sLHC

Update on SPL LLRF activities

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Outline

Introduction to LLRF simulations, aims

LLRF test bed with super conducting cavity at CEA Saclay

Conclusions

LLRF (Low Level RF System)

challenges for the LLRF:

- stabilize cavity field in amplitude and phase with minimal power overhead
- keep system stable when pulsing at a high repetition rate (SPL 50 Hz)
- Lorentz-Force detuning
- single klystron for multiple cavities

methods:

- use of feedback and feed forward, learning algorithms
- Piezo tuner to counter-act the Lorentz force detuning
- software controlled phasing of cavities

available infrastructure:

- 704 MHz power test stand + cryo infrastructure at CEA Saclay
- β=0.5 cavities and tuners built by CEA and INFN (Milano) under EU-FP6
- high power coupler developed at CEA, Saclay
- LLRF system prototype work on CERN LHC (+LINAC4) LLRF experience

Aims of LLRF simulations

- Determine power overhead using realistic parameters
- Test feedback algorithms
- Investigating the impact of errors:

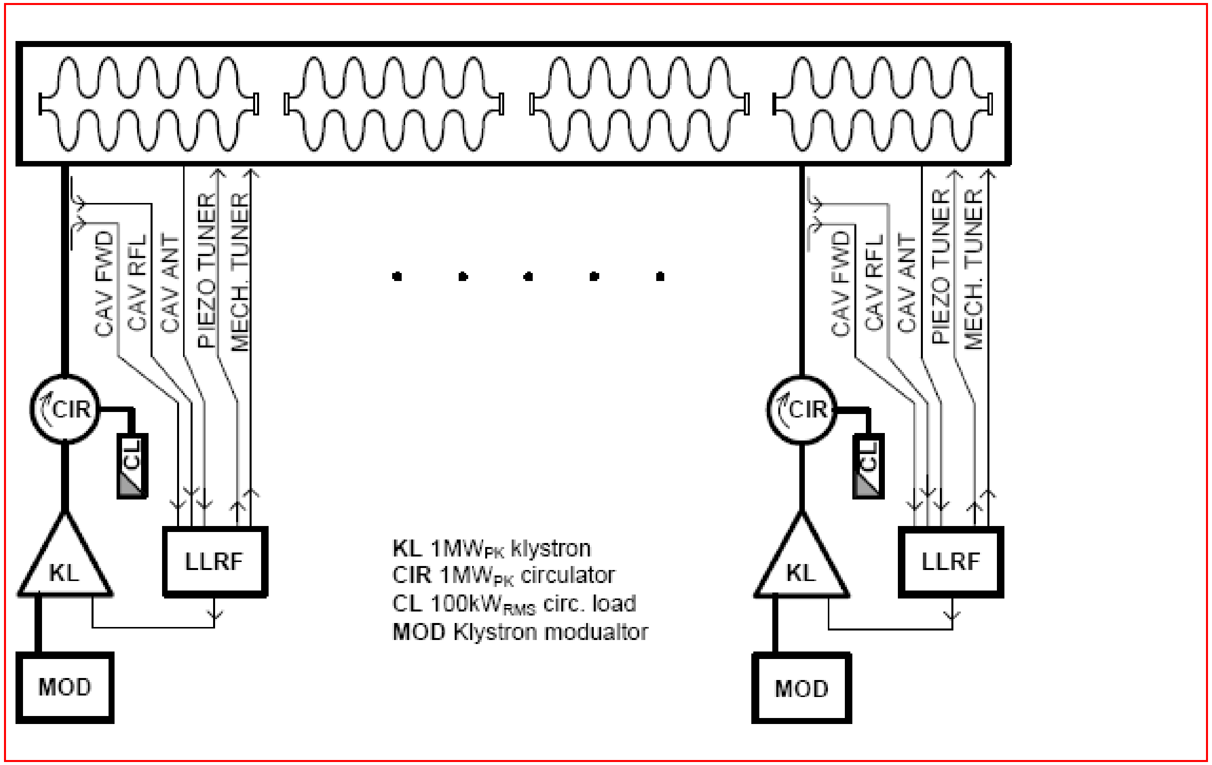
  beam current variation (along pulse and pulse-to-pulse)

