MICRON-SCALE VERTICAL BEAM SIZE MEASUREMENTS BASED ON TRANSITION RADIATION IMAGING WITH A SCHWARZSCHILD OBJECTIVE

L.G. Sukhikh*, A.P. Potylitsyn, A.V. Vukolov, Tomsk Polytechnic University, Tomsk, Russia
S. Bajt, G. Kube, DESY, Hamburg, Germany
I.A. Artyukov, P.N. Lebedev Physical Institute, Moscow, Russia
W. Lauth, Institute for Nuclear Physics, Johannes Gutenberg University, Mainz, Germany

Abstract

This report presents preliminary results of a measurement of a micron–scale vertical beam size based on imaging of optical transition radiation in the visible region. The visualization of point spread function dominated beam images was carried out using a Schwarzschild objective that provides high magnification and that is free of some of aberrations. According to the preliminary data treatment, a vertical rms beam size of 1.37 ± 0.07 μm was measured at the 855 MeV beam of the Mainz Microtron MAMI (Germany).

INTRODUCTION

Optical Transition Radiation (OTR) is generated when a charged particle crosses the boundary between two media with different optical properties. It is an important tool for beam diagnostics, mainly for transverse profile beam imaging in modern linear accelerators. OTR in backward direction is generated directly at the screen boundary in an instantaneous process with a linear response and a rather high light output. The radiation is emitted in the direction of the specular reflection in a small lobe with an opening angle which is defined by the beam energy. Unfortunately, the diffraction limit of the optical system imposes a limitation that makes the method ineffective for reliable diagnostics of micron–scale beams in modern accelerators.

The point spread function (PSF) defines the minimum beam size that can be resolved using OTR. The PSF was investigated for the first time by M. Castellano and V.A. Verzilov [1] and later in more details by A.P Potylitsyn [2], D. Xiang and W.-H. Huang [3] and by G. Kube [4]. It was shown that the PSF has a double lobe structure which is defined by the observation wavelength and the acceptance of the optical system. The minimum beam size that can be measured using OTR with a wavelength of 400 nm and a reasonable optical system is about 3 μm.

In principle it is possible to overcome the limitation by decreasing the observation wavelength used for the beam imaging. A proof–of–principle experiment that demonstrated the possibility to image beam profiles using backward transition radiation (BTR) in the Extreme Ultraviolet (EUV) region at $\lambda \simeq 20$ nm was published in [5].

In the case of small beams and OTR in the visible region, it is possible to obtain PSF dominated images that at the first glance could be treated as convolution of the PSF with the beam profile. In this situation, beam size information could be extracted as it was shown in [6–8]. In [6, 7], the authors used a thin lens as the main part of the optical system, and in the experiment described in [8] imaging was performed by a spherical mirror. Such optical schemes resulted in a decrease of the resolution because of aberrations, especially due to spherical and chromatical ones. In the present report we describe an experiment devoted to PSF dominated beam imaging using a Schwarzschild objective that is free of this kind of aberrations [9].

EXPERIMENTAL SETUP

The experiment was carried out at the 855 MeV electron beam of the Mainz Microtron MAMI (Institute of Nuclear Physics, Johannes–Gutenberg–University, Mainz, Germany). The quasi–continuous beam of the racetrack microtron (mean beam current 52 nA) was operated in macro–pulse mode with a pulse duration of 0.8 s in order to allow CCD frame readout in the gaps in between.

Figure 1 shows a scheme of the experimental setup. A set of targets was mounted onto a motorized stage which allowed rotational and linear motion across the beam axis in horizontal and vertical direction. The target set consisted of Mo and Al single layer targets, a Mo/Si multilayer target which was optimized to generate 20 nm wavelengths, two wire–scanners (10 μm thick and 4 μm thick tungsten wires), and a LYSO:Ce scintillator. The electron beam interacted with the target, generating OTR in a wide spectral range, and the beam spot was imaged using this OTR with

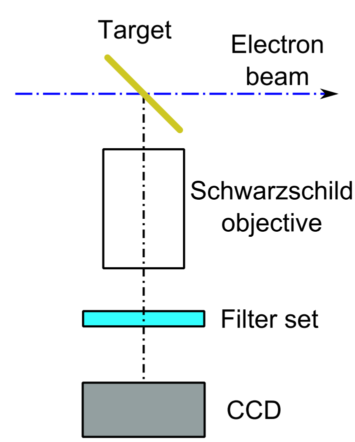

Figure 1: Experimental setup.

