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SUITABILITY OF GHz FREQUENCY BEAM POSITION MONITORS FOR ELECTRON BUNCH POSITION DISCRIMINATION IN THE AWAKE FACILITY

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Abstract

The AWAKE facility at CERN utilises proton beam-driven plasma wakefields to accelerate electron bunches in a 10-meter long rubidium plasma cell. Precise monitoring of the electron bunches in the presence of the more intense proton bunches, which have distinct temporal and spatial characteristics, requires a beam position monitor (BPM) operating in the tens of GHz frequency range, assuming Gaussian longitudinal particle distributions. Two types of BPMs, one based on Cherenkov diffraction radiation (ChDR), and the other utilising high frequency (HF) conical shaped pickups, have been explored as a method to distinguish the electromagnetic signals of the shorter electron bunches (a few ps) from those of the longer proton bunches (a couple of hundred ps) co-propagating in the AWAKE beam line. Recent tests of both BPMs in the AWAKE common beam line have been conducted at frequencies above 20 GHz. The sensitivity of the HF and ChDR BPMs to the electron beam position was determined under various beam conditions, with and without proton bunches present. The read-out, utilising an RF front-end developed by TRIUMF, is additionally discussed.

INTRODUCTION

The Advanced Proton-Driven Plasma Wakefield Experiment (AWAKE) at CERN employs a 400 GeV/c proton bunch from the SPS to excite wakefields in a 10 m rubidium plasma, with the aim of accelerating externally injected witness electron bunches to multi-GeV energies. For Run 2, stable and reproducible injection of the electron beam into the plasma cell requires sub-millimetre knowledge of its transverse position along the common beam line [1]. This measurement must be performed in the presence of the drive proton bunch, which carries between 1×10^{11} and 3×10^{11} protons with an RMS bunch length of 6–12 cm, corresponding to frequency content concentrated below a few GHz. In contrast, the electron bunch is typically between 50 and 150 pC with an RMS length of a few ps, yielding spectral components extending well into the tens of GHz regime.

Conventional electron stripline beam position monitors in the AWAKE transfer line operate at 404 MHz and are therefore dominated by the proton signal when both beams are present. For Gaussian bunch profiles, the spectral amplitude of the proton and electron beam are equal at 1.9 GHz; above this frequency, the shorter electron bunch becomes increasingly dominant. This motivates the development of BPM systems with an operational frequency band in the tens-of-GHz range to achieve electron-only sensitivity by exploiting the difference in bunch length.

Two novel high-frequency BPM concepts are investigated: a conical button-based BPM with a cut-off frequency around 40 GHz, and a Cherenkov diffraction radiation (ChDR) BPM utilizing dielectric radiators to couple to the high-frequency components of the electron bunch. Both designs target frequency bands above 10 GHz, where the spectral power of the electron bunch dominates, enabling spectral discrimination from the proton signal.

A HIGH FREQUENCY BUTTON BPM

Electrostatic, or capacitive, pickups are the most common type of non-invasive BPMs. A typical configuration employs four metallic electrodes mounted symmetrically around the beam pipe in the horizontal (x) and vertical (y) planes. As a charged particle bunch traverses the vacuum chamber, image charges are induced on the electrodes. The relative signal amplitudes provide information on the beam's transverse displacement with respect to the electric centre of the BPM.

Figure 1: (Left) Bottom view of the HF pickup with conical electrode and curved lower surface. (Right) Side view of the HF pickup.

For a button-type pickup, the induced voltage is proportional to the beam current and inversely proportional to the distance between the beam and the electrode surface, with polarity equal to that of the beam charge. By comparing the signals from opposing electrodes, the beam position can be reconstructed using the standard difference-over-sum method:

$$x = k_x \frac{(V_R - V_L)}{(V_R + V_L)}, \quad y = k_y \frac{(V_T - V_B)}{(V_T + V_B)}, \qquad (1)$$

where V_R, V_L, V_T, V_B are the voltages from the right, left, top, and bottom electrodes, and k_x, k_y are calibration factors that

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relate the normalized signal ratio to the beam displacement. The sensitivity of the BPM is the magnitude of the change in signal per unit beam displacement as is equal approximately $\approx 1/k_{x,y}$.

The HF BPM employed at AWAKE, originally developed at DESY for free-electron laser timing applications [2], is a refinement of this concept. It consists of four symmetrically arranged conical button electrodes coupled through 2.92 mm vacuum feedthroughs, as shown in Fig. 1. This geometry supports a mode-free transverse electromagnetic (TEM) response up to 40 GHz. By minimizing the pickup size, unwanted higher-order modes are suppressed, yielding clean broadband performance in the GHz range with first tests conducted at AWAKE reported in Ref. [3].

