CALCULATED PHOTON SPECTRA AT SEVERAL ANGLES
FOR 5- AND 50-MeV ELECTRON BEAMS
STRIKING SOLID AND GAS TARGETS

DE83 009174

Dennis R. Slaughter

Lawrence Livermore National Laboratory
University of California
Livermore, CA 94550
February 24, 1983Abstract

Coupled electron-photon transport calculations have been carried out to simulate the photon generation when a 5- or 50-MeV electron beam strikes a solid or gas target. Results indicate that a 5-MeV beam striking targets of tungsten wire, air, or air doped with Kr or Xe generates a photon spectrum sharply peaked in the forward direction and with approximately $1/E$ spectral intensity. At right angles to the beam the photon intensity is predominantly due to characteristic K x-rays. A 50-MeV beam striking the same targets generates substantially higher photon yield in the forward direction but the yield normal to the beam is similar to that due to the 5-MeV beam. However, positron-electron annihilation radiation constitutes a significant part of the photon radiation normal to the beam, and is more intense than characteristic K x-rays when the target is more than about one-third of the electron range.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Work performed jointly under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48 and for the Department of Defense under Defense Advanced Research Projects Agency ARPA Order No. 4395 A#12, monitored by Naval Surface Weapons Center under document number N60921-83-WR-W0113.

24

Introduction

Relativistic electron beams generate abundant secondary photons as they strike a target. The yield, energy spectrum, and angular distribution of these photons depends strongly on the beam energy as well as the geometry and atomic number of the target. At the low end of the spectrum where photon energies are comparable to molecular excitations, the chemical form of the target, the beam current density and energy deposition may be important as well. However, in the x-ray part of the secondary photon spectrum where photon energies are large compared to molecular excitations and to electron binding energies, the photon intensity is proportional to beam current. Thus the profile of current density in a relativistic electron beam may be determined from the spatial distribution of x-ray intensity emitted when the beam strikes a target.¹

Profiles at several points along the beam direction may be obtained by inserting thin metal foils or wires into the beam and forming an image of the resulting x-radiation. If the foils are thin compared to the electron range in the foil, this measurement imposes an acceptably small perturbation on beam transport. The beam may also pass through a gas target in which an image of the resulting x-rays may be used to monitor propagation and current density profile in the gas.

Equally important is the fact that time and space resolved measurements may be made with good resolution.¹⁻¹¹ Time-resolved x-ray imaging may then be used to monitor the temporal and spatial development of the current density profile in a relativistic electron beam as it strikes a solid target or propagates in a gas target.^{1, 8, 12}

Design of such an instrument for beam current profile diagnostics on ETA and ATA has begun. In order to optimize the design of the x-ray optical components and x-ray sensor, secondary photon energy spectra have

been calculated using the monte-carlo code SANDYL.¹³ Results are reported here for secondary photon spectra generated in several targets by 5 and 50 MeV electron beams. In each case, spectra were calculated at several angles relative to the incident electrons. Two generic target types were considered: a solid wire whose axis is perpendicular to the beam, and a gas target. Physical modeling of the electron-photon transport is described in Ref. 13. Model equations are solved by monte-carlo processes where each source electron is tracked until its energy is reduced below a preset cutoff. Secondary electrons and photons are also tracked until their energies are reduced below preset cutoffs. It is important to note that no collective plasma effects within the electron beam or target are simulated in the calculations. Similarly, no space charge or magnetic field effects in the beam or electrical conductivity effects in the target are incorporated into the physical model used.

The following processes were simulated and their resulting secondaries tracked:

1. Photoelectron production, ionization
2. Compton scattering
3. Bremsstrahlung photon generation
4. X-ray fluorescence from K, L, M, N shells
5. Auger electron production
6. Electron-positron pair production
7. Annihilation radiation following positron thermalization

Results of the calculations were normalized so that the intensities given below are those which arise when one electron enters the target. Since spectra at forward angles are expected to be characterized by bremsstrahlung radiation ($\phi(E) \sim \frac{1}{E}$) the data are plotted in the form of energy flux, i.e. $\Psi = E \phi(E)$. In those cases the energy flux, Ψ , is approximately constant with respect to photon energy.

