Pick-up requirements for crab cavity system and specification

Presented by W. Hofle, *CERN, SY-RF*

For discussion on CC PU, Oct 18th 2023

Options for crab cavity PU BPTQR

- Pick-ups design and construction managed by WP13
- Options presented by M. Krupa at 13th HL-collaboration meeting in Vancouver in October 2023
  - https://indico.cern.ch/event/1293138/contributions/5459115/attachments/2723253/4733385/230928_bptqr.pdf
- Four locations: next to crab cavities at short distance from Faraday cages that house the RF electronics (WP4), ~90 m + 10 m
- Location next to the crab cavities gives a high *closed* orbit response (cf R. de Maria et al.)
- Reminder: originally, APWLs (wall current monitor) chosen as the CC phase pick-ups managed by WP4 for the phase loop
- New baseline for WP4 proposed by WP13 is a pick-up ensemble for RF comprising per each IP side and beam
  - set of four button pick-ups (planes: crabbing and perpendicular)
  - short strip-line (matched termination on down stream port)
    - crabbing plane
  - baseline change: ECR 2499201
  - https://edms.cern.ch/ui/file/2893433/1/HL_LHC_BPTQR_analytical_response.pdf

HL-LHC Crab-Cavities underground layout [1]

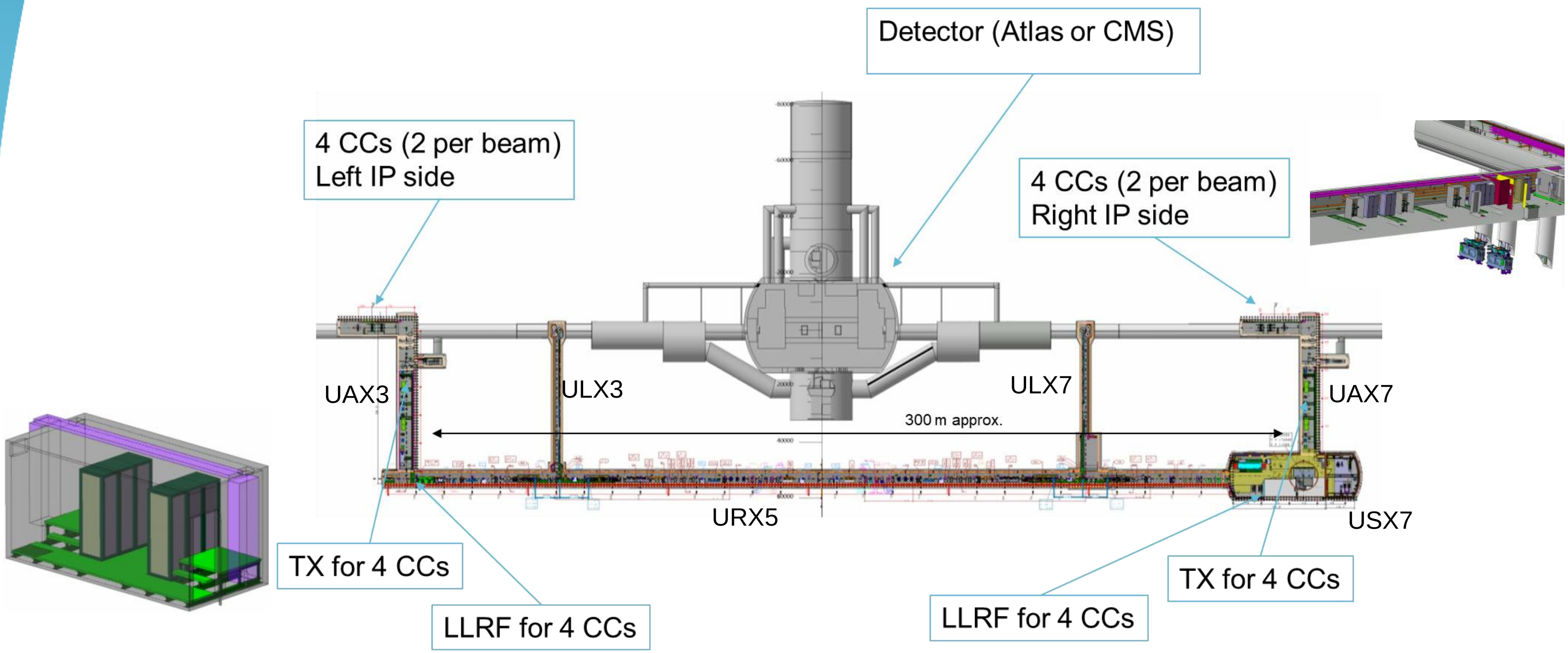


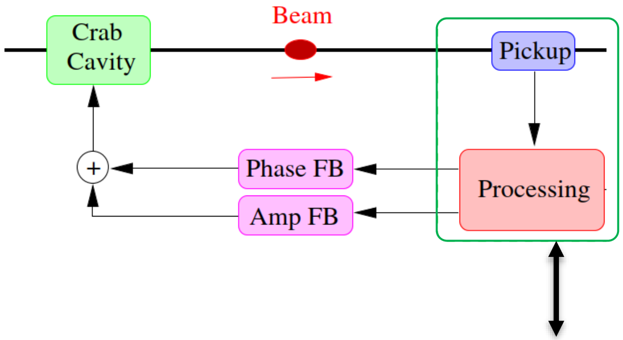
Fig – HL-LHC point 1 or 5 underground layout (Top view)

Why three pick-ups?

- RF will cover three separate functionalities
  - Functionality A: crab cavity phasing with beam using a narrow band processing representing a suitable average of the beam
    - different choices for averaging (bunch-by-bunch acquisition and subsequent digital averaging or narrow band analogue filter)
    - pair of buttons (sum signal: plane perpendicular to crabbing?)
  - Functionality B: for removal of direct coupled beam signal from cavity antenna signal
    - bunch-by-bunch signal needed
    - choice of cancelling beam signal directly in the analogue domain or in the digital domain with an adaptive technique
    - needed if still an issue is confirmed following the redesign of the cavity antenna coupler and no other probe available
    - pair of buttons (sum signal: plane of crabbing, ok?)
    - foresee dedicated cables if need confirmed

