# EXTREMELY LOW EMITTANCE BEAM SIZE DIAGNOSTICS WITH SUB-MICROMETER RESOLUTION USING OPTICAL TRANSITION RADIATION

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*Abstract*

Transition radiation (TR) appearing when relativistic uniformly moving charged particle (or bunch of particles) crosses a boundary between two media with different dielectric properties is widely used as a tool for diagnostics of particle beams in modern accelerator facilities. The best resolution which can be achieved using beam profile monitors based on TR in optical wave range has a limitation caused by a spatial resolution of an optical system. Using a method based on analyzing a visibility of the TR Point Spread Function one can achieve a sub-micrometer resolution. In this report we shall represent the recent experimental results of a micron-scale beam size measurement at KEK-ATF2. We shall discuss the hardware status and future plans.

## INTRODUCTION

Transverse electron beam diagnostics are crucial for stable and reliable operation of the future electron-positron linear colliders such as CLIC or Higgs Factory. The-state-of-the-art in transverse beam diagnostics is based on the laserwire technology [1]. It is capable to measure high power micron-scale beam sizes in a non-destructive way. This monitor was recognized by the scientific community as a primary emittance diagnostics for future linear colliders. However, the use of high power laser significantly increases the cost of the laserwire system. Moreover, the laser maintenance will require a team of high qualified experts, which will increase its operation cost. Therefore, a simpler and relatively inexpensive method is required. A beam profile monitor based on Optical Transition Radiation (OTR) is very promising. Although such monitor destroys the beam or the beam can destroy the monitor itself, it is still can be used as addition to the laserwire for diagnostics of low current "pilot" beams. The resolution of conventional OTR monitor is defined by a root-mean-square of the so-called Point Spread Function (PSF) - response of an optical system to a source distribution generated by a single charge. In optical wavelength range the resolution is diffraction limited down to a few micrometers. The best resolution achieved by conventional OTR monitors is about few micrometers [2]. However, in [3] 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 and the visibility of this 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. It gives an opportunity to diagnose an electron beam size in two directions in a single shot.

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## SETUP

In summer 2011 the experimental setup was relocated downstream the beamline to the beginning of the ATF2 final focus. In our previous reports [4, 5] the experimental setup was well described. However, during resent operation in spring 2013 the setup was slightly modified in order to study the optical system and achieve better resolution. A schematic of the setup is presented in Fig. 1.

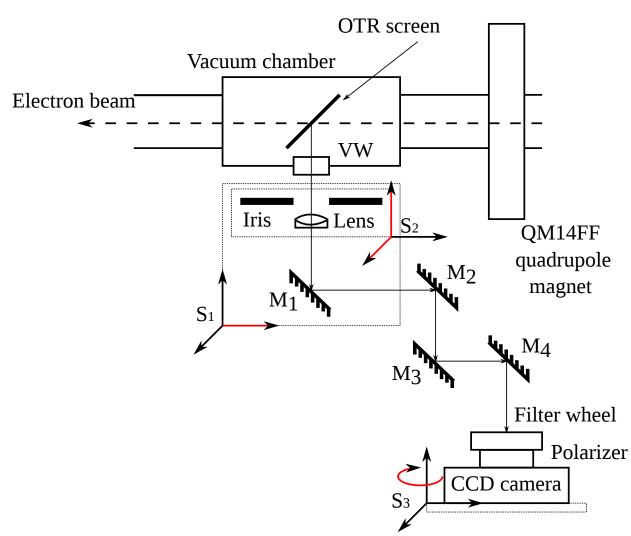


Figure 1: Schematic of the OTR beam profile monitor experimental setup.

To produce the OTR beam a 30×30×0.3 mm aluminized silicon target was used. The target was tilted at 45° with respect to the electron beam direction. Vertical position of the target was controlled by 4D vacuum manipulator installed at the top of the vacuum chamber. The OTR beam passes through the optical system which consists of a mo-

ISBN 978-3-95450-127-4

torized iris, a lens holder with a set of lenses, a periscope of mirrors, a filter wheel with a set of optical filters, a polarizer and a CCD camera. The iris and the lens holder were mounted on the same board to keep them centered. The lens holder mounted on the board has a possibility of 3D adjustment of the lens position. Filter wheel with a set of optical filters followed by the polarizer were attached to the CCD camera and mounted on a remotely controlled rotation stage. The whole setup was mounted on a bread board and placed in a light protective enclosure. The full specification of the main components is presented in Table 1.

