Crab Cavity RF Noise: Effect, issue, theory and mitigations. A status

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Why CC RF noise matters so much ?

- As CC acts in the transverse plane, its RF noise will increase the beam transverse emittance
- This results in loss of luminosity as it is inversely proportional to the normalized transverse emittance
- We have been given a budget for the loss of integrated luminosity (over a fill) caused by CC RF noise: **1 %** ([1],[3] tables 6-9, e-growth < 0.05 μm/h for 2.5 μm emittance)
- This corresponds to a maximum of **2%/hour** emittance growth due to CC at lowest β^* (15 cm)
- This is very small -> study of CC RF noise was encouraged from beginning of HL-LHC.

Transverse Emittance Growth. Theory

$$\frac{d\epsilon_n}{dt} = N_{cavities}\gamma\beta_{cc}\left(\frac{eV_o f_{rev}}{2E_b}\right)^2 \left\{e^{-\sigma_\phi{}^2}\left[I_o\left[\sigma_\phi{}^2\right] + 2\sum_{l=1}^{\infty} I_{2l}\left[\sigma_\phi{}^2\right]\right]\right\} \sum_{k=-\infty}^{\infty}\int_{-\infty}^{\infty} S_{\Delta\phi}\left[(k \pm \nu_b) f_{rev}\right]\rho\left(\nu_b\right) d\nu_b$$

$$= N_{cavities}\gamma\beta_{cc}\left(\frac{eV_o f_{rev}}{2E_b}\right)^2 C_{\Delta\phi}(\sigma_\phi)\,\frac{2\sigma^2_{\Delta\phi}}{f_{rev}}$$

$$= \frac{1}{\beta^*}\left[N_{cavities}\gamma\left(\frac{ec\theta_{cc} f_{rev}}{4\omega_{RF}}\right)^2\right] C_{\Delta\phi}(\sigma_\phi)\,\frac{2\sigma^2_{\Delta\phi}}{f_{rev}}$$

$$\frac{d\epsilon_n}{dt} = N_{cavities}\gamma\beta_{cc}\left(\frac{eV_o f_{rev}}{2E_b}\right)^2 \left\{e^{-\sigma_\phi{}^2}\sum_{l=0}^{\infty} I_{2l+1}\left[\sigma_\phi{}^2\right]\right\} \sum_{k=-\infty}^{\infty}\int_{-\infty}^{\infty} S_{\Delta A}\left[(k \pm \nu_b \pm \nu_s) f_{rev}\right]\rho\left(\nu_b\right) d\nu_b$$

$$= \frac{1}{\beta^*}\left[N_{cavities}\gamma\left(\frac{ec\theta_{cc} f_{rev}}{4\omega_{RF}}\right)^2\right] C_{\Delta A}(\sigma_\phi)\,\frac{4\sigma^2_{\Delta A}}{f_{rev}}$$

- Transverse emittance growth due to RF noise as derived in [2], Eq. (20) (22).
- Operational parameters: Little or no control. This term is effectively inversely proportional to 1/β* for constant full crabbing angle θ_{cc}. According to [3], we use 380 μrad full crabbing angle from the beginning of physics.
- Bunch length dependence: Effectively constant over operational range.
- RF noise: Depends on RF and LLRF technology (to be determined).

