ELECTRON BEAM STUDIES ON A BEAM POSITION MONITOR BASED ON CHERENKOV DIFFRACTION RADIATION

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Abstract

A beam position monitor (BPM) based on Cherenkov diffraction radiation (ChDR) is currently under investigation to disentangle the electromagnetic field of an electron bunch from that of a proton bunch travelling together in time and space in the beam-line of the Advanced Wakefield Experiment (AWAKE) at CERN. The signals from a horizontal pair of ChDR BPM radiators have been studied under a variety of beam conditions at the CERN Linear Electron Accelerator for Research (CLEAR) test facility. This paper summarizes the results using microwave signal processing at different frequency ranges.

INTRODUCTION

The AWAKE experiment at CERN studies electron bunch acceleration via the wakefields generated inside a 10 m long rubidium plasma cell by a proton bunch from the Super Proton Synchrotron (SPS) [1]. The protons, with a bunch charge of 48 nC and a length of 200 - 400 ps (1 σ), arrive from the SPS every 15 - 30 s, and propagate together with a short laser pulse used to ionise the Rubidium vapour and seed the self-modulation process (SSM) which modulates the $\sigma_z \approx 6$ - 12 cm long proton bunch into a train of micro-bunches with size and spacing of the order of the plasma wavelength $\lambda_{pe} \approx 1$ mm. These micro-bunches set up high gradient wakefields in which an electron bunch, if injected at the correct phase with-respect-to the proton bunch and travelling on the exact same beam trajectory through the cell, will be accelerated. The experiment demonstrated the SSM process [2] and the acceleration of the electrons [1] from 19 MeV to 2 GeV.

BPMs before and after the plasma cell are used to separately detect the transverse beam displacement of proton and electron bunches, and, therefore, enable the steering of the 19 MeV electron beam trajectory on that of the 400 GeV proton bunch. A major limitation of the current electron BPM system at AWAKE is its operating frequency, 404 MHz, which cannot discriminate the less-intense electron bunches (~ 600 pC bunch charge and a few ps bunch length) from the more-intense proton bunches. Thus, they cannot measure the electron bunch position in presence of a proton bunch. A novel BPM based on ChDR has been studied to address this problem.

ChDR is generated when a charged particle travels in close proximity to a dielectric medium with a velocity greater than the phase velocity of light in that medium [3]. It is a surface effect in which the atoms on the face of the dielectric exposed to the beam field get polarised, producing dipoles with oscillating atomic electrons that then produce currents and radiation. This radiation field, known as ChDR, propagates through the dielectric medium under the Cherenkov angle. The amount of ChDR generated by the dielectric is dependent on the amount of particle beam field intercepted. Hence, it is dependent on the particle bunch intensity, energy and position, and on the size of the radiator surface. By arranging four dielectric, so-called, ChDR radiators ("buttons") and spacing them symmetrically on the perimeter of the beam-pipe – two in the vertical plane and two in the horizontal plane – a non-invasive beam position measurement can be achieved [4, 5].

CHDR BPM DESIGN

An improvement to the current electron BPM system at AWAKE requires the electron BPMs in the common beam-line to be insensitive to the proton bunch signal. By considering the frequency content of the longer proton bunch and the shorter electron bunch, the electron signal intensity dominates at frequencies higher than a few GHz. By choosing a ChDR radiator with a dielectric material that can be installed in a vacuum compatible chamber, with a relative permittivity and cross-section size that results in a waveguide cut-off frequency higher than a few GHz, the majority of the proton bunch signal will not penetrate, whilst transmitting the majority of the electron bunch signal. From a series of numerical computations using the CST Studio Suite software, and for technical and practical reasons, the radiator was chosen to be a cylindrical alumina (Al_2O_3) rod with a relative

