SOLEIL LLRF and feedback systems

- SOLEIL main parameters
- Booster and storage ring low level RF system
- New digital Booster LLRF system under development
- Digital LLRF prototype for storage ring
- Microphonic measurements
- Direct and digital feedback simulation model
- Transverse bunch by bunch feedback operation

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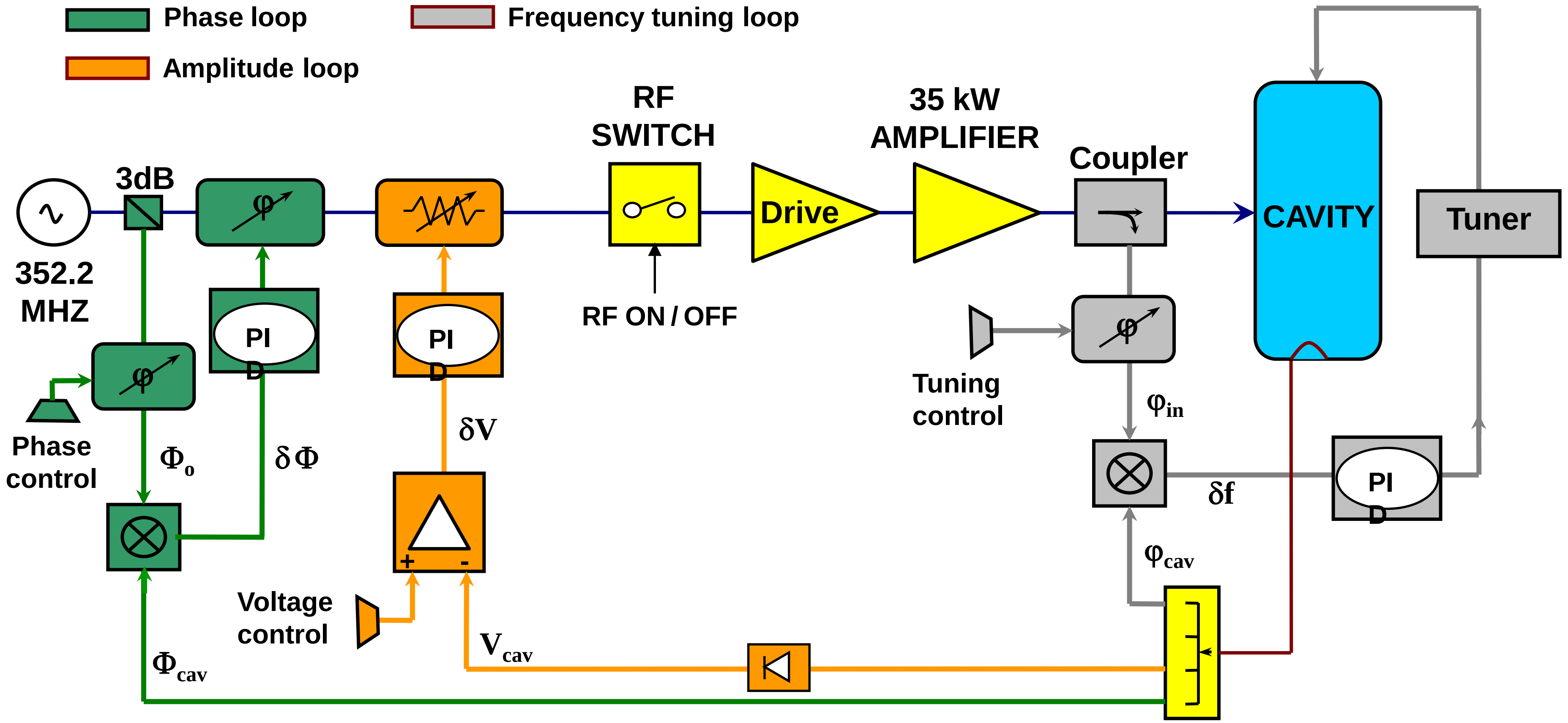
SOLEIL main parameters

	2 (1) cryomodules
RF frequency (MHz)	352.202
Harmonic number	416
Nominal energy (GeV)	2.75
Energy loss per turn (keV)	1050 (950)
Momentum compaction factor	$4.38\ 10^{-4}$
Energy damping parameter, D	$6.88\ 10^{-4}$
Cavity loaded quality factor	10^{5}
R/Q per cavity (Ohm)	45
Beam current (mA)	500 (300)
Total cavity voltage (MV)	4 (3)
Synchronous phase (°)	73.6 (71.5)

Booster LLRF system

3 conventional « slow » control loops for the frequency, amplitude & phase
remake of a LURE design adapted to the SOLEIL needs



	Amplitude	Phase	Frequency
Accuracy	0.25 %	0.4	30 Hz
3 dB BW	3 kHz	1.5 kHz	5 Hz

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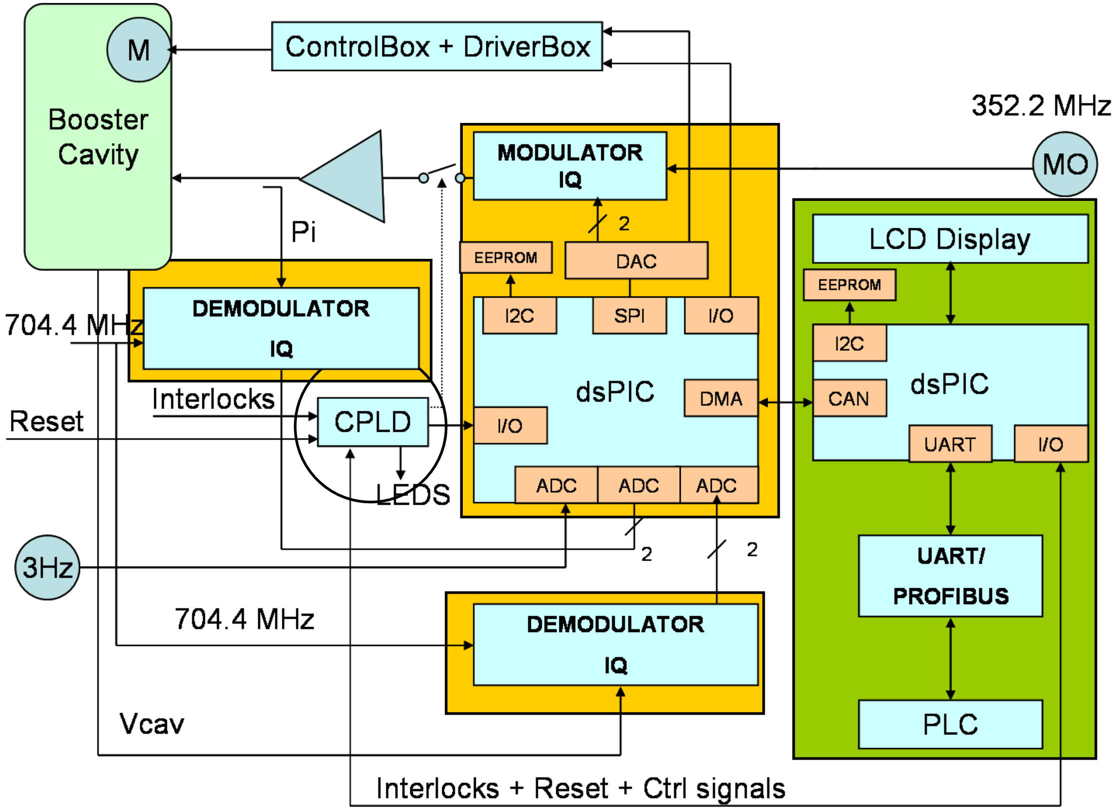
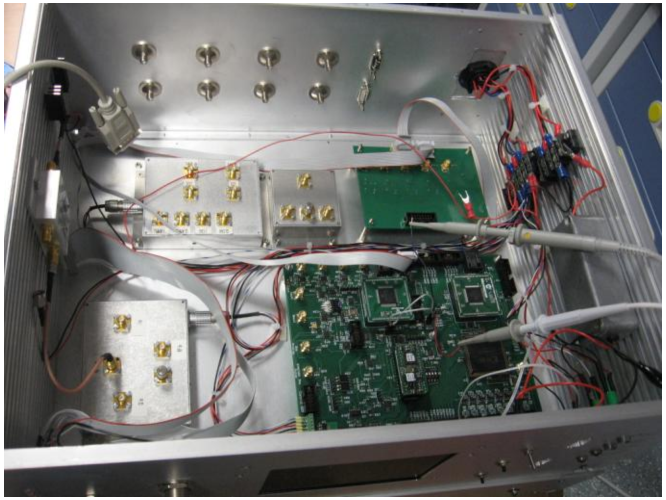
New digital LLRF Booster system