Photons Generated by a Wire Probe in a 5 MeV Beam

Spectra were calculated at several positions near a wire target which intersected the electron beam. Figure 1 shows the geometry used in the calculation. Except for the wire, which was perpendicular to the beam, the geometry is cylindrically symmetric about the Z axis. The beam was centered in an evacuated aluminum pipe which was surrounded by air at atmospheric pressure. A metal wire was placed across the diameter of the pipe. Due to limitations in the SANDYL geometry, the wire was represented by a square cross section as shown. In each case the incident electron beam was incident from the left and was assumed to be mono-directional with radius 1 cm. Since the wire thickness was less than the beam diameter many electrons did not enter the target. The energy flux, ψ , given below was normalized to a single electron which actually entered the wire target. Photon fluxes were recorded in several annular collector zones about the Z axis as shown in Fig. 1.

Problems were run for wires of two thicknesses, 1 mm and 3 mm, and three materials: tungsten, tungsten loaded graphite (10% tungsten by weight), and titanium. The wire was assumed to be uniform in composition. Secondaries were tracked down to cutoff energies of 50 keV for electrons and positrons, and to 5 keV for photons. In each case results were compared with those obtained when the air and pipe zones were replaced by vacuum. The discussion which follows describes the energy flux incident on various collector zones. The units for all the plots are defined by Eq. 1 below.

$$\psi = E \phi(E, \theta) \frac{\text{MeV} - \text{photons}}{\text{MeV} - \text{steradian} - \text{electron}} \quad (1)$$

where E and θ are the photon energy and angle, respectively, and ϕ is the double differential photon intensity (photons per unit energy per solid angle) normalized to one electron entering the target.

That is, the number of photons entering a collector zone has been divided by the solid angle subtended by the entrant face of the annular collector zone when viewed from the origin in Fig. 1, and by the number of source electrons actually entering the target.

Results for a 5 MeV beam striking a 1 mm thick tungsten wire are shown in Figs. 2-4. Mean electron ranges are shown in Table 1¹⁴ for reference. The results in the figures are based on transport of 1.5×10^5 source electrons, of which approximately 10^4 struck the wire. Spectra at several angles relative to the beam are shown in Fig. 2. At small angles the statistics are poor since the solid angle acceptance of the collector zones is very small, but the results obtained here are at least consistent with experimental measurements¹⁵ and theory.^{16, 17} Nevertheless, the photon intensity is shown to fall off by nearly two decades from $\theta=0$ to $\theta=90^\circ$. The high energy portion of the spectrum approaches a thick target bremsstrahlung distribution ($\phi(E) \sim \frac{1}{E}$) at small angles but is softer at large angles. The most prominent feature is the tungsten K-x-rays at 60 and 67 keV (K_α and K_β) which are approximately isotropic. Photon energy flux is seen to fall off rapidly at energies below the tungsten K-edge, presumably due to absorption within the wire.

Results shown in Fig. 2 are based on calculations where the pipe and air were replaced by vacuum. Figure 3 shows a comparison with a calculation where the air and pipe were included. The results are very similar indicating a very weak dependence of photon intensity on the wire surroundings for energies greater than 60 keV. A small increase in the intensity at $\theta=90^\circ$ and at low energies is caused by compton scattering of forward directed energetic photons in the pipe and air. Figure 4 shows a comparison of results at $\theta=90^\circ$ for several target materials including tungsten, graphite loaded with 10 weight percent tungsten, and titanium. Statistics were poor in the case of graphite since the tungsten content and photon yield are approximately two decades lower

than the tungsten wire. A titanium wire is seen to produce 50 times lower yield in its bremsstrahlung spectrum than the tungsten. Its characteristic K_{α} x-ray emission at 4.5 keV is not observed since it is below the energy cutoff in these calculations. Absolute intensity at $\theta = 90^{\circ}$ due to tungsten x-rays ($K_{\alpha} + K_{\beta}$) and bremsstrahlung (integrated from 80 keV to 5 MeV) are included in Table 2.

