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OPTIMIZATION STUDY OF BEAM POSITION AND ANGULAR JITTER INDEPENDENT BUNCH LENGTH MONITOR FOR AWAKE RUN 2

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Abstract

In this paper, a study using the Polarization Current Approach (PCA) model is performed to optimize the design of a short bunch length monitor using two dielectric radiators that produce coherent Cherenkov Diffraction Radiation (ChDR). The electromagnetic power emitted from each radiator is measuring a different part of the bunch spectrum using Schottky diodes. For various bunch lengths, the coherent ChDR spectrums are calculated to find the most suitable frequency bands for the detection system. ChDR intensities measured by each detector are estimated for different impact parameters to explore the dependence of bunch length monitor on beam position and angular jitter. It is found that, in the present configuration, the effects of beam position and angular jitter are negligibly small for bunch length measurement.

INTRODUCTION

In recent years, coherent Cherenkov Diffraction radiation (ChDR) has become a suitable candidate for non-invasive longitudinal bunch profile diagnostics with successful experimental validations [1,2]. Although, the exact solutions of the electromagnetic problems are often not known, and detailed computer simulations require extensive time and resources, the properties of the radiation are often derived from simplified models, that assume specific assumptions on the radiator shape [3].

The emission characteristics of ChDR can be calculated by Polarization Current Approach (PCA) which describes simultaneously generated DR and ChDR as a solution to the "vacuum" set of macroscopic Maxwell's equations [4]. Among the other theoretical models, PCA introduces some limitations on the longitudinal size of the radiator when calculating of the spectral-angular distribution of ChDR that makes it a powerful tool to calculate expected radiation yield and directivity of ChDR cone [5].

Considering a relativistic charged particle with energy $\gamma = 1/\sqrt{1-\beta^2}$ moving rectilinearly at a distance b from a prismatic dielectric target, such as in Fig. 1, the particle field flattened into a plane perpendicular to its motion having a relation between its components $E_\perp \gg E_\parallel$ and $H \approx E$ for $\beta = v/c \sim 1$. The Fourier component of $E_\perp$ is spatially restricted in a circle with a radius which is called the effective field radius $l = \gamma\beta\lambda/2\pi$, where λ is the radiation wavelength. Hence, the following the condition should be satisfied :

$$l \gtrsim b. \tag{1}$$

In this case the dielectric medium will be polarised and the polarization radiation will be emitted [6].

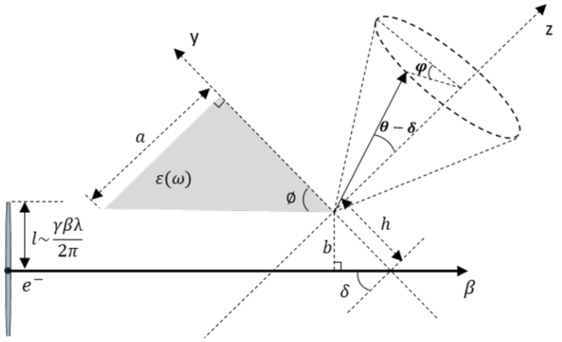

Figure 1: The geometry of ChDR emission by a relativistic charged particle moving rectilinearly at a distance b from the bottom surface of a prismatic dielectric target.

Therefore the spectral-angular distribution of ChDR can be calculated by Polarization Current Approach (PCA), as described in [4], in terms of its vertical and horizontal components with respect to particle trajectory and after the radiation is refracted out at the exit surface of the prism.

$$\frac{d^2W}{d\omega d\Omega} = S_e(\omega) = \frac{d^2W_\perp}{d\omega d\Omega} + \frac{d^2W_\parallel}{d\omega d\Omega}. \tag{2}$$

