

# LLRF FOR CRAB CAVITIES

15.11.2011

LHC-CC11, 5<sup>th</sup> LHC Crab cavity workshop, CERN  
P. Baudrenghien CERN-BE-RF

# Outline

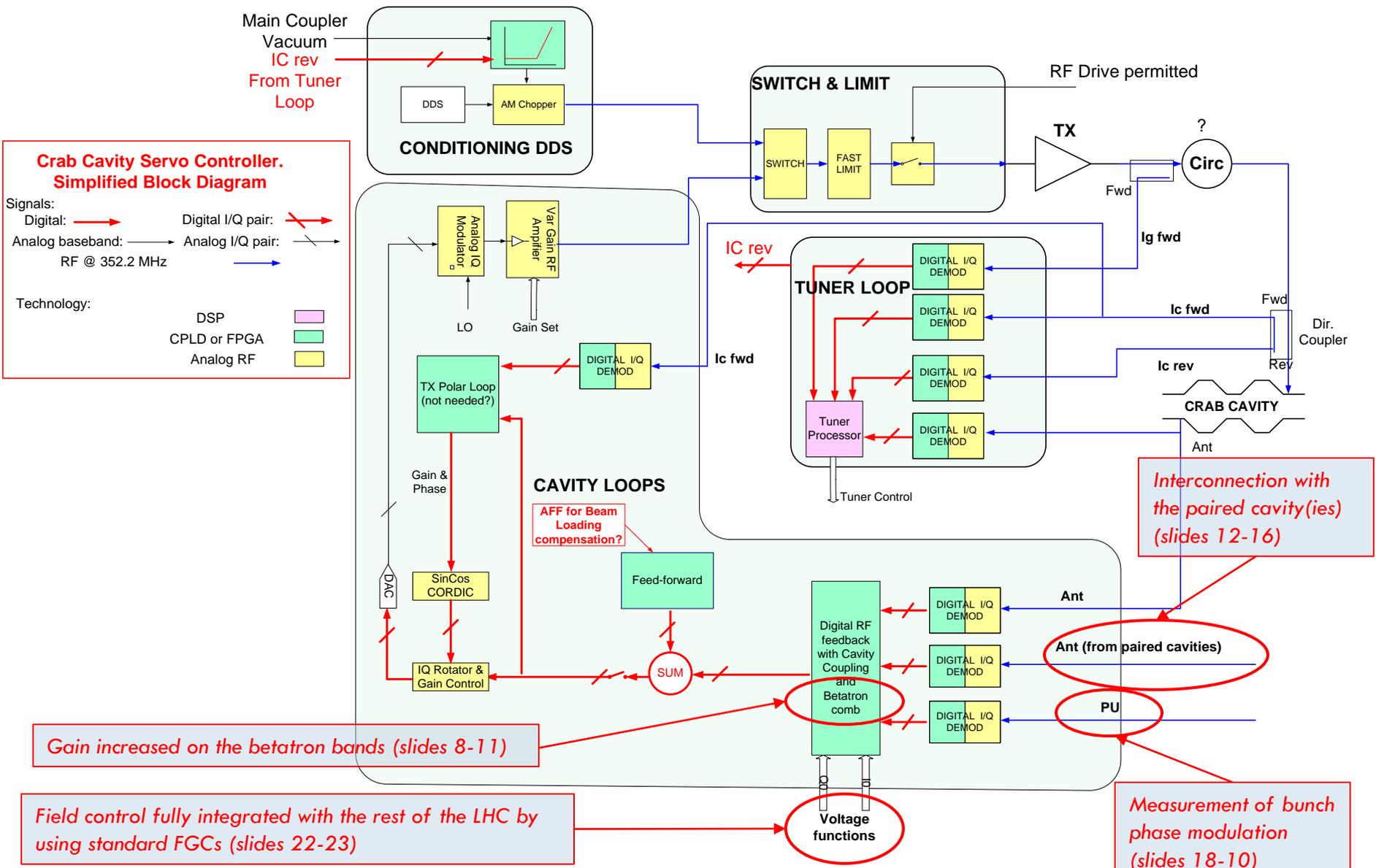
2

- **LLRF architecture**
- **Feedbacks**
- **Modulation of beam phase**
- **Operational scenario**
- **LLRF status**
- **Some conclusions**

