Tests of the new IT BPM read-out system at LHC

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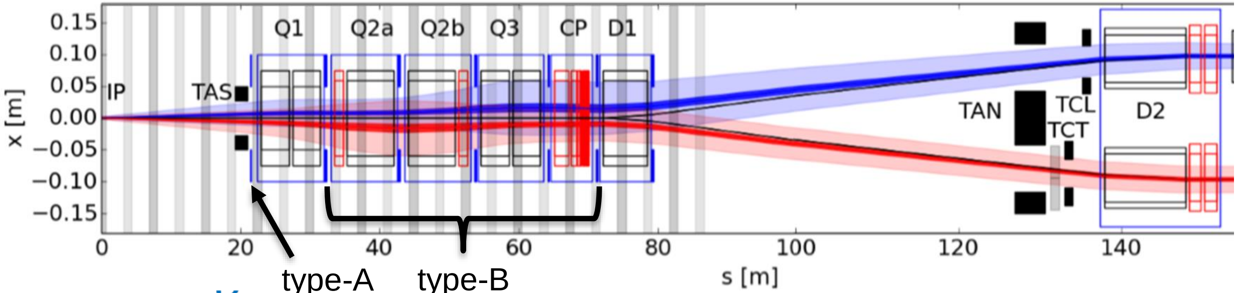
Contents

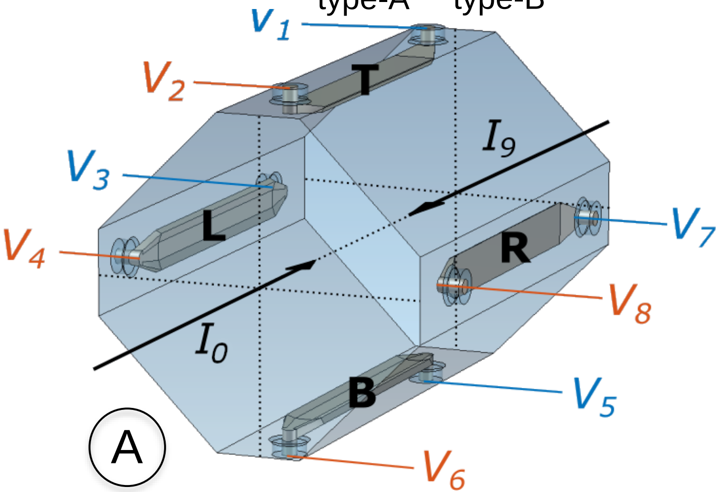
- Introduction
- Experimental setup
- Results
- Power compensation
- Outlook

BPM upgrade



BPM	Type	s [m]	bxt [ns]
Q1	A	21.853	3.92
Q2A	B	33.073	3.92
Q2B	B	43.858	6.82
Q3	B	54.643	9.72
CP	B	65.743	10.52
D1	B	73.697	7.36

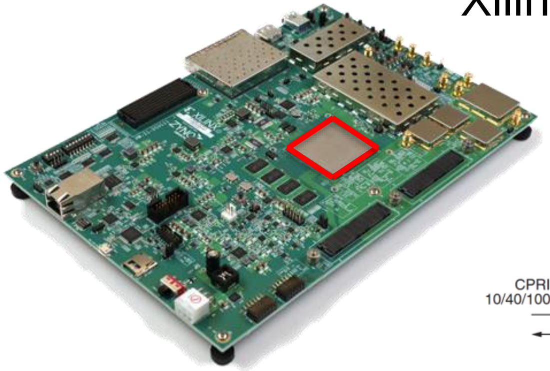
bxt = bunch crossing time
i.e. beam-beam delay



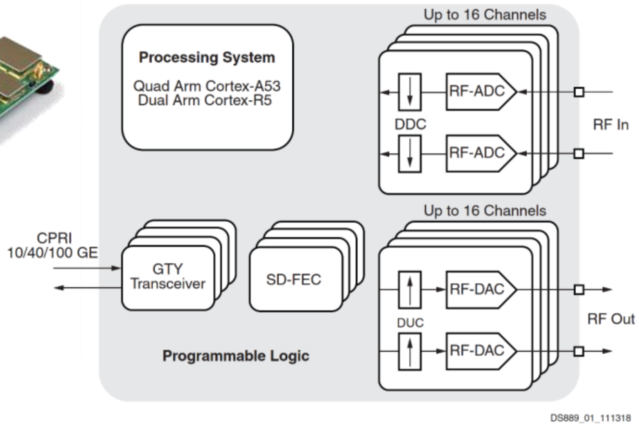
- New stripline BPMs in the immediate vicinity of interaction regions 1 (ATLAS) and 5 (CMS), where the two beams coexist within a single pipe
- Signals from all eight ports required to calculate the horizontal and vertical position of both beams
- Distortion of main beam signals due to presence of counter beam must be compensated for

RFSoC

- **R**adio **F**requency **S**ystem-**o**n-**C**hip: candidate BPM processor
- RF-ADCs/DACs, programmable logic, CPU in a single package
- Evaluation board “ZCU111” acquired for proof-of-concept tests



Xilinx Zynq XCZU28DR (gen. 1)

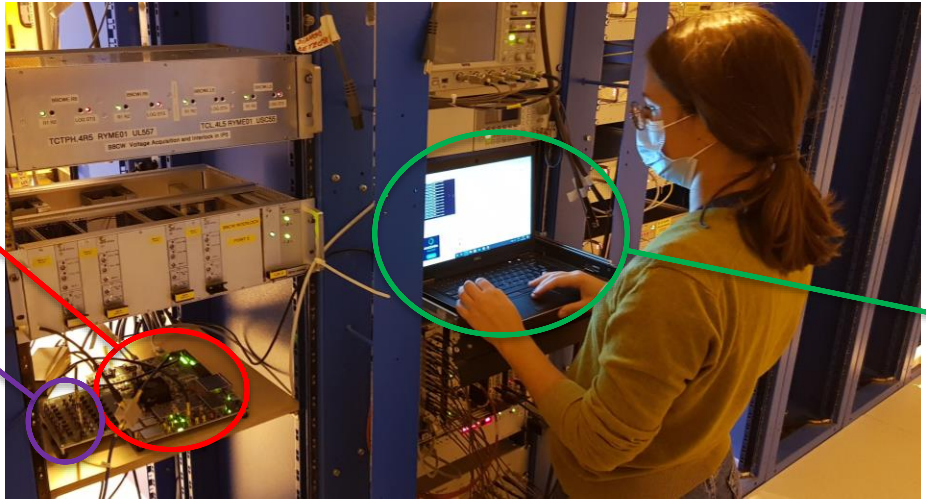


Source: *Zynq UltraScale+ RFSoC Data Sheet: Overview (DS889)*

RF 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

Experimental setup

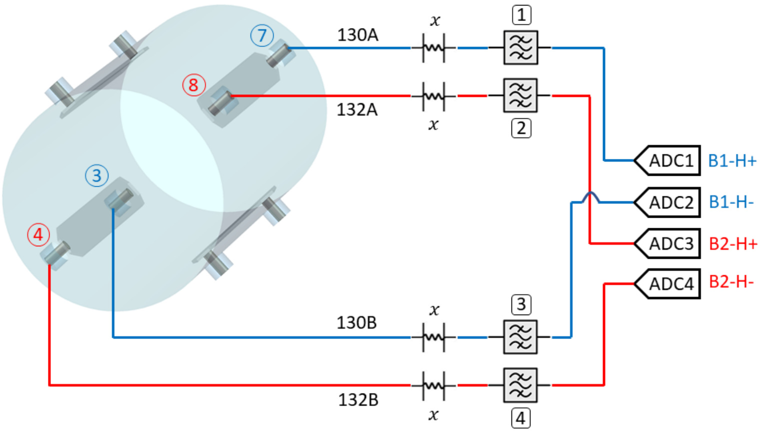
- Custom analogue front-end board by Selim Ozdogan
- Software/firmware developed by Irene Degl'Innocenti
- Board installed in region accessible during operation



