

Performance of the AWAKE Proton Beam Line BPM System

BI Day 2017

Manoel Barros Marin, Andrea Boccardi, Thierry Bogey, Juan Boix Gargallo, Jose Luis Gonzalez,
Lars, K. Jensen, Thibaut Lefevre, David Medina Godoy



BE-BI-QP

29/06/2017

Performance of the AWAKE Proton Beam Line BPM System

Outline:

- Introduction
- The Proton BPM System
- Performance
- Summary & Outlook



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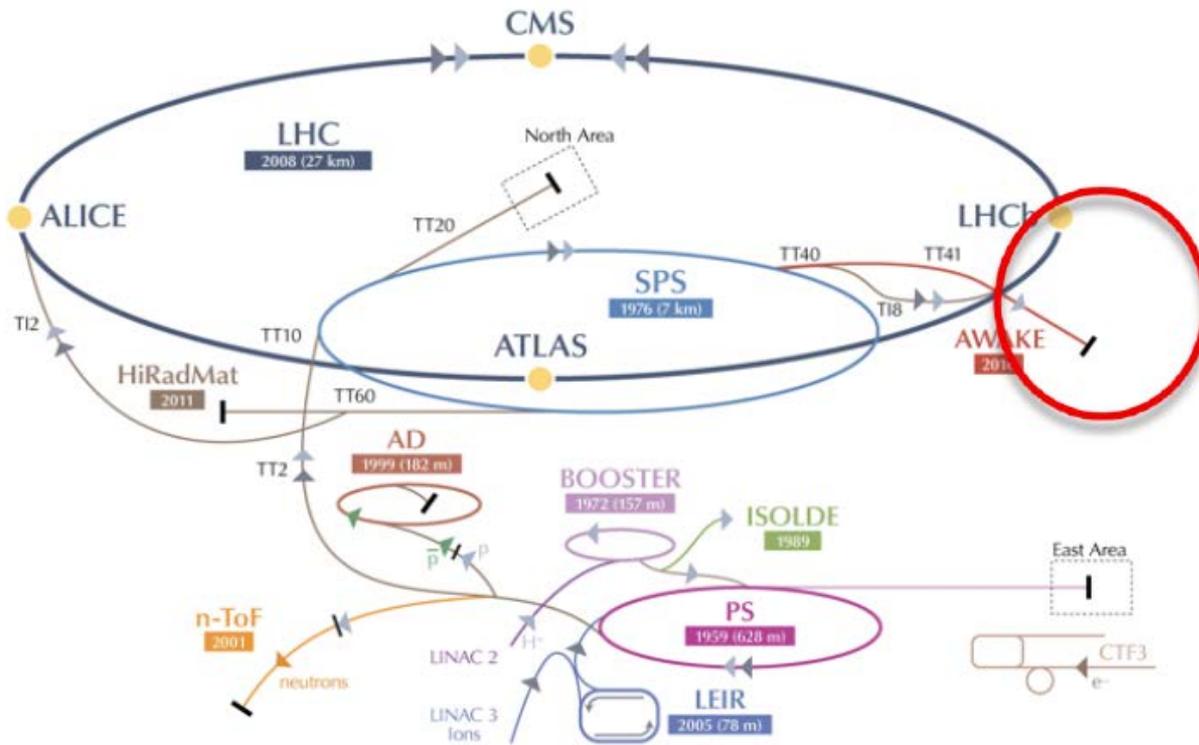
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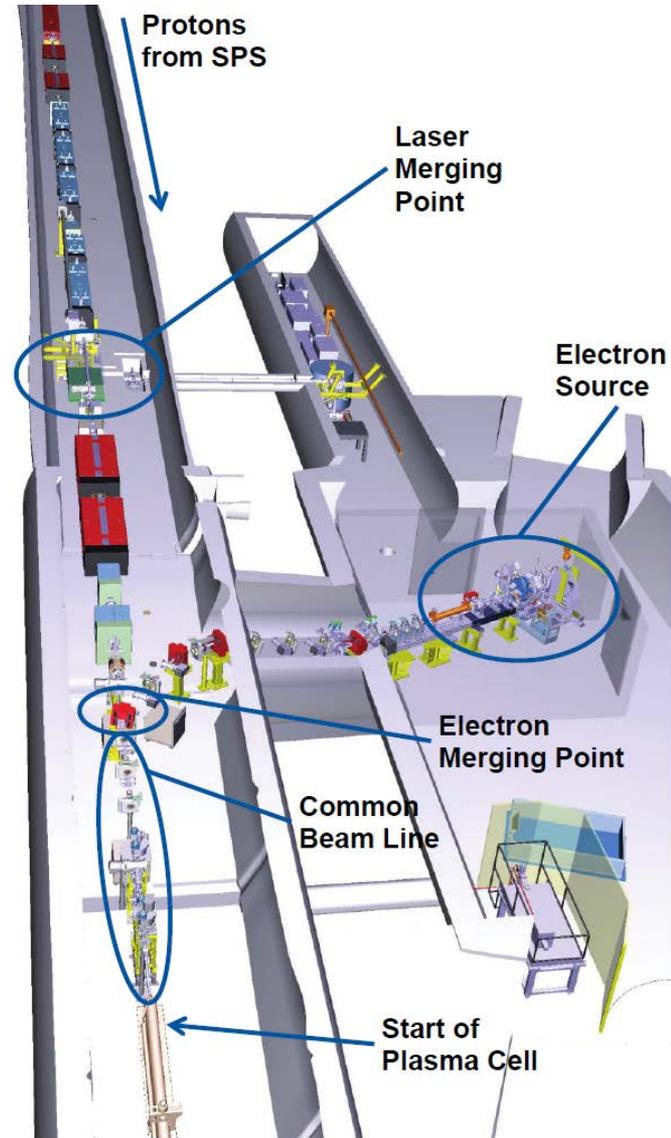
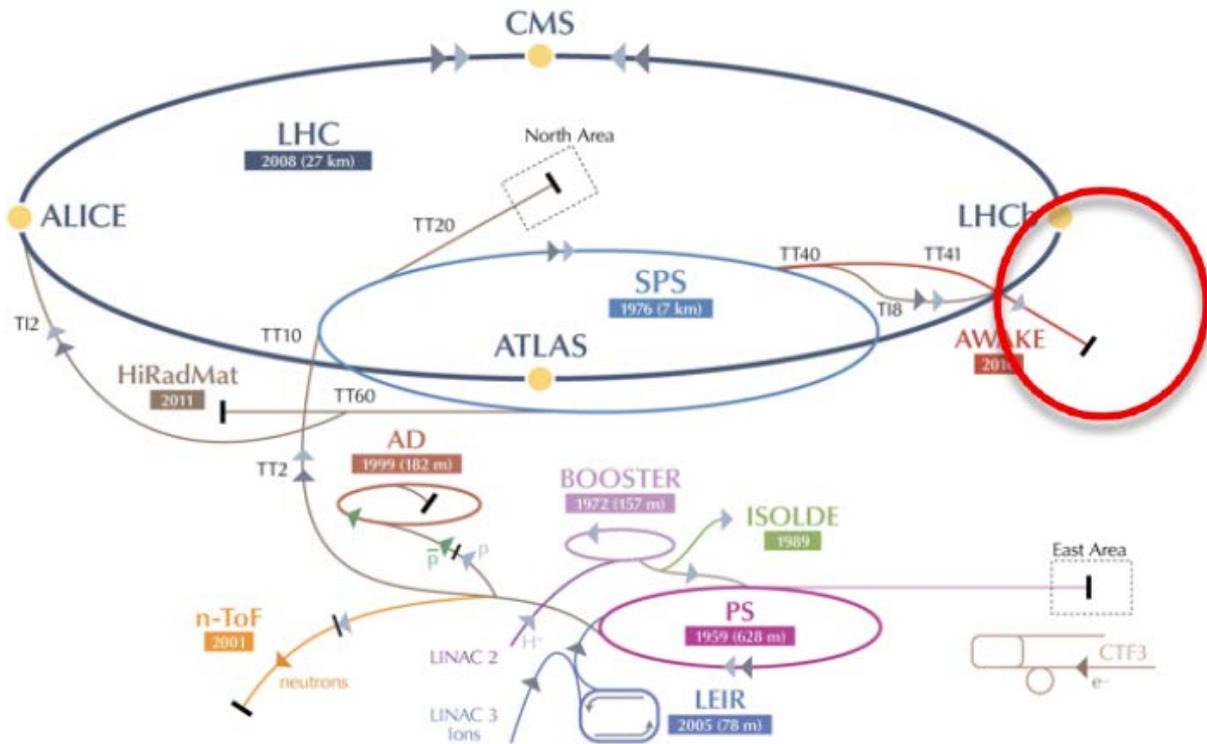
Introduction

AWAKE (A proton driven plasma WAKEfield acceleration Experiment)

- Proof-of-principle R&D experiment proposed at CERN
 - First beam driven wakefield acceleration experiment in Europe
 - First proton driven PWA experiment world-wide
- Use high-energy protons to generate wakefields in the plasma cell at the GV/m level
- Inject low energy electrons (~ 15 MeV/c) to be accelerated in the wakefield to multi-GeV energy range
- Advantages of using protons as driver: single stage acceleration
 - Higher stored energy available in the driver (\sim kJ)
 - Electron/laser driven requires many stages to reach the TeV scale.



Introduction



Performance of the AWAKE Proton Beam Line BPM System

Outline:

- Introduction
- The Proton BPM System
- Test Results
- Summary & Outlook



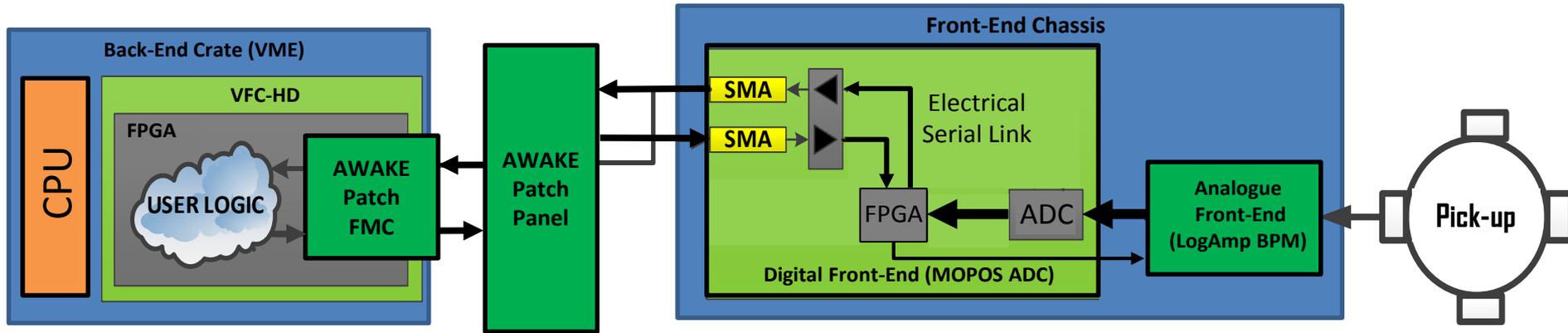
The Proton BPM System

Specifications

- **Single-bunch beams:**
 - Injection Rate: ~ 30 s
 - Charges per bunch: $5E9$ to $3.5E11$ (~ 37 dB)
 - Resolution: $100\mu\text{m}$
- **BPM System: 25 BPMs:**
 - TT40: 4 BPK monitors (striplines)
 - TT41: 17 button pick-ups
 - TSG4: 4 button pick-ups

