Zemax Simulations of Diffraction and Transition Radiation

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1 Abstract

Diffraction Radiation (DR) and Transition Radiation (TR) are produced when a relativistic charged particle moves in the vicinity of a medium or through 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 DR/TR are sensitive to various electron beam parameters. Several projects aim to measure the transverse (vertical) beam size using DR or TR. This paper reports on how numerical simulations using Zemax can be used to study such a system.

2 Motivation

- Theories to describe OTR and ODR are simplified, e.g. free-floating targets and single-electron pass.
- To take account of real optical elements (finite-size lenses, filters, targets, etc.) $\rightarrow$ Zemax.
- First step: get simulations to agree with theory, using same assumptions. This work only deals with free-space propagation.
- After agreement: diffraction limitations, misalignments and beam size effects can be studied.

3 Zemax

- Readily available commercial optical design software: standard tool to conceptualise, design, optimise, analyse and tolerance optical systems.
- Geometrical ray tracing is incomplete description of light propagation.
- Coherent process: wavefront travels through free space and interferes with itself $\rightarrow$ physical optics.
- Physical Optics Propagation (POP): Zemax mode that calculates wavefront propagation through an optical system surface by surface.
- Target as radiation source: initial electric field defined in 2D matrix (binary or text) or computed with Windows Dynamic Link Library (DLL).
- In POP: wavefront modelled with this array (dimension, sampling and aspect ratio are user-definable).
- Array then propagated in free space between optical surfaces $\rightarrow$ transfer function is computed at each surface $\rightarrow$ matrix is propagated from one side to the other.
- In this way, simulation of any source of light is possible (e.g. TR, DR, synchrotron radiation (SR)).

4 Theory

OTR

Angular distribution of intensity of a charged particle passing through a boundary between vacuum and an ideal conductor with ultra-relativistic approximation $(\theta_x, \theta_y, \gamma^{-1} \ll 1)$:

$$\frac{d^2W_{TR}}{d\omega d\Omega} = \frac{\alpha}{\pi^2}\frac{\theta_x{}^2+\theta_y{}^2}{\left(\gamma^{-2}+\theta_x{}^2+\theta_y{}^2\right)}$$

ODR

Charged particle moving 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. ODR vertical polarisation component convoluted with a Gaussian distribution:

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

with $t_{x,y} = \gamma\theta_{x,y}$ and $\psi = \arctan\left(\frac{t_y}{\sqrt{1+t_x{}^2}}\right)$.

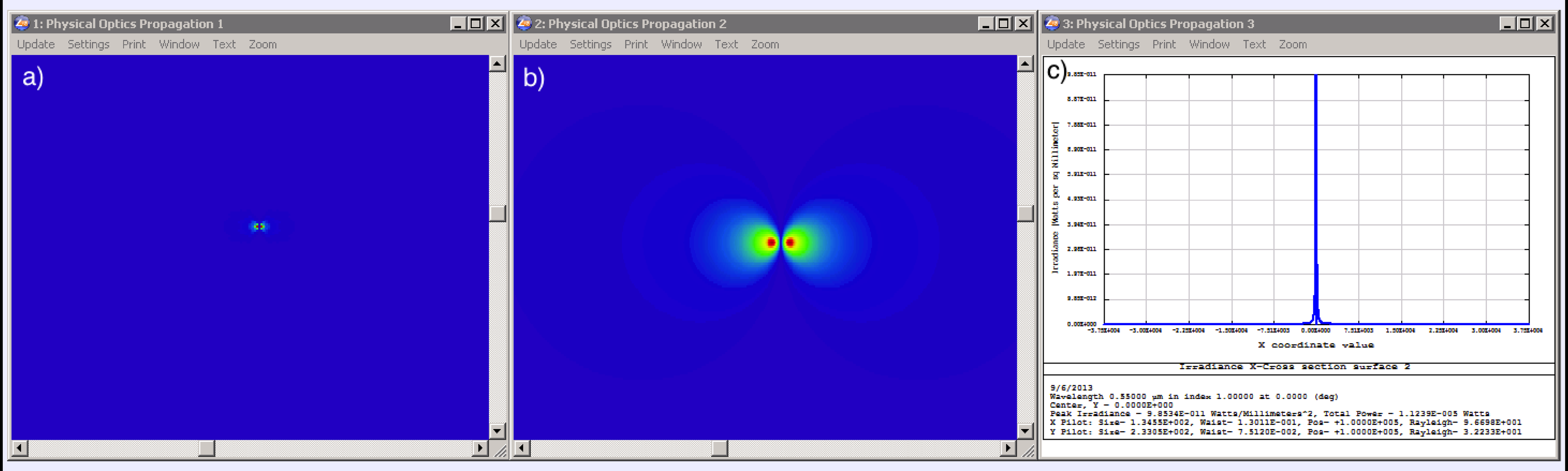
Valid when the transition radiation contribution from the tails of the Gaussian distribution is negligible (approx. $a \geq 4\sigma_y$).