The total radiation intensity generated by an electron bunch can be described by

$$S(\omega) = S_e(\omega)\,[N + N(N-1)]\,F(\omega), \tag{3}$$

where $S(\omega)$ is the experimentally measured spectrum, $S_e(\omega)$ is the theoretically calculated single electron spectrum, N is the number of electrons within the bunch and $F(\omega)$ is the longitudinal bunch form factor [7]. As an important feature of the radiation spectrum, the domination of the longitudinal bunch form factor on the radiation spectrum indicates how far the radiation intensity extends in the frequency range. The amplitude of the longitudinal form factor

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can be calculated as a modulus squared of a Fourier transform applied to the longitudinal charge distribution $\rho(z)$ within the bunch [8],

$$F(\omega) = \left| \int_0^\infty \rho(z) \exp\left(i \frac{\omega}{c} z \right) dz \right|^2 \tag{4}$$

and can be written in the following form for a bunch with Gaussian distribution,

$$F(\omega) = \exp\left(- \frac{\omega^2 \sigma_z^2}{c^2} \right) = \exp(-k^2 \sigma_z^2), \tag{5}$$

where $k = \omega / c = 2\pi / \lambda$ is the wave number. Finally, neglecting the contribution from incoherent emission, we can write

$$S(\omega) = N^2 \, S_e(\omega) \; F(\omega) \, . \tag{6}$$

CALCULATION METHOD

The measurement concept of the longitudinal electron bunch length monitor consists of three Alumina radiators placed on only one side of the electron bunch (see Fig. 2).

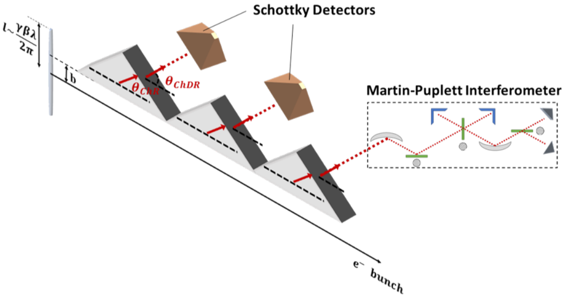

Figure 2: The geometry of ChDR emission by a relativistic charged particle moving rectilinearly at a distance *b* from the bottom surface of a prismatic dielectric target.

Two Schottky detectors having two different frequency ranges, is used to measure the ChDR from the first two radiators. Coherent ChDR spectral responses are measured by these two detectors and the longitudinal charge distribution of the bunch can be eliminated by by using a similar approach with [1].

$$\frac{S_1(\omega_1)}{S_2(\omega_2)} = \frac{S_{e1}(\omega_1) \, exp\left(-k_1^2 \sigma_z^2\right)}{S_{e2}(\omega_2) \, exp\left(-k_2^2 \sigma_z^2\right)} . \tag{7}$$

Thus, RMS bunch length can be calculated by,

$$\sigma_{z,rms} = \sqrt{\left| \frac{1}{k_2^2 - k_1^2} \ln\left(\frac{S_1(\omega_1) \, S_{e2}(\omega_2)}{S_2(\omega_2) \, S_{e1}(\omega_1)} \right) \right|} . \tag{8}$$

In order to calculate the ChDR radiation spectrum and intensity captured at the corresponding horn antenna aperture, the coordinate system in PCA equations is transformed into cartesian as depicted in Fig. 3. As ρ being the radius vector magnitude,

$$\begin{aligned} \sin\theta_x &= \frac{x}{\rho} = \sin\theta \sin\varphi \\ \sin\theta_y &= \frac{y}{\rho} = \sin\theta \cos\varphi . \end{aligned} \tag{9}$$

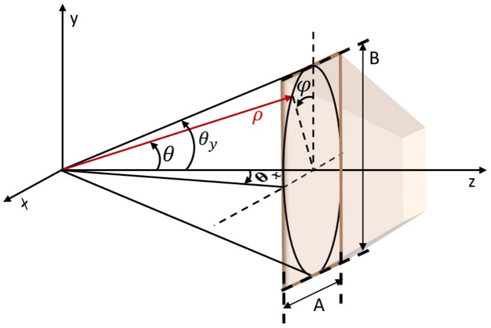

Figure 3: Transformation of coordinate system.

