Neutron Transport Calculations Using Monte-Carlo Methods

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Abstract

Fusion reactions from direct-drive inertial confinement fusion experiments at the Laboratory for Laser Energetics (LLE) release large amounts of stored nuclear energy. Most of it is given off as energetic neutrons. Plastic scintillators are used as detectors for these neutrons. The neutrons that interact with the scintillator produce photons that are recorded using a photomultiplier tube on a fast oscilloscope. The detector has a lead shield used to block x-rays that would flood the detector with energy. The neutrons travel throughout the target area interacting with several structures, such as the chamber wall, that significantly affect the neutron transport. In order to understand the effects of the target chamber and lead shield on the detected neutron signal, a Monte-Carlo simulation program (Geant4) was used to simulate neutron interactions. Geant4, a toolkit designed to calculate particle interactions with matter, is used predominantly in high-energy, nuclear, and accelerator physics. By changing the geometric dimensions and material properties of the structures in the target area, effects that cannot be tested experimentally have been simulated. It was found that the lead shield and the target chamber have a minimal effect (< 1%) on the full width at half maximum (FWHM) of the neutron signal.

1. Introduction

The long-term goal of fusion research is to design a sustainable fusion energy source that can produce energy cleanly from common fuel sources. The Laboratory for Laser Energetics conducts most of its experiments and research on the OMEGA laser system, which consists of 60 symmetrically oriented, high-power laser beams focused onto a target to obtain internal confinement fusion. The targets are composed of frozen hydrogen isotopes deuterium (^2H) and tritium (^3H), the most common reactants for fusion reactions. When the nanosecond laser pulse strikes the target, the outer shell rapidly expands, compressing and heating the fuel creating temperatures similar to those in the center of sun.

1.1 Neutron Production

Most of the energy from fusion reactions is given off in the form of energetic neutrons. These neutrons can be created by two distinct types of fusion reactions: deuterium-tritium (DT) and deuterium-deuterium (DD). DT reactions yield a 14.1 MeV neutron and a 3.0 MeV alpha particle, while DD reactions yield either a 2.45 MeV neutron and a 0.825 MeV helium-3 nucleus, or a 3.0 MeV proton and a 1.0 MeV triton.[1]

In order for the reaction to occur, the relative velocity of the reactants must be large enough to overcome the Coulomb force and release the stored nuclear energy. This energy is distributed between the two products as given above; however, since the net momentum of the reactants is not constant, the actual distribution of the energy between the two products varies in order to conserve momentum and energy. The resulting neutrons from each type of reaction (DD, DT) have a Gaussian distribution of energy such that the mean energy is equal to either 2.45 MeV (for DD) or 14.1 MeV (for DT). The width of the energy distribution is proportional to the square root of the temperature of the reactants. This temperature is significant because a high plasma temperature is necessary for the fusion reactions to occur.

1.2 Neutron Detection

In order to measure the width of the spread of neutron energies, the OMEGA laser system uses plastic scintillators (Bicron BC-422Q[2]) to measure the spread in the neutron time of flight, which can be correlated to a distribution of energies. To prevent the intense bremsstrahlung that would be produced in the detector from x-rays, a lead shield is placed directly in front of the detector. The cross section between x-rays and lead is much greater than the cross section between neutrons and lead, greatly decreasing the intensity of the x-rays entering the scintillator while having a significantly smaller effect on the neutrons. Neutrons produce a photon signal in the scintillator by transferring energy to a nucleus (hydrogen or carbon), whose electrons are ionized from the energy. These ions and electrons excite and de-excite nearby atoms, emitting photons, which are converted to current in a photocathode. The current is amplified using a microchannel plate and measured with a fast oscilloscope.[3] Figure 1 illustrates this process.