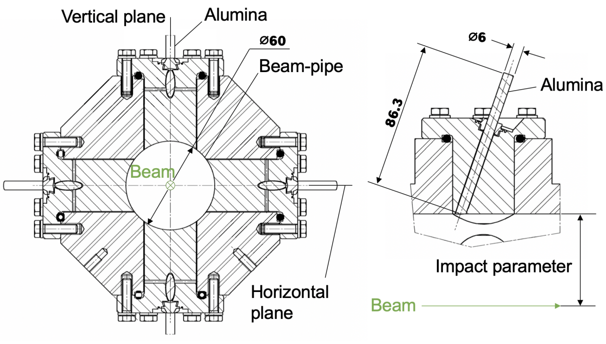

Figure 1: Mechanical representation of the ChDR BPM design for the AWAKE experiment with section views of the BPM in the transverse (left) and in the longitudinal plane (right).

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permittivity $\varepsilon_r \simeq 9.9$, diameter 6 mm, length 86 mm, and mounted under the Cherenkov angle (~71°) with respect to the beam pipe. These radiators form a circular waveguide with a TE11-mode cut-off frequency of 9.3 GHz, which has been verified via RF measurements in the laboratory [6]. The final mechanical design of the ChDR BPM for installation at AWAKE is shown in Fig. 1 and utilises existing proton button BPM bodies.

THE CHDR BPM SET-UP AT CLEAR

For dedicated electron beam studies, the horizontal plane of an AWAKE ChDR BPM was manufactured and installed at the CLEAR facility [7], where the electron bunch parameters are similar to those at AWAKE.

CLEAR comprises a 20 m long injector beam-line, followed by a 16 m long experimental beam-line. Being a beam test facility, CLEAR is equipped with a variety of beam diagnostic instruments along the beam-line. At beginning of the injector-line, there is a beam current transformer (BCT) to measure the bunch charge and at the end, there is an RF deflecting cavity (RFD) for measuring the electron bunch length. The experimental beam-line consists of a number of beam television (BTV) screens which can provide the bunch transverse sizes, inductive BPMs and a BCT located near the in-air test stand at the end of the line.

The ChDR BPM was installed ~7 m upstream of the in-air test stand. Figure 2 illustrates the ChDR BPM location in the CLEAR experimental beam-line, between two inductive BPMs (BPM 595 and 690), two screens (BTV 620 and 730), and three corrector magnets (DHJ 540, 590 and 710).

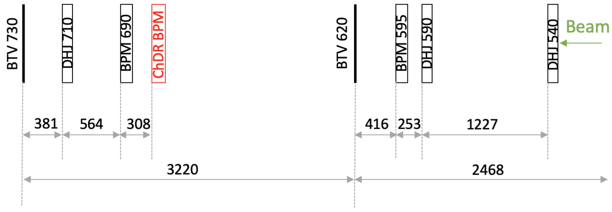

Figure 2: Schematic of the CLEAR beam-line around the location of the ChDR BPM located at ~7 m upstream of the end of the beam-line with distances given in mm.

The signal detection and processing chain consisted of a horn antenna, directed at the exit of the alumina waveguide radiator, connected to a Schottky diode detector. The detector rectifies the input signal and takes the envelope of the signal, which is then transmitted through a coaxial line to a 6 GHz, 25 GS/s oscilloscope located outside of the CLEAR tunnel. A typical setup with a WR15 rectangular waveguide, operating in a frequency range of 50 - 75 GHz is shown in Fig. 3. A similar signal processing chain was tested in two other frequency ranges, using WR28 (26.5 - 40 GHz), and WR10 (75 - 110 GHz) horn antennas and Schottky diodes.

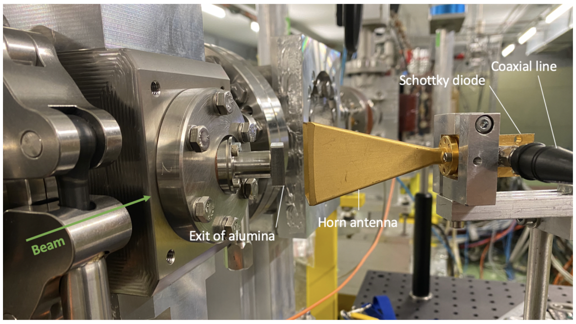

Figure 3: The signal processing chain for one of the two horizontal alumina radiators in the frequency range 50 - 75 GHz, i.e. using WR15 waveguide components.

