Using Libera Bunch-by-Bunch at ESRF

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Initial motivation:

Store 300mA instead of 200mA in our storage ring:

- Problem: longitudinal instabilities driven by RF cavities HOM.
- Temperature control of the cavities did not work above 200mA to avoid these instabilities
- We decided to solve the problem thanks to a longitudinal bunch by bunch feedback.

- We also wanted to have as much as possible of the development done by the industry

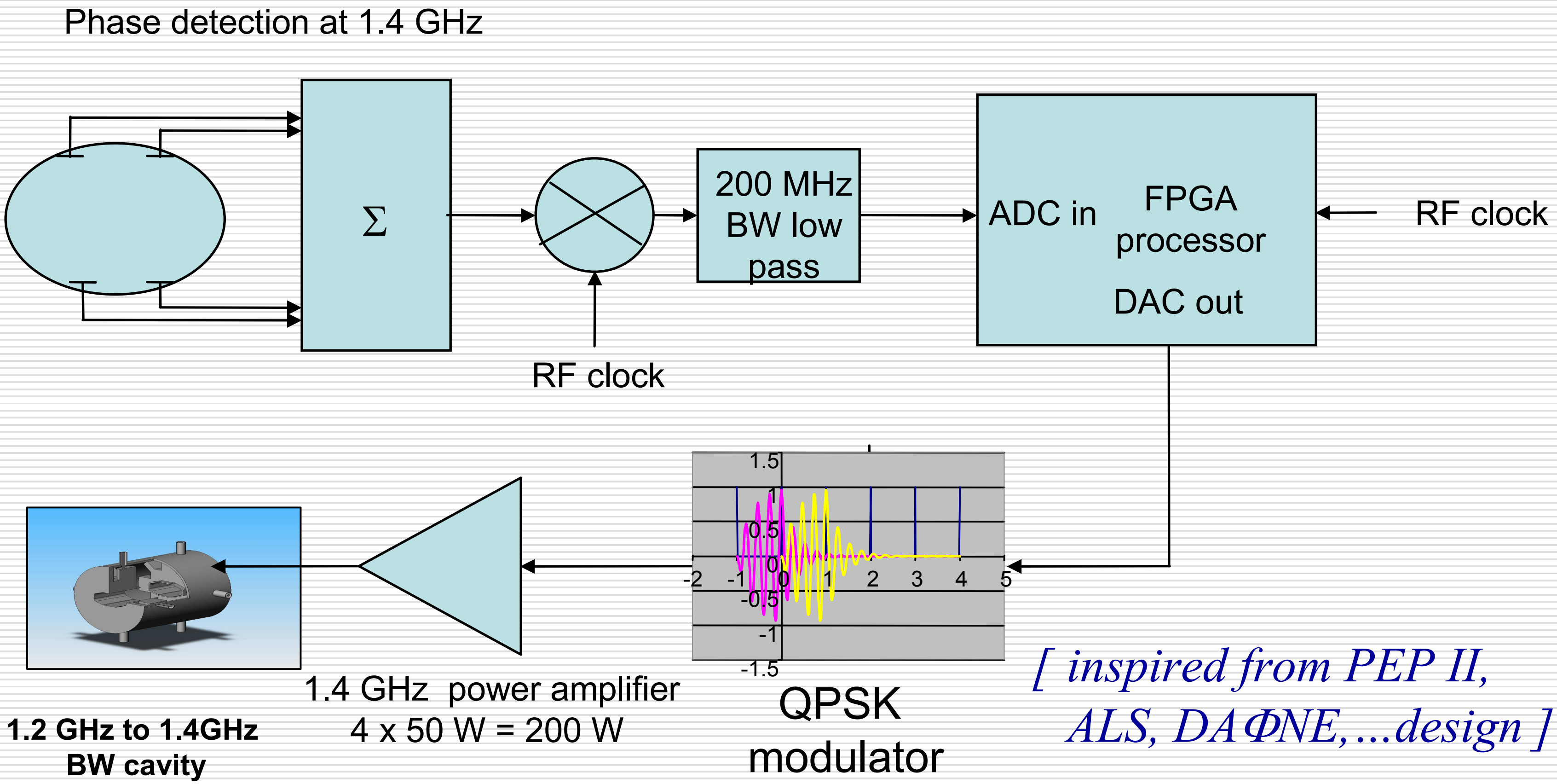
Requirement, constraints

ESRF storage ring parameters:

- 6 GeV
- 3ms longitudinal damping time
- 2KHz synchrotron frequency
- 352.2 MHz/992 buckets

Available correction kick/turn very weak:<1KV

LFB - Longitudinal feedback – principle



[inspired from PEP II, ALS, DAΦNE,…design]

Transverse feedback
(initialy a side issue for ESRF)

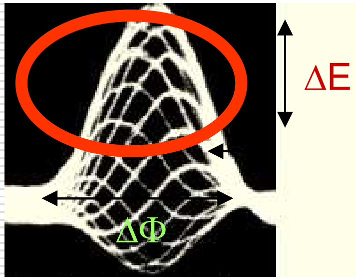
- More current could mean more severe transverse instabilities =>

Without transverse feedback:

More chromaticity needed=> lower lifetime

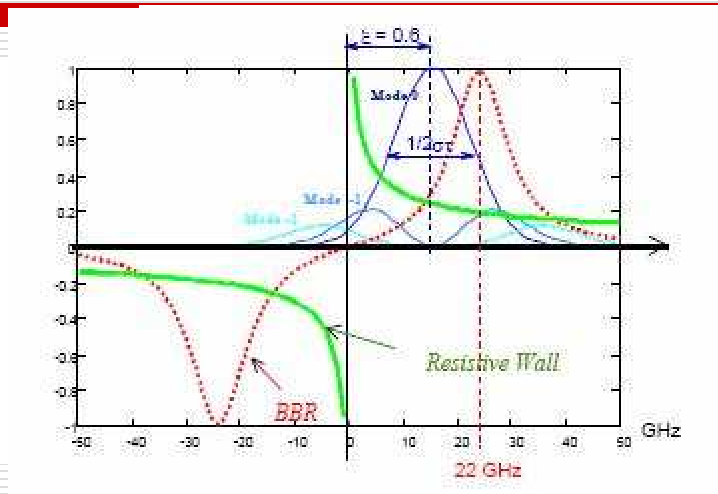
Non zero chromaticity: head tail modes

Using the sextupoles magnets we make the tune energy dependant…



Left: Pattern of a beam position readings inside a bunch for different revolutions with non zero chromaticity (mode 0) (CERN PS)

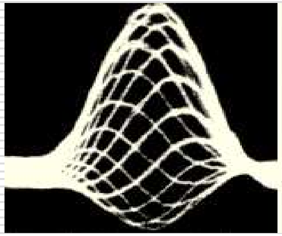
Right: typical pattern of a storage ring transverse impedance



Non zero chromaticity => coupling between particles inside each bunch will now affect the beam stability:

- ΔE/E=10-3 inside a bunch => different betatron phases inside the bunch=> beam position spectrum shift to microwave frequencies
- Head particles create fields seen by the tail particles (wake fields)
- Chromaticity sign=> phase lead/lag between head/tail particles
- This coupling will stabilize or destabilize the transverse modes of oscillation depending of the sign of the chromaticity and the order of the mode.

