Overview of the existing Head-Tail monitors in LHC

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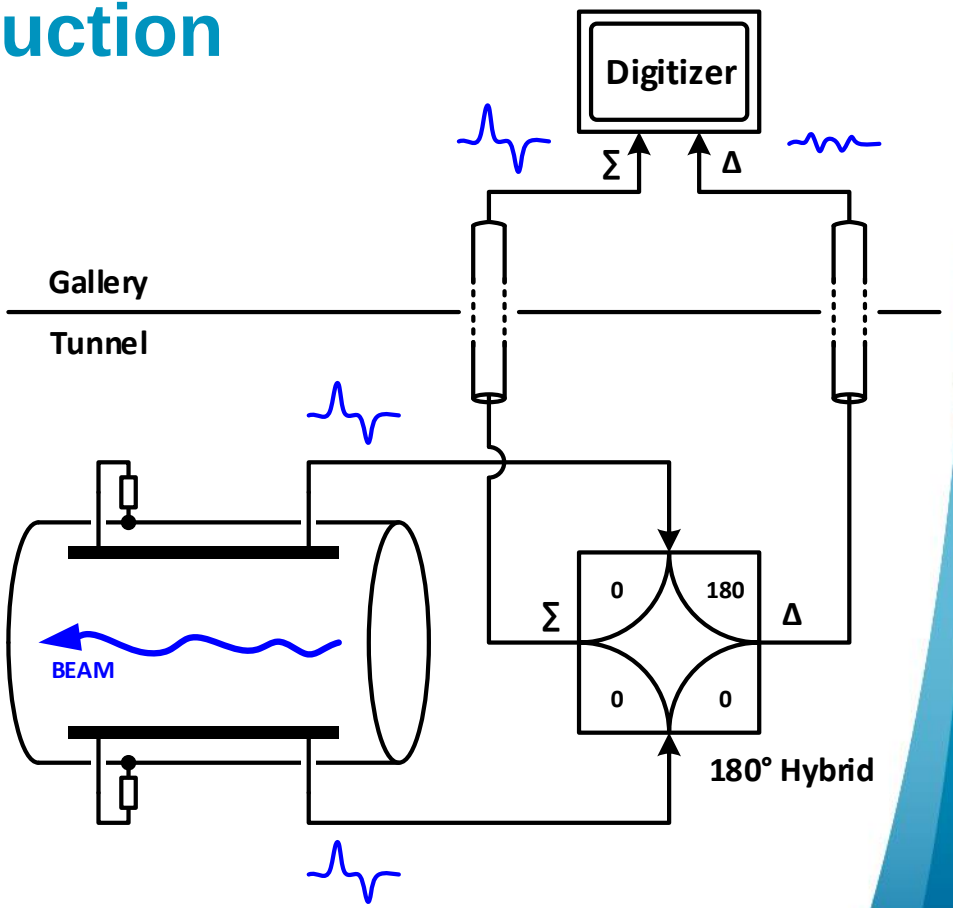
HL-LHC High Bandwidth Beam Position Monitor Review – 15th January 2025

Introduction

- Head-Tail Monitors are wideband beam position monitors capable of measuring intra-bunch beam position.
- A 180º hybrid calculates analogue sum and difference of long strip-line BPM electrodes.
- Signals are acquired after short cables by high-speed digitizer located in a service gallery.
- Originally installed in SPS/LHC for chromaticity measurements, now used primarily for instability diagnostics.