Under development





Actual stage: hardware Debug

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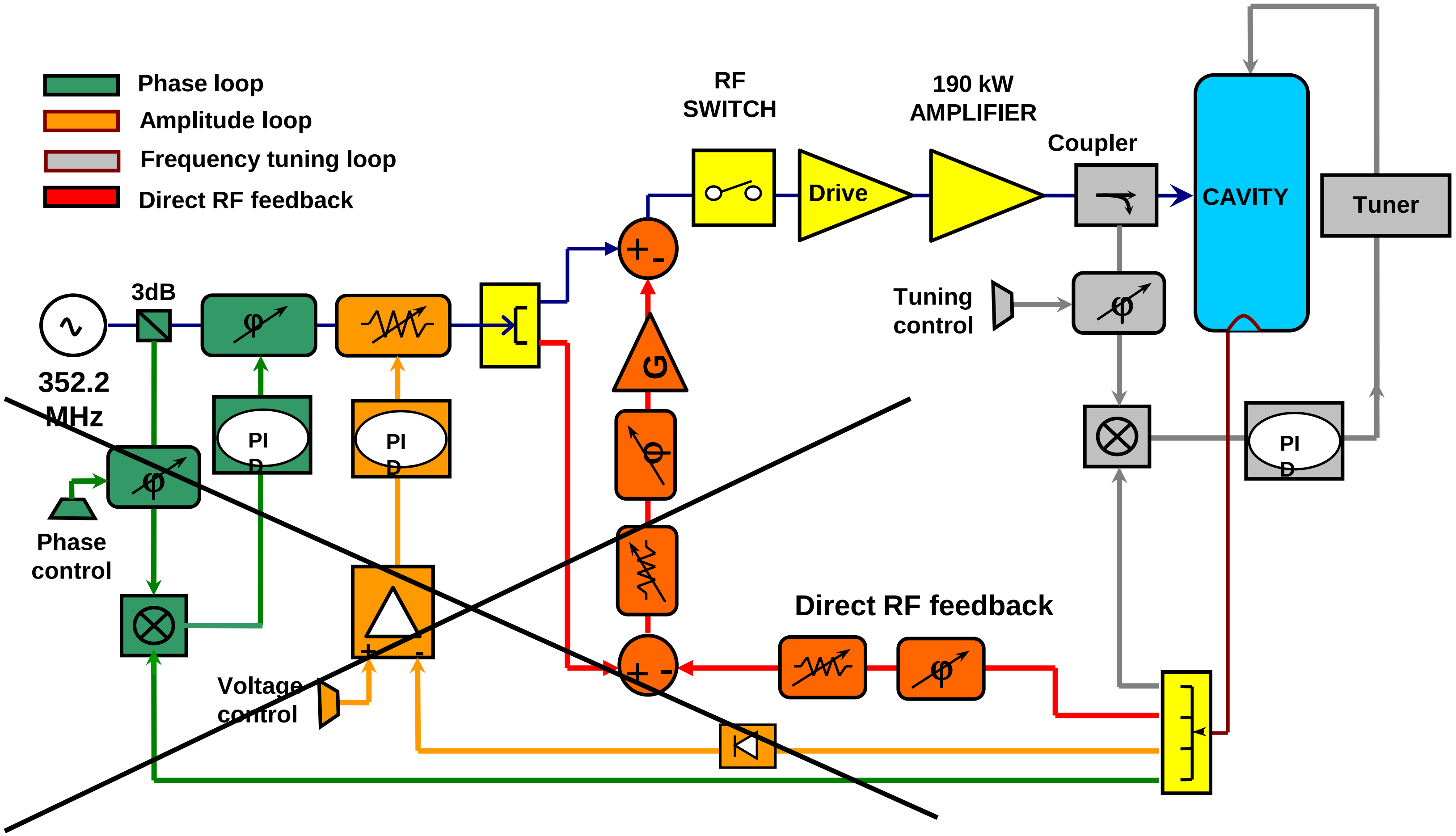
Storage Ring LLRF system phase 1

SR LLRF = BO LLRF + direct RF feedback



Role of Direct RF feedback loop :Beam loading problems (microphonics and Robinson)

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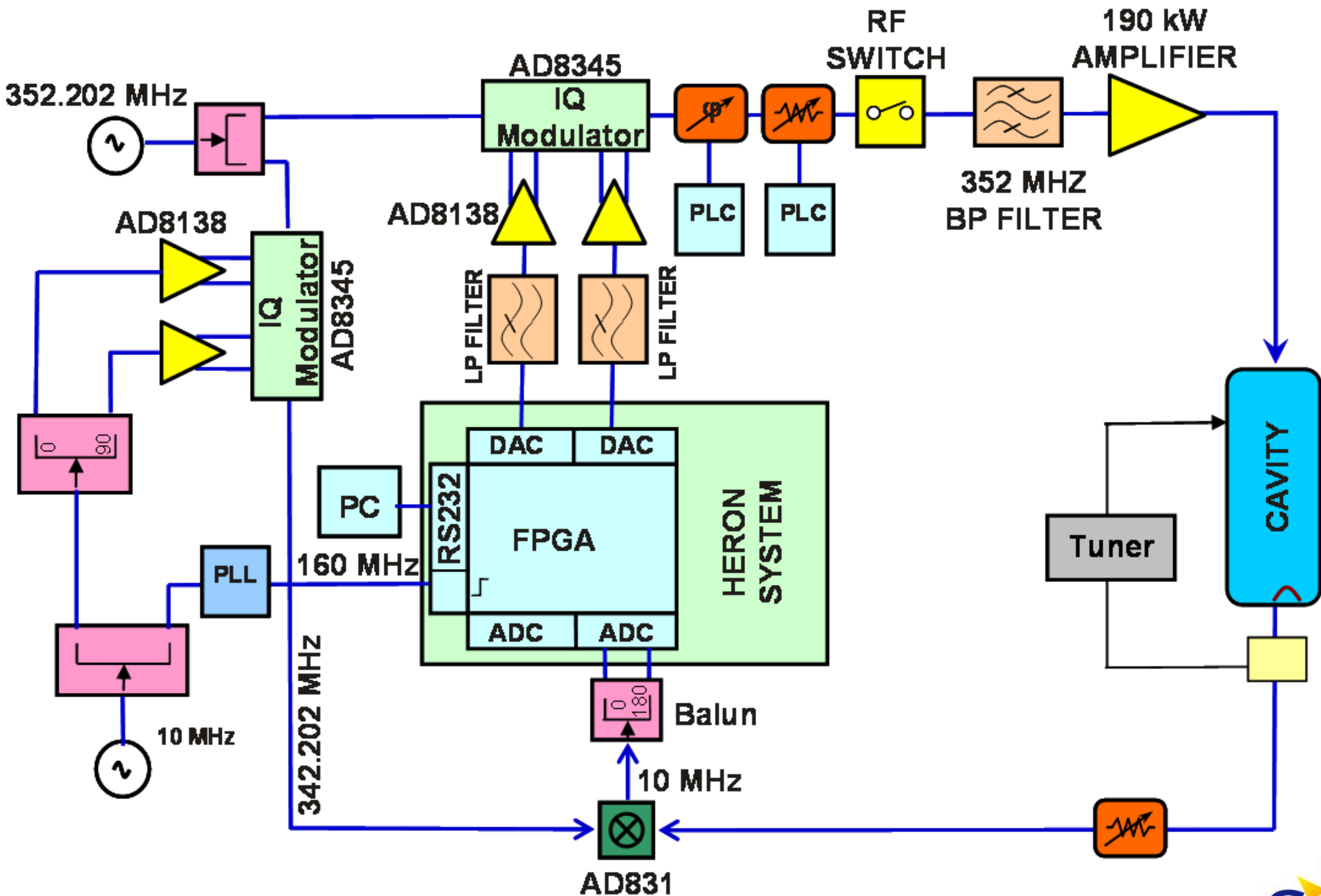
Storage Ring digital LLRF prototype

