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Feasibility of Diffraction Radiation for a Non-invasive Diagnostics of the SLAC Electron Beam

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The development of the non-invasive bunch size diagnostics based on the diffraction radiation is now in progress in frame of TPU-KEK-SLAC collaboration. The experimental test of a transverse beam size measurement was performed successful on the KEK-ATF extracted electron beam. However many difficulties emerge if we going from the one GeV electron energy to the several tenth GeV electron beams. The extremely high Lorenz-factor value gives rise to the some problems, such as large contribution of a radiation from an accelerator construction elements in sub-millimeter wavelength region, extremely pre-wave zone effect even in the optical range, exceeding of the electron beam divergence over the diffraction radiation cone, and so on. More over, the sensitivity of the method based on the optical diffraction radiation from flat slit target decrease catastrophic when an electron energy increase up to several tenth GeV. We suggest the new method 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 (crossed target technique) and present here the results of experimental test of this technique. Also we discuss the origins of indicated difficulties and suggest the ways of these problems solution.

1. INTRODUCTION

Treatments of the usage of optical diffraction radiation (ODR) from the relativistic electrons moving though a conductive slit for the non-invasive transverse beam size measurement (for example [1]) encounter hard limitation of the method sensitivity for the electron energy larger than 1 GeV. Lower we consider a possibility of application in a 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. This allows us to realize the non-invasive measurements of transverse size of supper-relativistic electron beams with the small emittance.
The extremely high Lorenz-factor value gives rise to the some problems. Firs one is an extremely pre-wave zone. The existing diffraction radiation models were developed for the far field approach, when the distance between a target and detector is larger than square Lorenz-factor multiplied by wavelength. For the optical radiation from the SLAC electron beam this value is more than one kilometer, i.e. we can carry out the measurements only in extremely pre-wave zone. For solution of this problem we developed the optical technique, which suppress the near field zone effect. For the last problem elimination (exceeding of the electron beam divergence over the diffraction radiation cone) we propose to use the diffraction radiation from a bent target. This method allows to increase the radiation divergence so that the electron beam divergence contribution became negligible. All of the preceding allows us to hope to create a tools for the non-invasive beam diagnostics of electron beam with Lorenz-factor higher than 60000.

2. 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.

2.1. Synchrotron radiation interferometer

This method (Fig.1) described in [2]) is based on synchrotron radiation angular pattern interference. It is of enough resolution for indicated electron beam size.

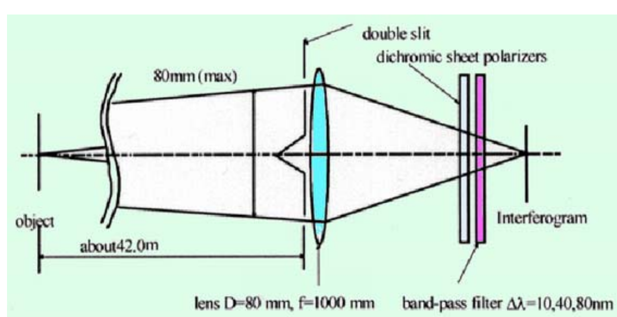

Fig.1. Setup of SR-interferometer

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

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2.2. Laser wire scanner [3]

This method (Fig. 2) 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.

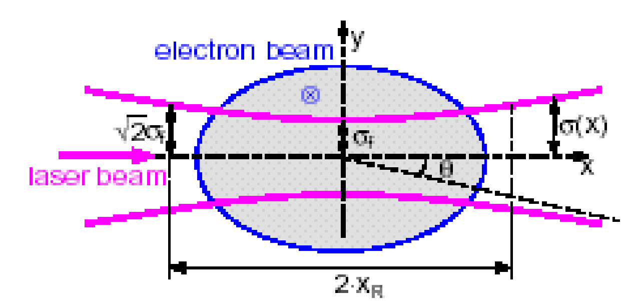

Fig. 2. Scheme of a gaussian laser beam focused to its diffraction limit.

However a small Compton scattering cross-section can not provide a single bunch measurement.

2.3. Transition radiation monitor [4]

This method (Fig.3), which represent a high resolute transition radiation microscope, is of enough resolution for indicated electron beam size measurement .

