

Zemax Simulations of Diffraction and Transition Radiation

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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.) → Zemax.
- First step: get simulations to agree with theory, using same assumptions.
- After agreement: diffraction limitations, misalignments and beam size effects can be studied.

Theory

■ OTR

- Angular distribution of intensity of a charged particle passing through a boundary between vacuum and an ideal conductor with ultra-relativistic approximation ($\theta_x, \theta_y, \gamma^{-1} \ll 1$) [1]:
$$\frac{d^2W_{TR}}{d\omega d\Omega} = \frac{\alpha}{\pi} \frac{\theta_x^2 + \theta_y^2}{(\gamma^{-2} + \theta_x^2 + \theta_y^2)}$$

■ 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 [2]:

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

with $t_{x,y} = \gamma\theta_{x,y}$ and $\psi = \arctan(t_y/(1+t_x^2))$. Valid when the transition radiation contribution from the tails of the Gaussian distribution is negligible (approx. $a \geq 4\sigma_y$).

[1] A. Potylitsyn, Nucl. Inst. And Meth. B 145 (1998) 169-179.

[2] P. Karataev et al., Phys. Rev. Lett. 93 (2004) 244802.

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 → 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 → transfer function is computed at each surface → 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)).

OTR Source

OTR electric field at the source for vertical polarization component induced by a single electron on a target surface [3]:

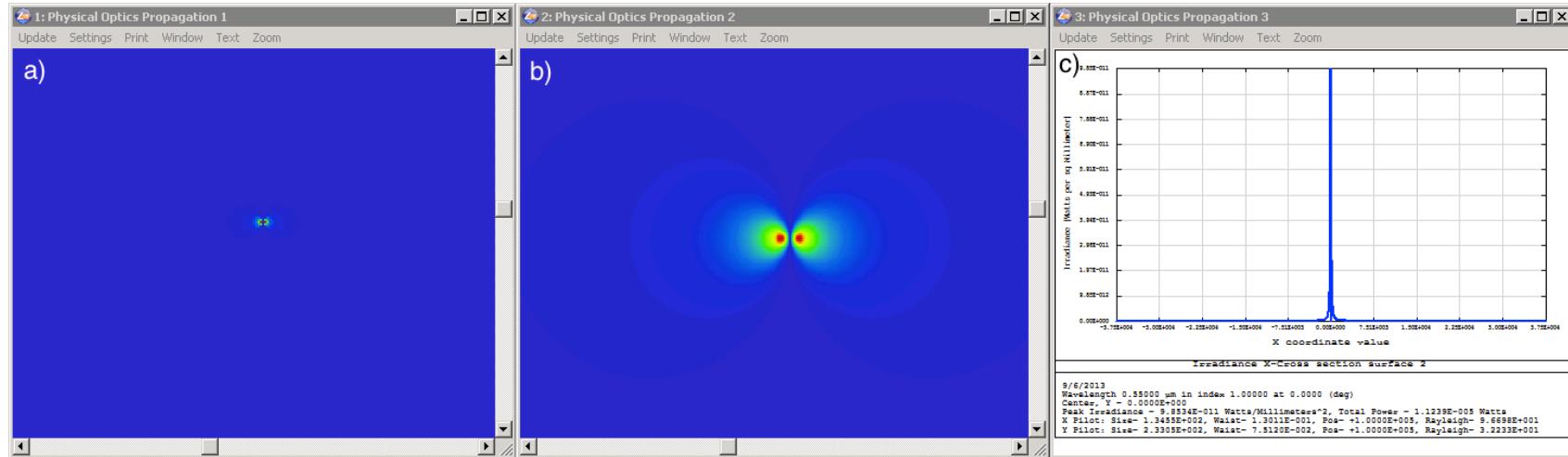
$$E_y = \text{const} \frac{y}{Z} \left[\frac{2\pi}{\gamma\lambda} K_1 \left(\frac{2\pi}{\gamma\lambda} Z \right) - \frac{J_0 \left(\frac{2\pi}{\lambda} Z \right)}{Z} \right]$$

where $Z = x+y$, $x = \rho \cos(\phi)$ and $y = \rho \sin(\phi)$ are two orthogonal coordinates of the target measured from the point of electron incidence, ρ and ϕ are the polar coordinates, γ is the charged particle Lorentz factor, λ is the radiation wavelength, K_1 is the first order modified Bessel function and J_0 is the zero order Bessel function.

[3] M. Castellano, A. Cianchi, G. Orlandi, V.A. Verzilov, Nucl. Inst. And Meth. A 435 (1999) 297.

OTR Simulations

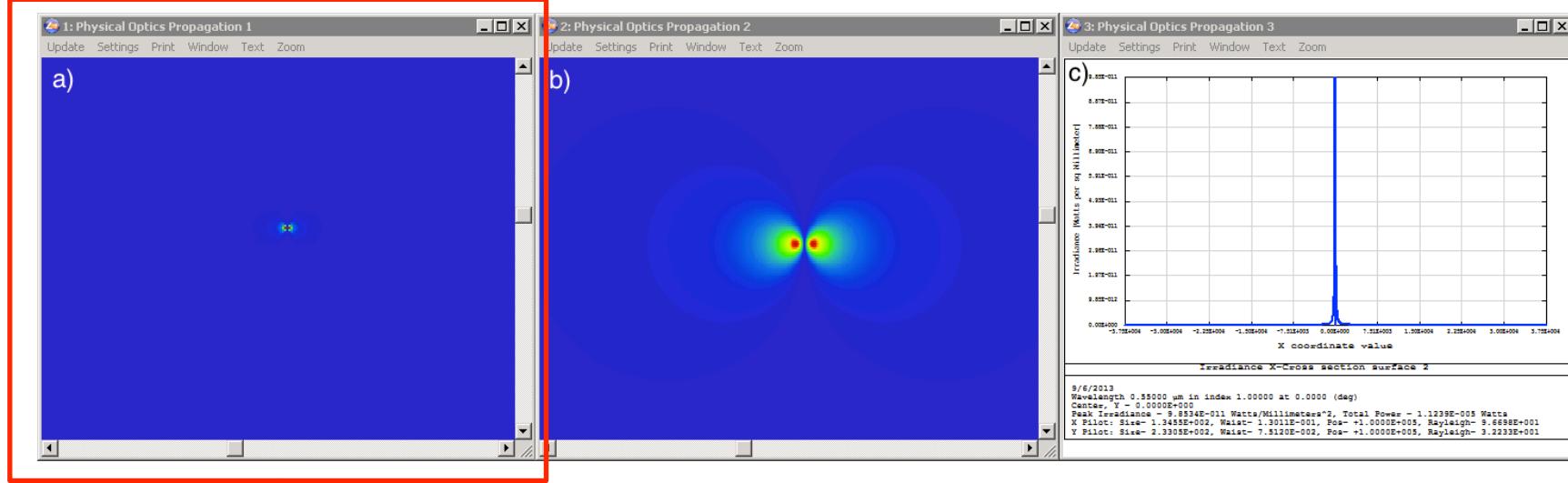
At the Accelerator Test Facility (ATF), the OTR monitor uses an observation wavelength of $\lambda = 550$ nm for a beam Lorentz factor of $\gamma = 2500$.