A CHERENKOV-BASED BPM

Cherenkov diffraction radiation occurs when a charged particle passes close to a dielectric medium at a velocity v exceeding the phase velocity of light in that medium. The radiation is emitted at a characteristic Cherenkov angle θ_{ch} given by:

$$\cos\theta_{ch} = \frac{1}{\beta n}, \tag{2}$$

where $\beta = v/c$ is the normalized particle velocity and n is the refractive index of the dielectric. This mechanism allows the generation of coherent, broadband signals that can be used for beam position monitoring.

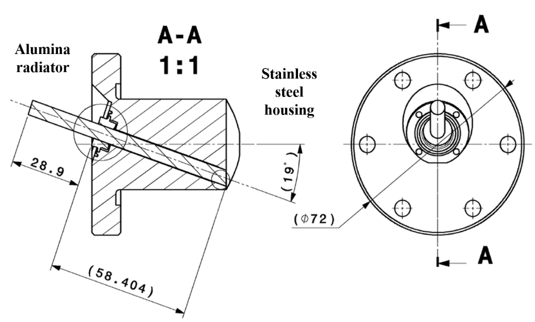

Figure 2: The technical drawing of the metallic button used to house the alumina radiator in preparation for installing into the BPM body in AWAKE [4].

Extensive prototyping and testing in the CERN Linear Electron Accelerator for Research (CLEAR) has been carried out [5, 6] with electron beam parameters similar to AWAKE in order to refine an operational BPM. The final pickup design as shown in Fig. 2 uses a 86 mm long alumina (Al_2O_3) cylinder with 6 mm diameter, encased in a stainless-steel button. This geometry corresponds to a cutoff frequency of 9.6 GHz and a Cherenkov angle of $\theta_{ch} = 71°$. To couple the signal, the Cherenkov signal is extracted via a WR28 rectangular waveguide. A quartz transition piece, designed as a quarter-wave transformer for maximum power transmission at 30 GHz with length 9.88 mm and dielectric constant $\sqrt{\epsilon_r}$, ensures impedance matching between the alumina radiator and free space in the waveguide. A surrounding copper sleeve minimizes reflections at the quartz–steel boundary, improving transmission efficiency.

RESULTS FROM AWAKE

The AWAKE Run 2 programme provided the opportunity to install and benchmark these BPMs under operational conditions. The BPMs were placed downstream of the 10 m plasma cell, where both a proton bunch and the injected electron bunch propagate. The distance between the 2 BPMs was around 2.5 m.

In order to directly compare the two systems, an experiment was conducted utilising identical Ka-band readout arms. Both BPM types pass a frequency range 20 to 32 GHz, given by the low-pass filter and the WR28 dimensions. At the end there is a Ka-Band diode detector. The ChDR radiator is connected through a quarter wavelength transformer to the WR28 read-out arm, whereas the HF-button utilizes a R281B coaxial-to-WG adapter and a flexible WR28 waveguide, the full acquisition chain of which is shown in Fig. 3. The averaged waveform for a centred electron bunch is compared in Fig. 4 for the HF and ChDR pickups. The amplitude of the Cherenkov signal is nearly three times larger than that of the conical pickup, and the peak corresponding to the conical HF pickup is less well defined. Therefore, the area under the waveform between 0.95 and 1.2 ns is determined as the integrated voltage, which is then used to calculate the difference-over-sum.

The AWAKE experiment runs for several weeks each year with both low- and high-intensity proton bunches extracted from the SPS. The proton bunch populations range from 1×10^{11} to 3×10^{11} protons. With both the electron and proton beams present, 300 oscilloscope shots were recorded over 30 seconds for each beam position, ensuring that at least one proton extraction from the SPS occurred within this period. Proton shots and their corresponding timestamps were identified using trigger thresholds (>0.5 V) using coaxial cable connected from a HF pickup to the oscilloscope. This procedure was carried out for both low-intensity (1×10^{11}) and high-intensity (3×10^{11}) proton bunches, after which the measured sensitivity was compared with that obtained using only the electron bunch. For low-intensity proton bunches using the ChDR pickup, the results are shown in Fig. 5. No error is reported for the combined proton and electron waveform measurements, as only a single shot contained the proton signal at each beam position. The error on the electron beam position is given by the standard deviation of the peak voltage magnitude across all other shots. Sensitivity was calculated to be 1.830 ± 0.002 %/mm for beam positions between -10 mm and 10 mm, and was consistent with values determined from electron beam data with and without the presence of protons. Similarly for the HF pickup, the sensitivity was consistent in the presence of low intensity proton bunches as 0.762 ± 0.005 %/mm.