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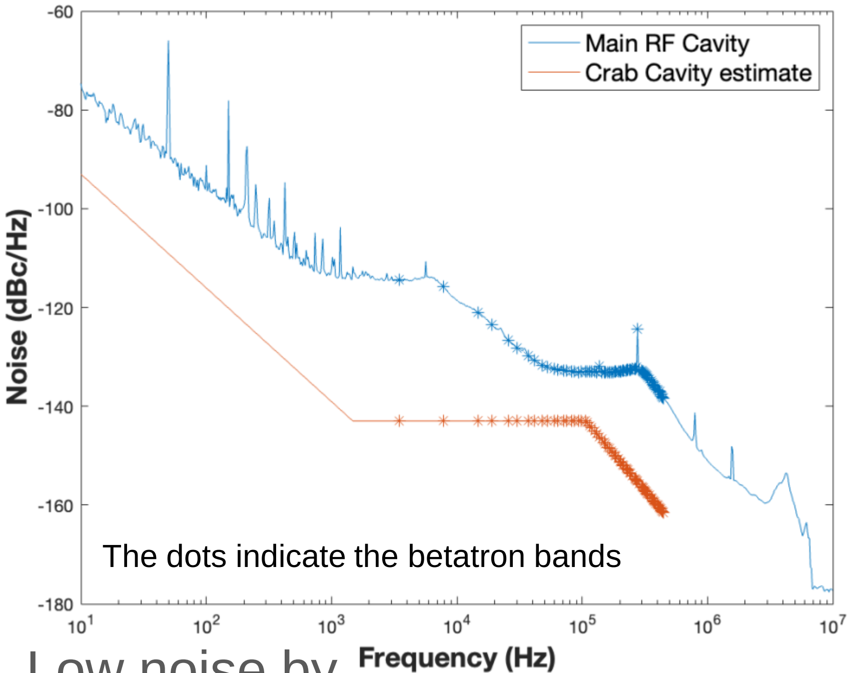
Maximum allowable RF noise

- With the analytical model we can compute the allowable RF noise to remain below 2%/h:
  - End of physics conditions: V_{cc}=3.3 MV, β_{cc}=3800, 4 cavities/plane, 1 ns 4σ bunch length), ε_n= 2.5 μm
  - The ADT damper will provide some reduction of phase noise (no effect on amplitude noise). With 50 turns damping ([3], tables 5,6,8,9), analytical formulas ([2], Fig.9) give a reduction factor of 0.32
  - Phase noise $\sigma_{\Delta\varphi}$**=14 μrad** will result in emittance growth 0.92 %/h with damper on
  - Amplitude noise $\sigma_{\Delta A}$**=14∗10^{-6}** will result in emittance growth 1.08%/h.

Mitigation 1. Low noise LLRF

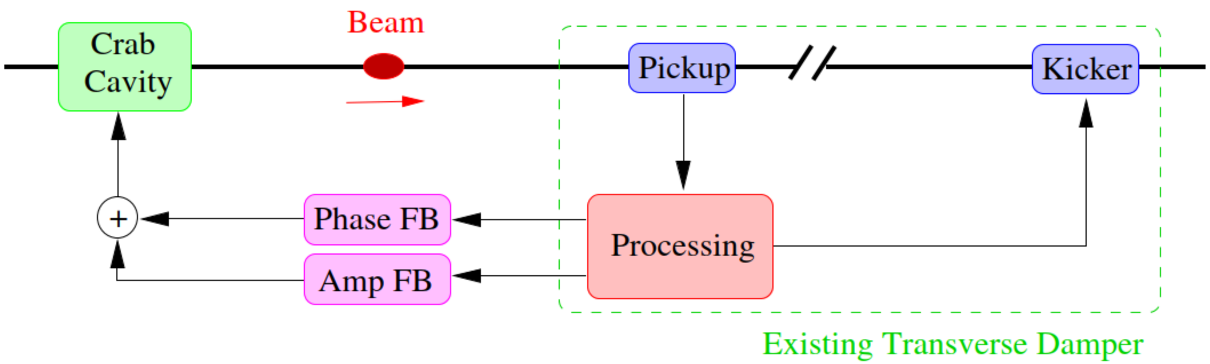
- The LLRF includes a proportional RF feedback that must reduce the cavity impedance at the fundamental by >100 linear. This results in a 136 kHz regulation BW [4] (Sec. 1)
- Comparison of the ACS phase noise and the CC target
- We aim at **-143 dBc/Hz** SSB phase noise and amplitude noise in the 3 kHz-136 kHz band [4]
- That is 10 dB better than ACS
- This will result in
  - **7.6%/h** e-growth due to phase noise
  - **9%/h** due to amplitude noise
- **Factor 10 excess!**