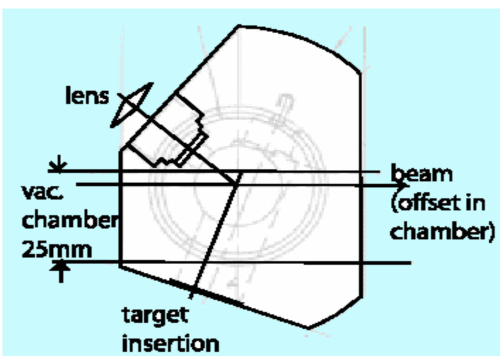

Fig. 3. High resolution

However it is an invasive method.

2.4. Laser interferometer [5]

In this method (Fig. 4) 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 (Fig. 5).

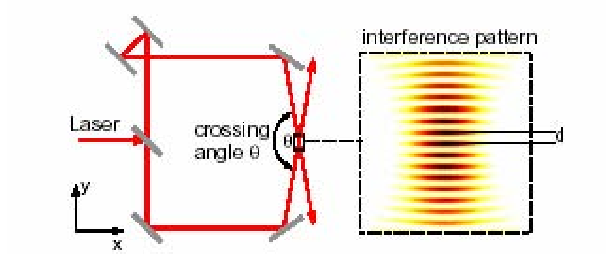

Fig. 4. Schema of the generation of an interference pattern using a split laser beam. D is the fringe spacing.

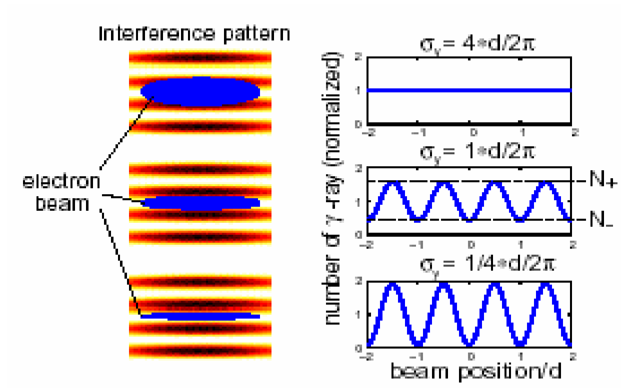

Fig. 5. Modulation of Compton scattered photons as a function of the vertical beam position for different beam sizes (top large, center medium, bottom small).

This method due to a small Compton scattering cross-section cannot provide a single bunch measurement.

The overview of these methods shows that they does not satisfy at once the all requirements for the beam size measurement. Therefore it should be useful to develop a technique, which may satisfy each indicated requirements.

Lover we try to show, that the method based on the Optical Diffraction Radiation may be considered as a one of such technique.

3. NON-INVASIVE DIAGNOSTICS BASED ON THE OPTICAL DIFFRACTION RADIATION

3.1. Short prehistory

The project on the creation of the noninvasive diagnostics method using ODR of electrons, passing through conductive slit (Fig.6) 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

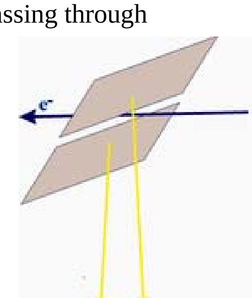

Fig. 6. ODR from flat slit target

parallel polarization radiation component (see Fig. 7). The measurement of these pattern was performed ([7]) in KEK ATF at 2004 (see Fig.7,8).

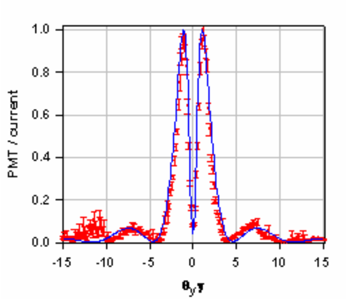

Fig. 7. ODR angular distribution from flat slit target.

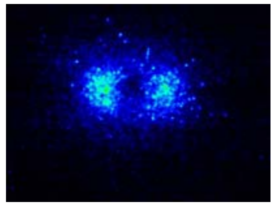

Fig. 8. Measured ODR interference pattern.