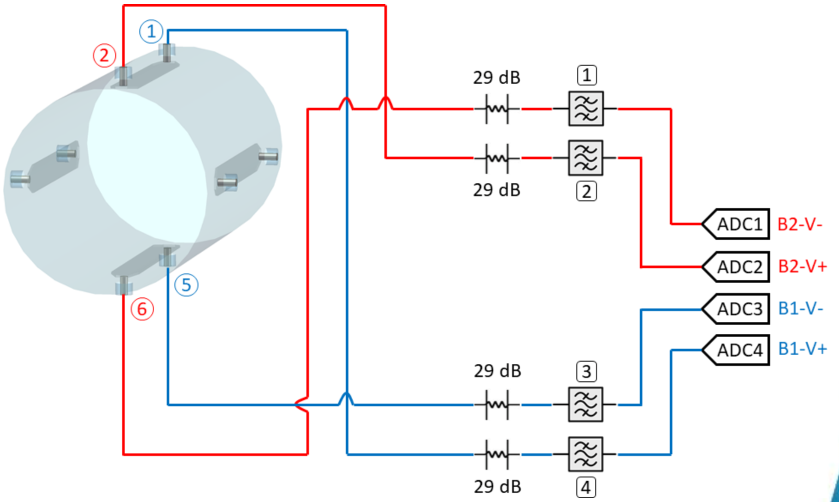
Experimental setup

- ZCU111 used to digitize up to four ports (out of eight)
- Measurements taken with two different BPMs across four sessions using multiple configurations (split ports, etc.)

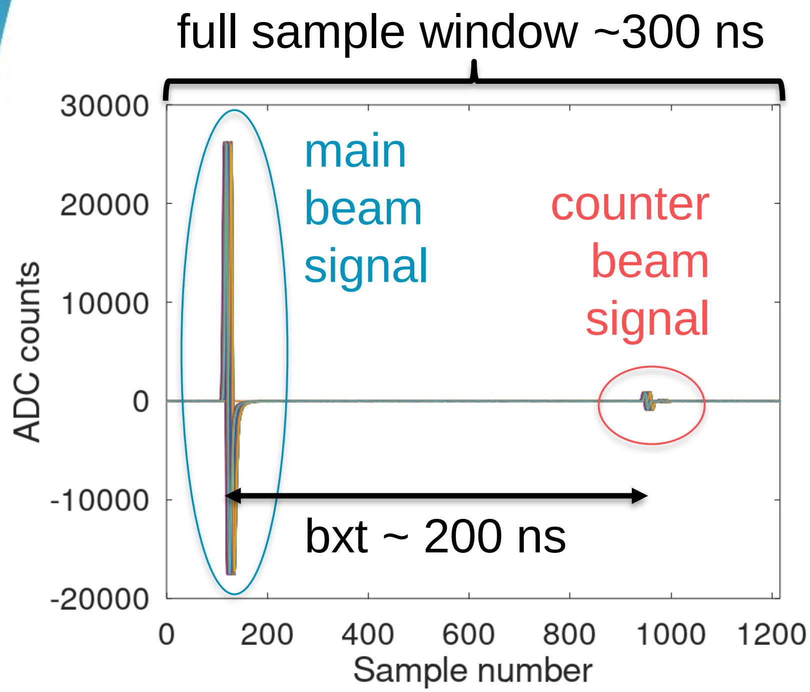
Wed 27 Oct 2021: BPM "**2L5**"



Fri 29 Oct 2021: BPM "**4L5**"

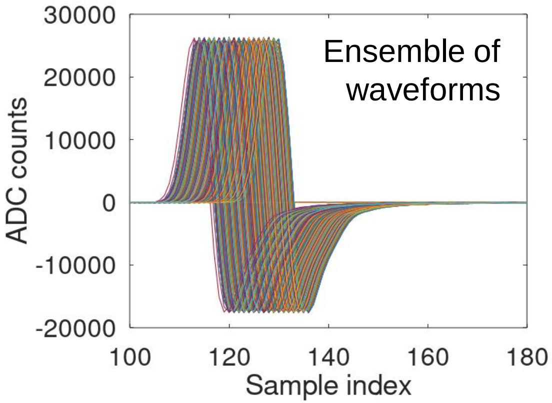


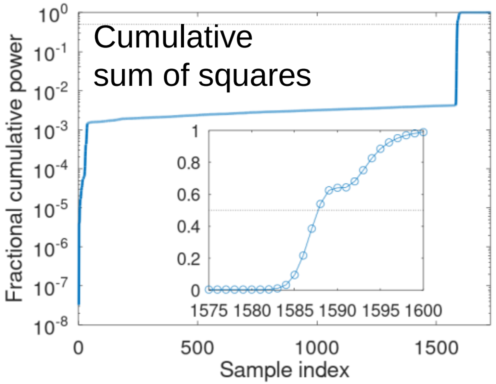
Analysis

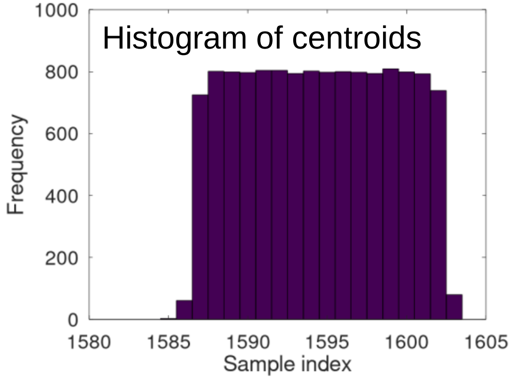


- Data stored as 5 column array (turn number, then ADC sample values for each of the four channels)
- Samples per turn set to accommodate signal from both beams ***(parasitic operation – not possible to change timing)***
- Number of turns set by operator (typically $\sim 10^3$)
- Sample clock asynchronous to beam, leading to smear when sample values from multiple turns are plotted together

