HIGH ENERGY MICRON ELECTRON BEAM NON-INVASIVE DIAGNOSTICS BASED ON DIFFRACTION RADIATION

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Abstract

A method of an optical diffraction radiation technique based on the phase shift on the slit target, consisting on the two semi-planes which are turned at a some angle one to other is suggested. The method of suppression of the pre-wave zone effect contribution is shown. This allows to realize the non-invasive measurements of transverse size of supper-relativistic electron beams with the small emittance for the single bunch diagnostics.

Last time a few techniques for measuring an electron beam size as small as 10 μ with resolution of 1 μ are being developed at the accelerator installations with different beam energies. However, a simple noninvasive method for beam-size measurement with a single shot is still absent.

BEAM SIZE MEASUREMENT EXISTING ADVANCED METHODS

There exist several well known beam size measurement methods. These methods have merits and demerits. Why we need a new method?

Let us consider more detail each of them. We will consider these methods possibilities in respect to SLAC FFTB conditions: electron energy up to 30 GeV, beam size about 10 μm, single bunch non-invasive measurement.

Synchrotron Radiation Interferometer

This method described in [2]) is based on synchrotron radiation angular pattern interference. It is of enough resolution for indicated electron beam size.

However a small SR intensity does not provide a single bunch measurement.

Laser Wire Scanner

This method [3] is based on a Compton scattering measurement when the thin laser beam crosses an electron beam. It is non-invasive and provides a necessary beam size resolution. However a small Compton scattering cross-section can not provide a single bunch measurement.

Transition Radiation Monitor

This method [4], which represent a high resolute transition radiation microscope, is of enough resolution for indicated electron beam size measurement . However it is an invasive method.

Laser Interferometer

In this method [5] a stable fine wave mode is provided by the split laser beam. Dependence of a Compton scattered phonon yield on the electron beam position relative to the laser interference picture depends on the electron beam size. This method due to a small Compton scattering cross-section cannot provide a single bunch measurement.

The overview of these methods shows that they do not satisfy at once the both requirements for the beam size measurement.

NON-INVASIVE DIAGNOSTICS BASED ON THE OPTICAL DIFFRACTION RADIATION

Short Prehistory

The project on the creation of the noninvasive diagnostics method using ODR of electrons, passing through conductive slit (Fig.1*a*) was started in 2000 in KEK ATF [6]. In this project we used the interference angular distribution pattern from both target semi-planes. The real criteria for the beam size assess is the relation Y_{min}/Y_{max} between minimum and maximum of ODR intensity in the angular distribution of the parallel polarization radiation component (see Fig. 1*b*). The measurement of these pattern was performed ([7]) in KEK ATF at 2004).

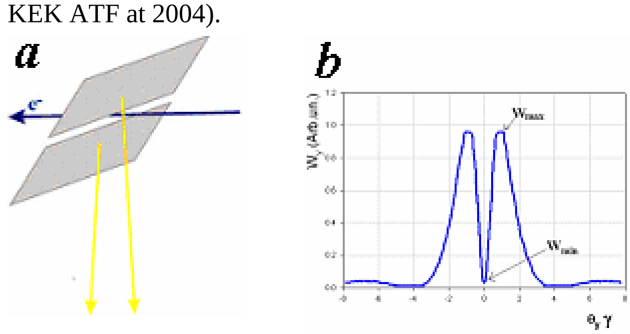

Figure 1: *a*: ODR from flat slit target. *b*: ODR angular distribution from flat slit target.

Using this technique the beam size of 10 microns KEK ATF extracted beam was measured. We must note that here we had reached the limit of method sensitivity.

Moreover in [8] was shown that the method sensitivity gets worse catastrophically if the electron energy increase up to 30 GeV. So we should modify ODR technique to provide the response on the beam size not depending on γ.

ODR Method Modification

The suggested technique is very close to the synchrotron radiation (SR) pattern interference method for beam size measurement, where mirrors are used for bringing together radiation patterns.

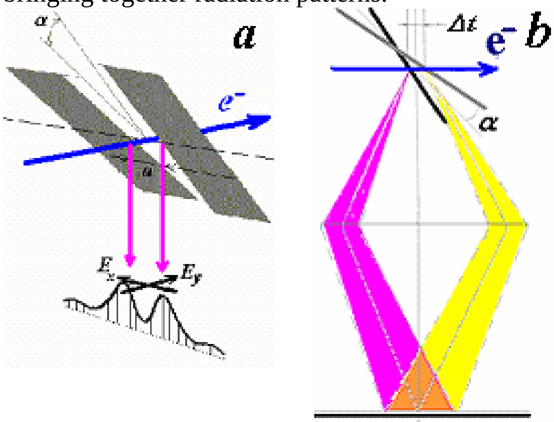

Figure 2: *a*: New target geometry. *b*: Radiation geometry.

