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MONTE CARLO 20 AND 45 MeV BREMSSTRAHLUNG
AND DOSE-REDUCTION CALCULATIONS

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Abstract

The SANDYL electron-photon coupled Monte Carlo code has been compared with previously published experimental bremsstrahlung data at 20.9 MeV electron energy. The code was then used to calculate forward-directed spectra, angular distributions and dose-reduction factors for three practical configurations. These are: 20 MeV electrons incident on 1 mm of W + 59 mm of Be, 45 MeV electrons of 1 mm of W, and 45 MeV electrons on 1 mm of W + 147 mm of Be. The application of these results to flash radiography is discussed.

Introduction

The new flash X-ray facility¹ constructed at LLNL can deliver 150 microCoulomb of 20 MeV electrons in 70 ns onto a spot less than 3 mm in diameter with a half-angular electron divergence of 6°. The bremsstrahlung photons from this accelerator will be used for a variety of radiographic investigations of both thick and thin objects under explosively driven conditions.

In order to properly design and interpret experiments, it is very useful to have a Monte Carlo code to simulate the coupled electron-photon processes that occur both in the creation of the bremsstrahlung as well as in the collimation, the materials being radiographed, and the detection system. One such code suitable for this purpose in many experimental situations is the SANDYL code.² First the code is compared with published data of O'Dell et al.³ for bremsstrahlung at 20.9 MeV. Reference 3 used linac produced bremsstrahlung to irradiate a D₂O secondary target cell. Neutrons from photodisintegration of the deuterium were energy analyzed by time-of-flight at 90° to the bremsstrahlung, and the disintegration cross-section tables were used to infer the bremsstrahlung spectrum. Our SANDYL calculations for the angular distribution of photon MeV are then compared to the data of Sandifer and George⁴ for the same target.

This work shows that by choosing a fine-enough electron substep size in the SANDYL code, agreement on the absolute spectral strength with the data of Ref. 3 is within 10%, and the angular distribution agrees well with that of Ref. 4. In addition, a simple formalism for calculating the dose-reduction factors due to finite electron incident angular divergence is presented. Spectra, angular distribution, and dose-reduction graphs are shown for three practical flash X-ray geometries.

Comparison of SANDYL with formulae and published data

SANDYL uses different cross-sections for the production of bremsstrahlung photons recommended by Koch and Motz⁵ as adapted by Berger and Seltzer.⁶ Different combinations of the formulae of Ref. 5 are used for different ranges of the screening parameter [Eq. (1) of Ref. 6] which depends on the electron and photon energies and the atomic number of the target (tungsten in the present case). Both Refs. 5 and 6 recommend using formulae 2CS of Ref. 5. This allows one to calculate bremsstrahlung over a limited range of photon energies and angles analytically for a very thin target, where no electron-photon transport is needed.

We have used formulae 2CS(c) with intermediate screening to calculate the angular distribution of 10.2 MeV photons emitted from 20 MeV electron-induced bremsstrahlung over the region of validity which extends from 0.3° to 7° in photon angle. This calculation was done analytically for the purpose of checking the approximate formulae used in SANDYL (p. 64 and p. 56 of Ref. 2) for the angular distribution of photons from a single atom. Figure 1 shows the comparison between the two calculations.

Figure 1. Comparison of two formulae used to calculate the photon angular distribution from a single tungsten target atom.

SANDYL uses an inherent angular distribution of bremsstrahlung photons which is not dependent upon the photon energy. In formula 2CS of Ref. 5, the angular distribution does depend slightly upon photon energy. They agree rather well, and the slight difference is probably not important for the 1 mm thick tungsten targets being considered as long as the electron angles or photon angles are not too large. For these real targets, the angular distribution is a convolution of the inherent scattering of Fig. 1 with a half-intensity angle of about 0.9° with the angular distribution of electron scattering in the target material. As will be shown later, the resultant angular distribution has a half-intensity angle of about 3.5° . Thus, small changes in the 0.9° inherent half-width do not significantly change the thick-target results. In fact, another Monte Carlo code called FGS⁷ assumes the inherent angular distribution is a delta function, where all created photons are emitted at a fixed angle (dependent only on electron energy) relative to the electron direction.

