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2nd HiLumi LHC/LARP
Frascati, Nov 15,2012

LLRF FOR CRAB CAVITIES

A FEW SELECTED ISSUES
AND
RELEVANT EXPERIENCE FROM THE LHC MAIN CAVITIES (ACS)

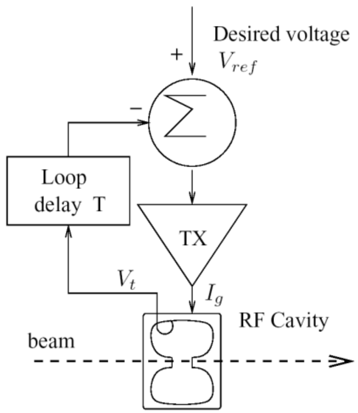
COUPLED BUNCH (IN)STABILITY

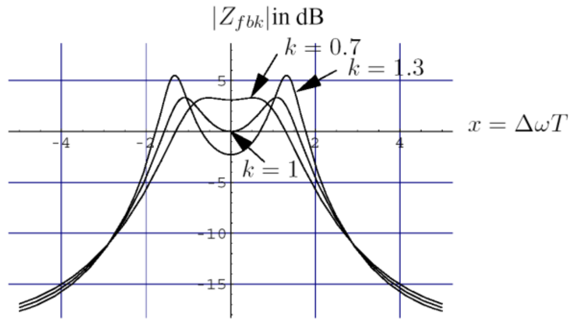
Reduction of Cavity Impedance at the fundamental mode

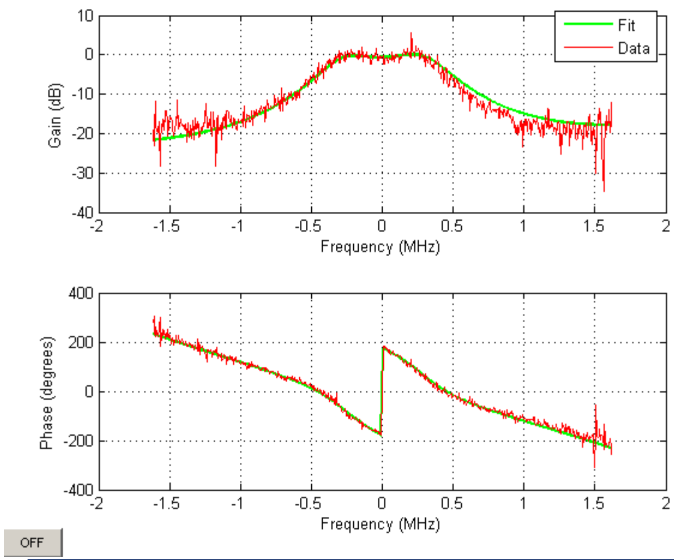
RF feedback

- With accelerating cavities, in high beam current machines, the problem of (in)stability caused by the cavity impedance at the fundamental is now routinely cured by active feedback. The amplifier driven by a feedback system feeds a current into the cavity which attempts to cancel the beam current
- The cavity impedance is effectively reduced by the feedback gain
- The limitation comes from the unavoidable delay in the loop. Above some gain level the delay will drive the feedback into electrical oscillations (not related to the beam)

Strong RF feedback. The LHC ACS







With an RF feedback the minimal effective impedance R_{min} and closed-loop single-sided bandwith $\Delta\omega$ scale with loop delay T

With the RF feedback we reduce the ACS cavity impedance at resonance by ~35 linear (Q_L=60k). The 21.6 MΩ are reduced to 0.6 MΩ.

F

R_{min}

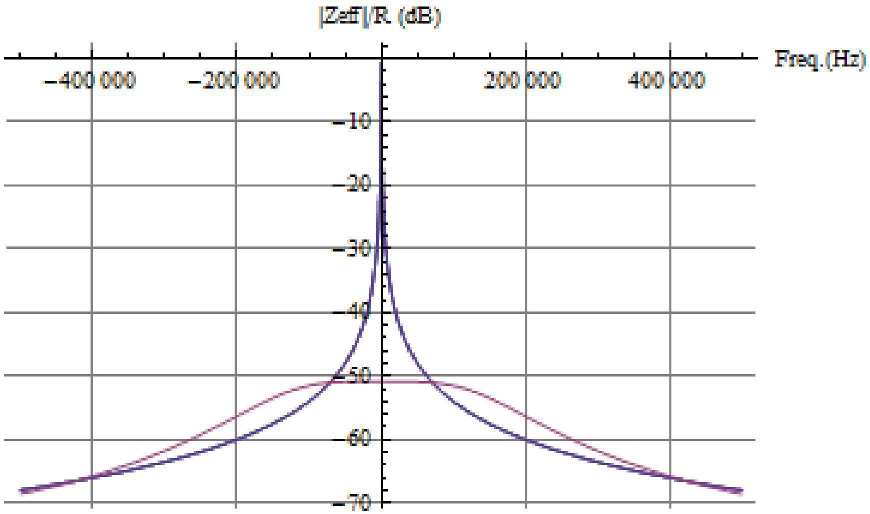
$\Delta\omega/2\pi$ = 320 kHz

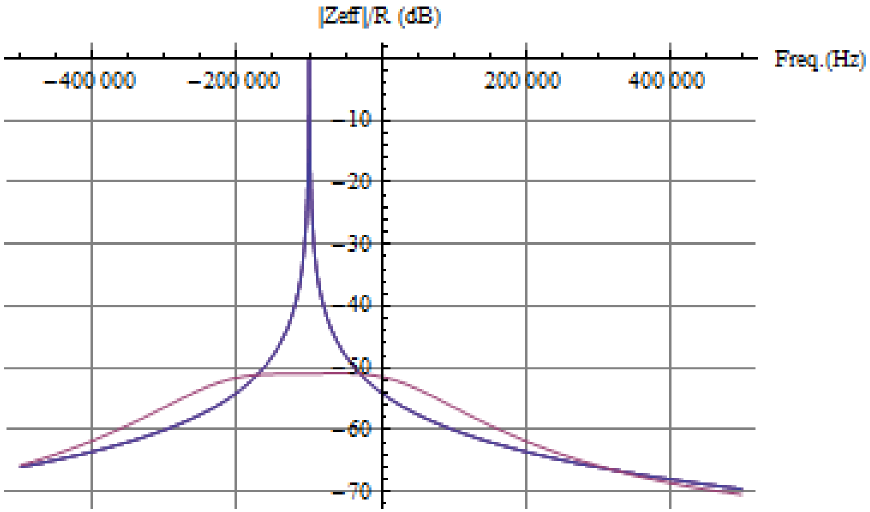
Measured Closed Loop response with the RF feedback. Q_L=60000 without feedback (~7 kHz 2-sided BW). With feedback we get 700 kHz BW. The effective impedance is reduced by ~ 35. The LHC cavities are equipped with movable couplers and Q_L can be varied from 10000 to 100000. But, with feedback, Q_{eff} ~600 in all positions.

The loop delay T was kept low in the LHC ACS

RF feedback on the Crab Cavity

- $Q_L=10^6$, 1 μs loop delay, 150 ns TX group delay
- RF feedback gain = 350 linear. Impedance reduced by 50 dB
- The open loop phase must be changed with the detuning. Not a problem. We do similar adjustment for the ACS, when changing Main Coupler Position





Cavity impedance with and without RF feedback.
Left: situation in physics with CC on tune
Right: situation during filling, ramping, squeeze, adjust, with CC detuned by -100 kHz

ACTUALLY THE IMPEDANCE REDUCTION CAN BE LARGER THAN THE FEEDBACK GAIN

NB resonator, longitudinal and transverse

- Longitudinal impedance of a longitudinal mode

$$Z^{\parallel}(\omega) = \frac{R_s}{1 + jQ\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)}$$

- Transverse impedance of a transverse mode

$$Z^{\perp}(\omega) = \frac{\omega_r}{\omega} \frac{R_{\perp}}{1 + jQ\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)}$$

- The growth rate and tune shift of coupled-bunch mode *l* (dipole only) can be computed from the cavity impedance

$$\sigma_l + j\Delta\omega_l = \frac{\eta \quad q \quad I_0}{2 \quad \beta^2 \quad \omega_s \quad E \quad T_{rev}} \sum_{p=-\infty}^{\infty} \omega \quad Z^{\parallel}(\omega)$$

- With $\omega=(p\,M+l)\,\omega_{rev}+\omega_s$.

