Update on Crab Cavity Pickup (BPTQR) specification in the HL-LHC and alignment tolerances

W. Hofle for WP4, *CERN, SY-RF*
Acknowledgement: P. Baudrenghien, J. Bento, A. Butterworth, R. Calaga, G. Hagmann, M. Krupa, H. Mainaud Durand and BE-GM team, R. de Maria, T. Mastoridis, D. Valuch, M. Wendt

Outline

- Context and functionality of different types of RF pick-ups requested by WP4 to WP13
- Scope of BPTQR specification
- choice of pick-ups and alignment requirements
- Next steps refinement of signal levels and tests for verification of signals for processing with beam

HL-LHC (superconducting) crab cavities

RF Dipole (RFD),
crabbing in horizontal plane
(IP1, ATLAS)

8 cavities

Double **Q**uarter **W**ave (DQW) resonator,
crabbing in vertical plane
(IP5, CMS)

8 cavities

$f_0 = 400$ MHz

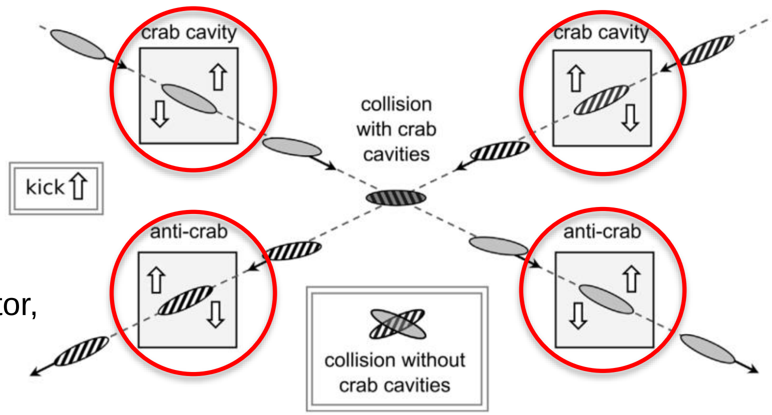
$V_T = 3.4$ MV/cavity

$(E_p, B_p < 40$ MV/m, 70 mT$)$

Beam aperture = 84 mm

RF power = 50 kW-CW

Operating Temp = 2 K



$$L = \gamma \frac{n_b N^2 f_{rev}}{4\pi \beta^* \varepsilon_n} R$$

LHC: θ_c = 320 μrad, β*=0.3 → R=0.6

HL-LHC: θ_c = ~500 μrad, β*=0.15 → R= 0.35

→ operate with crab cavities to recover peak luminosity

LLRF (low level RF) system with feedbacks to control crab cavity amplitude and phase and lock in frequency and phase to the beam and the main RF system

→ need for beam pick-ups

LLRF: G. Hagmann, this meeting
https://indico.cern.ch/event/1421594/contributions/6062565/attachments/2943583/5172287/HL-LHC%20annual%20meeting%20LLRF%2020241009.pdf

Context

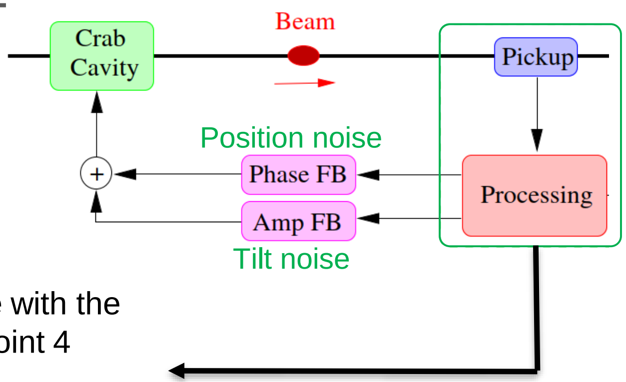
- Pick-ups' design and construction managed by WP13
  - following baseline change approved: ECR [2499201]
  - presented by M. Krupa at 13th HL-collaboration meeting in Vancouver in October 2023 https://indico.cern.ch/event/1293138/contributions/5459115/attachments/2723253/4733385/230928_bptqr.pdf
- Four 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 *crabbing closed* orbit response and high beta function
- New baseline agreed with WP13: WP4 requests a pick-up ensemble comprising per each IP side and beam
  - set of four button pick-ups (planes: crabbing and perpendicular)
  - short strip-line 120 mm (matched terminations)
    - in crabbing plane for noise feedback

Three pick-ups for RF per location (1)

- RF (WP4) will cover three separate functionalities
  - Functionality A: crab cavity phasing with beam using a narrow band processing representing a suitable average of the beam
    - averaging after bunch-by-bunch acquisitions after digitization pair of buttons (sum signal: plane perpendicular to crabbing)
    - minimum perturbance of residual crabbing desired
  - Functionality B: for removal of direct coupled beam signal from cavity antenna signal if needed
    - bunch-by-bunch signal needed
    - pair of buttons (sum signal or single side)
    - upgrade of cabling in latest DIC (3/8” →7/8”)

Three pick-ups for RF per location (2)

