Specifications for the HL-LHC BPM System

Read-out Electronics Consolidation

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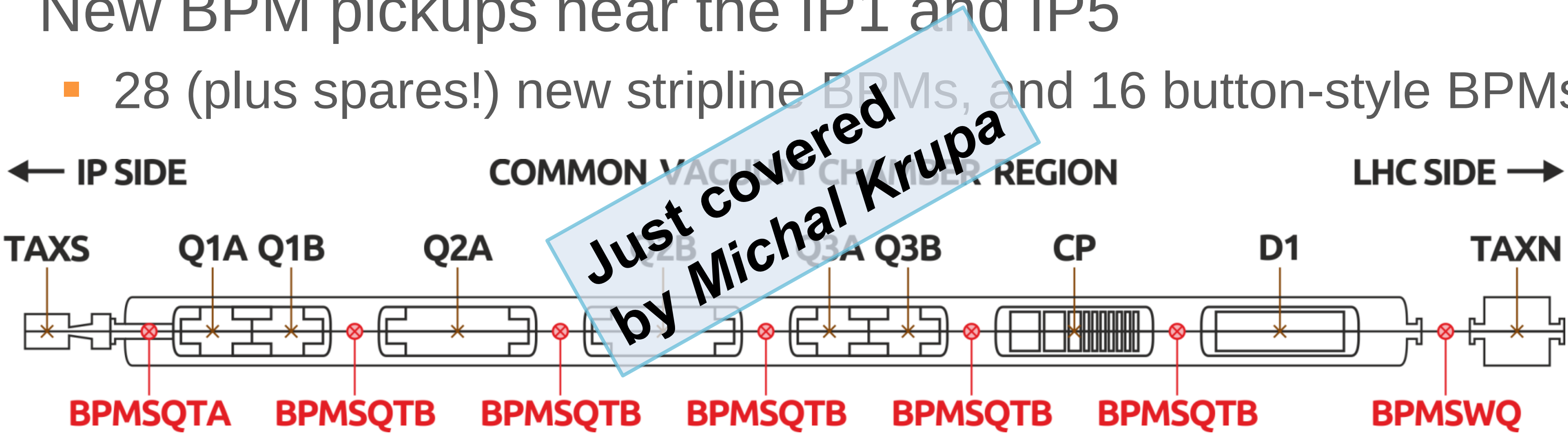
BPMs in frame of the HL-LHC Project

- New BPM pickups near the IP1 and IP5
  - 28 (plus spares!) new stripline BPMs, and 16 button-style BPMs



- **Consolidation of the BPM read-out electronics**
  - **~1100 BPMs (H and V) in both rings and transport-lines**
    - currently operated with WBTN electronics
  - Collimator and some low-β BPMs
    use the DOROS electronics

LHC BPM Specifications 2002

Observables: TRAJECTORY and OSCILLATIONS		
Parameter	*Use*	*Ref.*
Trajectory	Visual inspection	TR1
	Beam threading	TR2[4]
	Close trajectory on itself	TR3[4]
Position error at injection	Subtract orbit from trajectory and compute x,px,y,py at injection	TR4[4]
Momentum error	Deduce momentum from trajectory averaged over the azimuth	TR5[19]
b and m	Visual check of linear optics	TR6
	Search for focusing imperfections	TR7[20]
Local chromaticity	Dependence of b and m on momentum for the measurement of b3 versus azimuth	TR8[20]
Local impedance	Dependence of μ on beam intensity	TR9
Local coupling	Identify the local 4D transport	TR10
Transverse spectrum	Check on the presence and amplitude of harmonics of the betatron oscillation	TR11[21]
Fast Tune	Fast measurement of the tunes with all the BPM's	TR12
Phase space	Measure the phase space portrait for visual inspection	TR13
Frequency maps	Variation of (fast) tunes with initial conditions for visual inspection of the non-linearity	TR14

