

Beam-Size Measurement with Optical Diffraction Radiation at KEK Accelerator Test Facility

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An experiment on the investigation of optical diffraction radiation (ODR) from a slit target as a possible tool for noninvasive electron beam-size diagnostics has been performed at the KEK accelerator test facility. The experimental setup has been installed at the diagnostics section of the extraction line. We have performed the first incoherent ODR observation from a slit target. The measured angular distributions are in reasonable agreement with the theoretical expectation. The beam-size effect onto the ODR angular pattern has been observed. Moreover, the sensitivity to the beam size as small as 14 μm has been achieved.

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Nowadays a few techniques for measuring an electron beam size as small as 10 μm with resolution of 1 μm are being developed at the accelerator installations with different beam energies. That is the requirement for the accelerator installations of the next generations such as linear collider [1], where a small beam size at the interaction point is required to achieve a reasonable luminosity. A beam with 10 μm vertical size will be accelerated in the main linac. Therefore, it is extremely necessary to control the beam size at every stage of the accelerating process from injection to extraction. The modern accelerators preclude the use of any invasive techniques like wire scanners or transition radiation monitors due to a significant emittance growth. However, a simple noninvasive method for beam-size measurement with a single shot is still absent.

Optical diffraction radiation (ODR) appearing when a charged particle moves in the vicinity of a medium [2] is a very promising effect for beam-size monitoring. If the particle passes through a slit between two semiplanes (see, for instance, Fig. 1), it induces currents changing in time on both half planes. Those currents give rise in radiation. Two cones propagate in the direction of specular reflection producing an interference pattern, which is very sensitive to the transversal beam parameters. Since the particles do not directly interact with the target it allows keeping the beam parameters almost the same as the initial ones. The first observation and investigation of the ODR effect from a single edge target has been performed by us and represented in [3]. The experimental results were in reasonable agreement with the theory of ideally conducting infinitely thin target. In this Letter we represent ODR measurements from a slit and the beam-size effect.

The first theoretical consideration on the beam-size diagnostics using ODR technique appeared a few years ago [4,5]. In those papers it was shown that for the

geometry shown in Fig. 1 only the vertical polarization component is sensitive to the vertical beam size. The angular distribution of it convoluted with a Gaussian could be represented in the form

$$\frac{d^2 W_y^{\text{slit}}}{d\omega d\Omega} = \frac{\alpha \gamma^2 \exp(-z\sqrt{1+t_x^2})}{4\pi^2 (1+t_x^2+t_y^2)} \times \left\{ \exp\left[\frac{2z^2\sigma_y^2}{a^2}(1+t_x^2)\right] \times \cosh\left[\frac{2zb}{a}\sqrt{1+t_x^2}\right] - \cos[z t_y + 2\psi] \right\} \quad (1)$$

Here $\alpha = 1/137$ is the fine structure constant, γ is the particle Lorentz factor, a is the effective slit size (the real one is $a/\sin\theta_0$, where θ_0 is the target tilt angle), $t_{x,y} = \gamma\theta_{x,y}$ are the observation angles measured from the direction of specular reflection (see Fig. 1) in units of the γ^{-1} , $z = \omega/\omega_c = 2\pi a/\gamma\lambda$ is the emitted photon energy in units of the ODR characteristic energy ω_c , σ_y is the vertical rms beam size, b is the beam offset with respect to the slit center (see Fig. 1), and $\psi = \arctan[t_y/\sqrt{1+t_x^2}]$.

Figure 2(a) illustrates the two-dimensional angular distribution of the vertical polarization component. The intensity between two peaks strongly depends on the

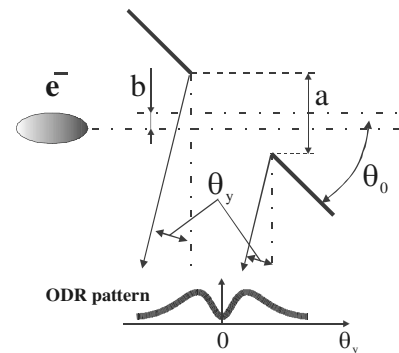


FIG. 1. Geometry of the ODR production.

