A novel method for sub-micrometer transverse electron beam size measurements using optical transition radiation

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Abstract. Optical Transition Radiation (OTR) appearing when a charged particle crosses a boundary between two media with different dielectric properties has widely been used as a tool for transverse profile measurements of charged particle beams in various facilities worldwide. The resolution of the monitor is defined by so-called Point Spread Function (PSF), source distribution generated by a single electron and projected by an optical system onto a screen. In this paper we represent the development of a novel sub-micrometre electron beam profile monitor based on the measurements of the PSF structure. The first experimental results are presented and future plans on the optimization of the monitor are discussed.

1. Introduction
Optical Transition Radiation (OTR) appearing when a charged particle crosses a boundary between two media with different dielectric properties has widely been used as a tool for transverse profile measurements of charged particle beams in various facilities worldwide. OTR monitors are simple, robust, and give a direct image of a two-dimensional beam profile. The resolution of the monitor is defined by so-called Point Spread Function (PSF) [1]. The PSF is the source distribution generated by a single electron and projected by an optical system onto a screen. The root-mean-square (RMS) size of the PSF is considered as a resolution quantity. All existing theories predict that the PSF is not a uniform function, but it is structured and has a minimum in the centre. Moreover, when considering such a small dimensions, the PSF form significantly depends on various parameters of the optical system like diffraction of the OTR tails, spherical and chromatic aberrations, etc. Recently the first observation of the PSF of OTR was made [2]. One of the biggest challenges for experimental verification is a difficulty in obtaining such a small electron beam size, i.e. much smaller than the PSF structure. The experimental results have clearly shown that the PSF structure with a minimum in the centre gives an opportunity to measure the beam size with micrometer resolution. And with proper optimization of the optical system sub-micrometer resolution can also be achieved.
2. Experimental setup

Last year the KEK Accelerator test facility (ATF) extraction line (see Fig.1) has been significantly upgraded. The ATF-II [3] is a final-focus test beam line that aims to focus the low-emittance beam from the ATF damping ring to a vertical beam size of about 37 nm, and at the same time to demonstrate nm beam stability, using numerous advanced beam diagnostics and feedback tools. The laser-wire (LW) system [4, 5] has also been upgraded in order to allow the measurement of micron-scale transverse electron beam size. In the course of this upgrade an OTR monitor has been integrated into the LW interaction chamber. The aims of the monitor were to simplify the tuning procedure for the micrometer electron beam optics to be used for the LW experiment and to investigate a possibility to cross check the LW micron-scale beam size measurements.

To observe the PSF of the OTR an optical system with large magnification factor was constructed. It consists of a 100mm focal length lens, two aluminum mirrors forming a periscope, an optical polarizer and a set of the optical filters which can be inserted onto the optical path right in front of a CCD camera (see Fig.2).

| Table. 1 Specification of the main components of the experimental setup |
|---|
| Aluminum-coated silicon target 30x30x0.3 mm. |
| Lens: Sigma-koki SLB-50.8-100PY2, 50mm diameter. |
| Linear Polarizer, 75mm diameter. |
| Top aluminum mirror, 50mm diameter. |
| Bottom aluminum mirror, 75mm diameter. |
| Set of optical filters: 459±18nm, 558±20nm, and 609±18nm center band pass wavelength, 25mm diameter. |
| CCD camera Alta E4000, 2048 X 2048 pixel array @ 7.4 microns and 16 bit resolution, input flange - 25mm diameter. |

![ATF schematic layout and partial zoom of the new ATF-II extraction line.](image)

![Experimental layout.](image)
The vacuum chamber with attached 2 inch travel motorized vacuum translator with rotatable axis was used to position the OTR target in the center of the vacuum chamber and at 45 degrees with respect to the electron beam trajectory. The 300 μm thick, square (size 30 mm) silicon wafer, coated with aluminum was used as the target. Transition radiation generated by the target was extracted out of the vacuum chamber through the fused silica vacuum window and then transported into the cooled CCD camera with peak QE 55% at 500 nm. Two axes of the 50 millimeter diameter top periscope mirror were remotely controlled by the ThorLabs Z706 DC-servo motors with minimal step of the order of 3 μrad allowing the adjustment of the OTR spot position at the CCD during the experiment.

