

TRANSVERSE BEAM PROFILE DIAGNOSTICS USING POINT SPREAD FUNCTION DOMINATED IMAGING WITH DEDICATED DE-FOCUSING

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Abstract

Transverse beam profile diagnostics in electron accelerators is usually based on direct imaging of a beam spot via visible radiation (transition or synchrotron radiation). In this case the fundamental resolution limit is determined by radiation diffraction in the optical system. A method to achieve resolutions beyond the diffraction limit is to perform point spread function (PSF) dominated imaging, i.e. the recorded image is dominated by the resolution function of a point source (single electron), and with knowledge of the PSF the true image (beam spot) can be reconstructed. To overcome the limited dynamic range of PSF dominated imaging, a dedicated de-focusing of the optical system can be introduced. In order to verify the applicability of this method, a proof-of-principle experiment has been performed at the Mainz Microtron MAMI (University of Mainz, Germany) using optical transition radiation. Status and results of this experiment are presented.

INTRODUCTION

Next generation electron accelerators as the linear collider projects ILC or CLIC and electron beam driven plasma accelerators require electron beam spots in the order of $10\ \mu\text{m}$ down to sub-micrometer sizes. Besides the challenge to generate such small beam spots, it must be ensured to monitor their sizes with high resolution in order to prove the achievement of the required beam parameters. Transverse beam profile diagnostics in electron linacs is widely based on optical transition radiation (OTR) as standard technique which is observed in backward direction when a charged particle beam crosses the boundary between two media with different dielectric properties. The working principle of a conventional OTR beam profile monitor is such that a beam spot is imaged via OTR onto a spatial resolving detector using a conventional optical system. Using this technique, the smallest beam size measurement reported so far amounted to $5\ \mu\text{m}$ (rms) with a resolution of about $2\ \mu\text{m}$ [1].

However, there exists a fundamental limitation in the imaging process which is usually discussed in terms of the point-spread-function (PSF). In case of an OTR monitor the PSF describes the image of a single electron, and the fundamental limitation arises due to diffraction in the optical system because of the wave nature of the emitted radiation. Keeping in mind that image formation is mathematically described as convolution of the object function with the PSF, it is obvious that in case of direct imaging a

smaller PSF results in a better resolution. The OTR PSF was theoretically investigated for the first time by Castellano and Verzilov [2], and later on in more details by Potylitsyn [3], Xiang and Huang [4], and by Kube [5]. In principle it is possible to achieve resolutions beyond the diffraction limit: in case of PSF dominated imaging the recorded image is dominated by the resolution function of a point source, and with exact knowledge of the PSF it is possible to reconstruct the true image (beam spot). In this case the information about the beam size is not extracted from the direct beam spot image but from the smearing out of the PSF fine structure. PSF dominated imaging was successfully applied in case of synchrotron radiation diagnostics [6], and in a recent experiment the observation of OTR PSF dominated beam images was reported which were measured at the ATF-II facility at KEK (Tsukuba, Japan) [7]. However, the observed double-lobe structures were significantly wider than theoretically predicted and beam images were seriously distorted. Besides this unsettled observation, PSF dominated imaging based on OTR suffers under a limited dynamic range which restricts the range of applicability to beam sizes typically smaller than $1\ \mu\text{m}$.

Based on the formalism derived in Refs. [3, 4, 5], a method of dedicated de-focusing is proposed which allows to extend the range of OTR based PSF imaging to in principle arbitrary beam sizes. A test experiment has been performed demonstrating the feasibility of this method, and first results are presented in this report.