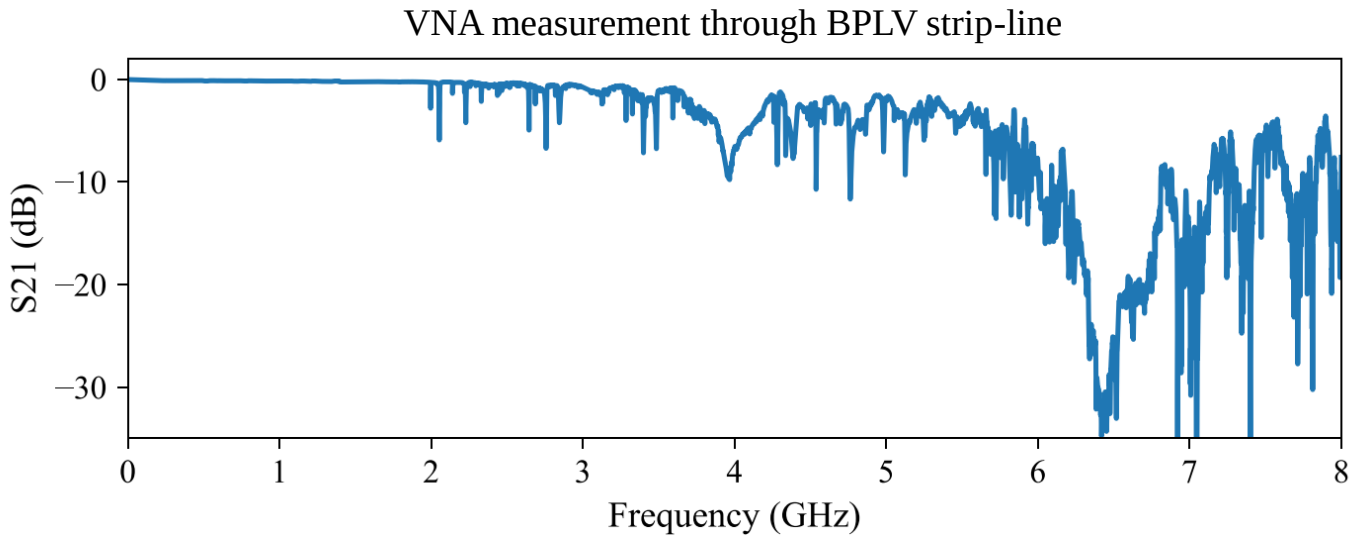
LHC Head-Tail Monitors

- Four 40 cm long BPLH/V type (single plane) BPMs installed close to Q5R4 and Q6R4 in LSS4.
  - Installed at positions with maximum beta functions.
- H-9 hybrid in tunnel calculates sum/difference.
- ~25m 7/8” coax cables to UA47 service gallery.
- Acquisition with high-speed oscilloscopes:
  - 10GSPS (100ps) with 4GHz bandwidth.
  - Maximum record size:
    - 460 turns (41ms) for 3564 bunches.
    - 64k turns (5.8s) for <24 bunches.
  - Readout speed (10-20 seconds) limits retrigger rate.

