Moderate energy flash x rays with large dose-area product produced by Aurora

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Compton backscatter of Aurora's flash gamma rays produces a pulse of moderate energy x rays over a 1 m^2 area, dose per shot of 25 Gy (2.5 krad), and uniformity better than 20%. The x-ray spectrum is similar to direct bremsstrahlung from a 1-MeV electron beam, with an additional low-amplitude tail of high-energy photons beyond 1 MeV. Advantages of the Compton backscatter technique over direct bremsstrahlung include a high shot rate, 6–8 shots per day at Aurora, and a spectrum that does not vary during the shot or from shot to shot.

INTRODUCTION

Flash x rays in the 30-keV–1-MeV range are commonly generated by decelerating fast electrons in a material with high atomic number, thus producing bremsstrahlung. The desired x-ray spectrum, often below ~1 MeV, can be obtained by selecting the proper peak energy of the electron, i.e., the maximum photon energy. It is, however, relatively inefficient to generate bremsstrahlung below about 1 MeV. For intense pulses it is therefore necessary to have large currents, i.e., a low-impedance diode. Unfortuntely, low-impedance diodes are difficult to build and to operate. In addition, in a low-impedance diode the bremsstrahlung converter dissipates the electrical energy in relatively little converter material, which is vaporized on each shot.

An alternative method[1] for producing x rays between 30 keV and 1 MeV is to generate bremsstrahlung photons efficiently with electrons around 5–10 MeV, and to convert the unwanted supra-1-MeV photons to lower energies by Compton backscatter. Backscatter works best in a material with low atomic number such as plastic (CH_2). Despite the low-energy efficiency of Compton backscatter, the overall conversion efficiency of the combined bremsstrahlung/backscatter process remains acceptable. The final factor in obtaining an appreciable x-ray dose-area product is sufficient electrical energy. The energy delivered to the four diodes of Aurora's gamma-ray simulator is ~2 MJ.

MEASUREMENT

Past experiments[2] on the backscatter concept successfully demonstrated the spectral softening. Figure 1 is a cross section of the geometry for the present experiment, which intends to increase the dose-area product by an order of magnitude. The benefit of this new geometry is principally in a much larger irradiation area, obtained by cutting ~0.5 m off all four Aurora transmission lines. Between the four Aurora anodes there is now a 1×1 m^2 measurement area, which is shielded from primary radiation by 10-cm-thick lead on the sides, and 5-cm lead in the back. The Compton backscatter material is a high-density polyethylene block of $2.4\times 1.8\times 0.5$ m^3, located 10 cm away from the measurement area. The converter, at 45° with respect to the machine centerline, consists of a 1.52-mm tantalum slab backed by 3.2 mm of steel.

In the center of the measurement area, the dose is measured by 13 differential shielded thermoluminescent dosimeters[3] (TLDs), whose responses can be unfolded to find an x-ray spectrum. The distribution of radiation over the area is determined by a square 5×5 array of 25 TLDs, each in a 1-g/cm^2-thick aluminum equilibrium shield.

Figure 2(a) is the spectrum measured for shot 6230.