Photons Generated by a Wire Probe in a 50 MeV Beam

Calculations for 50 MeV electron beams were carried out under the same conditions as above and the results are shown in Figs. 5-8. Electron mean ranges are given in Table 1 for reference. Results for 1.5×10^5 source electrons (10^4 striking the wire) and a 1 mm thick tungsten wire target are shown in Fig. 5 for several angles. The statistics are poor at small angles due to the small solid angle acceptance of the photon collecting zones. Nevertheless, it is clear that the spectrum at small angles approaches a classical thick target bremsstrahlung, whereas it is softer at large angles. The photon intensity at small angles is 3-4 decades larger than the intensity at large angles, a fact which will be important in the design of diagnostic instruments.

Calculated spectra at $\theta = 90^{\circ}$ for a 50 MeV beam striking a 1 mm thick tungsten wire are shown in Fig. 6. For comparison, results are shown with and without the aluminum pipe and surrounding air. The most prominent features are the two peaks due to tungsten K-x-rays and to annihilation radiation. Energy flux in these two peaks are approximately equal at $\theta = 90^{\circ}$. Absolute intensities are given in Table 2 for the K-x-rays and for the annihilation radiation. Compton scattering of the annihilation radiation in the pipe and air result in a small enhancement of the intensity at low energies when these environmental influences are included. Photon intensity at energies below the tungsten K-edge falls off rapidly due to absorption in the target.

Figure 7 compares the results of calculations at $\theta=90^\circ$ for tungsten targets of 1 mm and 3 mm thickness. The K-x-ray peak is unchanged in intensity when the target dimensions are trebled, indicating that the yield is limited by self absorption in the target. However, the annihilation radiation in the thicker target is enhanced by about a decade when the target thickness and beam energy loss is increased only a factor of three. (Statistics are better since three times more electrons strike the thicker target, but these results are also normalized to one electron actually entering the target.) This is thought to be due to the greater probability of positron thermalization in the thicker target. Finally, Fig. 8 compares photon spectra at $\theta=90^\circ$ for beams of 5 and 50 MeV striking a 1 mm thick tungsten target. Generally, the photon intensity is up to a decade lower for the 50 MeV beam than for the 5 MeV beam since the more energetic beam produces a radiation pattern which is more strongly peaked in the forward direction. Nevertheless, the x-ray peaks are the same at 5 and 50 MeV beam energies. The annihilation peak is relatively unimportant for a 5 MeV beam but is relatively intense for the 50 MeV beam.

Photons Generated by a 50 MeV Beam Striking an Air Target

Photon spectra have been calculated for a 50 MeV electron beam stopping in gas targets at atmospheric pressure. The physical model and transport limitations are identical to those in the wire-target calculation except that the photon energy cutoff was extended down to 1 keV in order to include the Ar K-x-rays in air. The problem geometry is shown in Fig. 9. Cylindrical symmetry about the Z axis is assumed and the electron beam starts in the gas at $Z=0$, initially directed along the Z axis, and is transported through 100 m of air at atmospheric pressure. That is about 2/3 of the mean range indicated in Table 1. Photons were recorded when they reached one of the annular counting zones indicated in the Figure. Three gas targets were considered. Their composition, in

atom-percent, were: 1) air (78.5% N, 20% O, 0.5% Ar), 2) Krypton doped air (75% N, 20% O, 5% Kr), and 3) Xenon doped air (75% N, 20% O, 5% Xe).

Since the photon radiation originates in a large volume these results were not normalized by the solid angle of the collecting zone as seen from the origin but to the collecting area instead. Results reported in this section were normalized to one source electron entering the gas target and divided by the entrance area of the collecting zone. The units are:

$$\psi = \frac{E \phi(E, \theta)}{A} \frac{\text{MeV} - \text{photons}}{\text{MeV} - \text{cm}^2 - \text{electron}} \quad (2)$$

where A is the area (cm^2) of the surface through which the photons pass at the collecting zones. E and θ are the photon energy and angle, respectively.

