ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-TUDC2

THE STUDY OF HIGH-FREQUENCY PICK-UPS FOR ELECTRON BEAM POSITION MEASUREMENTS IN THE AWAKE COMMON BEAMLINE

C. Pakuza*, M. Krupa, T. Lefèvre, S. Mazzoni, E. Poimenidou,
E. Senes, N. Z. van Gils[1], M. Wendt, CERN, Genève, Switzerland
P.N. Burrows, B. Spear, W. Zhang
John Adams Institute, University of Oxford, Oxford, United Kingdom
S. Liu, Fermi National Accelerator Laboratory, Illinois, USA
V. Verzilov, TRIUMF, Vancouver, Canada
[1]also at UMCG-PARTREC, University of Groningen, Groningen, Netherlands

Abstract

The common beamline of the AWAKE experiment at CERN involves the co-propagation of two particle beams: protons with 48 nC bunch charge and 250 ps bunch length, and electrons with up to 600 pC bunch charge and approximately 4 ps bunch length. The existing operational beam position monitors at AWAKE cannot measure the electron bunches whilst the more-intense proton bunches are present, due to their low operating frequency. In order to try to address this challenge, two different types of high-frequency pick-ups were studied, a conical-shaped button pick-up and a Cherenkov diffraction radiation-based pick-up designed to operate at around 30 GHz. Both devices were installed at AWAKE and were connected to two identical read-out systems designed by TRIUMF. This contribution presents and discusses the results obtained from beam-based measurements during the current experimental year.

INTRODUCTION

The AWAKE experiment uses proton bunches from the Super Proton Synchrotron (SPS) at 400 GeV beam energy to resonantly drive wakefields in 10 m-long plasma through a process called seeded self-modulation (SSM) [1]. SSM divides the several cm-long proton bunch into a train of mm-scale micro-bunches. If electrons are injected at the correct phase with respect to the proton bunch, they can be accelerated. During AWAKE Run 1 (2016-2018), the SSM of proton bunches, seeded by the relativistic ionization front (RIF) of a short laser pulse, was demonstrated [2], along with the acceleration of externally injected electrons [1]. The goal of Run 2, which began in 2021, is to accelerate electrons to high energies (~ 0.5-1 GV/m), while controlling the beam quality and to demonstrate the scalability [3].

For more precise control of the electron beam before the entrance into the plasma, knowledge of the electron beam position in the presence of the more-intense proton bunches is required. However, the current stripline beam position monitors (BPMs) designed by TRIUMF [4] operate at 404 MHz which is in a region where the frequency spectrum is dominated by the proton bunch signal. Hence, in order to measure the electrons in the presence of protons, a higher operating frequency is required which should lie within the electron spectrum and well outside the proton spectrum.

Two different types of BPMs operating at a relatively high frequency have been investigated, both numerically and experimentally, to try to address this challenge. These include a conical-shaped button pick-up, based on a design by DESY [5], which will be referred to as the high-frequency BPM (HF BPM), and the Cherenkov diffraction radiation (ChDR) pick-up which will be referred to as the ChDR BPM designed by JAI and CERN [6, 7]. The former comprises four symmetrically arranged cone-shaped electrodes with tapered transitions from the beampipe to the connectors which reduce resonances within the pick-up. The latter is based on the generation of ChDR from the polarisation currents generated on the surface a dielectric material as the beam passes in close proximity to the material. For the design of the ChDR BPM for AWAKE, 6 mm-diameter, 86 mm-long alumina rods angled at 71° with respect to the long axis of the beampipe were chosen as the pick-up design, based on a series of simulations and geometrical constraints [8].

Both pick-ups were connected to two separate, but basically identical read-out systems designed by TRIUMF, for an operation at approximately 30 GHz, which should be in a region of the frequency spectrum where the electron signal dominates, assuming perfect longitudinal Gaussian bunches. The set-up and first results from beam-based measurements will be presented and discussed.

