Bunch-by-Bunch Feedback

and

NC HOM Damped Cavities

for a Current Increase at the ESRF

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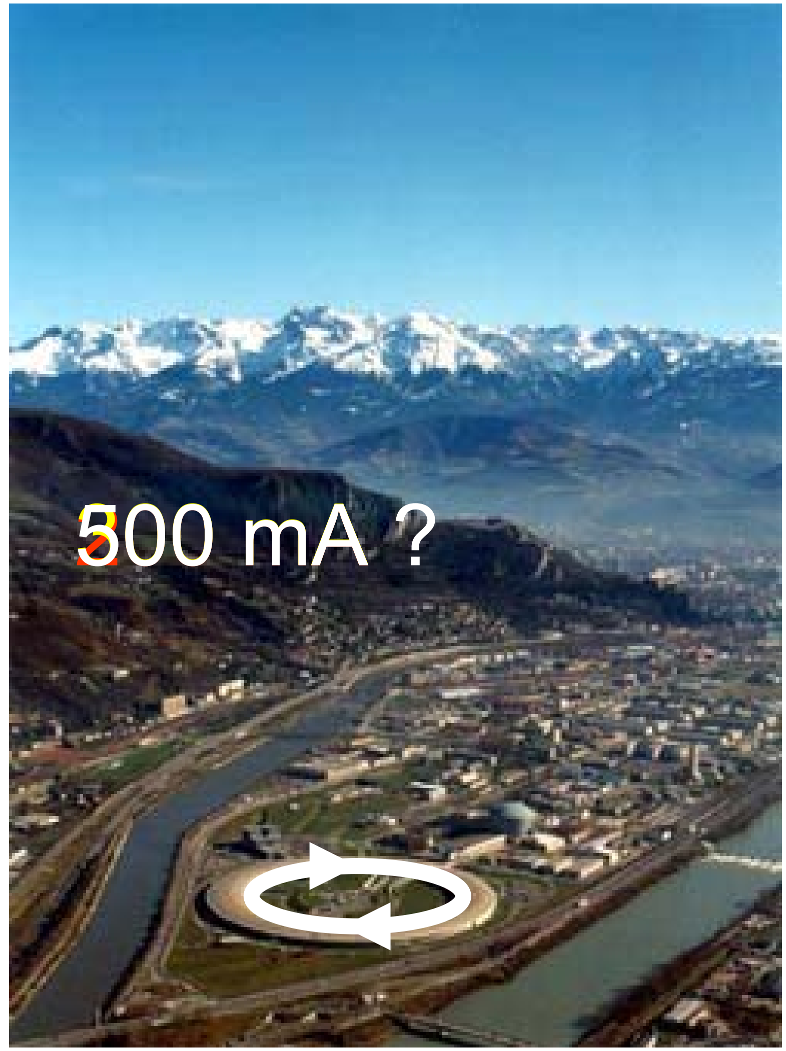


History of current increase at ESRF

ESRF machine commissioned in 1992

1992	100 mA	initial design current reached after a few months
1994		start of user's service operation, while steadily increasing the current
1995	200 mA	delivered to the users
1997		commissioning of a 3rd RF transmitter feeding a third pair of 5-cell copper cavities:
	→	reduced power per RF coupler and per klystron
	→	sufficient redundancy for reliable standard operation at 200 mA

On the way towards 200 mA

- Transverse instabilities:
  - ➢ Resistive wall instability
  - ➢ Ion trapping
  - → mastered by increasing the chromaticity
- Longitudinal Instabilities:
  - ➢ Longitudinal Coupled Bunch Instabilities (LCBI) driven by cavity Higher Order Modes (HOM) for $I_{beam} > 50\ mA$
  - → stabilized by **Landau damping** from transient beam loading in **partial filling** *(200 mA in non symmetric 1/3, later 2/3 filling)*
  - → 1998: new cavity **temperature regulation to ± 0.05ºC**, for precise control of HOM frequencies:

    ⇒ *stable at **200 mA** in **uniform** and symmetric **2 x 1/3** filling*

Further increase of the current

250 mA stored several times in machine physics shifts since 2002

- No limitation from RF power or radiation load
- However, **no** cavity temperature settings found to escape HOM driven LCBI over full 0 to 250 mA range

Two complementary strategies:

I. 300 mA in medium term / Bunch-by-bunch feedback

- LFB: to combat LCBI
- TFB to relax on chromaticity and increase the dynamic aperture
- LFB / TFB: Active damping of longitudinal and transverse multibunch instabilities by means of a broadband bunch-by-bunch feedback

II. 400 … 500 mA in long term / HOM damped cavities

- Temperature detuning (like at Elettra or presently at ESRF) not sufficient
- R&D of strongly NC HOM damped cavities

I. 300 mA at ESRF for users within coming years

- Higher heat load
  - Crotch absorbers: → close to limit ⇒ careful current ramping necessary
    → new crotch absorbers for 400…500 mA under development
  - Remaining storage ring absorbers → OK
  - Beam line front ends being upgraded → OK
  - Beam lines → vary Undulator Length and Gap
- Radiation
  - Bremsstrahlung in ID straights → OK with NEG coated chambers
  - Overall radiation shielding → OK, has been reinforced
- RF system
  - In terms of Beam power, number of cavities, power per RF window:
    - Before 1997: 2 transmitters / 4 cavities → OK for 200 mA
    - Since 1997: 3 transmitters / 6 cavities → OK for 300 mA
  - HOM driven LCBI → need to be cured
    ⇒ Longitudinal Feedback under commissioning

LFB / TFB

- Here: principle and design of bunch-by-bunch feedback explained in detail for LFB

- LFB & TFB developed in parallel

- LFB & TFB makes use of identical Digital Signal Processor hardware

Synchrotron equation - HOM - LFB

$$\tau = \hat{\tau} e^{j\omega t} \Rightarrow \quad \hat{\tau} e^{j\omega t} \left\{ \omega_{s0}^{\ 2} + \frac{2 j\omega}{\tau_s} - \omega^2 \right\} = \frac{\alpha V(t)}{T_0 E_0 / e}$$

External Perturbation

- HOM with

$$\omega_{HOM} \approx p\omega_{RF} + n\omega_0 + \omega_{s0}$$

$$\Rightarrow V(t) = \omega_{HOM} I_{beam} (jR_{HOM} - X_{HOM}) \hat{\tau} e^{j\omega t}$$

  - R_{HOM} produces anti-damping, which cancels natural damping for Coupled Bunch Mode of order n when:

$$I_{beam} = \frac{2\omega_s T_0 E_0 / e}{\tau_s \alpha \omega_{HOM} R_{HOM}}$$

- Feedback: must provide voltage to re-establish sufficient damping
  - Pick up + detector: measure $\hat{\tau} e^{j\omega t}$ (easy) or ~~$\hat{\varepsilon} e^{j\omega t}$ (difficult)~~
  - Calculate kick:

$$V(t) = -\ \text{Adjustable GAIN} \times \hat{\tau} e^{j\omega t}, \quad \rightarrow \text{differentiation!}$$

~~$$V(t) = -[\omega_{HOM} I_{beam} R_{HOM}]^{MAX} \frac{\alpha}{\omega_s E_0} \times \hat{\varepsilon} e^{j\omega t}, \quad \rightarrow \text{no differentiation!}$$~~

  - Apply the kick via an adequate kicker

LFB Correction calculation principle

- Error signal: time deviation
- Correction signal: energy kick
- Problem: the energy kick correction deviation is the derivative of the time deviation; this derivation is a very inaccurate and noisy DSP operation
- Solution: each bunch phase oscillation is a quasi sinusoidal oscillation at f_{sync}, so a derivation can be replaced by a band pass filtering at f_{sync} and a $\pi/2$ phase shift =>FIR digital filter

LFB Gain ?

- The natural damping time at the ESRF is
  - τ_s = 3.6 ms
- The digital signal processing algorithm will allow an active damping time of down to 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 can be compared with:*

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

  and

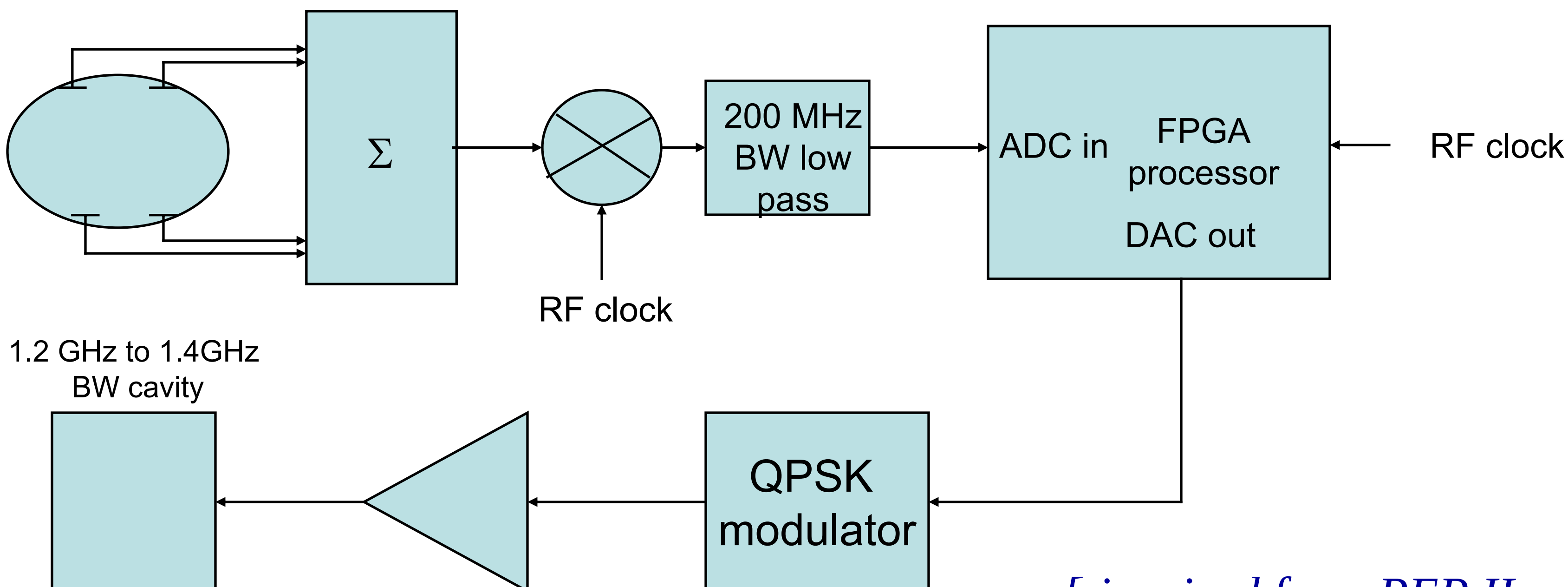
  $\Delta\varepsilon / \Delta\Phi_{352\ MHz} = 3.3\ MeV/°$

  considering that the correction adds up over the active damping time (≈ 160 turns)

LFB - principle

- Bandwidth: $f_{RF}/2 = 176\ MHz$
- Strength depends on quality of phase signal measurement:
  - Resolution (S/N, ADC, …)
  - Spurious signals: RF transmitter noise, Injection glitch, beam loading phase transients