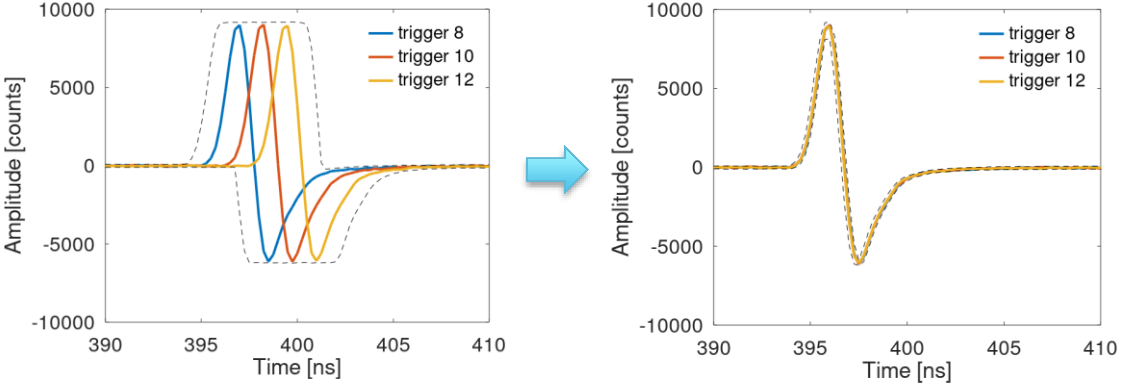
Asynchronous clock



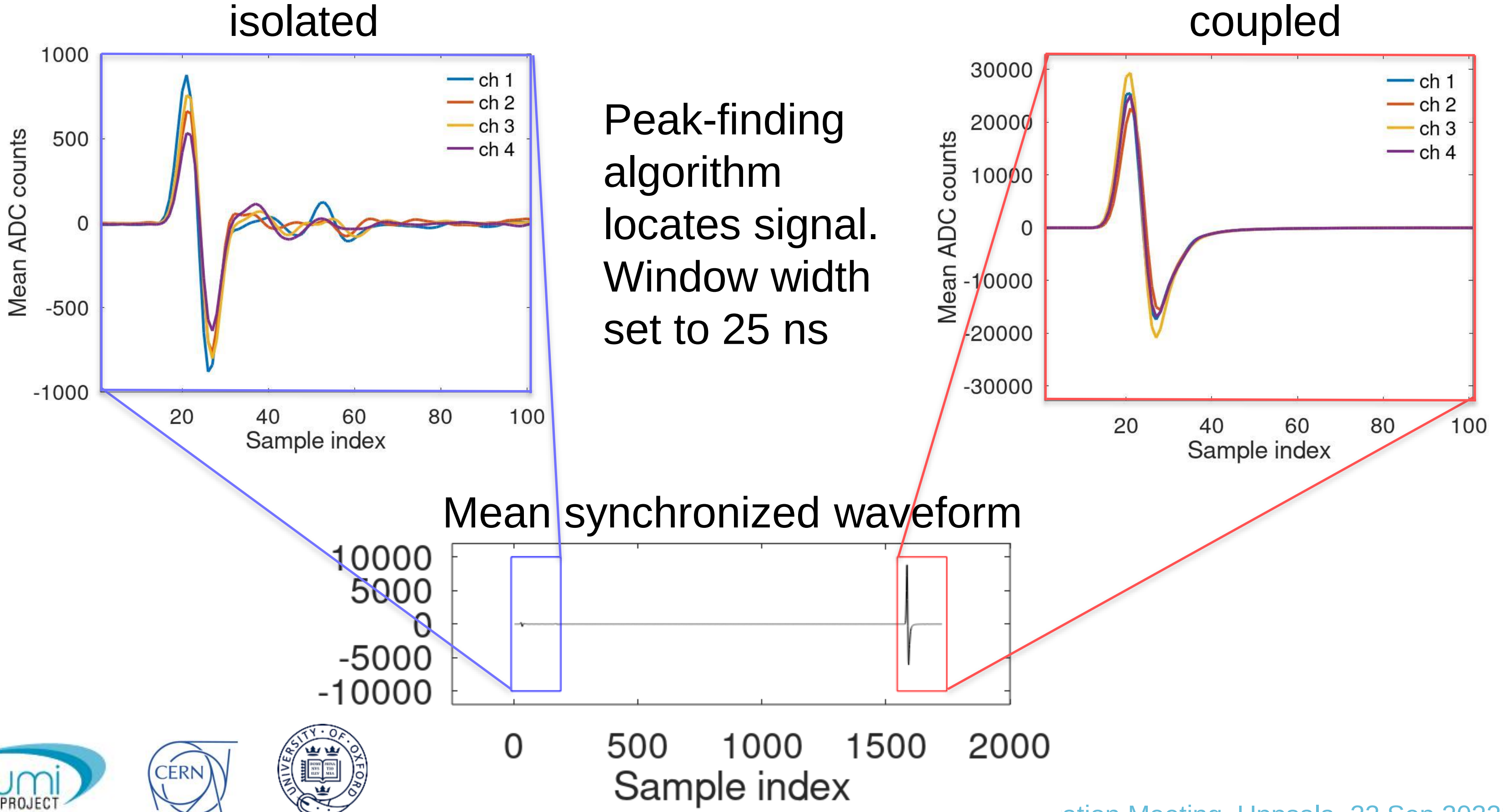




- Identify "temporal centroid" of each signal by finding the sample closest to the 50% of signal power point
- Trim necessary number of samples from start and end to synchronize



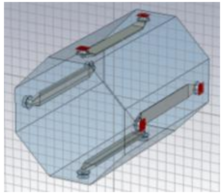
Signal windowing



Peak-finding algorithm locates signal. Window width set to 25 ns

Comparison with model

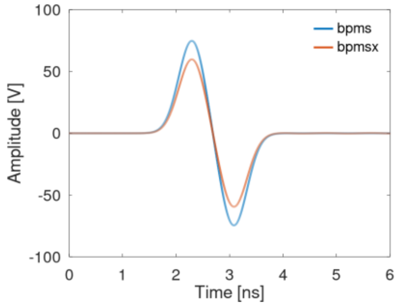
Stripline BPM



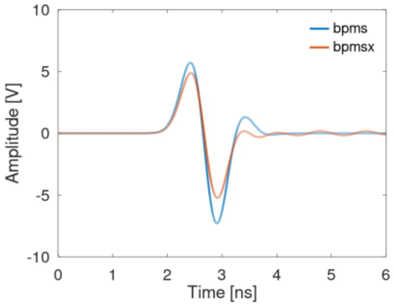
⇨ long cables ⇨ Low-pass filter ⇨ fixed attenuation ⇨