The SANDYL code was then used to calculate the angular distribution, spectral shape and strength of photons created in the geometry reported by O'Dell et al.³ The results are shown in Figs. 2 and 3. The geometry had axial symmetry about the direction of the parallel electron beam. The SANDYL-7X version of the SANDYL code was used, and the problem required 188 minutes on a CDC 7600 computer to run 200,000 source electrons. The running time is slow because special values were used for the electron substep size. The SANDYL code has a quantity called ISUB (p. 58 of Ref. 2) which must be large enough; otherwise this particular calculation will be quite inaccurate. We found that using the code's own default values for ISUB, the calculated photon strength at 0° is 60% higher than the measurements of Ref. 3. Tripling the values of ISUB resulted in a tripling of computer time and a reduction of the discrepancy by a factor of 3 from 60% to 18%. Finally the values of ISUB were made equal to 36 for tungsten and gold and 24 for aluminum, which is 6 times their default values. This made the computation time six times the original value, and the discrepancy is essentially gone, as Fig. 2 shows.

At the same time, the calculated angular distributions were too narrow compared to the data inferred from Ref. 4 for the default values of ISUB. Reference 4 shows that the photon angular distributions for electron energies ranging from 6.4 to 17.5 MeV can be superimposed into one curve if they are plotted as a function of MeV degrees. We have used their universal curve, assuming that it also applies at 20.9 MeV. The angular distribution depends upon the thickness of the target, but both Refs. 3 and 4 used the same target.

Increasing ISUB broadened the angular distribution to that shown in Fig. 3 which is a reasonable fit to the data. In summary, both the spectral strength and the width of the angular distribution match the calculations if ISUB is six times the default value, and presumably this is also true if ISUB is larger, since the percentage difference between the two was approaching zero as ISUB values were increased. It appears that if the electron energy grid is too coarse, the electrons in the code have not scattered in the tungsten to large enough angles, and thus the bremsstrahlung is directed too sharply in the forward direction. This causes the forward intensity to be too large. One sees from Fig. 3 that the distribution is much broader than the inherent 0.9° spread for single atom scattering. Electrons scattered to below 3 MeV and photons degraded to or created less than 0.2 MeV in energy were discarded in the calculations.

References 6 and 7 also show comparisons between the data of O'Dell et al.³ and their calculations with the ETRAN and ECS codes. The SANDYL comparison of our Fig. 2 matches closest to the data. In plotting the data of Ref. 3 in Fig. 2, we have noted the comment

Figure 2. Calculations and measurements of the photons in the 0° to 1° cone per MeV per steradian per electron.

Figure 3. Calculations and measurements of the photon MeV per steradian per electron.

on p. 627 of Berger and Seltzer⁶ that O'Dell's data must be divided by 1.12 if one wants the strength of the photon flux hitting their actual secondary D_2O target, which subtended a cone angle of about 1° as indicated in Fig. 2. O'Dell had multiplied his finite solid angle data by 1.12 to estimate what the flux at exactly 0° would be. We do not know if this was taken into account in the comparison made in Ref. 7.

Calculations for 20 MeV electrons on 1 mm of W + 59 mm of Be

The flash X-ray FXR electron accelerator at LLNL uses a thicker target and a different electron beam stop at a slightly different energy than that used by Ref. 3. The thickness of target which produces the most forward X-ray flux depends not only upon the electron energy and target material, but also upon the electron incident angular divergence. For parallel incident electrons, increasing the target thickness eventually causes forward flux reduction due to electron scatter and self attenuation of the X-rays. For converging incident electrons, the electron scattering takes a while to become comparable in spreading to the incident electron angular divergence, and the optimum target is probably somewhat thicker than for the parallel incidence case.

