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PERFORMANCE OF THE AWAKE PROTON BEAM LINE BEAM POSITION MEASUREMENT SYSTEM AT CERN

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Abstract

The Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE), based at CERN, explores the use of a proton driven plasma wake-field to accelerate electrons at high energies over short distances. This paper introduces the Beam Position Measurement (BPM) system of the proton beamline and its performance. This BPM system is composed of 21 dual plane button pickups distributed along the 700 m long transfer line from the CERN Super Proton Synchrotron (SPS) extraction point to beyond the plasma cell. The electrical pulses from the pickups are converted into analogue signals proportional to the displacement of the beam using logarithmic amplifiers, giving the system a high dynamic range (>50 dB). These signals are digitized and processed by an FPGA-based front-end card featuring an ADC sampling at 40 MSps. Each time a bunch is detected, the intensity and position data is sent over 1km of copper cable to surface electronics through a serial link at 10 Mbps. There, the data is further processed and stored. The dynamic range, resolution, noise and linearity of the system as evaluated from the laboratory and 2016 beam commissioning data will be discussed in detail.

INTRODUCTION

The Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) [1] is a proof-of-principle experiment installed in the former CERN Neutrinos to Gran Sasso (CNGS) facility and is the first proton driven plasma wakefield acceleration experiment world-wide. The AWAKE experiment aims to accelerate electrons from low energy (~15 MeV) up to the multi-GeV energy range over short distances (~10m). This is achieved using the wake-field of a plasma to accelerate electrons. The wake-field is induced in the plasma by a high-energy (~400GeV) proton bunch extracted from the CERN Super Proton Synchrotron (SPS) via a 700 m long transfer line.

THE PROTON BPM SYSTEM

The Beam Position Monitor (BPM) system of the AWAKE proton beam line, is composed of 21 dual plane button pickups, distributed along a 700 m beam transfer line. The read-out electronics is divided into two parts: the front-end electronics located close to the pick-ups in the tunnel and the back-end electronics sitting in a service gallery. The back-end communicates with all the different front-ends and concentrates the BPM control and data acquisition to a single point. The communication between the front-end and back-end is performed using a custom protocol running at 10 Mbps over 1 km of copper cable. This system has been optimized for the low repetition rate (~30 s) and high dynamic range (~40 dB) of the AWAKE proton beam. Its target resolution is better than 100 μm for nominal bunches ($3.5e^{11}$ protons).

Front-End Electronics

For each BPM, the front-end electronics is composed of two analogue, logarithmic amplifier boards (LogAmp), a Digital Front-End board (DFE) and a power supply unit. The LogAmp board receives the electrical pulses from the pickup and shapes them using 30 MHz band-pass filters, before processing them with logarithmic amplifiers and sending the resulting analogue signals to the DFE board for digitization. The LogAmp board also features an on-board calibrator emulating pickup signals of known displacement. The DFE is an FPGA-based digital board featuring a multi-channel ADC sampling at 40 MSps. Due to the low radiation levels expected in the AWAKE beam line, radiation-tolerant components are not required. An image of the pick-up and front-end electronics under test in the laboratory is shown in Figure 1.

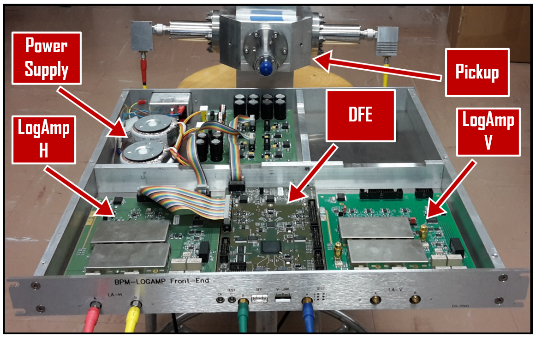

Figure 1: Pickup and front-end electronics.

