LLRF CONSIDERATIONS
FOR
CRAB CAVITIES

a first look….

16.12.2010

LHC-CC10, 4th LHC Crab cavity workshop, CERN

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Outline

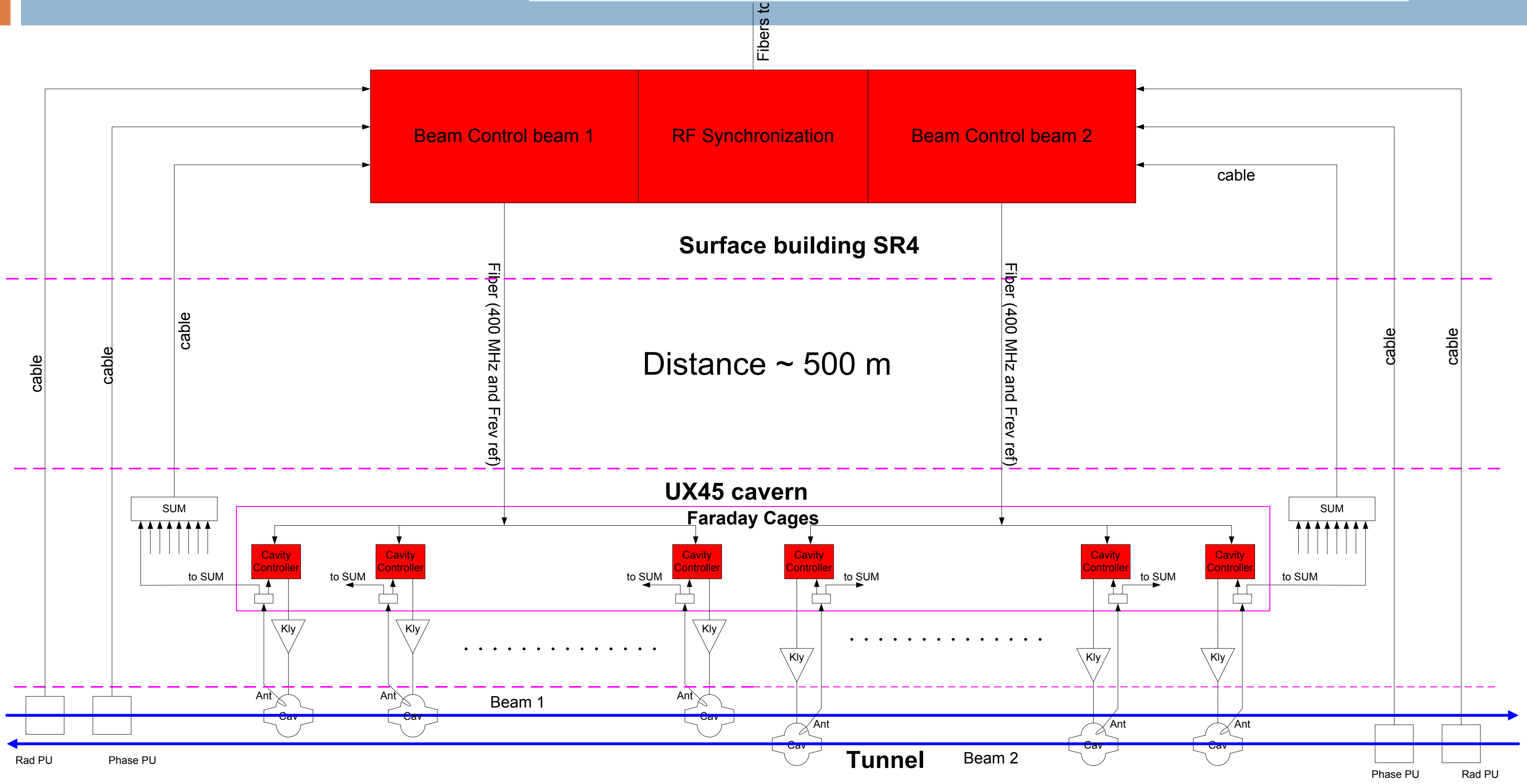
- **The LHC accelerating LLRF.** Generation of RF reference for each ring and control of the cavity field
- **Phase noise in an RF cavity.** Formalism including the effects of the various noise sources. Results with the ACS cavities. Extrapolation to crab cavities
- **LLRF architecture and Controls.** Interconnection with the accelerating RF. Voltage control
- **Operational scenario.** From filling with transparent crab cavities to luminosity leveling
- **Some (tentative) conclusions…**

The LHC accelerating LLRF

Two-level hierarchy

Beam control

- one system per ring
- uses beam-based measurements (avg position and phase)
- updates once per turn (11 kHz)
- generates a fixed amplitude RF reference sent to all 8 cavities



