Regulation of CC field vs. layout revisited

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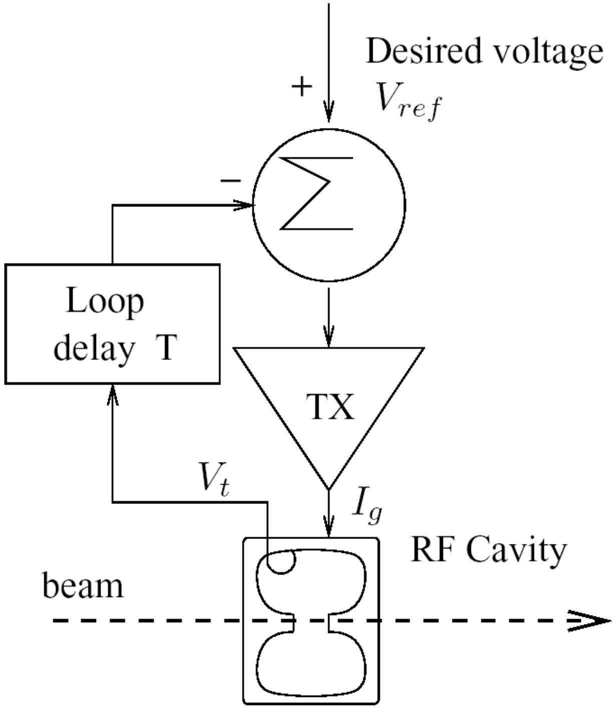
With useful comments from R. Calaga

Loop delay and Controls Bandwidth

RF feedback

- Widely used regulation system
- Principle: Measure the voltage in the cavity, compare it to the desired voltage and use the error to regulate the drive of the power amplifier
- Very efficient to compensate for unknown perturbations: Tune fluctuations, mechanical vibrations, beam loading
- But you cannot react before a perturbation is measured, processed and correction is applied to the cavity via the TX
- So performances are limited by the loop delay



RF or Direct Feedback

Analysis

- A cavity near the fundamental mode can be represented as an RLC circuit

$$Z(\omega) = \frac{R}{1 + j2Q\dfrac{\Delta\omega}{\omega_0}}$$

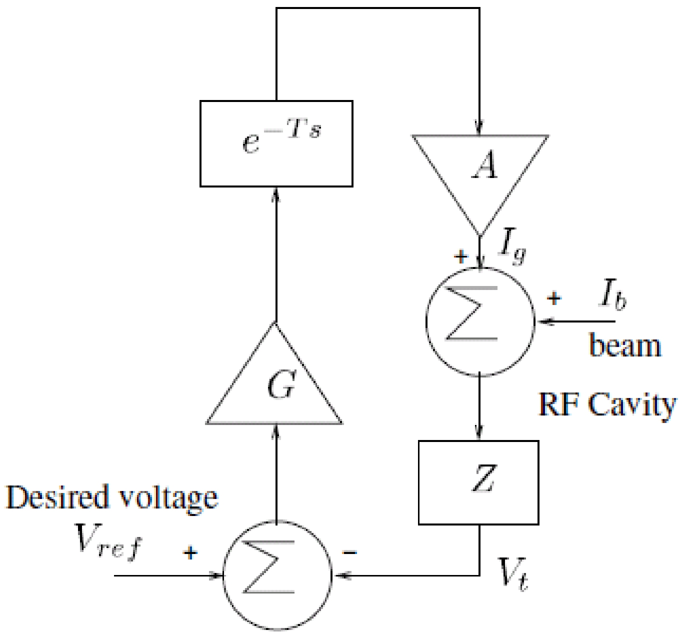
$$\Delta\omega = \omega - \omega_0$$

- With the feedback loop, the cavity voltage is

$$V_t(\omega) = \frac{Z(\omega)}{1 + G\,A e^{-iT\Delta\omega} Z(\omega)}\, I_b(\omega)$$

- A large gain G.A means good reduction of the perturbations (noise and beam induced voltage). Stability in presence of the delay T will put a limit. Outside its bandwidth the cavity is purely reactive and its impedance can be approximated

$$Z(\omega) \approx \frac{R}{j2Q\dfrac{\Delta\omega}{\omega_0}}$$



RF or Direct Feedback

- To keep a 45 degrees phase margin the open-loop gain must have decreased to 1 when the delay has added an extra -45 degrees phase shift, that is at $\Delta\omega=\pi/(4T)$

$$G\,A\left|Z\left(\frac{\pi}{4T}\right)\right|\le 1$$

$$G\,A\le\frac{\pi}{2}\,\frac{Q}{R\,\omega_0}\,\frac{1}{T}$$

- Flat response will be achieved with

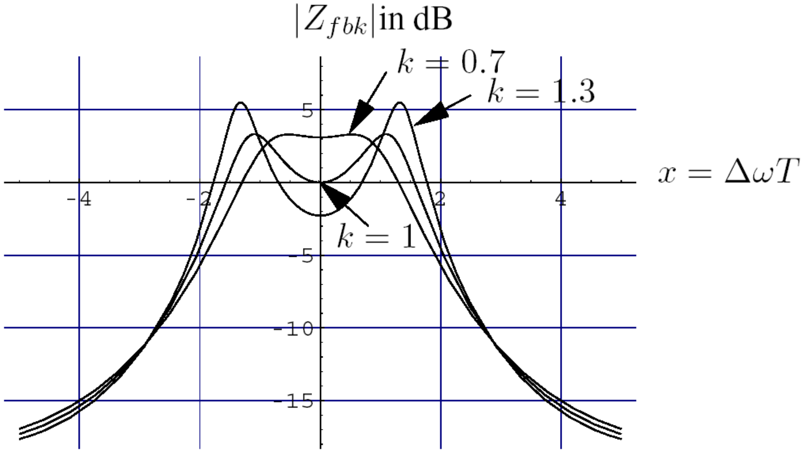
$$G\,A\approx\frac{Q}{R\,\omega_0}\,\frac{1}{T}$$