Non zero chromaticity: head tail modes



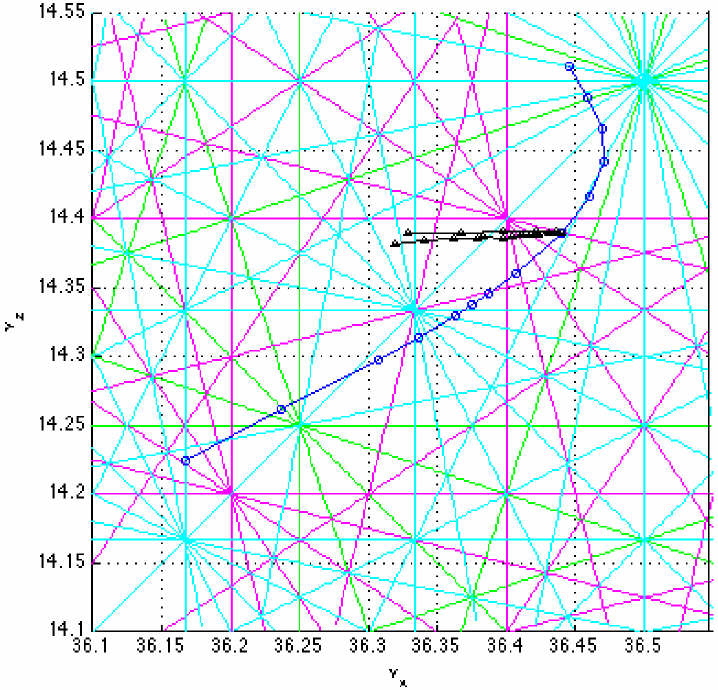
This is a free transverse feedback…

We use a moderate positive chromaticity (ξ_v=.24), to fight the resistive wall instability and the ion trapping instability in multibunch => nearly no lifetime reduction

And a high positive chromaticity (ξ_v=.6) in 16 and 4 bunch filling mode to fight special instabilities due to the high current /bunch
=> a severe lifetime reduction

Why does chromaticity spoil lifetime?

- Of momentum particles can hit resonances when their tune changes due to the chromaticity



Zero chromaticity should be the best situation, but others optics non linearity exist anyway (octupolar fields) so there is no real improvement below the ξ values that we use for multibunch filling.

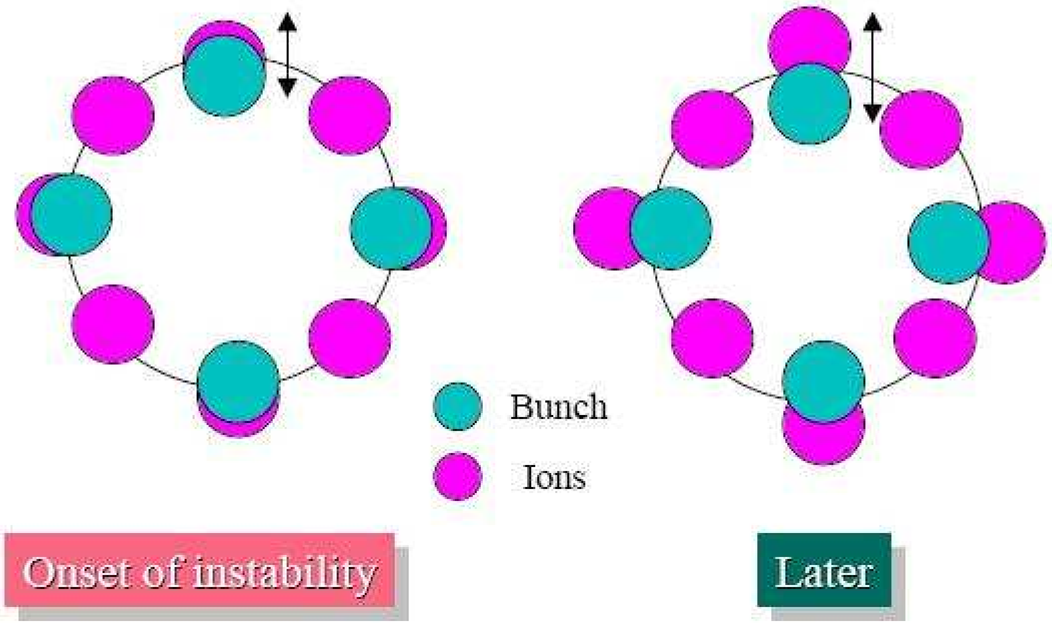
Transverse feedback
(initialy a side issue for ESRF)

- More current could mean more severe transverse instabilities:

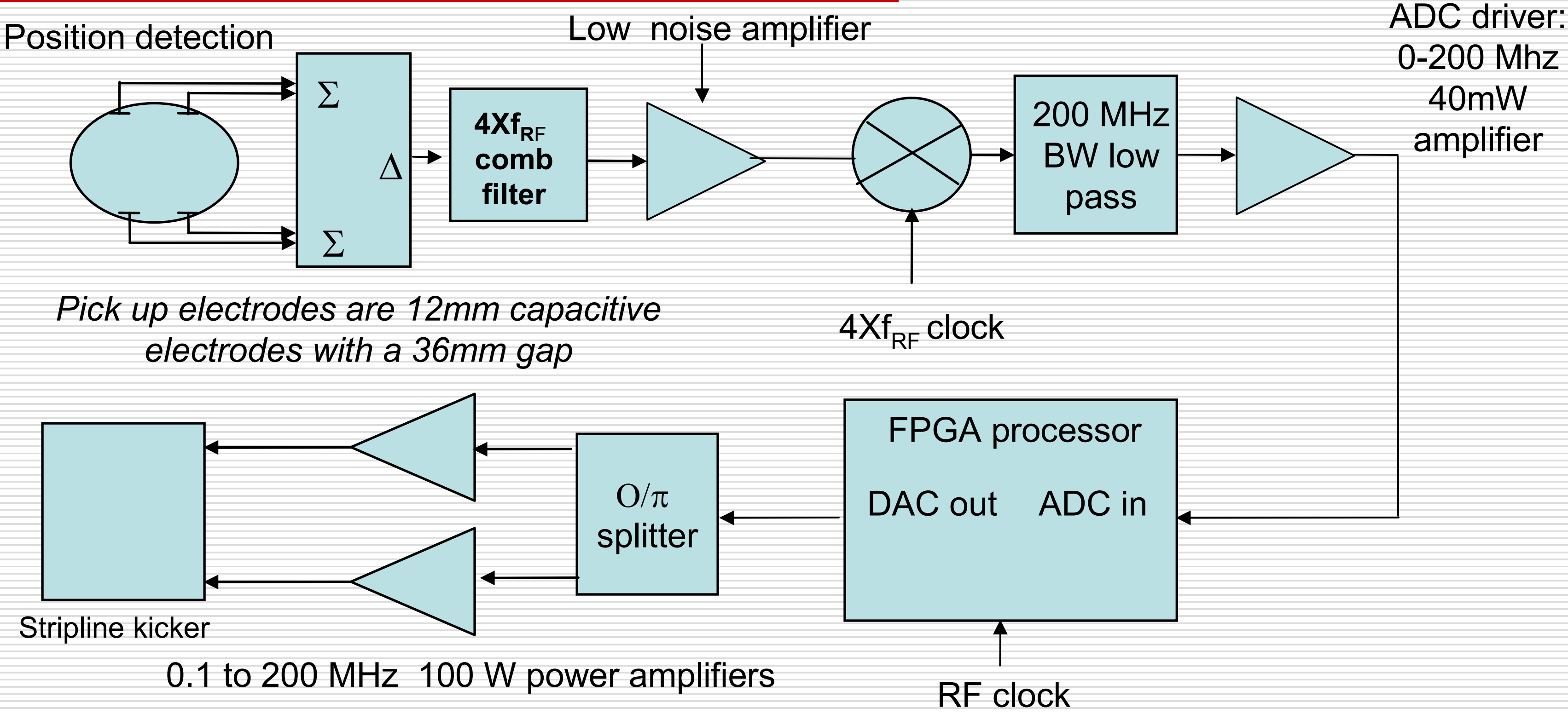
More ion trapping…

How will ion trapping cause instability

- Uniform filling of a beam
- No clearing of ions (saturation of ion population)
- Stationary state (even though unstable)
- Existence of threshold for onset of instability
- Narrow-band spectrum

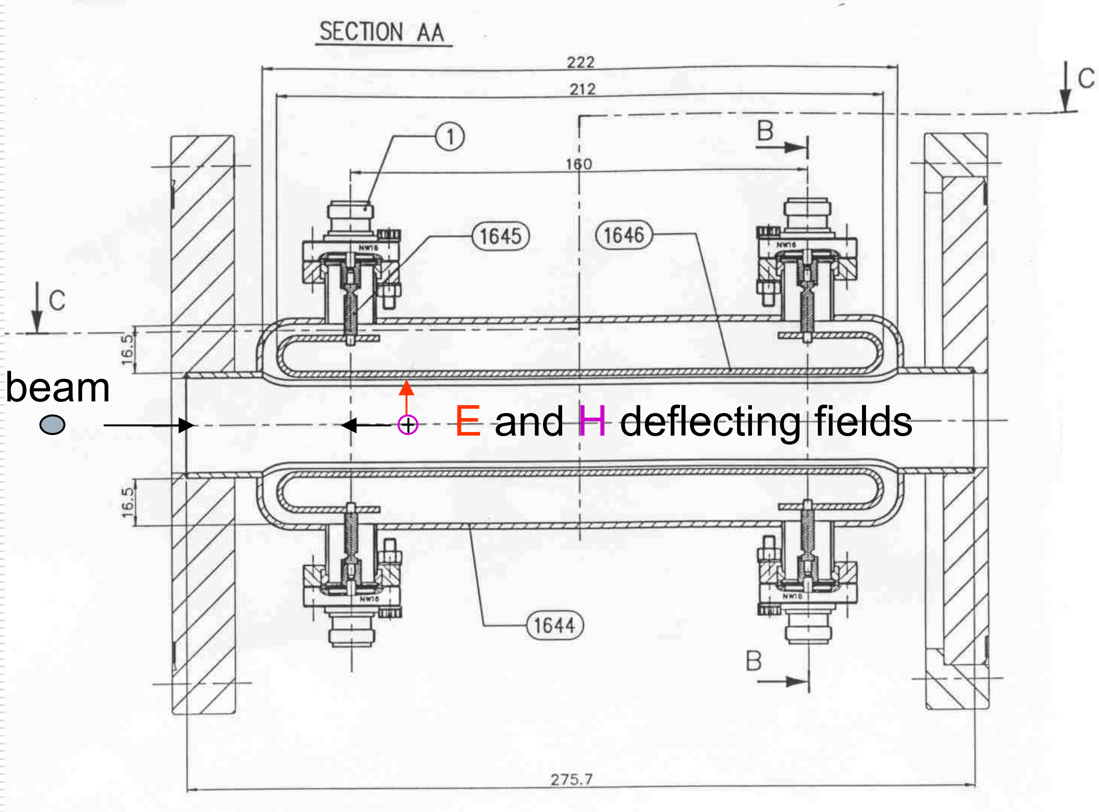


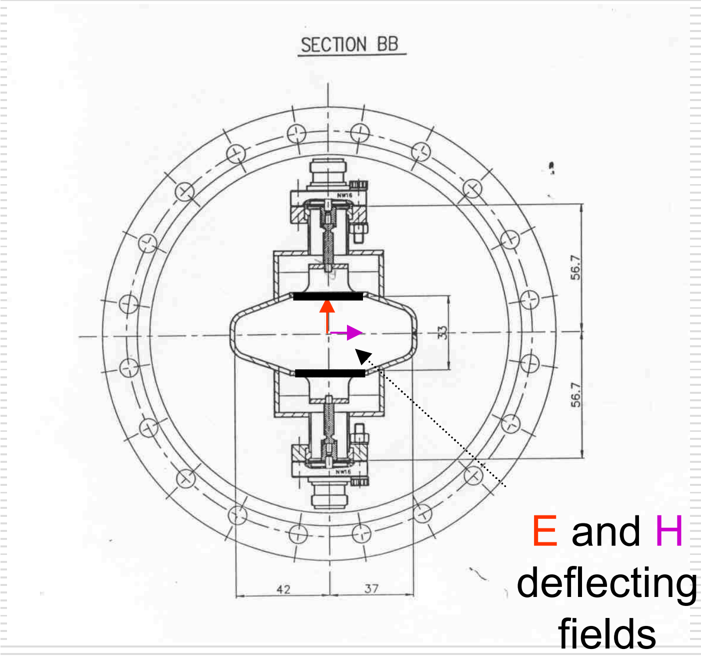
Transverse feedback



Detection of the pick up signals with a $4Xf_{RF}$ clock improves the resolution

Vertical kicker layout





Processor main features

- High ADC resolution at 352.2 MHz sampling rate: 14bits
- Same rate for the output DAC
- Processing power/data logging
- Flexible environment for the feedback algorithm debugging (*Xilinx System Generator*)
- Integration in our control system (Tango device server…)

=>I*tech developed the Libera Bunch-by-Bunch*

Why a14 bits ADC?

