RESULTS OF THE HIGH RESOLUTION OTR MEASUREMENTS AT KEK AND COMPARISON WITH SIMULATIONS

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Abstract

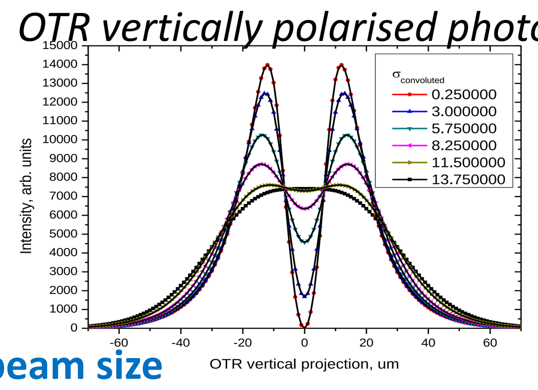
Optical Transition Radiation (OTR) is emitted when a charged particle crosses the interface between two media with different dielectric properties. It has become a standard tool for beam imaging and transverse beam size measurements. At the KEK Accelerator Test Facility 2 (ATF2), OTR is used at the beginning of the final focus system to measure micrometre beam size using the visibility of the OTR Point Spread Function (PSF). In order to study in detail the PSF and improve the resolution of the monitor, a novel simulation tool has been developed. Based on the physical optic propagation mode of ZEMAX, the propagation of the OTR electric field can be simulated very precisely up to the image plane, taking into account aberrations and diffraction. This contribution presents the comparison between Zemax simulations and measurements performed at ATF2.

Introduction

Challenge of the OTR system at ATF2: Measurements of sub-µm beam size

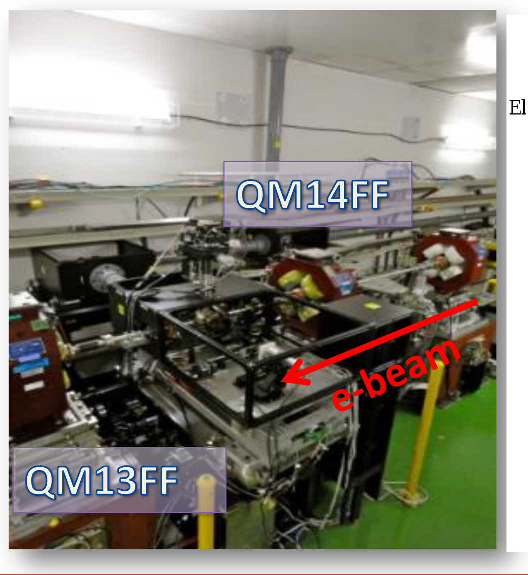
- ✓ The resolution (PSF) is determined by the source dimensions induced by a single particle plus distortion caused by the optical system (diffraction of OTR tails)
- ✓ If we consider a physical beam size, the resulting image on the camera is the convolution of the beam spatial distribution with the optical system PSF

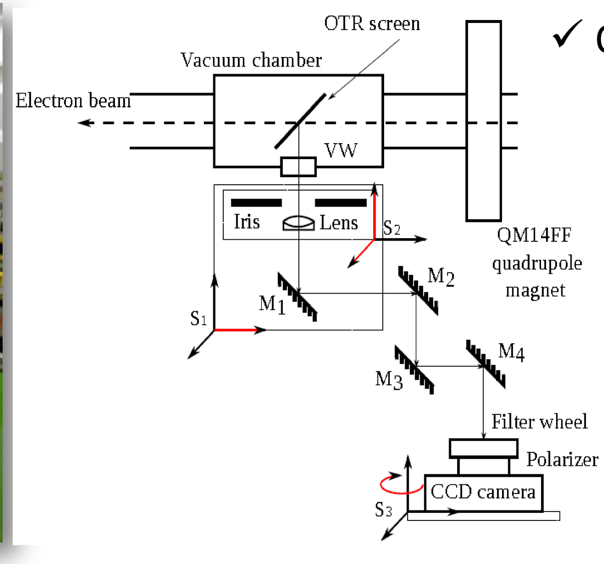
OTR vertically polarised photons



- ➢ **To visualize the beam, PSF has to be smaller than the beam size**
  - ➔ **Reduction of optical errors (aberration, diffraction, depth of field, misalignment…)**
  - ➔ **New software tool under development for a realistic simulation of the OTR PSF and for resolution improvement of the existing system (propose solutions for beam size<300nm)**

