High-Frequency BPM for HL-LHC

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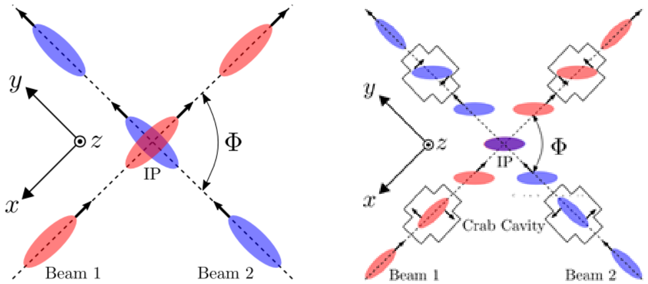
Motivation

- The High-Luminosity LHC (HL-LHC) project aims to increase the luminosity of the LHC by a factor of 10.

- The proton bunches will be rotated by **crab-cavities**:

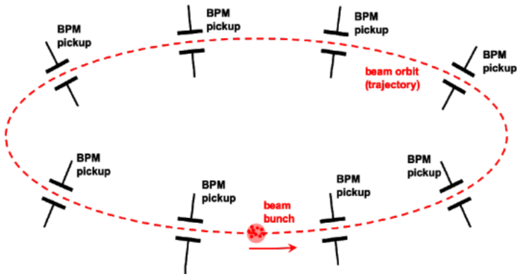


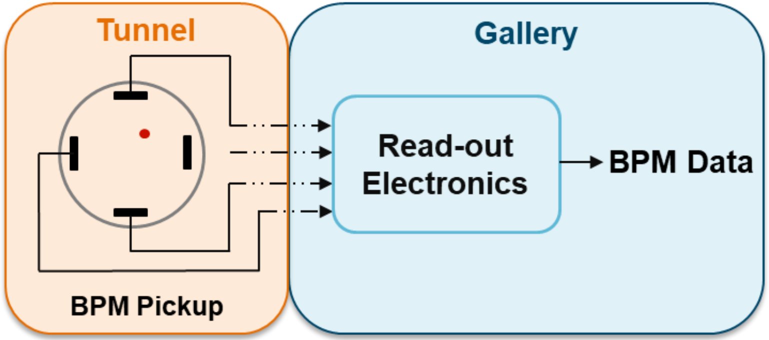
- Compensated collision angle.
- Higher bunch intensity.
- Larger number of populated bunches.
- $\Longrightarrow$ Increased risk of beam instabilities.

- Faster and more sensitive instruments capable of measuring intra-bunch transverse position: **High-Frequency BPM.**

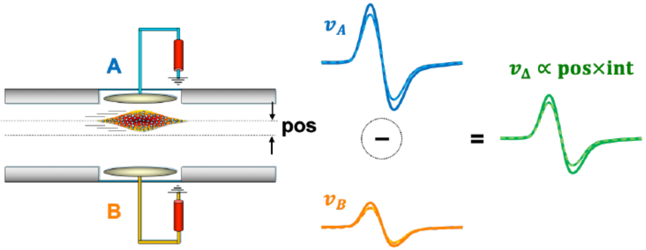
Beam Position Monitor

- The Beam Position Monitor (BPM) system measures the beam position in the vacuum chamber.





- The BPM principle is based on symmetry:



$$\text{Beam Position} \propto \frac{v_\Delta}{v_\Sigma} = \frac{v_A - v_B}{v_A + v_B}$$