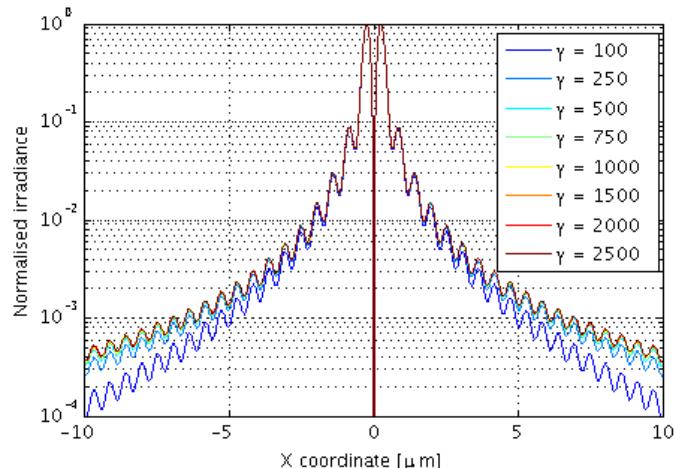
Zemax output: intensity at the source created by a single electron passing through an ideal conductor ($\gamma = 2500$, $\lambda = 550$ nm) (a), detector plane after 100-m free-space propagation (b) and horizontal cross-section of the detector plane (c).

OTR Simulations

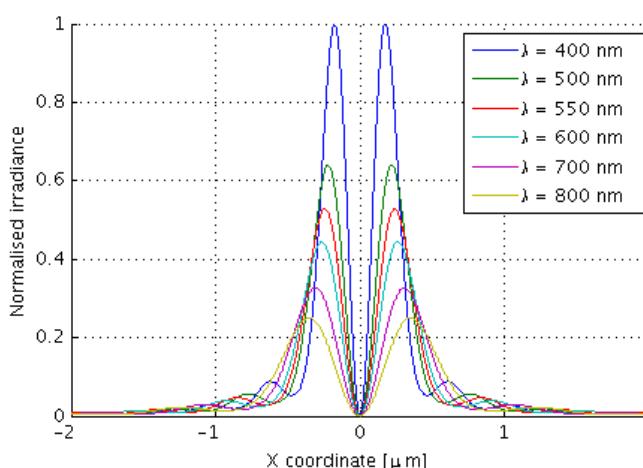
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Zemax output: intensity at the source created by a single electron passing through an ideal conductor ($\gamma = 2500$, $\lambda = 550$ nm) (a), detector plane after 100-m free-space propagation (b) and horizontal cross-section of the detector plane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



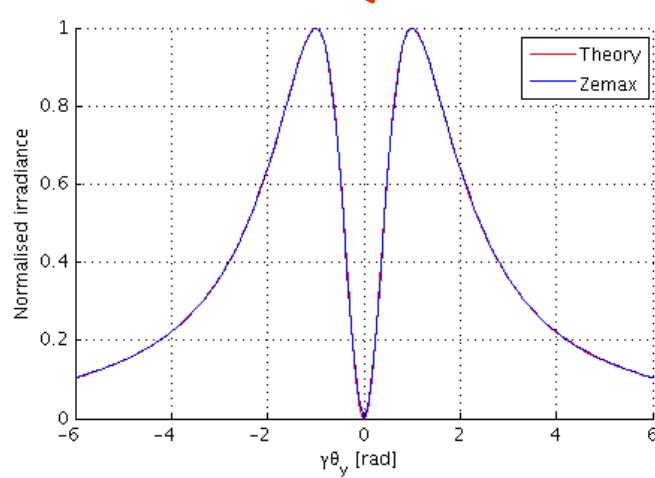
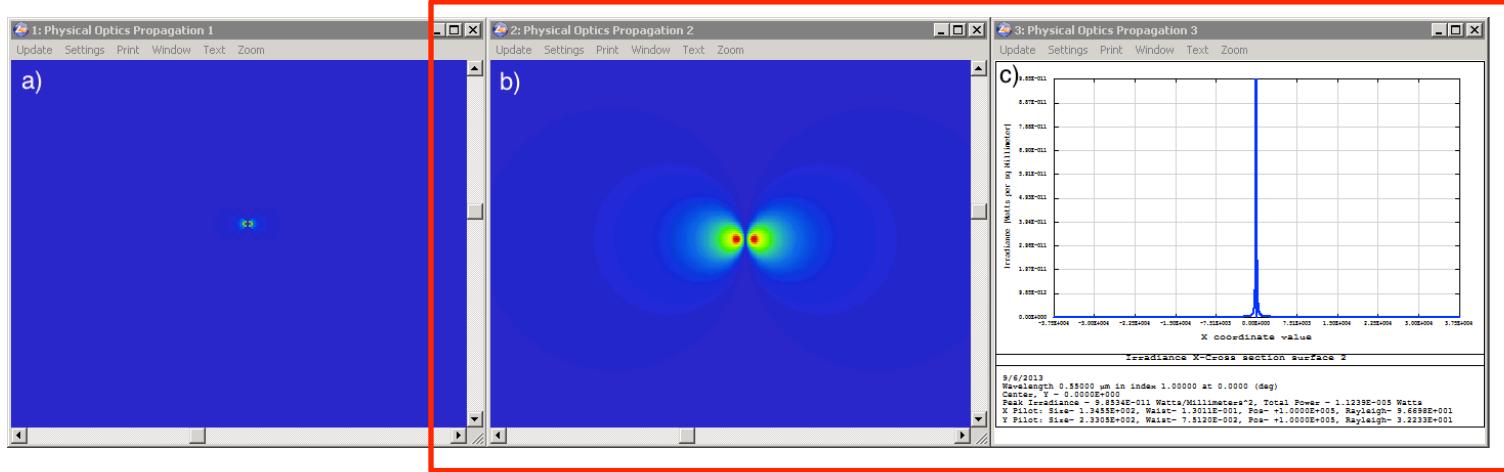
OTR irradiance horizontal cross section at the source for $\lambda = 550$.



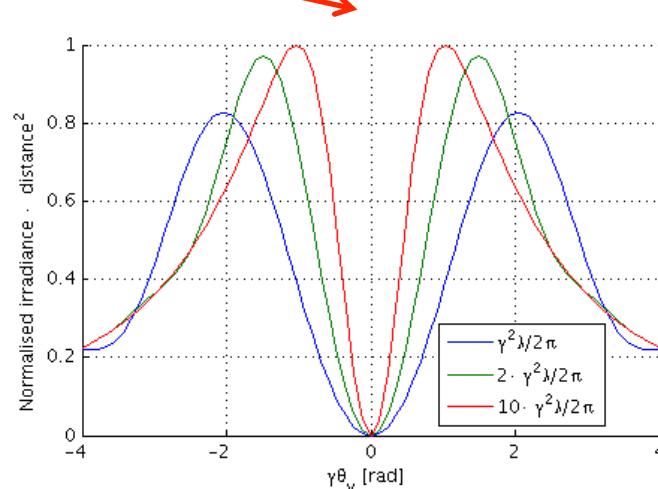
OTR irradiance horizontal cross section at the source for $\gamma = 2500$. 8

