Expected performance of the new BPM system in IP1/5

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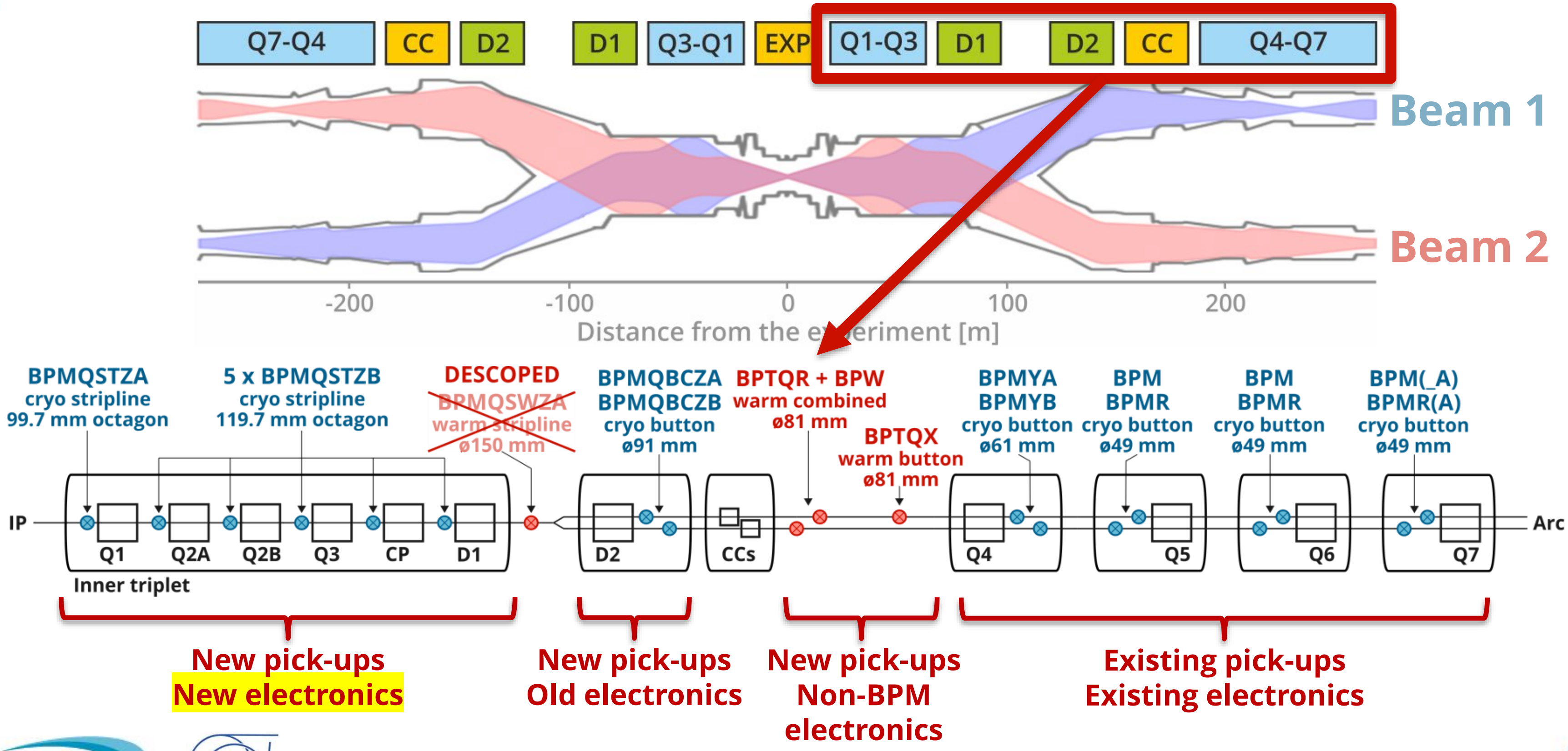
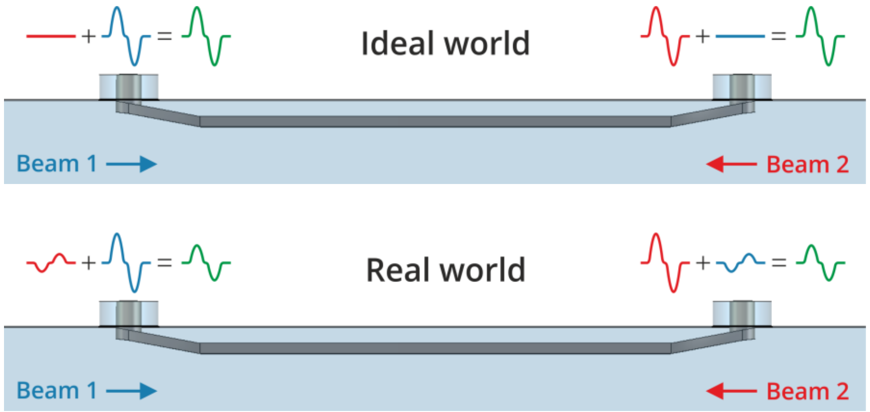
14th HL-LHC Collaboration Meeting, Genoa, 09/10/2024

