Update on Crab Cavity: Impedance (at fundamental), RF noise, operational scenario

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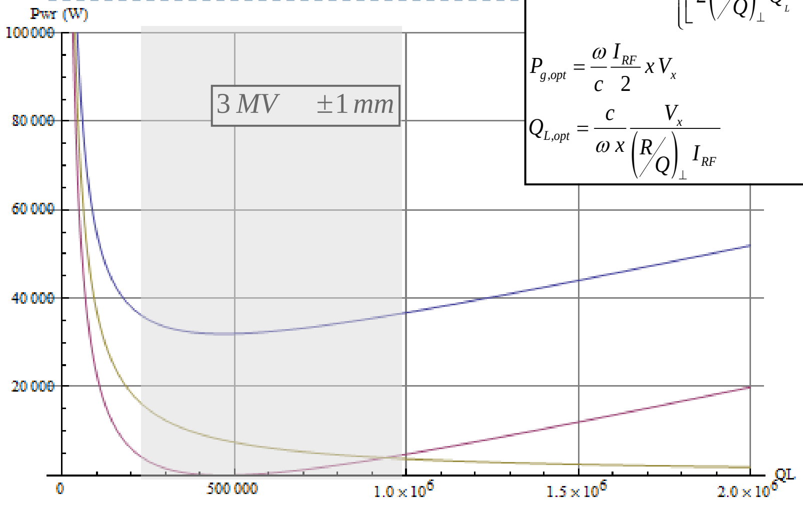
Tolerable beam offset

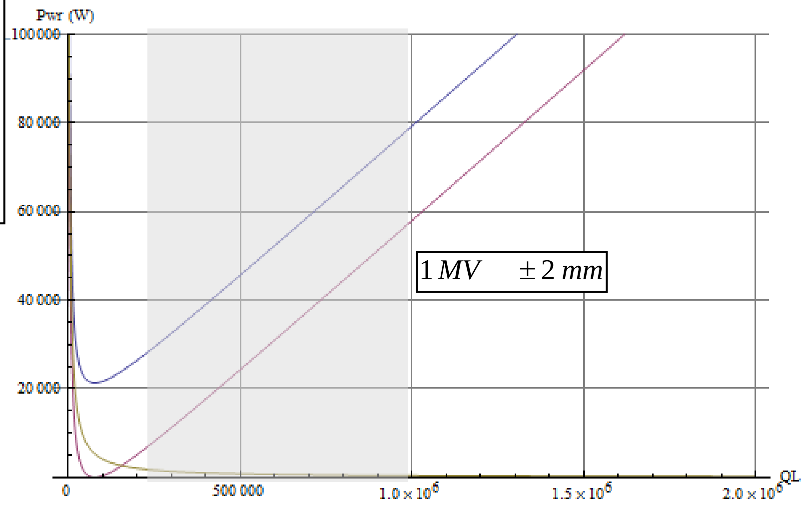
RF Power vs. Q_L for various RF voltages and beam offsets

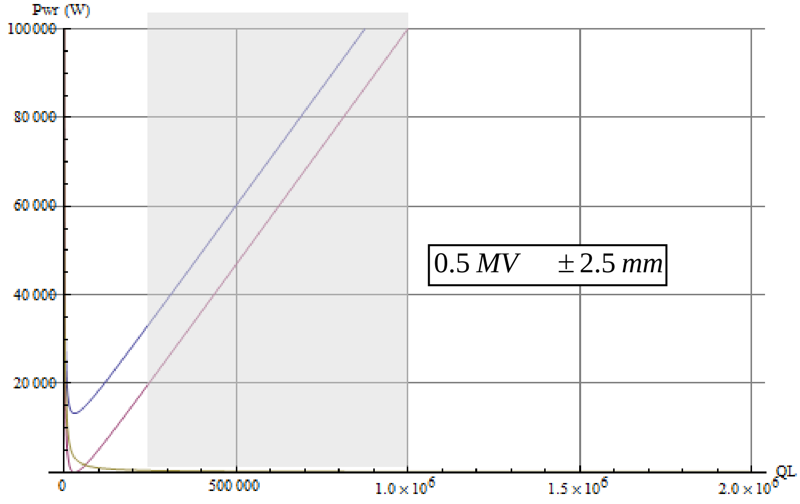
$$P_g = \frac{1}{2}\left(\frac{R}{Q}\right)_\perp Q_L \left\{\left[\frac{V_x}{2\left(\frac{R}{Q}\right)_\perp Q_L} + \frac{\omega}{c}\frac{I_{RF}}{2}x\right]^2 + \left[\frac{V_x\,\Delta\omega}{\omega\left(\frac{R}{Q}\right)_\perp}\right]^2\right\}$$

$$P_{g,opt} = \frac{\omega}{c}\frac{I_{RF}}{2}\,x\,V_x$$

$$Q_{L,opt} = \frac{c}{\omega\,x}\frac{V_x}{\left(\frac{R}{Q}\right)_\perp I_{RF}}$$







R/Q = 300 Ω. 1.11 A DC current, 1 ns 4σ bunch length with Cos² longitudinal profile (2 A RF component of beam current). Cavity on tune. During filling and ramping, we need voltage for tuning only. We can tolerate much larger beam offsets.