To align the optical system a special vacuum mirror was installed downstream the ZH4X steering magnet. That mirror allows us to send the alignment laser along the electron beam in the ATF-II extraction line. The laser system consists of a laser stage, a Helium-Neon (He-Ne) continuous wave (CW) laser (Melles Griot 05-LHP-121 laser head with oscillation wavelength of 632.8 nm), a spatial filter, and a focusing lens. Changing the distance between the spatial filter and the lens, one may focus the laser at any point of the experimental setup (screen monitors, target, and detector). The MS1FF screen located about 38 meters downstream of the vacuum mirror (Fig. 1) was used as a second reference point. The laser direction could be corrected using precise adjustment screws of the laser stage. When the laser alignment system was optimized, the OTR target placed at 45 degrees with respect to the beam line reflected the laser light away from the accelerator chamber, and the entire optical system was aligned.

Fig. 3 The CCD image of the OTR target edge (a), its differential intensity (b) and calibration curve with the linear fit (c).

The laser alignment tests showed that the alignment system accuracy was smaller than 0.05 mrad, which is quite enough for our purposes. The optical system has a large magnification factor which was measured using laser alignment system. The target was gradually moved out of the chamber until its edge image was observed on the CCD camera. At this point the lens longitudinal position was adjusted to provide a clear target edge image (see Fig. 3a). The lens height position and the angular corrections were applied in order to have no image position shifts while changing longitudinal lens position (i.e. reflected alignment laser beam passed through the center of the lens at a right angle of incidence to the tangent of the lens surface). The image was digitized and a vertical projection in a narrow horizontal box shown in Fig. 3a with white lines was differentiated (see Fig. 3b). The maximum of the differential intensity curve was defined as the position of the target edge. The relative position of the target was also obtained from the manipulator motor controller encoder system. The resulting dependence of the target position measured at the CCD camera versus manipulator readout was used as a calibration curve (see, for instance, Fig. 3c). The magnification factor extracted from the linear fit was \( m = 18.87 \pm 0.18 \, \mu m \).

Special electron beam optics was simulated using Strategic Accelerator Design (SAD) code [6] to generate a micron-scale transverse beam size at the OTR target location resulting in beam dimensions to be 1.5x20 μm. Figure 4 represents the SAD simulations of the ATF extraction line optics performed
for initial electron beam parameters summarized in Table 2. The target chamber is located after two quadrupole magnets QM19X and QD18X used to change the horizontal and the vertical beam sizes respectively. The ATF-II lattice was designed so that the first order dispersion could be corrected in the diagnostics section of the extraction line. The calculated beam sizes were confirmed by the wire-scanner (MW2X) measurements located at about 0.8 m downstream of the target chamber.

\[
\begin{align*}
\alpha_x &= 2.047 \\
\beta_x &= 14.795 \, \text{m} \\
\alpha_y &= -2.49 \\
\beta_y &= 3.656 \, \text{m} \\
\Delta E / E &= 6.4 \times 10^{-4} \\
\epsilon_x &= 1.86 E - 9 \, \text{m rad} \\
\epsilon_y &= 2.3 E - 11 \, \text{m rad}
\end{align*}
\]

Table 2.

Fig. 4 SAD simulation of the vertical and horizontal betatron ($\beta_x$, $\beta_y$), dispersion ($\eta_x$, $\eta_y$) functions and predicted electron beam sizes ($\sigma_x$, $\sigma_y$) for the ATF-II extraction line. The arrows shows interaction chamber and wire-scanner locations along the beam line.

All measurements were performed with a single-bunch 1.56 Hz repetition rate operation mode with 0.9 nC bunch charge. The Alta E4000 (100bT Ethernet interface) camera based on the large format interline Kodak KAI-4021M (monochrome) sensor with low dark current, low noise, and high resolution, 2048×2048 pixel array with 7.4 microns pixel size and 16 bit resolution along with the camera control and image acquisition software (MaxIm DL) [7] was applied. A LabView [8] based application for off-line data analysis has been developed. In order to increase the signal-to-noise ratio of the acquired images the $4 \times 4$ pixel binding was applied. A single-shot operation mode of the CCD camera allowed us to exclude the shot-by-shot electron beam instability effect such as the beam position jitter.

3. Experimental results and discussions

Fig. 5 CCD image of the OTR taken with linear polarizer and 550 nm optical filter (a) and two image projections: horizontal (b) and vertical (c).
Figure 5a shows the CCD image of the OTR taken with linear polarizer set to transmit the vertical polarization component and 550 nm optical filter. Figures 5b and 5c represent two image projections: horizontal (Fig. 5b) and vertical (Fig. 5c) derived from summation of the pixels intensities within the horizontal and vertical broad corridors.