BPMs for HL-LHC IP1/5

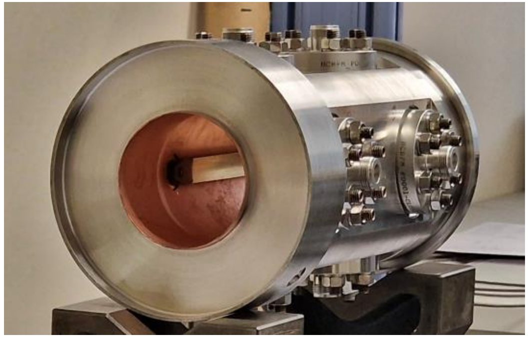


Stripline BPMs

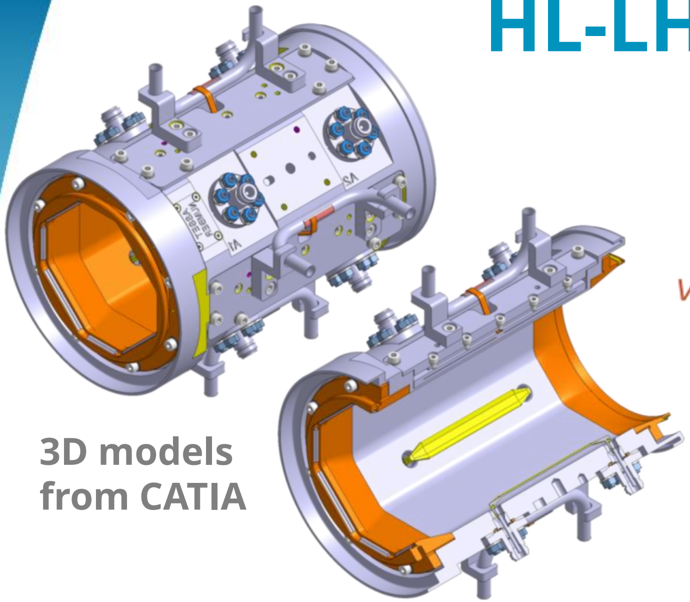
- BPMs closest to the collision point see both counter-rotating beams
- In a stripline BPM the signal is seen mostly at the upstream ports
  - Residual signal at the downstream port increases measurement error for the other beam
  - Optimal performance reached with electromagnetic simulations and manufacturing studies
  - Improved by installing the BPMs far from the beam-beam crossing locations



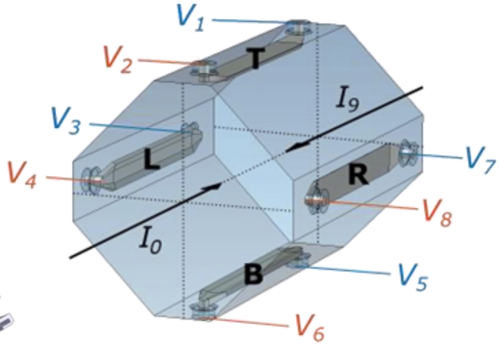
HL-LHC goal directivity ~ 26 dB (broadband)



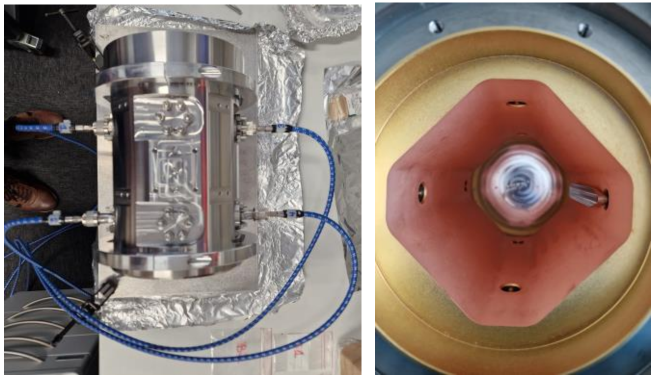
HL-LHC stripline BPMs



3D models from CATIA

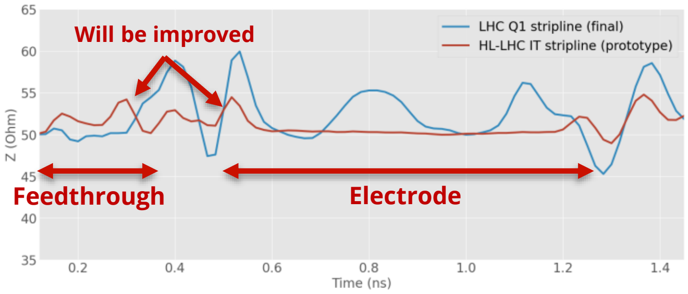


EM simulation model from CST



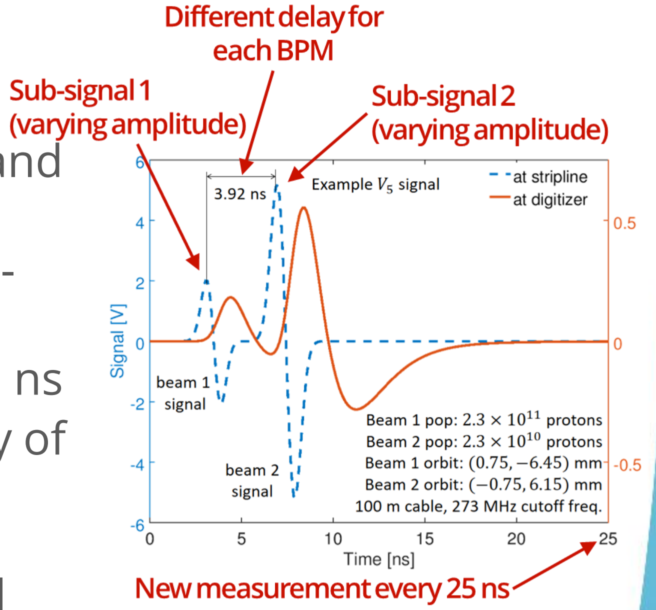
Pre-series assemblies for tests

- Most complex LHC BPMs to be ever built
- EM design objective: characteristic impedance of the electrode as close as possible to 50 Ω
  - Significant improvement over the existing LHC stripline BPMs
  - Excellent work by design (SY-BI & EN-MME), machining (EN-MME) and coating (TE-VSC) teams



