Transition X Rays from Medium-Energy Electrons

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(Received 25 September 1984)

Recent experiments exploring the use of transition radiation as an intense source of tunable, coherent x rays included a measurement of the energy spectra and angular distribution of transition radiation in the soft-x-ray energy range. The radiation was produced when 25-MeV electrons penetrated a stack of eighteen 1-μm-thick beryllium foils. The most striking result is the demonstration of coherence of the photons emitted at the two surfaces of a single foil.

PACS numbers: 41.70.+t

We measured the energy spectra and angular distribution of transition radiation (TR) produced by 25-MeV electrons traversing a stack of eighteen 1-μm-thick beryllium foils. The emission of TR is a fundamental electromagnetic process in which photons are emitted when an energetic electron (or other charged particle) crosses the boundary between two media having different dielectric constants.[1-3] For medium-energy electrons (10 to 100 MeV), the emitted TR lies in the soft-x-ray energy range. This conveniently available photon-energy range of a few hundred electronvolts to several kiloelectronvolts and the quasicoherent nature of this radiation make it an attractive photon source for potential applications in x-ray lithography, microscopy, and holography.

Nearly all of the previous work on TR has been done with ultrarelativistic particles (in the gigaelectronvolt energy range) and was directed at the use of TR for particle diagnostics.[4] This Letter reports the main results of a series of experiments directed toward the development and design of a practical x-ray source.[5]

Figure 1 shows the experimental arrangement. The Lawrence Livermore National Laboratory electron-positron linear accelerator supplied a beam of electrons at a pulse rate of 1440 s^{-1}. After passing through the foil stack, the beam was deflected by a sweeping magnet into a dump hole through a paddle-shaped scintillation detector that monitored the electron current.

Radiation spectra were measured with a gas-flow proportional counter. We determined background contributions to the spectra by inserting a 0.127-mm-thick aluminum foil between the foil stack and the detector to block the low-energy photons and repeating the measurement. The photon angular distribution was measured by moving the detector, which was collimated to a 3-mm$\times$10-mm aperture, across the beam profile. All data were recorded with a multichannel analyzer. In order to minimize spectral distortion, the average number of counts per electron-beam burst was kept below 0.1. This dictated the use of beam currents considerably smaller than 1 nA. At this low level, the absolute beam-current calibration was $\pm 20\%$. During any given run, however, beam-current pulses were reproducible to within $\pm 5\%$.

Figure 2 shows the measured TR spectrum emitted at an angle of 0.015 mrad with respect to the electron-beam direction. This figure also shows the theoretical-

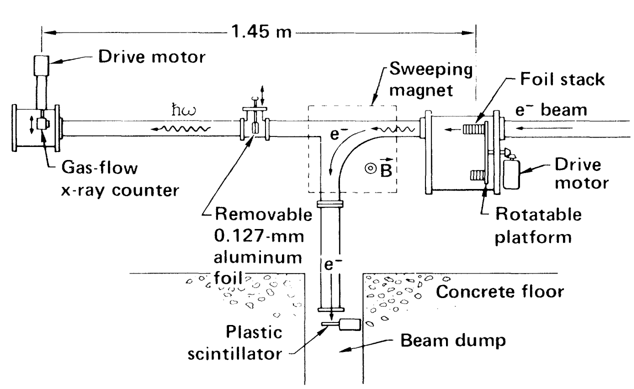

FIG. 1. Experimental apparatus for measuring photon spectra and angular distributions from various stacks of foils. The electrons enter from the right, pass through the foil stack, and are dumped into a deep hole in the floor. The photons travel 145 cm from the stack to a translatable gas-proportional detector. To measure the background in the room, a 0.127-mm-thick aluminum foil is inserted to block soft x rays.