NUMERICAL SIMULATIONS

The mechanical designs of the pick-ups are described in [5] and [6]. Simplified numerical models were created in CST Studio Suite to compare the expected signals from the two pick-ups for an electron bunch charge of 200 pC and the measured corresponding bunch length of 3.4 ps at AWAKE [9]. By processing the peak voltage of the output signal of two opposite BPM electrodes, $U_R(x)$ and $U_L(x) = U_R(-x)$ vs. the beam position x, the relative peak signal difference between the two pick-ups can be observed in Fig. 1. Assuming perfect symmetry, the difference-over-sum of the peak voltage signals $\Delta U/\Sigma U$ provides the expected position sensitivity S of the system from numerical

---

[*] collette.pakuza@cern.ch

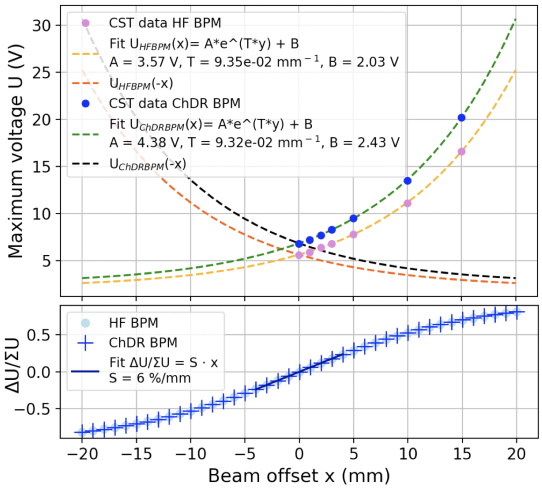

Figure 1: Signal characteristic of the pick-ups, modelled in CST as a function of the beam position, assuming perfect symmetry.

simulations, which is identical for the two pick-ups as can be seen by the bottom plot of Fig. 1.

SET-UP AND CALIBRATION

System Set-up

The two types of high-frequency pick-ups, HF BPM and ChDR BPM, were installed in the common beamline at AWAKE. Their locations are 872.5 mm apart and are shown with the neighbouring electron stripline BPMs in Fig. 2. Both, the HF and ChDR BPMs, were read-out with the same type of signal processing electronics.

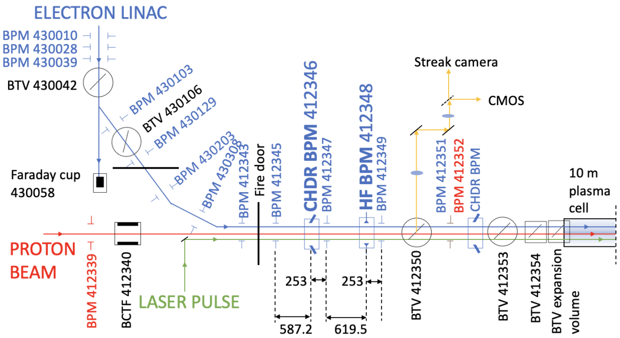

Figure 2: Schematic of the common beamline at AWAKE indicating the beam instruments.

A block schematic of the BPM system is shown in Fig. 3, it has the following functions:

- For the ChDR BPM, the beam field is coupled into the radiators through the generation of ChDR or, for the HF BPM, the particle bunches induce image charges on the HF BPM electrodes.
- For the ChDR BPM, a small fused silica piece is added between the alumina and the following WR28 waveguide network to act as a transition for maximising signal transmission at the BPM operating frequency [10].
- The HF pick-ups are connected to coaxial-to-WR28 waveguide adapters.
- Both pick-ups are connected to two identical signal processing electronics, which detect the BPM pick-up signals at the WR28 waveguides in the recommended frequency band between 26.5-40 GHz.
- In the RF front-end, the signals are passed through band-pass filters (BPF) with 30.5 GHz central frequency and 1 GHz bandwidth (BW) before being down-converted to an intermediate frequency (IF) of 2 GHz.
- The IF signals are demodulated and digitized in the following back-end electronics, designed by TRIUMF, and are further processed using results from CST numerical simulations for the calibration, before reaching the front-end computer, where the CERN front-end software architecture (FESA) [11] acquires the data.

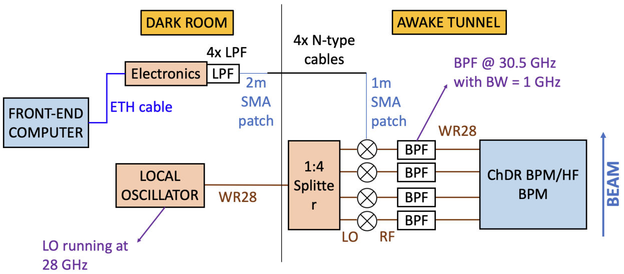

Figure 3: Schematic of the signal processing chain of the high-frequency BPMs at AWAKE.