Phase 2 : fast digital (FPGA based) phase and amplitude loops,
under development in collaboration with CEA



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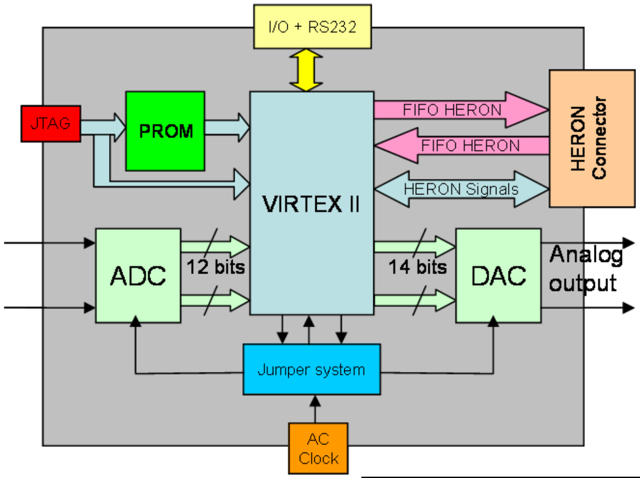
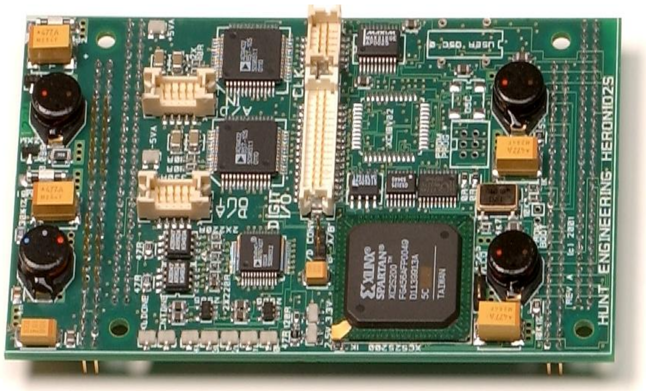
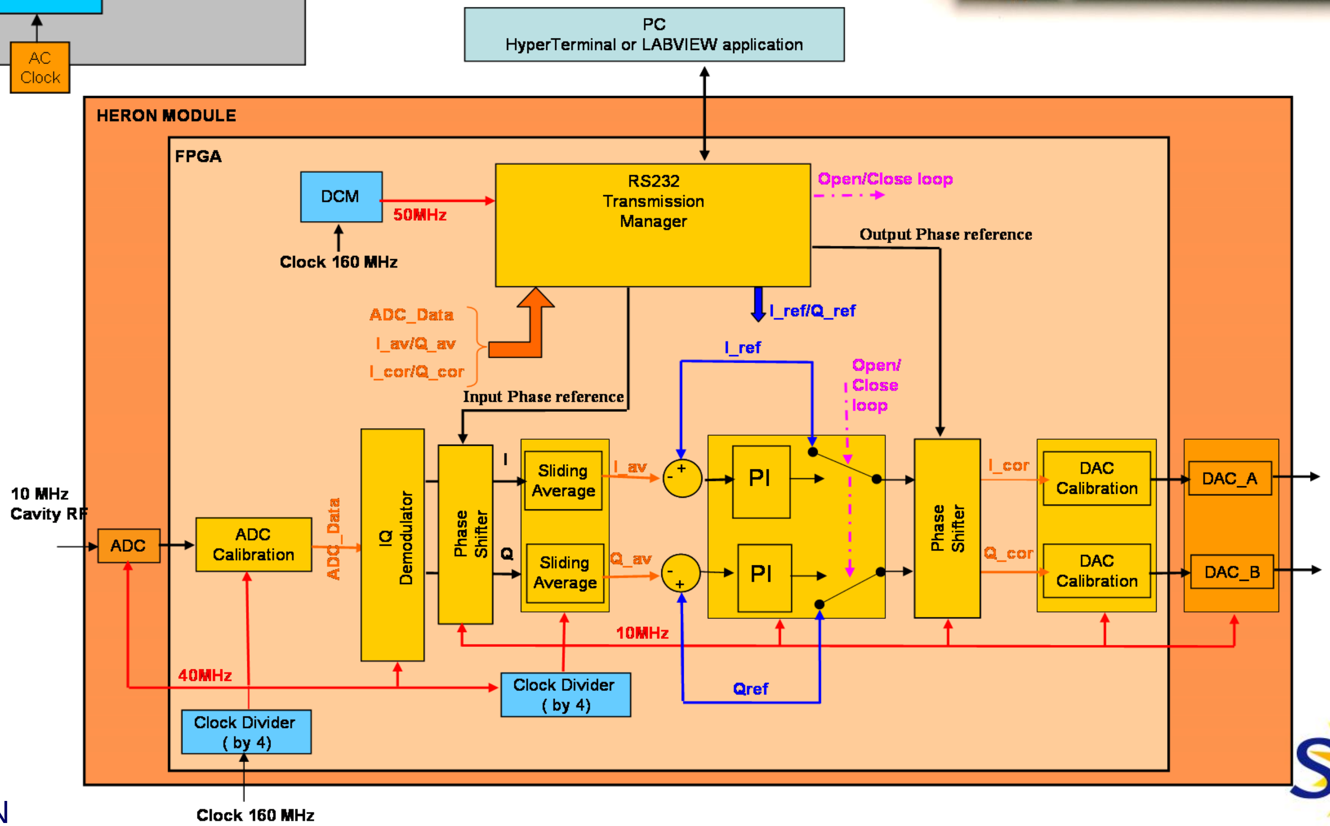
Architecture of FPGA

