DEVELOPMENT OF OPTICAL DIFFRACTION RADIATION BEAM SIZE DIAGNOSTICS AT KEK ACCELERATOR TEST FACILITY

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Abstract

Extremely low emittance high current beam is required for the accelerators of the next generation such as linear colliders to achieve a required luminosity. However, up to now there is no a simple non-invasive technique for beam diagnostics. A method based on optical diffraction radiation (ODR) appearing when a charged particle passes through a slit between two semi-planes is one of the promising candidates. The estimations show that it might be possible to measure the beam size as small as 10μm for a single shot. However, undoubtedly the experimental investigation of the ODR characteristics is required. In this paper we describe the measurement of ODR angular distribution performed using CCD camera with an Image Intensifier. A huge synchrotron radiation (SR) background from the upstream bending magnet was observed. For beam diagnostics it was extremely necessary to reject the background, because it significantly distorted the ODR angular pattern. For that purpose we installed SR mask in front of the target and cut off the dominant part of the SR photons.

THEORY

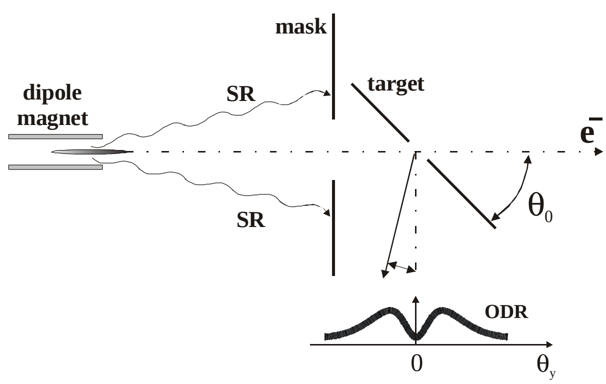

Figure 1: Geometry of the ODR production from a slit (right part) and the mask for SR suppression (left part).

Diffraction Radiation (DR) appears when a charged particle moves in the vicinity of a medium. A simple geometry is represented in Fig. 1. The particle moving in vacuum passes through a slit between two semi-planes (target) [1]. Since the particle does not directly interact with the target its trajectory is kept almost the same as the initial one. For a bunch of particles it allows keeping the beam parameters almost the same as the initial ones.

The first considerations on the feasibility of DR phenomenon for non-invasive beam diagnostics have appeared just about a few years ago [2-3]. However, experimentally the DR angular characteristics has not been properly investigated and compared with the theory.

In 2000 we have decided to start R&D project on the DR investigation in optical wavelength range (ODR) as a possible tool for non-invasive electron beam size diagnostics [4]. Two dimensional ODR spectral-angular distribution can be represented in the following form:

$$\frac{d^2W}{d\omega d\Omega}=\frac{\alpha}{4\pi^2}\frac{\exp\left[-z\sqrt{1+\gamma^2\theta_x^2}\right]}{\left(\gamma^{-2}+\theta_x^2\right)\left(\gamma^{-2}+\theta_x^2+\theta_y^2\right)}\times$$
$$\left\{\left[\theta_x^2\left(|R_x|^2+|R_y|^2\right)+\gamma^{-2}|R_y|^2\right]\exp\left[2z^2\sigma^2\left(1+\gamma^{-2}\theta_x^2\right)\right]\right.$$
$$\left.+\left[\theta_x^2\left(|R_x|^2-|R_y|^2\right)-\gamma^{-2}|R_y|^2\right]\cos\left[z\gamma\theta_y+2\psi\right]\right\}$$

Where α is the fine structure constant, γ is the Lorenz-factor, θ_x and θ_y are observation angles with respect to specular reflection, σ is the rms beam size in units of the target slit size, $z = 2\pi a / \gamma\lambda$, where a is the slit size, $\psi=\arctan\left[\theta_y/\sqrt{\gamma^{-2}+\theta_x^2}\right]$, R_x and R_y are the Fresnel reflection coefficients for vertical and horizontal polarization components [3] respectively.

The upper equation is applicable only in case when $\sigma<<1$, i.e. when the number of particles hitting the target is negligible. It necessary to notice that a = 0 (z = 0) the ODR expression is transformed into one for transition radiation from an infinite boundary. This effect is well investigated, and we used it to check our optical system.