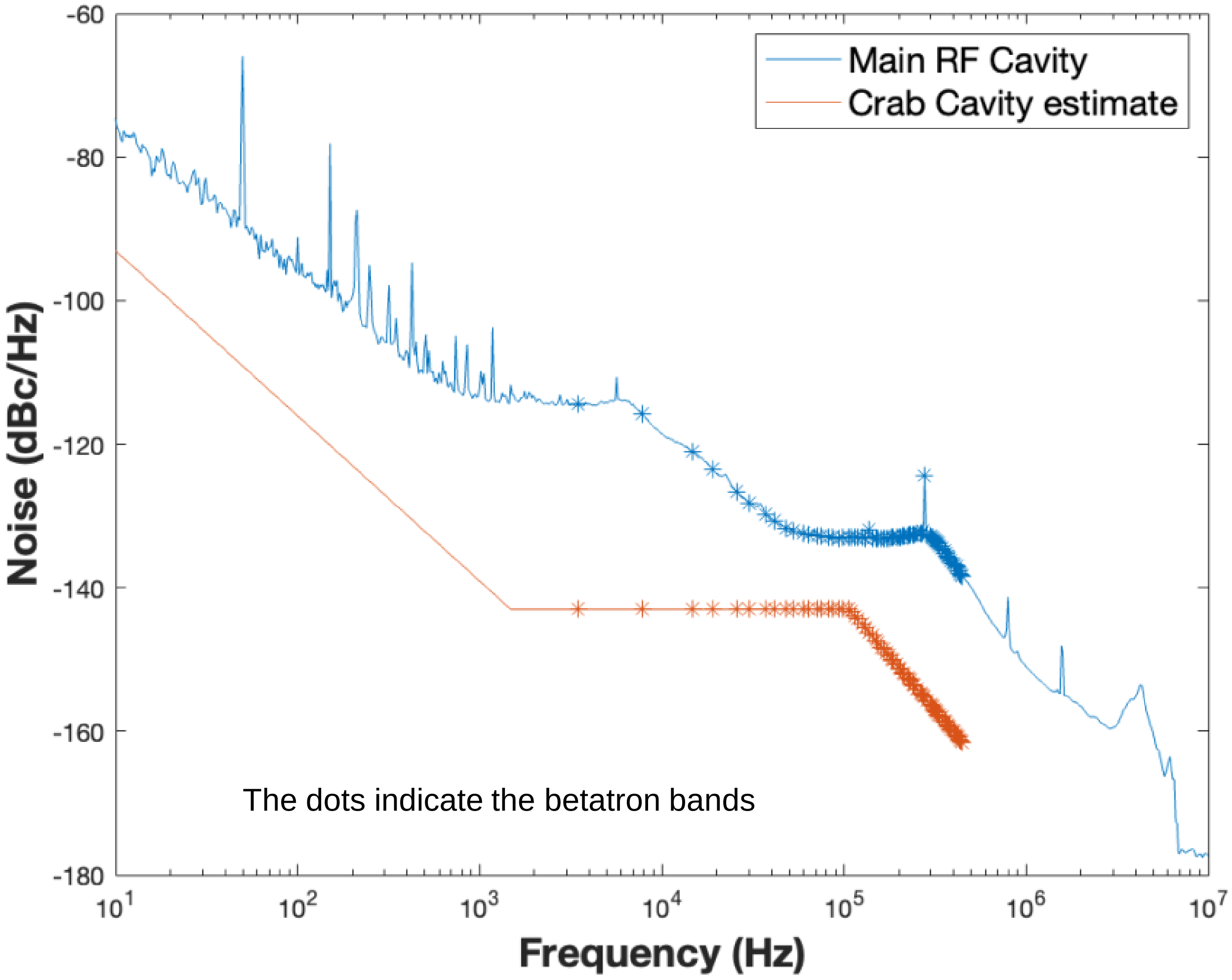
Why three pick-ups?

- Functionality C: crab cavity noise beam feedback (amplitude and phase)
  - essential to mitigate effect on the beam of amplitude and phase noise in the crab cavity
  - bunch-by-bunch signal needed
  - feedback will act within the bandwidth defined by the cavity with the cavity RF feedback around closed
  - injection of this feedback signal into the set-point for phase and amplitude



need for data exchange with the transverse damper in point 4 not excluded (fiber)