- The growth rate and tune shift of coupled-bunch mode *l* (dipole only) can be computed from the cavity impedance

$$\sigma_l + j\Delta\omega_l = \frac{c \quad q \quad I_0}{2 \quad \omega_b \quad E \quad T_{rev}} \sum_{p=-\infty}^{\infty} Z^{\perp}(\omega)$$

- With $\omega=(p\,M+l)\,\omega_{rev}+\omega_b$.

NB resonator, longitudinal

- With 25 ns bunch spacing (M=3564), and a resonance around 400 MHz, with BW below 40 MHz (with feedback), the infinite sum reduces to two terms (p= ±10)

$$\sigma_l + j\Delta\omega_l = \frac{\eta \quad q \quad I_0}{2 \quad \beta^2 \quad \omega_s \quad E \quad T_{rev}} \sum_{p=-\infty}^{\infty} \omega \quad Z^{\Box}(\omega)$$

recalling that $Z^{\Box}(-\omega) = \overline{Z^{\Box}(\omega)}$

$$\sigma_l + j\Delta\omega_l \approx \frac{\eta \quad q \quad I_0}{2 \quad \beta^2 \quad \omega_s \quad E \quad T_{rev}} \omega_{RF} \quad \left\{ Z^{\Box}(\omega_{RF} + l\omega_{rev} + \omega_s) - \overline{Z^{\Box}}(\omega_{RF} - l\omega_{rev} - \omega_s) \right\}$$

$$\sigma_l \approx \frac{\eta \quad q \quad I_0}{2 \quad \beta^2 \quad \omega_s \quad E \quad T_{rev}} \omega_{RF} \quad \left\{ \mathrm{Re}\left[Z^{\Box}(\omega_{RF} + l\omega_{rev} + \omega_s) \right] - \mathrm{Re}\left[Z^{\Box}(\omega_{RF} - l\omega_{rev} - \omega_s) \right] \right\}$$

- The growth rate is computed from the difference between real impedance on the two $\pm(l\ \omega_{rev}+\omega_s)$ sidebands of the ω_{RF}
- Much reduced if the real part of the effective impedance is symmetric around ω_{RF}. That is the case if the detuning is small compared to the closed loop BW (LHC ACS).

NB resonator, transverse

- Again, with 25 ns bunch spacing (M=3564), a resonance around 400 MHz, with a BW below 40 MHz, the infinite sum reduces to the two terms (*p*= ±10)

$$\sigma_l + j\Delta\omega_l = \frac{c \quad q \quad I_0}{2 \quad \omega_b \quad E \quad T_{rev}} \sum_{p=-\infty}^{\infty} Z^{\perp}(\omega)$$

recalling that $Z^{\perp}(-\omega) = -\overline{Z^{\perp}(\omega)}$

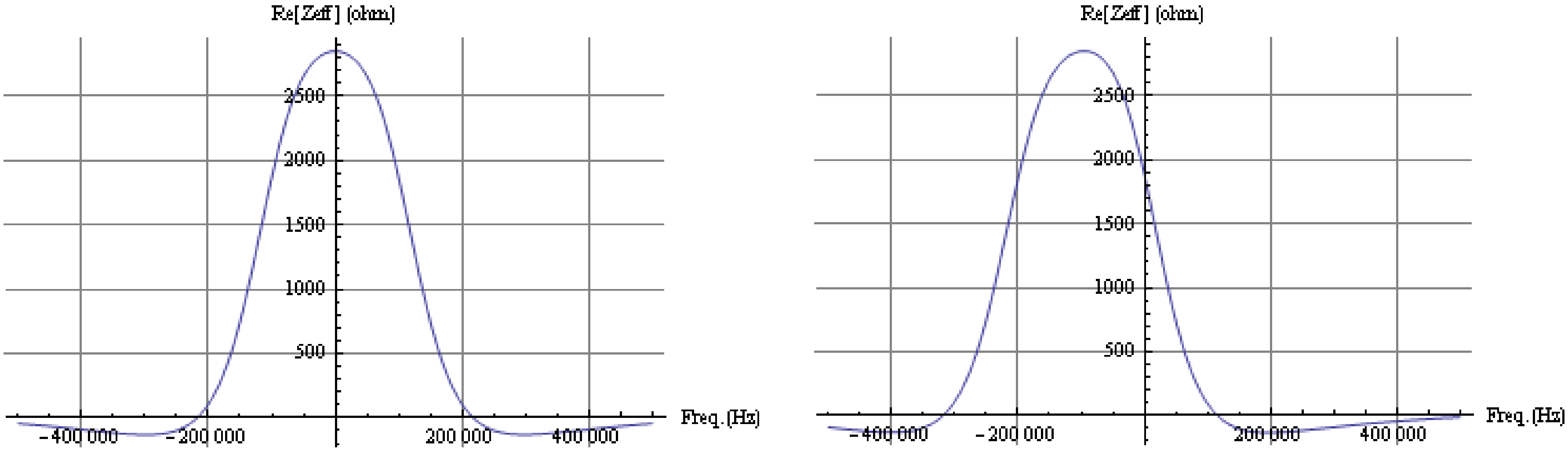
$$\sigma_l + j\Delta\omega_l \approx \frac{c \quad q \quad I_0}{2 \quad \omega_b \quad E \quad T_{rev}} \left\{ Z^{\perp}(\omega_{RF} + l\omega_{rev} + \omega_b) - \overline{Z^{\perp}}(\omega_{RF} - l\omega_{rev} - \omega_b) \right\}$$

$$\sigma_l \approx \frac{c \quad q \quad I_0}{2 \quad \omega_b \quad E \quad T_{rev}} \left\{ \mathrm{Re}\left[Z^{\perp}(\omega_{RF} + l\omega_{rev} + \omega_b) \right] - \mathrm{Re}\left[Z^{\perp}(\omega_{RF} - l\omega_{rev} - \omega_b) \right] \right\}$$

- Again, the growth rate is computed from the difference between real impedance on the two $\pm(l\ \omega_{rev}+\omega_b)$ sidebands of the ω_{RF}
- For example, with Q_b=60.3, the growth rate of mode *l*=-60 is computed from the difference between the real part of the impedance at ±0.3 ω_{rev}
- But is the real part of the effective impedance symmetric around ω_{RF} ?

RF feedback on the Crab Cavity

- $Q_L=10^6$, 1 μs loop delay, 150 ns TX group delay, 1 MΩ/m
- RF feedback gain = 350 linear



Real part of the cavity impedance with RF feedback.
Left: situation in physics with CC on tune
Right: situation during filling, ramping, squeeze, adjust, with CC detuned by -100 kHz

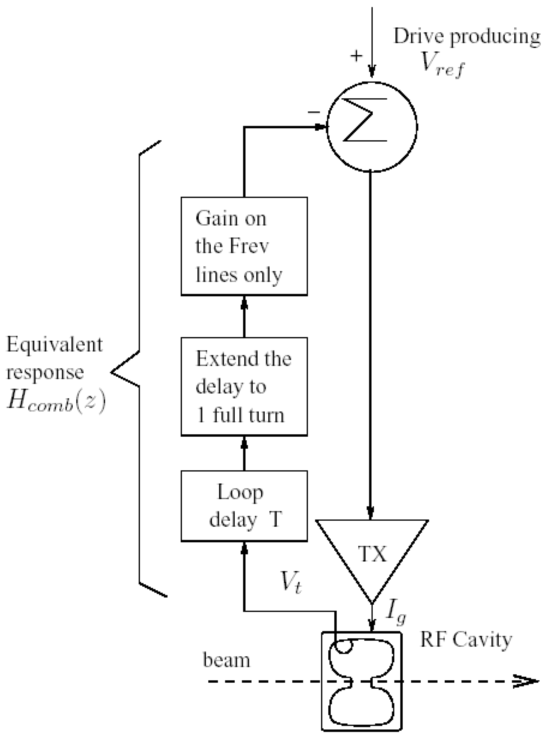
Important reduction to be expected in physics

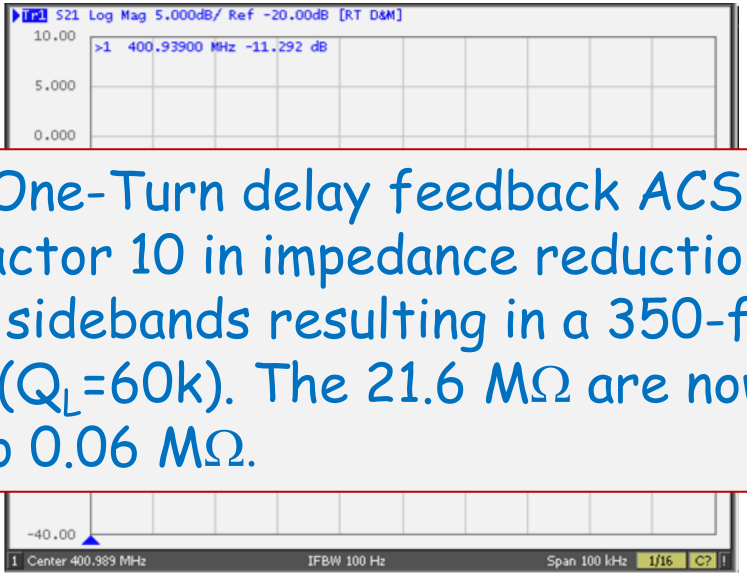
No reduction when cavity is parked (-100 kHz)

SO WHAT IF THE IMPEDANCE IS STILL TOO HIGH?