Module Architecture



Heron IO2V2 board





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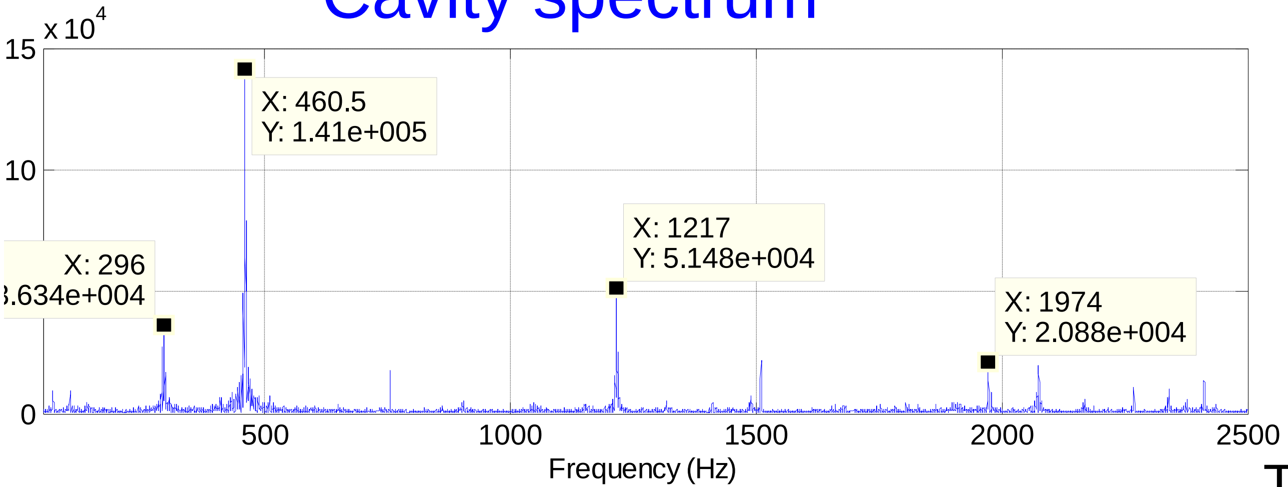
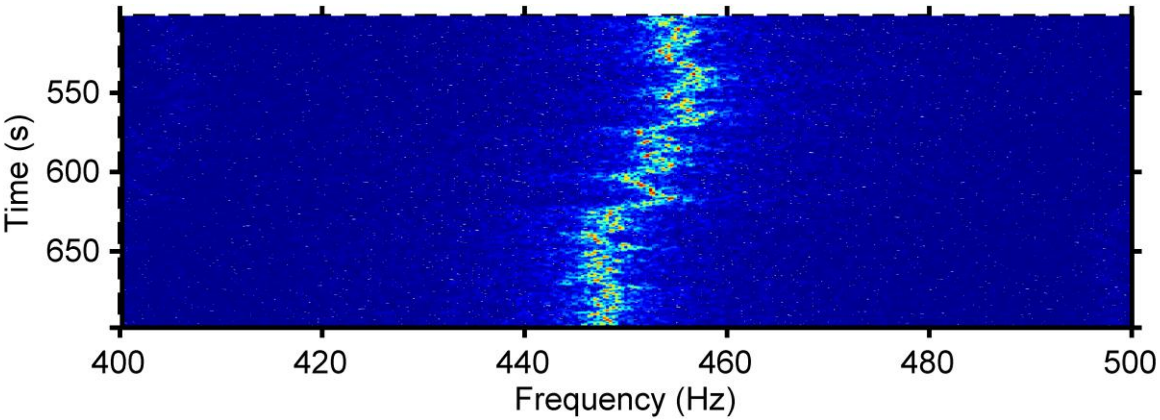
Microphonic measurements

Cavity spectrum



Cavity 2D spectrogram



Method :

Measurements of cavity microphonic using phase detector on tuning loop.

The major disturbance, around 460 Hz, is likely related to a mechanical eigenmode of the cavity

The eigenfrequency associated to this mode may change according to the helium pressure.

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Direct and digital feedback simulation model

First order cavity model

$$\dot{V}_{cr} = \frac{1}{\tau}\left[V_{gr} - V_{cr} - \tan\psi . V_{ci}\right]$$

$$\dot{V}_{ci} = \frac{1}{\tau}\left[V_{gi} - V_{ci} + \tan\psi . V_{cr}\right]$$

Beam loading

$$V_{cr}^{+} = V_{cr} + \omega_{RF}\left(\frac{R}{Q}\right) q \cos\phi_b$$

$$V_{ci}^{+} = V_{ci} + \omega_{RF}\left(\frac{R}{Q}\right) q \sin\phi_b$$

Synchrotron motion

$$\Delta E_i^{n+1} = \Delta E_i^n - V_c \cos\left[\phi_{b0} + (\delta\phi_b)_i^n - \phi_c\right] - \left(U_0 + D\,\Delta E_i^n\right)$$

$$(\delta\phi_b)_i^{n+1} = (\delta\phi_b)_i^n - \frac{2\pi\ f_{RF}\ \alpha}{f_0\ E_0}\left\{\Delta E_i^n - V_c \cos\left[\phi_{b0} + (\delta\phi_b)_i^n - \phi_c\right] - \frac{U_0 + D\,\Delta E_i^n}{2}\right\}$$

Direct feedback

$$\tilde{V}_g = \tilde{V}_{g0} + G\left(V_{c0} - \hat{D}\,\tilde{V}_c\right)$$

Fast I/Q feedback

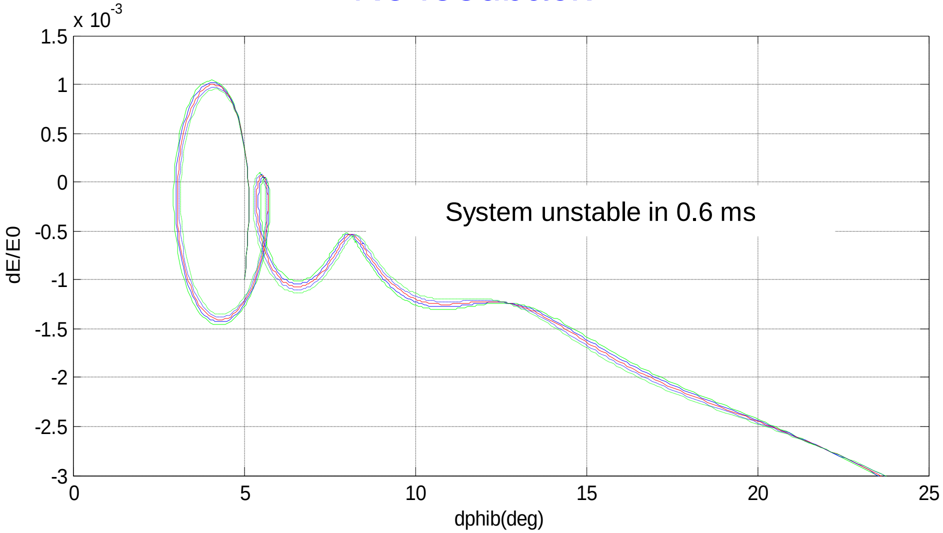
$$\tilde{V}_g = \tilde{V}_{g0} + G_I\left(V_{c0} - \hat{D}\,V_{cr}\right) - j\,G_Q \hat{D}\,V_{ci}$$