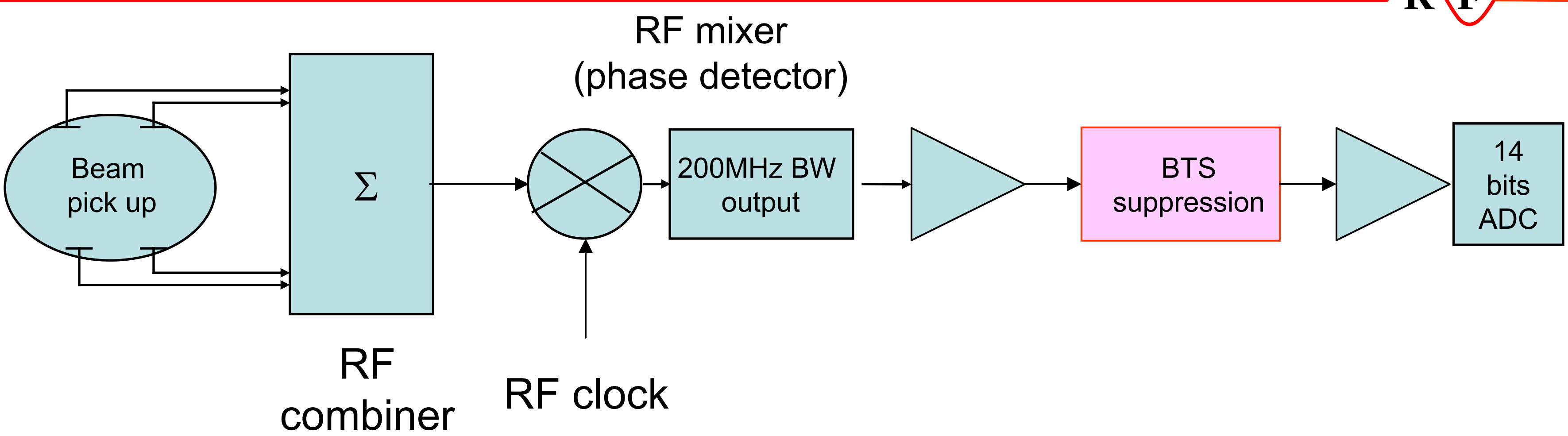
Phase detection at 1.4 GHz



1.4 GHz power amplifier
4 x 50 W = 200 W

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

LFB Phase measurement - Principle

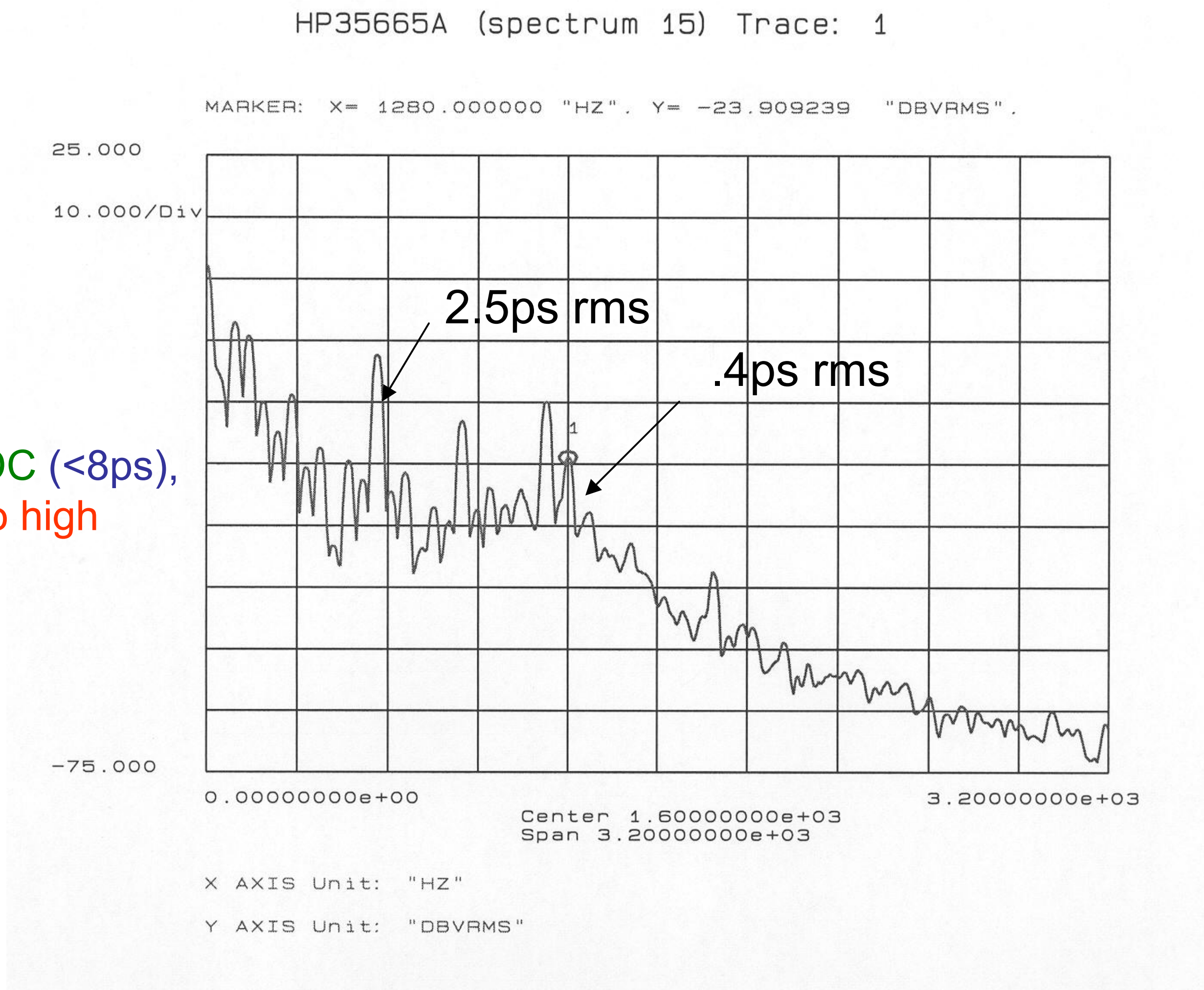


Phase detector sensitivity *[≠ f(freq)]*	$\approx$ *10 mV /°*
Thermal noise *(R = 50Ω, BW = 176 MHz)*	$V_{noise} = \sqrt{kTBR} \approx 6\mu V$
Phase detector turn by turn resolution:	$\approx 5\ 10^{-4}$° $\Rightarrow$ 4 fs$_{@352\ MHz}$
Work at *4 frf = 1.4 GHz* $\Rightarrow$ τ *resolution:*	$\delta\tau \approx$ *1 fs / turn*
14 bit ADC, *LSB = δφ, usable range ± 8000 LSB*	$\Delta\tau_{detect\text{-}range} \approx \pm 8$ *ps*
$\Rightarrow$ Suppression of spurious signal (RF noise, transients) below ±8 *ps !*	

LFB Spurious phase signals- mode 0 signals level

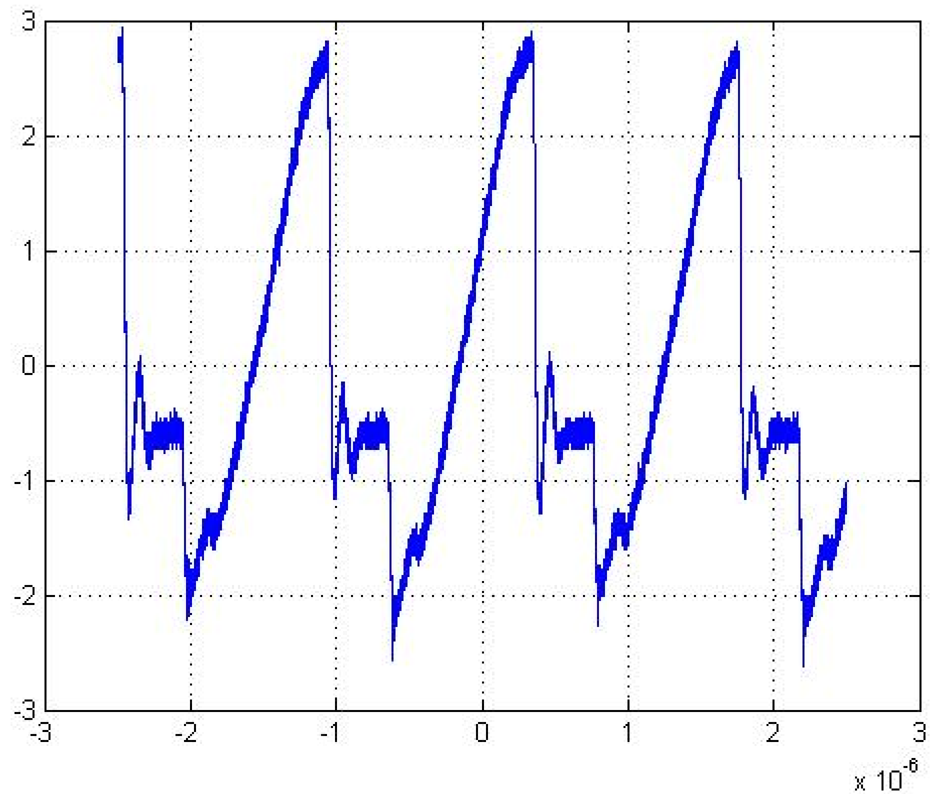
1V/ RF degree
7ps/degree

Will not saturate the ADC (<8ps), but would result in a too high correction signal



LFB Spurious phase signals: beam loading transients

- 2 x 1/3 filling
- Would put +/-15 V at the input of the ADC
- Must be reduced by 30dB (or 31) in the analog front end.



LFB: BTS - Beam Transient Suppression

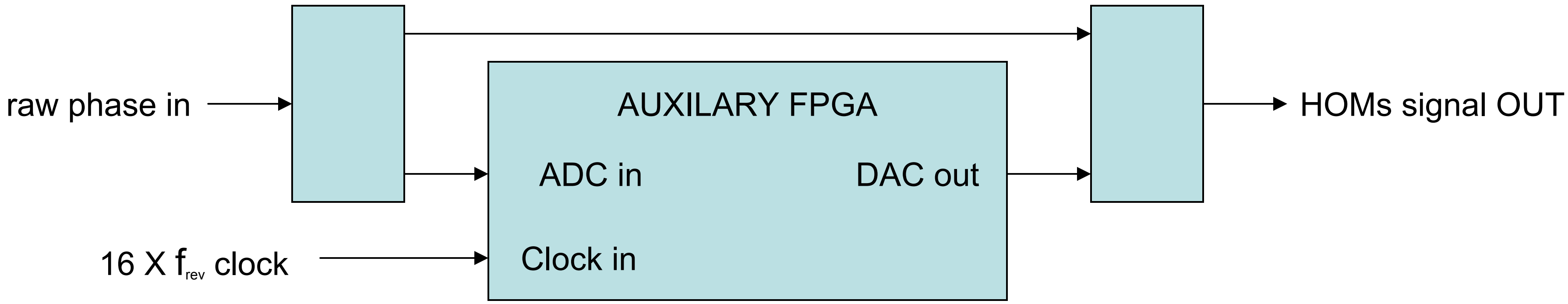
BTS using a dedicated auxiliary FPGA board

PRINCIPLE

- Take N sample per turn of the raw phase signal ϕ_n
- Compute the average $< \phi_n >$ of each sample ϕ_n over P turns with $P \times T_{rev} = T_{sync}$
- Use these $< \phi_n >$ values to generate a signal at the revolution frequency and substract it from the raw phase signal

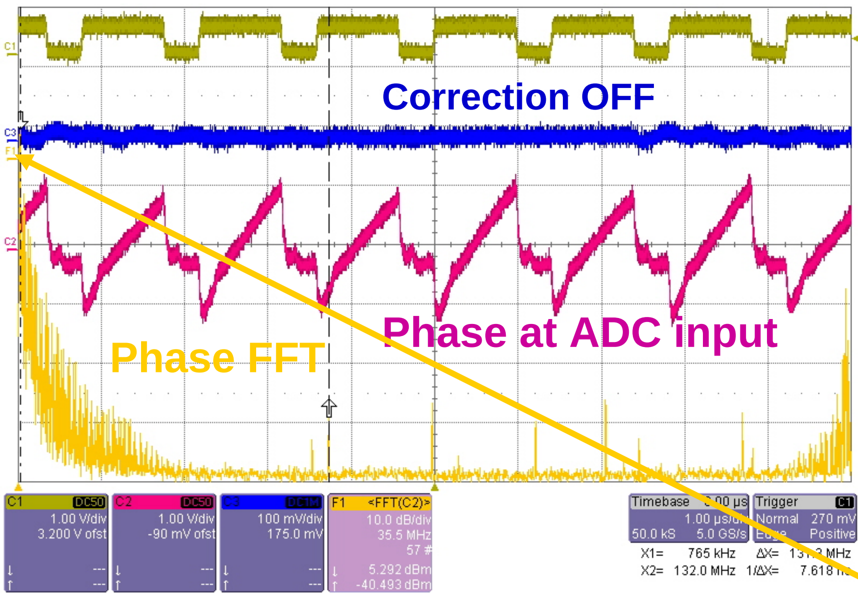
EFFECT

- Narrow bandwidth periodic notch filter removing all the harmonics of the revolution frequency without altering the HOM synchrotron sidebands