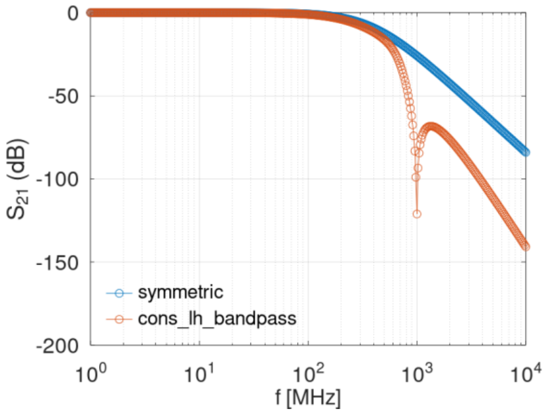
Digitizer

coupled



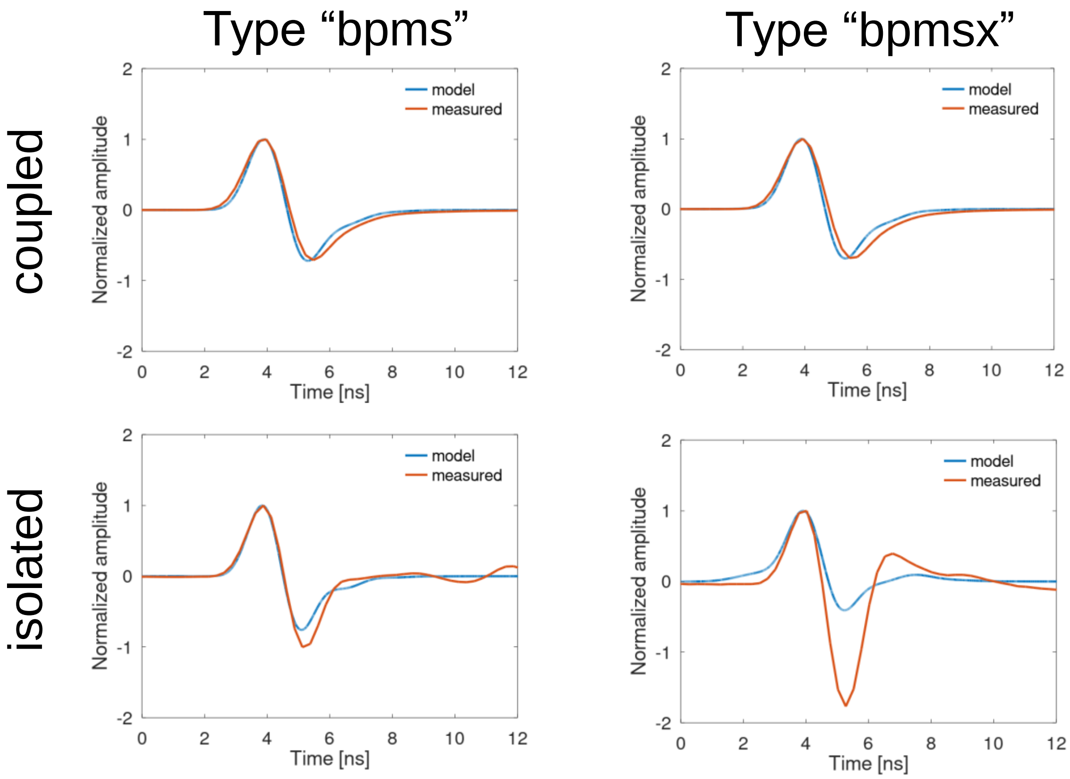
isolated



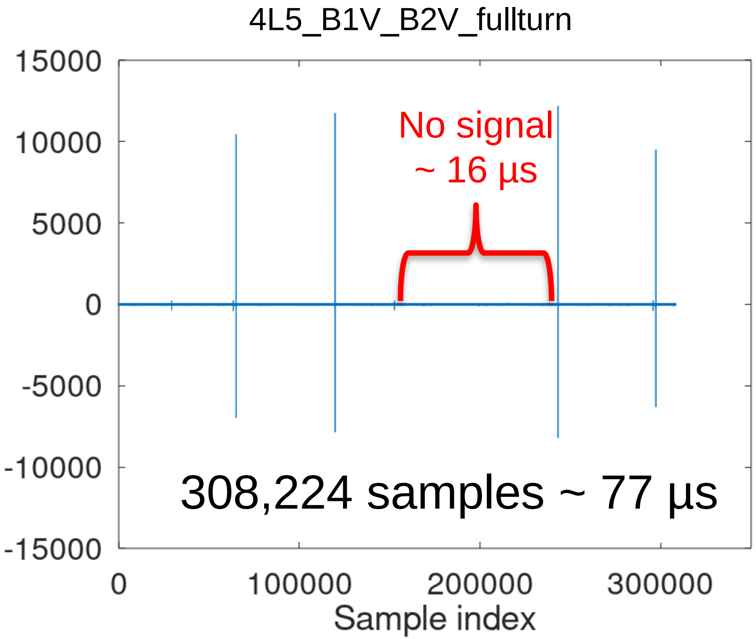


Filter too complex to easily replicate in Octave; apply the filter to the post-cable signal in LTspice

Comparison with model



Noise



$$\text{SNR} = 20\log_{10}\left(\frac{V_{rms}}{\epsilon_{rms}}\right) \qquad \text{ENOB} = \frac{\text{SNR} - 1.76}{6.02}$$

Ch.	ϵ_{rms} [cts]	ϵ_{rms} [V]	SNR	ENOB	NSD [dBFS/Hz]
1	26.8	0.41	58.73	9.46	−151.9
2	25.4	0.39	59.19	9.54	−152.3
3	27.2	0.42	58.61	9.44	−151.7
4	27.3	0.42	58.57	9.44	−151.7

Noise power per bin $= 10\log_{10}(f_s/2)$

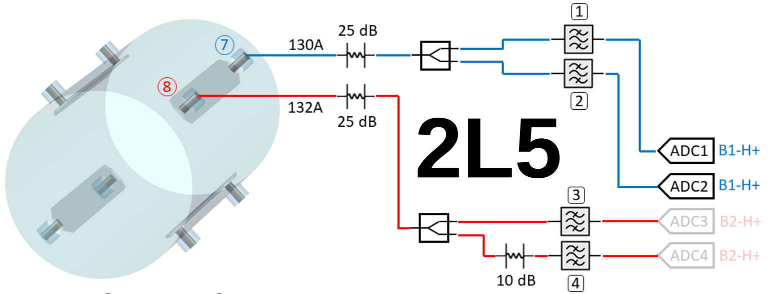
$f_s = 4$ GSPS → -93 dBFS/Hz

Noise spectral density averaged across the first Nyquist zone	Input at −35 dBFS (noise floor)	–	−153	−151	dBFS/Hz
	F_{IN} = 240 MHz	–	−152	−151	dBFS/Hz
	F_{IN} = 1.9 GHz	–	−151	–	dBFS/Hz
	F_{IN} = 2.4 GHz	–	−150	–	dBFS/Hz
	F_{IN} = 3.5 GHz	–	−148	−146	dBFS/Hz
	F_{IN} = 3.5 GHz, CW at −10 dBFS	–	−153	−150	dBFS/Hz
	F_{IN} = 3.5 GHz, CW at −20 dBFS	–	−153	–	dBFS/Hz

Xilinx DS926, Table 118 (p84)

