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

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Abstract

The AWAKE experiment studies the acceleration of electrons to multi-GeV levels driven by the plasma wakefield generated by an ultra-relativistic and high intensity proton bunch. The proton beam, being considerably more intense than the co-propagating electron bunch, perturbs the measurement of the electron beam position achieved via standard techniques. This contribution shows that the electrons position monitoring is possible by frequency discrimination, exploiting the large bunch length difference between the electron and proton beams. Simulations show that the measurement has to be carried out at a frequency of a few tens of GHz, which is far higher than the spectrum produced by the 1 ns long (4 sigma) proton bunch. As operating a conventional Beam Position Monitor (BPM) in this frequency range is problematic, an innovative approach based on the emission of coherent Cherenkov Diffraction Radiation (ChDR) in dielectrics is being studied. After describing the monitor concept and design, we will report about the results achieved with a prototype system at the CERN electron facility CLEAR.

INTRODUCTION

The AWAKE experiment successfully demonstrated the acceleration of an electron bunch in 10 meters of Rubidium plasma driven by a high energy proton bunch [1]. Due to the high accelerating gradients produced in the plasma, the research in this technology is promising for a new generation of compact high energy accelerators [2]. A new experimental run has started recently, the AWAKE Run 2, with the first protons delivered to the experiment during summer 2021. The AWAKE Run 2 is a new experimental program that aims to further study the proton-driven Plasma Wakefield Acceleration (PWFA) in the next decade, while finding technical solutions to apply the PWFA to operational accelerators. Among the copious experimental program, one finds the development of even stronger accelerating gradients, the conservation of the accelerated beam quality and the scalability of the acceleration scheme [3]. The present layout of the AWAKE experiment is shown in Fig. 1. A 400 GeV, 1 ns-long proton driver bunch is extracted from the SPS and reaches the AWAKE experiment through a dedicated transfer line. Few meters upstream to the plasma cell, it merges with a common beamline with the electron bunch and the plasma ionising laser pulse [4]. The electron bunch is considerably shorter and less intense than the proton bunch. The beam parameters are reported in Table 1. The two beams may travel with different trajectories, in order to select the merging point distance inside the plasma cell. The plasma is created out of rubidium vapour [5], ionised by a high power laser pulse [6]. Downstream the plasma cell, diagnostic devices can be inserted to analyse the beams [7]. The electrons are then sent to a spectrometer [8] to measure their energy, while the spent laser and proton beams are finally dumped.

Two different BPM systems measure the electron [9] and the proton [10] bunch transverse position, upstream the plasma cell. Due to the very different bunch structure of the electron and proton beam (see Table 1), the whole instrumentation installed in the common beamline is perturbed when both beams are present. This originates from the very different electromagnetic field of the proton bunch, that is considerably more intense than that of the electrons. As a result, the former overshadows the latter, limiting the possibility to measure the electron beam only n the absence of the proton beam. However, with shorter bunch length, the electron spectrum extends to higher frequencies compared to the proton spectrum and it would provide an opportunity to perform measurements on the electron beam in presence of the proton bunch. Currently, the experiment can operate either by setting up the two beams separately or by relying on the different repetition rate of the electron and proton beams. In fact, while the electrons are produced with a 10 Hz repetition rate, the protons are extracted every 30 s or more [11]. Therefore, during operation, the electron bunch position was extrapolated by the electron position in a number of shots before and after the proton pulse. This approach, although successful for a test experiment, may prove insufficient for an operational accelerator or to study beam-beam effects [12].

Table 1: AWAKE Beam Parameters

Beam	proton	electron
Charge [nC]	48	0.1 – 0.6
Length (1σ) [ps]	250	1 – 5
Energy [MeV]	4×10^5	16 – 20