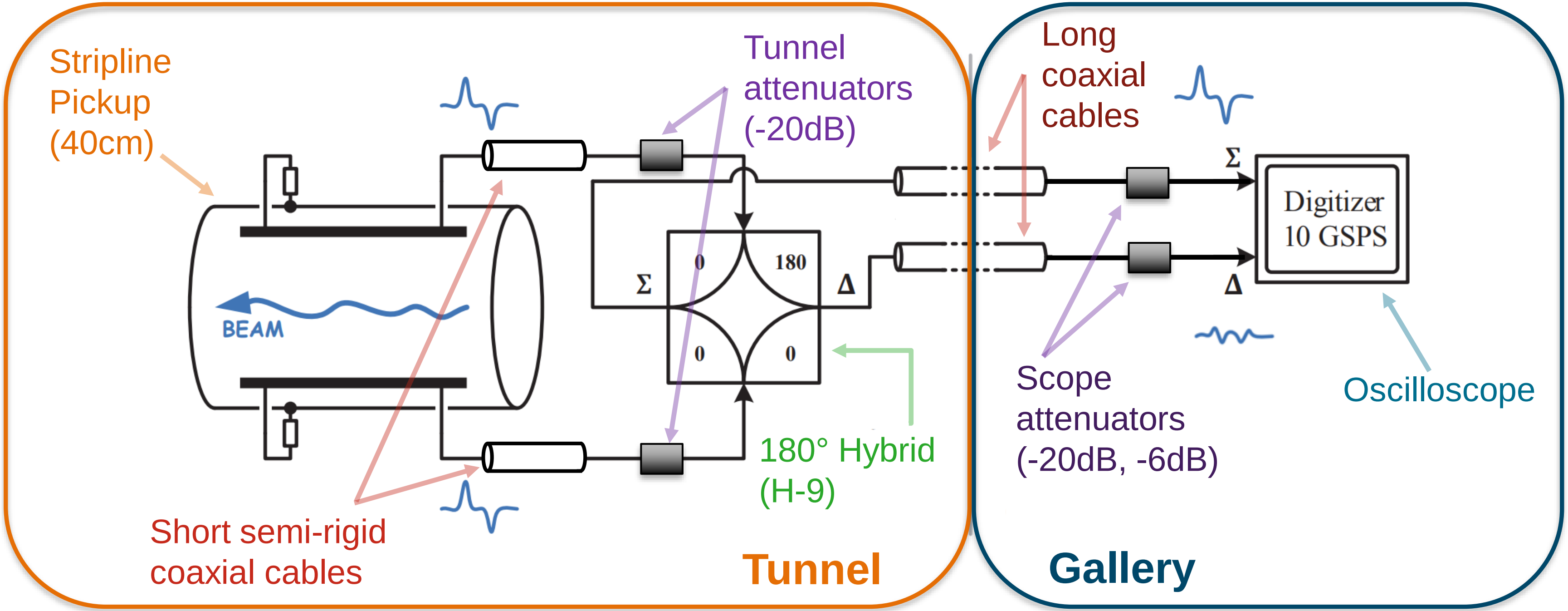
Beam Intensity Normalisation

Key Performance Criteria for HF-BPM

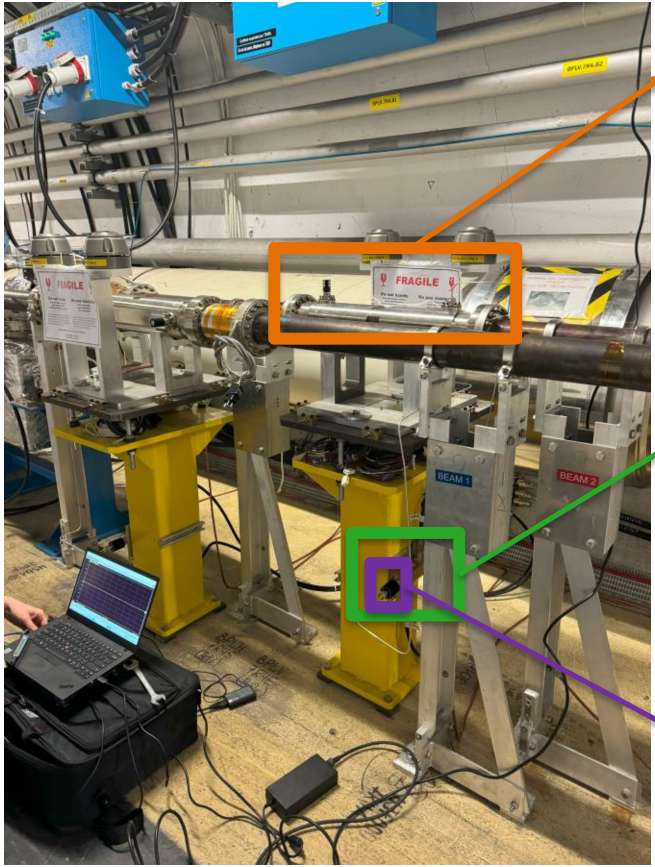
Criterion	Value
Single bunch, single pass resolution at bunch center for pilot bunch intensity	100 µm
Single bunch, single pass resolution at bunch center for nominal bunch intensity	10 µm
Low frequency cut-off (-3dB)	$\leq$ 1 MHz
High frequency cut-off (-3dB)	5 GHz
Time resolution for single bunch, single pass measurement	50 ps
Minimum time between two successive measurements	25 ns

LHC Head-Tail Monitor

- HT Monitors are wideband BPM capable of measuring intra-bunch beam position.



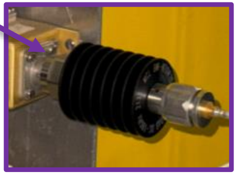
IP4 Head-Tail Monitor Measurement



Pickup

Hybrid

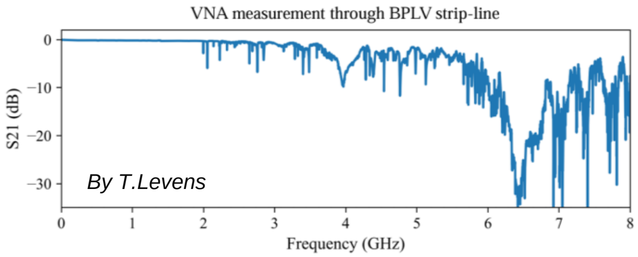
Short semi-rigid coaxial cable



Tunnel attenuator

Limitations of the existing LHC HT Monitor

- Limited **bandwidth** up to few GHz:
  - Frequency response of stripline pickups starts to show imperfections above 2GHz.
  - Frequency range of used H-9 Hybrid: 2MHz - 2GHz



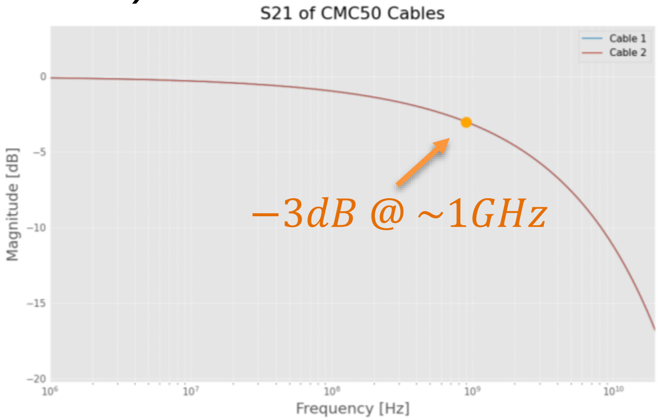
- Limited **dynamic range** and limited **acquisition memory** due to high-speed 10GSPS digitizers.
  - Bandwidth: 4GHz.
  - Maximum record size: 460 turns (41ms) for 3564 bunches,
    64k turns (5.8s) for <24 bunches.
  - Readout speed: 10-20 seconds.

