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BEAM STUDIES USING A CHERENKOV DIFFRACTION BASED BEAM POSITION MONITOR FOR AWAKE

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Abstract

A beam position monitor based on Cherenkov diffraction radiation (ChDR) is being investigated as a way to disentangle the signals generated by the electromagnetic fields of a short-pulse electron bunch from a long proton bunch co-propagating in the AWAKE plasma acceleration experiment at CERN. These ChDR BPMs have undergone renewed testing under a variety of beam conditions with proton and electron bunches in the AWAKE common beamline, at 3 different frequency ranges between 20-110 GHz to quantify the effectiveness of discriminating the electron beam position with and without proton bunches present. These results indicate an increased position sensitivity to the electron beam position in the highest frequency bands. Furthermore, high frequency studies investigating the proton bunch spectrum show that a much higher frequency regime is needed to exclude the proton signal than previously expected.

INTRODUCTION

In AWAKE, the Advanced WAKefield Experiment, 400 GeV proton bunches produced by the CERN Super Proton Synchrotron (SPS), with an energy of 19 kJ are used to drive the plasma wakefields [1] in rubidium (Rb) vapour. A 100 fs, 450 mJ laser pulse is used to ionize the Rb vapor column and seed the self-modulation (SSM) of the proton bunches which are initially between 6-12 cm long. These bunches are then split into microbunches that resonantly drive large amplitude wakefields in the plasma [2]. The proton beam is extracted up to 4 times per minute from the SPS with a bunch population ranging between 1 and 3×10^{11} and is focused to ≈ 200 µm transverse beam size before it enters the plasma. An electron beam injected into the plasma at the correct position and phase with respect to the proton bunch will then be accelerated through the plasma cell. Run 1 experiments (2016-2018) demonstrated the existence of the SM process [3] and the ability to accelerate electrons from 18 MeV to 2 GeV [1].

Table 1: AWAKE Nominal Beam Parameters

Beam	**proton**	**electron**
Energy / MeV	4×10^5	19
Charge /nC	48	0.1-0.6
Bunch Length /ps	250	1-5

The beam structure in AWAKE is unique to the experiment as seen in Table 1. The difference in bunch length and intensity leads to a frequency spectrum dominated by the different bunch types in different regimes shown as such in Fig. 1. The current eBPMs operating at 404 MHz see a much higher signal contribution from the protons than the electron beam, therefore the electron position is indistinguishable when both beams are present. At 1.88 GHz the two beams have equal spectral power. Therefore to measure only the electron signal, a much higher working regime of tens of GHz is required.

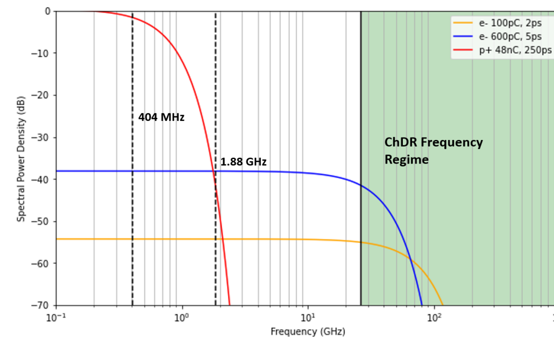

Figure 1: The Frequency spectra of the proton and electron bunches at AWAKE, assuming a Gaussian longitudinal bunch profile.

ChDR is the generation of radiation by a charged particle passing in the vicinity of a dielectric medium where its velocity is greater than the phase velocity of light in that medium [4]. The atoms on the surface of the material that are exposed to the EM field of the charged particle are polarised, and it is this polarisation front which propagates through the material at the cherenkov angle. Due to the non-invasive method of production of ChDR, it is an attractive technique for beam instrumentation, and the development of particle beam diagnostic devices using this phenomenon has become of great interest in recent years [5, 6].

A CHERENKOV DIFFRACTION RADIATION BASED BPM

The design and study of a novel BPM utilising Cherenkov diffraction radiation has been investigated as a way to improve on the current eBPM system at AWAKE. Extensive prototyping and testing in the CERN Linear Electron Accelerator for Research (CLEAR) has been conducted [7, 8] with similar electron beam parameters to AWAKE to refine an operational BPM. The final pickup design (Fig. 2) utilises an 86 mm long alumina (Al_2O_3) cylinder, ⌀ 6 mm, encased in a stainless steel button, corresponding to a cut off frequency of 9.6 GHz and a Cherenkov angle of $\theta_{ch} = 71°$. Using 4 pick-ups set in an existing proton BPM body, each with

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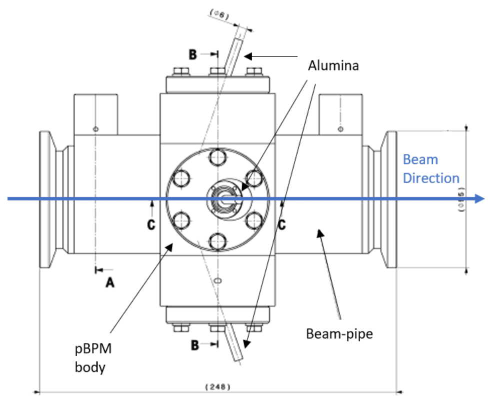

Figure 2: Mechanical drawing of the ChDR BPM body as installed in the AWAKE common beamline.

identical radiators, the BPM is designed to be sensitive to vertical and horizontal position of an electron beam, while rejecting the majority of the signal from the proton beam.

