HL-LHC IP and Ring BPMs:
Read-out Technology and expected Performance

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and many other colleagues

176th WP2 meeting, 6/2/2020

Outline

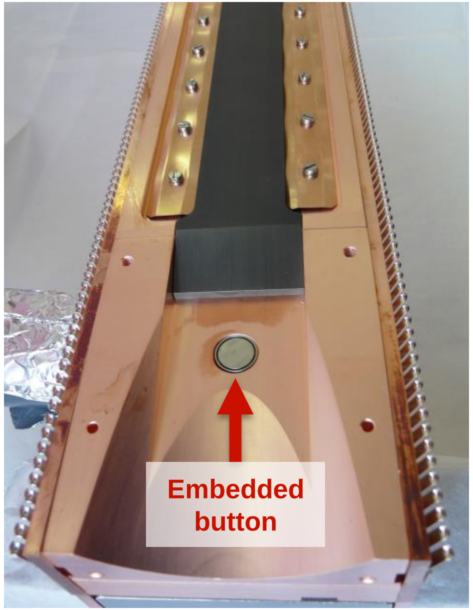
- Overview on LHC BPM activities
- The LHC BPM status quo
- The LHC ring BPM consolidation project
- The HL-LHC IR BPM system
- Summary

Overview of LHC BPM Activities

- **Interlock BPM consolidation**
  - **8 stripline BPMs left & right of point 6**
  - **New read-out electronics consolidation**
    - ***initially triggered by operational problems with doublet-bunches***
  - **Prototype tested with beam during run 2**
    - ***on BPMS.4L5v***
    - ***Time-multiplexed BPM electrode signals***
    - ***Band-pass comb filter allows doublet bunch signal processing***
      - However, with reduced performance
    - ***VFC-based commercial 14-bit FMC ADC operating at 2.6 GB/s***
  - **Final prototype to be installed end of LS2**
    - ***Details have been worked out in close collaboration with MPP***
  - **Deployment of the entire system during an upcoming YETS…**

Overview of LHC BPM Activities (cont.)

- **Integrated Collimator BPMs**
  - **Buttons embedded in collimator jaws to speed up set up since 2013**
  - **Uses high-precision DOROS BPM acquisition system**
  - **Collimator jaw position now interlocked on BPM readings**
  - **Challenging integration and component procurement: coaxial SiO_2 RF cables**
  - **All HL-LHC collimators will be equipped with BPMs**



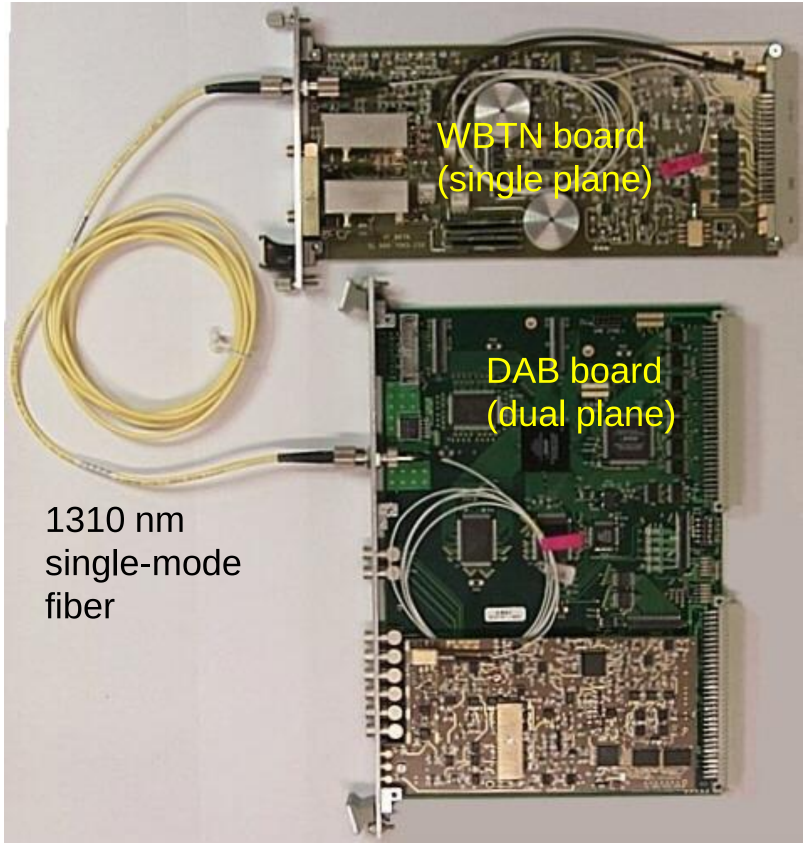
- **HEL Stripline BPM**
  - **Needs to monitor the hollow-electron beam and the LHC proton / ion beams**

Overview of LHC BPM Activities (cont.)

- **HL-BPMs (IR BPMs)**
  - **32 new BPMs**
    - ***"cold" BPMs inside the cryostat***
    - ***24 stripline BPMs to monitor of both beams in the same beam pipe***
    - ***8 button BPMs in separate beam pipes (D2)***
  - **Requires a new read-out system**
    - ***Final prototyping with beam before LS3!***
    - ***Deployment of the entire system by end of LS3!***

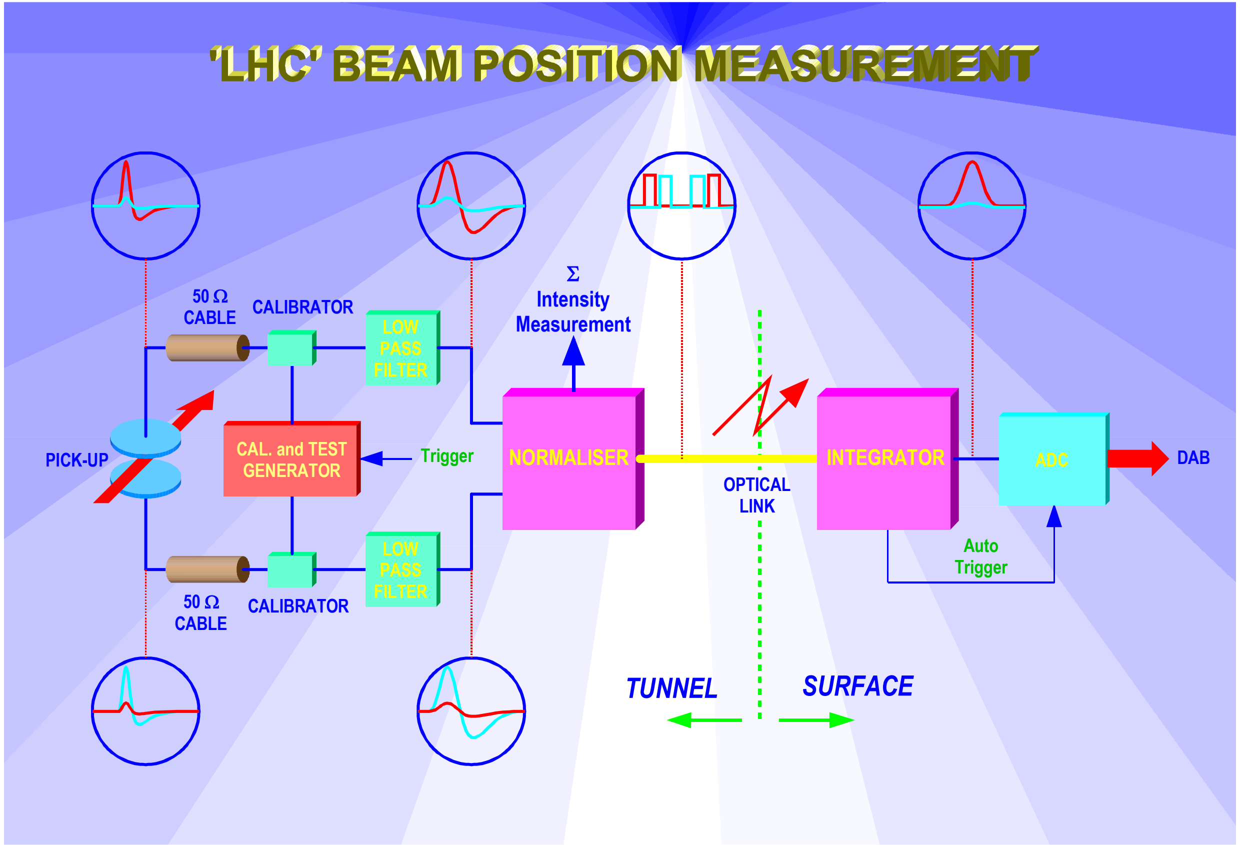
- **Ring BPM consolidation**
  - **New read-out electronics for ~1100 LHC BPMs**
    - ***Based on the given infrastructure***
    - ***Radiation tolerant tunnel electronics***
    - ***Prototyping during run 3***
    - ***Deployment LS3/LS4?***