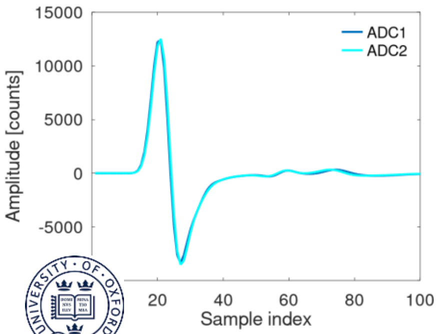
Resolution estimate with split signals

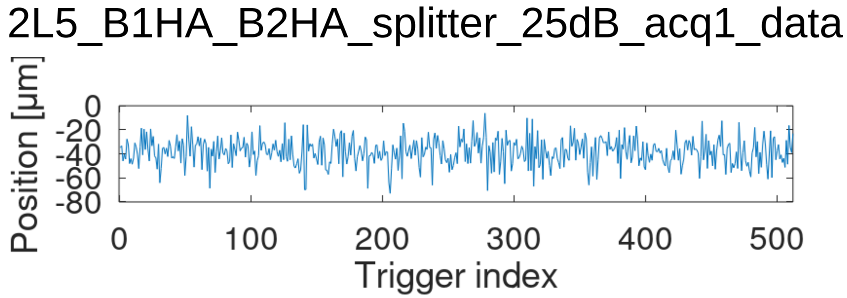
- BPM sensitivity estimated using CST

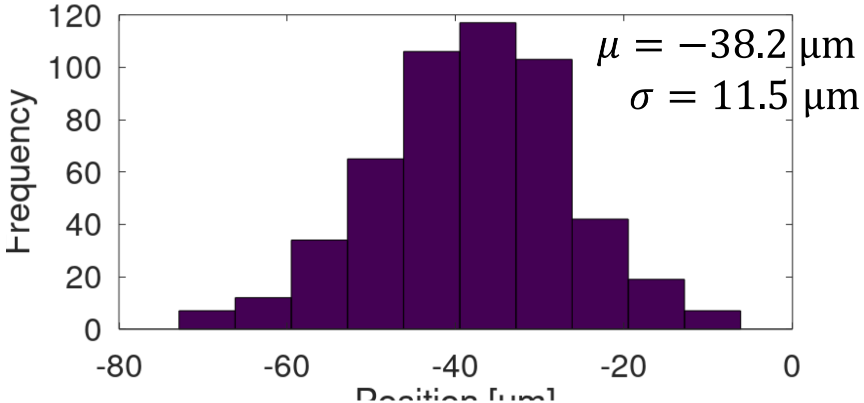


$$y = \frac{\phi_1 - \phi_2}{\phi_1 + \phi_2}$$

$$\phi_1 = \sqrt{\sum V_1^2}$$







Resolution estimate with split signals

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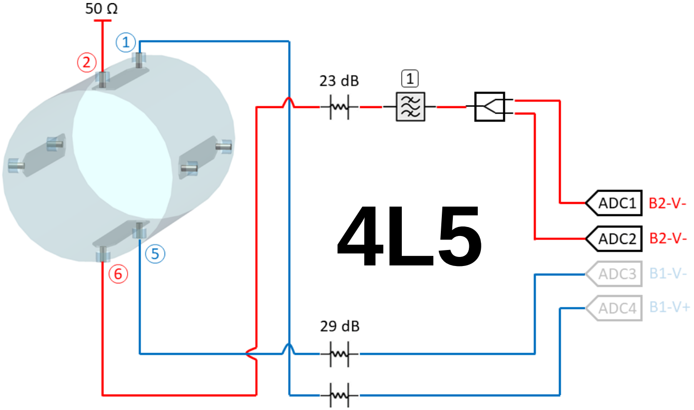
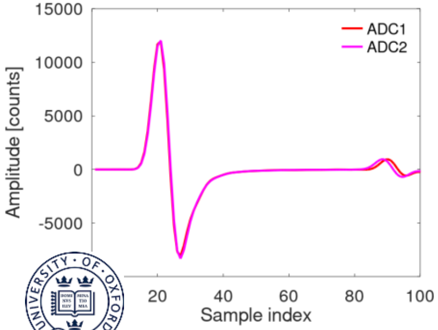
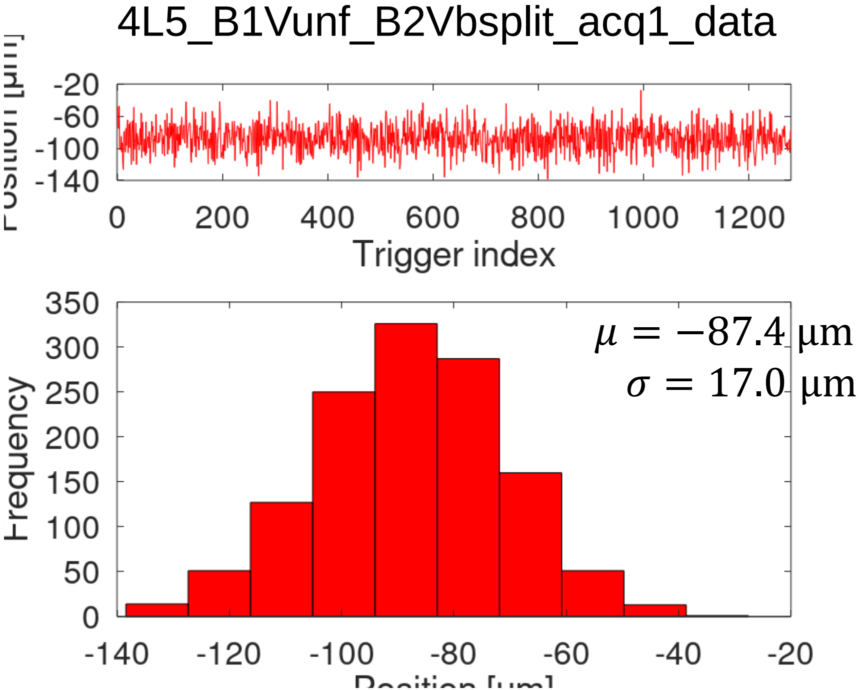
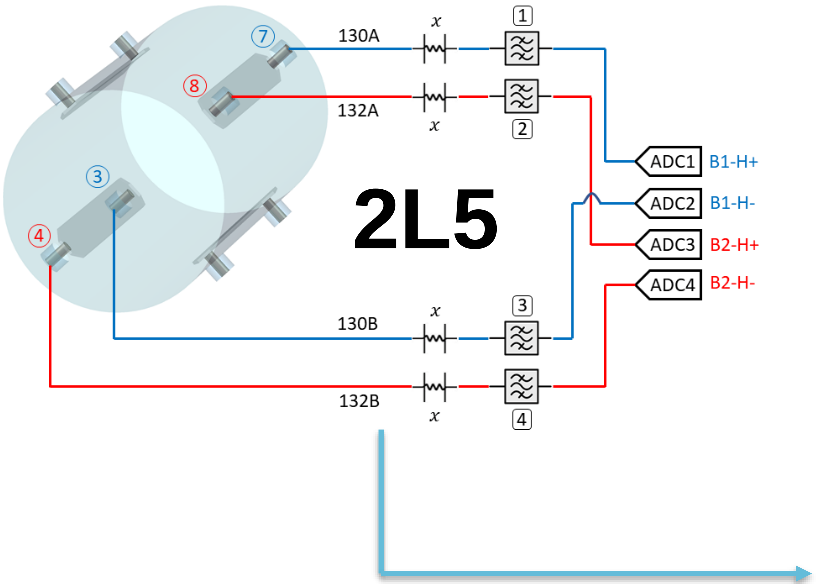


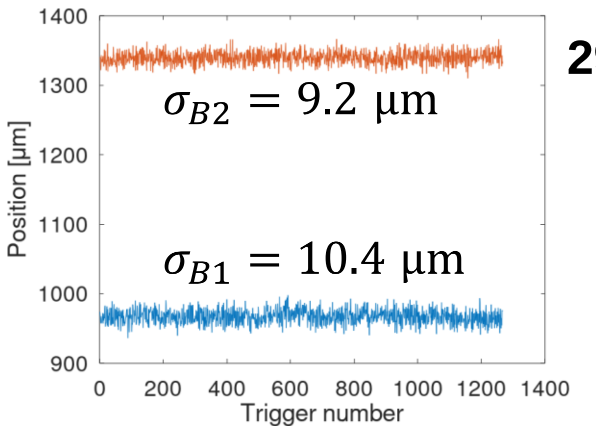




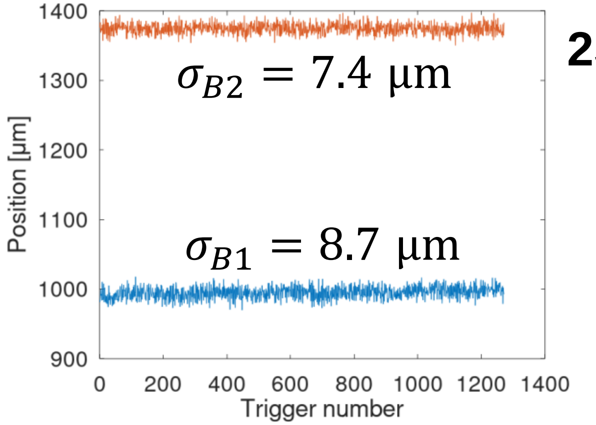
Beam position (bpms)



