Spectral softening through Compton scattering

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Flash bremsstrahlung with peak energy below 0.5 MeV can be obtained from multi-MeV electron beams by Compton backscatter from a material with low photoelectric absorption. The efficiency is low but interesting, about 30 krad per megajoule electron beam energy, irrespective of electron voltage from 3 to 10 MeV.

I. INTRODUCTION

Flash x-rays due to bremsstrahlung are commonly produced by letting high current, high voltage electron beams interact with a tantalum target. Often it is desirable for the x-ray energy to be below a certain maximum, typically on the order of 1 MeV. With this restriction, the electron beam energy in a conventional x-ray generator is limited to 1 MeV or so, and the x-ray energy per pulse can be increased only by increasing the beam current, necessitating very low impedance systems with their attendant problems. This paper suggests using high voltage electron beams instead, and limiting the x-ray energy by Compton backscattering from a material with low photoelectric absorption such as lithium hydrite, paraffin, or graphite.

A single Compton scattering converts an x-ray with energy over 1 MeV to an x-ray with energy on the order of the electron rest mass, and multiple scattering decreases the energy even further, in a manner inversely proportional to the number of scatterings. Hence, backscattering acts to filter energetic x-rays exceeding an electron rest mass, while passing the less energetic ones.

That scattered x-rays are softer than the primary radiation has been known since the early part of the century,[1] and data on the spectrum scattered from low Z scatterers such as humans were gathered in a medical context[2] up to the early 60's. Of course, radiation shielders routinely use backscattering and radiation buildup in their calculations; but in their case the scatterers are higher atomic number materials such as concrete, iron, and lead, wherein scattering is less important. The use of spectral softening through Compton scattering for flash x-ray production seems to be new.

Conversion from hard x-rays to soft backscattered x-rays is energetically unfavorable, since the x-ray energy remaining is inversely proportional to primary x-ray energy. On the other hand, x-ray production efficiency is proportional to electron energy, so that these two factors tend to cancel. Therefore, the conversion efficiency from electron beam to backscattered x-rays is insensitive to voltage in the multimegavolt range of 3–10 MeV.

The utility of scattering lies in the separation between x-ray requirements and pulse power limitations. With scattering it is conceivable to use relatively trouble-free higher impedance devices without sacrificing current and electron beam energy.

Quantitative evaluation of Compton backscattering can be done with an x-ray transport code such as SANDYL.[3] In the following, one computation is discussed in detail. From a graphite scatterer the result is 30 krad dose in 5-mil Si over 1000 cm^3, per megajoule of electron beam.

II. EVALUATION

A suitable electron beam energy and scatterer material follows directly from the data shown in Fig. 1, where the total Compton cross section σ_c is compared with the sum of photoelectric and pair production cross sections σ_p. A photon in a Compton collision only loses energy, while the photon disappears in a photoelectric or pair production event: for minimal photon loss and optimal scattering the photon should remain away from the contour $\sigma_c/\sigma_p = 1$, and stay preferably with $\sigma_c/\sigma_p = 100$. The upper limit on photon energy is therefore about 4 MeV, and the electron beam energy should be less than about 10 MeV. On the low energy side, the cutoff is around 20 keV, decreasing somewhat with atomic number Z.

In the geometry of Fig. 2 monoenergetic, undirectional electrons impinge on a spherical converter. A 2-cm-thick heavy metal shield is provided around the test area. Scattering material is placed at a certain distance from the test area,

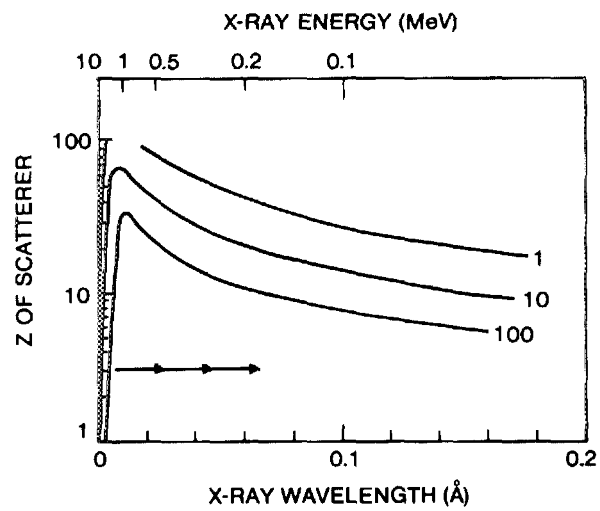

FIG. 1. Comparison between total Compton cross section σ_c and photoelectric plus pair production cross section σ_p. Lines show contours of $\sigma_c = \sigma_p$, $\sigma_c = 10\ \sigma_p$, and $\sigma_c = 100\ \sigma_p$ as indicated. The three arrows at $Z = 3$ (LiH) illustrate the spectral softening from 3 to 0.2 MeV with three 90° scatterings. Photoelectric absorption is unlikely in this energy range.