Table 1: Beam parameters related to trajectories and oscillations

Observable: AVERAGE BEAM ORBIT		
Parameter	*Use*	*Ref.*
Closed orbit	Visual inspection	CO1
	Correct to minimize the aperture requirement	CO2[5]
	Monitor/Log the closed orbit	CO15
Beam position at critical points	Fine control of the orbit at the aperture limits (collimators, TDI...) and orbit feedback	CO3[18, 5]
	Fine control of the orbit at the interaction points	CO4[5]
Alignment and BPM errors	Search for misalignments and BPM errors. Beam-based alignment of the low-β straight-sections.	CO5
Integer tunes	Fourier analyse the closed orbit	CO6
Position at injection	Subtract orbit from trajectory and compute x,px,y,py at injection	CO7[4]
Momentum error	Deduce momentum error from averaged closed orbit	CO8[19]
Dispersion	Closed orbit versus momentum deviation	CO9[5]
β and μ	Closed orbit displacement after a dc kick for visual checks	CO10
	Search for optics imperfections	CO11
Linear optics model	Measure β and μ, BPM resolution, corrector calib. a la Safranek.	CO12
b2/a2 to b5	Measure the arc multipoles	CO13
b2/a2 to b4/a4	Measure the low-b multipoles (orbit and tune response to bumps)	CO14[22]

Table 2: Beam parameters related to the closed orbit

Particle	*Bunch charge*	*Number of bunches*	*Bunch spacing*	*RMS Bunch length*
	q		*ns*	*ns*
proton	$5\ 10^9 \rightarrow 1.7\ 10^{11}$	$1 \rightarrow 2808$	24.95 -> 88925	.28 -> .62-> 1.25
Pb	$5.6\ 10^9 \rightarrow 8.2\ 10^9$	592	100	

HL: 5e9…2.3e11 (~33 dB)

Table 3: Range of LHC beam parameters

Type of Beam	*Number of bunches*	*Bunch charge*	*Bunch spacing*
		q	*ns*
Pilot beam	1	$5\ 10^9$	88925
Intermediate 75	24	$5\ 10^9$ -> $8.5\ 10^{10}$	74.85
Intermediate 25	72	$5\ 10^9$ -> $3\ 10^{10}$	24.95
Nominal 75	936	$1.1\ 10^{11}$	74.85
Nominal 25	2808	$1.1\ 10^{11}$	24.95
Ultimate	2808	$1.7\ 10^{11}$	24.95
TOTEM	36	$1.1\ 10^{11}$	2470

Table 4: Expected LHC beams

Table 5: Ranges of beam positions

	Closed orbit	Momentum Dev.	Crossing angle	Beam σ	Range for operation R1	Range for Studies R2(7σ)	Ultimate Range R3(10σ)
Standard BPM's	± 4 mm	± 2 mm	0	1.2 mm	± 6 mm	± 14.5 mm	± 18 mm
Low-β BPM's	± 4 mm	± 1 mm	± 7 mm	1.5 mm	± 12 mm	± 22.5 mm	± 27 mm

LHC BPM Specifications 2002 (cont.)

Measurement	P	Range	Accuracy	Scale error	Offset	Non-linearity	Resolution
			peak	peak	peak	peak	rms
TR2	*	R2	±2000μm	+	+	+	+
TR3	*	R1	±500μm	+	NR	+	+
TR4	*	R1	±500μm	+	NR	+	+
		R1	±50μm	+	NR	+	+
TR5	*	R1	±1500μm	+	NR	+	+
		R1	±250μm	+	NR	+	+
TR7/TR8	*	± 1 mm ⊂ R1	±400μm	+	NR	+	+
			±50μm	±4%	NR	+	+
TR11		R2		NR	NR	±500μm	50μm
CO2	*	R1	±500μm	+	±250μm (±750μm)	+	+
CO3		± 1 mm ⊂ R1	±20μm	NR	NR	NR	+
CO4		± 1 mm ⊂ R1	±30μm	+	+**	+	+
CO7		R1			±100μm	±200μm over ±4mm	1000μm
CO8		R1	±250μm	+	NR	+	+
CO9 IP		± .1 mm ⊂ R1	±15μm	+	NR	+	+
CO9 other		± 1 mm ⊂ R1	±175μm	+	NR	+	+
CO14		± .1 mm ⊂ R1	±10μm	+	NR	+	5μm

Table 6: Precision required either on the trajectory (TR) or on the closed orbit (CO) according to the measurement goals and conditions.