THEORETICAL CONSIDERATION

The spectral angular radiation intensity in the image plane is given by

$$\frac{d^2W}{d\omega d\Omega} = \frac{c}{4\pi^2} (R_x |E_{x_i}|^2 + R_y |E_{y_i}|^2) \quad (1)$$

with $R_{x,y}(\alpha, \lambda)$ the Fresnel coefficients which depend on the target inclination angle α and on the photon wavelength λ . According to Ref. [5], in case of de-focused OTR imaging the electric field vectors for the PSF calculation can be expressed as

$$E_{x_i, y_i}(\omega) = \frac{2e}{\lambda M v} \frac{x_i, y_i}{R_i} \times \int_0^{\theta_m} d\theta \frac{\theta^2}{\theta^2 + 1/\gamma^2} J_1(\zeta\theta) e^{-i\frac{\pi}{\lambda} \theta^2 (\Delta a + \frac{\Delta b}{M^2})} \quad (2)$$

with $\Delta a, \Delta b$ the misalignment in object and image distances from the ideal case $1/f = 1/a - 1/b$, γ the Lorentz

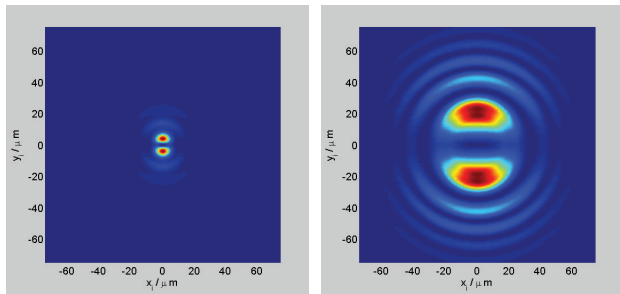


Figure 1: OTR PSF for (left) perfect alignment and (right) assumed misalignment of $\Delta a = 1.5\text{mm}$ in the object distance. The calculations were performed for $\lambda = 400\text{ nm}$ and 1:1 imaging with a lens acceptance angle $\theta_m = 45\text{ mrad}$ and 855 MeV beam energy, corresponding to the parameters used in the experiment. The Fresnel coefficients amounted to $R_x = 0.05$ and $R_y = 0.7$, leading to a suppression of the horizontal polarization component.

factor, v the electron velocity, M the optical magnification, θ_m the acceptance angle of the imaging lens, and $\zeta = \frac{2\pi R_i}{\lambda M}$ with $R_i = \sqrt{x_i^2 + y_i^2}$ for an arbitrary point (x_i, y_i) in the image plane.

Figure 1 shows calculated PSFs for an OTR monitor assuming perfect alignment (left) and a misalignment of 1.5 mm in the object plane (right) for parameters corresponding to the ones used in the experiment. As can be seen, a slight misalignment results in a drastic PSF broadening. Keeping in mind that image formation is mathematically described as convolution of the object function (here: beam distribution) with the PSF, it is obvious that a misalignment in the optical setup increases the sensitivity on the PSF properties. With a proper preselection of this misalignment, the PSF sensitivity can be adjusted to arbitrary beam sizes.

EXPERIMENTAL SETUP

The experimental setup which is shown in Fig. 2 was originally optimized for the detection of transition radiation in the extended UV (EUV) spectral region and is described in detail in Refs. [8, 9]. Therefore only a short description will be given in the following.

The experiment was carried out at the 855 MeV electron beam of the Mainz Microtron MAMI (Institute for Nuclear Physics, Gutenberg University, Mainz, Germany). The quasi-continuous beam of the racetrack microtron (mean beam current 2.4 nA) was operated in macropulse mode with a pulse duration of 0.8 s in order to allow CCD frame readout in the gaps in between.

The target which consisted of a 50 nm thick molybdenum layer evaporated onto a 0.7 mm thick silicon substrate was mounted onto a motorized stage which allowed rotation and linear motion along and across the beam axis. The electron beam interacted with the target and generated transition radiation in a wide spectral range. The angle between electron beam and target normal amounted to 74° (graz-