14 bits/125 Msps was the best resolution available in 2005, so we asked for it ...

not only:

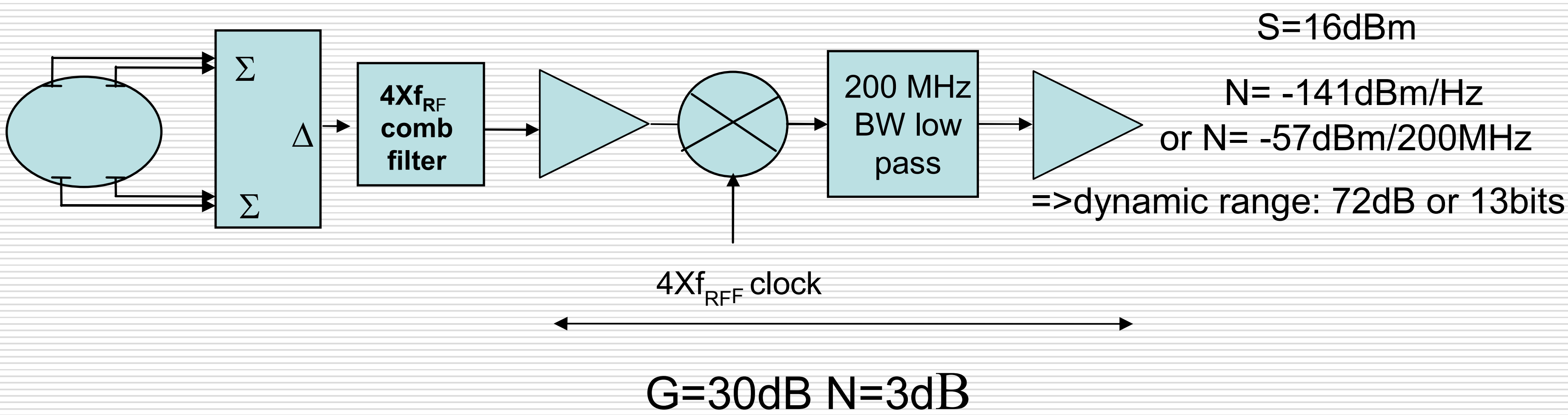
More relevant concerns:

- To be consistent with the RF front end output noise level
- To avoid saturating the longitudinal kicker amplifier
- To avoid spoiling the beam vertical emitance

Why a 14 bits ADC?

Preservation of the resolution of the RF front end

Position detection



The resoluton of the14 bit ADC used in the bunch by bunch Libera is actually 13bits according to its manufacturer (TI), so it just fit our resolution requirement...

Why a 14 bits ADC longitudinal feedback

- The natural damping time at the ESRF is τ_s = 3.6 ms
- The digital signal processing algorithm can allow an active damping time as low as about:

  τ_{damp} = 0.5 ms ≈ τ_s /7 (limited by the loop delay)

  for which the gain will have to be:

$$\frac{\hat{V}_{kick}}{\hat{\tau}} = [\omega_{HOM} I_{beam} R_{HOM}]^{MAX} = 7 \times \frac{2\omega_s T_0 E_0 / e}{\tau_s \alpha} = 4.7 \text{ V/fs}$$

This figure is derived from:

$d\tau/dt \approx \alpha\, \varepsilon/E_0 \;\Rightarrow$ $\quad \hat{\varepsilon} / \hat{\tau} = 0.4 \;\; keV \;/\; fs$

and

$\Delta\varepsilon / \Delta\Phi_{352\ MHz} = 3.3$ *MeV/ °*

Since the kicks adds up over the active damping time(≈ 160 turns)

Why a 14 bits ADC longitudinal feedback

- 600V kicker =>up to 150fs oscillation can be damped
- 1.4 GHz phase detection => +/- 150ps full scale
- =>we need to kill an oscillation before it reaches 10^{-3} of the phase detection full scale

So the 14 bits resolution looked necessary also in this respect

Actually the situation is not that serious:

We average the detection of an oscillation over the rise time/damping time = 100 turns which give us an extra 3 bits of resolution so maybe even 10 bits would have been enough….

Why a 14 bit ADC ? transverse feedback

Dynamic range set by the parasitic oscillation caused by the injection bump imperfection:

- 100 μm without sextupoles in the bump
- Up to 2mm of horizontal oscillation with sextupoles in the bump (ESRF, Spring8)
- We aim at turn by turn resolution of a few μm
- Damping time can be as low as 10 turns => less filtering than in the longitudinal case

So we may need 12bits…

If we have hybrid /camshaft filling, the some extra bits are needed => 14 bits are useful

Feedback algorithm

- Relatively standard:
- We assume that each bunch oscillation occurs at a well known frequency
- The easiest error signal to measure is the phase (or position)
- The easiest correction to apply is an energy (or angle) kick.
- The correction should be a derivative of the error signal
- We approximate the derivation with a $\pi/4$ phase shift

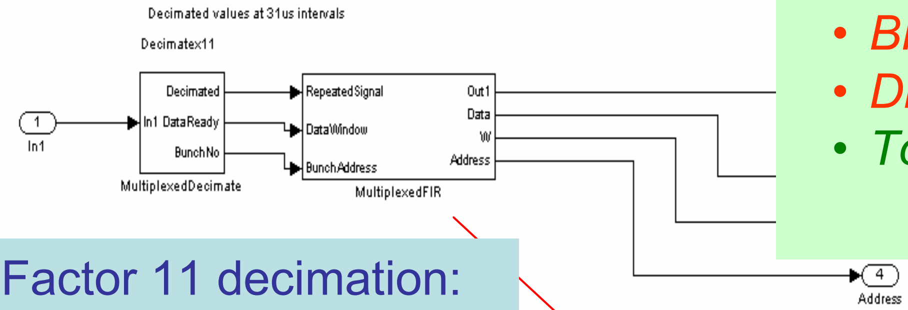
Feedback algorithm

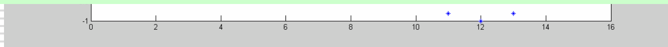
- Phase shift is done with a FIR
- Various FIR shape (sine, constant phase versus frequency …)
- Our guideline: the shorter and the simpler the best => sine shape
- 7 and 8 taps for the transverse
- 11 turn averaging + 16 taps for the longitudinal
- For both longitudinal and transverse feedback => delay is about half a synchrotron or betatron period….

FPGA – Filter block: decimation + FIR + mode 0 removal

16 TAP FIR: *16 x 31 μs = 0.5 ms = $T_{synchrotron}$*

- *BP filter at fs*
- *Differentiation ($V_{kick} \sim j\tau$): phase shift by 90°*
- *Total averaging 176, sensitivity: 1fs -> 0.08 fs*