Using this technique the beam size of KEK ATF extracted beam was measured. Fig. 10 shows the beam size measured using ODR from flat slit target in comparison with wire scanner reading according the scheme on Fig.9. We must note that here we hav reached the limit of method sensitivity.

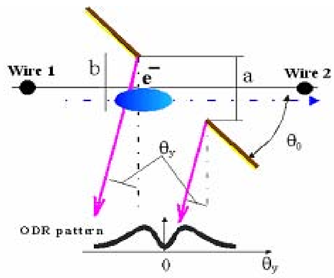

Fig.9. Scheme for beam size measurement.

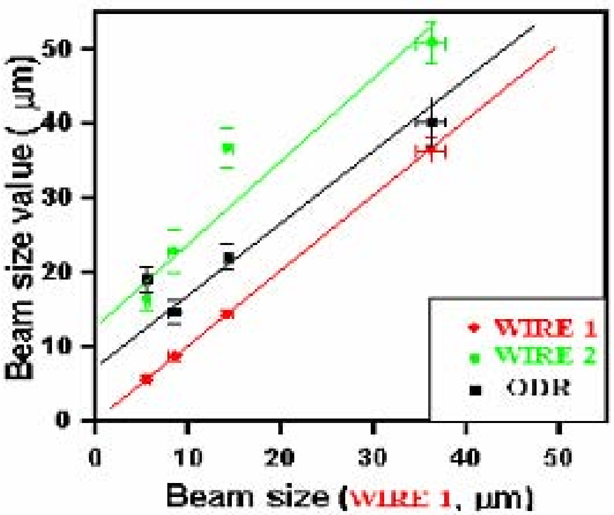

Fig.10. Beam size measured using ODR in comparison with wire scanners reading.

Moreover in [8] was shown that the method sensitivity gets worse catastrophically if the electron energy increase up to 30 GeV. The cause of such small method sensitivity is the first order of response on the beam size in respect to $1/\gamma$ (here γ is the Lorenz-factor). So if we want to measure a beam size using ODR for high-energy electron beam, we should modify ODR technique to provide the response on the beam size not depending on γ.

4. ODR METHOD MODIFICATION

The suggested technique is very close to using of synchrotron radiation (SR) pattern interference for beam size measurement, where mirrors are used for bringing together radiation patterns. However ODR intensity from slit target is comparable to optical transition radiation (OTR) one in contrast to the SR. This allows us to hope on the single shot beam size measurement.

Lower we present the simple principle explanation and some results of the method test.

4.1. 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 (see Fig.11) around the horizontal axis both semi-planes of the slit target, relative one to other. We name this target a “crossed target”.

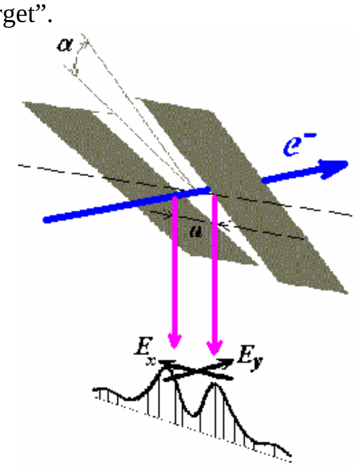

Fig.11. New target geometry

ODR will emit from each semi-plane at the direction of a specular reflection (see fig. 13) and these ODR beams will defer only by the phase difference $\Delta\varphi$ defined by the time difference Δt (Fig.12), which depends on the electron position Δz. So that $\Delta\varphi = i \cdot \omega \cdot \Delta t = i \cdot 4\pi \cdot \alpha \cdot \Delta z / \lambda$.

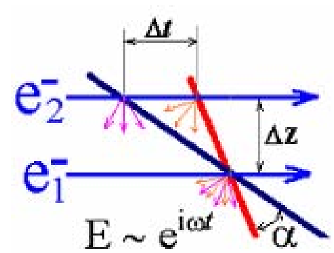

Fig.12. Phase difference shaping for different electron positions.