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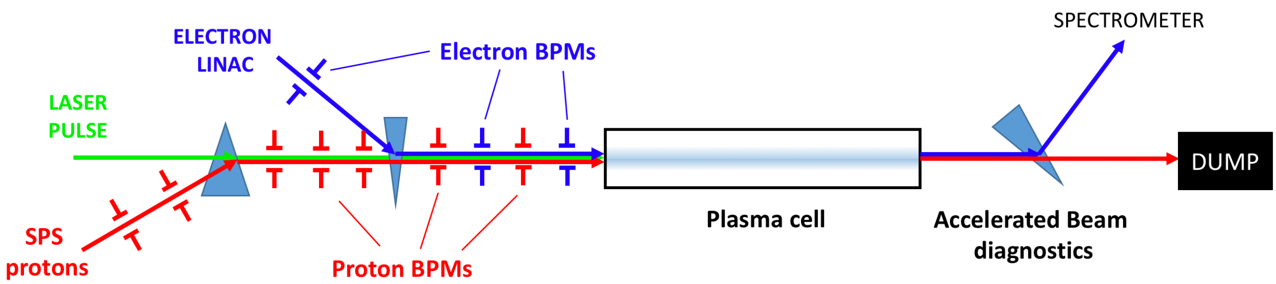

Figure 1: The present layout of the AWAKE experiment.

In fact, besides accelerating high quality beams, also the beam stability and reproducibility is essential.

POSITION DETECTION BASED ON THE BUNCH LENGTH DIFFERENCE

The bunch length difference of the electron and proton beam can be exploited in order to measure the position of both beams simultaneously. In fact, the bunch length difference translates in a different extension of the coherent beam spectrum in the frequency domain. Figure 2 shows the proton and electron beam spectra calculated for the AWAKE beams parameters mentioned in Table 1, under the approximation of Gaussian longitudinal bunch distributions. The detection frequency of the existing electron BPM system is also reported (vertical solid line). The proton and electron bunch present the same spectral power at a frequency of about 2 GHz. This explains why the present BPM system, working at 400 MHz, is not capable of measuring electrons when the two beams are present. It should however be possible to measure the electron beam position, provided that the detection is carried out at a sufficiently higher frequency where the proton signals would not be dominating the measurement.

Additional care must be taken in determining the target working frequency point for the new electron BPM system. The assumption of proton beams with a Gaussian longitudinal distribution is in fact not realistic, and imperfections or the presence of a sub-structure cause the proton spectrum to leak at higher frequency than the initial estimation. The presence of a sub-structure of the proton bunch has also been assessed via streak camera measurements of the light pulse from an optical transition radiation (OTR) screen. A series of investigations concluded that a safe operation frequency for the electron BPM system in presence of protons is of around the order of 30 GHz.

It should be noted that the rather large 60-mm-diameter beampipe presents a cutoff frequency of 2.93 GHz. It is therefore likely that any measurements performed above that frequency may become sensitive to the wakefield and electromagnetic fields in general propagating inside the beampipe.

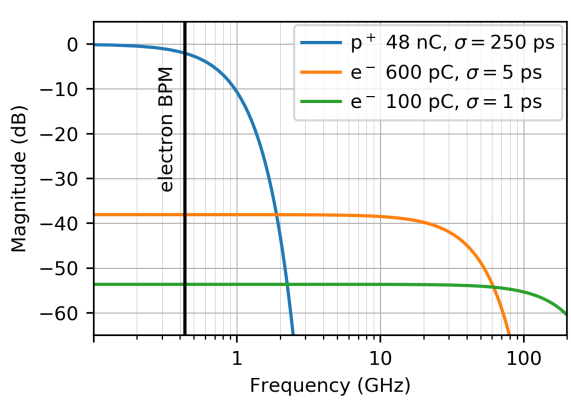

Figure 2: Bunch spectrum for the AWAKE beams assuming Gaussian bunch shape.

A CHERENKOV DIFFRACTION RADIATION-BASED BPM

The Cherenkov Diffraction radiation (ChDR) is a particular type of polarization radiation that is produced in a dielectric material when a particle is passing in its vicinity while travelling faster than the speed of light in the dielectric [13]. The radiation is produced at the characteristic Cherenkov angle

$$\cos(\theta_{Ch}) = \frac{1}{\beta n} \quad (1)$$

where θ_{Ch} is the angle of emission, β is the velocity of the particle in units of the speed of light in vacuum, and n is the index of refraction of the dielectric. Compared to other radiation production techniques, ChDR offers a higher photon fluence while being non-interceptive [14]. The possibility of realising non-intercepting beam diagnostic devices has drawn a considerable interest in the study of ChDR in recent years [15, 16].