- 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 processing chosen, *position and tilt*
    - averaged in digital domain as needed for bandwidth
    - has to work in commissioning scenarios with less dense bunch patterns → bunch-by-bunch acquisition is advantageous
  - 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 of CC LLRF



T. Mastoridis,
P. Baudrenghien [1]

need for data exchange with the transverse damper in point 4 (digital data via fiber)

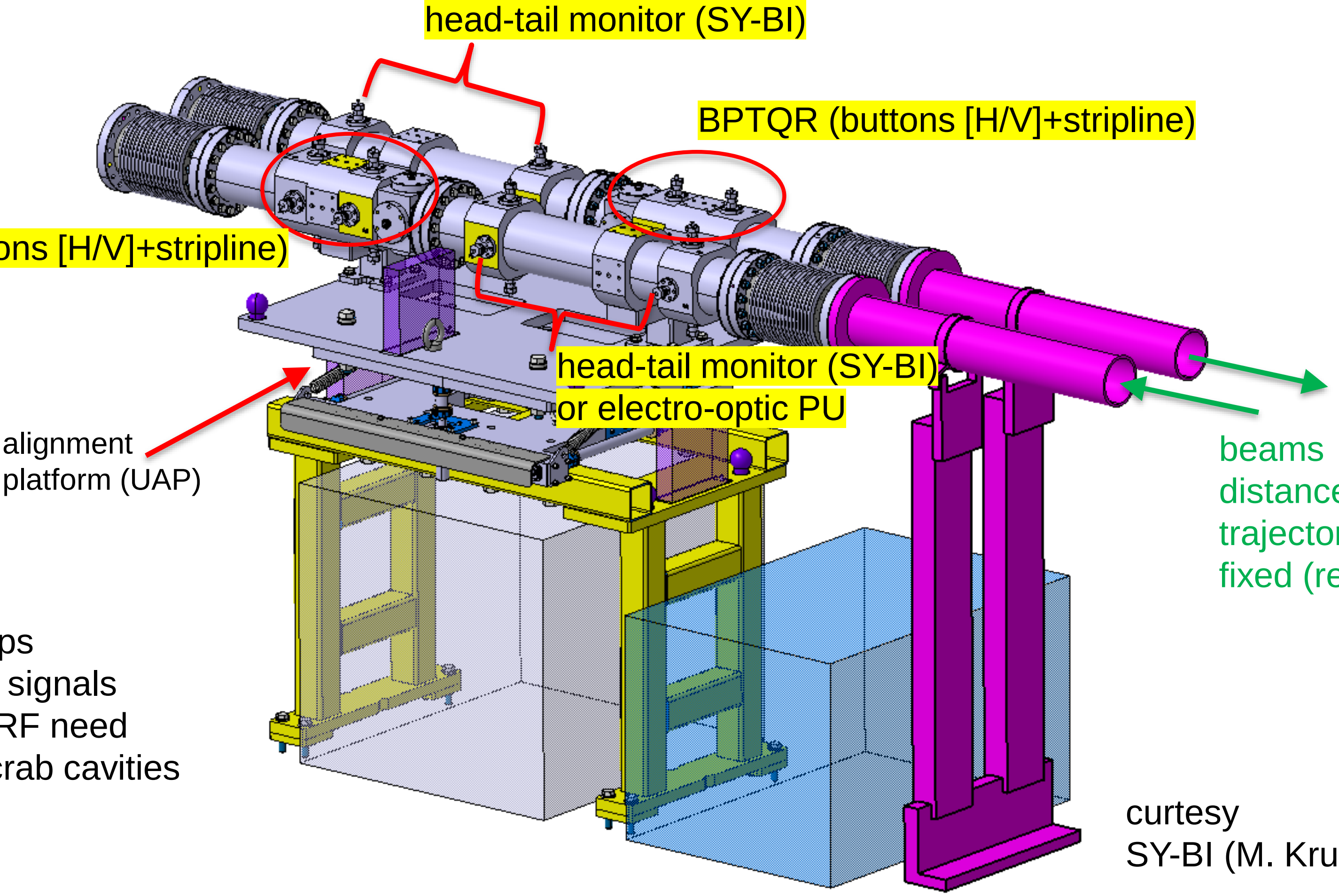
Scope of RF BPQTR Specification

EDMS: 3069868

- define the number of pick-ups to be built, their type and location
  - summarize the considerations leading to this choice
- provide the key parameters for the two types of pick-ups agreed with WP13 and targets for tolerances
- set targets for the dynamic range needed for the signal treatment compatible with a coherent set of parameters for nominal operation
  - crab cavity noise feedback and phase loop
  - alignment of the pick-ups
  - beam offsets and residual crabbing
- summarize the requirements and precautions to be taken to meet the targets for the required dynamic range, including for commissioning → important not to saturate electronics and achieve the accuracy / resolution required within the operational envelope for the parameters

BPTQR pick-up - BPM

- point 1 and 5 in LHC, left and right adjacent to crab cavities
- eight pick-up objects share common alignment platform
  - accuracy of aligning all eight axes to beam reference



