Electron Reflection in Monte Carlo Simulations with the code GEANT

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Abstract

Target preheat is a significant concern in inertial confinement fusion experiments because, when the temperature of the target becomes too large, the areal density (density times radius) required for ignition cannot be attained. The majority of preheat comes from fast electrons produced when the laser interacts with the target. When these energetic electrons are slowed by collisions, they release high-energy x rays. The energy profile of these x rays is thus a very useful diagnostic of the preheat problem. This energy profile has been obtained from Monte Carlo simulations using the code GEANT. The GEANT code simulates electron transport in the target ending either with the electron's loss of all kinetic energy through collisions or with its escape. In reality, only a negligible number of electrons escape before the target becomes charged enough to reflect the remaining electrons back into the target. A FORTRAN program was written to model the specular reflection of these electrons back into the target. The results of this program are then used as input for another GEANT run with the reflected electrons. This allows for more accurate simulation of electron transport and of the profile of the x rays generated. Nevertheless, it has been found that electron reflection is not a major factor in CH coated Cu spheres.

Introduction

Target preheat is one of the major obstacles to achieving ignition in ICF experiments. Because the fast electrons produced by the laser-target interaction heat the DT fuel in the target before it has been compressed, they prevent the compression of the target to the requisite areal density. The areal density of the fuel has to be large enough for the energy in the alpha particles (helium ions) produced by the initial fusion reactions to be re-deposited in the DT core. The laser pulse itself can only provide the energy for fusion reactions in the central hot core; the main fusion reactions will result from the heating by the kinetic energy of the alpha particles produced by the initial reactions. While some of the helium nuclei will escape, when that proportion is reduced by increasing the areal density, more energy will be re-deposited in the core, and more fusion reactions will occur.

One cause of target preheat is from fast electrons (> 20 keV) produced in the corona by the two-plasmon decay instability, which results from the interaction of the high intensity laser beam with the expanding plasma. The main diagnostic used to measure the fast electrons is the hard x-rays (HXR) produced as the electrons are slowed down in the target. Experiments were carried out by Yaakobi[1] to measure both the preheat level and the HXR emission from a copper sphere coated with a plastic layer. The analysis was carried out with Monte Carlo simulation of electron transport, which produced a HXR emission that could be compared with that obtained in experimental results. These Monte Carlo simulations did not include the reflection of the electrons at the target outer surface due to the electric field created by a small number of escaping electrons. This paper explores the effects of electron reflection in the Monte Carlo simulation of HXR emission by the fast electrons.

Shortcomings of Previous Monte Carlo Simulations

In his investigation of the relation between preheat and HXR emission, Yaakobi used Monte Carlo simulations to compare to the HXR spectrum generated experimentally.[1] These simulations were run with the code GEANT,[2] a Monte Carlo code designed to model the transport of particles through matter. A large number of electrons are run through the code as a set of discrete random paths set with a certain collision probability between the electrons and background material, resulting in the electrons slowing down and scattering. The model is time independent. When Yaakobi did his analysis with GEANT, he did not take into account the fact that most of the electrons scattered in the outward direction are reflected at the outer edge of the target by a “sheath.” After the first electrons created escape the target, an electrostatic sheath is established at the target outer edge as the target becomes positively charged. The electrostatic field forces most of the electrons subsequently arriving at the sheath back into the target. It is possible that these electrons could create significant amounts of HXR's, which would change the results of the simulations.