Longitudinal: One-Turn delay feedback (OTFB) on ACS

- The One-Turn delay Feedback (OTFB) produces gain only around the revolution frequency harmonics
- It further reduces the transient beam loading and effective cavity impedance (factor of 10)





With the One-Turn delay feedback ACS we gain another factor 10 in impedance reduction on the revolution sidebands resulting in a 350-fold reduction (Q_L=60k). The 21.6 MΩ are now reduced to 0.06 MΩ.

Effective Cavity Impedance with RF feedback alone (smooth trace) and with the addition of the OTFB (comb). The cavity centre frequency is 400.789 MHz. We look at a band offset by +200 kHz to +300 kHz. Frev= 11 KHz. The OTFB provides ~ 20 dB additional impedance reduction on the Frev lines.

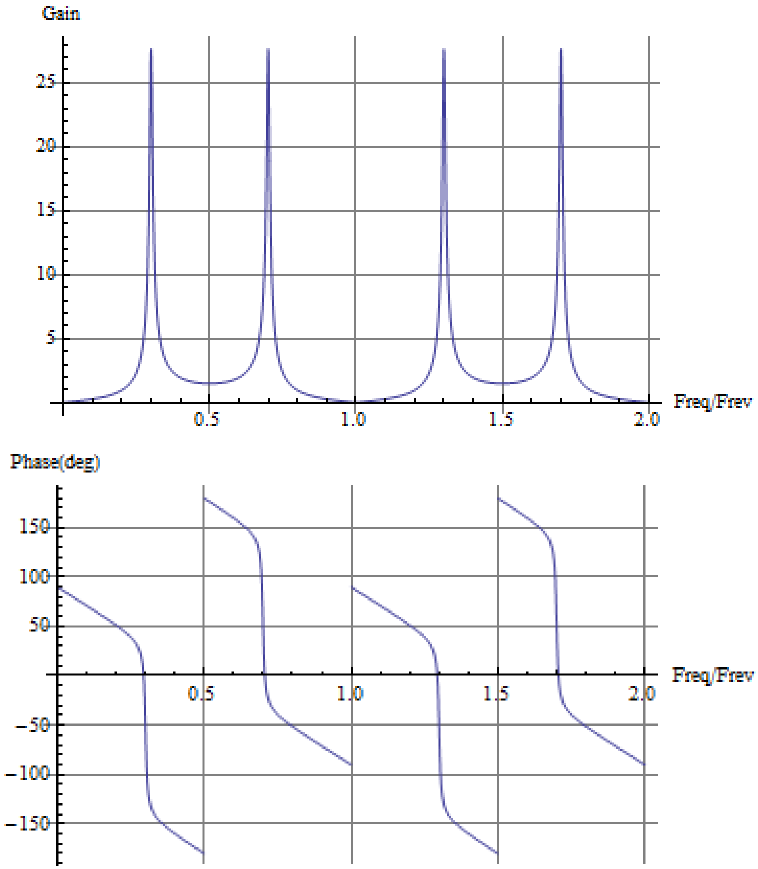
Transverse: Betatron Comb filter

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

$$H(z) = \frac{\left(1 - z^{-N}\right) z^{-N}}{\left(1 - a\, e^{i\,2\pi Q} z^{-N}\right)\left(1 - a\, e^{-i\,2\pi Q} z^{-N}\right)}$$

- To keep 10 dB gain margin, the gain on the betatron lines is limited to ~ 6 linear (16 dB)
- 2 N Poles on the betatron frequencies
  - Reduction of noise PSD where the beam responds
  - Reduction of the effective cavity impedance thereby improving transverse stability
- Zeros on the revolution frequency lines
  - No power wasted in transient beam loading compensation with off centered beam

Some details in CC11 presentation. Study ongoing…

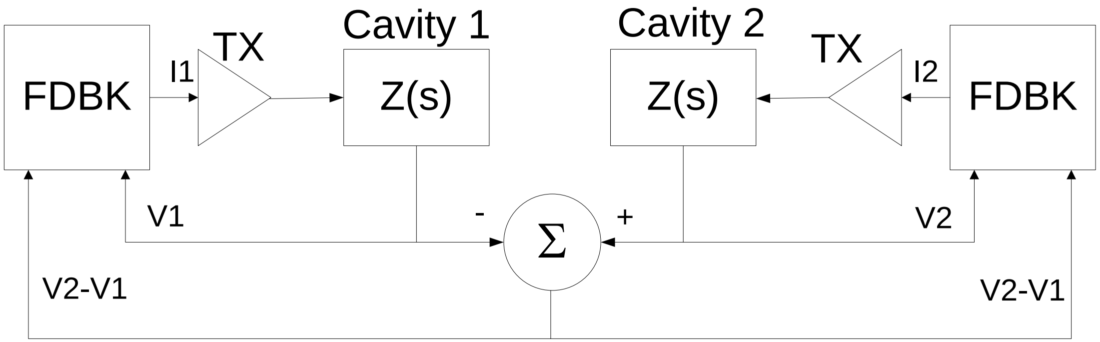


Betatron comb filter response with a=31/32 and non-integer Q=0.3. Observe the high gain and zero phase shift at (n ±0.3) frev

Commission in the SPS

Coupled feedback

- For perfect closure of the orbit and to minimize the overall effect of one-cavity fault, we look at the possibility of coupled feedback
- Taking a pair of cavities on each side of a given IP (crabbing and un-crabbing), we 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.