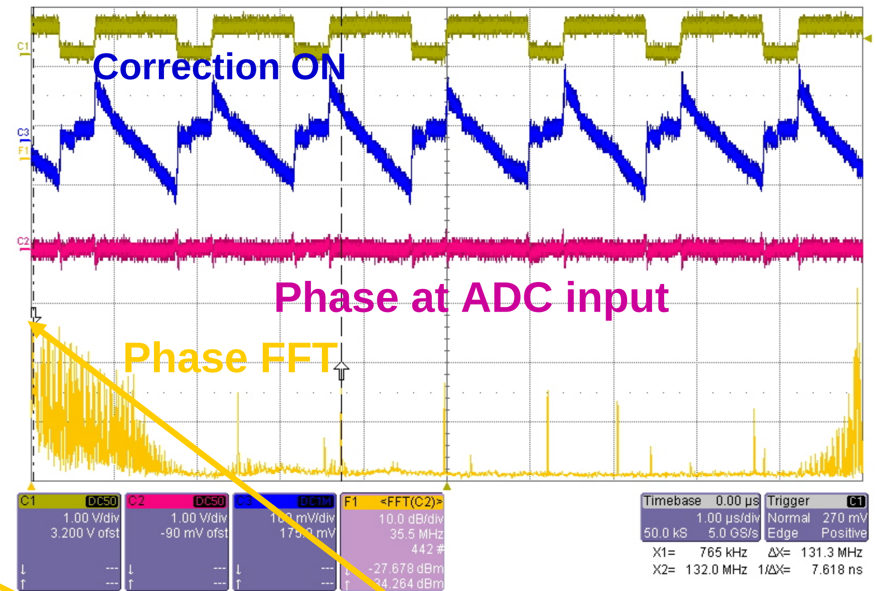


LFB: BTS measured performance in 2 x 1/3 filling

BTS OFF:

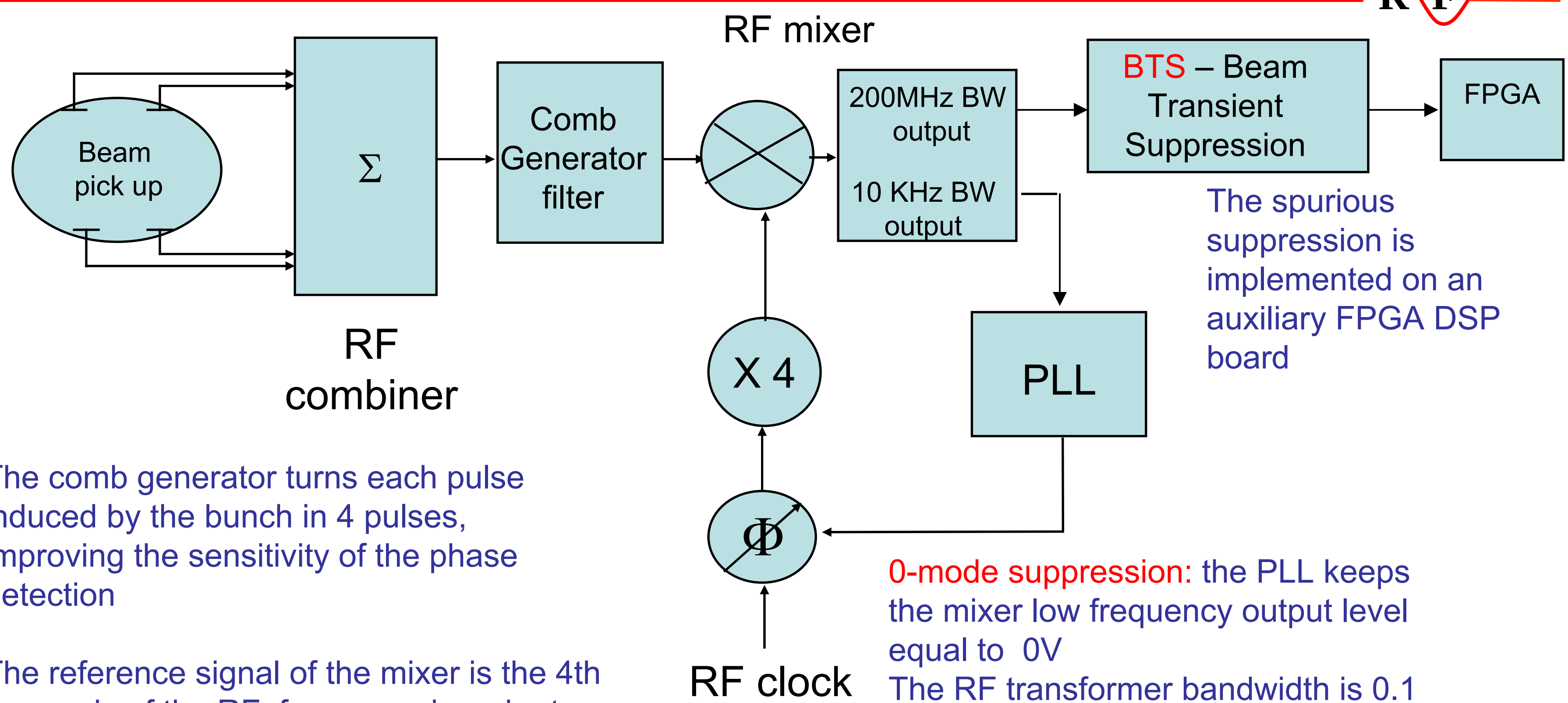


BTS ON:



Phase FFT at f_0 due to partial filling reduced from 5 dBm to -28 dBm

LFB: Phase measurement - pick-up and RF front end



The spurious suppression is implemented on an auxiliary FPGA DSP board

The comb generator turns each pulse induced by the bunch in 4 pulses, improving the sensitivity of the phase detection

The reference signal of the mixer is the 4th harmonic of the RF frequency in order to multiply the phase resolution by 4

0-mode suppression: the PLL keeps the mixer low frequency output level equal to 0V
The RF transformer bandwidth is 0.1 MHz to 200 MHz, attenuating the 0 mode signal by an extra 30 dB

LFB: Output dynamic range: kicker strength

- Remember:

$$\frac{\hat{V}_{kick}}{\hat{\tau}} = 4.7\ \mathrm{V/fs}$$ for 0.5 ms damping time

- So, <u>without safety margin:</u>

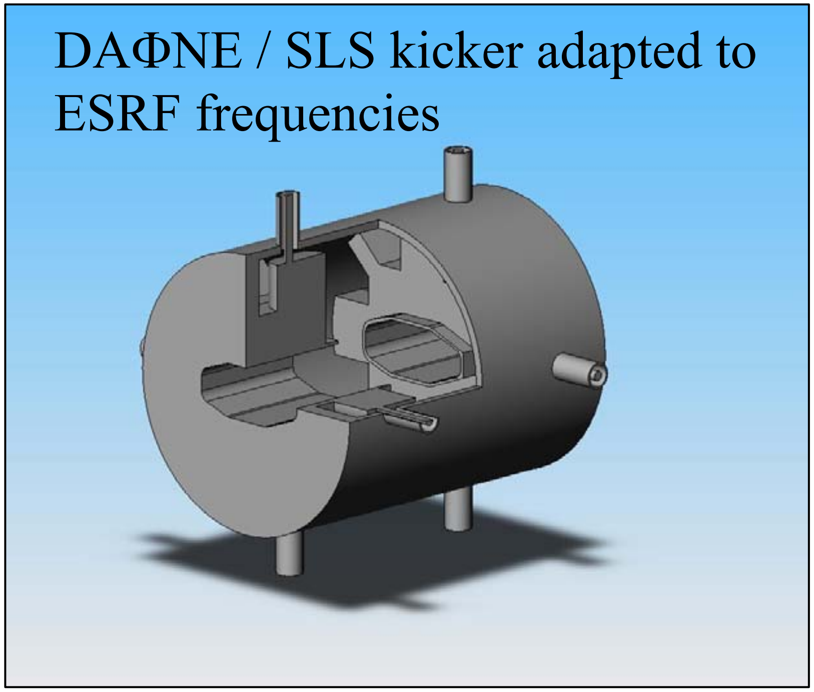
ϕ detector sensitivity $\rightarrow$ 1 fs/turn

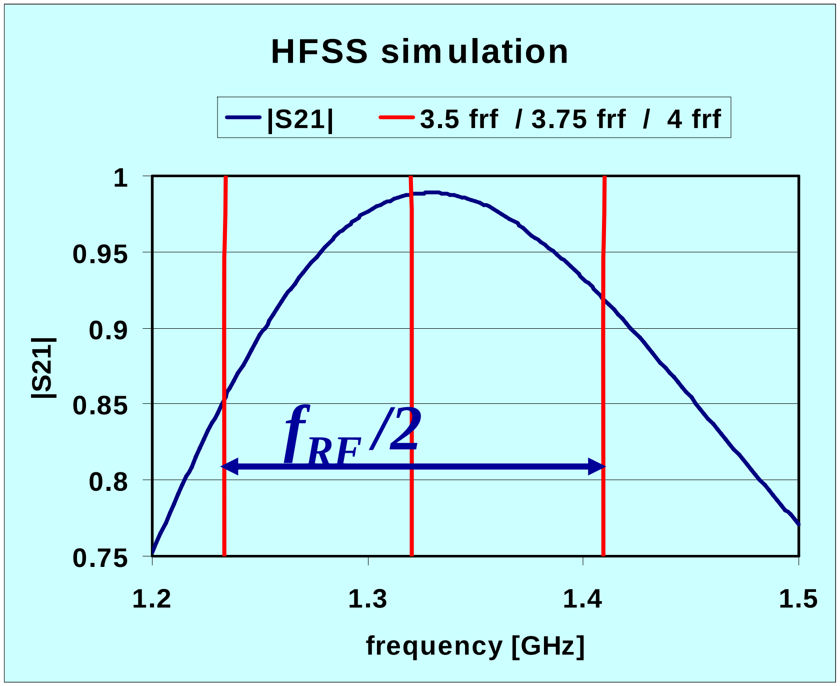
$\Downarrow$

$$\hat{V}_{kick}^{\min} = 4.7\,V$$

LFB: Longitudinal Kicker

- Design:





$$R_{s-loaded} = 1700\,\Omega$$

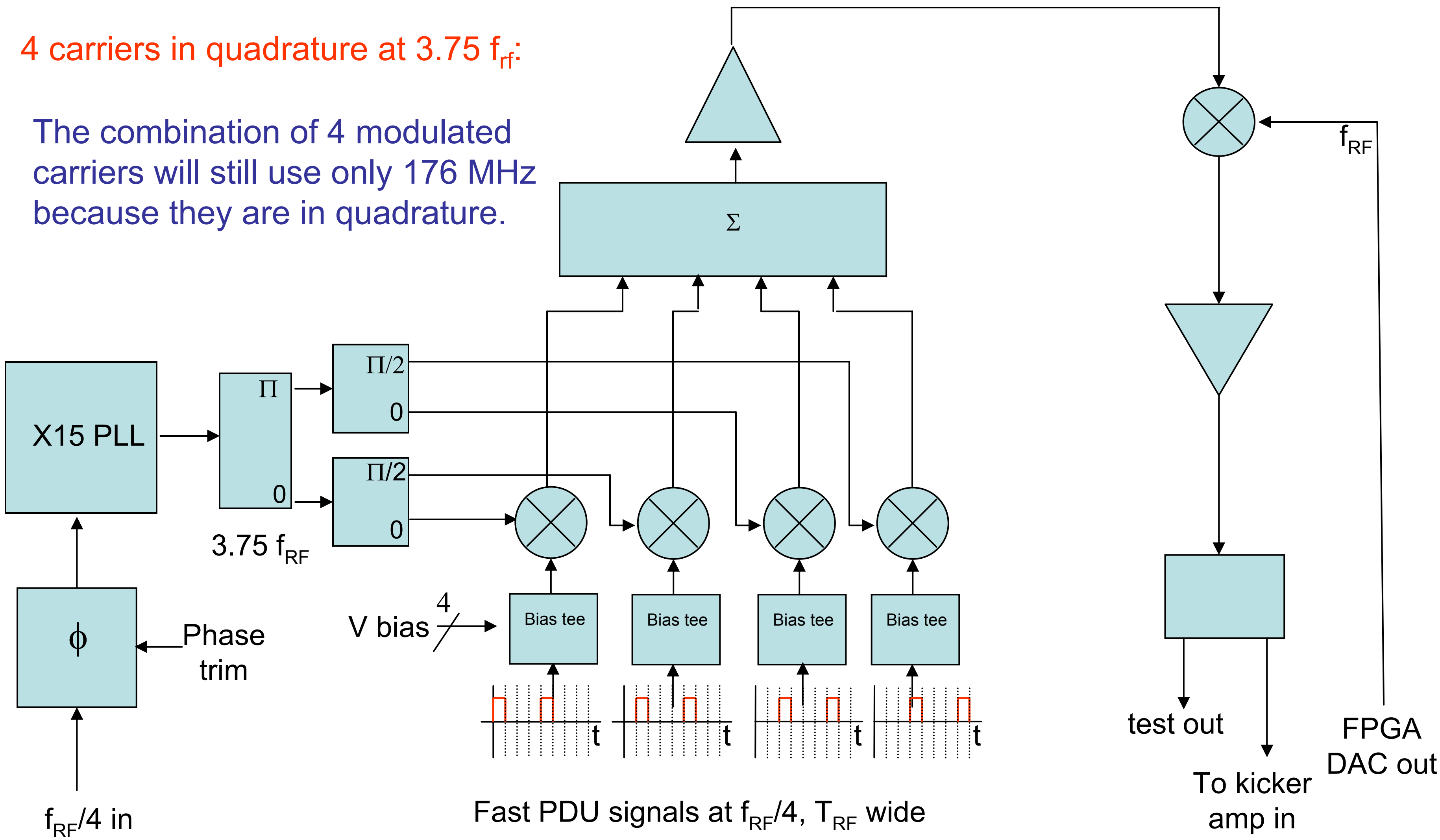
$$\hat{V}_{kick} = \sqrt{P_{incident} \cdot 2R_{s-loaded}} \Rightarrow \hat{V}_{kick} > 600V \text{ for } P_{amplifier} = 200W$$

