MEASUREMENT OF ELECTRON BEAM DIVERGENCE USING OTR-ODR INTERFEROMETRY

R. B. Fiorito*, A. G. Shkvarunets and P. G. O'Shea, Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, MD. 20742, USA

Abstract

Optical transition radiation (OTR) interferometry has been shown to be a useful diagnostic for measuring the divergence of electron beams over a wide range of beam energies (15 MeV - 230MeV) [1]. However, beam scattering in the first foil of the interferometer ultimately limits the useful range of such a device. To overcome this effect we have designed and tested a perforated front foil interferometer to measure divergence of electron beams in the range of 100-1000 micro radians. Unscattered beam electrons passing through the holes in the screen produce optical diffraction radiation (ODR), while those passing through the solid portion produce OTR. For the proper hole size, number and screen thickness, the ODR-OTR interferences are readily observable above an incoherent background produced by the scattered electrons. The fringe visibility provides a measurement of beam divergence. The results of proof of principle measurements are presented. In addition, we introduce a novel design for an interferometer useful for the diagnosis of low energy, low emittance beams.

INTRODUCTION

Conventional OTRI cannot be used for lower energy beams (E≤10 MeV) or high energy beams with very low divergence because scattering in the first foil of the OTR interferometer dominates and obscures the beam divergence. To overcome this problem we have devised a perforated foil (mesh) - solid foil interferometer, which produces a combination of ODR from the holes and OTR from the solid portion of the mesh. These radiations interfere with backward reflected OTR produced from the second mirrored foil as shown in Figure 1.

The presence of the perforations produces a complication as far as analysis is concerned since no analytic theory for diffraction radiation from a matrix of holes in a metallic foil exists. To overcome this difficulty we have devised a simulation code (BEAMDR), which calculates the electric and magnetic fields at any distance from a radiating foil for any geometry of single or multiple holes. The results of BEAMDR are combined with analytic calculations of OTR from the mirror to produce far field ODR-OTR interference patterns.

A second code is used to convolve the ODR-OTR interference pattern with a given distribution of particle trajectory angles (usually a Gaussian distribution of angles) and a given optical band pass function. The latter is needed to produce distinct visible fringes for a given range of divergence. Divergence measurements are obtained by fitting the final code results for various rms divergences with measured interference patterns. A complete description of these codes is given in [2].

In Section I. of this paper we present a detailed comparison of theoretical predictions and experimental data taken with both conventional OTR and ODR-OTR interferometry to demonstrate its viability as a diagnostic method.

In Section II. we describe a new type of interferometer, useful for low energy beams, which uses forward directed radiation from a metal mesh and a *dielectric* foil. The design, operation and predicted performance of this novel device are discussed in detail.

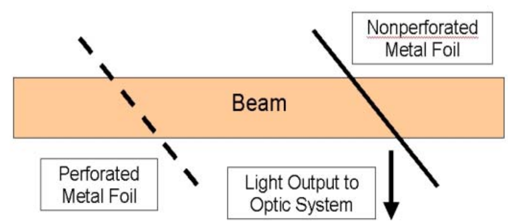

Figure 1: ODR-OTR interferometer; interferences between forward directed ODR from a mesh inclined at 45^0 and backward reflected OTR from a parallel mirror are observed at 90^0 with respect to the beam direction.

PROOF OF PRINCIPLE EXPERIMENT

Both ODR-OTR and conventional OTR-OTR interferometers were use to measure the divergence of the Naval Postgraduate School's 95 MeV electron beam linac. The average current of this machine is about 0.1 μA, and the macropulse repetition rate is 60 Hz.

A detailed description of the ODR-OTR and OTR interferometers used in our proof of principle experiment and the optical layout is fully described in [3], so that we will only briefly mention the relevant details of the interferometers.

A 5 μm thick, rectangular aperture copper micromesh (750 lines per inch, 33 micron period) is used as the first foil for the ODR-OTR interferometer, and a 0.7 micron aluminum foil is used as the first foil in the conventional OTR interferometer. The latter produces a calculated rms scattering angle of about 0.1 mrad, which is much less than the expected rms beam divergence, θ_{rms} ~1 mrad. An aluminized silicon mirror serves as the second foil for both systerms. The foil spacing L= 25.4 mm. A 650nm X 70 nm band pass filter was used to observe the interferences.