- Low noise by
  - Fixed-frequency clocks and LO, we can use narrow phase-lock loops to improve the demodulator LO and thereby reduce the RF phase noise at the first two betatron sidebands
  - Using IOTs instead of klystrons
  - Reducing the RF demodulator noise by **at least 10 dB**

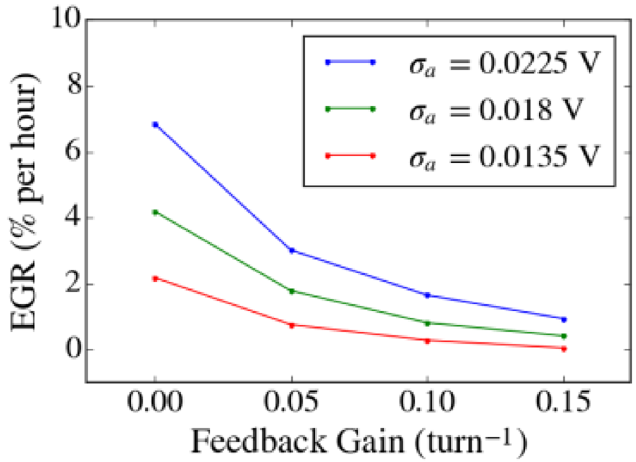
Mitigation 2. CC feedback

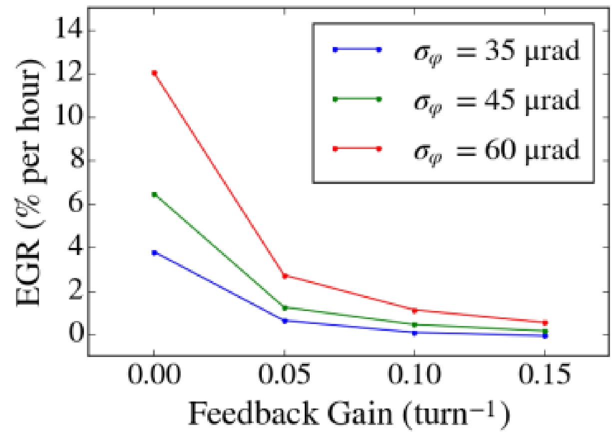
- Dedicated feedback system to counteract crab cavity noise could be developed [6],[8] to provide the extra factor 10
  - Such a system could work in conjunction with the ADT
  - Its performance will be limited by the **pickup measurement noise** (pickup specs later in this presentation.
  - Theory and simulations have shown very promising performance [6][8].



