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DETERMINATION OF DETECTOR FREQUENCY RANGES FOR AN ELECTRON BUNCH LENGTH MONITOR FOR AWAKE RUN 2C

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Abstract

The AWAKE 150 MeV electron beamline at CERN is used to provide a witness bunch for plasma wakefield acceleration, with a bunch length shorter than the plasma wavelength to ensure efficient capture and acceleration. To accomplish this, a real-time, non-invasive bunch length monitor is essential. A monitor is being studied to calculate the RMS bunch length by measuring coherent Cherenkov diffraction radiation with 3 Schottky diodes across different frequency ranges. In this paper, we present theoretical bunch length calculations based on the polarization current approach (PCA) to determine the appropriate frequency ranges for the Schottky diodes. Results show that while higher frequencies are more sensitive to variations in bunch length, they are also influenced by the skewness of a Gaussian longitudinal bunch profile.

INTRODUCTION

The goal of the Advanced Wakefield Experiment (AWAKE) is to accelerate externally injected electrons using a plasma wakefield driven by a 400 GeV proton bunch [1]. AWAKE Run 2 started in 2021 with the aim to accelerate injected witness electron bunches while preserving the quality of the beam with short bunch lengths of around 200 fs [2]. An electron bunch length monitor based on coherent Cherenkov diffraction radiation (ChDR) is being developed for AWAKE which has been manufactured and experimentally verified to measure shot-by-shot RMS bunch lengths between 100 – 1200 fs demonstrating coherent ChDR as a suitable technique for non-invasive bunch length measurements [3].

Cherenkov radiation (ChR) occurs when a relativistic charged particle passes through a medium faster than the phase velocity of light of that medium. The emitted radiation forms coherent wavefronts that interfere constructively, producing a cone of radiation at a well-defined angle

$$n\beta \cos(\theta_{ChR}) = 1, \tag{1}$$

where n is the refractive index of the medium and $\beta = v/c$. Cherenkov diffraction radiation (ChDR) is produced when the charged particle travels close to a dielectric medium, by inducing polarization currents within the dielectric. ChDR has become a popular mechanism for non-invasive diagnostic tools and its advantages have been studied over the recent years [4, 5].

PCA THEORY

The spectral angular distribution of ChDR from a point charge traveling in close vicinity to a finite size dielectric prism, as illustrated in Fig.1, can be described using the polarization current approach (PCA). The radiation arises from the polarization current induced at the interface between the dielectric and a medium. This occurs when the effective field radius of the electron, $r_e = \beta\gamma\lambda/2\pi$, where γ is the Lorentz factor and λ is the wavelength of the emitted polarization radiation, is greater than the impact parameter, b [6].

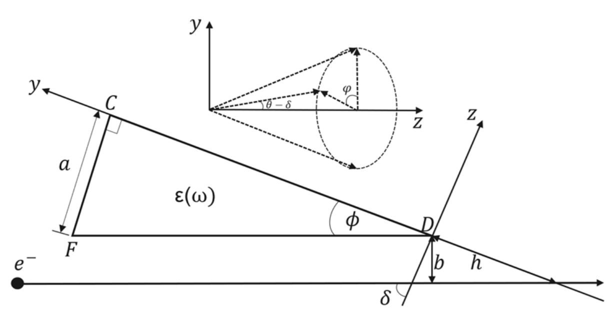

Figure 1: A point-charge electron traversing in close vicinity to a dielectric prism with a cone representing the direction of emitted polarization radiation.

The spectral angular distribution is obtained from Maxwell's equations and Fresnel coefficients. The derivation and more details can be found in Ref. [7] for this particular geometry.

The prism size along the x-axis is assumed to be infinite. This approximation is appropriate when the condition $a/\tan(\phi) >> \lambda$ is satisfied.

METHODOLOGY

The setup of the monitor for the single-shot RMS bunch length measurements, as shown in Fig. 2, consists of zero-bias Schottky diode detectors with horn antennas 10 cm away from the exit of three alumina radiators. The radiator

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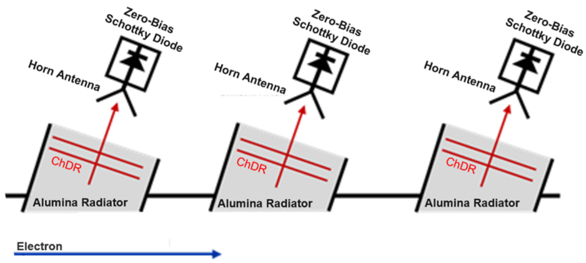

Figure 2: Schematic of the single-shot RMS bunch length monitor consisting of three zero-bias Schottky diodes with horn antennas placed at the exit of each radiator.

angle was chosen so that the ChDR would exit the prism perpendicular to the surface.

