Optical Effects in High Resolution and High Dynamic Range Beam Imaging Systems

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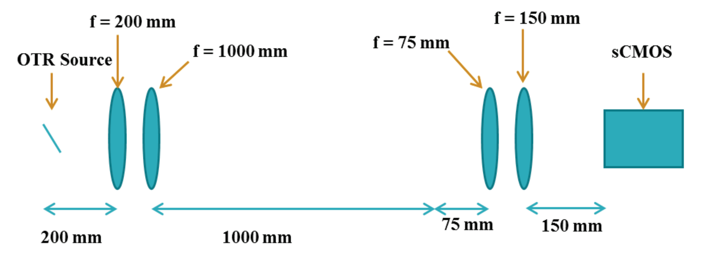
Abstract

Optical systems are used to transfer light in beam diagnostics for a variety of imaging applications. The effect of the point spread function (PSF) of these optical systems on the resulting measurements is often approximated or misunderstood. It is imperative that the optical PSF is independently characterised, as this can severely impede the attainable resolution of a diagnostic measurement. A high quality laser and specially chosen optics have been used to generate an intense optical point source in order to accomplish such a characterisation. The point source was used to measure the PSFs of various electron-beam imaging systems. These systems incorporate a digital micro-mirror array, which was used to produce very high (>10^5) dynamic range images. The PSF was measured at each intermediary image plane of the optical system; enabling the origin of any perturbations to the PSF to be isolated and potentially mitigated. One of the characterised systems has been used for optical transition radiation (OTR) measurements of an electron beam at KEK-ATF2 (Tsukuba, Japan). This provided an application of this process to actively improve the resolution of the beam imaging system. Presented here are the results of our measurements and complementary simulations carried out using Zemax Optical Studio.

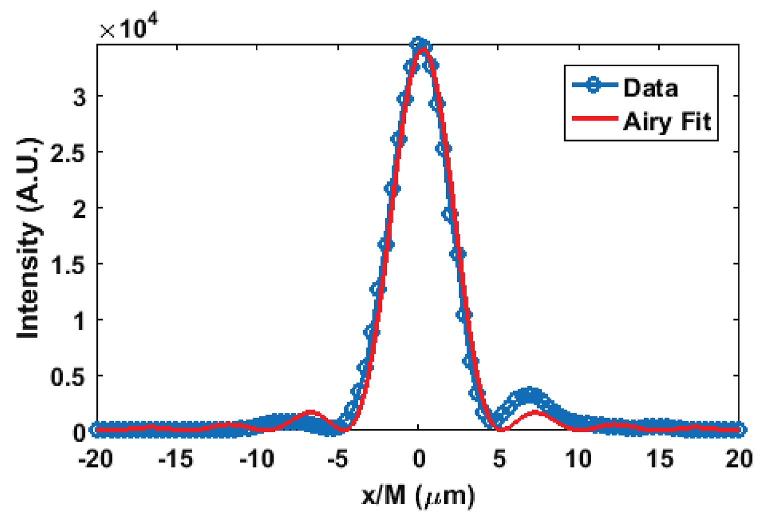
PSF Measurements

After an investigation into the PSF of an OTR imaging system currently in use [3], an achromatic imaging system with comparable performance was designed. A schematic of this system can be seen below. The PSF of a similar system was measured following the technique outlined in [1].

This system differed from the final system as the third lens was changed. This changed the magnification of the optics from 25 to 10 to increase the intensity of the measured OTR signal.