Disturbed beam stability study

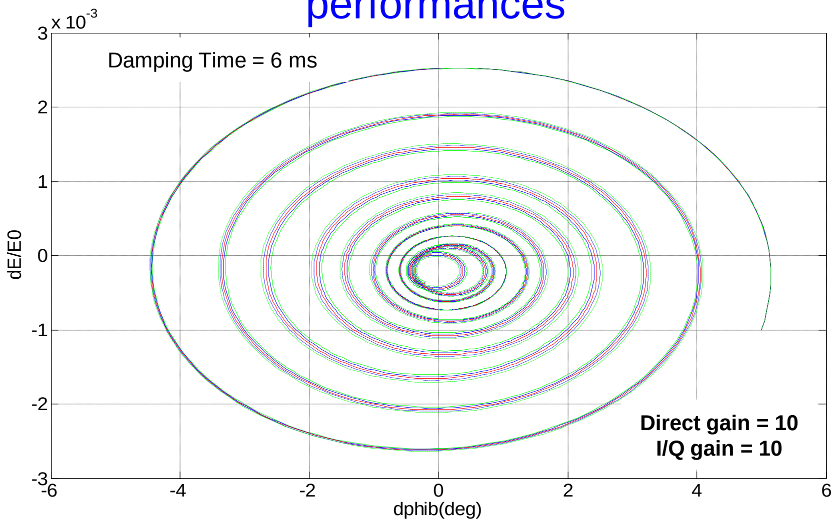
Disturbance parameters used in simulation

Injection phase error (°)	5
Relative injection energy error (%)	-0.1
'Real' microphonics (~200 Hz pk-pk detuning)	

No feedback



Direct RF and Digital I/Q feedback loop performances



Stabilized steady state : microphonics disturbance included

Cavity phase residual error	0.6 pk-pk
Cavity voltage residual error	0.08 %

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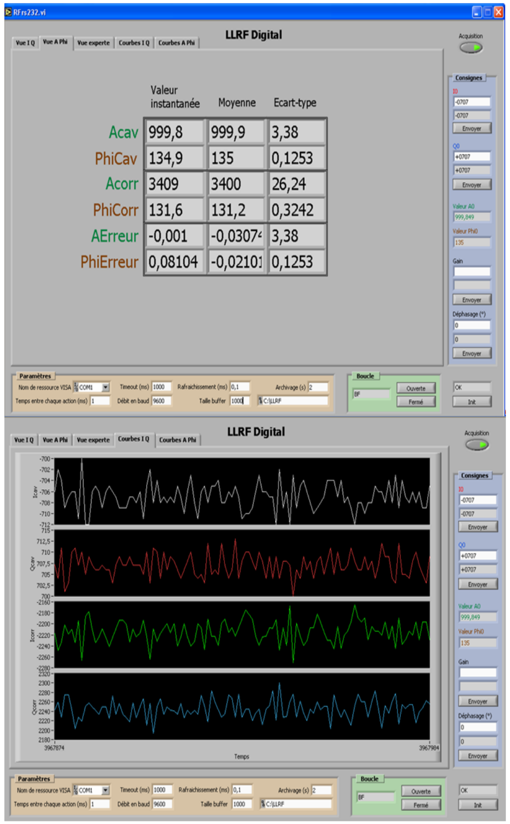
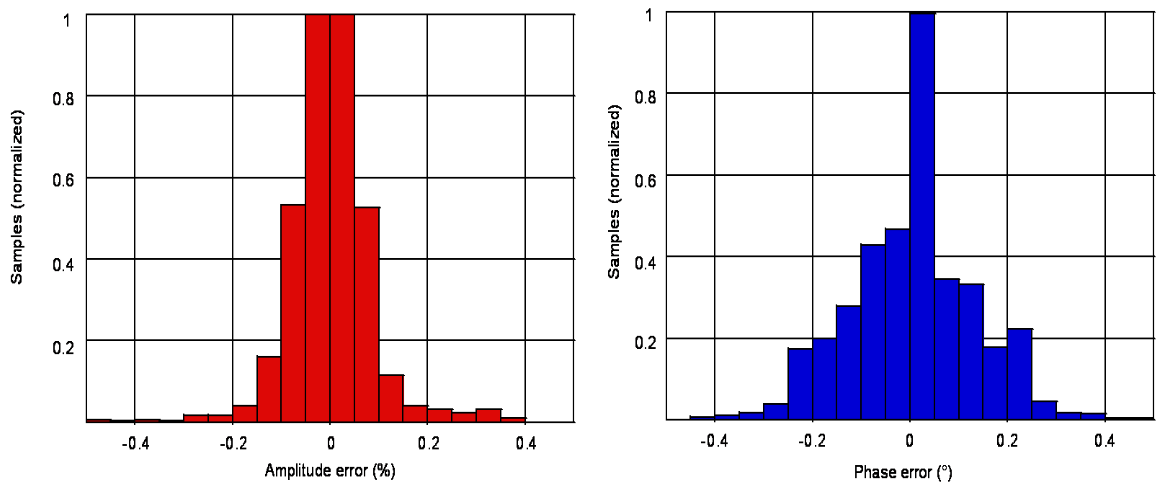
Experimental results

with a beam current up to 300 mA



LABVIEW data display (Ibeam = 300 mA)



Amplitude (left) and phase (right) error distributions

Measured errors

Amplitude error: 0.3% rms
Phase error: 0.2° rms

Successful achievement of this prototype
Future Plan : make our own versatile digital board with new generation components