- Measurement at ESRF: ≈ 500 V kick have been verified

LFB: QPSK modulator: bunch by bunch & $BW = f_{rf}/2$

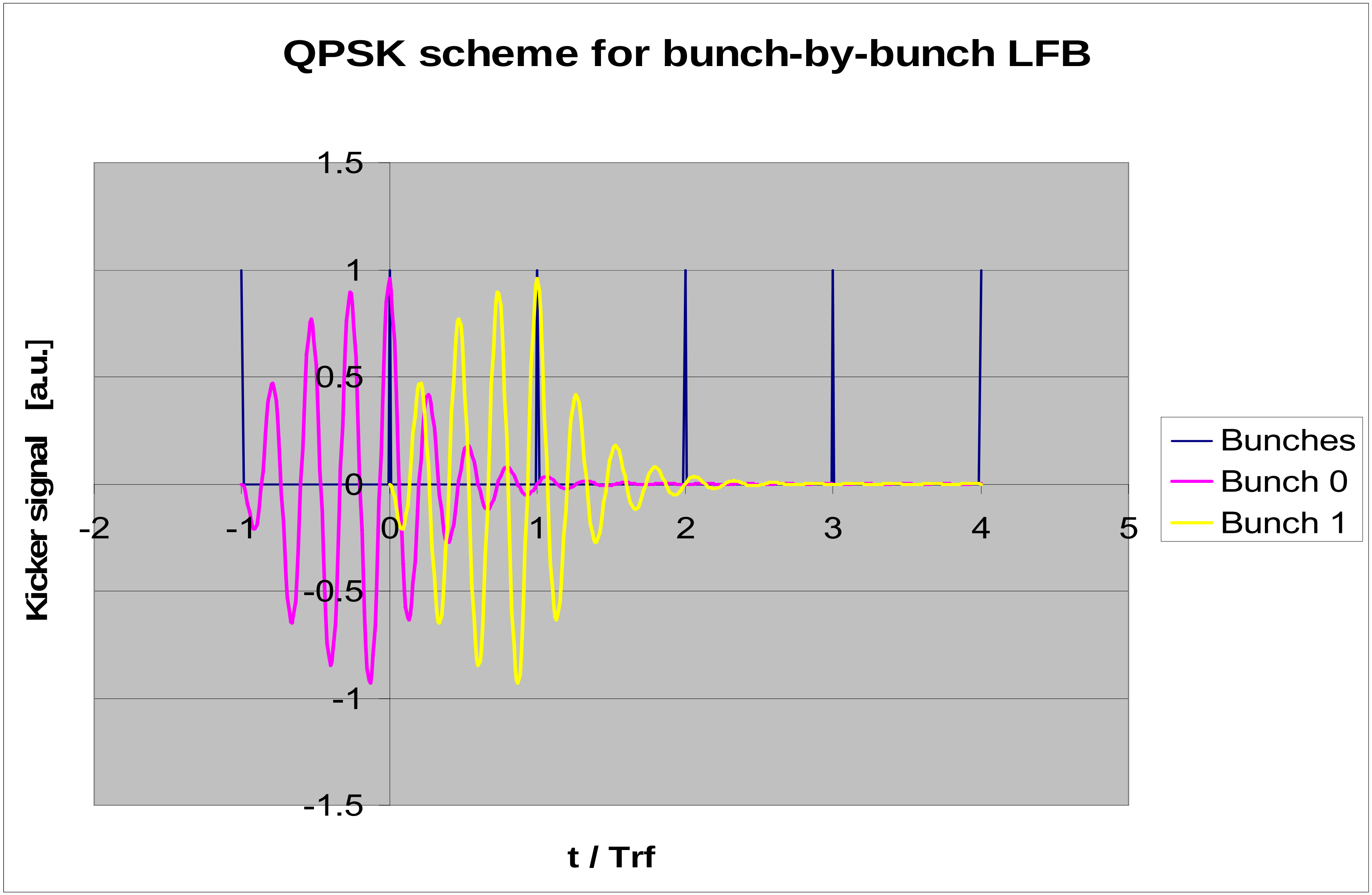
4 carriers in quadrature at 3.75 f_{rf}:

The combination of 4 modulated carriers will still use only 176 MHz because they are in quadrature.



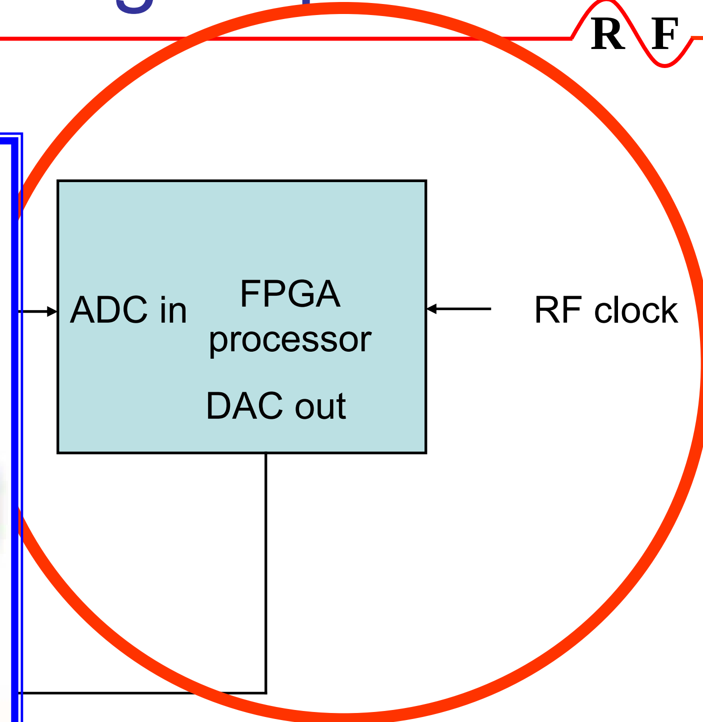
QPSK built up in house using components of the ESRF fast timing system

LFB: QPSK modulator - Bunch by bunch kick



LFB / TFB: FPGA – digital signal processor

Phase detection at 1.4 GHz



Bunch by bunch feedback:

- parallel processing of all 992 bunches
- processes shifted by $T_{rf} = 2.84\ ns$
- Each process sequenced at $T_0 = 2.8\ \mu s$

LFB / TFB: FPGA – digital signal processor

- Virtex-II from Xilinx
  - 100 Gops
  - Code development with System Generator (Xilinx / The MathWorks)
  - Data transfer in and out:
  - Four 14 bit ADC channels 4 x 88 MHz
  - One 14 bit DAC (DDR) at 352 MS/s
  - Fast DDR2 RAM – 64 MB

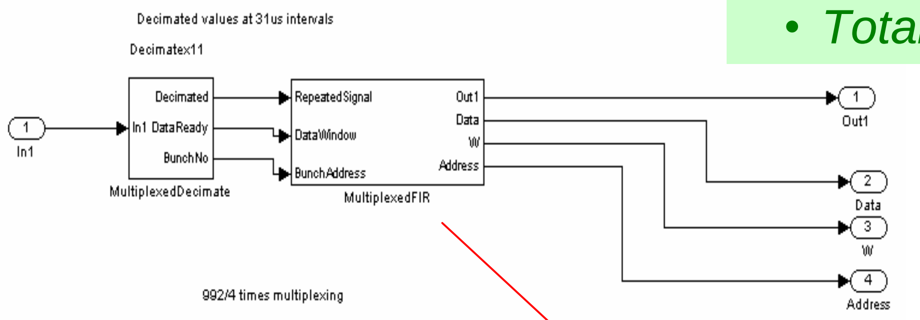
LFB: FPGA – Decimation + FIR + Further mode 0 removal

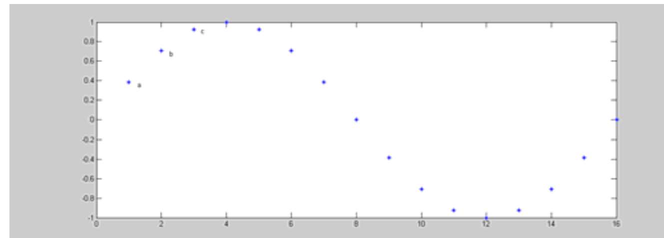
Factor 11 decimation:

$11\ T_0 = 31\ \mu s$

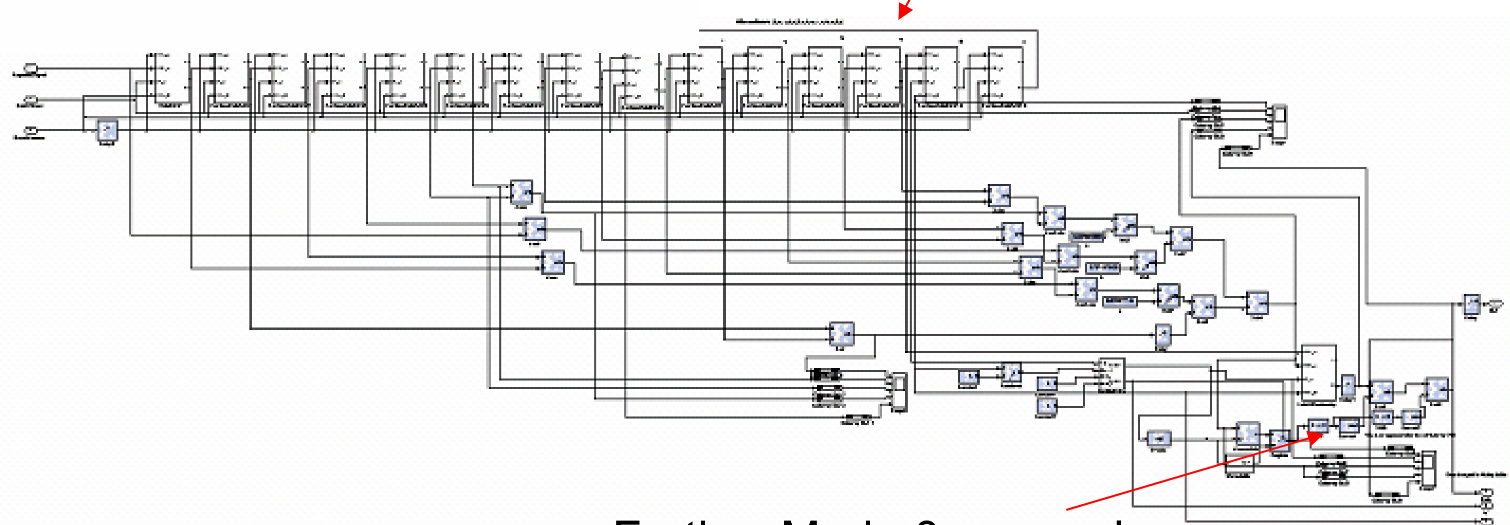
16 TAP FIR: *$16 \times 31\ \mu s = 0.5\ ms = T_{synchrotron}$*

