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.

INTRODUCTION

The impact the PSF of an optical system has on a measurement is often ignored as it is usually not the main limiting factor on resolution. When making high resolution measurements this is not true. Any uncertainty can result in a restriction in the precision of the measurement. The imaging systems in use at recent OTR and ODR studies [1, 2, 3] are an example of such a case. The distribution of PSFs usually takes the form of an Airy disc, with the resolution determined by the width. OTR from a single electron is distinct, in that it contains a zero valued central minimum [4]. The detailed shape of the distribution provides a greater effective resolution than its width [1, 2]. The image of OTR from an electron distribution, with a width comparable to the FWHM of the single electron distribution, displays a central minimum but with a finite non-zero value [1, 2]. This convolution with the transverse profile of an electron beam provides a previously unattainable level of resolution on beam size measurements. In practise however the beam size is not the sole contributor to intensity increase found in the centre of the distribution. There are many other effects, all of which restrict the attainable resolution. A prominent example is the PSF of the optical system used to image the OTR. The diffraction and aberration effects of this PSF will broaden the OTR PSF and degrade the resolution of beam size measurements. If the performance of the optics could be independently assessed, then it would be possible to minimise the impact of the optical PSF on the measured OTR profiles. Another limiting factor is the overall intensity of the OTR. For small beam sizes the sensitivity in the centre can be masked by noise and background [1, 2]. If the intensity of the signal could be increased this central value would be lifted away from the background, the rms noise would become statistically less significant, and smaller beam size measurements could be achieved. This intensity increase would also make future studies into high dynamic range (HDR) OTR imaging possible, as this technique currently relies on high signal levels and masking using a digital micro-mirror array (DMD) [5]. It follows that if the low intensity details of the OTR distribution were measured with HDR, this would further increase the resolution of the beam diagnostic measurements utilising OTR. The effect of the DMD on the optical PSF has been investigated previously [3], but the impact on OTR measurements is still to be assessed.

OPTICAL SYSTEM

PSF Measurements

After an investigation into the PSF of an OTR imaging system currently in use [3], an achromatic imaging system with comparable performance has been designed. Figure 1 shows a schematic of this system. The PSF of a similar system was measured following the technique outlined in [3]. This system differed from system in Fig. 1 in that the focal length of the third lens was changed. This was to change the overall magnification of the system from 25 to 10, as this improved the intensity of the OTR signal measured.

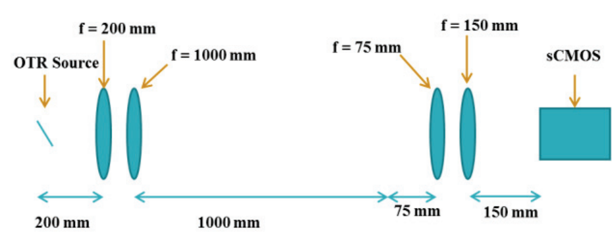

Figure 1: Schematic of OTR imaging system.

As the PSF of an optical 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. The PSF measured is shown in Fig. 2.

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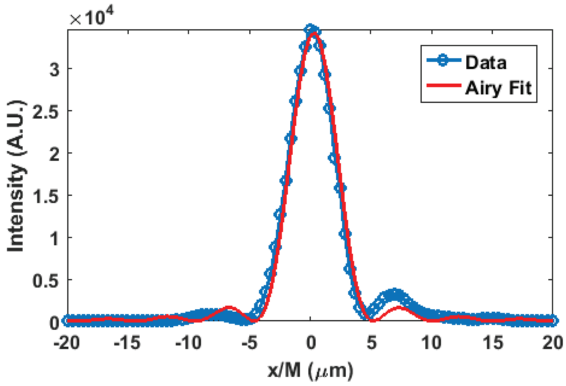

Figure 2: PSF of the OTR imaging system.