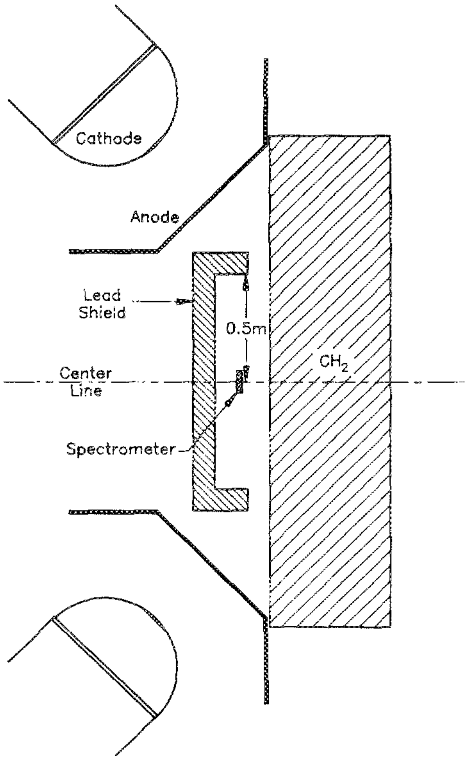

FIG. 1. Geometry showing two of four Aurora anodes, with lead shielded measurement area in between, high-density polyethylene backscatter material in front, and a measurement location 2.5 cm inside the lead shield.

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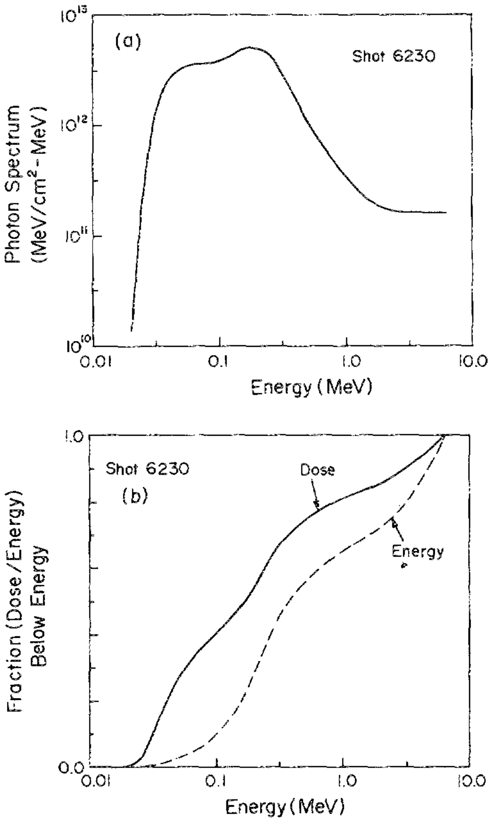

FIG. 2. (a) X-ray spectrum measured in the center of the test area. (b) Fraction of the total energy (lower line) below a given photon energy for the spectrum of (a). The upper line is the fraction of the dose in 0.5-mm silicon below a given photon energy.

The spectrum has a peak at about 200 keV and exceeds the half-maximum between 40 and 400 keV. Beyond 0.8 MeV the spectrum is one order of magnitude lower than the peak. Similar x-ray spectra are obtained from the primary bremsstrahlung produced by electrons in the 0.8–1.0 MeV range. The principal difference is that such spectra have no photons harder than the peak electron energy. In contrast, the backscattered spectrum decreases rapidly beyond the 0.5-MeV electron rest mass, but contains a high-energy component. It should be noted that the measurement technique is unable to determine the shape of the x-ray spectrum at these higher energies. Therefore, the shape of the high-energy tail in Fig. 2(a) is arbitrary, and simply indicates the contribution to the dose of some high-energy photons.

Although the spectral amplitude of the tail is low, the total energy in the tail is appreciable, about 35% of the total energy. Figure 2(b) shows the fraction of the energy fluence for the spectrum below a given photon energy (lower line). However, the tail's contribution to the dose in silicon is much smaller, about 18%. The upper line in Fig. 2(b) is the fraction of the dose for all photons below a given energy. Here the dose is defined as the average dose in an unshielded 0.5-mm silicon slab, as has become traditional[4] for moderate-energy flash x-ray machines. This dose is computed from the spectrum as 25 Gy (2.5 krad; 1 Gray = 1 J/kg = 100 rad).

Figure 3 shows the dose over the test area as inferred from the 25 field-mapping TLDs. The outer 10-cm-wide rim is not shown, because the dose in this area falls outside the TLDs, and would have to be extrapolated, but the rim dose should be similar to the dose elsewhere. Note that the dose is 20% higher along the $y = 0$ edge than the other three edges. This asymmetry reflects a higher radiation output of the diode adjacent to this edge, probably from the additional tantalum converter material on the conical walls of this diode. The dose in the center combined with the uniform dose over the measurement area gives a dose-area product of 25 Gy m^2, or 2.5×10^7 rad cm^2.