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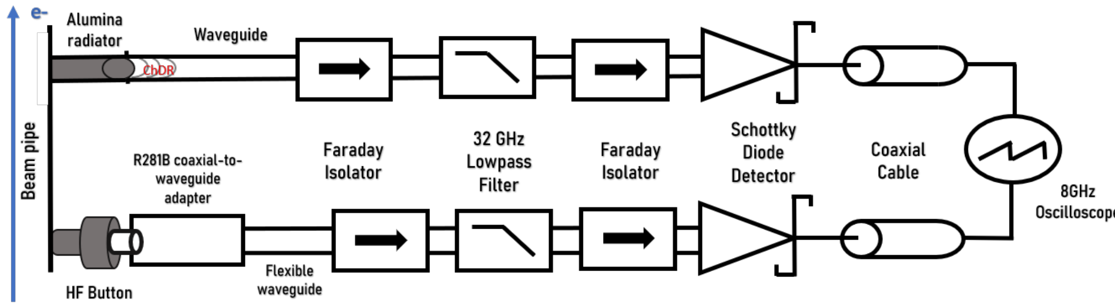

Figure 3: Schematic of the signal acquisition for the ChDR (top) and HF BPM (bottom). The ChDR couples the signal directly to the waveguide, while the HF BPM uses an R281B coaxial-to-waveguide adapter. Signal processing is identical for both systems.

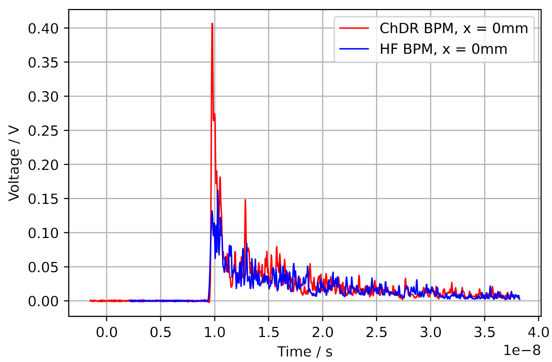

Figure 4: A single shot waveform of the voltage response to the electron beam passing in the centre of the beam pipe for the HF BPM (blue) and ChDR BPM (red) using Ka-band waveguide filtering.

At high intensities for both the HF and ChDR BPMs, the shot-by-shot voltage signal with the proton bunch is increased from the electron background, and the sensitivity is no longer consistent with the expected BPM response in the presence of electrons. The increased signal observed for higher proton bunch populations contradicts the initial assumption on the expected frequency spectrum of the proton bunch.

Following successful beam testing, a front-end electronic system was designed and commissioned at TRIUMF, optimised for operation in the 30 GHz frequency range with a bandwidth of approximately 1 GHz [7]. The detection chain down-mixes the 30.5 GHz intermediate frequency using WR28 waveguides, after which the signals are transported to the front-end via SMA coaxial cables. Following the configuration outlined, the horizontal and vertical planes of the Cherenkov-based BPM and high-frequency button BPM were connected to the available channels of the electronics. The system was subsequently integrated into CERN's Front-End Software Architecture (FESA) and the AWAKE graphical user interface (GUI), enabling continuous logging and monitoring of the BPM signals.

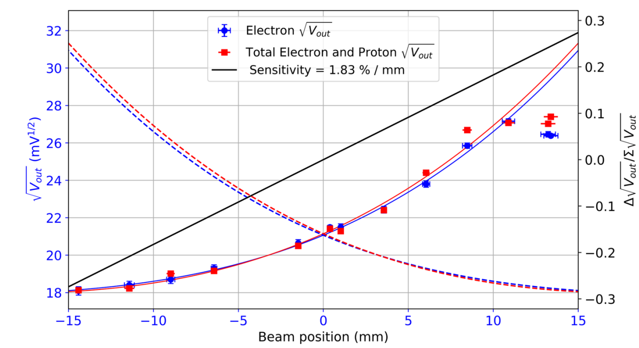

Figure 5: The square-root of the average signal $\sqrt{V_{out}}$ peak vs the electron beam position (left axis) for the ChDR pickup. The fit to the signal response for shots without and with the proton bunch present are shown by the solid blue and red lines respectively. A symmetrical pickup response is modelled and plotted as the dashed blue and red lines. The sensitivity to the electron only signal is calculated from the Δ/Σ (right axis) of the ChDR pickups to be 1.83 %/mm, plotted as the solid black line and is consistent with the value calculated for the combined electron and proton sensitivity (not shown).

CONCLUSION

Comparison of the two technologies in the Ka-band regime showed that the ChDR produces a larger output signal than the HF BPM for a 100 pC electron beam, with higher sensitivity to beam position (1.830 ± 0.002) %/mm vs. (0.762 ± 0.005) %/mm. For both the ChDR and HF BPM, the electron beam response remains unchanged in the presence of low-intensity proton bunches making both BPMs types suitable for electron position monitoring in this case. However, at higher bunch intensities an excess signal appears in both pickups, and the electron beam position response deteriorates. A 30 GHz central frequency front-end is used to process the signal for the vertical and horizontal beam position for both BPM types.

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