Keysight DSOS404A

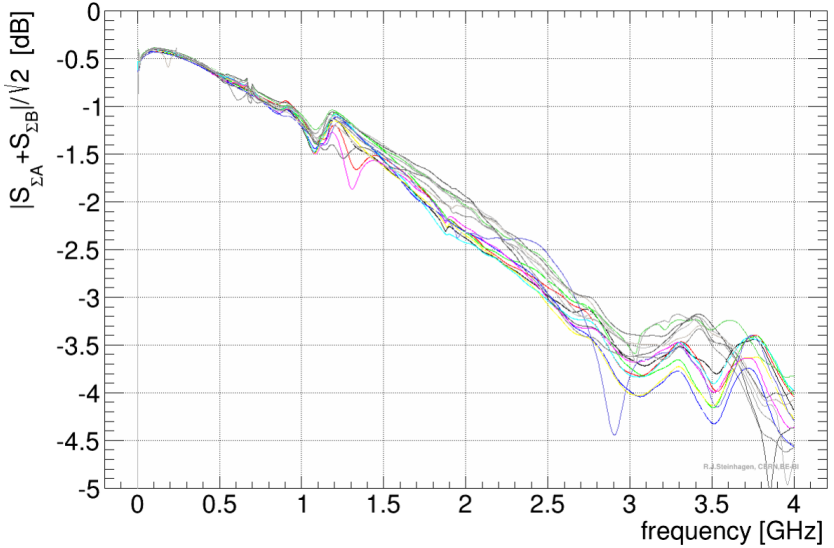
Limitations I

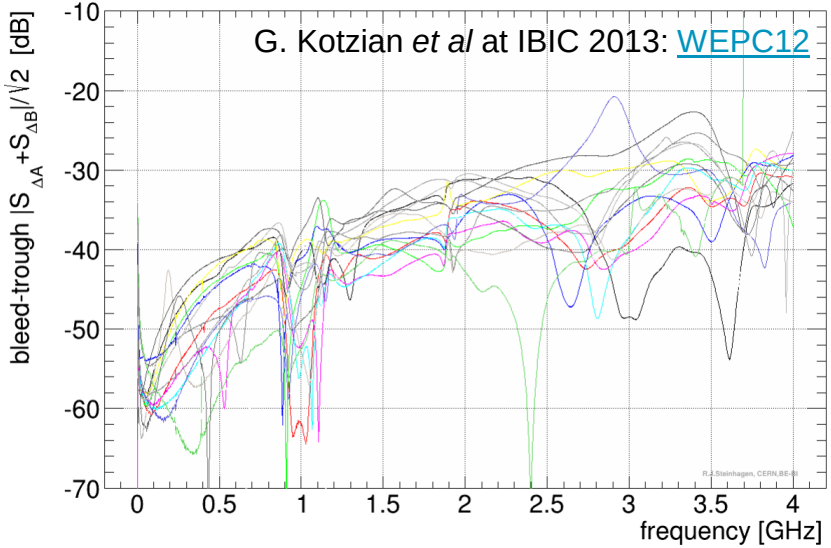
- Frequency response of BPLH/V strip-lines starts to show imperfections above 2GHz:



Limitations II

- H-9 hybrids used are specified from 2MHz to 2GHz.
  - -30dB CMMR up to 2GHz, large spread, good ones “usable” to higher freq.

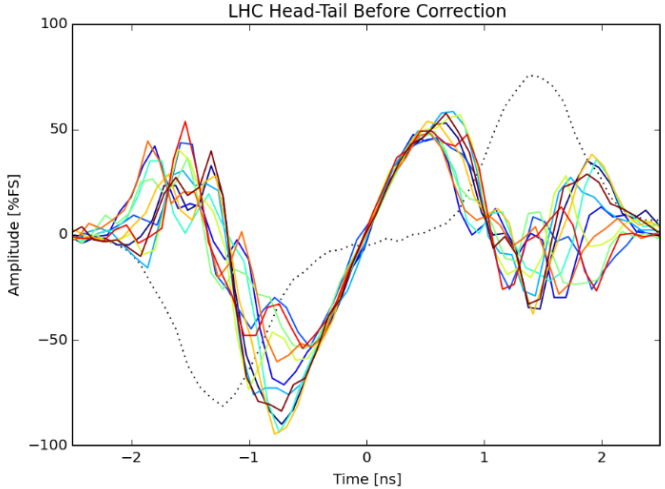


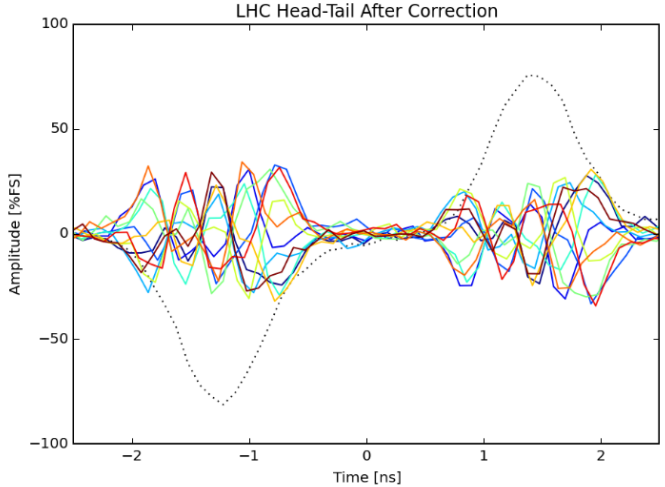


- Unfortunately, no better option has been identified up to now…

Limitations III

- Significant “residual” difference signal measured on HT monitor.
  - Pattern is different for each system and exact source is unclear.