Results for 50 MeV electrons stopping in air are shown in Figs. 10-11. Figure 10 shows spectra at forward angles where an approximate thick target bremsstrahlung distribution is exhibited. The intensity is sharply peaked in the forward direction so that at $\theta=75$ -100 mrad the intensity is reduced by a factor of ten compared to that on axis. The intensity is also observed to fall rapidly with decreasing energy below $E_\gamma \sim 30$ keV. These qualitative observations are in good agreement with similar calculations carried out by Lindgren.¹⁸ However, Lindgren's work which considered an infinite slab of air, 151 m thick, arrived at absolute intensities which were factors of 4 to 6 higher in the energy range 1-25 MeV. This discrepancy is due to differences in the air thickness included and to spatial spreading of the beam which effects the result here, but not Lindgren's.

Photon intensities at $\theta=90^\circ$ for several axial locations have also been calculated. Figure 11 shows the results. The most important feature to note is that the intensities at $\theta=90^\circ$ are approximately 1 to 2 decades lower than at small angles. Energy flux is approximately constant, with respect to energy, and very large, in the range 30 keV-1 MeV. Absolute intensities at the collecting zones (20 m from the beam) are included in Table 2. The large yield shown in the Table indicates a very large intensity in the case of the ATA beam in air and corresponds to 1.3×10^{13} photons/cm²-sec at R=20 m from a beam with a current of 10^4 A. It is also important to note that photon intensity at $\theta=90^\circ$ falls off rapidly with photon energy above 1 MeV.

It must be clearly kept in mind that the caveats given in the introduction are important here. In particular, there is no magnetic or electric field in this problem and there is no gas conductivity. Consequently the beam is allowed to diverge in the calculation as it scatters in the gas rather than pinch to a reduced diameter. As a result, the angular distribution of photon radiation is probably less sharply peaked in this simulation than in nature. Photon intensity calculated here may overestimate the yield at $\theta=90^\circ$ by up to one or two orders of magnitude. Nevertheless, the photon intensity is still expected to be very large at distances of R~20 m from the ATA beam in a gas target.

Photons Generated by a 50 MeV Beam Striking a Kr Doped Air Target

In order to evaluate the feasibility of an x-ray diagnostic based on detection of characteristic K-x-ray emission in Kr and Xe doped air, calculations have been carried out for these mixtures. Figure 12 shows results for 50 MeV electrons stopping in Kr doped air. The Kr K-x-rays at 12.6-14.3 keV are prominent in the results. Absolute intensities at Z=35 m are included in Table 2. Even more prominent is the annihilation radiation which was negligible in dry air. The photon spectrum in air

above 0.5 MeV is not significantly changed by the addition of 5% Kr and the total intensity at $\theta=90^\circ$ is increased by less than 50% so that requirements for shielding the experiment are unaltered.

Photons Generated by a 50 MeV Beam Striking a Xe Doped Air Target

Calculations for a Xe doped air target are shown in Fig. 13. These results are qualitatively the same as for Kr doped air. The Xe K-x-rays at 29-34 keV are prominent. Again, the annihilation radiation is even more pronounced in the results and, together with the K-x-rays, accounts for 25% of the total intensity at $\theta=90^\circ$. For purposes of comparison, Fig. 14 shows the above results at $Z=35$ m for beams striking targets of air, Kr doped air, and Xe doped air.

Conclusions

Diagnostic access limitations require that an x-ray diagnostic which measures the electron current density profile must be located at a large angle where photon yield from most targets is substantially reduced. Nevertheless, characteristic K-x-rays in high Z targets are expected to be abundant at 90° . High energy beams also generate abundant annihilation radiation at 90° . The former is limited by self-absorption in the target so that no advantage is gained by the use of a thick target. The latter is not limited and the photon yield increases rapidly with target thickness. In either case a detector with relatively narrow spectral response centered on one of these emissions should provide a strong signal and one which can be distinguished from background due to scattering of the forward directed radiation.