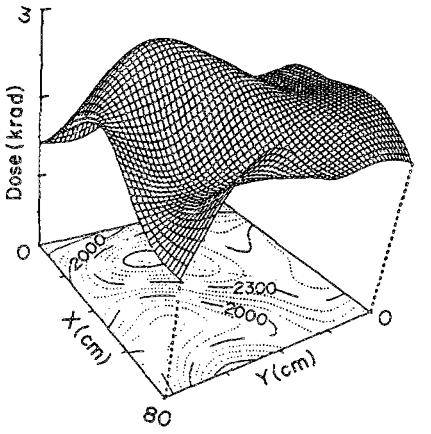

FIG. 3. Dose distribution over inner 80×80 cm^2 area seen by the 25 TLDs shielded by 1-g/cm^2 aluminum.

The total energy in the backscattered x rays is about 4.6 kJ, for an energy conversion efficiency from high-voltage electrons to backscattered photons of 0.23%. This is about $\frac{1}{4}$ of the energy efficiency for direct conversion of low-energy photons to bremsstrahlung, about 1%. However, the ability to provide 2 MJ in electrical energy through four ~30-Ω high-impedance diodes in parallel still results in a respectable dose-area product.

COMPUTATIONS

Computations[5] are in good but not perfect agreement with the measurements. The electron source parameters used for the computations are deduced from a series of separate dose measurements on a single diode. Diode voltage and current traces give the electron energy spectrum of Fig. 4. The peak electron energy is 8 MeV, while the average energy

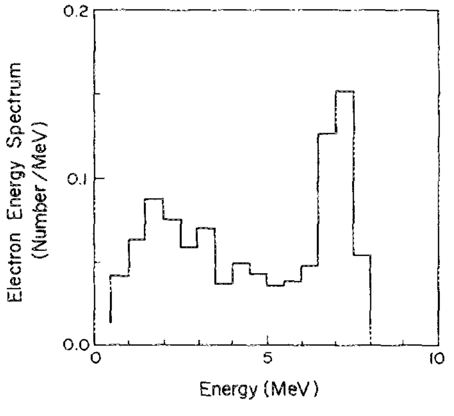

FIG. 4. Electron energy spectrum used for computations.

is much lower, only 4.5 MeV. the total energy into the diodes is ~2.0 MJ.

For convenience in the computations, the four diodes are replaced by a single electron source centered 10 cm behind the edge of the lead shield, see Fig. 5. The electrons are assumed to hit the converter within a 20-cm-radius disk, although measurements of the dose on the anode face plate suggest a gradual intensity decrease beyond the 20-cm radius. The electrons have an angular spread of at most 20° from normal incidence. To maintain a fourfold symmetry in the computations, the Compton backscatter is a $1.8\times1.8\times0.5$ m^3 block of plastic (CH_2), with density 1.2 g/cm^3, located 23 cm in front of the center of the electron source. The lead shield is 13 cm back from the plastic. The corners of the plastic are opposite the diodes, while the corners of the test area are in between the diodes, i.e., the plastic and the test volume, are rotated by a 45° angle with respect to each other.

Dosimetry in the computation consists of determining the dose in two layers of 0.5-mm silicon, 2.54 cm inside the shield, with vacuum on both sides. The top layer is subdivided into two equal areas, an outer ring and an inner square, to allow an estimate of the uniformity.

The computations suggest an average dose of 10 Gy per MJ in electrical energy of the electrons. With 2 MJ in electrical energy, and a 1×1 m^2 area, the computed dose-area product becomes 20 Gy m^2, 20% less than the measured value of 25 Gy m^2. The agreement is good given the shot-to-shot variation of the machine and the statistical uncertainty in the computations, both on the order of 10%.