Figure 4 shows the spectrum calculated to exit the Be electron stopper for 20 MeV parallel electrons. The electrons lose about 6 MeV in the W and the electron angles in both the W and Be increase with distance penetrated. The relevant angular range for the photons is from 0° to 1° for many hydrodynamic experiments involving flash radiography of thick objects, and this is what is plotted in Fig. 4. It is actually the spectrum entering zone 5 shown in Fig. 4 for angles between 0° and 1° . Another edit was taken of the photon spectrum entering zone 6 with angles between 0° and 1° . Zone 6 is specially configured to subtend a cone with a 1° HWHM relative to the point of intersection of the electron beam with the W. The spectrum entering zone 6 is the same as that entering zone 5, but the magnitude of the zone 6 flux is 3% lower. This is because not all of the photons entering zone 5 appear to be coming from a point source.

The meaning of the vertical scale for Fig. 4 is the following. The SANDYL code provided the number of photons per incident electron entering zone 5 with angles less than 1° . We took that result, divided by the width of the photon energy bin in MeV and divided by the steradian content of the 0° to 1° cone, and plotted the result in Fig. 4. Thus, the vertical scale is the number of photons per MeV per electron per steradian, averaged from 0° to 1° . There are expected to be 0.21 photons per steradian near 0° per electron between 6 and 7 MeV photon energy. It is impractical to edit in angular bins smaller than 1° , because of the long computing time required. Figure 4 required 280 minutes on the CDC 7600 computer.

The minimum photon and electron energies used in the calculation were 0.75 and 3 MeV, respectively. Photons transported below these cutoff energies were discarded. The calculation for Fig. 4 is the histogram and the error bars are statistical only. The smooth curve is simply drawn through the histogram.

Figure 5 shows the angular distribution of photon energy content for parallel incident electrons, and a smooth curve is drawn through the histogram. The photon MeV plotted represents the sum of the number of photons in an energy bin times that bin's average energy, summed from 0.75 MeV to infinity.

Formalism for calculating the dose-reduction factor

Figure 6 shows the energy content reduction factor as a function of electron angular divergence, to approximate what happens in real accelerators that do not use parallel electrons incident on the target. Keeping in mind that the SANDYL code uses an inherent

Figure 4. Bremsstrahlung spectrum for 20 MeV parallel electrons on 1 mm of tungsten + 59 mm of Be according to the SANDYL code version HANDYL7X.

Figure 5. Angular distribution of photon MeV for parallel 20-MeV electrons on 1 mm of W + 59 mm of Be according to SANDYL.

X-ray distribution which does not depend upon photon energy, it is still possible to make a good approximation, to the effects of incident electron angular divergence, for small electron and photon angles. We assume as in Fig. 6 a cone uniformly filled with incident electrons. Then the number of incident electrons per unit solid angle can then be written as

$$\begin{aligned} dN_e/d\Omega_e &= \frac{1}{2\pi(1 - \cos \theta_e^{\max})} & \text{for } 0 < \theta_e < \theta_e^{\max} \\ &= 0 & \text{for } \theta_e^{\max} < \theta_e \end{aligned} \quad (1)$$

This distribution is normalized to one incident electron. $\theta_e^{\max}$ is the maximum electron angle contained in the incident beam.

Figure 6 Dose reduction factor vs electron angular divergence for 20-MeV electrons on 1 mm of tungsten + 59 mm of Be