Beam propagation in air generates a very large photon intensity at $\theta=90^\circ$ and the spectrum is a broad structureless continuum extending from 30 keV to 1 MeV. Attenuation in air is critical at energies below 30 keV and the photon intensity at $\theta=90^\circ$ falls rapidly at energies

above 1 MeV so that an effective diagnostic instrument should find the strongest signal in this energy range. Addition of small amounts of Kr or Xe generates a distinctive and penetrating K-x-ray radiation as well as annihilation radiation without significantly increasing the total radiation normal to the beam or reducing the range. Signal strength (or energy flux) is sufficiently high for a 10^4 A beam striking solid or gas targets so that x-ray imaging with small collimators or pinholes should be feasible and good spatial and time resolution obtained.

References

1. A. T. Alttyntsev, V. I. Krasov, N. V. Lebedev, V. L. Papernyi, V. G. Simonov; Sov. J. Plasma Physics, 8, pps. 65-68, (1982), Fiz. Plazmy 8, pp. 115-120 (1982).
2. K. W. Doan, J. Chang, SPIE 106, X-ray Imaging, pp. 172-188 (1977).
3. J. E. Bateman, Nuc. Inst. Meth. 144, pp. 537-545 (1977).
4. G. R. Riegler, K. A. More, IEEE Transactions Nuclear Science NS-20, pp. 102-106 (1973).
5. W. Parkes, R. Gott, K. A. Pound's, IEEE Transactions Nuclear Science NS-17, pp. 360-366 (1970).
6. P. J. Bjorkholm, L. P. Van Speybroeck, M. Hecht, SPIE 106, X-ray Imaging, pp. 189-195 (1977).
7. N. M. Ceglio, G. F. Stone, A. M. Hawryluk, "Microstructure for High Energy X-ray and Particle Imaging Applications," LLNL, UCRL 85506 (1981).
8. W. E. Martin, "X-ray Imaging Diagnostic Techniques", Beam Physics Memo #43, October 20, 1982.
9. G. H. McCall, SPIE 106, X-ray Imaging, 2-7, (1977).
10. A. J. Toepfer, L. P. Mix, H. J. Trussel, Ibid. pp. 47-53.
11. N. M. Ceglio, Ibid. pp. 55-62.
12. J. N. Olsen, Ibid. pp. 144-151.
13. H. M. Colbert, "SANDYL: A Computer Program for Calculating Combined Photon-Electron Transport in Complex Systems", Sandia Laboratories, Livermore, CA., SLL-74-0012 (1974).
14. M. J. Berger, S. M. Seltzer, "Tables of Energy Losses and Ranges of Electrons and Positrons," National Aeronautics and Space Admin., NASA-SP-3012 (1964).
15. A. A. O'Dell, Jr., C. W. Sandifer, R. B. Knowlen, W. D. George, Nuc. Inst. Meth. 61, 340-346 (1968).
16. M. J. Berger, S. M. Seltzer, Phys. Rev. C2, 621-631 (1970).
17. H. Ferdinande, G. Knuyt, R. Van de Vijver, R. Jacobs, Nuc. Inst. Meth. 91, 135-140 (1971).
18. R. A. Lindgren, "Calculated Photon Spectra and Radiation Dose from 50 MeV Electrons Stopping in Air," NRL Memorandum Report, June 1976.

TABLE 1
Mean Electron Ranges (cm)¹⁴

	Beam Energy	
	<u>5 MeV</u>	<u>50 MeV</u>
Tungsten	0.18	0.76
Graphite loaded with 10% by weight tungsten	1.36	10.3
Titanium	0.72	4.2
Air	2.20×10^3	1.51×10^4
Air containing 5% (atom percent) Kr	2.06×10^3	1.36×10^4
Air containing 5% (atom percent) Xe	1.94×10^3	1.23×10^4