+ : component included in the calculation of the accuracy

NR: non-relevant or negligible

**: difference between beam1 and beam2 positions (low-β triplets)

HL: ±2 μm long-term stability

Precision goal	Coarse (pilot pulse)	High (other beams)
Scale error	NR	±4%
Roll	NR	±1 mrad
Offset	±750μm	±100μm (relative offset < ±30μm in IR's)
Non-linearity	NR	±200μm over ±4mm, ±500μm over R1
Resolution	200μm rms	50μm rms (traj.), 5μm rms (orbit)

Table 7: Specification for the accuracy of the BPM's

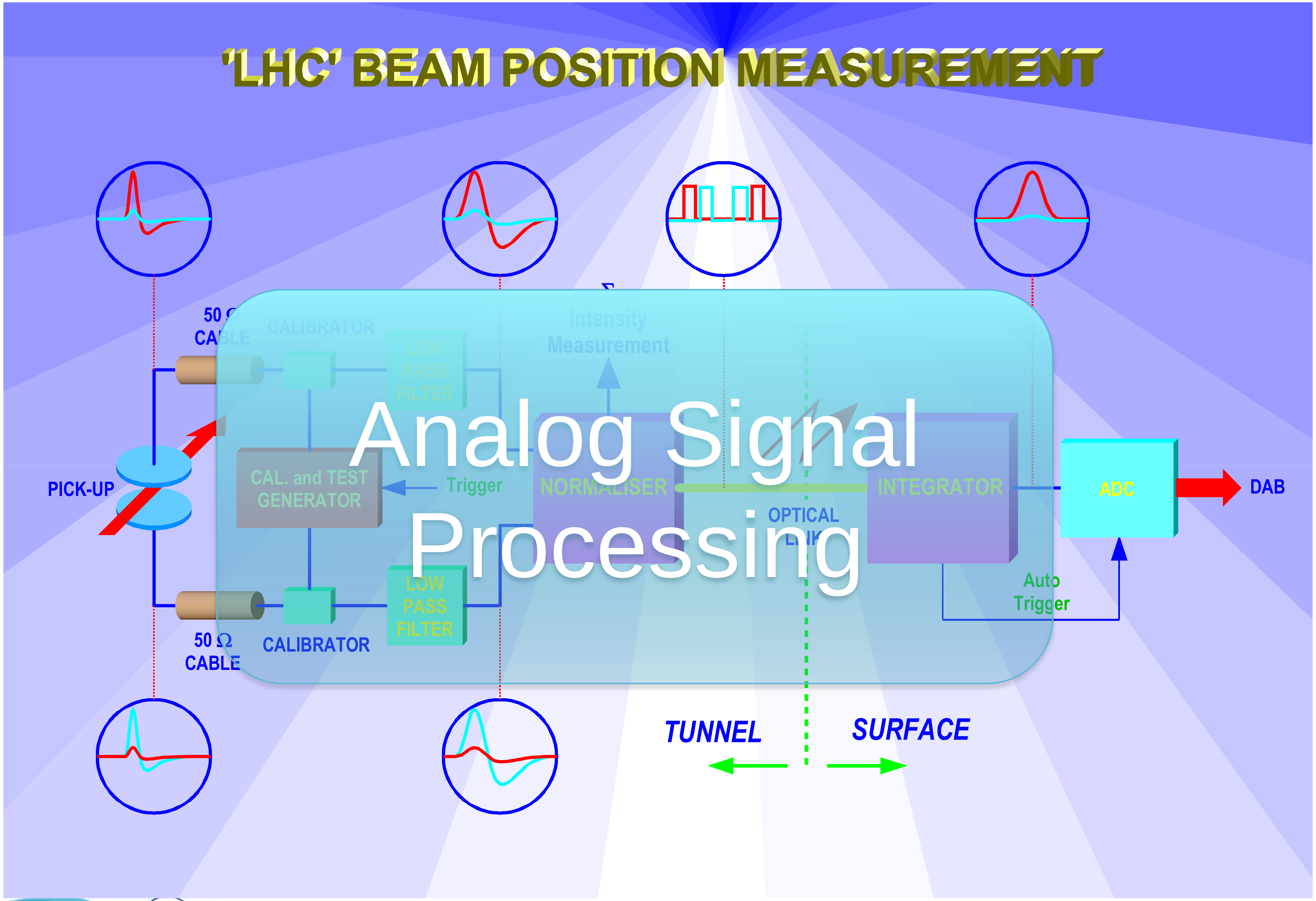
From:

LHC-BPM-ES-0004 rev 2.0

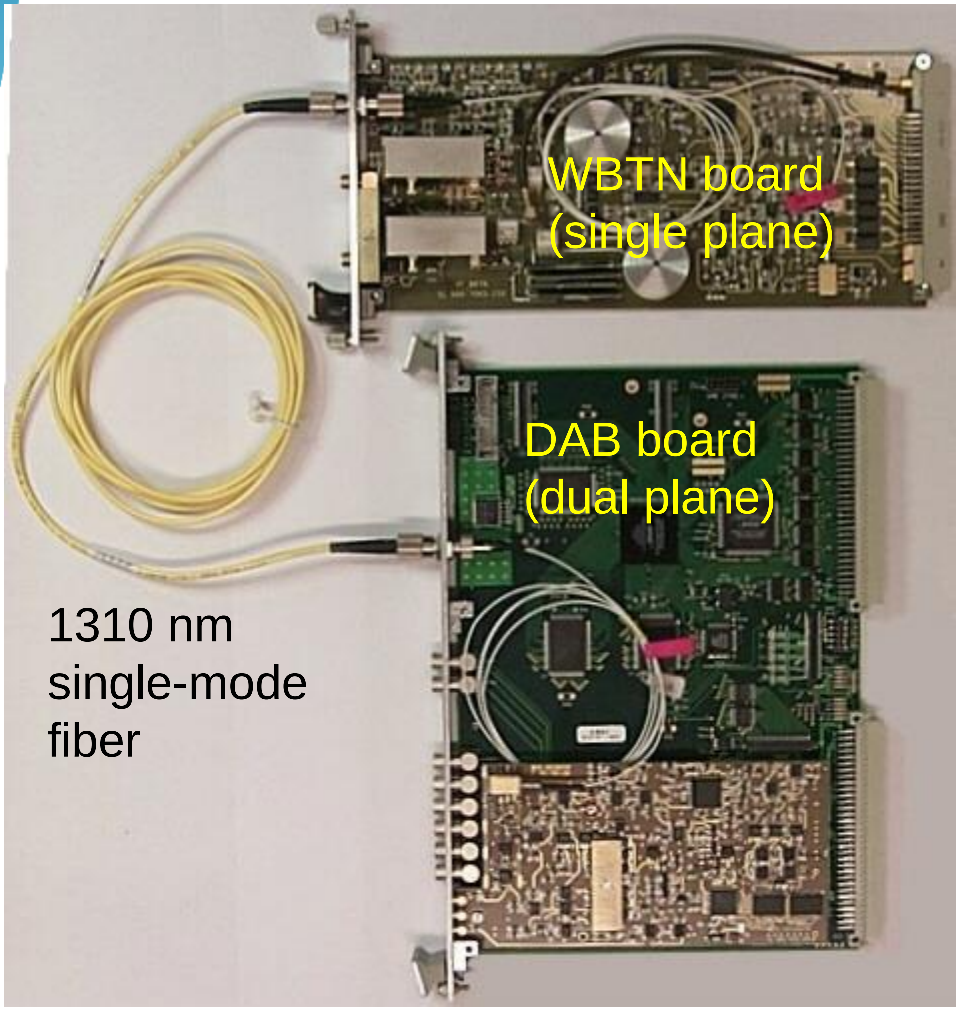
Functional Specification

MEASUREMENT OF THE BEAM POSITION IN THE LHC MAIN RINGS

Present LHC BPM Hardware



Present LHC BPM Front-end Hardware



- **Given infrastructure boundary (arc BPMs)**
  - 6 optical fibers (+ 2 spares)
    - 4 x BPMs & 2 x BLMs
  - 2 BPM pickups
    - Beam 1 & 2, H and V
    - Internal cryo coaxial cables

LHC BPM Consolidation: WHY?!

