© 1987 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE. CHARGED PARTICLE BEAM DIVERGENCE MEASUREMENTS

USING TRANSITION RADIATION*

by

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<u>Abstract</u>

We have developed single and double foil techniques to measure current density, energy, and divergence of intense relativistic charged particle beams from the transition radiation produced at a foil-vacuum interface. Single foil optical transition radiation (OTR) measurements have been made using a high intensity beam of 10-25 MeV electrons from the EG&G/EM linac, in which the entire OTR distribution is captured with an imaging system.¹ Here we describe the results of similar experiments utilizing a two-foil interferometer, which has potential for making high precision energy and emittance measurements of very cold beams.

Introduction

Radiation is emitted by any charged particle which crosses a boundary between media with different dielectric properties. This transition radiation (TR) has an extremely broad spectrum of frequencies, depending on the energy of the producing particle, but is quite weak (on the order of 1 photon produced/100 transitions). Since the prediction of TR by Ginsburg and Frank² a vast body of theoretical work has arisen on the subject, with reviews by Ter-Mikaelian,³ and Ginsburg and Tsytovich.⁴

Because the number of TR photons produced has a strong dependence on particle velocity, most experimental work has involved the use of TR in particle discrimination at extremely high energies.⁵ At such energies much of the TR is emitted as x-rays.

However, the dependence of the TR angular distribution on particle energy, and the behavior of polarization of the TR, make it useful as a diagnostic of charged particle radiation at much lower energies where the TR is emitted relatively more in the visible portion of the spectrum. The use of optical transition radiation (OTR) as an accelerator beam diagnostic was developed some time ago by Wartski and coworkers.⁶ In the experiments of Wartski OTR patterns were measured from a single metallic foil exposed to a relatively low current 35-70 MeV electron beam. The shape and intensity of the patterns were in good agreement with theoretical predictions. A two-foil interferometer was developed and, by measuring variations in fringe spacing, used to measure beam energy to an accuracy of 1%. Wartski also observed that the fringe visibility was sensitive to beam angular divergence, and that he could measure changes in divergence introduced by thin scattering foils.

The work reported here is an extension and refinement of Wartski's techniques, with the goal of developing time and spatially resolved diagnostics for the energy, emittance, and intensity profiles of very high current beam pulses. Analytical methods have been developed by Rule and Fiorito' for predicting the effect of beam divergence on single foil, two-foil interferometer, and polarization OTR patterns. These models have been successful in explaining our data taken with a single OTR foil,¹ and OTR polarization data.⁹ Here we report the results of the two-foil interferometer experiments, and compare to predictions of the Rule and Fiorito model.

Theory

Considering the case of a charged particle incident normal to a thin foil in vacuum, transition radiation is emitted both forward and backward from the foil. For relativistic particles $(y = [1-\beta^2]^{-1/2} >> 1)$ the radiation intensity peaks at small angles relative to the particle axis, occurring at $\theta \sim 1/y$, and the radiation pattern is azimuthally symmetric. The radiation is linearly polarized, with the electric vector lying in the plane formed by the particle axis and the axis of observation.

If the particle is incident on the foil at an oblique angle the forward pattern is unchanged, but the backward pattern is produced about the angle of specular reflection. In this case the angular distribution takes the form of that produced by a single foil times a Fresnel reflection coefficient for scattering at the specular reflection angle and is no longer symmetric about the reflection angle, although for large y the asymmetry is small. (Oblique incidence backward TR is of particular interest experimentally because such an arrangement removes the observation point from the beam line of sight and forward-directed bremsstrahlung cone). Expressions for a particle obliquely incident on a single foil have been derived by Pafomov, 9 and reviewed by Ter-Mikaelian.³

For a Wartski interferometer -- two parallel foils positioned obliquely in the beam -- the forward TR from the first will interfere with the backward TR from the second, and an interference pattern will be formed which is centered about the angle of specular reflection. Following Wartski,⁶ the TR intensity distribution for the component in the plane of the particle and observation axes (the perpendicular component is of similar form; we discuss only the

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parallel case because our analysis code at present treats only this component) may be written

$$\frac{d^{2}I_{\parallel}}{d\omega d\Omega} = F(\psi, \theta, \omega) - \frac{e^{2}\beta^{2}}{4\pi^{2}c} \times \frac{\sin^{2}\theta}{(1 - \beta \cos\theta)^{2}} |1 - e^{-i\phi}|^{2}$$
(1)

Here ω is the photon frequency, Ω is the solid angle, ψ the angle of specular reflection, θ the angle of observation relative to ψ , and β = v/c for the particle. The first term, F, is a Fresnel reflection coefficient, the second term the TR production for a single foil, and the third an interference term for two amplitudes differing in phase by ϕ . The phase difference between forward OTR produced on the first foil and backward OTR from the second is

$$\phi = \left(\frac{2\pi L}{\lambda\beta}\right) \quad (1 - \beta \cos\theta) \tag{2}$$

where L is the foil separation and λ is the OTR photon wavelength. For relativistic particles, $\beta \rightarrow 1$ and $\theta \sim \gamma^{-1} << 1$, F becomes essentially independent of θ , and Eq. (1) reduces to

$$\frac{d^{2}I''}{d\omega d\Omega} \approx 4 F(\psi, \omega) \frac{e^{2}}{\pi^{2}c} \frac{\theta^{2}}{(y^{-2} + \theta^{2})^{2}} \times \sin^{2}\left(\frac{\pi L}{2\lambda} (y^{-2} + \theta^{2})\right)$$
(3)