Thus, coherent ChDR spectrum can be calculated by

$$\frac{dW}{d\omega} = N^2 \, exp(-k^2 \sigma_z^2) \int_{\frac{-\Delta\theta_x}{2}}^{\frac{\Delta\theta_x}{2}} \int_{\theta_{ChDR}-\frac{\Delta\theta_y}{2}}^{\theta_{ChDR}+\frac{\Delta\theta_y}{2}} \frac{d^2 W}{d\omega d\Omega} d\theta_x \, d\theta_y . \tag{10}$$

Hence ChDR intensity, $S(\omega)$, can be found by integrating Eq. (10) over each corresponding detector horn aperture with their frequency detection ranges.

PCA ANALYSIS

Since RMS bunch length is calculated by taking ChDR intensity ratios of detectors to be determined, it is important to find the most suitable frequency range of Schottky detectors operates in such a way that one should be used as normalization detector which measures nearly the same ChDR intensity independent from the bunch length while the other one should be sensitive to the bunch length. For that purpose, a variety of Schottky diode detectors and corresponding pyramidal and diagonal horn antennas available from Millitech [9] and Virginia Diodes [10] considered to determine the most suitable frequency bands of detectors to be used for this specific calculation method by using simulation parameters including the AWAKE Run 2 electron bunch parameters [11] in Table 1.

Table 1: Simulation Parameters

Parameter	Value
Bunch Energy, E	150 MeV
Bunch Length, σ_z	200 fs
Bunch Size, σ_r	5.25 m
Position Jitter	$< \sigma_r$
Impact Parameter, b	15 mm
Dielectric constant, $\varepsilon_{Alumina}$	9.5
Radiator Angle, ϕ	19
Radiator Length, a	16.28 mm

As coherent ChDR spectrum extend up to THz range for such a short electron bunch length, the diffraction effects dominate in lower frequencies while the domination of the bunch form factor begins at higher frequencies of the spectrum.These two effects lead us to have the advantage to choose the Schottky diodes to be used with different purposes considering the aim of the RMS bunch length calculation method. ChDR spectrum and intensity of each selected Schottky detector are shown in Fig. 4. According to the PCA simulations,the detectors which operate between 60-90 GHz and between 400-600 GHz are selected as normalization and sensitivity detector, respectively.

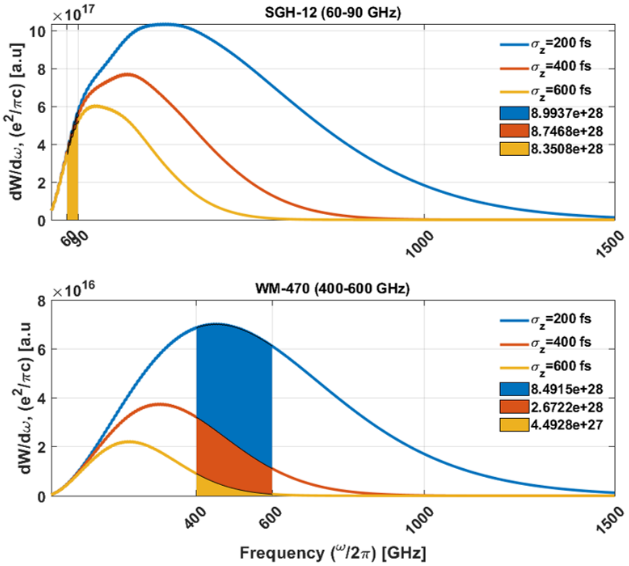

Figure 4: ChDR spectral responses calculated by using theoretical PCA model considering frequency ranges of each selected detector and its corresponding horn aperture.

Beam position and angular jitter is investigated with the selected Schottky detectors and results shown in Figs. 5 and 6, respectively. Although beam position jitter for AWAKE Run 2 is specified as less than σ_r, ChDR intensity captured by each detector is calculated for ±1 mm to check the intensity ratio in wider range. It is found that the ±1 mm beam position jitter causes 6% change in ChDR intensity ratio of the detectors while it is 0.03% in the range of $\pm\sigma_r$ as shown in Fig. 5.