3

# LLRF Architecture

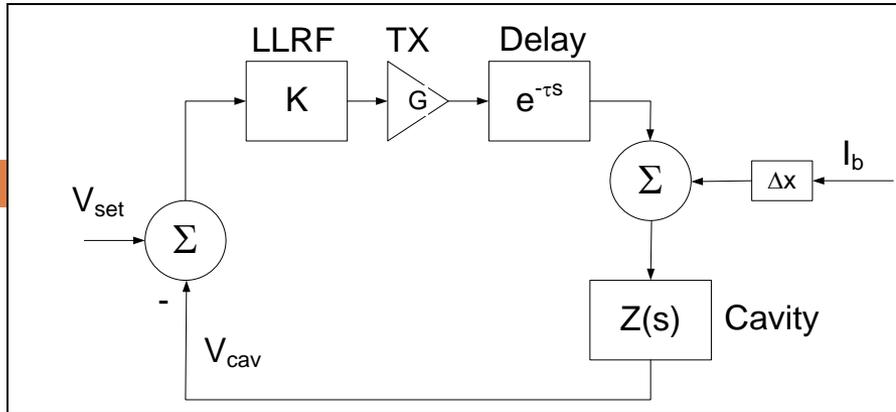




Version: 20111111

# Feedbacks

- Direct RF feedback and loop Delay
- Betatron Comb filter
- Coupled Feedback



# RF feedback

- The Open-Loop gain is limited by loop stability consideration. We get

$$[KG]_{\max} \approx \frac{Q}{R\omega_0 T}$$

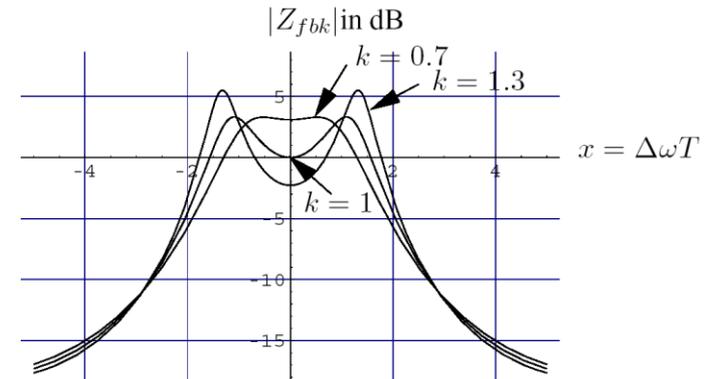
- leading to the effective cavity impedance at resonance

$$Z_{\text{eff}}(0) = \frac{\frac{R}{Q} Q_L}{1 + KG \frac{R}{Q} Q_L} \approx \frac{R}{Q} \omega_0 T$$

- and the 2-sided closed loop BW with feedback  $\Delta\omega_{-3} \approx \frac{2.6}{T}$

[Boussard1] D. Boussard, Control of Cavities with High Beam loading, IEEE Transaction on Nuclear Science, Oct. 1985

P. Baudrenghien (BE-RF)



Effective impedance for varying gains.

- The **final bandwidth** and **beam loading performances** depend on **Loop delay T** and **cavity geometry R/Q**. It does not depend on the actual  $Q_L$
- Lesson: **Keep delay short** and **TX broadband** to avoid group delay.

# Betatron Comb filter 1/3

8

- One-turn delay filter with gain on the betatron bands

$$H(z) = \frac{(1 - z^{-N})z^{-N}}{(1 - a e^{i2\pi Q} z^{-N})(1 - a e^{-i2\pi Q} z^{-N})}$$

- 2 N Poles on the betatron frequencies

$$p_{k+} = \sqrt[N]{ae^{i2\pi\frac{Q}{N}}} e^{i2\pi\frac{k}{N}}$$

$$p_{k-} = \sqrt[N]{ae^{-i2\pi\frac{Q}{N}}} e^{i2\pi\frac{k}{N}}$$

$$k = 0, 1, \dots, N-1$$

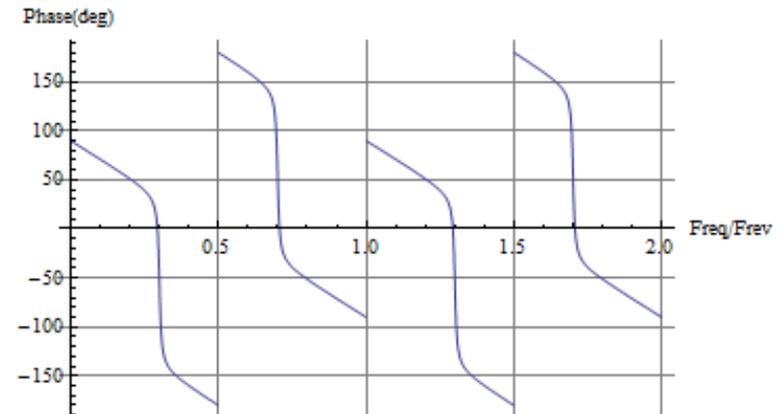
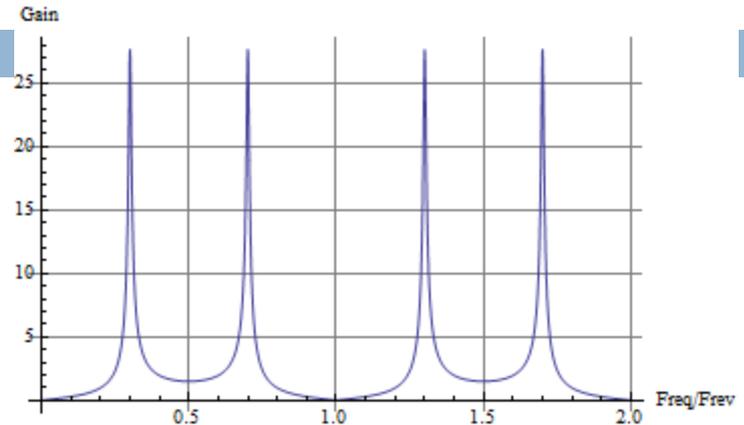
- Reduction of noise PSD **where the beam responds**
- Reduction of the effective cavity **impedance thereby improving transverse stability**
- Zeros on the revolution frequency lines

$$z_k = e^{i2\pi\frac{k}{N}}$$

$$k = 0, 1, \dots, N-1$$

- No power wasted in transient beam loading compensation with off centered beam

P. Baudrenghien (BE-RF)



Betatron comb filter response with  $a=31/32$  and non-integer  $Q=0.3$ . Observe the high gain and zero phase shift at  $(n \pm 0.3)$  freq