AWAKE EXPERIMENTAL CAMPAIGN

The ChDR BPM Setup in AWAKE

The ChDR BPM is installed into the AWAKE common beamline, approximately 5 m after the merge of the proton and electron beams, and 2 m upstream of the plasma cell.

First dedicated testing of the ChDR BPM with both protons and electrons was conducted over the course of the last beam year, investigating the response of the ChDR BPM in different frequency bands. This was done using an acquisition system through rectangular waveguides of WR28, WR15 and WR10 specifications, where the aperture of the waveguide determines the cutoff frequency of the system. This cutoff ranges from 21.1 GHz for WR28 and 75 GHz for WR10. From the end of the radiator, a typical signal processing chain is composed of a gain horn, isolator and Schottky diode detector as shown in Fig. 3, connected via a coaxial cable to an 8 GHz oscilloscope.

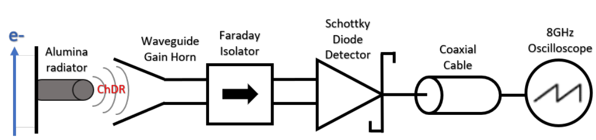

Figure 3: A example of the signal processing on one side of the horizontal plane of the ChDR BPM. The ChDR is coupled out of the end of the radiator using waveguide components.

Electron Beam Studies

A measurement of the ChDR BPM sensitivity operating over the different frequency bands was conducted using the electron beam without protons present in the beamline. The charge of the electron beam was measured using a faraday cup to ensure the power output of the Schottky diodes operated in a linear regime. The electron beam was then steered in the horizontal plane using an upstream corrector magnet. The electron beam position was logged on the stripline BPMs so that the beam position at the location of the ChDR BPM can be calculated. The raw waveform signals for a single pickup in the horizontal plane, with a WR15 (50-75 GHz) acquisition can be seen in Fig. 4.

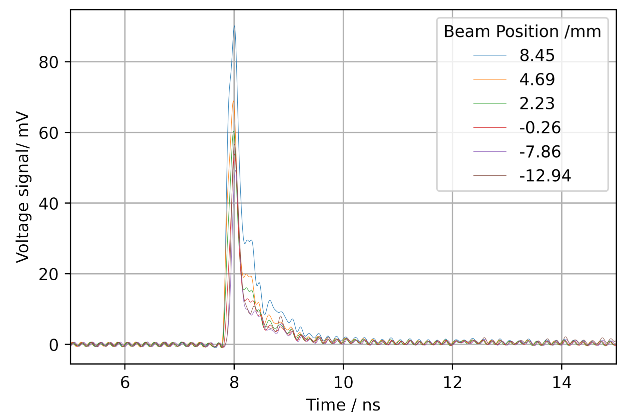

Figure 4: The averaged waveforms of the output signal of the diodes for a WR15 setup over a range of horizontal electron beam positions.

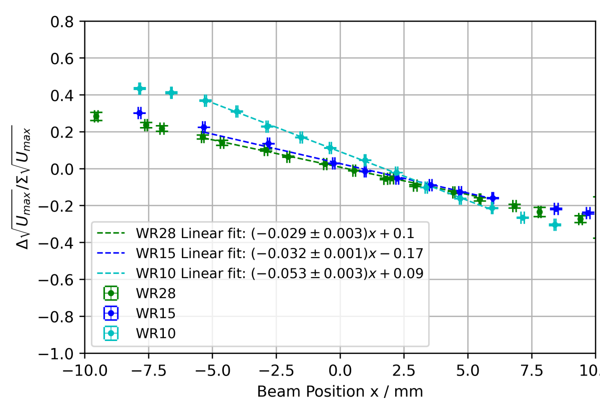

Figure 5: Normalised beam position signal $\frac{\Delta\sqrt{U_{max}}}{\Sigma\sqrt{U_{max}}}$ as a function of the horizontal beam position.

As the beam is moved across the horizontal, with the beam centred in the vertical plane, the incident voltage increases and decreases dependent on its proximity to the alumina. With a symmetrical setup on both the left and right of the beampipe, the two sets of waveforms can be used to calculate a normalised beam position signal. Using an average of the square root of the peak voltage of the waveforms recorded on the oscilloscope, the difference over sum ($\Delta U/\Sigma U$) calculation can be performed to determine the sensitivity, S_x of the BPM using:

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$$x \approx \frac{1}{S_x} \frac{\Delta U_x}{\Sigma U_x} \tag{1}$$

This was then repeated for the WR28 (20-40 GHz) and WR10 (75-110 GHz) frequency ranges. The results are shown in Fig. 5, with sensitivity in %/mm taken from the gradient of the linear fit of the position scan. As predicted by theory, the position sensitivity increases as the detection band frequency increases.