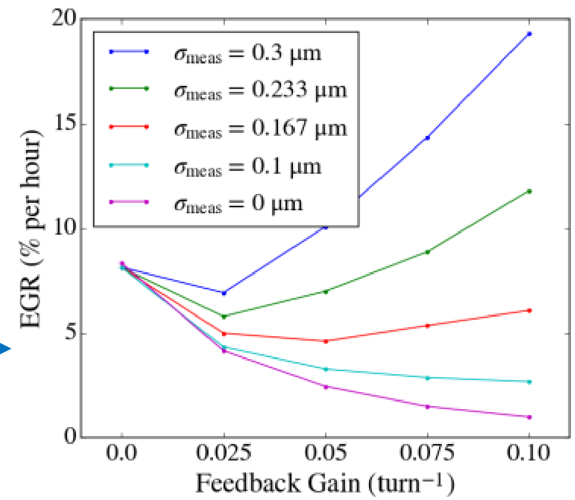
Feedback system using CC as kicker

- This system is very promising in simulations

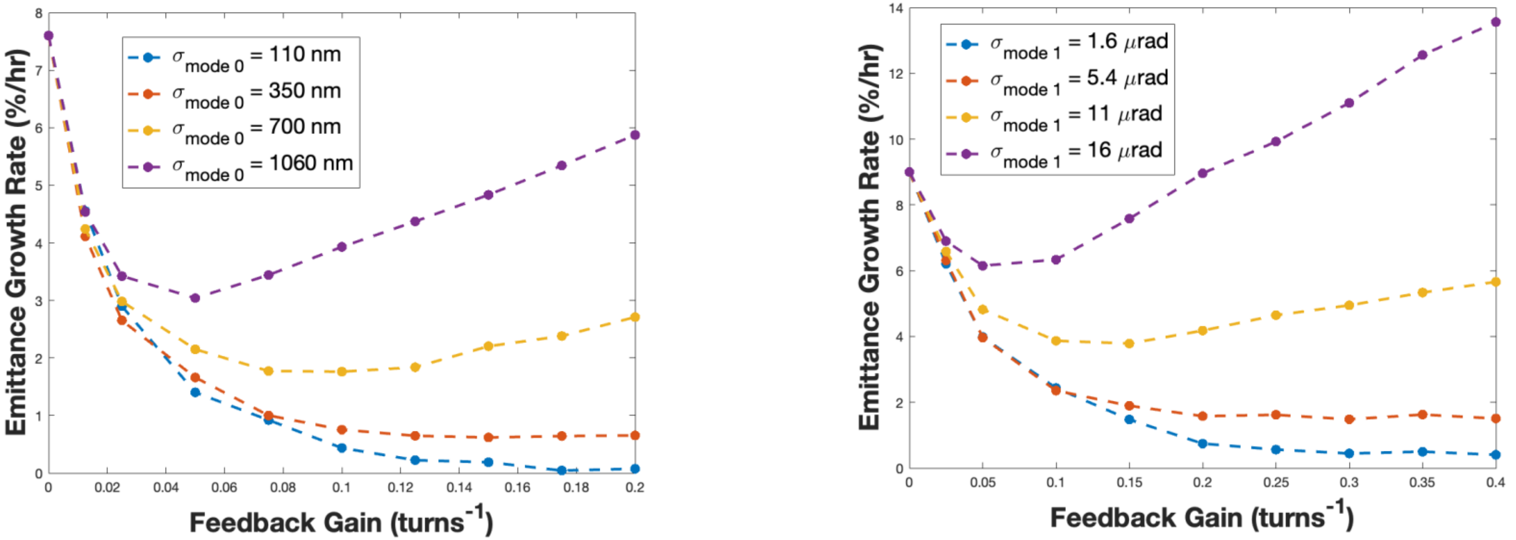




- But the performance is limited by the measurement noise level. Emittance growth rate curves with varying magnitudes of measurement error in the presence of both phase and amplitude noise
- Need for a **low-noise bunch displacement** (mode 0) and **tilt** (mode 1) measurement chain.



- What measurement precision is required?



- For single bunch we get **440 nm** for mode 0 and **4.5 µrad** for mode 1
- As the CC noise spectrum extends to 136 kHz only, while measurement noise is white (25 ns spacing -> 20 MHz BW), an *optimal* filter will reduce measurement noise by **12** linear-> in batch mode
  - **5.3 µm** for mode 0
  - **55 µrad** for mode 1
- See [6] for analytical derivations and more simulations.

LLRF processing (tentative)