In order to integrate the ChDR radiator in an accelerator, the dielectric target in which the radiation is produced needs to be integrated in the vacuum pipe. In the case of AWAKE, the choice of dielectric target fell onto cylindrical ceramic bars for fabrication convenience reasons. The dielectric bar is oriented at the Cherenkov angle to limit the internal reflections of the ChDR wavefront, and cut flush with the internal side of the beampipe. A longitudinal section of this device is

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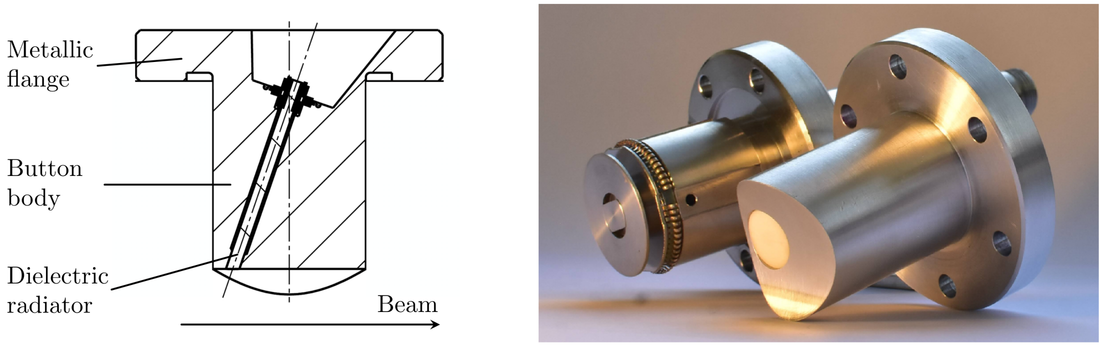

Figure 3: On the left, the longitudinal section of a ChDR button. The ceramic and metal part are indicated. On the right, a picture of a ChDR button (front), compared to a traditional capacitive BPM button (back). The white ring is the ceramic insert in the metal button.

shown in Fig. 3. The design of the button affects the properties of the radiation that is emitted at the end of the radiator. De facto, the dielectric bar enclosed in the metal structure is a loaded waveguide, where different electromagnetic modes can thus propagate through the radiator itself. Therefore, the radiator diameter would define the low cut-off frequency of the produced radiation. For a circular dielectric-loaded waveguide, the cut-off frequency of the fundamental mode is

$$f_c = 1.8412 \frac{c}{2\pi r} \frac{1}{\sqrt{\epsilon_r}} \qquad (2)$$

where c is the speed of light, r is the radiator radius, and ϵ_r is the relative permittivity of the dielectric material [17]. As the radiator coupling to the beam field cannot be easily treated with analytical calculations, a simulation campaign was launched using CST Studio Suite [18]. Via numerical simulations, the radiator dimensions were selected to optimize the cut-off frequency and the power radiated [19, 20]. The impact of the change of radiator diameter on the spectrum of emission is shown in Fig. 4 for Polytetrafluoroethylene (PTFE) circular radiators ranging from 2 to 18 mm diameter. It is evident that the cut-off frequency is increased as the radiator diameter is reduced, as expected from waveguide theory. The vertical dashed lines mark the theoretical cutoff frequency for the base mode of a circular loaded waveguide of the same diameter (see Eq. (2)). In the specific case of AWAKE, the cut-off frequency, i.e. radiator diameter, can be set to reject the strong signal component of the protons below few GHz, while enabling the emission of the electrons at higher frequency.

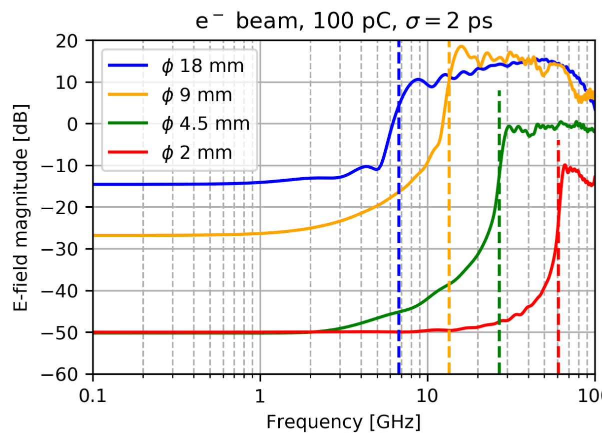

Figure 4: Spectrum of the ChDR emission at 1 cm from the radiator end calculated with CST Studio for different PTFE radiator diameters. The vertical dashed lines are the analytical base mode cutoff frequency of a dielectric-loaded circular waveguide with the same diameter.