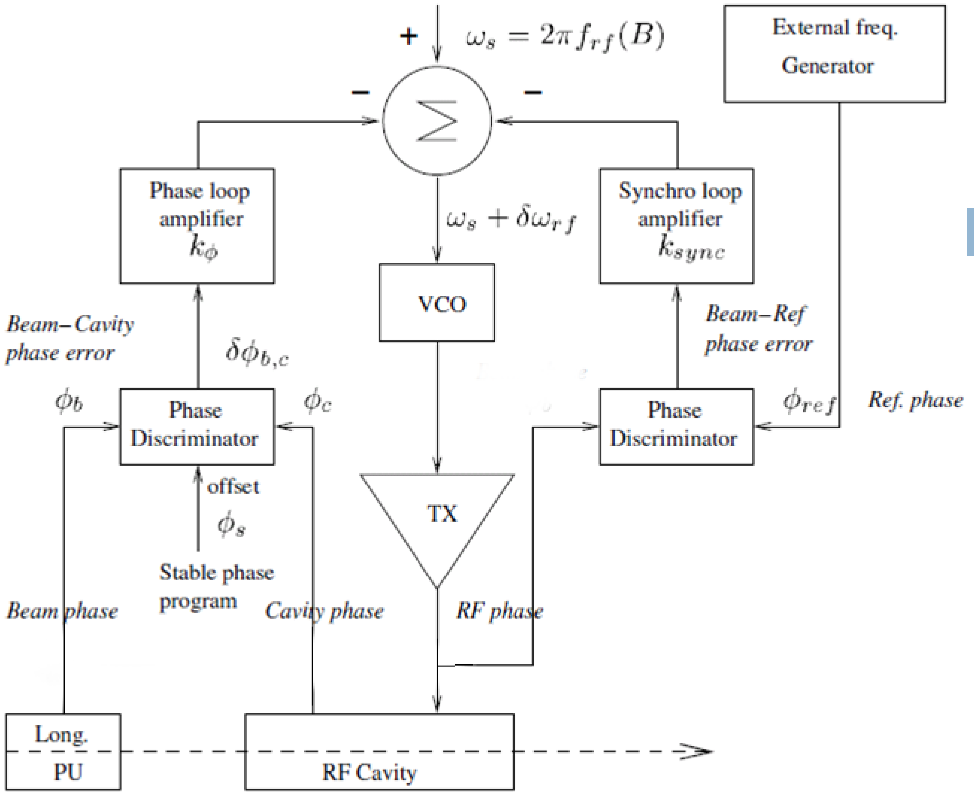
Cavity Controller

- one system per cavity
- uses klystron and cavity field measurements
- updates at every bunch (40 MHz)
- generates the klystron drive (plus tuner control)

16.12.2010

Beam control

- The Synchronization loop keeps the VCXO tracking the frequency program. It is a weak slow loop with cut-off below the Synchrotron frequency
- The main phase loop minimizes the error between the beam phase (PU) and the vector Sum of the eight cavities. It is a strong fast loop
- The beam phase is computed by averaging over all bunches in one turn
- The main phase loop therefore damps synchrotron dipole mode zero only, that is theone excited by noise at $f_{RF}+-f_{s0}$



Classic combination for proton and ion synchrotrons: Phase loop and Synchro loop. In the LHC we use a VCXO and the phase loop uses a vector Sum of the eight cavities

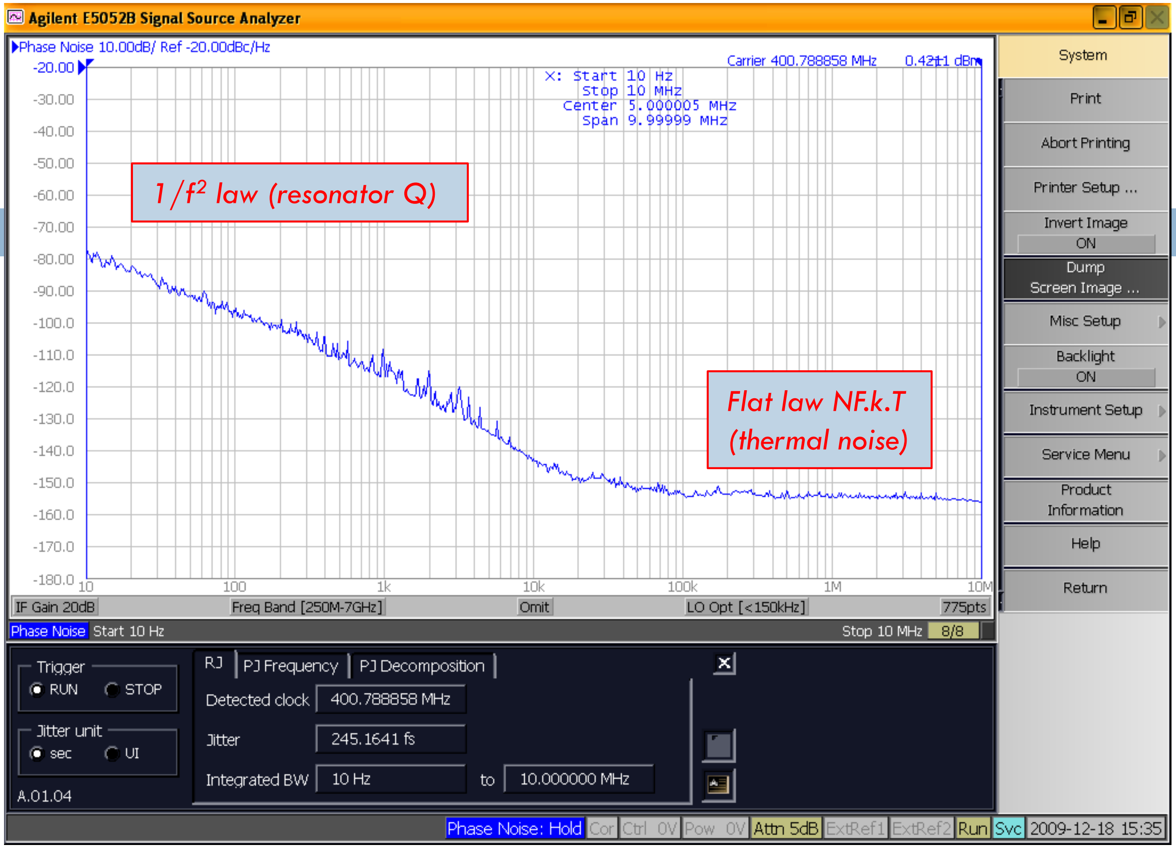
RF Phase noise

For the ACS cavities we had two challenges: RF noise (as this could limit luminosity lifetime in physics conditions) and beam loading (as this can limit the stable beam current limit).

