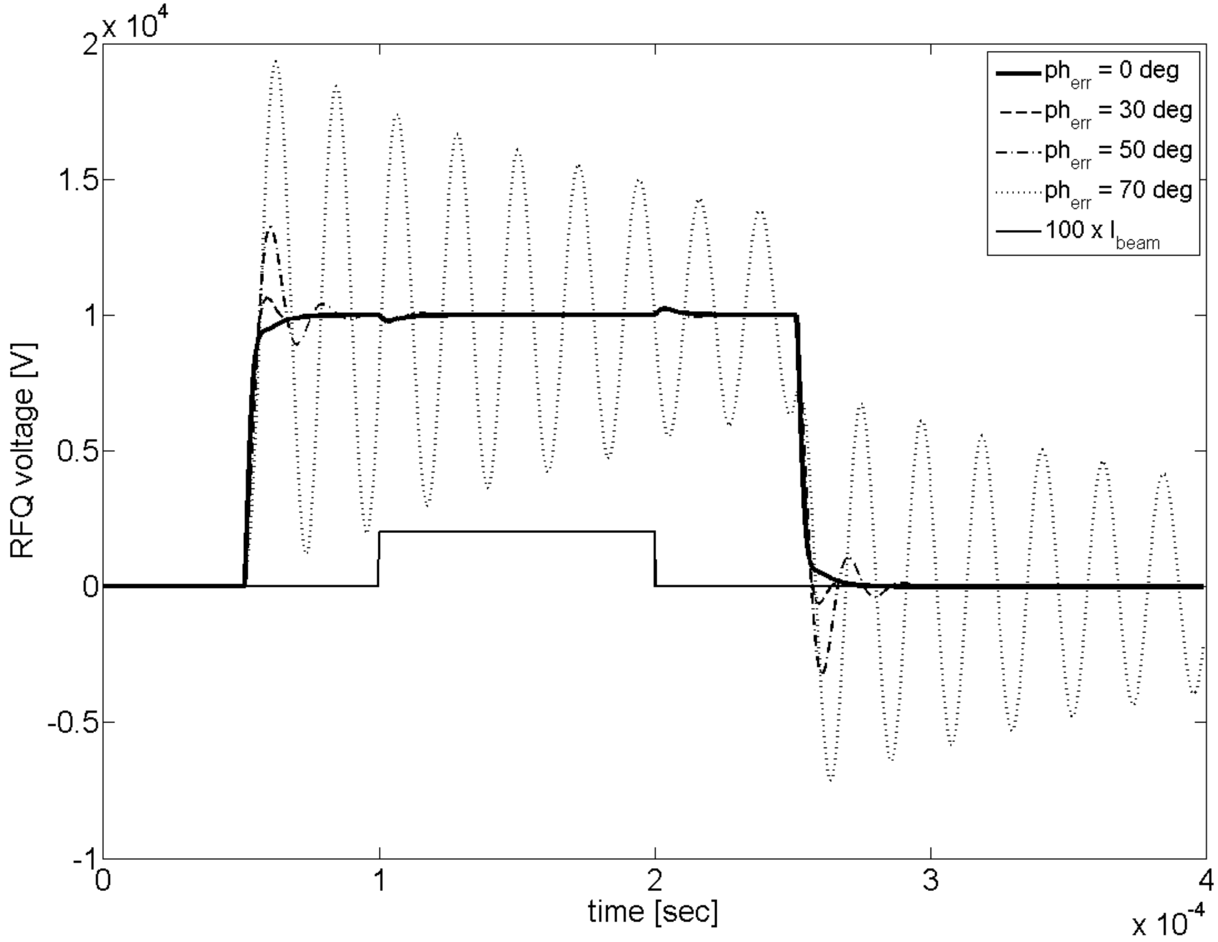
Baseband-eq. model of the LLRF loop



Baseband-eq. simulation of the LLRF loop



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