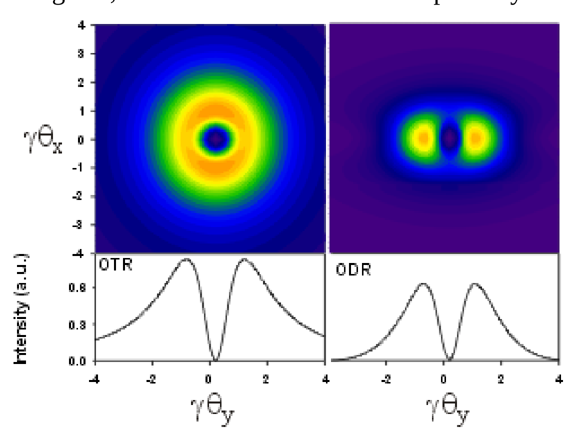

Figure 2: Calculated OTR (left) and ODR (right) angular distributions. Lower plots represent OTR and ODR one-dimensional angular distributions. The calculation parameters:λ=550nm,γ=2500,θ_x=0,a=0.185mm, reflection coefficients for gold are $|R_x|^2$=91.42 and $|R_y|^2$=83.57 [5].

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Figure 2 illustrates the OTR (left) and ODR (right) angular distributions calculated for a gold target. For an ideal conductor ($|R_x|^2=|R_y|^2=1$) the OTR angular pattern is azimuthally symmetric and has a crater like shape with polar angle of γ^{-1}. One may see a slight azimuthal asymmetry in OTR pattern. Since the target is tilted at 45 deg. to the beam trajectory, the Fresnel reflection coefficients are different. This aspect causes the asymmetry. Actually, Figure 2 represents the OTR and ODR spots, which we expected to observe experimentally.

SETUP

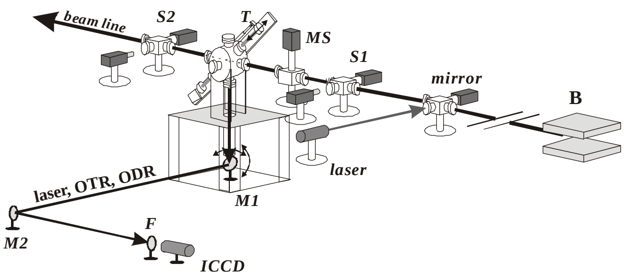

Figure 3: Experimental layout.

KEK-ATF consists of a S-band high gradient linac, a transport line, a damping ring and an extraction line [6]. The experimental set-up was installed in the diagnostics section of the KEK-ATF extraction line. The relevant parameters of the ATF extracted beam are listed up in Table1.

Table 1: KEK-ATF beam parameters.

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

The experimental layout for ODR experiment is represented in Fig.3. The target chamber (T) has a very precise target movement mechanism (linear gauge >0.5μ). The target is mounted at 45 deg. to the beam trajectory. The target is a silicon wafer with 7×9mm dimensions covered with gold for better reflectivity. The plate has rectangular hole of 0.26×5mm^2. To be able to consider the target as a slit between two semi-planes, the horizontal hole size must be larger than $2\gamma\lambda$ = 2.8mm. Therefore, our target configuration satisfies this condition. Such target has been chosen to avoid its misalignment. As the target is not completely cut, two halves of it are naturally co-planar. Since the target is tilted, the effective slit size a = 0.26 sin(45) = 185μm. The target thickness is 0.3mm. Our main idea is that the electron beam must not touch the target at all. For that purpose the slit edges have an oblique shape [7]. It allowed us to reduce the slit size and increase the ODR photon yield.

Optical system consists of a double axis remotely controlled rotatable mirror (M1) for alignment correction, a reflecting mirror (M2), an optical filter with 550±20nm wavelength, and a CCD camera (JAI corp. CV-M10) with an Image Intensifier (Hamamatsu, C4078-01, sensitivity wavelength range – 185-900nm), which is indicated in Fig. 3 as ICCD. The optical system is aligned by a laser alignment system consisting of laser system (He-Ne laser, spatial filter, and a lens with 100mm focus), reflecting mirror, and two screen monitors (S1 and S2). The laser is reflected along the beam trajectory. The laser and the beam positions can be observed at screen monitors. The laser direction can be adjusted in order to coincide with the beam direction. The first experiment has shown that the alignment accuracy is better than γ^{-1}, which is enough for starting experiment. The final beam-based alignment is performed using rotatable mirror.

For a long time we have been experiencing some difficulties related to a synchrotron radiation (SR) background. KEK-ATF extraction line contains many magnetic devices, which are supposed to change the particle trajectories [6]. However, the main SR source was a bending (dipole) magnet (**B** in Fig. 3) situated 8m upstream our target. One of the present paper authors have performed a detailed analysis of the SR background [8]. It has been noted that the SR might be comparable to ODR effect. We reduced the target size to reduce the reflecting surface. We also tried to adjust the beam orbit. The SR contribution became smaller, but it still was big. Another solution we have found was a SR mask. We designed a mask chamber and installed it 0.3m upstream the ODR target (MS in Fig. 3). The mask itself is a ceramic plate with 1×2mm hole in it. A schematic geometry for the SR suppression is represented in Fig. 1.