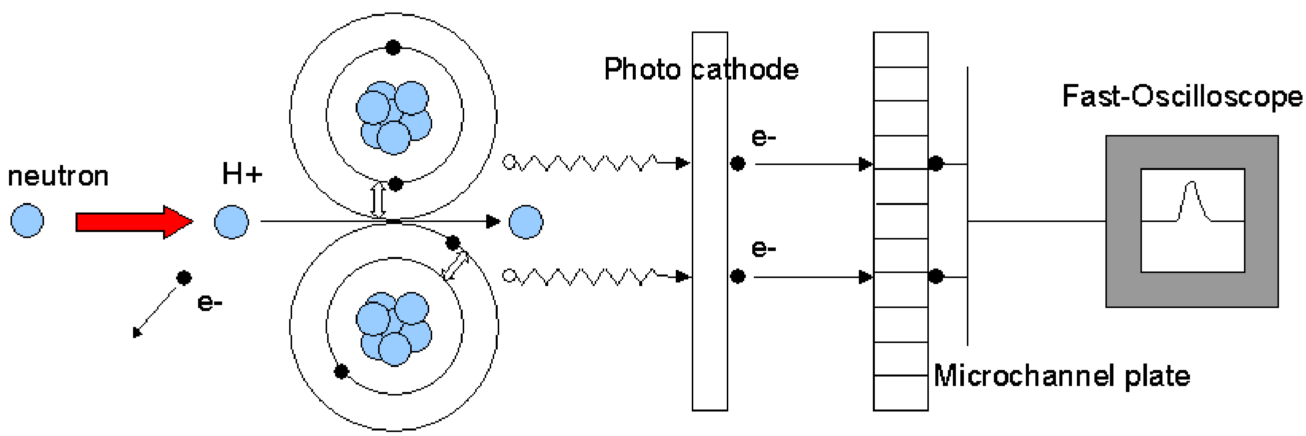

Figure 1: Scintillation process – A neutron collides with the nucleus of an atom such as hydrogen. The atom becomes ionized and excites and de-excites nearby atoms, emitting photons. The photons generate current in a photocathode. The current is amplified by a microchannel plate and read by a fast oscilloscope.

Although the lead shield reduces x-ray data, it also scatters neutrons, which could significantly alter the FWHM, used to measure the time of flight spread of the arriving neutrons. Because the detector requires the lead shield in order to collect data, the effect of the shield on the neutron signal cannot easily be determined experimentally. It is also extremely difficult to determine theoretically. The same holds true for the aluminum target chamber, which is required to create a vacuum to ensure that the focused laser energy reaches the target with its beam quality preserved. The primary goal of this study is to model the effects of the target chamber and lead shield on the neutron time of flight spread.

1.3 Geant

Geant[4] is a Monte-Carlo simulation toolkit for the passage of particles through matter. A Monte-Carlo simulation uses random or pseudo-random numbers and interaction probabilities to simulate an experiment. Geant tracks the energies of each particle (projectile) until it decreases below a certain value known as the "cut value." At this point, Geant no longer tracks that energy and disperses it among the local particles, increasing the thermal energy of the volume. Any particle near a boundary is tracked below the cut value because there is a significant probability that the particle will travel into the next volume. Geant allows the user to select different physics processes, cut values, magnetic fields, material types, and many other settings in order to simulate the desired experiment. Like an experiment, Monte-Carlo simulations generate data that requires statistical analysis. The simulations also require extended runtimes in order to create meaningful data.

2. The Program

Using the Geant toolkit, a program was written to simulate the neutron transport in the target area. The LHEP[5] physics library was used to manage the physics processes, including hadronic and electromagnetic processes. The hadronic processes model strong-force interactions between neutrons and nuclei, while the electromagnetic processes model the ionization of electrons. The conversion from electron energy to photon energy was not modeled because the conversion efficiency is known to be a constant ratio.

Dimensions

Room Length = 30 m
Room Width = 15 m
Room Height = 15 m

Chamber Thickness = 8.89 cm
Chamber Outer Diameter = 6 m

Detector Distance
from Target = 12 m

Detector Diameter = 4 cm
Detector Height = 1 cm
Shield Diameter = 4 cm
Shield Height = 2 cm

Materials

Detector Material = Plastic
Chamber Material = Aluminum
Wall Material = Concrete
Room Material = Air
Shield Material = Lead

Figure 2: Default dimensions and materials used for the simulations.