LHC BPM Read-out Systems: Status Quo in LS2

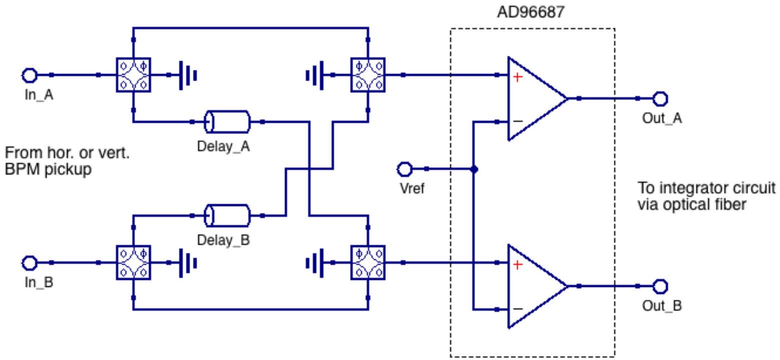


- WBTN BPM System
  - Time encoded bunch-by-bunch signal processing
  - 2 optical fibers per BPM
- DOROS BPMs
  - Narrowband electronics
  - Collimator & IR BPMs

LHC BPM Wide-Band Time-Normalizer (WBTN) Functional Principle



WBTN BPM Performance and Limitations



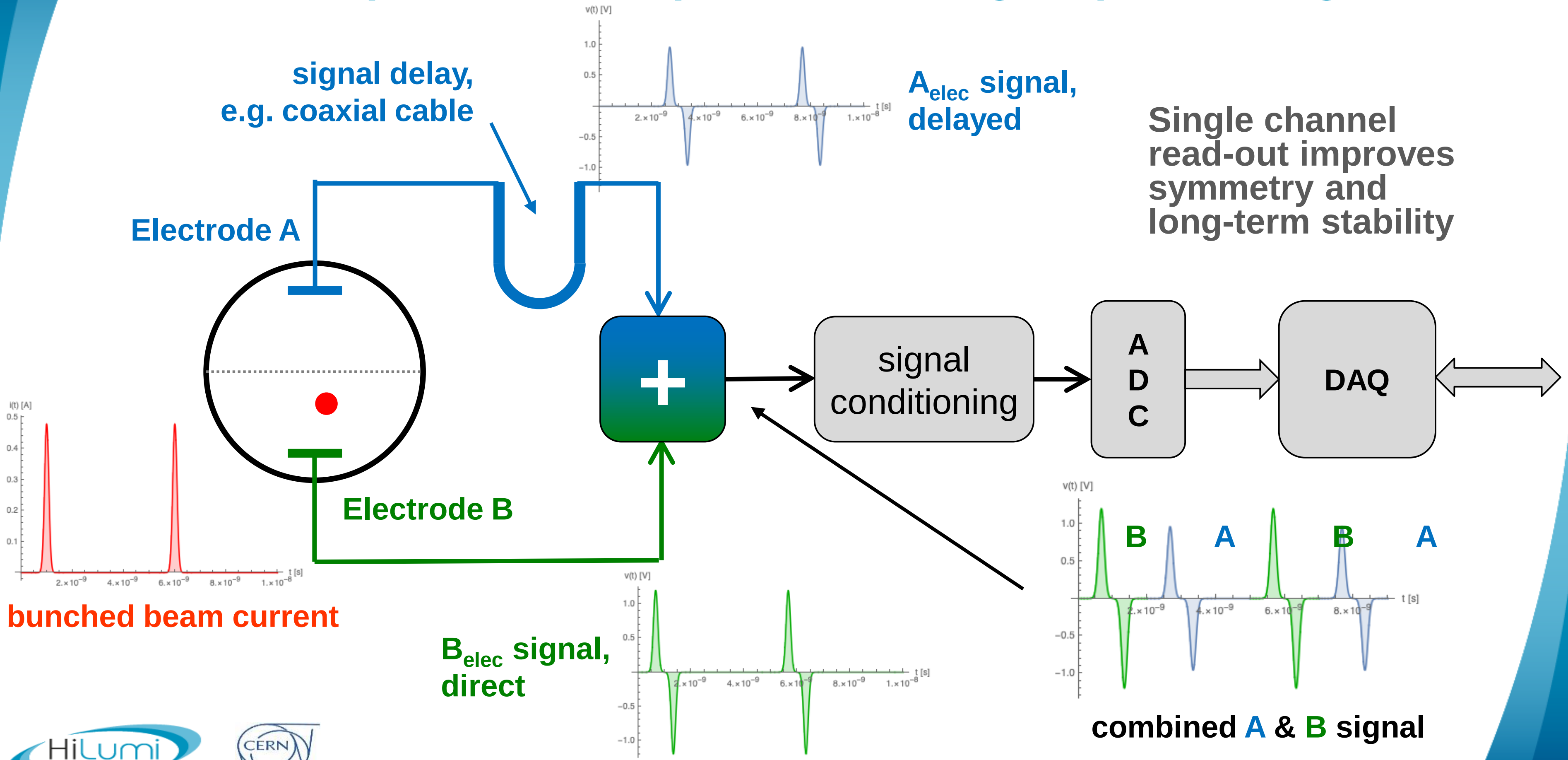
- **70 MHz LPF & AD96687 analog comparator define the core performance of the LHC BPMs**
  - **<=46 dB dynamic range (single bunch intensity)**
  - **Vref set to**
    - ***2mV: HI sensitivity***
    - ***67mV: LO sensitivity***
  - **50…100 µm single-bunch resolution**
    - ***Adaptive orbit-mode IIR filter BW: 20…40 Hz, typically few µm resolution in orbit-mode***

- **Still fulfills most requirements, BUT:**
  - **Residual temperature sensitivity**
    - ***Despite temperature controlled racks for the VME-based analog integrators***
  - **Aging effects, e.g. "electronic" offset drifts**
    - ***Analog electronics components***
  - **Sensitive to signal reflections between BPM pickup and read-out electronics**
  - **Dynamic range limitations**
    - ***Defined by the dual analog comparator circuit***
  - **Long-term maintainability, spares, calibration, etc.**
    - ***Complex analog signal conditioning circuit***
    - ***Will be 20 years in operation after LS3***