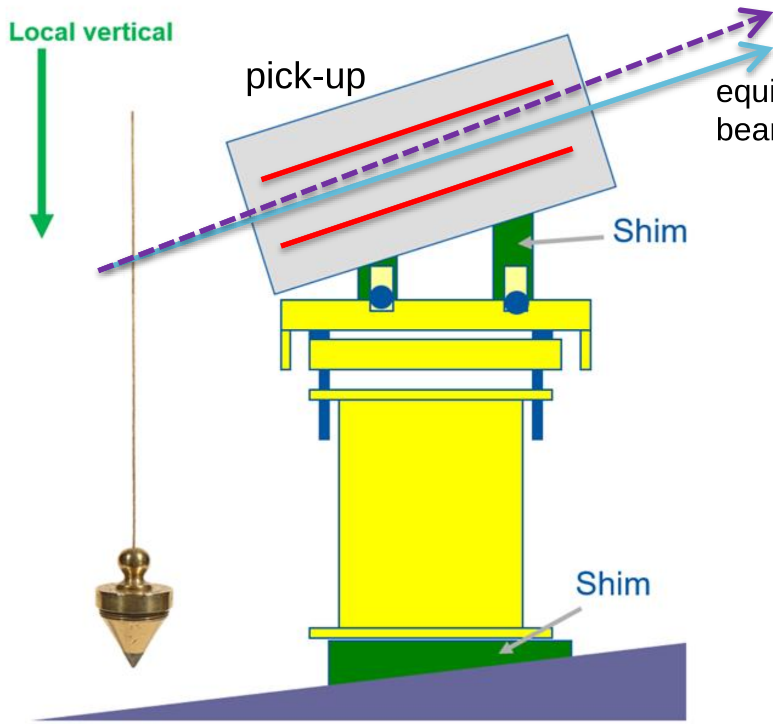
BPTQR pick-ups
Will provide all signals
the LLRF and RF need
related to the crab cavities
feedbacks

curtesy
SY-BI (M. Krupa)

alignment approach with common UAP under validation
tolerance stack analysis by SY-BI

UAP requirement

- support part of UAP needs to be shimmed to have the platform supported perpendicular to local gravity (BE-GM requirement to SY-BI)
  - local gravity

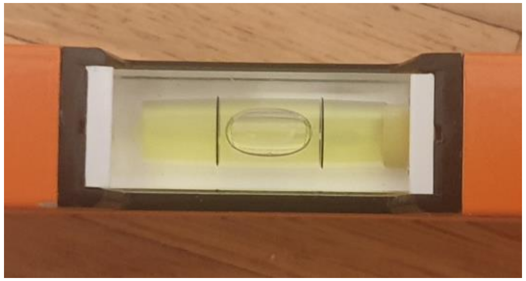


https://edms.cern.ch/ui/file/2708664/1.0/LHC-G-EN-0001-1-0.pdf

LHC/LEP plane inclination 1.41%
→ 14 mrad, CMS, beam 2 uphill

spirit level (my test at home)

- 2 mrad



“0” mrad

+ 2 mrad

(1.6 mm over 800 mm → 2 mrad)
100 μrad → 1 sheet of paper over 1 m
above “manual” measurement resolution
+/- 300 μrad (+/- 3 “post-its” of 0.25 mm)

Specification (EDMS 3069868)

- parameters for buttons and striplines

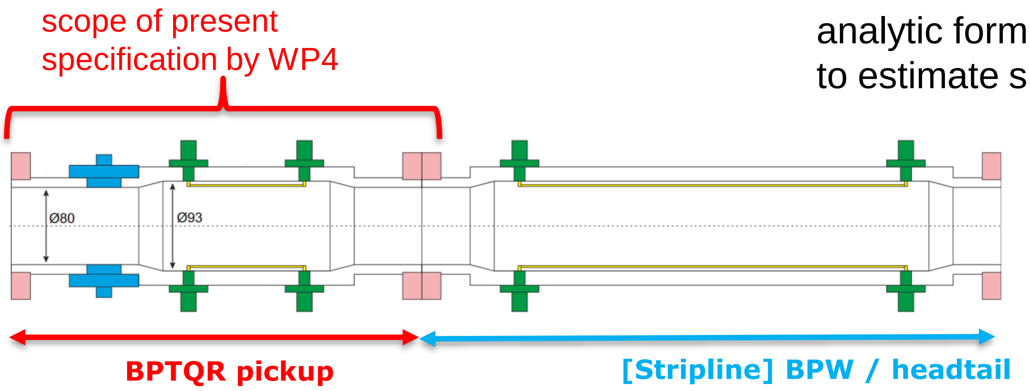
button

Parameter	value		tolerance		comment
Pick-up diameter D_{PU}	81	mm			
Button head radius r_{b}	16.75	mm			
resonance free up to	>3	GHz			no ringing within beam spectrum
Capacitance (per button) C_b	15	pF	± 0.5	pF	absolute value
pairing of buttons better than	± 0.1	pF			between sides
feedthrough impedance Z_{FT}	50	Ω	± 1.5	Ω	N-type (f) connector
matching cable side Z_{L}	50	Ω	± 1.5	Ω	N-type (m) connector