However ODR intensity from slit target is comparable to the optical transition radiation (OTR) one in contrast to the SR. This allows us to hope on the single shot beam size measurement.

Principle

We suggest to introduce the additional radiation phase shift which depends on a transverse electron position. For this purpose we suggest to turn at the small angle α around the horizontal axis (see Fig. 2*a*) both semi-planes of the slit target, relative one to other. We name this target a "crossed target". ODR is emitted from each semi-plane at the direction of a specular reflection (see fig. 2*b*) and these ODR beams will defer only by the phase difference $\Delta\varphi$ defined by the time difference Δt (Fig.3*a*), which depends on the electron position Δz.

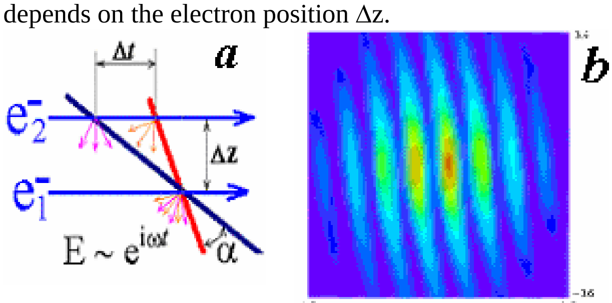

Figure 3: *a*: Phase difference shaping for different electron positions. *b*: Calculated interference picture from a crossed target.

So that $\Delta\varphi = i\cdot\omega\cdot\Delta t = i\cdot 4\pi\cdot\alpha\cdot\Delta z/\lambda$.

If we bring both ODR beams together like in Fig. 2*b* saving the phase shift $\Delta\varphi$, we obtain an interference picture shown in Fig. 3*b*. The position of W_{min} depends on an electron position and as a result for the total beam the relation W_{min}/W_{max} depends on a beam size. It should be taken attention that this dependence does not depend on the Lorenz-factor. Therefore this method may be used for high-energy electron beam. If slit width $a \ll \gamma\lambda$, then ODR intensity is close to the OTR one.

So the response on the beam size may be comparable to the OTR intensity. But OTR angular distribution has been measured in our experiments on the KEK ATF electron beam for single bunch using CCD camera. So a single bunch beam size measurement for suggested technique may be realized.

Angular Pattern Bringing Together.

The detail analysis of the radiation evolution shows that we can not use a usual prism, lens or mirrors for radiation patterns bringing together, because these optical schemes neglect the initial phase difference from the crossed semi-planes and the interference picture does not depend on a beam size. However using a Frenel bi-prism (see Fig. 4), we can obtain the expected effect.

Figure 4: Frenel bi-prism based on the Frenel lens technology

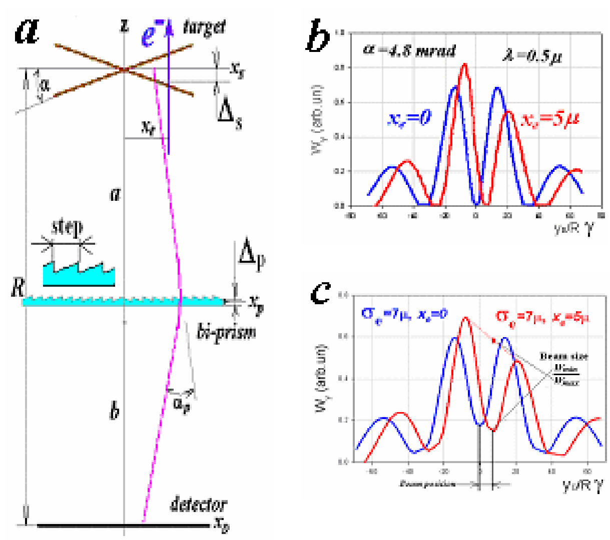

Figure 5: *a*: Beams evolution scheme. *b*: ODR angular distribution for different electron positions. *c*: ODR angular distribution for beam size and beam position measurement.