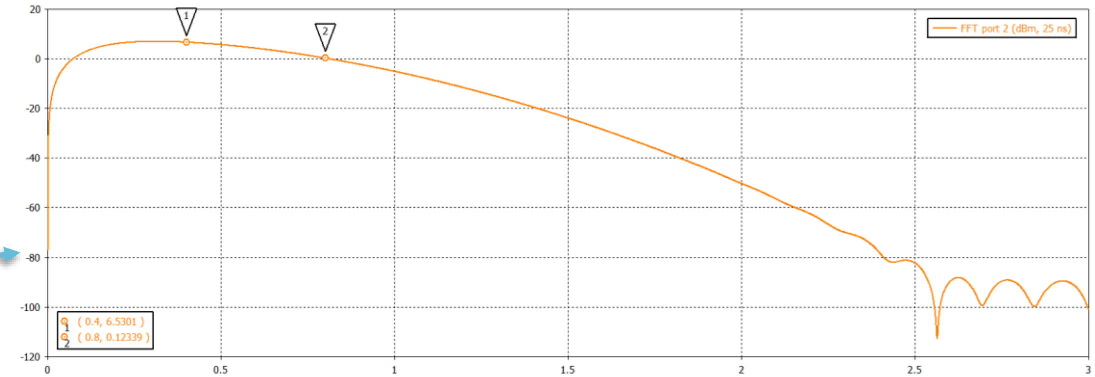
- Except for the novel use of a CC as kicker, it is a *classic* transverse feedback with mode 0 (displacement) and 1 (tilt)
- We plan to follow processing shown in [7] Eq. (16) to extract mode 0 and 1 signals, at least for SPS test bench
  - Delta/Sigma signals from WB PU
  - Filtering with 400 MHz BPF
  - Analog mixer with 375 MHz LO
  - ADC clocked at 100 MHz
  - I/Q demodulation
  - Optimal filter to increase SNR
  - Then we compute Delta/Sigma. The signal has both dipole (real-valued I = mode 0) and tilt (imaginary Q = mode 1) info. See [7]

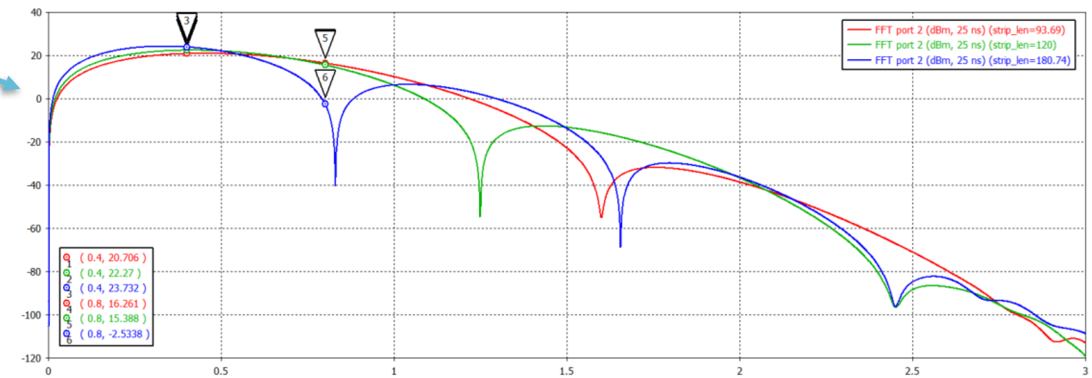
$$X_N = \frac{I_\Delta I_\Sigma + Q_\Delta Q_\Sigma}{{I_\Sigma}^2 + {Q_\Sigma}^2} + j\frac{Q_\Delta I_\Sigma - I_\Delta Q_\Sigma}{{I_\Sigma}^2 + {Q_\Sigma}^2}$$

- We then apply phase shift (around betatron tune) to have 90 degrees, including latency and PU-CC phase advance, plus BPF for SNR
- We modulate CC set-point in phase (phase fdbk) and amplitude (amplitude fdbk)
- To be tested in SPS in 2024.