For the crab cavities control we must optimize for RF noise mainly… if the beam is kept centered…

Beam control

SSB Phase noise (in dBc/Hz) of the VCXO output



Agilent E5052B Signal Source Analyzer

Phase Noise 10.00dB/ Ref -20.00dBc/Hz

Carrier 400.788858 MHz 0.42±1 dBm

```
X: Start  10 Hz
    Stop  10 MHz
  Center  5.000005 MHz
    Span  9.99999 MHz
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1/f² law (resonator Q)

Flat law NF.k.T (thermal noise)

IF Gain 20dB | Freq Band [250M-7GHz] | Omit | LO Opt [<150kHz] | 775pts

Phase Noise Start 10 Hz | Stop 10 MHz | 8/8

Trigger: ● RUN ○ STOP

Jitter unit: ● sec ○ UI

A.01.04

Detected clock: 400.788858 MHz

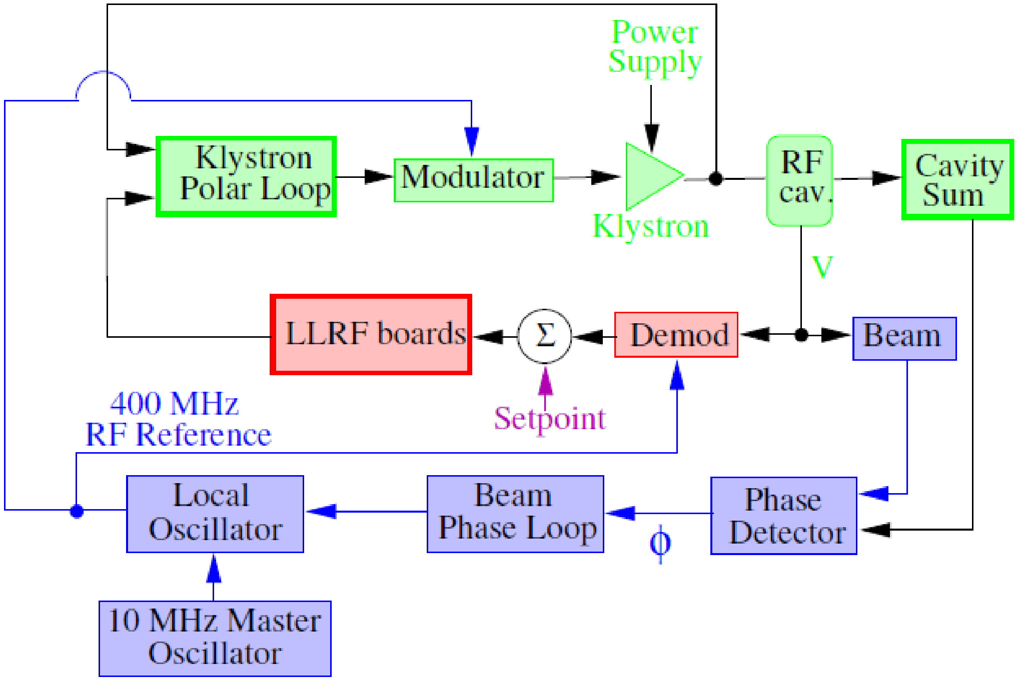
Jitter: 245.1641 fs

Integrated BW: 10 Hz to 10.000000 MHz

Phase Noise: Hold | Cor | Ctrl 0V | Pow 0V | Attn 5dB | ExtRef1 | ExtRef2 | Run | Svc | 2009-12-18 15:35

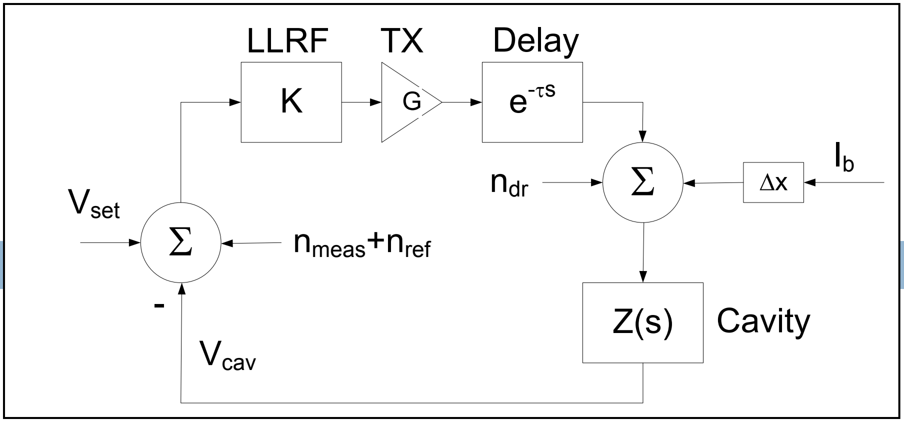
- Single Side Band (SSB) phase noise spectrum of the VCXO output (RF reference) at injection in dBc/Hz
- 1/f² characteristic below ~ 20 kHz (loss in resonator)
- Flat spectrum above ~ 20 kHz, at ~ -155 dBc/Hz, thermal noise
- Above is the no-beam situation. With beam the Main Phase loop reduces the noise around the synchrotron frequency (see next slides)

Beam Control plus Cavity Controller



- 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 eight 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} transformed at the accelerating gap. It includes also the LLRF noise not related to the demodulator
  - The Beam Loading $I_b \, \Delta x$