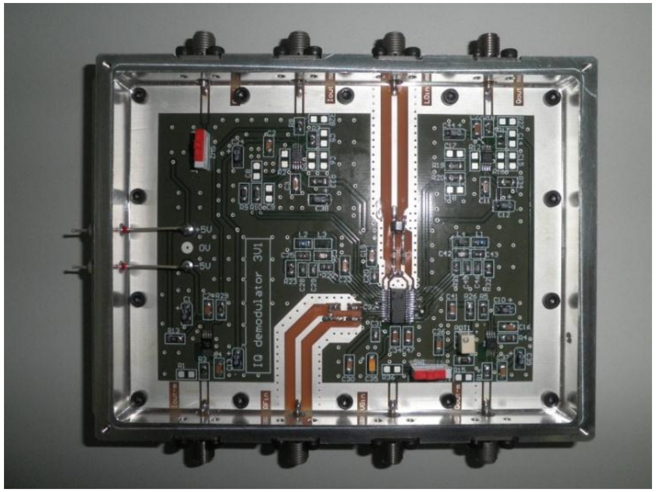
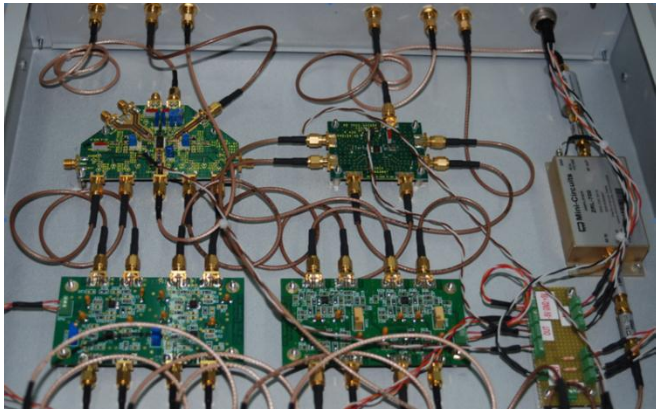
Implementation



In-house developed IQ dem.



Analog front-end unit

DLLRF prototype (UPV/EHU RF lab)