  Q_{ext} variations pulse-to-pulse

  Lorentz force detuning coefficient variations, cavity to cavity

  → use error files to fit model, use model to create sample SPL machines to study the impact (full linac beam dynamics simulation, P. Posocco)

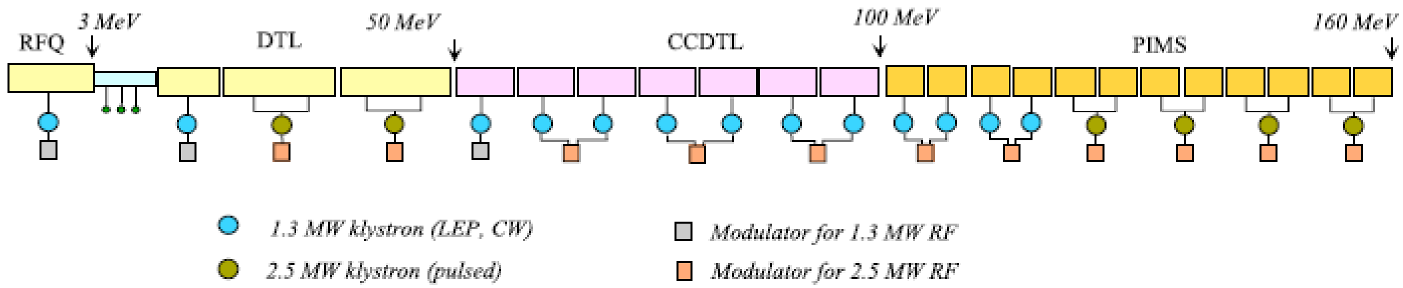
Likely choice for high energy part of HPSPL



1 klystron per cavity: individual control possible without RF vector modulator
Disadvantage: Many klystrons required
Advantage: Easiest for control, considered adopted solution for low energy part
Individual Lorentz-force detuning compensation with a fixed pulse on the piezo or an adaptive feed forward (pulse-to-pulse)