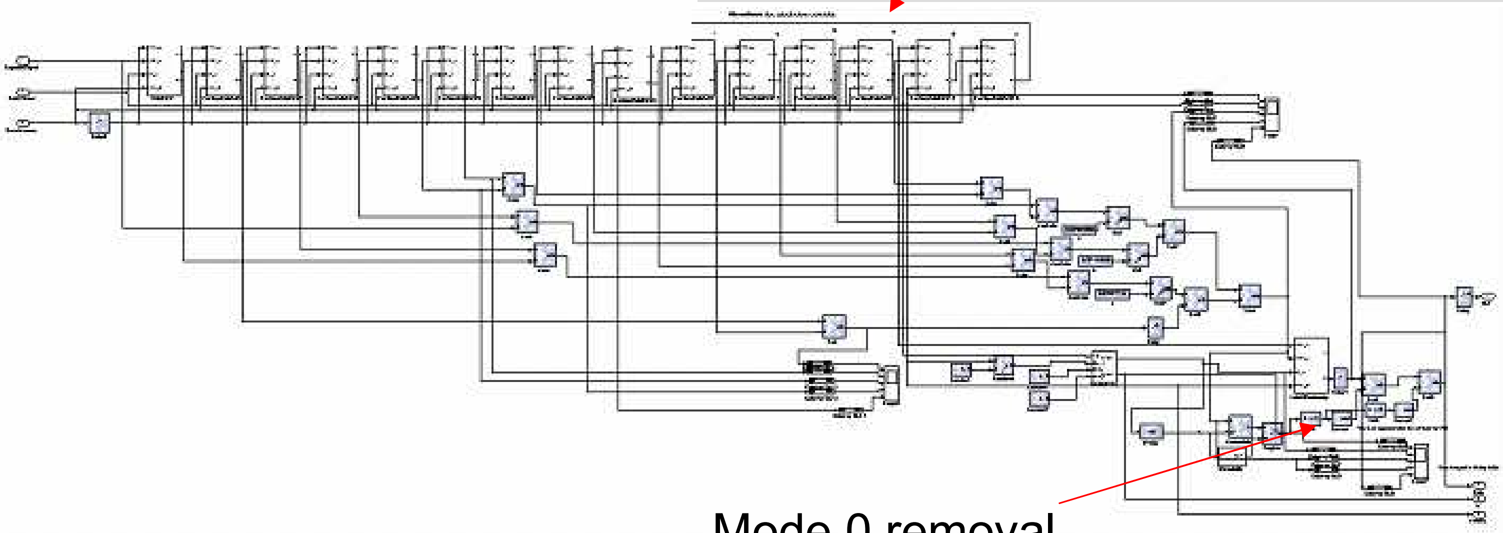




Factor 11 decimation:

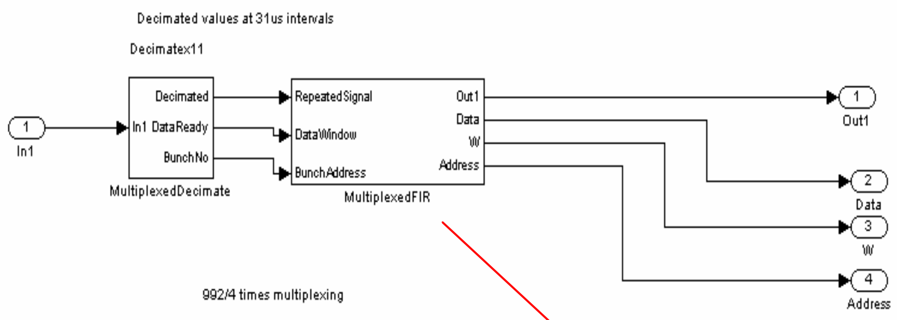
11 T_0 = 31 μs

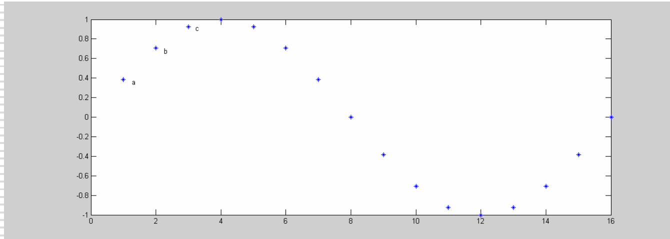
FIR: (a,b,c,1,c,b,a,0,-a,-b,-c,-1,-c,-b,-a,0)



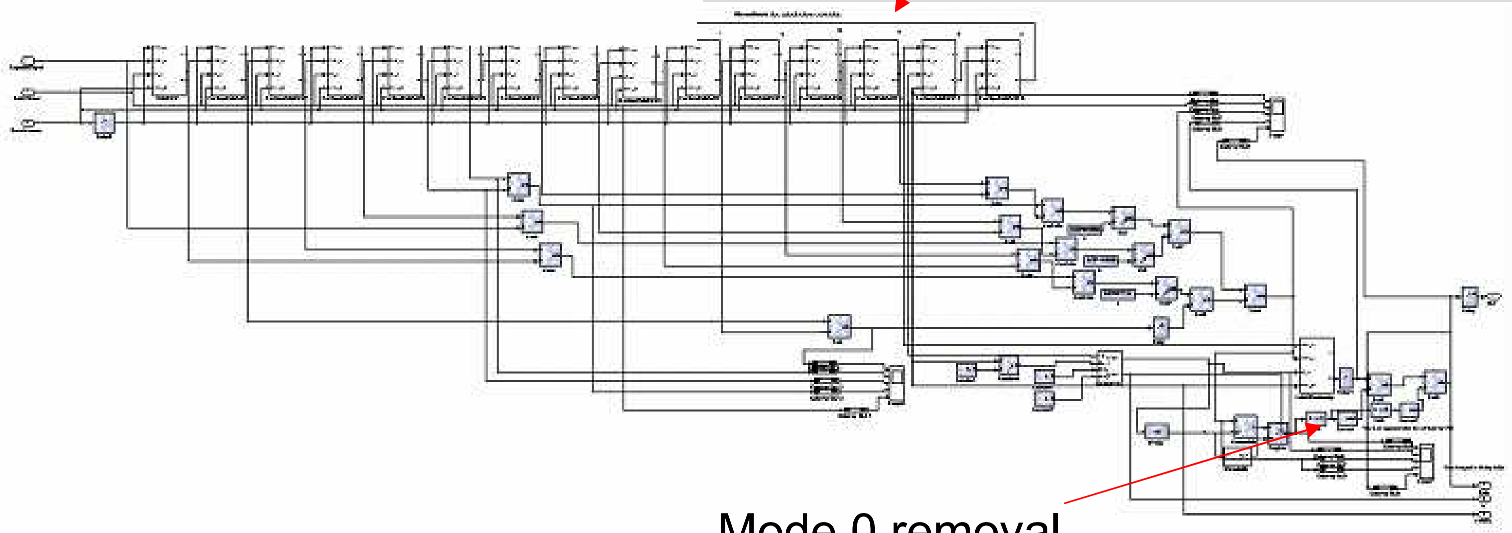
Mode 0 removal

FPGA – Filter block: decimation + FIR + mode 0 removal





FIR: (a,b,c,1,c,b,a,0,-a,-b,-c,-1,-c,-b,-a,0)