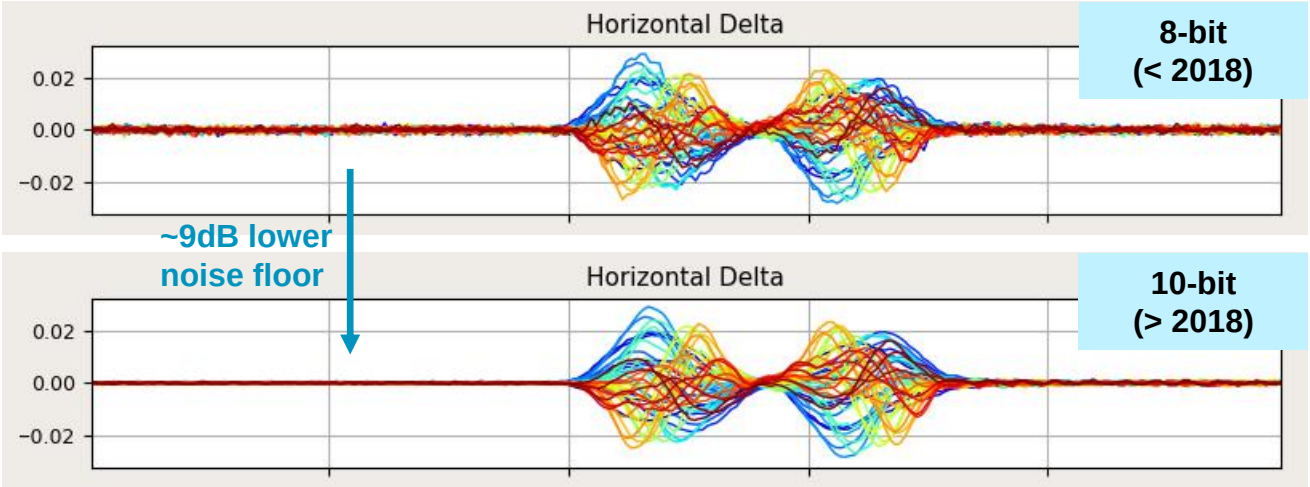




- Corrected in post-processing for instability measurements but limits dynamic range → correction will be more difficult for static effects of CC.

Limitations IV

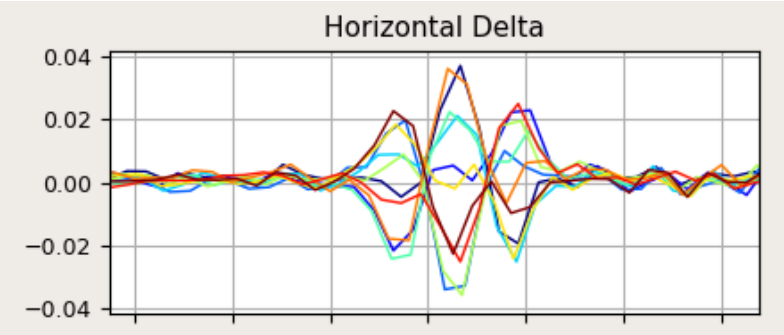
- Limited dynamic range due to high-speed 10GSPS digitizers.
- Upgrade from 8 to 10-bit digitizers (2018) improved dynamic range.