PCA determines the far-field spectral angular distribution after the polarization radiation exits the prism. To capture the polarization radiation collected by the horn aperture for PCA analysis, the coordinate system can be transformed into cartesian coordinates to account for the position and dimensions of the horn antenna. The full description of this transformation is described in a paper shown in Ref. [8]. The single-electron spectrum, defined as the radiation intensity as a function of frequency integrated over an area, can be expressed using the following equation for a given horn antenna aperture.

$$\frac{dW}{d\omega} = \int_{-\frac{\theta_x}{2}}^{\frac{\theta_x}{2}} \int_{\theta_{ChDR}-\frac{\theta_y}{2}}^{\theta_{ChDR}+\frac{\theta_y}{2}} \frac{d^2W}{d\omega\Omega} d\theta_x d\theta_y. \tag{2}$$

The radiation collected by the horn aperture from a single electron over a given frequency range, $I_e(\omega)$, can be calculated by integrating Eq. (2).

$$I_e(\omega) = \int_{\omega_{min}}^{\omega_{max}} \frac{dW}{d\omega} d\omega. \tag{3}$$

The total radiation from an electron bunch, $I(\omega)$, can be determined by the following:

$$I(\omega) = I_e(\omega)\left[N + N(N-1)\left|F(\omega)\right|^2\right], \tag{4}$$

where N is the number of electrons in the bunch and $F(\omega)$ is the form factor, which is the Fourier transform of the normalized longitudinal charge distribution, $\rho(t)$ of a bunch. This equation can be approximated assuming the total radiation is dominated by the coherent term characterized by the form factor as in:

$$I(\omega) \approx I_e(\omega) N^2 \left|F(\omega)\right|^2. \tag{5}$$

Experimentally, we use the ratio of coherent radiation intensities of two Schottky diodes in different frequency ranges to mitigate the fluctuation in charge and beam jitter. In the setup, we have three Schottky diodes. One of the diodes is used as a normalization detector where the coherent radiation intensity is not very sensitive to changes in the bunch length in the fs/ps range. The other two diodes are used in frequency ranges where the bunch length is sensitive. This formula can simply be written as:

$$\frac{I_S(\omega)}{I_N(\omega)} = \frac{I_{eS}(\omega_S)\left|F(\omega_S)\right|^2}{I_{eN}(\omega_N)\left|F(\omega_N)\right|^2}, \tag{6}$$

where $I_S(\omega)$ and $I_N(\omega)$ relates to the coherent radiation intensity captured by one of the Schottky detectors in the sensitive frequency range and the diode in the normalization frequency range, respectively.

In this paper, we define $\rho(t)$ as a skew-Gaussian distribution, written as

$$\rho(t) = \frac{1}{\sigma_t\sqrt{2\pi}} e^{-\frac{t^2}{2\sigma_t^2}} \left[1 + \mathrm{erf}\left(\frac{\alpha t}{\sigma_t}\right)\right], \tag{7}$$

where σ_t is the longitudinal bunch length, and α is a constant relating to the skewness of the Gaussian. When $\alpha = 0$, the equation becomes a Gaussian distribution. Calculating the Fourier transform of this to find the form factor, as derived in Ref. [3], gives

$$F(\omega) = e^{-\frac{\sigma_t^2\omega^2}{2}} \left[1 - \mathrm{erf}\left(i\frac{\alpha\sigma_t\omega}{\sqrt{1+2\alpha^2}}\right)\right]. \tag{8}$$

Eq. (8) can be substituted into Eq. (6) and rearranged to find the bunch length

$$\sigma_t = \sqrt{\left|\frac{1}{\omega_N - \omega_S} \ln\left(\frac{I_S(\omega_S) I_{eN}(\omega_N)\left|F_{sk}(\omega_N)\right|^2}{I_N(\omega_N) I_{eS}(\omega_S)\left|F_{sk}(\omega_S)\right|^2}\right)\right|}, \tag{9}$$

where $F_{sk}(\omega)$ is the skewness term of the form factor shown in Eq. (8) in the squared brackets. The σ_t term within the skewness term cannot be removed as it is inside an error function. For the difference in angular frequency, $\omega_N - \omega_S$, we use the midpoint of the two frequency ranges. This equation allows us to verify the relationship between bunch length and the ratio of coherent ChDR from two detectors with different frequency bands, accounting for the skewness of a known bunch.