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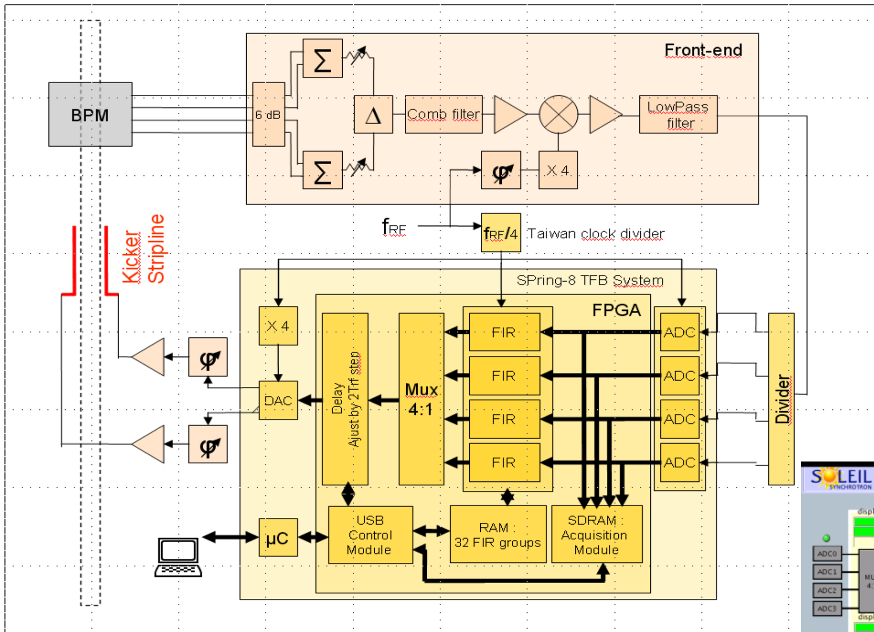
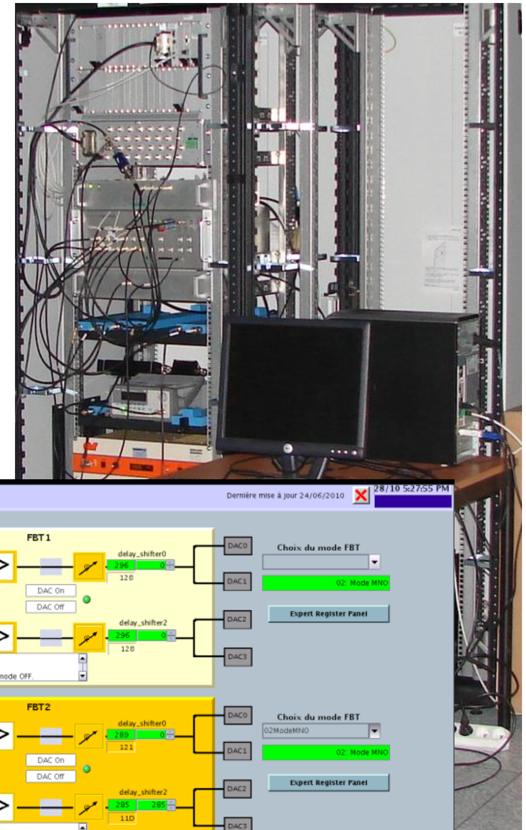
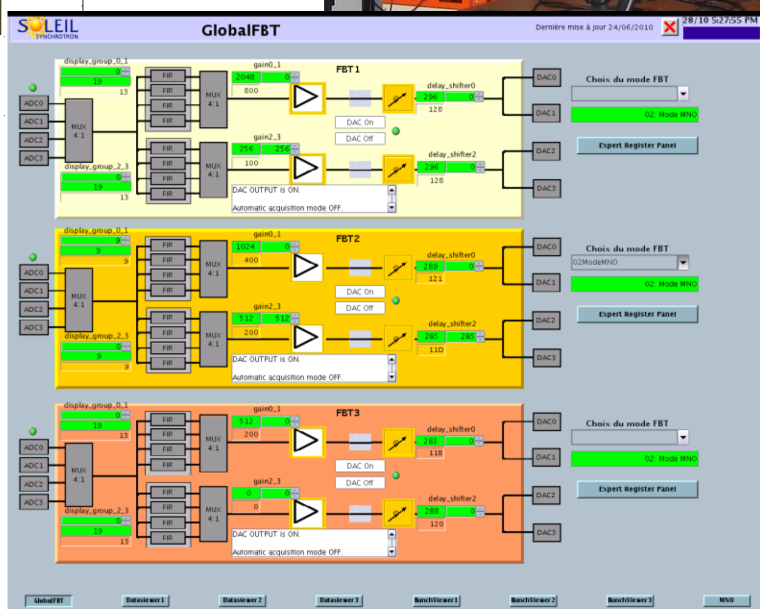
Transverse bunch by bunch feedback operation

Main reasons : resistive wall, Fast Ion, TMCI (Transverse Mode Coupling Instability) in H and V plane







Collaboration with SPring-8
TED made the digital system

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Transverse bunch by bunch feedback operation

◊ Different Modes of Operation and the Digital Filters:

- Purely H, V and the diagonal mode. In the diagonal mode, only the diagonal electrodes of the BPM and the stripline are used. Despite the tune difference of 0.1, the diagonal mode works well at SOLEIL .

- Digital (FIR) filters employed:

Least square fit of the betatron motions, developed by T. Nakamura (EPAC2004):

Fit the betatron motion function in the following form

$$x[k] = A \sin[(1+\Delta)\phi_k + \psi] + B$$

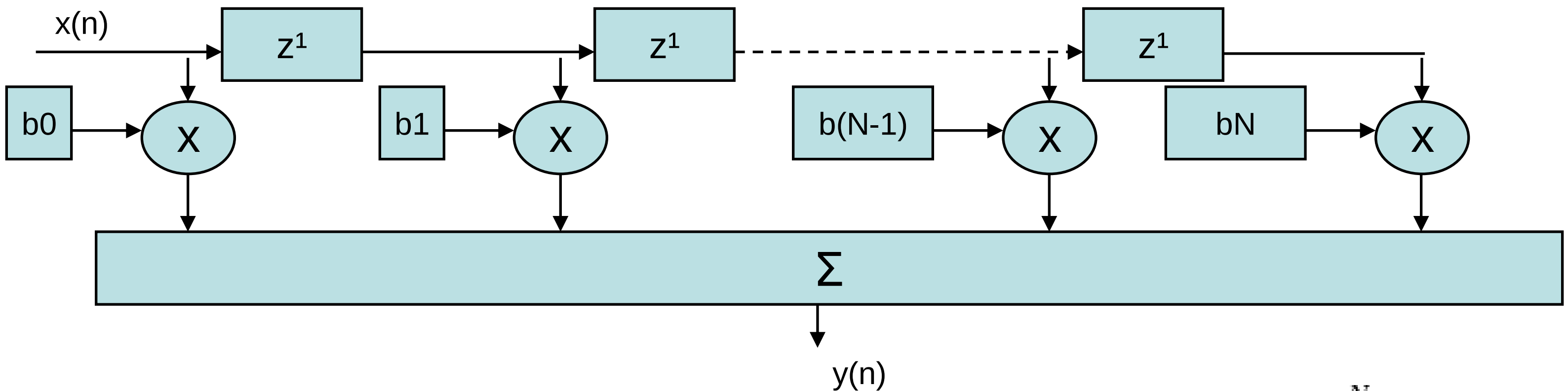
$$\equiv P_0 \cos\phi_k - P_1\, \phi_k \sin\phi_k + Q_0 \sin\phi_k + Q_1\, \phi_k \cos\phi_k + B + \text{higher-order terms}$$

Determine the coefficients P_0, P_1, Q_0, Q_1, B, … via least square fit of

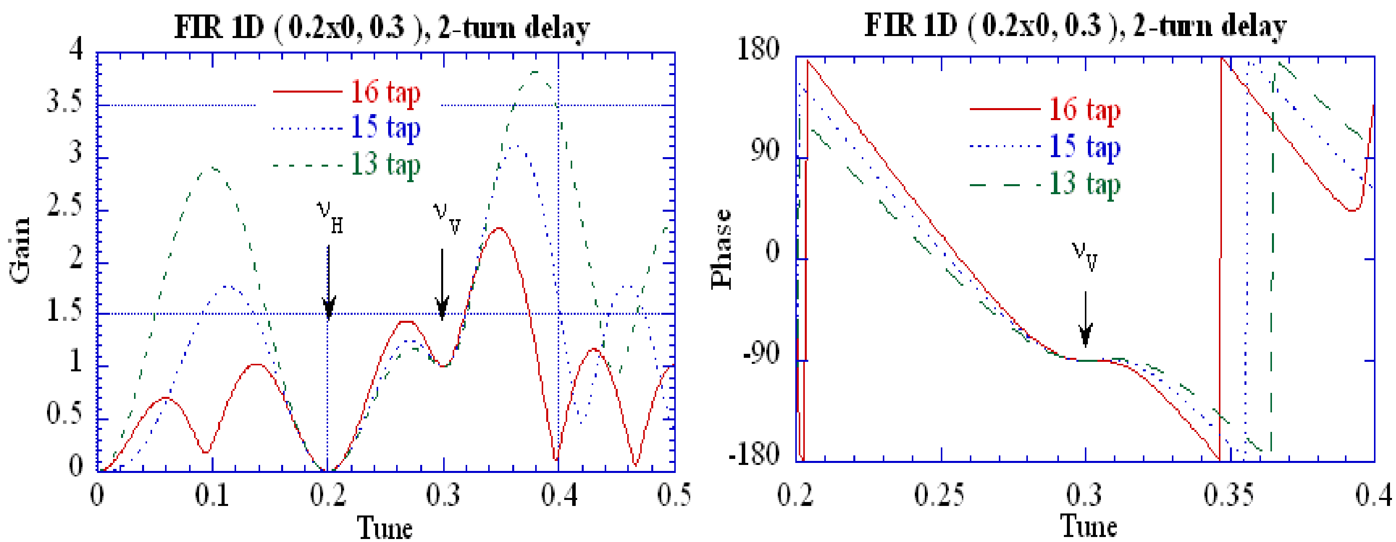
$$F \equiv \sum_{k=0}^{N-1} \left(x_k - x[k]\right)^2,$$

which can be solved by the standard matrix inversion method.