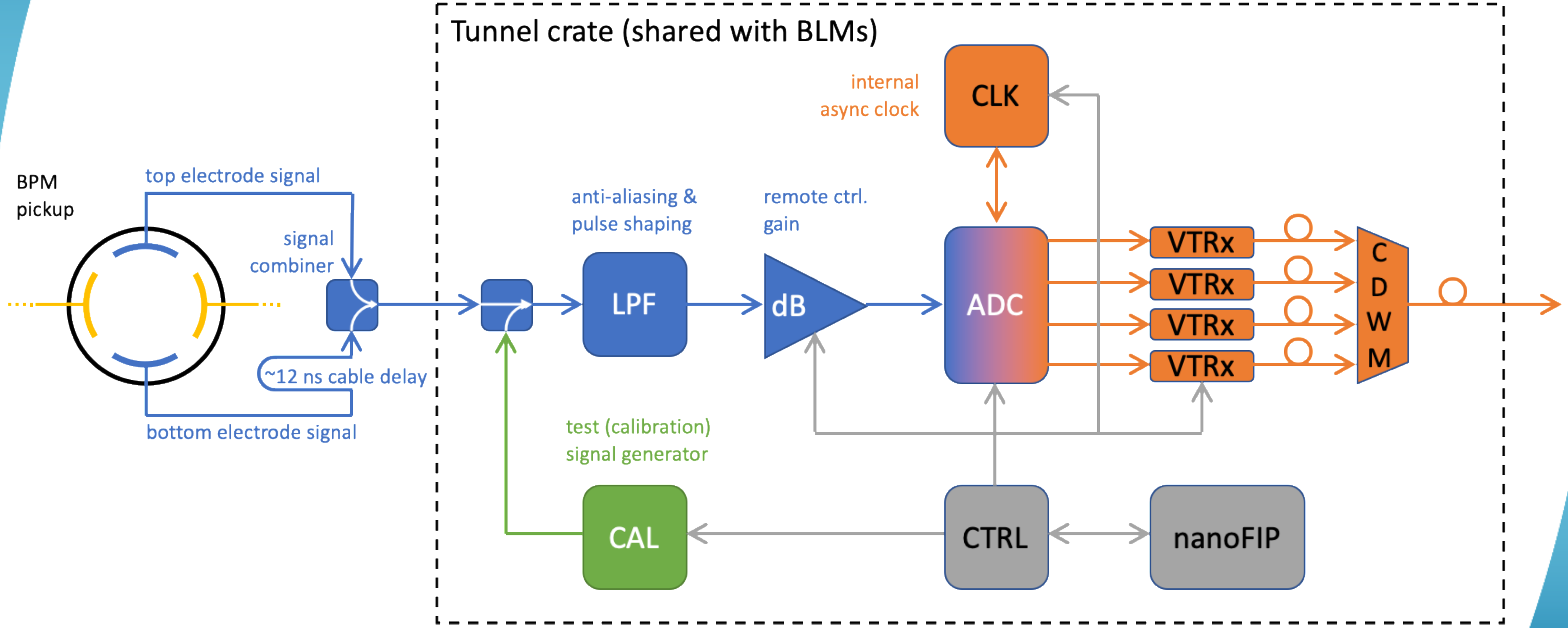
LHC Ring BPM Consolidation

- **Requirements**
  - **Should meet ALL requirements of the present LHC BPM read-out system**
  - **PLUS some improvements, e.g.**
    - ***Resolution, reproducibility over long time periods, additional flexibility through gateware-based signal processing***
  - **Two main "customers":**
    - ***LHC OP: pilot, but mostly full machine with nominals, beam orbit mode, OFB, stability, reproducibility***
    - ***ABP: (fat) pilot, TbT mode, SB resolution***
- **Boundaries**
  - **Keep the existing infrastructure**
    - ***BPM pickups, optical fibers***
  - **Requires radiation tolerant components!**

Concept: Time-multiplexed BPM signal processing

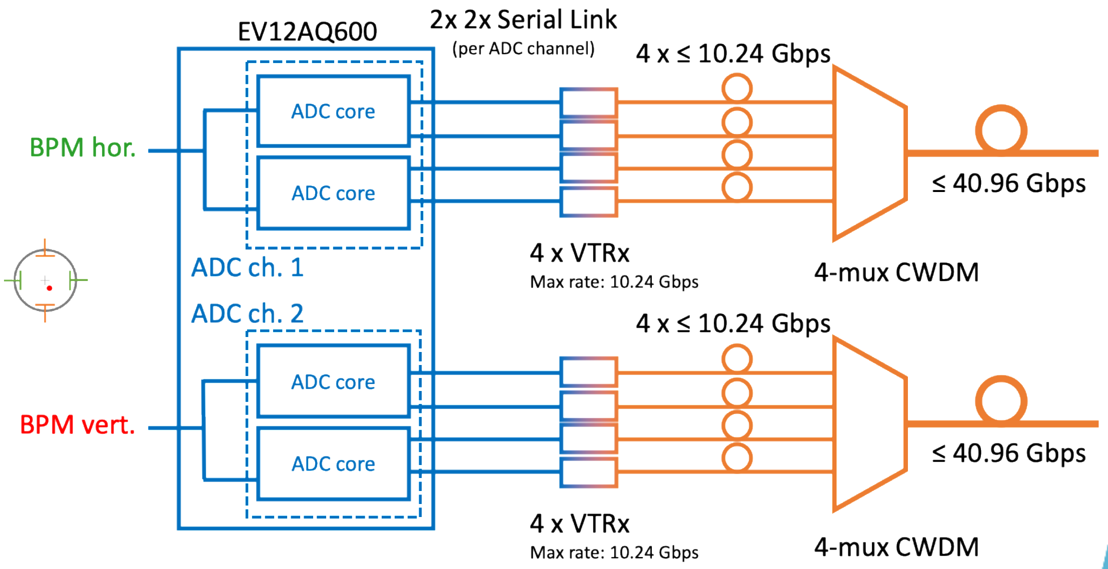


LHC Ring BPM Consolidation: Proposed Layout



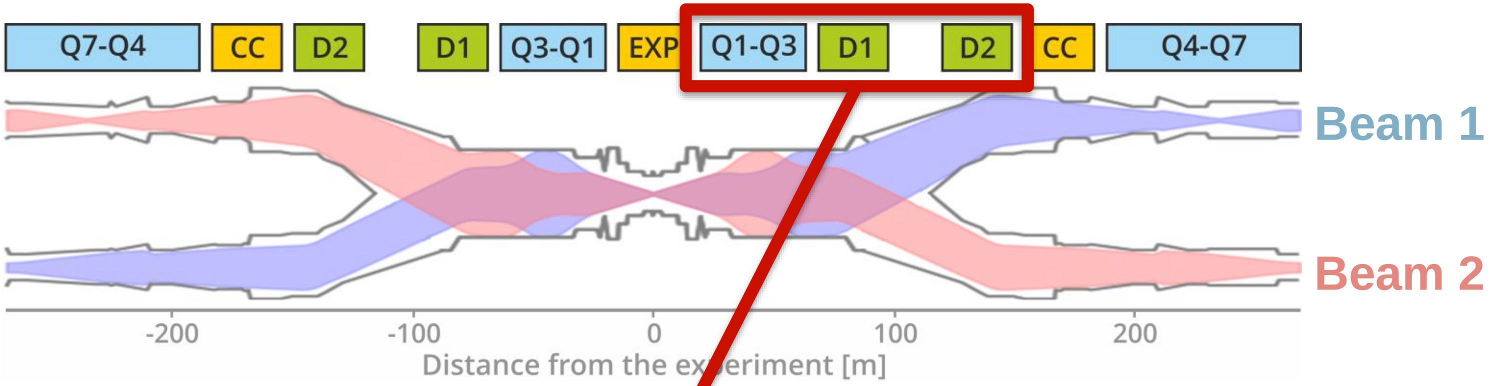
LHC Ring BPM Consolidation (cont.)