CC feedback PU

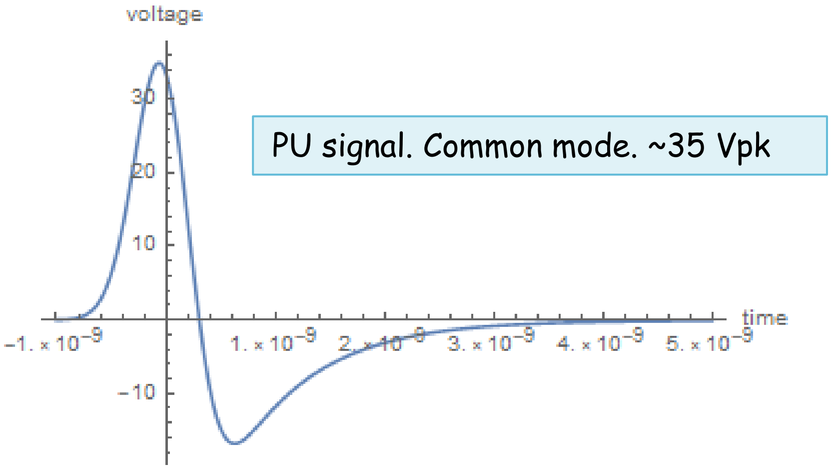
- We have a PU next to each cryostat (cavity pair)
- We have 2 available PU candidates
  - Button
  - Stripline
- We consider operation (demodulation) at 400 or 800 MHz-> 120 mm stripline (green) and button are good options
- The frequency responses of the two Pus are very similar
- The stripline gives **~20 dB more signal**. Can we make use of it ?