The program constructs geometries and their corresponding materials, representing the structures in the target area that contribute the most to neutron scattering. The dimensions and materials are shown in Figure 2. Figure 3 illustrates the structural setup. The concrete walls have a minimal effect on the neutron detection and were added for completeness. The neutrons that do scatter off the chamber walls and reach the detector arrive much later than the significant neutron signal. The scintillator was constructed as a "sensitive detector" meaning that it records energy deposited within the volume by each particle. The program records specific information for each quantity of energy deposited that can be statistically analyzed.

For all simulations, 14.1 MeV mono-energetic neutrons were projected from the center of the target chamber. Mono-energetic neutrons were used to clearly observe the extent of the neutron scattering.

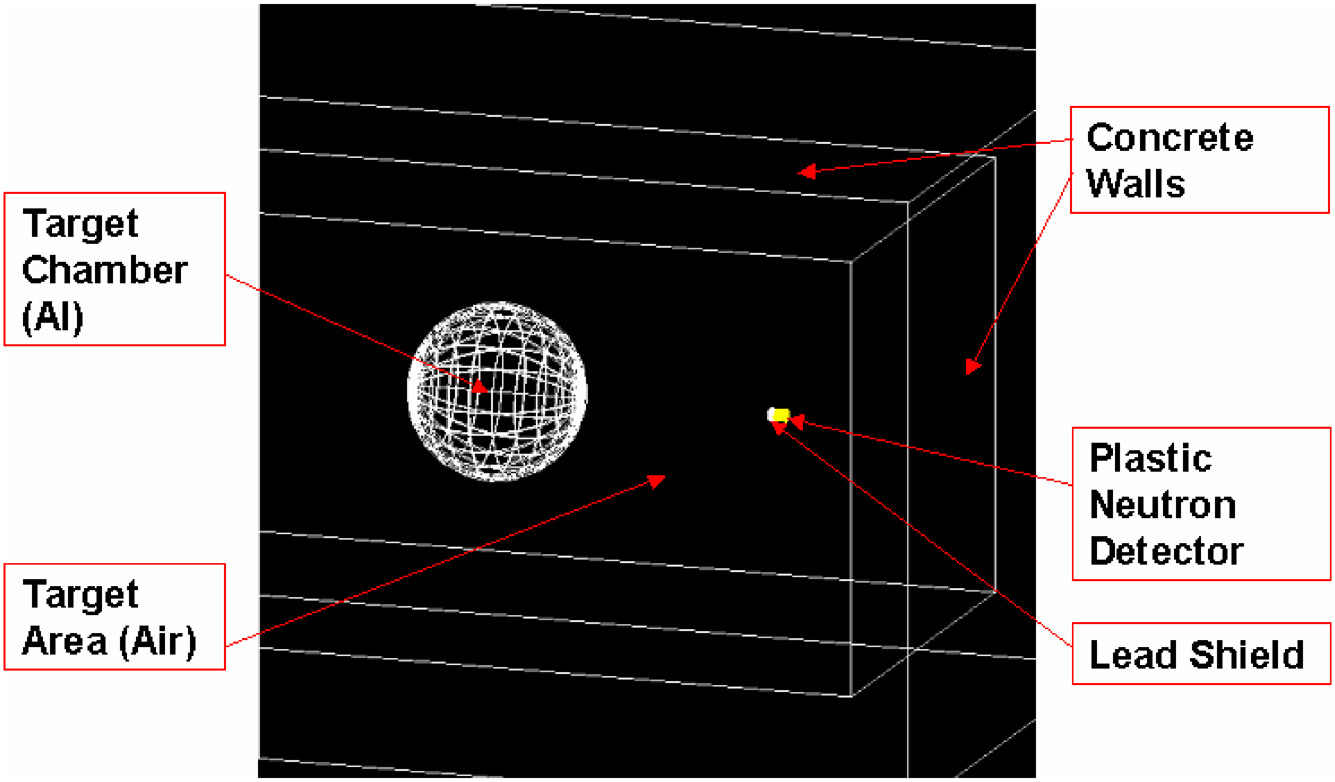

Figure 3: Materials used in the program – Each region was assigned a material with a temperature, density, and pressure.