Some details in CC11 presentation. Study ongoing… Loop delays critical…

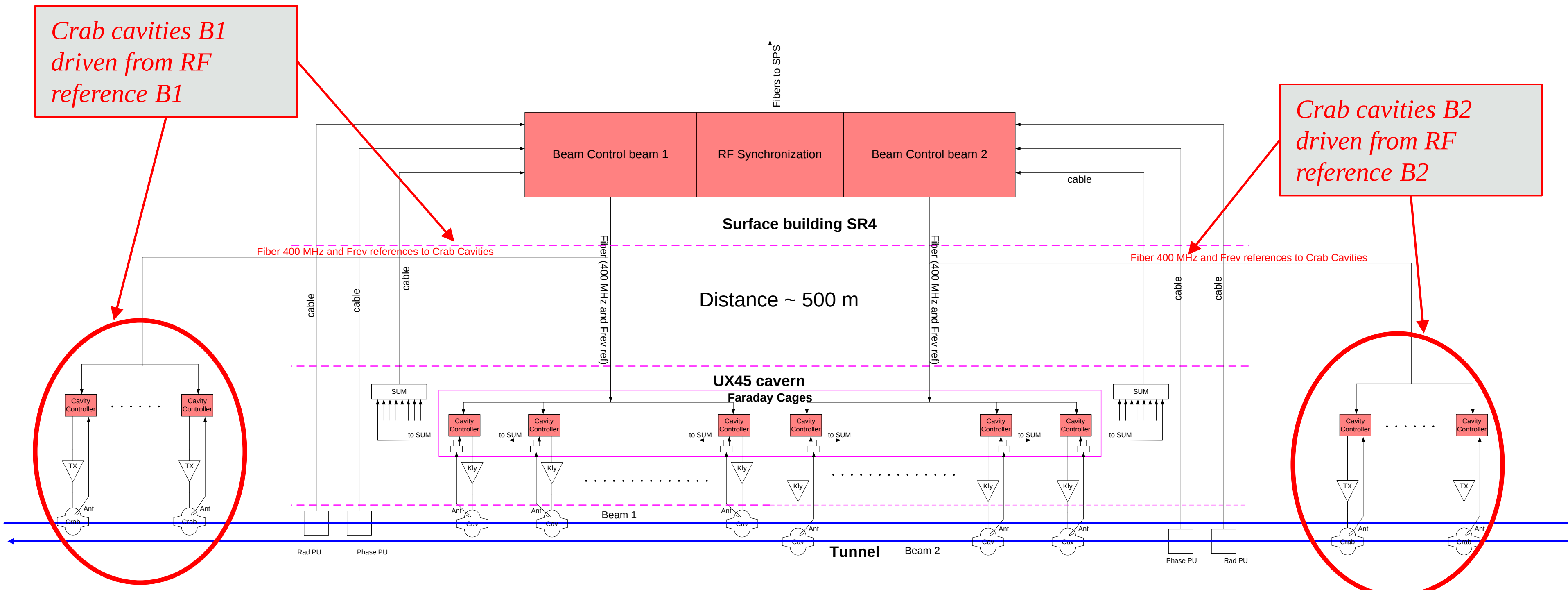
Commission in the SPS

BUT THAT HAS NO EFFECT ON THE HOM/LOM

RF NOISE

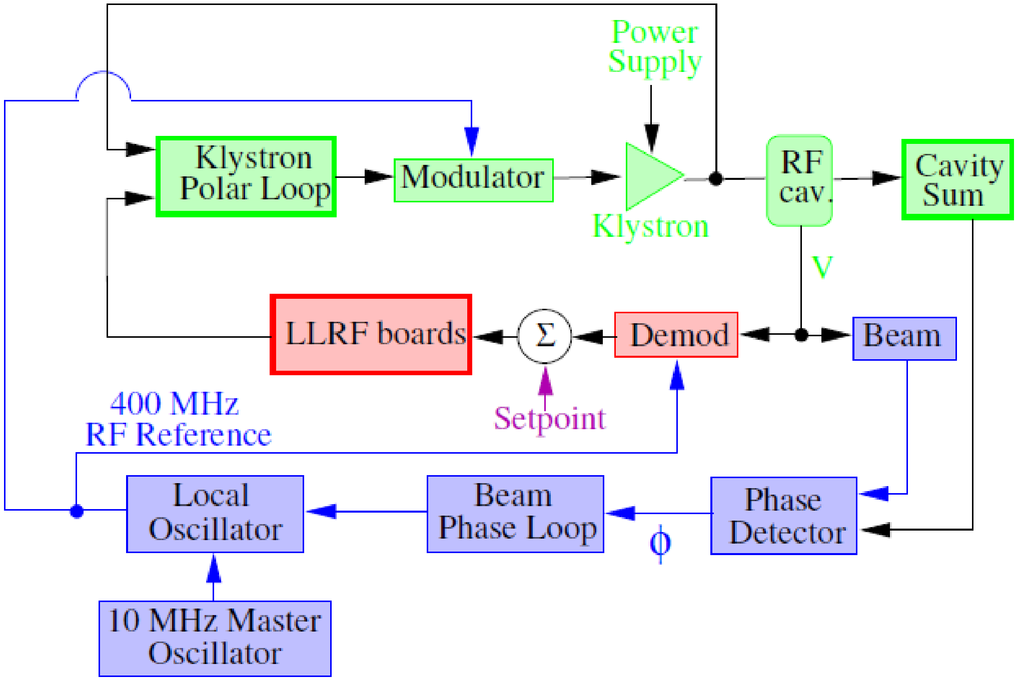
Random noise only. Assuming perfect beam loading compensation.

Architecture



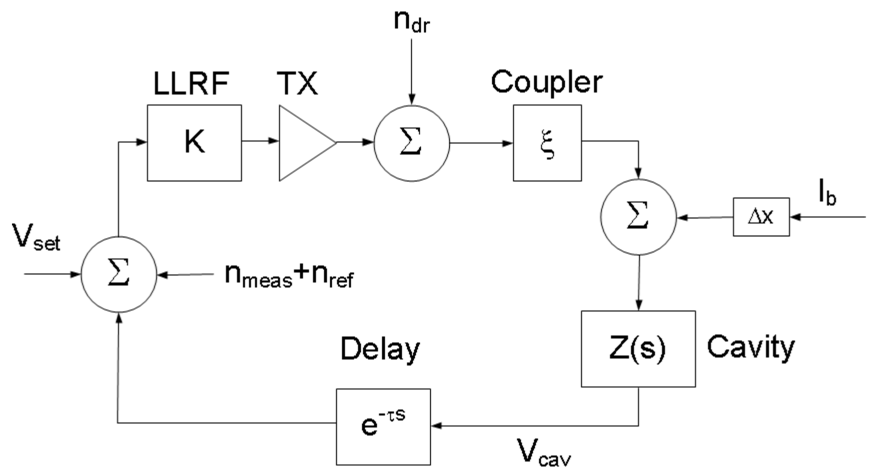
We propose to drive the Crab Cavities from the RF reference (Beam Control, VCXO out), and count on strong RF feedback to set the demanded field in the cavities

Beam Control plus Cavity Controller LHC ACS



- Two major noise sources:
  - The RF reference noise from the Beam Control, introduced during the modulation/demodulation process in the Cavity Controller. This noise is coherently injected in all cavities
  - The noise injected in the Cavity Controller electronics and the Klystron noise. This noise is uncorrelated from cavity to cavity

Cavity RF Noise



- RF feedback noise sources:
  - The RF reference noise n_{ref}
  - The demodulator noise (measurement noise) n_{meas}
  - The TX (driver) noise n_{dr} . It includes also the LLRF noise not related to the demodulator
  - The Beam Loading I_b Δx
- We get

$$Z(s)=\frac{\frac{R}{Q}Q_L}{1+2Q_L\frac{s}{\omega_0}}$$

with $s=j\,\Delta\omega$

Main coupler

$$V_{cav}=\frac{K\;G\;e^{-\tau s}Z(s)}{1+K\;G\;e^{-\tau s}Z(s)}\left[V_{set}+n_{ref}+n_{meas}\right]+\frac{Z(s)}{1+K\;G\;e^{-\tau s}Z(s)}\left[\Delta x\;I_b+\sqrt{\frac{Z_0}{\frac{R}{Q}Q_L}}\,n_{dr}\right]$$

Closed Loop response CL(s)

- Equal to ~1 in the CL BW
- Increase of K increases the BW
- Within the BW, reference noise and measurement noise are reproduced in the cavity field

Beam Loading response = effective cavity impedance Zeff(s)

- Equal to ~1/KG in the CL BW
- Increase of K decreases Zeff within the CL BW
- Within the CL BW, TX noise and beam loading are reduced by the Open Loop gain KG