- We get

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

with $s = j \Delta \omega$

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

Closed Loop response CL(s)
- Equal to ~1 in the CL BW
- Increase of K increases the BW
- Final BW limited by loop delay τ
- 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

Loop Delay

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

$$[K\,G]_{\max} \approx \frac{Q}{R\,\omega_0}\,\frac{1}{T}$$

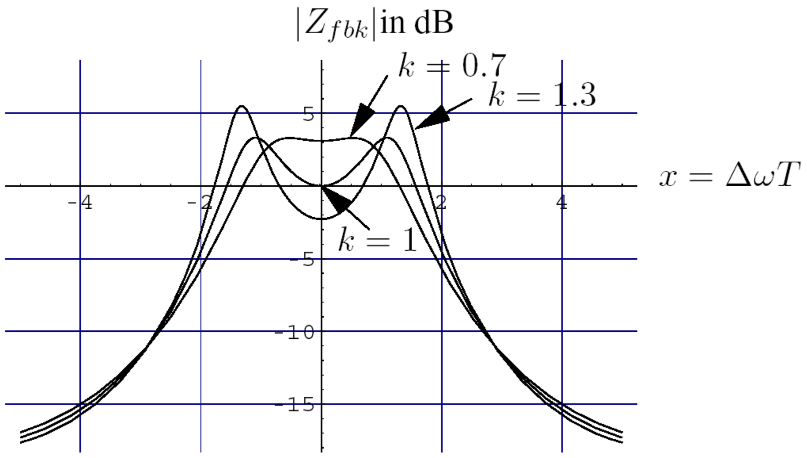
- leading to the effective cavity impedance at resonance

$$Z_{eff}(0) = \frac{\frac{R}{Q}Q_L}{1 + K\,G\,\frac{R}{Q}Q_L} \approx \frac{R}{Q}\omega_0\,T$$

- 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

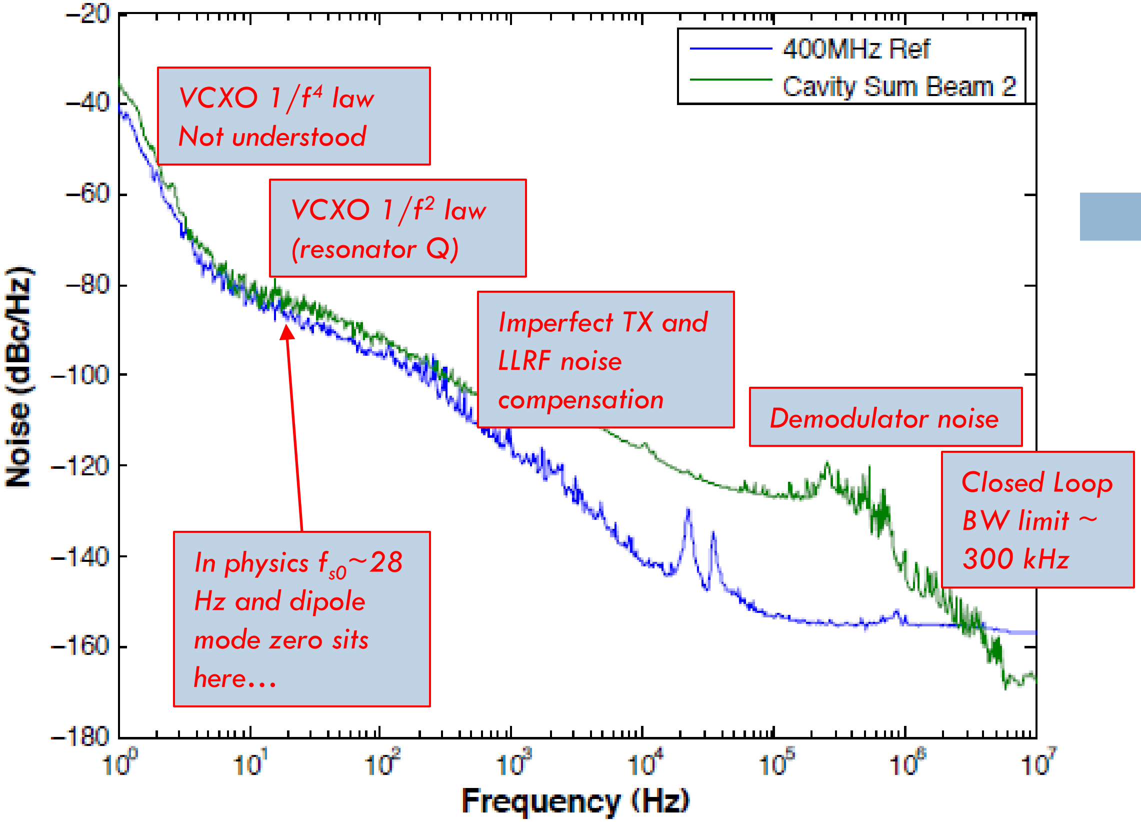


Effective impedance for varying gains.

- 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
- Note: The TX noise transforms into a gap current noise with the ratio $1/Q_L$
- Lesson: Keep delay short and TX broadband to avoid group delay. Work with high Q_L for TX noise compensation

ACS cavities 1/3

SSB Phase noise (in dBc/Hz) of the Vector Sum of the eight cavities B2 (green) compared to the RF reference (blue).
No beam



VCXO $1/f^4$ law
Not understood

VCXO $1/f^2$ law (resonator Q)

Imperfect TX and LLRF noise compensation

Demodulator noise

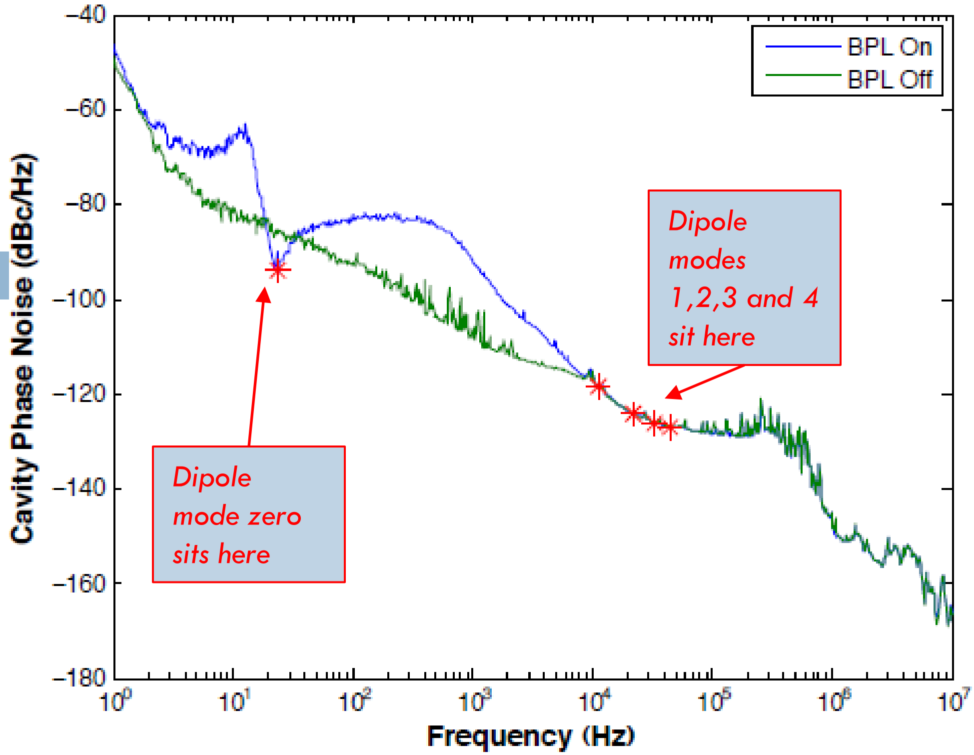
Closed Loop BW limit ~ 300 kHz

In physics f_{s0}~28 Hz and dipole mode zero sits here…

- The Closed Loop bandwidth is ~ 300 kHz (single sided), limited by the 650 ns loop delay