If we bring both ODR beams together like in Fig. 13,

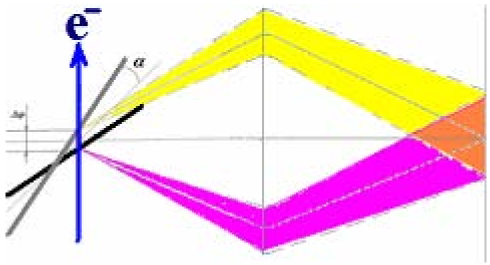

Fig.13. Radiation geometry.

we obtain an interference picture (Fig. 14).

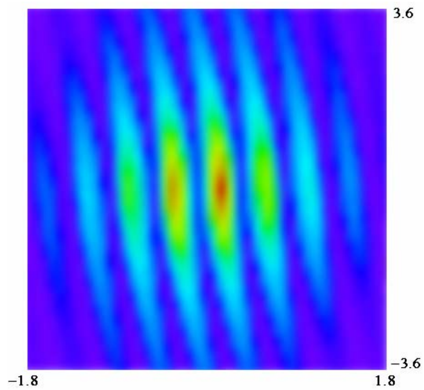

Fig.14. Calculated interference picture from a crossed target.

The relation between minimal (W_{min}) and maximal (W_{max}) intensity on this picture and the position of W_{min} depends on an electron position. Here for method demonstration we used the simple expression for field amplitude and phase like (1). After convolution of the radiation intensity with a Gaissian transverse electron distribution in a beam we can obtain the dependence of the W_{min}/W_{max} dependence on a beam size (see Fig. 15).

Fig.15. Relation between minimal and maximal intensity at the interference picture as a function of a beam size for radiation wave length λ.

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 in (1) slit with a<<1, then ODR intensity will be comparable to the OTR intensity. So the response on the beam size shown on Fig. 15 may be comparable to the OTR intensity. Therefore as on our experience the single bunch OTR angular distribution may be easy measured, than a single bunch beam size measurement used suggested ODR technique may be realized.

4.2. Test of ODR interference from the crossing target

To be sure that the shown interference take place, the simple experimental scheme (Fig. 16) was realized

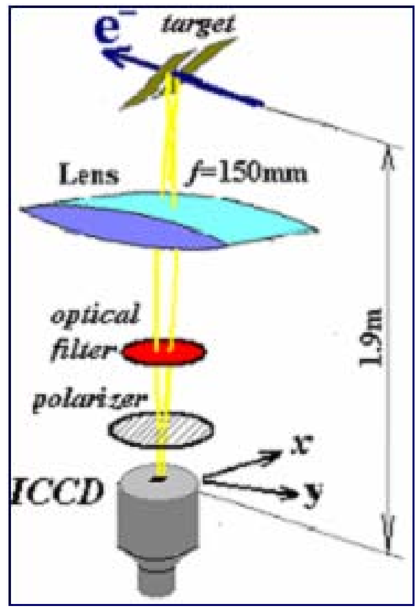

Fig.16. Experiment scheme.

and the interference picture shown on Fig. 17 was measured using CCD camera.

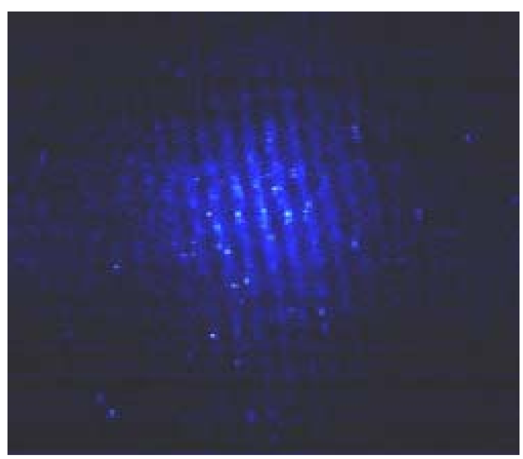

Fig.17. ODR pattern interference picture, measured using CCD camera.

In this scheme an optical lens was used to bring together the ODR pattern. Such scheme do not allows us to measure a beam size, but only demonstrate the possibility of the interference picture register. It is why that using the optical lens we obtain source image pattern interference, but not angular distribution pattern interference.