The distributions central peak follows that of an Airy distribution. There are slight deviations in the higher order peaks; this may have been caused by aberrations or misalignments, which will be studied further using Zemax [6]. Achromatic lenses provide a more consistent performance with varying wavelengths and, in certain setups, can provide an improved resolution, when compared to a simple singlet lens. It was for these reasons that an achromatic system was implemented. As the lenses are designed to perform best in an infinite conjugate setup [7], the optics were arranged in two confocal pairs. This design also 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

OTR Imaging with No Interference Filter

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 in Fig. 3. The transverse profile of the entire beam can be seen. The horizontal size could be acquired here by simply fitting a Gaussian to a horizontal projection of this image. However, the small size in the vertical axis is masked by the OTR distribution as expected.

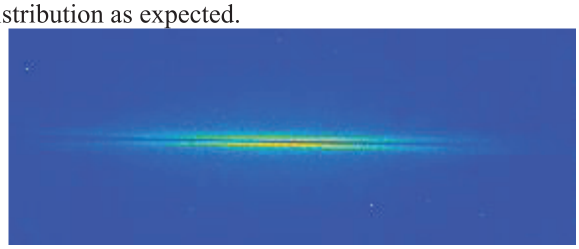

Figure 3: Single-shot OTR with no interference filter.

The vertical projection of Fig. 3 is presented in Fig. 4. The signal has been integrated over 70 pixels across the centre of the image. The window of integration was calculated as described in [1]. Figure 4 has been magnification corrected to provide an OTR source distribution. 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.

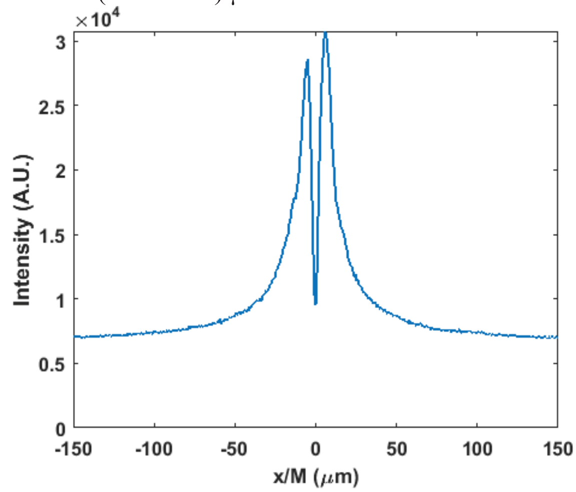

Figure 4: Vertical OTR profile, with a 70 pixel integration window, for unfiltered OTR.

OTR Imaging with an Interference Filter

The measurement process was then repeated for several different interference filters. The best results were found for 650 nm with a 40 nm bandpass, the result of which is displayed in Fig. 5.

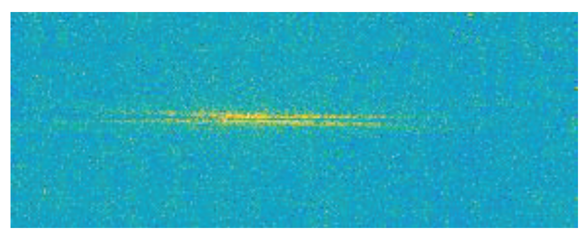

Figure 5: Single-shot OTR with 650(40) nm interference filter.

An integration window of 70 pixels was again calculated using the method outlined in [1]. The resulting profile is presented in Fig. 6. 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.

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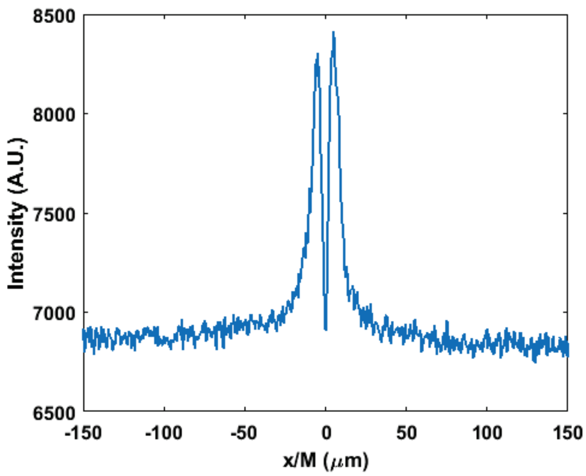

Figure 6: Vertical OTR profile, with a 70 pixel integration window, for filtered OTR.