Schematic of the OTR imaging system

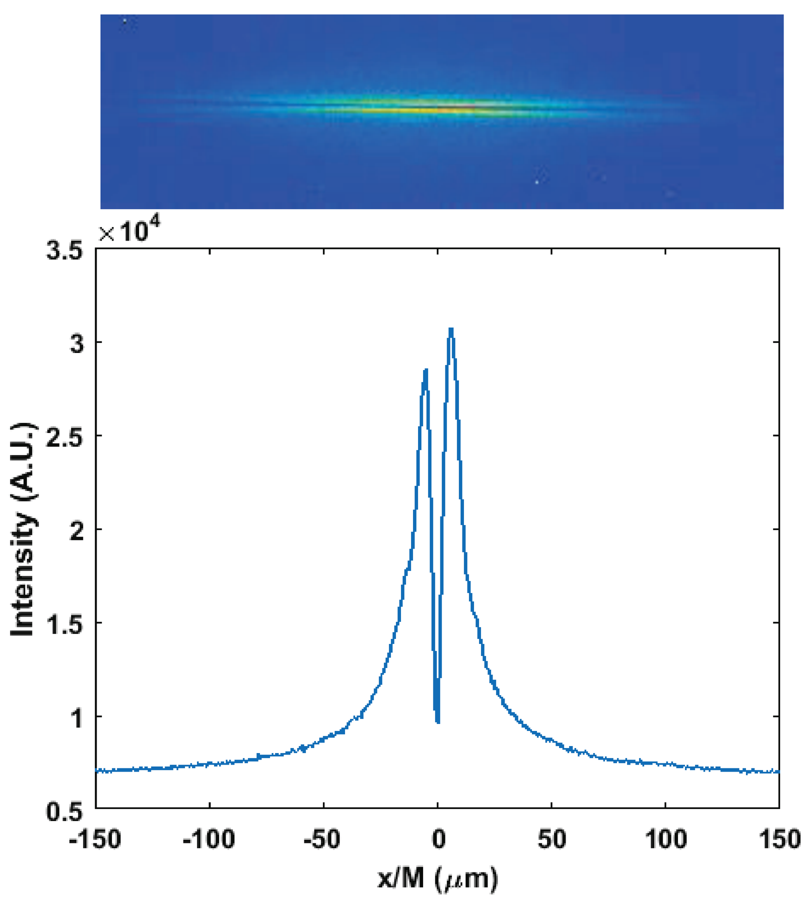


PSF of the OTR imaging system

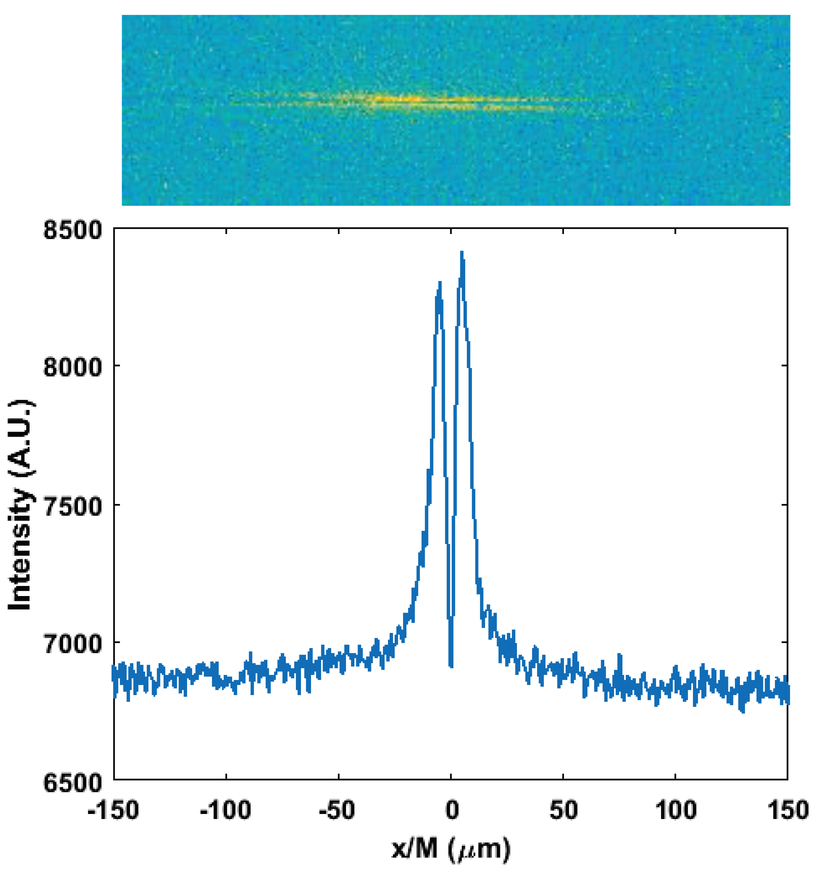
The PSF of a system is dominated by the first aperture of the system, the substitution of the third lens for another similar lens would have had a negligible impact on the PSF. This design provided a means of investigating the effect of bandpass on the OTR distribution, as images could be taken without the use of interference filters.