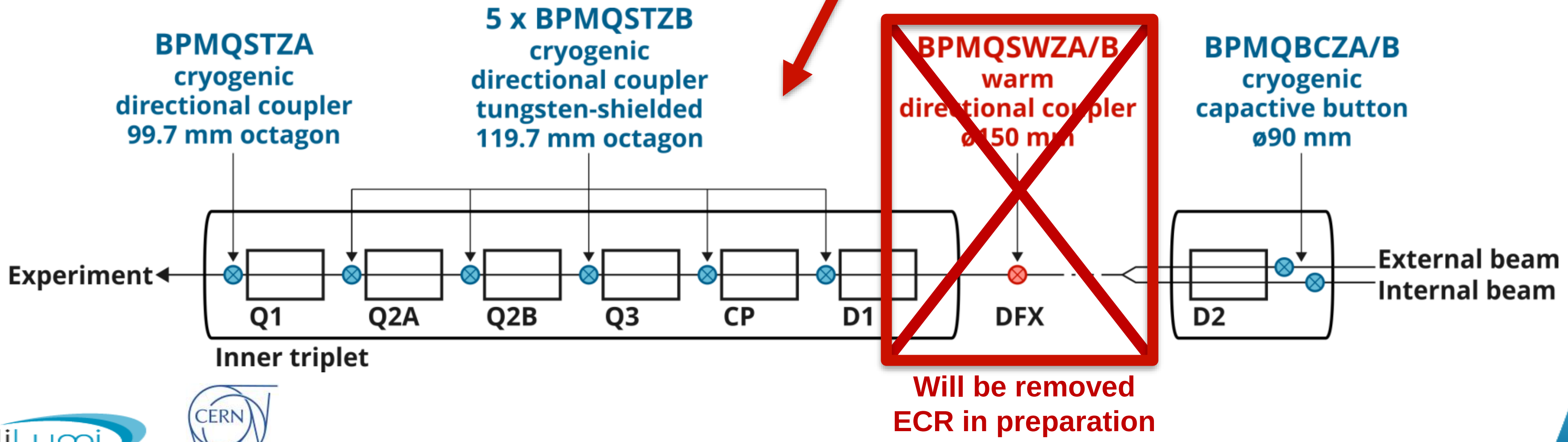
- **Challenges**
  - **Radiation tolerant components for the in-tunnel hardware**
    - ***Space-grade, radiation-tolerant 12 or 14-bit multi GB/s ADCs***
      - Teledyne e2v EV12AQ600
        12-bit, 6.4 GS/s, 4-cores, ~8.7 ENOB
      - TI ADC12DJ3200QML-SP
        12-bit, 6.4 GB/s, 2-cores, ~8.7 ENOB
    - ***Low-jitter clock generator & PLL***
    - ***VTRx transceiver***
      - Currently under development
  - **Maximum raw data throughput limited by existing fiber installation**
    - ***With 4x coarse wavelength division multiplexer ≤40.96 GB/s***



- **Expected Performance**
  - **Single bunch resolution 10…15 µm**
    - ***Depending on ADC ENOB and CLK rate, and 2-in-1 or 4-in-1 time multiplexing schema***
    - ***“fat” pilot bunch, ~2e10 cpb***

BPMs for Interaction Regions



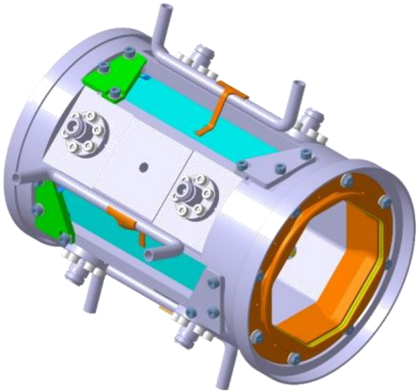


HL-LHC BPM overview

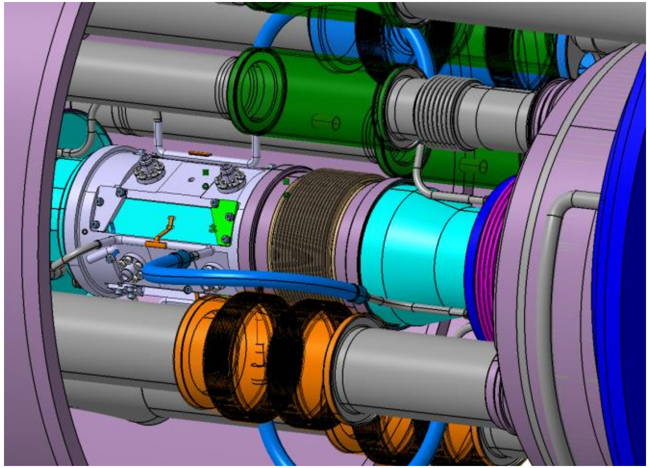
Code	Location	Distance to IP [m]	Aperture [mm]	Type	Tungsten shielding	Electrode position	Beam time separation [ns]
BPMQSTZA	Q1 (IP side)	21.853	Octagonal 101.7 / 99.7	Stripline	No	0° / 90°	3.92
BPMQSTZB	Q2A (IP side)	33.073	Octagonal 112.7 / 119.7	Stripline	Yes	45° / 135°	3.92
BPMQSTZB	Q2B (IP side)	43.858	Octagonal 112.7 / 119.7	Stripline	Yes	45° / 135°	6.82
BPMQSTZB	Q3 (IP side)	54.643	Octagonal 112.7 / 119.7	Stripline	Yes	45° / 135°	9.72
BPMQSTZB	CP (IP side)	65.743	Octagonal 112.7 / 119.7	Stripline	Yes	45° / 135°	10.52
BPMQSTZB	D1 (IP side)	73.697	Octagonal 112.7 / 119.7	Stripline	Yes	45° / 135°	7.36
BPMQBCZA BPMQBCZB	D2 (arc side)	151.930	Round Ø 90	Button	No	0° / 90°	N/A

“Cold” Directional-Coupler BPMs

- **Technology**
  - 125 mm long stripline electrodes,
“45^0 rotated” installation (type B BPMs)
  - ~26 dB directivity to improve the disentanglement of the B1/B2 signals
  - Tungsten shielding:
lower TID on Q2B magnet by ~15 %
  - Amorphous carbon coating:
Electron cloud effects decreased by 40x
  - Active cooling with liquid He:
To evacuate up to 6 W of head load

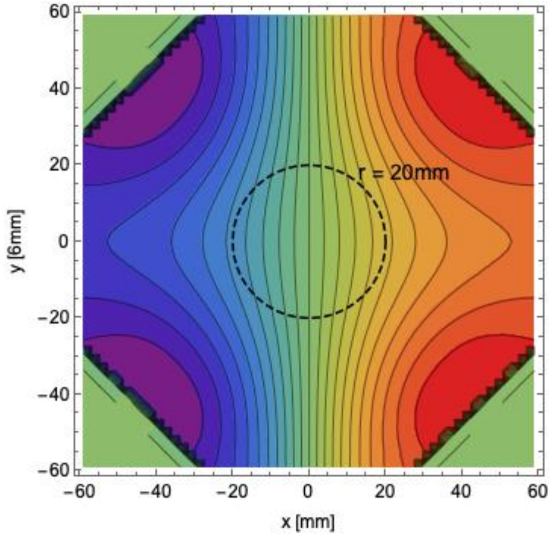


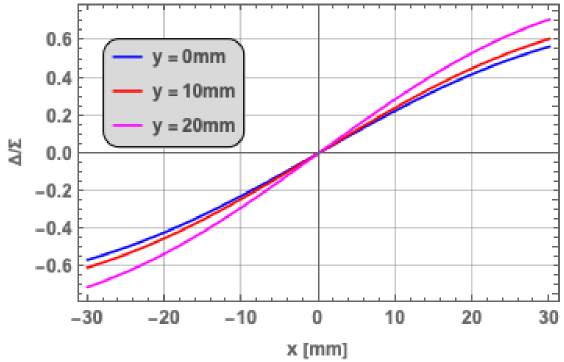
- **Status / Milestones**
  - BPM prototype production launched
  - Started procurement of tungsten absorbers (with WP12) and cryogenic RF feedthroughs
    - *Qualification of RF feedthroughs in 2020 (?!)*
  - In-kind contribution of BPM body manufacturing
    - *Collaboration agreement with Russia finalized*
  - Coaxial SiO_2 RF cables
    - *Market survey and procurement start for mid 2020*
    - *In combination with cables required for the collimator BPMs*