OTR Simulations

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



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

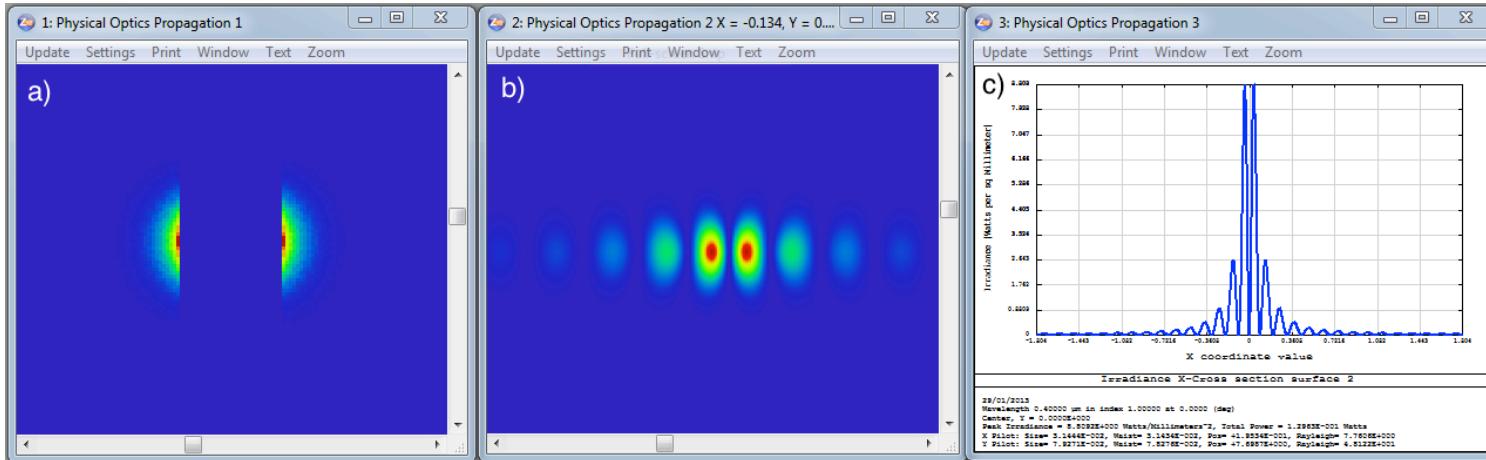


Zemax simulation of the OTR angular distribution for different distances from the source.

Compare: [4] P. Karataev, Phys. Lett. A 345 (2005) p.428-438.

ODR Simulations

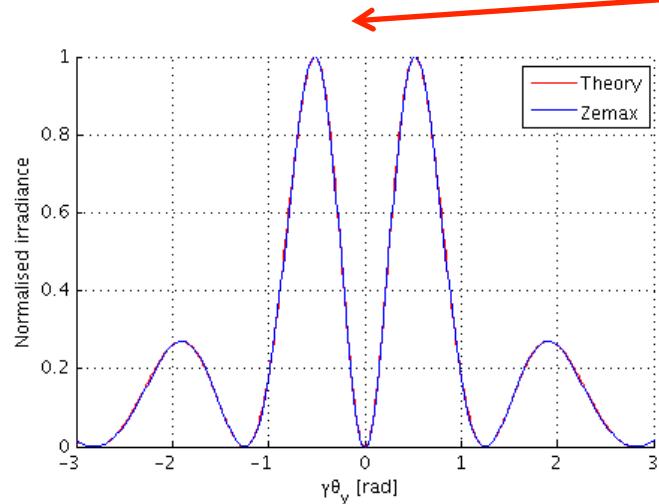
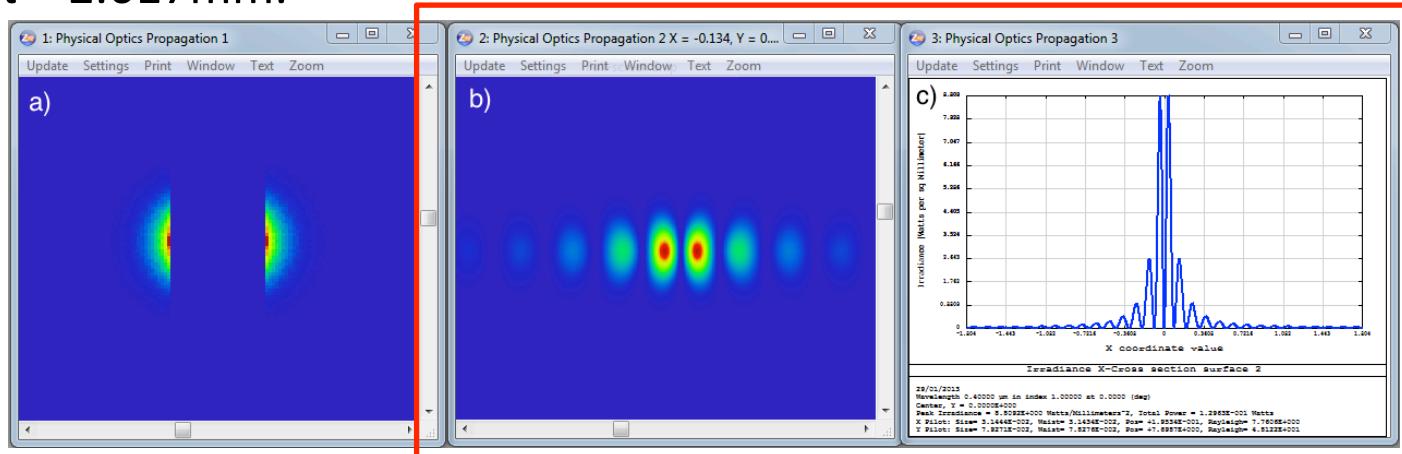
At the Cornell Electron Storage Ring (CesrTA), the ODR monitor uses a target with a 1-mm slit at an incident target angle of $\theta_0 = 70^\circ$, an observation wavelength of $\lambda = 400$ nm and a Lorentz factor of $\gamma = 4110$.



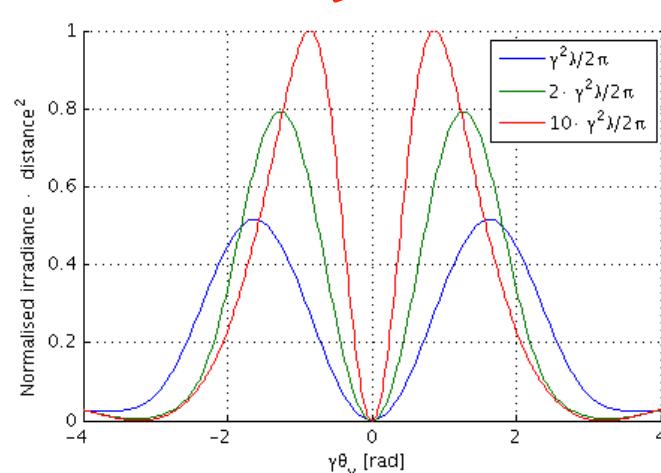
Zemax output: intensity at the source created by a single electron passing through a 1-mm vertical slit ($\gamma = 4110$, $\lambda = 400$ nm) (a), detector plane after 100-m free-space propagation (b) and horizontal cross-section of the detector plane (c)

ODR Simulations

The far-field condition is fulfilled for a distance is $L \gg \gamma^2\lambda/2\pi = 1.08$ 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 $r_{\max} = 10 \cdot \gamma\lambda/2\pi = 2.617$ mm.