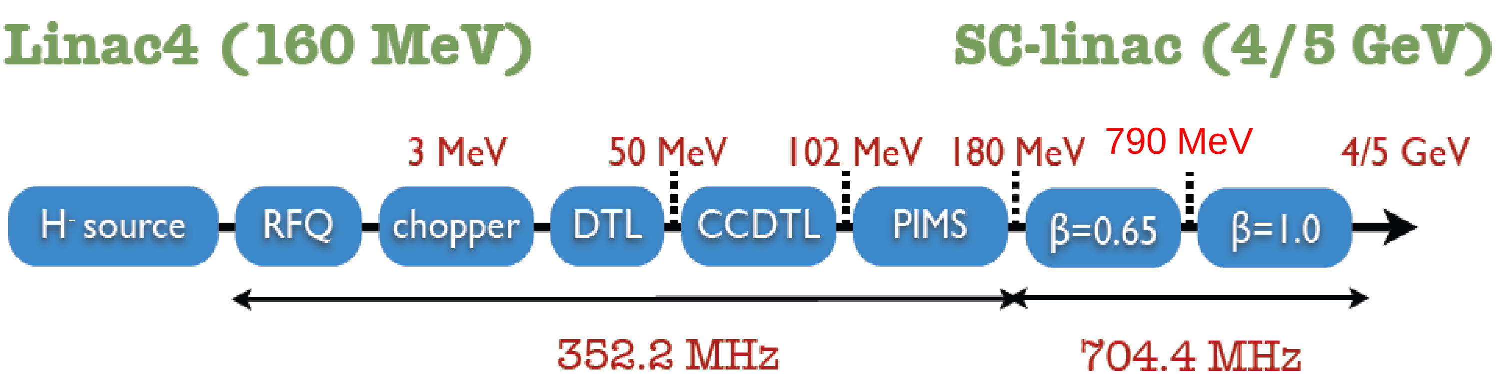
LINAC4 and SPL

Linac4 updated design



$1x10^{14}$ H- / per pulse, 2 Hz repetition rate

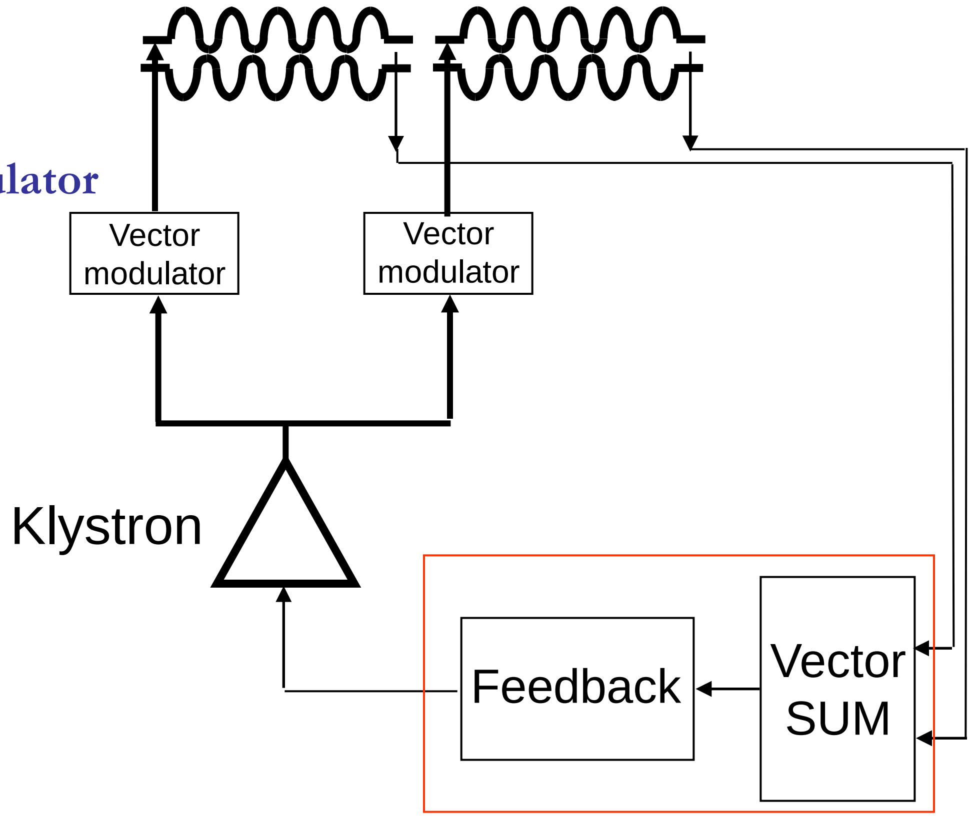
Future extension for SPL, 50 Hz pulsing repetition rate;
for PS2: $1.5x10^{14}$ H- / per pulse (1.2 ms)