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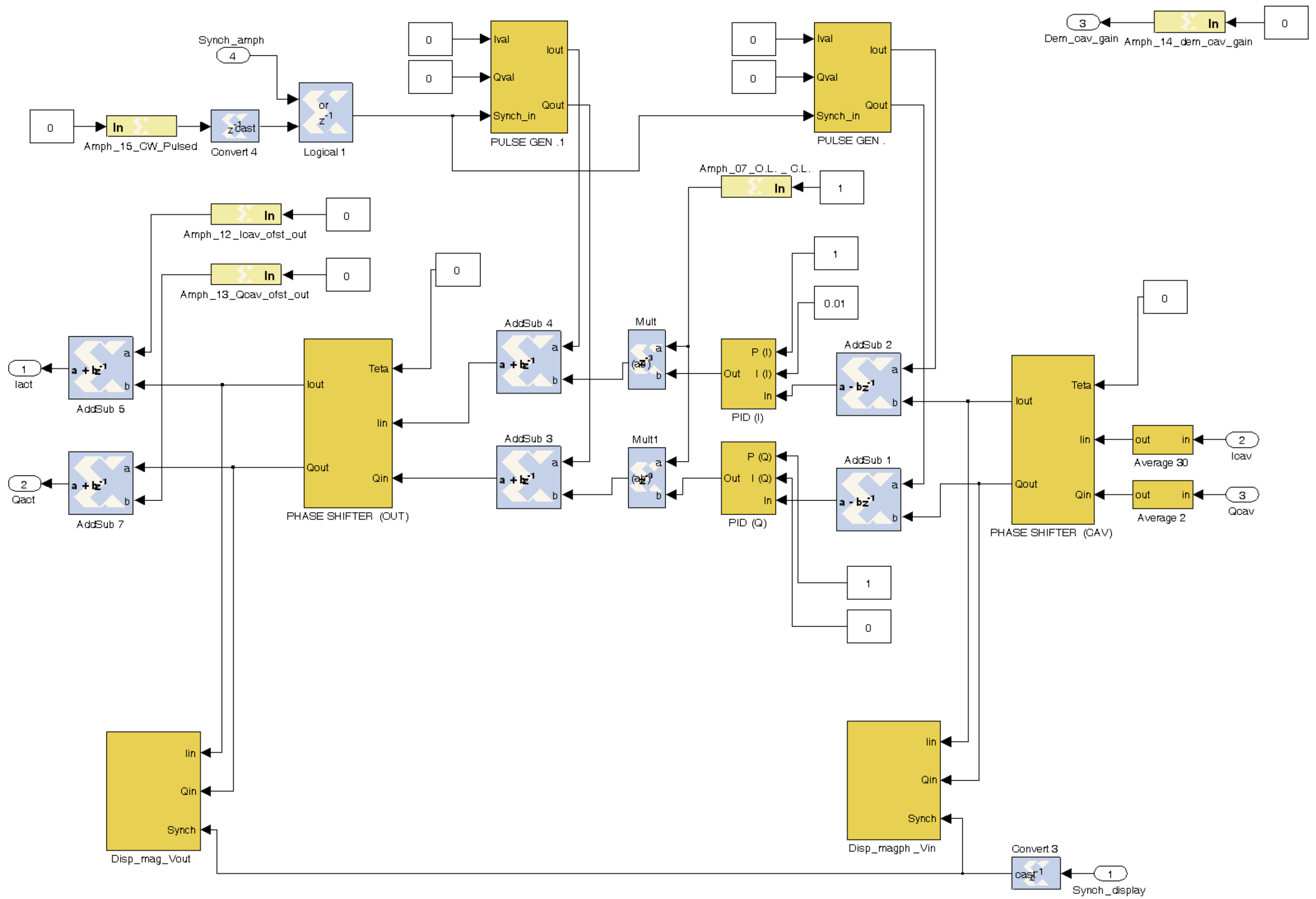
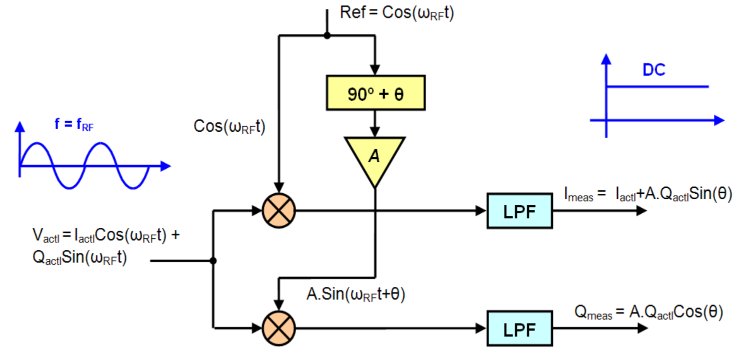
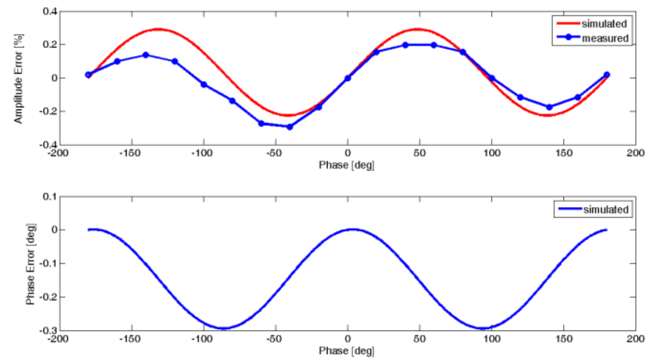
FPGA programming (model-based)



