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SIMULATION STUDIES OF DIFFRACTION RADIATION

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Abstract

Transition Radiation (TR) and Diffraction Radiation (DR) are produced when a relativistic charged particle moves through a medium or in the vicinity of a medium respectively. 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 TR/DR are sensitive to various electron beam parameters. Several projects aim to measure the transverse (vertical) beam size using TR or DR. This paper reports on recent studies using Zemax, presenting studies on finite beam sizes and the orientation of the beam ellipse.

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 as well as to create the angular distribution.

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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 vertical beam size. 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 $\psi = \arctan\left(t_y/\sqrt{1+t_x{}^2}\right)$. This model is applicable when the transition radiation contribution from the tails of the Gaussian distribution is negligible, which means approximately $a \geq 4\sigma_y$.

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

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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. The two-dimensional 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 two-dimensional 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 shows the electric field at the source, created by a single electron passing through a 0.5-mm vertical slit with an offset r_0 with respect to the optical axis. The field is then propagated through the optical system to achieve the angular distribution at the image plane.

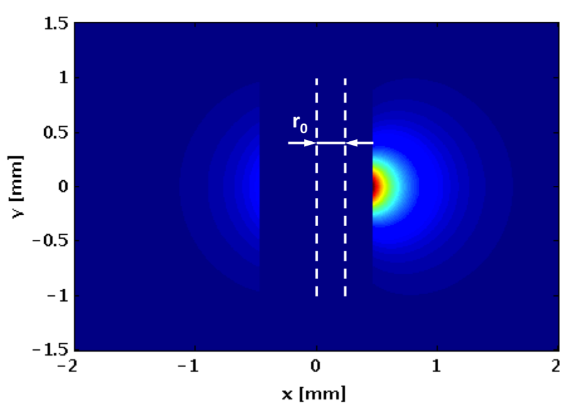

Figure 1: Source field for a single particle passing through a slit with an offset r_0.

The optical system at CesrTA is a dual purpose system. An achromatic lens is used to image the target. To observe the DR interference pattern, the achromatic lens is removed and replaced by a plano-convex lens. Bandpass filters are used to select the wavelengths of interest (400 and 600 nm). A polariser is required to select the vertical polarisation component which carries the vertical transverse beam size information. The same camera is used for imaging the target and the DR angular distribution.

For the studies presented in this paper, an observation wavelength of λ = 400 nm and a Lorentz factor of γ = 4110 is used. The target slit aperture is 0.5 mm. The target tilt angle θ_0 with respect to the electron beam is 70°. This corresponds to the experimental conditions at the ODR monitor at the CesrTA.

Beam Size Studies

In order to study effect of a finite beam size, single electron angular distributions were simulated for various offsets of the single particle with respect to the optical axis. Assuming a Gaussian electron beam profile, these single electron profiles were weighted and summed up to achieve the angular distribution of a finite beam. Fig. 2 shows the summed angular distribution patterns for beam sizes from 0 to 60 µm.

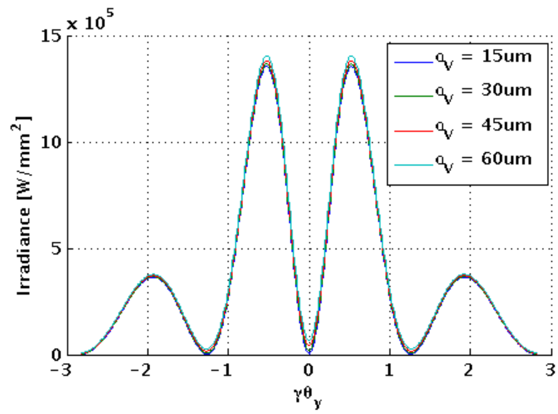

Figure 2: DR angular distribution for various beam sizes at 400 nm.

In Fig. 3, the evolution of the aforementioned visibility versus the electron beam size is compared between the two wavelengths used at CesrTA, λ = 400 and 600 nm.

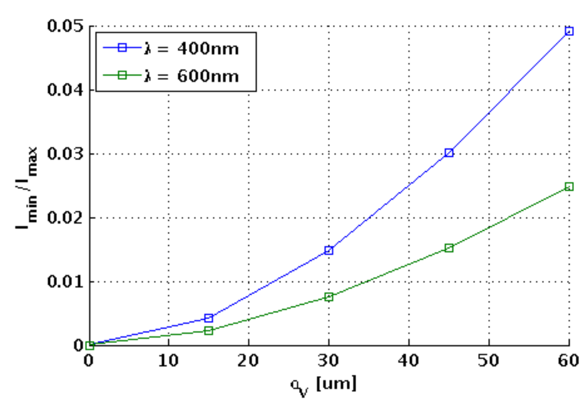

Figure 3: Simulated visibility versus beam size.

