OPTICAL TRANSITION RADIATION DIAGNOSTICS FOR LOW EMITTANCE, HIGH ENERGY, CHARGED PARTICLE BEAMS

by

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Abstract

We describe several new diagnostic methods that we have developed for measuring the time resolved emittance and energy of intense relativistic electron beams. These methods are based on the observation of optical transition radiation (OTR) produced by the beam as it transits one or two thin foils. These techniques are capable of spanning several orders of magnitude in emittance values, and are of particular use for low emittance, high power applications such as the free electron laser.

Introduction

Transition radiation (TR) is produced whenever a charged particle crosses the boundary between two media with different dielectric constants. The spectrum of TR can range from microwaves to X rays, depending on the energy of the producing particle. Ginsburg and Frank published the first theoretical treatment of TR in 1946 [1]. Ter-Mikaelian [2] and Ginsburg and Tsytovich [3] have reviewed the extensive literature on this phenomenon.

TR has a number of distinctive features which make it attractive for diagnostic applications: its intensity and angular distribution are strong functions of the energy of the producing particle; it has a broad spectrum with an upper limit proportional to the Lorentz factor γ; it is polarized with the electric vector lying in the plane defined by the normal to the surface and the observation direction; and it has a prompt production time relative to beam time scales.

The most extensive previous work on TR beam diagnostics was carried out by Wartski and co-workers [4-5]. Wartski demonstrated that single foil OTR patterns could be used to measure energy to an accuracy of a few percent on low current linac beams of 50-90 MeV and he measured beam current profiles in TR light. He also developed an OTR interferometer [5] and used the fringe spacing to measure energy to ~1% accuracy. He showed that the fringe visibility was affected by beam divergence and that it could be used to measure the multiple scattering produced by thin foils placed in the beam.

The application of OTR based techniques to the determination of beam emittance requires detailed quantitative knowledge of the effect of beam divergence on the shape of the TR patterns and on the polarization of the radiation. We have, therefore, derived analytical expressions for OTR intensities produced by beams with finite divergence [6]. The validity of these expressions has been verified by comparing them to the results of single foil OTR experiments and experiments using the Wartski interferometer [7]. Here we report comparisons of theory and experiments performed using the EG&G linac for electrons in the 10-25 MeV range and using the National Bureau of Standards (NBS) L-band linac at 80 MeV.

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 ($\gamma = [1-\beta^2]^{-1/2} \gg 1$) the radiation intensity peaks at small angles relative to the particle axis, occurring at $\theta \sim 1/\gamma$, 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 in 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 γ 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 may be found in the review by Ter-Mikarlian [2]. We have previously given the corresponding expressions including beam divergence [6].

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 parttern will be formed which is centered about the angle of specular reflection. Following Wartski [5], the TR intensity distribution for the component in the plane of the particle and observation axes may be written

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

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 $\beta = v/c$ 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

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

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

$$\frac{d^2 I_{\parallel}}{d\omega d\Omega} = 4\, F(\psi,\omega)\, \frac{e^2}{\pi^2 c}\, \frac{\theta^2}{(\gamma^{-2} + \theta^2)^2} \times \sin^2\left(\frac{\pi L}{2\lambda}\,(\gamma^{-2} + \theta^2)\right) \qquad (3)$$

We have derived analytic expressions for the convolution of Eq. (3) with Gaussian distributions of projected beam divergence angles of the form

$$[2\pi\sigma^2_{\parallel,\perp}]^{-1/2}\, e^{-\alpha^2/2\sigma^2_{\parallel,\perp}}$$

where $\sigma_{\parallel}$ is the root mean square (rms) beam divergence angle projected into the plane containing the beam axis and the observation direction and $\sigma_{\perp}$ is the projected angle in the orthogonal plane containing the beam axis. The resulting expressions are rather lengthy and we omit them here because of space limitations. In the results below, we have assumed $\sigma_{\parallel} = \sigma_{\perp} = \sigma$, but this is not necessary.

The Experiments

The apparatus for the experiments at EG&G and NBS are very similar. Figure 1 illustrates the configuration used at EG&G.

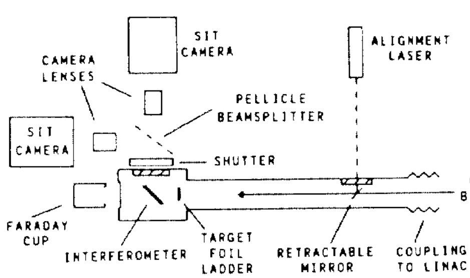

Figure 1. Diagram of the arrangement for OTR experiments employing silicon intensified target (SIT) cameras.

The electron beam from the EG&G linac was focused through a vacuum extension pipe to a target foil ladder containing several thin aluminum scattering foils. A pellicle of aluminized cellulose nitrate was placed at 45° to the beam axis and about 6.4 cm from the scattering foil ladder. For the interferometer experiments, a second 5 µm thick clear pellicle was added to the aluminized one, separated from it by 1 mm spacers, giving 1.41 mm projected separation along the beam axis.

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 imaging systems consisting of an 85 mm f/1.4 lens and a TV camera. 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 angular distribution. Additional beam monitoring was provided by a faraday cup outside a 25.4 µm (0.001-in.) thick stainless steel window, with the output observed on an oscilloscope by the linac operator.

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

The NBS experiment was similar to that at EG&G except that only one SIT camera was employed. The interferometer was constructed by using an aluminized quartz plate for the back surface and a 2 µm stretched Mylar membrane for the front surface. The spacing of the interferometer was 7.62 mm giving a projected separation of 1.08 cm. A remotely actuated translator was used to change the focus of the camera lens from infinity for detecting the angular pattern, to the position of the quartz plate, in order to image the beam spot in OTR.