Crab cavity phase noise



Philippe Baudrenghien

HL-LHC LLRF architecture

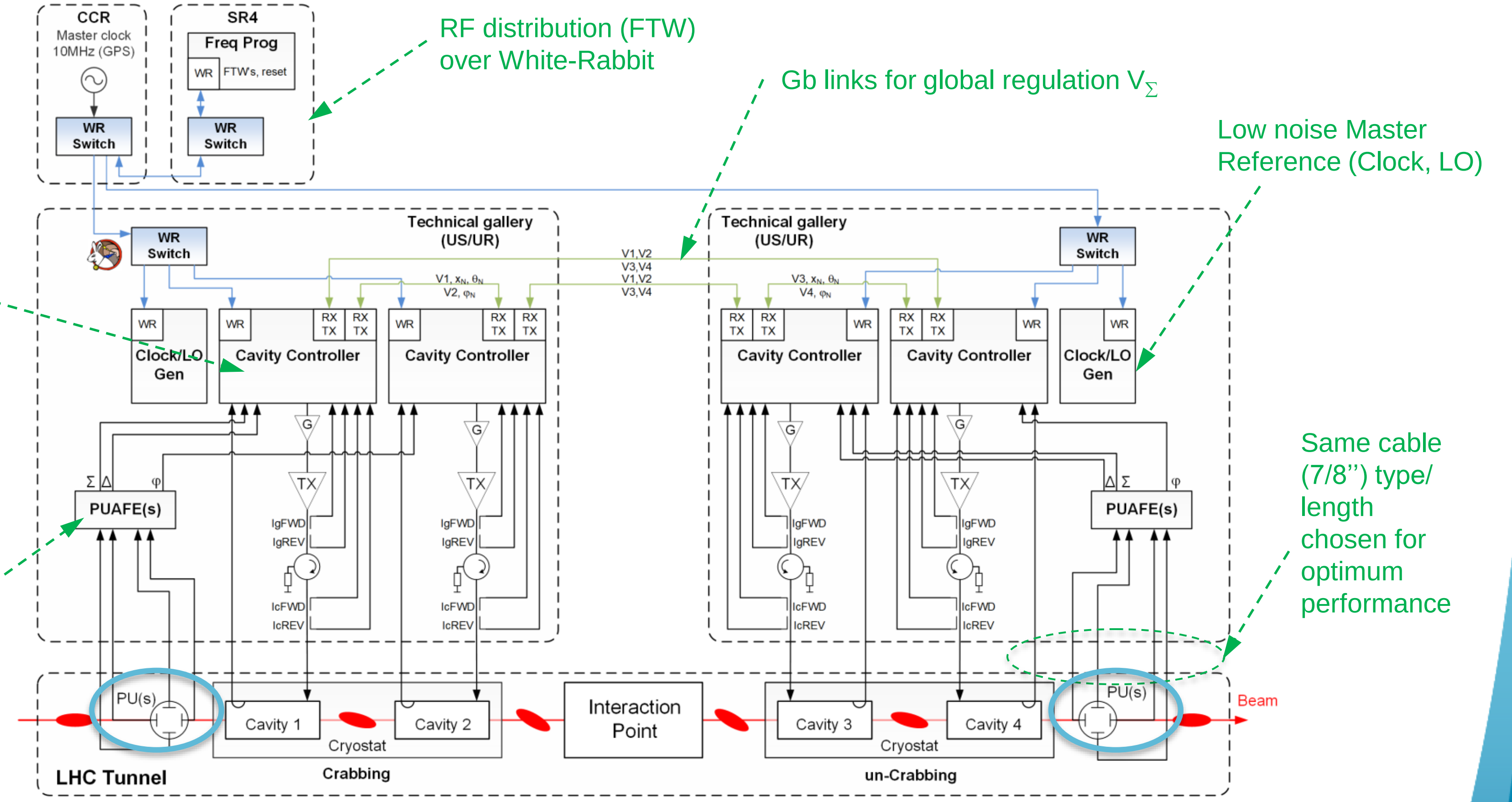


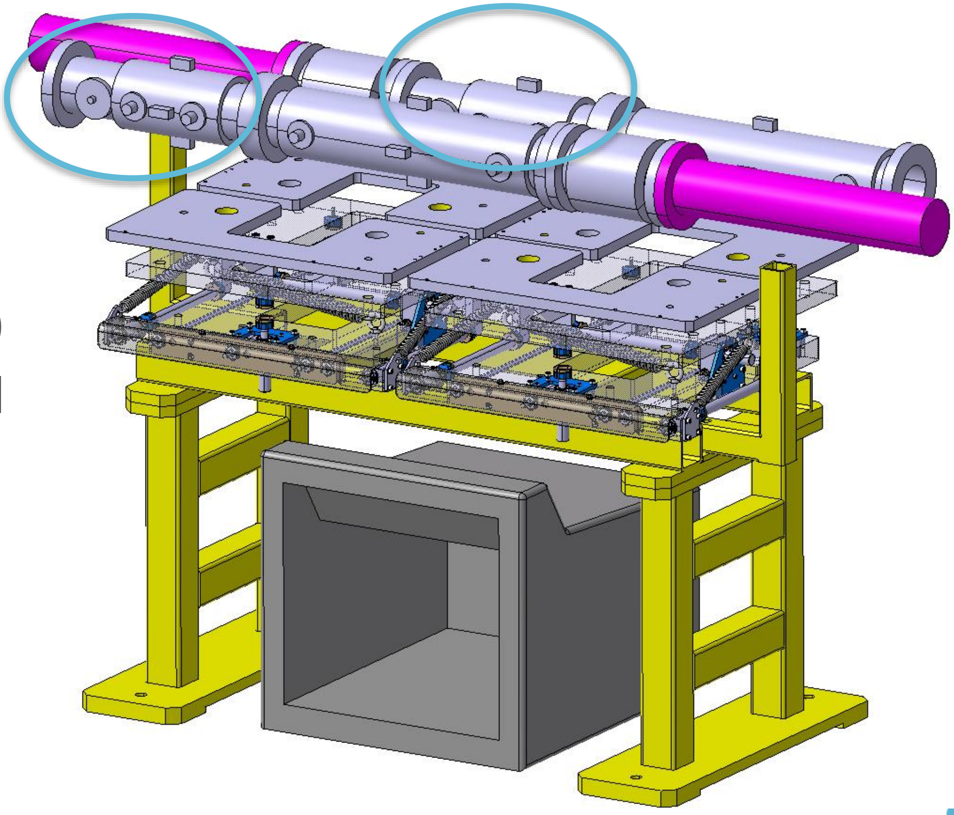
Fig – HL-LHC Crab cavities LLRF architecture (per beam and IP!)

Pick-up ensemble of **3 PUs** (functionality A,B,C only schematically shown)

G. Hagmann et al.

Integration

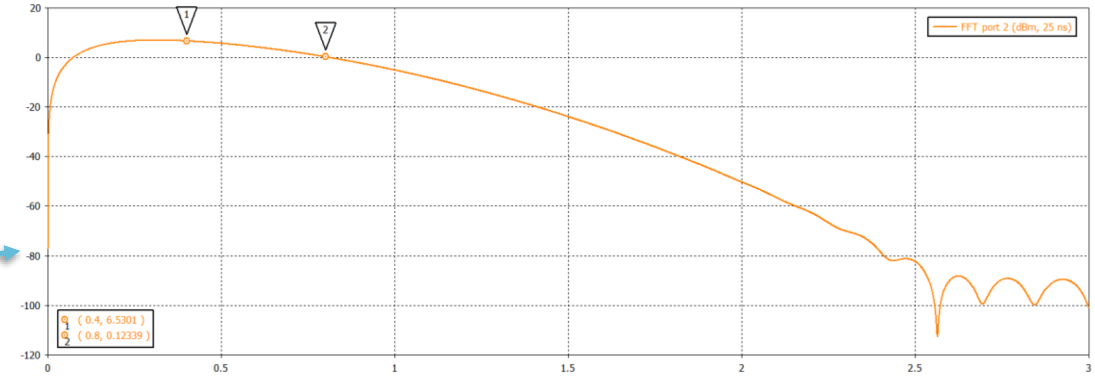
- Integration of supports for the adjacent drift chambers under discussion
- Requests for long cables done by WP4 in 2020:
  - 1 x 7/8” cable to the Faraday Cage per APWL (now BPTQR)
  - updated request from WP4 will be four 7/8’’ cables at least
  - This is not enough for the 4 buttons + 2 striplines
  - Cabling request to be updated if all three pick-ups need to be used concurrently (using spare cables already planned may be an option)

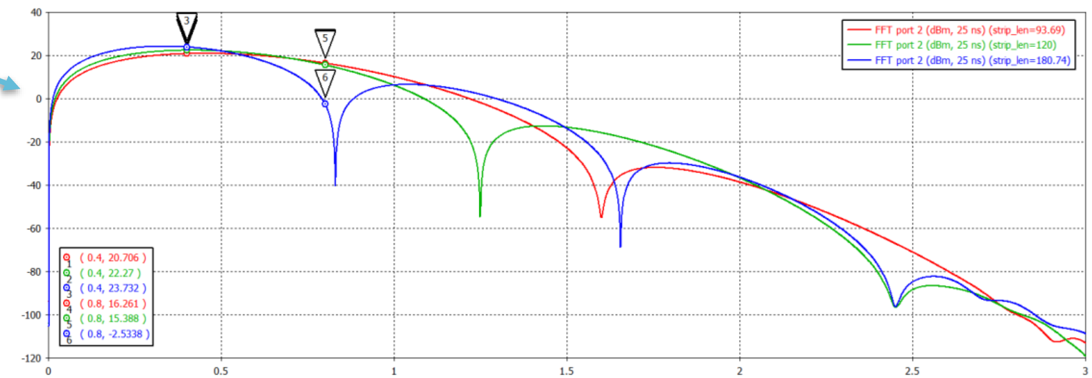


M. Krupa et al.

CC feedback PUs

- 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

From last meeting: Philippe Baudrenghien

Demodulation also possible at other harmonics of 40 MHz or other frequencies

Alignment

- In operation the crab cavities can be dynamically aligned with respect to the beam without accessing the tunnel
- This will result in an offset (mm range) of the beam in the pick-up
- For functionality A and B the alignment of the pick-up with respect to the beam is not an issue as only the longitudinal signal is needed
- For functionality C an offset has an influence on the dynamic range and during the set-up of the electronics
  - Electric centering is considered to be an option
    - https://accelconf.web.cern.ch/IBIC2013/papers/wepc12.pdf
  - The need to implement an electric centering can be decided once study and prototyping of the electronics is sufficiently advanced and a boundary for the beam position defined