Tilt of the Beam Ellipse

The two-dimensional cross-section of a particle beam could have a non-zero orientation inside the slit. To study the possibility of observing such a tilt in the beam ellipse, the same principle as above was used for the imaged source. Several images of the irradiated slit were simulated for various offsets in x and y. Symmetry was used in order to speed up the process (see Fig. 4a). A two-dimensional Gaussian beam profile was assumed with a vertical beam size of σ_V = 20 µm, varying horizontal beam sizes and beam ellipse tilts (see Fig. 4b). Summing the thus weighted single

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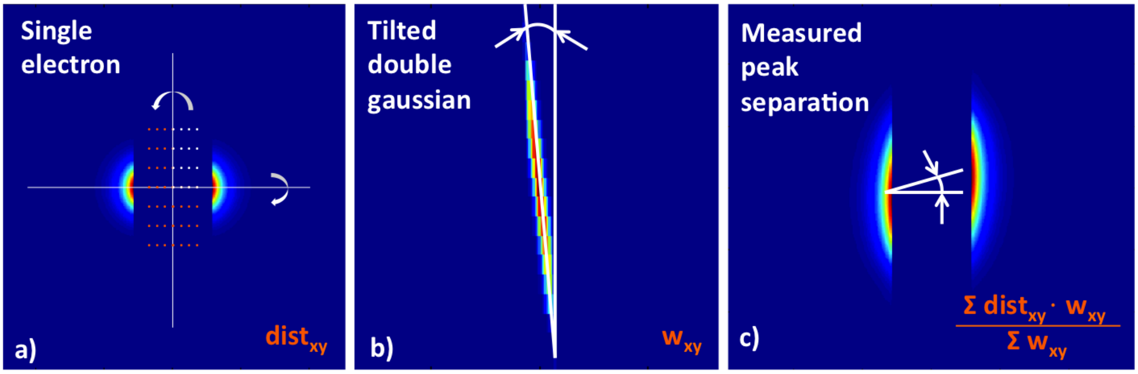

Figure 4: Imaged irradiance from a single electron (a), two-dimensional gaussian beam profile (b) and imaged irradiance from a two dimensional beam (c)

electron irradiance images up, leads to an imaged irradiance from a two-dimensional beam (see Fig. 4c).

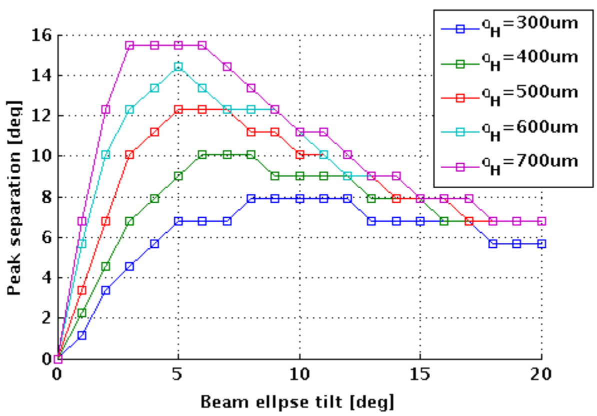

Figure 5: Peak separation between the left and right tine versus the input beam ellipse tilt for λ = 400 nm.

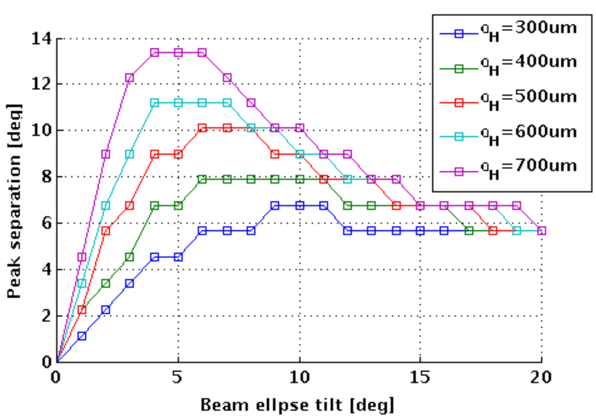

Figure 6: Peak separation between the left and right tine versus the input beam ellipse tilt for λ = 600 nm.

In Fig. 5 and 6, the dependence of the peak difference between the left and right side of the slit on the tilt of the beam ellipse is shown for λ = 400 and 600 nm respectively. It can be seen that as the beam ellipse tilts, the peak separation between the two tines increases until the vertical projection of the beam ellipse reaches its maximum size. The bigger the horizontal beam size is compared to the vertical, the faster this increase happens. The asymmetry in DR intensity for an off-set beam is bigger for shorter wavelengths, which leads to the slight difference between Fig. 5 and 6.

CONCLUSIONS

Zemax was used to simulate the setup of the real optical system at the ODR monitor at CesrTA. The effect of a finite beam size on the angular distribution pattern was investigated. Furthermore, the possibility of detecting a possible tilt of the two-dimensional beam ellipse by looking at the imaged source was studied.

The next steps are comparing analytical equations for angular distributions for a finite beam size with Zemax simulations. Simulations will also be compared with real data.

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