Signals

- Each BPM measures both counter-rotating beams and produces 8 wideband (DC-6 GHz) analogue signals
- At each bunch passage, a signal composed of 2 sub-signals associated with the two beams is generated
  - Measurement of the total signal energy within 25 ns
  - Advanced signal processing to remove the energy of the "unwanted" beam
    - Reference measurements with one isolated bunch per beam needed at the start of each fill
  - In corner cases, the signal to be corrected for is larger than the signal to be measured
- Calculating the position of each bunch requires precise measurements and processing of the 8 BPM output signals in "real" time



BPM location	Beam-beam delay [ns]
Q1	3.92
Q2A	3.92
Q2B	6.82
Q3	9.72
CP	10.52
D1	7.36

Measurement modes

- **Closed orbit (AKA asynchronous orbit)**
  - Average position of all bunches published at 25 Hz (used by the orbit feedback)
  - Aiming for a possibility to configure a higher publishing rate (50 – 100 Hz)
- **Bunch-selection orbit (AKA synchronous orbit)**
  - Average position of a user-selected subset of bunches published at the same rate as the closed orbit
  - Aiming for several (~ 4) independent masks that can be used at the same time
- **Bunch-by-bunch turn-by-turn trajectory (AKA capture)**
  - Turn-by-turn positions of selected bunches published as an array after all data is acquired
  - Aiming for 1M bunch-turns (8 times more than in the LHC)
- **Expert raw waveform acquisition**
  - Analogue signals generated by the BPM + analogue front-end
  - For debugging and expert analysis
- **Postmortem**
  - Turn-by-turn average position of all bunches over the final ~1000 turns
  - As implemented in the LHC
- **On-demand postmortem**
  - Same as above but can be triggered (independently) on demand

The challenge of designing a BPM system for HL-LHC IR1/5

- Larger BPM aperture (50% less sensitivity to beam displacement)
- Better precision requested (5x)
- Increased maximum bunch intensity (~1.5x)
- Need to correct the beam cross-talk (not done in the LHC)
- Very high power of the signals – significant impact on cables and electronics!
- Why using existing BPM systems was excluded:
  - **WBTN** (existing LHC system) – thermal drifts, insufficient precision
  - **DOROS** (high-precision system for collimators) – lack of some requested functionalities, e.g. bunch-by-bunch, turn-by-turn measuremetns
  - **CONS** (future LHC system) – lower foreseen performance

Table 1: Main Beam Parameters for different operational scenarios relevant for the BPM specifications.

Particle	Bunch Charges	Number of bunches Min	Number of bunches Max	Min bunch spacing [ns]	Bunch length FWHM [ns]
Protons	5×10^{9}-2.3×10^{11}	1	2760	25	0.7-1.2
Ions	5×10^{9}-5×10^{10}	1	1240	50	0.7-1.2
Pilot (p or ions)	5×10^{9}-1×10^{10}	1	3	≈30 μs	0.7-1.2
vdM scans (pp)†	$9 \times 10^{10\,\ddagger}$	50	150	525	0.7-1.2

Table 2: BPM Types. The maximum range is defined as the BPM aperture, while the operational range is taken as half the maximum range. The minimum inter-bunch spacing is taken from Ref. [22] and from direct computation. The signal spacing in the Triplet BPMs refers to the center of the strip line; the values listed apply to routine physics operation and for vdM-scan conditions when bunches are more isolated - see Table 1.

Type	Two-beam operation	Operational range (OP) [mm]	Max. range for studies [mm]	Inter-bunch signal spacing [ns] physics	Inter-bunch signal spacing [ns] vdM-scan
Arc	No	±9	±18	25	>525
Matching section	No	±12	±24	25	>525
Triplet Point 2/8	Yes	±14	±27	6	>140
Triplet Point 1/5	Yes	$\pm 29^{\dagger}$	$\pm 58^{\ddagger}$	3.8	>140