To align the optical system a special alignment laser system was used. This system is located approximately 50 m upstream the beam line and consists of a laser stage, a continuous wave (CW), He - Ne (Helium - Neon) laser with 632.8 nm output wavelength, a spatial filter, a focusing lens and a vacuum mirror. The vacuum mirror is used to send the laser along the beam line to the ATF2 extraction line. Changing the distance between spatial filter and the focusing lens one can focus the laser beam at each point of the optical system. After tuning the laser and sending it to the beam pipe an OTR screen was placed at 45 degrees with respect to the beam line to reflect the laser out from the vacuum chamber and to align the entire optical system.

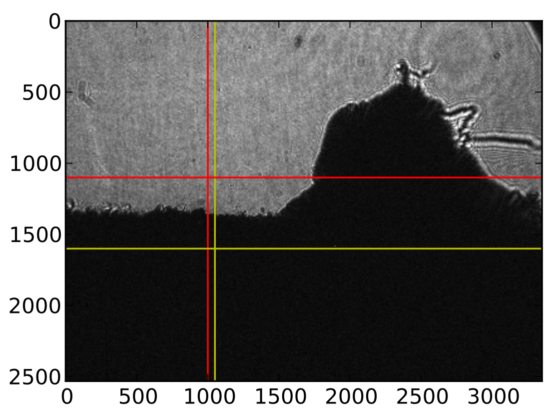


Figure 2: CCD image of the screen edge.

In order to calibrate the optical system and measure the magnification factor the following procedure was used. The OTR screen was gradually moved out of the vacuum chamber. At each step the image of the OTR screen edge was recorded by the CCD. A position of the target was obtained from the manipulator motor controller encoder system with ± 5 $\mu$m precision. To obtain a position of the screen edge the image of the target was digitized and vertical projection in a rectangular box (see Fig. 2) was fitted using Eq. (1). The vertical projection of the screen edge image with the fit function is presented in Fig. 3.

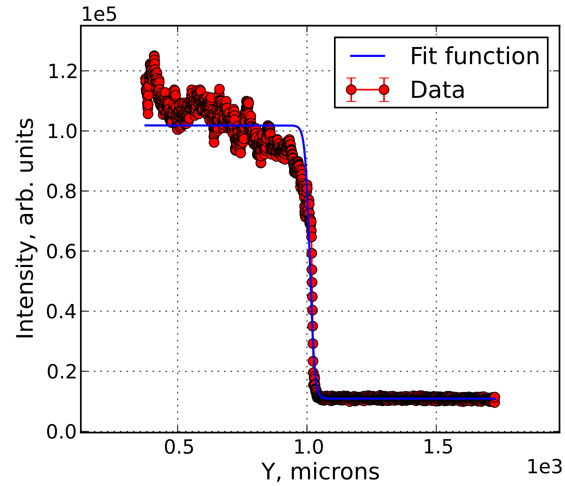


Figure 3: Vertical projection of the screen edge.

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

Here, $a_0, a_1, a_2, a_3$ are the free fit parameters. Parameter $a_2$ represents the screen edge position. The dependence of the screen edge position measured at the CCD versus manipulator position was used as a calibration curve. Then, the calibration curve was fitted using linear function (see Fig. 4). Gradient of the line is the magnification factor which was 7.17.

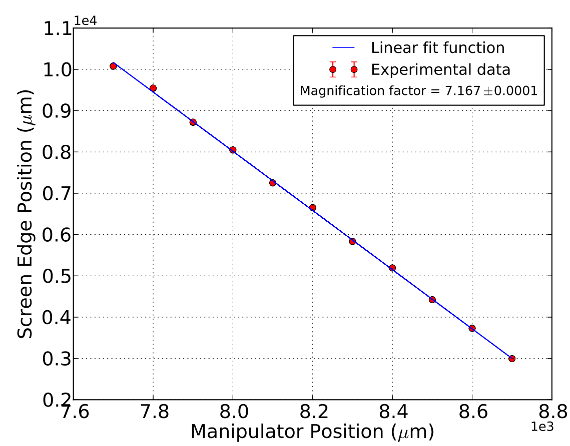


Figure 4: Calibration curve.