stripline

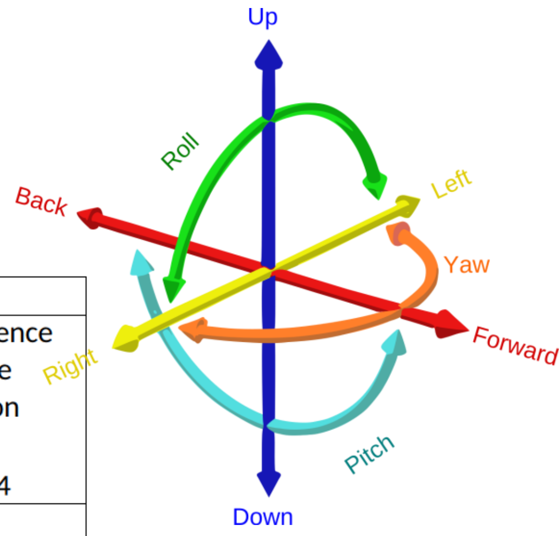
Parameter	value		tolerance		comment
Pick-up diameter D_{PU}	91	mm			
Stripline length l_{s}	120	mm			
Impedance of stripline Z_{s}	50	Ω	± 2.5	Ω	
pairing of strips better than	± 1.5	Ω			uniformity (active length)
feedthrough impedance Z_{FT}	50	Ω	± 1.5	Ω	N-type (f) connector
assumed load matching Z_{L}	50	Ω	± 1.5	Ω	N-type (m) connector

analytic formulas can be used to estimate signal levels



Alignment

- Tables with alignment tolerances

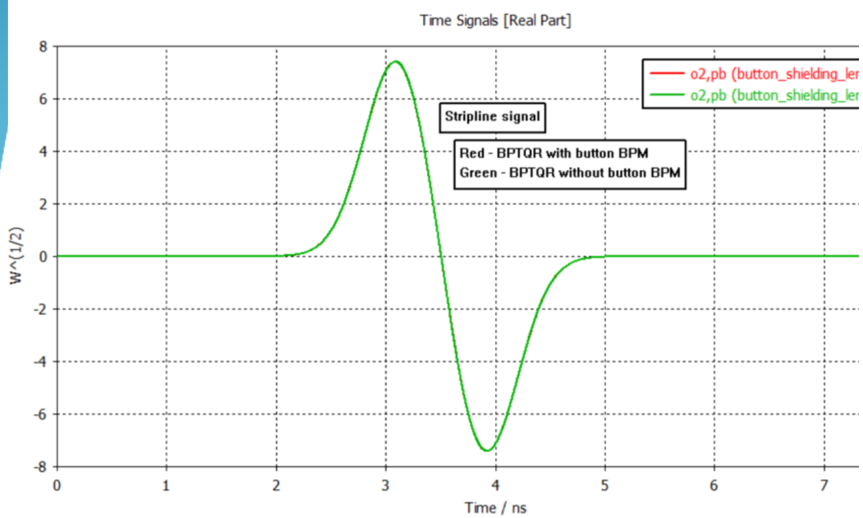


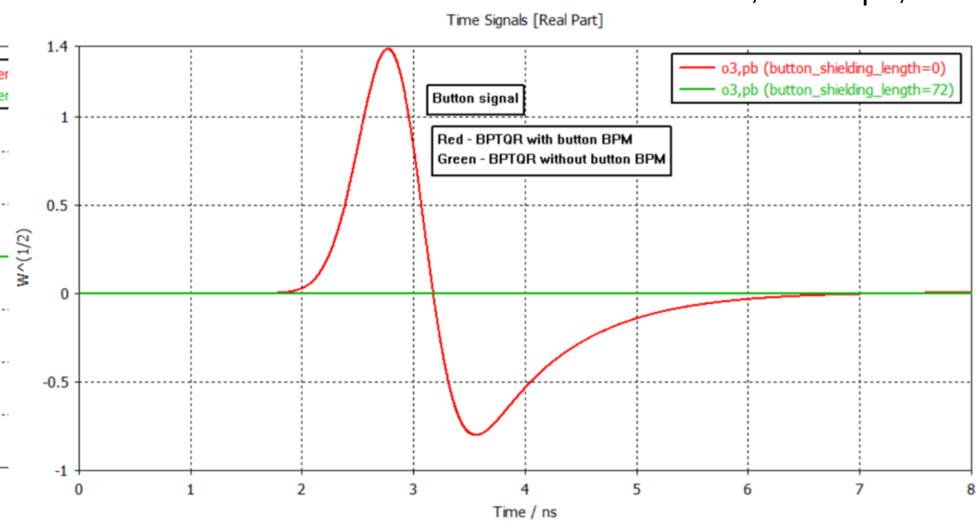
Parameter	value		comment
mechanical alignment offsets (H/V)	± 0.5	mm	pick-up electric axis to UAP reference
mechanical alignment offsets (H/V)	± 1	mm	UAP yearly correction possible
beam orbit variation	± 1	mm	occurs dynamically in operation
acceptance of electrical centering	± 3	mm	dynamically during fill
electrical centering to better than	± 0.5	mm	as needed, responsibility WP4
single bunch position noise (SB)	< 0.32	μm	rms from simulations [1]
position dynamic range needed (SB)	63.9 (73.4)	dB	with (without) electronic centering
position avg. noise (3.6 $\mu s \equiv 135$ kHz BW)	< 3.9	μm	relaxed rms per bunch for 25 spacing [1]
position dynamic range needed (25 ns)	42.2 (51.7)	dB	with (without) electric centering