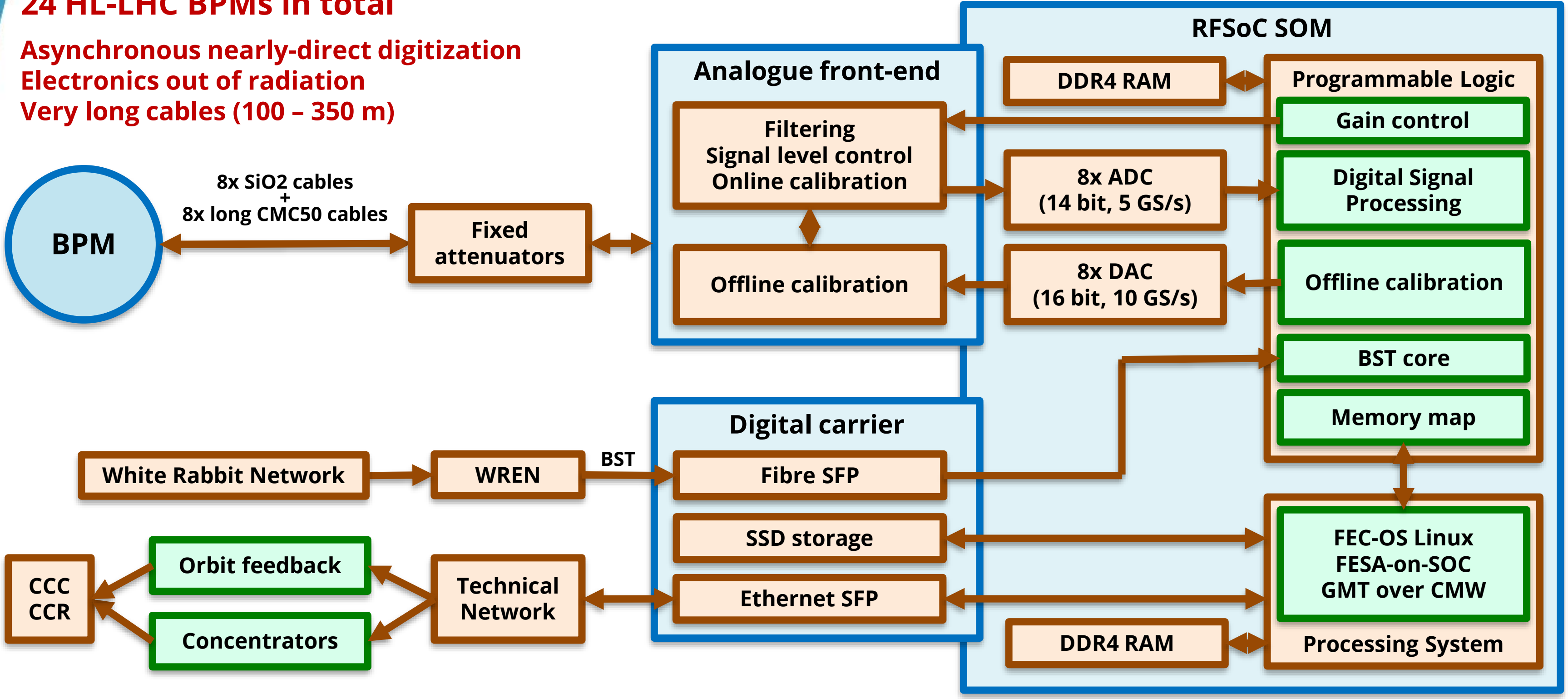
	BPM output (1 electrode)	After 100 m CMC50 coax
Single pilot bunch at min displacement	1.1 Vpp negligible PWR	0.64 Vpp negligible PWR
Full nominal beam at max displacement	807 Vpp 74 W	432 Vpp 22 W

Max displacement increases the power by factor ~10
Power scales with the sqrt of the ratio of filled bunches
57 dB dynamic range in input signal amplitude

HL-LHC BPM architecture

24 HL-LHC BPMs in total

Asynchronous nearly-direct digitization
Electronics out of radiation
Very long cables (100 – 350 m)



Conceptual specification

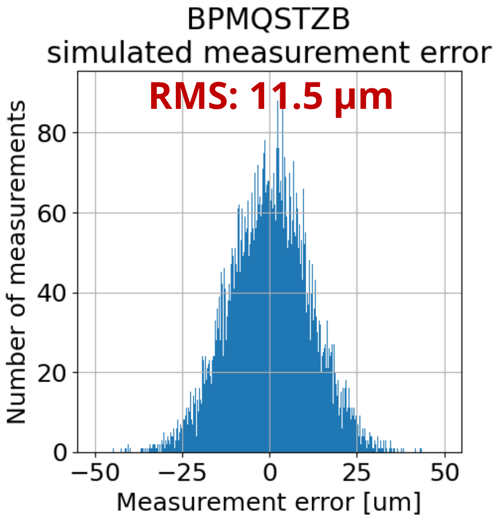
- Conceptual specification for the entire LHC BPM system in the HL-LHC era prepared by optics experts (BE-ABP), operations (BE-OP), and the experiments
  - EDMS 2387369
  - The main LHC BPM system will not be consolidated before LS4
- Overall, three different use cases:
  - Optics experts require precise (i.e. good resolution) turn-by-turn bunch-by-bunch trajectory over a very wide beam position range - TR
  - Operations require precise orbit with good long-term stability - CO
  - Experiments require extremely accurate, precise, linear and stable orbit for the Q1 measurements over a small beam position range - vdM

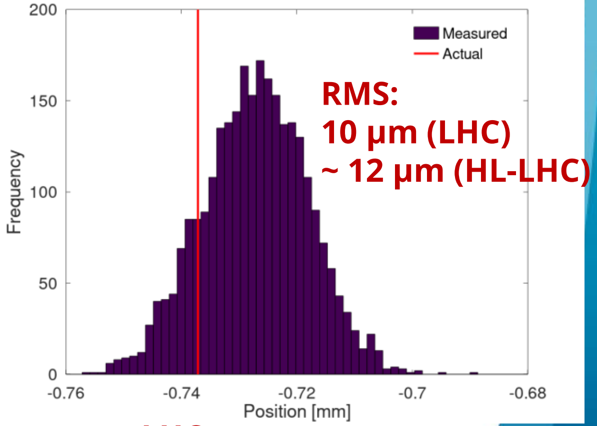
Table 11: Summary specification. Values are expressed as r.m.s.. Where applicable, a reference within this document is specified. Note that averaging times and/or number of bunches for different CO specifications might be considerable different, as detailed in the previous sections.