15.11.2011

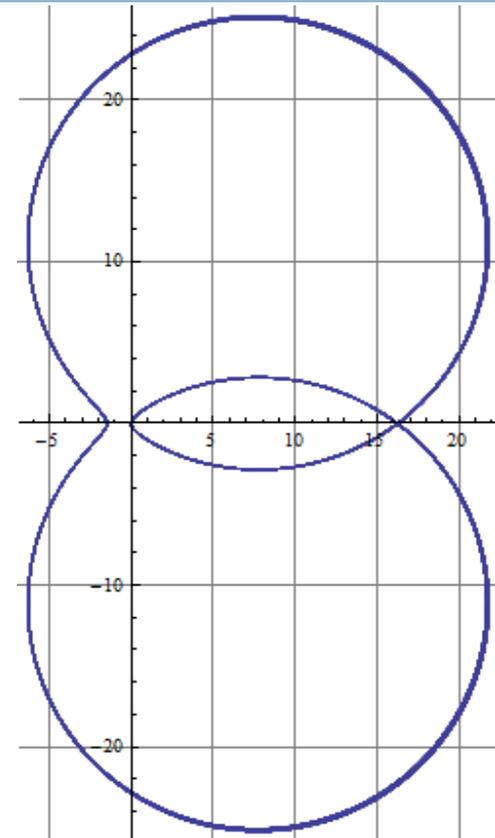
# Betatron Comb filter 2/3

9

- The gain is limited by the 180 degrees phase shift between two revolution frequency lines
- To keep 10 dB gain margin, the gain on the betatron lines is limited to  $\sim 6$  linear (16 dB)
- The BW around the betatron resonances is fixed by the parameter  $a$

$$\Delta f_{-3dB,s-sided} \approx \frac{1-a}{2\pi} f_{rev}$$

- With  $a=31/32$  we get 54 Hz
- The stability requires that the **cavity response be first flattened using a strong broadband RF feedback -> low loop delay**
- Performances can probably be improved with a more sophisticated filter. Similar work on-going for the LHC longitudinal damper (resonances at  $(n \pm Q_s)$   $f_{rev}$ . To be installed in 2012

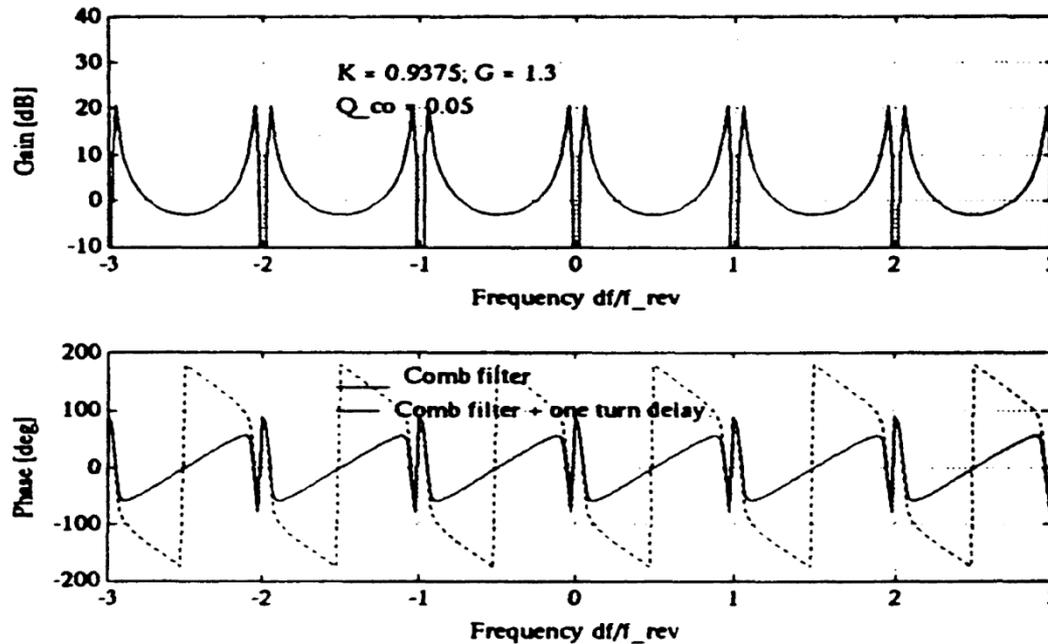


Nyquist plot of the Betatron comb filter response with  $a=31/32$  and non-integer  $Q=0.3$ .