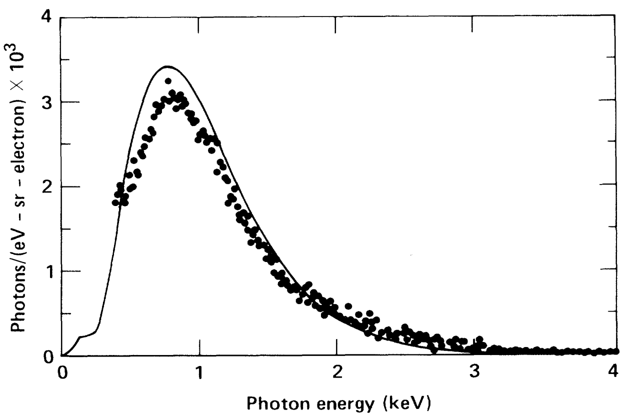

FIG. 2. Comparison of the measured and calculated TR spectra at 15 mrad for 25-MeV electrons incident on a stack of eighteen 1-μm-thick beryllium foils. The calculation (solid curve) includes the spectral dependence of the detector efficiency but ignores unobservable interference between foils in the stack.

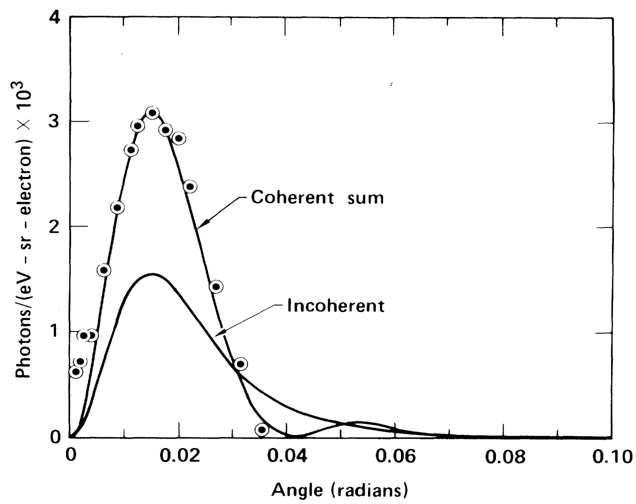

FIG. 3. Comparison of the TR angular distribution for 1-μm-thick beryllium foils calculated with [see Eq. (4)] and without the effects of coherent interference between the two surfaces of each foil. The measured intensity and angular distribution clearly demonstrate interference between the two foil surfaces.

ly calculated spectrum for these conditions. This calculation includes the effect of the theoretical spectral dependence of the proportional-counter efficiency. Figure 3 compares the measured angular distribution with theoretical calculations of the expected distribution. It is apparent from the 0-deg minimum that bremsstrahlung and other background contributions were small.

The differential cross section for TR production per frequency interval per solid angle is given by an expression of the form[3]

$$d^2N(\omega)/d\omega d\Omega = F_1F_2F_3, \tag{1}$$

where $N(\omega)$ is the TR photon number and ω is the photon radial frequency. The first factor F_1 is the contribution from a single vacuum-beryllium interface and is given by[1,2]

$$F_1 = (\alpha\omega \sin^2\theta/16\pi^2c^2)(Z_1 - Z_2)^2, \tag{2}$$

where $\alpha = 1/137$ is the fine-structure constant and Z_1 and Z_2 are "formation lengths" in vacuum and in beryllium, respectively. The Z_i are given by

$$Z_i = 4(c/\omega)\beta/[(1/\gamma)^2 + (\omega_i/\omega)^2 + \theta^2], \tag{3}$$

where γ is the ratio of the electron energy to its rest mass, β is v/c, θ is the scattering angle, and ω_i is the relevant plasma frequency when the dielectric constant of the medium is approximated by $\epsilon_i = 1 - (\omega_i/\omega)^2$.

The second factor F_2 accounts for the coherent superposition of radiation from the two surfaces of a single foil. If the incoherent effects of electron collisions within the foil and the photon attenuation through the foil are ignored, F_2 assumes the familiar two-source interference pattern[3]

$$F_2 = 4\sin^2(l_2/Z_2), \tag{4}$$

where l_2 is the thickness of the beryllium foil. The factor-of-4 increase in peak intensity is the most striking manifestation of the two-surface constructive interference.