The Proton BPM System

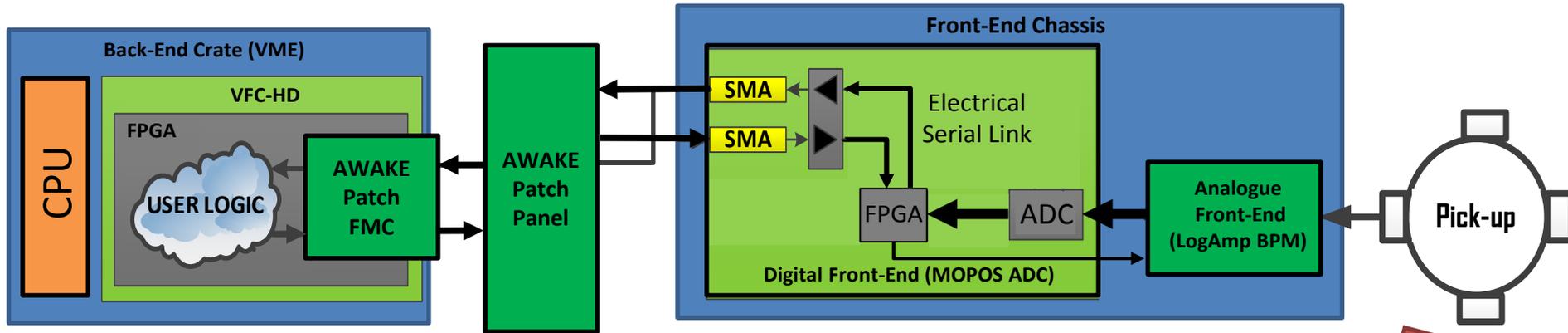
Block Diagram



Electrical Serial Link
(10Mbps over 1km of copper cable)

The Proton BPM System

Block Diagram

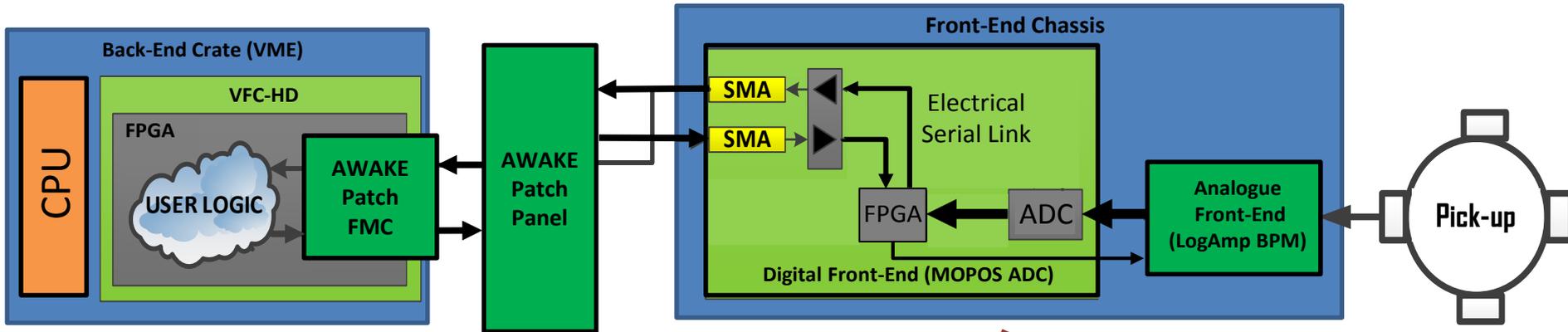


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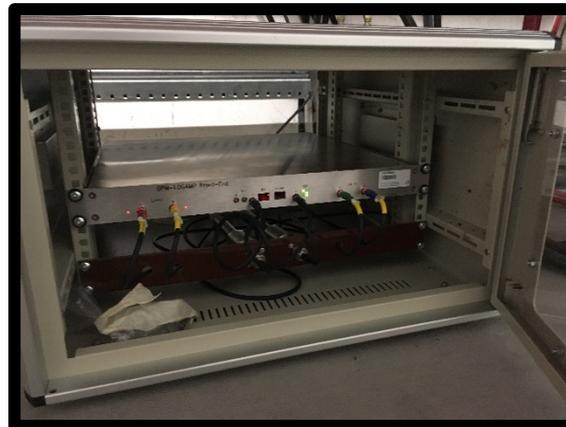


The Proton BPM System

Block Diagram

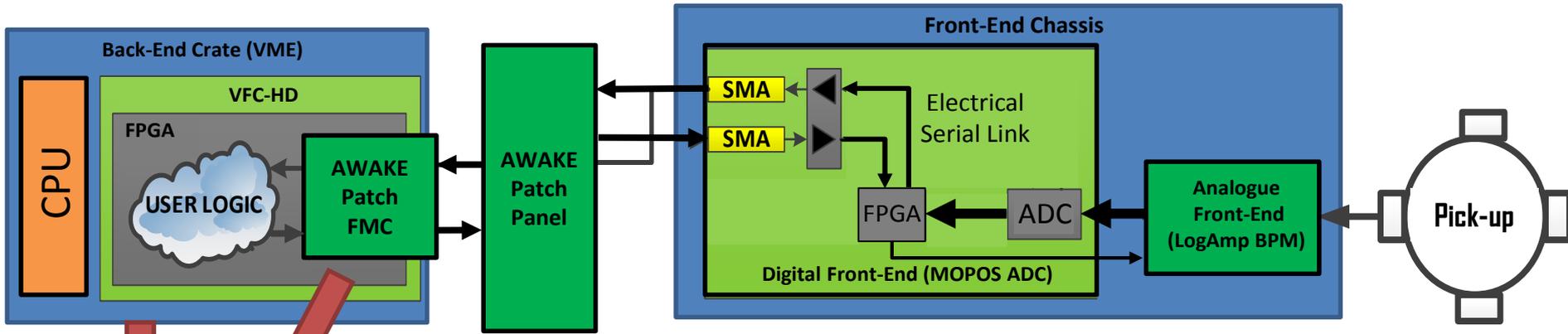


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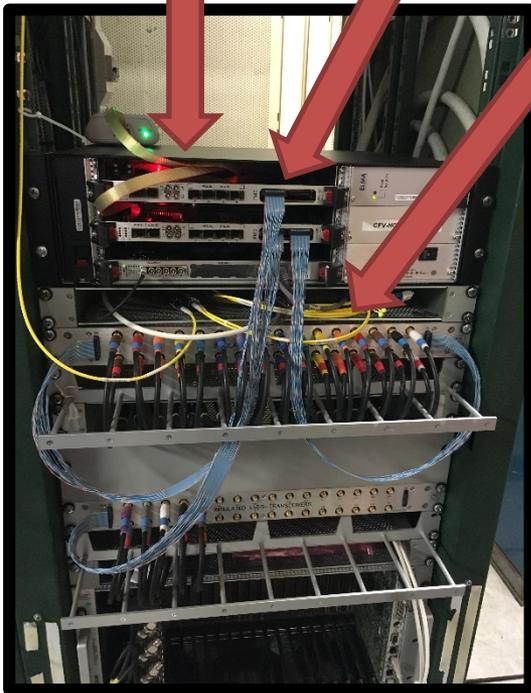


The Proton BPM System

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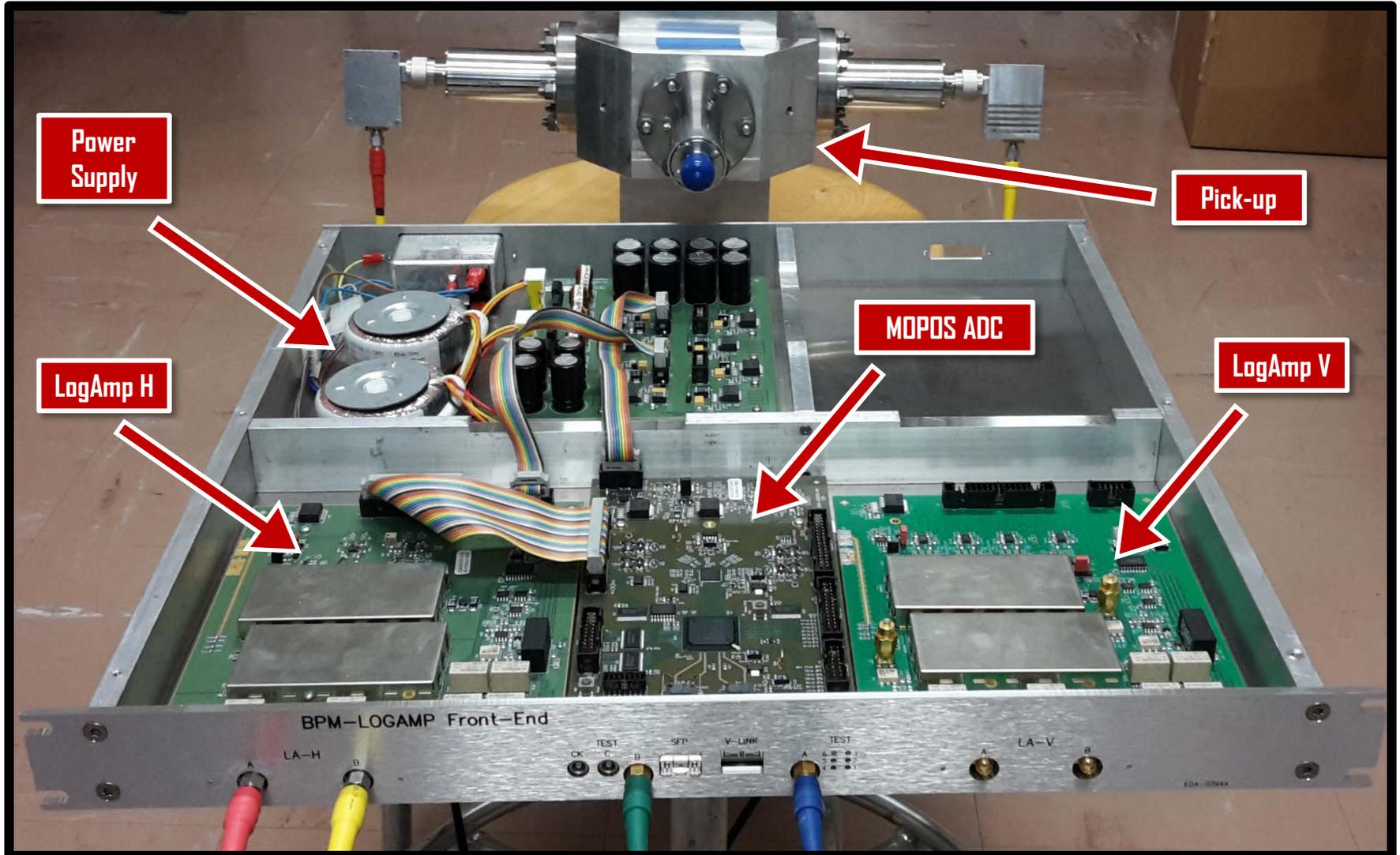