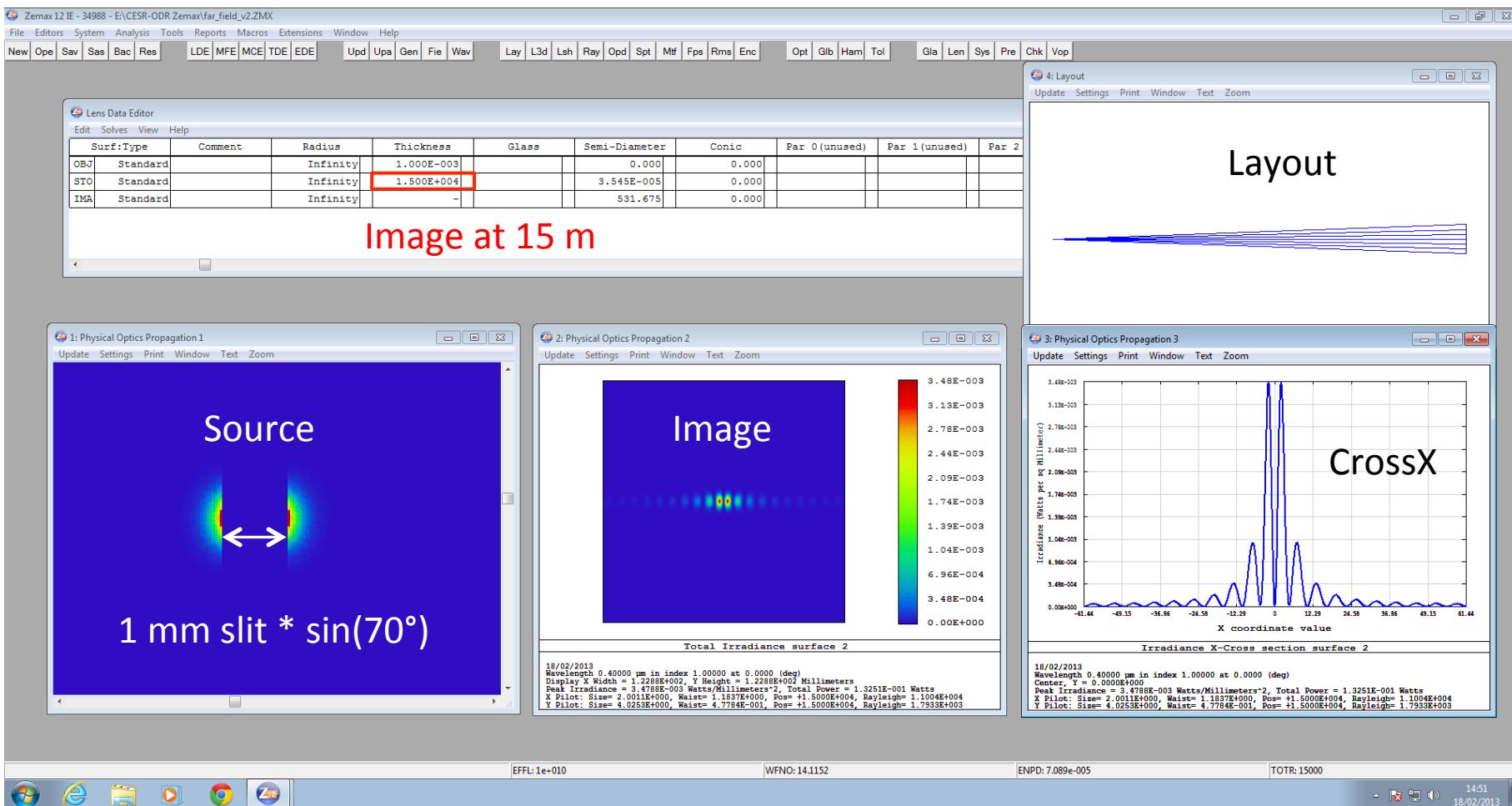


Comparison of the theoretical ODR angular distribution in far-field condition with the Zemax simulation.



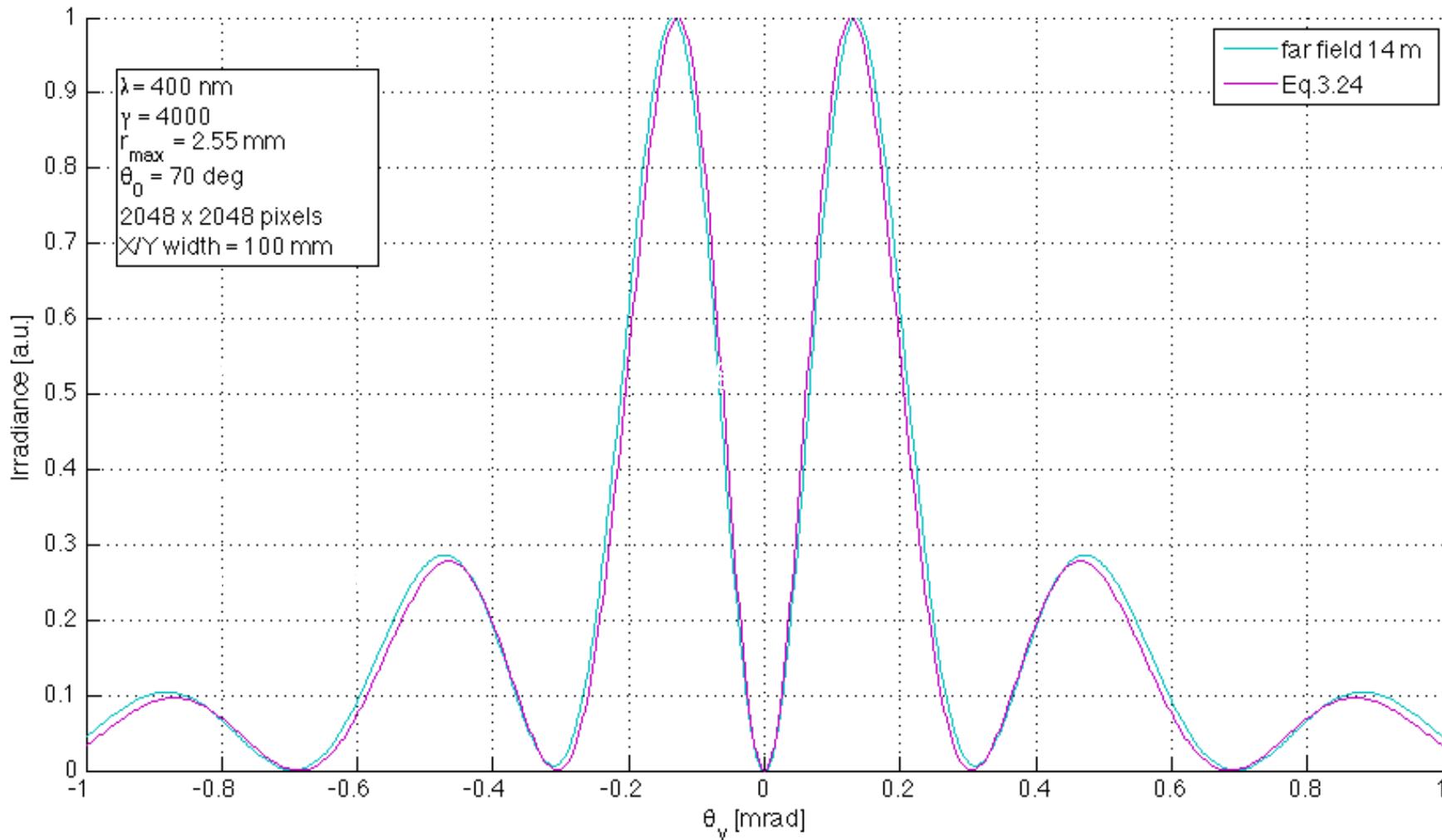
Zemax simulation of the ODR angular distribution for different distances from the source (300 μ m slit).