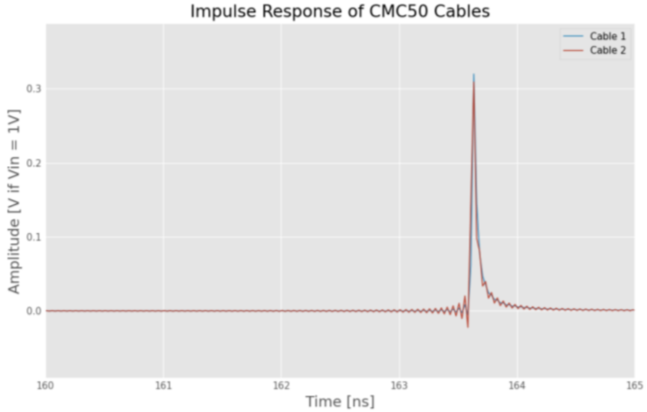
Keysight DSOS404A

Limitations of the existing LHC HT Monitor

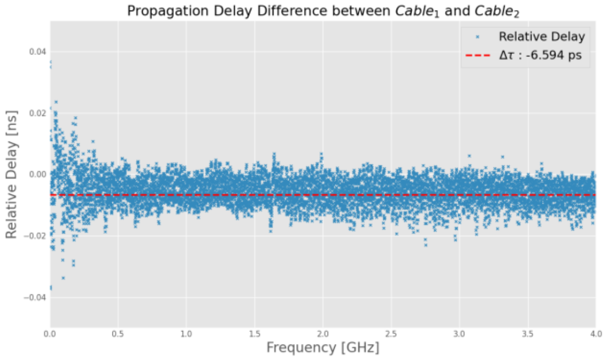
- Long Cables (CMC50)

$$a_1 = a_2$$
$$b_1 = b_2$$
$$\tan\delta_1 = \tan\delta_2$$
$$L_1 \neq L_2$$





$$\Delta\tau = \frac{\varphi_{S11_{cable1}} - \varphi_{S11_{cable2}}}{4\pi f}$$



$$\Delta\tau \simeq 7\text{ ps} \Rightarrow \Delta L \simeq 1.9\text{ mm}$$

$$L_1 \simeq 43.3039\text{ m}$$

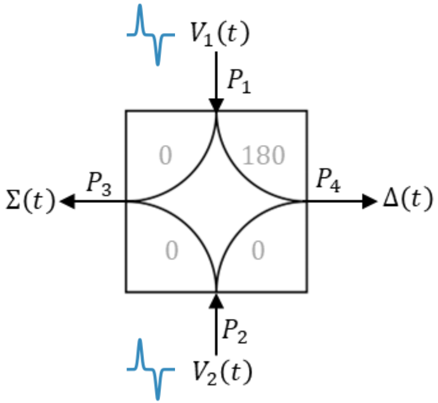
$$L_2 \simeq 43.3020\text{ m}$$

Limitations of the existing LHC HT Monitor

- Presence of a **residual contribution** in the difference signal $\Delta(t)$.

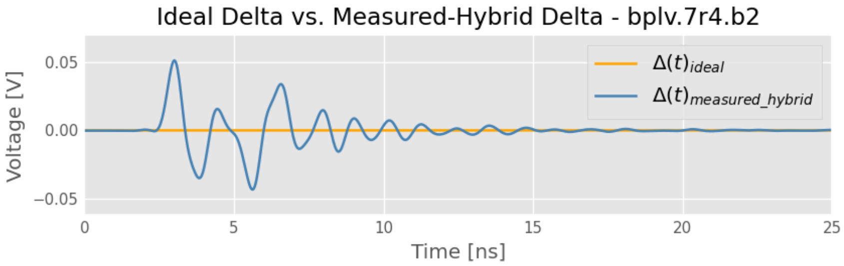
$$\Delta(t) = V_2(t) - V_1(t) + \delta(t)$$

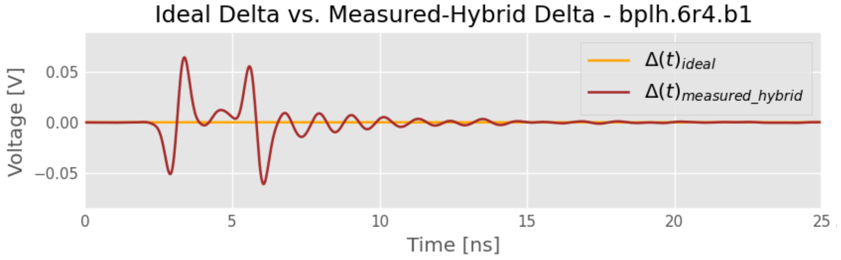
Different pattern for each system



180° Hybrid Coupler

$$S = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & j \\ 0 & 0 & 1 & -j \\ 1 & 1 & 0 & 0 \\ j & -j & 0 & 0 \end{pmatrix}$$





$$\Delta(t)_{ideal} = \frac{1}{\sqrt{2}}[V_2(t) - V_1(t)]$$

$$\Delta(t)_{measured\_hybrid} = V_1(t) \otimes h_{41}(t) + V_2(t) \otimes h_{42}(t)$$

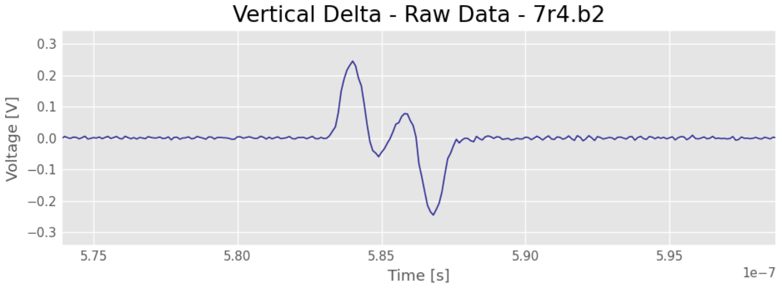
Empirical Correction

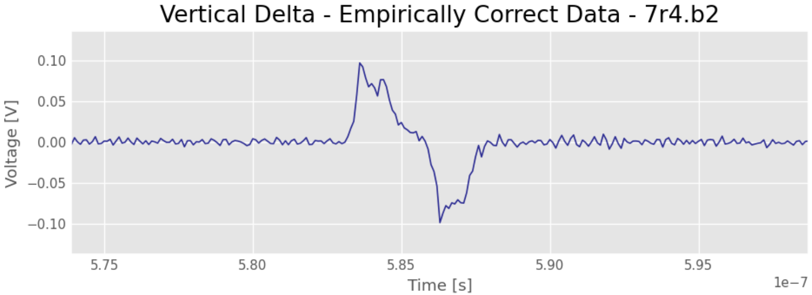
- The current residual correction is based on an **empirical method:**
  - Observe the bunch over multiple turns (up to the maximum storable by the scope).
  - Align the difference signals turn-by-turn.
  - Calculate the average of the aligned signals.
  - Subtract the static contribution from each measured Δ signal.