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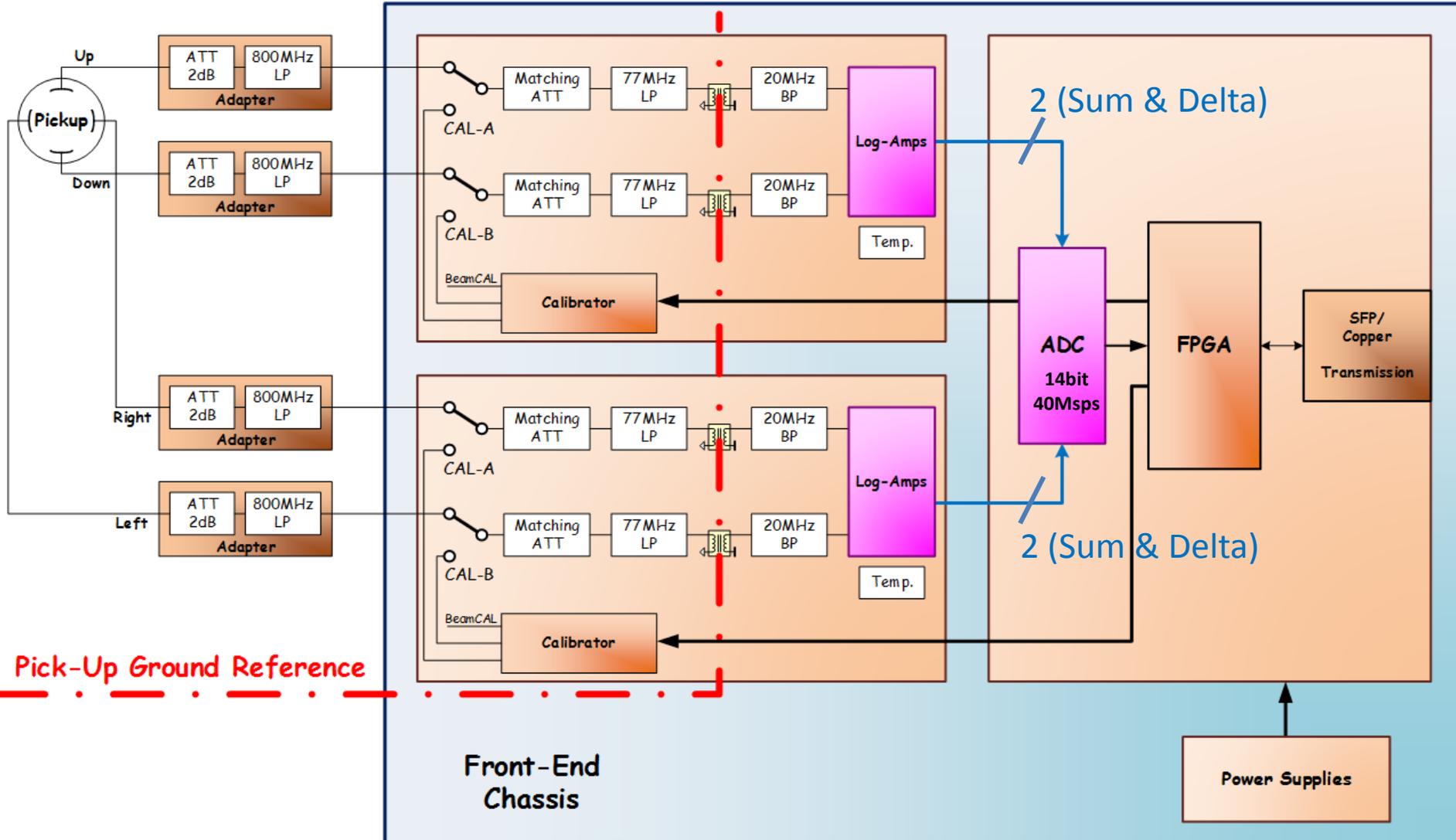
The Proton BPM System

Pick-up & Front-End Chassis



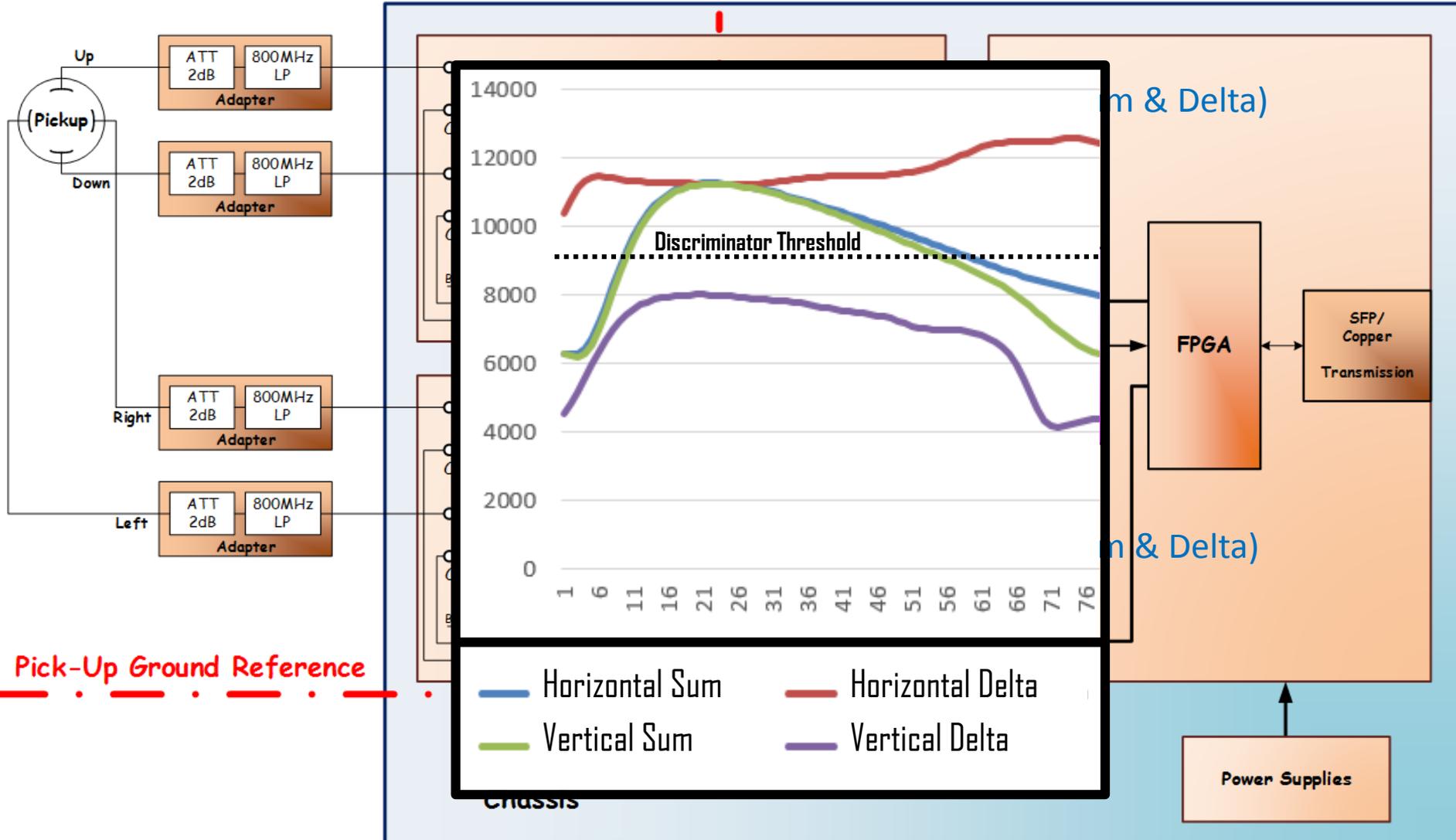
The Proton BPM System

Pick-up & Front-End Chassis



The Proton BPM System

Pick-up & Front-End Chassis

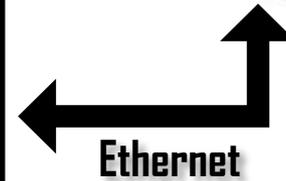
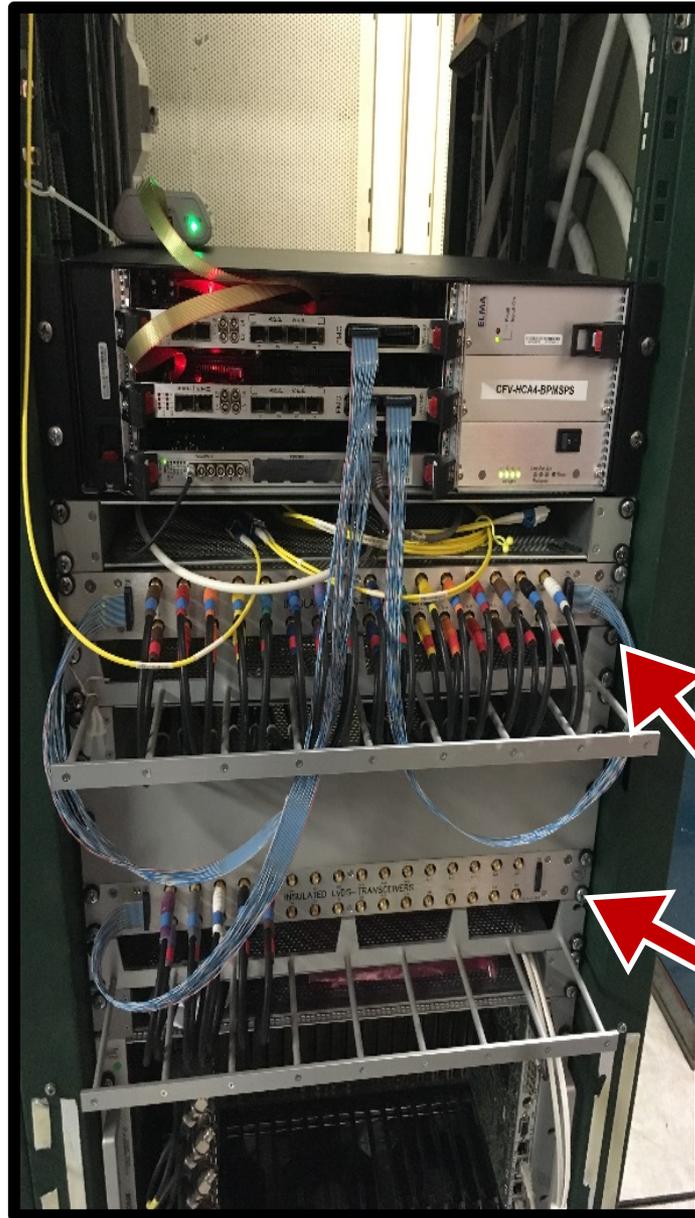
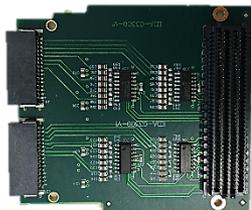


The Proton BPM System

Back-End Crate



AWAKE Patch FMC



VFC-HD Stores Raw Sum & Delta (ADC bin)

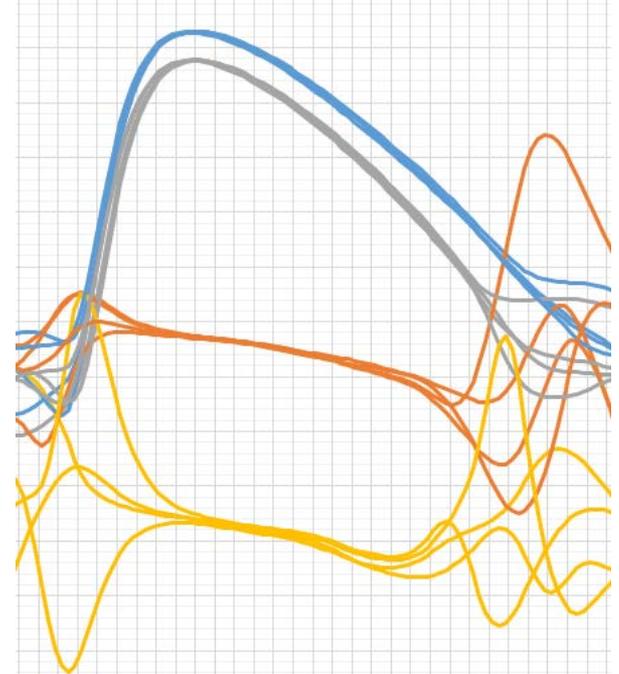
AWAKE Patch Panel

The Proton BPM System

System Calibration

1) Multiple acquisitions of raw Sum & Delta for H & V (ADC bin):

- Sum -> Used as reference point
- Delta -> Proportional to beam displacement in ADC bins...