ODR Simulations - Far Field

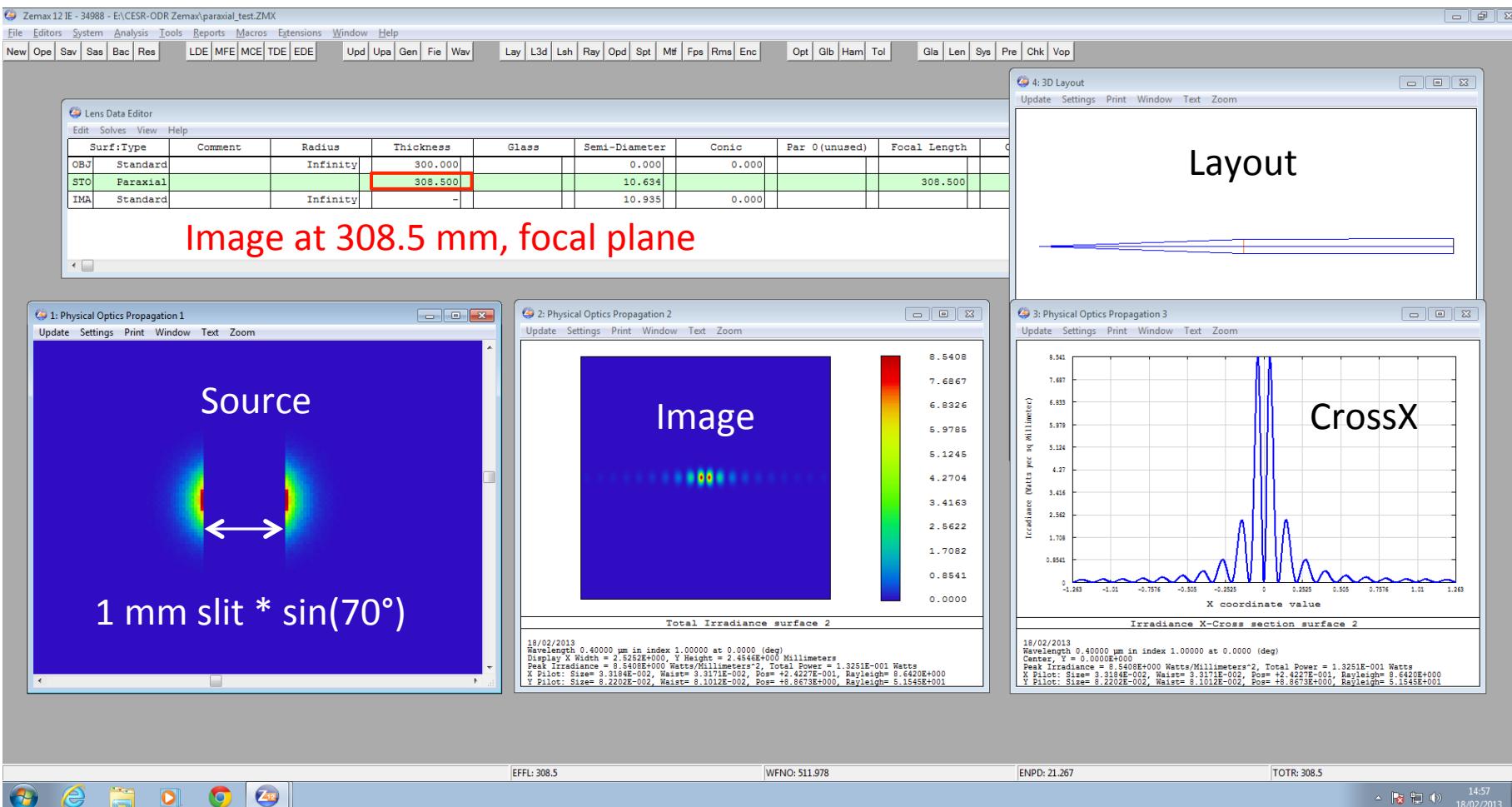


CrossX shows spatial distribution in [mm] at image plane, needs to be converted to angular distribution