EXPERIMENTAL TEST CAMPAIGN

A dedicated measurement campaign was carried out on a prototype in air at the CERN Linear Electron Accelerator for Research (CLEAR) [21], with the goal of studying the response of the beam position monitor. The prototype device was installed in the in-air test stand located at the end of the beamline, and equipped with motorized translation stages. The beam position is kept constant and stable, and it is monitored by a scintillating screen after the test device. The relative beam position in the BPM is varied by moving the test device around the beam. Electron bunches with charges ranging between 50 and 400 pC were used, and bunch length between 1.1 and 4.8 ps (1σ).

The detection system is based on zero-bias Schottky diode RF detectors, working in the Ka band (26.5-40 GHz). The ChDR emission of two opposite ChDR radiators is coupled to the detection in the accelerator bunker by means of horn antennas. Downstream the antennas, two bandpass filters are installed with a central frequency of 30 GHz and a bandwidth of 300 MHz. The filtered signal is delivered to the detection outside the bunker through a 15 m-long WR28 waveguide network. The signal is appropriately attenuated before the diode detector to make sure that the diode is driven in the linear regime. The signal, demodulated by the diodes, is then amplified by a low noise amplifier, and sampled with an oscilloscope.

The sensitivity to the beam position is calculated by computing the Δ/Σ quantity, i.e. dividing the difference of the output voltage of each detection channel by the sum of the outputs. The measured sensitivity of the BPM is shown in Fig. 5. Per each position, 200 beam shots were acquired

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and averaged to compensate for the accelerator charge jitter. The image current model curve [22] is also shown for comparison with a traditional BPM ideal response. The measured sensitivity is roughly half the ideal sensitivity from the image current model. Partially, this can be attributed to the non optimized test detection system, that privileged flexibility over the absolute performance. In fact, direct Cherenkov radiation is produced in the air along the test-stand, contributing to the background. It would be eliminated by carrying out the tests in vacuum. Additionally, the horn antennas pointing and distancing from the radiators is a relevant source of asymmetry in the detection of different radiators, that can be limited by realizing a closed metallic transition between the radiator and the waveguide. Further performance improvements can be obtained by designing a specific superheterodyne-based detection system optimized for the AWAKE beam parameters.

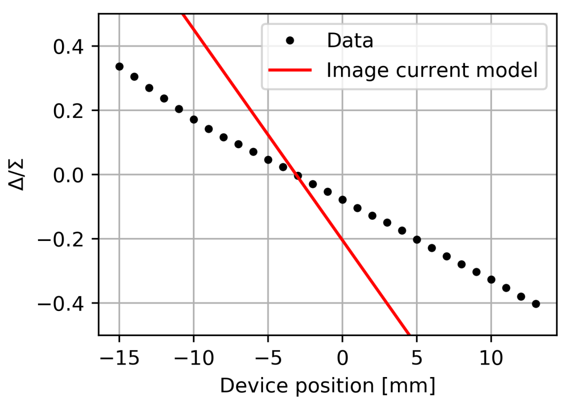

Figure 5: Beam position sensitivity of the test device compared to the image current theoretical model. A test beam of single bunches with a charge of 140 pC and a σ of 2 ps was used.

CONCLUSIONS AND FUTURE DEVELOPMENTS

For the AWAKE experiment, the challenges in the detection and characterization of proton and electron beams simultaneously have been described in this paper. The R&D efforts in the development of an electron beam position monitoring system that is functioning in the presence of an intense proton beam has been reported. Initial tests of a Cherenkov- Diffraction radiation dielectric pick-up have been performed on the CLEAR facility at CERN in order to assess the feasibility of the concept. Some limitations in providing a quantitative characterisation of the monitor were found and explained due to the fact that tests were performed in-air. A vacuum compatible Pick-up design is currently being manufactured, together with a custom based detection system at 30 GHz that would enable to provide an operational BPM based on ChDR. This new system should be tested on CLEAR again before its installation in the AWAKE experiment foreseen in 2022.

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