# Betatron Comb filter 3/3

10

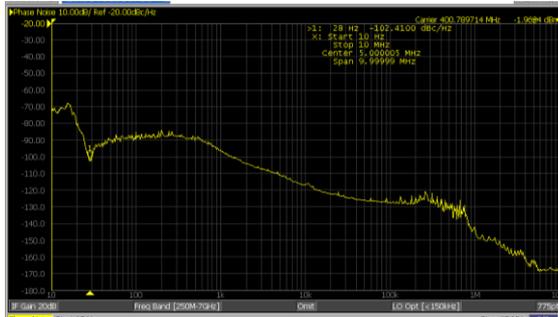
- The filter is identical to the double peak comb filter used at PEP-II on the accelerating cavities, for the reduction of the longitudinal impedance at the fundamental frequency. It had resonances on the synchrotron side-bands ( $Q_s=0.05$ )



Frequency response of the PEPII double peak comb filter.  
F. Pedersen, RF Cavity Feedback, CERN-PS-92-59-RF

- In LHC-CC10, I presented the RF noise performances of the LHC and extrapolated to the CC

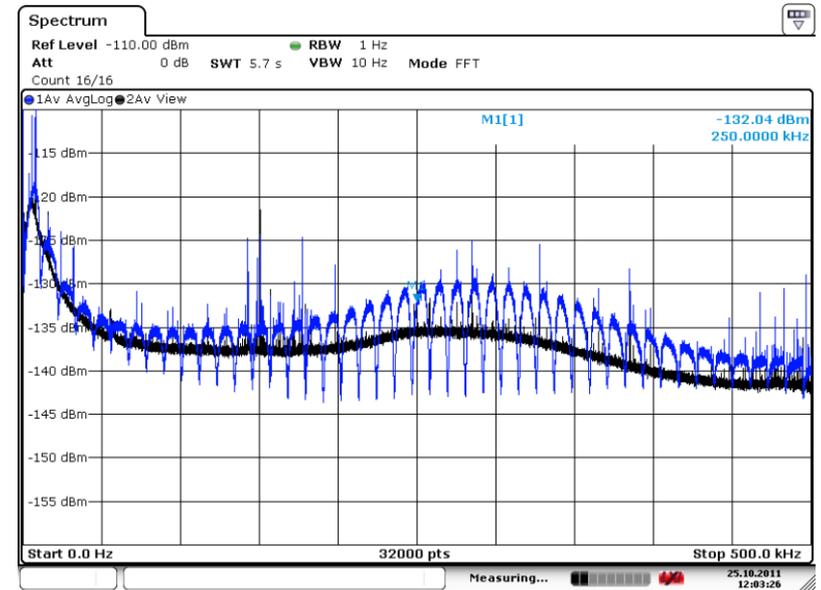
- Assume a SSB phase noise of  $-125$  dBc/Hz or  $6.3E-13$  rad<sup>2</sup>/Hz



- Assume that only the noise in the **betatron bands** have effect and take **0.01 tune spread (300 Hz band)**
  - Now summing the noise PSD from DC to + 300 kHz over all betatron bands, we get  $300/11 \times 2 \times 300 \times 6.3E-13$  rad<sup>2</sup> =  $1E-8$  rad<sup>2</sup>
  - Conclusion: a “copy” of the LHC ACS design would generate  $1E-4$  rad rms or  **$5E-3$  deg rms phase noise @ 400 MHz, all in the betatron band.**

# Phase noise revisited

- In the meantime the 1-T feedback has been commissioned on the LHC, further **reducing the RF noise on the synchrotron sidebands**



Date: 25.OCT.2011 12:03:26

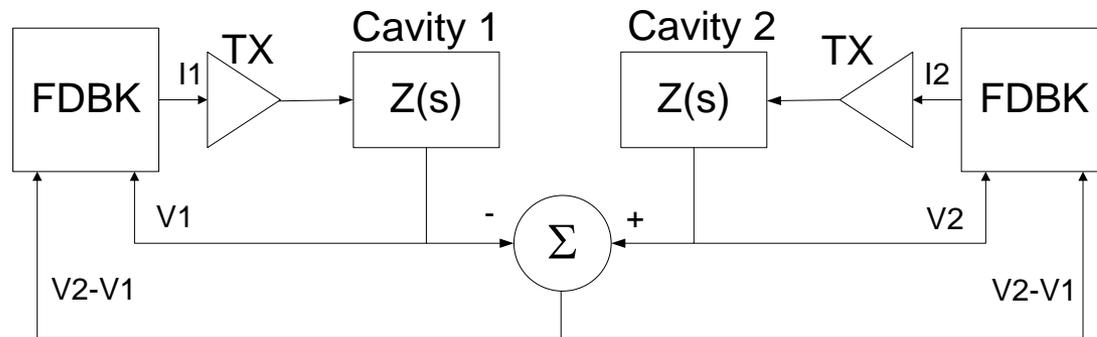
LHC Cav1B1, 1.5 MV, QL=60k. Phase noise PSD from DC to 500 kHz. Observe the reduction of the PSD on all frev lines (Qs= 2E-3), and the increase in between.

- A similar improvement can be expected from the **Betatron Comb filter**

# Coupled feedback

12

- For perfect closure of the orbit and to minimize the overall effect of one-cavity fault, we look at the possibility of coupled feedback
- For example, taking a pair of cavities on each side of a given IP, we may wish to keep the two voltages equal
- That can be done if the FDBK for a given TX considers also the voltage difference  $V_2 - V_1$



Two cavities on opposite sides of an IP: We wish to regulate the individual voltages AND the voltage difference.

- But how do we set the feedback gains to balance the weight given to the tracking of individual set-point and the minimization of voltage difference?