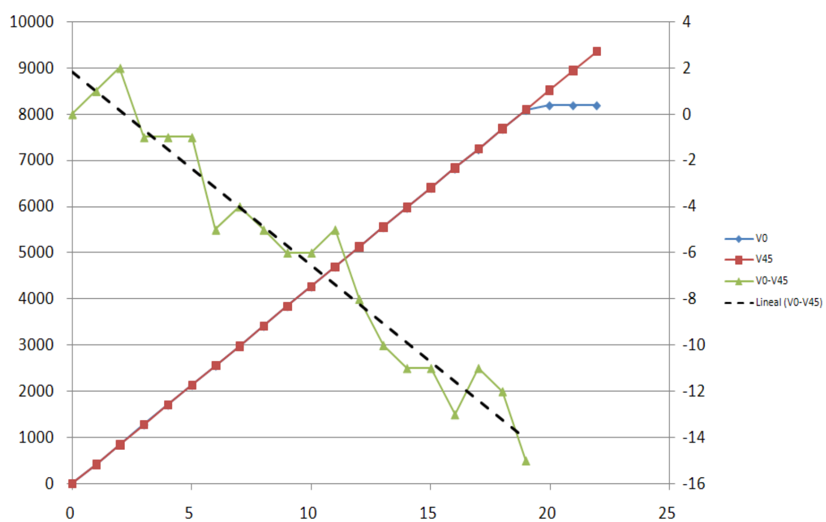
IQ dem. error compensation



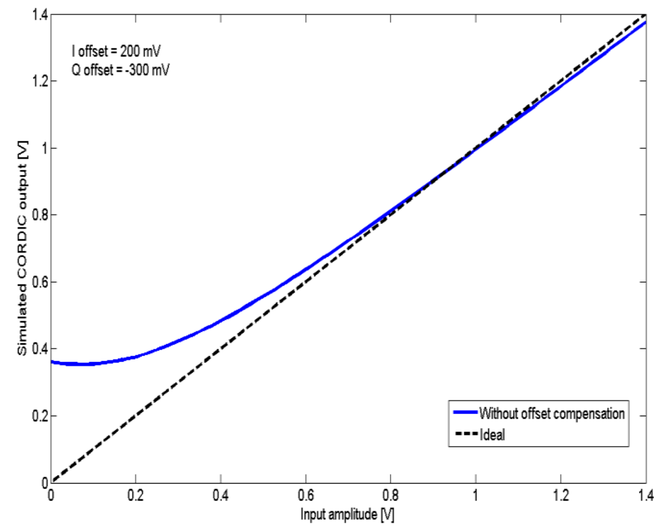
IQ dem. schematics



Amp/ph errors due to gain/ph imbalances



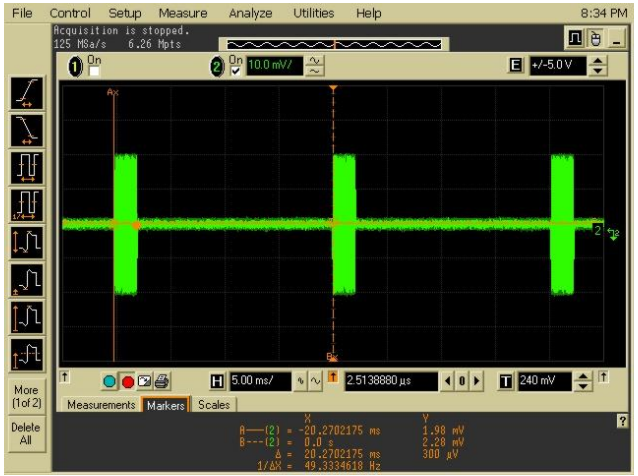
IQ dem. linearity with input phase of 0° and 45°