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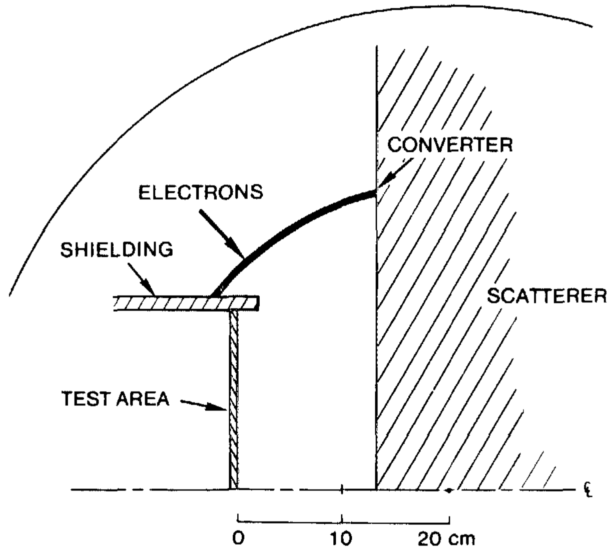

FIG. 2. Scattering geometry. Electrons hit a converter under an angle with respect to the axis of symmetry. Bremsstrahlung x-rays are scattered before they reach the 5-mil-thick Si detector that forms the test area.

which is directly exposed to the scattered radiation. Behind the test area is a perfect x-ray absorber that prevents backscattering from behind. The converter package is a Ta converter optimized for fluence, followed by a thick Al electron scavenger.

Table I gives computational parameters and results. In evaluating the results one should note that the electron beam is narrow, monoenergetic, and undirectional. This idealized beam tends to give a higher x-ray generation efficiency than is obtainable with realistic electron beams, which are wide and vary in energy and angle of incidence. On the other hand, the backscattered electrons are not returned to the converter. To assist in converting these computations for a particular machine, the table includes the conversion efficiency, the forward x-ray fluence divided by the electron beam energy, and the percentage of diode electrons that are backscattered. In a real diode these electrons are returned to the converter, albeit with lower energy.

The final result for the dose to beam energy ratio is roughly 30 krad/MJ using graphite as a scatterer. Other computations, with a variety of scatterers, geometries, and electron beam voltages give comparable results.

The direct x-ray spectra from 3- and 8-MeV electrons in

TABLE I. Computational parameters and results.

Electron beam energy	8 MeV
Beam position	22 cm from axis
Electron direction	30° with respect to symmetry axis
Ta converter thickness	1 mm
Al electron stopper	9 mm
Shielding	2-cm lead
Scatterer	Graphite
Distance of test plane	10 cm
X-ray conversion efficiency	12%
Dose (per megajoule electrons)	30 krad/MJ
Electrons backscattered	15%

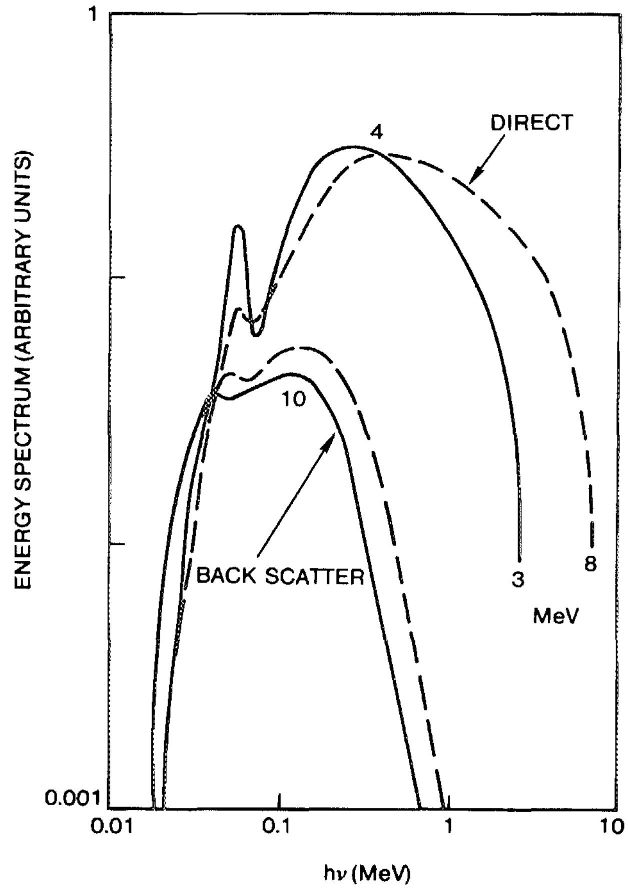

FIG. 3. Direct x-ray energy spectrum into the scatterer (upper line) and the scattered spectrum in the test area (lower line) at 3-MeV (solid) and 8-MeV (dashed) electron beam energy.