Results and Discussion

Figure 2a illustrates the result of a measurement done at EG&G, of the angular distribution of unpolarized OTR generated by a 23.7 MeV ±1.5% electron beam traversing a single foil. The data shown (solid curve) were obtained by taking a horizontal slice through the center of the pattern. The dashed curve was generated by fitting our theoretical expression [6] for the total intensity to the data. This least squares fit yields an energy of 24.6 MeV (3.8% error) and a divergence of 3.96 mrad. Figure 2b shows a comparison of theory and data after introducing a 12.7 µm (.0005 in.) aluminum scattering foil into the beam. A least squares fit of this data yields a measured energy of 24.25 MeV (2.3% error) and a beam divergence of 5.42 mrad. The latter value is consistent with adding the multiple scattering of the foil in quadrature with the ambient beam divergence obtained from Fig. 2a.

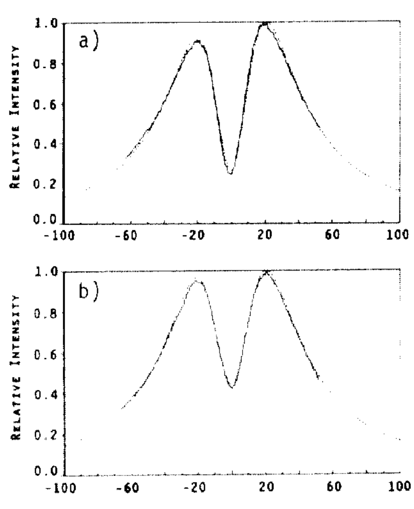

Figure 2. Single foil OTR patterns generated by 23.7 MeV electrons (solid curve) and theoretical fits to the data (dashed curve). a) No scattering foil b) 12.7 µm (0.0005 in.) aluminum scattering foil.

Figure 3 is similar to Fig. 2, except that the beam energy was 80 MeV. In this case, Fig. 3a shows a fit to the data taken at NBS which yields an energy of 79.5 MeV (0.6% error) and a beam divergency of 1.62 mrad. Figure 3b illustrates the result of inserting a 12.7 μm (0.0005 in.) aluminum scattering foil into the beam. The theory gives a beam energy of 80.5 MeV (0.6% error) and divergency of 1.76 mrad. As in Fig. 2b, the increase in the value of beam divergence is consistent with the theoretical value of multiple scattering within ~10% . Also shown in Fig. 3, are the theoretical curves for the contribution to the total intensity I_T which comes from the perpendicular polarization $I_\perp$ of OTR.

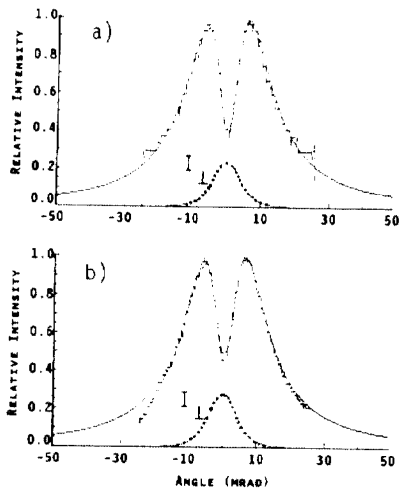

Figure 3. Single foil OTR patterns generated by 80 MeV electrons (solid curves) and theoretical fits of the data (dashed curve). a) No scattering foil b) 12.7 μm (0.0005 in.) aluminum scattering foil.

Figure 4 contains a horizontal scan of an unpolarized interferogram produced at EG&G with 23.7 MeV electrons using a Wartski TR interferometer. The dashed curve was generated by evaluating our analytical expression for the intensity distribution produced by a beam with a projected divergence angle of 2.5 mrad. The data were taken with a 400 x 50 nm filter and the theoretical curve includes the finite bandwidth. The slight discrepancy (~ 6%) of the interference peaks on the right side of the pattern may be a result of approximations made in our theoretical expressions. A careful analysis of the experiment has failed to yield any explanation of this discrepancy based on systematic instrumental errors. Similar results have been obtained in the case of the 80 MeV interference experiments done at NBS.

The experimental and theoretical comparisons given in this paper are representative of the results we have obtained in several similar experiments. The good agreement between data and theory demonstrates that OTR can be used to measure beam divergence. This information can be combined with measurements of the root mean square rms beam radius r_{rms} as determined by imaging a beam waist in OTR, in order to evaluate the local rms emittance, $\varepsilon_{rms} = \theta_{rms}\, r_{rms}$, where θ_{rms} is the measured beam divergence. Although the results presented were time integrated over many beam pulses, in the case of intense beams, time resolved OTR measurements of beam energy, emittance, and radial current profile will be possible. This OTR based technique should prove useful in applications such as free electron laser diagnostics [8].

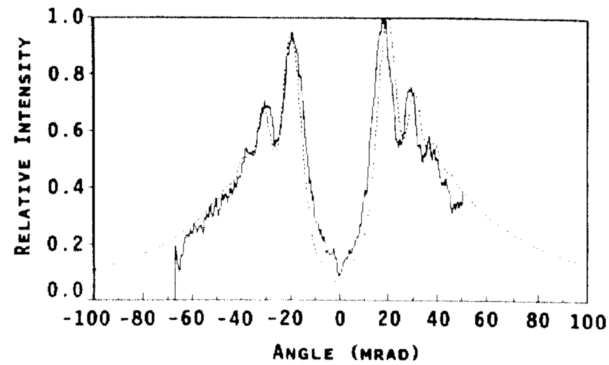

Figure 4. OTR interferogram produced by a 23.7 MeV beam using a 400 x 50 nm filter, compared to a theoretical plot generated with a beam divergence of 2.5 mrad.

Acknowledgement

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