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



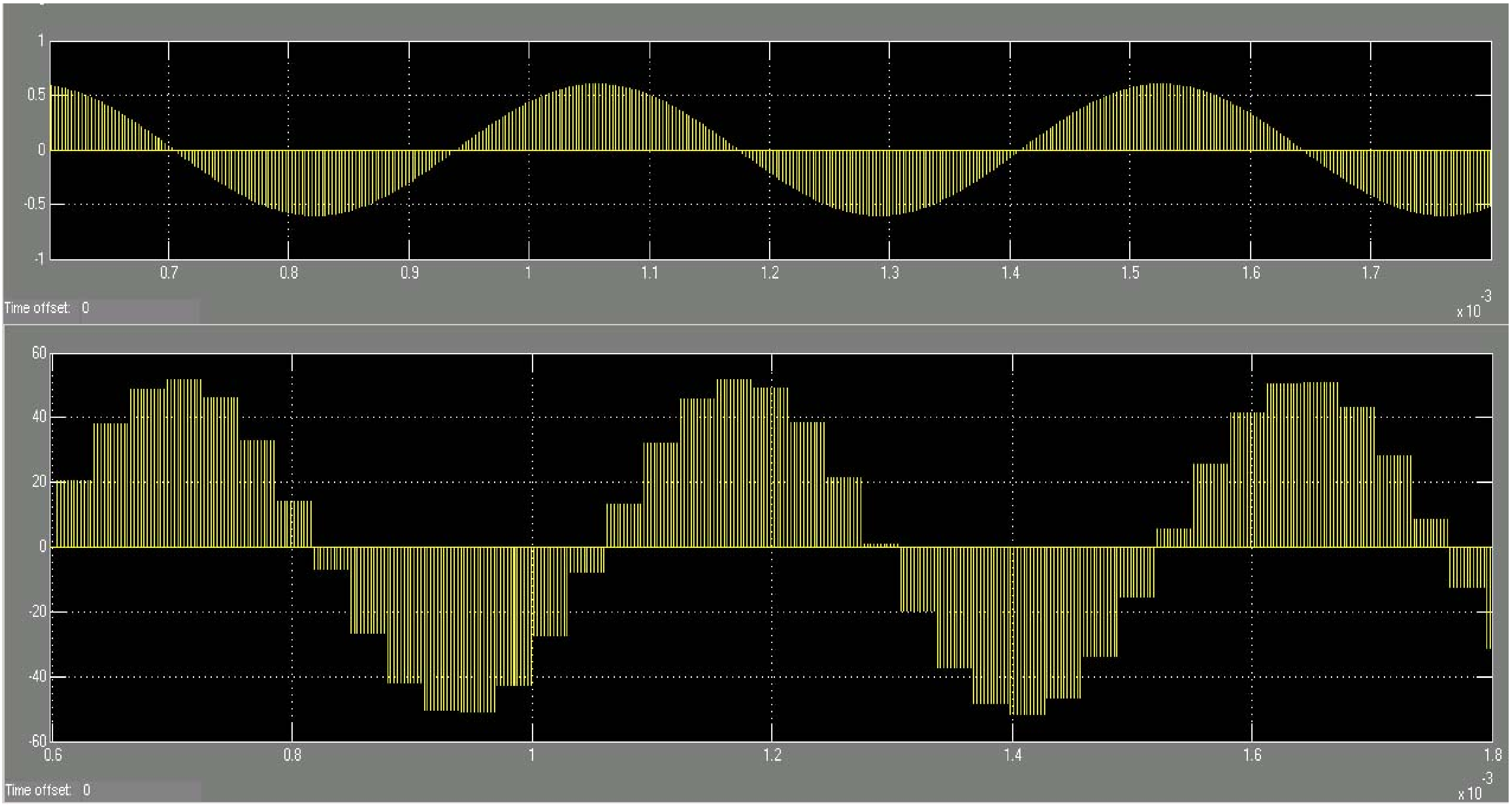


FIR: (a,b,c,1,c,b,a,0,-a,-b,-c,-1,-c,-b,-a,0)

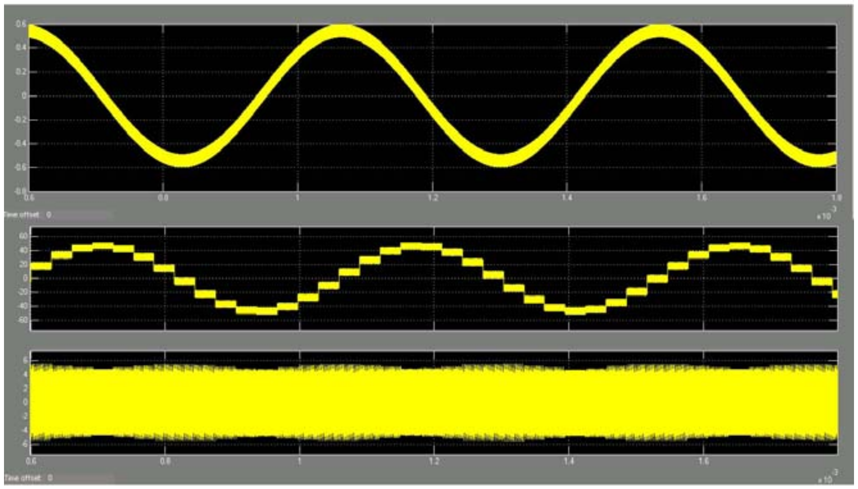


Further Mode 0 removal

LFB: FPGA Simulation - Decimation & FIR



LFB: FPGA Simulation: **further** Mode 0 and Phase transient suppression



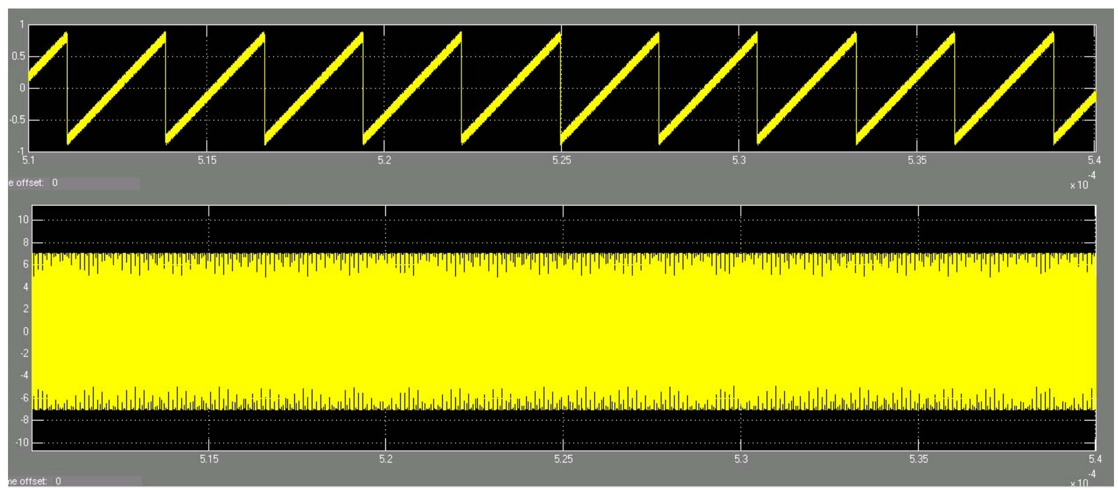
Input Signal

Output correction

Correction with Mode 0 removed

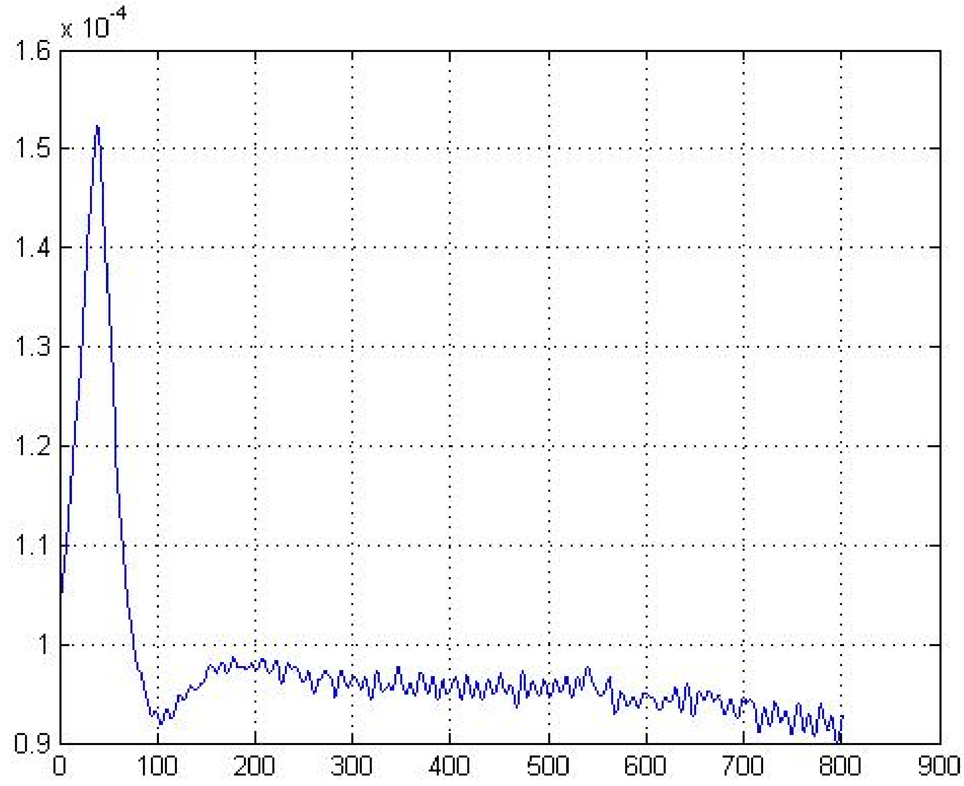
Input Signal with
phase drift during a turn

Output correction



LFB prototype: Measured Rise time /damping times

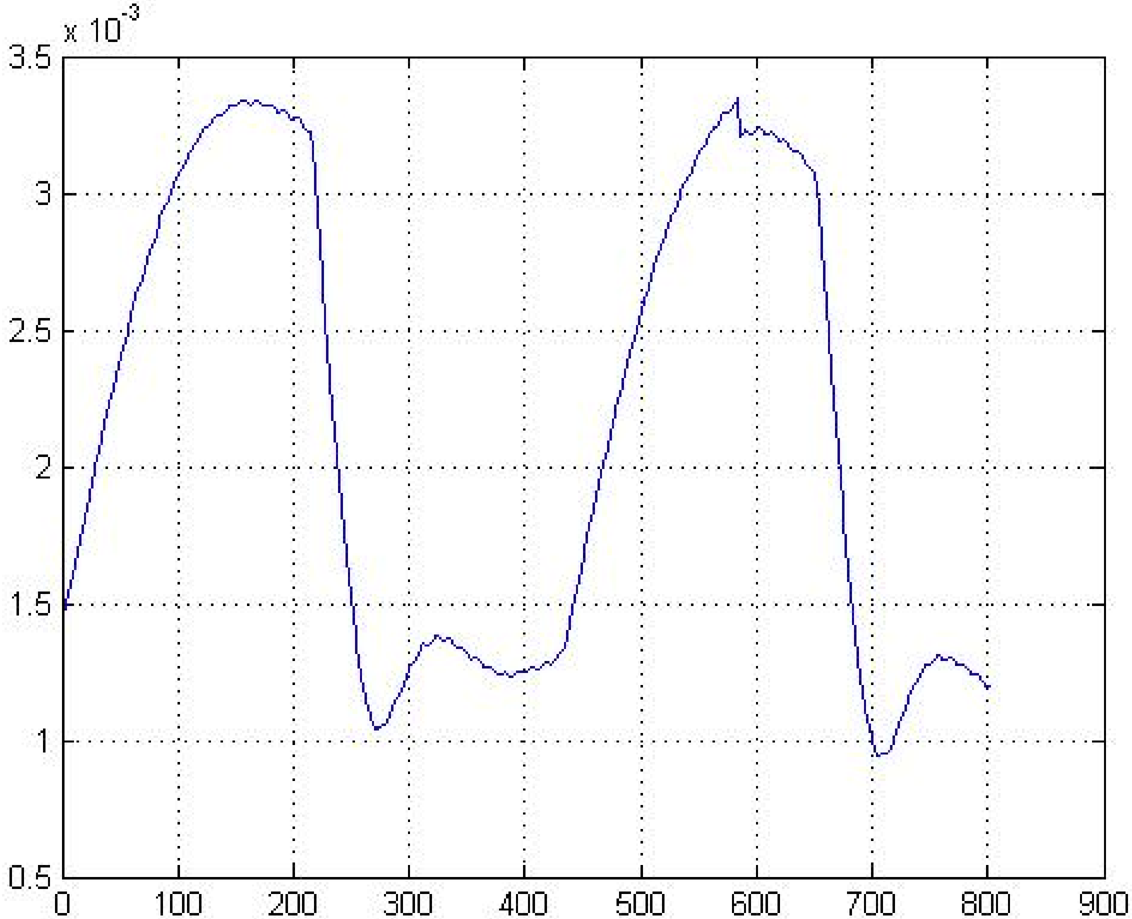
Case of an unstable beam: grow/damp measurement by means of a gated feedback interruption