Source: LINAC4 / SPL web pages

Layout with 2 cavities per klystron

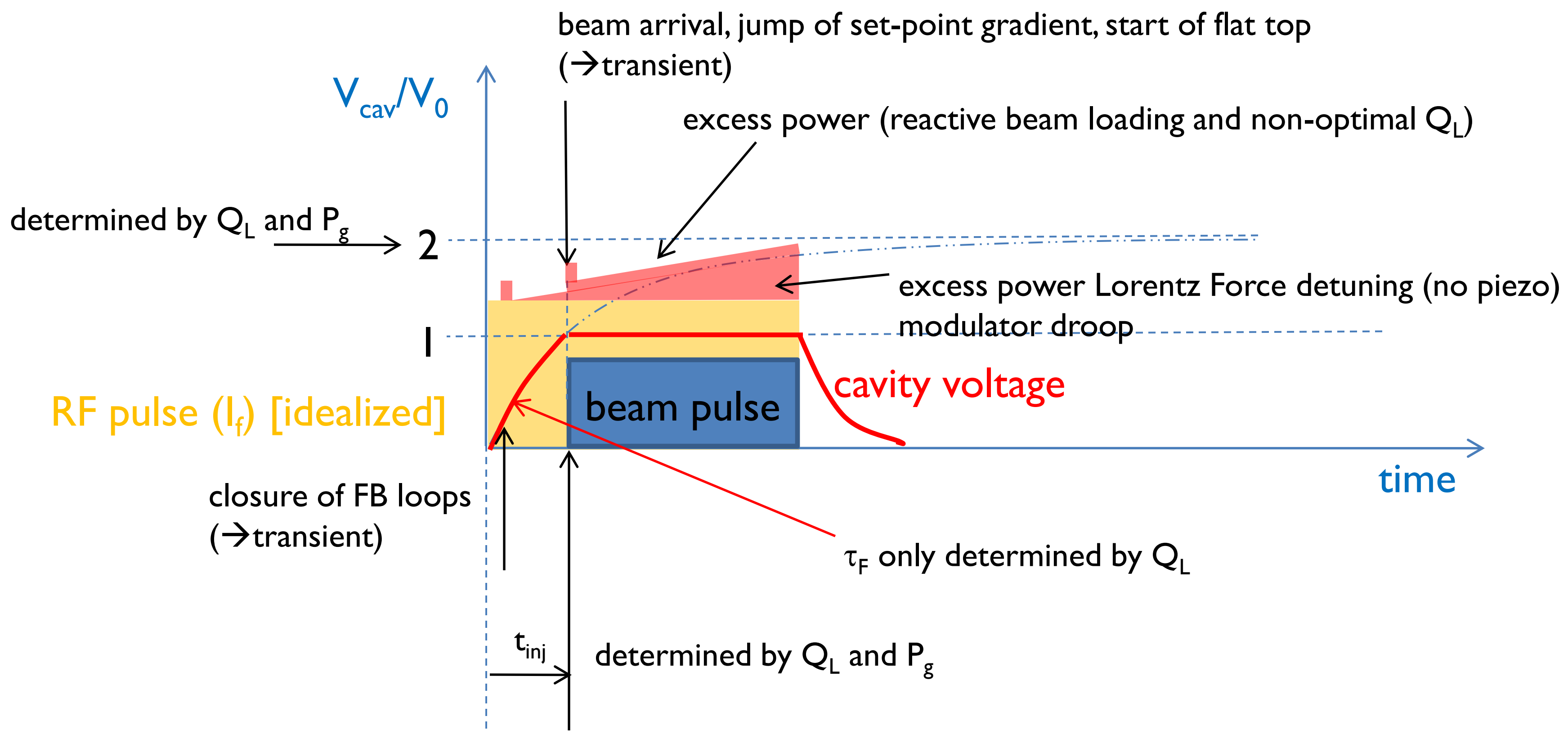
optional
RF vector modulator



Simulation program developed for LLRF simulations, user interface for 1, 2 and 4 cavities per klystron, see presentation by M. Hernandez Flano

Principle of pulsed operation

SPL (with beam)



Parameters for 40 mA operation, optimized coupling for zero reflected power during beam pulse

frequency:	704.4 MHz
accelerating gradient of β=1 cavities:	25 MV/m
length of cavity L=β5λ/2:	1.06 m
cavity accelerating voltage for β=1	26.5 MV
synchronous phase angle ϕ_s	15 degrees

power delivered to beam $$P_b = I_b \cdot V_{acc} \cdot \cos\varphi_s = 1.0239 \text{ MW}$$

zero refl. power during beam pulse $$Q_{ext} \approx Q_L = \frac{V_{acc}}{(R/Q) I_b \cos\varphi_s} = 1.3064 \times 10^6$$

filling of cavity $$V(t) = 2V_0 \left(1 - e^{-t/2\tau_F}\right) = 2V_0 \left(1 - e^{-t/\tau_V}\right)$$

filling time $$\tau_V = 2\tau_F = \frac{2Q_L}{\omega_0} = 0.5903 \text{ ms}$$

beam injected at $$t_{inj} = \tau_V \ln 2 = \tau_F \ln 4 = 0.4092 \text{ ms}$$

forward power for filling 1.0239 MW

$$P_{fwd} = \frac{V_{fwd}^2}{(R/Q) Q_L}$$

$$V_{acc} = V_0 = V_{fwd}$$

Parameters for 20 mA operation, with optimized coupling for zero reflected power during 40 mA beam pulse

frequency:	704.4 MHz
accelerating gradient of β=1 cavities:	25 MV/m
length of cavity L=β5λ/2:	1.06 m
cavity accelerating voltage for β=1	26.5 MV
synchronous phase angle ϕ_s	15 degrees

power delivered to beam

$$P_b = I_b \cdot V_{acc} \cdot \cos\varphi_s = 512\ \text{kW}$$

chosen (optimal value for 40 mA)