* rfiorito@umd.edu

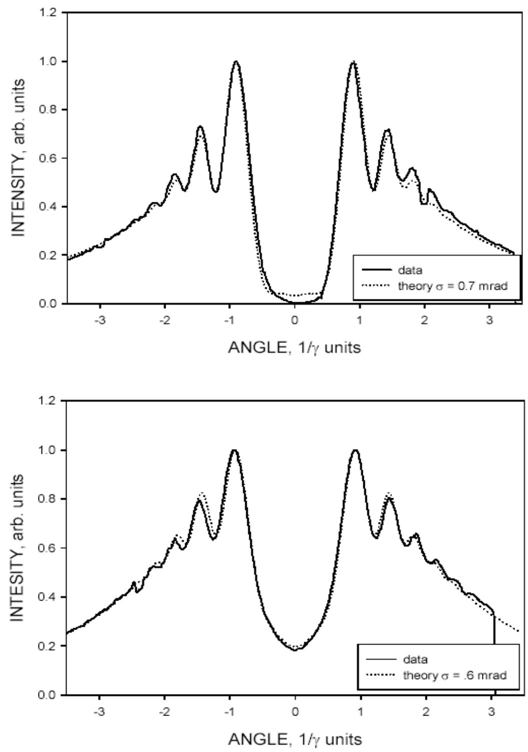

Figure 2: (top): fit of a vertical scan of OTR-OTR interference pattern to computer generated simulation; (bottom): similar fit to vertical scan of ODR-OTR interference pattern with theoretical calculation.

Figure 2. (top) shows a vertical (y) scan of an OTR interferogram taken at a vertical (y) beam waist condition together with a fitted theoretical scan. The fitted value of the rms (y) divergence of the beam, σ_y=0.7±0.05 mrad. Figure 2. (bottom) shows a similar scan of an ODR-OTR interferogram taken under the same beam conditions. The fit to the data is obtained from a simulation code that we developed to analyze ODTRI [2]. The divergence measured with ODTRI, σ_y=0.6±0.05 is in good agreement with that obtained using OTRI. Note the increased filling in and reduced visibility of the fringe pattern due to the presence of the incoherent background from scattered electrons in the solid portion of the mesh.

NEW, LOW ENERGY INTERFEROMETER CONCEPT

For low energy beams the inter foil spacing $(L \sim \gamma^2\lambda)$ is too small to directly observe backward reflected OTR and reflected ODR from an inclined mesh - foil interferometer. For example, at beam energy E = 10 MeV and λ = 650nm, L < 1 mm.

We introduce a new type of interferometer to solve this problem which observes interference between forward directed ODR from a mesh and forward directed radiation from a thin dielectric foil as shown in Figure 3. We refer to the radiation produced in the dielectric as dielectric optical radiation or DOR. The interferences are

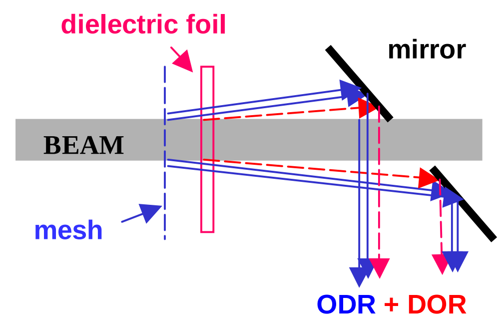

Figure 3: Mesh-dielectric foil interferometer.

collected by a downstream mirror which has a circular hole to allow the beam to pass through. The size of the hole, *a* >>($\gamma\lambda/2\pi$) the impact parameter for the generation of ODR from the mirror, but is small enough so that most of the angular interference pattern will be observed.

There are two important questions that immediately arise regarding the performance and design of this device, namely: (a) what are the properties of dielectric optical radiation and (b) what is the effect of multiple scattering of electrons in the dielectric on this radiation?

To answer (a) we have taken three approaches to calculate DOR at observation angles in the range of (1- 4)/γ, the angular region of interest.

(1) An *analytic solution due to Pafomov* [4], in which all components of the radiation are calculated including multiple reflections within the dielectric.

(2) A *polarization current model* in which radiation is generated from each of a series of infinitesimal layers produced by the electron as it passes through the dielectric material. This radiation has an component in the vicinity of 1/γ as well as at the Cherenkov angle. OTR from the boundaries and refraction effects are included.

(3) A *transparent "metal" model* in which each surface produces radiation with an intensity equal to that of OTR from a metal-vacuum interface. Again the refraction of OTR from the first boundary is included as in model (2).

Our calculations show that the angular distributions obtained from these three different calculations give nearly identical results in the angular region of interest. This means that we can safely employ the simplest, i.e. the two metal OTR model, to calculate the response of either a solid metal foil - dielectric interferometer or a perforated foil - dielectric interferometer.

Figure 4. shows a comparison between the Pafomov solution for DOR and the two metal OTR model for two wavelengths. Apart for small differences near the maxima, the results are the same. We see that the intensity of DOR can be controlled by proper choice of thickness and wavelength. In particular, it can be adjusted to equal that of OTR from a single metal foil. Once this is done, the ODR-DOR interferometer will have the same

properties as the ODR-OTR interferometer described above in Section I.