leading to the effective cavity impedance at resonance

$$\boxed{R_{\min}=\frac{R}{1+G\,A\,R}\approx\frac{R}{Q}\,\omega_0\,T}$$

and the 2-sided closed loop BW with feedback

$$\boxed{\Delta\omega_{-3}\approx\frac{2.6}{T}}$$

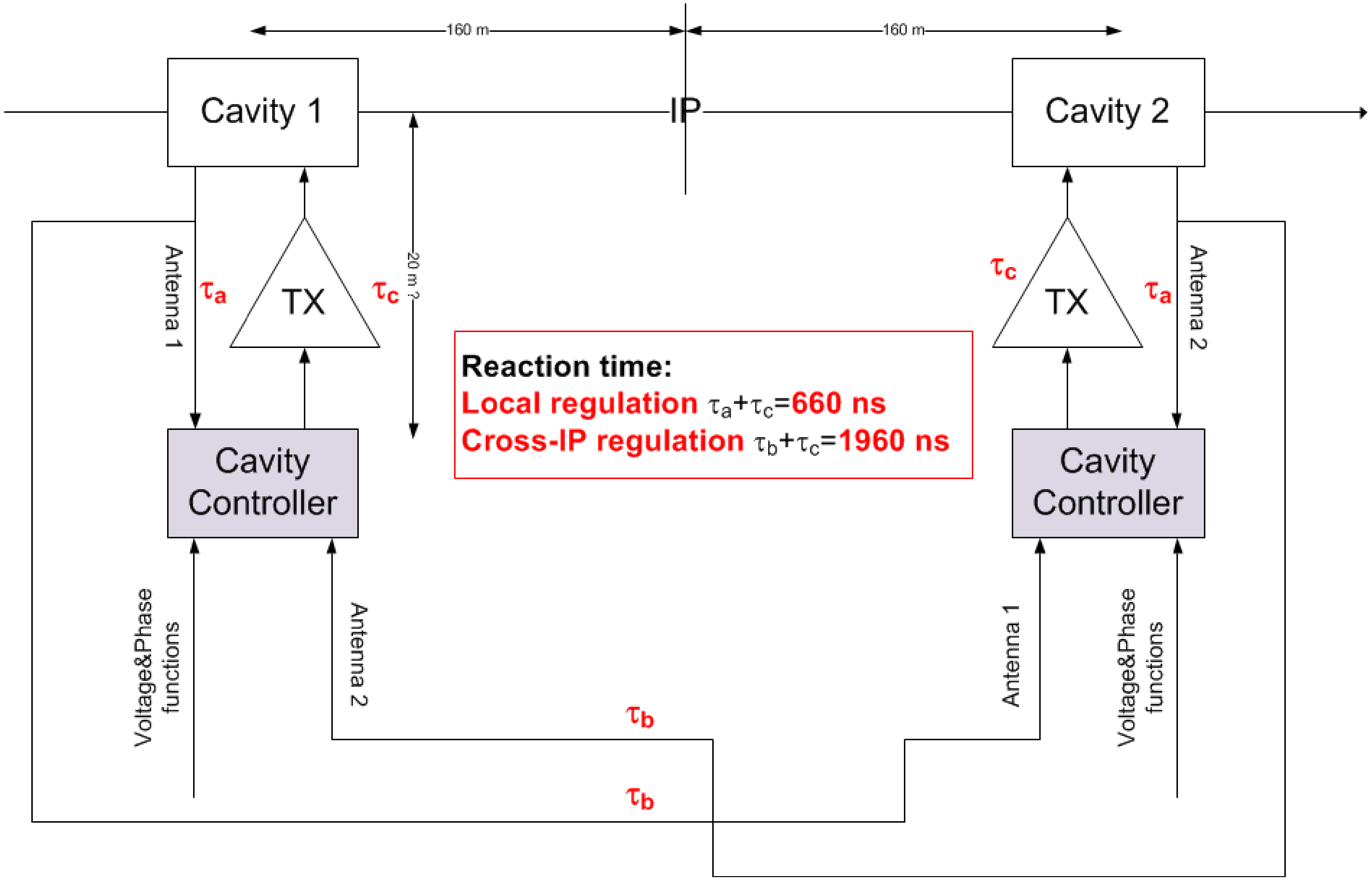


Closed Loop response for varying gains. K=1 corresponds to the maximal gain. The optimally flat is obtained for k=0.7