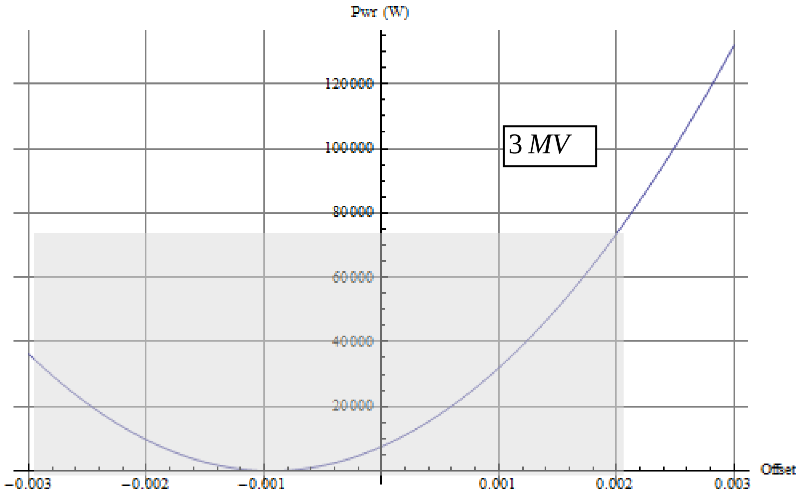
The important parameter is the product R/Q Q_L

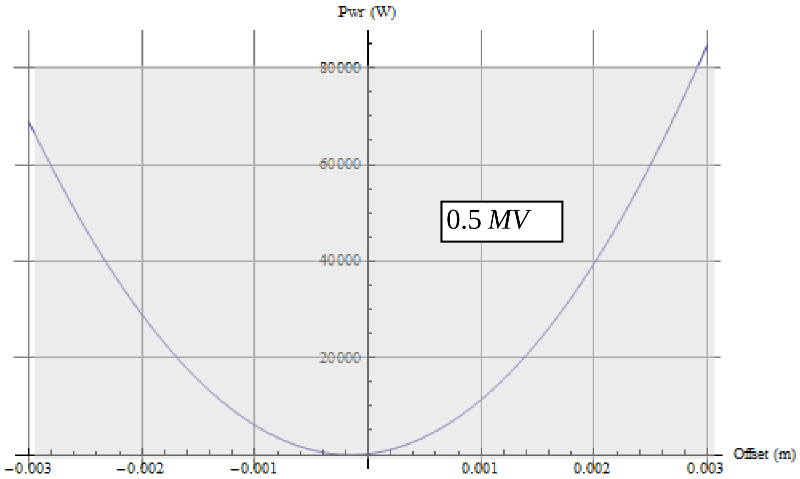
RF Power vs. Offset

$$P_g = \frac{1}{2}\left(R/Q\right)_{\perp} Q_L \left\{ \left[\frac{V_x}{2\left(R/Q\right)_{\perp} Q_L} + \frac{\omega}{c}\frac{I_{RF}}{2} x \right]^2 + \left[\frac{V_x\,\Delta\omega}{\omega\left(R/Q\right)_{\perp}} \right]^2 \right\}$$

$$P_{g,opt} = \frac{\omega}{c}\frac{I_{RF}}{2} x V_x$$

$$Q_{L,opt} = \frac{c}{\omega x}\frac{V_x}{\left(R/Q\right)_{\perp} I_{RF}}$$





Q_L=500000 R/Q = 300 Ω. 1.11 A DC current, 1 ns 4σ bunch length with Cos² longitudinal profile (2 A RF component of beam current). Cavity on tune.

With 80 kW, we can tolerate 2 mm offset during physics (3 MV) and 3 mm during filling (0.5 MV).

Impedance issues, fundamental mode

Case 1: Idling cavity (RF OFF)

NB resonator, transverse

- Transverse impedance of a transverse mode

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

- The damping rate and tune shift of coupled-bunch mode *l* (rigid 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, transverse

- With 25 ns bunch spacing (M=3564), for a resonance around 400 MHz, with a BW much below 40 MHz, the infinite sum reduces to the two terms ($p=\pm 10 \rightarrow p\,M\,\omega_{rev} = \pm\,\omega_{RF}$)