Figure 6(a) compares the experimental spectrum with the spectrum computed for the central slab of silicon, assuming that 2 MJ of electrical energy goes into the diodes. The spectra agree well: the major difference is that the computation does not reproduce the x-ray tail beyond the 1 MeV seen experimentally.

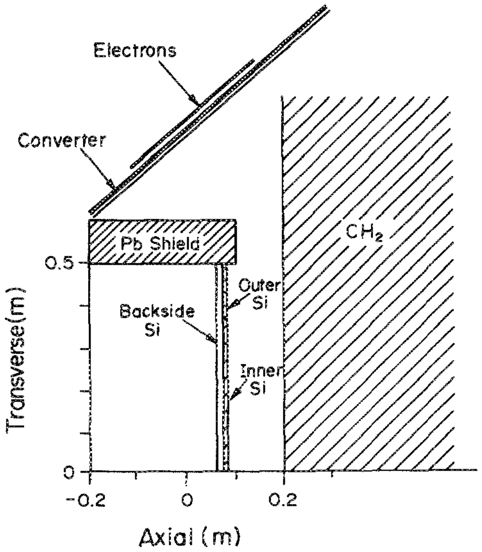

FIG. 5. A cross section through the backscatter geometry as used in the computations. The converter (top left) is at 45° with respect to the axis. The electron source is a 20-cm-radius disk centered 13 cm behind the edge of the lead shield that surrounds the test area. The 50-cm-thick plastic backscatter material is 10 cm to the right of the shield.

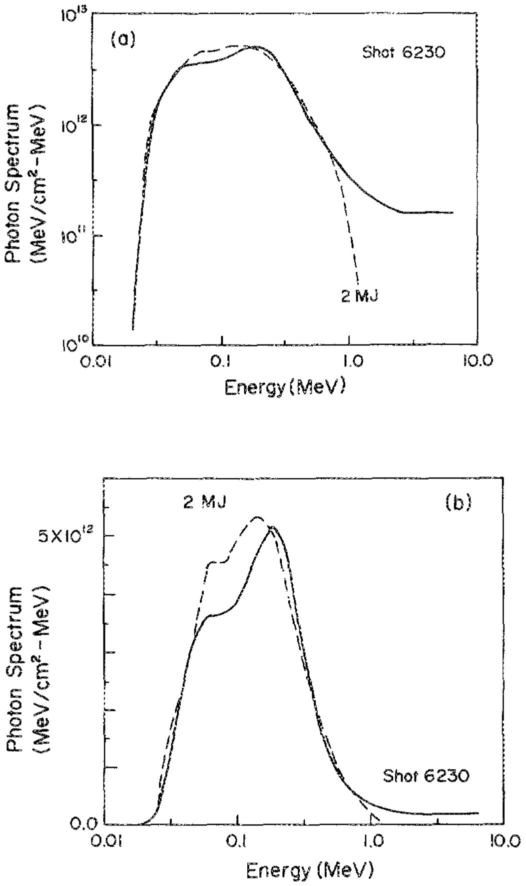

FIG. 6. Comparison between measured (solid line) and computed (dashed line) x-ray spectra: (a) logarithmic scale and (b) linear scale.

The absence of high-energy photons in the computation may be related to the idealized electron source. This electron source is uniform over a 20-cm radius, with no electrons outside. In the experiment, however, the electron source falls off rapidly beyond 20 cm, but does not vanish altogether, as evidenced by the larger output of the diode with tantalum on the diode side walls. In this case some of the primary radiation from the side may slip by the lead shield, and enter the test area. A more realistic electron source can be easily implemented in the Monte Carlo code. This will be done in connection with a future experiment wherein the anodes will be at 70° with respect to the normal, almost parallel with the test area. With this improved geometry, the photons generated at the edge of the anode can no longer slip by the shield.