4 dB of attenuation removed



29 dB

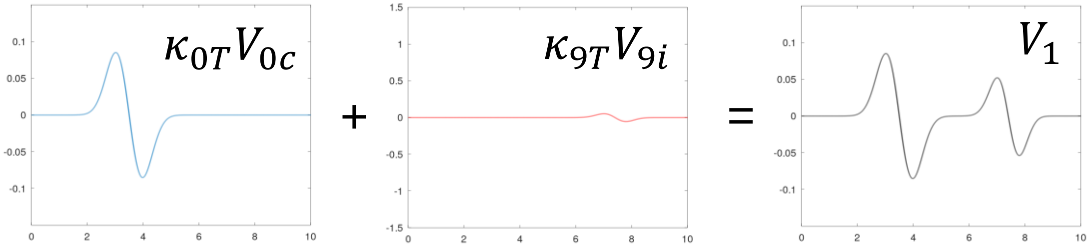


25 dB

Power compensation concept

- Primary challenge of the IT BPM system is the simultaneous presence of signals from both BPMs
- Studies using simulated waveforms suggest the power from a single beam can be estimated from the total power at both ends of a single stripline and some calibration parameters that vary with the bunch crossing timing

Each waveform can be expressed in the form: $V_1 = \kappa_{0T} V_{0c} + \kappa_{9T} V_{9i}$



κ scale factor sets amplitude of each term according to intensity, position of beam

Power compensation algorithm

"Power" of the V_3 waveform

$$\psi_3 = \sum V_3^2$$

Standard position calculation (Δ/Σ)

$$x_{B1} = \frac{\sqrt{\psi_7} - \sqrt{\psi_3}}{\sqrt{\psi_7} + \sqrt{\psi_3}}$$

Power compensation

$$X_{B1} = \frac{\kappa_7 - \kappa_3}{\kappa_7 + \kappa_3}$$

$$\kappa_7 = \sqrt{a\psi_7 + b\psi_8} + c\sqrt{\psi_8}$$

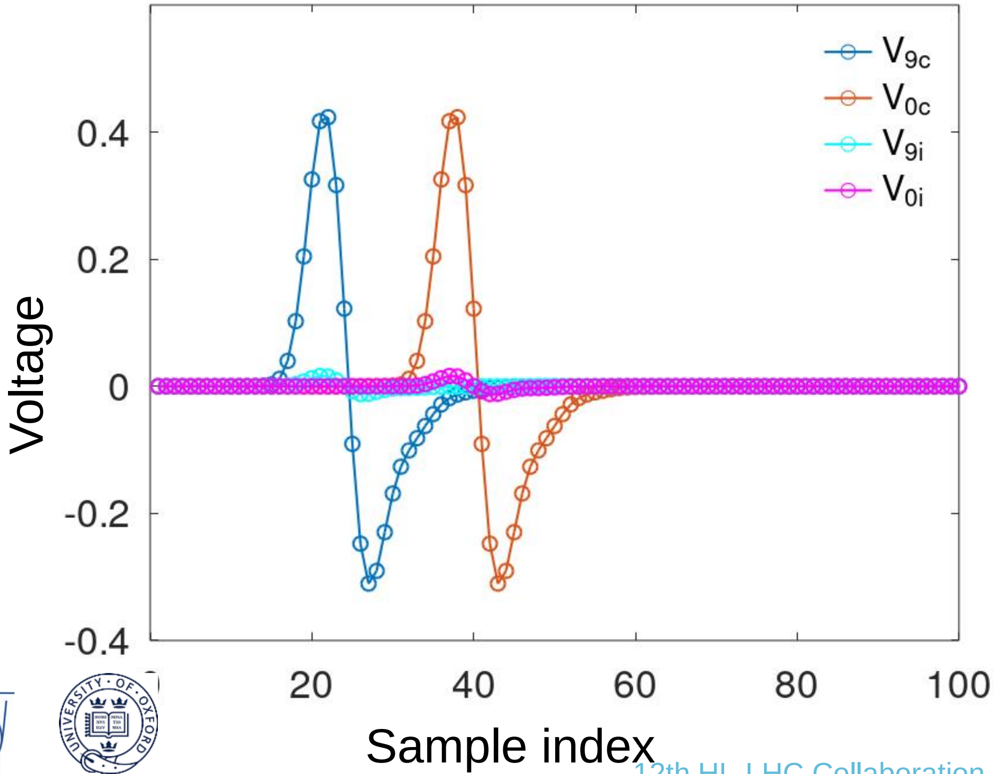
ψ_7, ψ_8 calculated in real time

a, b and c calculated in advance from reference waveforms

$$a = \frac{1}{\psi_{9c}} \qquad b = \frac{1}{\psi_{0c}}\left[\left(\frac{\chi_{9c0i}}{\psi_{9c}}\right)^2 - \frac{\psi_{0i}}{\psi_{9c}}\right] \qquad c = -\frac{1}{\sqrt{\psi_{0c}}}\left[\frac{\chi_{9c0i}}{\psi_{9c}}\right]$$

Reference waveforms

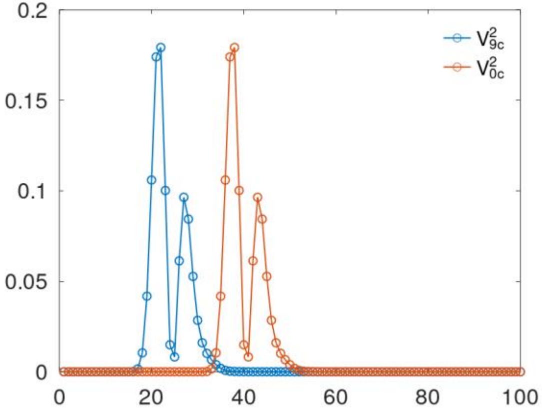
Reference waveforms sourced from model or (single-beam) observations



Power compensation parameters

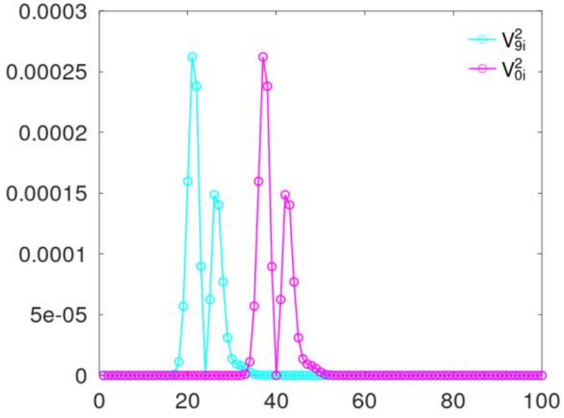
The parameters are functions of the elementwise sums of the below waveforms