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

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

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

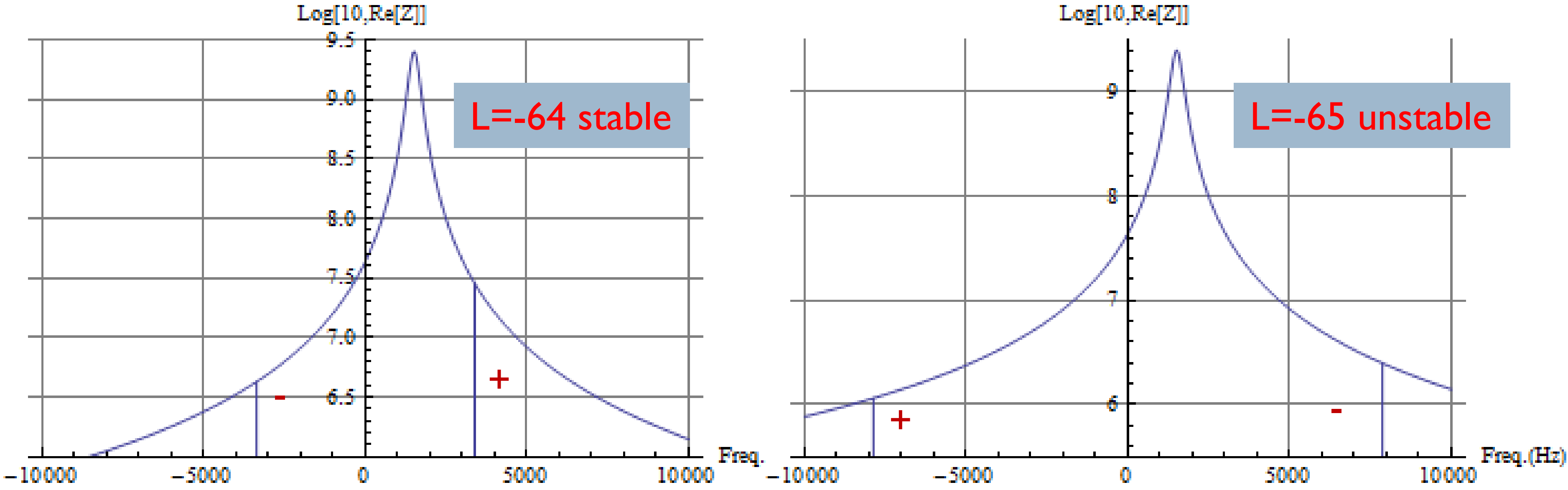
$$\sigma_l \approx \frac{c\;\;q\;\;I_0}{2\;\;\omega_b\;\;E\;\;T_{rev}}\left\{\mathrm{Re}\left[Z^{\perp}\left(\omega_{RF}+l\omega_{rev}+\omega_b\right)\right]-\mathrm{Re}\left[Z^{\perp}\left(\omega_{RF}-l\omega_{rev}-\omega_b\right)\right]\right\}$$

- The damping 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=64.3, the damping rate of mode l=-64 is computed from the difference between the real part of the impedance at $\pm 0.3\;\omega_{rev}$
- Negative damping rate -> instability

Cavity idling and detuned

- With a positive non-integer tune (Q_h=64.3, ω_b/ω_{rev} above an integer), the cavity should be tuned above the RF frequency to make the mode *l*=-64 stabilizing

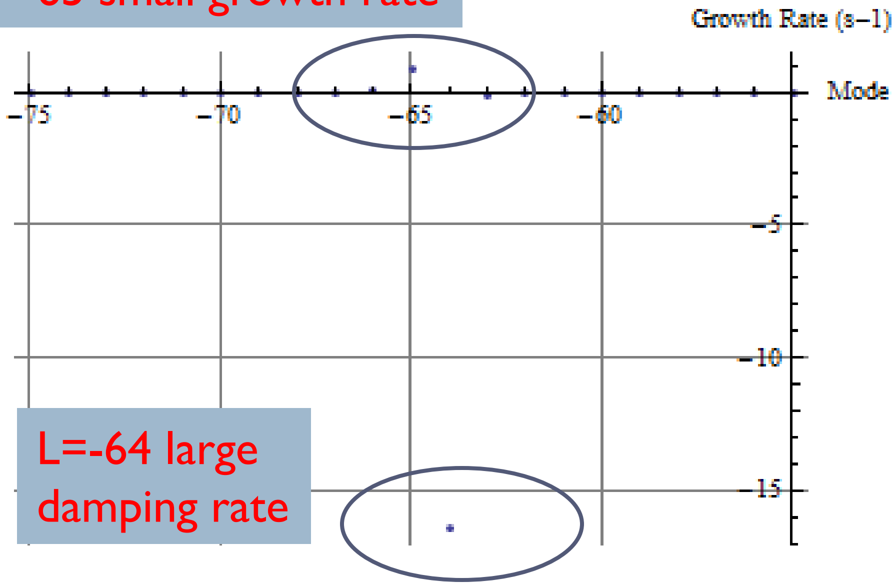
$$\sigma_l \approx \frac{c \quad q \quad I_0}{2 \quad \omega_b \quad E \quad T_{rev}}\left\{\mathrm{Re}\left[Z^{\perp}\left(\omega_{RF}+l\omega_{rev}+\omega_b\right)\right]-\mathrm{Re}\left[Z^{\perp}\left(\omega_{RF}-l\omega_{rev}-\omega_b\right)\right]\right\}$$



Real part of the cavity impedance with 1.5 kHz detuning (log scale)

- Left: mode l=-64. The damping rate is computed from the difference in Real[Z] evaluated at +0.3 Frev and -0.3 Frev. STABLE
- Right: mode l=-65. The damping rate is computed from the difference in Real[Z] evaluated at -0.7 Frev and +0.7 Frev. UNSTABLE but very low growth rate

L=-65 small growth rate



L=-64 large damping rate

Growth rate (per cavity) with cavity parked idling at 1.5 kHz detuning. Assuming beta function at location of crabbing equal to average

	most unstable mode	
detuning (kHz)	damping rate (s-1)	mode index
-1.5	-17	-64
-1	-8.5	-64
-0.5	-3.5	-64
0	0	
0.5	-0.28	-65
1	-0.58	-65
1.5	-0.9	-65
2	-1.3	-65
3	-2.4	-65
3.5	-3	-65
4	-4	-65
5	-8	-65
6	-20	-65
7	-85	-65
8	-1200	-65
9	-52	-65
10	-15	-65

For stability, the optimal is a zero or small positive detuning.