4.3. Angular pattern bringing together using wending bi-prism

If we take the well known expression for ODR field from semi-plane in far field zone

$$E_y = \frac{i \cdot e^{-\pi a\left(\sqrt{1+\theta_x^2}+i\cdot\theta_y\right)}}{4\pi^2\left(\sqrt{1+\theta_x^2}+i\cdot\theta_y\right)} \qquad (1)$$

(here slit width a is in units $\gamma\lambda$ and angles θ_x,θ_y are in units of $1/\gamma$ in respect to the direction of specular reflection)

and take into account the effective phase shift, shown in Fig.18,

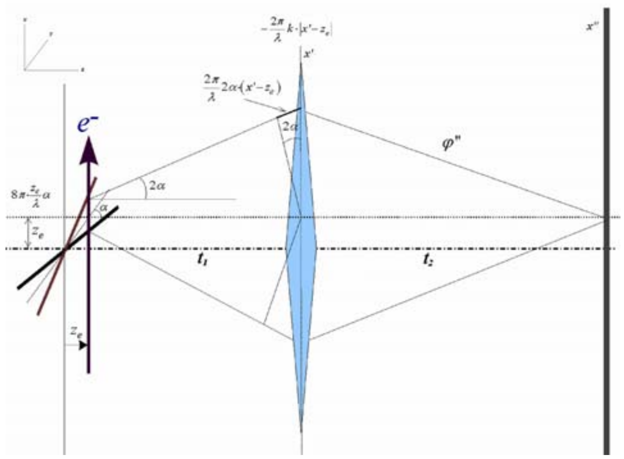

Fig.18. Effective phase shifts of a full optical system

then we can calculate the y- component $W_y=|E_y|^2$ of ODR intensity angular distribution for different electron position

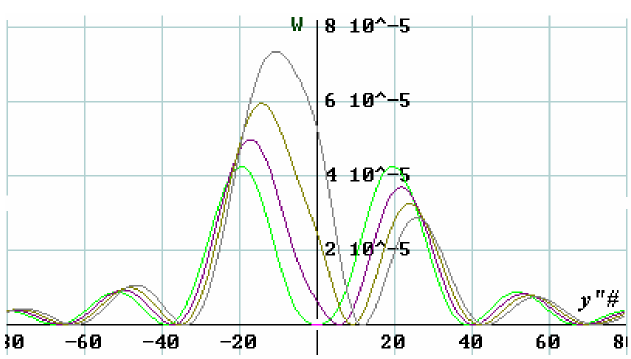

Fig.19. y- component of angular distribution for different electron position x_e=0, 2, 4, 6 μ. Here γ=2500, $y''\#=\gamma y''/t_1$, x''=0, a=0.4mm, α=12mrad, t_1/t_2=0.1, t_2=3m

We may see on Fig.19, that the variation of an electron position in x direction causes a shift of an ODR angular distribution minimum in y direction. This is the basis for the beam size measurement possibility.

The similar results were obtained in the independent test using mirrors instead prism. This scheme (Fig.20) is more understand, because not any phase shifts are contributed by mirrors. Only phase shift on dis-phased target determines an angular pattern interference.

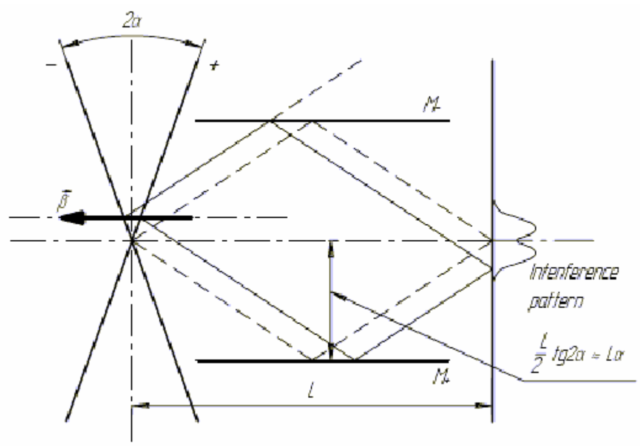

Fig. 20 Schematic diagram of the ODR photon propagation from target to detector with two mirrors

As a result one may see the similar pattern interference (see Fig.21). We can see here also the shift of angular distribution minimum, which depends on the electron position.