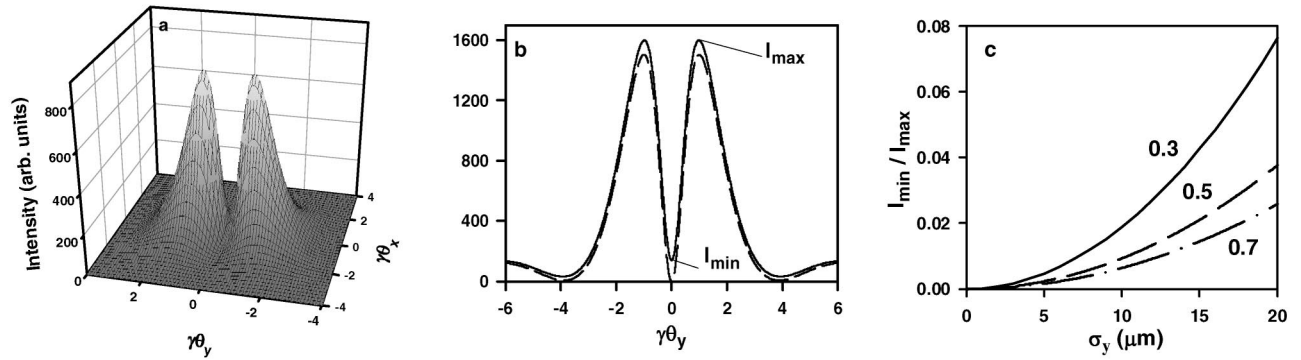


FIG. 2. (a) Two-dimensional vertical polarization component pattern calculated for $\gamma = 2500$, $\lambda = 500$ nm, $a = 0.2$ mm, $\theta_0 = 45$ deg, and $b = 0$. (b) Projected vertical polarization component calculated for $\sigma_y = 0$ (dashed line), and $\sigma_y = 30$ mm (solid line). (c) Minimum-to-maximum ratio for projected vertical polarization component calculated for different photon wavelengths shown near the curves, in μm .

beam size (for a single electron the intensity is zero). Therefore, the best way is to measure the projection of the polarization component (integrate over θ_x). The projection calculated for two beam sizes is represented in Fig. 2(b). One may see that the distribution is deformed while the beam size increases. As a criterion for the sensitivity we have chosen the minimum-to-maximum ratio. The ratio shown in Fig. 2(c) is calculated for three different photon wavelengths. From Eq. (1) it is seen that the sensitivity to the beam size is determined by the ratio $\sigma_y^2/\gamma^2\lambda^2$. From Fig. 2(c) it is clear that the sensitivity to the beam size is better for a shorter wavelength.

This method is applicable for extremely low emittance beams, when the effect of the angular divergence is negligible. KEK-ATF (accelerator test facility) vertical beam emittance is 1.5×10^{-11} m rad. Assuming $10 \mu\text{m}$ rms beam size the rms angular divergence is $1.5 \mu\text{rad}$, which is more than an order smaller than the case considered in [4]. During the experiment preparation we have performed a lot of estimations on this issue [5,6], and have become sure that the beam-size effect is dominant.

The experimental setup for the ODR experiment has been installed in the diagnostics section of the KEK-ATF extraction line [7]. The extracted beam parameters are listed in Table I. The experimental layout is represented in Fig. 3. The target chamber (T) has a very precise target movement mechanism with a linear gauge having a precision better than $0.5 \mu\text{m}$. The target is a very important element in our experiment. Even a small target deformation may significantly distort the ODR interference pat-

tern [8]. The final solution we found was a silicon wafer of 7×9 mm dimensions coated with gold for better reflectivity. The silicon has a 0.26×5 mm hole. For an optical wavelength the target could be considered as a slit between two semiplanes. Since the target is not completely cut, two halves of it are naturally coplanar. The target is mounted at 45 deg to the beam trajectory. The optical system consists of a double axis rotatable mirror (M1) for measuring the angular distribution, two reflecting mirrors (M2 and M3), a polarizer (P), an optical filter with 550 ± 20 nm wavelength (F), a photomultiplier (PMT, H1161 of the Hamamatsu Photonics Company, with the photocathode wavelength efficiency range from 300–650 nm), and a collimator in front of it. The collimator size was chosen to be 0.25×21 mm (plane collimator for measuring the projected vertical polarization component). Since the target-to-detector distance was 3.56 m, the collimator angular acceptance was $\Delta\theta_y = 0.07$ mrad $= 0.176\gamma^{-1}$ and $\Delta\theta_x = 5.9$ mrad $= 14.7\gamma^{-1}$. To align the optical system we designed a laser alignment system (accuracy $< \gamma^{-1} = 0.4$ mrad) consisting of a laser focusing system, a vacuum mirror, and two screen monitors (S1 and S2). The laser spot and the beam can be observed at the screen monitors. If the laser direction did not coincide with the beam trajectory, the laser could

TABLE I. Beam parameters [7].