Fig. 3 are typical of filtered bremsstrahlung including a rather low fluorescence peak and a maximum at about 0.5 MeV. The conversion efficiency is only 12%; the remainder of the x-ray energy produced is absorbed in the converter package, and is radiated backwards.

The scattered x-ray spectrum is much softer than the original spectrum. At 0.5 MeV the spectrum is ten times less

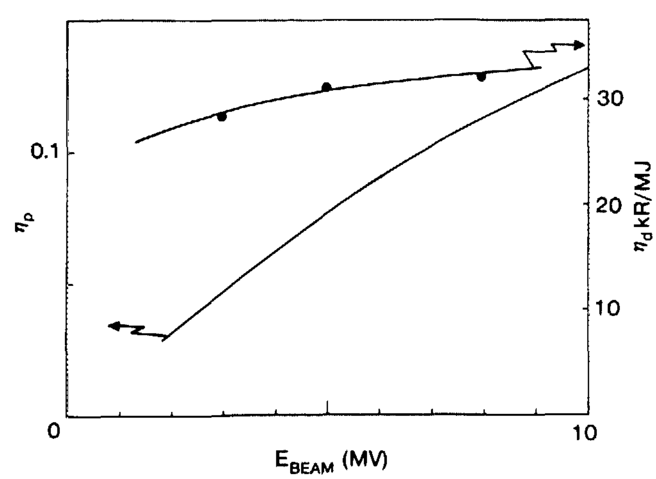

FIG. 4. Electron beam to bremsstrahlung conversion efficiency in optimized converter (left scale), and dose-to-beam energy conversion efficiency (right scale), as a function of electron energy.

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than the peak, which occurs between 70 and 200 keV, and fluorescence is no longer visible. Below 30 keV the scattered spectrum is enhanced up to an order of magnitude over the direct spectrum. The scattered spectra vary little with initial electron energy.

Variation of the dose parameters with electron energy is minimal. Figure 4 shows increasing conversion efficiency between e-beam energy and x-ray fluence from the converter with electron energy. However, the dose in the test area divided by beam energy stays around 30 krad/MJ over the range from 3 to 10 MeV. A possible weak dependence in energy is not excluded, but the estimated statistical errors in the Monte Carlo procedure preclude any trend from emerging.

It would be useful to replace extensive Monte Carlo computations with analytical calculations. Unfortunately, analytical work[4] on scattering is largely confined to a one-dimensional slab geometry with monochromatic photons and isotropic scattering, or at most a simple sinusoidal approximation to anisotropy. The problem under consideration here is neither of these. However, it is possible to get some analytic insight by considering numerically the scattering of a single photon in the geometry at hand. The dose-to-beam ratio can then in principle be computed from an integral over the angle and energy of the bremsstrahlung spectrum, and the angle and energy-dependent scattering spectrum for single photons; in practice this is cumbersome.

Figure 5 shows the backscattered photon spectrum in the test area for monoenergetic photons emerging from the converter with energy 0.1, 0.3, 1, and 3 MeV that subsequently scatter in graphite. Softening of the photons is particularly pronounced for 3 MeV where nothing above 1 MeV is backscattered as expected. Everything at higher energy than the "hump" at about 0.3 MeV in the backscatter spectrum for 1 and 3 MeV is probably due to single scattering; the smooth soft spectrum below about 0.2 MeV is from multiple scattering.

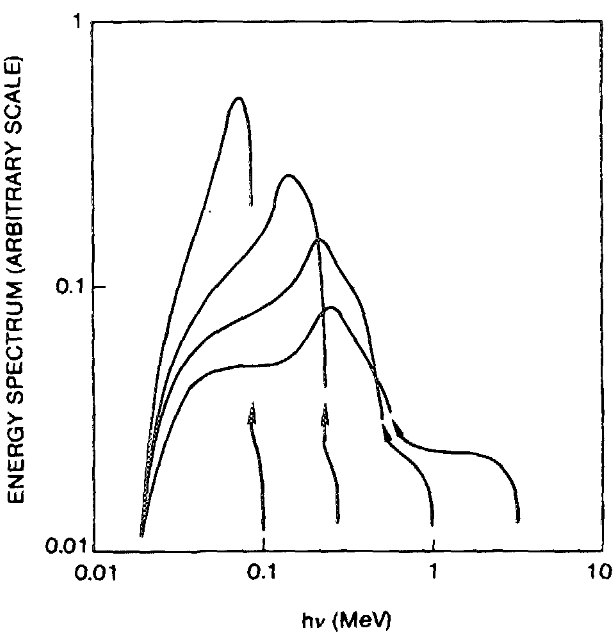

FIG. 5. Backscattered photon spectrum in test plane from monoenergetic photon with energy indicated by arrow emerging perpendicularly from converter under 45° with the z axis.