* sukhikh@tpu.ru

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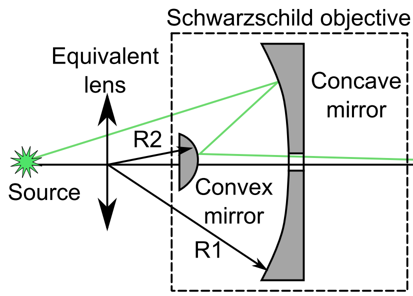

Figure 2: Schwarzschild objective scheme.

the Schwarzschild objective. The resulting beam image was recorded with a CCD detector. A set of filters was mounted in front the CCD camera in order to selectively detect different parts of the spectrum. The present report describes results obtained for the Mo/Si multilayer target and a bandpass filter with central wavelength $\lambda = 400$ nm and full width half maximum equal to 140 nm. Beam size measurements using the LYSO:Ce scintillator are reported in [10].

The working principle of the Schwarzschild objective is illustrated schematically in Fig. 2. It consists of two spherical mirrors, one is concave and the second convex. Both mirrors have the same center of curvature, and the equivalent thin lens is located in this center [9]. A Schwarzschild objective used for our experiment was developed and produced at the Lebedev Physical Institute (Moscow, Russia). It consisted of two mirrors with a multilayer coating which was optimized for wavelengths of about 20 nm, nevertheless it had also a good reflectivity in the visible part of the spectrum. The nominal numerical aperture amounted $NA = 0.19$ and the equivalent lens focal length was equal to 26.9 mm. In the experiment, the distance from the target to the lens amounted 27.54 mm and the distance from the lens to the CCD 1155.46 mm. As result, the magnification was equal to $M = 41.95$. Due to the fact that the secondary mirror of the Schwarzschild objective blocked most of the OTR radiation when the target was tilted at 45 deg, a tilt angle of 49 deg was chosen in order to maximize the radiation intensity.

The beam images were recorded with a scientific grade CCD camera (ANDOR DO434-BN-932) with 1024 × 1024 pixels and a pixel size of $13 \times 13 \mu m^2$. Special feature of this in–vacuum CCD camera was a rather high sensitivity in the range from 1 eV up to 10 keV due to the back illuminated chip without coating. The CCD was cooled down to −40 °C in order to decrease dark current and CCD noise. Both, background and CCD noise were measured with the beam while the optical path was blocked by a 1 mm thick aluminum plate.

BEAM IMAGING IN THE VISIBLE REGION

Figure 3 shows a beam image accumulated over 10 accelerator shots which was obtained in the visible region using

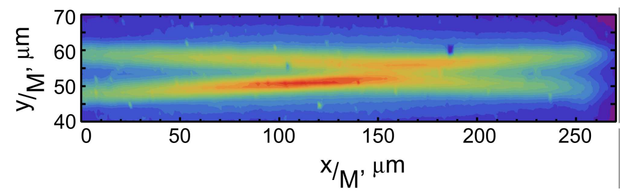

Figure 3: Beam image obtained in the visible region.

the bandpass filter. The radiation intensity is expressed in CCD counts per pixel.

The recorded image shows a pronounced double lobe shape that is a clear signature for a PSF dominated image in the case of a measurement using the vertical OTR polarization component [6,7]. In the measurement Fig. 3 no external polarizer was used, the obtained image is the result of the natural polarization due to the reflection at the target. The banana–like shape is caused by the depth–of–focus effect, the target was tilted and the beam tails are out of focus. For details concerning this topic see also [8, 11]. In the present experiment, no possibility exists to determine the horizontal beam size because the left part of the beam image is out of the view field of the CCD camera. This is the payback for the high magnification of the Schwarzschild objective, but nevertheless it is possible to determine the vertical beam size using the PSF dominated image.