The front-end electronics provides both a difference signal (Dif) and a summation signal (Sum) per plane. As for all BPM systems based on logarithmic amplifiers, the Dif signal is obtained from the difference in the logarithm of opposite electrodes, Log[electrode1] – Log[electrode2] = Log[electrode1/electrode2] and is directly proportional to the normalized beam position. The Sum signal is obtained by summing the logarithmic signal of both electrodes and is a function of the beam intensity. The Sum signal is used for auto-triggering the acquisition system. All signals are

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processed by the FPGA on the DFE board that continuously compares the digitized Sum with a pre-set threshold value. A beam presence flag is generated when the threshold is surpassed. This flag initiates the data transmission to the back-end acquisition electronics through the electrical serial link. A block diagram of the front-end electronics as well as a plot of the Sum and Dif data for a single bunch after digitization at 40 MHz are depicted in Figures 2 and 3 respectively.

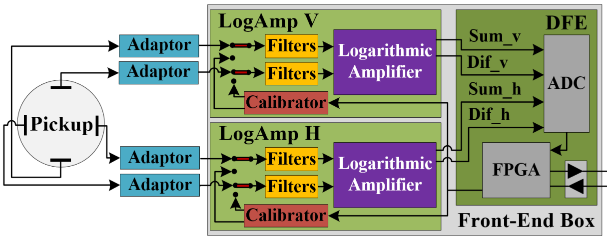

Figure 2: Diagram of the pickup and front-end electronics.

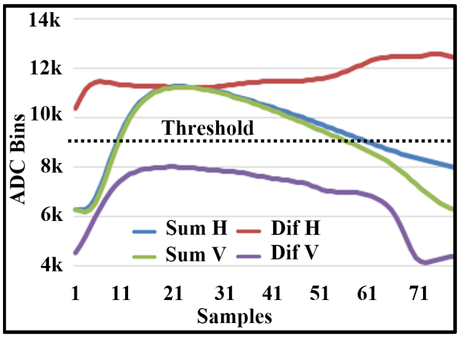

Figure 3: Sum and Dif signals after digitization at 40 MSps and showing the auto-trigger threshold.

Back-End Electronics

The back-end electronic comprises two VME boards (VFC-HD) [2], and their respective auxiliary electronics boards (AWAKE Patch Panel and AWAKE Patch FMC). The VFC-HD is the standard back-end FPGA-based (Altera Arria V GX), FMC-HD carrier board used by the CERN Beam Instrumentation Group. This board receives and stores the raw Sum and Dif data from different front-ends (up to 16 front-ends per VFC-HD) for further processing. After each proton beam extraction from the SPS, this data is made available to the operational software. The role of the AWAKE Patch Panel and Patch FMC is to interface the VFC-HD to all the serial communication link cables coming from the BPM front-ends. An image of the back-end electronics as installed is shown in Figure 4.

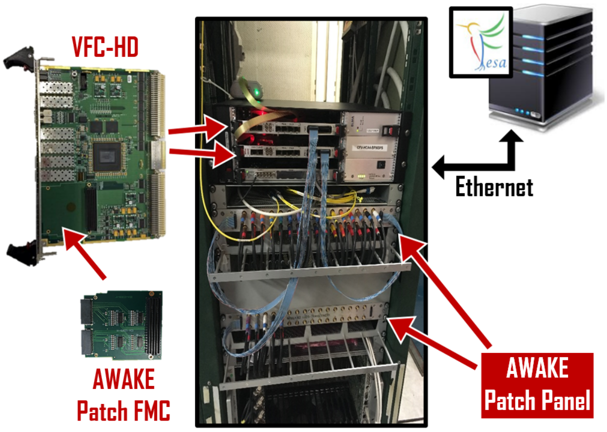

Figure 4: Back-end electronics.

