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A BEAM POSITION MONITOR FOR ELECTRON BUNCH DETECTION IN THE PRESENCE OF A MORE INTENSE PROTON BUNCH FOR THE AWAKE EXPERIMENT

C. Pakuza†, P.N. Burrows, John Adams Institute for Accelerator Science, Oxford, United Kingdom
R. Corsini, W. Farabolini, P. Korysko, M. Krupa, T. Lefevre, S. Mazzoni, E. Senes, M. Wendt,
CERN, Geneva, Switzerland

Abstract

The Advanced Proton Driven Plasma Wakefield Experiment (AWAKE) at CERN uses 6 cm long proton bunches extracted from the Super Proton Synchrotron (SPS) at 400 GeV beam energy to drive high gradient plasma wakefields for the acceleration of electron bunches to 2 GeV within a 10 m length. Knowledge and control of the position of both copropagating beams is crucial for the operation of the experiment. Whilst the current electron beam position monitoring system at AWAKE can be used in the absence of the proton beam, the proton bunch signal dominates when both particle bunches are present simultaneously. A new technique based on the generation of Cherenkov diffraction radiation (ChDR) in a dielectric material placed in close proximity to the particle beam has been designed to exploit the large bunch length difference of the particle beams at AWAKE, 200 ps for protons versus a few ps for electrons, such that the electron signal dominates. Hence, this technique would allow for the position measurement of a short electron bunch in the presence of a more intense but longer proton bunch. The design considerations, numerical analysis and plans for tests at the CERN Linear Electron Accelerator for Research (CLEAR) facility are presented.

INTRODUCTION

The AWAKE experiment uses the wakefields generated by a long proton bunch with length of the order of a few hundred ps to accelerate short electron bunches [1]. The set-up is shown in Figure 1. The proton bunches arrive every 15-30 s from the SPS and their typical parameter ranges are given in Table 1. They then propagate colinearly with a 120 fs long, 780 nm central wavelength laser pulse inside a 10 m long rubidium (Rb) vapour source. The laser is used to singly ionise the Rb vapour to a plasma with the same density as the vapour. This density can be chosen in the range 1-10×10^{14} cm^{-3} required for the generation of wakefields of the order of 1 GV/m [2]. To effectively drive large amplitude wakefields, the drive bunch should have transverse and longitudinal sizes of the order of the plasma wavelength which for the given plasma density range is ~1 mm. Since the proton bunch is several cm long, the generation of large amplitude wakefields relies on a process called seeded self-modulation (SSM). Here, the proton bunch is divided into a train of micro-bunches with longitudinal size less than and period equal to the plasma wavelength [3]. The relativistic ionisation front of the laser pulse seeds the self-modulation process creating a reference phase for the correct injection of electrons in order for them to be focussed and accelerated. During Run 1 (2016-2018), the self-modulation of an SPS proton bunch into a train of over 20 micro-bunches and the acceleration of electrons from 19 MeV to 2 GeV in a 10 m plasma cell was successfully demonstrated [1]. The goals for Run 2 (2021-2024) include SSM via electron bunch seeding and the addition of a density step in the vapour source for maintaining wakefield amplitudes at maximum level over longer distances [4].

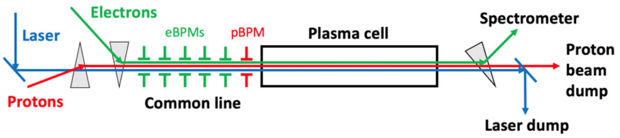

Figure 1: Schematic of the AWAKE experiment.

Amongst the diagnostics for measuring the occurrence of SSM in the proton bunch and the electron beam parameters after acceleration, the measurement of the beam position of the electron and proton bunches before the plasma cell for alignment purposes is a crucial aspect of the experiment. The beam position monitoring system for the protons is composed of 21 dual plane button-style beam position monitors (BPMs) between the extraction point from the SPS to downstream of the plasma cell [5]. For the electrons, there are 5 shorted stripline BPMs in the common beam line as shown in Figure 1. The electron BPMs operate at 404 MHz with position resolution of 10 µm in both planes [6].

Table 1: Proton and Electron Parameters at AWAKE [7]

Parameter	Protons	Electrons
Energy/GeV	400	0.01-0.02
Bunch length/ps	200-400	0.3-10
Bunch charge/nC	48	0.1-1

MOTIVATION FOR A HIGH FREQUENCY ELECTRON BEAM POSITION MONITOR

In the common beam line at AWAKE, both proton and electron bunches are present. The electron BPM system operating at 404 MHz are able to detect electrons when the protons are not present. If both beams are present, the proton signal dominates and prevents the position

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† collette.pakuza@physics.ox.ac.uk

measurement of the electron bunch. This is shown via the spectra of the bunches in Figure 2 assuming Gaussian bunches. Currently, the beam position of the electron bunches is determined by utilizing the different repetition rates of both beams. The electron bunches are produced at a rate of 10 Hz while the protons arrive every 15-30 s. The position of the electron bunch when the protons are present is extrapolated from shots before and after the proton bunch. In order to make a more meaningful measurement, a BPM to measure the electron bunch in the presence of a proton bunch is required. This is done by exploiting the different bunch lengths of the particle beams and operating at a high enough frequency where the electron signal dominates.

