Softening of hard bremsstrahlung by Compton backscattering

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Multimegavolt bremsstrahlung backscattering from paraffin yields a photon spectrum mainly below 0.6 MeV. The measured dose in the backscattered radiation agrees with Monte Carlo computations to within 10%.

An experiment was conducted to demonstrate the feasibility of producing useful doses of low-energy x rays by spectrally softening high-energy bremsstrahlung, and to verify theoretical code predictions for dose and spectrum. Conventional flash x-ray sources for submegavolt bremsstrahlung production face difficult electron-beam transport problems that may limit their output.[1] A possible alternative[2] is to use Compton backscattering of multimegavolt radiation. Although Compton backscattering is energetically inefficient, the energy loss in scattering is largely compensated by more efficient bremsstrahlung production at higher electron energy.

As discussed further in Ref. 2, the maximum soft x-ray yield in backscatter from LiH or paraffin is about 30 krad(Si) over 1000 cm^2/MJ in the electron beam at 8 MeV electron energy. This is about half the typical yield in direct radiation, e.g., 60 krad(Si)/MJ in the beam, at 1.5 MeV electron energy.

The 12-MeV (peak) Aurora flash x-ray machine[3] at Harry Diamond Laboratories is ideally suited to verify spectral softening and dose predictions. A 50-cm-thick 1.2×1.2 m block of paraffin in front of the existing machine is the only modification to obtain the experimental geometry shown in Fig. 1. Backscattered radiation is observed inside a 10-cm-sq lead pipe placed between the four anodes opposite the paraffin. Teledyne-Isotopes SD-CaF_2:Mn-0.4 thermoluminescent dosimeters (TLD's) measured the total dose from the direct and backscattered radiation halfway between the paraffin and the anodes. The lead-pipe wall was 10 cm thick; this shielding attenuated the primary radiation to less than 300 rad(Si).

Figure 2 gives the computed x-ray spectra that should exist at various locations. The primary spectrum incident on the center of the backscatter material (long-dash line) is a normal Ta thick-target bremsstrahlung spectrum with a peak at about 600 keV. The backscattered spectrum at this location (short-dash line) is much softer, with a peak at 150-keV and no photons over 1 MeV. These are all Compton photons: bremsstrahlung from secondary electrons is not significant. The direct dose as measured in the experiment, 35 krad(Si)/MJ in the electron beam, results from the sum of the primary and backscattered spectra.

The solid line in Fig. 2 is the computed x-ray spectrum at a point 2.5 cm into the pipe, the location where the spectrum is measured experimentally. This spectrum cuts off at 300 keV, even lower than the backward primary spectrum; its peak again occurs at roughly 150 keV. The dose from this spectrum is 1 krad(Si)/MJ in the electron beam.

The goal of the experiment was to verify the predictions of x-ray spectrum and dose in the backscattered radiation inside the lead pipe where the hard primary radiation intensity was relatively low.