Overview of the OTR system at ATF2





- ✓ OTR system composed of:
  - ➢ An OTR target (Silicon, coated Al)
  - ➢ A motorized iris upstream of the lens
  - ➢ A lens with 3D adjustment and a periscope of mirrors
  - ➢ A filter wheel (chromatic aberration)
  - ➢ A vertical polarizer (σ_x>>σ_y) and a CCD camera mounted on a remotely controlled rotation stage
  - ➢ A special alignment laser system

SIMULATION TOOL

Design specifications for PSF simulation

- ✓ ***Exact description of the source***, i.e. OTR field emitted by a single particle (e.g. significant contribution to the PSF of the large OTR tails through a narrow aperture due to diffraction)
- ✓ **Vertical polarization component:** Since the typical beam size in ATF2 has a flat shape with much larger horizontal beam size (~100µm) than the vertical one (~few µm), the only way to measure such small size is to measure the visibility of the PSF of vertically polarised photons
  - ➔ Need to simulate the PSF for vertical polarization component
- ✓ ***Near field conditions:*** For radiation from relativistic particles, the optical elements are located in most cases at distances from the source so that near field conditions must be considered (a<< $\lambda\gamma^2$ with a: distance source-lens; λ: radiation wavelength; γ: charged particle Lorentz factor)
- ✓ **Accurate reproduction of errors:** Diffraction, aberrations, misalignments, depth of field (from e.g. a 45° OTR screen) with realistic optical elements

Simulation of the OTR PSF using Zemax

- ✓ ***Zemax:*** Widely used optical and illumination design software for standard sequential ray tracing through optical elements, non-sequential ray tracing and physical optics propagation (POP)
- ✓ **Ray tracing with Zemax:** Calculation of the PSF in the focus using Fraunhofer diffraction (far field conditions), angular distribution of the OTR source possible but the source is a single point
- ✓ **POP with Zemax:** Propagation, using diffraction laws, of the wavefront of any light source through arbitrary and realistic optical lines (e.g. commercial lenses), taken into account all optical errors
- ✓ **OTR electric field as input to the POP mode of Zemax:** Vertical (E_y) polarization component induced by a single electron on a target surface

$$E_y = const\,\frac{y}{\sqrt{x^2+y^2}}\left[\frac{2\pi}{\gamma\lambda}K_1\left(\frac{2\pi}{\gamma\lambda}\sqrt{x^2+y^2}\right)-\frac{J_0\left(\frac{2\pi}{\lambda}\sqrt{x^2+y^2}\right)}{\sqrt{x^2+y^2}}\right]$$

EXPERIMENT AND SIMULATION

Improved experimental set-up for a "single-lens" system to decrease aberrations

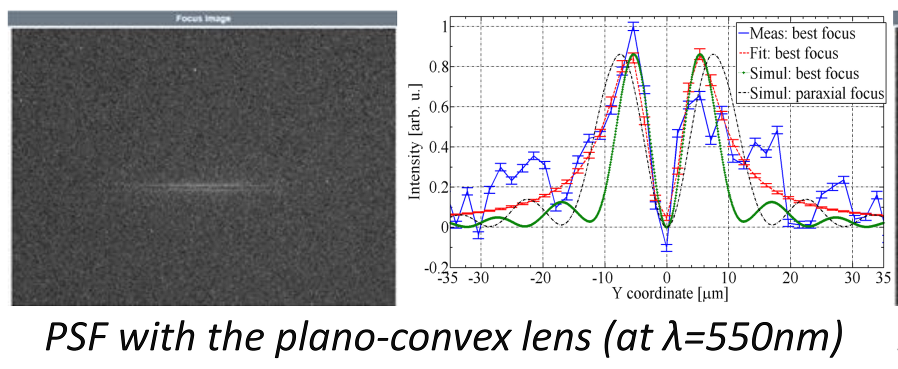
- ✓ **Accurate lens alignment** (mounted now on a motorized XY translation stage): From simulations, a lens misalignment from ±2mm make the PSF size increase and an asymmetry of the two lobes
- ✓ **Optimization of lens diameter:** From simulations, the diameter of the lenses, initially 50.8mm, has been decreased down to 30mm to minimize aberrations without adding diffraction
- ✓ **Optimization of the type of lens:** Comparison between a plano-convex lens (SLB-30-100-PY2 from Sigma-Koki with FL=100mm) and an achromat doublet lens (DLB-30-120-PM from Sigma-Koki with FL=120mm) since this last one should give less aberrations according to simulations