We can clearly see the two lobe distribution in the vertical projection of the OTR spot (Fig. 5c) well described in [2]. The visibility of the distribution significantly depended on the electron beam size. When the vertical beam size was changed from 1.75 μm to 10.16 μm (according to the SAD simulations) the minimum in the centre of the distribution disappeared (see Fig. 6a). Further increase in the beam size transferred our system into a conventional OTR monitor with the resolution of about 22 μm. Such a strong dependence of the visibility on the transverse electron beam size can be applied for the beam size measurements at micrometer level.

Since the horizontal beam size is much larger than the vertical one the horizontal projection shown in Fig. 5b still proportional to the horizontal electron beam size. A simple Gaussian fit was applied to the image projections in order to extract the horizontal RMS beam sizes \(x_\sigma\).

To analyze the vertical projection, especially OTR spot minimum behavior, a special empirically found fit function had been introduced:

\[
f(x) = a + \frac{b}{1 + [c(x - \Delta x)]^4} \left[1 - e^{-2c^2\sigma^2} \cos[c(x - \Delta x)] \right]
\]

where \(a, b, c, \sigma\), and \(\Delta x\) are free parameters of the fit function, namely: \(a\) is the vertical offset of the distribution with respect to zero which included a constant background; \(b\) is the amplitude of the distribution; \(c\) is the distribution width; \(\sigma\) is the smoothing parameter dominantly defined by the beam size; and \(\Delta x\) is the horizontal offset of the distribution with respect to zero. An example of the OTR image vertical projection and the fit is represented in Fig. 6b.

From Figure 6b, one can see that the fit function can approximate the experimental data fairly well. To demonstrate the new method application to the beam size measurements, two independent quadrupole scans were performed. At first the strength of the QF19X quadrupole magnet was changed. That corresponded to the horizontal beam size change. The horizontal image projections were fit with Gaussian distribution, and the resulting horizontal RMS beam size as a function of the QF19X strength is represented in Fig. 7a. The data show a good agreement with SAD expectations. A small discrepancy in the right part of the dependence could be explained by the fact that the residual dispersion was not well corrected during the measurements. This effect need to be further investigated.
Nevertheless the data confirm that the monitor can be used for the horizontal beam size measurements as a conventional OTR monitor.

In a similar manner a second quadrupole (QD18X) scan was done. Figure 7b shows the dependence of the smoothing parameter $\sigma$ (Eq. 1) dominantly defined by the vertical beam size versus QD18X quadrupole magnet strength (red dots) along with SAD predictions of the vertical beam size for the same magnet strengths (black dots). Large error bars at both ends of the scan could be explained by a poor signal-to-noise ratio of the acquired images what degraded its quality and increased the fit errors.

![Figure 7a](image1.png)  
**Fig. 7** Horizontal RMS beam size as a dependence of the QF19X strength (a) and the dependence of the smoothing parameter $\sigma$ (Eq. 1) versus QD18X quadrupole magnet strength. Red dots – measured data, black dots – SAD predictions of the vertical beam size for the same magnet strengths.

4. Conclusion

The present result clearly demonstrates that the method based on the analysis of the PSF structure visibility gives an opportunity to measure the beam size with a micrometer resolution. In [9] a similar method based on measurements of vertical polarization component of synchrotron radiation (SR) PSF was applied at Swiss Light Source. The difficulty related to the SR measurements is that it is difficult to put the optical system close enough to the emission point. As a result the diffraction effect significantly increases the PSF and, therefore, degrades the resolution for beam size measurement. In case of OTR submicrometer resolution might be achieved.

As it was demonstrated in [2] the chromatic aberrations result in significant broadening of the OTR PSF leading to degradation of the potential resolution. In order to improve the beam size measurement technique additional efforts toward the optimization of the optical system, a better understanding of the beam size effect and an increase of the signal-to-noise ratio of the detecting system is required. To be able to achieve our goals and demonstrate sub-micrometer resolution we intend to employ an achromat to minimize the chromatic aberrations in the optical system. We shall also reduce the magnification factor to increase the light density at the CCD camera and improve the signal-to-noise ratio. We shall implement a few more optical filters covering the wavelength range from 350 to 800nm with 50nm step to be able to investigate the spectral characteristics of the OTR PSF in more detail.

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