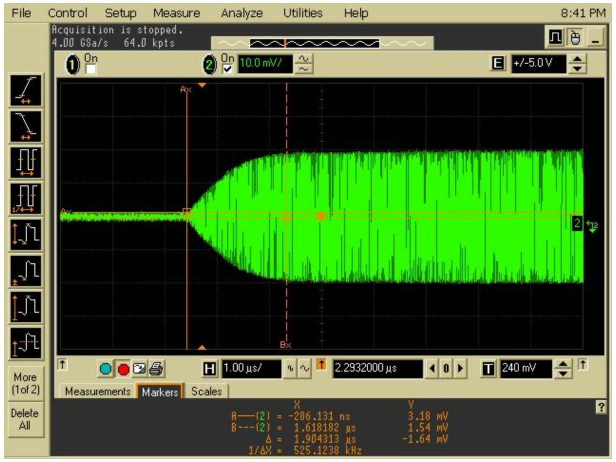
IQ dem. Linearity due to I/Q DC offsets

Phys. Rev. ST Accel. Beams **14**, 052803 (2011)

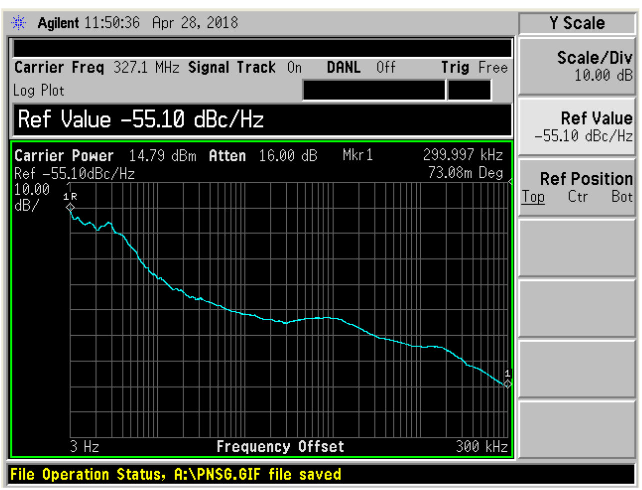
DLLRF experimental results (pill-box cavity)