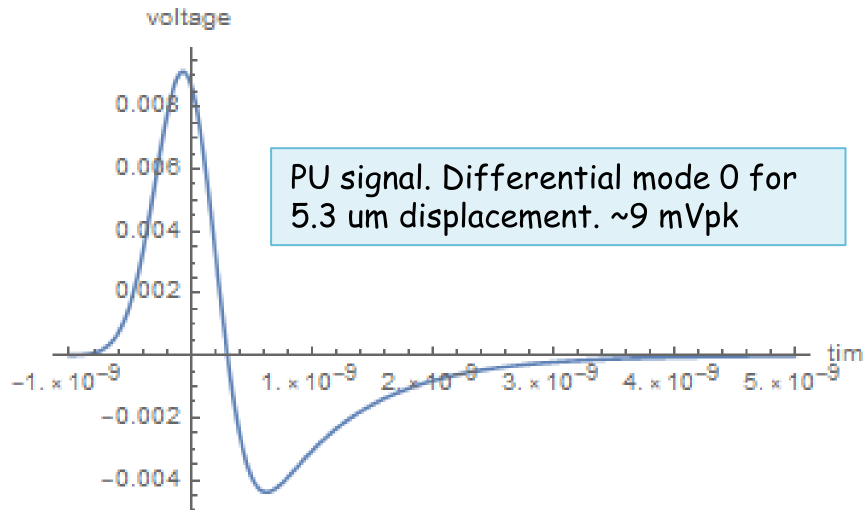


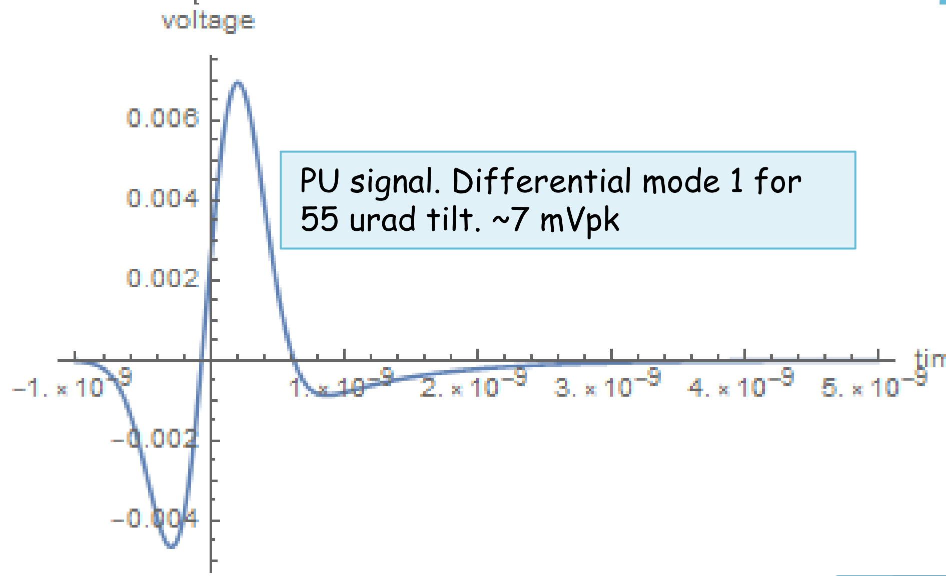


Courtesy of M. Krupa

Signals from button PU before demodulation

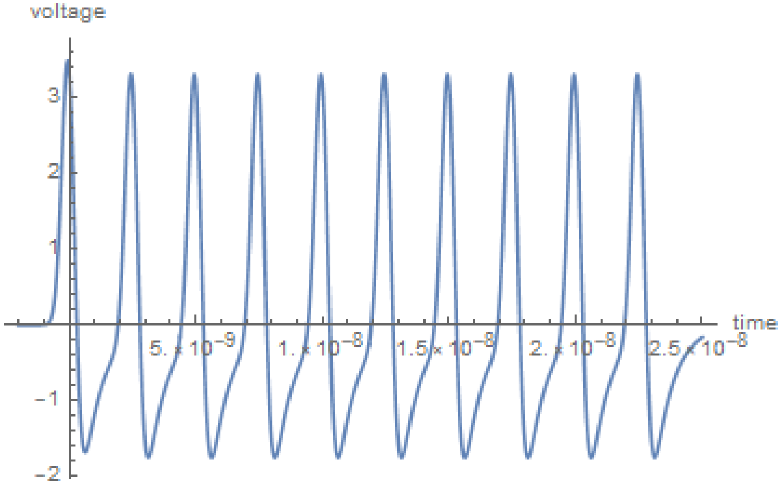




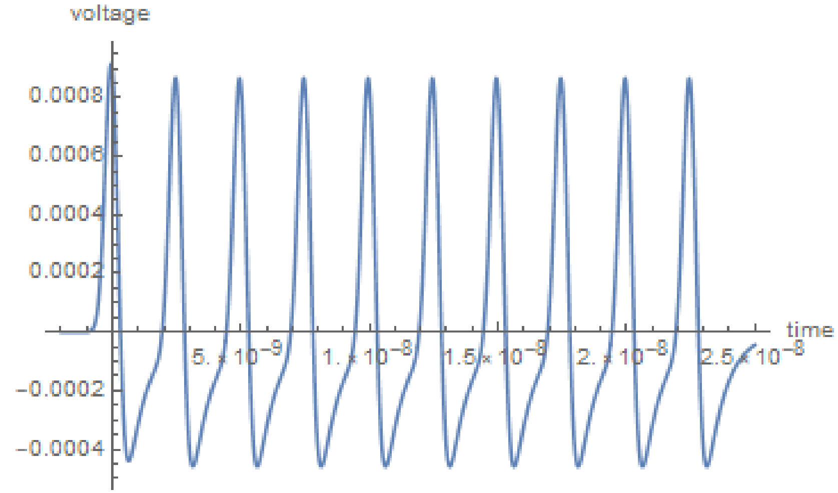


- Single bunch, 1.05 ns, 2.3e11 ppb
- For the required resolution (5.3 um and 55 urad) the mode 0 and 1 signals have similar peak amplitude. Good
- But they are **4000-5000** below common mode
- Assuming 20 dB rejection from delta hybrid (can we get more?) we would still have common mode **400-500** times larger than mode 0 or 1 measurements