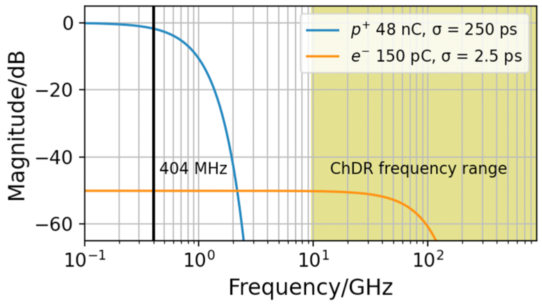

Figure 2: Spectra of the proton and electron bunches at AWAKE assuming Gaussian longitudinal distributions.

A BPM BASED ON CHERENKOV DIFFRACTION RADIATION

Theory of Cherenkov Diffraction Radiation

The theory of Cherenkov radiation developed by Frank and Tamm in 1937 [8] describes the generation of radiation as a charged particle traverses a medium at a velocity greater than the phase velocity of light in that medium. A coherent wavefront is formed at the Cherenkov angle. Cherenkov diffraction radiation (ChDR) refers to a charged particle travelling in close proximity to, but not inside, a dielectric target and polarises the atoms on its surface [9]. The radiation emitted from this interaction, known as ChDR, propagates through the medium at the Cherenkov angle. Due to its non-invasive nature and well-defined angle of emission, ChDR could provide a useful tool for particle beam diagnostics [10,11]. In the context of beam position monitoring, dielectric buttons, also referred to as radiators, can be used to generate ChDR to couple to the beam field for detection.

Design Considerations

To utilise the already limited space available in the common line at AWAKE, the ChDR radiators were designed to fit into the button housing that are compatible with the existing proton BPM (pBPM) body. This was in view of converting the pBPM before the plasma cell into a ChDR BPM and installing an additional ChDR BPM in the furthest drift section upstream of the plasma cell in the common line. Due to the geometry of the pBPM buttons and the radiation tolerance, alumina with a relative dielectric permittivity of 9.4 and Cherenkov angle of 71° was chosen as the radiator material. The design is shown in Figure 3.

From previous streak camera measurements of the proton bunch profile at AWAKE, it was found that the spectral content of the proton bunches extends to frequencies higher than expected for an ideal Gaussian bunch [12]. For typical electron parameters, the frequency range in which the electrons dominate is between 20-40 GHz. If the filtering of the electron signal is to be done at the radiator, then this would require radiator diameters less than a few mm. This poses limitations in the power output and increases the fragility of the radiator. As a result, a diameter of 6 mm corresponding to a cut-off frequency of 9.6 GHz was chosen to partially filter the signal whilst the remainder of the high-pass filtering is realised by commercially available WR28 rectangular waveguides operating in the Ka-band (26.5-40 GHz) with a cut-off of 21.1 GHz. Due to the availability of in-house components, an operating frequency of 30 GHz was chosen.

Since the signal needs to be transmitted efficiently from the circular alumina waveguide to the WR28 waveguide at the chosen operating frequency, a transition was designed based on a quarter-wave impedance transformer for maximum power transmission between the two dominant modes of the waveguides. The design involves a ∅6 mm, 9.9 mm long fused quartz piece inserted between the alumina and WR28 waveguide. This corresponded to 99% power transmission at 30 GHz. The transition can be attached to the extended end of the alumina shown in Figure 3.

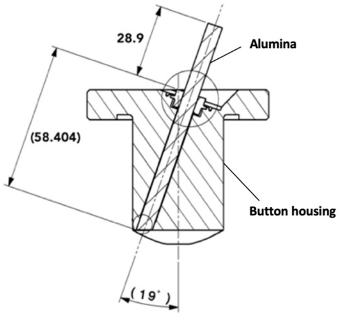

Figure 3: Schematic of ChDR BPM button with radiator angled at 71°.