The Proton BPM System

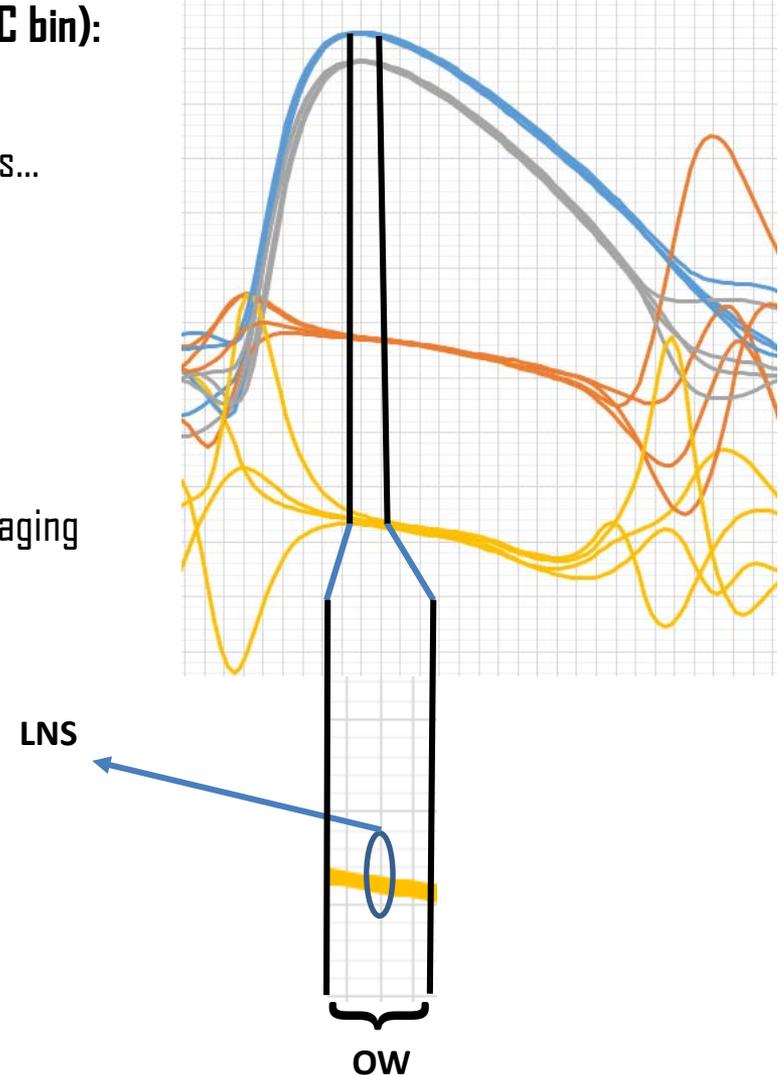
System Calibration

1) Multiple acquisitions of raw Sum & Delta for H & V (ADC bin):

- Sum -> Used as reference point
- Delta -> Proportional to beam displacement in ADC bins...

2) Select best Delta samples for averaging:

- 1) Identify the Less Noisy Point (LNS) around Sum Max.
- 2) Identify the Optimal Window (OW) around LNS for averaging
- 3) Calculate mean value of OW

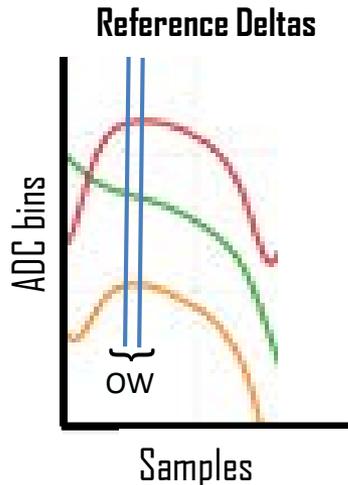


The Proton BPM System

System Calibration

3) ADC bin to distance (mm) conversion:

- Based on on-board calibrator & calculations
- 3 reference deltas:
 - Max delta (Attenuation Left(H)/Up(V)) **(Red Line)**
 - Min delta (Attenuation Right(H)/Down(V)) **(Orange Line)**
 - Electrode Offset (No Attenuation) **(Green Line)**

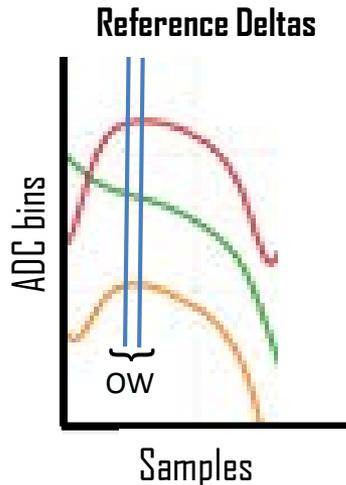


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$$CalLevelDb = 6.0$$

$$BpmKf = 15.25$$

$$ElecScale = \frac{Max\ Delta - Min\ Delta}{2}$$

$$BpmScale = BpmKf \left[\frac{-1 + 10^{\frac{CalLevelDb}{20}}}{1 + 10^{\frac{CalLevelDb}{20}}} \right] = 5.0672$$

$$Position = \left[\left(\frac{BpmScale}{ElecScale} \right) (AvgDelta - ElecOffset) \right] - PhysicalOffset$$

Nonlinear corrections do not applied

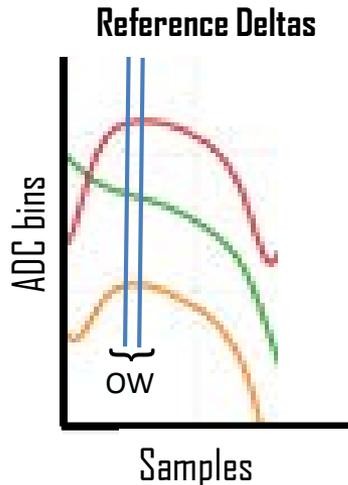
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Deterministic behavior
(Just one calibration required)



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$$BpmKf = 15.25$$

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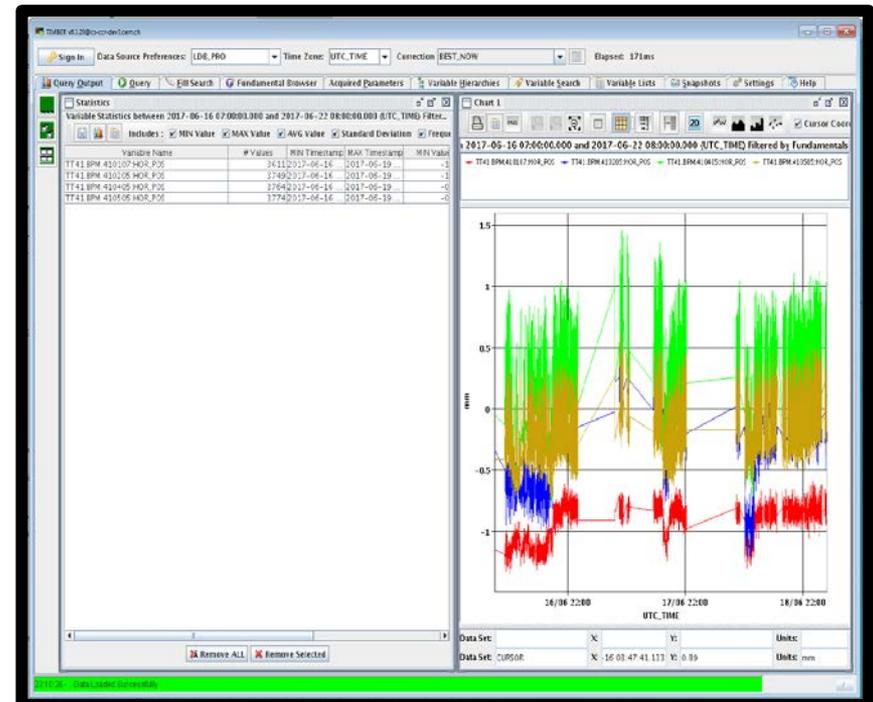
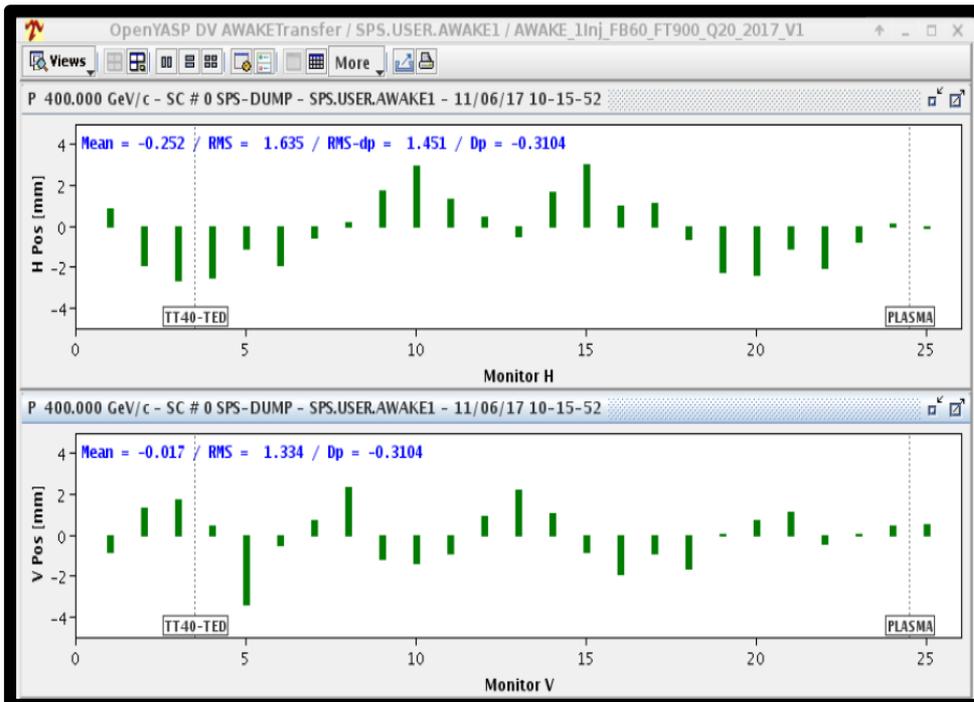
The Proton BPM System

System Operation

First proton beam in July 2016
&
Commissioned in September 2016

OpenYasp (Control & Real Time Data)

TIMBER (Offline Data Analysis)



Performance of the AWAKE Proton Beam Line BPM System

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Performance

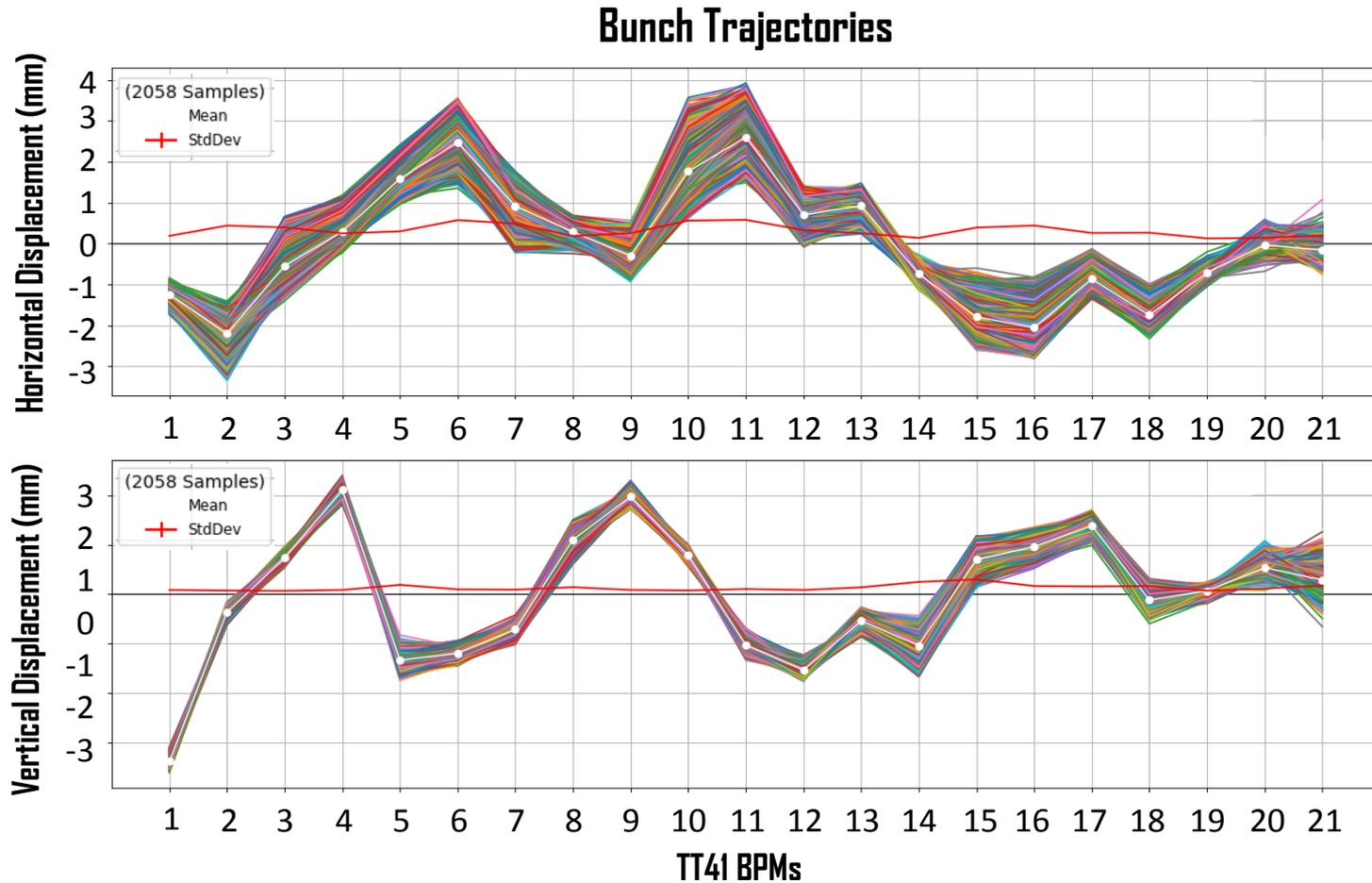
Figures of Merit

- **Noise (Resolution)**
- **Linearity**
- **Dynamic Range**

Performance

Noise (Resolution)