TABLE 2

Absolute Photon Yield At $\theta=90^\circ$

5 MeV Beam			50 MeV Beam		
	K-x-rays	$\int_0^{5 \text{ MeV}} \phi(E) dE$ 80 keV	K-x-rays	511 keV	$\int_0^{10 \text{ MeV}} \phi(E) dE$ 80 keV
<u>Wire Targets</u> (photons/steradian per electron)					
1 mm tungsten	5.2×10^3	4.1×10^{-2}	4.3×10^{-3}	2.0×10^{-3}	8.6×10^{-3}
3 mm tungsten			1.7×10^{-2}	6.1×10^{-2}	2.4×10^{-1}
1 mm titanium		1.1×10^{-3}			
1 mm tungsten loaded graphite	9.2×10^{-5}	3.2×10^{-5}	1.5×10^{-4}	3.2×10^{-5}	2.9×10^{-5}
<u>Gas Targets at $Z=35m$</u> (photons/cm ² per electron at $R=20 \text{ m}$)					
Air					2.0×10^{-10}
Kr Doped Air (12-14 keV x-rays)			1.4×10^{-12}	2.8×10^{-11}	2.9×10^{-10}
Xe Doped Air (29-34 keV x-rays)			2.7×10^{-11}	5.5×10^{-11}	3.2×10^{-10}

Figure 1. Problem geometry for x-ray wire calculation. All volumes except the wire are cylindrically symmetric about the Z axis. The wire is square in cross section.

Figure 2. Photon energy flux spectrum in vacuum for a 5 MeV electron beam incident on 1 mm thick tungsten target. All zones contain vacuum except the wire. Data plotted are for the four angles: 1) 6.6-16.6 mrad, 2) 33-66 mrad, 3) 70 mrad, 4) 1.57 rad (90°).

Figure 3. Comparison of results at $\theta = 90^\circ$ for a 5 MeV beam when pipe and air are present and when they are replaced by vacuum. The target is a 1 mm tungsten wire. Results shown are: 1) vacuum, 2) Al pipe and 21 cm air present.

Figure 4. Comparison of results for a 5 MeV electron beam striking several targets. Results shown are for spectra at $\theta = 90^\circ$ and 1 mm thick wire targets of: 1) tungsten, 2) titanium, 3) tungsten loaded graphite.

Figure 5. Photon energy flux spectra at several angles due to a 50 MeV electron beam striking a 1 mm thick tungsten wire in vacuum. Data shown are for angles: 1) 0-6.6 mrad, 2) 6.6-16.6 mrad, 3) 700 mrad, 4) 1.57 rad (90°).

Figure 6. Comparison of results at $\theta = 90^\circ$ for 50 MeV beam striking 1 mm thick tungsten wire for the cases: 1) vacuum and 2) aluminum pipe and 21 cm air surrounding the wire.

Figure 7. Comparison of results at $\theta = 90^\circ$ for 50 MeV electron beam striking tungsten wire targets of thickness: 1) 1 mm and 2) 3 mm.

Figure 8. Comparison of results at $\theta = 90^\circ$ for beams striking a 1 mm thick tungsten target at energies: 1) 5 MeV and 2) 50 MeV.

Figure 9. Problem geometry for gas target calculations.

Figure 10. Photon spectra at forward angles for 50 MeV electron beam stopping in air. Data shown are for photons recorded at $Z = 100$ m for the angles: 1) 0-25 mrad, 2) 25-50 mrad, 3) 50-75 mrad, 4) 75-100 mrad.

Figure 11. Photon spectra at $\theta = 90^\circ$ for 50 MeV electron beam stopping in air. Data shown are for axial locations: 1) 95 m, 2) 65 m, 3) 35 m, 4) $Z = 0$. (Intensity units are the same as in Fig. 10.)

Figure 12. Photon spectra at $\theta = 90^\circ$ for a 50 MeV electron beam stopping in air doped with 5% krypton. 1) $Z = 95$ m, 2) $Z = 65$ m, 3) $Z = 35$ m, 4) $Z = 0$. (Intensity units are the same as in Fig. 10.)

Figure 13. Photon spectra at $\theta = 90^\circ$ for a 50 MeV electron beam stopping in air doped with 5% Xenon. 1) $Z = 95$ m, 2) $Z = 65$ m, 3) $Z = 35$ m, 4) $Z = 0$. (Intensity units are the same as in Fig. 10.)

Figure 14. Photon spectra at $\theta = 90^\circ$, $Z = 35$ m for a 50 MeV electron beam propagating in gas. 1) Dry air, 2) air doped with 5% Kr, 3) air doped with 5% Xe. (Intensity units are the same as in Fig. 10.)