MULTIPLE PARAMETER CHARACTERIZATIONS FOR ELECTRON BEAM WITH DIFFRACTION RADIATION

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Abstract

There are growing interests in developing non-intercepting method for real-time monitoring electron beam parameters for international linear collider (ILC) and X-ray free electron lasers (XFEL). In this paper we briefly review the theories on using optical and coherent diffraction radiation (ODR and CDR) to measure electron beam profile, divergence, emittance and bunch length. We focus on using ODR to direct image electron beam profile. A new method for bunch length measurement with diffraction radiation deflector is introduced. We also report the preliminary study on radiation spectrum distortion that generally occurs when using CDR to measure bunch length with Martin-Puplett or Michelson interferometers.

INTRODUCTIONS

There are growing interests in developing non-intercepting methods to characterize beam parameters as is motivated by the challenge of ILC and XFELs where the high intensity beam excludes the use of the intercepting method for which the beam directly hits the target. Such direct interaction on the one hand causes huge heat deposition to the target, and on the other hand, results in emittance growth by randomly increasing the beam divergence from Coulombic scattering. DR is considered to be one of the most promising candidates for beam diagnostics due to its non-intercepting and multi-parameter capabilities.

Using ODR angular distribution to measure relativistic electron beam size and divergence from rectangular slit [1-3] and circular aperture [4-5] have been widely studied. Recently the experimental demonstration of the method has been reported [6]. Using ODR to direct image the beam profile and monitor beam position is also suggested and experimentally tested [7-8]. As for the long wavelength component, CDR has been used to measure electron bunch length and longitudinal shape [9-10]. The problem of bunch length measurement with CDR is that there is spectrum distortion during its propagation. In this paper, we report our preliminary experiment to calibrate the spectrum distortion with a blackbody. We also introduce a new method which does not suffer from the spectrum distortion problem.

DR PROPERTIES IN PRACTICAL CONDITIONS

DR is generated when there is optical inhomogeneity in space the presence of which would induce changing currents that generate the radiation. In ideal case when the target has infinite size and the observation is made in far field, the DR problem can be treated by solving Maxwell's equations. However, in practical conditions neither the DR target is infinitely large nor the observation could always be made in far field, and the properties of DR may largely deviate from that obtained for ideal case. We have applied the Fresnel-Kirchhoff diffraction model to effectively treat this problem [11]. In this model, the field of an electron is quantized into virtual photons that's locked to the electron and cannot propagate freely. But when transmitted through or reflected by the metallic target, the virtual photons can convert to real photons which propagate along the direction of velocity and the specular reflection direction. Consider the target as secondary wave, the real photon field for a given frequency component is found by Fresnel diffraction integration [11],

$$\tilde{E}_{x,y}(z,\rho,\phi,\omega) = -\frac{i}{\lambda}\iint_S \frac{e\alpha}{\pi v} K_1\left(\alpha\rho_0\right) \begin{Bmatrix} \cos\phi_0 \\ \sin\phi_0 \end{Bmatrix} \frac{e^{ikR'}}{R'} dS,$$

Properly formulating the distance from the secondary wave to the observation point and performing the integration for the specific target allows us to study the DR for finite size target and in pre-wave zone. Generally speaking, the most prominent deviation for DR from finite size target and in pre-wave zone from that from infinite size target in wave zone is that the angular distribution peaks at a larger angle and the intensity is lower.

USING ODR ANGULAR DISTRIBUTION TO MEASURE BEAM SIZE

When electron beam passes through a rectangular slit, the DR fields from the upper plane and that from the lower plane will interfere. The interference pattern is a representation of the spatial coherence and gives the information about the beam size. The larger the beam size, the lower the visibility of the angular distribution. Since the case when electron beam passes through a rectangular slit has been widely studied [1-3], here we focus on ODR from circular aperture [5].

Take the horizontal component as an example. Assuming the beam has Gaussian distribution in horizontal direction with rms size σ_x, the angular distribution for a whole beam is found by convoluting that for a single electron with the beam distribution. The results are shown in Fig.1 for various beam sizes. The parameters are $a/\gamma\lambda = 0.5$ where a is the radius of the aperture. Fig.1 shows that the intensity in the velocity direction is very sensitive to the beam size. In ideal case where beam has no divergence, one could use the ratio of the intensity in the velocity direction to the peak intensity to predict the beam size.