Button pick-up versus strip-line

- Button pick-ups
  - offer well paired electrodes by design and serial manufacturing process
  - not phase linear (RC, large button additional convolution with diameter/bunch length to be taken into account)
  - smaller sensitivity (10x)
  - need to be well matched at all frequencies within the bunch spectrum in order not to create artifacts due to reflections
    - may require for this reason an additional attenuator before using the signal → additional signal loss
- Strip-line pick-ups
  - are phase linear and therefore more suitable for broadband applications or time domain observation
  - can create artifacts if electrodes not well paired and deviate from nominal and at feedthroughs / loads

Strip-line pick-up

- matching: feedthrough, load: -35 dB (WP4 wish)
- uniformity: 50 Ω +/- 1.5 Ω (WP4 wish)
- above specs were found to give balanced result with imperfections introduced by commercially available hybrid (H9) in the past (https://accelconf.web.cern.ch/IBIC2013/papers/wepc12.pdf)
- length suggested by WP13 ok (120 mm)
- Proximity of buttons and strip-line shall not lead to artifacts
  - to be assessed, i.e. to be compared with the 35 dB matching quoted above
  - influence of matching error of strip-line on button can be high
  - need CST simulation of string of pick-ups
- Cable type needs testing
  - within minimum bandwidth of 40 MHz for bunch-by-bunch observation the cable can also introduce some artifacts and a non-linear phase with frequency

Why do I worry about these small effects?

- Non-linear phase with frequency (could also be compensated in an analogue way) may entangle amplitude and phase modulation in the detection, we want the detection system to separate these contributions (how much cross talk can we tolerate?)
- Ideally the detection is bunch-by-bunch and there is no crosstalk of the detected signal from one bunch to the adjacent bunches.
- Reflections will lead to a cross talk between bunches and, overall, the signal we use for the noise feedback (although the cavity averages), will contain a contamination, this could be like an additional noise contribution

Questions needing attention

- Power required for the crab cavity noise feedback
  - as it is a noise like signal the extra power will have peaks in time domain (usually a factor 3 compared to the rms in voltage)
  - power requirements will be higher for large frequency offsets
    - the signal is injected into the set-point, RF feedback will push cavity drive for the signal contents with large f-offsets
- The orbit response function is valid to my understanding in the steady state case (same kick every turn)
  - There is a part of the noise (close to 400 MHz) that is correlated indeed ~100% from turn to turn
  - The noise with contributions further away from the carrier is less or not correlated from turn to turn
  - For this latter part the validity of the orbit response function deserves a check (for case of wanted noise feedback damping time being of the same order of, or exceeding the settling time of the orbit response function (in turns)

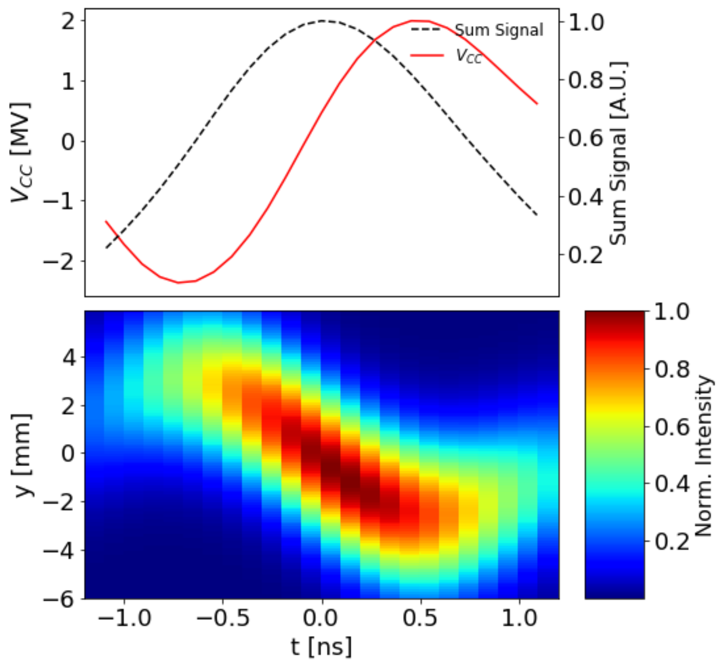
My Conclusions

- String of pick-ups suggested by WP13 looks ok
  - Maintain short strip-line in baseline
  - CST simulations to exclude mutual influence of pick-ups
  - Matching and uniformity of strip-line
  - Influence of finite size of button on transfer function
  - Cable sample measurement
  - No active mechanical alignment requested by WP4
- Check of a number of questions within WP4 and between WP2 and WP4 needed

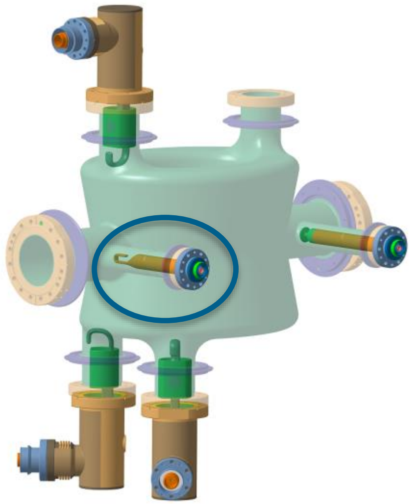
Spare Slides
from contributors to previous meetings and discussions

Functionality A: CC-beam phasing

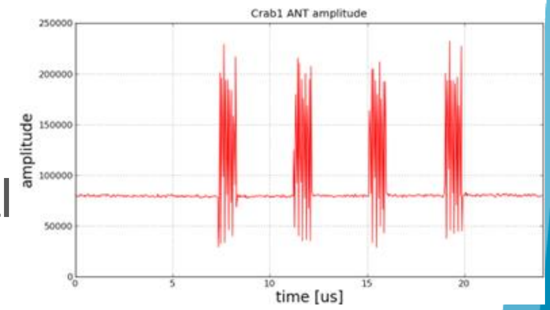
- Longitudinal beam position defined by the 400 MHz system in SR4 / UX45
- CCs controlled by electronics installed in 4 Faraday cages in IP1/5
- WP requirement: monitoring of the phase of the 400 MHz beam current component close to the CC location to correct the crabbing phase
- ECR proposal: 2 button electrodes for narrowband longitudinal measurements, next to the CC