The x-ray spectrum was determined by unfolding the

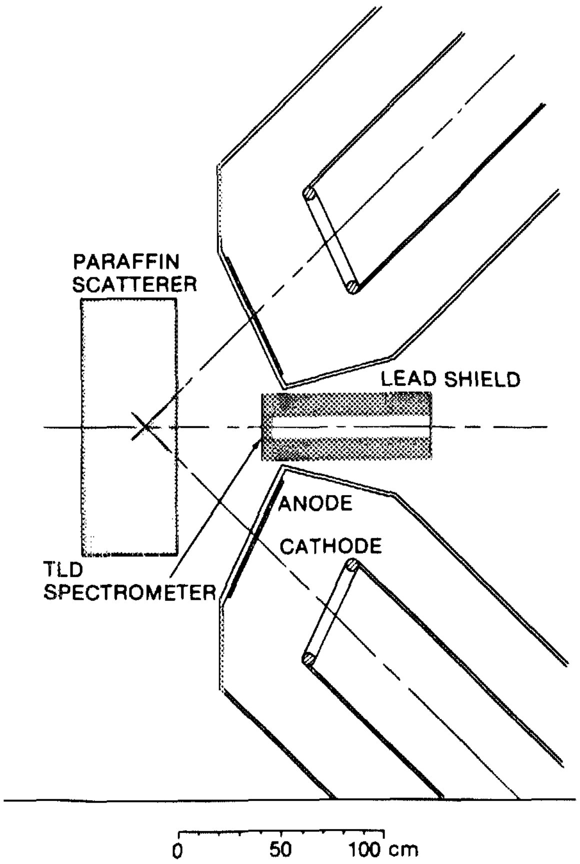

FIG. 1. Geometry showing two of four Aurora anodes, with lead shield pipe between them, backscatter material (paraffin) in front, and measurement location, 2.5 cm into pipe.

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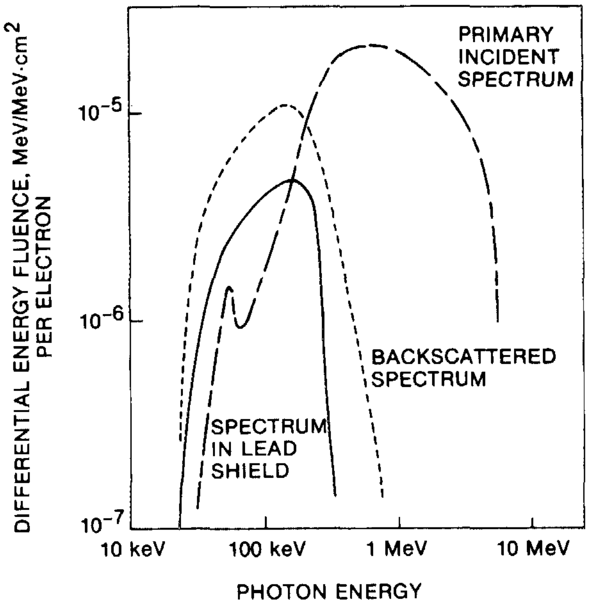

FIG. 2. Computed x-ray spectra at center front face of scatterer in forward and backward directions, and at measuring position 2.5 cm into lead pipe.

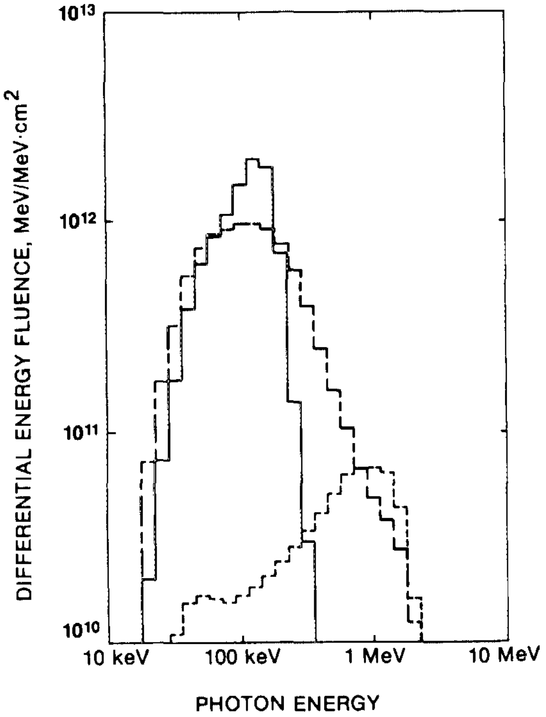

FIG. 3. Measured spectrum without backscatter (dashed) and with backscatter in place (dotted). Solid line is spectrum obtained by deconvolution dose differences in 13 TLD's.