System Timing and Calibration

As the system is using logarithmic processing, the Dif data is not meaningful unless the Sum data exceeds a certain minimum value. To find the optimal integration window during which processing can take place, the following procedure was followed. The first step was the storage of hundreds of acquisitions in the laboratory using a beam emulator. A software algorithm was then used to search for the Least Noise Sample (LNS) in the Dif data by evaluating the standard deviation at each point using a sliding window after the point corresponding to the maximum of the Sum data. Once the LNS has been identified, the algorithm averages the LNS with its two adjacent samples. If the standard deviation of the resulting average is less than the noise of the LNS, the process is repeated, adding two new samples until the standard deviation of the new window is higher than that of the previous window. The window with the lowest standard deviation is considered the Optimal Window (OW). An example of LNS and OW is depicted in Figure 5. The defined OW found in the laboratory using this method is used with beam to give the optimal window where all ADC samples are summed to give a value (Δ_{avg}) for calculating the beam position. The standard deviation of each sample, used to calculate the LNS, as well as that for the window length, used to calculate the OW, are illustrated in Figure 6. For converting Δ_{avg} to distance units (x), it is necessary to apply the scaling factor derived from the on-board calibrator (Δ_{Offset} (0 dB), Δ_{Max} (+6 dB) and Δ_{Min}(-6 dB)), linear corrections related to the pickup geometry as well as any physical offset of the pick-up ($Offset_{Phy}$):

$$Scale_{Cal} = \frac{\Delta_{Max} - \Delta_{Min}}{2} \tag{1}$$

$$x = \left[\left(\frac{5.0672}{Scale_{Cal}}\right)\left(\Delta_{avg} - \Delta_{Offset}\right)\right] - Offset_{Phy} \tag{2}$$

Operation

The first proton beam for AWAKE was extracted from the SPS in June 2016 whilst the beam line was further commissioned in September 2016. Since then, the system has successfully accumulated hundreds of hours of operation. During operation, the proton beam position is monitored and stored on a shot-by-shot basis for beam steering or further analysis (see example in Figure 7).

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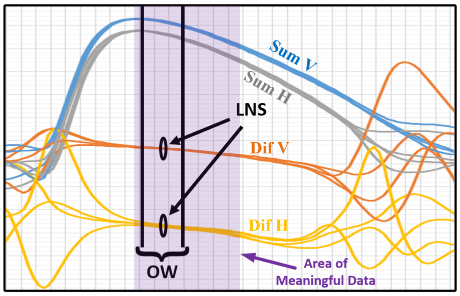


Figure 5: Example of LNS and OW.

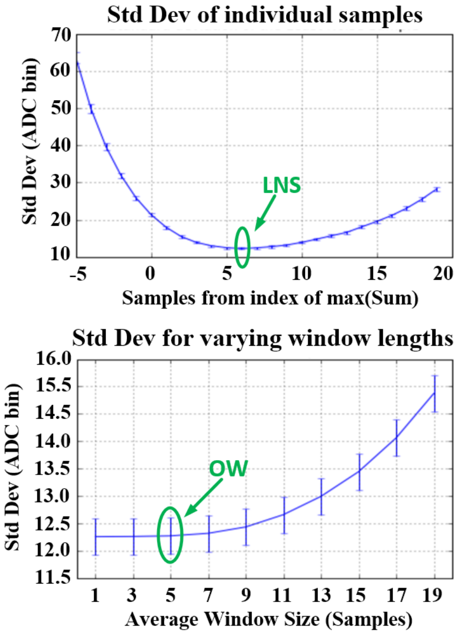
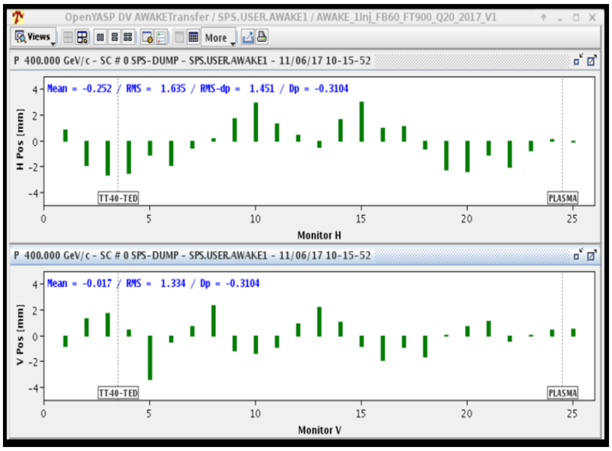


Figure 6: Standard deviation of the individual samples showing the LNS (top) and standard deviation for varying window lengths showing the OW (bottom).