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

Proposed layouts and resulting Controls Bandwidth

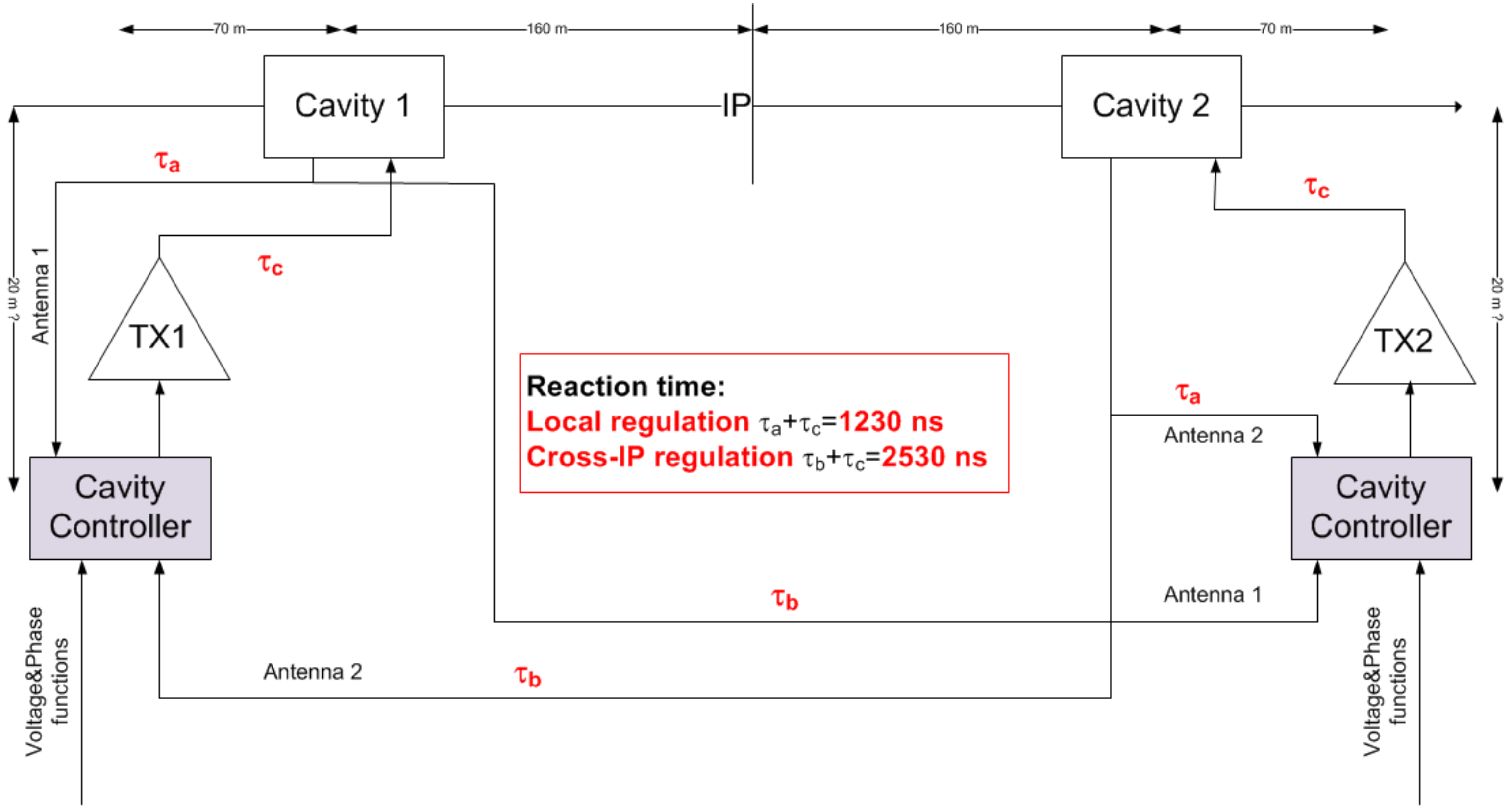
New galleries with LLRF, TX, circulator next to the cavities



Reaction time:
Local regulation $\tau_a+\tau_c$=660 ns
Cross-IP regulation $\tau_b+\tau_c$=1960 ns

Asymmetric architecture:
τ_a is the delay of the local antenna signal 20 x 3.7 ns = 74 ns rounded to **80 ns** (10 % margin)
τ_b is the delay of the opposite antenna signal (320+20) x 3.7 ns = 1258 ns rounded to **1380 ns**
τ_c is the drive path delay, including LLRF, TX, circulator and coax = 300 ns + 100 ns + 50 ns + 20 x 3.7 ns = 524 ns rounded to **580 ns**

Installation of LLRF, TX, circulator in the **existing RRs**



Reaction time:
Local regulation $\tau_a+\tau_c$=1230 ns
Cross-IP regulation $\tau_b+\tau_c$=2530 ns