doses from differentially shielded CaF_2:Mn TLD's (Harshaw TLD-400).[4] The graded absorbers are thirteen spherical shells, with central cavities of 0.95 cm in diameter and wall thicknesses ranging from 0.16 to 1.43 cm of Al, Ti, Cu, and depleted U. The materials and thicknesses are chosen to produce a series of uniformly spaced energy-response functions. These functions were calculated for each shield-TLD combination from broad-beam x-ray attenuation coefficients[5] and cross checked by measurements on a series of heavily filtered x-ray spectra and with Cs^{137} and Co^{60} radiation. Additional verification was provided by a Monte Carlo computation.[6] The effect of any hard primary radiation that penetrates the 10-cm lead shield is removed by subtracting the individual detector responses on a shot without the scatterer from those with the scatterer in place. This procedure was preferred over subtracting two spectra, since the differential shielding is not effective for radiation above 1 MeV. Moreover, the hard radiation is a measure of the shot-to-shot variability, allowing more accurate normalization between the two shots. Reference 4 contains further discussion of the method.

Figure 3 shows the spectra as measured at 2.5 cm inside the lead pipe. Without the scatterer (dotted line), the spectrum shows a peak at 1 MeV with radiation extending to about 30 keV. The peak around 1 MeV is due to the sideways-emitted primary radiation that penetrates 10 cm of lead. In reality, the radiation measured at 1 MeV should be spread out to 8 MeV to correspond to the primary spectrum of Fig. 2, since the differential shielding is not effective above 1 MeV. Although this 1-MeV peak is not accurate, this contribution to the spectrum should be the same in either case, and is subtracted.

The spectrum with the scatterer in place (dashed line) has its peak around 100 keV, and decreases by an order of magnitude beyond 15 and 600 keV. The high-energy tail between photon energies $h\nu = 100$ keV and $h\nu = 3$ MeV falls off roughly as $(h\nu)^{-2}$; again the spectrum above 1–2 MeV is not meaningful.

The pure backscattered spectrum is obtained by normalizing the differentially shielded doses to those in the thickest U shield. Subtraction and subsequent unfolding give the solid line in Fig. 3. There is no radiation over 300 keV left in the spectrum, in agreement with the computed spectrum in Fig. 2.

Figure 4 allows a closer comparison of measured and computed backscatter spectra. It is evident that the overall

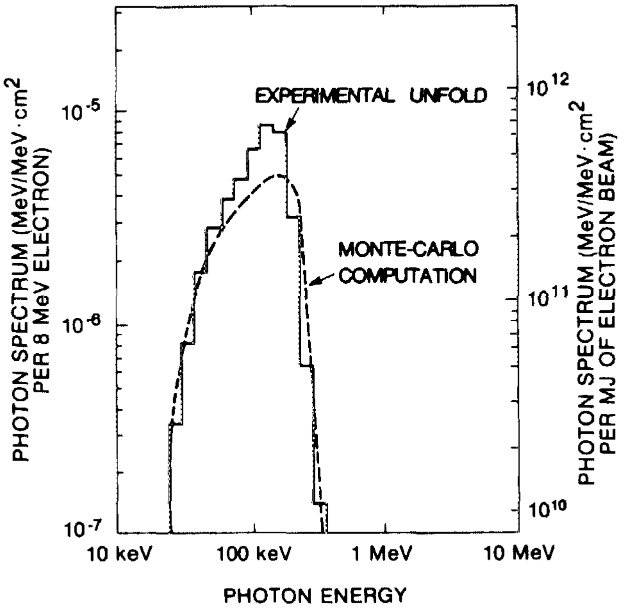

FIG. 4. Comparison of computed and measured x-ray spectra shown in Figs. 2 and 3.

agreement between the computed and measured spectral shape is excellent, except for the peak in the measured spectrum. Conceivably, the peak may be a feature of the fitting procedure, since the spectrum in this region exceeds the measured spectrum without background correction.

The surface dose in Si as calculated from the measured spectrum is 1.4 krad(Si). This compares well with the predicted dose of 1.3 krad(Si). The dose found from the computed dose-to-beam-energy ratio for the monoenergetic 8-MeV electrons is 1 krad(Si)/MJ of electron-beam energy. The equivalent beam energy, 1.3 MJ, was inferred from TLD's located in the primary bremsstrahlung.

We conclude that the experimental results are sufficiently positive to warrant future experiments aimed at increasing the dose.

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