Goal	Tolerance LHC [2]	Tolerance HL–LHC	In-doc ref.
BPM length-scale	2%§	1.5% over OP range (TR, Arc)‡	Tab. 9
fractional		0.8% over OP range (TR, P1/5)‡	Tab. 9
uncertainty (k)		2% over OP range (TR, P2/8)‡	Tab. 9
Stability of k	n.a.	0.4 μm over $\pm$300 μm (vdM†, 24h, P1/2/5/8)	Tab. 8
Roll	1 mrad (Arc)*	1 mrad (CO, Arc)	Tab. 6
	0.5 mrad (Triplet)*	0.5 mrad (CO, P1/2/5/8)	Tab. 6
Offset	50 μm§	50 μm (CO, Arc)	Tab. 6
		50 μm (CO, P1/2/5/8)	Tab. 6
Non-linearity	100 μm over $\pm$4 mm (CO)§	100 μm over $\pm$4 mm (CO)	Tab. 6
	250 μm over OP range (CO)§	250 μm over OP range (CO)	Tab. 6
		0.2 μm over $\pm$300 μm (vdM†, 25 min, P1/2/5/8)	Tab. 8
Precision	5 μm (CO, Arc)§	5 μm (CO, 10h, Arc, P2/8)	Tab. 5
(r.m.s.(x_{error}))	5 μm (CO, Triplet)§	1 μm (CO, 10h, P1/5)	Tab. 5
		0.1 μm over $\pm$50 μm (vdM†, 30s, P1/2/5/8)	Tab. 8
		1.5 μm over $\pm$300 μm (vdM†, 25 min, P1/2/5/8)	Tab. 8
	50 μm (CO, Run-Run)††	50 μm (CO, 24h, Arc, P2/8)	Tab. 5
	10 μm (CO, Run-Run, Coll.)††	14 μm (CO, 24h, P1/5)	Tab. 5
	200 μm (TR, Pilot)§	100 μm (TR, Pilot, Arc)	Tab. 9
	50 μm (TR)§	$<$50 μm (TR, 1×10^{11} ppb)	Tab. 10
		100 μm (TR, Pilot, P2/8)	Tab. 9
		15 μm (TR, Pilot, P1/5)	Tab. 9
Two-beam cross-talk	n.a.	0.2 μm over B1(2)$\pm$300 μm (vdM†, 25 min, P1/2/5/8)	Tab. 8
r.m.s.($\langle x_{B1}\rangle - \langle x_{B2}\rangle$)	15 μm (CO, Triplet)§	20 μm (CO, P1/2/5/8)	Tab. 7

Precision (resolution)

- Sensitivity to the beam displacement defined by the BPM aperture: ~ 3.3-3.9 % / mm
- Optics team request BPM resolution of 15 μm, i.e. signal change of 0.05% must be detected (66 dB dynamic range required)
- Resolution of the acquisition system is limited by the noise (or dynamic range) of the analogue front-end and the digitizer
  - 68 dB DR for the ADC with 40 MHz digital signal processing
  - Noise of the analogue front-end about 6 dB below the ADC quantization noise
- We expect to provide the resolution required for optics measurements but with little margin!
- Resolution of the orbit measurements scales with sqrt(number of turns x number of bunches)
  - ~ 1000 for 2760 bunches measured at 25 Hz



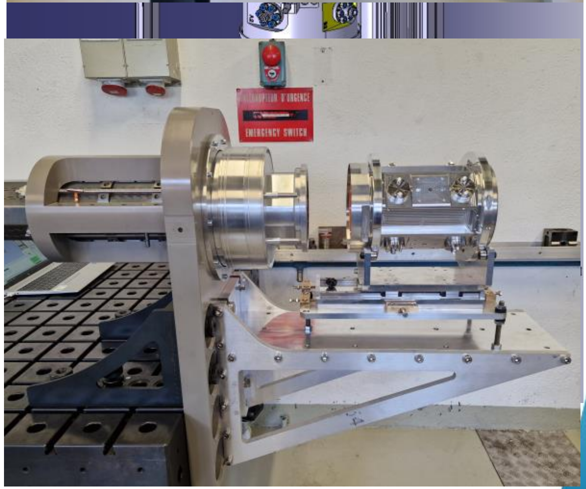


LHC measurements

Accuracy – BPM pick-up offset and roll

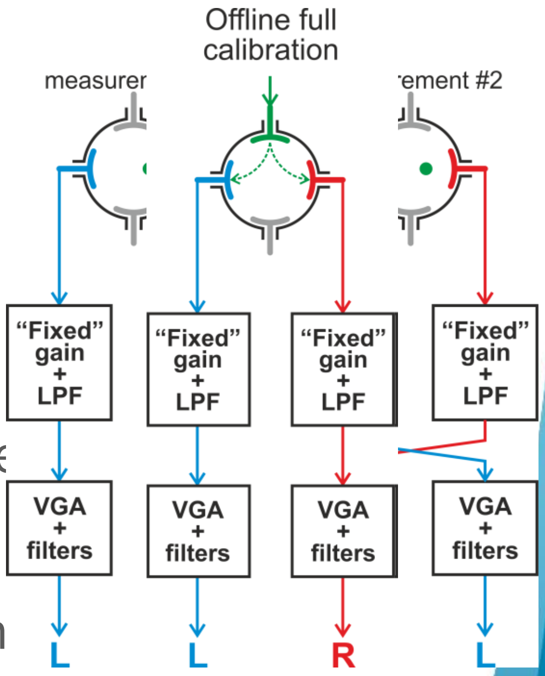
Goal	Arc BPM	Triplet BPM	
		Point 1/5	Point 2/8
Offset	50 μm	50 μm	50 μm
Roll	1 mrad	0.5 mrad	0.5 mrad