$$Q_{ext} \approx Q_L = 1.3064 \times 10^6$$

reflected current in steady state with beam

$$I_r = \frac{V_{acc}}{(R/Q)} \frac{1}{Q_{ext}} - I_b \cos\varphi_s = 19.3\ \text{mA}$$

reflected power in steady state with beam

$$P_{refl} = \frac{1}{4}(R/Q) \cdot Q_{ext} \cdot |I_r|^2 = 64\ \text{kW}$$

forward current in steady state with beam

$$I_f = \frac{V_{acc}}{(R/Q)} \frac{1}{Q_{ext}} + I_b \cos\varphi_s = 58.0\ \text{mA}$$

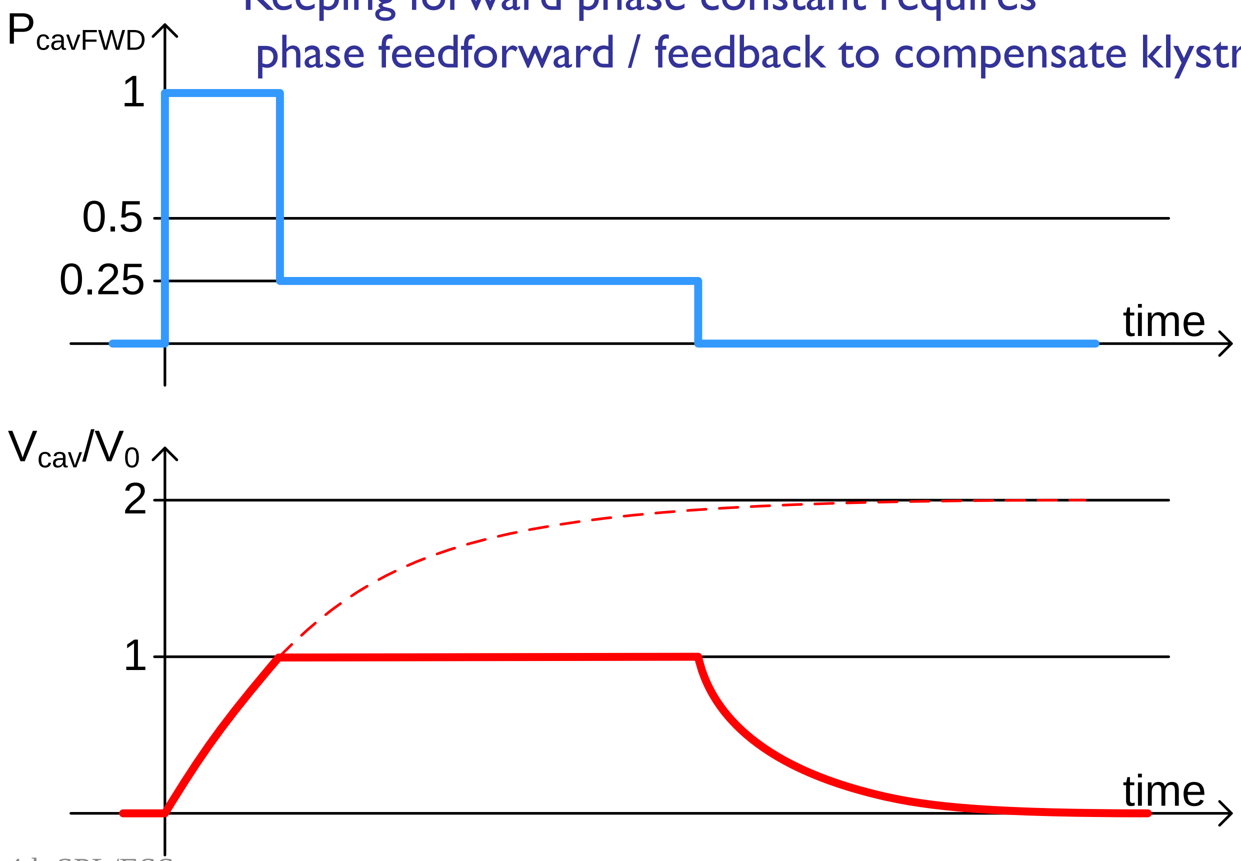
forward power in steady state

$$P_{fwd} = \frac{1}{4}(R/Q) \cdot Q_{ext} \cdot |I_f|^2 = 576\ \text{kW}$$

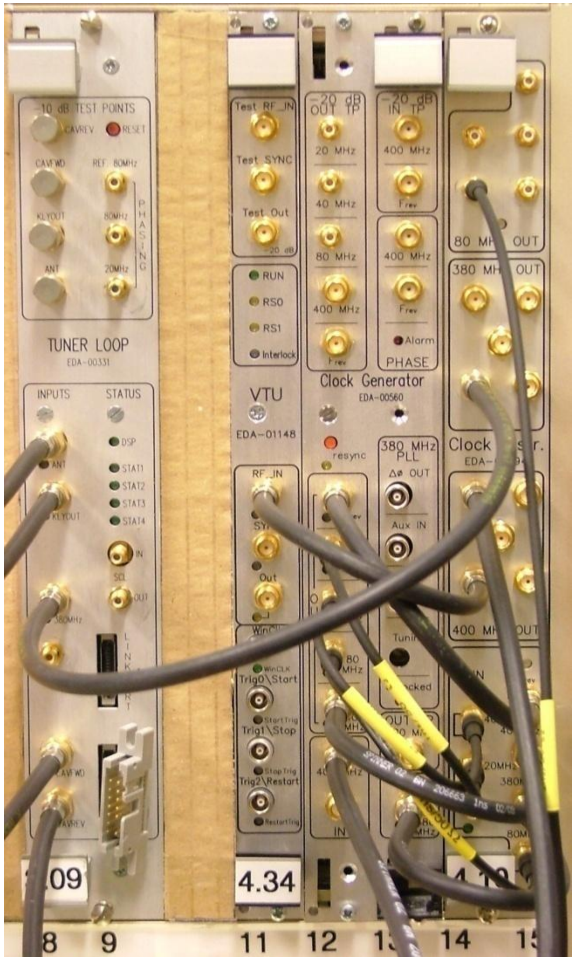
Typical waveforms for tests without beam

- Cavity filling transient without beam for test-stand

Keeping forward phase constant requires
phase feedforward / feedback to compensate klystron phase change