Non-linear Calibration of the Diode Detectors

The analog back-end uses RF diode detectors to demodulate the IF burst signals of the BPMs. The behaviour of these detectors is non-linear and temperature dependent. Furthermore, there are differences from channel to channel. The following calibration was performed to compensate for these variations.

The calibration set-up is shown in Fig. 4, using a pulse generator made by TRIUMF to feed a fast signal into the electronics module (shown by the dotted box). Everything outside of the box, i.e. P_0, IL and A_{xdB}, was known and pre-calibrated. To calibrate for the response of each diode, and include the effects of the attenuators inside the box and the ADC averaging, a LabVIEW software written by TRIUMF was used to step through the range of the digital-controlled RF step attenuator (written as the variable attenuator in the schematic), whilst recording the averaged ADC signal.

Figure 5 shows, as an example, the un-calibrated signal for channel A (ChA), which corresponds to the left arm of the pick-up when looking downstream,for both the HF BPM and the ChDR BPM at a thermo-electric cooler (TEC) temperature of 34 °C. For the calibration of the HF BPM electronics, $IL = 20$ dB and for the ChDR BPM calibration, $IL = 11$ dB, as of the expected signal difference predicted by the CST simulation. The setting of the second digitally-controlled step attenuator inside the box (written as the digital attenuator in the schematic) was at 6 dB for the HF BPM, whilst for the

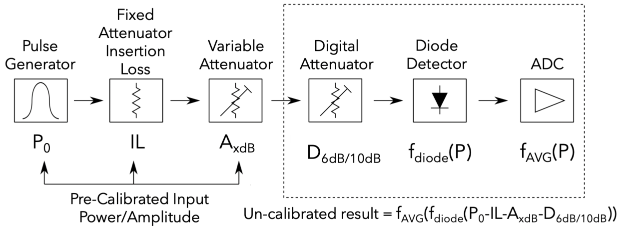

Figure 4: Schematic of the components used for the calibration of the TRIUMF BPM read-out electronics.

ChDR BPM, the setting was 10 dB. 6th-order polynomials were then fitted to this data for all channels of both electronics boxes. As visible from the red trace, the input signal amplitude should be kept below approximately 800 mV for the HF BPM. Above, the behavior of the curve reverses to negative values. In addition, for the ChDR BPM, at approximately 2000 mV input amplitude the ADC values indicated a saturation from the clipping of the measured waveform. Therefore, the input signal should be kept below this in the case of the ChDR BPM.

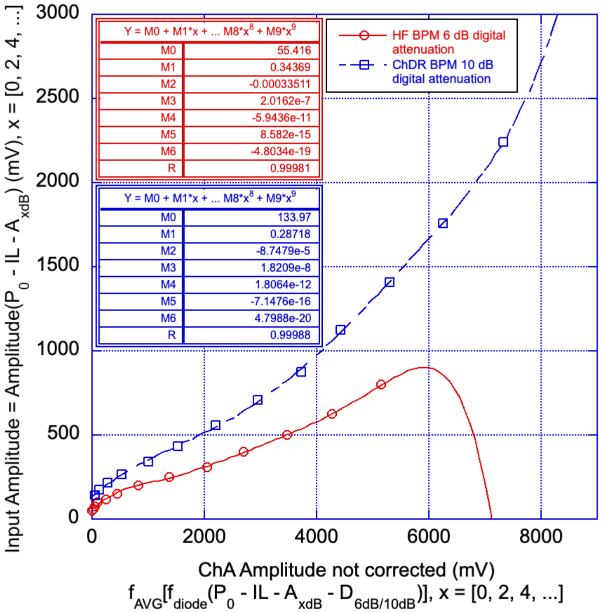

Figure 5: Plot of the input signal amplitude from the pulse generator against the amplitude reading (not corrected) of ChA for both the HF BPM electronics and the ChDR BPM electronics.

The polynomial fitting allows for the function $f_{AVG}(P)$ to be determined which can then be accounted for in the LabView software resulting in the electronics boxes to be calibrated.

To test if both boxes had been successfully calibrated, the same signal from the pulse generator was sent through each channel and the variable RF attenuator setting outside of the box was changed. The averaged ADC readings before and after the non-linear correction are shown in Fig. 6 and Fig. 7 respectively. Obviously, the non-linear response of the diodes and variations between channels were successfully corrected.