7 Conclusion / Outlook

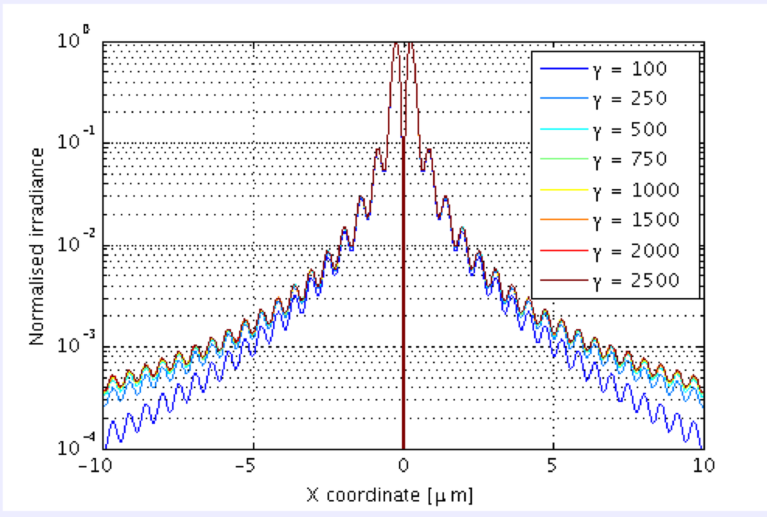
With assumptions similar to theoretical boundary conditions, Zemax simulations of OTR and ODR agree with the analytical expressions. Next step: comparing analytical equations with Zemax simulations for a finite beam size (convolution or Monte Carlo). After this, the software will have been proven useful for studies of any type of optical system using OTR or ODR. It will enable simulations of all misalignment errors and optimisation of a real optical system to be implemented in a real diagnostic station.

5 OTR Simulations

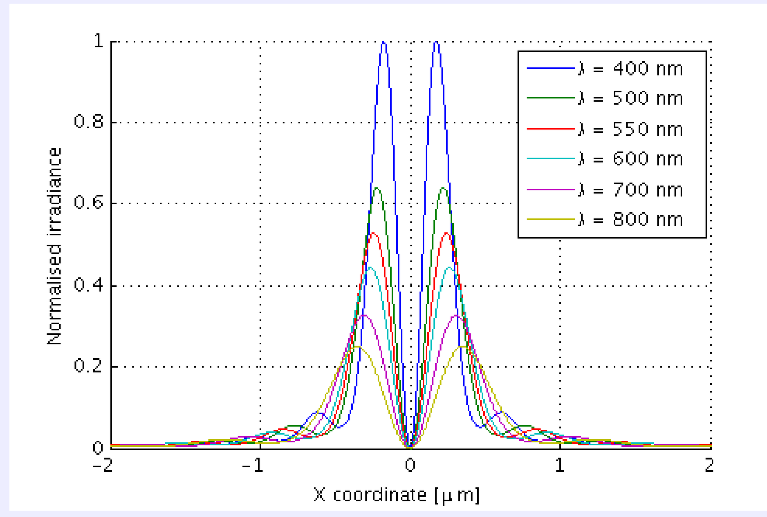
At the Accelerator Test Facility (ATF), the OTR monitor uses an observation wavelength of $\lambda = 550$ nm for a beam Lorentz factor of $\gamma = 2500$.



Zemax output: intensity at the source created by a single electron passing through an ideal conductor ($\gamma = 2500$, $\lambda = 550$ nm) (a), detector plane after 100-m free-space propagation (b) and horizontal cross-section of the detector plane (c).