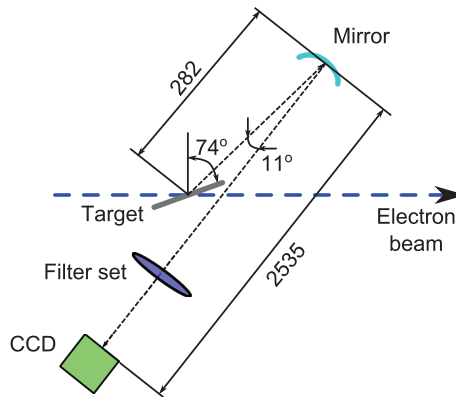


Figure 2: Sketch of the experimental setup.

ing incidence angle 16°), resulting in a suppression of the horizontal polarization component as indicated in Fig. 1. The radiation was focused and additionally monochromatized in the EUV region by a spherical multilayer mirror designed for 20 nm radiation, the resulting beam image was recorded with a scientific grade CCD detector (ANDOR DO434-BN-932 with 1024×1024 pixels and a pixel size of $13 \times 13\ \mu\text{m}^2$). The distance from the target to the mirror was about 282 mm, the distance from the mirror to the CCD 2535 mm, resulting in an optical magnification of $M \approx 9$. A set of filters was mounted in front the CCD camera in order to selectively detect the optical or EUV part of the spectrum. For the experiment described in this report an optical bandpass filter with central wavelength $\lambda = 400\text{ nm}$ was used.

MEASUREMENT AND RESULTS

For each individual measurement 20 images were taken, both for signal and background. The mean background was subtracted from the corresponding mean signal image, resulting in a background corrected beam spot. After this correction a median filter was applied in order to remove the remaining salt and pepper noise originating from high energetic background interaction in a single pixel.

In Fig. 3 (left) an OTR beam spot measurement is shown for the observation wavelength $\lambda = 400\text{ nm}$. The distinct feature of this recorded spot is the vertical splitting indicating a double lobe structure. In order to demonstrate that the course of the observed splitting is not the electron beam

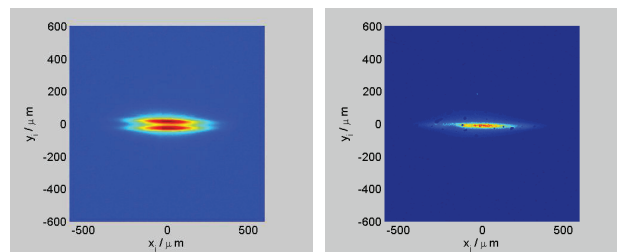


Figure 3: Measured beam spots for an observation wavelength of $\lambda = 400\text{ nm}$ (left) and $\lambda = 20\text{ nm}$ (right).

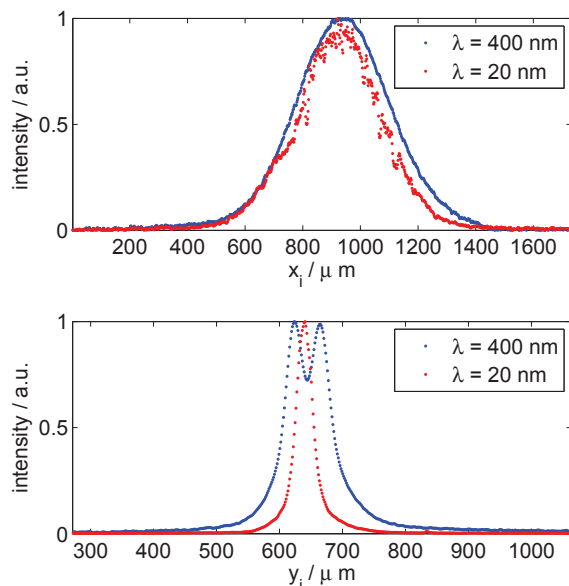


Figure 4: Horizontal (top) and vertical (bottom) projections of the beam spots from Fig. 3 measured with transition radiation at observation wavelengths of 400 nm (blue dots) and 20 nm (red dots).

itself, the measurement was repeated under the same experimental conditions but at an observation wavelength of $\lambda = 20$ nm, c.f. Fig. 3 (right). As can be seen, the double lobe structure disappeared and the observed beam spot resembles the expected two-dimensional Gaussian beam shape. In the horizontal plane, a splitting cannot be observed due to the larger beam size and the suppression of the horizontal polarization component. For better comparison, Fig. 4 shows the horizontal (top) and vertical (bottom) projections of the measured beam spots for both observation wavelengths. While the horizontal beam projection is slightly broadened in the optical spectral region, the vertical one undergoes a dramatic change in shape.