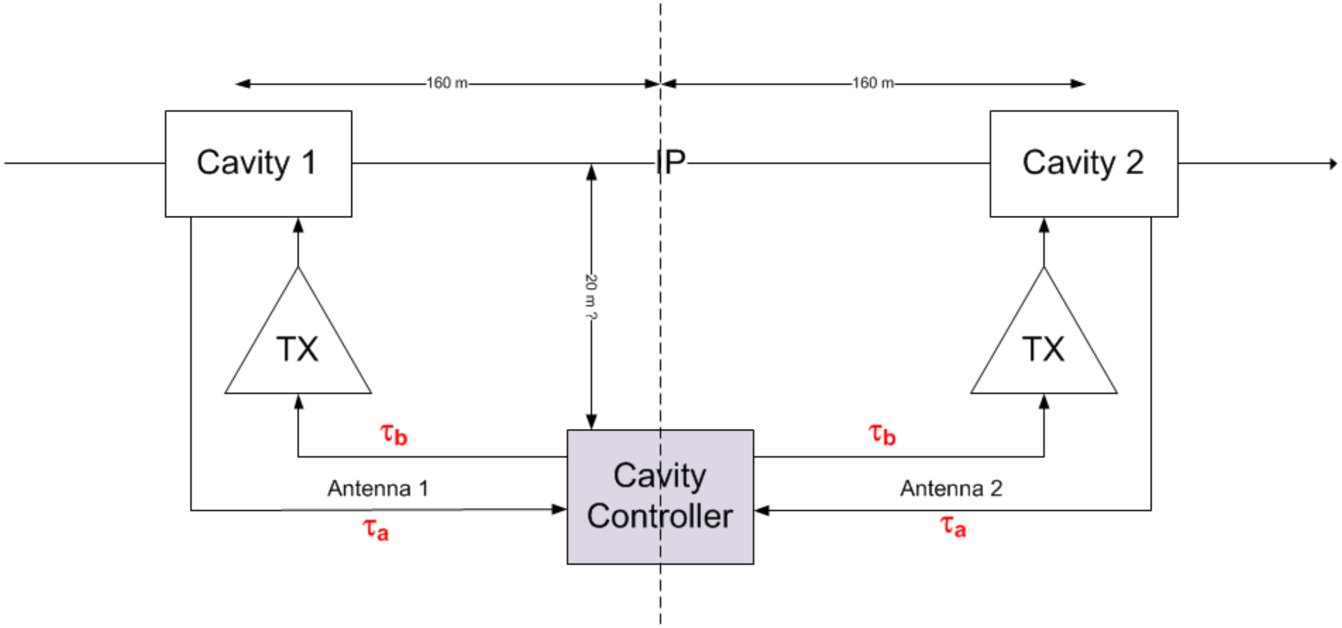
RR cavern architecture:

τ_a is the delay of the local antenna signal (20+70) x 3.7 ns = 333 ns rounded to **370 ns**

τ_b is the delay of the opposite antenna signal (320+70+20) x 3.7 ns = 1517 ns rounded to **1670 ns**

τ_c is the drive path delay, including LLRF, TX, circulator and coax = 300 ns + 100 ns + 50 ns + (20+70) x 3.7 ns = 783 ns rounded to **860 ns**

Installation of LLRF, TX, circulator in the **existing IPs**



Reaction time:
Local regulation $\tau_a+\tau_b$=1970 ns
Cross-IP regulation $\tau_a+\tau_b$=1970 ns

Symmetric architecture:
τ_a is the delay of the antenna signal (160+20) x 3.7 ns = 666 ns rounded to **740 ns**
τ_b is the drive path delay, including LLRF, TX, circulator and coax. = 300 ns + 100 ns + 50 ns + (160+20) x 3.7 ns = 1116 ns rounded to **1230 ns**

Summing it all….

LLRF and TX installed in….	**…new galleries**	**…existing RR**	**… at the IP**
Local Loop reaction time (ns)	660 ns	1230 ns	1970 ns
Cross-IP reaction time (ns)	1960 ns	2530 ns	1970 ns
Local loop BW (single-sided) (Hz)	313 kHz	168 kHz	105 kHz
Cross-IP loop BW (Hz)	105 kHz	82 kHz	105 kHz

- The new galleries have a definite advantage for the local loop (factor 2-3 in BW)
- The three options have similar performances for the cross-IP regulation

Why do we need BW?

- BW is required if we want to quickly modulate the CC field, or to react to high frequency noise sources
- The CC are operated at constant voltage
- The "fast" perturbation comes from the 3 microsec long abort gap (transient beam loading)

Beam loading

- Beam-cavity-TX interaction for a crab cavity. General case

$$V_\perp(t) = A_\perp(t)e^{i\omega t}$$

$$J_g(t) = \frac{A_\perp(t)}{2\left(R/Q\right)_\perp}\left[\frac{1}{Q_L} - 2i\frac{\Delta\omega}{\omega}\right] + \frac{dA_\perp(t)}{dt}\frac{1}{\omega\left(R/Q\right)_\perp} + i\frac{\omega}{c}x\frac{I_{RF}(t)}{2}e^{-i\phi_s(t)}$$

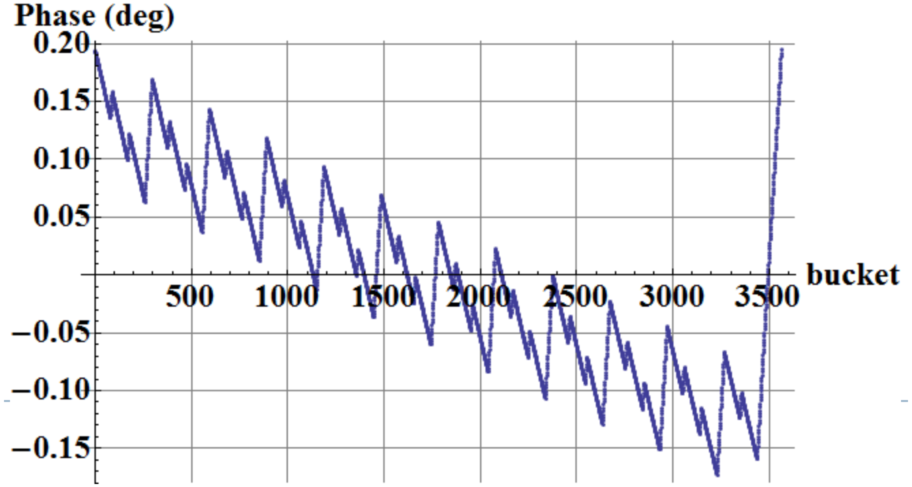
$$P_g(t) = \frac{1}{2}\left(R/Q\right)_\perp Q_e\left|J_g(t)\right|^2$$