If a Gaussian distribution of beam angles with mean angle σ_{II} (=projected angle in plane of I_I) is folded with the approximation (3), and averaged over particle angles σ , we arrive at

$$\frac{d^{2}I}{d\omega d\Omega} = 4 F(\psi, \omega) \frac{e^{2}}{\pi^{2}c} \int_{-\infty}^{\infty} \frac{(\theta - \alpha)^{2}}{\left(y^{-2} + (\theta - \alpha)^{2}\right)^{2}} \times \sin^{2} \left(\frac{\pi L}{2\lambda} \left(y^{-2} + (\theta - \alpha)^{2}\right)\right) \times \left(2\pi\sigma_{\pi}^{2}\right)^{-1/2} e^{-\alpha^{2}/2\sigma_{\pi}^{2}} d\alpha \qquad (4)$$

The integral can be solved analytically, and the result is the basis of the analysis code used for calculations discussed later.

The Experiment

An experiment employing a Wartski interferometer was done with the apparatus shown in Figure 1. The electron beam from the EG&G/EM linac was focused through a vacuum extension pipe to a target foil ladder containing several thin aluminum scattering foils. About 2.5-inches away, the two foil interferometer -- the first foil of clear cellulose nitrate, the second with a reflective (rear) coating of aluminum -- was mounted at 45° to the beam axis. The foil separation along the beam axis was 1.41 mm.

The OTR pattern, after passing through a quartz window, was split with an uncoated pellicle beamsplitter into two channels with relative intensity of about 1:10. Each then passed to identical 85 mm camera lens + TV camera imaging systems. The lower intensity reflection channel was used to image the beam spot from either the scattering foil or the interferometer. This served as a real time monitor of the beam spot size, shape, and intensity during the experiment. The transmission channel, with the TV camera at the lens focus, gave the image of the interference pattern. Additional beam monitoring was provided by a faraday cup outside a 0.001-inch-thick stainless steel window, with the output observed on an oscilloscope by the linac operator.



Images were captured and stored with a TV fram memory, and were typically averaged over 20 pulses. , remote optical shutter was used to subtract an equal number of frames of background.

Results and Discussion

Before measuring OTR interference patterns, data were taken at 23.7 MeV from a single aluminized pellicle at 45° to the beam axis. This was done both for the nominal "cold" beam tune, and then with a 0.0005-inch-thick aluminum scattering foil in the beam. In Figure 2 are shown raw video images of the single foil patterns, with profiles sliced along the plane defined by the beam axis and observation point. Profiles in this plane exhibit the full asymmetry of the oblique incidence TR pattern. We note that the data in Figure 2 cut off just where expected based on the angular acceptance of the SIT cathode at the focal plane of the camera lens.



a) No scattering foil, calculated for $\sigma = 4$ mrad.





b) 0.005-inch-thick aluminum scattering foil, calculated for $\sigma = 5.2$ mrad.

Figure 2. Single foil OTR images and profiles at 23.7 MeV, compared to calculations (dashed lines).

The calculated curves have been normalized only in amplitude, and follow the data extremely well. The σ value used for the calculated curve in Figure 2b was obtained by folding in quadrature a divergence for the scattering foil, calculated using the Bethe-Ashkin model,¹⁰ with the cold beam value of 4 mrad suggested by Figure 2a. Images and profiles obtained from the Wartski interferometer at two energies and several wavelength regions are shown in Figure 3. These profiles are all slices along the axis perpendicular to the plane defined by the beam and observation axes (i.e., perpendicular to the plane of the profiles for the







d) 23.7 MeV, 630 nm cut-on filter.



e) 23.7 MeV, 695 nm cut-on filter.

Figure 3. Two-foil interferometer OTR images and profiles compared to calculations (dashed lines) done with $\sigma = 4$ mrad.

single foil data); such profiles are expected to be symmetric with respect to the minimum. The asymmetries observed in the peak heights of these profiles are due to slight optical misalignment.

Qualitative differences in the relative spacings and visibilities of the interference fringes for the various cases are rather striking. The calculations, using the cold beam divergence of 4 mrad which described the single foil data so well, and including only the I^H component (Eq. [4]), do remarkably well in each case. In particular, the peak positions and relative heights are well reproduced. The most significant failure of the model is the underfilling of the minimum, and this discrepancy is expected to improve with inclusion of the I_L term.

In conclusion, we have found from past and present work that OTR angular distribution patterns can be analyzed in detail to yield such information as beam energy and emittance. We expect further refinement to allow single-foil patterns to be used in beam divergence regimes down to a few mrad; and multiple foil patterns to be used to distinguish beam divergences on the order of a few tenths of a mrad.

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