Mode 407
Unstable (I=250mA)
Time scale: 4ms/div
Vertical scale:10fs/div

LFB prototype: Measured Rise time /damping times

Case of a stable beam: grow/damp measurement using a gated excitation of the beam with a generator at a HOM frequency:



Mode 407
Stable (200mA)
Time scale: 4ms/div

Status of Multibunch Feedbacks

- Main LFB components within the specs:
  - RF front end , QPSK, Libera processor, cavity, amplifier…
- First tests with prototype LFB successful:
  - damping time of tests signals correct all over the span
  - real HOM instabilities damping observed and measured
  - 250mA stored in uniform mode
- *But still a lot to do*
  - Device server and applications
  - Auxiliary subsystems being implemented (tuning help, protection against 4X10mA induced signals…)
  - Build up the system for a reliable day-to-day operation
- Transverse Feedback
  - TFB will follow about 6 months behind
  - Using the same FPGA and very similar software
  - All hardware, including kickers in house

II. Cavity R&D for 400 … 500 mA at ESRF

- Heat load ⇒ issue for vacuum system, photon absorbers and beam lines
- Possibility of implementing canted undulators to obtain more beam lines per straight section
- RF power issue, e.g. for present ESRF parameters:
  - E_0 = 6 GeV
  - U_0 = 5 MeV/turn

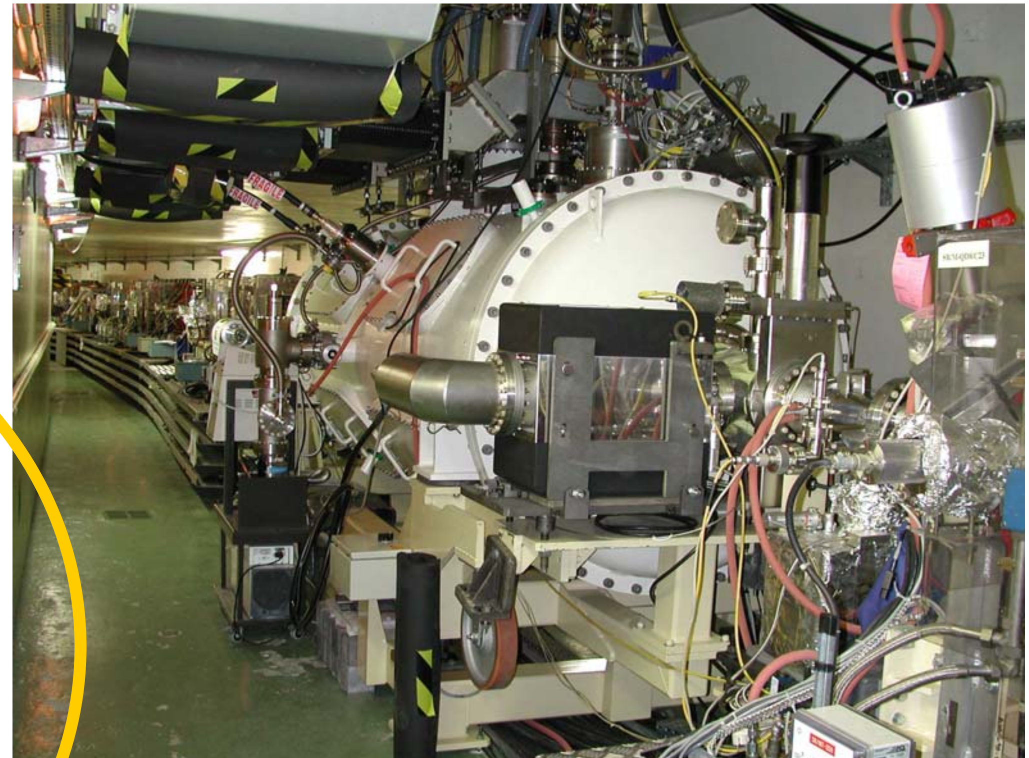
  ⇒ beam loading: P_{beam} = 2.5 MW at 500 mA ($P_{tot} \approx$ 2.6 … 3.3 MW)
  while V_{acc} = 9 MV is very modest
  - 6 existing ESRF five-cell cavities / each having 2 RF windows are no longer adequate:
    - ◊ RF window power and coupling ⇒ $I_{beam} \leq$ 300…350 mA
    - ◊ Whereas available voltage: 15 MV (more than required)
  - RF Power issue ⇒ **new cavities required** with at least **1 coupler/cell**
- HOM driven LCBI or TCBI

  ⇒ **Feedback** and **HOM damped cavities !**

  NB: LFB → reasonably ≈ 5 x $I_{threshold}$

Strongly HOM damped SC Cavity - e.g. SOLEIL cavity -

- Successful test at ESRF in 2002
- 3 modules provide 9…15 MV
- Excellent HOM suppression (CBI thresholds of several Amp's)
- But
  - ➢ 6 cells & 6 couplers in total
  - ➢ Max 200…250 kW/coupler
    - ⇒ $P_{beam} < 1500$ kW
    - ⇒ $I_{beam} < 300$ mA
- 500 mA would require R&D on RF couplers:
  - ➢ Either 500 kW/coupler
  - ➢ Or 2 couplers per cell
- Reliability of Cryogenic System for a light source?



Superconducting SOLEIL cavity at ESRF

Not the preferred solution for ESRF current upgrade

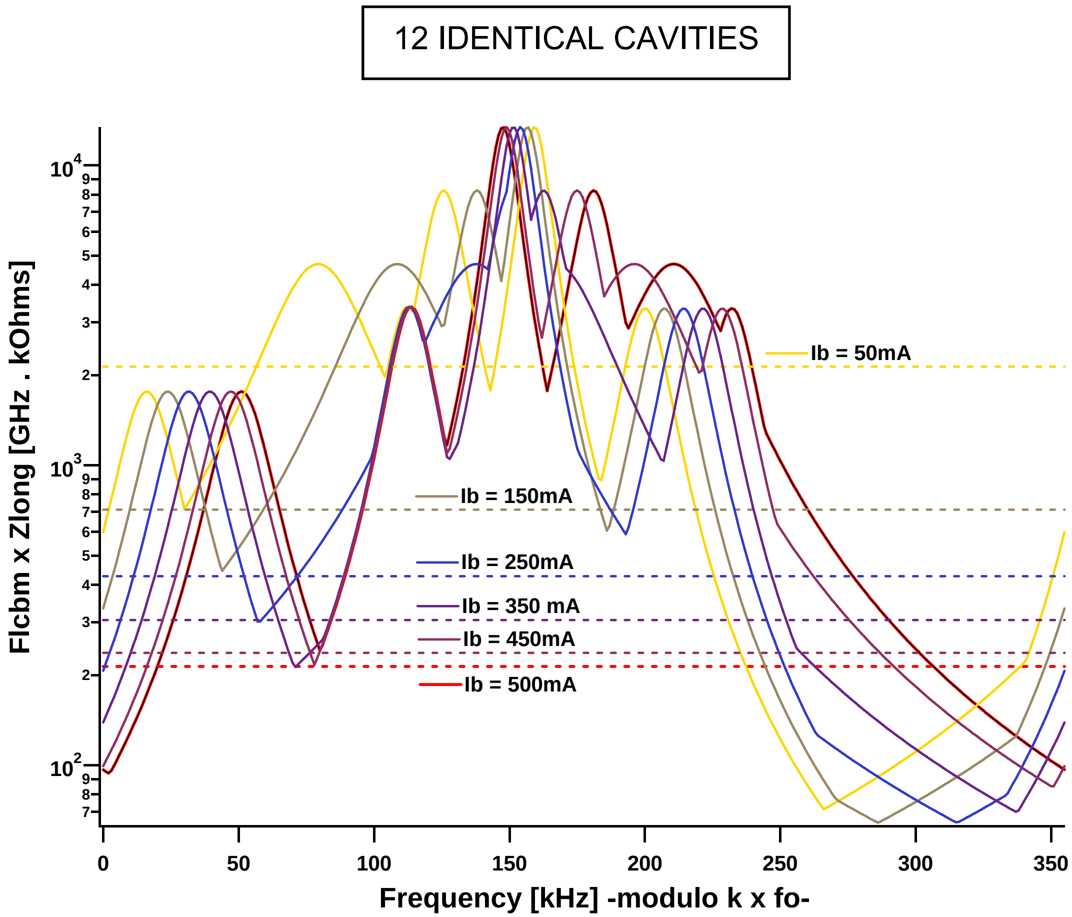
Single cell NC cavities

- 500 mA at ESRF: 18 single cell cavities
  - 6 cavities x 3 RF sections (presently 2 five-cell cavities / RF section)
  - Conservative in terms of power handling
    - ≈ 160 kW/coupler
    - 0.5 MV/cavity
    - still some redundancy for high reliability
- HOM ?
  - Temperature detuning of HOM as done systematically with Ellettra cavities (Elettra, ANKA, SLS,…) and at ESRF on 5-cell cavities

  or

  - Strong HOM damping as at PEP, BESSY, soon ALBA, …

Simulation: T° detuning of HOM – 12 identical cavities

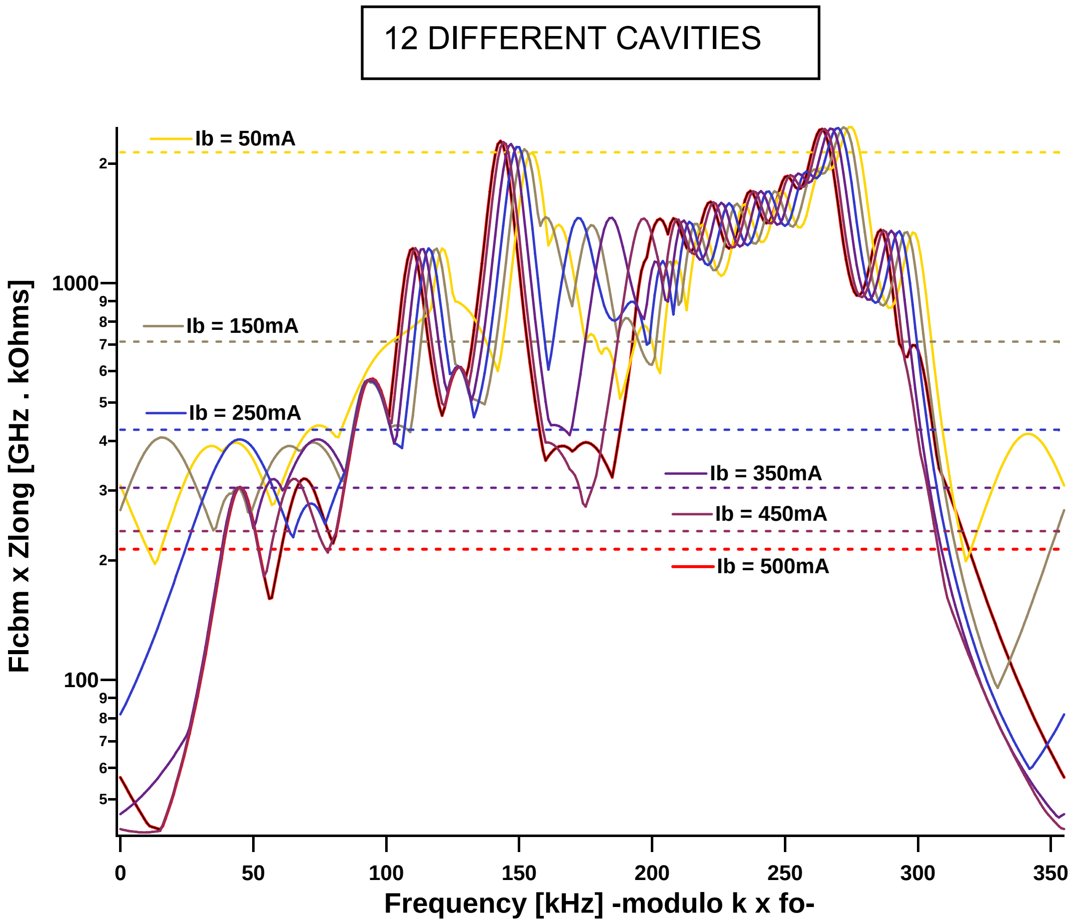


Assumption:

- 12 identical Elettra cavities scaled to ESRF frequencies
- Curves represent the worst impedance at the considered frequency
- Stability ⇔ impedance near kf_0 = k x 355 kHz, i.e. near 0 and 355 kHz on the graph lower than threshold
- Here a narrow stable working point is found

Cavity Numb.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Temp / ºC	60	60	60	60	60	60	60	60	60	60	60	60

Simulation: T° detuning of HOM – 12 different cavities

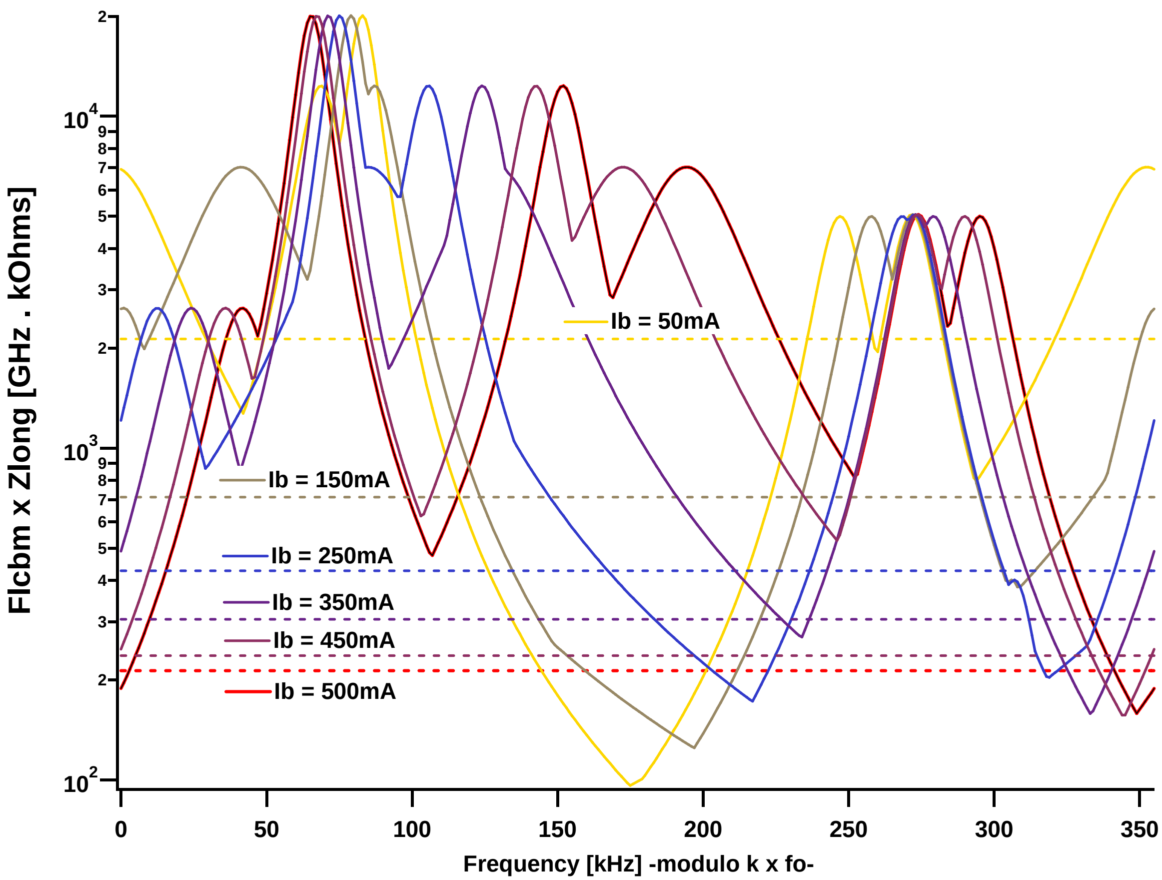


Assumption:

- 12 scaled Elettra cavities with a spread in their HOM frequencies corresponding to measured manufacturing tolerances
- Here again a stable working point is found

Cavity Numb.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Temp / °C	62.5	58	49.5	63.5	49.5	57	43.5	55	43	60.5	56	41.5

Simulation: T° detuning of HOM – **18 identical** cavities



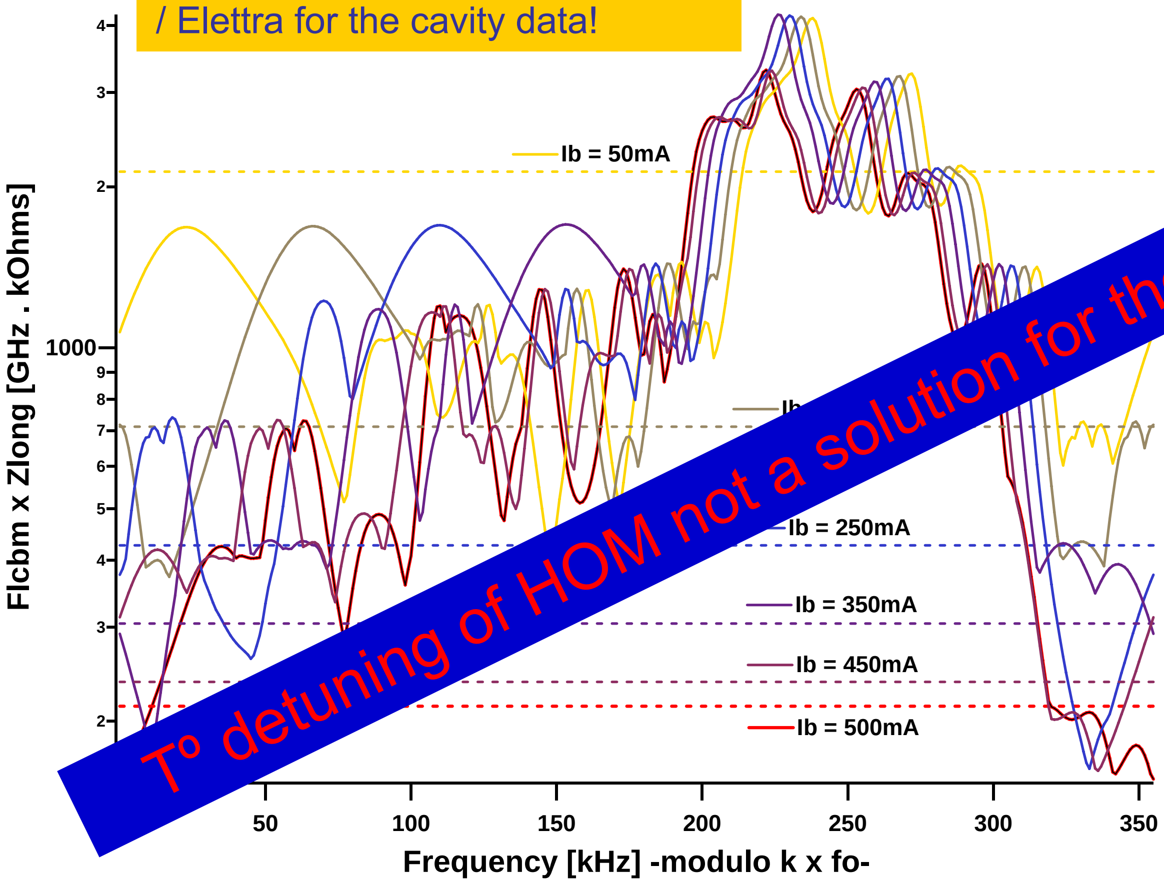
Assumption:

- 18 scaled identical Elettra cavities
- No stable working point was found, covering the injection from 0 to 500 mA
- The working point found here is only stable at 500 mA, but not below
- NOT acceptable for stable operation at ESRF
- Transverse HOM have even not yet been considered !

Cavity Numb.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*
Temp / ºC	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71

Simulation: T° detuning of HOM – **18 different** cavities

Many thanks to Michele Svandrlik / Elettra for the cavity data!



Assumption:

- 18 scaled diff... cavities ... in their HO... es ... ding to measured ... ufacturing tolerances

...s for 18 identical cavities:

- Again no stable working point was found, covering the injection from 0 to 500 mA
- The working point found here is only stable at 500 mA, but not below
- NOT acceptable for stable operation at ESRF
- Transverse HOM have even not yet been considered !

Cavity Numb.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Temp / ºC	51.5	56.5	44	57	47.5	51	44	51	48.5	49	51	47	42	57.5	45	53	55.5	55.5