- The Reference noise n_{ref} dominates at low frequencies (below 200 Hz)
- Imperfect compensation of the driver noise is responsible for the 200 Hz to 20 kHz range
- From 20 kHz to the 300 kHz closed-loop BW, the spectrum is flat, dominated by the measurement noise n_{meas}

ACS cavities 2/3

SSB Phase noise (in dBc/Hz) of the Vector Sum of the eight cavities B2 with Main Phase Loop OFF (green) and ON (blue).
With beam at 3.5 TeV



Dipole modes 1,2,3 and 4 sit here

Dipole mode zero sits here

- The Main Phase Loop reduces the noise on the dipole mode 0 synchrotron sidebands (f_{s0} ~ 28 Hz). Without it the Phase noise at +- f_{s0} lead to 300-400 ps/hour bunch lengthening [Mastorides1]
- Notice how the Phase Loop actually increases the noise PSD outside the synchrotron band, below 10 kHz. But the beam does not react
- The phase noise will also excite the beam on the higher dipole modes: @ +- n f_{rev} +-f_s
- What counts is the power that falls in the synchrotron bands only

[Mastorides1] T. Mastorides et.al., LHC Beam diffusion Dependence on RF noise: Models and Measurements, IPAC 2010

ACS cavities 3/3

SSB Phase noise (in dBc/Hz) of the Vector Sum of the eight cavities B2 with beam at 3.5 TeV. The Phase Jitter integrated from 10 Hz to 10 MHz is 818 fs. But what counts is the sum of the noise power in the synchrotron side-bands (of width = tune spread = 4.4 Hz) from mode 0 at 28 Hz to the full 300 kHz noise BW


Agilent E5052B Signal Source Analyzer

Marker 1 28.31488350753 Hz

Phase Noise 10.00dB/ Ref -20.00dBc/Hz

Carrier 400.789714 MHz -1.9684 dBm