ODR Simulations - Far Field: Zemax vs. Theory

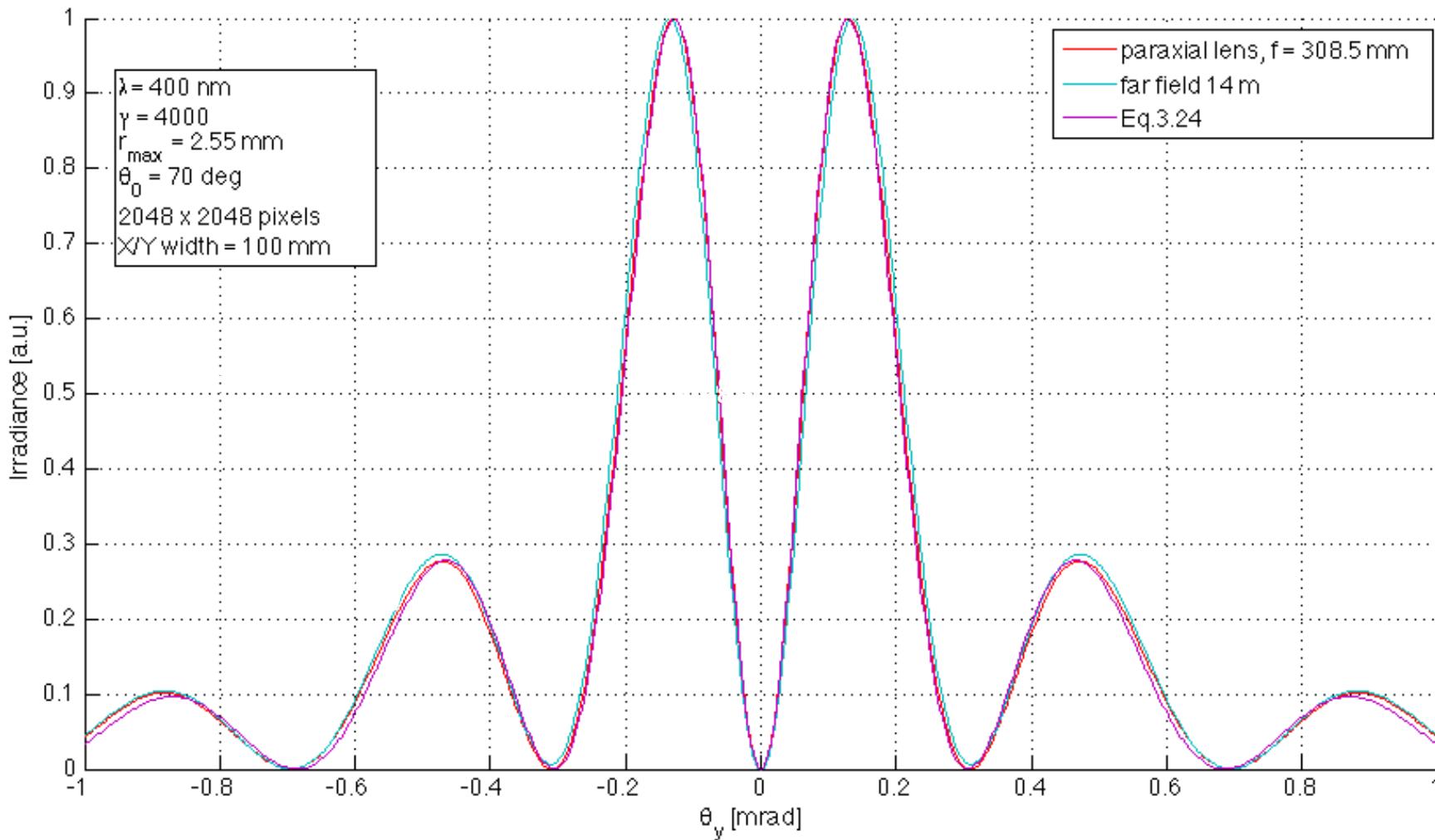


ODR Simulations – Paraxial Lens

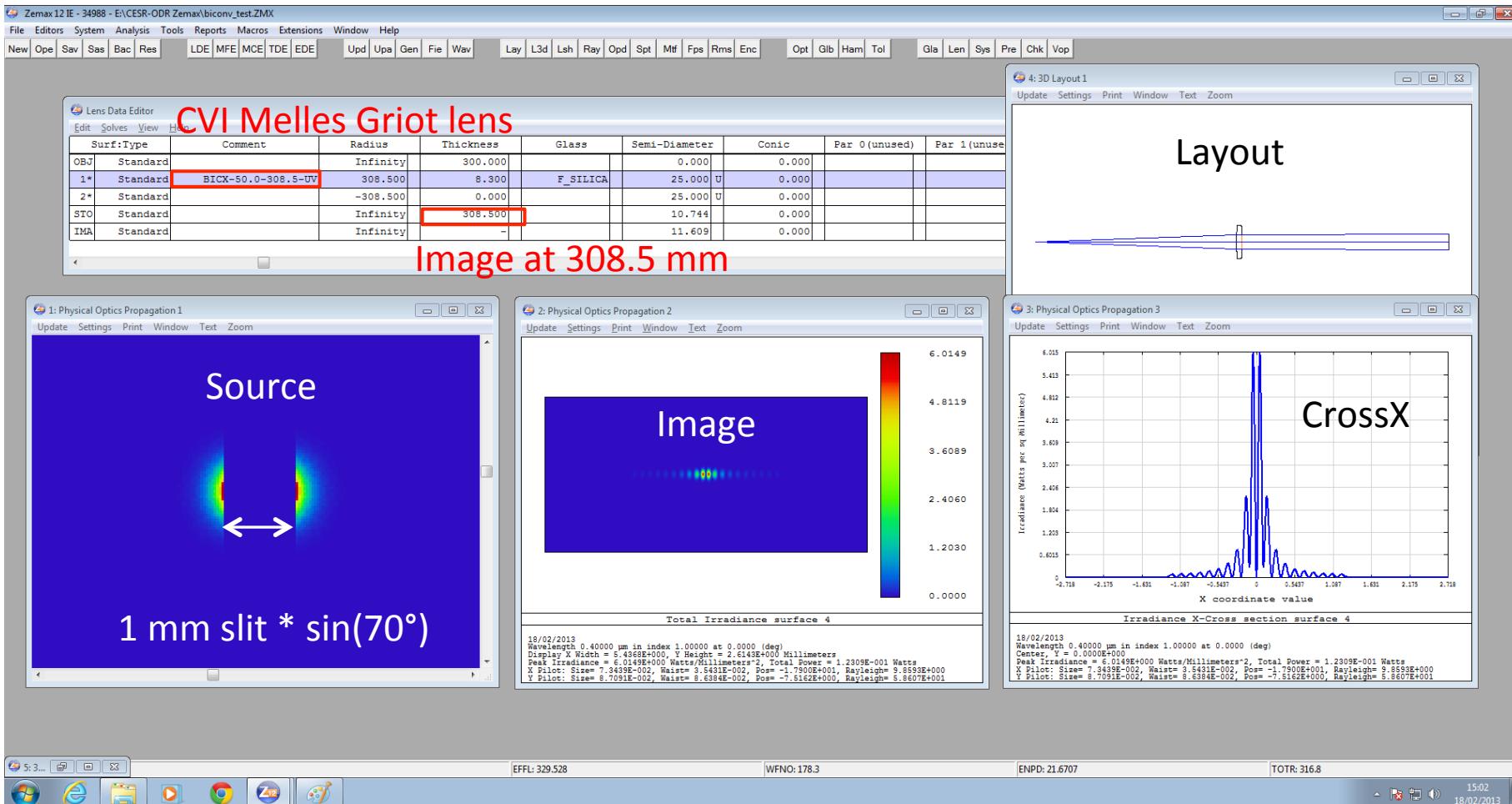


CrossX shows spatial distribution in [mm] at image plane, needs to be converted to angular distribution by $\theta = \arctan(X/308.5\text{mm})$