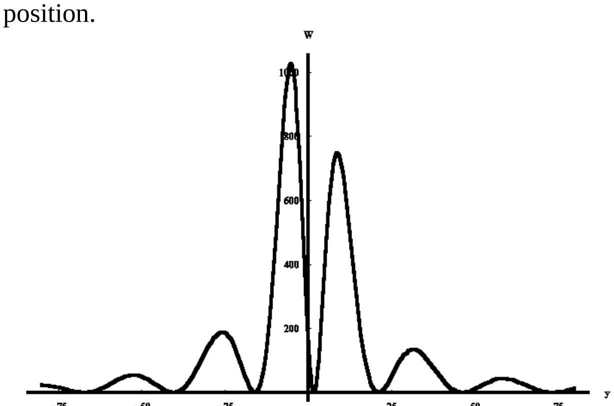

Fig.21 Spatial distribution of E_y component of the field with mirrors for a=0.04, $\alpha=7/\gamma$, $z_e=0.004\,\gamma\lambda$, L=1.1 $\gamma^2\lambda$. Here y= $\gamma y''/(0.1\,\gamma^2\lambda)$, x''=0

Both tests show the feasibility of the crossed target technique based on a ODR angular pattern interference for application to the single bunch transverse beam size measurement.

4.4. Example for KEK ATF extracted beam

Using this simple model we can calculate the convolution of the radiation intensity with a Gaissian transverse electron distribution (Fig. 22,23,24) in a beam for different beam sizes σ for KEK ATF condition γ=2500, α=5.6mrad, λ=0.5µm:

$$W_{\sigma} = \int W_y\left(z_e\right) \cdot \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{z_e^2}{2\sigma^2}} dz_e \,.$$

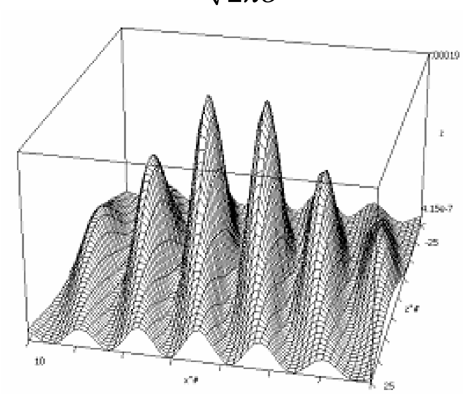

Fig.22. Interference picture for σ=2µm

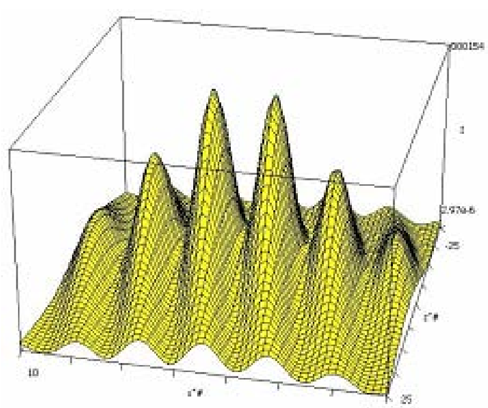

Fig.23. Interference picture for σ=6µm

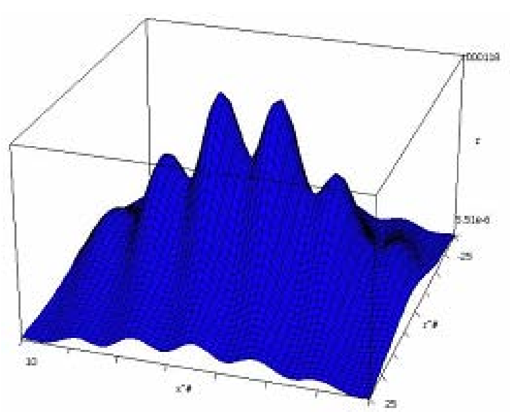

Fig.24. Interference picture for σ=10µm

Figures 22,23,24 show that the relation between minimum and maximum in ODR angular distribution depends on the beam size. This dependence may be used for a beam size measurement. The test of this possibility is planed in KEK ATF at 2006.