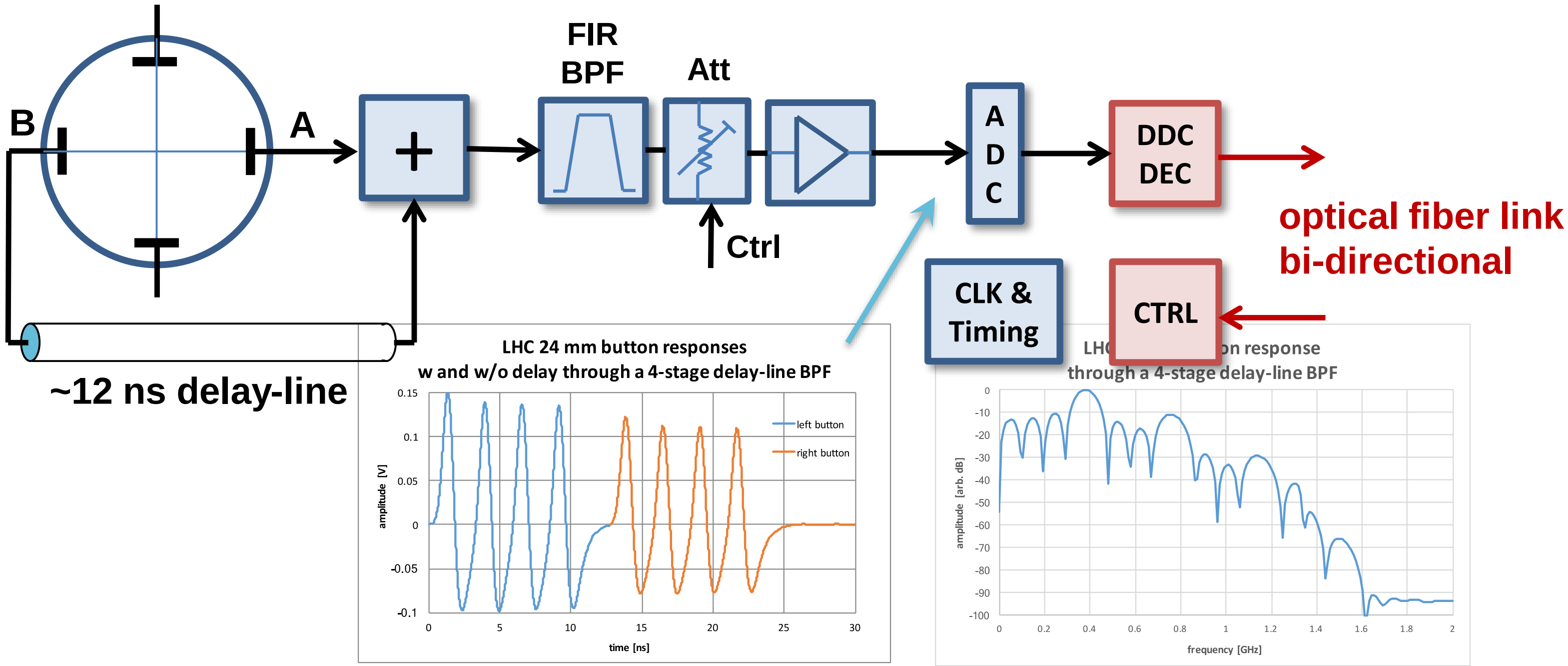
- **There is nothing really wrong with the current LHC BPMs!**
  - Reliable operation (~98 % of the LHC BPMs are up and running!)
  - Meets current specifications and functional requirements
    - 5e8 – 1.7e11 ppb, sufficient resolution, accuracy and stability (since temperature controlled crate upgrade)
    - Bunch-by-bunch, turn-by-turn, & orbit modes, injection and post mortem analysis, etc.
- **However…**
  - Aging analog electronics gets prone to malfunctions
    - Troubleshooting tends to be more difficult in large scale analog systems
    - Maintenance of >2000 BPM channels is difficult to cover in short access periods.
    - WBTN and integrator repairs requires a complicated re-calibration procedure
    - Electronics components start to get obsolete
  - Some shortcomings
    - Sensitive to signal reflections between BPM pickup and WBTN
    - ”Leakage” between bunches requires different calibration sets for SB and trains
    - Cannot adapt the system for exotic beam formatting, e.g. doublet bunches
- **BPM upgrade will be based on digital signal processing**
  - Based on existing infrastructure
  - Optical fiber links will serve as backbone of the data transmission
    - Their maximum data throughput determines the conceptual signal processing design