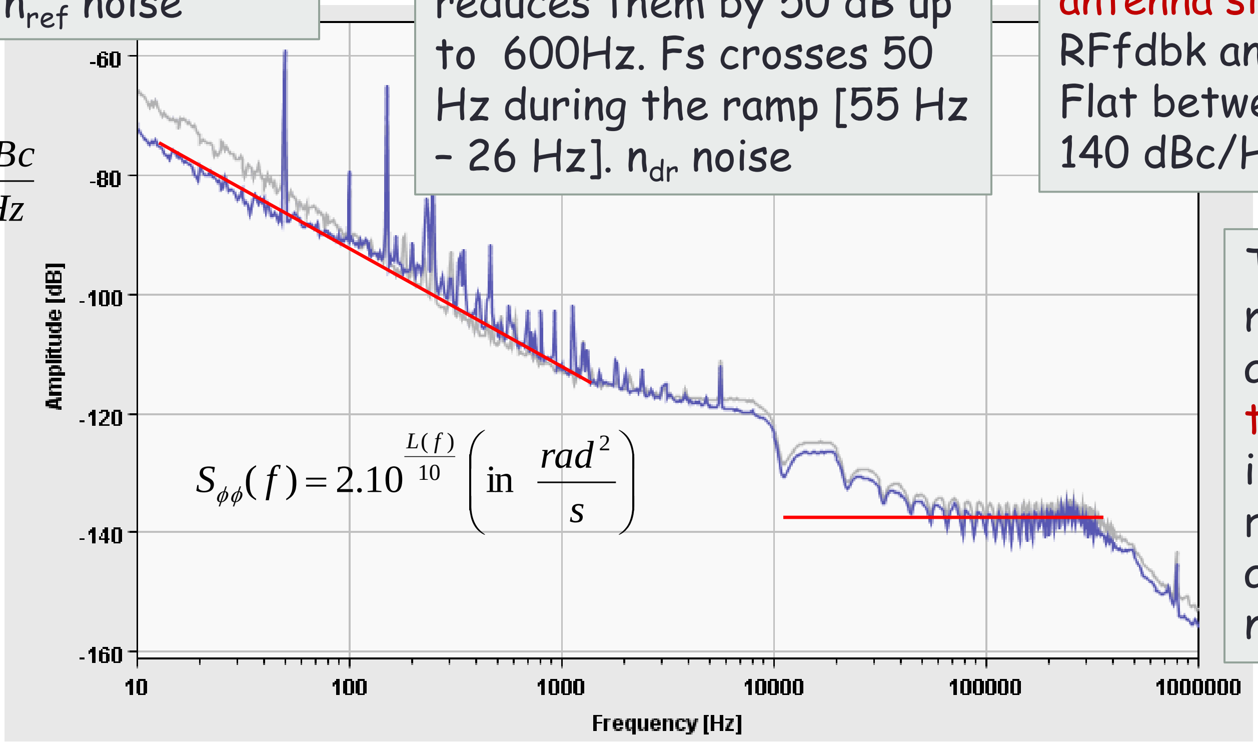
RF noise without beam. ACS

Noise in the 10Hz-1kHz range is caused by the VCXO limited Q (-20 dB/decade). n_{ref} noise

50 Hz and harmonics come from the klystron HV ripples. The klystron loop reduces them by 50 dB up to 600Hz. Fs crosses 50 Hz during the ramp [55 Hz – 26 Hz]. n_{dr} noise

In the 10kHz-400 kHz range the noise level is defined by the demodulation of the antenna signal in the RFfdbk and OTFB loops. Flat between -135 and -140 dBc/Hz. n_{meas} noise

$L(f)$ in $\frac{dBc}{Hz}$



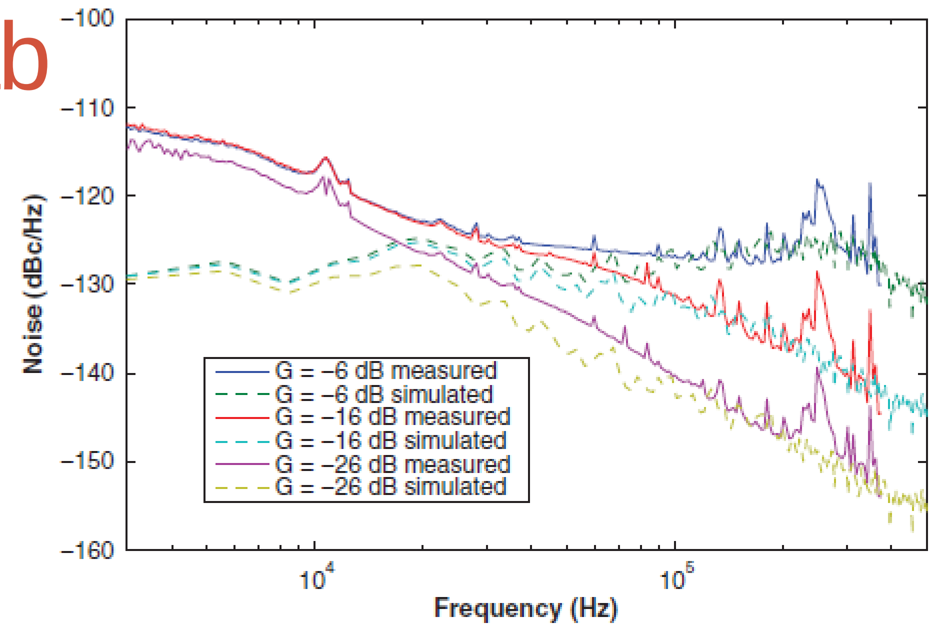
$$S_{\phi\phi}(f) = 2.10^{\frac{L(f)}{10}} \left(\text{in } \frac{rad^2}{s} \right)$$

The dips at multiple of Frev are the action of the OTFB that increases regulation gain and decreases noise level

- In the transverse plane the first betatron band is at 3 kHz. Reference noise is not an issue. The performances will be defined by TX noise and measurement noise

Scaling the ACS to crab

- The beam will sample the noise in all betatron side-bands
- The integrated effect of the measurement noise increases with the closed loop BW, that is proportional to the feedback gain



SSB phase noise in an ACS cavity with varying feedback gains. Measured and calculated [1]

- Assume a SSB phase noise of *L*= -135 dBc/Hz or *S*= 6.3E-14 rad^2/Hz
- Now summing the noise PSD from DC to + 300 kHz over all betatron bands, we get 300/11 x 2 x 6.3E-14 rad^2/Hz =3.4E-12 rad^2/Hz from DC to the revolution frequency
- Conclusion: a “copy” of the LHC ACS design (300 kW klystron !) would generate 3.7E-8 rad^2 white noise
- That is 2E-4 rad rms or 1.1E-2 deg rms phase noise @ 400 MHz

But what counts is the power in the betatron band only

Trade-off for CCs

- A weak coupling (large Q_L)
  - Reduces the effect of TX and LLRF noise. Good
  - Make cavity field sensitive to mechanical vibrations. Bad
- A large feedback gain
  - Reduces the instability growth rates. Good
  - Limits the effect of TX and LLRF noise. Good
  - Increases the integrated effect of measurement noise by increasing the BW. Bad
- Trade-off required
  - Will depend on the TX noise

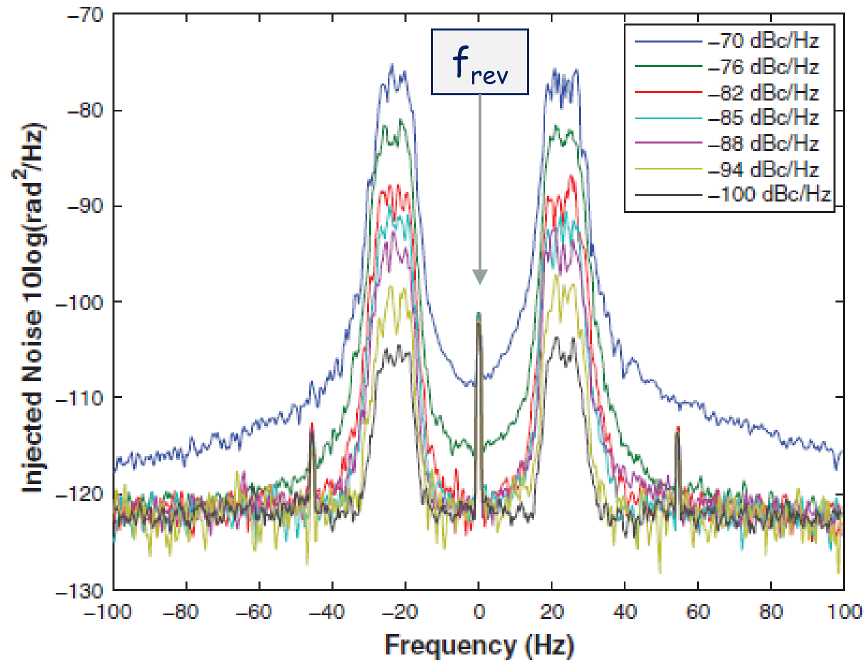
First Hadron machine with CCs…. First Hadron machine with klystrons