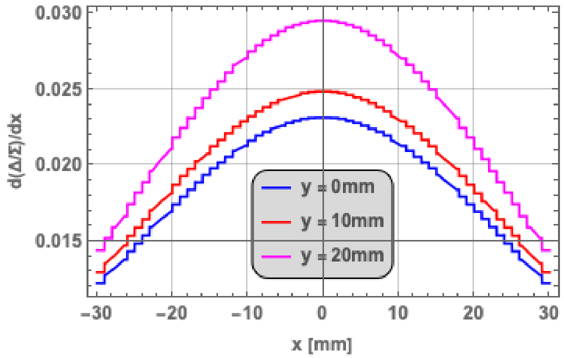


Impact of large aperture, rotated BPMs

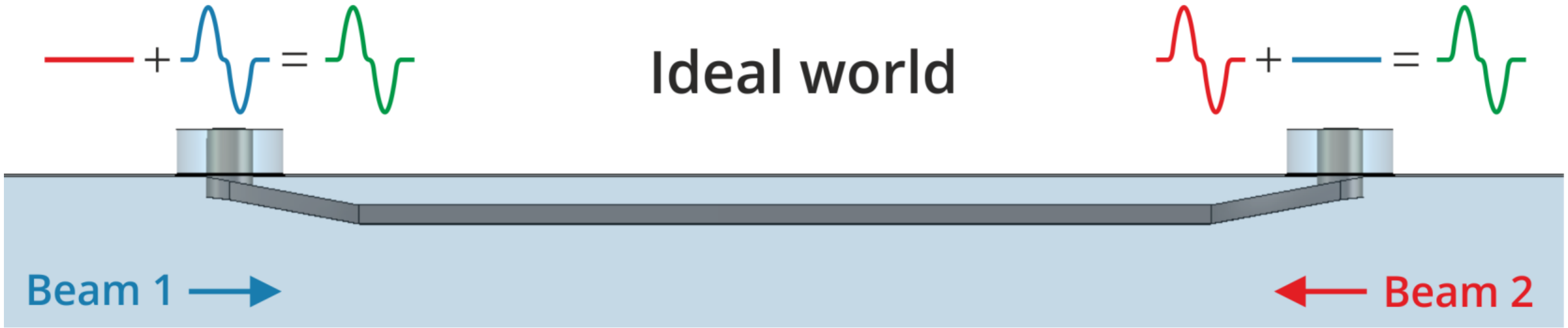
- Reduced coupling, 7.5 % for a centered beam
- Reduced BPM sensitivity, 0.4 dB/mm at the BPM center
- Increased position non-linearities



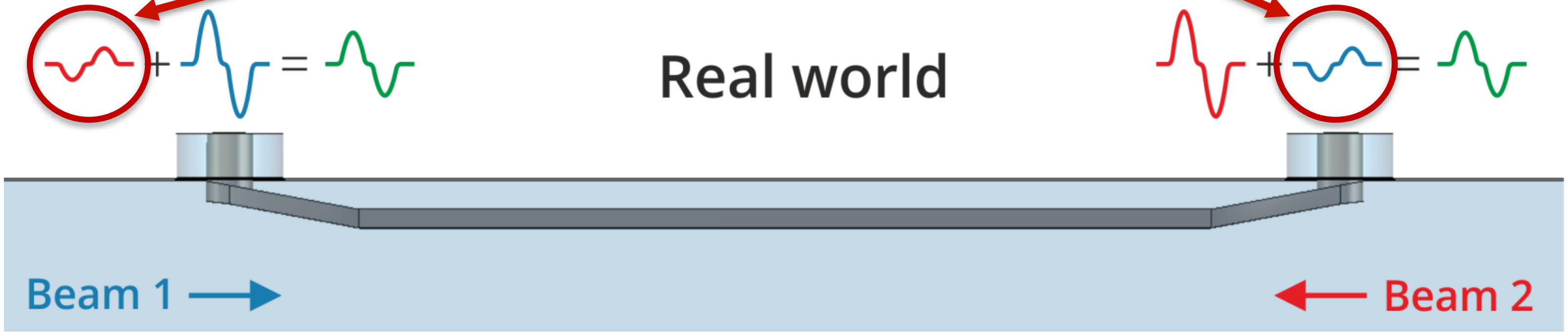




Directional couplers have a finite “directivity”

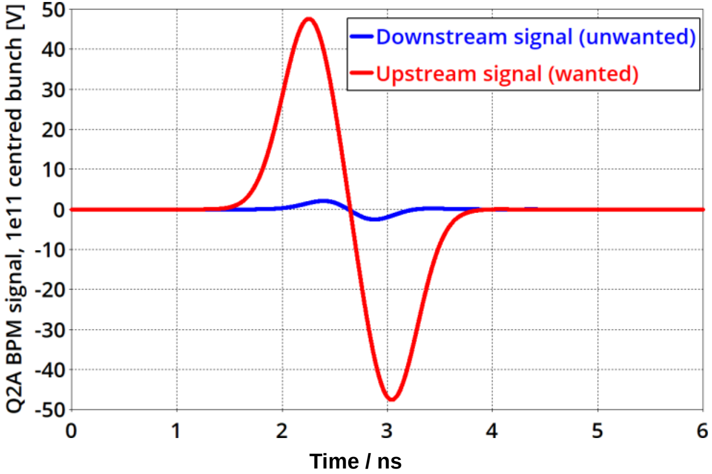


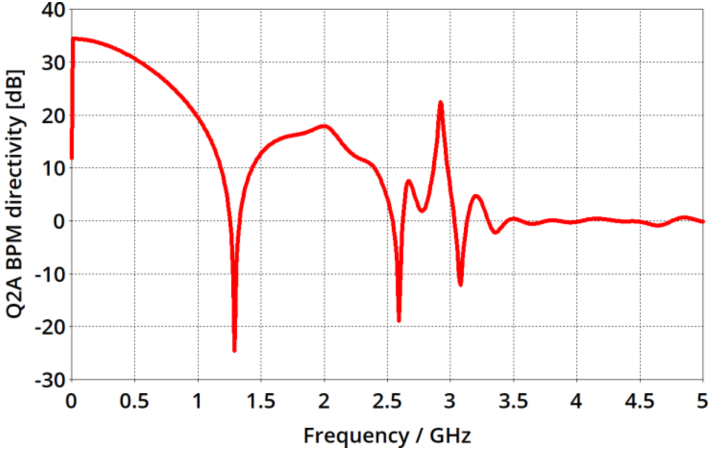
Unwanted parasitic signal



Directivity

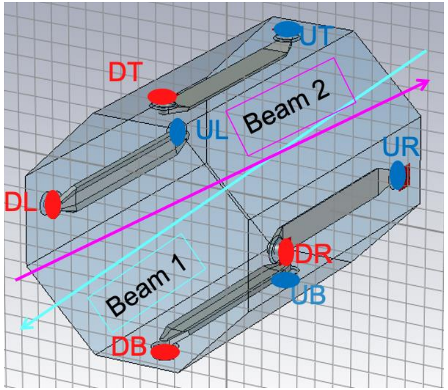
- *Directivity* – the ratio of the upstream (wanted) signal to the downstream (unwanted) signal
- Ways of improving the directivity:
  - Careful RF design of the BPM (constant 50 Ω impedance)
  - Operating at lower frequencies
  - Installing the BPM in a location where the two beams are separated in time
- HL-LHC BPM directivity: ~ 26 dB

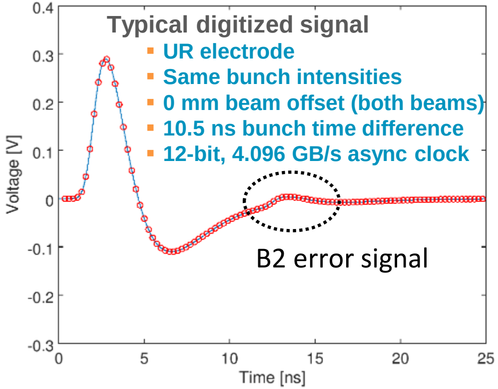


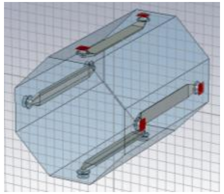


IR BPM Signal Processing

- **Study or B1-B2 compensation schemas**
  - **Bunch-by-bunch signal processing**
    - *25 ns time window*
  - **Up to 10x intensity variation**
    - *Between counterrotating bunches*
  - **up to 17 mm beam offsets**
    - *Injection orbit at IR1*
  - **Uncompensated bunch lengthening**
  - **Accuracy errors, resolution**







Stripline BPM

pickup → long cable (60-140 m) → Low-pass filter → variable attenuator → Digital processor