Functionality B: Filtering of beam interference on the CC antenna signal

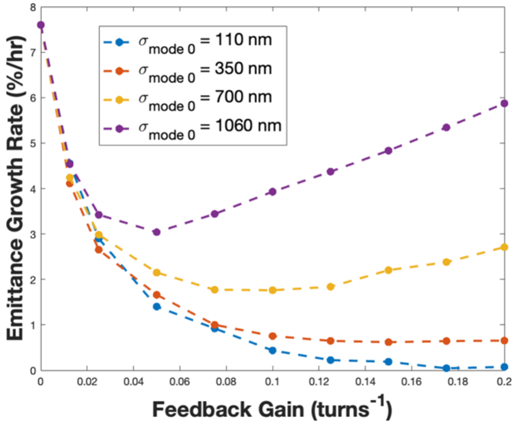


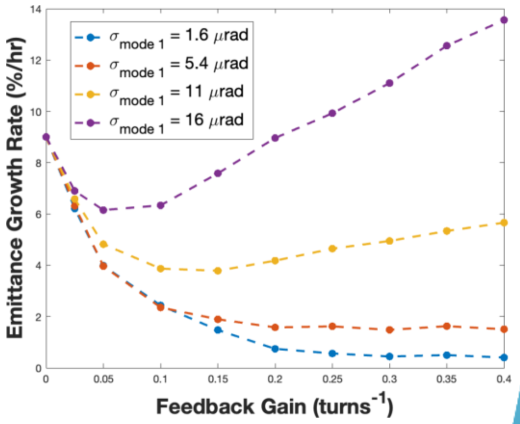
- An antenna installed outside the CC generates a signal used to regulated the CC field
- Undesired coupling to the beam field to be removed through Adaptive Noise Cancelling techniques
- WP4 requirement: Monitoring of the beam current in the 360–440 MHz band close to the CC location. Sensitivity from a single pilot bunch to a full nominal beam
- ECR proposal: 2 button electrodes for longitudinal measurements, next to the CC



Functionality C: CC noise FB

- Excessive CC noise results in an additional bunch tilt outside of the crabbing region
- WP4 requirement: Monitoring of bunch tilt in a high β location with a suitable phase advance from the CC
- Noise floor of 5.3 μm for rigid bunch displacement, 55 μrad for bunch tilt
  - Assumes β=2000 at the BPTQR location
  - Assumes FB regulation BW of 136 kHz (~ 150 bunches)
- ECR proposal: 2 stripline electrodes for transverse HT measurements





LLRF Solutions: Cavity-Controller

- Power amplifier: IOT
- Tuning loop
  - We must keep the cavity on-tune the entire LHC fill (filling/rampling/collision)
- Polar-loop
  - Slow regulation around the amplifier (Gain&phase drift, reduce amplifier noise)
- RF feedback
  - Control cavity field + Impedance reduction
    - Fast loop around cavity-amplifier
    - Slow global loop regulating the vector sum: crabbing-uncrabbing voltages

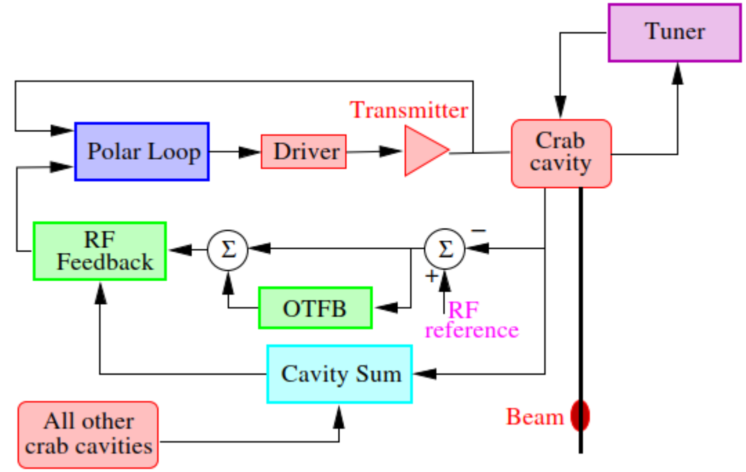
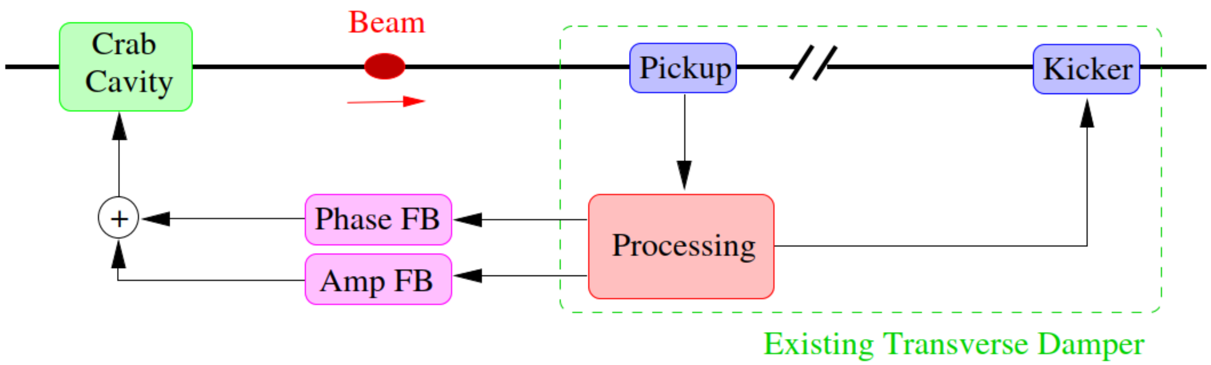


Fig – Crab Cavity Low-Level RF block diagram [13]

