ZEMAX SIMULATIONS FOR AN OPTICAL SYSTEM FOR A DIFFRACTION RADIATION MONITOR AT CESRTA

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Abstract

Diffraction Radiation (DR) is produced when a relativistic charged particle moves in the vicinity of a medium. The target atoms are polarised by the electric field of the charged particle, which then oscillate thus emitting radiation with a very broad spectrum. The spatial-spectral properties of DR are sensitive to various electron beam parameters. Since the energy loss due to DR is so small that the electron beam parameters are unchanged, DR can be used to develop non-invasive diagnostic tools. The aim of this project is to measure the transverse (vertical) beam size using incoherent DR. To achieve the micron-scale resolution required by CLIC, DR in the UV and X-ray spectral-range must be studied. During the next few years, experimental validation of such a scheme will be conducted on the CesrTA at Cornell University, USA. This paper reports on simulations carried out with ZEMAX, studying the optical system used to image the emitted radiation.

INTRODUCTION

Over the last 30 years Optical Transition Radiation (OTR) [1] has been widely developed for beam imaging and transverse profile measurement. However OTR based systems are invasive and do not permit the measurement of high charge density beams without risking damage to the instrumentation. Beam diagnostics using Diffraction Radiation has been proposed as an alternative [2, 3].

In the optical wavelength range the use of diffraction radiation (ODR) as a high-resolution non-invasive diagnostic tool for transverse beam size measurement has been widely investigated; at the Accelerator Test Facility at KEK in Japan [4], at the FLASH test facility at DESY [5] and at the Advanced Photon Source at Argonne, USA [6]. At ATF the achieved beam size sensitivity was as small as 14 µm [4].

For next generation linear colliders such as the Compact Linear Collider (CLIC) [7], transverse beam size measurements must have a resolution on the micron-scale. Currently, laser wire scanners [8] are the main candidate for non-invasive high resolution measurements. However, over a distance of more than 40 km many laser wire monitors would be required. This is both costly and difficult to maintain, so DR could offer a simpler and cheaper alternative. Our aim is to develop a non-invasive beam size monitor with micrometer resolution for electron and positron beams of a few GeV energy. In the CLIC machine layout [7], these devices would then be used both from the Damping ring exit to the entrance of the Main beam linac and in the CLIC Drive beam complex (2.4 GeV).

The Cornell Electron Storage Ring, with beam parameters as shown in Table 1 was primarily reconfigured as a test accelerator (CesrTA) [9] for the investigation of beam physics for the International Linear Collider damping rings. An experimental program was recently proposed to develop and test a Diffraction Radiation monitor to be installed in the straight section of the ring where small beam sizes can be achieved. The sensitivity to beam-size is improved at shorter observation wavelengths, so the experimental program has been divided into two consecutive phases. The first phase, which we have recently implemented aims to measure the beam size in the 20-50 µm range using visible and UV light. If successful a second phase will be launched in order to push the detector sensitivity down to few micrometers using shorter wavelengths in the soft X-ray range. This paper reports on the current status of the simulations carried out with ZEMAX, studying the optical system used to image the emitted radiation.

Table 1: Phase 1 experiment parameters for CesrTA and comparison with the CLIC damping ring complex [10].

	E (GeV)	σ_H (µm)	σ_V (µm)
CesrTA	2.1	320	∼9.2
	5.3	2500	∼65
CLIC	2.86	∼10-200	∼1-50

ODR MODEL

The ODR model considers the case when a charged particle moves through a slit between two tilted semi-planes i.e. only DR produced from the target is considered. The vertical polarisation component is sensitive to beam size [4]. Eq. 1 gives the expression for the ODR vertical polarisation component convoluted with a Gaussian distribution [4], where α is the fine-structure constant, γ is the Lorentz factor, θ_0 is the tilt angle of the target, $t_{x,y} = \gamma\theta_{x,y}$ where $\theta_{x,y}$ are the radiation angles measured from the mirror reflection direction, λ is the observation wavelength, σ_y is the rms vertical beam size, a is the target aperture size, a_x is the offset of the beam centre with respect to the centre of the slit and $\psi = \arctan\left(\frac{t_y}{\sqrt{1+{t_x}^2}}\right)$. This model is applicable when the transition radiation contribution from the tails of the Gaussian distribution is negligible, which means approximately $a \geq 4\sigma_y$.