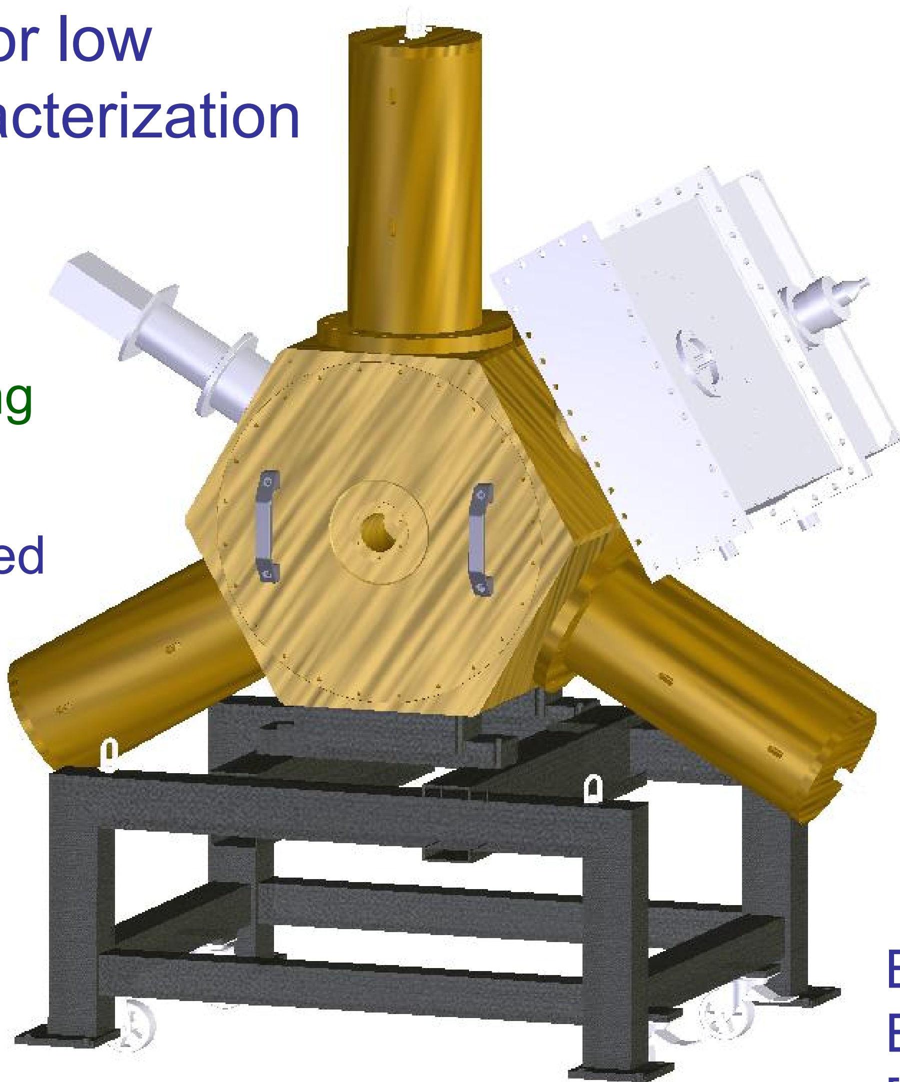
R&D: HOM damped NC single cell cavity

Lab prototype for low power RF characterization & optimization

3 D Model / drafting office : complete

Body: manufactured

HOM dampers: detailed drawings being finalized

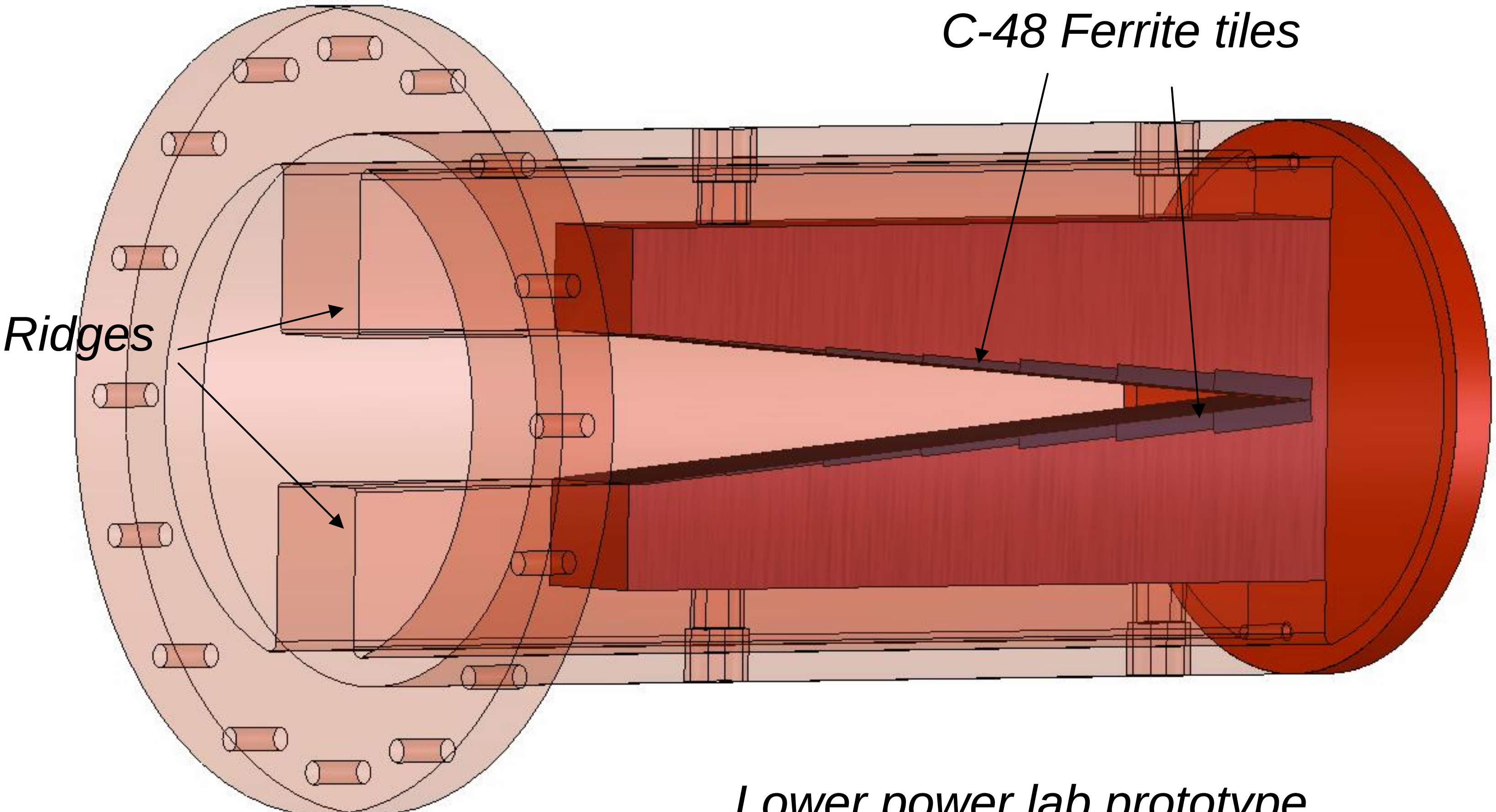


Based on 500 MHz EU cavity design [BESSY]

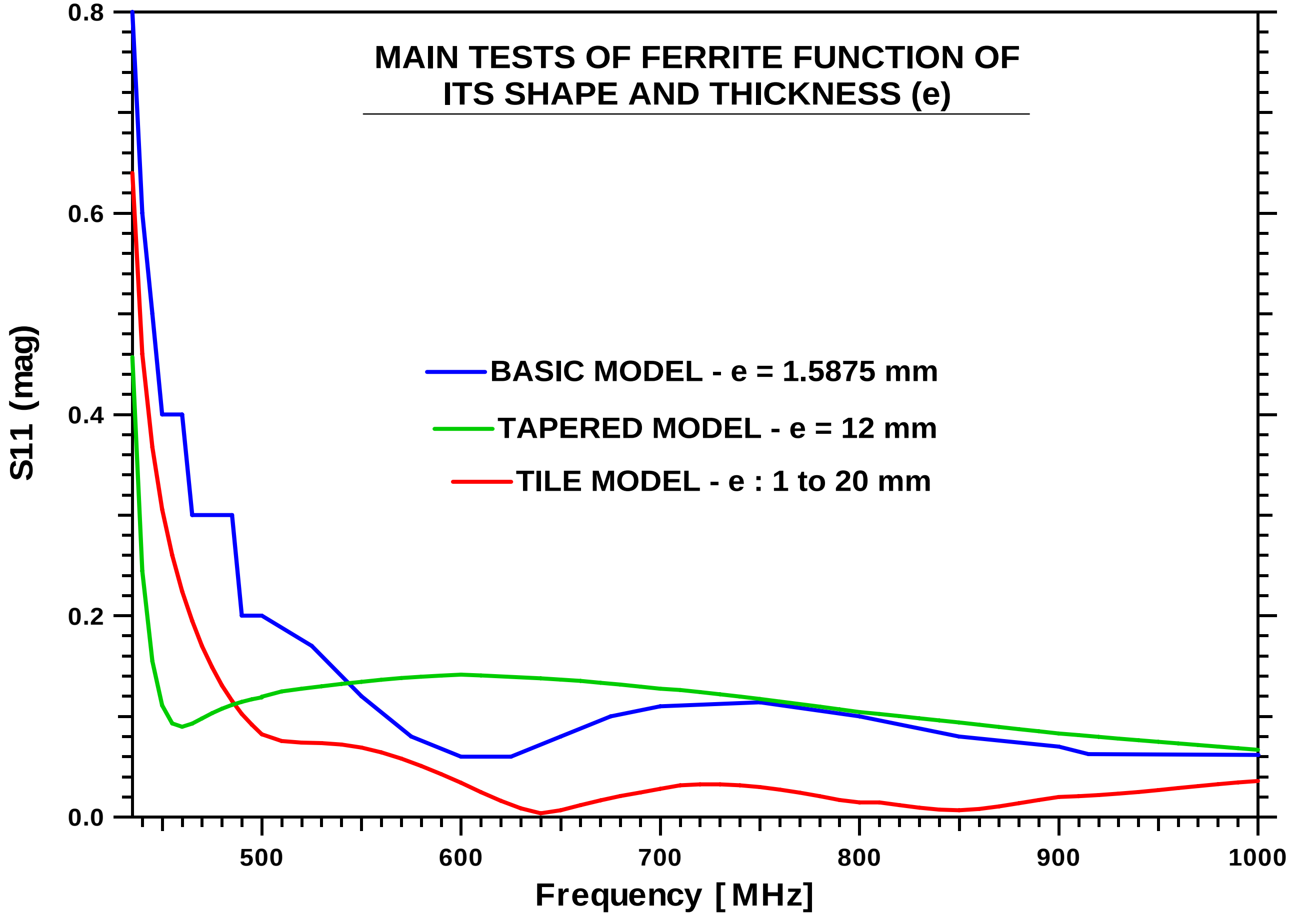
Optimization of nose cone cell geometry

	ESRF design – 1st iteration (based on "EU" cavity model) GdfidL simulation for the naked cavity	Existing ESRF 5-Cell Cavity URMEL simulation for a single cell
fo (MHz)	352.200	352.200
Qo	47 500	47 300
Rs (kΩ)	7100	6 700
Rs/Q (Ω)	150	142

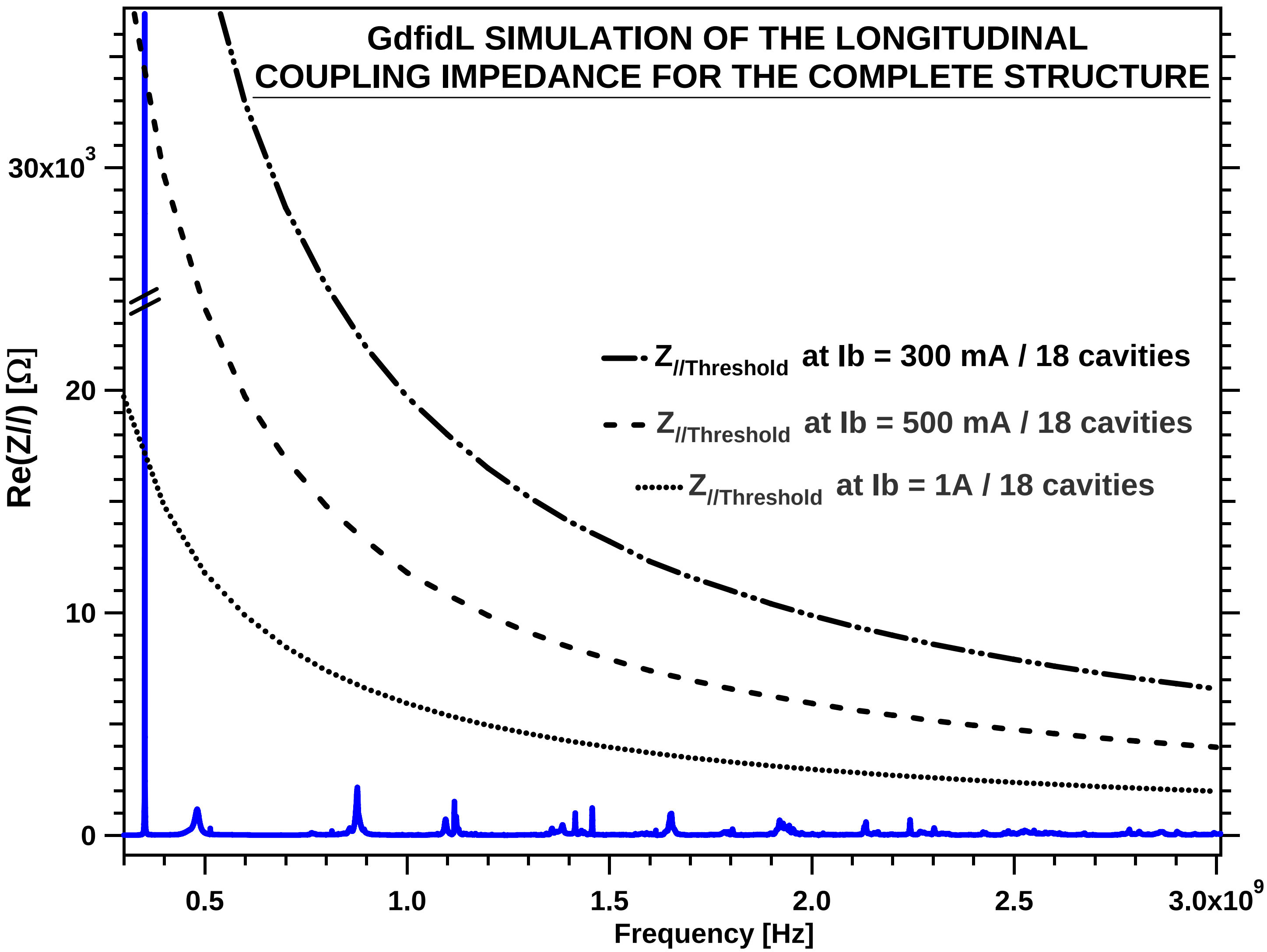
HOM damper with ferrite absorbers



HFSS Optimization of ferrite geometry



GdfidL simulation of HOM damped cavity



CONCLUSION

1. 300 mA soon

   - LFB system Prototype successfully tested
   - Machine physics runs: stable 300 mA at the ESRF expected in the coming months
   - In User Service Mode: Ramp the current slowly / regular checks of crotch absorbers

2. 400 … 500 mA in longer term, still needs a lot of R&D:

   - Single cell strongly HOM damped NC cavities under development
   - New crotch absorber design required
   - Many Other power / vacuum issues