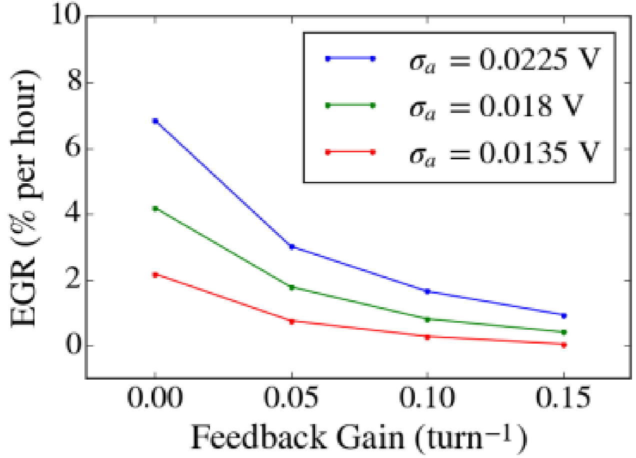
Mitigation 2. CC feedback

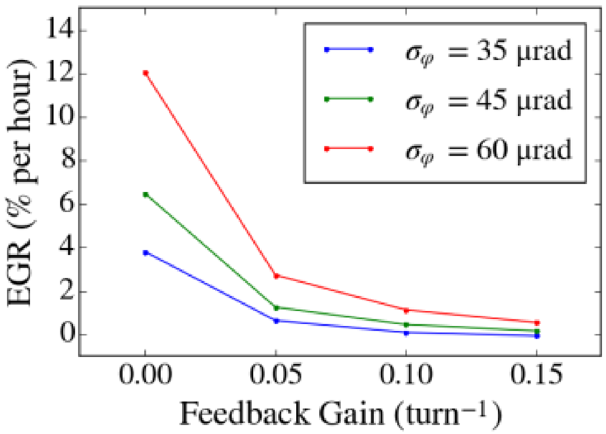
- Dedicated feedback system to counteract crab cavity noise could be developed [6],[8] to provide the extra factor 10
  - Such a system could work in conjunction with the ADT
  - Its performance will be limited by the **pickup measurement noise** (pickup specs later in this presentation.
  - Theory and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



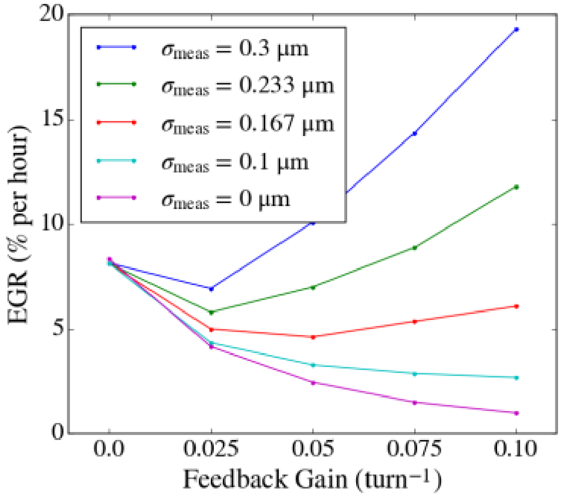
Feedback system using CC as kicker

- This system is very promising in simulations



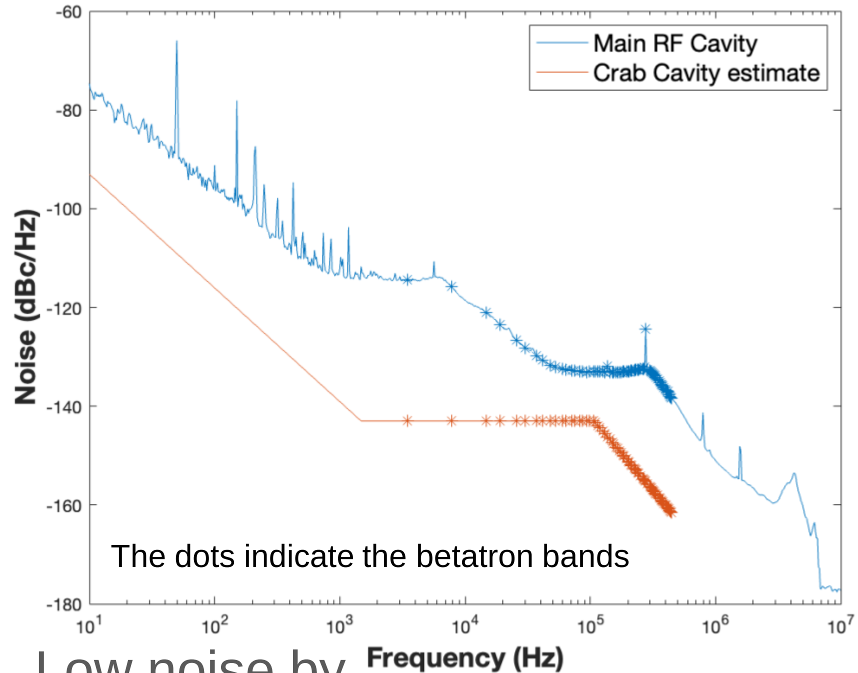


- But the performance is limited by the measurement noise level. Emittance growth rate curves with varying magnitudes of measurement error in the presence of both phase and amplitude noise
- Need for a **low-noise** bunch displacement (mode 0) and tilt (mode 1) measurement chain.



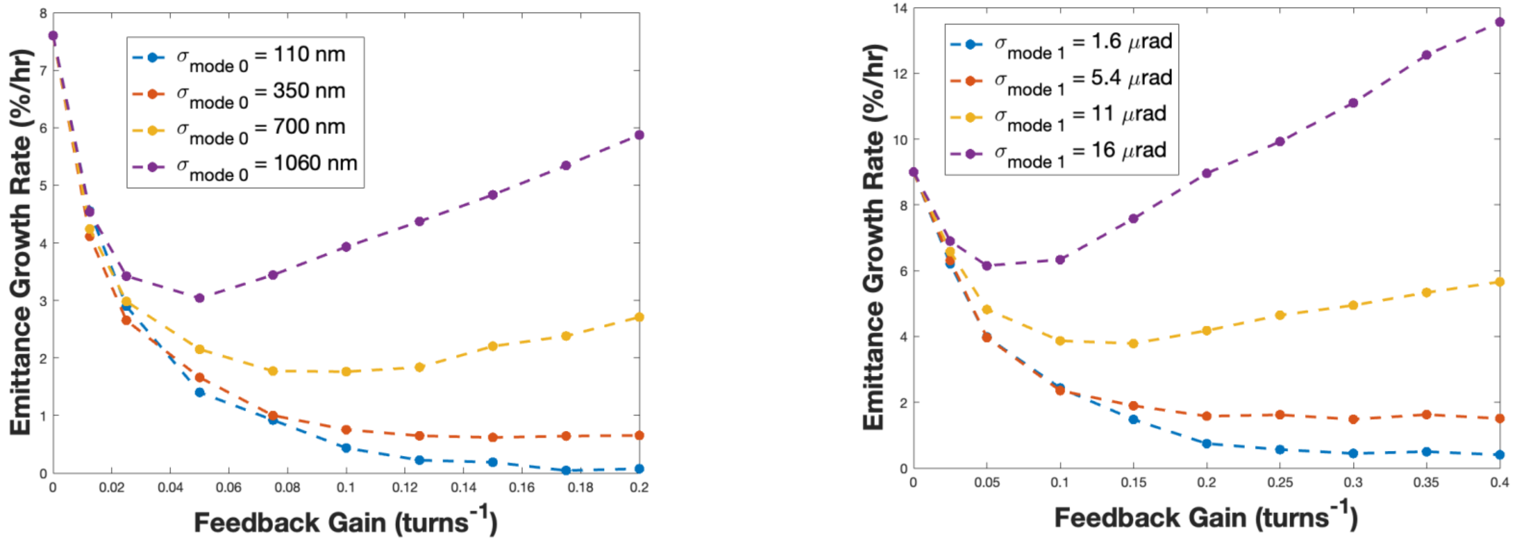
Mitigation 1. Low noise LLRF

- 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**

- 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)