```
>1:  28 Hz  -102.4100 dBc/Hz
 X: Start 10 Hz
     Stop 10 MHz
   Center 5.000005 MHz
     Span 9.99999 MHz
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-125 dBc/Hz noise floor

IF Gain 20dB | Freq Band [250M-7GHz] | Omit | LO Opt [<150kHz] | 775pts

Phase Noise Start 10 Hz Stop 10 MHz 8/8

Trigger ● RUN ○ STOP

Jitter unit ● sec ○ UI

A.01.04

Detected clock: 400.789710 MHz

Jitter: 818.0701 fs

Integrated BW: 10 Hz to 10.000000 MHz

Set RF ATT 0dB | Phase Noise: Hold | Cor | Ctrl 0V | Pow 0V | Attn 5dB | ExtRef1 | ExtRef2 | Run | Svc | 2009-12-12 14:55

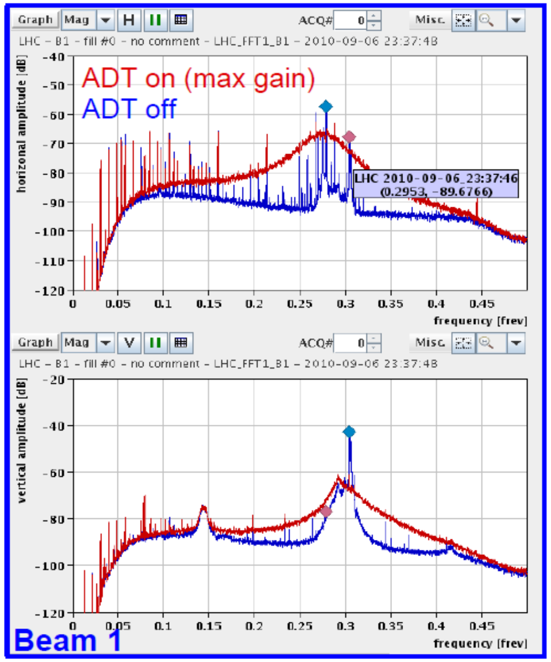
- Except for mode zero where the PSD cannot be measured due to the instrument resolution, we have a noise level of ~ -125 dBc/Hz from 10 kHz to 500 kHz. This corresponds to 6.3E-13 rad^2/Hz, causing a bunch lengthening of less than 10ps/h
- For comparison the Tevatron RF phase noise is 5E-11 rad^2/Hz [Zhang]
- Much more on the LHC LLRF and RF noise in [Mastorides2]…

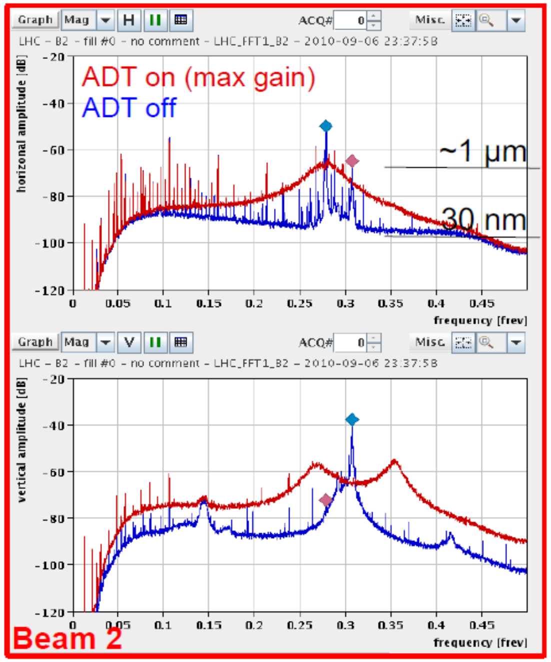
[Zhang] X. Zhang et.al., Generation and Diagnositc of uncaptured beam in the Fermilab Tevatron and its control by electron lenses, Physical Review Special Topics Accelerators and Beams, 2008
[Mastorides2] T. Mastorides et.al., RF system models for the CERN LHC with application to longitudinal dynamics, Physical Review Special Topics Accelerators and Beams, 2010

Back to crabs…

- Assume a SSB phase noise of -125 dBc/Hz or 6.3E-13 $\mathrm{rad}^2/\mathrm{Hz}$
- Assume that only the noise in the betatron bands have effect and take 0.01 tune spread (300 Hz band)
- In the LHC case the RF feedback BW was maximized for cavity impedance reason. Not clear what the optimal BW is for a crab cavity. Will depend on the TX noise BW. Take 300 kHz
- Now summing the noise PSD from DC to + 300 kHz over all betatron bands, we get 300/11 x 2 x 300 x 6.3E-13 rad^2 =1E-8 rad^2
- Conclusion: a “copy” of the LHC ACS design (300 kW klystron !) would generate 1E-4 rad rms or 5E-3 deg rms phase noise @ 400 MHz, all in the betatron band. Relatively in line with the tolerance quoted at LHC-CC08 but it must be confirmed by simulations with all noise power in the betatron bands
- Klystron are reputed noisy. Predictions must be refined with candidate TX noise spectrum (IOT, Tetrode, Solid State) and cavity Q_L

Why integrate on betatron bands only?





The noise injected by the ADT kickers leads to broadband excitation of the beams that are measured by the Tune system. Outside the betatron band the ADT is virtually open-loop as there is no coherent reaction from the beam.
However this broad-band noise does not lead to emittance blow-up.

[Steinhagen] R. Steinhagen, Feedbacks: Status, Operational Dependencies and Outlook for 2011, LHC Beam operation workshop, Evian, Dec 8, 2010

Modulation of bunch phase 1/2

- So far we have studied the absolute RF phase noise. What counts is the noise with respect to the centre of the bunch
- Bunches are not perfectly centered with the RF reference because the compensation of transient beam loading is not perfect (longitudinal)
- Without RF feedback, a gap in the beam current will induce a beam loading transient that changes the RF phase by [Boussard2]

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

- With 1.7 A at 400 MHz, 16 MV, and 45 ohm R/Q, the 3 μs long abort gap causes a phase change of 1 degree @ 400 MHz
- For Q_L=60k, the RF fdbk reduces the impedance by ~40 linear. The phase drift would be ~0.025 degree
- Still too much? Use 1-T fdbk to further reduce the effective impedance. As this perturbation reproduces at each turn, Adaptive Feed Forward (AFF) can also be used on the ACS cavities
- The above effect is not a noise but a precision problem. It displaces the kick w.r.t. the bunch centre. But, for a given bunch, the error is constant from turn to turn. No damage? To be studied.