# State-space model

13

- We start with the simplest model
  - ▣ Cavities on-tune represented as first order linear difference equation (LPF)
  - ▣ TX represented by a constant gain

$$v_1(n+1) = a v_1(n) + g i_1(n)$$

$$v_2(n+1) = a v_2(n) + g i_2(n)$$

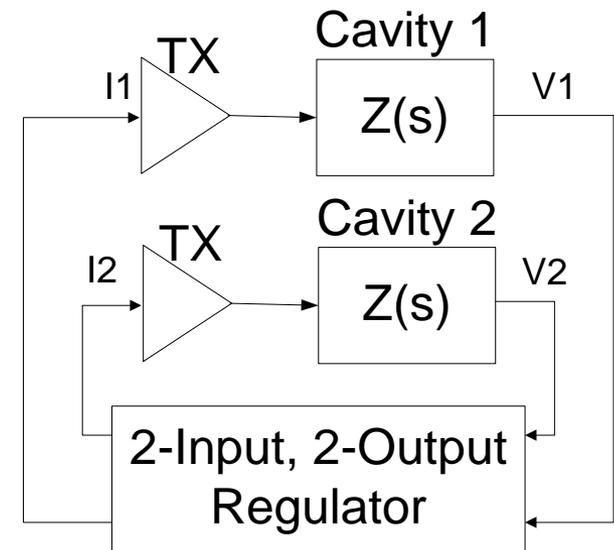
- In matrix form
- We want to design a linear regulator (matrix  $K$ ), that is a proportional feedback generating corrections on  $I(n)$  from measurement of  $V(n)$

$$I(n) = -K V(n)$$

- With the regulator, the state equations become

$$V(n+1) = [A - bK] V(n) + b I(n)$$

- The feedback changes the state-transition matrix
- The choice of the  $K$  matrix coefficients can be done using the Linear Quadratic Regulator (LQR) theory



$$V(n+1) = A V(n) + b I(n)$$

with

$$V(n) = \begin{bmatrix} v_1(n) \\ v_2(n) \end{bmatrix}$$

$$I(n) = \begin{bmatrix} i_1(n) \\ i_2(n) \end{bmatrix}$$

$$A = \begin{bmatrix} a & 0 \\ 0 & a \end{bmatrix}$$

$$b = \begin{bmatrix} g & 0 \\ 0 & g \end{bmatrix}$$

$$K = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix}$$

# Linear Quadratic Regulator LQR

14

- Assume that the state is displaced at time zero (non-zero initial cavity voltage), and observe the transient while the system is brought back to the zero state
- Let us define a cost function that is a quadratic function of the state variables ( $V$ ) and the regulation input ( $I$ )

$$J = \sum_{n=0}^{\infty} [V^t(n) Q V(n) + I^t(n) R I(n)]$$

- With the matrix  $Q$  and  $R$ , we give different weight to the state error ( $Q$ ) and the needed regulation power ( $R$ )
- We will use a diagonal  $R$  matrix so that the second term is proportional to the klystron power needed in the restoring transient
- With the  $Q$  matrix elements we can give more or less coupling between the two feedbacks. With a diagonal matrix, the feedbacks are fully decoupled
- By balancing  $q_0$  and  $q_1$  in the matrix below, we give more importance to the voltage difference

$$Q = \begin{bmatrix} q_0 + q_1 & -q_1 \\ -q_1 & q_0 + q_1 \end{bmatrix}$$

$$V^t(n) Q V(n) = q_0 [v_1(n)]^2 + q_0 [v_2(n)]^2 + q_1 [v_1(n) - v_2(n)]^2$$

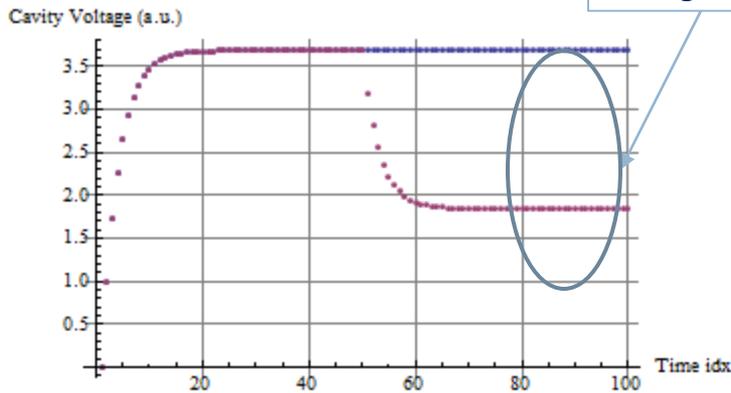
## Independent feedbacks

$$Q = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Diagonal A matrix

$$\left( \begin{array}{cc|cc} 0.728582 & 0. & 1. & 0. \\ 0. & 0.728582 & 0. & 1. \\ \hline 1. & 0. & 0. & 0. \\ 0. & 1. & 0. & 0. \end{array} \right)^s_1$$