LHC.BQHT.B2_20250816_175054.h5
Turn = 10
Bunch = 22

$$\Delta_c(t) = \Delta(t) - \sum_{\tau=1}^{T} \frac{\Delta(\tau)}{T}$$

→ **Static Contribution of the difference signal**
residual + static position





Beyond Empirical Correction

- **Limitations of the Empirical Method**:
  - Does not identify the sources of the residual contribution.
  - Removes useful information (e.g., static bunch position).

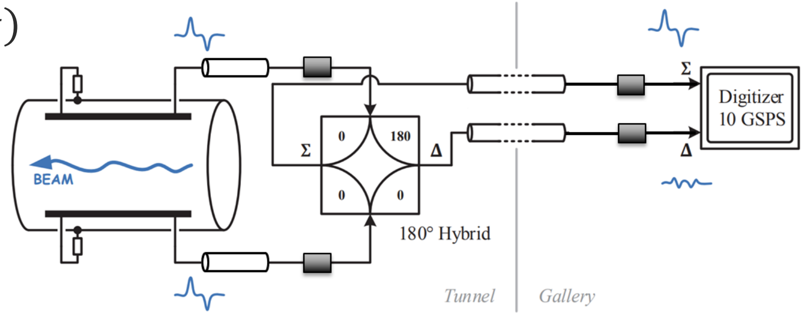
Can we develop a Scientific Correction?

- Provides a theoretical foundation.
- Ensures generality and robustness.

Scientific Correction - Concept

- **Reconstruct the original pickup signals** by traversing the HT Monitor chain backwards → remove the effect of each component using measured S-parameters.

Original Pickup Signals: $V_1(t), V_2(t)$



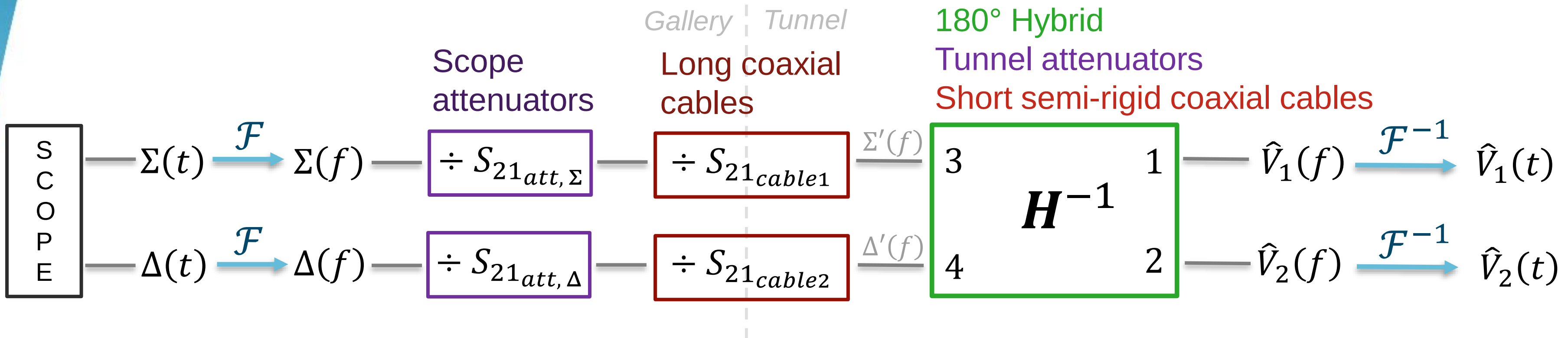
Oscilloscope (Raw Data): $\Sigma(t), \Delta(t)$

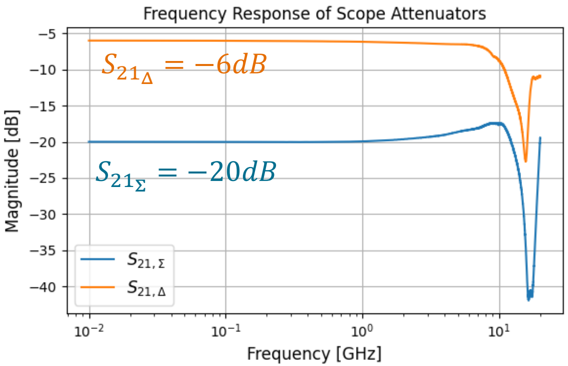
- **Bypass the physical hybrid** → compute Σ(t) and Δ(t) digitally using the hybrid theoretical formulas:

$$\Sigma(t) = \frac{1}{\sqrt{2}}\left(V_2(t) + V_1(t)\right) \qquad \Delta(t) = \frac{1}{\sqrt{2}}\left(V_1(t) - V_2(t)\right)$$

Scientific Correction - Implementation

- Reconstruction of the original pickup signals:





CMC50 Cable Model

Open−circuit condition

$$L = \frac{\varphi_{S_{11}}}{4\pi f} \cdot 0.88v \simeq 43m$$

$$\vec{a} = \boldsymbol{H}^{-1}\vec{b}$$

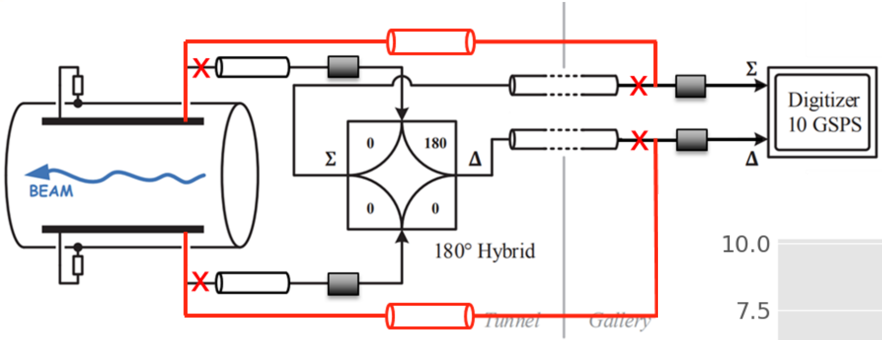
$$\vec{a} = \begin{bmatrix} \hat{V}_1(f) \\ \hat{V}_2(f) \end{bmatrix} \quad \vec{b} = \begin{bmatrix} \Sigma'(f) \\ \Delta'(f) \end{bmatrix} \quad H = \begin{bmatrix} S_{31} & S_{32} \\ S_{41} & S_{42} \end{bmatrix}$$

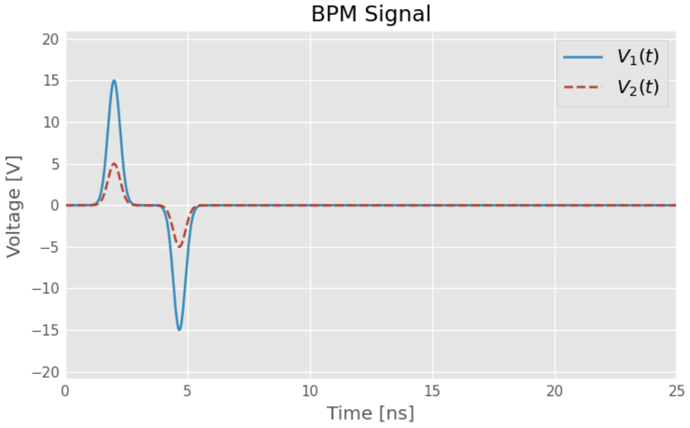
$$\hat{V}_1(f) = \left[\frac{1}{(x+y)\left(\frac{1}{x}+\frac{1}{y}\right)-4}\right]\left[z_1(x+y)-2z_2\right]$$

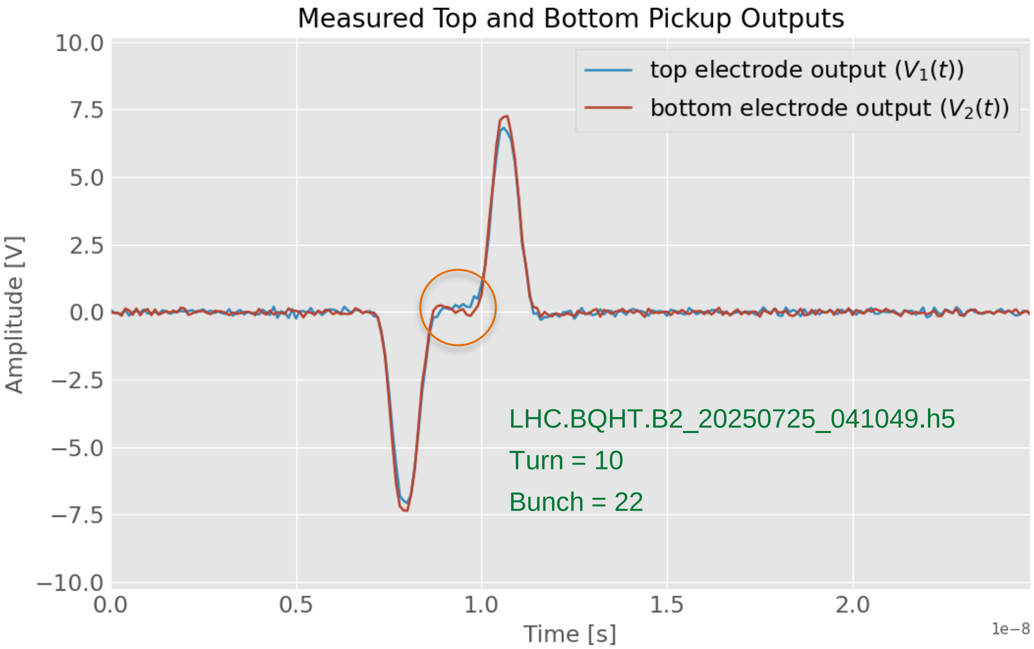
$$\hat{V}_2(f) = \left\{\frac{1}{x+y} + \frac{4}{(x+y)\left[(x+y)\left(\frac{1}{x}+\frac{1}{y}\right)-4\right]}\right\} z_1 - \left(\frac{2}{(x+y)\left(\frac{1}{x}+\frac{1}{y}\right)-4}\right) z_2$$

$$x = \frac{S_{42}}{S_{41}} \qquad y = \frac{S_{32}}{S_{31}} \qquad z_1 = \frac{\Sigma'(f)}{S_{31}} + \frac{\Delta'(f)}{S_{41}} \qquad z_2 = \frac{\Sigma'(f)}{S_{32}} + \frac{\Delta'(f)}{S_{42}}$$