- If we can keep the cavity properly detuned, the impedance at the fundamental is not a serious problem for stability. The damping time of the ADT is in the order of 1 ms at 7 TeV (damping rate 1000 s^{-1}).
- The detuning amplitude should be set to keep the beam induced kicks (for an off-centered trajectory) within reasonable bounds

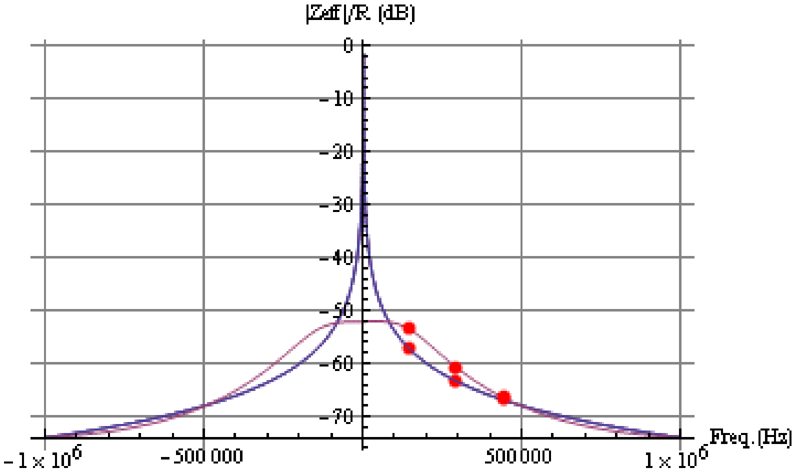
Operation with idling cavities seems feasible if they are properly detuned

Impedance issues, fundamental mode

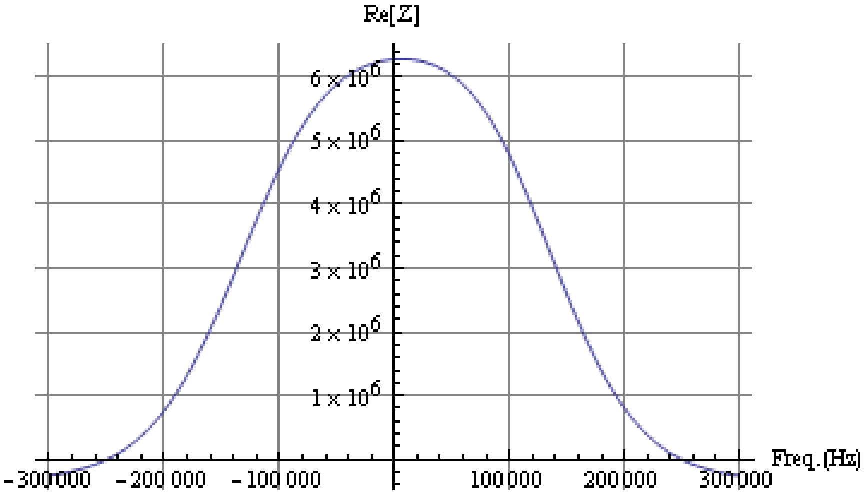
Case 2: RF feedback ON

RF ON

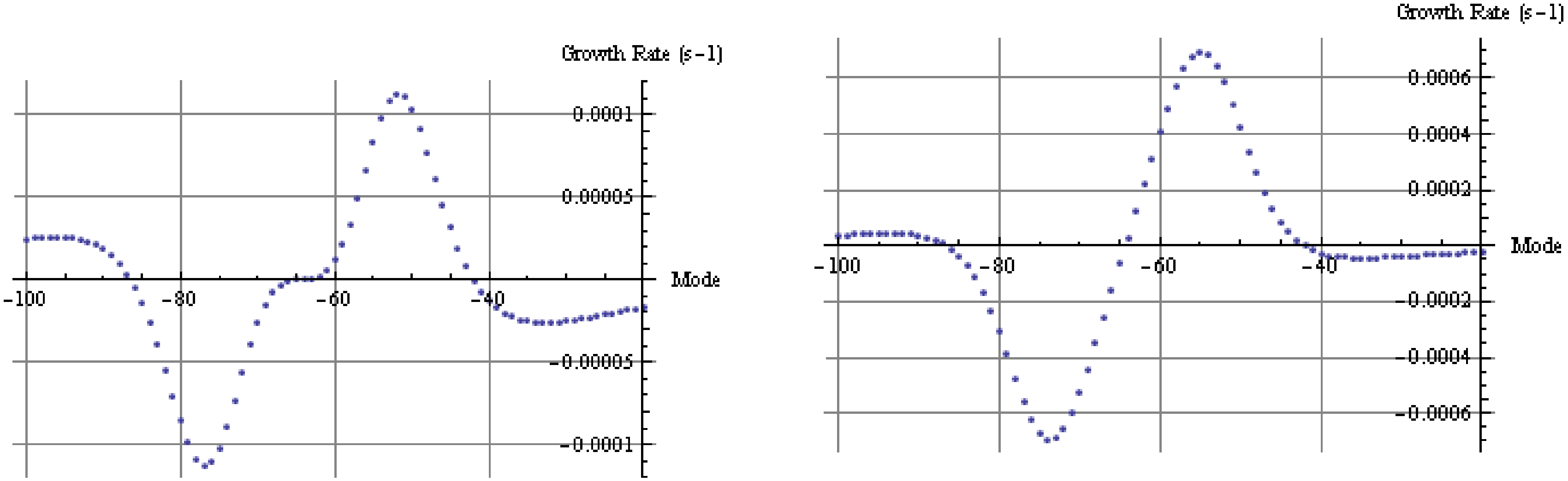
- In physics, with the crabbing on, we must have an active RF feedback for precise control of the cavity field
- The RF feedback reduces the peak cavity impedance and transforms the high Q resonator into an effective impedance that covers several revolution frequency lines
- The actual cavity tune has no big importance for stability anymore
- The growth rates and damping rates are much reduced, and we have no more dominant mode



Comparison of the modulus of the cavity impedance without and with RF feedback.