ODR Simulations – Paraxial Lens: Zemax vs. Theory

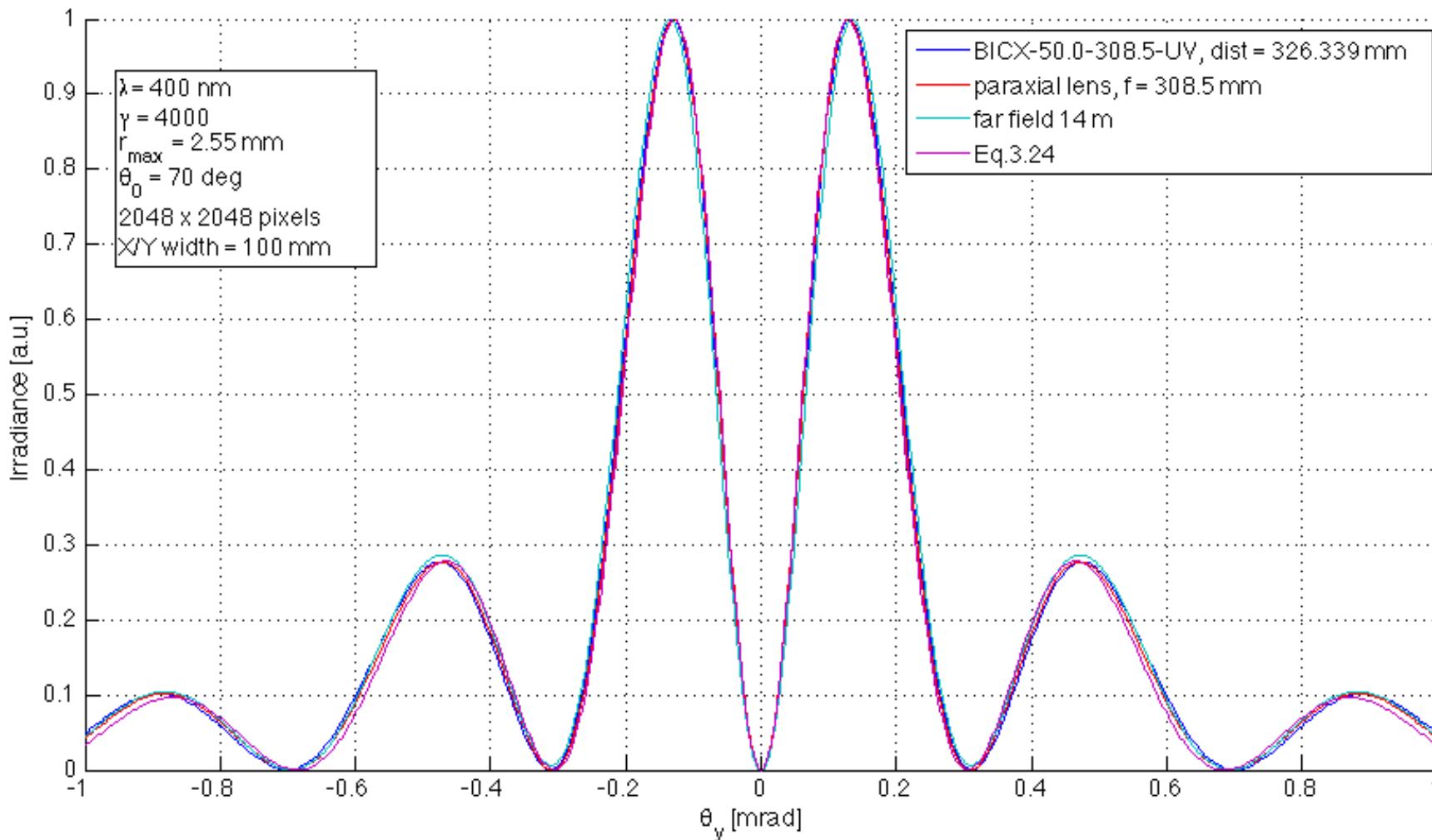


ODR Simulations – Biconvex Lens

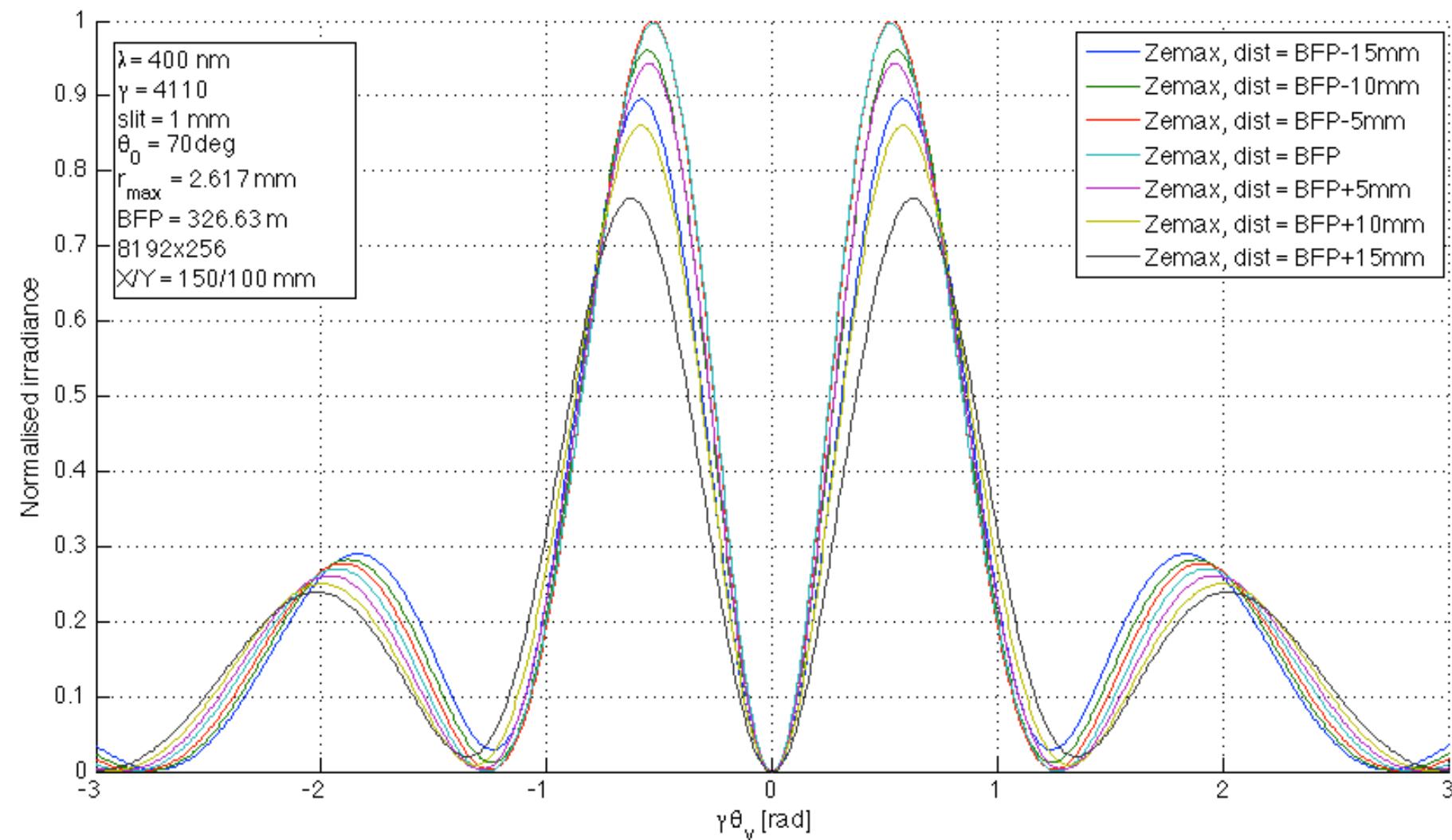


- ODR angular distribution is very sensitive to distances away from the focal plane. The detector must therefore be exactly in the back focal plane.
- Extensive lens and glass catalog