## RESULTS

Initially the accelerator was carefully tuned to minimize the background level and provide a stable working regime during the data taking. 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 mea-



ISBN 978-3-95450-127-4

Table 1: Specification of the Main Components of the Experimental Setup

| Component | Properties |
|---|---|
| VW | Vacuum window: CVI W2-PW-2050-UV-532-0-27 |
| $M_1$ | motorized aluminum mirror, ø = 50 mm , mount: Thorlabs PT1-Z8, motor: Z625B |
| $M_2$- $M_3$ | aluminum mirror, ø = 50 mm |
| $M_4$ | aluminum mirror, ø = 75 mm |
| $S_1$ | lens transverse stage: PI-410.2S |
| $S_2$ | lens focus stage: Thorlabs PT1-Z8, motor Z625B<br>lens vertical stage: Sigma-koki SGSP 60-10ZF |
| $S_3$ | rotation stage: Suruga seiki K402-160-5 |
| Lens | ”CVI Laser Optics” cemented achromat, $f$=120 mm, ø=30 mm |
| Iris | Standa 8MID98-4-90 |
| Filter wheel | Thorlabs FW102B |
| Polarizer | Sigma-koki SPF-50C-32 |
| CCD camera | SBIG-ST8300M based on Kodak KAF-8300 (monochrome) sensor with 5.4 $\mu$m pixel size, 3352×2532 pixel array and ∼50% quantum efficiency |

surements were performed with a single bunch mode, with bunch repetition rate of 3.25 Hz and ∼1 nC bunch charge.

Figure 5 represents a typical CCD image of the OTR spot taken with the linear polarizer and the 550 nm optical filter. Analyzing either vertical or horizontal projections of the OTR image one can retrieve corresponding beam sizes.

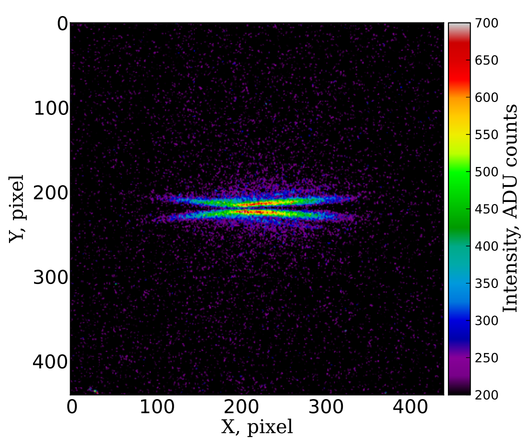


Figure 5: Typical image of the OTR spot taken with linear polarizer and 550±20 nm optical filter.

In order to analyze the OTR images and extract the beam size a special LabView and Python based software for off-line data analysis has been developed.

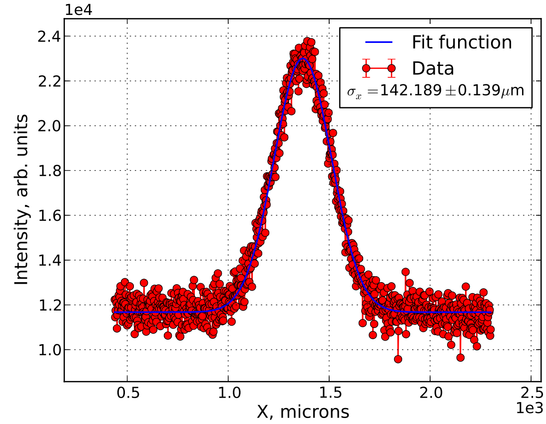


Figure 6: Horizontal projection of the OTR image.

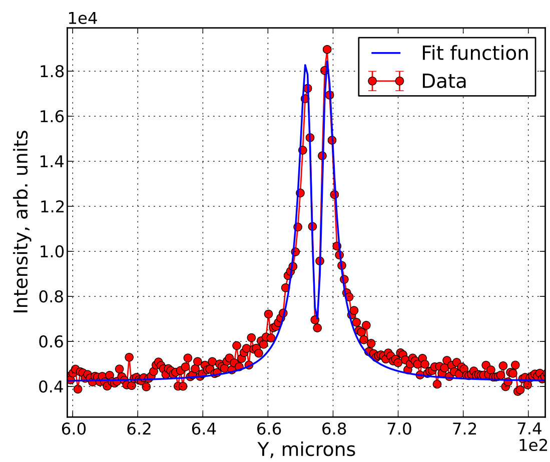


Figure 7: Vertical projection of the OTR image.

Since the horizontal beam size much bigger than the vertical one, it can be directly extracted from the simple gaussian fit applied to the horizontal projection of the OTR image. From the projection shown in Fig. 6 the horizontal beam size was 142 $\mu$m, which was consistent with expectations predicted by the SAD (Strategic Accelerator Design [6]) code.

To analyze the vertical projection a special empirically found fit function has been proposed (see Eq. 2).

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

Where the fit parameters are: $a_0$ is the vertical offset of the distribution with respect to zero, $a_1$ is the amplitude of the distribution, $a_2$ is the smoothing parameter, $a_3$ is the horizontal offset of the distribution with respect to zero

ISBN 978-3-95450-127-4

and $a_4$ is the distribution width. An example of the vertical projection with the fit function is presented in Fig. 7.