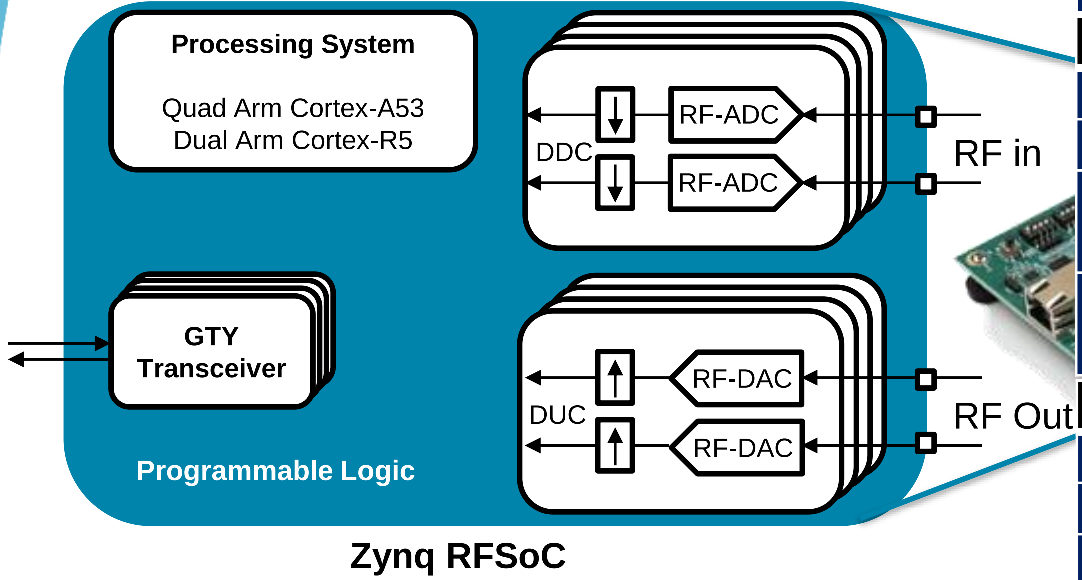
Processor is not rad-hard, electronics must be located in the service gallery

Anti-aliasing filter also stretches signal to make efficient use of the digitizer

Match signal level to ADC range

Candidate Digital Signal Processor

- *Xilinx* Zynq RFSoC (= radio frequenc
- Model ZU28DR (Zynq UltraScale arc



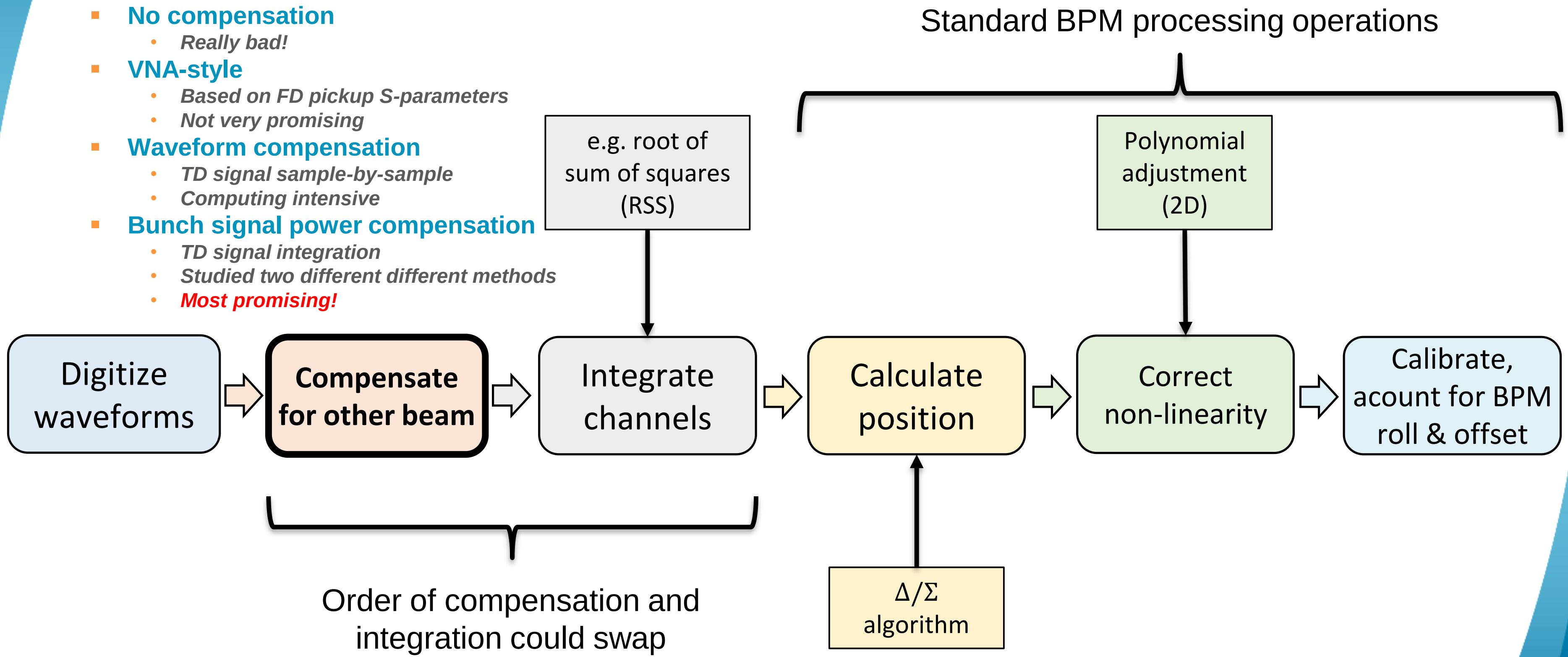
Processing System Features	
Application Processing Unit	Quad-core Arm Cortex-A53 up to 1.33 GHz
Real-Time Processing Unit	Dual-core Arm Cortex R5 up to 533 MHz

Direct-RF Signal Chain Features		
Max. RF input Frequency (GHz)		4
Decimation / Interpolation		1x, 2x, 4x, 8x
12-bit RF-ADC	# of ADCs	8
	Max Rate (GSPS)	4.096
14-bit RF DAC	# of DACs	8
	Max Rate (GSPS)	6.554

Programmable Logic	
System Logic Cells (K)	930
DSP Slices	4,272
Memory (Mb)	60.5
33G Transceivers	16
Maximum I/O Pins	347

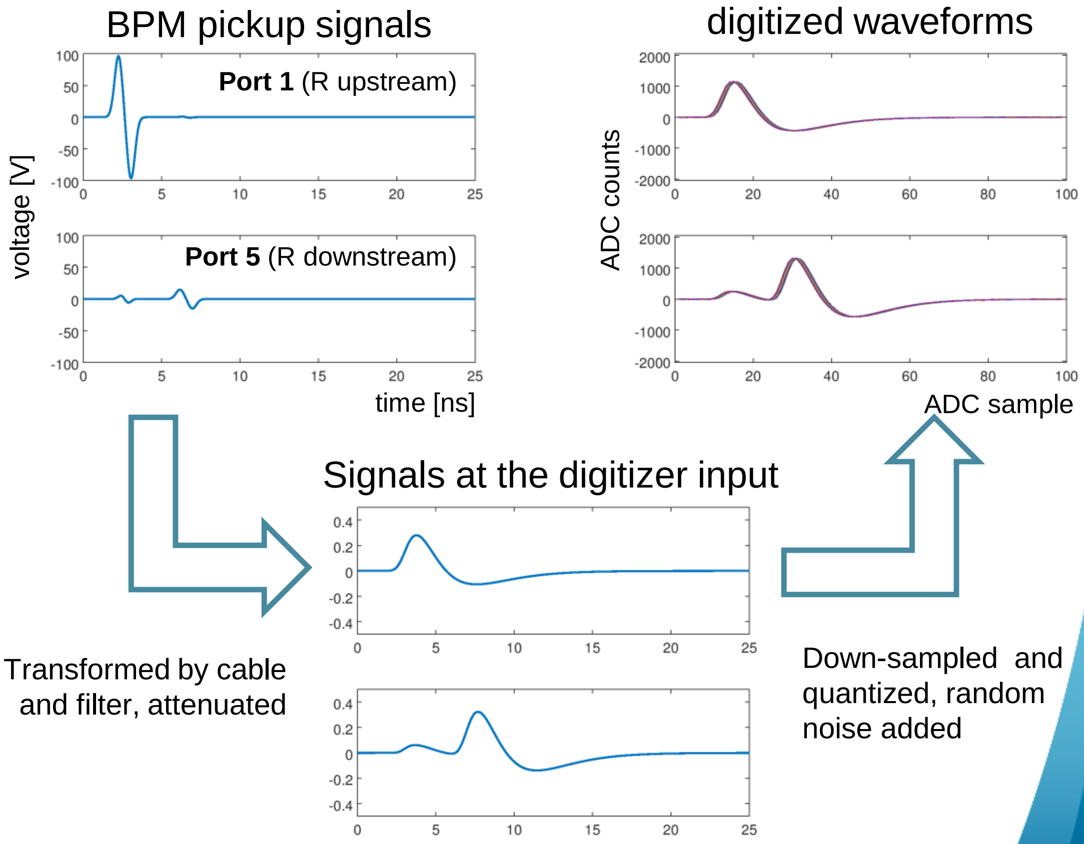
Digital Signal Processing Simulation Framework