MEASUREMENT PROCEDURE

To characterise the ChDR BPM response, a variety of systematic beam measurements were performed, including a bunch charge scan, and an impact parameter scan, i.e. a beam position scan in both the horizontal and vertical planes. A typical data taking procedure began by measuring or verifying bunch charge and length, which were done with the BCT and RFD in the injector-line. Once the bunch length matched the required value, the beam was directed to the ChDR BPM in the experimental-line and a loss-free beam transport was checked via the BCT located at the in-air test stand. For a high bunch charge setting, and with zero current in the corrector magnets DHJ 590 and 710, the beam was centred by reading the two inductive BPMs on either side of the ChDR BPM. The YAG screen of BTV 730 was then inserted and recorded as the reference zero position. With the beam centered, a charge scan was performed, which provided valuable information about the response of the Schottky diodes and the so-called square-law regime, which had to be identified.

For a Schottky diode detector, the output voltage V_{out} is related to the input power P_{in} via

$$V_{out} = K(\sqrt{P_{in}})^{\alpha}, \tag{1}$$

where K is a constant. Below a certain level of input power the diode operates in the square-law regime, $\alpha \approx 2$. Since the bunch charge is proportional to the input voltage to the diode, the input power is proportional to the square of the bunch charge. Hence, the output voltage is also proportional to the square of the bunch charge. It was advantageous to operate the diode in this regime so that no non-linear corrections needed to be applied to the data.

Once the bunch charge was adjusted to a suitable level ensuring the diodes operate in the square-law regime, a beam position scan in the horizontal plane was done by changing the current in corrector magnet DHJ 540. The position of the beam was recorded via BTV 730 as the readings from the inductive BPMs showed to be inaccurate at low bunch charge. A 1 mm displacement on screen BTV 730 corresponded to a 0.75 mm displacement at the location of the ChDR BPM by considering the distances between the instruments since the beam is ballistic after DHJ 540. Similarly, the beam position was also scanned in the vertical plane to test the cross-coupling of the ChDR BPM. The beam position scans were repeated for different frequency ranges by changing the components of the signal processing chain.

RESULTS

Figure 4 shows the response $\sqrt{V_{out}} = f(q_{bunch})$ of the WR15 waveguide Schottky diode detector vs. the charge of a single electron bunch. For each bunch charge setting, the data of 100 beam shots was acquired with the oscilloscope, and the square-root of the averaged peak value of the $V_{out}(t)$ waveform is plotted against the bunch charge. The measurement result clearly identifies the square-law regime for bunch charges less than approximately 50 pC.

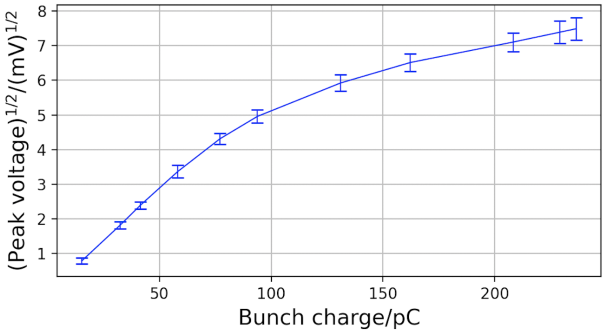

Figure 4: Plot of square-root of the peak output voltage of the diode versus the bunch charge for detection in the WR15 frequency range.

