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RECORDING TWO-BEAM LHC BPM SIGNALS TO VALIDATE A TECHNIQUE FOR EXTRACTING INDIVIDUAL BEAM POSITIONS

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Abstract

As part of the High Luminosity upgrade for the Large Hadron Collider (HL-LHC), 24 new directional-coupler (stripline) BPMs will be installed near the ATLAS and CMS experiments where the two counter-rotating beams exist within a single vacuum chamber. For the BPMs closest to the collision point, the bunches of the second beam arrive at the BPM location just 4 ns after those of the first and the BPM signals from the two beams overlap significantly. Using simulations of the expected BPM output, a novel scheme for digitally processing these two-beam signals in order to extract the true position of each beam has been developed. The data-driven validation of this technique requires genuine two-beam signals. In October 2022, suitable signals were acquired using an early proof-of-concept digital BPM processor connected to an existing room-temperature stripline BPM close to the CMS detector. During this period of data acquisition, RF cogging was used to vary the difference in arrival time of the two beams at the BPM location and orbit bumps were used to vary the beam-beam displacement in order to ultimately be able to determine the performance of the digital processing scheme.

INTRODUCTION

The Large Hadron Collider (LHC) will undergo major upgrades in the context of the High Luminosity LHC (HL-LHC) project with the goal of delivering 3000 fb^{-1} of integrated luminosity over twelve years of operation from 2027. New Inner Triplets consisting of high-gradient focusing magnets around the ATLAS and CMS experiments will squeeze the proton beams to a 7.1 µm RMS beam size at the collision point. To achieve reliable collisions with beams of this size, each triplet will feature a set of BPMs in the region where both proton beams circulate in a common vacuum chamber [1]. In cases where the two counter-rotating bunches arrive at the BPM within a time comparable to the bunch length, the unwanted signal induced by the counter beam can lead to a significant measurement error on the position of the main beam. This issue can be partially mitigated by using directional-coupler (stripline) BPMs installed in locations where the difference in the time of arrival of the two beams is as large as possible.

Figure 1 illustrates the scenario where two oppositely-directed beams enter a single Inner Triplet stripline BPM. Due to the natural directivity of stripline BPMs, most of the signal power generated by the passage of a beam is measured at the entry end ports and only a residual signal is seen on the exit end ports. The beam I_9 produces a large signal at the odd ports and only a residual signal at the even ports. The opposite is the case for I_0, the counter beam that enters at the other end. The signals expected on the downstream and upstream ports of an Inner Triplet stripline due to the passage of a single bunch were obtained through electromagnetic simulations and are shown in Figure 2.

In the worst case scenario, bunches arrive at the BPM location separated by just 4 ns leading to a non-negligible mixing of the signals. This issue can be further exacerbated if there is a large position offset between the two beams or a large imbalance in intensity.

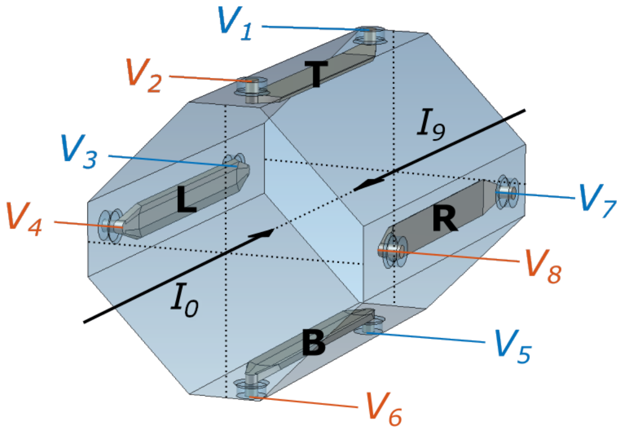

Figure 1: Annotated CST model of one of the new interaction region striplines. The eight stripline ports are numbered 1 through 8, and the two beam "ports" are designated 0 and 9. The odd ports are labelled in blue and the even ports in red.

A framework [2] simulating the signals from the new interaction region BPMs for the HL-LHC was used to test the design of a signal processing method that would allow accurate measurement of the individual position of each beam despite the presence of the residual signal from the other [3]. This "counter beam compensation" performs well on simulated waveforms comprised of the signals from two oppositely-directed beams, but true verification of the method requires actual signals from a beam position monitor. The experimental set-up used to acquire such signals will be described in the next section.