OTR Measurements

The measurements were carried out at the ATF2 facility at KEK, Japan. The ability to focus an electron beam down to the micron level made this facility ideal for this type of beam size study. The first measurements were carried out using no interference filter to assess the chromatic performance of the optics. This also provided a baseline signal to noise (S/N) measurement, to which the measurements using an interference filter could be compared. The OTR signal measured from a single-shot is presented to the right. Below this is the vertical projection of the image integrated over 70 pixels. The analysis method used is detailed in [2].



OTR image with no interference filter (above); Vertical projection of image over 70 pixels (below)

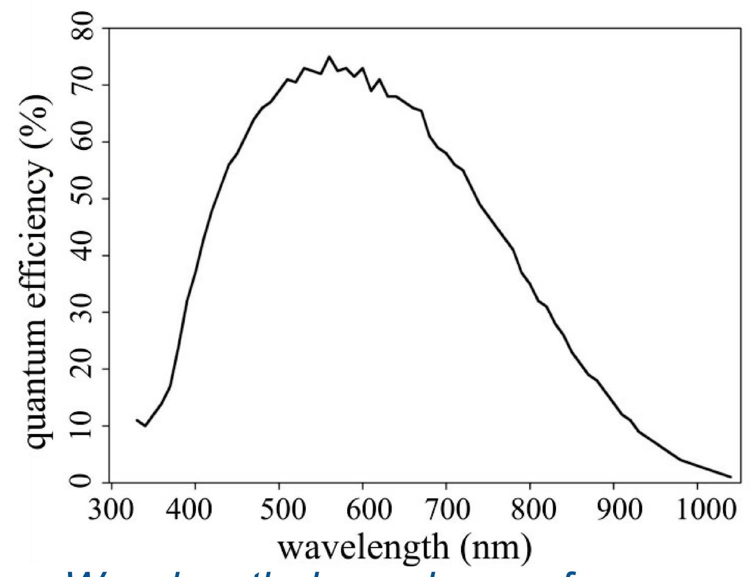


OTR image with 650(40) nm interference filter (above); Vertical projection of image over 70 pixels (below)

The peak-to-peak distance of the OTR distribution is indicative of the resolution, and provides a means of direct comparison between different imaging methods. For this distribution this distance is (10.5 ± 0.5) μm. The S/N ratio is 4.6. The measurement process was then repeated for a 650 nm filter with a 40 nm bandpass, which can be seen to the left. The peak-to-peak distance of this profile is (10.0 ± 0.5) μm, which is comparable to the unfiltered result. The S/N ratio is 1.2, which is a factor of 3.8 less than the unfiltered result. The beam size calculated from these results [2] show that the unfiltered result, (2.0 ± 0.5) μm, was double that of the filtered result, (1.0 ± 0.5) μm.