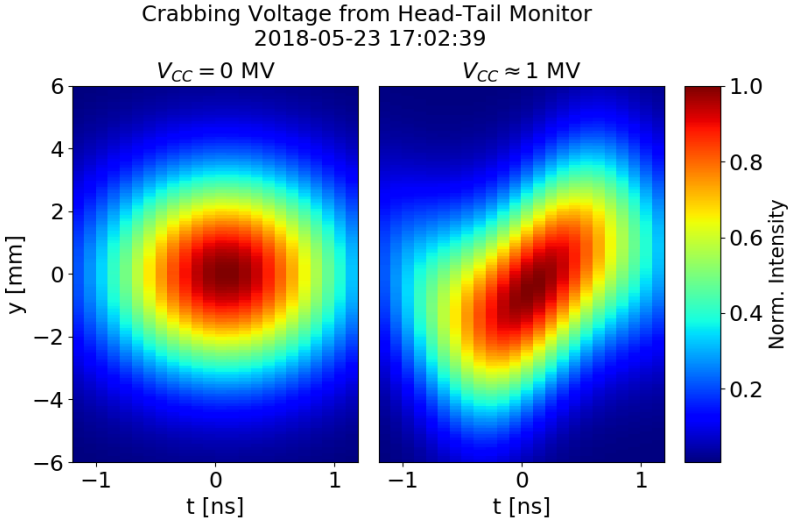


- State of the art today is “12-bit” digitizers at 10GSPS.
  - But, in reality, ENOB is only increased from 7.8 to 8.1-bits!

Results

- Despite these limitations the Head-Tail monitors are simple, robust and operationally reliable → key qualities to maintain in the future!
- Good results have been achieved for instability measurements in SPS & LHC and crab-cavity tests in SPS…
  - Resolution ~20-50um achieved turn-by-turn.





Can we do better?

- Limited potential for improvements using electromagnetic techniques.
  - No better alternative to H-9 hybrids identified.
  - Dynamic range of digitizers close to physical limits.

- Electro-optical techniques identified > 10 years ago as having potential to improve performance.
  - Collaboration agreement with Royal Holloway University, as part of HL-UK(2), to develop EO-BPMs for HL-LHC.
  - Long development history → talk of Stephen

- Note: WP13 is only considering wide-band time-domain acquisition options for the BPW.
  - Serving as a complement to narrow-band measurements being developed by WP4 as part of the CC noise feedback system → talk of Daniel

HL-LHC BPW specifications

- BPW performance criteria given in LHC-BPW-ES-0001 (v1.2) are based on an extrapolation from existing HT specifications.
  - Aim to improve resolution, bandwidth and sampling rate…

Criterion	Key	Target	Units
Single bunch, single pass resolution at bunch centre for pilot bunch intensity	100	50	um
Single bunch, single pass resolution at bunch centre for nominal bunch intensity	10	5	um
Precision[1] of the measurement for nominal bunch intensity	10	5	um
Long term stability[2] of the offset for nominal bunch intensity	50	20	um
High frequency cut-off (-3dB)	5	10	GHz
Low frequency cut-off (-3dB)	≤ 1	≤ 0.5	MHz
In-band (between -1dB low and high cut-off roll-off) response variation	≤ 1	≤ 1	dB
Time resolution for single bunch, single pass measurement	50	25	ps
Acquisition length for a single bunch measurement on successive turns	> 1000	10000	turn
Minimum time between two successive measurements	25	25	ns

- But, these were not specifically written with Crab Cavity diagnostics in mind!

Location of HL-LHC BPW

- Baseline for HL-LHC was to install BPW in LSS4.
  - Space reservation: LHC-BPW-EC-0001 (v0.1)
- Subsequent study by WP2 indicated that LSS4 is not optimal for CC diagnostics.
  - Would require pairs of BPMs with π/2 phase advance to achieve <10um residual crabbing, optics dependent.
- The best location is close to the CC in IP1/5…
  - Significant additional constraints → talk of Michal

HT diagnostic close to IP (APWL about 165 m from IP)

i.e. beside the CC

Amplitude of the ideal $0.03\sigma_{x,y}$ leakage (phase advance & ATS independent)

Round optics — H crossing IP1, V crossing IP5

β* (cm)	x [IP1 L] (μm)	x [IP1 R] (μm)	y [IP5 L] (μm)	y [IP5 R] (μm)
15 (B1/B2)	**30.4**/19.0	20.8/**28.3**	20.7/**28.4**	**30.3**/19.1
50 (B1/B2)	**30.4**/18.8	20.8/**28.3**	20.7/**28.3**	**30.2**/19.0

Flat optics with CC — V crossing IP1, H crossing IP5

β* (cm)	y [IP1 L] (μm)	y [IP1 R] (μm)	x [IP5 L] (μm)	x [IP5 R] (μm)
18/7.5 (B1/B2)	20.8 /**28.3**	**30.4**/19.0	**30.2** /19.1	20.7/**28.4**

N.B. there is another flat optics with H, V crossing not shown here.