- With cavity on tune, and beam current in quadrature with the deflecting voltage

$$\frac{dA_\perp(t)}{dt} + \frac{\omega}{2Q_L}A_\perp(t) = \omega\left(R/Q\right)_\perp J_g(t) - i\frac{\omega^2}{2c}\left(R/Q\right)_\perp x\,I_{RF}(t)$$

- With 300 Ω R/Q, Q_L=500000, and 1 mm offset, the beam loading is 2.2 MV. The phase error due to the transient beam loading (abort gap) is ±0.2 degree

Thanks to the high Q_L, the transient beam loading is small and need not be corrected by a fast feedback.



RF Noise

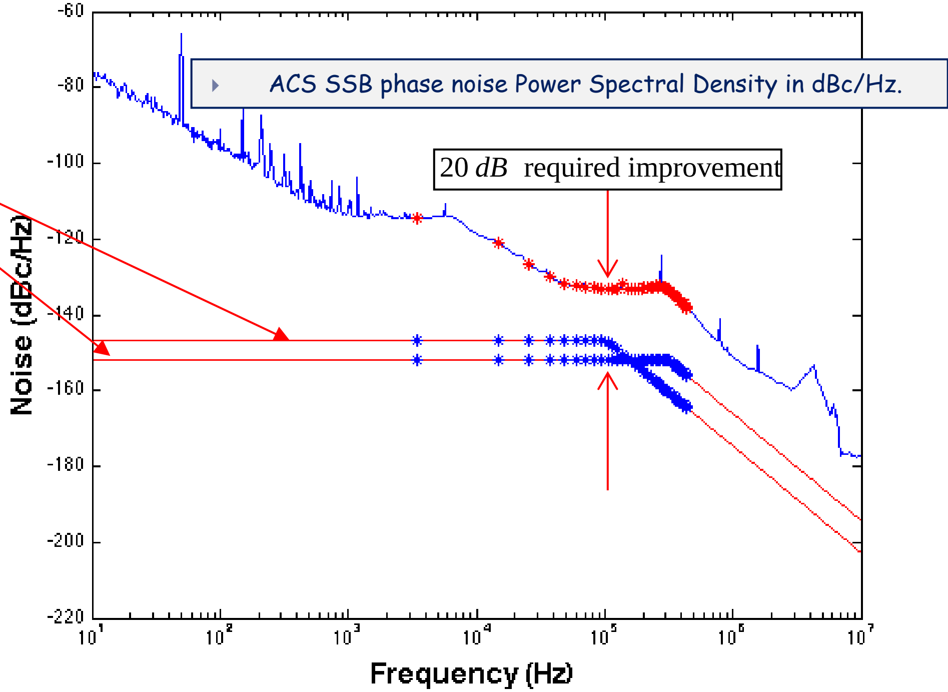
This should be 0.006. We loose another 6 dB in acceptable noise PSD….

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

- Regulation is required to reduce the effect of RF noise
- Phase Noise

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

  - 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 estimate is for 8 cavities per beam per plane.