In an additional measurement, the beam spot size was increased by changing the current in the upstream focusing quadrupoles. In this case no double lobe structure was observed but a simple broadening of the measured beam spot at $\lambda = 400$ nm in comparison to the one at $\lambda = 20$ nm [9].

The observations shown in Figs. 3 and 4 are interpreted such that the observed beam splitting in the vertical profile is caused by PSF broadening which is in the order of the vertical beam size due to misalignment. Because of the larger horizontal beam size and the suppression of the horizontal PSF component, no splitting is observed in the horizontal plane. According to Eq.(2), the influence of diffraction broadening is drastically reduced at the smaller wavelength and as a result, there is no indication for a double lobe structure in the measurement at $\lambda = 20$ nm. However, by inspecting the vertical projection for the EUV spectral region it is to note that the shape does not perfectly resemble a Gaussian profile because of the pronounced tails

which also indicate an increased PSF contribution. Finally, the missing of a double lobe structure for the measurement with a larger beam spot can simply be explained by a reduced contribution of the PSF with respect to the beam spot size.

A preliminary analysis of the measured beam sizes indicate that a phase contribution in Eq.(2) from a misalignment corresponding to an offset in the object distance of about $\Delta a = 1.4$ mm would explain the observed profiles. While the extracted horizontal beam size is in the order of $\sigma_x \approx 150 \mu\text{m}$, the vertical ones amount $\sigma_y \approx 10.5 \mu\text{m}$ for both observation wavelengths and show an excellent agreement.

CONCLUSION

In this report OTR beam profile measurements based on PSF dominated imaging are presented. It is shown both theoretically and experimentally that a misalignment in the optical setup affects the shape of the PSF, leading to a broadening of the imaged beam spot and opening a way to resolve fine structures in the PSF distribution. A vertical beam profile as small as $10 \mu\text{m}$ could be resolved for two observation wavelengths from different spectral regions, indicating the potential of this method to resolve even smaller beam spots.

The advantage of using a dedicated de-focused optical system is that the OTR PSF can in principle be adjusted to any arbitrary beam size, the lower limit imposed by the PSF of a perfectly aligned light optics: with a proper selected misalignment, the fine structure of the PSF can be adapted to probe any beam size. If the misalignment is known a priori the PSF can be calculated, and with knowledge of the PSF it should in principle be possible to reconstruct the whole two-dimensional beam distribution by applying conventional image restoration methods.

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REFERENCES

- [1] M. Ross *et al.*, Proc. BIW '02, Upton, New York, USA, AIP Conf. Proc. **648** (2002) 237.
- [2] M. Castellano and V. A. Verzilov, Phys. Rev. ST Accel. Beams **1** (1998) 062801.
- [3] A.P. Potylitsyn, in *Advanced Radiation Sources and Applications* ed. by H. Wiedemann (2006) 149.
- [4] D. Xiang, W.-H. Huang, Nucl. Instr. Meth. Phys. A **570** (2007) 357.
- [5] G. Kube, TESLA-FEL 2008-01 (2008).
- [6] Å. Andersson *et al.*, Nucl. Instr. Meth. A **591** (2008) 437.
- [7] P. Karataev *et al.*, Phys. Rev. Lett. **107** (2011) 174801.
- [8] L.G. Sukhikh, S. Bajt, G. Kube *et al.*, Proc. IPAC '12, New Orleans, Louisiana, USA, MOPPR019 (2012) 819.
- [9] L. Sukhikh *et al.*, submitted to Phys. Rev. ST Accel. Beams.