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ANALYTICAL AND NUMERICAL CHARACTERIZATION OF CHERENKOV DIFFRACTION RADIATION AS A LONGITUDINAL ELECTRON BUNCH PROFILE MONITOR FOR AWAKE RUN 2

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Abstract

In this paper, CST simulations of the coherent Cherenkov Diffraction Radiation with a range of parameters for different dielectric target materials and geometries are discussed and compared with the theoretical investigation of the Polarization Current Approach to design a prototype of a radiator for the bunch length/profile monitor for AWAKE Run 2. It was found that the result of PCA theory and CST simulation are consistent with each other regarding the shape of the emitted ChDR cone.

INTRODUCTION

It is possible to measure the longitudinal bunch profile either directly by using streak camera [1], electro optic sampling (EOS) [2] in time-domain or indirectly by using beam-induced radiative processes such as transition radiation (TR) [3], diffraction radiation (DR) [4, 5], Smith-Purcell radiation (SPR) [6], Cherenkov radiation (ChR) [7] in frequency-domain [8]. Radiation intensity depends on the relation between the bunch length and the radiation wavelength. In the case of bunch length equal to or smaller than the radiation wavelengths, particles emit photons coherently and the radiation intensity is proportional to the square of the number of the particles within the bunch. Theoretically, frequency-domain techniques have no intrinsic limit to the resolution while time-domain techniques have a limited resolution due to response time constraints. Additionally, time-domain techniques might have destructive effects besides being expensive compared to the frequency-domain techniques.

In recent years, coherent Cherenkov Diffraction radiation (ChDR) has become a suitable candidate for non-invasive longitudinal bunch profile diagnostics with successful experimental validations [9]. In this paper, we present a new, non-invasive diagnostic tool that simultaneously measures the RMS bunch length and profile of the electron bunch as an application of coherent ChDR, proposed to be implemented in the AWAKE Run 2 experiment at CERN.

PROPERTIES OF CHERENKOV DIFFRACTION RADIATION

The interaction between a target and a charged particle depending on the position of the target and material leads to the dynamic polarization of the medium resulting in the emission of different types of electromagnetic radiation representing polarization radiation family. The difference between the emission characteristics arises due to the presence of interfaces which require different conditions to be satisfied [10]. ChDR refers to the emission of the electromagnetic radiation through the Cherenkov effect due to the dynamic polarization of surface charges by the electromagnetic field of a moving charge travelling at a distance from and parallel to the surface of a dielectric medium.

Consider a charged particle moving rectilinearly at a distance b, called impact parameter, from a prismatic dielectric target with a relativistic factor $\gamma = 1/\sqrt{1-\beta^2}$ as shown in Fig. 1.

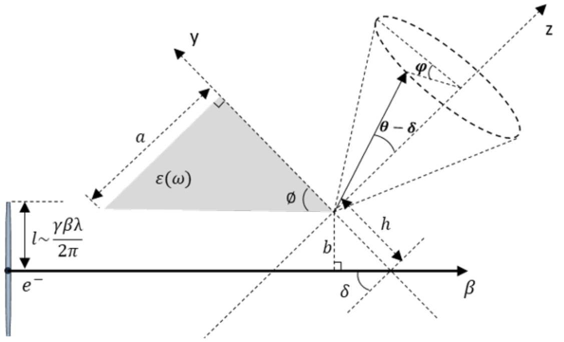

Figure 1: The geometry of ChDR emission by a relativistic charged particle moving rectilinearly at a distance b from the bottom surface of a prismatic dielectric target.

The Fourier component of perpendicular E-field of the particle is spatially confined in a circle with a radius called 'effective electron field radius, $l = \gamma\beta\lambda/2\pi$' should be larger than impact parameter to polarize the dielectric medium.

Generated ChDR propagates in the dielectric medium with a narrow, well-defined radiation cone around a characteristic Cherenkov angle determined by the relation $\theta_{ChR} = \cos^{-1}(1/\beta n)$, where n is the refractive index of the dielectric and exits the dielectric with θ_{ChDR} due to the refraction at the exit interface. The emission characteristics of ChDR can be calculated by Polarization Current Approach

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(PCA) which describes simultaneously generated DR and ChDR as a solution to the "vacuum" set of macroscopic Maxwell's equations [11].