Mode 0 removal

Diagnostics features

- Feedback tuning diagnostics:
- *Open loop measurement:*

mode by mode amplitude and phase response

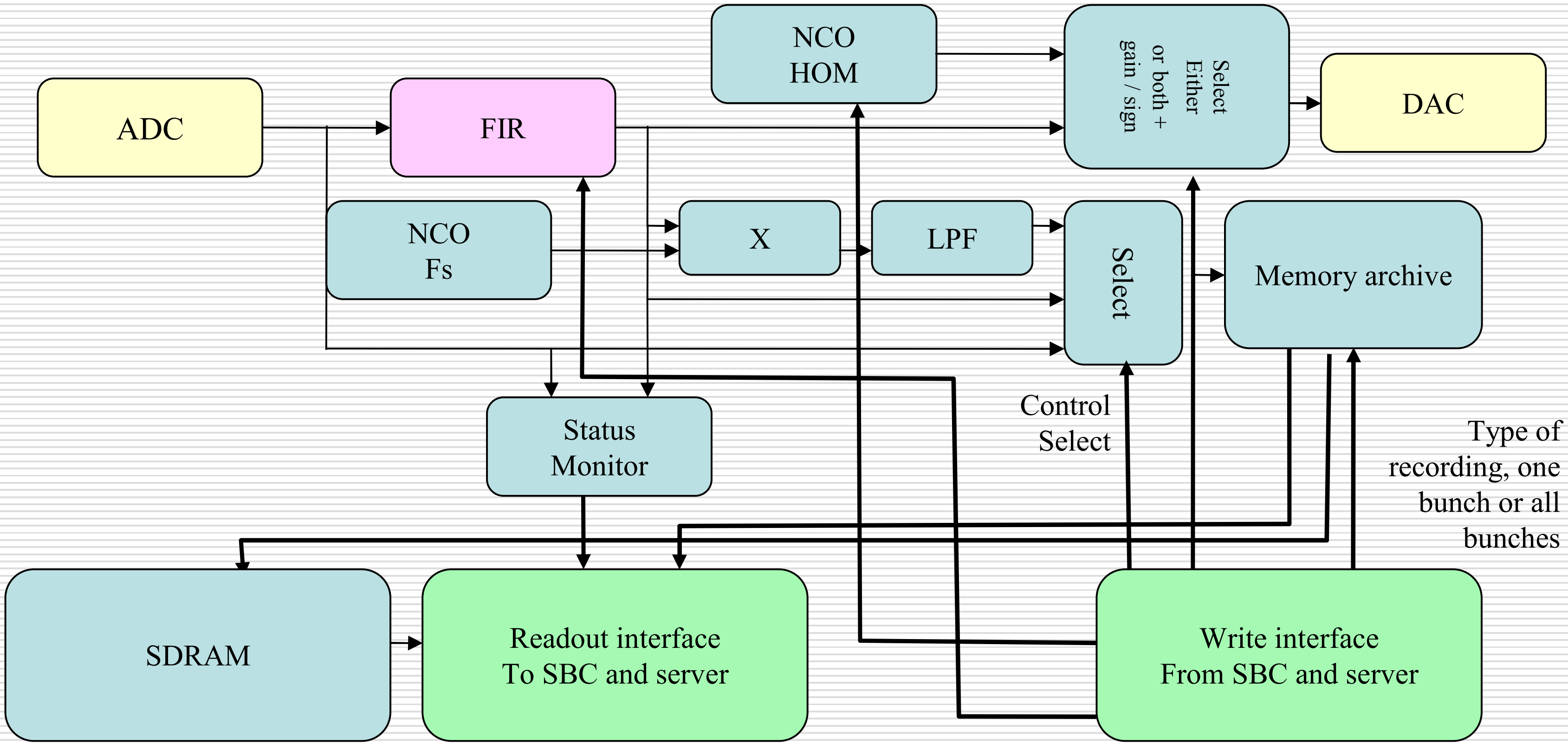
- *Closed loop measurement:*

Grow damp measurement

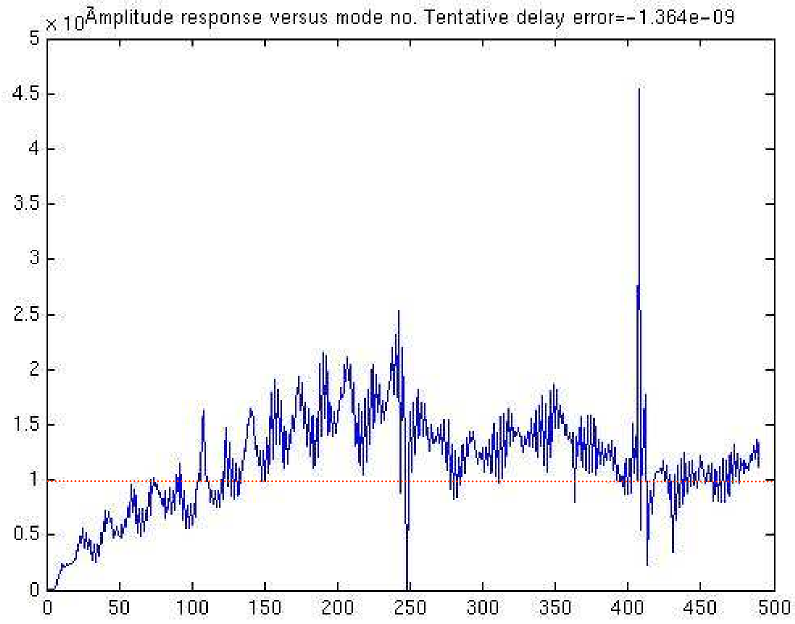
- General purpose diagnostics:

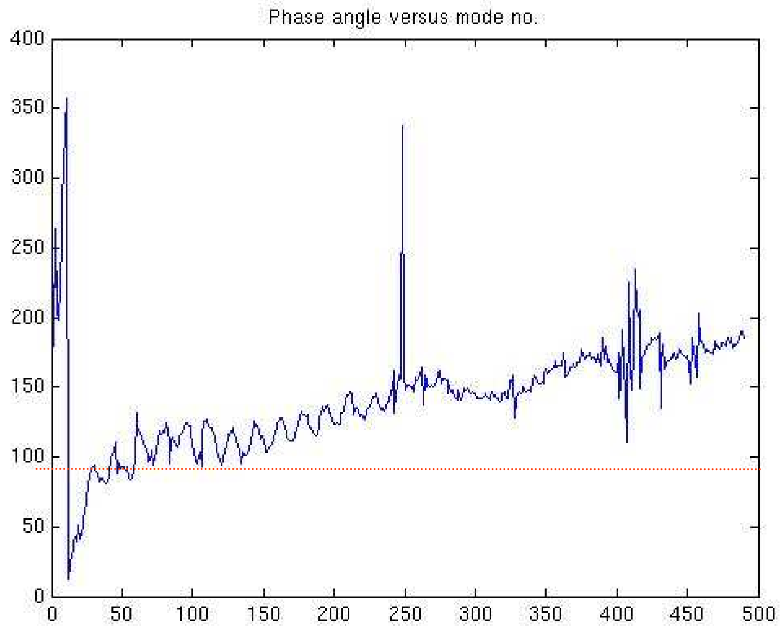
Tune monitor, spectrum analyzer, bunch by bunch BPM….