Figure 4 shows the vertical projection with a projection width of 1.5 μm, taken at the horizontal CCD position $x = 160$ μm in Fig. 3. Together, the blue dots and the green triangles in this figure represent the measured vertical projection. In order to estimate the beam size, the following approximation for the central part of the distribution was proposed in [11]:

$$f(y) = q_3 + \frac{q_0\, q_1^2}{q_2\sqrt{2q_1^{-2} + q_2^{-2}}}\,\frac{2q_2^4 + q_1^2(q_2^2 + y^2)}{(q_1^2 + 2q_2^2)^2}\, e^{-\frac{y^2}{q_1^2+2q_2^2}}, \quad (1)$$

with y the vertical coordinate and q_0, q_1, q_2, q_3 free fit parameters. Parameter q_1 defines the peak position and q_2 the vertical rms beam size (see [11] for details). Parameters q_0 and q_3 serves for scaling of the distribution amplitude and zero level.

The red solid line in Fig.4 shows a fit to the experimental data according to Eq. (1), and it was carried out only for the points indicated by the green triangles. The reason for this restriction is that the beam size in mainly sensitive on the contrast ration between the maxima and the central dip of the distribution, the distribution tails are far less sensitive on beam size effects. The selected data range allowed to carry out the best fit using Wolfram Mathematica built–in function `NonlinearModelFit`. The fit procedure resulted in the following parameter values: $q_1 = (2.04 \pm 0.04)$ μm, $q_2 = (1.37 \pm 0.07)$ μm.

In the experiment with the LYSO:Ce scintillator carried out at the same time under the same conditions, an rms beam size of $\sigma_y = 1.44$ μm was deduced [10].

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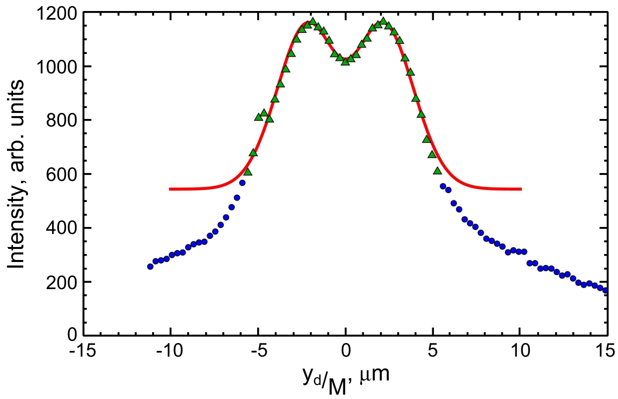

Figure 4: Beam image projection. Green triangles - experimental points used for the approximation, blue dots - experimental points excluded from the approximation, solid line - fit function Eq. (1).

The obtained value for the q_1 fit parameter is very surprising due to the fact that it is equal to $q_1 \simeq 5\lambda$ at $\lambda = 400$ nm. According to the OTR PSF theory, in an ideal optical system the PSF peak position is defined by the numerical aperture and the radiation wavelength [1,4]. In the case of $NA = 0.19$ and $\lambda = 400$ nm, the peak position should be equal to approx. 1 μm. The obtained value of $q_1 = (2.04 \pm 0.04)$ μm is more expected at the $NA \simeq 0.1$ at $\lambda = 400$ nm. In the LYSO:Ce experiment, the numerical aperture value was estimated to be equal to $NA = 0.2$ that is much closer to the manufacturer information [10]. This measured difference is not clear yet and may be caused by the fact that the scintillator light is emitted isotropically while the OTR cone is very narrow. This fact needs additional theoretical investigations.

SUMMARY AND OUTLOOK

This report presents preliminary results of an experiment devoted to the measurement of micron–scale vertical beam size using OTR in the visible range with a Schwarzschild objective based optical scheme. The advantage of the selected Schwarzschild objective was a high magnification and low aberrations that allow a precise measurement of PSF dominated images. Based on the fit proposed in [11] a beam size was deduced that amounted $\sigma_y^{=}(1.37 \pm 0.07)$ μm, showing very good agreement with scintillator measurements performed in the same experiment [10]. Such an agreement for micron–based beam size measurements is very promising and indicates the high potential of the optical scheme used.

Despite the fact that the agreement in the beam size measurement is rather good, the numerical aperture of the Schwarzschild objective deduced from both beam size measurements is different: according to the manufacturer it is $NA = 0.19$, the scintillator measurement best fit results in $NA = 0.2$, and from the OTR measurement it is expected to be $NA \simeq 0.1$. Such a difference is not clear yet and may be caused by the fact that scintillator light is emitted isotropically while OTR obeys a strong directivity with a very narrow emission cone. However, this fact needs additional investigations and will be carried out as one of the next steps.

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