EXPERIMENTAL SET-UP

Hardware Configuration

The device used for the measurement was a Xilinx ZCU208 Evaluation Kit [4]. This board is equipped with a Generation 3 (Gen-3) Zynq UltraScale+ Radio Frequency System-on-Chip (RFSoC), a device uniting hard processor

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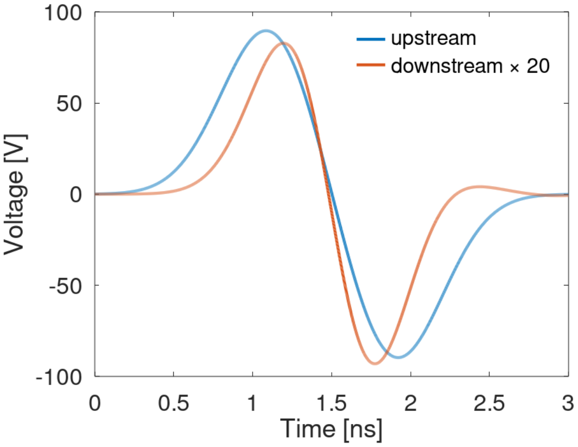

Figure 2: Model predictions for the signals induced on both upstream (blue) and downstream (red) ends of a stripline by the passage of a single bunch of charged particles. The downstream signal has been scaled by a factor of 20 for viewing purposes.

cores, the programmable logic of a field-programmable gate array (FPGA), and RF data converters (ADCs and DACs) together on a single chip. For the purposes of this study, the device was only required to function as an on-demand digitizer that acquired data upon receipt of a user command. The Gen-3 RFSoC contains 8 ADCs capable of operating at a sampling rate of up to 5 giga-samples per second (GSPS). For this study only 4 ADCs sampling at 4 GSPS were enabled in the firmware (FW) and signals were only acquired from the four ports of a single BPM plane.

The ZCU208 was connected through 75 m low-loss coaxial cables to a stripline BPM located 58 m away from the CMS experiment (functional position BPMSY.4L5). The electronics were installed in a radiation-free area along with a prototype of the minimal analogue front-end foreseen for the Inner Triplet BPMs which featured 170 MHz non-reflective low-pass filters, fixed 28 dB attenuators to match the signal levels to the ADC input dynamic range, and RF baluns to interface the ADCs. The analogue front-end components were measured in the laboratory before beam measurements to account for any asymmetries.

The signal acquisition was triggered manually through a remote connection to the ZCU208. The ADC clock, common for all ADCs, was free-running and not phase-locked to the beam. To make multi-revolution measurements possible, the ZCU208 was also supplied with a synchronous beam revolution clock provided by the LHC RF system which was used by the FW to identify and count each beam revolution.

Beam Configuration

The two proton beams are designated B1 and B2 and the measurement was performed in the notional vertical axis. During the measurement campaign, each proton beam consisted of two[1] bunches of nominal intensity (1.1×10^{11} protons) and the absolute maximum signal observed was just over 60% of the ADC full scale range. The relative timing of the beams was such that the first bunch from each beam arrives at the BPM at approximately the same time. These bunches are the test bunches and the difference in their arrival times is referred to as the bunch crossing timing. The other bunch from each beam arrives at the BPM separated by 2 µs. As these signals are unperturbed by the other beam, these are the reference bunches.

The measurement campaign consisted of a two-dimensional scan of the bunch crossing timing, which was scanned over the range ±10 ns in steps of approximately 1 ns, and the beam-beam position offset in the measurement plane, which was scanned from 0 mm to 3 mm in steps of 1 mm (the beam-beam offset in the other plane was kept constant at the nominal value of 12.4 mm to avoid unwanted collisions at the BPM).

Changing the bunch crossing timing was achieved through "RF cogging", in which the relative phase between the clocks driving the RF cavities of B1 and B2 is changed. The exact beam-beam phase difference was measured by the RF system diagnostics for each programmed step. The different beam-beam offsets were obtained by controlling the beam-beam separation distance at the CMS interaction region. The applied beam-beam offset steps at the BPM location were approximately 0, 1.5, 3, and 4.5 mm, which are approximately 150% of the separation distance programmed at the CMS experiment. The precise online monitoring of this offset was not necessary as the true beam position can be calculated from the signals generated by the reference bunches.

RESULTS

After receiving a trigger signal, the digitizer captures three windows of 416 samples each (104 ns at 4 GSPS) over 11,264 consecutive revolution periods. The first window corresponds to the arrival of the test bunches, and the second and third windows to the arrival of the reference bunch from B2 and B1, respectively. This scheme is illustrated in Figure 3.

Window 1 shows the scenario where the signals from the test bunches interfere with each other and compensation for the other beam is necessary in order to accurately determine the position of each individual beam[2]. The example shown in Figure 3(a) corresponds to the scan setting where the B2 test bunch arrives 10 ns before the B1 test bunch and the beam-beam offset at the BPM location is approximately 0 mm in the measurement plane.

Windows 2 and 3 contain the reference bunch signals that allow the B2 and B1 positions to be determined in the absence of signal from the other beam. The position of these reference bunches are taken as the true position of the beams

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[1] A low-intensity pilot bunch for B1 was not measured.

[2] The first design of this "counter beam compensation" is described in [3]; the final design is the subject of a forthcoming paper.