Structure of FIR Filter



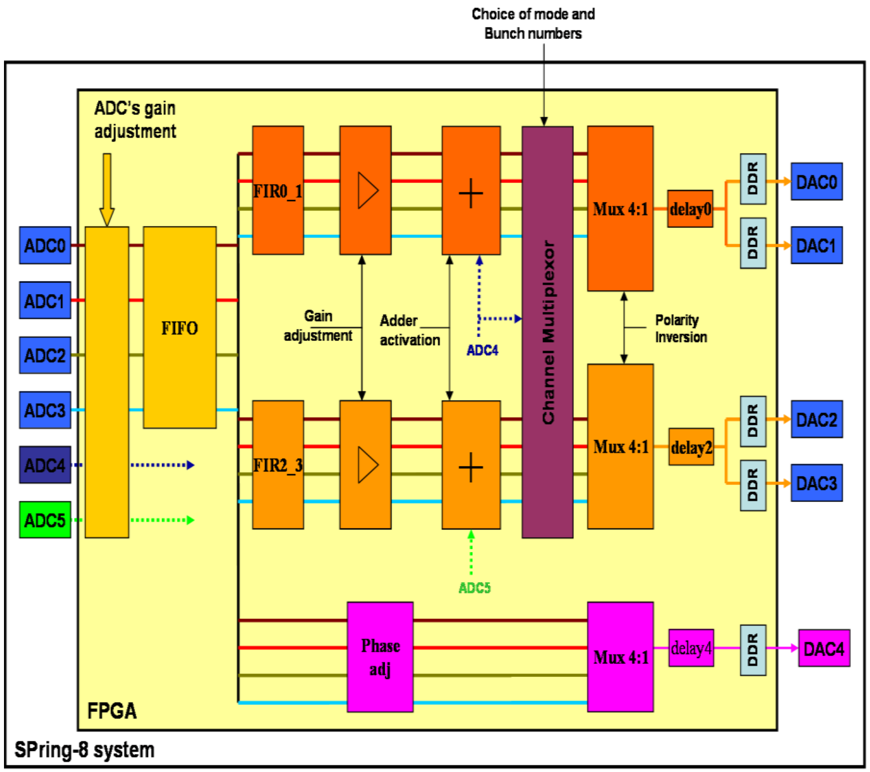
$$y[n] = b_0 \cdot x[n] + b_1 \cdot x[n-1] + b_2 \cdot x[n-2] + ... + b_N \cdot x[n-N] \qquad y[n] = \sum_{k=0}^{N} b_k \cdot x[n-k]$$