Bandpass Convolution Analysis

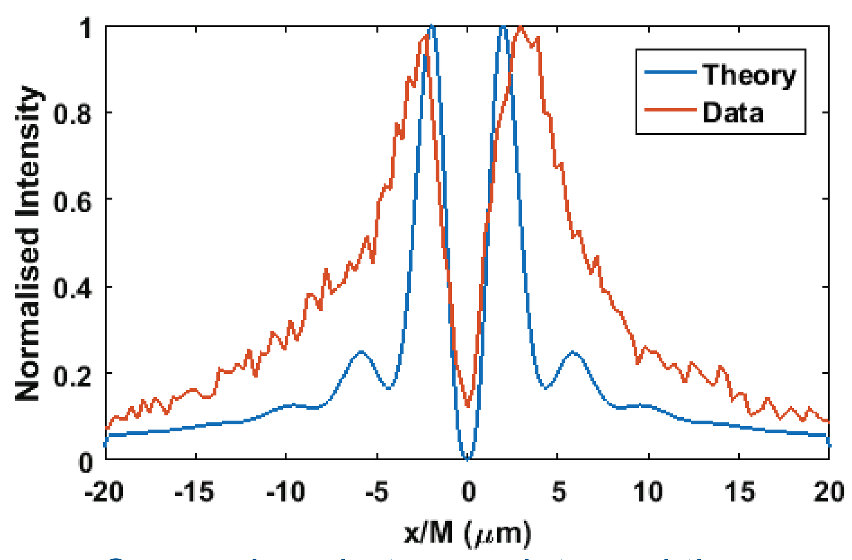
The beam size results point to an optimum bandpass value, which would provide an improved S/N ratio whilst maintaining the resolution of the measurement. OTR contains an inherent dependence on wavelength. The OTR distribution of a single electron [3] was spatially convolved with a Gaussian (σ = 1 μm). This simulated what could be theoretically expected from a 1 μm electron beam with no other effects taken into account. The distribution was then convolved with various distributions in the wavelength domain. This simulated the effect of an interference filter.



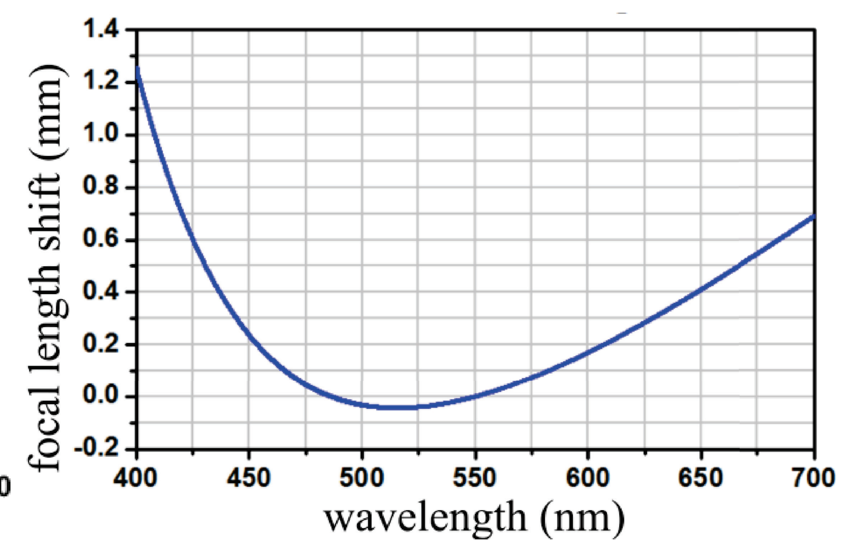
Wavelength dependence of camera performance [4]

Analysis is still underway, but initial results show that a change from 40 nm to 100 nm in bandpass has a minimal effect on the resulting distribution. If analysis continues to show this effect, it would be possible to conclude from these results that the OTR source distribution is not the limiting factor on bandpass choice for an OTR imaging system. However, other limitations include the wavelength dependent response of the camera used, presented left [4].

By convolving this distribution with the theoretically calculated distribution, a comparison with the unfiltered data could be made. This comparison is presented below left. It is clear that there is an unaccounted effect which is limiting the resolution of the measurement. The only effect not being accounted for is the chromatic aberrations of the optics. The optics are achromatic, but they still have a wavelength dependence. An example wavelength dependence for the lenses in the setup is shown below right [5]. For a large bandpass the optics will introduce a defocussing effect. This will fill in the central minimum and limit the resolution of the measurement.



Comparison between data and theory



Wavelength dependence of lenses [5]

Conclusions

Results:
- Achieved equivalent resolution to previous measurements [1], with achromatic system.
- Began to isolate cause of loss of resolution in unfiltered OTR imaging.

Plans:
- Optimise chromatic aberrations of the imaging system and repeat OTR measurements.
- Increase the resolution further by using PSF measurements [3].
- Systematic background analysis to improve S/N ratio further.
- Repeat convolution analysis for optical diffraction radiation.

References

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