Sub-micrometer transverse beam size diagnostics using optical transition radiation

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Abstract. Optical transition radiation (OTR) arising when a relativistic charged particle crosses a boundary between two media with different optical properties is widely used as a tool for diagnostics of particle beams in modern accelerator facilities. The resolution of the beam profile monitors based on OTR depends on different effects of the optical system such as spherical and chromatic aberrations and diffraction. In this paper we present a systematic study of the different optical effects influencing the OTR beam profile monitor resolution. Obtained results have shown that such monitors can be used for sub-micrometer beam profile diagnostics. Further improvements and studies of the monitor are discussed.

1. Introduction

Transverse electron beam diagnostics are crucial for stable and reliable operation of the future electron-positron linear colliders such as CLIC [1] or ILC [2]. Sub-micrometer resolution beam profile monitors are required to measure high-energy particle beam emittance. The-state-of-the-art in transverse beam diagnostics is based on the laserwire technology [3, 4], i.e. when a high power laser is focused in the interaction region down to a micrometer dimension and is scanned across the electron (positron) beam generating intense inverse Compton scattered photon beam. The photon intensity is proportional to the number of particles in the beam and to the laser power and position with respect to the beam center. By measuring the Compton photon yield versus laser position one can directly measure the transverse beam profile. However, the use of high power laser significantly increases the cost of the laserwire system. In linear colliders over 70 such stations are required. Therefore, a simpler and relatively inexpensive method is required. A beam profile monitor based on Optical Transition Radiation (OTR) is very promising. Although such a monitor destroys the beam or the beam can destroy the monitor itself, it still can be used as an addition to the laserwire for diagnostics of low current “pilot” beams.

The resolution of a conventional OTR monitor is defined by the root-mean-square of the so-called Point Spread Function (PSF) [5]. The PSF can be defined as the source distribution generated by a single electron and projected by an optical system onto a detector. In the optical wavelength region the resolution is limited and defined by diffraction and aberration effects of
the optical system. Such effects lead to the broadening of the PSF and to a lower resolution. The best resolution achieved by conventional OTR monitors is about a few micrometers [6]. However, in [7] we demonstrated that the OTR PSF differs from a conventional PSF of an optical system. The vertical polarization component of the OTR PSF has a two-lobe structure, the visibility of which can be used to monitor vertical beam size with sub-micrometer resolution. On the other hand if the beam is flat, which is true for linear colliders, the horizontal projection of the distribution represents a direct measurement of the horizontal beam size that is much larger than the vertical one. It gives an opportunity to diagnose an electron beam size in two directions in a single shot.

2. Experimental setup
The measurements were performed at the Accelerator Test Facility 2 (ATF2) in KEK (Tsukuba, Japan). The accelerator consists of 1.3 GeV linac followed by damping ring to produce a very low emittance beam and extraction line [8]. The ATF2 is an upgrade of the ATF that was performed in 2008 that extends the extraction line and aims to focus the electron beam to a vertical beam size of about 37 nm [9].

In our previous works [10,11] the experimental setup of the OTR monitor was well described. In this section we briefly overview the major components of the setup. In recent operation the setup was slightly modified. The schematic setup and photograph of the OTR monitor is presented in figure 1.

![Schematic a) and photograph b) of the OTR beam profile monitor setup.](image)

The setup consists of 30×30×0.3 mm aluminized silicon target tilted at 45 degrees with respect to the electron beam line. The target was mounted on a 4D vacuum manipulator that allows remote control of its vertical and angular position, and manual adjustment of the transverse position. From the target, the OTR passes through an optical system to a CCD camera, which consists of a motorized iris, lens holder with a set of focusing lenses (“CVI Laser Optics” cemented achromat with $f=120$ mm; “Sigma Koki” achromatic doublets with $f=120.1$ mm and $f=100.7$ mm and “Sigma Koki” spherical plano-convex lens with $f=100$ mm), four aluminum coated mirrors forming a periscope, set of optical filters with bandwidth from 500±20 to 600±20 nm placed in a remotely controlled filter wheel and a linear polarizer placed in front of a CCD camera mounted on a remotely controlled rotation stage. Both the iris and the lens holder were mounted on a same board to keep them centered. The lens holder mounted on the board has a possibility of 3D adjustment of the lens position. The whole setup was mounted on an optical bread board surrounded by a light-tight enclosure. To record the OTR
images a high resolution (~8 megapixel), cooled CCD camera (SBIG-ST8300M) based on Kodak KAF-8300 (monochrome) sensor with 5.4 μm pixel size and ~50% quantum efficiency was used.