- Electric – asymmetry between the opposing electrodes (production and assembly tolerances)
  - Measured on a special stretched-wire test bench after full BPM assembly
  - Expected accuracy: ±50 µm
- Mechanical – imperfect alignment and installation
  - Measured and controlled during BPM installation
  - Installation on the beam screen tested with the vacuum (TE-VSC) and survey (BE-GM) teams
  - Expected accuracy:
    - ±25 µm against the beam screen interface
    - **±0.5 mm (known to ±0.1 mm) against the magnet reference axis**



Accuracy - electronics offset

- Uneven attenuation / gain between the two opposite channels (e.g. horizontal positive and horizontal negative) is equivalent to an erroneous beam displacement
- 3 types of calibration methods foreseen
  - Online (with beam) for “fast” drift correction – crossbar switching like light sources or DOROS
  - Offline local (without beam) for “slow” drift connection – sending a known signal through the front-end electronics
  - Offline full (without beam) for checking cables – sending a signal to the BPM, cross-coupling to th adjacent electrodes, measuring the asymmetry



Accuracy - linearization

- Signals generated by BPM pick-ups have a non-linear dependance on the beam displacement
  - Very strong effect for large displacements
  - Must be corrected in 2D
- Acquisition electronics also feature some nonlinearities – to be mitigated by precise gain control and calibration

Optics

Goal	Arc BPM	Triplet BPM	
		Point 1/5	**Point 2/8**
BPM length-scale fractional uncertainty (k)	1.5%§	0.8%†	2%‡
Non-linearity over OP range*	$\ll$ 1.5 % ($\ll$ 135 μm)	$\ll$ 0.8 % ($\ll$ 232 μm)	$\ll$ 2 % ($\ll$ 280 μm)

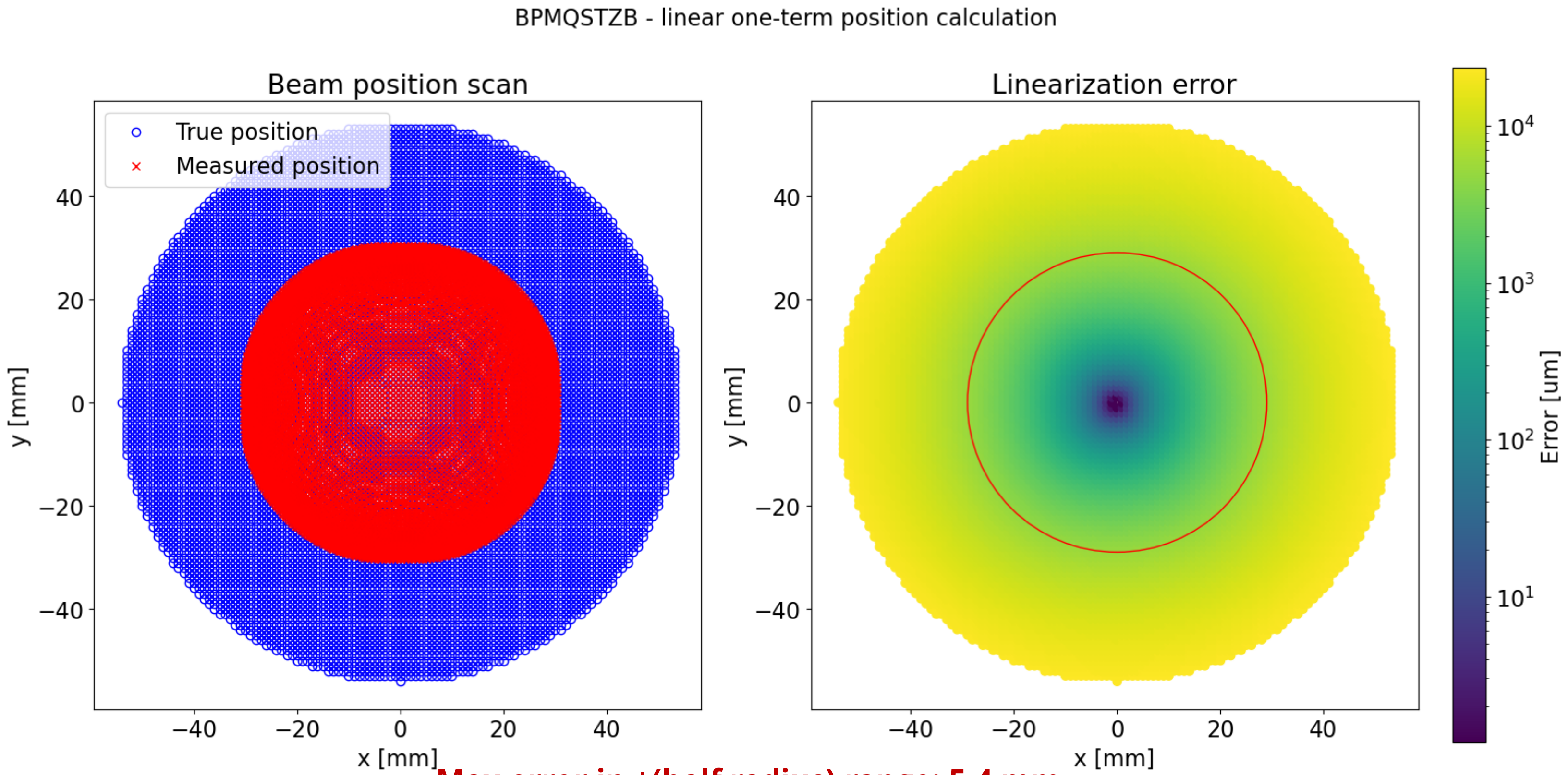
VdM

4.	Linearity over one single H or V scan ($\sim$25 min)	$\pm$300 μm	Residual non-linearity	$<$ 0.05 %
			(equiv. displacement @ IP	$<$ 0.15 μm)
			(equiv. displacement @ BPM	$<$ 0.20 μm)