Best focus

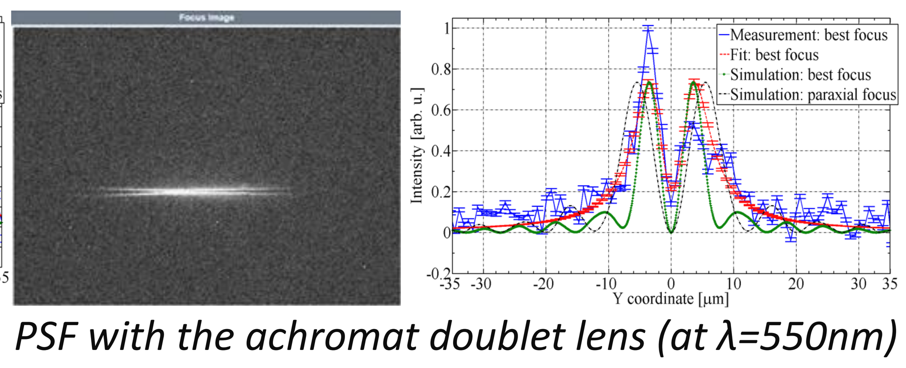
- ✓ **Experimentally:** Minimization of the distance between the two peaks of the OTR main lobes **(**Lens moved longitudinally by step of 100µm thanks to a stepping motor)
- ✓ **In simulations:** Lens moved around the paraxial focus of the lens in order to find a magnification (distance between the two peaks) similar to what is measured experimentally at best focus

(Distance OTR-target-lens and lens-CCD camera can only be measured within few mm accuracy)

- ✓ **Plano-convex:** Shifted by *200µm* from paraxial focus to be at best focus (PSF decreases by *28%*)
- ✓ **Achromat:** Shifted by *150 µm* from paraxial focus to be at best focus (PSF decreases by *35%*)



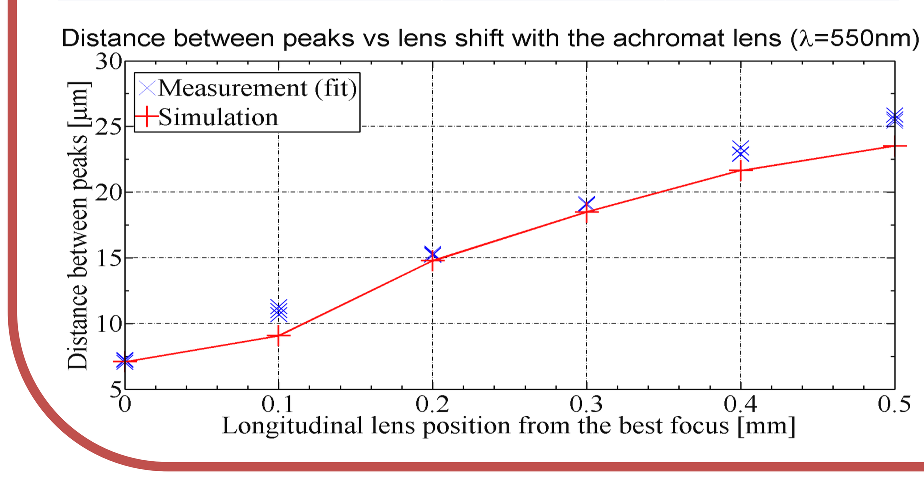
PSF with the plano-convex lens (at λ=550nm)