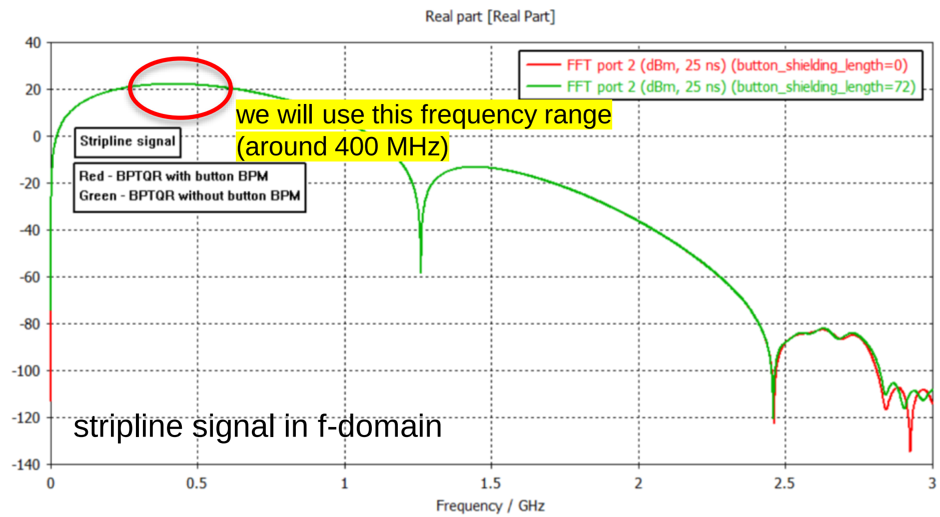
Parameter	value		comment
alignment roll	± 100	μrad	PU electric axis to UAP reference
roll of UAP reference to beam nominal trajectory	± 100	μrad	yearly correction possible
alignment $\perp$ CC-axis, pitch (IP1), yaw (IP5)	± 100	μrad	PU electric axis to UAP mean
alignment $\perp$ CC-axis, pitch (IP1), yaw (IP5)	± 100	μrad	UAP mean, yearly correction
operational margin, pitch (IP1), yaw (IP5)	± 100	μrad	beam operational margin
alignment $\parallel$ CC-axis, yaw (IP1), pitch (IP5)	± 100	μrad	pick-up axis to UAP mean
alignment $\parallel$ CC-axis, yaw (IP1), pitch (IP5)	± 100	μrad	UAP mean, yearly correction possible
operational margin, yaw (IP1), pitch (IP5)	± 100	μrad	beam operational margin
residual crabbing tilt (nominal)	< 400	μrad	closed crabbing
residual crabbing tilt	< 10000	μrad	worst case (open crabbing bump)
single bunch tilt noise	< 8.3	μrad	rms from simulations [1]
tilt dynamic range needed (SB)	38.5 (61.9)	dB	closed crabbing case (open crabbing)
averaged noise (3.6 $\mu s \equiv 135$ kHz BW)	< 100	μrad	relaxed rms per bunch for 25 ns spacing [1]
tilt dynamic range needed (25 ns)	16.9 (40.3)	dB	closed crabbing case (open crabbing)

Signals from stripline and button / next steps

CST simulations, M. Krupa, SY-BI







- mutual influence of stripline and button investigated by CST simulation to validate distance between pick-ups and cavity (possible leakage of 400 MHz needs to be excluded
- Measurements on pick-ups by SY-BI in lab set-up to validate feasibility of tolerances for alignment
- need for modelling, to propagate assumed alignment errors and manufacturing tolerances to the pick-up output signal and then through the planned receiver to validate the design and planned processing
- analytic PU responses and CST simulations
- possible beam tests with existing pick-ups and processing systems (LHC, SPS)

LLRF processing for noise feedback

- 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 [5] 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 (or suitable bunch spacing harmonic)
    - Analog mixer with (LO frequency and exact receiver design to be decided)
    - ADC clocked at 100 MHz, e.g.
    - 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:

$$\mathrm{X}_N = \frac{I_\Delta I_\Sigma + Q_\Delta Q_\Sigma}{{I_\Sigma}^2 + {Q_\Sigma}^2} + j\frac{Q_\Delta I_\Sigma - I_\Delta Q_\Sigma}{{I_\Sigma}^2 + {Q_\Sigma}^2}$$

- 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)
- Option to test in SPS or in LHC with signals to be considered