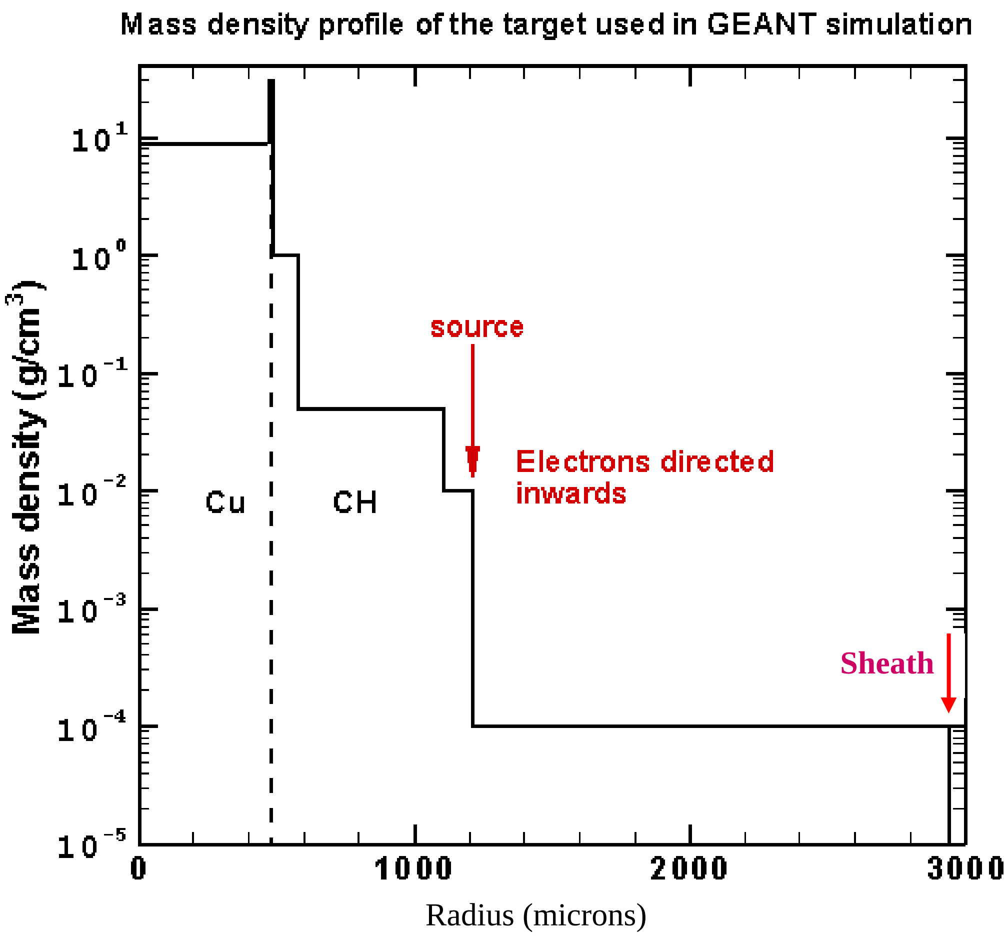

Figure 1: Density profile from the hydrodynamic simulation used in the GEANT simulation.

The target used in our simulations was a solid 600-μm-radius Cu sphere coated with 10 μm of CH. Unlike in the Yaakobi simulation, which was carried out with the solid target, a representation of the actual density profile from the hydrodynamic simulations was used, as shown in Fig. 1. A step profile was constructed to model the continuous density profile because of the discreet nature of the GEANT material input. The electron source was a beam of energy 100 keV created at the position in the corona where the laser beam interacts with the expanding plasma.

Electron Reflection Model

Since GEANT does not include reflection of the electrons at the outer boundary, the simulations are carried out in at least two steps. In the first step, the electrons are transported from a given source, and the position, angle and energy, of electrons reaching a boundary are recorded in a file. In the next step, the reflected electrons are used as a source for further transport; another step can be taken if necessary. In the model the electrons are specularly reflected at the outer boundary of the target. Neglecting the energy loss to the outward motion of the sheath upon reflection, the kinetic energy of the reflected electron will be the same as that of the incident electron. This allows us to set the kinetic energy of the reflected electrons, for the second GEANT run, equal to the kinetic energy output by the initial GEANT run.

The direction to be used as a source in the second GEANT run is computed from the outgoing angle formed with the radius vector at the point on the sphere of exit and the exit velocity, as shown in Figure 2. In reality, electrons exit the target, are turned around by the field in the vacuum and reenter the target at a different position, as seen in Figure 2(a). Since the re-entry angle is the same as the exit angle, the reflection can be modeled with a specular reflection at the target outer boundary, as shown in Figure 2(b).