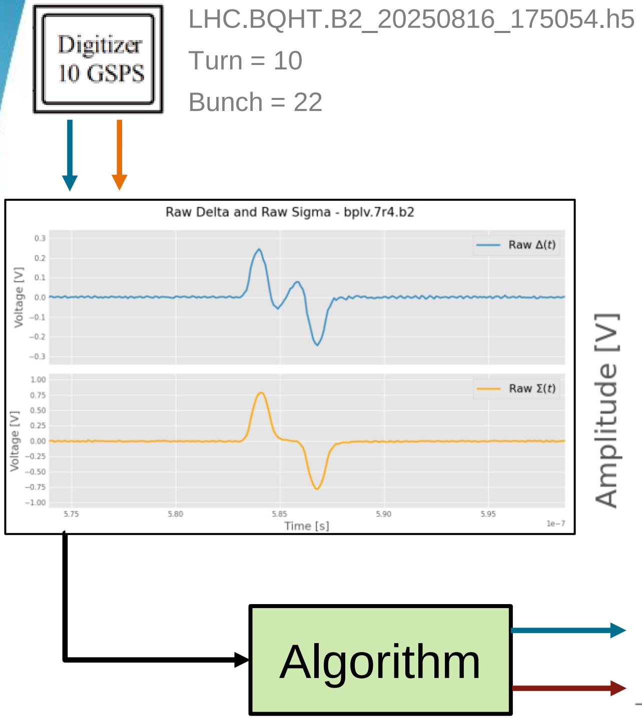
Measurement of Pickup Signals

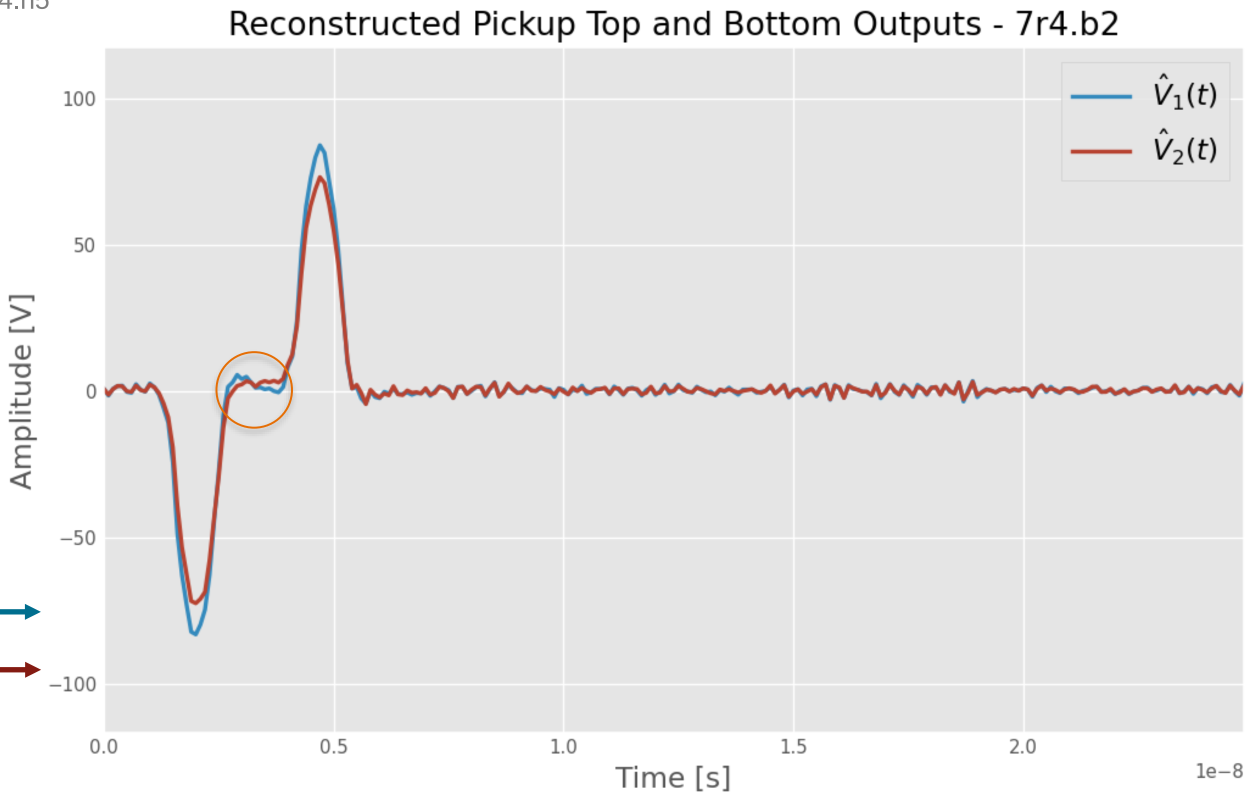




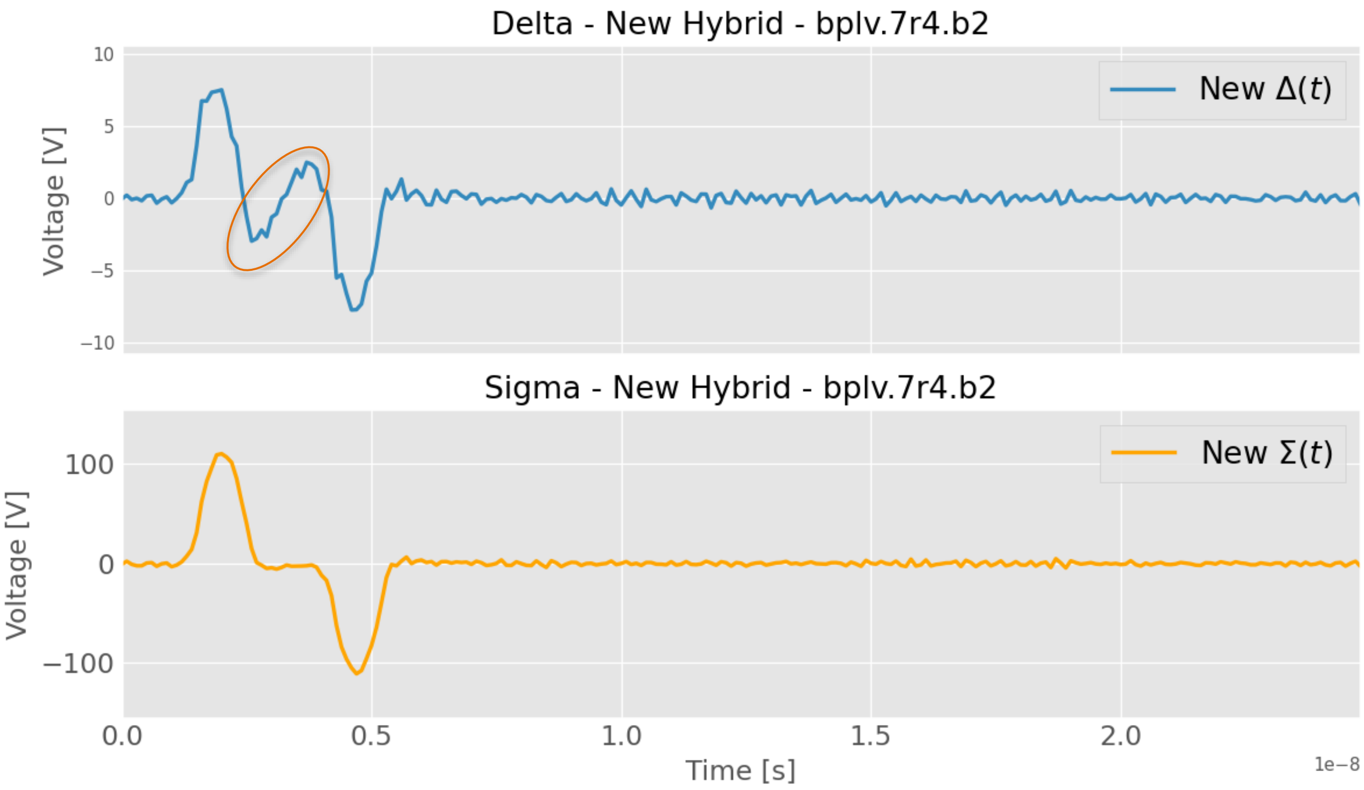