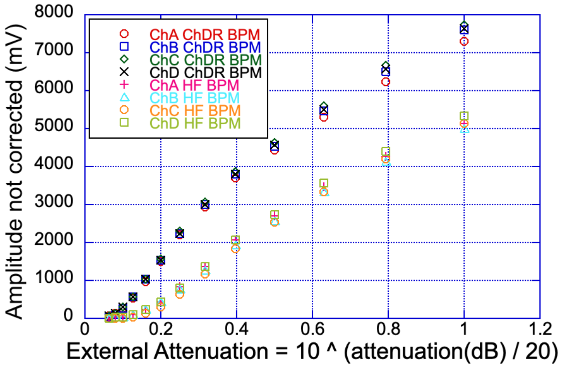

Figure 6: Averaged ADC amplitudes (not corrected) as a function of the external variable attenuator setting.

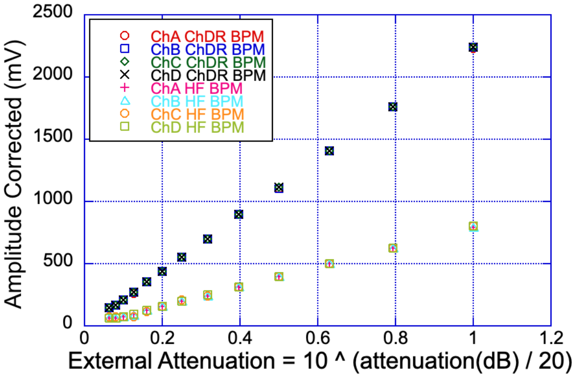

Figure 7: Averaged ADC amplitudes (corrected) as a function of the external variable attenuator setting.

BEAM MEASUREMENTS

During the experimental Run 2 of AWAKE, the ChDR BPM and HF BPM systems were tested with an alternative set-up to the one described above where the detection chain was simpler and involved a WR28 waveguide transmission line connected to a Schottky diode detector and oscilloscope. This was tested with both electron beam only, and electron and proton bunches simultaneously [12, 13]. The results showed that the measured sensitivity is lower for the HF BPM than for the ChDR BPM with the same detection set-up. It also showed that the measured sensitivity is consistent to within 3 standard deviations with the presence of the low-intensity proton bunches (16 nC bunch charge). However, there is some perturbation from proton bunches at the higher bunch charge of 48 nC. Since the non-linear response of the diodes was not accounted for in this case, there could also be some effect from this on the results.

One advantage of the read-out electronics designed by TRIUMF, and as already described above, is that the non-linear response of the diodes can be corrected for. Although more tests are required to better understand the electronics calibration with the beam signal and to test which configuration of the digital attenuation works best for the two systems,

ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-TUDC2

here, the first, preliminary results are presented with the un-calibrated systems.

The measurements included a horizontal electron beam position scan, with all magnetic elements between the location of the correction (steering) magnet, used as deflector for the beam scan (located next to BPM 412345), and the last BPM 412349 turned off and degaussed. This ensured a ballistic trajectory of the particle beam between BPMs 412345 and 412349. The ChDR BPM 412346, BPM 412347 and HF BPM 412348 are located between BPM 412345 and BPM 412349 (Fig. 2). The horizontal position signals of the HF and ChDR BPM, and the neighbouring stripline BPM are shown in Fig. 8.

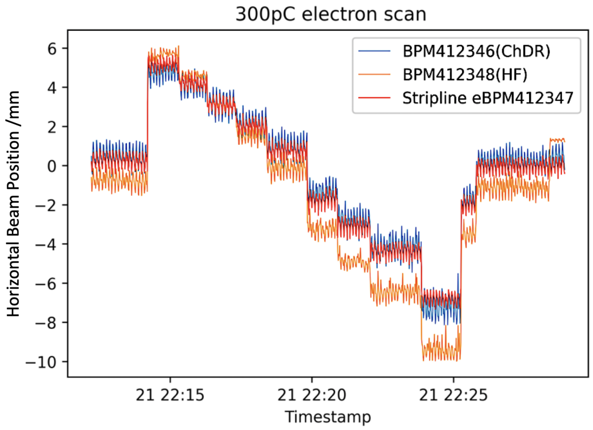

Figure 8: Horizontal electron beam position of the ChDR, HF and neighbouring stripline BPM with only the presence of the electron bunches.