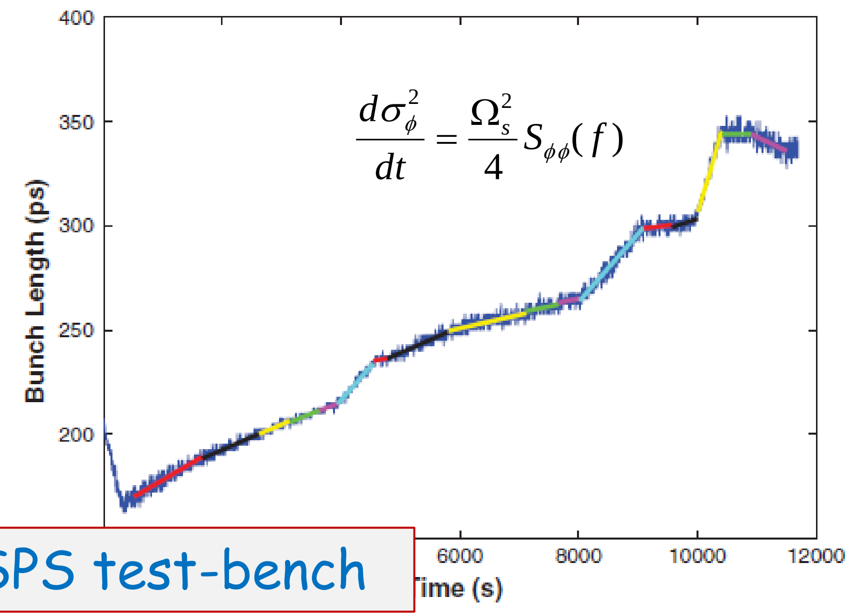
Importance of the SPS test-bench

EMITTANCE GROWTH MEASUREMENT

- How can we measure the effect of RF noise if it is not dominant in the emittance growth?
- We faced a similar problem in the LHC as longitudinal emittance growth driven by IBS is much stronger than the growth caused by RF noise
- Measurements were done with ions at 3.5 Z TeV in Nov 2010 with four equi-distant bunches per ring [1]

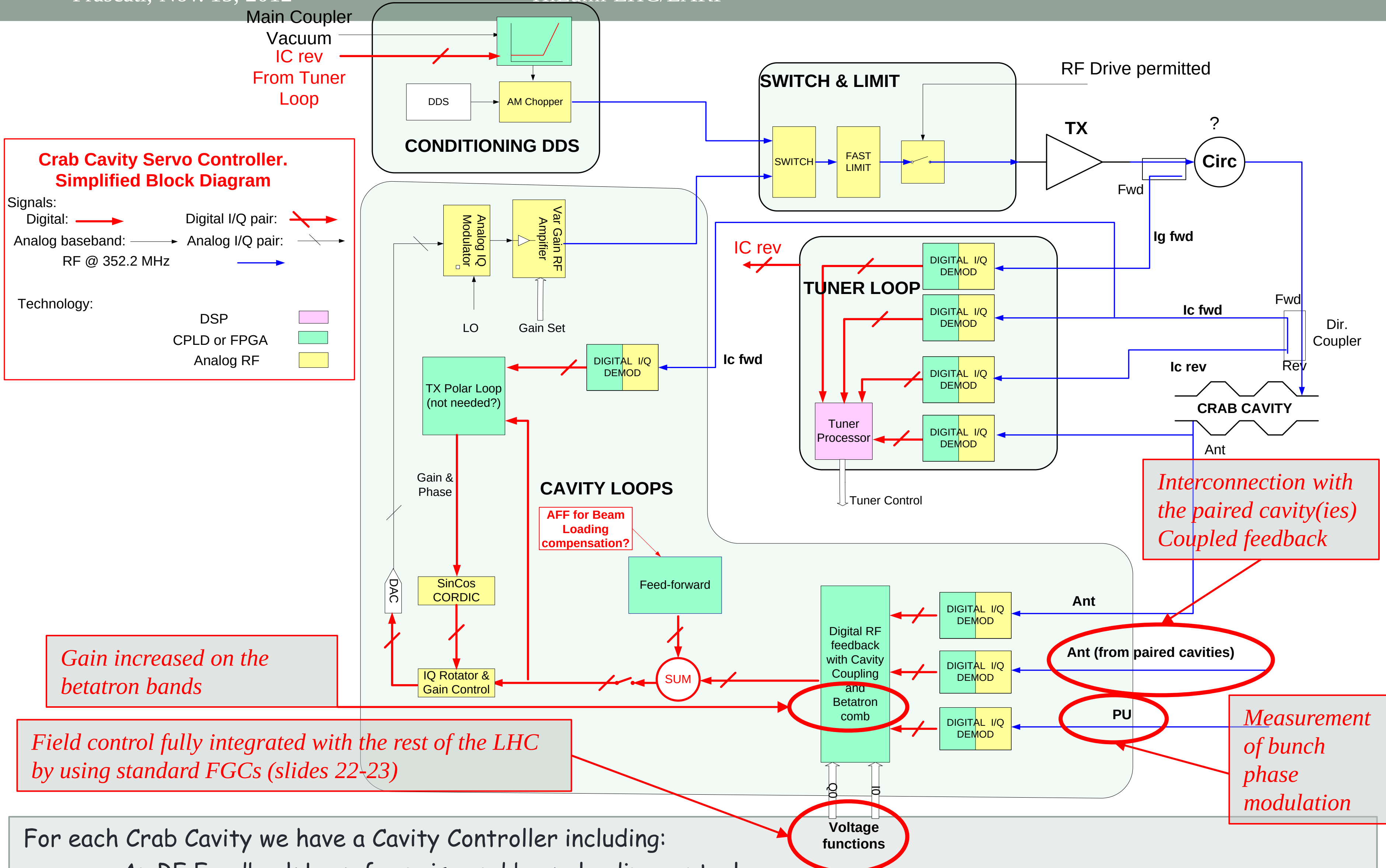
- Phase noise was injected in one RF cavity, with a bandwidth of 10 Hz, centered on the first revolution band: $f_{rev} \pm f_s$
- The power of the injected noise was varied during the test
- Bunch length was monitored
- With large noise power, the effect became dominant, allowing for a good calibration of emittance growth (slope of bunch lengthening) vs RF noise power