PERFORMANCE

In order to evaluate the performance of the system, qualification studies in terms of resolution, linearity and dynamic range have been carried out. The details of these studies are presented in the following sections.



P 400.000 GeV/c - SC # 0 SPS-DUMP - SPS.USER.AWAKE1 - 11/06/17 10-15-52

Mean = -0.252 / RMS = 1.635 / RMS-dp = 1.451 / Dp = -0.3104

P 400.000 GeV/c - SC # 0 SPS-DUMP - SPS.USER.AWAKE1 - 11/06/17 10-15-52

Mean = -0.017 / RMS = 1.334 / Dp = -0.3104

Figure 7: Trajectory measurements as shown by the AWAKE BPM software. Each individual bar represents the position from one BPM.

Resolution (Noise)

For qualifying the resolution of the system, more than 2000 acquisitions of the reference bunch trajectory were analysed. The standard deviation of these trajectories include both the shot-to-shot jitter of the extracted beam and the electronic noise of the system. The acquired trajectories, as well as the standard deviation for each plane of each BPM, are plotted in Figures 8 and 9. It is clearly seen that there is a large difference between the values for the horizontal and vertical plane clearly pointing to beam reproducibility issues as electronics is the same for both planes.

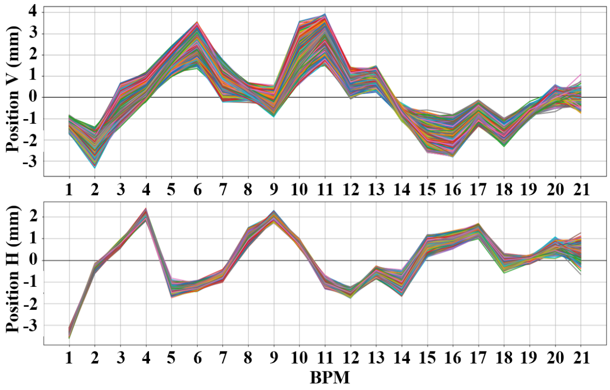


Figure 8: Proton beam trajectories.

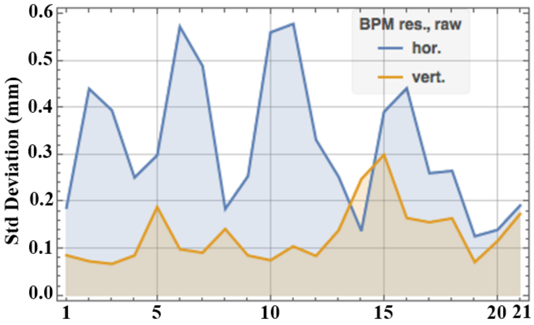


Figure 9: Standard deviation in horizontal and vertical planes.

As a consequence, to estimate the electronic resolution, it was necessary to remove the correlated beam motion effects from the measurement. This was performed using Singular Value Decomposition (SVD). Typically this correlated beam motion in a linac/transport-line can be decomposed into four dominant “modes”, those related to: beam position (x), beam angle (x'), beam energy and beam phase. In this case, 2058 synchronous beam measurements (p) of 21 BPM (m) were arranged in a matrix B(p × m). This matrix was then de-composed by applying the SVD technique. The correlated beam motion can be subtracted from the measurement by setting the 4 highest eigenvalues (modes) in the decomposed matrix to zero and recalculating B. This correlation is illustrated in Figure 10, while the measurements with this correlated beam motion subtracted are presented in Figure 11. The actual resolution of the electronic acquisition system can then be estimated to be between 50–80 µm for most BPMs.