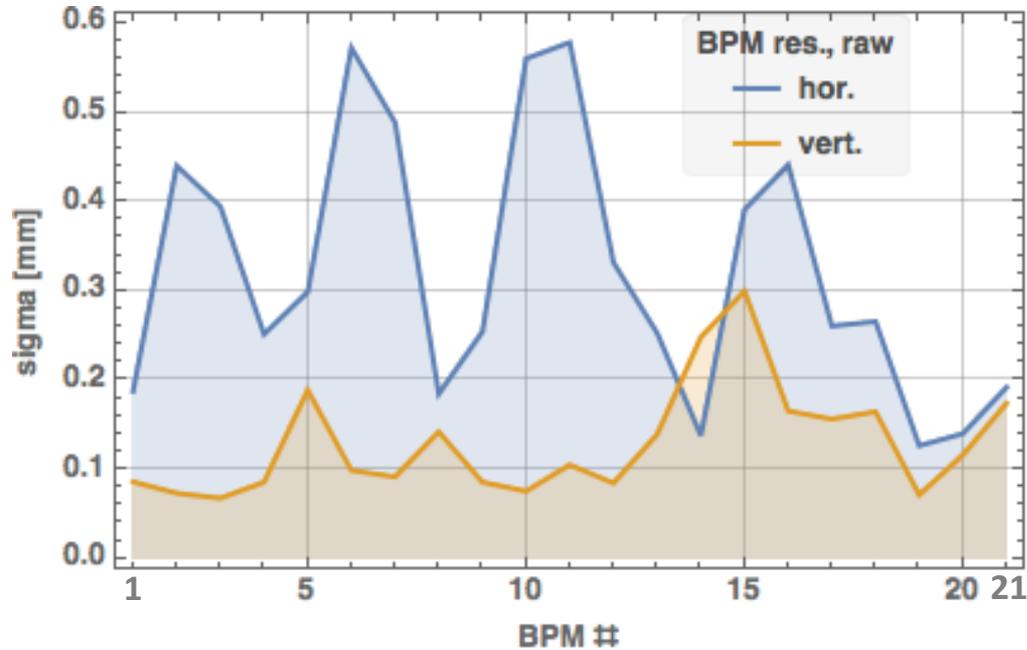
Over 2000 acquisitions of AWAKE beam "Golden Orbit" at Nominal Intensity



Performance

Noise (Resolution)

Standard Deviation with Raw Data

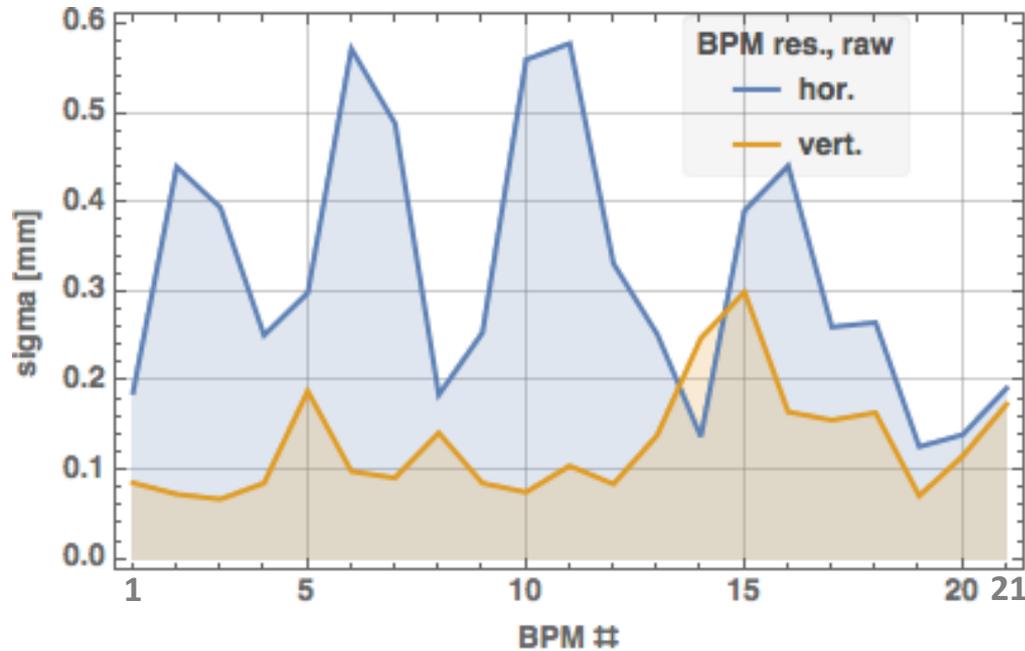


Big difference between H and V

Performance

Noise (Resolution)

Standard Deviation with Raw Data



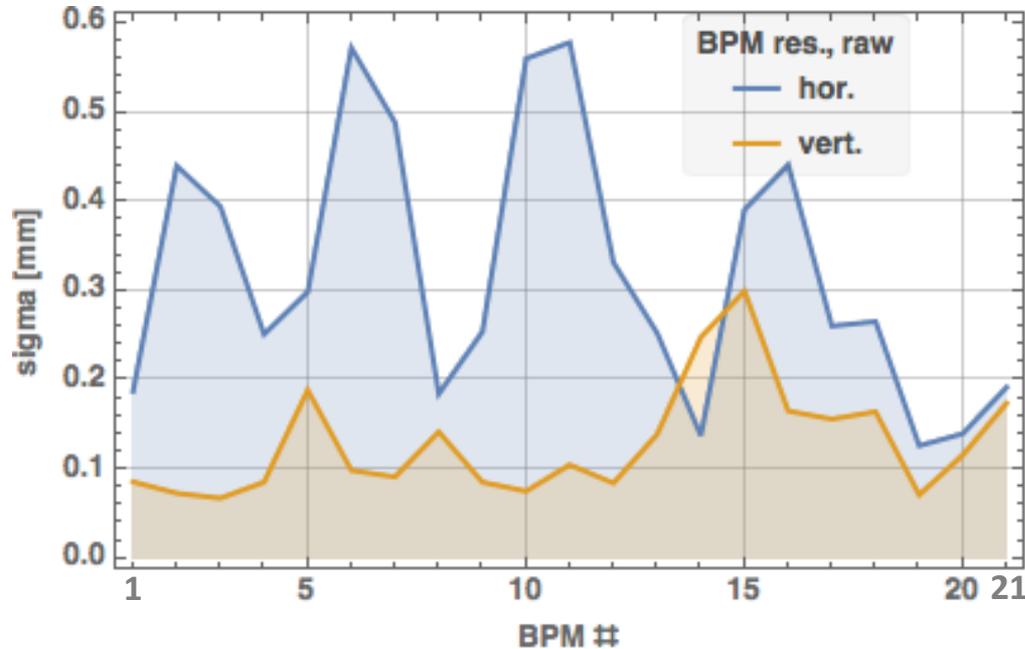
Big difference between H and V

- **But... BPM resolution does not depend on the measurement plane!!!**
 - Horizontal Resolution \sim Vertical Resolution

Performance

Noise (Resolution)

Standard Deviation with Raw Data



Big difference between H and V

- **But... BPM resolution does not depend on the measurement plane!!!**
 - Horizontal Resolution ~ Vertical Resolution
- **Apply some Singular Value Decomposition (SVD) "magic" ...**
 - To remove correlated beam motion effects

Thanks to Manfred Wendt

Performance

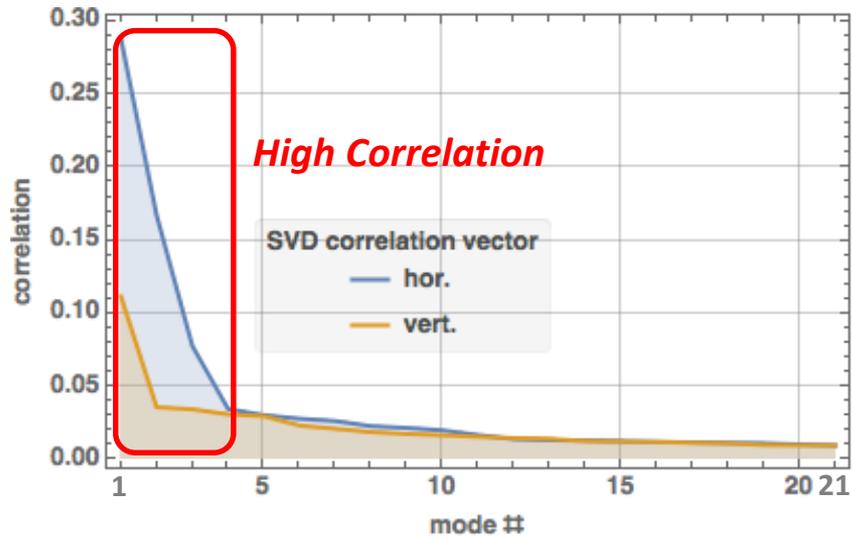
Noise (Resolution)

- **Typically four "modes" of beam motion are dominant in a linac / transport-line:**
 - Beam position (x)
 - Beam angle (x')
 - Beam energy
 - Beam phase
- **The SVD procedure:**
 - 1) Take p (2058) synchronous beam measurements of m (21) BPM
 - 2) Arrange matrix \mathbf{B} [$p \times m$]
 - 3) Decompose \mathbf{B} in $\mathbf{B} = \mathbf{U} \mathbf{S} \mathbf{V}^T$
 - Temporal matrix \mathbf{U} [$p \times p$]
 - Spatial matrix \mathbf{V} [$m \times m$]
 - Diagonal eigenvector of the matrix \mathbf{S} [$p \times m$] which shows the correlation between \mathbf{U} and \mathbf{V}
- **We set the 4 highest eigenvalues (modes) to zero, recalculate the SVD from that the resolution of the BPMs**

Performance

Noise (Resolution)