Proton Beam Studies

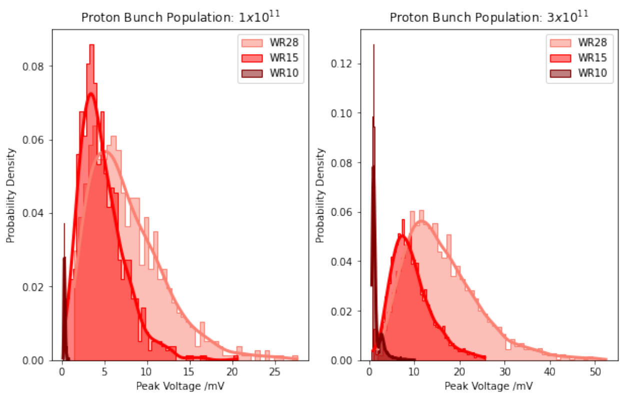

Figure 6: The distribution of the peak voltages recorded at the oscilloscope over a large number of proton shots represented with a histogram for each investigated frequency band at high (right) and low (left) proton intensities. The curves show a fitted probability density function to the distribution.

It was important to confirm that the frequency band chosen for operation provided the necessary discrimination of the electron bunch from the proton bunch. Therefore, a study looking at the response of the ChDR BPM during one of AWAKE's proton-only runs was conducted, with the aim of gaining an understanding of the distribution of the frequency content of the proton bunches. From our understanding of the frequency spectrum of the AWAKE proton bunches, it was expected that we would see little to no proton signal on the oscilloscope, especially in the highest frequency bands.

There were two populations of proton bunch over the run, with proton numbers of 1×10^{11} and 3×10^{11}. For each frequency channel, a minimum of 2000 shots were recorded. From each voltage signal recorded at the oscilloscope, the peak voltage was identified and deposited into a histogram in order to view the distribution of the proton contribution, presented in Fig. 6. For all configurations the proton signal contribution is lower for the lower intensity protons. The distribution suggests the frequency content of the proton bunches is highly shot-by- shot dependent and the signal contribution in the WR15 and WR10 frequency bands is not inconsequential. Compared to theory, the frequency content of the SPS protons extends to higher regimes than predicted. The Cherenkov pickup measuring at these high frequencies and installed on the proton beam line only could provide an on-line monitoring on the proton bunch spectrum quality.

Combined Beam Tests

For testing with both the electron and proton beam propagating simultaneously, the ChDR radiator is connected through a quarter wavelength transformer to the WR28 readout arm, with the addition of a 20 GHz lowpass filter. With both the beams present, for each beam position, 500 shots were taken with the oscilloscope, a long enough period for at least 3 proton shots to be extracted. This was repeated for both low intensity (1×10^{11}) and high intensity (3×10^{11}) proton bunches. The signals containing the proton shots were then identified and separated from the shots recording the electrons, and the difference-over-sum calculation performed. For proton bunches of population 1×10^{11}, shown in Fig. 7.

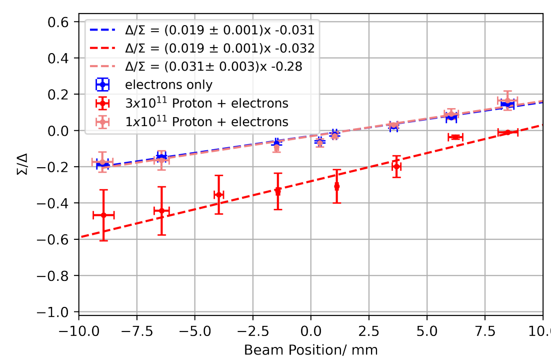

Figure 7: Position sensitivity of the ChDR BPM with 320pC electrons only (blue) and electrons with low (light red) and high (dark red) intensity protons. The best fit is calculated between -5 and 5 mm.

The position sensitivity is consistent to within 3σ when the low intensity proton beam is present. This indicates that there is a negligible contribution of the proton signal using this configuration, and the BPMs can successfully discriminate the electron signal for beam position measurements.

Conversely, the peak voltage increases when high intensity protons are present, manifesting into an increased sensitivity, however the measurement is no longer consistent with the electron only position scans. The large shot-by-shot variation is represented in the large vertical errors on each measurement.

CONCLUSION

A Cherenkov Diffraction based BPM has been investigated as a beam position monitor for the AWAKE electron beam in frequency bands from 20-110 GHz. Proton studies revealed the extensive frequency content of the high intensity proton bunches, which leads to significant contribution of the proton signal on top of the electron signal and breakdown of the electron position sensitivity with these beam parameters. However, it has been successfully demonstrated that by using low intensity proton bunches, the ChDR BPM is able to discriminate the electron bunch with good sensitivity.

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