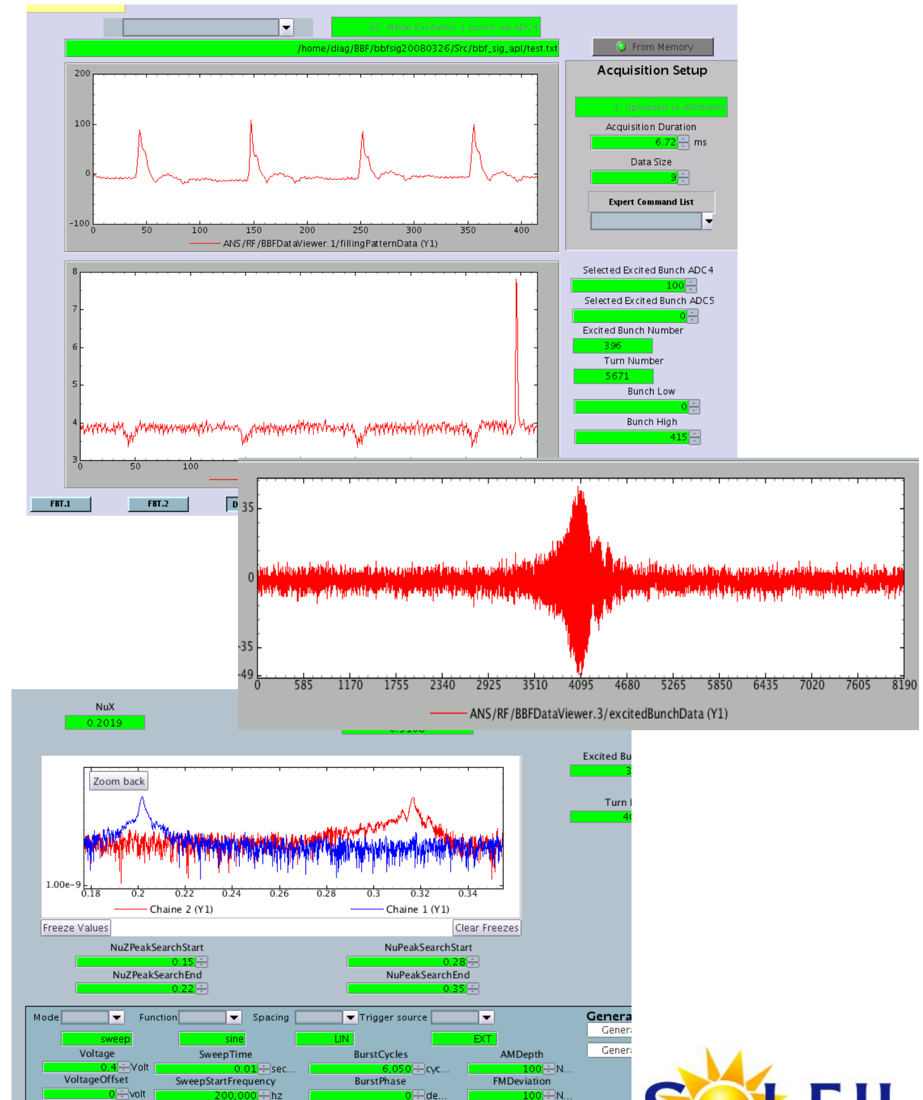


Gain and phase of a 16-tap vertical FIR filter

Some home made development

on our SPring-8 based System





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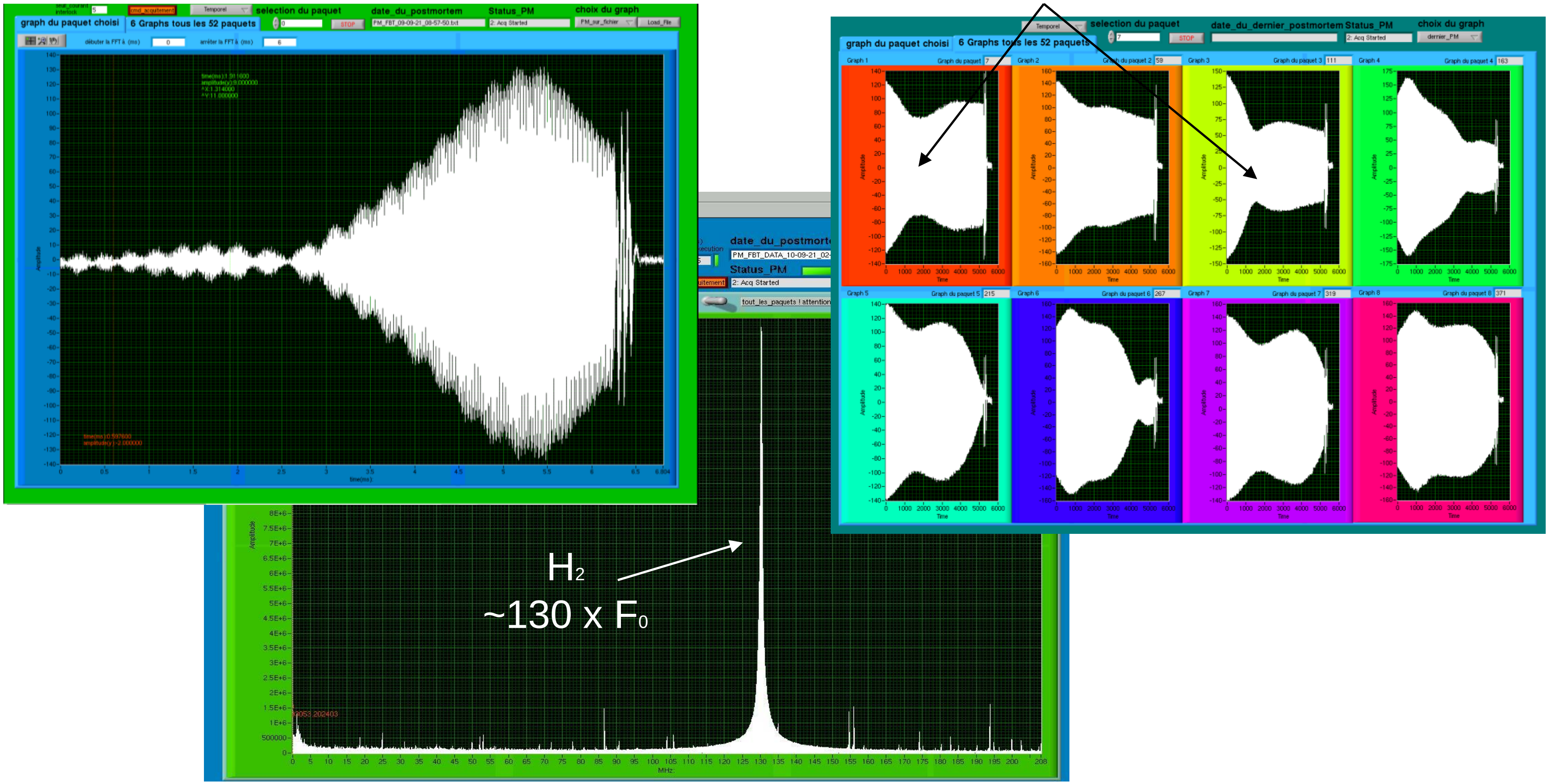
Postmortem application

Behavior of each bunch



Collaboration with SPring-8 : Soleil development was shared

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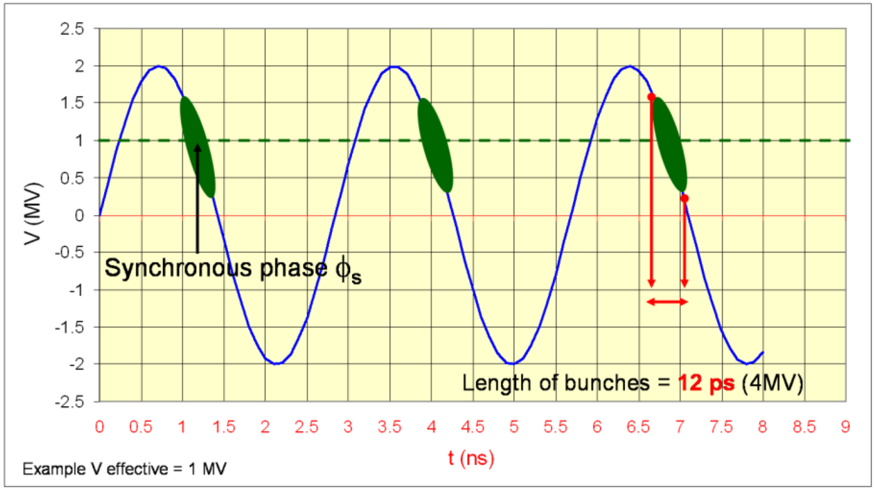
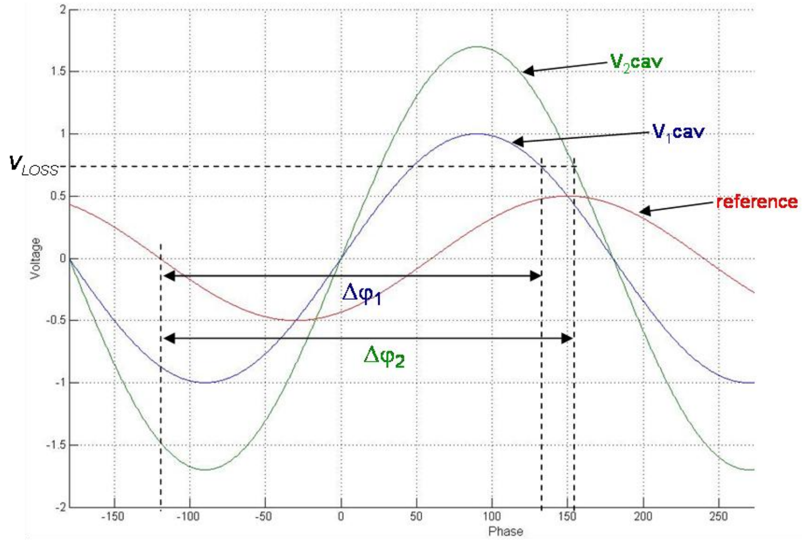
Link between transverse feedback and RF

Electrons form a bunch around a stable point of RF period.



1.18 μs / 2.84 ns = **416** maximum bunches



Phase compensation with PLC program in RF ramped mode:
With very low beam current we have 1MV total RF voltage with 4 cavities
then the voltage increase with beam current.

The problem is: our amplitude loop detector is not very linear at low voltage,
so the phase correction is not perfect. In this way, the bunch position can change a little bit.

As the TFB is synchronized by the RF reference signal clock, the kick can also shift a little bit.
In consequence, the TFB efficiency can decrease.

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SUMMARY

TBBFB activities:

• We reached stable 500 mA beam current with TFB and reduced RF voltage

• To be implemented soon :

Phase feedback and automatic calculation of FIRs coefficients from tune value

Digital LLRF activities:

•Finalize our Digital Booster LLRF system

•Versatile digital board with new generation components

Future projects (500MHz) :

•Collaboration with SESAME on LLRF and feedbacks

•LLRF and feedbacks for ThomX (Compact X-ray source, based on a 50 MeV ring)