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

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

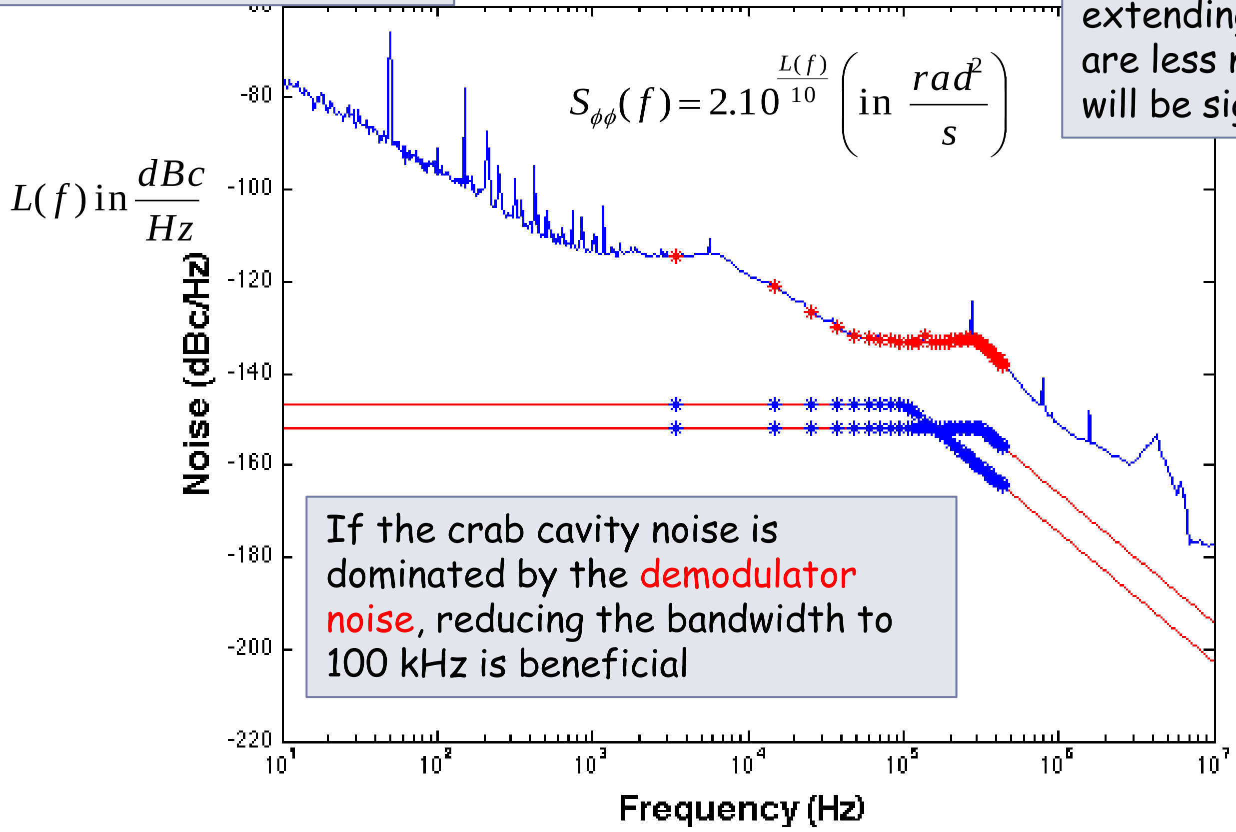
$$\frac{\Delta V}{V} = \Delta\varphi$$

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

RF noise sources

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.



If the crab cavity noise is dominated by the demodulator noise, reducing the bandwidth to 100 kHz is beneficial

We will have an high-bandwidth loop around the LLRF-TX-Circulator to reduce the TX noise, and a moderate-bandwidth RF feedback around LLRF-TX-Cavity