CHARACTERIZATION OF CHERENKOV DIFFRACTION RADIATION

AWAKE Run 2

The Advanced Wakefield Experiment (AWAKE) at CERN is a proof-of-principle experiment [12, 13] using 400 GeV Super Proton Synchrotron (SPS) beam as a drive beam for the first time in plasma wakefield acceleration. The process of the seeded self-modulation (SSM) of SPS proton bunch and the acceleration of an externally injected electron bunch up to 2 GeV in a 10 m long plasma channel was successfully demonstrated in Run 1 [14–20]. Next, AWAKE Run 2 aims to bring the R&D of proton-driven PWFA to a point where a number of high energy physics applications can be proposed and realized [21]. The major goals of AWAKE Run 2 are to accelerate the externally injected electron bunch to high energies with low energy spread and preserved normalized emittance [22]. A two-stage plasma target is planned, a 10 m long self-modulator to achieve saturation and stabilisation of SSM and followed by a 10 m long accelerator where externally injected electron bunch undergoes acceleration.

Bunch Length/ Profile Measurement Concept

It is important to ensure the injection of witness electron bunch into one single plasma wavelength that is the spacing between micro proton bunches and hence preserve the bunch quality during the acceleration. Thus, a precise, non-invasive longitudinal electron bunch length diagnostics is needed to monitor before the beam loading.

We proposed to use a new longitudinal electron bunch length/ profile monitoring tool for Run 2 based on the measurement concept depicted in Fig. 2. Longitudinal electron bunch length/ profile measurement concept is based on the usage of 3 prismatic dielectric radiators placed on one side of the bunch. Two Schottky detectors, which have two different frequency ranges, will be used to measure the ChDR from the first 2 radiators. Coherent ChDR spectral responses are measured by these two detectors. Calculating theoretically the single electron corresponding response for each Schottky detector in their corresponding frequency ranges enables us to evaluate the rms munch length by using,

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

where $k = \omega / c$ is wave number, S is the coherent ChDR spectral response of detectors and S_e is the theoretical single electron spectra corresponding response for each detectors.

Concerning the third radiator, ChDR will be measured in the full frequency range by using Martin-Pupplett Interferometer for detailed analysis. The longitudinal bunch profile will be reconstructed using the Kramers-Kronig method probed in [23]. The usage of two independent methods will allow us to monitor electron bunch profile and RMS bunch length simultaneously and provide a cross-check in the measurements.

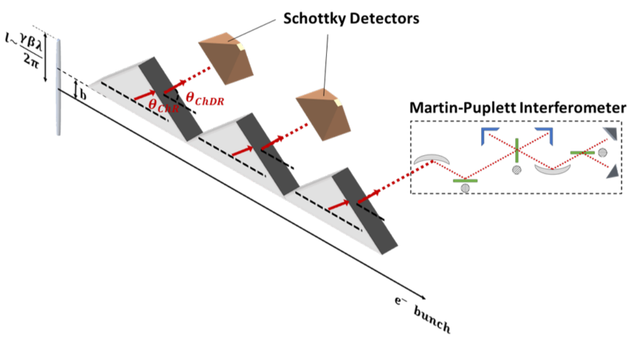

Figure 2: The measurement concept of the longitudinal electron bunch length/profile monitor for AWAKE Run 2.

Determination of ChDR Radiator

As ChDR is refracted out at the exit interface, the radiator was designed with an appropriate angle, i.e. when the ChDR wavefront is parallel to the output interface to minimize the distortion due to refraction and to provide an effective emission. Table 1 shows typical ChDR emission angles for different materials calculated with relative permittivies from CST database.

Table 1: ChDR Emission Angles for Different Dielectric Materials Calculated With Given Relative Permittivities at 1 MHz

Material	**Relative Permittivity**	**ChDR Angle**
Quartz (Fused)	3.75	58.9°
Diamond	5.68	65.2°
Alumina	9.40	71.0°

According to the PCA model, ChDR intensity is proportional to the relative permittivity of the dielectric material. Alumina is chosen as the radiator material because of it is vacuum compatibility and high relative permittivity leading to emission of high ChDR intensity as summarised in Table 1.

CST Simulation

The investigation of ChDR emission from a 30 mm long Alumina radiator with the passage of an electron bunch with gaussian distribution was carried out by using the wakefield solver in CST Particle Studio [24]. According to the electron injector design of Run 2 the electron bunch is 200 fs. The electron bunch length was 2 ps due to the computing limitations of big simulation calculation domain. ChDR spectrum was calculated by PCA model for different bunch lengths as in Fig. 4. CST simulation performed between 0 to 200 GHz for 2 ps to compare with PCA model in terms of emitted ChDR cone.