[Boussard2] D. Boussard, RF Power Requirements for a High Intensity Proton Collider, PAC, San Francisco, 1991

Modulation of bunch phase 2/2

- Intentional modulation of the Cavity Voltage phase was proposed to minimize the klystron power transients [Tuckmantel]. The idea is to let the bunches settle at slightly shifted positions (not strictly equal bunch spacing) to make the RF power constant over the turn
- With nominal (0.5 A DC) it is shown that the klystron power can be constant at the expense of a +-50 ps (+-7 degrees @ 400 MHz) modulation in RF phase
- The intent was to implement the phase modulation in the cavity controller, by letting, for each cavity the voltage set point adapt to minimize klystron power transients
- It does not seem easy to make this phase modulation compatible with precise phasing of the crab cavity RF kicks
- However, just like the uncorrected transient beam loading, the above effect is a precision problem. It displaces the kick w.r.t. the bunch centre. The error is constant from turn to turn. No damage? To be studied.

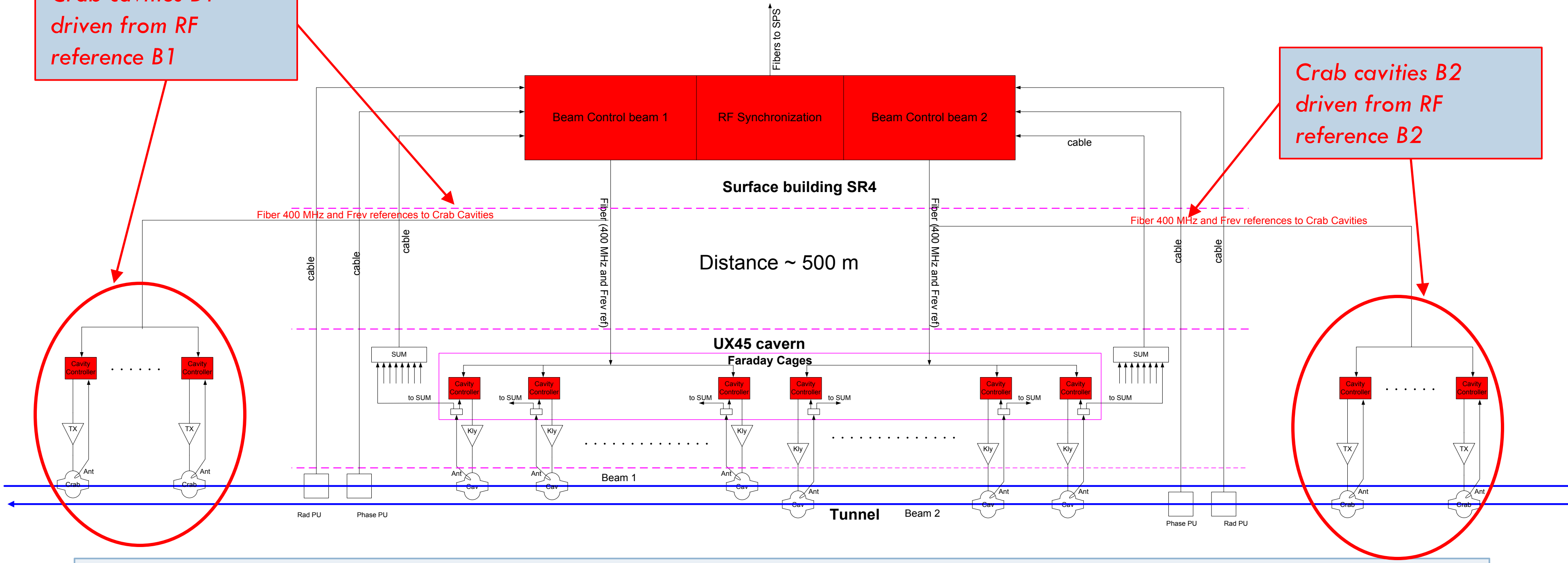
[Tuckmantel] J. Tuckmantel, Adaptive RF transient reduction for high intensity beams with gaps, EPAC 2006

LLRF Architecture and Controls

A large part of the following material overlaps with Andy's presentation at the CC Workshop 2009

See http://indico.cern.ch/getFile.py/access?contribId=105&sessionId=10&resId=1&materialId=slides&confId=55309