Real part of the effective impedance with RF feedback. Reduced from 2.5 GΩ/m to 6 MΩ/m



Growth rate (per cavity) in physics, with RF feedback

- Left: cavity on tune
- Right: cavity detuned by -100 Hz

Assuming beta function at location of crabbing equal to average

With RF feedback ON the growth rates are 3 orders of magnitude smaller than with a cavity idling and detuned at + 1.5 kHz.

Tentative conclusion (impedance at the fundamental) 1/2

- Filling and ramping: Scenario A = Cavity on tune, RF ON with counterphasing
  - The cavity is tuned at the RF frequency
  - Each cavity has a small (0.5-1 MV?) set point, with counterphasing
  - The RF feedback is ON
  - The available power is sufficient even for large offsets (3 mm)
  - The growth rates are negligible
- Filling and ramping: Scenario B = Parked cavity, RF OFF
  - The cavity must be tuned above the RF frequency
  - The growth rates are small and correspond to low-frequency modes, where the damper gain is maximum
  - Question: How do we control/check tune with RF OFF? Using phase PU and Antenna?

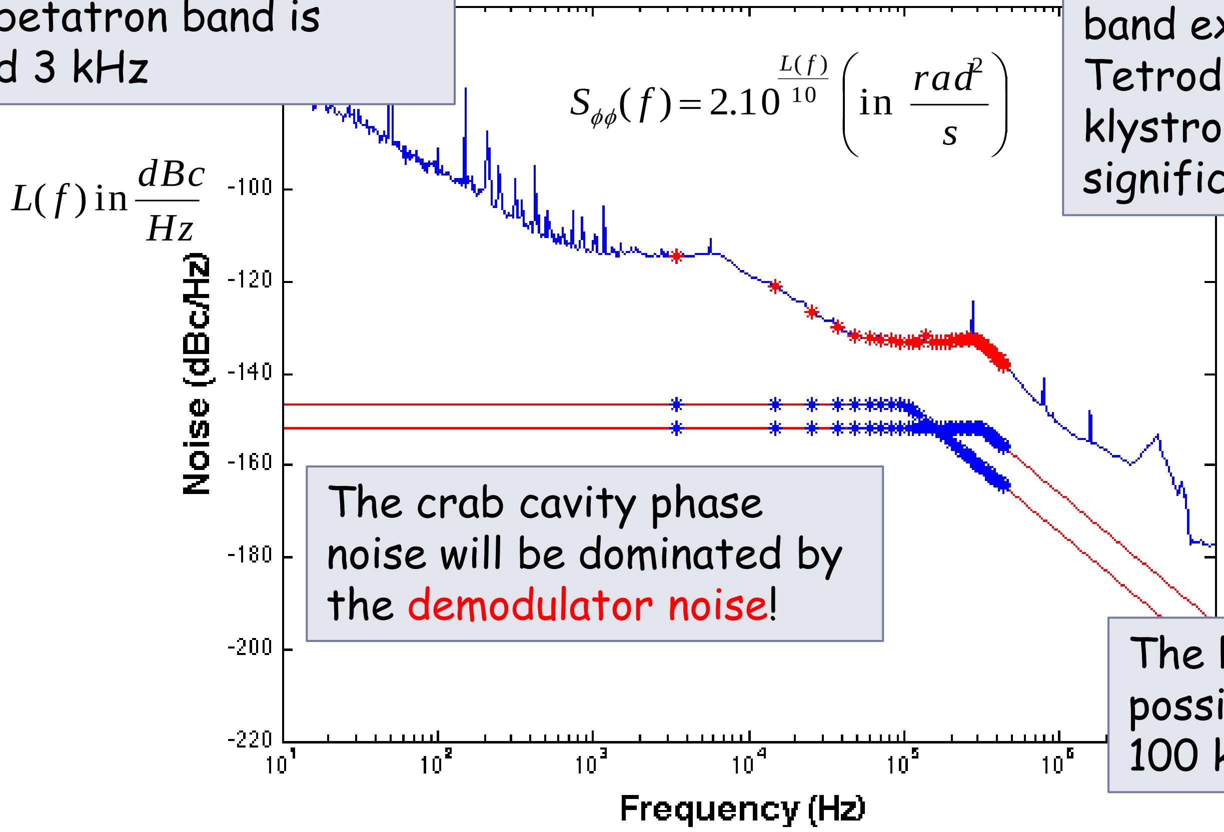
Tentative conclusion (impedance at the fundamental) 2/2

- Crabbing
  - The cavity will be on-tune
  - The RF feedback is needed for precision of the kicks and reduction of TX noise
  - It will reduce the growth rate to values compatible with the damper. The unstable modes correspond to low frequency transverse oscillations

RF noise

Scaling the ACS noise to CCs

Noise in the 10Hz-1kHz range is not an issue as the first betatron band is around 3 kHz



TX noise is important in the band extending to 20 kHz. Tetrodes are less noisy than klystrons, so it will be significantly reduced.