Radiator geometry and vacuum chamber including the beam and wakefield integration direction which is demon-

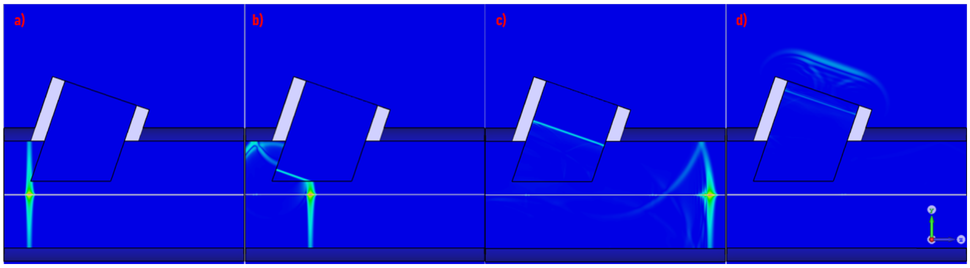

Figure 3: Generation and propagation of ChDR. a) 2 ps Gaussian electron beam travelling along +z direction interacts with Alumina radiator. b) Only ChDR propagates through the radiator since DR generation is blocked with PEC coating of radiator front face. c) ChDR wavefront is not affected by reflection of the beam field from the end edge. d) ChDR wavefront exits the radiator with some reflection backwards from the outer interface.

strated with blue and orange coloured arrows, respectively are shown in Fig. 5. Both faces of the radiator, in the direction of the beam, were covered with a perfect electrical conductor (PEC) material to prevent the propagation of the DR that emerged from the edges along the radiator. The generation and propagation of ChDR are shown with the snapshots of Power Flow (Poynting vector) monitor in Fig. 3. The passage of 100 pC electron bunch causes wakefields in the metallic vacuum chamber and the interaction of these fields with the radiator results in polarization of dielectric medium. ChDR wavefront propagates in the medium with θ_{ChR} and exits the outer face with some diffraction and reflection.

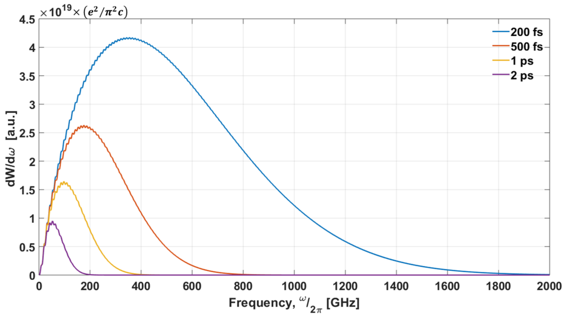

Figure 4: Coherent ChDR spectrum for different bunch lengths calculated by PCA model. Electron bunch is assumed to have Gaussian distribution having 6.2 × 10^8 particles in the bunch.

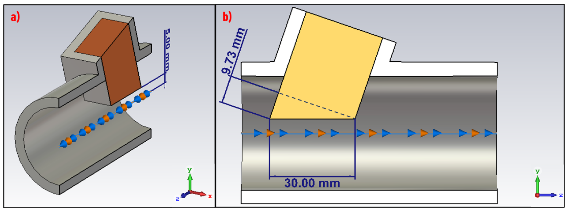

Figure 5: Radiator geometry and vacuum chamber design.

In Fig. 6, the spectral-angular distribution of emitted ChDR was measured with a far-field monitor for the defined volume demonstrated with a green box in the 2D image out of the vacuum chamber. Measurement frequency was chosen as 110 GHz in order to observe the bunch form factor dominated part of the spectrum for 2 ps bunch. These results were compared with PCA theory in terms of normalized intensities. Emitted ChDR has a peak around 71° for both PCA model and CST simulation. The shift in CST simulation might be caused by the interference since the PCA model does not take into account diffraction from the edges.

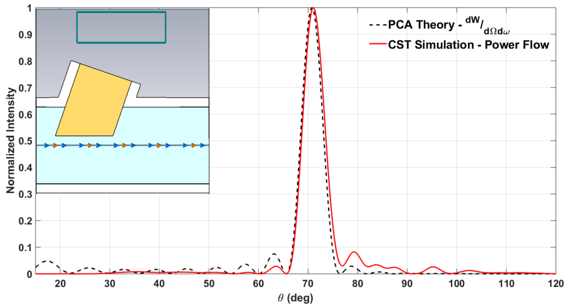

Figure 6: Spectral-angular distribution of ChDR for far-field power monitor of CST and PCA model. Far-field monitor is shown with green box in the 2D view in inset.

CONCLUSION AND FUTURE PLANS

A new, non-invasive bunch length/profile measurement concept was introduced to be used in AWAKE Run 2 as an application of coherent ChDR process.

It was found that the result of PCA theory and CST simulation are consistent with each other regarding the shape of the emitted ChDR cone.

The vacuum chamber will be manufactured and tests will be performed in the CLEAR facility at CERN to demonstrate the suppression of beam position and angular jitter influence on RMS bunch length measurement and the dependence of ChDR spectra on different impact parameters.

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