Daniel Cocq: “The wide band normalizer”
NIM-A 416 (1998) …getting vintage

From Requirements to Specifications…

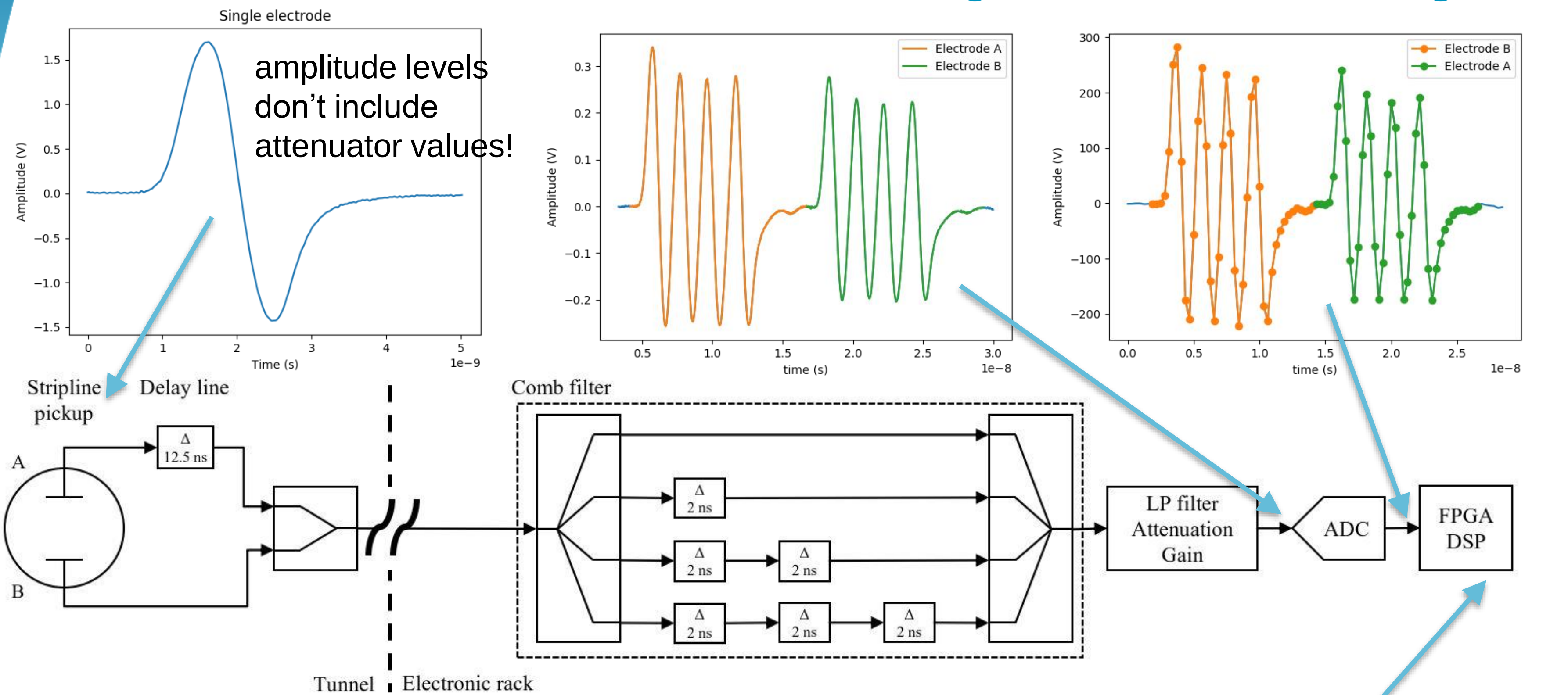
- **Only some BPM specifications are relevant wrt. read-out electronics!**
  - Most of the functional specifications
    - Bunch-by-bunch, turn-by turn, close orbit, etc. measurement capabilities
    - Calibration & test signals
    - Exotic beam conditions, e.g. doublet bunches (???!!!)
  - Some performance specifications
    - Single bunch dynamic range & integration time performance
    - Electronic offsets, long term stability and reproducibility
    - Scaling accuracy and non-linear correction algorithms
    - BPM resolution related to electronic noise
  - NOT:
    - BPM pickup mechanics, e.g. alignment, offset & roll, etc.
      - Except for the new IP BPM pickups
    - Signal reflections due to low quality and/or degraded cables and adapters between BPM and read-out electronics