The crab cavity phase noise will be dominated by the demodulator noise!

The bandwidth will be possibly reduced to about 100 kHz.

- ACS SSB phase noise Power Spectral Density in dBc/Hz.

We can specify demodulator noise levels for acceptable emittance growth

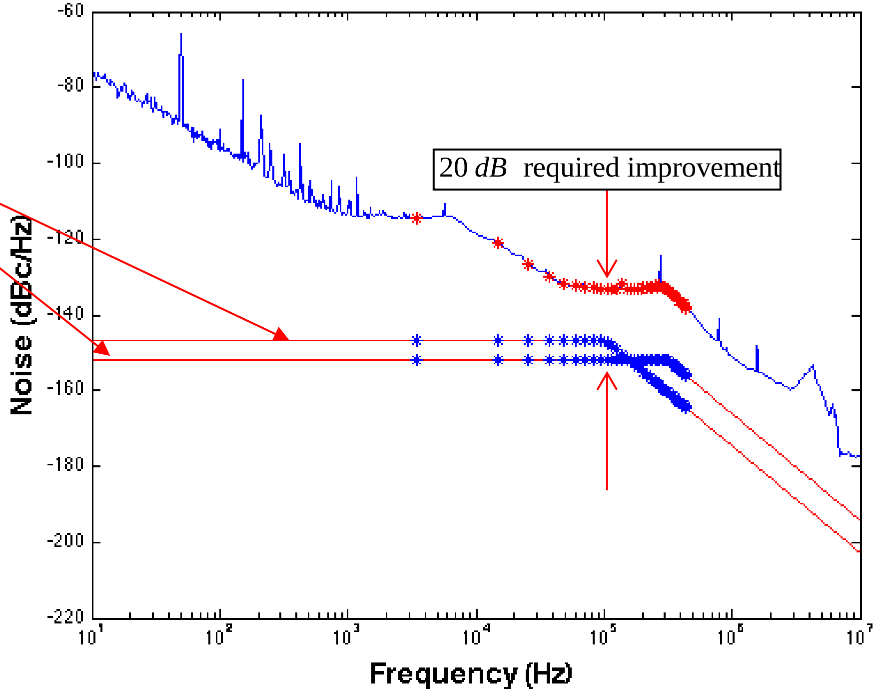
Phase Noise

v	64.31
Δv	0.0015
θ_c (μrad)	500
V_c (MV)	3
β* (cm)	20
β_{cc} (m)	4000
g_{ADT}	0.1

- Phase Noise

$$\frac{d\varepsilon}{dt} = \frac{16\pi^2\Delta\nu^2}{g^2}\frac{1}{2\beta^*}\left(\frac{c\tan(\theta/2)\,f_{rev}}{\omega_{RF}}\right)^2\sum_{n=-\infty}^{\infty}S_\varphi((\nu-n)f_{rev})$$

  - For an emittance growth rate of approximately 5%/hour the demodulator noise level should be in the order of -147 dBc/Hz with a 100 kHz challenging, or -152 dBc/Hz (very challenging) with a 300 kHz bandwidth,
  - This specification could be relaxed by 6 dB or so by increasing the ADT gain at low frequencies.
  - This estimate is for 8 cavities per beam per plane.



Amplitude Noise

- Amplitude Noise

$$\frac{d\varepsilon}{dt} = \frac{\beta_{CC}}{2}\left(\frac{e\sigma_{\varphi} f_{rev}}{E_b}\right)^2 \sum_{n=-\infty}^{\infty} S_{\Delta V}((\nu_b \pm \nu_s - n) f_{rev})$$

  - The ADT cannot act on amplitude noise.
  - Since the crab cavity phase noise is dominated by the demodulator

$$\frac{\Delta V}{V} = \Delta\varphi$$

  - An emittance growth rate of approximately 2.5%/hour is estimated with the power spectral density specified above.

Operational scenario

Operational scenario (1)

- The RF is ON, with strong RF feedback and tune controls at all time. Cavities are on-tune at all time.
- During filling, ramping or operation with transparent crab cavities, we keep them on-tune with a small field requested for the active Tuning system (scenario A). As the crabbing kick is provided by three cavities we use counter-phasing to make the total field invisible to the beam. The RF feedback is used with the cavity tuned 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 we drive counter-phasing to zero. Any luminosity leveling scheme is possible by synchronously changing the voltage or phase in each crab cavity as desired.

Operational scenario (2)

- In case of a CC TX problem, we can still operate the machine
  - The corresponding cavity must be detuned above the RF frequency
  - The growth rate can be damped by the damper
  - But…the cavity must be at cryogenic temperature.