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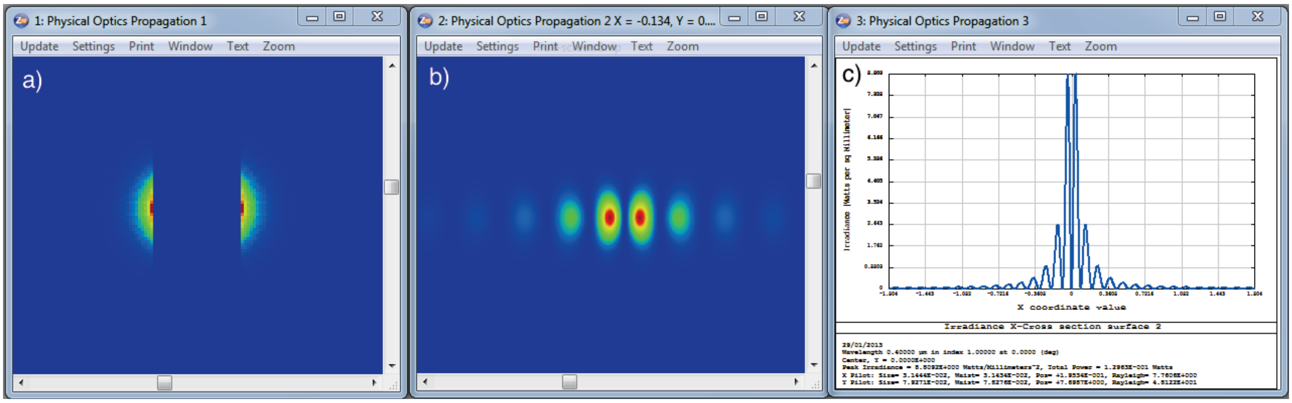

Figure 1: Zemax output: source (a), detector plane (b) and horizontal cross-section of the detector plane (c).

$$
\begin{aligned}
\frac{d^2W_y^{slit}}{d\omega d\Omega} &= \frac{\alpha\gamma^2}{2\pi^2}\frac{\exp\left(-\frac{2\pi a\sin\theta_0}{\gamma\lambda}\sqrt{1+{t_x}^2}\right)}{1+{t_x}^2+{t_y}^2} \\
&\times\left\{\exp\left[\frac{8\pi^2{\sigma_y}^2}{\lambda^2\gamma^2}\left(1+{t_x}^2\right)\right]\cosh\left(\frac{4\pi\overline{a_x}}{\gamma\lambda}\sqrt{1+{t_x}^2}\right)\right. \\
&\left.-\cos\left(\frac{2\pi a\sin\theta_0}{\gamma\lambda}t_y+2\psi\right)\right\}
\end{aligned}
\tag{1}
$$

Generally, DR intensity is inversely proportional to the aperture size and the sensitivity to beam size is inversely proportional to the observation wavelength. The sensitivity to beam size is dependent on the visibility (I_{min}/I_{max}) of the DR angular distribution, where I_{min} is the minimum intensity taken at the centre of the distribution between the two main lobes. Therefore the maximum and minimum intensities of the DR angular distribution must be measured accurately.

SIMULATIONS

As a first step, only the single particle case is considered, therefore the beam size σ_y in Eq. 1 is set to 0. The 2D distribution of the electric field at the source position is used as an input file to Zemax. This is done using a user-defined DLL representing a 2D matrix. Running Zemax in the Physical Optics Propagation (POP) mode, propagates the fields through an optical system surface by surface using either a Fresnel diffraction propagation or an angular spectrum propagation algorithm. Fig. 1 (a) shows the electric field at the source, created by a single electron passing through a 1-mm vertical slit. The field is then propagated in free space. Fig. 1 (b) and (c) show the electric field at the detector plane.

Far-field

For an observation wavelength of $\lambda = 400$ nm and a Lorentz factor of $\gamma = 4000$, the distribution at the detector plane for varying distances L from the source can be found in Fig. 2, using a slit width of 1 mm and an incident target angle of $\theta_0 = 70°$. It can be seen, that for $L > 10$ m, the angular distribution is fully defined. This is known as the far-field condition and it is fulfilled for a distance $L \gg \frac{\gamma^2\lambda}{2\pi} = 1.02$ m, as described by Eq. 1.

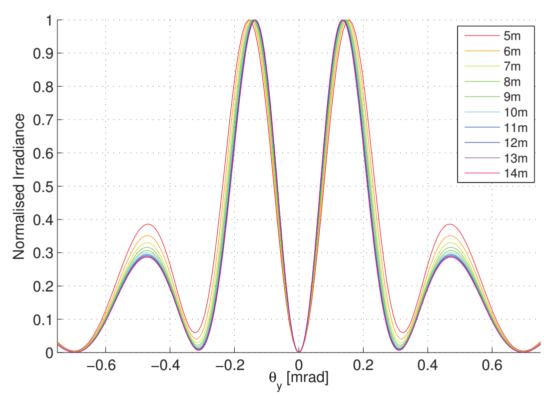

Figure 2: Far-field condition.