P. Baudrenghien et al. (mod.)

Summary

- Decisions taken concerning requests for RF pick-ups
- Specification for these BPTQR pick-ups in circulation
- Integration work with common alignment platform advanced
- Cabling and infrastructure requirements defined
- Importance of pick-up manufacturing and alignment tolerances highlighted as they have impact on the needed dydnamic range of the detection of position and tilt for noise feedback
- Tests with beam planned before LS3 in SPS and LHC to validate signal levels and signal processing principle

References

1. T. Mastoridis, P. Baudrenghien, P. Baudrenghien, T. Mastoridis, Transverse Emittance Growth due to RF Noise in Crab Cavities: Theory, Measurements, Cure, and High Luminosity LHC estimates Phys. Rev. ST Accel. Beams 27, 051001 (2024), https://doi.org/10.1103/PhysRevAccelBeams.27.051001
2. M. Krupa and T. Lefevre, “Replacement of APWL pick-ups in HL-LHC IR1 and IR5 by a new pick-up designed by WP13”, LHC-BPMQ-EC-0002, rev. 1.0, EDMS 2499201, https://edms.cern.ch/document/2499201/1.0, CERN, Geneva, Switzerland, 2022.
3. P. Baudrenghien, R. Calaga,T. Mastoridis, "CC Feedbacks and Pick-up", HL-LHC TCC, 2.12.2021 https://edms.cern.ch/document/2667132/1
4. P. Baudrenghien, HL-LHC CC PU, WP2/WP4 internal meeting, 03.08.2023, https://indico.cern.ch/event/1313576/
5. G. Kotzian, W. Höfle, D. Valuch, "Sensitivity of the LHC Transverse Feedback System to Intra-Bunch motion", IPAC2017, https://doi.org/10.18429/JACoW-IPAC2017-TUPIK093

Spare

Tolerances and CC noise feedback (1)

Parameter	value	comment
mechanical alignment offsets (H/V)	± 0.5 mm	pick-up electric axis to UAP reference
mechanical alignment offsets (H/V)	± 1 mm	UAP yearly correction possible
beam orbit variation	± 1 mm	occurs dynamically in operation
acceptance of electrical centering	± 3 mm	dynamically during fill
electrical centering to better than	± 0.5 mm	as needed, responsibility WP4
single bunch position noise (SB)	< 0.32 μm	rms from simulations [1]
position dynamic range needed (SB)	63.9 (73.4) dB	with (without) electronic centering
position avg. noise (3.6 μs $\equiv 135$ kHz BW)	< 3.9 μm	relaxed rms per bunch for 25 spacing [1]
position dynamic range needed (25 ns)	42.2 (51.7) dB	with (without) electric centering

- without electric centering
  - single bunch dynamic range: 20 dB $\log_{10}$ (2000 / 0.32) = 73.4 dB
    - 2000 µm ← 1 mm + 1 mm {attenuators to remove fixed misalignment B1/B2}
- with electric centering
    - single bunch dynamic range: 20 dB log10 (500 / 0.32) = 63.9 dB
- multi bunch dynamic range:
  - averaging over 144 (25 ns) slots for 135 kHz BW: $144^{0.5}$
    - requirement relaxed by factor 12 (by 21.5 dB) for 25 ns spacing
- discussion took place on common UAP for both beams (BE-GM, SY-BI)

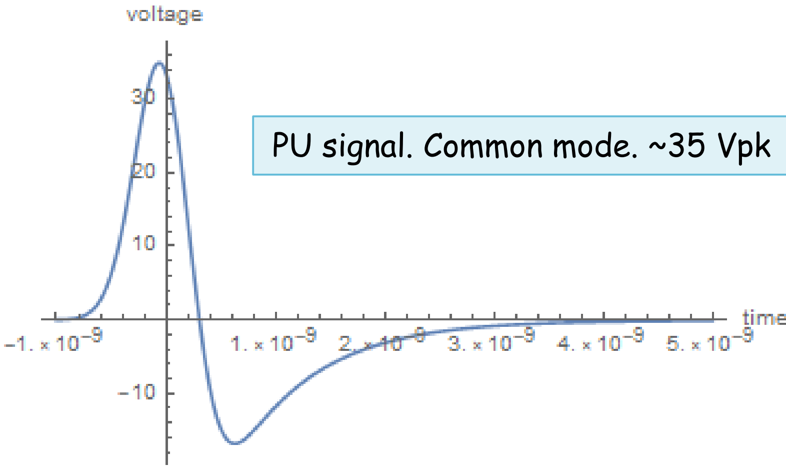
Tolerances and CC noise feedback (2)