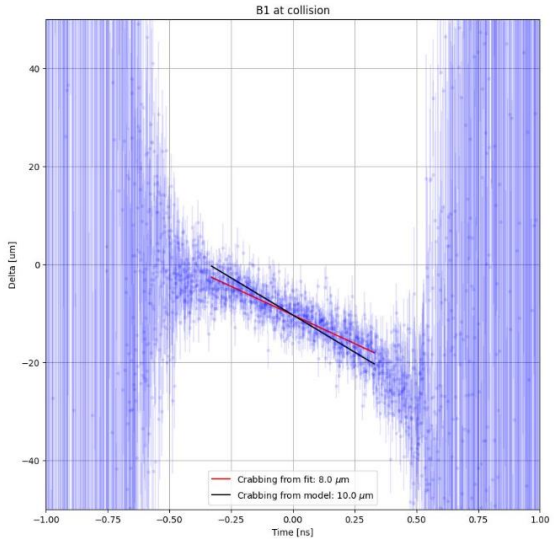
Approx. 30um residual signal in all cases!

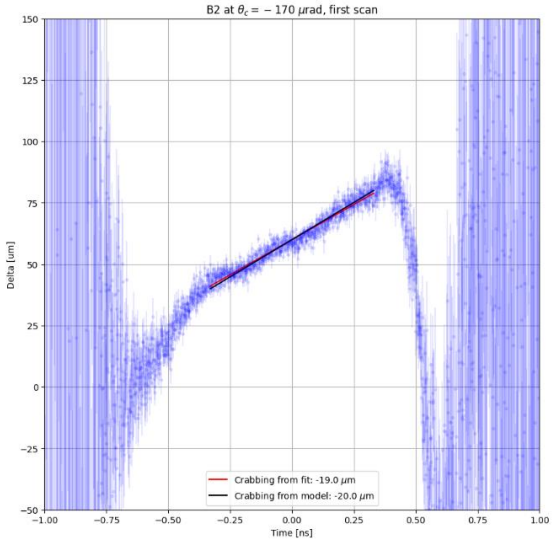
Limits of traditional Head-Tail

- With optimal BPM locations (IP1/5) need to measure ~30um signal.
- Given existing HT, 30um corresponds to a ~3mV signal.
- Baseline signals of ~20mV need to be digitized.
  - Current HT scopes have ~175uVrms noise for these signal levels.
  - **~10% of signal level.**
- No FRAS foreseen for these BPMs, can expect ~mm offset between beam and BPM electrical center.
  - Resulting in an additional ~200mV baseline from the beam offset.
  - Current HT scopes have ~750uVrms noise for these signal levels.
  - **~25% of signal level.**
- Since residual crabbing is a static effect, we can take advantage of averaging to reduce noise…

Limits of traditional Head-Tail

- Recent measurements by A. Fornara have demonstrated the possibility to measure ~10um crabbing due to beam-beam effects with the HT monitor in the LHC with averaging of 1k turns:





Conclusion

- Existing wide-band “Head-Tail” monitors are installed in LHC LSS4 and used primarily for instability monitoring.
- A number of limitations with the existing instruments identified and found difficult to solve with EM techniques.
  - Launched the development of EO-BPMs in collaboration with RHUL as part of HL-UK(2).
- WP13 mandated to install new wide-band BPMs (BPW) for crab-cavity diagnostics in HL-LHC.
  - The optimal location is close to the crab cavities in IP1/5.
- Despite their limitations, existing HT monitors are simple, operationally reliable and have given good results!
  - First crabbing measurements demonstrated in LHC in 2024!

Thank you…