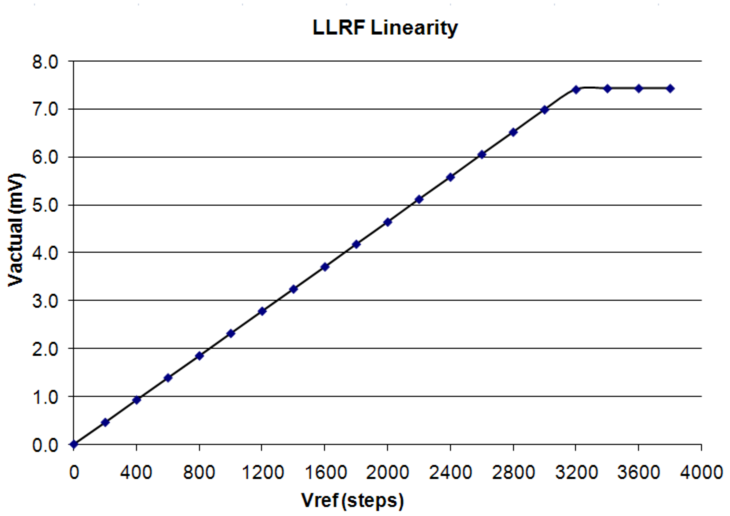


Settling time = 1.9 µs

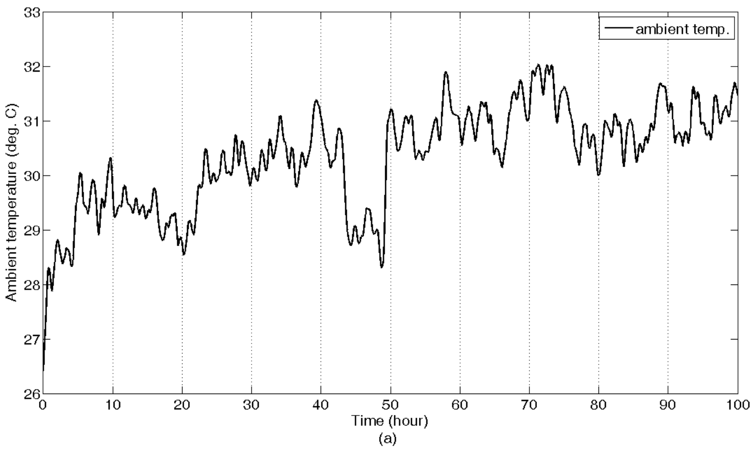


Phase noise = 0.074°

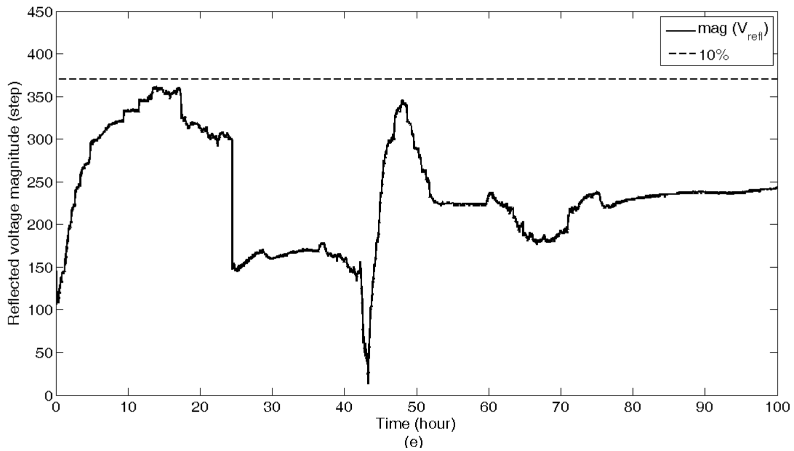




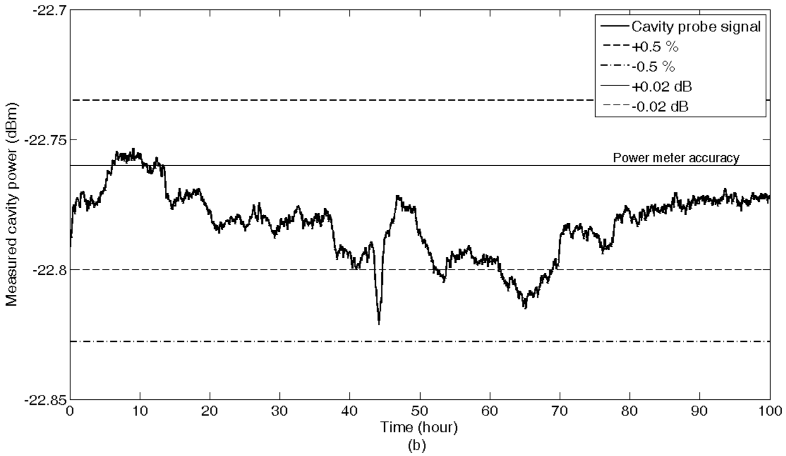
DLLRF experimental results (100-h tests)