Near-field

To obtain the DR angular distribution in the near-field, a biconvex lens with the detector positioned in the back focal plane is used to remove the spatial contribution. Fig. 3 compares the distribution at the detector plane for three different setups: far-field, near-field using an ideal paraxial lens with a focal length of $f = 308.5$ mm and near-field with a CVI Melles Griot BICX-50.0-308.5-UV lens as used in the real optical setup at CesrTA. The result of all three setups are in excellent agreement.

Full Optical System

The optical system has two purposes, to image the target and also to observe the DR interference pattern. An achromatic lens is used to image the target. To switch to DR operation, the achromatic lens is removed and replaced by a biconvex lens (see Fig. 4). A compact system is preferable for alignment and installation although this introduces some complications when imaging the DR angular distribution as the detector will be located within the prewave

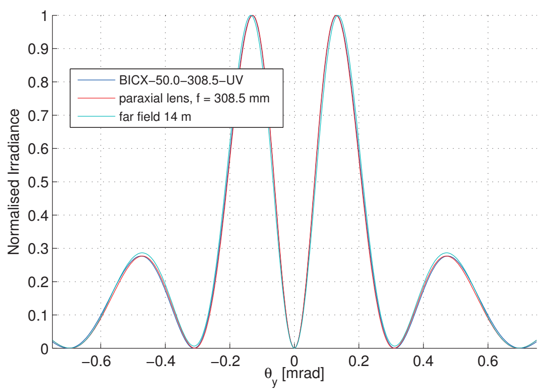

Figure 3: Comparison of the angular distribution in far-field condition, in the near-field using an ideal and also a real biconvex lens.

zone [11], which corresponds to the near-field. The system is inside a black box to reduce background.

Fig. 4 shows the main optical components. Bandpass filters are used to select the wavelengths of interest. A polariser is required to select the vertical polarisation component which carries the vertical transverse beam size information. An ICCD camera is used for imaging the target and the DR angular distribution.

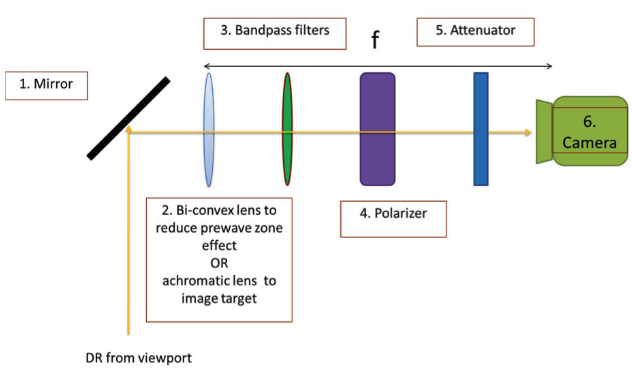

Figure 4: Schematic of optical system.

Zemax is also used to optimise the optical system, e.g. simulate a possible offset and tilt of the lens or how much the position of the focal plane changes if using filter and polariser. For a single particle, the irradiance at the first minimum of the interference pattern is 0 according to Eq. 1. Fig. 5 shows how the position of the focal plane, achieved when the irradiance reaches a minimum, can move up to several mm when a bandpass filter and polariser are inserted into the optical line. It can be seen that ODR angular distribution is very sensitive when the detector is positioned away from the back focal plane of the biconvex lens. The camera CCD must therefore be exactly in the real back focal plane.

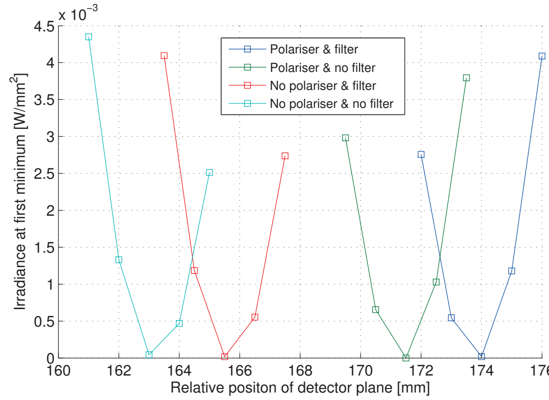

Figure 5: Changing the position of the focal plane if using filter and polariser.

SUMMARY AND CONCLUSION

Zemax was used to simulate the setup of the real optical system. The far-field condition was established and a biconvex lens was used to remove all spatial information and transform the distribution at the detector plane into a purely angular one. The sensitivity of the setup with respect to finding the focal plane of the biconvex lens was also studied.

The next steps are comparing analytical equations for angular distributions with Zemax simulations for a single particle as well as for a finite beam size. Also, a second system will be developed for $\lambda = 200$ nm to measure smaller beam sizes. Finally, both systems will be compared with real data to verify the simulation.

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