Reconstructed Pickup Signals





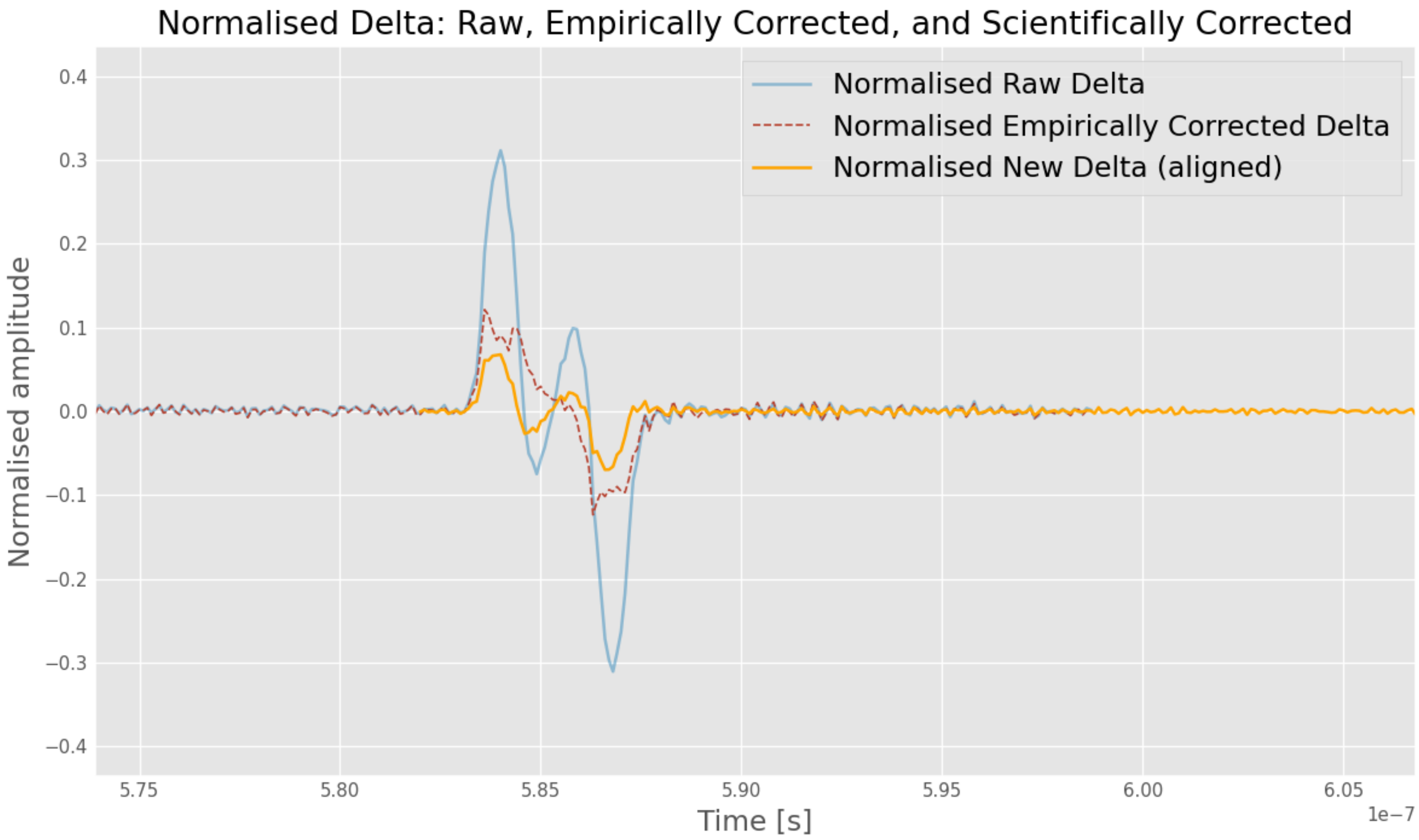
Sigma & Delta using Scientific Correction