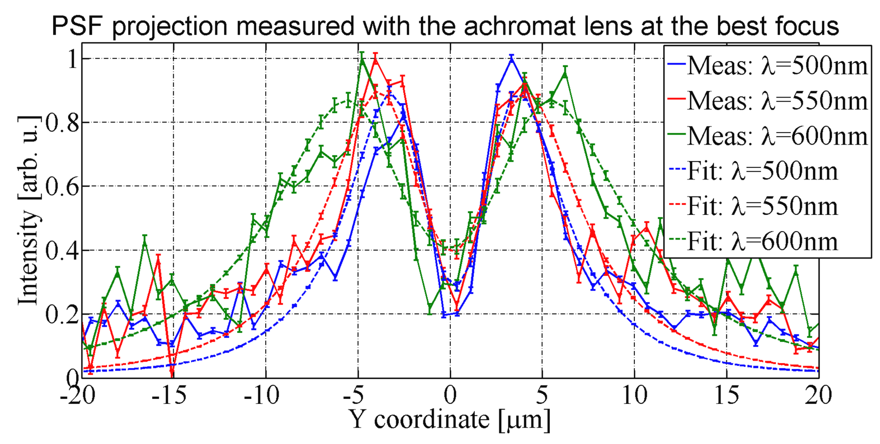


PSF with the achromat doublet lens (at λ=550nm)

Distance between peaks for λ=550nm	Plano-convex	Achromat doublet
Paraxial focus	15.1 µm	10.9 µm
Best focus	10.8 µm	7.1 µm

Filters	Measurements	Simulations
500 nm	6.34±0.10 µm	5.74 µm
550 nm	7.06±0.19 µm	7.14 µm
600 nm	9.89±0.26 µm	8.65 µm

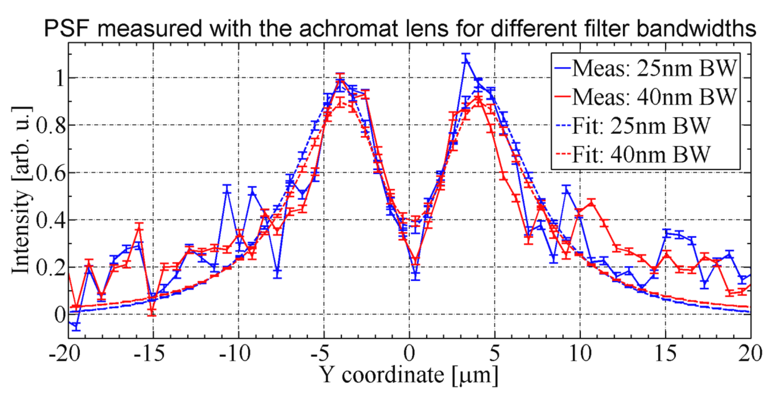


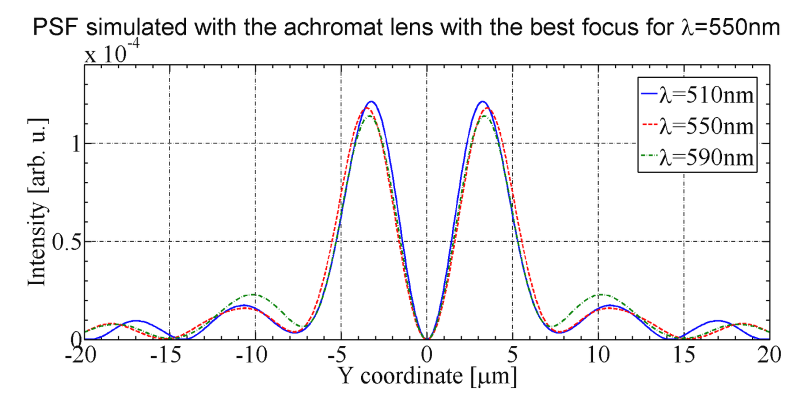


Test procedure for the two types of lenses (with similar beam charge)

- ✓ **Best focus:** Adjusting the longitudinal position of the lens
- ✓ **Vertically polarized photons:** Rotating the polarizer
- ✓ **Misalignment minimisation:** Adjusting the vertical height of the lens
- ✓ **Smallest beam size:** Adjusting the quadrupole strength
- ✓ **PSF minimization:** Changing the diameter of the iris located just upstream the lens
- ✓ **Studying chromatic effects:** With 550nm filters of 40nm and 25nm bandwidth
- ✓ **Measuring how the PSF changes for different wavelengths:** With 500, 550 and 600 nm filters