ODR Simulations – Biconvex Lens: Zemax vs. Theory

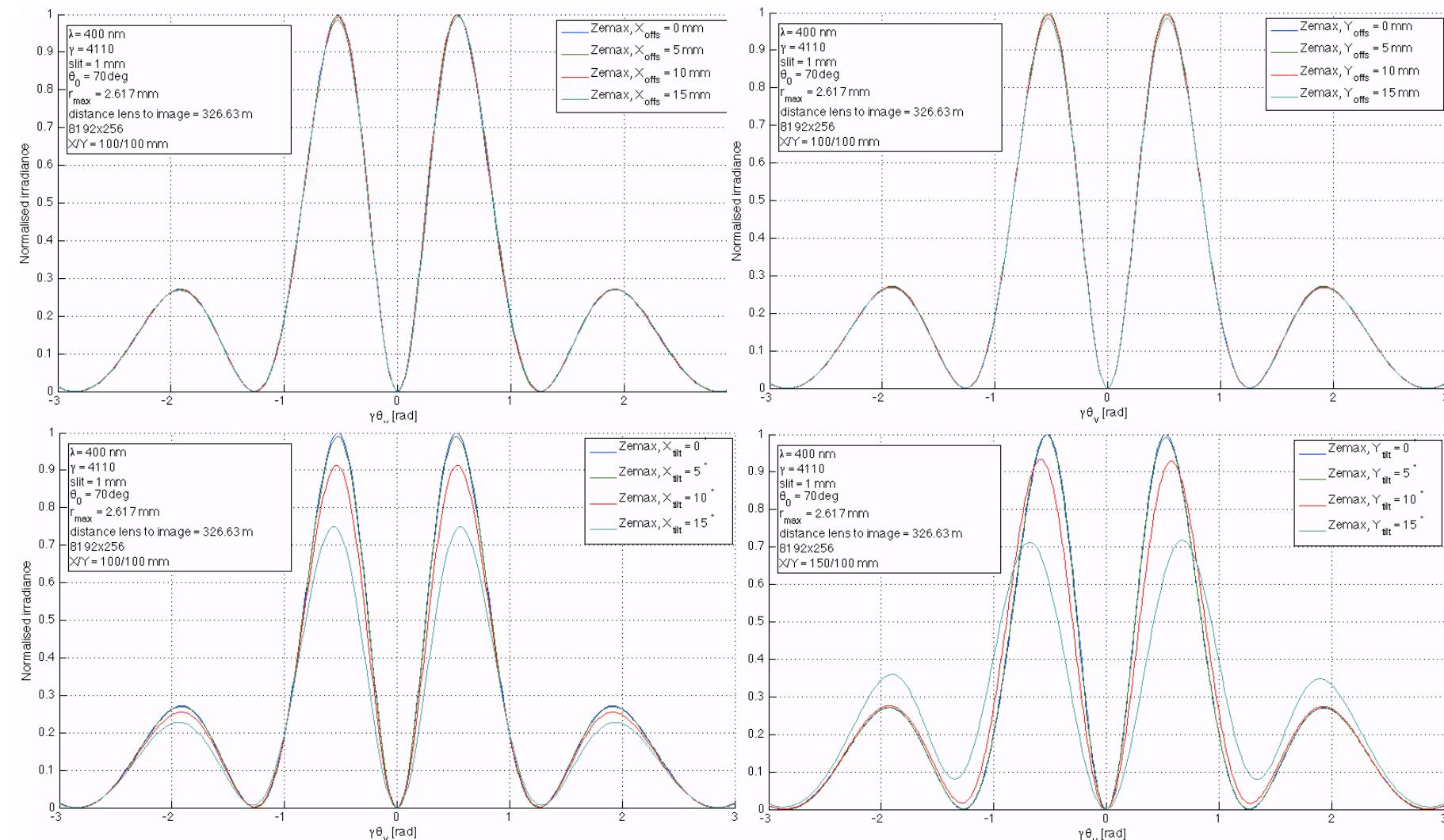


ODR Simulations – Biconvex Lens: Move Image Plane

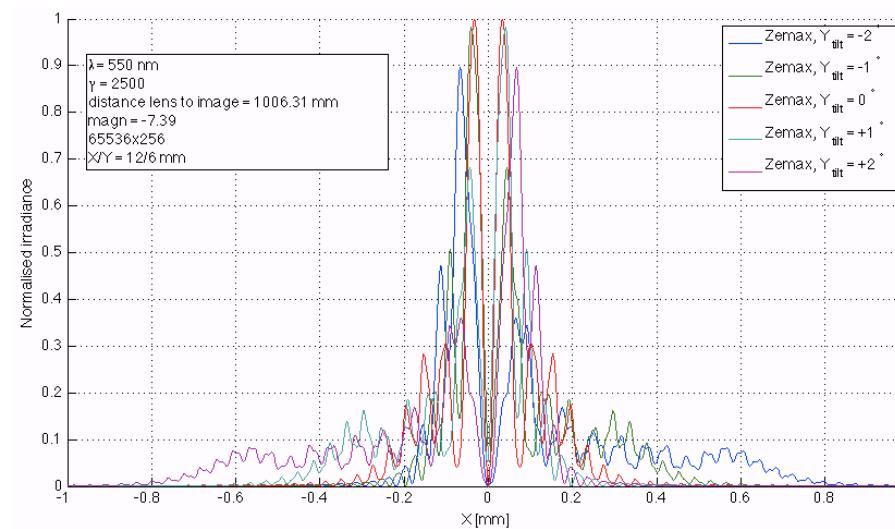
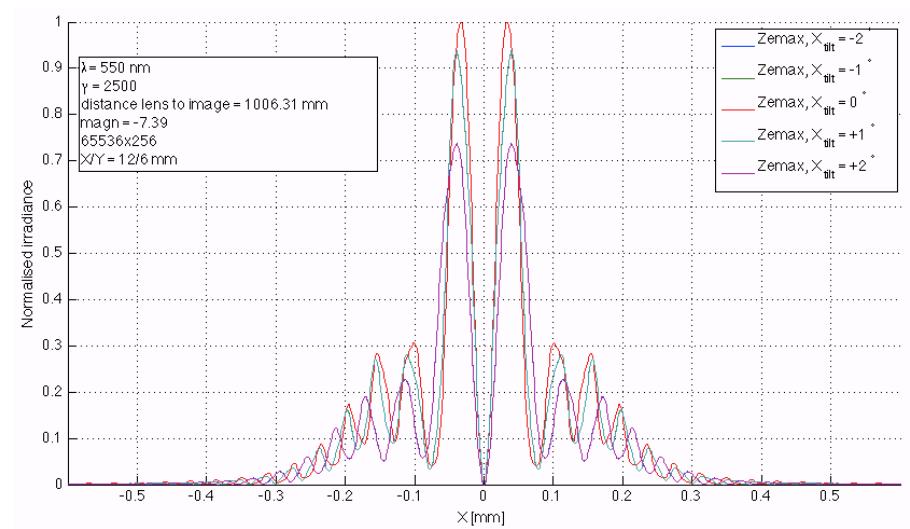
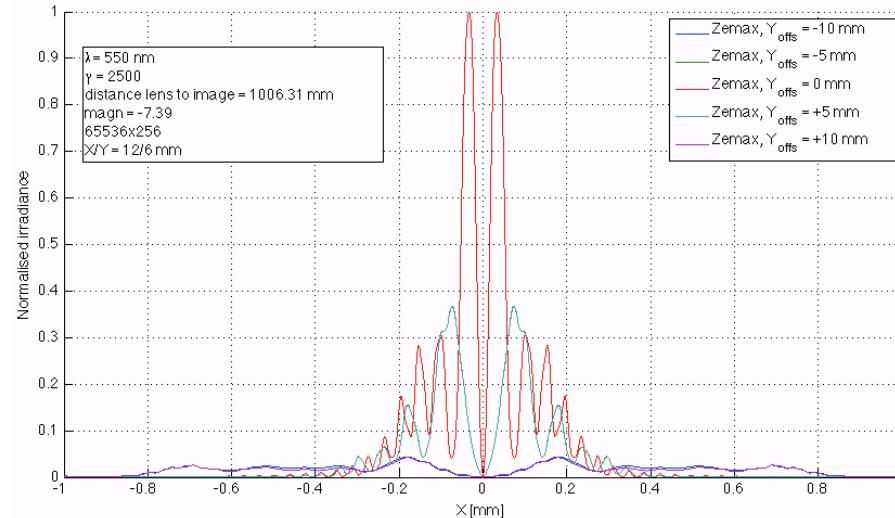
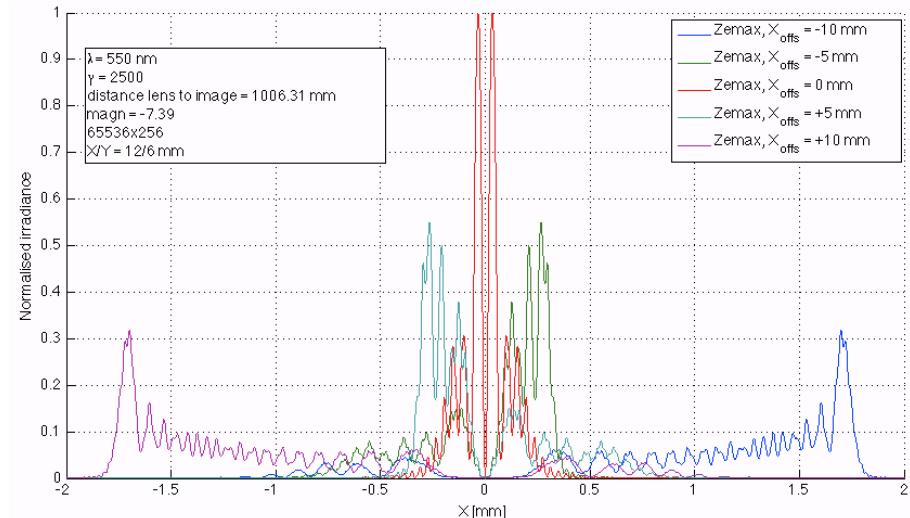


ODR angular distribution for various positions of the image plane (BFP is the position of the back focal plane).

ODR Simulations – Biconvex Lens: Move/Tilt Lens



OTR PSF Simulations – Achromat Lens: Move/Tilt Lens



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.
- Enable simulations of all misalignment errors and optimisation of a real optical system to be implemented in a real diagnostic station (viewports, polarisers, filters, etc.).