$$\Delta_{new}(t) = \frac{1}{\sqrt{2}}\left(\hat{V}_1(t) - \hat{V}_2(t)\right)$$

$$\Sigma_{new}(t) = \frac{1}{\sqrt{2}}\left(\hat{V}_2(t) + \hat{V}_1(t)\right)$$

Data Comparison



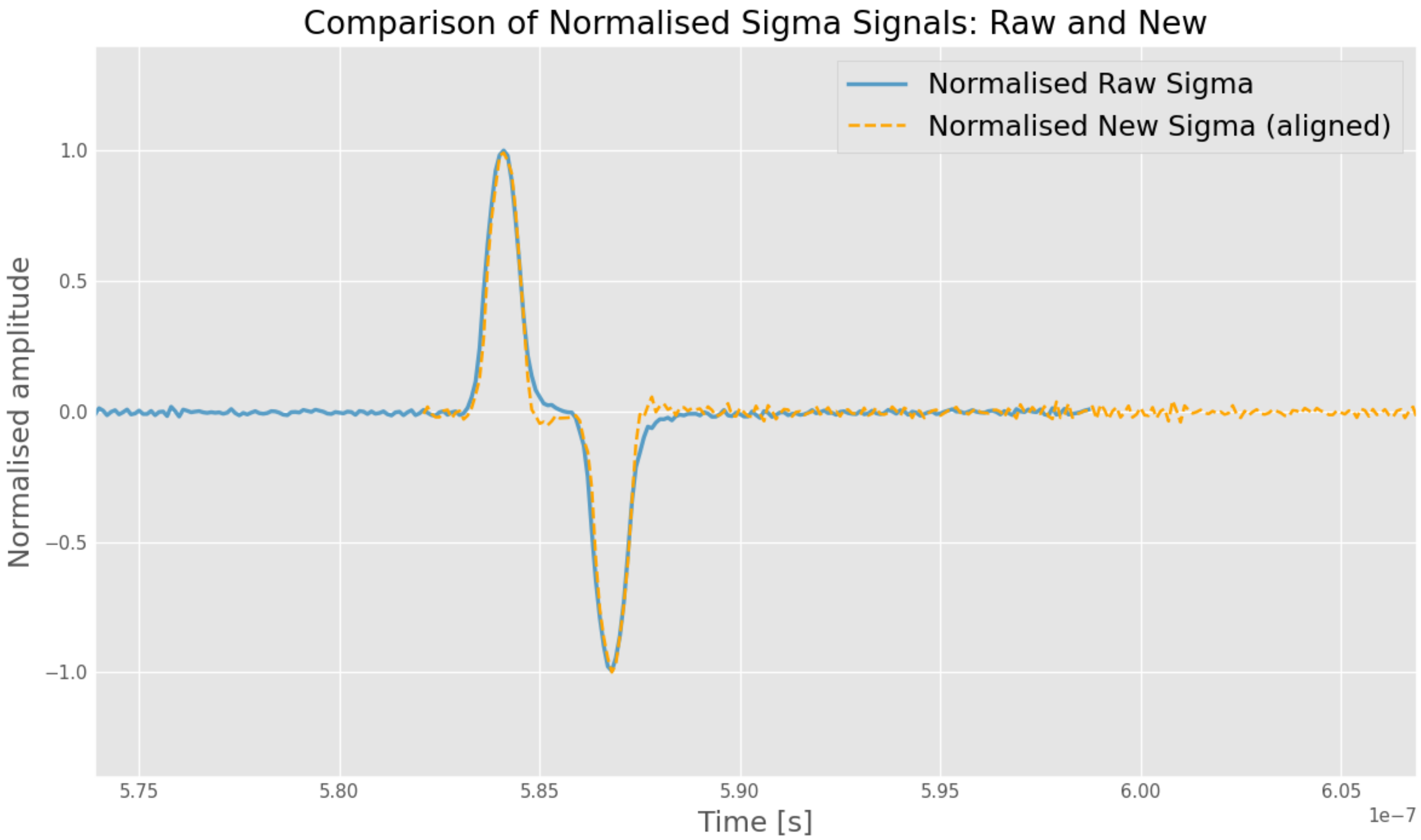
Conclusion and Next Steps

- Development of a **new signal correction technique** for wideband pick-ups.
- **Step-by-step signal observation**, understanding the contribution of each element of the HT monitor chain.
- No ambiguity in defining the pickup's true zero → **absolute position measurement** is now possible.
- Align the new Delta and Sigma signals, compute their point-by-point ratio, and derive the beam position in mm.
- Modeling and simulation of the pickup in CST.
- Design of an improved high-frequency BPM Pickup.

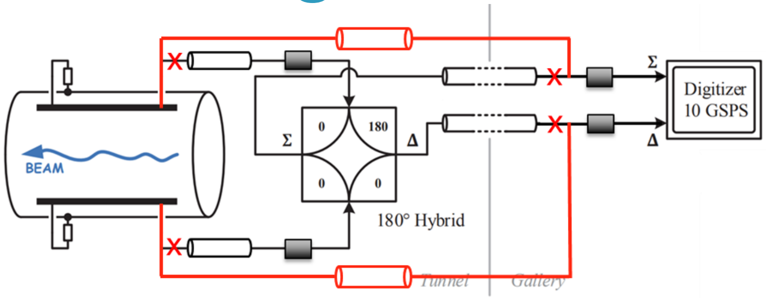
Thanks for your attention

Merry Christmas!

Spare Slides


Comparison of Normalised Sigma Signals: Raw and New
Normalised Raw Sigma
Normalised New Sigma (aligned)
Normalised amplitude
1.0
0.5
0.0
−0.5
−1.0
5.75
5.80
5.85
5.90
5.95
6.00
6.05
Time [s]
1e−7

Delta and Sigma from Measured Pickup Outputs



$$\Delta(t) = \frac{1}{\sqrt{2}}\left(V_1(t) - V_2(t)\right)$$

$$\Sigma(t) = \frac{1}{\sqrt{2}}\left(V_2(t) + V_1(t)\right)$$