Kly1 ignores Cav2 voltage drop



Cavity 1  
Cavity 2

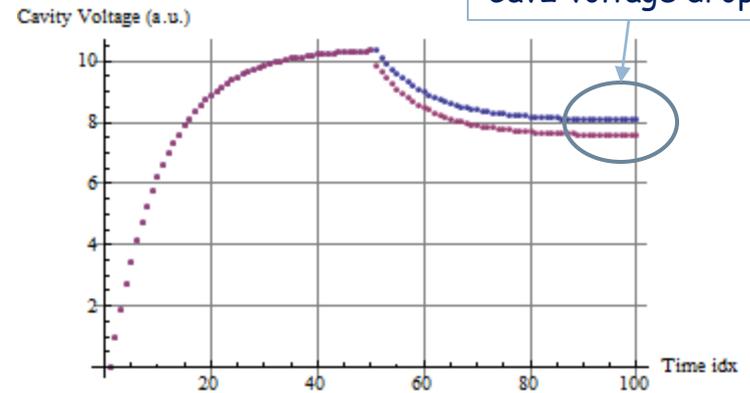
## Strongly coupled feedbacks

$$Q = \begin{bmatrix} 100.01 & -100 \\ -100 & 100.01 \end{bmatrix}$$

Large off-diagonal values  $\rightarrow$  strong coupling

$$\left( \begin{array}{cc|cc} 0.454434 & 0.449533 & 1. & 0. \\ 0.449533 & 0.454434 & 0. & 1. \\ \hline 1. & 0. & 0. & 0. \\ 0. & 1. & 0. & 0. \end{array} \right)^s_1$$

Kly1 tries to track Cav2 voltage drop



Cavity voltage following a unit step of both klystrons at time zero, and a half-unit step reduction of klystron 2 alone at time 50.

When observing one loop at the time, the regulation with independent klystrons is better: It is 3 times faster and the static error is three times smaller.

When the **transient is on one klystron only** (kly2, red), there is no compensation on cavity 1 for the independent feedbacks, resulting in a static error of  $\sim 2$ . **With the coupled feedbacks, kly1 (blue) reacts to the drop in cavity 2 voltage** and the final voltage difference is  $\sim 0.5$ .

# Coupled feedback

16

- The above analysis is much simplified (no loop delay)
- It however shows the possibility to regulate on voltage difference (or voltage sum, or any linear combination)
- The distance between cavities will limit its potential (delays will limit the BW of such coupled compensations)
- More study is required to confirm its usefulness
- In the meantime we will gain expertise by applying it to the upgrade of the SPS TWC200MHz feedback as well (regulation of cavity Sum)

P. Baudrenghien et al., Reducing the impedance of the Travelling Wave Cavities Feed-forward and one turn delay feed-back, Chamonix 2000

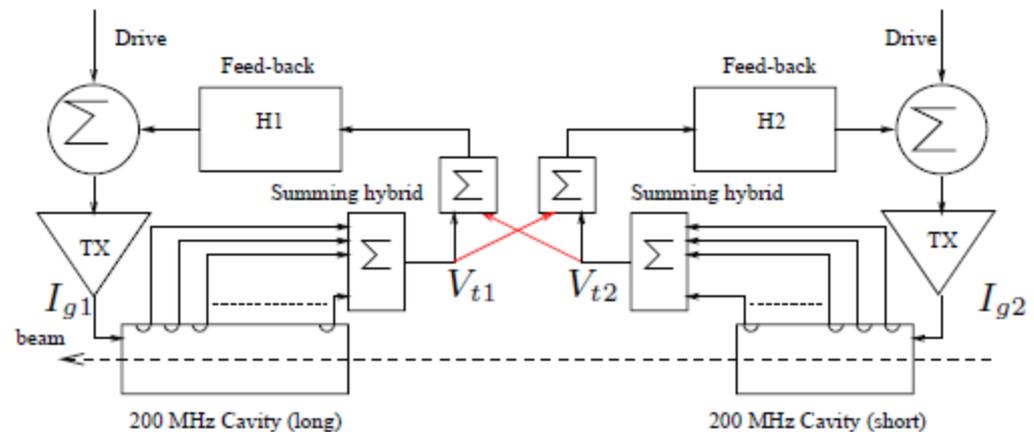


Figure 19: Coupled feedback on two cavities of different lengths.