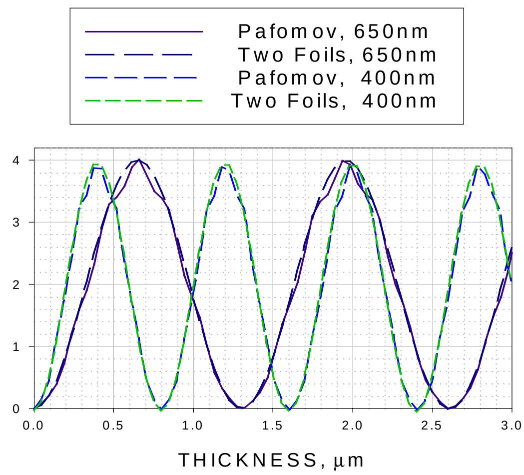

Figure 4: The Pafomov and two metal foil model of dielectric foil radiation for two different wavelengths.

Effect of Scattering in the Dielectric

Code calculations have been performed using the two metal surface model for a beam energy E=10 MeV, dielectric thickness d=5.438 µm, dielectric constant ε = 2.25, inter foil spacing L = 5mm, observation wavelength λ=650nm and band pass $\Delta\lambda$=0. This set of parameters produces a net intensity of DOR equal to unity in metal - vacuum OTR intensity units. When electrons are scattered in the dielectric with the same scattering angle considered above for a mesh – solid foil interferometer (σ_{foil} = 10 mrad), the intensity distribution of DOR is only mildly affected by this heavy scattering. Thus we conclude that scattering in the dielectric does not significantly affect the angular distribution and intensity of DOR.

Figure 5. shows the effect of beam divergence on the interferences of an OTR-DOR interferometer with a scattering σ_{foil} = 10 mrad in the dielectric.

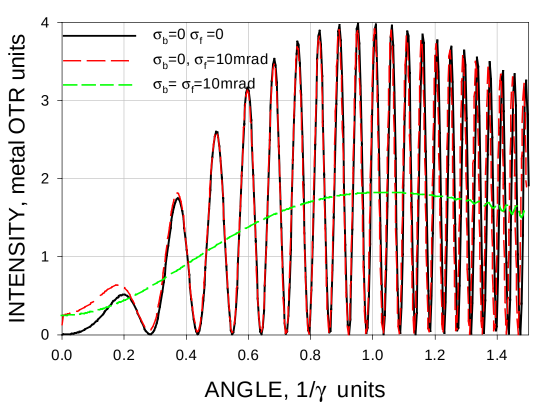

Figure 5: Effect of beam divergence on OTR-DOR interferences.

The dashed (red) and solid (black) curves are nearly indistinguishable except for small observable angles. Thus

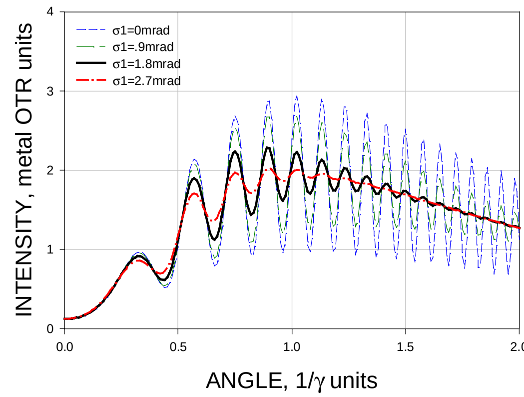

Figure 6: Effect of beam divergence on OTR-DOR interferences

scattering in the dielectric has a negligible effect on the vast majority of the observed interferences.

The reason for this result is that the path length between the foils primarily determines the difference in phase of the photons generated at the first and second foils. This difference is negligibly affected by the optical path length and scattering introduced by a thin dielectric foil. However, the relative phase is still strongly affected by *scattering in the first foil*. For this reason a mesh or perforated foil must be used in combination with a dielectric foil to measure the beam divergence for low energy beams.

Figure 6. shows the effect of beam divergence on ODR-DOR interferences in the presence of scattering in the dielectric foil, σ_{foil}=10mrad. In this case E=8 MeV, L=1.5 mm, d=5.449µm, λ=650nm and $\Delta\lambda$=0.

CONCLUSIONS

Experiments have verified that ODR-OTR interferometry is a viable diagnostic method to measure beam divergence for moderate energy beams. We have demonstrated computationally that ODR - DOR interferometry is an new, effective divergence diagnostic for low energy, low emittance electron beams.

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