BPM Signal Processing in the LHC Tunnel

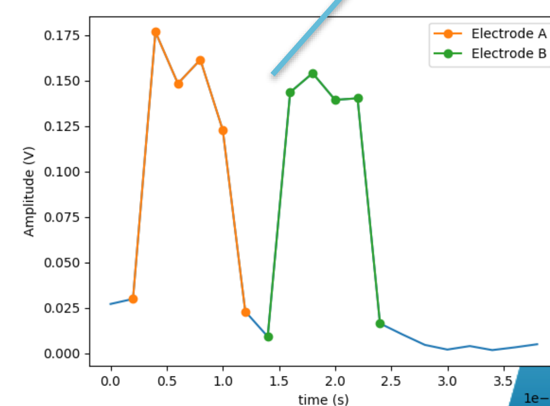


- **Single channel time-multiplexed BPM electrode signal processing schema**
  - Current R&D on the LHC interlock BPMs looks very promising
  - Based on a FIR delay-line BPF and
    a 12…14-bit, >3GSPS radiation tolerant ADC, DDC and decimation
    - e.g. dual ch. TI ADC12D1620QML-SP 12-bit, 3.2 GSPS, S/N >58 dB, TID 3 kGy
  - Use of the existing single-mode fibers
    - New VTRx data payload: ~8 GBPS uplink, ~2 GBPS downlink

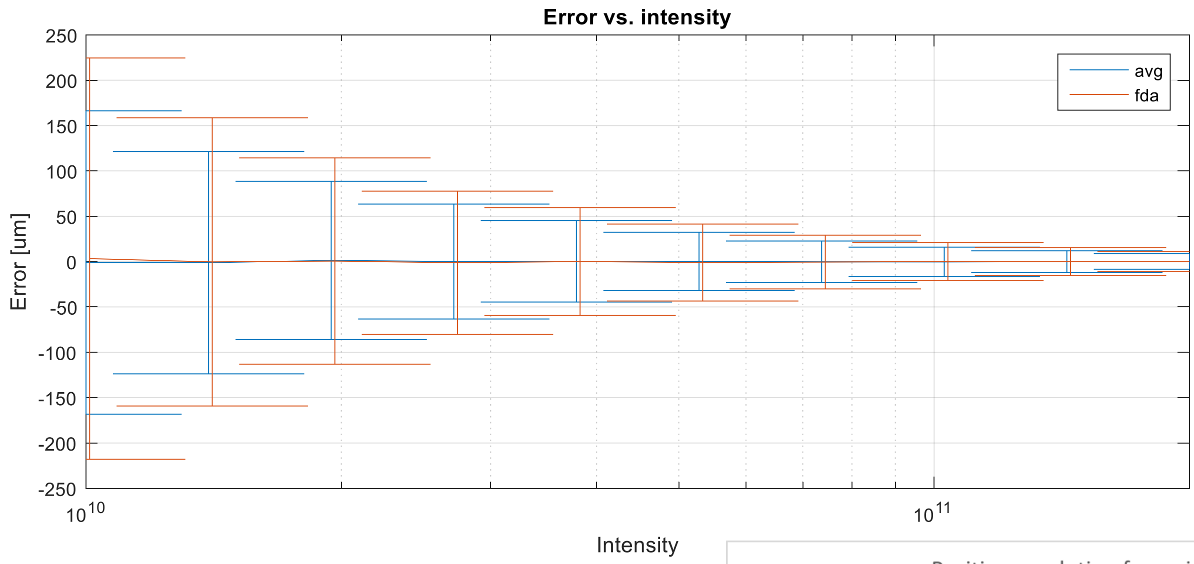
LHC interlock BPM R&D: Signal Processing



- Stripline BPM measurements at LHC point 5
  - 12-bit ADC operating at 3.2 GBPS
  - I-Q sampling, down-convertion and decimation /4 (work in progress…)