- **Studied different compensation algorithms**
  - **No compensation**
    - ***Really bad!***
  - **VNA-style**
    - ***Based on FD pickup S-parameters***
    - ***Not very promising***
  - **Waveform compensation**
    - ***TD signal sample-by-sample***
    - ***Computing intensive***
  - **Bunch signal power compensation**
    - ***TD signal integration***
    - ***Studied two different different methods***
    - ***Most promising!***



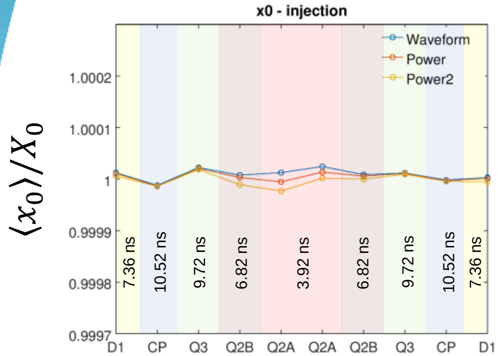
Simulation Methodology

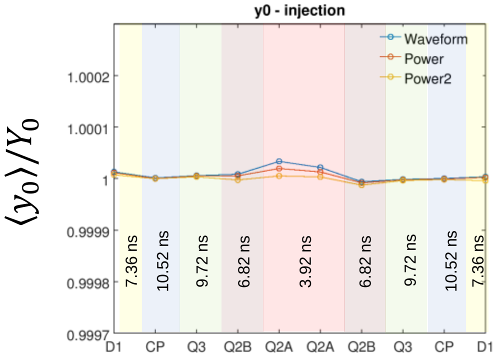
- Calculate the signals expected on the stripline ports for a given pair of beam bunches, characterized by their:
  - Positions in the BPM plane
  - Bunch crossing timing
  - Intensities
  - (Gaussian) bunch lengths
- Also include the effects of:
  - long coaxial cables
  - filter stage
  - variable attenuator (given step size)
- The resulting signals are used as the basis for an ensemble of waveforms generated from a digitizer with an asynchronous clock with given:
  - sample frequency
  - random noise amplitude

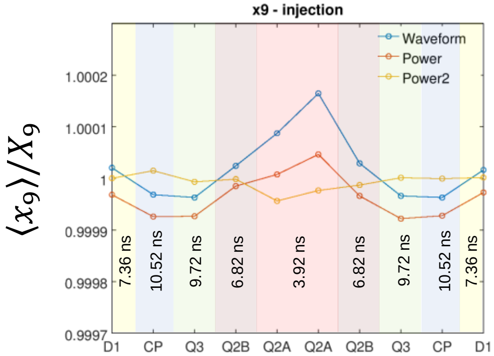


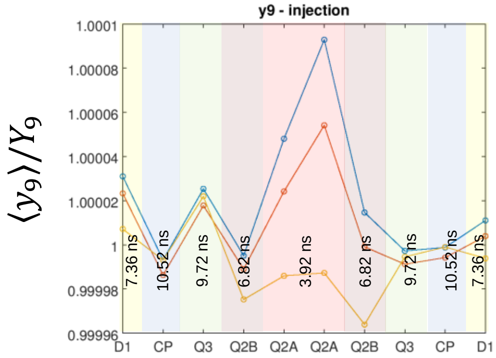
Typical Results – Relative Accuracy Errors

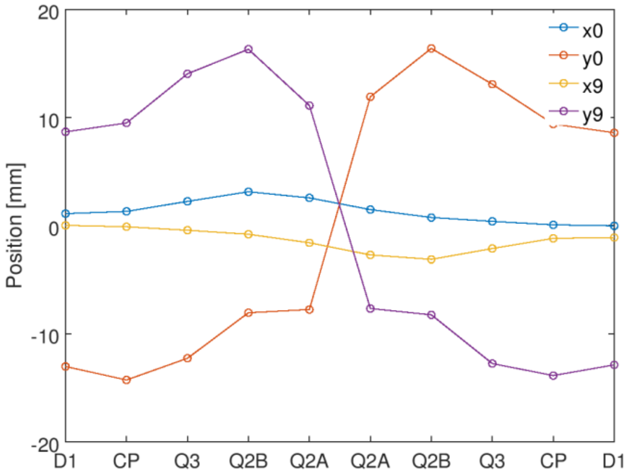
- **IR1 – injection orbit**
  - $i_0 = i_9 = 3 \cdot 10^{11} cpb$
  - $\sigma_0 = \sigma_9 = 75\ mm$











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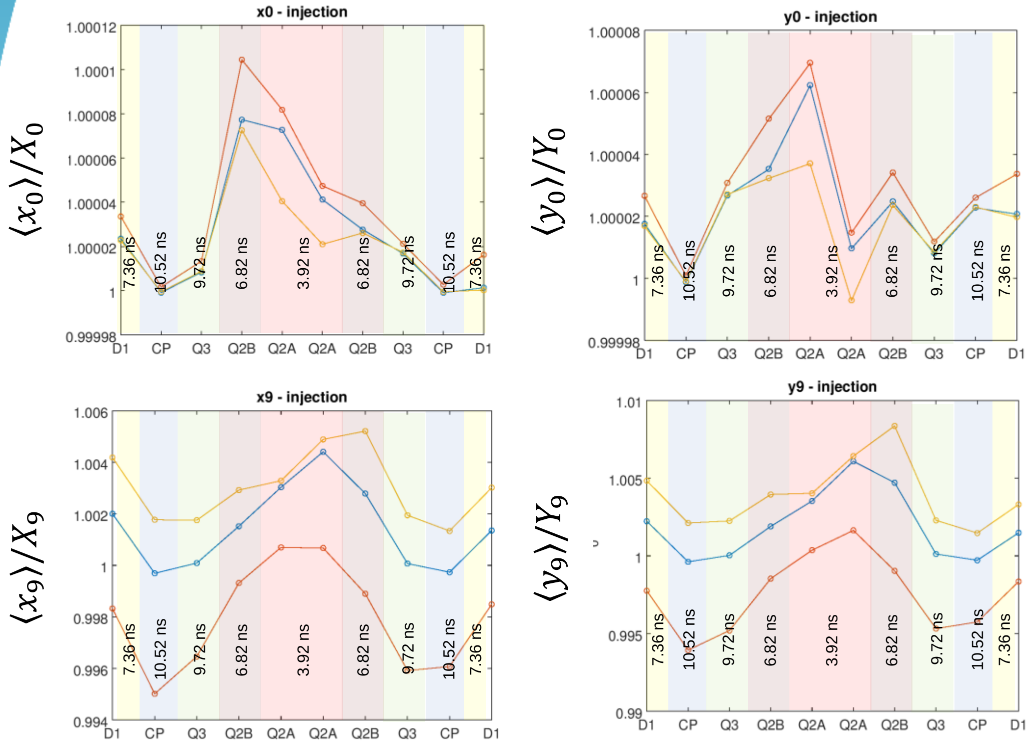
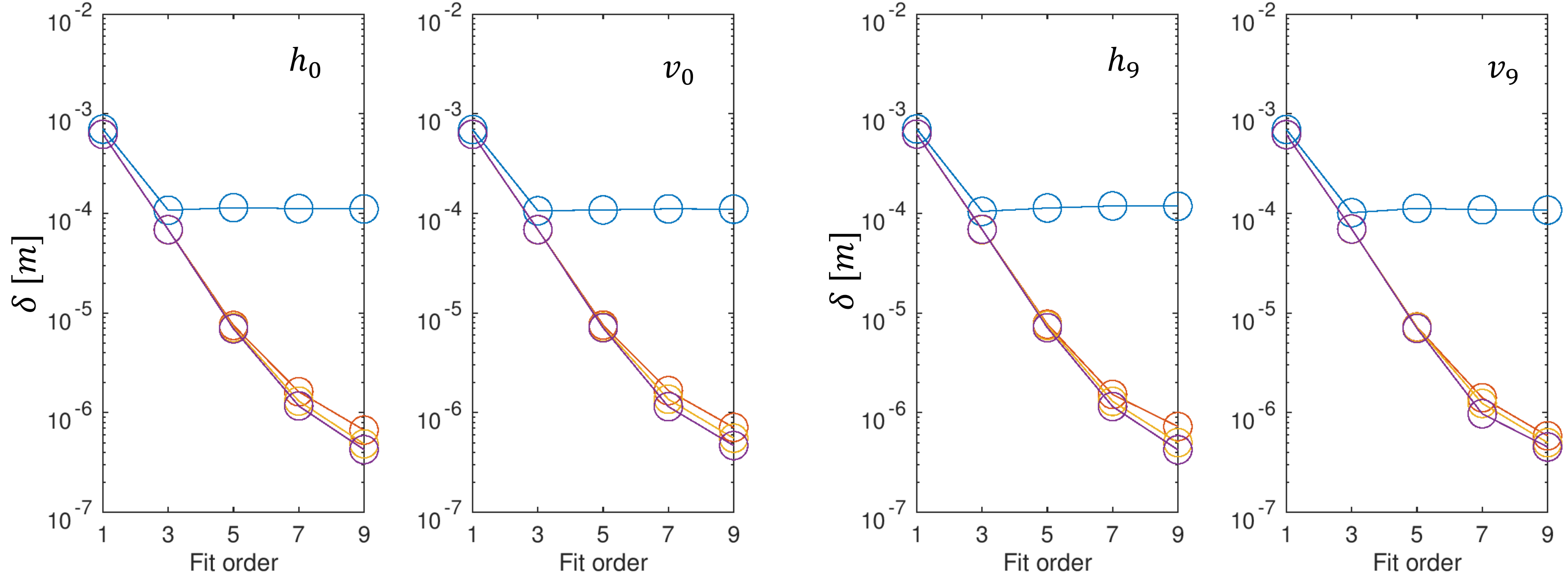