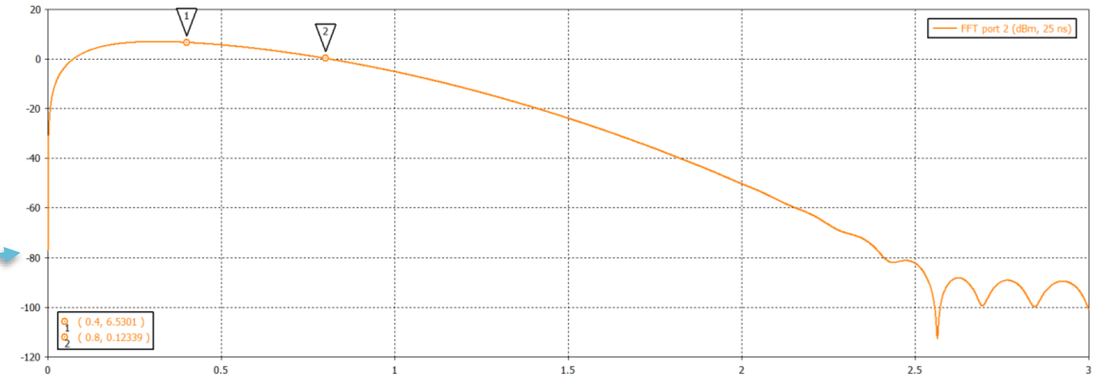
- Except for the novel use of a CC as kicker, it is a *classic* transverse feedback with mode 0 (displacement) and 1 (tilt)
- We plan to follow processing shown in [7] Eq. (16) to extract mode 0 and 1 signals, at least for SPS test bench
  - Delta/Sigma signals from WB PU
  - Filtering with 400 MHz BPF
  - 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]

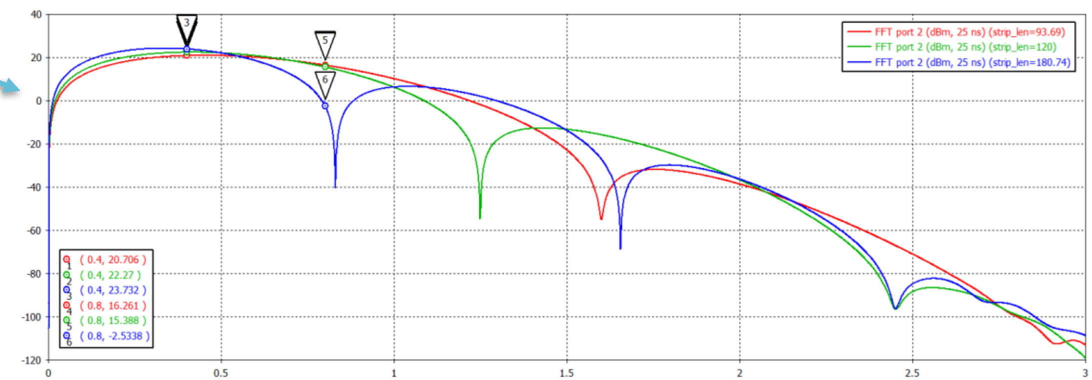
$$X_N = \frac{I_\Delta I_\Sigma + Q_\Delta Q_\Sigma}{I_\Sigma^2 + Q_\Sigma^2} + j\frac{Q_\Delta I_\Sigma - I_\Delta Q_\Sigma}{I_\Sigma^2 + Q_\Sigma^2}$$

- 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

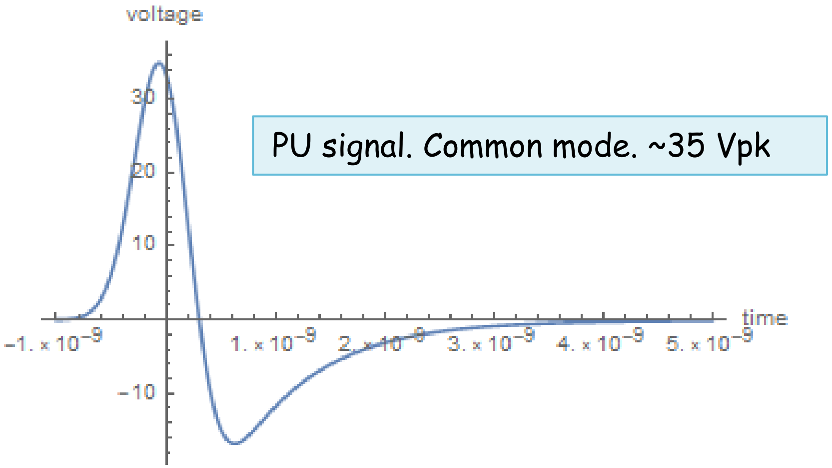
- We have a PU next to each cryostat (cavity pair)
- We have 2 available PU candidates
  - Button
  - Stripline
- We consider operation (demodulation) at 400 or 800 MHz-> 120 mm stripline (green) and button are good options
- The frequency responses of the two Pus are very similar
- The **stripline**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