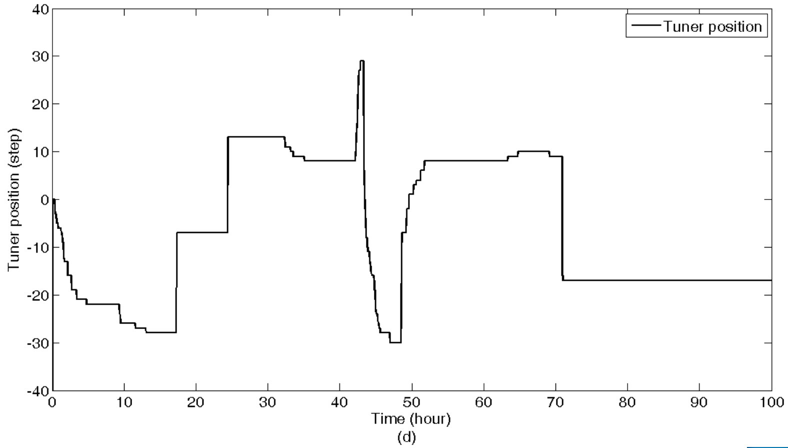
Ambient temperature



Reflected voltage



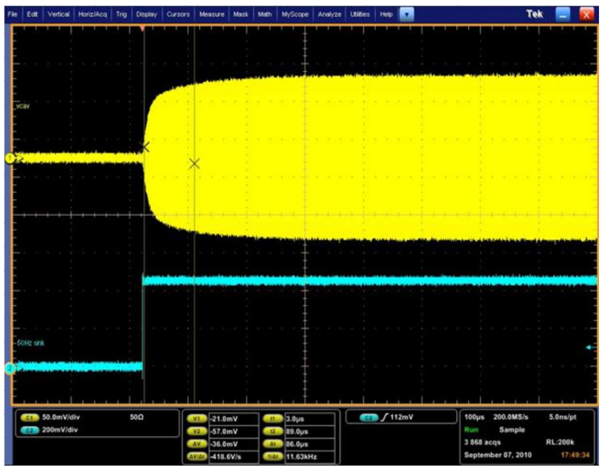
Cavity voltage

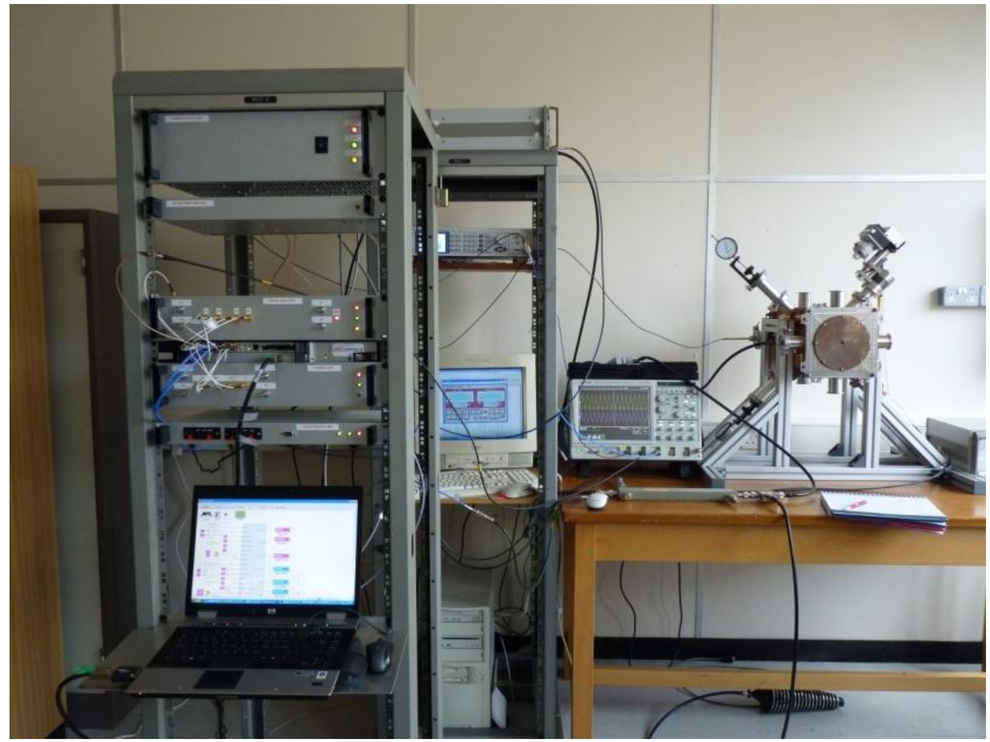


Tuner position

DLLRF tests with an RFQ copper model

Settling time < 100 µs





LLRF test setup (Imperial College London)

The test results with the RFQ cold model were very similar to the ones from the pillbox cavity except the settling time which was much larger due the RFQ quality factor.