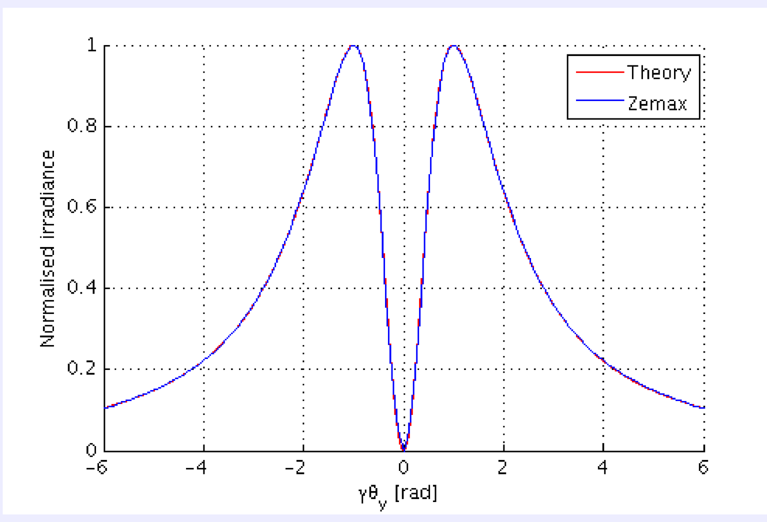


OTR irradiance horizontal cross section at the source for $\lambda = 550$.

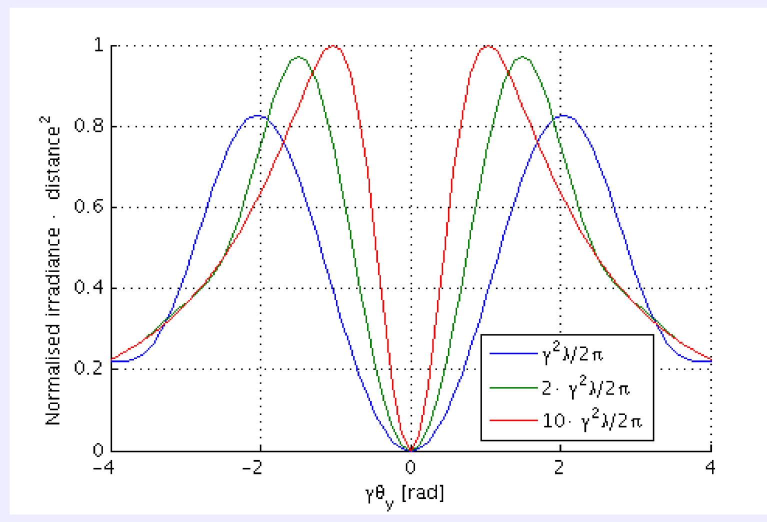


OTR irradiance horizontal cross section at the source for $\gamma = 2500$.

The far-field requirement for OTR is $L \gg \frac{\gamma^2\lambda}{2\pi} = 0.55$ m, therefore distance between source and detector plane for the simulation was set to 100 m. The size of the source was $r_{max} = 10 \cdot \frac{\gamma\lambda}{2\pi} = 2.188$ mm.



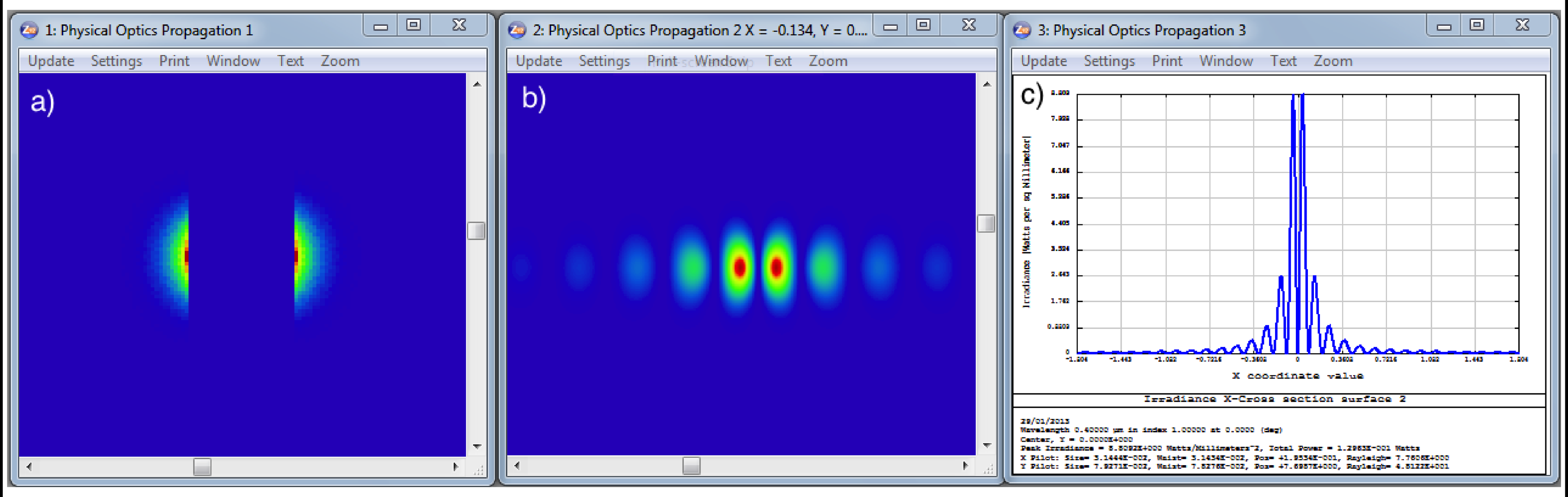
Comparison of the theoretical OTR angular distribution in far-field condition with the Zemax simulation.