The third factor F_3 describes the summation of contributions from each foil in the stack. Again, there is a superposition of M (the number of foils) coherent sources. In its simplest form,

$$F_3 = \sin^2MX/\sin^2X, \tag{5}$$

where $X = (l_1/Z_1) + (l_2/Z_2)$, and l_1 is the interfoil spacing. If the cumulative photon attenuation through the successive foils is included, then F_3 takes the form[6]

$$F_3 = \frac{1 + \exp(-M\sigma) - 2\exp(-\frac{1}{2}M\sigma)\cos(2MX)}{1 + \exp(-\sigma) - 2\exp(-\frac{1}{2}\sigma)\cos(2X)}, \tag{6}$$

where $\sigma = \mu_1l_1 + \mu_2l_2$ and μ_i are the x-ray absorption coefficients. Finally, if the distances l_1 or l_2 are not exact or if the angular and spectral structure associated with Eq. (6) cannot be resolved by the experiment, then Eq. (6) must be averaged over X. This yields

$$\bar{F} = [1 - \exp(-M\sigma)]/\sigma, \tag{7}$$

which is the appropriate form for comparison with our results.

Integration over energy and angle of the data in Figs. 2 and 3 yields a net production efficiency of about 10^{-2} photons per incident electron. The peak intensity varies rapidly with electron energy. For medium-energy electrons, the integrated intensity is roughly proportional to the electron energy.[4] This energy dependence suggests that TR originates from the virtual-photon spectrum of the incident electrons and lends intuitive physical insight into the nature of the TR process. This conclusion also can be reached by comparison of the calculational techniques used to determine virtual-photon and TR densities.[2,7]

The absolute intensity in Fig. 3 suggests that we have observed single-foil coherence of the emitted photons because of the excellent agreement with the theoretical expression that includes the interference term [the factor of 4 in Eq. (4)]. Without this contribution, the peak intensity would be reduced to one-half of this value. The single-foil photon coherence also is demonstrated by the angular dependence of the measured intensities. The results of theoretical calculations with and without the single-foil interference term are compared with the data of Fig. 3. Independent of the accuracy of the absolute intensity of the measured data, the relative intensities are accurate to about 5%. For angles greater than 0.005 rad, the form of the intensity distribution that assumes coherence of the scattered photons closely matches the experimental data whereas the measured angular distribution is clearly narrower than the single-interface form. For angles near zero, the nonzero solid angle subtended by the detector precludes such a comparison.

If we assume that the photons are coherent, the angular and spectral distribution of TR from a foil stack is analogous to the angular-transmission characteristics of an optical Fabry-Perot interferometer.[8] In the present case, we see from Eq. (6) that the 5-mm interfoil separation implies submilliradian angular structure in the emission intensity, as is shown in Fig. 4(a). Since our detector resolution was about 2 mrad, these effects were not observable. But if the interfoil separation were reduced to about 2 μm, then the emission intensity would be characterized by angular structure on a scale of the order of 20 mrad, as is shown in Fig. 4(b). Both distributions have the same integrated intensity, but only that from the stack with 2-μm foil separation has resolvable angular structure. The peak intensity of the structure is proportional to M^2 while the angular width is proportional to $1/M$. In many cases, the stack parameters can be chosen so that most of the TR is emitted into one particular angular peak. A TR source of this type would have an integrated intensity proportional to M and spectral and angular widths proportional to $1/M$.

Two phenomena limit the exploitation of this process. First, absorption of the TR effectively limits the number of foils that can be used by constraining the total thickness of the stack foils to a value comparable with the absorption mean free path of the foil material. Second, the cumulative effect of electron multiple scattering gradually suppresses coherence between the electrons and the emitted TR. This latter effect, however, is difficult to calculate and is best determined through comparative measurement of angular distributions from a series of stacks having different numbers of foils.