Measurement set-up
for tuner characterization and control



modified LHC hardware:
four channels analog down conversion to IF

f_{RF} = 704.4 MHz

f_{LO} = (39/40) f_{RF} = 686.79 MHz

f_{IF} = f_{RF} - f_{LO} = 17.61 MHz

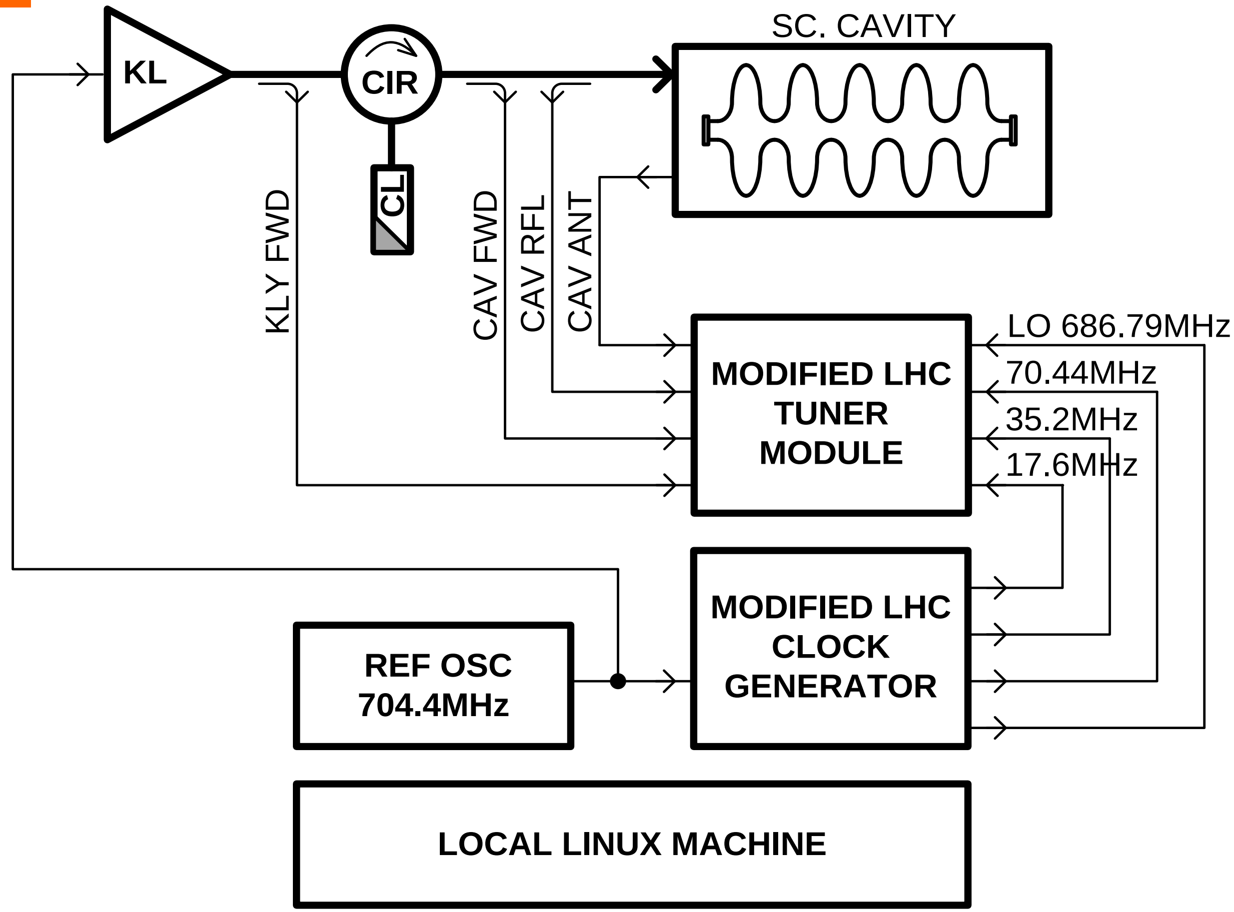
digital IQ demodulation with
sampling at 4xf_{IF} = 70.44 MHz

rate of (I,Q) samples: 17.61 MS/s

actual bandwidth lower and
depending on desired precision

Next steps → evolution to full LLRF system

Test-stand set-up



LO frequency 39/40*RF

Observation memory 128k data points for each of the four channels

Max. observation rate 35.22 MSps and decimation in powers of two

full rate→ resolution 28.4 ns/point, record length 3.7 ms

down to a resolution of 0.93 ms/point, record length 122 s

Calculating the tune state of the cavity from measurement

Tune state of the cavity **without beam** can be calculated from the cavity forward and antenna signals, a calibration is needed