Other considerations

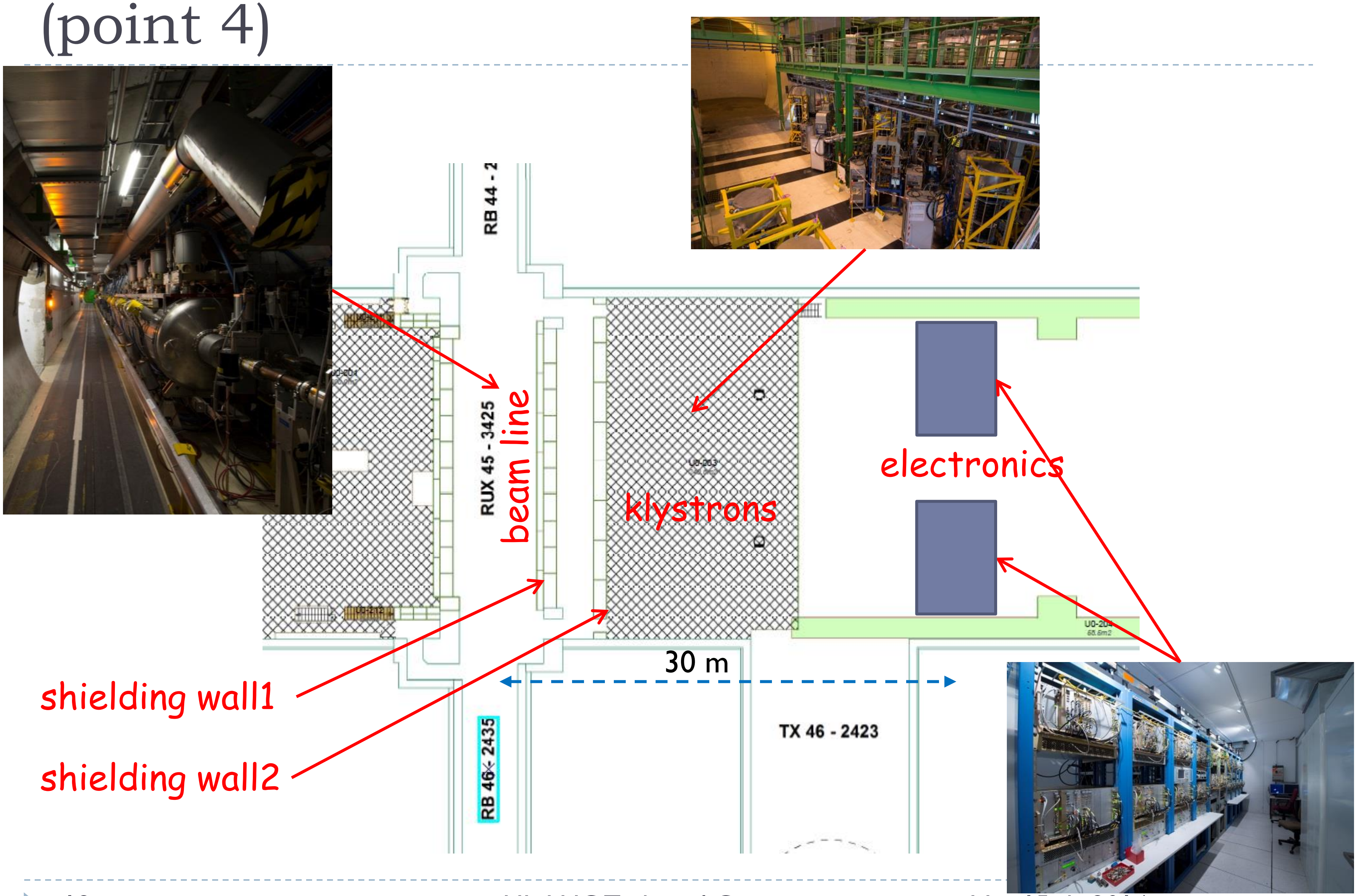
Accessibility

- During the commissioning of the system we want access to the LLRF and power plant with RF in the cavities
- That requires shielding between cavities and manned area, as the cavities emit X-rays during operation
- Access with RF ON appears easy for the New Galleries and IP options. It must be studied for the RR option
- Circulators will connect to the cavities through large coaxial lines (260 mm diam). Routing these 8 lines in the tunnel will be an issue with layout "IP"

Radiation damage to the equipment

- The LLRF electronics implements processing in FPGAs
- These are sensitive to Single Event Upset (SEU) caused by High Energy Hadrons (HEH) impacting the chip
- The sensitivity of a chip is characterized by the SEU cross-section (in cm^2/bit). Virtex V (family widely used in the existing LHC LLRF) cross-section has been estimated at $2\ 10^{-14}$ cm^2/bit. For a device with a 20Mb logic configuration SRAM, we get a device cross-section of $4\ 10^{-7}$ cm^2
- During the HL-LHC, the annual HEH dose is expected around $5\ 10^9$ cm^{-2} in the RR. For a non rad-hard device as the VirtexV this dose leads to 2000 SEE per year
- Installation of non rad-hard electronics in the RR is not acceptable

An example: The ACS installation in UX45 (point 4)



Conclusions

Conclusions (1/2)

- Precise regulation of the CC field is important
  - The Cross-IP regulation will reduce the beam losses in the interval between a quench and beam dump (3 turns max). The reaction time is limited by the distance between paired cavities (crabbing-uncrabbing). The layout has no significant influence on the performances
  - With cavities operated at constant field, the main function of the local loop is to reduce the effect of RF noise. We plan to design a strong feedback around the TX . This is not influenced by the choice of layout, as long as the LLRF remains close to TX and circulator. In addition there will be a slower regulation around the cavity. For this, the New Gallery design has an advantage, but it is not clear that the achievable BW will be needed
  - The present modular design with one TX per cavity is ideal for regulation. Using a single TX for several cavities we cannot avoid synchronized oscillations (ponderomotive for example) with cavities oscillating at identical frequency but different phases summing to zero Cavity Sum signal. A fault in one cavity is also likely to affect all cavities if they share one TX via a Cavity Sum feedback.

Conclusions (2/2)

- The equipment (TX, LLRF) must be accessible with RF in the cavities, at least during commissioning. For the RR option, this question must be studied.
- Given the expected doses of HEH in the RR, shielding and radiation-hard design are required

Thank you for your attention

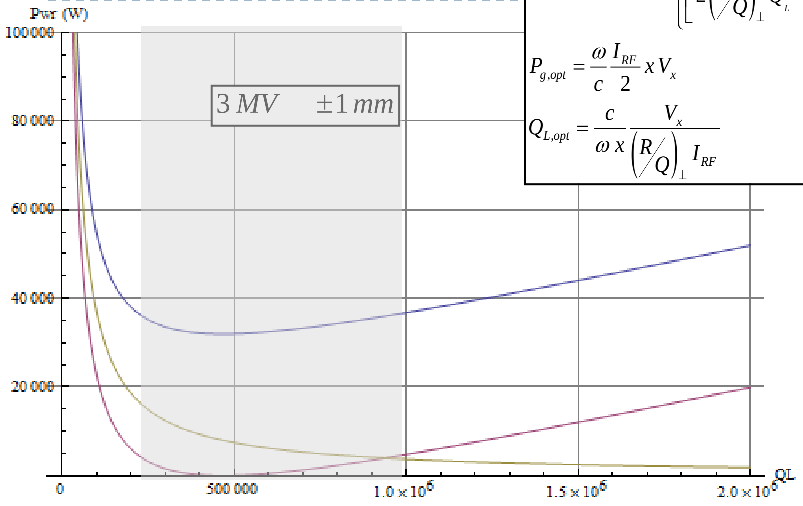
Back-up slides

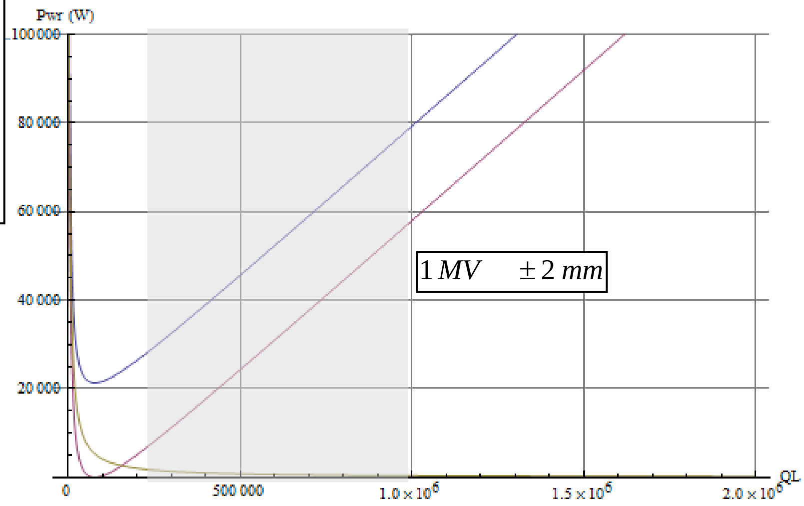
RF Power vs. Q_L for various RF voltages and beam offsets