Chromatic aberration

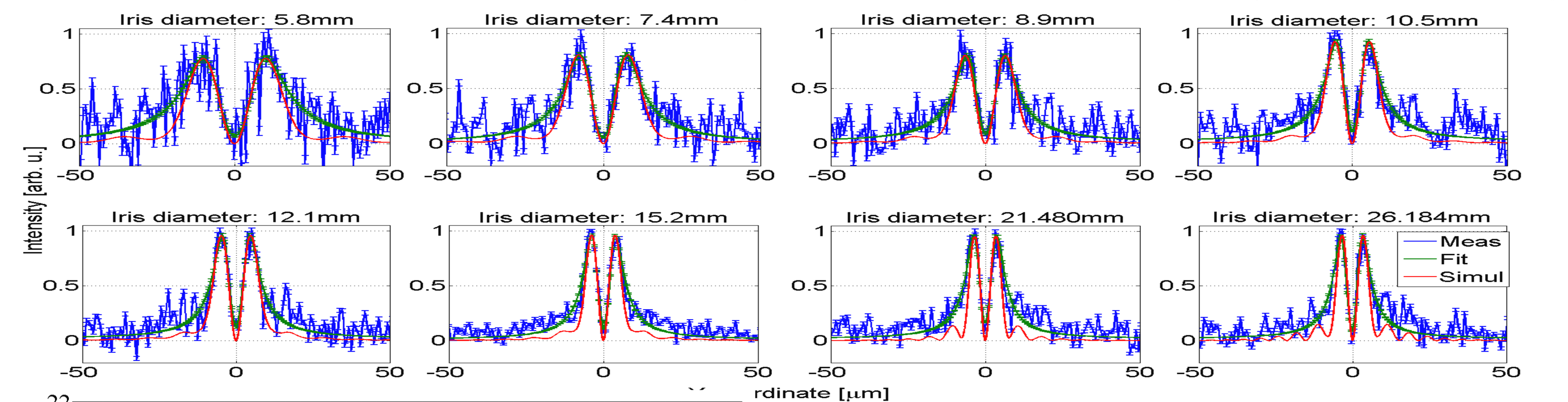


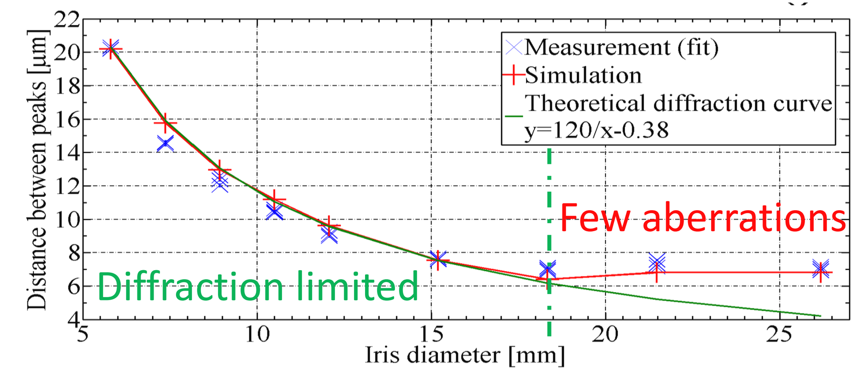


- ➢ Using narrower bandpass filters do not improve the resolution but only decreases light intensity
- ➢ Chromatic aberrations are thus not considered to be a limitation to the actual monitor resolution

Iris scan: Study the contribution of aberration and diffraction on the PSF

- ✓ An iris has been inserted at one centimetre upstream the achromat lens (study with 550nm filter)





Following this optimization to provide the smallest PSF, the system was used to measure vertical beam size using the visibility of the PSF (see the proceeding: K. Kruchinin et al., Proc. IBIC, Oxford, UK, 2013)

Conclusion

We developed simulation tools to calculate the OTR Point Spread Function using the physical optics propagation mode of ZEMAX. The code gives very accurate predictions that were compared with measurements taken at the ATF2 facility and allowed the design of an improved optical system with one of the best resolution achieved so far in beam imaging system. As future developments, we will use the code to study a possible design for beam size measurements below 300nm. The code will be improved to take into account realistic conditions that will include the key beam characteristics such as transverse dimensions, divergence and energy spread.

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