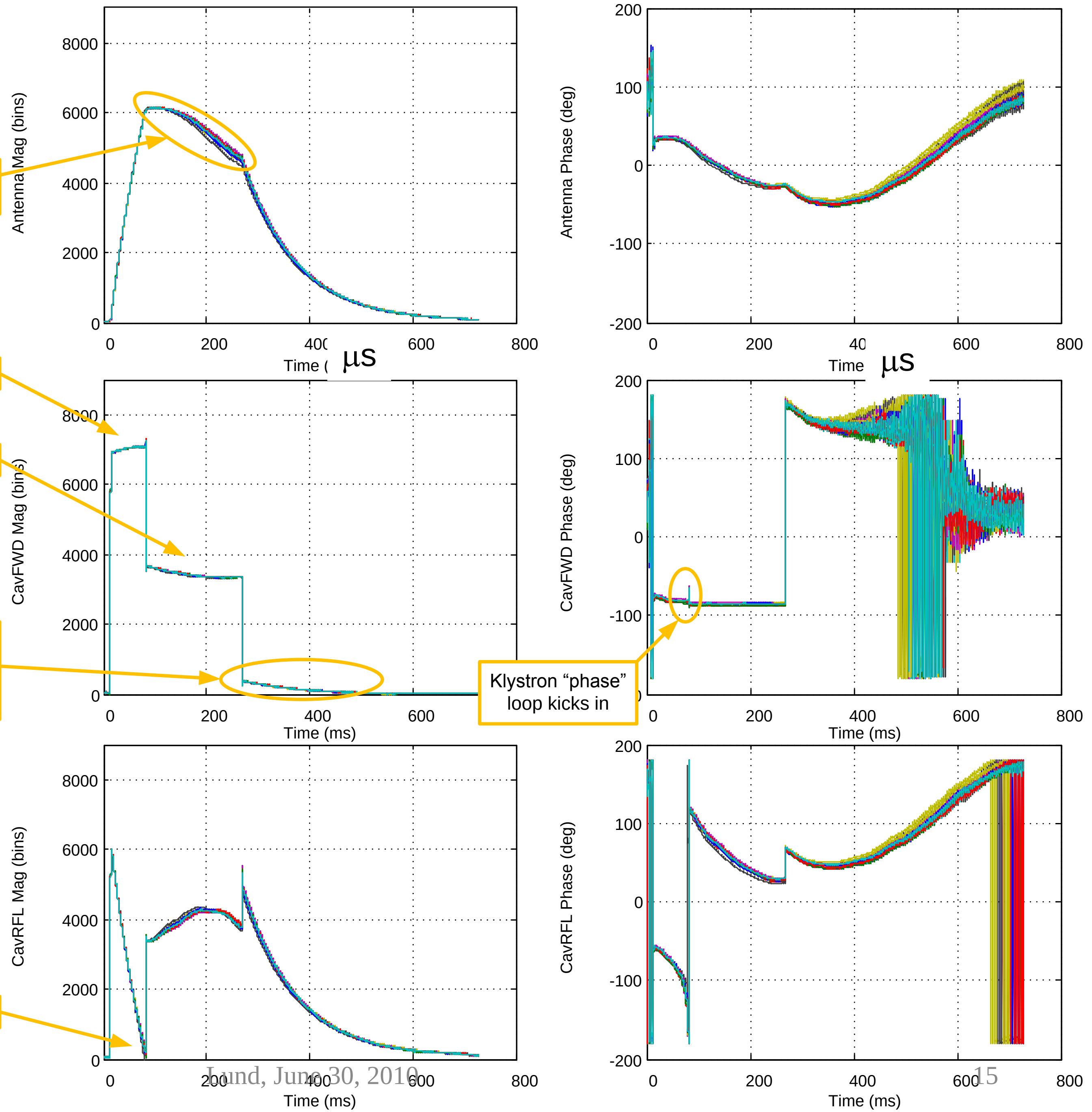
$$\Delta\omega = \frac{d\phi_{ANT}}{dt} - \omega_{12}\frac{V_{FWD}}{V_{ANT}}\sin(\phi_{FWD} - \phi_{ANT})$$

Term1 - cavity phase

Term2 - cavity with RF drive

Preliminary results

- Acquired data showing a typical linac RF pulse
- The beam was simulated by lowering the forward power to ¼ nominal
- A set of 25 measurements showing pulse reproducibility



D.Valuch

Test periods at CEA with CERN participation

date	cryo	rep rate	RF pulse /ms	filling	flat-top	cavity field	filling time
07.10.2009	4.2 K	5 Hz	0.05-0.2	variable			
08.10.2009	4.2 K	5 Hz	1	100 kW	25 kW		
09.10.2009	2 K	5 Hz to 1 Hz	2	80 kW	15 kW		
12.10.2009	2 K	1 Hz	2	variable			
13.10.2009	2 K	1 Hz	2	variable			
18.11.2009	2 K	2 Hz	2	147 kW	38 kW	15-16 MV/m	
25.01.2010	4.2 K	8.33 Hz	cond.				
26.01.2010	2 K	8.33 Hz	2	62 kW	15 kW		
27.01.2010	2 K	25 Hz to 50 Hz	2	125 kW	31 kW	13.3 MV/m	0.6 ms

next steps:

calibration required with cw excitation in order to calculate exact detuning

address circulator matching and coupler directivity

improve the LLRF set-up to acquire full time period of 20 ms between pulses

Conclusions

simulations of LLRF system important in the design stage (advancement see next talk)

parameter variations will have an impact on required power overhead and performance

test stands indispensible for the development of the LLRF systems, plans exist to build a test stand at CERN for 704 MHz, currently collaboration with CEA Saclay

having a test stand at CERN would be very important to build up momentum at CERN in the area of LLRF developments