Figure 6(b) shows the same data on a linear scale. Here it is evident that the spectra also differ slightly at lower energies. The difference is probably due to the difficulty of unfolding the low-energy spectrum from the differentially shielded TLDs in the presence of a large amount of harder x rays.

DISCUSSION

The original estimates[1] of the Compton backscatter technique for softening the flash x-ray spectrum predicted a dose-area product of 60 Gy m^2, three times more than obtained here. However, it is very difficult to realize part of those increases, for example, the monoenergetic unidirectional 8-MeV electrons easily specified in the computer are hard to come by in reality.

Even when the necessary modifications are possible they may not be desirable, e.g., when the modifications are incompatible with some of the advantages of the present source. Shot rate is a prime example. In contrast to other bremsstrahlung sources of comparable strength, the Aurora diodes survive after the shot. Therefore, the diode need not be repaired after the shot, a considerable savings in time and money. With survivable anodes the shot rate is limited by other considerations, usually turnaround of the diagnostics. At Aurora the shot rate can be a relatively rapid 6–8 shots per day. The original computations[1] specified an electron point source, an idealized small, high-power density diode. However, such a diode would blow up after every shot, and negate the shot rate advantage.

Another ~40% increase in the dose is obtainable by replacing the plastic by lithium hydride (LiH). This dose increase comes largely from the lower photoelectric cutoff of lithium compared to carbon, which shifts the x-ray spectrum slightly toward low energies.

Another feature of the Compton backscatter process should be mentioned. Unlike a direct bremsstrahlung flash x-ray source, the spectrum of the backscattered radiation depends little on the energy of the primary electron. Instead, the spectrum is determined[1] by the average number of scatterings and the rest mass of the electron. Therefore, it is difficult to soften the spectrum even further by reducing the pulse power voltage, as one would do with a conventional bremsstrahlung source. This feature turns into an advantage when a well-characterized spectrum of constant shape is desired, because the x-ray spectrum retains its shape during the pulse. Only the intensity increases with electrical power. Figure 7 compares the computed spectrum for the most energetic 50% of electrons, having an average energy 6.6 MeV, with the spectrum computed for the least energetic 50% of electrons, having an average energy 2.4 MeV (compare the electron energy spectrum in Fig. 4). The top curve is the computed x-ray spectrum for the complete pulse, obtained in a separate computation, already shown in Fig. 6. The three x-ray spectra are virtually identical in shape, although the amplitudes differ by an order of magnitude. Experimental verification of this computational result is not yet possible.

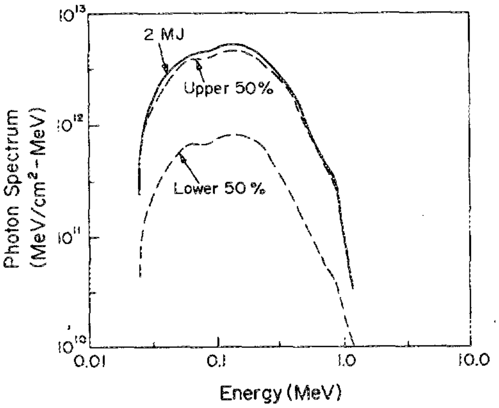

FIG. 7. Spectrum computed for the most energetic 50% of electrons compared to the spectrum computed for the least energetic 50% of electrons. The top line is the x-ray spectrum of Fig. 6.

In summary, the 1×1 m^2 backscatter geometry on Aurora is a powerful flash x-ray source, with dose-area product of 25 Gy m^2 and a spectrum comparable to bremsstrahlung from a 0.8 to 1 MeV (peak) electron beam. The measurements are largely consistent with computations, with the minor exception of a small supra-1-MeV tail observed in the experiment. The Compton backscatter source possesses a high shot rate, and a spectrum whose shape does not vary during the pulse or from pulse to pulse.

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