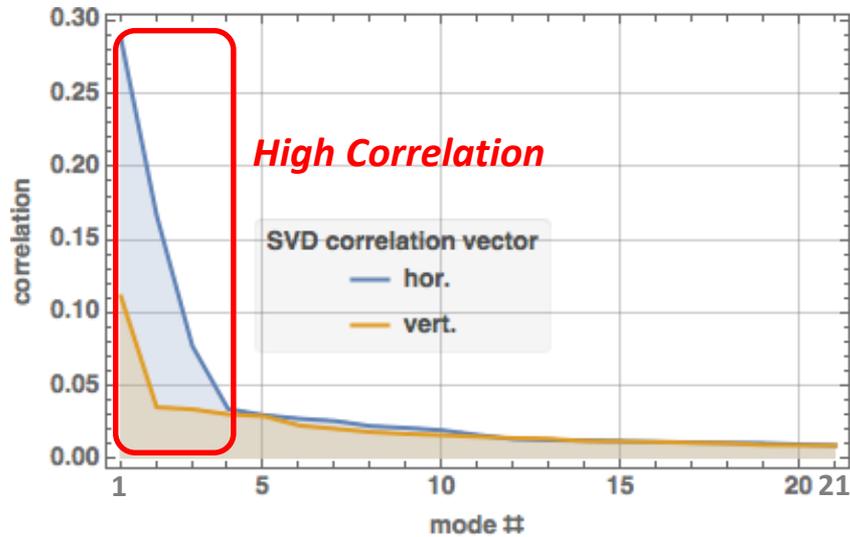
Diagonal Eigenvector of S



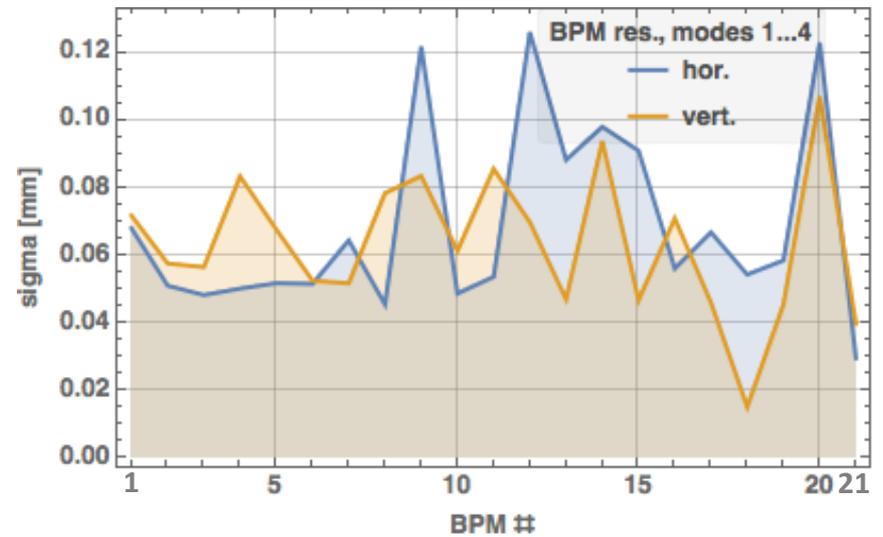
Performance

Noise (Resolution)

Diagonal Eigenvector of S



Standard Deviation after SVD

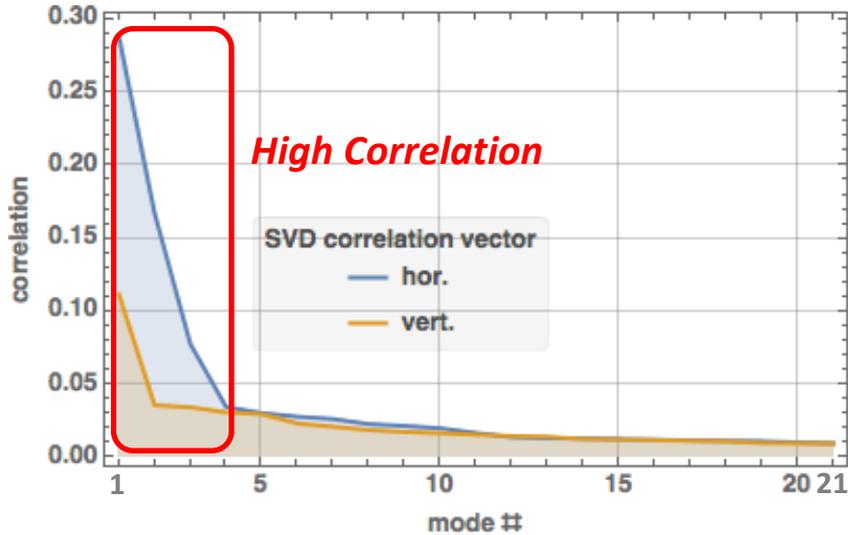


Average Noise $\sim 70\mu\text{m}$ in H and V after removing beam motion effects

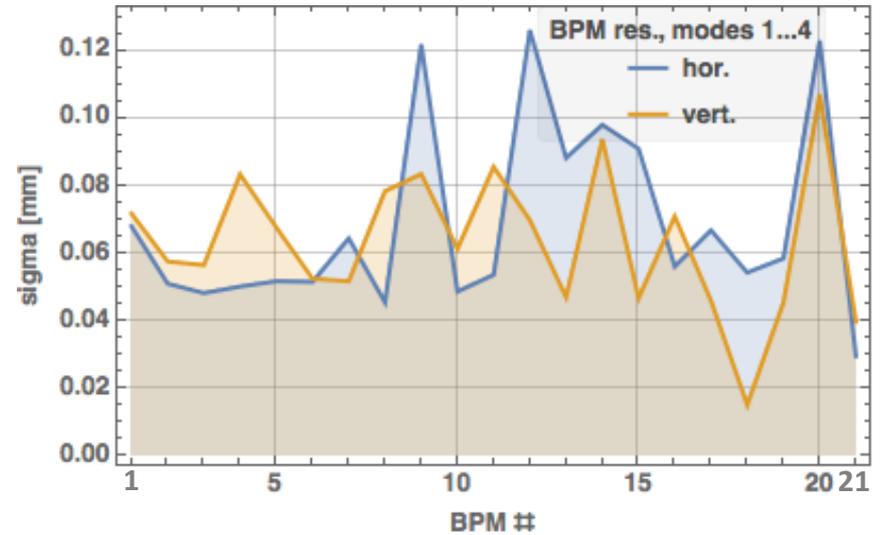
Performance

Noise (Resolution)

Diagonal Eigenvector of S



Standard Deviation after SVD



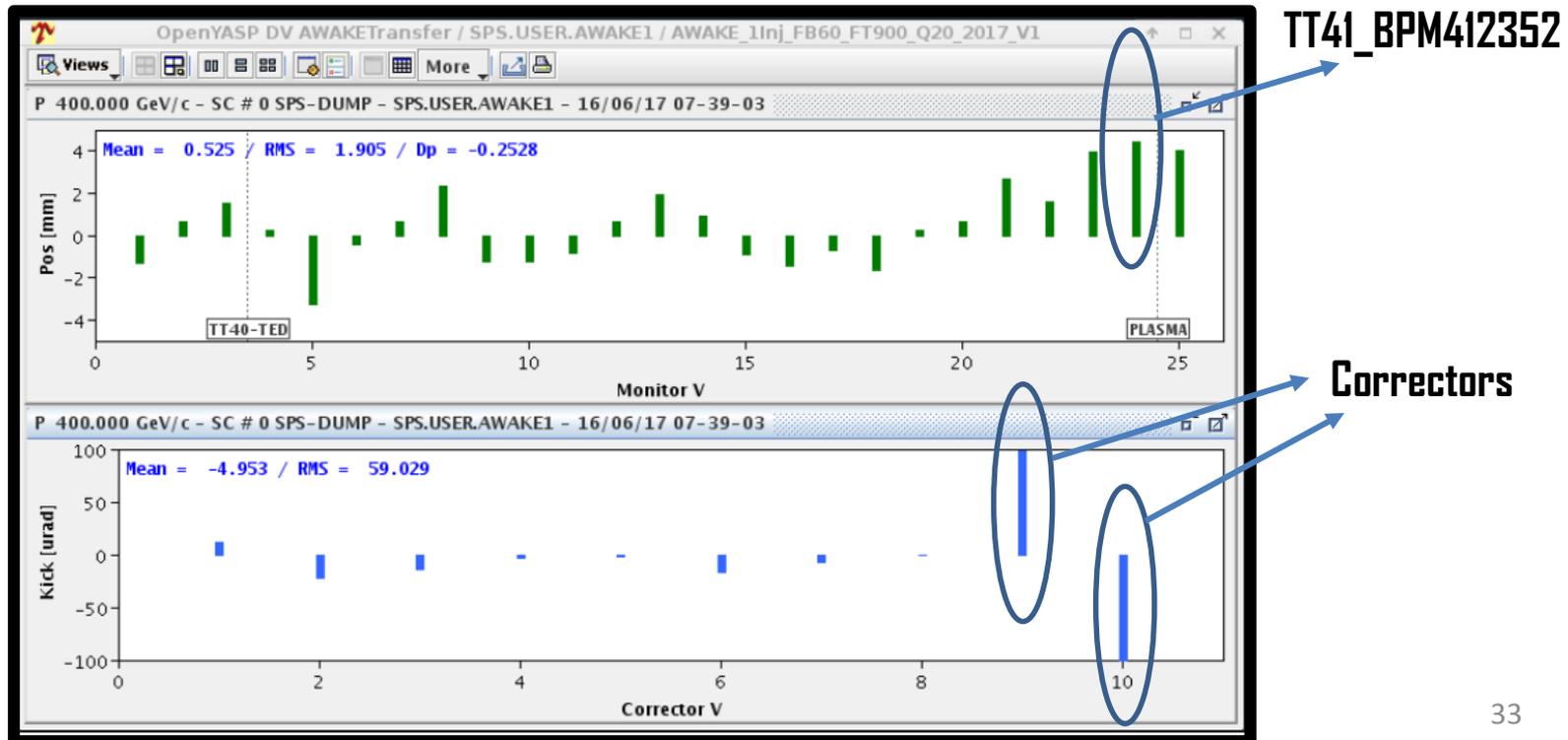
Average Noise $\sim 70\mu\text{m}$ in H and V after removing beam motion effects

Within Specs 😊

Performance

Linearity

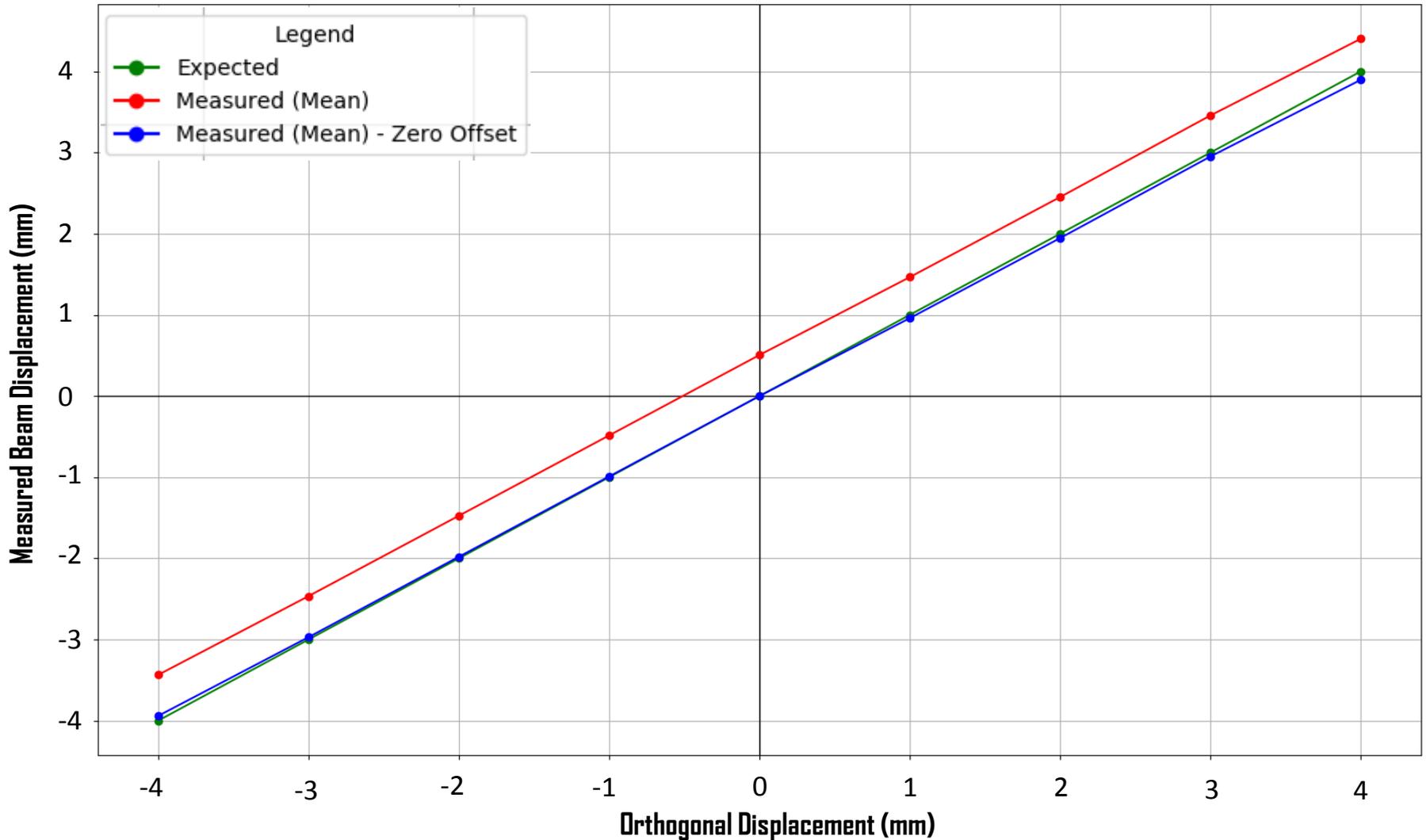
- **Orthogonal displacement at single BPM (TT41_BPM412352)**
 - Only vertical plane (lower noise)
 - Orthogonal displacements: -4, -3, -2, -1, 0, 1, 2, 3, 4 (mm)
 - 50 measurements per orthogonal displacement
- **No nonlinear elements between corrector and BPM**
- **Expected Displacement based on the measured trajectory and the kicker strength**