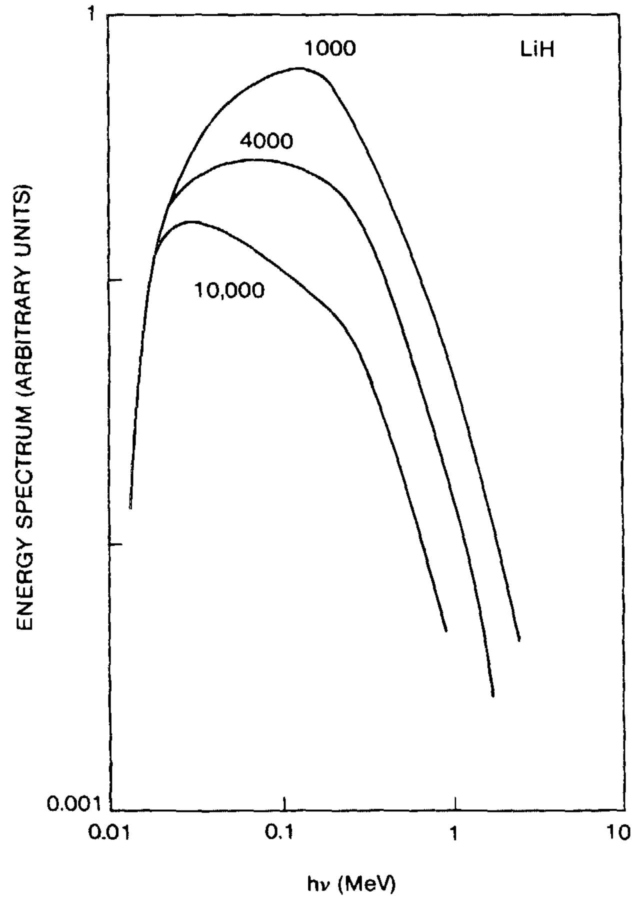

FIG. 6. Comparison between the scattered x-ray spectra for LiH scatterer and 1000-, 4000-, and 10 000-cm^2 test areas.

The dose in test areas larger than 1000 cm^2 can be scaled from results presented here by simply enlarging the geometric scale length in the correct proportion, and also by reducing the density of the scatterer by the same factor; e.g., using a porous material instead of a solid with maximum density. Besides obvious geometric parameters such as angles and aspect ratios, there is a further parameter, the scattering length over the geometric scale length. This parameter is kept constant by changing the density of the scatter. An increase in test area by a factor A gives a dose/beam energy change by a factor $1/A$. If the electron beam area and total current increase by the same factor, the dose does not change, while the dose-area product increases.

Increasing the test area without corresponding reduction in the density of the scatterer forces the photons to scatter relatively more often, and the result is a softening of the spectrum. Figure 6 compares the scattered spectra for a LiH scatterer with density 0.82 g/cm^3 over a 1000-4000-, and 10 000-cm^2 test area. The spectrum for 4000 cm^2 is comparable to that for 1000 cm^2 with a Be scatterer (density 1.82 g/cm^3), but the spectrum is harder than this for 1000 cm^2 and softer for 10 000 cm^2, as expected. The dose to beam energy ratio is also inversely proportional to test area A in this case.

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III. CONCLUSION

Compton scattering of low-Z materials such as LiH or C can be an attractive method to produce a relatively soft bremsstrahlung spectrum from high-voltage electron beams without increasing the complexity in pulse power requirements. In particular, existing high-voltage flash x-ray machines can readily be converted into 1-MV (peak) bremsstrahlung irradiators by adding a scattering option. For example, the 8-MeV Aurora facility[5] at Harry Diamond Laboratories has 2 MJ total electron beam energy (in four beams): according to computer projections it could produce up to 70 krad over 1000 cm^2 with some modification in the diodes.

The proposed geometry may have additional advantages in that electron beam energy is directed away from the test plane. Protection of the test plane from mechanical shock, heating, and other potentially deleterious influences thus becomes much easier.

ACKNOWLEDGMENTS

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