Orbit

Goal	Arc BPM	Triplet BPM	
		Point 1/5	**Point 2/8**
Non-linearity over $\pm$4 mm	100 μm	100 μm	100 μm
Non-linearity over OP range	250 μm	250 μm†	250 μm

Accuracy - linearization

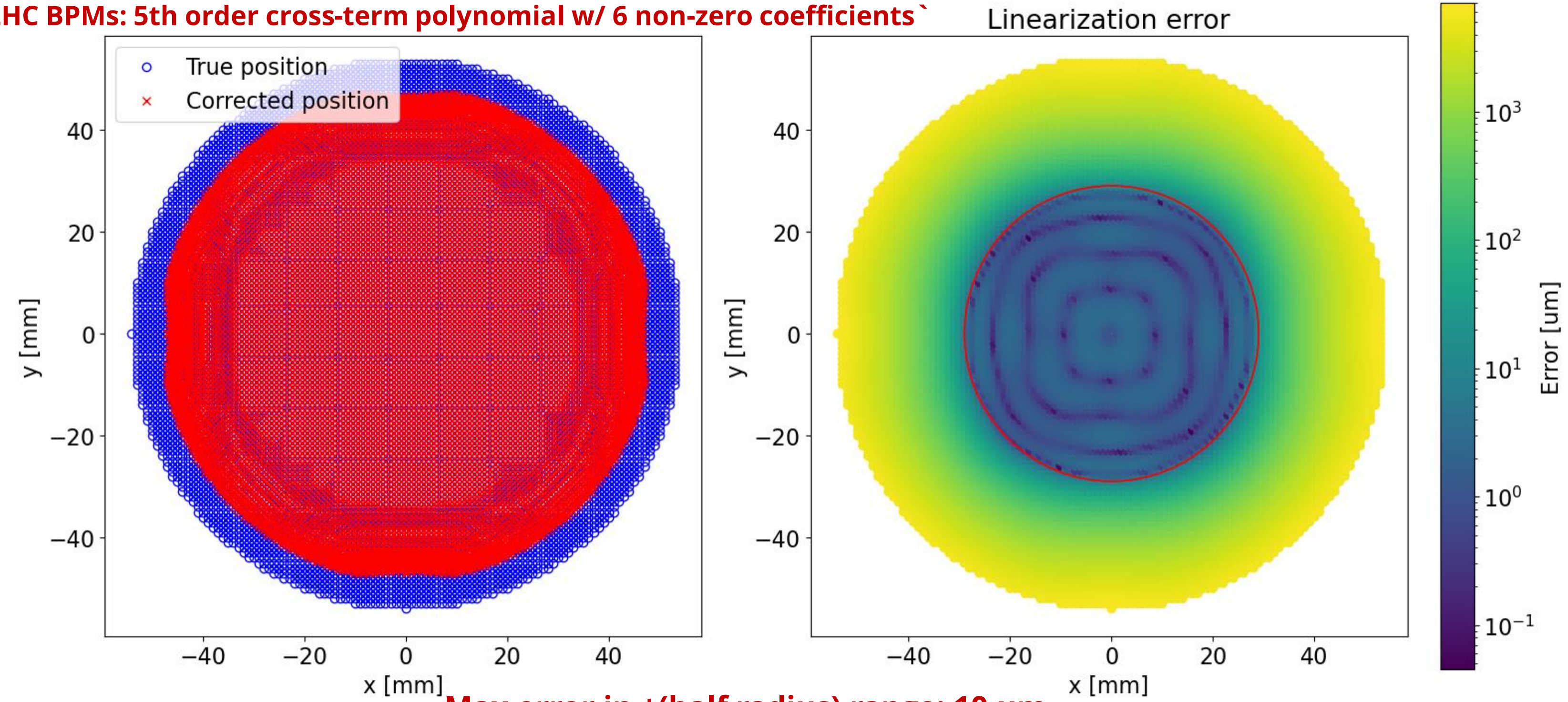


Max error in ±(half radius) range: 5.4 mm
Max error in VdM range: 1.2 µm

Accuracy - linearization

BPMQSTZB - Cross-term polynomial position correction

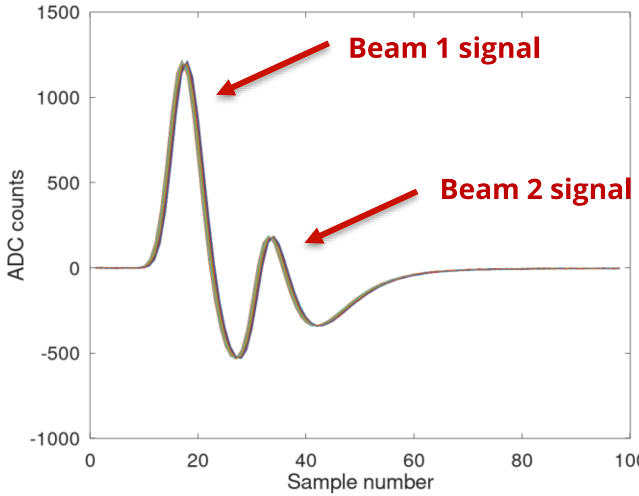
7th order cross-term polynomial w/ 17 non-zero coefficients
LHC BPMs: 5th order cross-term polynomial w/ 6 non-zero coefficients`