5. FEARURES FOR SLAC ELECTRON BEAM

Beam parameters of SLAC electron beam at station A:
E_e = 28.5 GeV (γ = 57 000);
σ ≈ 20µm;
bunch population: 1~3×10^{10}

5.1. Near field 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. For SLAC $\gamma^2\lambda$ ≈ 1800 m;

$$\frac{R}{\gamma^2\lambda} \approx \frac{20m}{57000^2 \cdot 0.5 \cdot 10^{-6}} \approx 0.011;$$

We see, that an extremely near field zone take place in these conditions. This results for example a transformation of the OTR angular distribution in far field zone (Fig. 25) to the one shown on Fig. 26, and may cause difficulties for a beam size prediction.

However this effect may be suppressed using a simple optics (Fig. 26). Let us place the detector in a lens focus *f*. If a radiation field in a lens plane is $\tilde{E}\left(r\right)$, than we can calculate the radiation field in detector plane using (2). This results for example for OTR the intensity distribution in detector plane presented on Fig. 27.

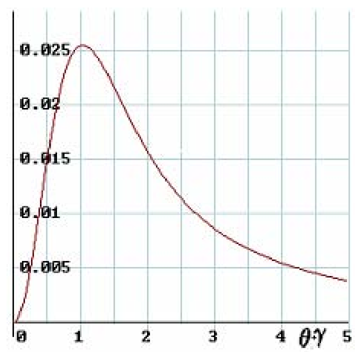

Fig. 25. OTR angular distribution in far field zone

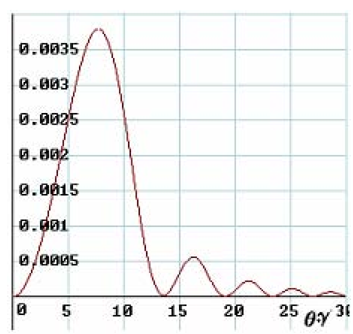

Fig. 25. OTR angular distribution for $\frac{R}{\gamma^2\lambda} = 0.011$

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

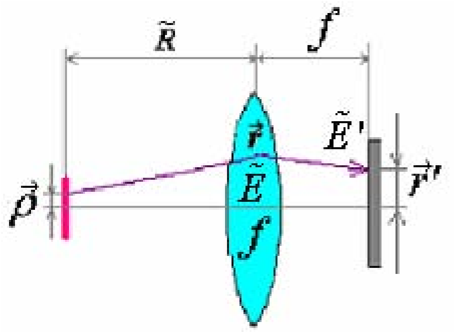

Fig. 26. Optics for a near field zone effect suppression.

We can see in Fig. 27, that with accuracy to the scale the OTR distribution in the focus plane coincides with the OTR angular distribution in a far field zone.

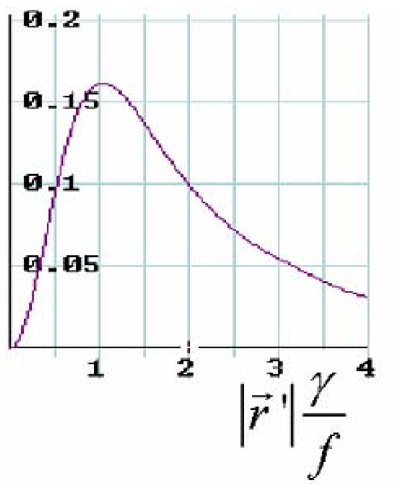

Fig.27. OTR angular distribution in the focus of lens.

Some more complicate optics allows us to obtain a necessary size of an angular distribution image on a detector.

6. CONCLUSION

The theoretical test of crossed target technique with an optical system based on thin prisms and the verification of this technique, using the simple model based on ordinary mirrors application, as well as the experimental test on the interference pattern measurement, allows us to hope on a positive result in an experimental test on single short beam size measurement. Experimental test of single shot 5μm beam size measurement is at KEK ATF extraction line at the end of 2006 is planed (see KEK ATF experiment proposals on http://atf.kek.jp/collab/)

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