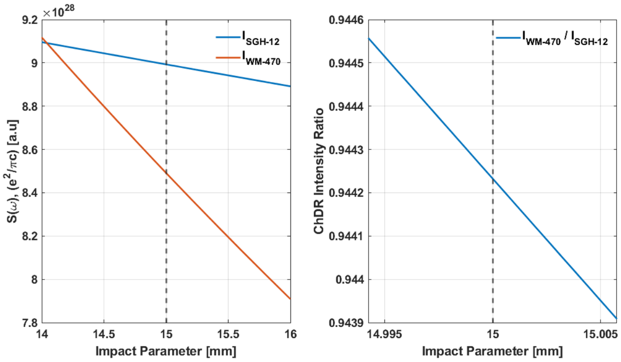

Figure 5: Impact parameter scan.

Following the same principle, angular jitter is also calculated in a wider range for a conventional accelerator, ±1 mrad, and the change in the ChDR intensity ratio is found 0.9% as shown in Fig. 6.

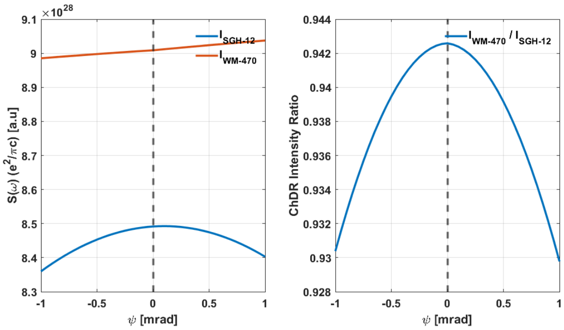

Figure 6: Angular jitter scan.

By having less than 1% sensitivity to beam position and angular jitter we can clearly say that the RMS bunch length calculation is independent from these effects.

The goal of RMS bunch length calculation method is not only being insensitive to the beam position and angular jitter but also being highly sensitive to any change in the bunch length simultaneously. Thus, bunch length sensitivity of the ChDR intensity ratio is calculated in the range of ±10 fs. Figure 7 shows ChDR intensity for each selected detector and the intensity ratios in that range. It is found that ±1 fs change in the bunch length causes 5% change in the ChDR intensity ratio.

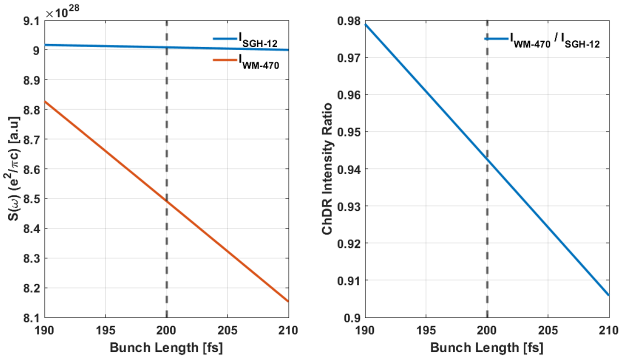

Figure 7: Bunch length sensitivity scan.

CONCLUSION AND FUTURE PLANS

The determination of the Schottky diodes and most suitable frequency ranges to be used for the detection of the ChDR was made by using PCA investigation of ChDR spectrum and intensity among a variety of Schottky diodes from Millitech and Virginia diodes. The dependence of ChDR intensity ratio to the beam position and angular jitter besides bunch length sensitivity of the calculation method was invenstigated. It was found that RMS bunch length calculation is independent of beam position and angular jitter by having < 1% change in the CHDR intensity ratio while having 5% for ±1 fs bunch length change.

The commissioning of the bunch length monitor has been started and tests are on going in the CLEAR facility at CERN. Comprehensive analysis and the details will be published in a journal in the future.

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