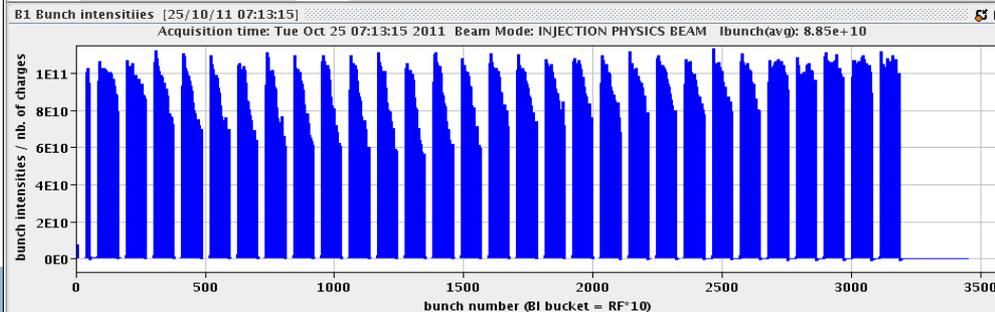
17

# Modulation of beam phase

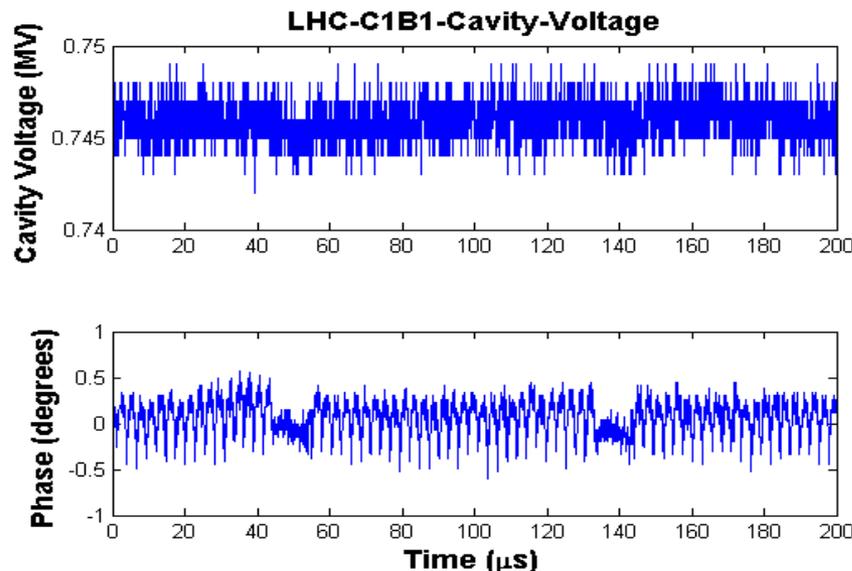
# Modulation of cavity phase

18

- The LHC is designed with an (almost) perfect beam loading compensation including a strong RF feedback plus 1-T feedback
- On Oct 25<sup>th</sup>, we injected 2100 bunches at  $\sim 1E11$  p/bunch (nominal is  $1.1E11$  p) and circulated them at 450 GeV
- With 0.75 MV/cavity, the phase modulation over one turn was kept below 0.5 deg pk-pk @ 400 MHz
- No attempt was done to accelerate. However the result can be scaled: As we double cavity voltage we expect half the transient, that is **0.25 deg pk-pk or 2 ps pk-pk**
- This result is made possible by the half-detuning policy proposed by D. Bussard: The cavity is detuned for half peak current, so that, with a constant cavity field set point, the required klystron power does not change significantly between beam and no-beam segments
- With the **300 kW** peak RF klystron power, we can keep this policy **up to nominal bunch intensity, 25 ns spacing... but not above...**



Fast BCT showing the 2100 bunches. Notice the 10  $\mu$ s long gap



Amplitude and phase of the Cav1B1 field with the beam shown above. The uncompensated transient beam loading appears as a periodic modulation of the phase. The no-beam gap is clearly visible. The phase modulation is 0.5 deg pk-pk

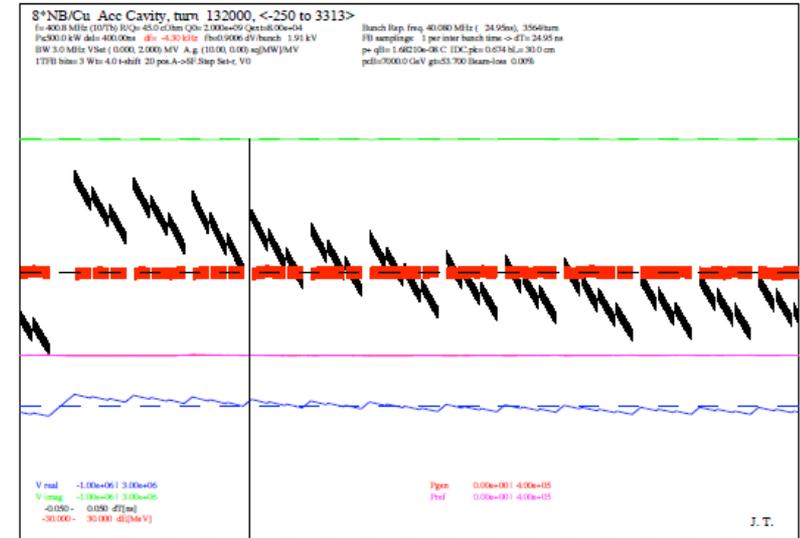
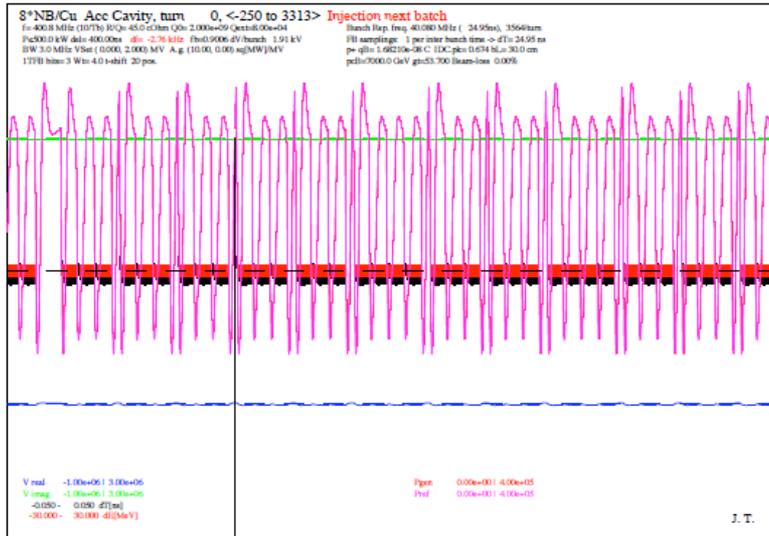
D. Bussard, RF Power Requirements for a High Intensity Proton Collider, PAC, San Francisco, 1991

# Modulation of the cavity field set point

19

- To reach  $1.7E11$  p/bunch, with the existing klystron power, we will modulate the voltage set-point along the turn to minimize the power peaks required to compensate the transient beam loading
- With a  $3 \mu\text{s}$  long abort gap and  $1.7E11$  p/bunch, the bunch phase would slip by 11 degrees @ 400 MHz (76 ps) over one turn, with 1.5 MV/cavity (conservative: assumes RF beam current equal to twice the DC current)

$$\Delta\phi = \frac{1}{2} \frac{R}{Q} \omega_0 \frac{I_b}{V} t_{gap}$$



Bunch phase (black bands) and energy deviations (red bands), klystron power (pink), cavity voltage (I,Q) green and blue. Left: The cavity phase is kept constant along the turn, resulting in large power transients. Right: The cavity phase is modulated along the turn. The bunches are not strictly equi-spaced, resulting in a lowered and constant klystron power.