Energy	1.28 GeV ($\gamma = 2505$)
Vertical emittance	1.5×10^{-11} m rad
Horizontal emittance	1.4×10^{-9} m rad
Bunch population	1.2×10^{10}
Bunch length	~ 8 mm

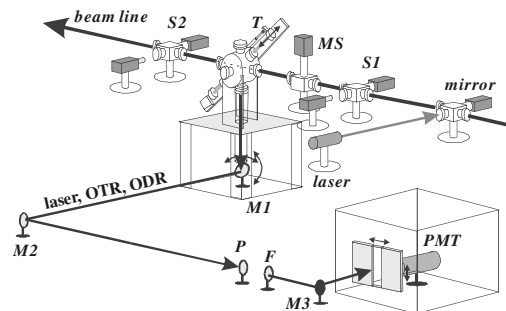


FIG. 3. Experimental layout.

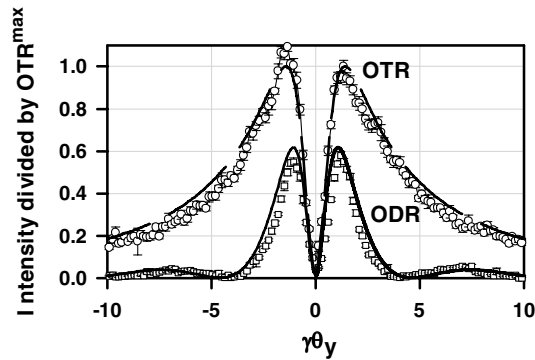


FIG. 4. Measured OTR (open circles) and ODR (open squares) projected vertical polarization component distributions and calculated OTR (dashed line) and ODR (solid line) ones including detector angular acceptance, optical filter bandwidth, and $10 \mu\text{m}$ beam size.

be corrected using precise adjustment screws of the laser stage. Reflecting the laser from the target we could align the optical system (see Fig. 3).

The ATF extraction line contains many different magnetic devices. They are supposed to change (correct) the beam trajectory. It may lead to the appearance of the synchrotron radiation (SR) photons. The main radiation source was a dipole bending magnet installed 8 m upstream of our target. To avoid the SR contribution a mask has been installed half a meter upstream of the target to cut the SR off. The mask itself is a ceramic plate with a $1 \times 2 \text{ mm}$ hole in it [8]. The measurements have shown that the mask cuts off a dominant part of the SR background.

Optical transition radiation (OTR) has been used for checking our optical system because it is experimentally and theoretically studied very well [2]. OTR was obtained using the same target when the beam moved through the target material at the distance from the slit $> \gamma\lambda = 1.4 \text{ mm}$.

Figure 4 illustrates OTR projected vertical polarization component angular distribution normalized by maximum: open circles, experiment; dashed line, theory. One may see that the measured distribution is slightly asymmetric. The asymmetry might be caused by the left part of the SR photons propagating through the mask slit. For normalization we have chosen the right maximum where the SR contribution is smaller. The open squares and solid line in Fig. 4 represent the measured and calculated ODR projected vertical polarization component, respectively, normalized by OTR maximum. One may see a clear interference pattern in ODR distribution. That is the result of interference of ODR photons produced by the particles at two halves of the target. Of course, the total ODR photon yield is much smaller than the OTR one. However, the interference leads to increasing of the ODR zero diffraction order. The ODR maximum intensity is $58 \pm 4\%$ of the OTR one. That is

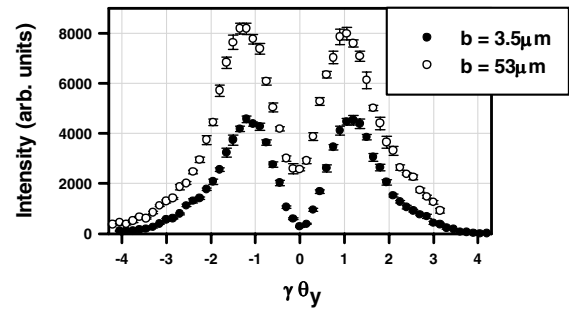


FIG. 5. ODR projected vertical polarization component measured at two different offsets with respect to the slit center.

consistent with the theoretical expectation (62%). It gave us a good possibility to measure ODR distribution with a proper accuracy.