DETERMINATION OF FREQUENCY RANGES

Using PCA analysis and the methodology above, we can determine the coherent radiation collected from the horn antennas for different frequency ranges. The horn antenna dimensions and frequency ranges that were considered are manufactured from Virginia diodes [9].

Table 1 shows the PCA simulation parameters used for this analysis based on the AWAKE parameters, the geometry of our bunch length monitor radiators, and the parallel trajectory of the electron relative to line FD in Fig. 1.

As shown in Fig. 3, the coherent radiation spectrum for a Gaussian bunch indicates that at lower frequencies the intensity is less affected by changes in bunch length. For this reason, the WR-15 waveguide band (50–75 GHz) was selected for the normalization detector.

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Table 1: PCA Simulation Parameters

Parameter	**Value**
Beam Energy, E	150 MeV
Bunch Length, σ_t	100 – 1500 fs
Dielectric Constant, ε	9.5
Radiator Length, a	16.28 mm
Impact Parameter, b	15 mm
Radiator Angle, ϕ	19°
Flight Angle, δ	71°

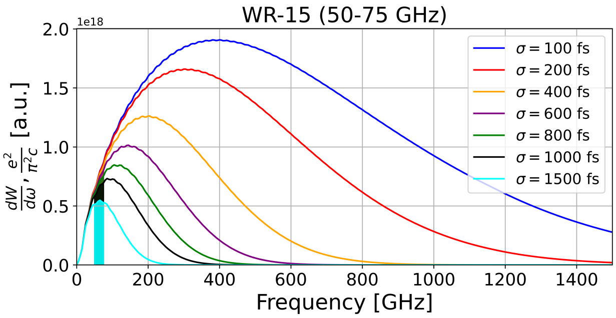

Figure 3: Coherent ChDR captured from a Gaussian bunch by the normalization detector over a frequency range, placed 10 cm away from the exit of the radiator.

Since the other two detectors are used for their sensitivity to changes in bunch length, their frequency bands must increase beyond the normalization region of the spectrum. The use of two sensitivity detectors in different frequency ranges allows a larger range of bunch length monitoring. The two waveguide bands chosen were WR-8.0 (90–140 GHz) and WR-1.9 (400–600 GHz), as highlighted in Fig. 4.

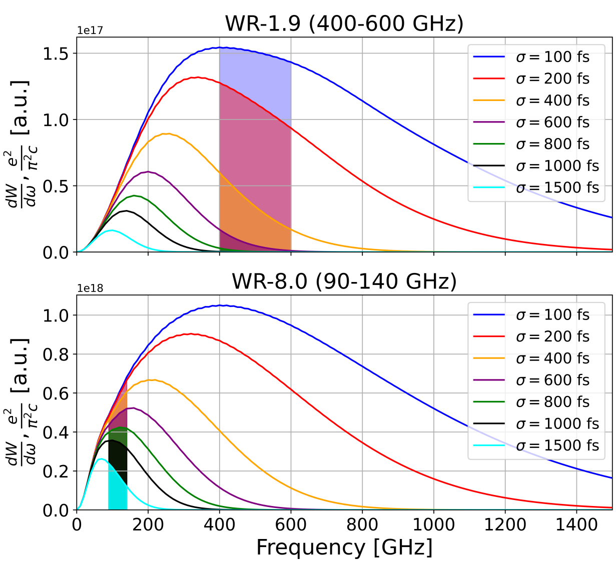

Figure 4: Coherent ChDR captured from a Gaussian bunch by the sensitivity detectors over a frequency range, placed 10 cm away from the exit of the radiator.

These two detectors together can provide bunch length measurements in a large range from sub 100 fs to over 1500 fs, which is well within the range of AWAKE bunch length requirements. The 400–600 GHz detector can be used from sub 100 fs, however, at higher bunch lengths, the skewness of the bunch has a greater impact on the accuracy of the bunch length measurements. Figure 5 shows that a deviation from a Gaussian bunch begins to occur above 600 fs for the 400–600 GHz detector but a minimal difference for the 90–140 GHz detector.