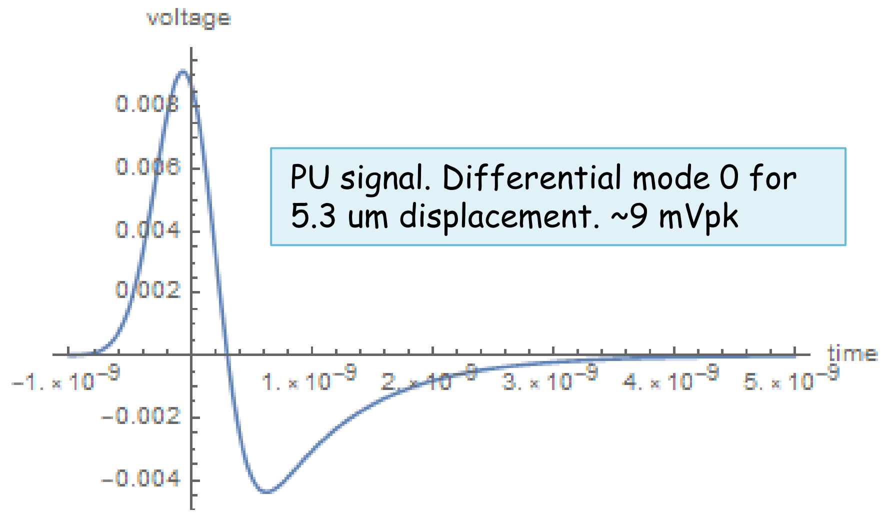


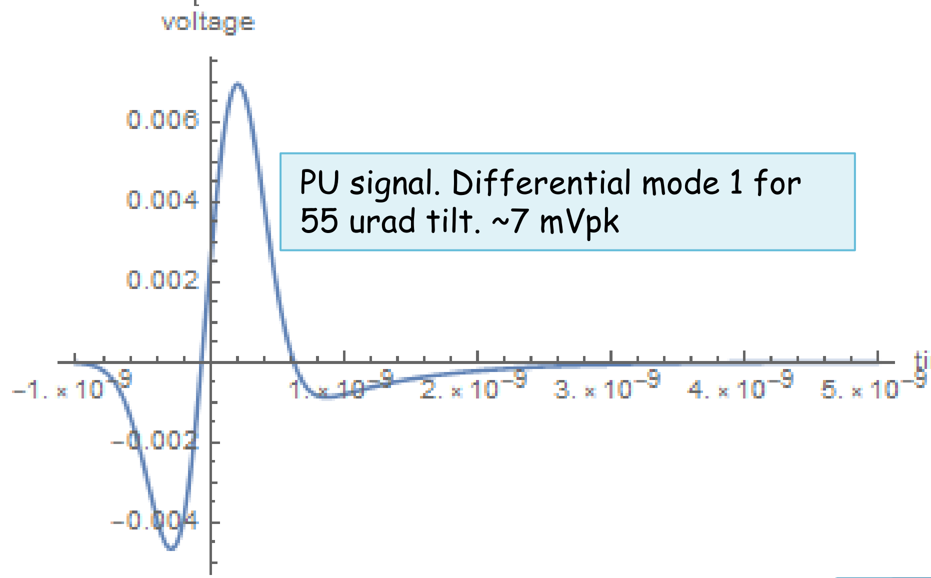


Courtesy of M. Krupa

Signals from button PU before demodulation

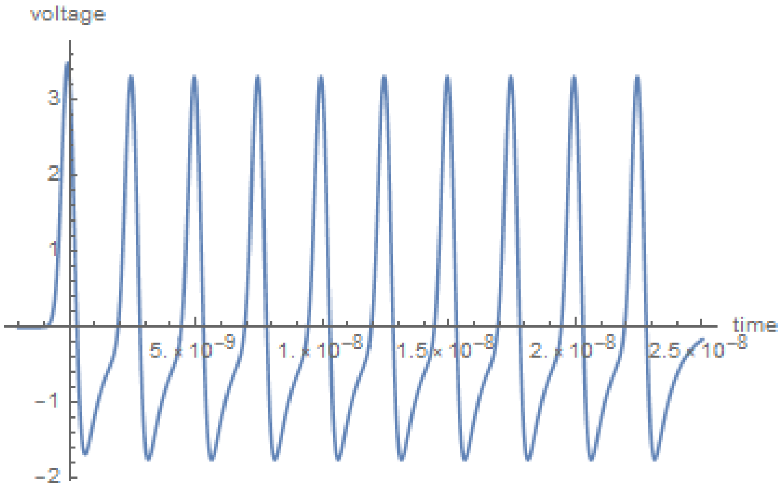




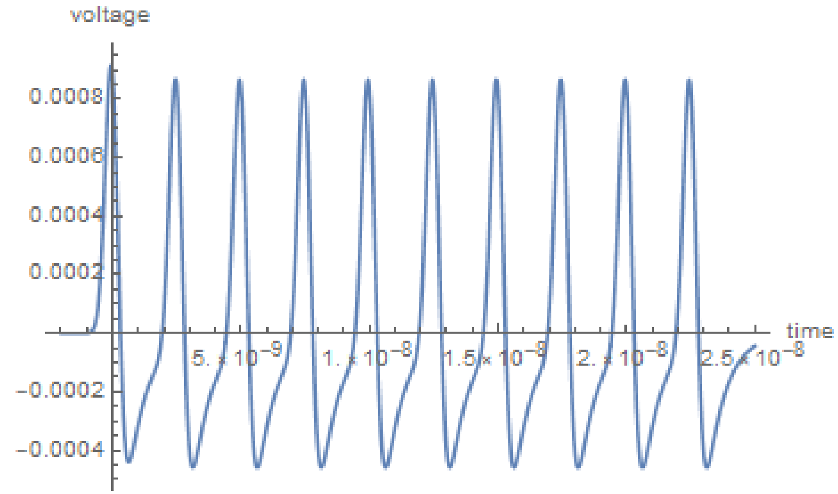


- Single bunch, 1.05 ns, 2.3e11 ppb
- For the required resolution (5.3 um and 55 urad) the mode 0 and 1 signals have similar peak amplitude. Good
- But they are **4000-5000** below common mode
- Assuming 20 dB rejection from delta hybrid (can we get more?) we would still have common mode **400-500**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

Signals from button PU after 400 MHz BPF

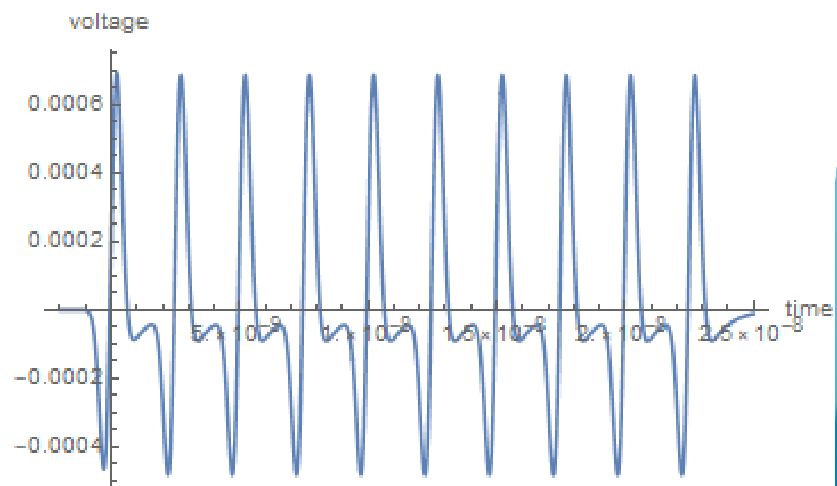


Common mode. ~5 Vpkpk (blue).



Differential mode 0 for 5.3 um displacement. ~1.3 mVpkpk

- 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.



Differential mode 1 for 55 urad tilt. ~1.1 mVpkpk