Diagnostics functions

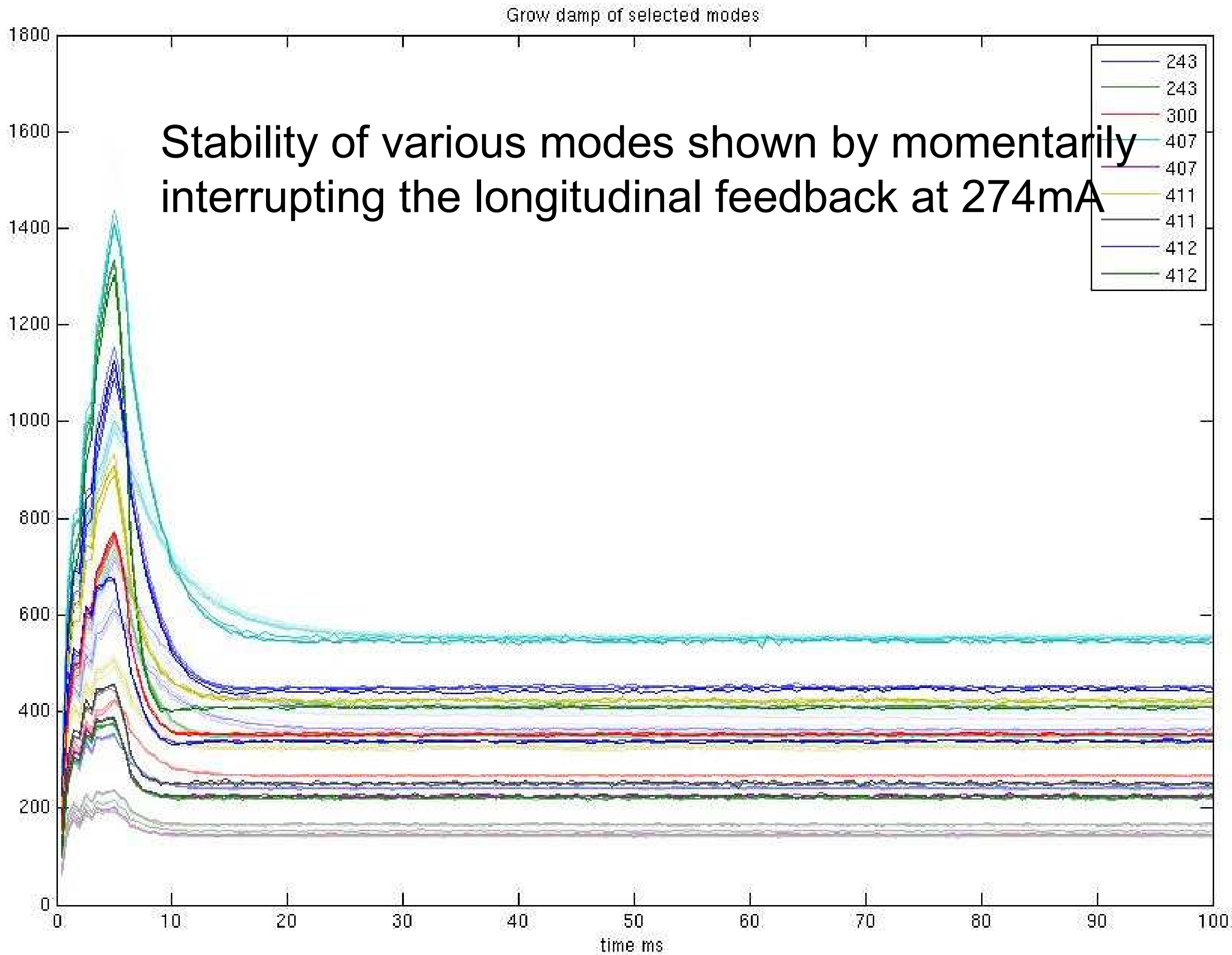


Amplitude/phase response scan



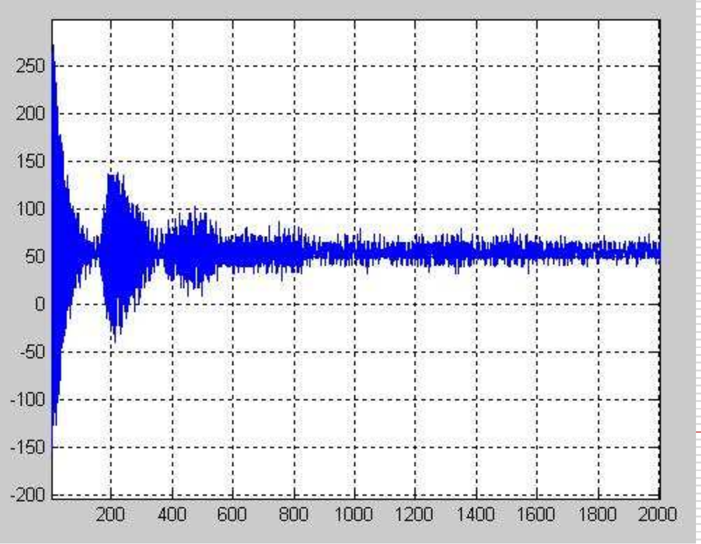


Growth and damping time measurements



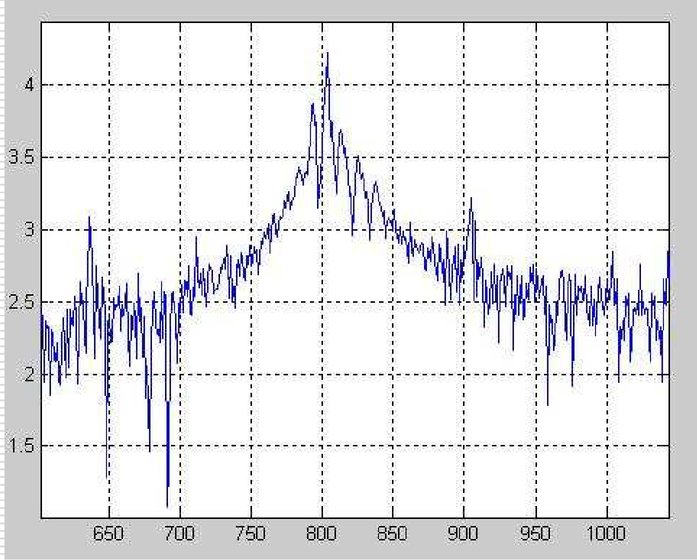
Tune measurement with the Bunch by Bunch Libera

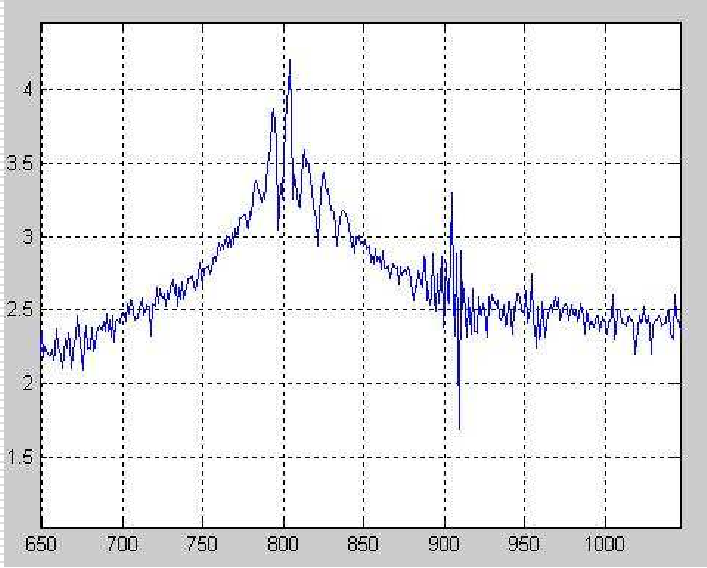
- 4Ksamples buffers of preprocessed turn by turn data
- 992 X 2048 SDRAM buffers with raw position or FIR filtered bunch by bunch over 2048 turns data
- FPGA embedded NCO and band pass limited noise source to excite any coupled bunch mode
- Digital down converter to perform a zoom on any coupled bunch mode
- Single turn, pulse, noise or sine excitation available