Will be done on the SPS test-bench

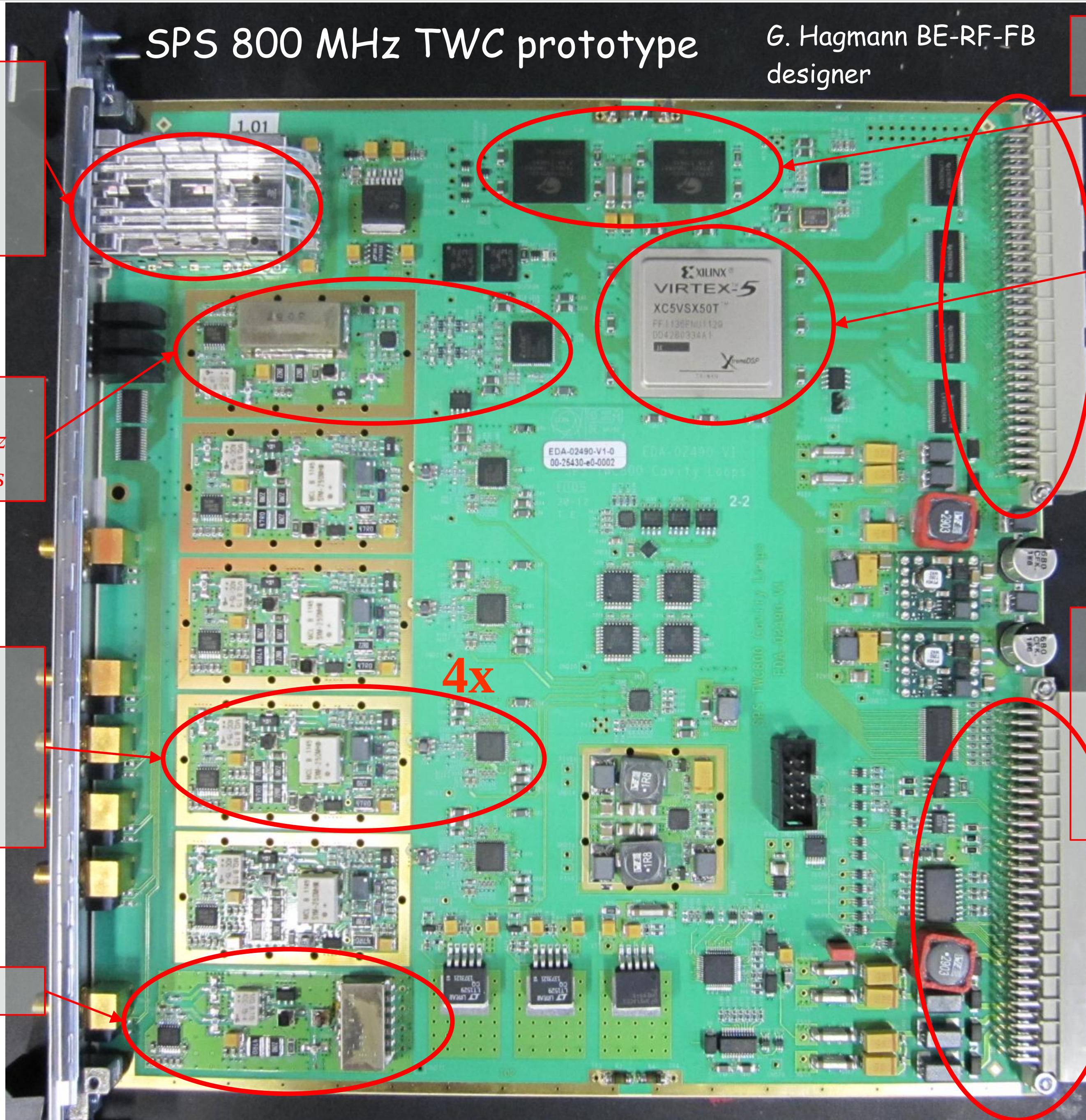
HARDWARE



For each Crab Cavity we have a Cavity Controller including:

- An RF Feedback Loop for noise and beam loading control
- A TX Polar Loop to reduce the TX noise and stabilize its gain/phase shift
- A Tuner Loop to shift the cavity to a detuned position during filling and ramping. Then smoothly bring the cavity on-tune with beam for physics
- A field Set Point for precise control of the cavity field.

Version: 20111111


SPS 800 MHz TWC prototype
G. Hagmann BE-RF-FB designer
2 x Duplex Optical Serial Links
2 in & 2 out
2Gbits/s
(≤3.2Gbits/s)
SRAM 2x8 Mbyte for diagnostics
Xilinx Virtex 5 SX
VME P1 backplane for slow controls/read out
SSB Modulator
IF (I & Q) ≈25MHz
Dual TxDac 16 bits
4x
RF Demodulator
RF&LO mixing
IF ≈25MHz
14 bits ADC
Fs=4·IF ≈100MHz
Dedicated backplane (P2):
•Power Supply
•Clocks
•Interlocks
•…
LO Distribution

SPS 800 MHz TWC prototype

2 x Duplex Optical Serial links

2 inputs

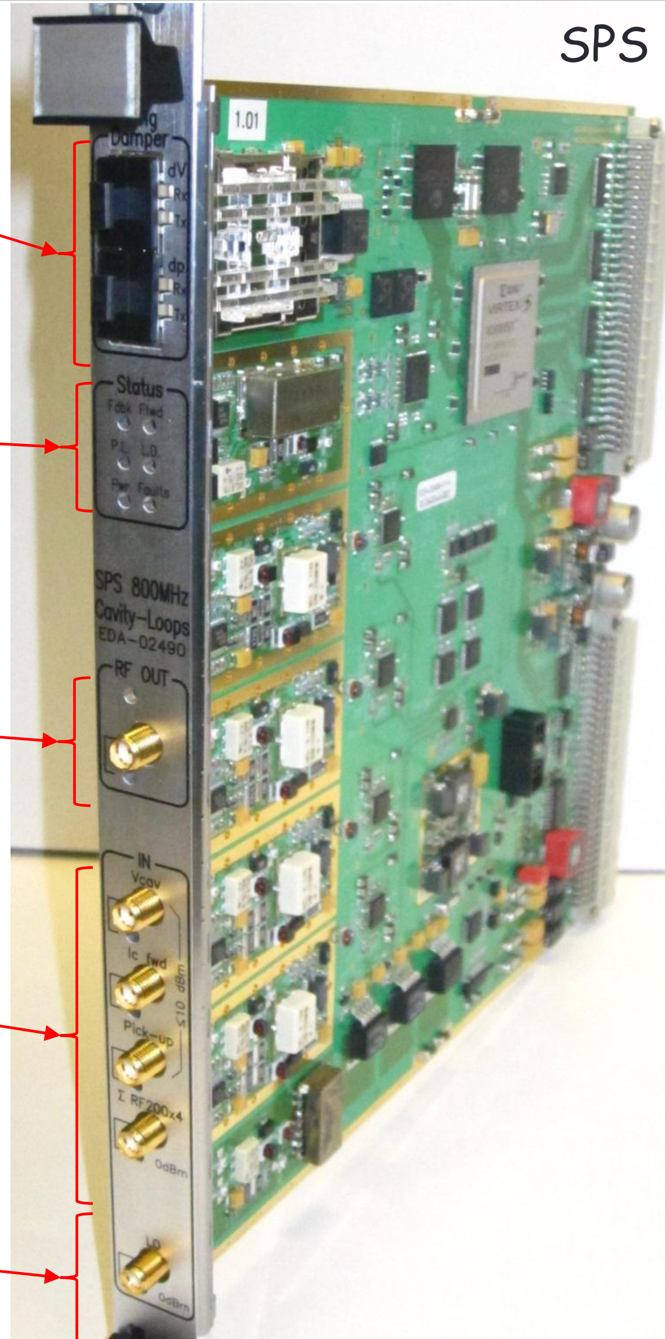
2 outputs

Status LED

RF output

RF inputs (4x)

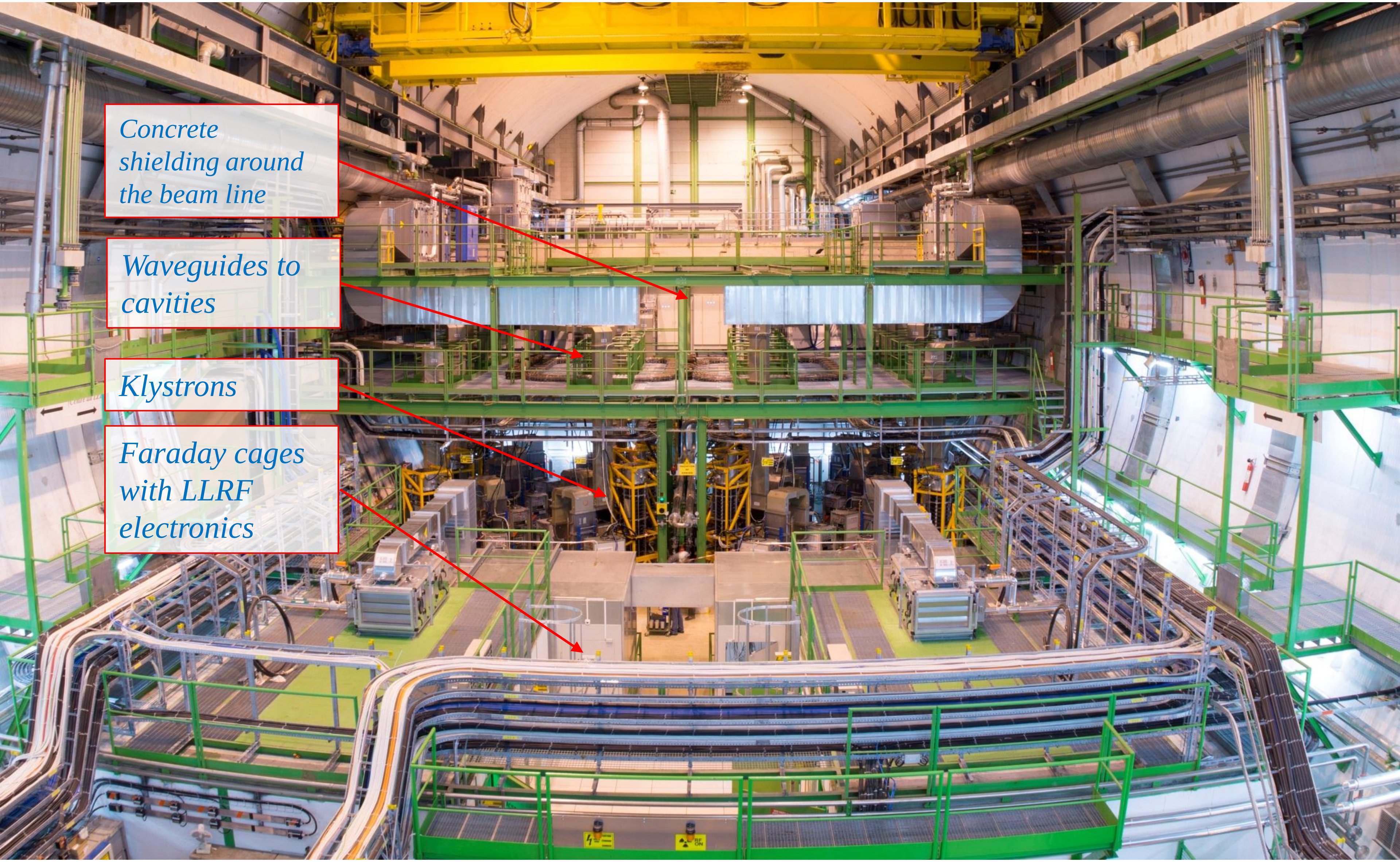
LO input



G. Hagmann BE-RF-FB

designer

ACS LLRF. 1 rack/ 2 VME crates per cavity in a Faraday Cage in the UX45 cavern



ACS RF in the UX45 cavern

Operational scenario

Operational scenario (revisited)

- Strong RF feedback and tune controls are ON at all time
- 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 provide stability and 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. 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.