Conclusions

Conclusions

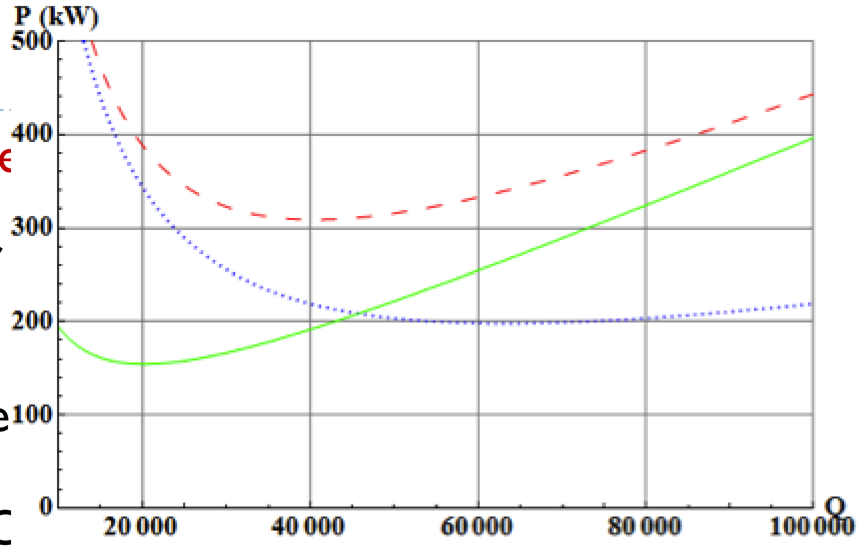
- We propose to keep the cavity on-tune during filling and ramping, with a small voltage (0.5 MV?). With 80 kW RF power we can accept offsets of 3 mm
- During physics the RF power can deal with 2 mm offset (at 3 MV)
- The RF power measurement is used to drive the beam centering
- The impedance at the fundamental is not a problem, thanks to the RF feedback
- We have formulas for the transverse emittance growth caused by RF noise
- The phase noise effects can be reduced by the transverse damper. With a 10 turns damping time (7 TeV), the transverse emittance growth is 5% per hour, if we reduce the phase noise level by 20 dB, compared to the ACS system. This specification could be relaxed by 6 dB or so by doubling the ADT gain at low frequencies
- The amplitude noise cannot be mitigated by the transverse damper. With the RF noise level mentioned above, we estimate the emittance growth around 2.5% per hour.

Back-up slides

ACS phase modulation scheme

Present scheme

- RF/LLRF is currently setup for extremely stable RF voltage (minimize transient beam loading effects). Less than 1 RF phase modulation over the turn with 0.35 A DC (7 ps)
- To continue this way, we would need at least 300 kW of klystron forward power at ultimate intensity (1.7E11 ppb)
- Klystrons saturate at 200 kW with present DC parameters (ultimately 300 kW).
- Sufficient margin necessary for reliable operation, additional RF manipulations etc.
- At 7 TeV, 1.1 A DC, the synchrotron radiation loss is 14 keV per turn, or 27 pW
- All RF power is dissipated in the circulator loads
- The present scheme cannot be extended much beyond nominal.

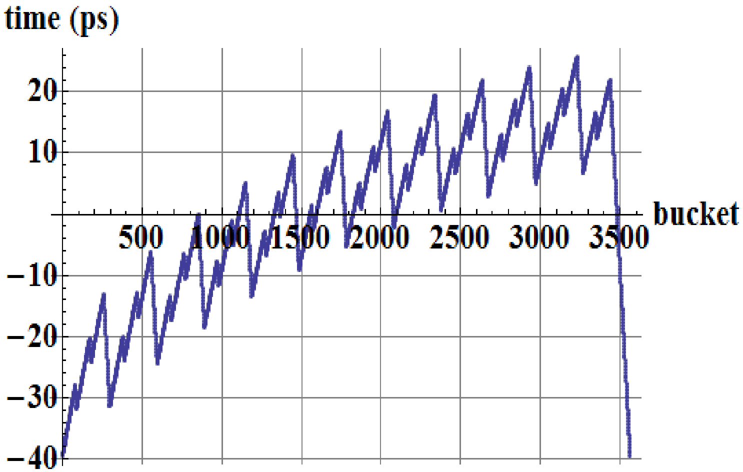


Required klystron power for
1.15e11 ppb, 25 ns, 7 TeV,
1.7e11 ppb, 25 ns, 450 GeV,
1.7e11 ppb, 25 ns, 7 TeV

P. Baudrenghien, T. Mastoridis, "Proposal for an RF Roadmap Towards Ultimate Intensity in the LHC", IPAC 2012

Proposed RF phase modulation scheme

- **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).

Consequences for the CC (1)

- **If the CC follows the phase modulation**
  - Forcing the CC to follow the fast phase modulation (-10 degrees @ 400 MHz in the 3.2 μs long abort gap) results in huge power requirement
  - With the HiLumi parameters (2808 bunches, 2.2E11 p/bunch, 1.11 A DC, 3.2 μs long abort gap), assuming 3 MV per crab cavity, 300 Ω R/Q, we need an absolute minimum of 170 kW per cavity. This minimum is achieved with a Q_L=44000
  - With Q_L=500000, we need 950 kW

Consequences for the CC (2)

- **Fixed CC phase**
  - Keeping the Crab Cavity phase constant over the turn will result in a phase error $\delta\phi$, with respect to the individual bunch center
  - This phase error causes an offset of the bunch rotation axis, resulting in a transverse displacement Δx at the IP