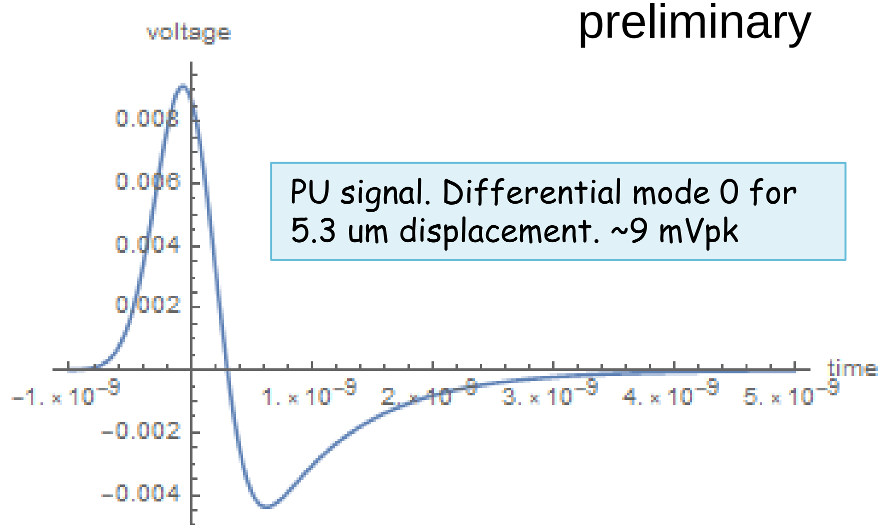
Parameter	value		comment
alignment roll	± 100	μrad	PU electric axis to UAP reference
roll of UAP reference to beam nominal trajectory	± 100	μrad	yearly correction possible
alignment $\perp$ CC-axis, pitch (IP1), yaw (IP5)	± 100	μrad	PU electric axis to UAP mean
alignment $\perp$ CC-axis, pitch (IP1), yaw (IP5)	± 100	μrad	UAP mean, yearly correction
operational margin, pitch (IP1), yaw (IP5)	± 100	μrad	beam operational margin
alignment $\parallel$ CC-axis, yaw (IP1), pitch (IP5)	± 100	μrad	pick-up axis to UAP mean
alignment $\parallel$ CC-axis, yaw (IP1), pitch (IP5)	± 100	μrad	UAP mean, yearly correction possible
operational margin, yaw (IP1), pitch (IP5)	± 100	μrad	beam operational margin
residual crabbing tilt (nominal)	< 400	μrad	closed crabbing
residual crabbing tilt	< 10000	μrad	worst case (open crabbing bump)
single bunch tilt noise	< 8.3	μrad	rms from simulations [1]
tilt dynamic range needed (SB)	38.5 (61.9)	dB	closed crabbing case (open crabbing)
averaged noise (3.6 $\mu s \equiv 135$ kHz BW)	< 100	μrad	relaxed rms per bunch for 25 ns spacing [1]
tilt dynamic range needed (25 ns)	16.9 (40.3)	dB	closed crabbing case (open crabbing)

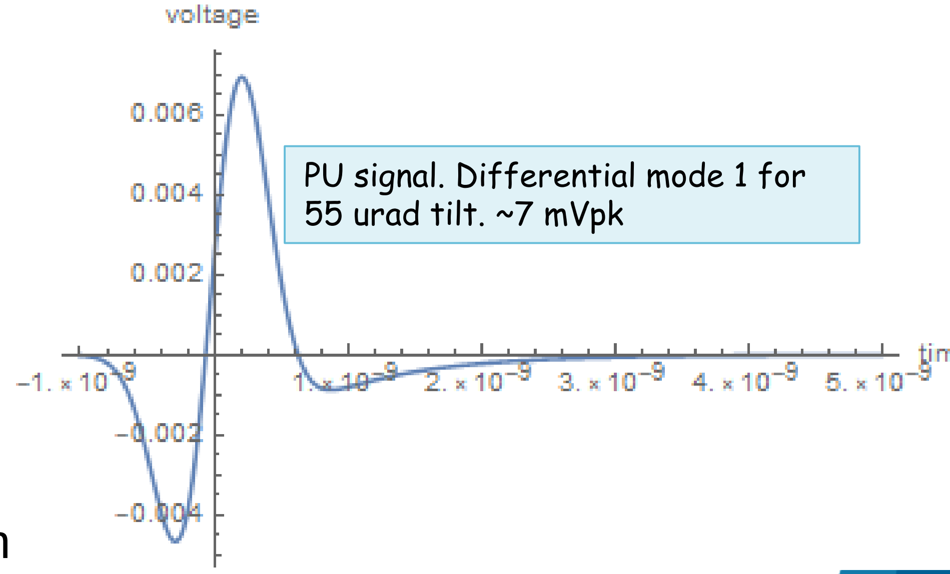
- no electric centering for tilt measurement, closed bump case (worst of best case) and open bump (worst case, if noise feedback needs to work under these conditions)
  - single bunch dynamic range: 20 dB $\log_{10}$ (700 / 8.3) = 38.5 dB
    - 700 μrad ← (100 + 100 + 100 + 400) μrad
  - single bunch dynamic range: 20 dB log10 (10300 / 8.3) = 67.2 dB
    - 10300 μrad ← (100 + 100 + 100 + 10000) μrad
- discussion took place for common UAP for both beams with BE-GM, SY-BI