EXPERIMENTAL RESULTS

In the experimental part we present single shot measurements. Figure 4 represents the OTR (left) and ODR (right) measurement using ICCD. One may see a clear interference pattern. That is the interference with synchrotron radiation. The interference pattern depends on the electron beam orbit tuning and stability. That is impossible to perform the beam diagnostics while the SR contribution exist. Therefore, a method for SR suppression was strongly required.

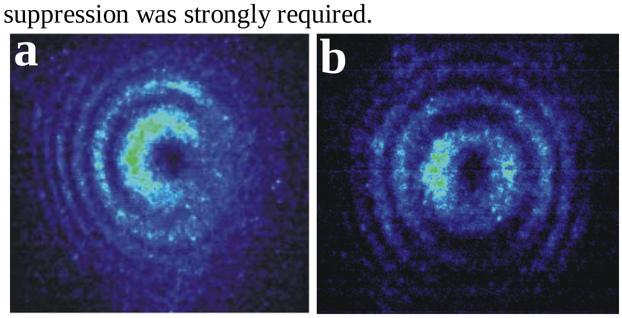

Figure 4: OTR (a) and ODR (b) spots measured with 550±20nm optical filter. Here horizontal axis - θ_y and vertical axis - θ_x.

For that purpose we have designed a SR mask to be able to cut the SR photons off from upstream. Since the distance from the dipole magnet to the target is about 8m, the SR spot in the vicinity of the target is very wide. The

SR photons reflect from the target and interfere with the OTR or the ODR. That can be seen from Fig. 4. Obviously while the SR contribution exists the beam diagnostics is impossible. The SR mask covered the dominant part of the target surface.

Figure 5 illustrates the OTR (left) and ODR (right) measurements with the mask. One may see that the interference pattern has disappeared. That is the effect of the mask. Figure 5 proves that the mask is really effective, and the beam size measurement can be performed.

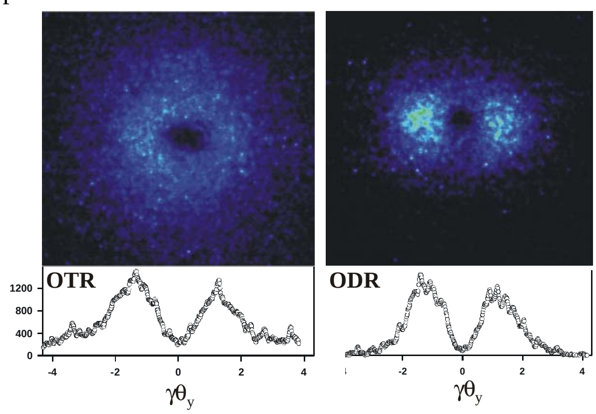

Figure 5: OTR (left) and ODR (left) spots measured with 550±20nm optical filter after SR suppression using mask. Lower plots represent OTR and ODR one-dimensional angular distributions integrated over 20 CCD channels.

The OTR and ODR spots are consistent with the calculated ones shown in Fig. 2. However, a slight asymmetry in OTR image exists. In fact a part of SR photons propagate through the mask hole. We assume that the asymmetry is effect of the left part of the SR. In case of DR the SR is much smaller, because a part the SR photons propagating through the mask hole keep moving through the target slit and do not reflect from the target. Therefore, the real contribution of the SR background is even smaller.

Unfortunately it is impossible to perform the beam diagnostics with the ICCD. There are two reasons. One of them is that the dynamic range is only 8 bit. For our purpose at least 14 bit is required [4]. Another reason is that the accuracy of the ICCD is not enough. However, ICCD is very useful for the first step investigations.

CONCLUSION

In this paper we represent the first observation of incoherent ODR two-dimensional angular distribution measured for a single shot. To be able to investigate the beam size effect onto the ODR angular pattern we have applied the photomultiplier (PMT). The signal from PMT was acquired by a charge sensitive ADC with 14 bit dynamic range, which was quite enough for our purpose. The beam size effect onto the ODR angular pattern was investigated [9]. We have achieved the sensitivity to the beam size as small as 15μm. However, we suppose that a systematic error exists, which might be caused by the left part of SR photons, experimental hall X-ray background. To be able to measure the beam size smaller than 10μm, we shall have to understand and reduce the systematic error.

Obviously the measurements with the PMT are not single shot ones. But, undoubtedly that is the a reasonable first step of the ultimate goal. To be able to perform the single shot measurement we consider to use a multi-anode PMT in order to measure all points of the ODR angular distribution. In that case a single shot beam size measurement might be possible

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