The contrast ratio (minimum to maximum ratio) of the distribution strongly depends on the electron beam size. Using the fit function Eq. (2) one can calculate the contrast ratio and then convert to the vertical beam size. In order to recalculate the contrast ratio into the vertical beam size a special self-calibration procedure was introduced. The description of the self-calibration procedure can be found in [7].

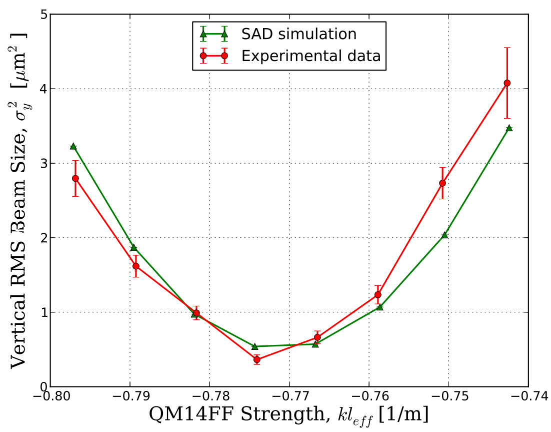


Figure 8: Vertical RMS beam size as a dependence of the QM14FF quadrupole strength.

Using described above method of beam size measurements a quadrupole scan was performed. The current of the QM14FF quadrupole magnet was changed in a range from -89 A to -95 A with -1 A step. For each value of the quadrupole current, three OTR images were taken in order to minimize statistical errors. The vertical projection of the acquired image was fitted with Eq. (2) and the resulting vertical RMS beam size as a function of the QM14FF quadrupole is presented in Fig. 8. As one can see, the measured vertical beam size shows a good correlation with SAD simulations. The difference between the minimal beam sizes can be explained by the fact that at such small sizes small variations of the beam parameters at extraction can change the beam size in the waist.

## CONCLUSION

In this paper we presented recent experimental results of transverse beam size measurements using the method based on the analysis of the OTR PSF structure. We learned that improvements in the experimental setup (such as using achromatic doublets), improving analysis software and minimizing different optical effects (such as diffraction and spherical and chromatic aberration) allows to achieve a sub-micrometer resolution. The minimum measured vertical beam size was 0.754±0.034 $\mu$m which is approximately 5 times better than the resolution of conventional OTR monitors.

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 tools for optical calculations (such as ZEMAX [8]) in order to better understand of the PSF behavior and optimize the optical system. It was shown in [9] that using such tools give good agreement with the experimental data. In the next step we are planning to use ZEMAX to optimize the optical system, apply either a multi-element optics or a reflective optics to reduce the resolution of the monitor even further. For example using an off-axis parabolic mirror can reduce the chromatic 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. Using reflective elements for OTR beam profile measurements as well as its influence on the resolution needs to be further investigated.

## ACKNOWLEDGMENT

We would like to acknowledge the Laserwire team, ATF II collaboration and, in particular, T. Okugi for their support. This research was partially supported by the oPAC: FP7 Marie Curie Initial Training Network under contract PITN-GA-2011-289485, Quantum Beam Technology Program of the Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT) and SASAKAWA foundation (Grant No. 3875), JSPS KAKENHI Grant No. 23226020.

## REFERENCES

[1] L. J. Nevay *et al.*, "Sub-Micrometre Resolution Laserwire Transverse Beam Size Measurement System", MOPF16.

[2] M. Ross, S. Anderson, J. Frisch *et al.*, SLAC Pub. 9280, (2002).

[3] P. Karataev, A. Aryshev, S. Boogert *et al.*, Physical Review Letters 107, 174801, (2011).

[4] A. Aryshev, S. T. Boogert, D. Howell *et al.*, Journ. of Physics: Conf. Series 236, 012008, (2010).

[5] A. Aryshev, N. Terunuma, J. Urakawa, "Sub-micrometer resolution transverse electron beam size measurement system based on optical transition radiation", IPAC'10, Kyoto, May 2010, MOPEA052, p. 193, http://www.JACoW.org.

[6] SAD, Strategic Accelerator Design, http://www.acc-physics.kek.jp/SAD.

[7] A.Aryshev, N. Terunuma, S. T. Boogert *et al.*, "Sub micrometer resolution transverse electron beam size measurement system based on optical transition radiation", IPAC'11, San Sebastian, September 2011, WEOB01, p. 164, http://www.JACoW.org.

[8] "ZEMAX", software for optical design, http://www.zemax.com.

[9] B. Bolzon *et al.*, "Results of the high resolution OTR measurements at KEK and comparison with simulations", MOPF04.



ISBN 978-3-95450-127-4