This may be shown on the simple example for the backward ODR shown on Fig. 5*a*. Using the pseudo-photon reflection approach we can present the y-component of radiation field in detector plane by next expression:

$$E_y^{\pm}(x_D,y_D)=\iint dx_s dy_s \iint dx_p dy_p \frac{1}{R}\times \left(\frac{-2e}{\gamma\lambda}\frac{y_s}{\sqrt{(x_s-x_e)^2+y_s^2}}K_1\left(\frac{2\pi}{\gamma\lambda}\sqrt{(x_s-x_e)^2+y_s^2}\right)\cdot e^{i\varphi^{\pm}}\right) \quad (1)$$

where K_1 is the Bessel function. For the condition $\frac{x_s,x_p,x_D,y_s,y_p,y_D}{a,b}<<1$ the phase may be presented as:

$$\varphi^{\pm}=\frac{2\pi}{\lambda}\left(\Delta_s+\frac{(x_p-x_s)^2+(y_p-y_s)^2}{2a}+\Delta_p+\frac{(x_D-x_p)^2+(y_D-y_p)^2}{2b}\right),$$

where $\Delta_s=\pm 2x_s\alpha$; $\Delta_p=\frac{step\cdot x_s}{|x_s|}\,frac\left(\frac{x_s}{step}\right)\cdot\alpha_p$.

The expression for a radiation intensity *y*- componen: $W_y=\left|E_y^+(x_D,y_D)+E_y^-(x_D,y_D)\right|^2$ Two integrals over bi-prism in (1) may be solved analytically, but integrals over the target surface are to be calculated numerically. ODR intensity angular distribution calculated using this expression for different electron position is shown on Fig. 5*b*. We may see that the variation of an electron position in *x* direction causes the shift of an ODR y-component angular distribution. This is the basis for the beam size measurement possibility.

On Fig. 5*c* is shown the result of convolution of the radiation angular distribution with gaussian electron distribution for two electron beams with different average position. The W_{min}/W_{max} relation indicate a beam size and the shift of the angular distribution minimum indicate a beam position. So the suggested method may be used for a beam size and beam position single bunch measurement.

PRE-WAVE ZONE EFFECT

Near field (pre-wave) zone effect take place if $\frac{R}{\gamma^2\lambda}<1$, where R is a distance from target to the observation point.

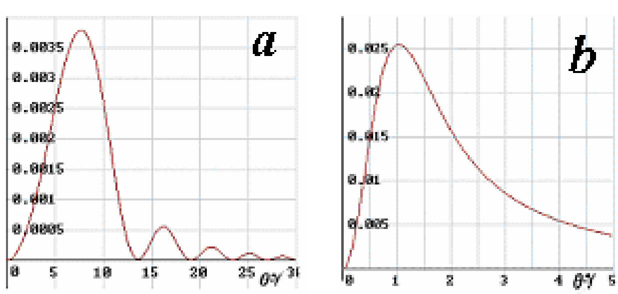

Figure 6: *a*: OTR angular distribution for $\frac{R}{\gamma^2\lambda}=0.011$

b: OTR angular distribution in far field zone.

For E_o=30 GeV $\gamma^2\lambda$ ≈1800 m. In these conditions experiments may be carried out only in extremely pre-wave zone. This results for example a transformation of the OTR angular distribution in far field zone (Fig. 6*b*) to the one shown on Fig. 6*a*, and may cause difficulties for a beam size prediction.

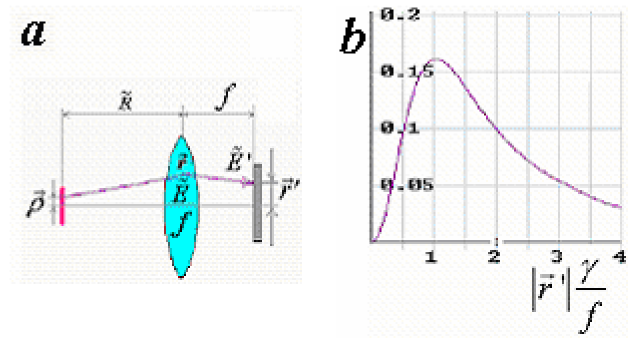

Figure 7: *a*: Optics for a near field zone effect suppression. *b*: OTR angular distribution in the focus of lens.

However this effect may be suppressed using a simple optics (Fig. 7*a*). Let us place the detector in a lens focus *f*. If a radiation field in a lens plane is $\tilde{E}(r)$, than we can calculate the radiation field in detector plane using (2). This results for example for OTR the intensity distribution in detector plane shown on Fig. 14.

$$\tilde{E}'=\int_0^b \tilde{E}(r)\cdot r\cdot J_1(-2\pi\cdot R\cdot r\cdot r')dr, \quad (2)$$

We can see in Fig. 7*b*, that with accuracy to the scale the OTR distribution in the focus plane coincides with the OTR angular distribution in a far field zone.

CONCLUSION

The theoretical test of crossed target technique with an optical system based on Frenel bi-prism, as well as the experimental test on the single bunch OTR angular distribution measurement, allows us to hope on a positive result in an experimental test on single bunch beam size measurement.

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