Conclusions from OTR Measurements

A quadrupole scan was carried out with each setup and the resulting data was analysed as in [1]. This provided a beam size measurement of (1.0 ± 0.5) µm for the filtered light, and a beam size of (2.0 ± 0.5) µm for the unfiltered light. This shows that the lack of a filter causes unwanted intensity to leak into the central minimum and obscure the beam size. However, the S/N ratio found in the unfiltered results was nearly four times better than that of the filtered results. This result points to an optimum bandpass value, which would provide an improved S/N ratio whilst maintaining the resolution of the measurement.

BANDPASS CONVOLUTION STUDIES

The Effect of Bandpass on OTR

As OTR contains an inherent dependence on wavelength, the first step to finding an optimum bandpass must be to understand how a bandpass effects an OTR distribution. The OTR distribution from a single electron was calculated [4], then spatially convolved with a Gaussian with σ = 1 µm. This result 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 different size Gaussian distributions in the wavelength domain, at a fixed wavelength. This simulated the effect of an interference filter at various bandpasses. Analysis is still underway, but the initial results of these calculations shows that the change from a 40 nm bandpass to a 100 nm 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 the bandpass choice for and OTR imaging system.

Other Bandpass Limitations

Another limitation on the bandpass of an OTR imaging system is the wavelength dependence of the response of the camera used. The camera used in the OTR measurements was a pco.edge 4.2LT [8], the response of which is shown is Fig. 7.

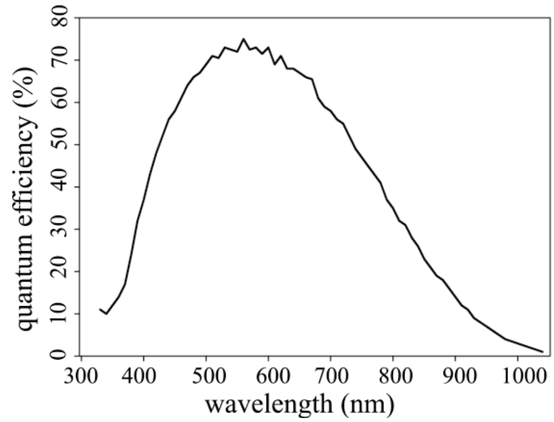

Figure 7: The dependency of quantum efficiency on wavelength of the pco.edge 4.2LT [8].

This wavelength dependence is itself a bandpass filter, and will have acted as such in the unfiltered OTR measurements. By convolving this distribution with the theoretically calculated distribution mentioned previously, a comparison with the unfiltered data can be made. This comparison is presented in Fig. 8.

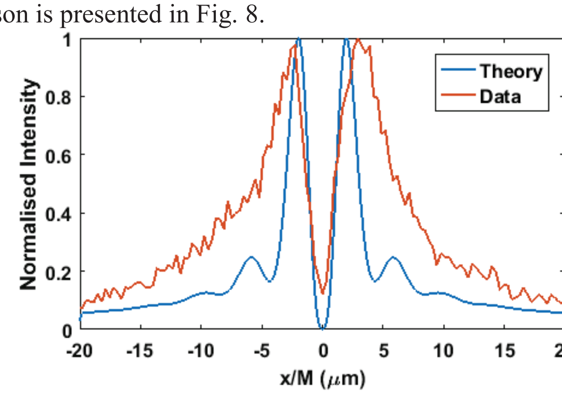

Figure 8: Comparison between the unfiltered OTR data, and the theoretically calculated distribution.