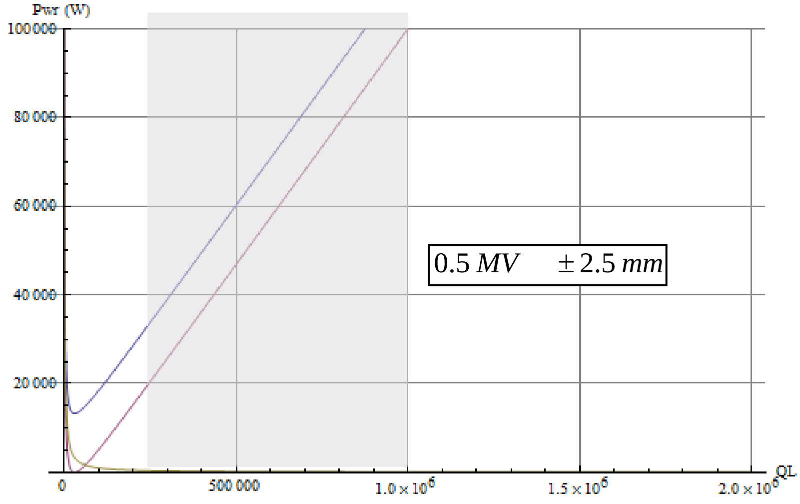
$$P_g = \frac{1}{2}\left(R/Q\right)_\perp Q_L \left\{ \left[\frac{V_x}{2\left(R/Q\right)_\perp Q_L} + \frac{\omega}{c}\frac{I_{RF}}{2} x \right]^2 + \left[\frac{V_x \Delta\omega}{\omega \left(R/Q\right)_\perp} \right]^2 \right\}$$

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

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







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.

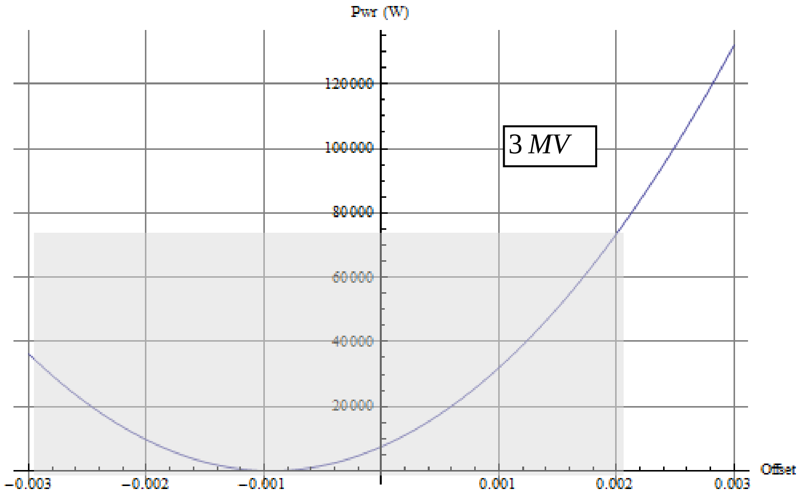
The important parameter is the product R/Q Q_L

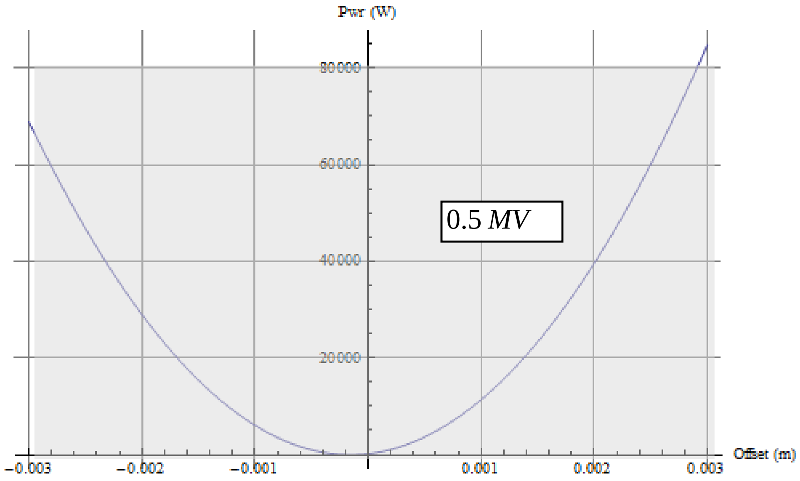
RF Power vs. Offset

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

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

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





Q_L=500000 R/Q = 300 Ω. 1.11 A DC current, 1 ns 4σ bunch length with Cos^2 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).

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.