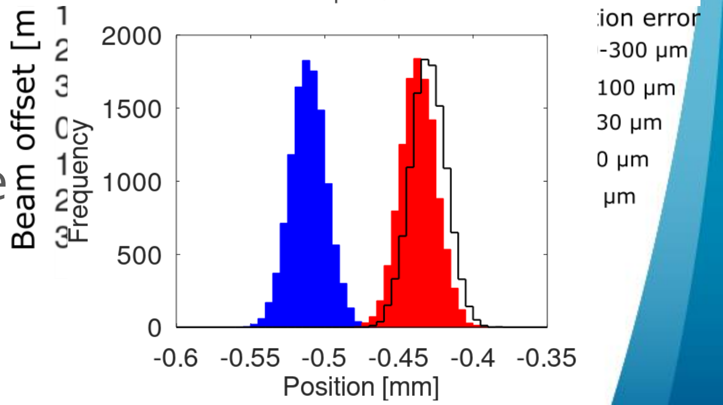


Max error in ±(half radius) range: 10 μm
Max error in VdM range: 0.9 μm

Beam-beam compensation

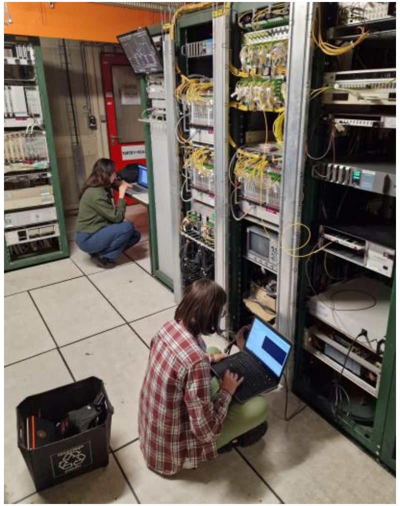
- Various digital signal processing methods investigated
- Most promising so far: “Power Compensation Algorithm” developed in collaboration with University of Oxford
  - Prerequisites: known beam-beam delay; reference waveform measurements at the beginning of each fill
  - Details: [EDMS 2669844]
- Disclaimer: for high-accuracy measurements (e.g. optics measurements, van der Meer scans, special MDs) we recommend using filling patterns where the two beams don’t cross each other in the IT (i.e. 550+ ns bunch spacing)

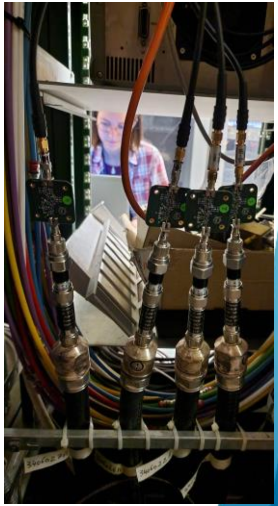




Testing with beam

- **Already tested:**
  - Dedicated MD with RF cogging (variable beam-beam delay), orbit steering, bunch length control – proof that the Power Compensation Algorithm works
  - Raw waveform capture (in LHC, SPS, and AWAKE) for resolution estimation and signal processing developments – proof that the RFSoC technology is suitable for beam position measurements
- **Planned by end of 2024:**
  - Continuous acquisition, “light” processing, publishing, and logging of uncorrected orbits throughout the LHC cycle – proof of the possibility of integrating the RFSoC technology with the CERN controls infrastructure
- **Planned in 2025:**
  - Test of prototype analogue front-end – proof of achievable noise levels (i.e. precision) and linearity
- **Planned in 2026:**
  - Test of the first pre-series system with “light” online signal processing – proof of full system integration
- **Planned in ~2029:**
  - Commissioning in AWAKE (similar quantities as in HL-LHC)





External dependencies

- We rely on the availability of Beam Synchronous Timing (BST) – through the existing network (considered legacy after LS3) or through the White Rabbit + WREN solution
  - BST needed for precise bunch-by-bunch measurements
  - Without timing, the system will work in degraded mode (e.g. no counter-beam compensation, no capture etc.) – useful for commissioning
- We rely on the availability of and support for FESA on SoC and FECOS on SoC
  - Very motivated Task Force recently established, chaired by the lead digital electronics engineer of HL-LHC BPMs
- For compatibility with the existing tools, the new system must look like any other LHC BPM (same API with extra features)

Timeline

- RFSoC SOM procurement in 2024-25
- Electronics production 2025-26
  - Proof-of-concept and prototype units available for measurements with beam – additional dedicated MD time might be valuable
- Gateware, firmware and software development – ongoing, will last until the end of beam commissioning
- Installation – after EN-EL cabling campaign in LS3
- NB. we will produce the same system for AWAKE and potential deployment in LHC IP2/8 (through LHC CONS)

Summary and outlook

- Cutting edge BPM system under development for HL-LHC ITs
  - Extremely-high-quality BPM pick-ups produced at CERN
  - Modern approach: nearly-direct digitization in radiation-free areas
  - Expected performance is mostly in line with the specification
  - Development and test campaign progressing as foreseen
- Points to be aware of:
  - Very high max power of the signal for the corner case defined in the conceptual specification
    - It might become necessary to put a safety limit on the max number of bunches at max displacement
  - Alignment to within 50 µm of the design position not possible
  - Unclear if the demanding requirements of the experiments (VdM) can be realistically satisfied
  - Some large procurement still remains to be completed
  - Integration with CERN controls infrastructure will be commissioned with beam in AWAKE before LHC Run 4

Thank you for your attention