The signal level was then maintained below the signal level corresponding to a 50 pC bunch charge for the entire range of the position scans. Figures 5 and 6 show the raw signals for the left (when looking downstream) radiator, taken from the oscilloscope as an average of 100 shots for each beam position in the horizontal and vertical plane respectively. It can be seen that as the horizontal beam position is scanned from left to right, the signal level decreases as expected. When the beam is moved back to the centre and scanned vertically, there is then no significant change to the signal levels, as can be seen from Fig. 6.

The scans were repeated for the two other frequency ranges. In the case of the WR28 waveguide frequency range, there were enough component pairs available to record data from both radiators at the same time. The normalised beam position signal was calculated as difference-over-sum from the square-root of the peaks of the waveforms (since $\sqrt{V_{out}} = V_{in}$, where V_{in} is the input voltage of the diode) to provide an estimation of the position sensitivity of the ChDR BPM. This was also done for the WR15 and WR10 frequency ranges by assuming a symmetric system and mirroring the response on the opposite radiator. The results are presented in Fig. 7 where the position sensitivity is the gradient of the linear fits. It was found that the sensitivity increases with increasing detection frequency, as predicted by the theory.

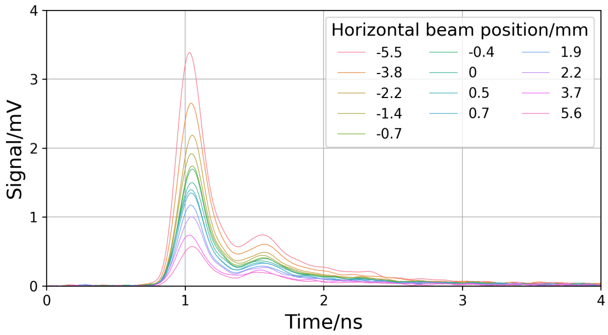

Figure 5: Plot of output signal of the diodes against time for varying horizontal beam positions with detection in the WR15 frequency range. The beam is centred in the vertical.

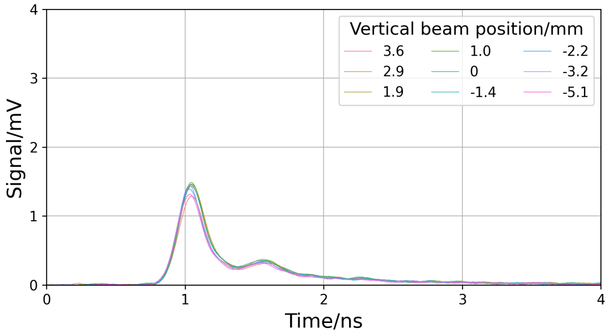

Figure 6: Plot of output signal of the diodes against time for varying vertical beam positions with detection in the WR15 frequency range. The beam is centred in the horizontal.

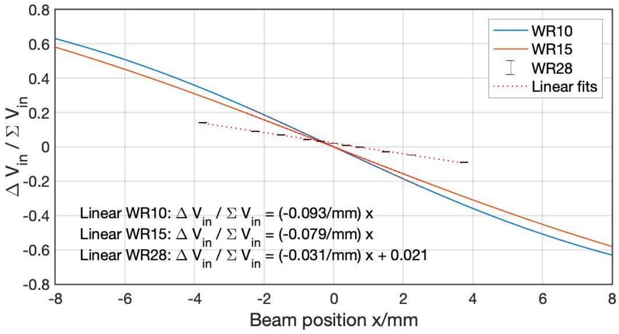

Figure 7: Normalised beam position signal as difference-over-sum from the square-root of the peaks of the waveforms as a function of the horizontal beam position x.

CONCLUSIONS

A novel ChDR BPM, composed of two alumina radiators in the horizontal plane was characterised with electron bunches, analyzing the radiation in three different frequency ranges, 26.5 - 40 GHz, 50 - 75 GHz and 75 - 110 GHz. Charge scans were done to provide the response of the Schottky diode detectors. Systematic horizontal and vertical beam position scans were performed to test the response of the ChDR BPM which provided an estimate of the position sensitivity of the ChDR BPM.

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