Numerical Simulations of the ChDR BPM

To better understand the behaviour of the propagation of ChDR inside the radiator, one arm of the pick-up (PU) was modelled and simulated in CST Studio Suite Wakefield solver [13]. The model is shown in Figure 4. It includes the ∅60 mm AWAKE beampipe, one ∅6 mm alumina angled at 71°, and the electron beam shown by the blue and orange arrows. The electron bunch parameters are similar to those at AWAKE. The background material is set as a perfect electrical conductor. From the time evolution of the field shown in Figure 4, it can be seen that the ChDR is generated as the particle beam passes the surface of the radiator and propagates at the Cherenkov angle inside the radiator. In addition, radiation generated from the finite geometry of the PU is also coupled out of the PU and can be seen by the succeeding wavefronts that are not propagating at the

Cherenkov angle. As these fronts travel along the alumina, they undergo multiple reflections.

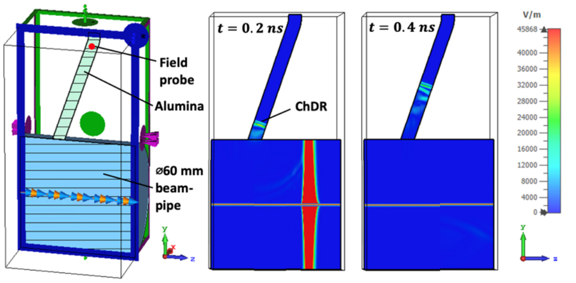

Figure 4: 3D CST model of one arm of the monitor (left) and time evolution of the radiation generated as the beam passes the radiator presented as a contour plot of the absolute E-field (right).

A field probe was placed at a location 86 mm inside the alumina to measure the E-field as a function of time. This was recorded for varying vertical beam offsets. The peak field was plotted as a function of the beam offset and is shown in Figure 5. Assuming the system is symmetric, this behaviour was mirrored for the opposite arm of the PU. By taking the difference over sum of the measured peak fields as a function of the beam offset, a position sensitivity of 5.8 %/mm was obtained from the linear region as shown in Figure 6.

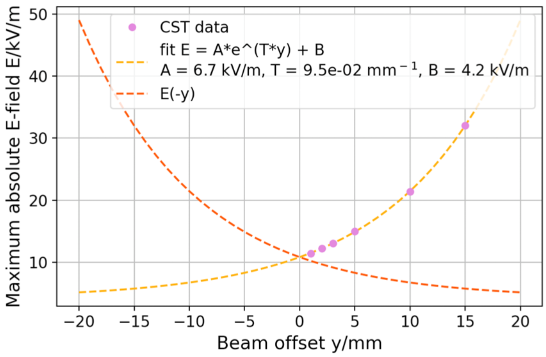

Figure 5: Peak absolute E-field from CST for different vertical beam offsets. The dotted lines are the behaviour of both arms of the plane assuming a symmetric system.

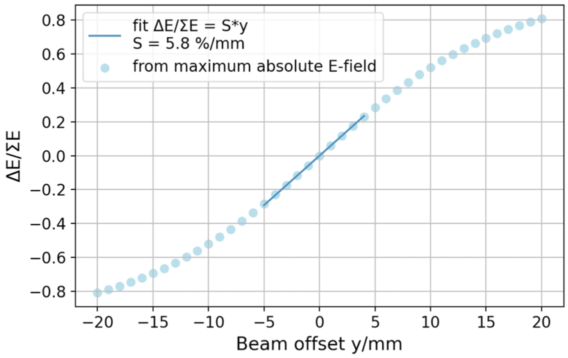

Figure 6: Difference over sum of the E-field measured from the two arms in the vertical plane of the monitor as a function of vertical beam position. The position sensitivity is 5.8 %/mm in the linear region.

A ChDR Monitor for Tests at CLEAR

Beside the first successful beam tests at AWAKE following the recent installation of one ChDR BPM [14], a BPM with two ChDR buttons in the horizontal plane is foreseen for dedicated beam studies at CLEAR this year [15]. The monitor will be installed in vacuum approximately 7 m upstream of the beam dump. It will be mounted on a translation stage for position scan measurements. The detection system for each arm will comprise a 30 GHz, 300 MHz bandwidth (BW) band-pass filter (BPF), a variable attenuator and a Ka-band zero-bias Schottky diode detector. The signals will then be measured via a scope. The goal is to scan the parameter space of the electron bunch, measure the signals, and compare them to what is expected from analytical and numerical models. This would provide important information for the continued commissioning of the two ChDR BPMs at AWAKE.

CONCLUSION

The chosen design of the ChDR BPM was modelled and simulated in a numerical electromagnetic solver. The results showed the generation of ChDR at the Cherenkov angle inside the dielectric medium as expected from theory. It also provided the position sensitivity of an ideal ChDR BPM system with ∅6 mm alumina buttons angled at the Cherenkov angle which is 5.8 %/mm. To benchmark the simulation results, in-vacuum tests will be performed at CLEAR this year.

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