Example of the turn by turn data for a single bunch among 992 after a single turn kick.
50µm initial amplitude, 200mA uniform filling=>.2mA/bunch

FFT analysis

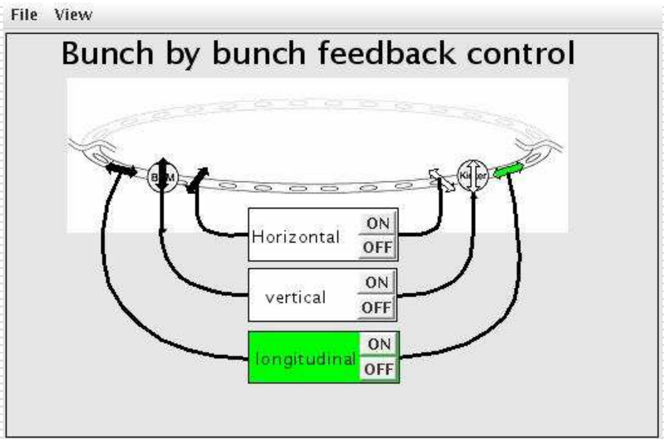


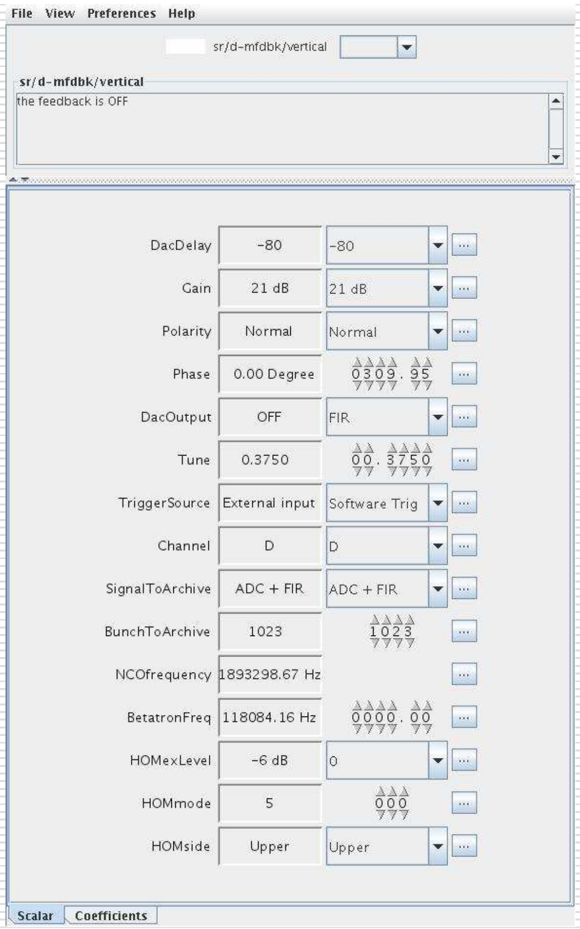


- 40KHz zoom on the FFT of the previous signal.
- Left: single bunch data.
- Right: averaging over 300 bunches
- Vertical scale : 6dB/div

Tango device server

Generic control application available immediately

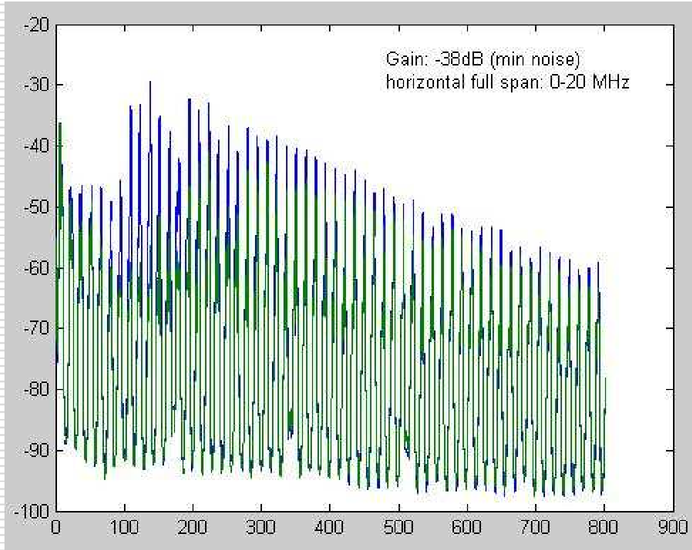


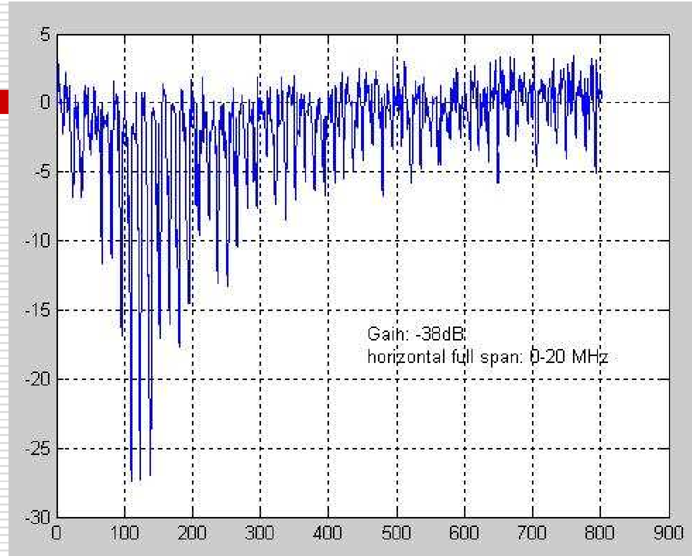


Feedback: results achieved

- Longitudinal feedback: 300 mA stored
- Transverse feedback: 200mA stored with zero chromaticity in both planes
- Damping of the vertical instabilities caused by ion trapping in uniform filling
- Reduction of the chromaticity required to store high charge bunches (effect on the head tail instability and on the TMCI)

vertical oscillation





Left plot:

- Blue: betatron lines amplitude without feedback
- green:betatron lines amplitude with feedback

Right plot:

- Relative level of the betatron lines with and without feedback

An upgraded bunch by bunch Libera...

ADC front end: higher sampling rate to sample the position of vertical and transverse position

DAC output: more outputs to drive both the vertical and transverse kicker, or two kickers with different bandwidthes