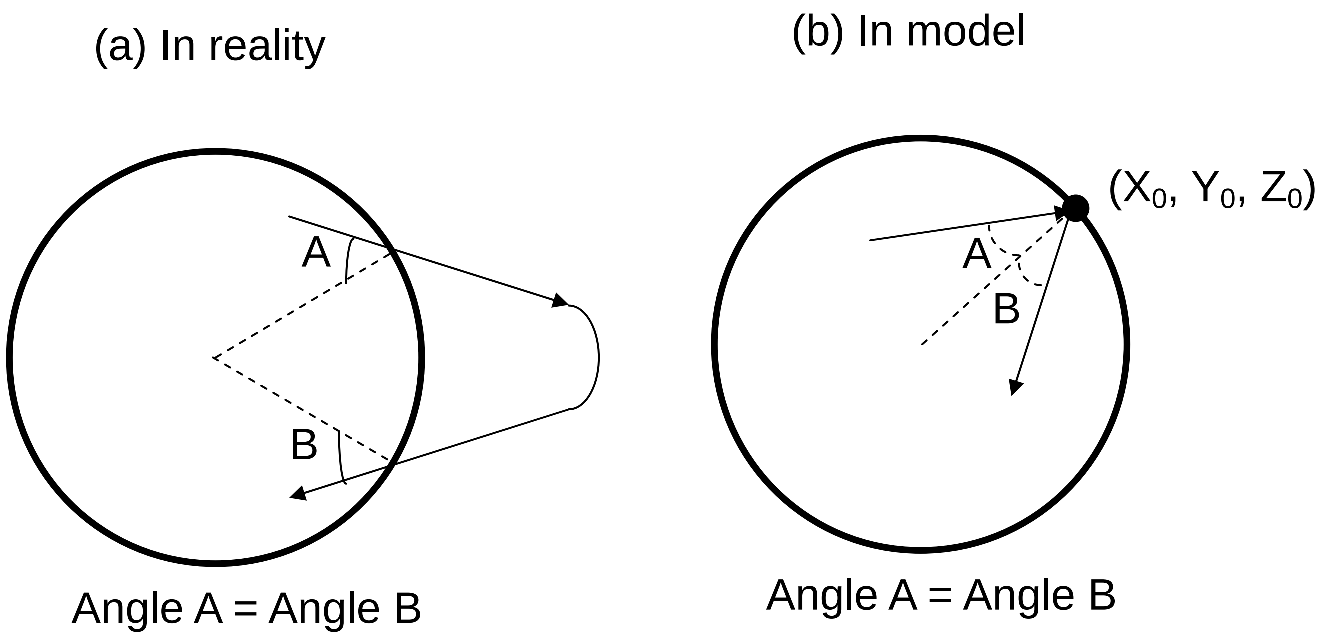

Figure 2: The path of electrons in the code and in reality

The angle between the incoming velocity and the radius is set equal to the angle between the outgoing velocity and radius. The angle between two lines is equal to the difference of the arctangents of their slopes: $\arctan(V_x/V_y)-\arctan(X_0/Y_0) = \arctan(X_0/Y_0)-\arctan(Vx_0/Vy_0)$, where X_0,Y_0, and Z_0 are the coordinates of the position at the target surface (outer edge of the corona) where the electron is reflected, Vx_0, Vy_0, and Vz_0 are the directional cosines of the incident trajectory, and V_x V_y, and V_z are the reflected directional cosines. This is done twice in two planes to account for all three dimensions. As a result, we can calculate the ratios of the directional cosines (V_x, V_y, and V_z) of the reflected direction:

$$A=V_x/V_y= \tan(2.0*\arctan(X_0/Y_0)-\arctan(Vx_0/Vy_0)) \quad (1)$$

$$B=V_x/V_z= \tan(2.0*\arctan(X_0/Z_0)-\arctan(Vx_0/Vz_0)). \quad (2)$$

Since Vx_0 and Vy_0 are directional cosines, $V_x^2+V_y^2+V_z^2=1$. Because the method outlined above calculates a line for the reflected velocity, the direction, into or out of the sphere, is indeterminate. In order to calculate this direction and to guarantee that the electrons are reflected back into the target, the dot product of the reflected velocity with the target normal ($X_0V_x+Y_0V_y+Z_0V_z$) is set less than zero. Using Eqns. (1) and (2) for V_y and V_z, we require that $V_x(X_0+Y_0/A+Z_0/B)<0$. If $(X_0+Y_0/A+Z_0/B)<0$, then Vx>0. If $(X_0+Y_0/A+Z_0/B)>0$, then Vx<0. The sign of Vx is thus -Abs($X_0+Y_0/A+Z_0/B$)/($X_0+Y_0/A+Z_0/B$)). Therefore:

$$V_x= - (\mathrm{Abs}(X_0+Y_0/A+Z_0/B)/(X_0+Y_0/A+Z_0/B)) /\mathrm{SQRT}(1+(A^{**}-2.0)+(B^{**}-2.0)). \qquad (3)$$

Using this value we can also calculate V_y and V_z. This equation loses accuracy as Vx_0 approaches zero, so all the velocities are calculated from the largest incoming velocity. For example, if Vy_0 is the largest of the incoming velocities, V_y is calculated first, then V_x and V_z are calculated in terms of V_y. These values are then used as inputs for a second GEANT run for the reflected electrons, the results of which would show the effects, or lack thereof, of electron reflection. In retrospect, much of this process was unnecessary as $V_x=-Vx_0$, $V_y=-Vy_0$, $V_z=-Vz_0$, sending the electrons along the same path that they came, would have yielded the same results due to spherical symmetry.