ψ_{9c} ψ_{0c}



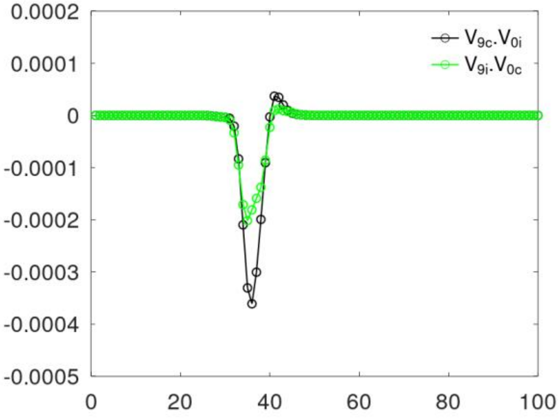
coupled × coupled

ψ_{9i} ψ_{0i}



isolated × isolated

χ_{9c0i} χ_{9i0c}

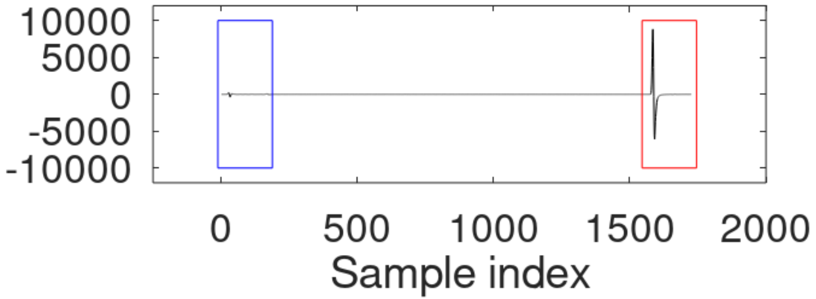


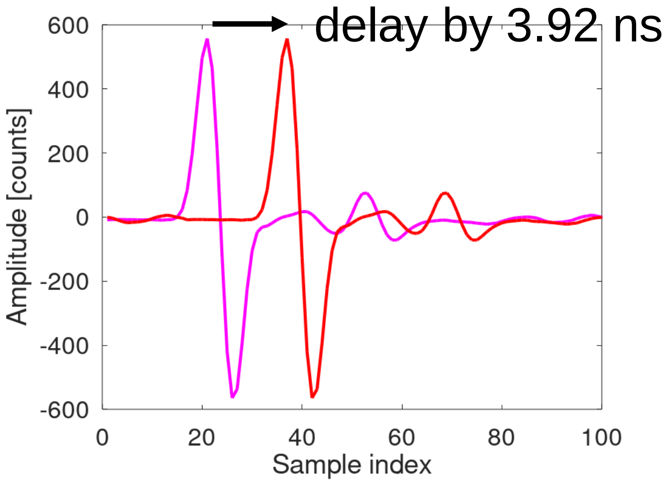
coupled × isolated

Pseudo two-beam waveforms

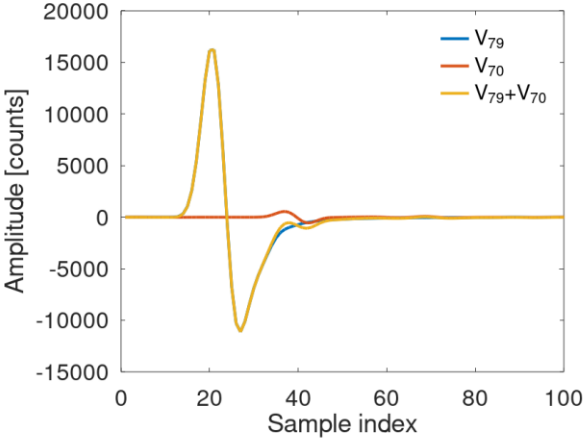
- Bunch crossing timing too large to effectively probe the performance of the power compensation algorithm using waveforms “as is”
- Analysis already generated 25 ns versions of the coupled and isolated waveforms, so form “pseudo two-beam” waveforms by delaying one by the desired bunch crossing timing and then adding the two