Signals from button PU before demodulation

preliminary



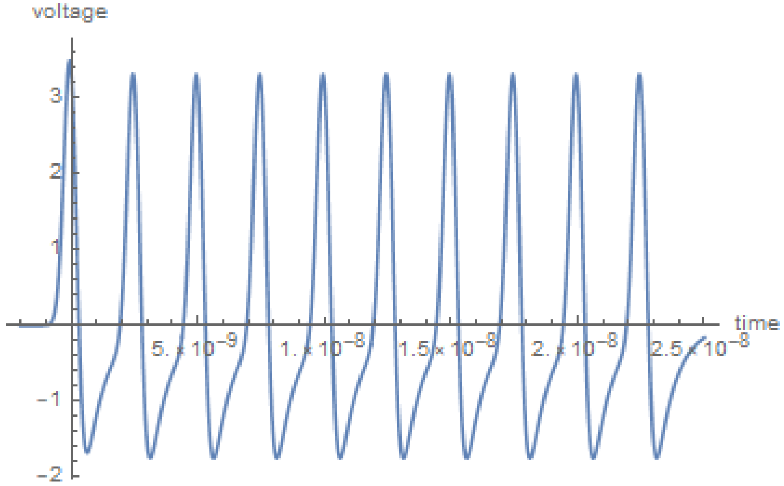




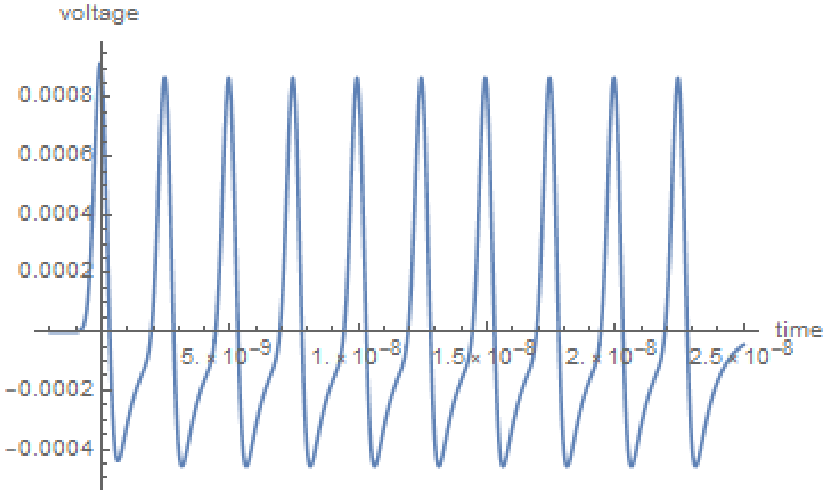
- Single bunch, 1.05 ns, 2.3e11 ppb
- For 5.3 um and 55 urad the mode 0 and 1 signals have similar peak amplitude. Good
- But they are **4000-5000** below common mode
- Assuming 20 dB rejection from delta hybrid (can we get more?) we would still have common mode **400-500** times larger than mode 0 or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

P. Baudrenghien

Signals from button PU after 400 MHz BPF

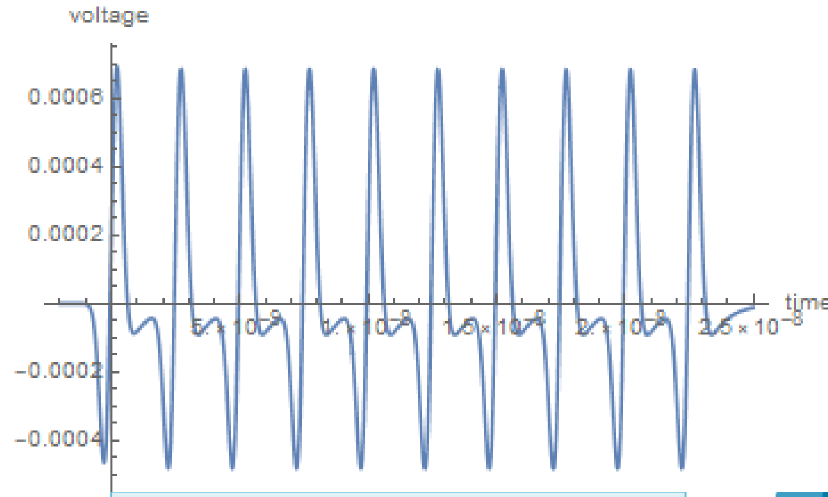


Common mode. ~5 Vpkpk (blue).



Differential mode 0 for 5.3 um displacement. ~1.3 mVpkpk

- Again, for 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

P. Baudrenghien

HL-LHC Project (High-Luminosity LHC)

- Point 4 Surface (SR4)
  - Beam-Control (WR frame master)
- Point 4 underground (UX45)
  - Accelerating cavities (ACS)
  - Transverse Damper (ADT)
- Point 1 underground (ATLAS)
  - RFD Crab-cavities
- Point 5 underground (CMS)
  - DQW Crab-cavities

- 25 ns bunch spacing, >2000 bunches
- bunch intensity 2 x nominal : 2.3×10^{11}
- tenfold integrated luminosity