Performance

Linearity

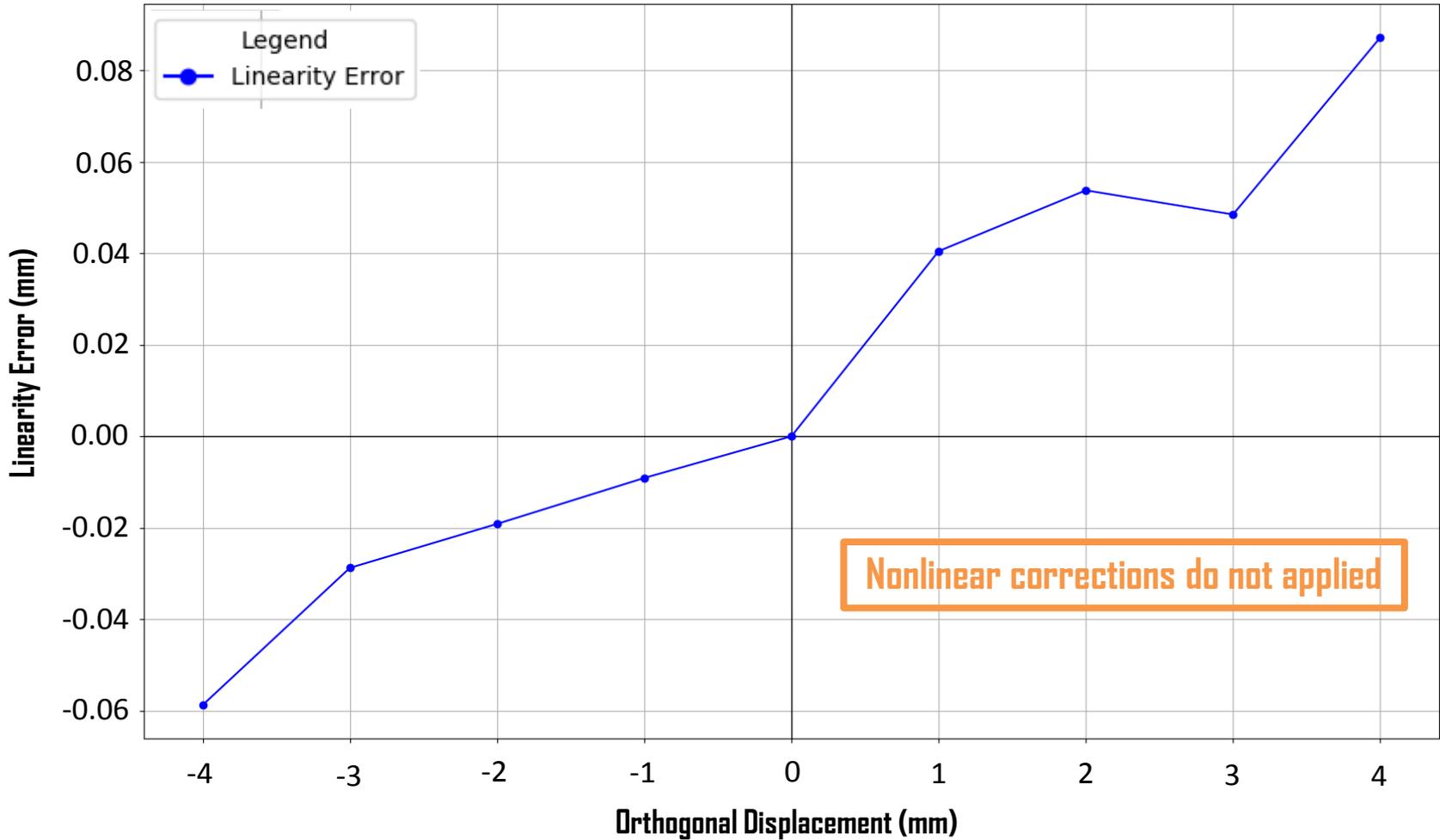
Measured Beam Position VS Orthogonal Displacement



Performance

Linearity

Linearity Error VS Orthogonal Displacement

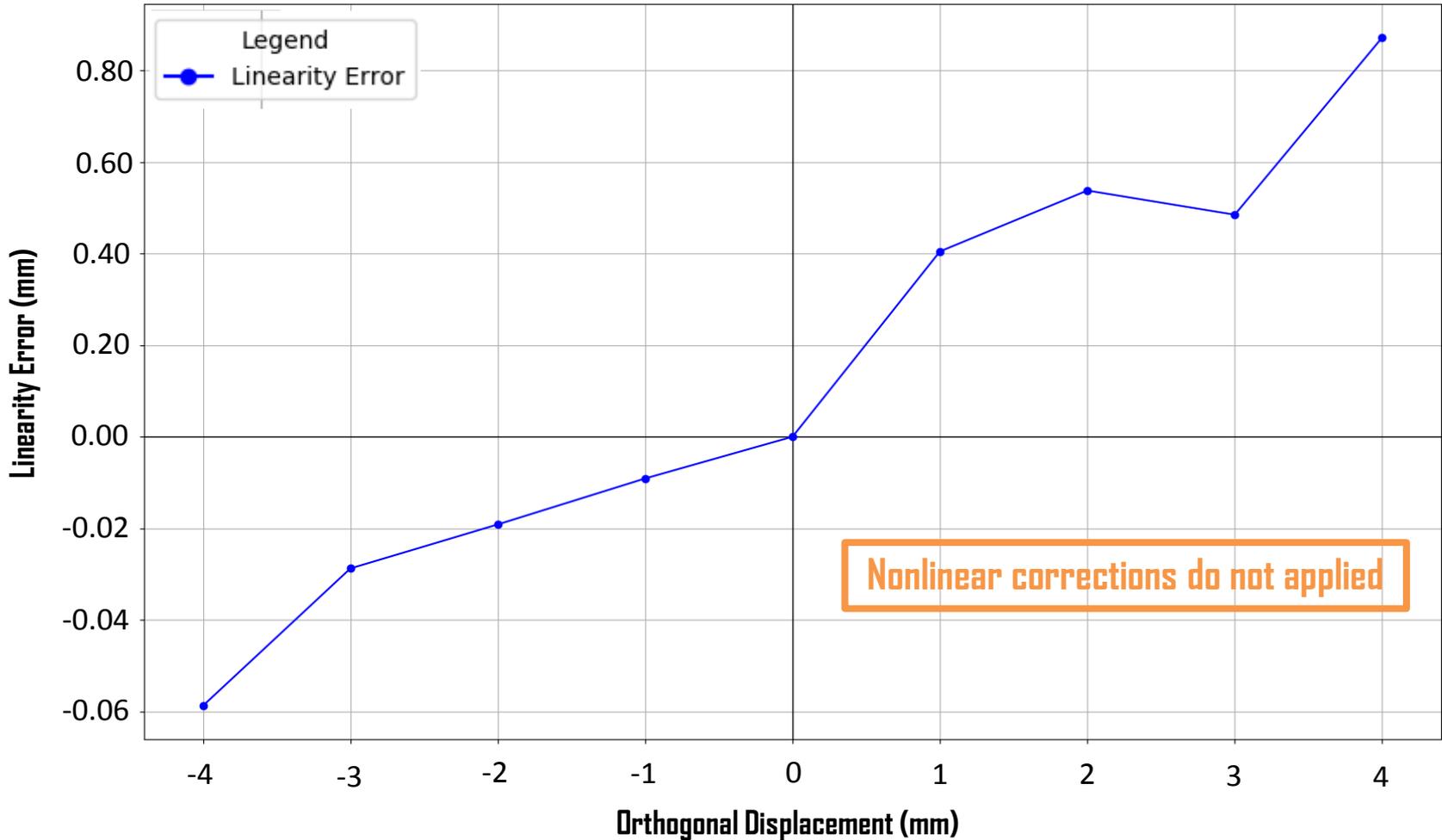


Linearity Error < 100um over +-4mm

Performance

Linearity

Linearity Error VS Orthogonal Displacement



Linearity Error < 100um over +/-4mm

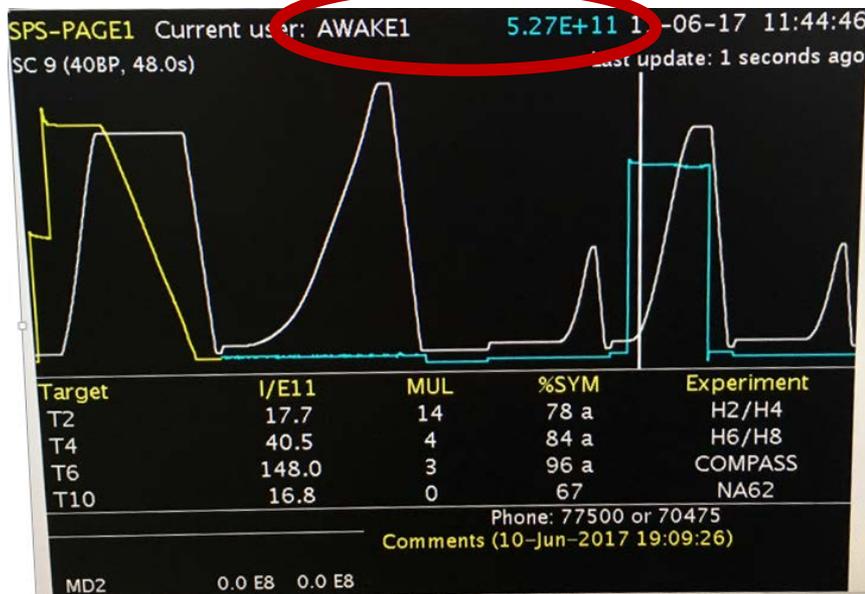
Within Specs 😊

Performance

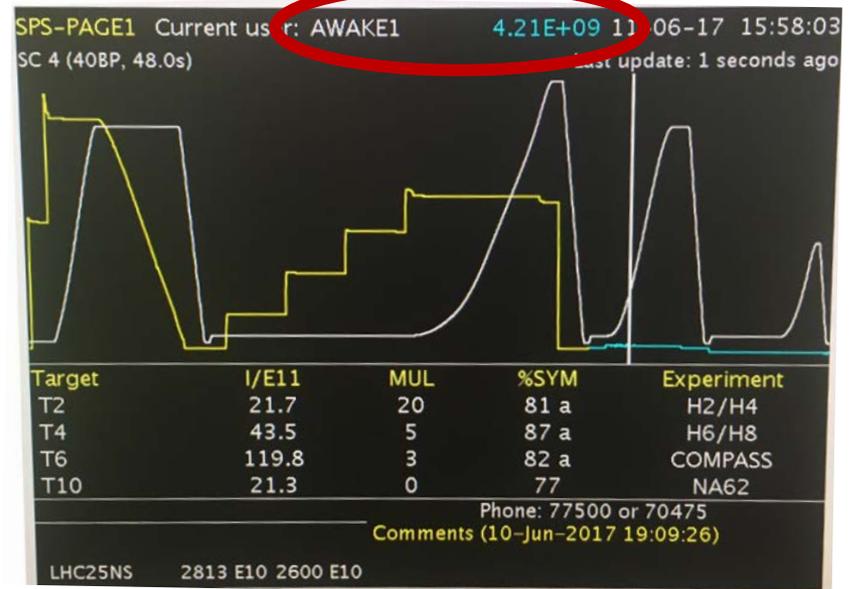
Dynamic Range

- Absolute value may vary depending on LogAmp Board calibration
- Only two intensities of interest:
 - **Nominal** Intensity at high resolution ($\sim 100\mu\text{m}$)
 - **Pilot** Intensity at low resolution
- **Nominal & Pilot acquisitions of "Golden Orbit"**