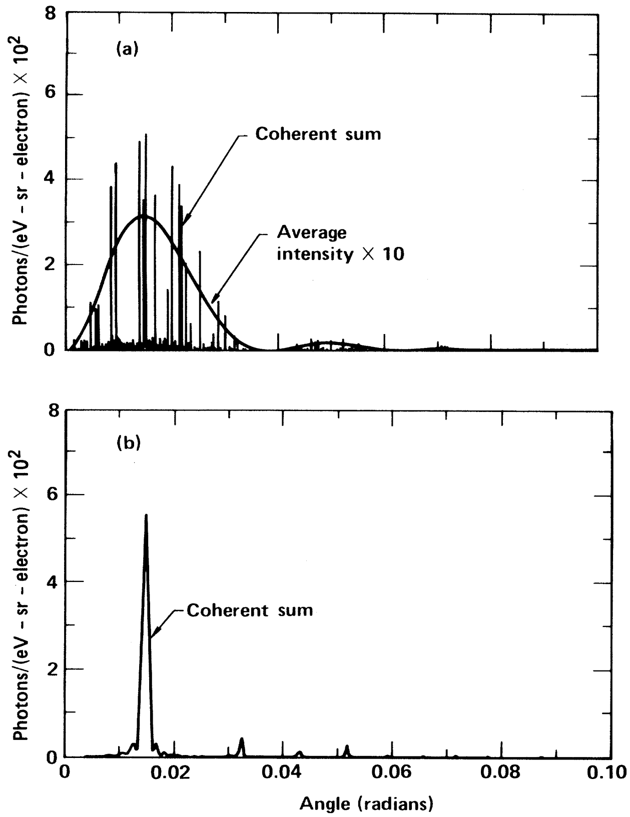

FIG. 4. Comparison of calculated photon angular distributions from two beryllium foil stacks. (a) Angular distribution for a stack of eighteen 1-μm-thick beryllium foils separated by 5 mm of vacuum. The smooth curve gives the angular averaged intensity calculated from Eq. (7); it was evaluated for 1-keV photons and is identical to the curve labeled "coherent sum" in Fig. 3. (b) Effect of reducing the vacuum spacing to 2 μm; one peak at 15 mrad becomes dominant as a result of resonant contributions from Eq. (6).

These results demonstrate that both the energy spectra and the angular distribution of TR are described correctly by classical electromagnetic theory. However, further study of TR coherence and intensity is needed for optimum design of such sources. The relationships between inelastic scattering of the incident electrons and the absolute radiation intensity and coherence of TR are straightforward to measure and directly affect TR practicality.

The most striking result of the present measurements is the demonstration of coherence of the TR emitted at the two surfaces of a foil. If this coherent behavior can be extended to an entire stack of foils, then the peak intensity of the TR would become an order of magnitude greater, and the potential applications mentioned above would become even more attractive. This is because the TR emission of a stack of foils is strongly reminiscent of the transmission characteristics of an optical Fabry-Perot resonator, and the spectral and angular definition of a Fabry-Perot resonator suggests direct analogs with the emission behavior of TR coherent-foil stacks.

We are grateful to Noel Peterson and Casey McGoff for the design and construction of the proportional counter. George R. Leipelt (recently deceased) was most helpful in setting up the x-ray detector system. One of us (P.J.E.) wishes to acknowledge innumerable research contributions over the past twenty years by his late friend and colleague.

This work was performed at Lawrence Livermore National Laboratory under the auspices of the U. S. Department of Energy under Contract No. W-7405-ENG-48 and was supported in part by the Office of Naval Research under Contract No. N00014-78-C-0403.

[1]V. L. Ginzburg and I. M. Frank, J. Phys. (USSR) **9**, 353 (1945).

[2]M. L. Ter-Mikaelian, Nucl. Phys. **24**, 43 (1961). Also see M. L. Ter-Mikaelian, *High Energy Electromagnetic Processes in Condensed Media* (Wiley-Interscience, New York, 1972).

[3]M. A. Piestrup, P. F. Finman, A. N. Chu, T. W. Barbee, R. M. Pantell, R. A. Gearhart, and F. R. Buskirk, IEEE J. Quantum Electron. **19**, 1771 (1983).

[4]M. L. Cherry and D. Müller, Phys. Rev. Lett. **38**, 5 (1977); M. L. Cherry, G. Hartmann, D. Müller, and T. A. Prince, Phys. Rev. D **10**, 3594 (1974).

[5]An expanded account of the results and interpretations from the present experiments is being prepared for journal publication.

[6]C. W. Fabjian and W. Struczinkski, Phys. Lett. **57B**, 483 (1975).

[7]W. K. H. Panofsky and M. N. Phillips, *Classical Electricity and Magnetism* (Addison-Wesley, Cambridge, Mass., 1962). Related comments can also be found in W. Heitler, *Quantum Theory of Radiation* (Clarendon Press, Oxford, 1954), 3rd ed.

[8]M. Born and E. Wolf, *Principles of Optics* (Pergamon, Oxford, 1970), 4th ed.