# Modulation of bunch phase

20

- First consider the main accelerating cavities
  - The **reference RF** generated by the SR4 Beam Control will **not be modulated** (slide4)
  - The Cavity Field Set-Point of the accelerating cavities will be modulated in the Cavity Controller (adaptive algorithm intended to minimize the klystron power)
  - It will be tested in 2012
- Now for the **CC**
  - We propose to **drive** their Cavity Controller **with the reference RF** (no modulation)
  - A PU signal (see slide5) is demodulated, the bunch-by-bunch phase is extracted (and filtered). Then it is used to **gently shift the phase Set-Point in the CC Cavity Controller bunch per bunch**. This correction will be periodic at Frev with very slow evolution.
  - That will **keep the CC kick on the bunch centre**.

21

# Operational scenario

*a very first look ...*

# Operational scenario 1/2

CC10 presentation revisited

22

- Boundary conditions:
  - During **filling, ramping and for physics with crab cavities off**, the cavities must be **detuned**. The cavities are not needed and the radial displacement would be too large for good beam loading compensation
  - Bringing the cavities **from detuned to on-tune** can only be done **with active RF feedback ON**. Else, the beam will be unstable (Transverse Impedance)
  - In **varying conditions** (change of cavity tune) and given the unavoidable fluctuations of key parameters (for example varying cavity tune caused by the fluctuations of the He pressure) the situation can only be controlled if **some** (hopefully very small) **field is present in the cavity** to get on-line “measurements”.

# Operational scenario 2/2

23

- Proposed scenario:
  - During filling, ramping or operation with **transparent** crab cavities, we detune the cavity but **keep a small field requested** for the **active Tuning system**. If the crab kick is provided by a pair of cavities we could use **counter-phasing** to make the small cavity field invisible to the beam. Else amplitude/phase can be optimized among the cavities of same Beam/IP to minimize effects. The **RF feedback is used with the cavity detuned** to keep the Beam Induced Voltage zero if the beam is off-centered. We can use the demanded TX power as a measurement of beam loading to guide the beam centering
  - ON flat top
    - **Reduce the detuning while keeping the voltage set point very small** but sufficient to get tune and Closed Loop response measurements. The RF feedback keeps the cavity impedance small (beam stability) and compensates for the beam loading as the cavity moves to resonance
    - Once the cavity detuning has been reduced to zero, use the functions to **synchronously change the voltage in all crab cavities as desired**. Any luminosity leveling scheme is possible.

24

# LLRF Status

# LLRF status

25

- Test bench
- SPS

# Test bench

26

- A prototype cavity controller can be designed by adapting the **on-going developments** for **Linac4** and **SPS 800 MHz cavities**. Only problem is manpower...
- For the LLRF the benefits of a full-scale test bench (Cavity-TX-LLRF) are
  - ▣ Optimization of a single-cavity **RF feedback**
  - ▣ Measurement of **RF noise**
  - ▣ **Tuning** algorithm

# Test in the SPS

27

- For the LLRF the benefits of a **test in the SPS** are
  - ▣ Measure the effect of RF noise on **transverse emittance growth**
  - ▣ Optimize the **Betatron comb filter**
  - ▣ Test the **various procedures**
    - Injection with detuned cavity
    - Moving cavity on-tune with beam
    - Ramping cavity field with beam
  - ▣ TX **power needed** for beam loading compensation -> *optimal* QL
  - ▣ **Coupled feedback** on two cavities (each side of IP). Intentionally trip a TX and optimize the feedback to ramp down the companion cavity
- It is assumed that we install a **low loop delay feedback** in the LSS4 cavern
- CAUTION: The **phase noise of the SPS main accelerating system** could make extrapolations to the LHC impossible

28

# Some conclusions

# Some conclusions

29

- The **integration** of the CCs with the existing RF system and LHC controls **is simple**. Even with the bunch phase modulation scenario
- Benefiting from on-going developments in other systems (LHC longitudinal damper, Linac4 Cavity Controller, SPS 200MHz and 800MHz upgrade) the LLRF can further **reduce RF noise** in the sensitive betatron bands, **reduce the transverse impedance** caused by the cavity at the fundamental, and keep a **good precision between the kicks** affecting one beam (coupled cavities feedback)
- However the **BW** of all these regulations will be fixed by the **layout**. For the main RF system of the LHC the loop delay is 650 ns only. The layout was optimized for that. Similarly the ACN cavities would be installed with TX and LLRF in the nearby klystron galleries. **A similar compact layout must be studied for the CC**
- The implications of loaded Q on the LLRF must be studied soon.

# Thank you for your attention...

*... and a suggestion for next year:*

*Schedule the CC workshop after machine stop....*