Nominal



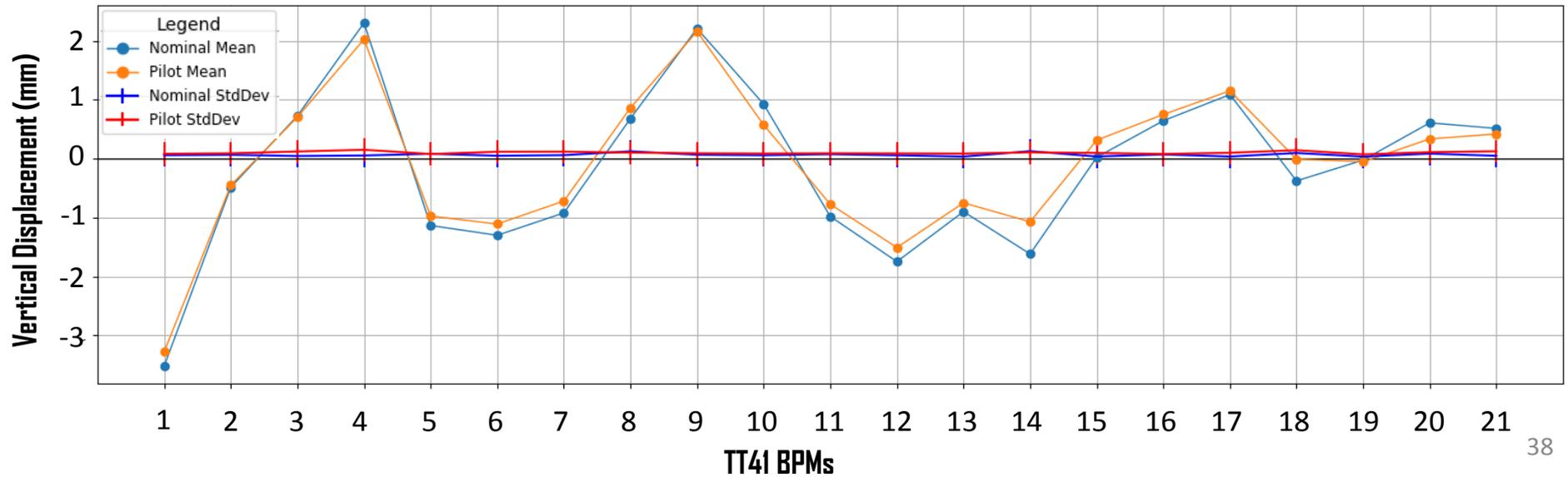
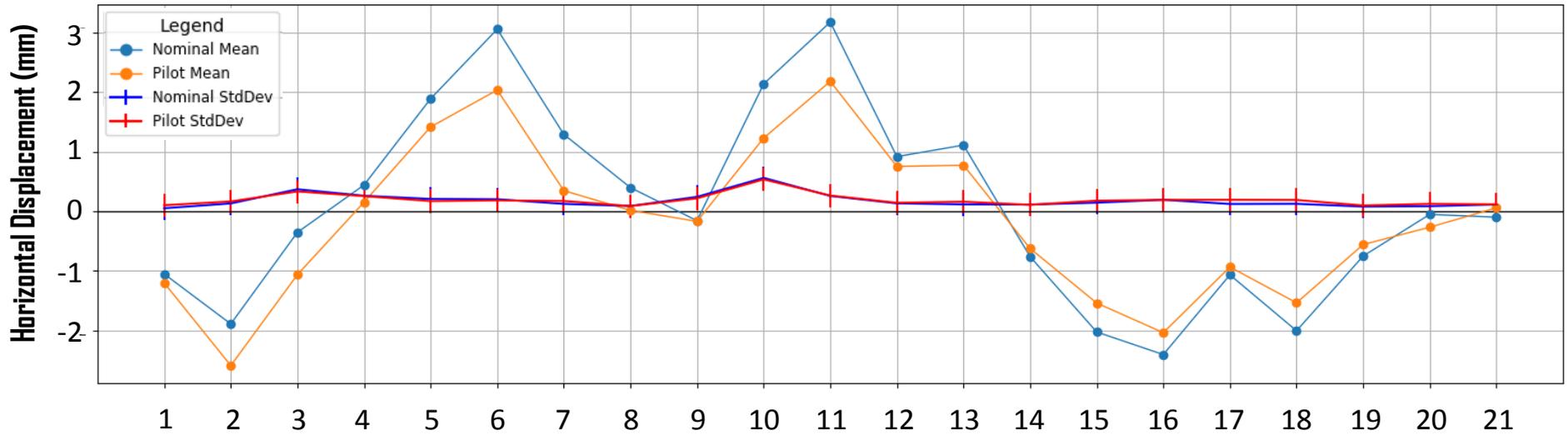
Pilot



Performance

Dynamic Range

Nominal VS Pilot - Bunch Trajectories

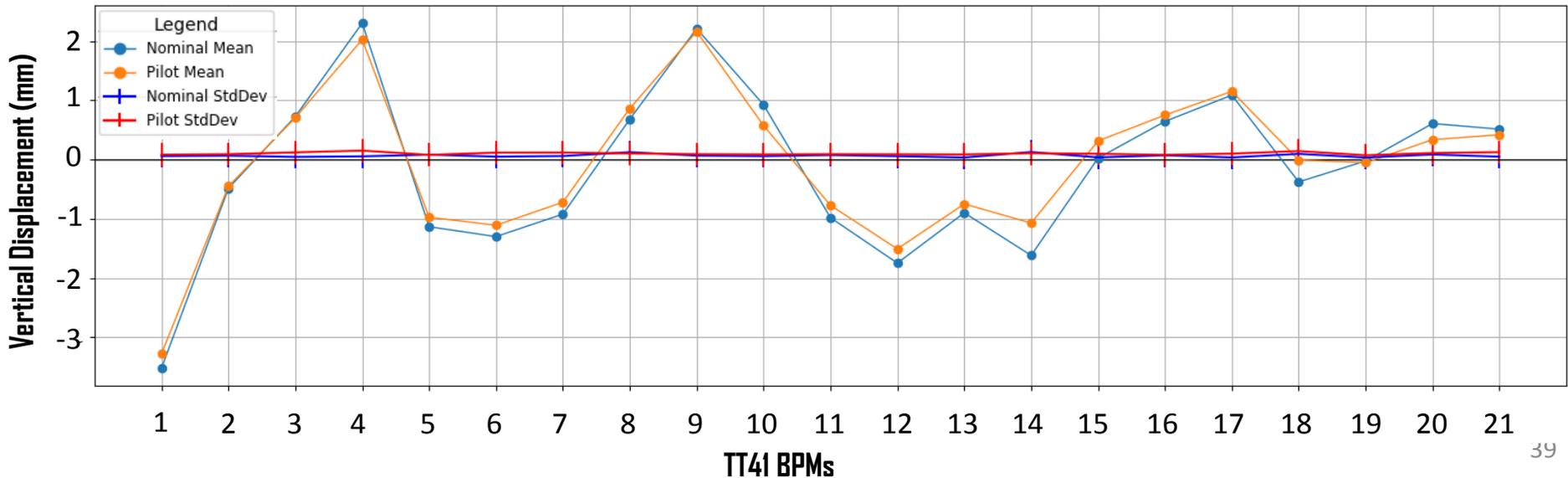
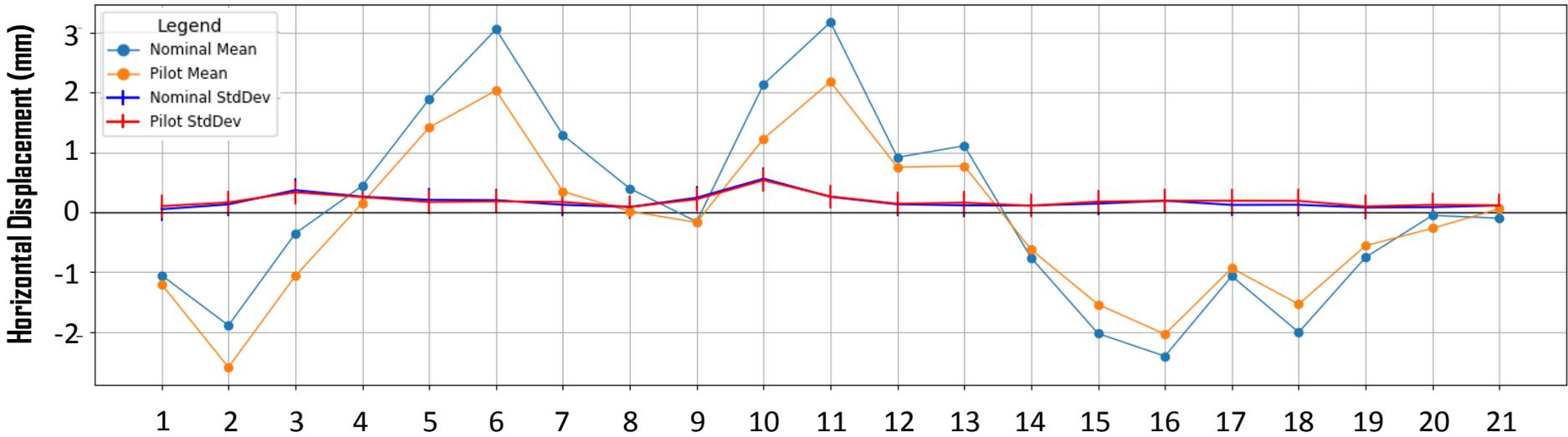


Performance

Dynamic Range

Within Specs 😊

Nominal VS Pilot - Bunch Trajectories



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Summary & Outlook

Summary

- **AWAKE proof of concept accelerator**
- **Proton BPM system developed by BE-BI-QP & BE-BI-SW**
 - Single bunch, low rate, high dynamic rate, 100um resolution
 - 25 BPM across the proton beamline
 - Analogue electronics based on logarithmic amplifiers
 - Sum & Delta signals per plane (V & H)
 - Beam position extracted from Delta
 - Beam position calculated with linear corrections
- **Performance**
 - Noise Resolution: $\sim 70\mu\text{m}$ (100um required)
 - Linearity: $< 100\mu\text{m}$ over $\pm 4\text{mm}$ displacement
 - Dynamic Range: Pilot Noise (Resolution) similar to Nominal



Within Specs 😊

Summary & Outlook

Outlook

- Compare BPM performance with BTV measurements & MADX calculations
- Beam position calculated with nonlinear corrections?
- Presentation & paper for IBIC17

Thank you

manoel.barros.marin@cern.ch



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