The incident electrons contained between angles θ_e and $\theta_e + d\theta_e$ will contribute a photon energy content flux per steradian at 0 equal to

$$\frac{2\pi \sin \theta_e d\theta_e}{2\pi(1 - \cos \theta_e^{\max})} \cdot \frac{dE_\gamma}{d\Omega_\gamma} \text{ [evaluated at } \theta_\gamma = \theta_e \text{]} \quad (2)$$

where the first term is the number of such electrons contributing and the second factor is the photon energy content per unit solid angle per electron produced at a photon angle θ_γ equal to the electron angle θ_e under consideration. $dE_\gamma/d\Omega_\gamma$ can be taken directly from Fig. 5. The total photon energy content per steradian at 0° per electron is the integral of the above expression from $\theta_e = 0$ to $\theta_e^{\max}$, thus

$$\frac{dE_\gamma}{d\Omega_\gamma}(0, \text{ for convergent electrons}) = \int_0^{\theta_e^{\max}} \frac{dE_\gamma}{d\Omega_\gamma}(\theta_e) \sin \theta_e d\theta_e \quad (3)$$

$$1 - \cos \theta_e^{\max}$$

Figure 6 was obtained by approximating the integral in the above expression by a summation over angular bins 1° wide, and then dividing by the result from Fig. 5 in the first angular bin for parallel electrons incident on the target. This is the approximation to the dose-reduction factor. For example, if $\theta_e^{\max}$ for the 20 MeV electron beam is 6°, Fig. 6 indicates that the forward-directed dose at angles less than 1° is only about half of what it would be for parallel incident electrons.

Calculated results for the two other geometries

Figure 7 shows the spectrum for 45 MeV electrons onto 1 mm of W. This energy is being considered as a possible modification to the 1 XR accelerator. Figures 8 and 9 show the angular distributions and dose-reduction results. Similar results for 45 MeV electrons onto 1 mm of W + 147 mm of Be as a beam stop are shown in Figs. 10, 11, and 12.

Figure 7 - Bremsstrahlung spectrum for 45 MeV parallel electrons on 1 mm of tungsten according to the SANDYL code versus HANDYL7X

For deep-penetration radiography, it is useful to know the integrated number of photons emitted over various energy ranges centered around 4 MeV, since they are the ones that survive best without scattering. Table 1 shows integrals for the three geometries for parallel incident electrons. Then the dose-reduction curves given above can be used to estimate the loss due to finite incident electron angles.

Summary

The results calculated above are being used at LLNL to calculate the limiting radiographic resolution determined by the statistics of a limited number of X-rays reaching the detection system. The phase space occupied by the electrons in an accelerator determine the minimum spot size that can be attained for a given electron angular divergence determined by focussing magnets close to the X-ray target. In general the trade off between spot size and electron angle can be worked out from the dose-reduction curves if the goal is, for example, to maximize the forward-directed flux of X-rays per unit area of the electron spot on the target, keeping in mind that the dose-reduction curves are more inaccurate with increasing angle because of the approximations used in SANDYL.

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Figure 8. Angular distribution of photon MeV for parallel 45-MeV electrons on 1 mm of W according to HANDYL7X.

Figure 9. Dose reduction factor vs electron angular divergence for 45-MeV electrons on 1 mm of tungsten.

Figure 10. Bremsstrahlung spectrum for 45 MeV parallel electrons on 1 mm of W + 147 mm of Be according to HANDY7X.

Figure 11. Angular distribution of photon MeV for parallel 45-MeV electrons on 1 mm of W + 147 mm of Be, according to HANDY7X.

Figure 12. Dose reduction factor vs electron angular divergence for 45-MeV electrons on 1 mm of tungsten + 147 mm of Be.

Table 1. Results Integrated Over Photon Energy Range.

Photon Energy Integration Limits in MeV	Photons with $0 \leq \theta \leq 1^\circ$ Per 150 μC of Parallel Electrons		
	20 MeV + 1 mm W + 59 mm Be	45 MeV + 1 mm W	45 MeV + 1 mm W + 147 mm Be
4-5	5.09×10^{11}	1.72×10^{12}	9.76×10^{11}
2.37-7.5	1.60×10^{12}	8.92×10^{12}	4.83×10^{12}
1.80-10.0	2.40×10^{12}	1.19×10^{13}	6.98×10^{12}

For a FAR pulse of 150 μC and 6° half angular divergence simulating 1983 FXR parameters, multiply the photon fluxes in the 20 MeV column above by 0.49

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