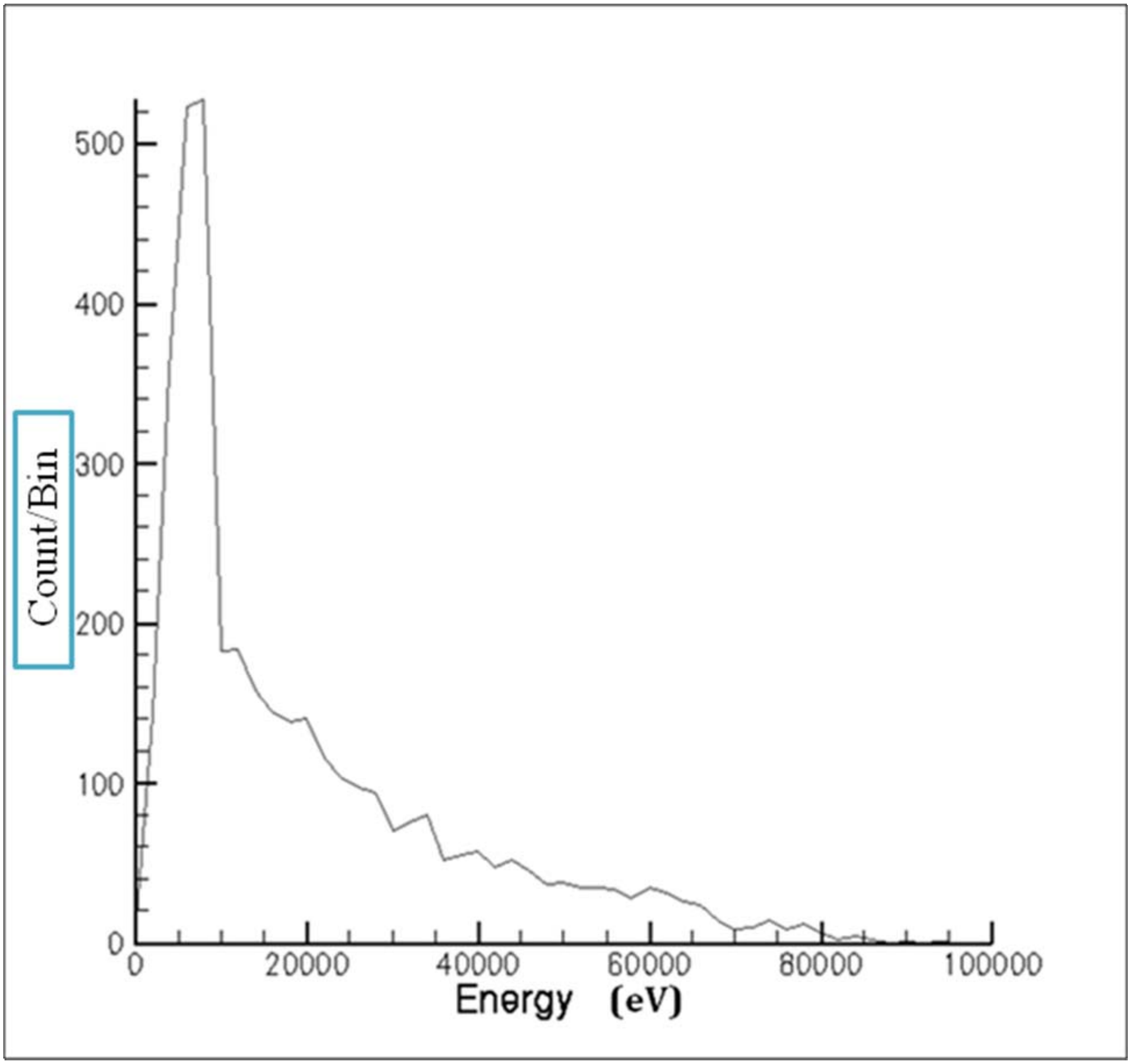

Figure 3: The Energy Profile of x rays produced in the first run

Results of simulations

The results of the second GEANT run with the reflected electrons did not produce a single new HXR as compared to the number produced in the first run as seen in the number of HXR "particles" shown in Figure 3. The reflected electrons were just not numerous or energetic enough to create a single x-ray event. It is possible that using a larger number of electrons in the first run would have resulted in a larger number of reflected electrons and, hence, in the emission of a small number of HXR's, much fewer than were produced in the first run. The result of this analysis confirms the accuracy of the previous analysis done by Yaakobi by showing that electron reflection is not a factor in Monte Carlo analysis of preheat.

Conclusion

A methodology was developed to determine whether reflecting the escaped electrons in simulations with the Monte Carlo code GEANT modified the results of previous analysis of the HXR emission from fast electrons in a plastic-coated copper ball. The escaping electrons were collected and used as a source for a second GEANT run. The lack of HXR emission from the second GEANT run confirms the estimation by Yaakobi that electron reflection is not a major factor in his Monte Carlo simulation of fast electron transport.

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