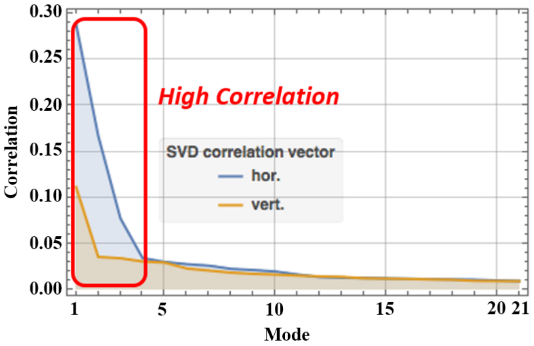


Figure 10: SVD modes correlation.

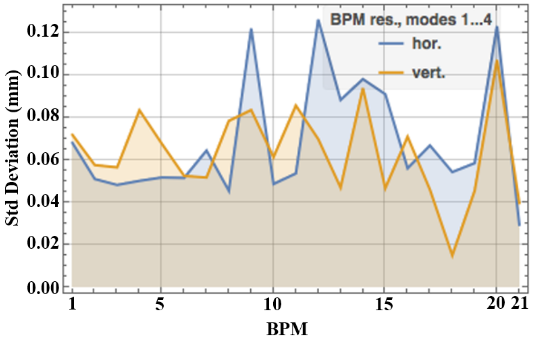


Figure 11: Standard deviation in horizontal and vertical planes after SVD.

Linearity

The linearity of the system has been qualified by measuring orthogonal displacements from -4mm to 4mm with a granularity of 1mm using a single BPM with no non-linear elements between it and the corrector used to produce the displacement. An average of 50 acquisitions per orthogonal displacement was used. To minimize the impact from beam jitter all the measurement were acquired in the vertical plane. The linearity error was measured to be lower than 15 µm over the range of the measurement, well within specification (see Figure 12).

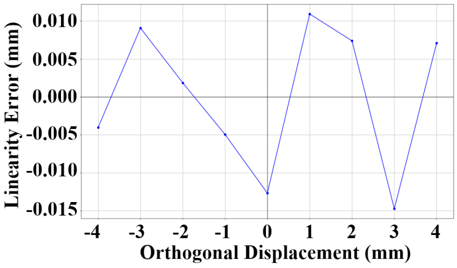


Figure 12: Linearity error.

Dynamic Range

As previously mentioned, the AWAKE proton bunch has a nominal intensity of $3.5e^{11}$ protons, but can also have an intensity as low as $5e^{9}$ protons (pilot bunches), typically for set-up purposes. The minimum dynamic range of the BPM system must therefore be ∼40 dB. A comparison of the trajectories of nominal and pilot bunches (see Fig. 13) demonstrated that the dynamic range of the system is adequate, with measurements at both intensities giving similar reproducibility, indicating that shot-to-shot trajectory variation remains the dominant source of this non-reproducibility. The resolution of the BPM system for pilot bunches is therefore much better than the reproducibility of the extracted trajectory.

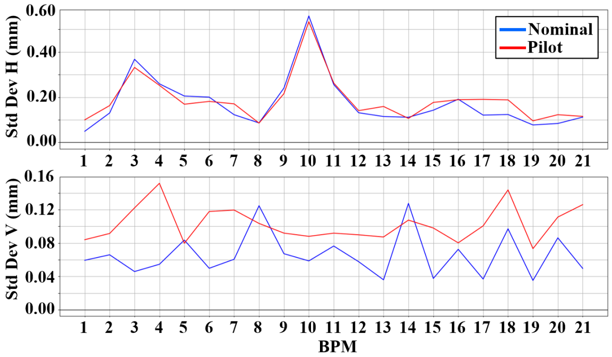


Figure 13: Comparison of the reproducibility of the BPM readings for nominal and pilot bunch trajectories.

CONCLUSION

The Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE), based at CERN, explores the use of a proton driven plasma wake-field to accelerate electrons up to multi-GeV energy range over short distances (∼10 m). A BPM system for the AWAKE proton beam line has been designed, implemented and successfully commissioned. The performance of this proton BPM system, based on logarithmic amplifiers, has been successfully qualified with beam and shown to have a single bunch, single pass resolution better than 80 µm, a linearity better than 0.4% in the area of interest and a dynamic range of 40 dB.

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