From Fig. 8 it is clear that there is an effect which is not being accounted for and is limiting the resolution of the measurement. The only other effect not being accounted for is the chromatic aberrations of the optics. Although the optics are achromatic, they still have a wavelength dependence. An example wavelength dependence for the type of lens used in the measurements is shown in Fig. 9.

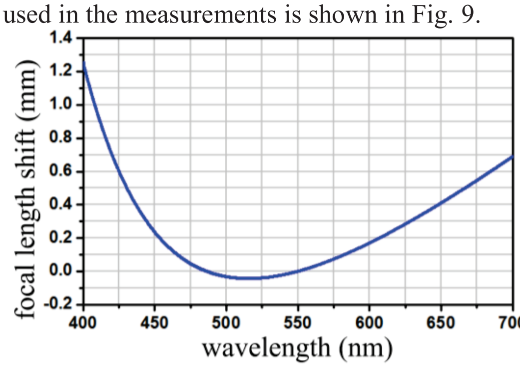

Figure 9: The wavelength dependence of a cemented achromatic doublet from Thorlabs [7].

It is clear from Fig. 9 that there is still a small wavelength dependency on focal length. This means that for a larger bandpass the optics will begin to introduce a defocussing effect to the OTR image. This will fill in the central minimum and ultimately limit the resolution of the beam size measurement.

CONCLUSION

The measurements taken at ATF2 have led to the conclusion that the defining limitations of this beam size monitoring technique are background light pollution and rms noise. This on-going analysis has begun to direct our attention towards a possible method of combatting these issues; thus improving the resolution of OTR imaging based diagnostics. By optimising the chromatic performance of the optics in the imaging system, a much larger bandpass filter could be used. This would improve the S/N ratio, hereby reducing the impact of rms noise and lifting the value at the centre of the distribution away from the DC background. The achromatic system tested at ATF2 provided a resolution comparable to that of previous measurements [1, 2]. By optimising this system there is potential to increase the resolution to beam size to the sub-micron level. The current plans for this study are to investigate methods of optimising the imaging system via the use of air-spaced doublets, triplets or cylindrical lenses. The next step would be to repeat the OTR measurements at ATF2 with the optimised system. If the sensitivity is indeed increased, then other effects will need to be taken into account. For example, the PSF of the imaging system could no longer be ignored. The effects of diffraction and geometrical aberrations would have to be filtered out of the measurements to improve the resolution further. Measurements to aid in this process have already begun [3]. A systematic analysis of background sources would also help to improve the S/N ratio further.

REFERENCES

[1] K. Kruchinin *et al.*, “Sub-micrometer transverse beam size diagnostics using optical transition radiation”, *Jour. of Phys. Conf. Series*, vol. 517, no. 1, p. 012011, May 2014.

[2] B. Bolzon *et al.*, “Very high resolution optical transition radiation imaging system: Comparison between simulation and experiment”, *Phys. Rev. ST Accel. Beams*, vol. 18, no. 8, p. 082803, Aug. 2015.

[3] J. Wolfenden *et al*., “High Resolution and Dynamic Range Characterisation of Beam Imaging Systems”, in *Proc. 7th Int. Particle Acc. Conf. (IPAC’16)*, Busan, Korea, May 2016, paper MOPMR045, pp. 354-356.

[4] D. Xiang *et al.*, “Theoretical considerations on imaging of micron size electron beam with optical transition radiation”, *Nucl. Instr. and Meth. in Phys. Res. A*, vol. 570, no. 3, p. 357-364, Jan. 2007.

[5] H. Zhang *et al.*, “Beam halo imaging with a digital optical mask”, *Phys. Rev. ST Accel. Beams*, vol. 15, no. 7, p. 072803, Jul. 2012.

[6] Zemax Optical Studio, optical design and simulation software, URL: http://www.zemax.com

[7] Thorlabs, optical research equipment retailer, URL: http://thorlabs.de

[8] PCO, camera manufacturer and retailer, URL: http://www.pco.de

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