It can be seen that the position measurements of the HF and ChDR BPM follow closely the response of the stripline BPM where it is clearly demonstrated that both the HF and ChDR BPMs are sensitive to the beam position. To characterise the systems together with the TRIUMF read-out, more beam tests are required. To further understand the effect of the presence of the proton bunches, beam tests with simultaneous electrons and protons are also necessary.

CONCLUSION

Two high-frequency pick-ups were installed and tested in the AWAKE common beamline. They were connected to two identical read-out systems. Those read-out electronics, designed by TRIUMF, were successfully calibrated and integrated in the CERN FESA accelerator control and DAQ software for data collection. A horizontal position scan of the electron beam showed that both BPMs are sensitive to the beam position. More beam tests with the calibrated electronics are required in order to fully characterise the systems, and data with the presence of the proton bunches are also needed to better understand this might affect the system performance.

REFERENCES

[1] AWAKE Collaboration, “Acceleration of electrons in the plasma wakefield of a proton bunch”, *Nature*, vol. 561, pp. 363-367, 2018. `doi:10.1038/s41586-018-0485-4`

[2] E. Aldi *et al.* (AWAKE Collaboration), “Experimental observation of proton bunch modulation in a plasma, at varying plasma densities”, *Phys. Rev. Lett.*, vol. 122, pp. 054802, 2019. `doi:10.1103/PhysRevLett.122.054802`

[3] P. Muggli (AWAKE Collaboration), “Physics to plan AWAKE Run 2”, *J. Phys. Conf. Ser.*, vol. 1596, no. 1, pp. 012008, 2020. `doi:10.1088/1742-6596/1596/1/012008`

[4] S. Liu *et al.*, “The installation and commissioning of the AWAKE stripline BPM”, in *Proc. IBIC’18*, Shanghai, China, Sep. 2018, pp.253-256. `doi:10.18429/JACoW-IBIC2018-TUPB01`

[5] A. Angelovski *et al.*, “High bandwidth pickup design for bunch arrival-time monitors for free-electron laser”, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 15, no. 11, pp. 112803, Nov. 2012. `doi:10.1103/physrevstab.15.112803`

[6] C. Pakuza *et al.*, “Electron Beam Studies on a Beam Position Monitor based on Cherenkov Diffraction radiation”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 4806-4809. `doi:10.18429/JACoW-IPAC2023-THPL146`

[7] E. Senes *et al.*, “Selective electron beam sensing through coherent Cherenkov diffraction radiation”, *Phys. Rev. Res.*, vol. 6, no. 2, pp. 023278, Jun. 2024. `doi:10.1103/PhysRevResearch.6.023278`

[8] C. Pakuza *et al.*, “A Beam Position Monitor for Electron Bunch Detection in the Presence of a More Intense Proton Bunch for the AWAKE Experiment”, in *Proc. IPAC’22*, Bangkok, Thailand, Jun. 2022, pp. 381-384. `doi:10.18429/JACoW-IPAC2022-MOPOPT053`

[9] E. Senes, “Development of a beam position monitor for co-propagating electron and proton beams”, Ph.D. thesis, Phys. Dept., University of Oxford, Oxford, United Kingdom, 2020.

[10] C. Pakuza, “Development of a beam position monitor based on Cherenkov diffraction radiation for the AWAKE experiment at CERN”, Ph.D. thesis, Phys. Dept., University of Oxford, Oxford, United Kingdom, 2023.

[11] A. Topaloudis and C. Rachex, “Visualisation of real-time front-end software architecture (FESA) developments at CERN”, in *Proc. ICALEPCS’17*, Barcelona, Spain, Oct. 2017, pp. 1853-1856. `doi:10.18429/JACoW-ICALEPCS2017-THPHA180`

[12] B. Spear *et al.*, “Beam studies using a Cherenkov diffraction based beam position monitor for AWAKE”, in *Proc. IPAC’24*, Nashville, Tennessee, USA, May 2024, pp.2327-2330. `doi:10.18429/JACoW-IPAC2024-WEPG49`

[13] B. Spear *et al.*, “Electron bunch position determination using a high frequency button beam position monitor in the AWAKE facility”, presented at the 13th Int. Beam Instrumentation Conf. (IBIC’24), Beijing, China, September 2024, paper TUP21, this conference.