3. Test Simulations

In order to confirm that the results produced by Geant are accurate, two simple tests were performed. In each test, all materials except the detector itself were changed to vacuum, and mono-energetic neutrons were launched directly at the detector. In the first test (Figure 4), which measured the energy deposition over time, the results were as expected. At the front of the signal, there is a very steep increase in the deposition energy. The signal then decreases exponentially over time until the neutrons reach the end of the detector, when the signal drops sharply. The remainder of the graph is background generated by neutrons that lose some of their energy near the front and deposit additional energy near the back at a time after the signal drop. The 0.8 ns FWHM correctly corresponds to the height of the 4 cm detector divided by the speed of a 14.1 MeV neutron (5.14 cm/ns).

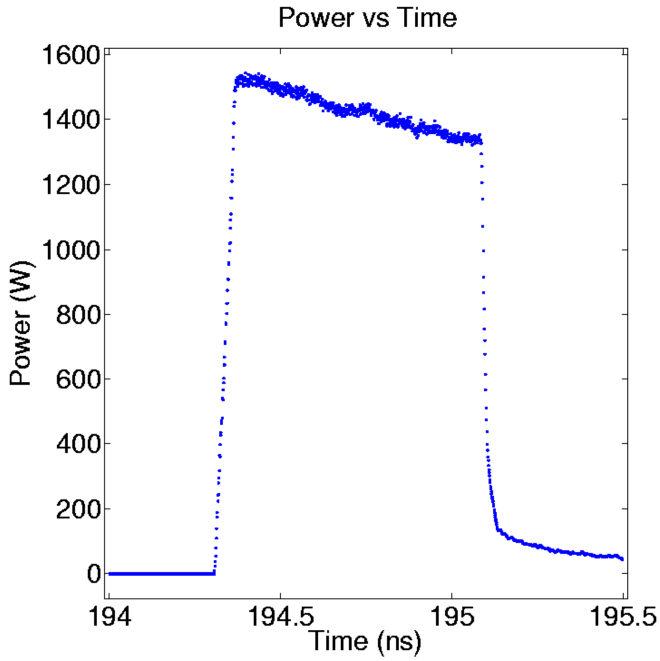

Figure 4: First Test – Energy deposition signal for 14.1 MeV neutrons through a 4 cm detector placed 10 m away from the target. The sharp rise and drop of the signal correctly correspond to the times at which the non-interacting neutrons pass through the detector. Between these times, the signal drops off exponentially.

A second test was performed to calculate the mean-free path of neutrons through a plastic scintillator. The detector was lengthened to 200 cm and all other conditions were the same as in the first test; however, instead of recording the energy deposition, the distance traveled by each neutron before its first interaction was recorded. The data was used to create a graph (Fig 5) of the percentage of non-interacting neutrons (y) versus length (x). The graph is well fit by an exponential of the form: $y = e^{-x/b}$, where b is the mean-free path. The mean-free-path value produced by Geant is 11.00 cm, while the literature value is 10 cm.[6] This favorable comparison confirms that Geant is producing meaningful data.

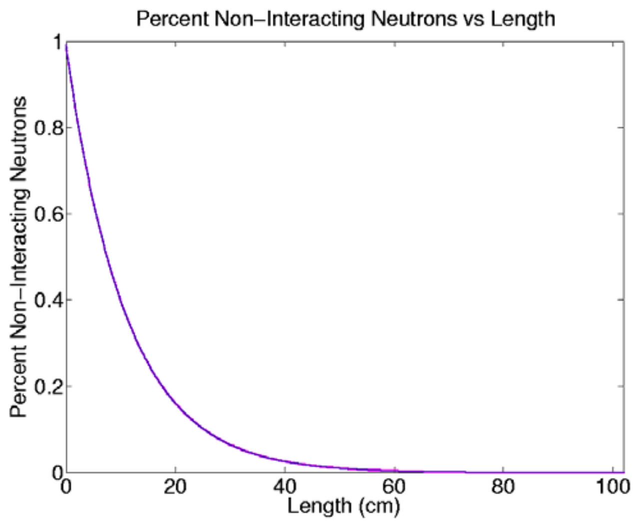

Figure 5: ***Second Test – The attenuation graph for 14.1 MeV neutrons in a plastic scintillator reveals the simulated mean free path to be 11.00 cm^{-1}.***