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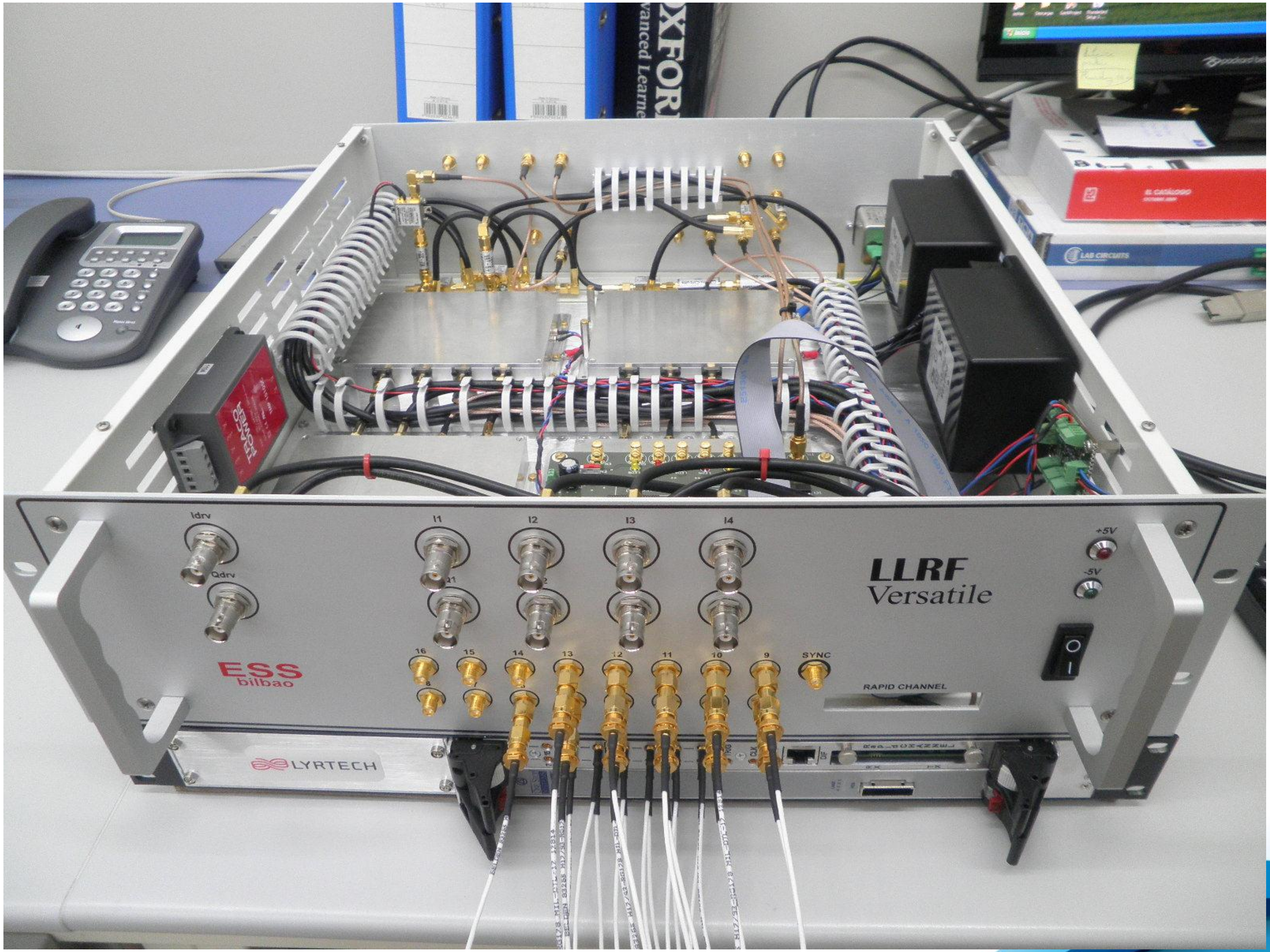
Final version of the DLLRF system



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