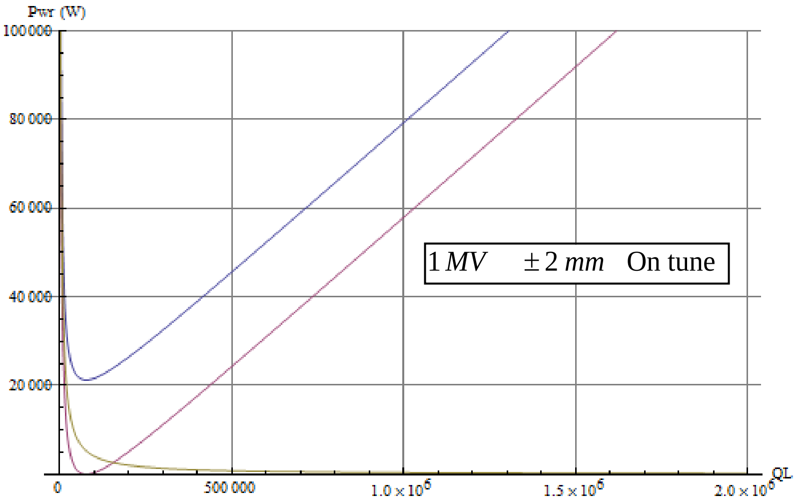
$$\Delta x = \frac{c\phi}{\omega_{RF}}\delta\varphi$$

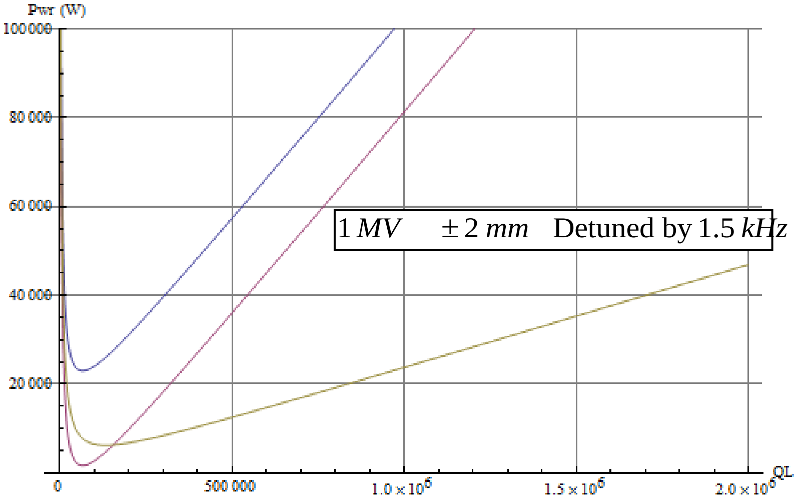
  - For a phase drift of 30 ps, the transverse displacement is 5 μm, approximately equal to the transverse beam size
  - Fortunately the filling patterns are identical for both rings (except for the first six or twelve bunches batch) and the phase errors will be equal for colliding pairs in IP1 (ATLAS) and IP5 (CMS) because the bucket numbering convention makes the bucket one of both rings (first bucket after the abort gap) “collide” in IP1 and IP5
  - There will therefore be no loss of luminosity, only a modulation of the transverse position of the vertex over one turn. This is acceptable by the experiments

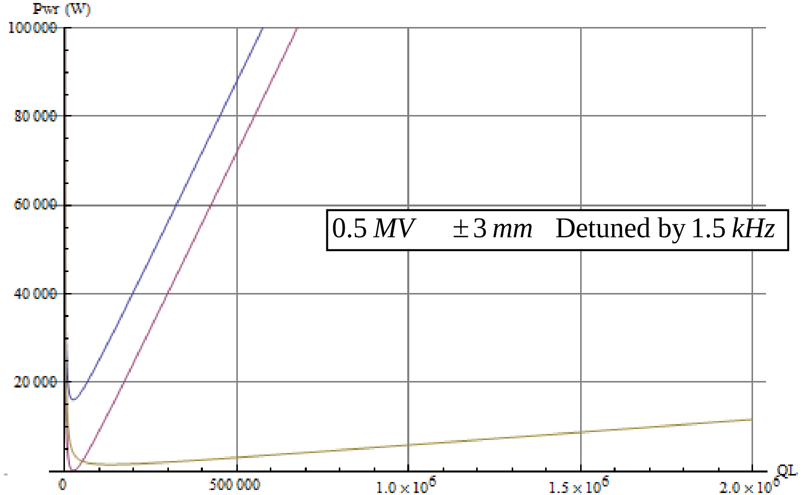
RF Power vs. Q_L for various detuning and beam offsets

$$P_g = \frac{1}{2}\left(R/Q\right)_\perp Q_L \left\{\left[\frac{V_x}{2\left(R/Q\right)_\perp Q_L} + \frac{\omega}{c}\frac{I_{RF}}{2}x\right]^2 + \left[\frac{V_x\,\Delta\omega}{\omega\left(R/Q\right)_\perp}\right]^2\right\}$$

The important parameter is the R/Q.
An high value is favorable







R/Q = 300 Ω. 1.11 A DC current, 1 ns 4σ bunch length with Cos^2 longitudinal profile (2 A RF component of beam current). Cavity on tune (left) and detuned by 1.5 kHz.
During filling and ramping, we can have the RF feedback ON with cavity detuned