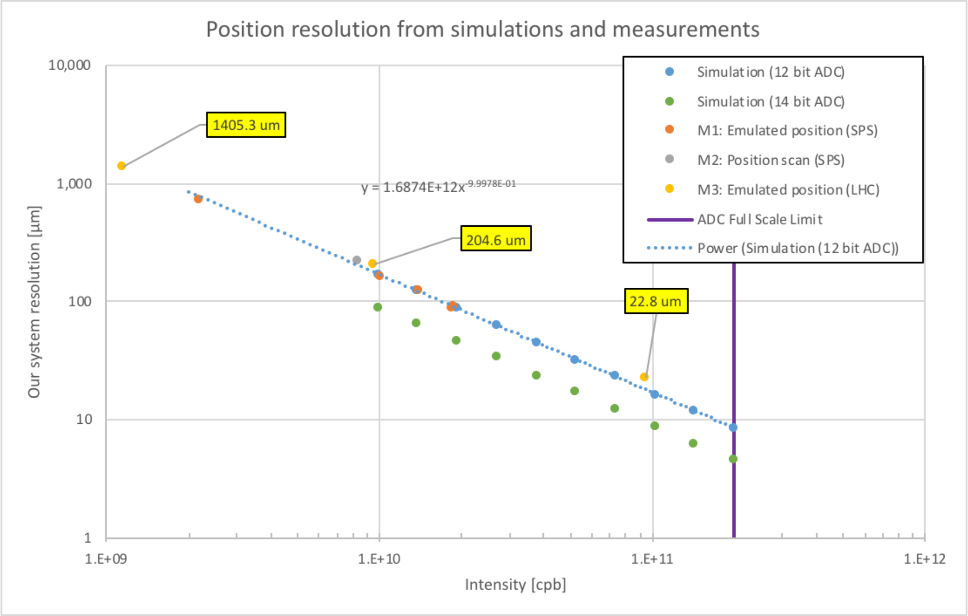


LHC interlock BPM R&D: Performance



Sim. parameters:
- 12 bits @ 3.2 GHz
- Random position
- Random time shift
- $\sigma_{noise} = 380\ \mu V$

- Single bunch resolution due to ADC quantization
  - Mean value (beam position) remains constant at lower bunch intensities
  - Good agreement between simulations and measurements
  - 14-bit ADC can improve the the resolution by ~2x



LHC Radiation Levels

Location	Expected radiation level			
	HL-LHC Annual		HL-LHC Lifetime	
	HEH ($cm^{-2}yr^{-1}$)	SEU rate (yr^{-1}) (*)	TID (Gy)	1 MeV n_{eq} (cm^{-2})
LHC arc (**)	1×10^9	500	20	1×10^{10}
Dispersion Suppressor (below dipoles)	1×10^{10}	5×10^3	200	1×10^{11}
UJ (IP1 and IP5)	5×10^9	5×10^3	100	5×10^{11}
UL (IP1 and IP5)	1×10^8	100	2	5×10^{10}
RR (IP1 and IP5)	3×10^9	2×10^3	60	3×10^{11}
RR (IP7) (***)	2×10^8	150	5	2×10^{10}

- **Expected HL-LHC TID (10 years)**
  - ~20 Gy in the arcs (?!)
  - ~200 Gy near dispersion suppressors, below dipoles, etc.
  - Radiation levels can exceed those values at specific locations by 5x…10x
  - Design goal for the BPM FE electronics is TID **???** Gy
    - Don’t like to over specify the electronics components!
    - Redundancy of LHC BPMs?

HL-BPM FE Electronics Specification Summary

- **BPM read-out electronics consolidation is based on the given infrastructure and environment**
  - BPM pickups, coaxial cables, SM fibers, radiation levels, etc.
- **Functional specifications basically remain**
  - Bunch-by bunch, turn-by-turn, closed orbit capabilities, capture and post-mortem modes, etc.
  - BUT: Doublet bunch measurement capability at reduced performance
- **Improved performance and better maintainability**
  - Design goals for nominal bunch intensities:
    - < 10 μm bunch-by-bunch resolution
    - < 50 μm long term drift (electronics offset)
  - Digital BPM signal processing in the LHC tunnel
    - More easy to maintain and adapt
    - Improves performance, e.g. reproducibility, resolution

Thank you!