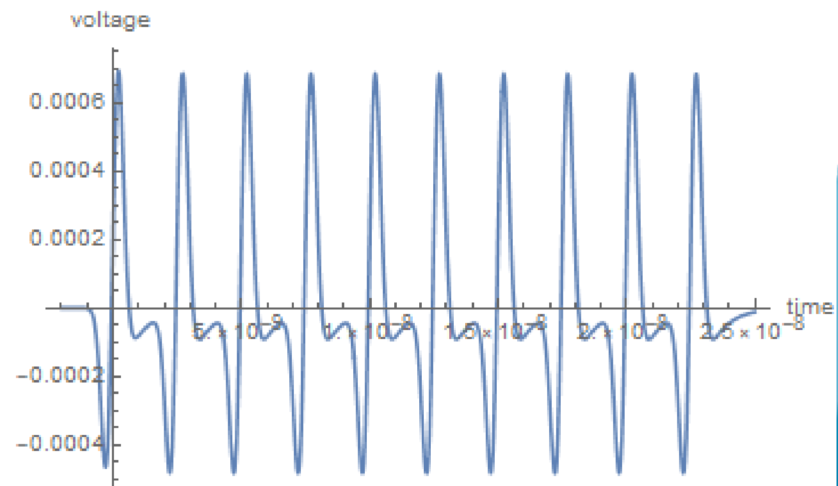
Signals from button PU after 400 MHz BPF



Common mode. ~5 Vpkpk (blue).



Differential mode 0 for 5.3 um displacement. ~1.3 mVpkpk



Differential mode 1 for 55 urad tilt. ~1.1 mVpkpk

- Again, for the required resolution (5.3 μm and 55 μrad) the mode 0 and 1 signals have similar 400 MHz component. Good
- But they are still 4000-5000 below common mode
- Note that the mode 0 and mode 1 signals, after 400 MHz BPF, are indeed in quadrature.

Plans. Near future (2023-mid 2024)

1. Design an RF feedback that fulfills the noise requirement: -143 dBc/Hz max on all betatron lines from first (3 kHz) to fdbk BW (136 kHz)
2. Test the CC fdbk in SPS
    1. Cabling existing (button) PU, add hybrid and 400 MHz BPF
    2. Check/deploy demodulation for the Sigma Delta PU signal in CavLoop module
    3. Implement the Delta/Sigma operation, extract mode 0 and 1 signals
    4. Design the optimal filter
    5. Implement BPF with proper phase shift on the mode0 and 1 signals
    6. Feedback on CC voltage set point

    NB: In the SPS CC the RF noise is much higher than HL-LHC goal, with measured SSB around -125 dBc/Hz at first betatron band. Plus we can inject RF noise -> we can design CC FDBK tests with much larger PU measurement noise level
3. Select PU and PU front end for the HL-LHC CC
    1. Button or coupler? Urgent
    2. Study the front-end. Can we live with common mode? Do we still have enough resolution for the 5.3 μm, 55 μrad precision?

Thank you for your attention.
Questions? Comments?

References

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[2] P. Baudrenghien, T. Mastoridis, *Transverse emittance growth due to RF noise in the high-luminosity LHC crab cavities*, Phys. Rev. ST Accel. Beams 18 (2015) 101001 https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.101001

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[4] P. Baudrenghien, T. Mastoridis, HL-LHC Crab Cavity Field Regulation and Resulting RF Noise Spectrum, CERN-ACC-NOTE-2023-0006 (2023) https://cds.cern.ch/record/2859258/files/CCnoiseNoteFinal.pdf?

[5] P. Baudrenghien, T. Mastoridis, Crab Cavity RF Noise Feedback and Transverse Damper Interaction, CERN-ACC-NOTE-2019-0006, 2019-03-08 https://cds.cern.ch/record/2665950/files/CERN-ACC-NOTE-2019-0006.pdf

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[7] G. Kotzian et al., Sensitivity of the LHC Transverse Feedback System to Intra-Bunch motion, IPAC2017, Sensitivity of the LHC Transverse Feedback System to Intra-Bunch Motion (cern.ch)

[8] P. Baudrenghien, T. Mastoridis, Crab Cavity RF Noise: Update, HL-LHC WP2/WP4 meeting, March 23rd 2021, https://indico.cern.ch/event/1013753/