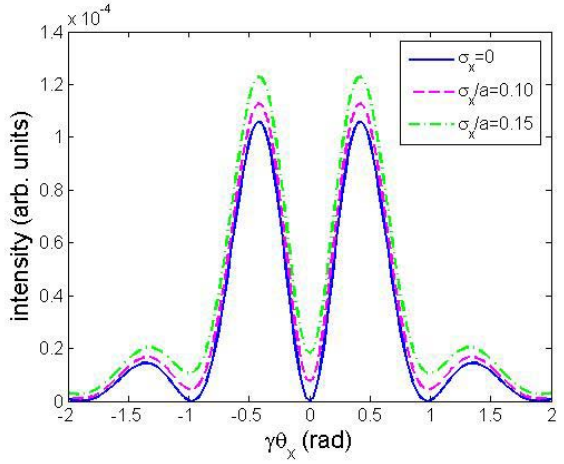

Fig.1 Angular distribution of a beam with various sizes

We also see from Fig.1 that the smaller the beam size, the smaller the ratio. This feature may make the measurement for very small beam difficult. We have suggested a new scheme for measuring very small beam size with ODR from a rectangular slit in which the rectangular slit is scanned transversely [5]. By recording the intensity in beam's velocity direction as a function of beam offset, the beam size can be determined. The most attracting feature of this method is that the sensitivity increases as the beam size decreases, which makes this method very suitable for small beam size measurement.

IMAGING OF HIGH-ENERGY ELECTRON BEAM WITH ODR

The main drawback of beam size determination with ODR angular distribution is that generally both the beam size and divergence contributes to the angular distribution. Theoretical studies have been done which show how the divergence and beam size effects can be separated [2-3, 5]. However, up to now the angular distribution of ODR has only been employed to measure beam size for cases when the divergence effect is negligible [6]. Likewise, the method pre-assumes a Gaussian distribution for the beam profile and thus only predicts the rms beam size rather than the detailed profile which is typically obtained by direct imaging.

The image formation process can be understood as a 2 dimensional convolution. We follow a standard method to find the image of a beam, which is to first obtain the point spread function (PSF) for the specific imaging system, and then to convolve the real beam distribution with the PSF. As for imaging with ODR, the PSF should only involve the image of a single electron.

Consider a rectangular slit with width 200 μm, the image of a single electron formed with vertical component of ODR is calculated [8] and shown in Fig.2.

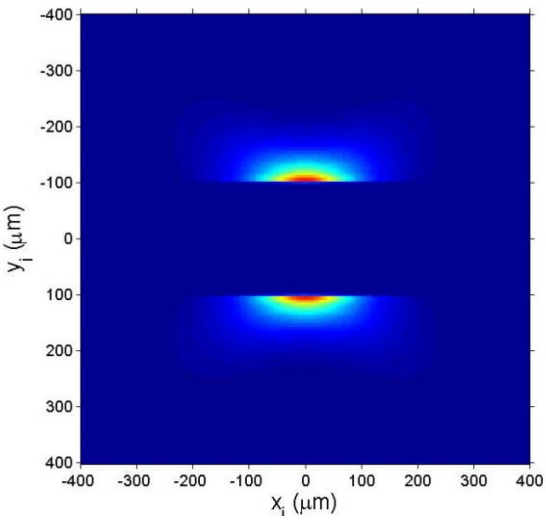

Fig. 2 PSF of ODR with vertical component.

We have used the parameters $\gamma = 2500$, $\lambda = 0.5$ μm; the acceptance angle of the lens is 0.1 rad and the magnification factor is unity. The beam image is found by convoluting the PSF with the beam's distribution. For a Gaussian beam with rms beam size 100 μm, the image is shown in Fig.3.

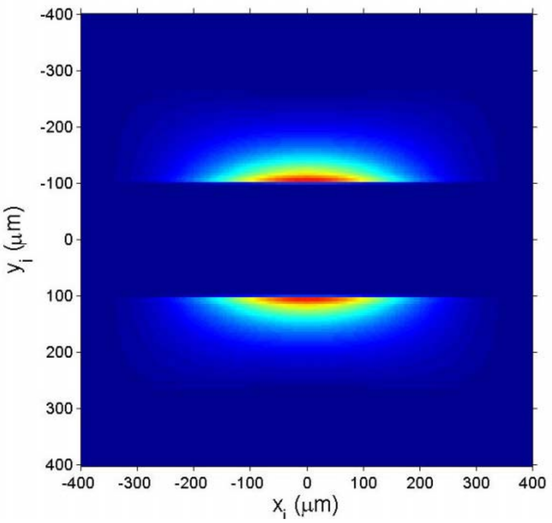

Fig.3 Beam image formed with ODR

We have shown in [8] that even though the beam image largely deviates from the real beam distribution, after deconvolution the beam distribution can be restored with high precision. The experimental results for direct imaging of high-energy electron beam with ODR has been reported and the results are encouraging [7].