CONCLUSIONS

- We propose to use a strong RF feedback around the CC
  - By reducing the effective cavity impedance by orders of magnitude, the requirements for the Transverse Damper are relaxed
  - It strongly reduces the TX noise
  - It provides for precise control of the crabbing voltage
  - It calls for a compact layout
  - It brings requirements on the TX: linearity, BW, group delay
  - It has no effect on HOMs
- RF noise
  - Optimization depends on the importance of TX noise compared to measurement (antenna demodulation)
- The tuning with very low field (much smaller than beam loading) must be solved. We will study the system used on the SC 352 MHz cavity installed in the SPS for e+e- [2][3]
- The SPS test is essential

REFERENCES

- [1] T. Mastoridis et al., Radio Frequency noise effects on the CERN Large Hadron Collider beam diffusion, PRST AB, 14, 092802 (2011)
- [2] D. Boussard et al., RF Feedback applied to a Multicell Superconducting Cavity, EPAC 1988
- [3] F. Pedersen, A novel RF cavity tuning feedback scheme for heavy beam loading, IEEE NS-32, No 5, Oct. 1985

BACK-UP SLIDES

Higher beam intensity: stability

- With the strong RF feedback and OTBF, the cavity impedance at the fundamental can easily accept 2.2E11 p/bunch, 25 ns spacing

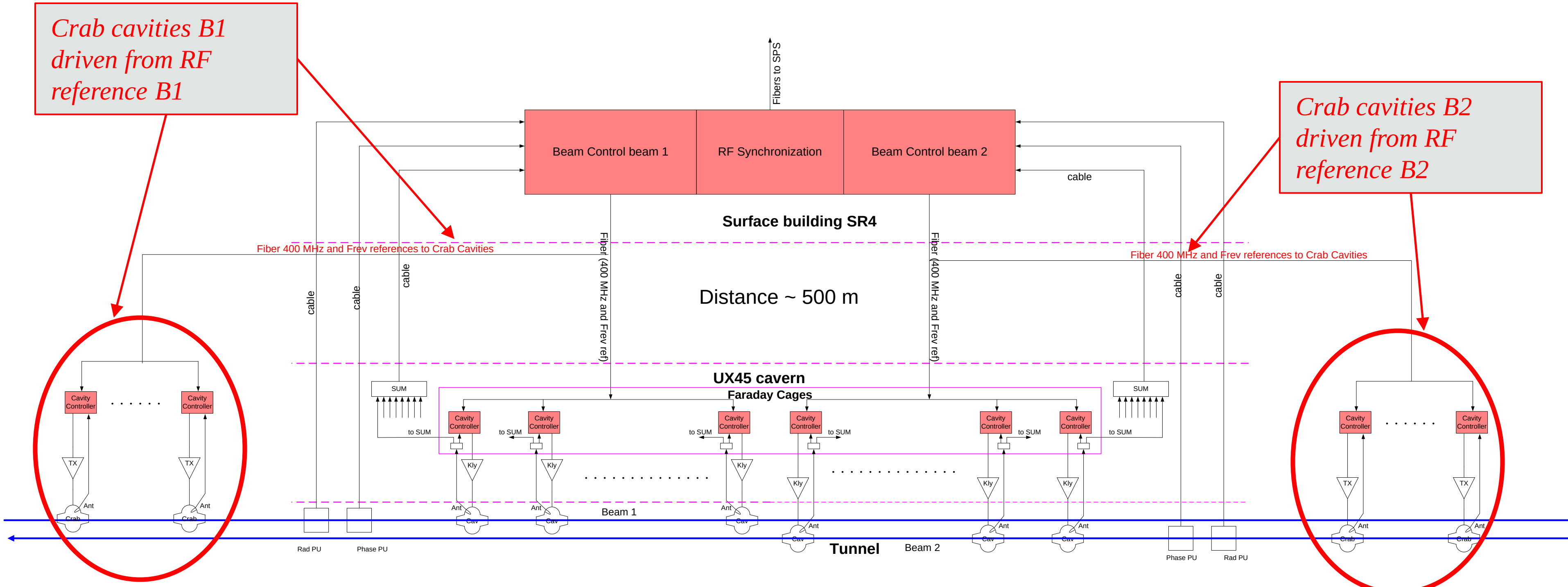
Growth rate of the coupled-bunch mode. Max over all modes

Landau damping limit (1/4 tune spread)

Momentum (GeV/c)	QL	Detuning (kHz)	Total RF Voltage (MV)	Synchrotron Frequency (Hz)	σ_{max} without fdbk (s-1)	σ_{max} with RFfbk and OTFB (s-1)	$\Delta\Omega_s/4$ (s-1)
450	20000	-12.5 (half)	6	54.8	150	0.06	13.3
450	20000	-19.8 (full)	6	54.8	150	0.07	13.3
7000	60000	-9.9 (full)	12	19.8	80	0.01	4.8

Calculations done for after LS1 conditions: 2835 bunches, 2.2E11 p/bunch, 25 ns spacing, 1.25 ns, 1.12 A DC

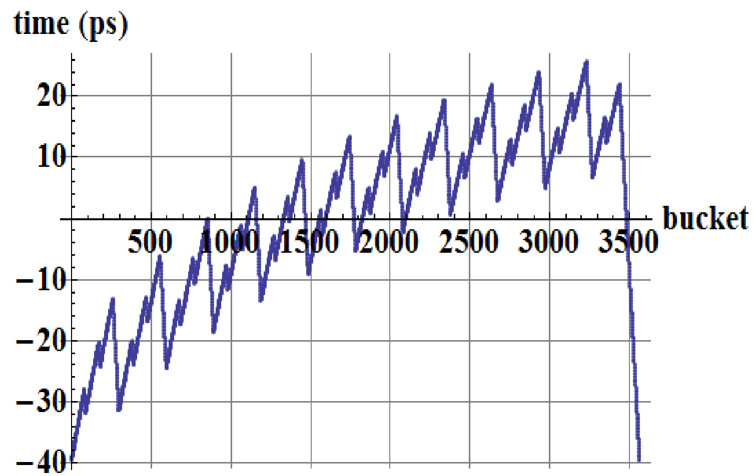
Architecture



We propose to drive the Crab Cavities from the RF reference (Beam Control, VCXO out), and count on strong RF feedback to set the demanded field in the cavities

RF phase modulation

- **In physics**
  - We will accept the modulation of the cavity phase by the beam current (transient beam loading) and adapt the voltage set point for each bunch accordingly
  - The klystron drive is kept constant over one turn (amplitude and phase)
  - The cavity is detuned so that the klystron current is aligned with the average cavity voltage
  - Needed klystron power becomes independent of the beam current. For Q_L=60k, we need 105 kW only for 12 MV total
  - Stability is not modified: we keep the strong RFfdbk and OTFB
  - The resulting displacement of the luminous region is acceptable
- **During filling**
  - It is desirable to keep the cavity phase constant for clean capture. Thanks to the reduced total voltage (6 MV) the present scheme can be kept with ultimate.



Modulation of the cavity phase by the transient beam loading in physics. 2835 bunches, 1.7 10^{11} p/bunch, 1.5 MV/cavity, QL=60k, full detuning (-7.8 kHz).