3. Experimental results
Initially the accelerator was carefully tuned to minimize the background level and provide a stable working regime during the data taking. The longitudinal position of the focusing lens was adjusted to provide a clear OTR image with a minimum distribution width. After that, the monitor was ready to perform beam size measurements. All measurements were performed in single-bunch mode, with a bunch repetition rate of 3.25 Hz and ~0.3 nC bunch charge.

A typical CCD image of the OTR spot taken with linear polarizer and 550±20 nm optical filter is presented in figure 2a. Since the horizontal beam size is much bigger than the vertical size, it can be directly extracted from the simple gaussian fit applied to the horizontal projection (figure 2c) of the OTR image. The vertical projection of the OTR image has a two-lobe structure (figure 2b) and the vertical beam size can not be directly obtained from the fit function applied to the vertical projection. The idea of the vertical beam size extraction is based on fact that the contrast ratio (minimum to maximum ratio) of the vertical projection strongly depends on the real beam size. To calculate the contrast ratio a special empirically found fit function has been proposed:

\[
f(x) = a_0 + \frac{a_1 \left(a_4 + (x - a_3)^2\right)}{1 + (a_2 (x - a_3))^4},
\]

where fit parameters are: \(a_0\) the vertical offset of the distribution with respect to zero; \(a_1\) the amplitude of the distribution; \(a_2\) the smoothing parameter; \(a_3\) the horizontal offset of the distribution with respect to zero and \(a_4\) the distribution width. In order to calculate the vertical beam size from the contrast ratio, a special self-calibration procedure was introduced [12,13].

![Figure 2.](image)

**Figure 2.** a) CCD image of the OTR spot taken with linear polarizer, 550±40 nm optical filter and DLB lens with \(f = 120\) mm; b) vertical projection; c) horizontal projection.

Recent results of the vertical beam size measurements are presented in figure 3. The horizontal and vertical beam size could be controlled by changing the current in the nearest quadrupole magnet. We performed the measurements using four lenses with different optical properties in order to understand how the optical effects such as chromatic and spherical aberrations influence the measured beam size. The use of achromatic doublets (see figure 3a, b) allowed to achieve a sub-micrometer resolution, while using a simple singlet lens without aberration corrections (see figure 3c) leads to lower resolution. The smallest beam size measured in the experiment is consistent with the SAD [14] prediction within uncertainty.

The form of the PSF, and hence the resolution of the OTR monitor, strongly depends on the diffraction and aberration effects of the optical system, which lead to broadening of the PSF.
and a lower resolution. The broadening can be easily measured as the distance between peaks in the vertical projection of the image.

In order to study such effects a series of measurements with different optical elements was performed. Firstly, to study chromatic aberration effects, we performed a several focus-scans (measuring a distance between peaks of the distribution at different longitudinal lens positions) with different optical filters in a wavelength range 500±20 - 600±20 nm. The resultant dependencies are presented in figure 4a. These measurements were performed using “Sigma Koki” achromatic doublet with a focal length of 120.1 mm and 30 mm diameter. As one can see from the picture, the focus positions are different for different optical filters even for the lens designed to minimize the chromatic aberrations. Therefore for any lens its position must be carefully adjusted to maximize the resolution of the instrument.

Another optical effect that decreases the resolution is the diffraction of the OTR tails by the hard aperture of the optical elements. To study this effect, an iris was mounted in front of the lens (see figure 1). Similar to aberrations, diffraction effects lead to broadening of the distribution and, consequently, to a decrease in resolution. In order to estimate the influence of the diffraction on distribution width the distance between peaks as a function of the iris aperture diameter was measured (see figure 4b). It is clear that diffraction effect becomes noticeable at the iris diameter of \( \sim 15 \) mm \((\sim 360 \, \gamma^{-1})\). This means that the diameter of the focusing lens can be reduced down to 15 mm, thereby the lens can be manufactured thinner which leads to reduction of the spherical aberrations.

**Figure 3.** Vertical beam size as a function of the QM14FF quadrupole magnet current for different lenses: “CVI Laser Optics” cemented achromat with 120 mm focal length a), “Sigma Koki” achromatic doublet with focal length of 100.7 mm b), “Sigma Koki” plano-convex lens with 100 mm focal length c).

**Figure 4.** a) Distance between peaks as a function of the lens position for different optical filters and b) distance between peaks as a function of the iris diameter for different lenses.
4. Aberration test bench

In order to study chromatic and spherical aberration effects more deeply a special test stand was developed. The schematic picture and photograph of the stand is presented in figure 5, 6.

![Schematic of the test bench.](image)

Figure 5. Schematic of the test bench.