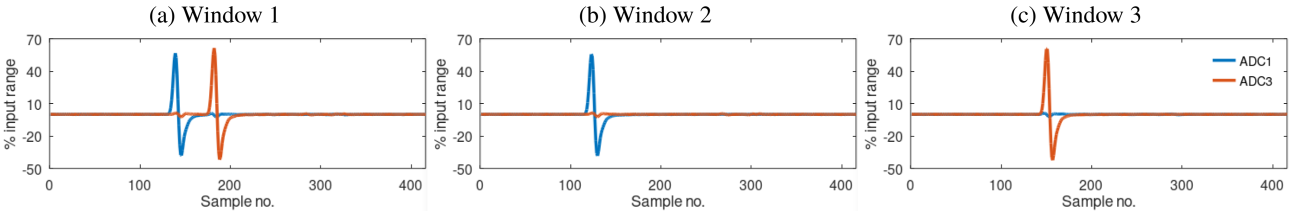

Figure 3: Example acquisition. The blue and red lines correspond to signals from opposite ends of a single electrode.

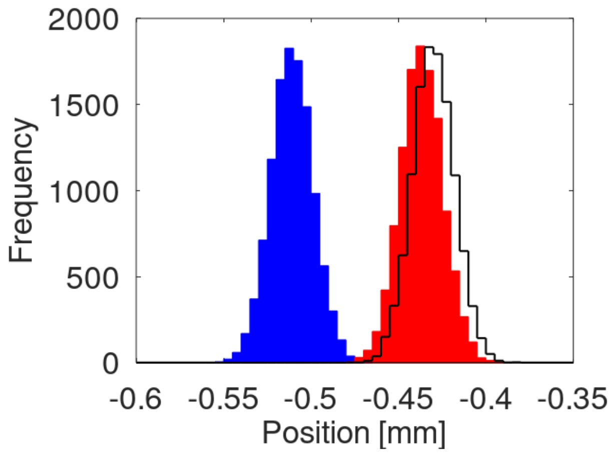

Figure 4: Histograms of the B1 position calculated using the test bunch waveforms (blue); using the test bunch waveforms and applying the technique of counter beam compensation (red); using the reference bunch waveforms (black).

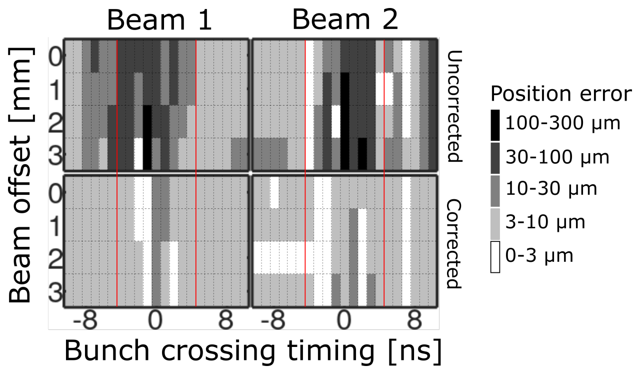

Figure 5: Difference between the mean position of test and reference bunches for B1 (left column) and B2 (right column). The top row corresponds to the case where the waveforms are used “as is” and the bottom row to the case when the counter beam compensation is applied.

and thus used to determine the performance of the counter beam compensation algorithm.

Figure 4 shows an example of the application of counter beam compensation. The histograms show the distribution of positions for the two bunches of B1 when the B1 test bunch arrives ~4 ns after the B2 test bunch and the beam-beam position offset is ~0 mm. The black outline histogram corresponds to the position of the B1 reference bunch calculated from the one-beam waveforms (window 3 for B1). The blue and red histograms correspond to the position of the B1 test bunch calculated from the two-beam waveforms, with blue being the result when the waveforms are used as is and red when counter beam compensation is applied. The result shows counter beam compensation reducing the beam measurement error from about 80 μm down to less than 7 μm.

Figure 5 provides a sense of the effectiveness of the counter beam compensation technique over the entire range of the scan. Note that here the beam offset is based on the machine settings rather than the measured offset at the BPM itself.

Dark areas of the grid correspond to combinations of the bunch crossing timing and beam-beam offset that resulted in a large error when counter beam compensation is not applied; predictably, the darkest areas of the grid are found between the red lines where the bunch crossing timing is less than 4 ns. Outside of this area, the residual error after correction is always less than 10 μm.

CONCLUSION

A ZCU208 Evaluation Kit was used to take waveform data from stripline BPMSY.4L5 while the LHC delivered two beams of two bunches each. The difference in arrival time of the first bunch from each beam and the beam-beam position offset were scanned over a range of ±10 ns and 0 – 3 mm respectively. A counter beam compensation algorithm was applied to the waveforms featuring signal from both beams to calculate the positions of the individual beams. The results show that for bunch crossing timings more than 4 ns, the error due to the presence of the other beam is reduced to less than 10 μm.

Future measurements are planned to take place using upgraded designs for the software and firmware running on the RFSoC. In particular, the ability to take data from all eight channels and a move away from manual triggering towards integration with the LHC control system are planned [5].

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