4. Results

In order to accurately determine the effect of the target chamber and lead shield on the neutron signal, one must consider all angles (4π steradians) of initial trajectories; however, this would produce limited data because the detector is so far away from the neutron source. When the detector is 2 cm in radius and 12 meters from target, one out of every 1.44×10^6 neutrons will be initially launched toward the detector. Although it is clear that the average neutron traveling toward the detector will deposit much more energy than the average neutron traveling in a different initial direction, it is questionable whether the average neutron traveling toward the detector will deposit more energy than 1.44 million neutrons traveling in different directions.

Two simulations using all of the default conditions (Figure 2) were performed in order to address this question. The first simulation used neutrons with initial direction varying less than 0.1 degrees from the direction of the detector, which corresponds to a solid angle of 9.57×10^{-6} steradians (encompassing the entire detector). The second simulation used neutrons with all other initial directions. When comparing the energy deposition per neutron density (neutrons per solid angle), it was found that the first simulation accounted for 27% of the energy deposition over all angles; however, when considering only the energy deposition occurring during times of significant signal strength (233 ns to 234 ns), the first simulation accounted for 96% of the total energy deposition. This allows simulations to be performed using a millionth of the neutrons (and one millionth of the run time) while sacrificing only 4% of the significant deposition. Figure 6 shows the visualization created by Geant of the neutron scattering.

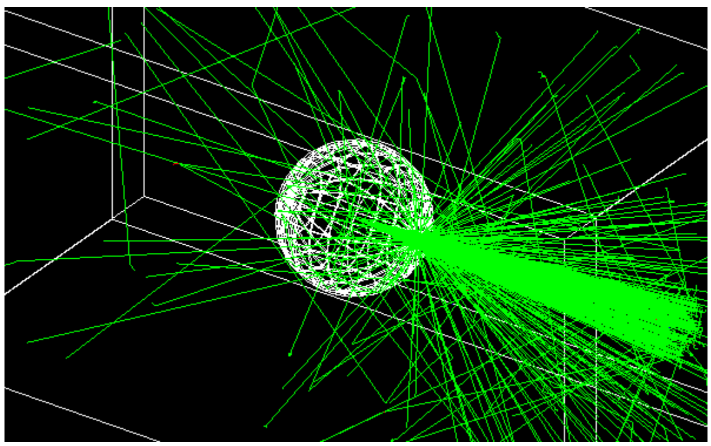

Figure 6: Neutron Scattering – Neutrons (green) with directions within a cone (increased solid angle for visualization) are scattered by the target chamber. The majority of scattered neutrons are deflected by a small angle (< 45 deg).

In order to determine the effects of the lead shield and the target chamber on the neutron signal, three simulations were performed. The first used neither the lead shield nor the target chamber, the second used the lead shield, and the third used both. Each simulation used 14.1 MeV mono-energetic neutrons with incidence angles within a 0.1-degree cone. In order to accurately compare the shapes of the signal graphs, each graph was normalized to 1 at its maximum intensity, as shown in Figure 7. Figure 8 shows the ratio of the signal graph with the specified structure to the signal graph without the specified structure. The plot for the shield and target chamber (blue) appears to have a constant value of 1 with noise at either end. From this, it can be inferred that the target chamber has a minimal effect on the signal from neutrons with incidence angles within a 0.1-degree cone. The lead shield (green) appears to have a greater effect on the background signal. Although 4% of the neutrons that have incidence angles outside the 0.1-degree cone hit the detector between 233 ns and 234 ns, a significantly smaller percentage hit the detector between times of 233.5 ns and 233.8 ns. It can be presumed that this will not significantly alter the neutron time of flight spread. The effect of the lead shield and the target chamber on the FWHM from neutrons with incidence angles within the 0.1-degree cone is less than 1%.