Figure 5 depicts the ODR distribution measured at two beam positions with respect to the slit center. The beam size and beam position affect the distribution distortion in a similar way. Therefore, we had to take care about the beam centering. From Fig. 5 it is possible to determine the minimum-to-maximum ratio. Figure 6(a) represents the ratio as a function of the target position. By making a parabolic fit of this dependence we could determine the minimal ratio corresponding to the slit center and its error. The beam size and its error are found by comparing the measured and calculated ratio [see Fig. 6(b)].

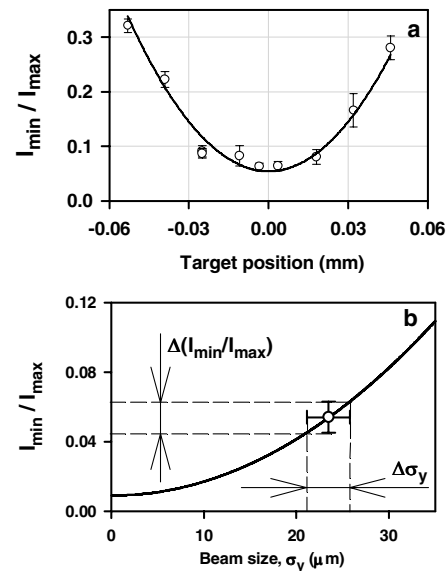


FIG. 6. (a) Measured minimum-to-maximum ratio of the ODR distribution as a function of the target position. The solid line represents the parabolic fit. (b) Minimum-to-maximum ratio as a function of the beam size calculated including angular acceptance and optical fiber bandwidth. The open circle represents the ratio and its error determined from the parabolic fit from (a).

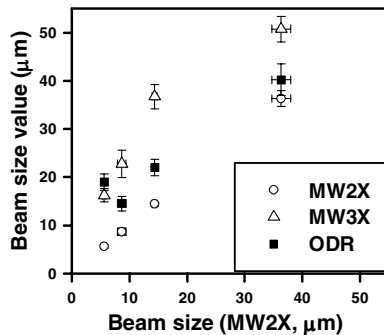


FIG. 7. The correlation between the beam size measured with ODR (black squares) and two wire scanners installed upstream (open circles) and downstream (open triangles) of the target.

Afterwards, beam position monitors can be used to control the slit center.

To investigate the beam-size effect onto the ODR angular pattern we used a set of wire scanners to measure the beam size. The beam size was changed by the beam optics of the extraction line and measured with wire scanners installed 0.7 m upstream (MW2X) and 1.51 m downstream (MW3X) of the target and with an ODR monitor. The correlation between the wire scanners and the ODR measurements are represented in Fig. 7. One may see that the beam size measured with ODR is in between the wire scanners and keeps increasing starting from 14 μm . This picture shows that the ODR angular pattern is sensitive to the electron beam size. Moreover, the sensitivity to the beam size as small as 14 μm is achieved. This is the first time in beam diagnostics that the ODR technique was successfully applied to measure beam sizes. One of the possible ways to increase the accuracy of the method is to calibrate the ODR pattern by a wire scanner at the right position. In that case it is necessary to install a small wire into the target chamber in order to measure the beam size precisely near the target.

The errors shown in Fig. 7 are statistical ones. However, one should say that there is a systematic error, which does not allow us to measure the beam size smaller than 10 μm . It might be caused by an uncontrolled part of SR photons in the minimum of the distribution propagating through the mask hole and reflected from the target.

One of the possible ways to reduce the error is to use a smaller mask aperture.

At present it takes about 10 min to measure one ODR angular distribution. The goal of our investigations is a single shot beam-size diagnostics. For that purpose in the nearest future we plan to use a multianode photomultiplier tube to measure all points of the ODR distribution, which will make single shot measurement possible.

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