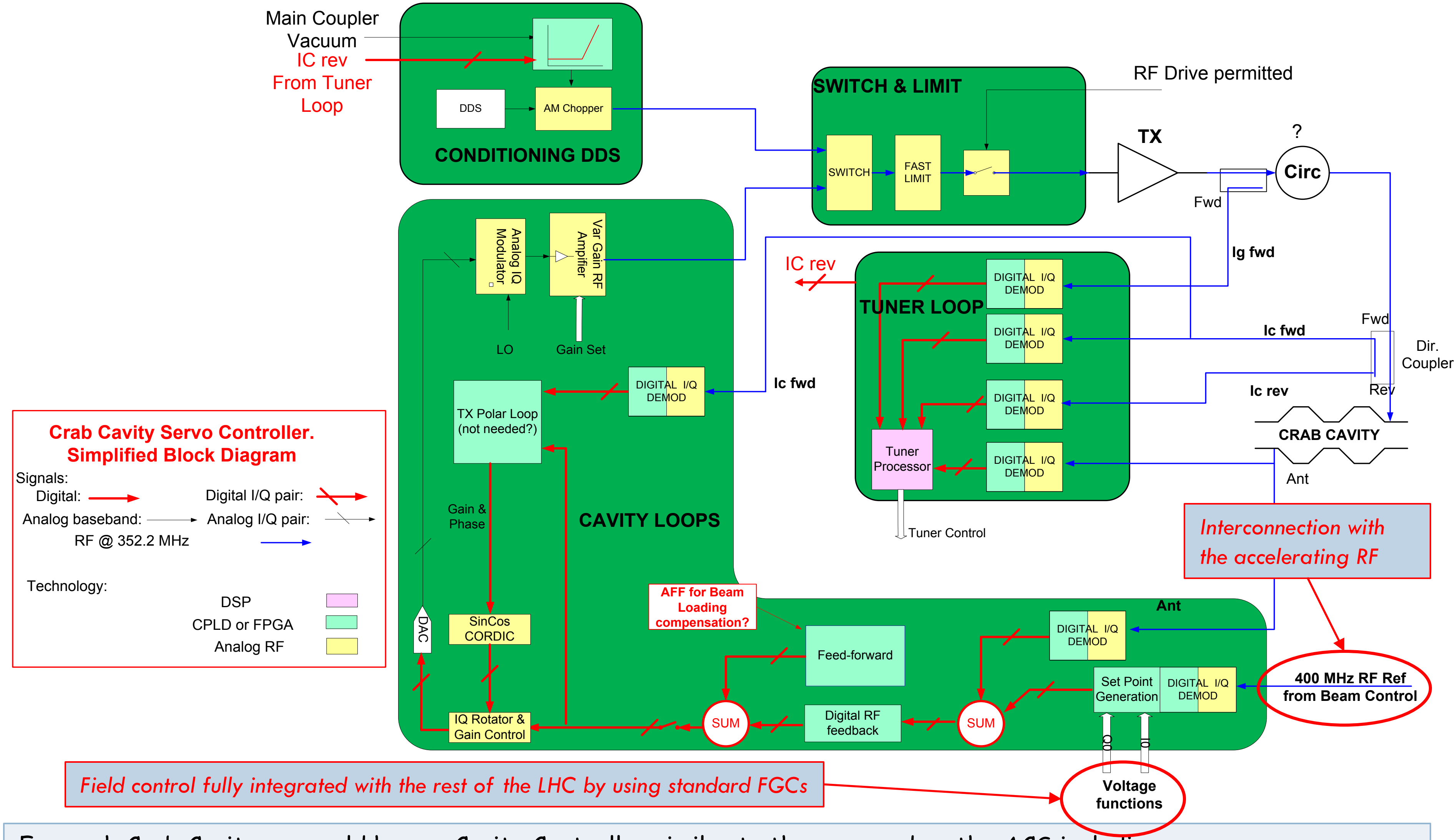
Architecture



Crab cavities B1 driven from RF reference B1

Crab cavities B2 driven from RF reference B2

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



Crab Cavity Servo Controller. Simplified Block Diagram

Interconnection with the accelerating RF

Field control fully integrated with the rest of the LHC by using standard FGCs

For each Crab Cavity we would have a Cavity Controller similar to the one used on the ACS including:

An RF Feedback Loop for noise and beam loading control

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. We propose to use standard LHC functions to drive the cavity voltage with the classic LHC Controls tools (FGCs developed for the LHC Power Converters and used by the LHC RF).

Operational scenario

a very first look …

Operational scenario 1/2

This slide has been modified, after the presentation, following very relevant input received during the discussion. Thanks a lot!

- Boundary conditions:
  - During filling, ramping and for physics with crab cavities off, the cavities must be detuned by ½ f_{rev} to keep the beam stable (issue of Transverse Impedance budget)
  - Bringing the cavities from detuned to on-tune can only be done with active RF feedback ON. Else, the beam will be unstable (again…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". If it is given measurements, LLRF can do wonder…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
- Now comes the proposed scenario:
  - During filling, ramping or operation with transparent crab cavities, we detune the cavity by ½ f_{rev} with a small field. Amplitude/phase can be optimized among the cavities of same Beam/IP to minimize effects. The tuning system is ON. The RF feedback is used with the cavity detuned to keep the Beam Induced Voltage zero if the beam is off-centered. This calls for a study: Needed TX power? Higher Q_L not favorable anymore. 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 gain/phase must be continuously adjusted as the cavity moves towards tune (easy). The RF feedback keeps the cavity impedance small (beam stability) 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… at will… Any luminosity leveling scheme that ABP can think of…

Operational scenario 2/2

- If a TX or Cavity trips
  - We can trigger the Beam Dump…easy…
  - Or we can think of something more clever. It is not obvious to propagate emergency voltage trims to the other cavities. In the proposed hierarchy these trims can come though the Real-Time channel of the FGCs. This method is very successfully used for orbit and tune feedback in the LHC, with 100 ms update rate. But the response time required here is at least three orders of magnitude faster. An ad-hoc implementation is probably required. To be studied…

Some conclusions…

very tentative…

Some conclusions

- Compared to the ACS achievements, the RF phase noise budget appears manageable but we must count on a strong RF feedback and that calls for a small loop delay. Layout must be studied: TX and LLRF crate close to the cavities (ex-Lep klystron galleries? SPS test bench?). More detailed studies can be done after selection of TX technology and cavity Q_L
- The integration of the Crab Cavity with the ACS system and with the LHC High-Level Controls appears easy: We propose to use the 400 MHz RF reference from the Beam Control, for the Crab Cavities. The voltage is controlled via the FGCs that would generate voltage set-points used by the RF feedbacks. The proposal to use RF feedback on detuned cavity during filling/ramping must be studied. It may orient the design towards lower Q_L

Thank you for your attention…

…and your suggestions…