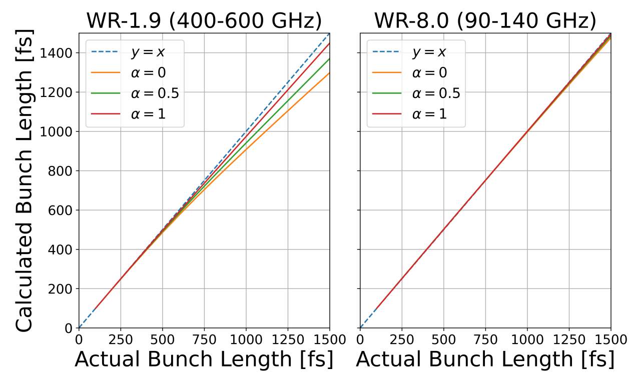

Figure 5: Bunch length calculated from Eq. 9 for different skew-Gaussian profiles using two different sensitivity detectors.

This PCA method of skewness dependence was compared using experimental data and included in a paper where the bunch skewness was measured to be around $\alpha = 1.5$ in Ref. [3].

CONCLUSION

This paper presents a simulation study of the frequency ranges suitable for Schottky diode detectors in a coherent Cherenkov diffraction radiation–based bunch length monitor for AWAKE Run 2c. Using the polarization current approach and a skew-Gaussian longitudinal distribution, the results show that higher frequencies provide greater sensitivity to changes in bunch length but are also influenced by skewness in the bunch profile. The three most suitable detector ranges were determined to be 50–75 GHz, 90–140 GHz, and 400–600 GHz.

Experiments were recently carried out at the CLEAR facility at CERN to test the bunch length dependence of the selected detectors, and the data is currently under analysis.

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REFERENCES

[1] R. Assmann *et al.*, "Proton-Driven Plasma Wakefield Acceleration: A Path to the Future of High-Energy Particle Physics" *Plasma Phys. Control. Fusion*, vol. 56, no. 8, pp. 084013–13, 2014. doi:10.1088/0741-3335/56/8/084013

[2] E. Aldi *et al.* (AWAKE Collaboration), "Experimental observation of proton bunch modulation in a plasma, at varying plasma densities", *Phys. Rev. Lett.*, vol. 122, pp. 054802, 2019. doi:10.1103/PhysRevLett.122.054802

[3] C. Davut *et al.*, "Design and experimental verification of a bunch length monitor based on coherent Cherenkov diffraction radiation", *Phys. Rev. Res.*, vol. 7, no. 1, pp. 013193, Feb. 2025. doi:10.1103/PhysRevResearch.7.013193

[4] E. Senes *et al.*, "Selective electron beam sensing through coherent Cherenkov diffraction radiation", *Phys. Rev. Res.*, vol. 6, no. 2, pp. 023278, Jun. 2024. doi:10.1103/PhysRevResearch.6.023278

[5] A. Curcio *et al.*, "Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation", *Phys. Rev. Accel. Beams*, vol. 23, no. 2, pp. 022802, Feb. 2020. doi:10.1103/PhysRevAccelBeams.23.022802

[6] P. V. Karataev, "Pre-wave zone effect in transition and diffraction radiation: Problems and solutions", *Phys. Lett. A*, vol. 345, no. 4–6, pp. 428–438, 2005, doi:10.1016/j.physleta.2005.08.080

[7] M. Shevelev and A. Konkov, "Peculiarities of the generation of Vavilov-Cherenkov radiation induced by a charged particle moving past a dielectric target", *J. Exp. Theor. Phys.*, vol. 118, no. 3, pp. 501–511, Mar. 2014. doi:10.1134/S1063776114030182

[8] C. Davut *et al.*, "Optimization Study of Beam Position and Angular Jitter Independent Bunch Length Monitor for AWAKE Run 2", in *Proc. IBIC'22*, Kraków, Poland, Sep. 2022, pp. 465–468. doi:10.18429/JACoW-IBIC2022-WEP29

[9] Virginia Diodes, https://www.vadiodes.com/en/products-6/straight-waveguides-tapers-horn-antennae