USING CDR TO MEASURE BUNCH LENGTH

When the radiation wavelength is larger than or comparable to the length of electron bunch, the radiation becomes coherent and the electrons within the bunch can be considered as radiating with the same phase. On the one hand, the radiation power is enhanced by N times, where N is the number of electrons within a bunch and coherent radiation, e.g. coherent synchrotron radiation (CSR), CTR, CDR and coherent Smith-Percell radiation could be used as a strong far-infrared (FIR) source. On the other hand, since the coherent radiation contains much information on the bunch itself, CSR, CTR and CDR have been widely used for bunch length and longitudinal profile measurements [9-10].

The method generally uses interferometer (Michelson or Martin-Puplett) or spectrometer to obtain the radiation spectrum which is further used to predict the bunch length. The main problem of this method is that the accurate measurement of the spectrum is not trivial because the radiation measured by the detector could largely deviate from that originally generated by the electron bunch due to window transmission, diffraction loss, water and carbon oxide absorption in air, detector response, etc. To quantify the spectrum distortion, we have built a setup for calibration with a blackbody. The layout is shown in Fig.4.

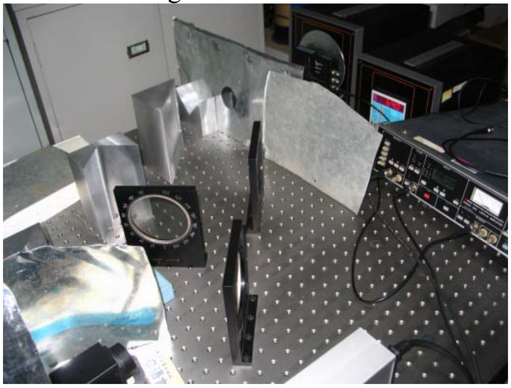

Fig.4 Layout for the calibration experiment.

The Martin-Puplett interferometer is mounted on an optical table. A diaphragm with diameter of 2 mm is put in front of the blackbody to form a point source. The diverging signal is converted into parallel with an off-axis parabolic mirror. Three wire grid polarizers are used as polarizer, beam splitter and analyzer, respectively. The FIR and mm wave is detected with a Golay cell. Some metallic plates are used to block the unwanted stray signals. With a lock-in amplifier, we are able to detect the weak signal which is about 0.2 mV.

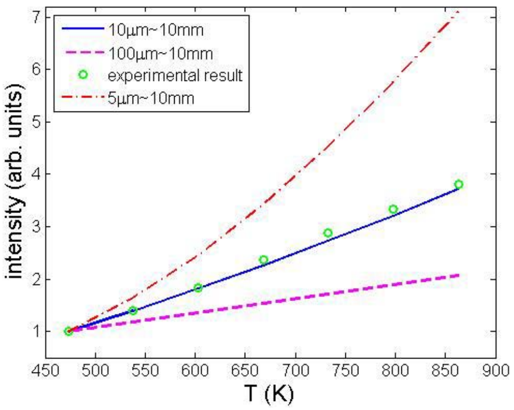

Fig.5 Radiation intensity as a function of temperature.

However, we fail to obtain the autocorrelation curve when changing the path length of the movable roof-mirror. This may be due to the fact that the signal is dominated by high frequency components. To verify this, we measured the signal as a function of temperature. The result is shown in Fig.5. The theoretical curve of blackbody radiation intensity when integrated within various bandwidth is also shown for comparison.

It seems the detected signal is most likely to be dominated by high frequency component around 10 μm which makes the autocorrelation curve difficult to measure. We plan to use a low pass filter in the future to block the high frequency component and the autocorrelation curve may be obtained.

To avoid the spectrum distortion problem, a new method called DR deflector is proposed in [12]. The DR deflector is composed of a DR radiator and 3 beam position monitors (BPM). When electron beam passes through a metallic aperture which is tilted by 45 degrees with respect to its trajectory, backward DR that propagates perpendicular to the beam's trajectory is generated which adds a transverse deflection to the beam as a result of momentum conservation. The deflection is found to be largely dependent on the bunch length and could be easily observed with a downstream BPM. Detailed investigations show that this method has wide applicability, high temporal resolution and great simplicity. An experiment is also in preparation to demonstrate the applicability of this method.

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