The whole setup was assembled on an optical table. Three continuous wave (CW) lasers with 532 nm, 400 nm and 632 nm wavelengths were used as sources of light. The lasers were placed on a stage that allows to change the lasers without changing the alignment. Alignment of the laser beam was performed using two aluminum coated mirrors with diameter of 50 mm and two irises. To imitate the OTR screen a “ThorLabs” R3L3S1P - positive USAF target was used. A lens was mounted on the remotely controlled linear stage. The image of the pattern was detected by the CCD camera and recorded by the camera software. Images were recorded as a function of the lens position. Focusing properties of the lens were measured by analyzing the target images.

![Photograph of the test stand setup with parabolic mirror (left) and with lens (right).](image)

Figure 6. Photograph of the test stand setup with parabolic mirror (left) and with lens (right).

One way to reduce chromatic aberrations is to use reflective optics instead of refractive one. In order to compare these two approaches we performed the measurements of the focusing properties using both an achromatic lens and an off-axis parabolic mirror. In figure 7, a typical focused CCD image of the target taken with the parabolic mirror (figure 7a) and the lens (figure 7b) is presented. Figure 7c represents the vertical projection of the strip edge. As one can see, the image taken with the lens is well focused and has small distortion caused by geometrical aberrations. Whereas the image taken with the parabolic mirror is focused only in a small region and significantly distorted because of the aberration effects. Such distortion of the image taken using the parabolic mirror is caused mainly by imperfections in the mirror alignment. A parabolic mirror has to be perfectly aligned both vertically and horizontally.
because even small deviations of the beam from center leads to significant distortion of the image. Moreover, an off-axis parabolic mirror surface does not form an ideal image due to coma-like geometrical aberrations. For that purpose an elliptical mirror might be used. However design and manufacturing of such mirror with an optical quality might take time.

![Figure 7.](image_url)

To study the chromatic aberrations of the lenses three lasers with different wavelengths were used. Every lens was gradually moved along the laser beam through the focus. At each lens position the image of the target was recorded by a CCD. A part of the image containing a strip edge was selected (see figure 7b, c). Then vertical projection of this selected area was fitted using the following fit function:

\[
f(x) = a_0 + \frac{a_1}{1 + \exp\left(\frac{x - a_2}{a_3}\right)}.
\]

Here, \(a_0\) is the vertical offset of the distribution with respect to zero; \(a_1\) is the amplitude of the distribution; \(a_2\) represents position of the strip edge. Parameter \(a_3\) of the fit function strongly depends on the image contrast and can be used as a measure of the focusing (e.g. if \(a_3 \to 0\) the image is perfectly focused). The final dependencies of the focusing parameter versus the lens position are presented in figure 8.

As one can see, achromatic doublets (figure 8a, b) have small chromatic aberrations because the position of the best focus (i.e. the minimal \(a_3\) parameter) is nearly the same. While singlet lens shows a strong chromatic aberration (figure 8c) for presented wavelength. These results demonstrate a good correlation with beam size measurements described in the previous section. Beside chromatic aberrations spherical aberrations of the lenses can be investigated using these data. However, the data are still under analysis, and the method of extracting the degree of spherical aberration needs to be further developed.

5. Conclusion
The results presented demonstrate progress in the optimization of an OTR beam profile monitor system based on analysis of the PSF structure. Changes in the experimental setup as well as improvement of the analysis allowed a better understanding of the monitor to be achieved. It was demonstrated that the use of a specially developed optics, such as achromatic doublets and optical filters, leads to decreasing of aberration effects. The presence of aberrations (spherical or chromatic) as well as diffraction effects lead to significant degradation of the potential resolution.
Figure 8. Chromatic aberration study for different lenses: “CVI Laser Optics” cemented achromat with 120 mm focal length a); “Sigma Koki” achromatic doublet with focal length of 100.7 mm b); “Sigma Koki” plano-convex lens with 100 mm focal length c).

In order to further improve the resolution of the monitor, effects (mainly aberrations of the imaging system) significantly influencing the PSF width, need to be reduced. One way is to use a special simulation tool for optical calculations (such as ZEMAX [15]) in order to better optimize the optical system. It was shown in [16] that the use of such tools gives good agreement with the experimental data. In the next step we are planning to apply either a multi-element optics or a reflective optics to reduce the resolution of the monitor even further. For example, the use of an elliptical mirror can reduce the aberration effects. However, using such mirror in the real experiment becomes challenging because of the mirror alignment. Even small deflection of an incidence angle leads to significant image distortion due to coma-like geometrical aberrations.

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