- **IR1 – injection orbit**
  - $i_0 = 3 \cdot 10^{11} cpb$
  - $i_9 = 3 \cdot 10^{10} cpb$
  - $\sigma_0 = \sigma_9 = 100\ mm$
    - *However, bunch lengthening effect not considered*

Typical Results – Absolute Position Errors

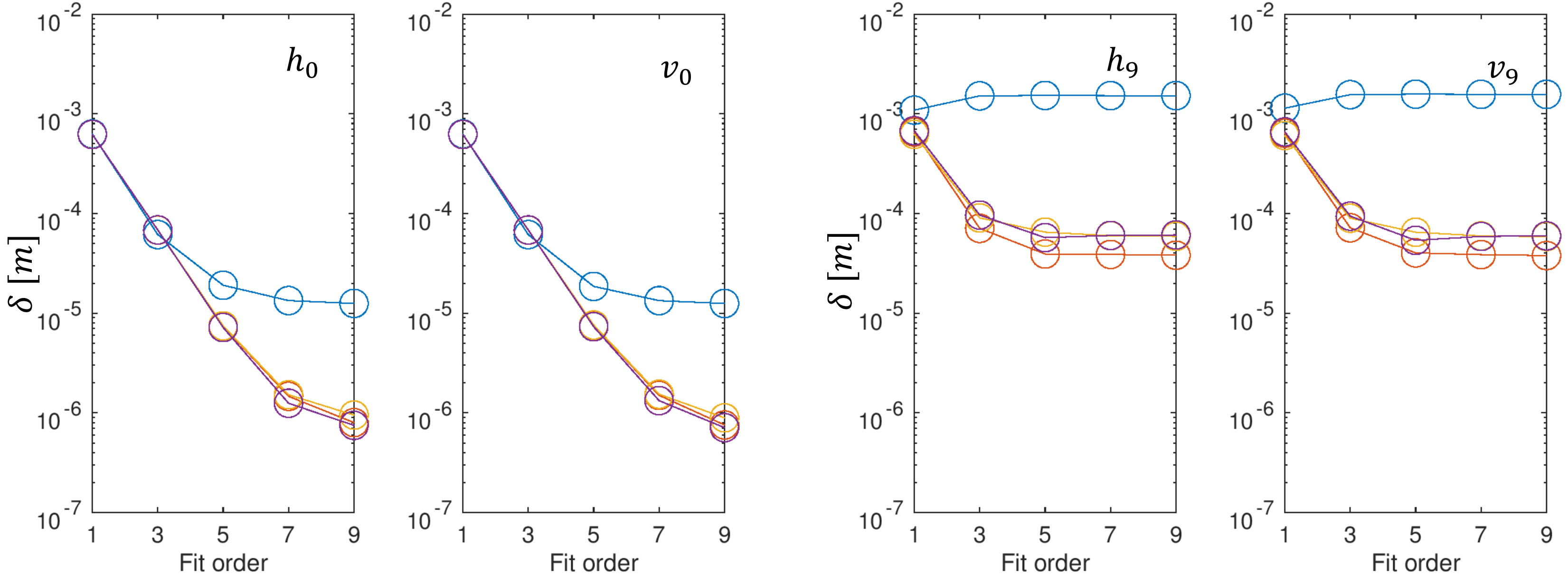
- Position error for maximum beam displacement
  - $i_0 = i_9 = 3 \cdot 10^{11} cpb$
  - $\sigma_0 = \sigma_9 = 75\ mm$
  - True beam position $= (H_0, V_0)$
  - "Measured" (mean) beam position $= (h_0, v_0)$
  - Position error $\delta_0 = h_0 - H_0$
- Compensation
  - none
  - waveform
  - power
  - power (alt)



Typical Results – Absolute Position Errors

- **Position error for maximum beam displacement**
  - $i_0 = 3 \cdot 10^{11} cpb$
  - $i_9 = 3 \cdot 10^{10} cpb$
  - $\sigma_0 = \sigma_9 = 75\ mm$
  - **True beam position** $= (H_0, V_0)$
  - **"Measured" (mean) beam position** $= (h_0, v_0)$
  - **Position error** $\delta_0 = h_0 - H_0$

- **Compensation**
  - **none**
  - **waveform**
  - **power**
  - **power (alt)**



HiLumi HL-LHC PROJECT CERN

Summary

- **Various LHC BPM activities are underway**
  - **Collimator BPMs, interlock BPM CONS, HL-LHC IR BPMs, LHC ring BPM CONS**
  - **An (incomplete) snapshot of the ongoing R&D efforts was presented**
- **Digital signal processing is a key element for any future LHC BPM read-out system**
  - **Reproducibility and performance improvements**
  - **Signal processing schema assumes 25 ns bunch spacing**
    - ***Except interlock BPM consolidation can also handle doublet bunches***
- **Expected performance**
  - **Single bunch resolution 10…15 µm, orbit resolution <1 µm**
    - ***Sampling in the 1st Nyquist passband, >8.7 ENOB, slow AGC***
  - **IR BPM accuracy:
~7 µm for compensation of same intensity counterrotating bunch
~70 µm for compensation of 10x lower intensity counterrotating bunch
(assuming 2D 5th order polynomial for correcting non-linearities)**
- **During run 3…**
  - **Parasitic and dedicated beam studies with prototype hardware**
    - ***Xilinx Zynq RFSoC evaluation-board with modified input stage***
  - **Dedicated MD on stripline BPMS.4L5**
    - ***Single bunch in B1 and B2 with cogging between them***