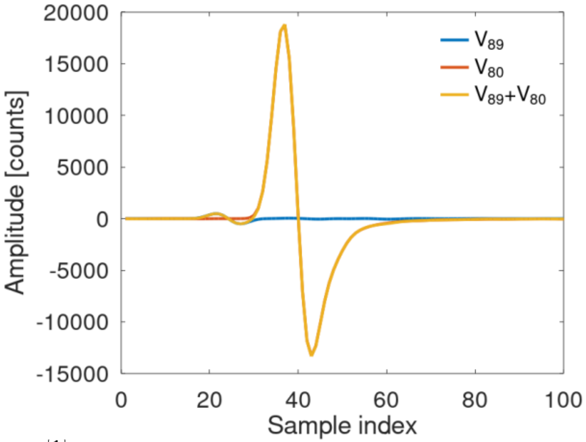
Mean synchronized waveform

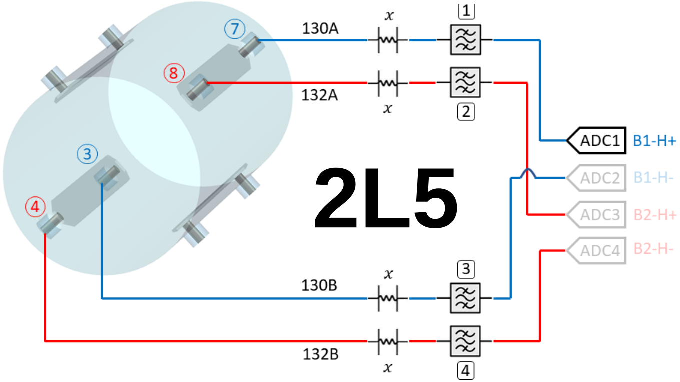




Pseudo two-beam waveforms

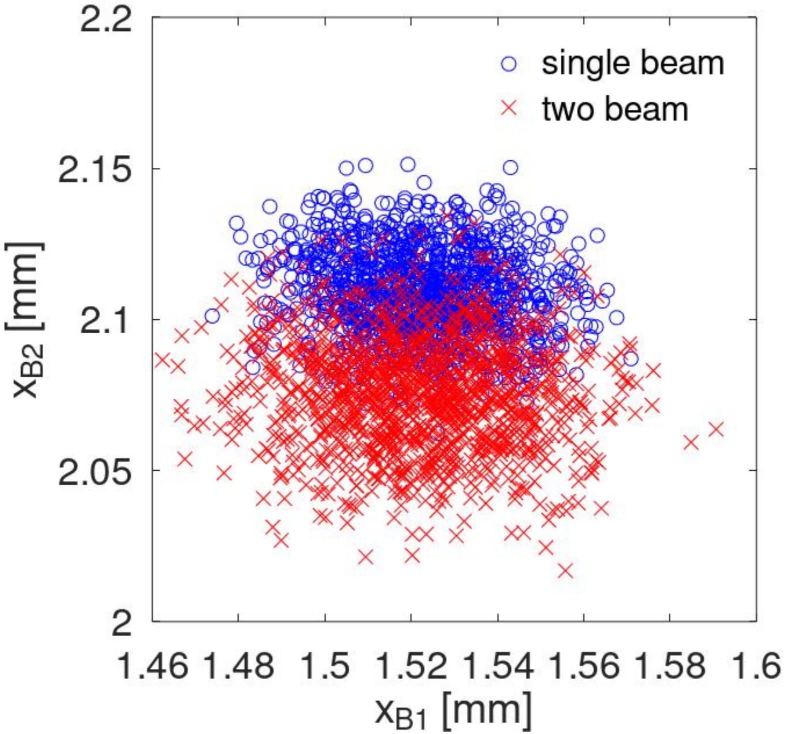


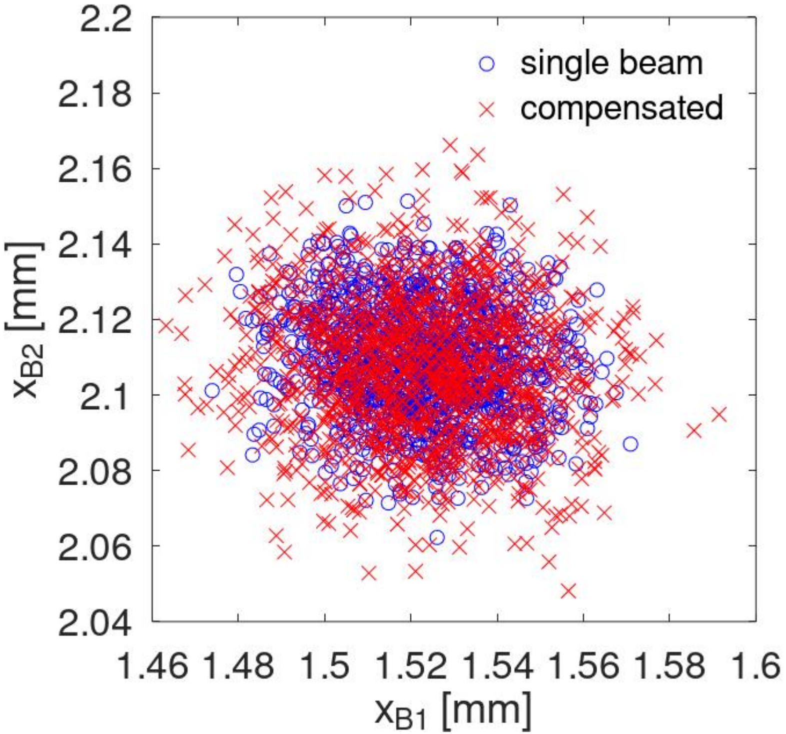




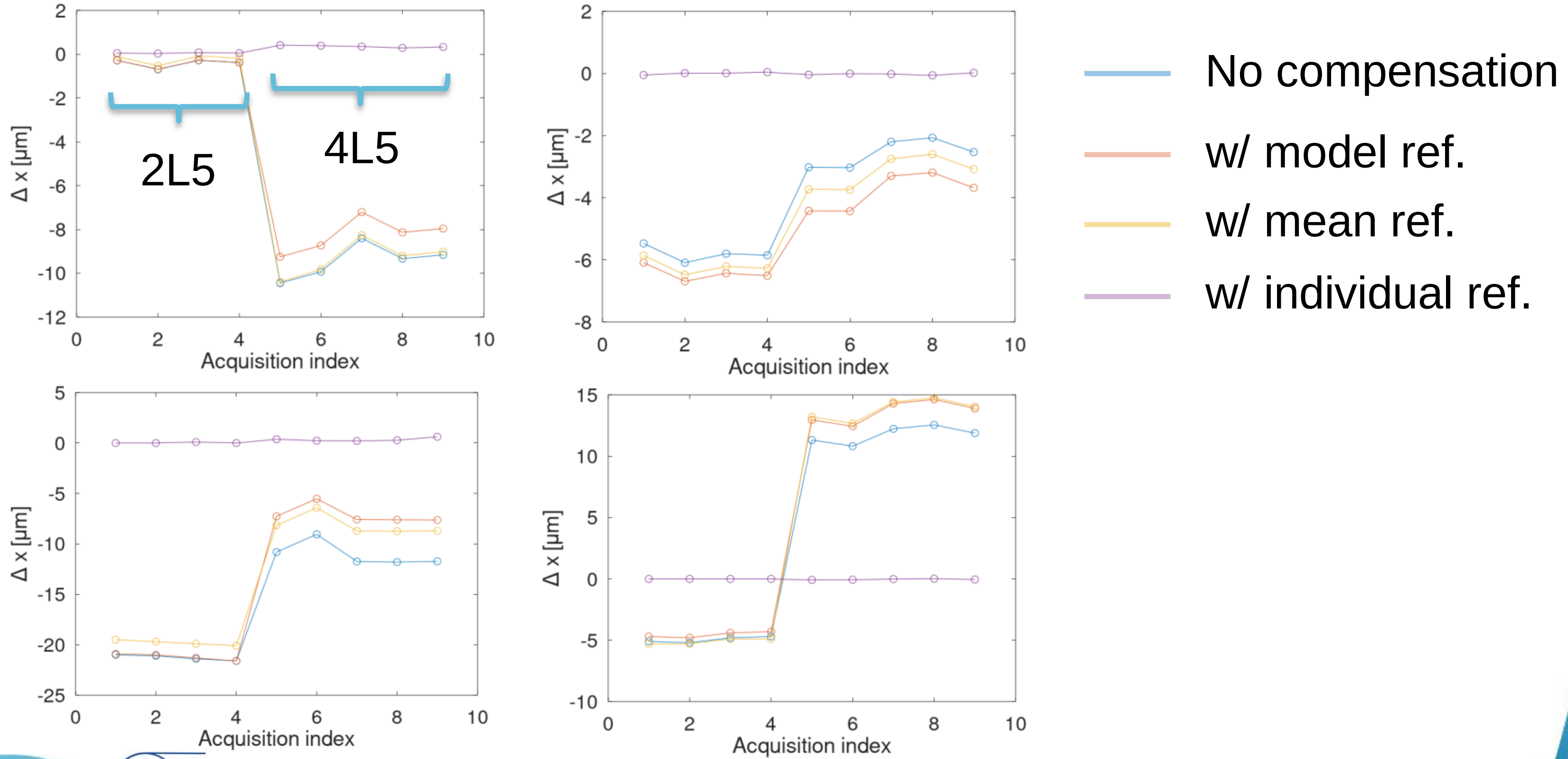
Shift 1, config. 1

Power compensation example

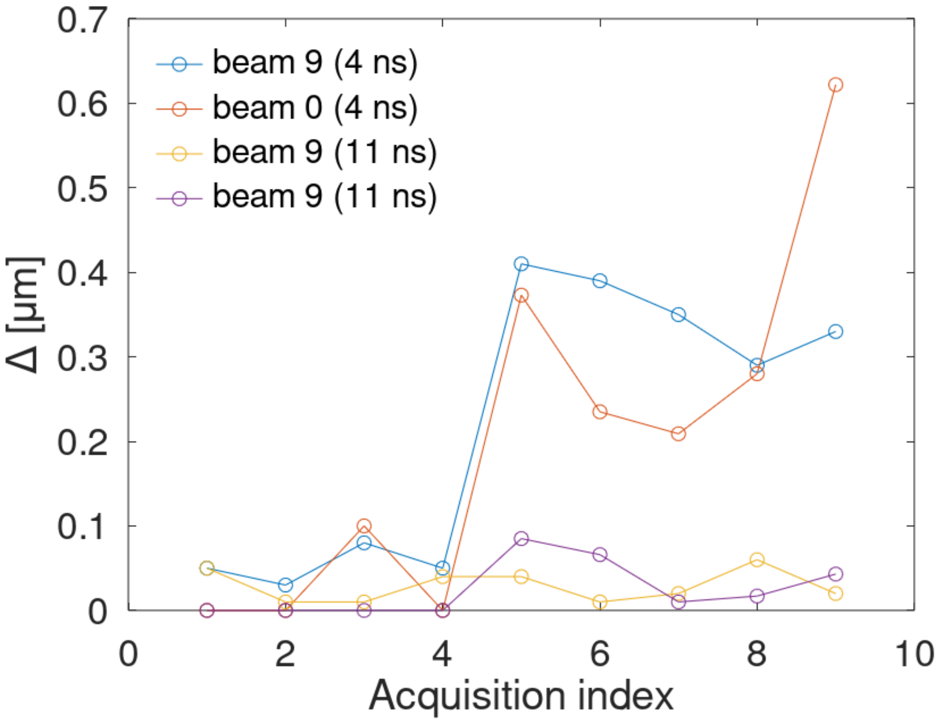




All power compensation results



Residual error after compensation



Comparison between:

position calculated from pseudo two-beam waveforms with compensation

and

single-beam position

OUTLOOK

- Parasitic data has been very valuable so far as a tool for judging the suitability of the RFSoC as a BPM processor
- The ability to change the bunch crossing timing in order to study waveforms where signal from both beams interfere in real time would be the best validation for the power compensation algorithm
- Work continues on the RFSoC software and firmware