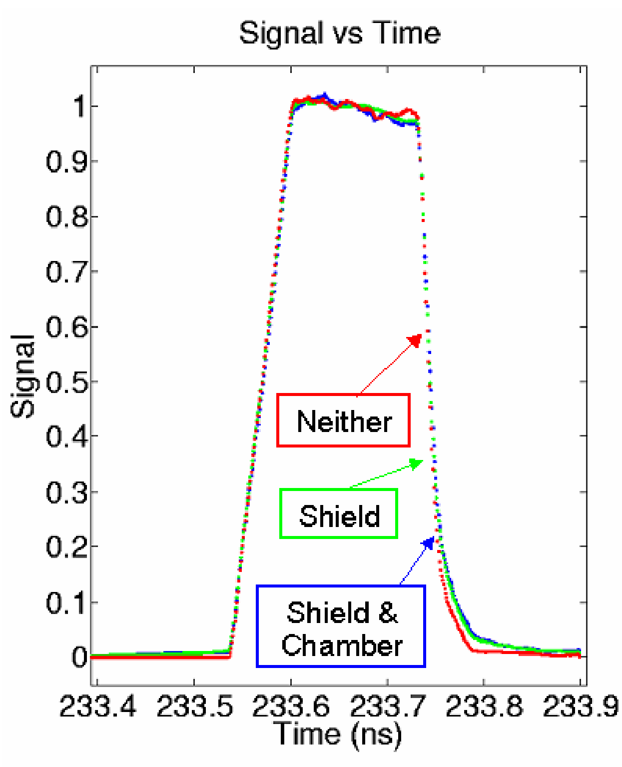

Figure 7: Relative signal strengths for 14.1 MeV neutrons in a 1-cm detector passing through various materials.

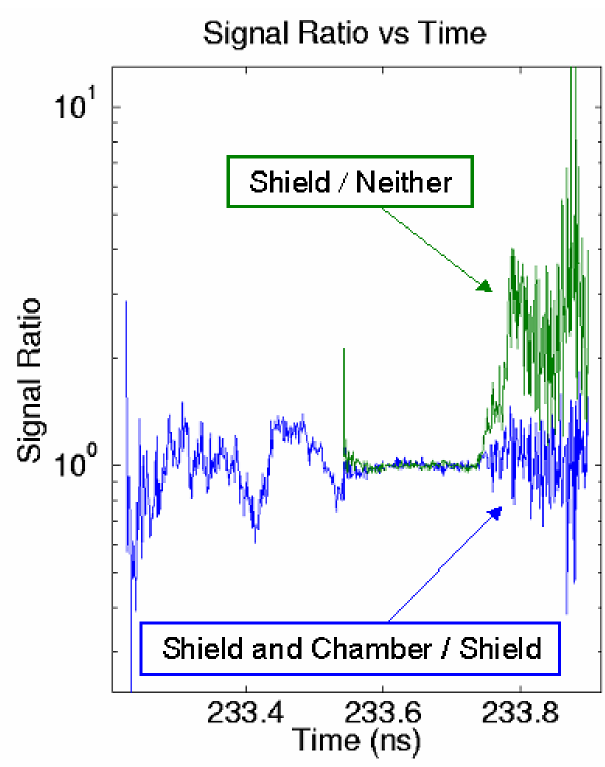

Figure 8: Ratios of signal strengths from Figure 8.

5. Conclusion

A Monte-Carlo simulation program was used to simulate neutron interactions in order to understand the effects of the target chamber and lead shield on the detected neutron signal. The neutron signal can be used to determine the initial velocities of the reacting ions or the temperatures required for fusion. It was determined that the lead shield creates more neutron background than the target chamber creates for 14.1 MeV neutrons with initial velocities within a 0.1-degree cone. It was also determined that neither structure significantly alters (< 1%) the full width at half maximum (FWHM) duration of the signal.

6. Acknowledgements

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7. References

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