Zemax simulation of the OTR angular distribution for different distances from the source.

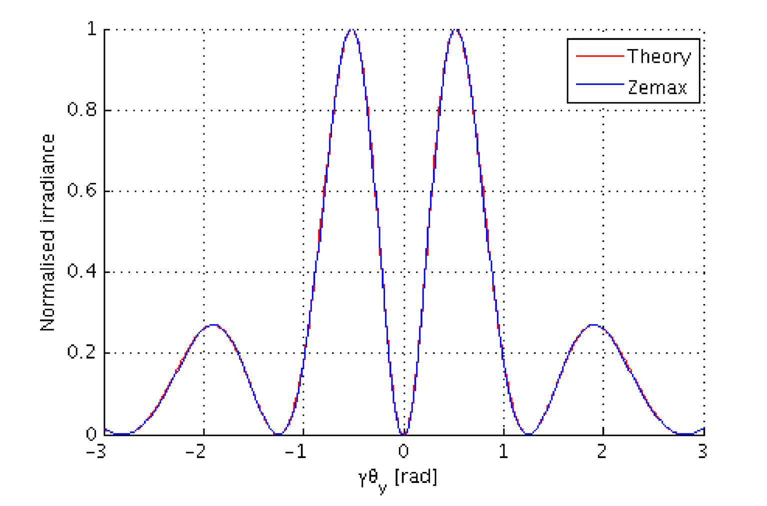
6 ODR Simulations

At the Cornell Electron Storage Ring (CesrTA), the ODR monitor uses a target with a 1-mm slit at an incident target angle of $\theta_0 = 70°$, an observation wavelength of $\lambda = 400$ nm and a Lorentz factor of $\gamma = 4110$.

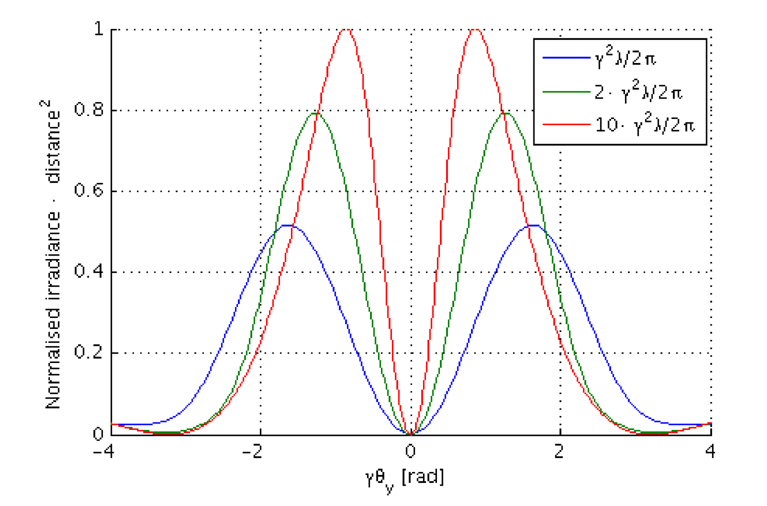


Zemax output: intensity at the source created by a single electron passing through a 1-mm vertical slit ($\gamma = 4110$, $\lambda = 400$ nm) (a), detector plane after 100-m free-space propagation (b) and horizontal cross-section of the detector plane (c)

The far-field condition is fulfilled for a distance $L \gg \frac{\gamma^2\lambda}{2\pi} = 1.08$ m. The distance between source and detector plane was set to 100 m, therefore angular distribution is fully defined. The size of the source was $r_{max} = 10 \cdot \frac{\gamma\lambda}{2\pi} = 2.617$ mm.



Comparison of the theoretical ODR angular distribution in far-field condition with the Zemax simulation.



Zemax simulation of the ODR angular distribution for different distances from the source (300 μm slit).