Opacity effects in inertial confinement fusion implosion

Jesse Pan

Webster Thomas High School, 800 Five Mile Line Road, Webster, NY, 14580

LLE Advisor: Suxing Hu

March 2013

1. Abstract

During direct-drive inertial confinement fusion (ICF) implosion experiments, laser beams are used to compress a deuterium-tritium (DT) capsule. However, radiation from the coronal plasma surrounding the capsule can be absorbed by the capsule's shell, which thereby becomes preheated. LLE's simulation programs, such as the one-dimensional hydrodynamics code LILAC, use the Astrophysics Opacity Table (AOT) to determine the x-ray absorption by the DT fuel shell. Recent studies have shown that Quantum Molecular Dynamics (QMD) simulations are more accurate for calculating the opacities and can result in a DT absorption coefficient many times higher than the AOT prediction, varying directly with the photon energy. To examine this absorption-enhancement effect on ICF implosions, multipliers to the AOT opacities were used in LILAC simulations. The simulation results show that a factor-of-2 increase in the opacity can lead to dramatic effects in target performance: the peak density drops 20%, the areal density ρR decreases by 10%, and the neutron yield decreases by 40%.

2. Introduction

At the University of Rochester's Laboratory for Laser Energetics (LLE) and the National Ignition Facility (NIF), research is done on laser fusion. There are two main types of laser fusion: direct drive and indirect drive. The Laboratory for Laser Energetics deals mainly with direct drive. Direct drive means that a target is irradiated directly by the laser beams, as opposed to indirect drive, where the target's surrounding is hit by the laser beams, heating the area as well as the capsule.

The target is a spherical cryogenic capsule approximately 10 µm thick with a diameter of ~860 µm, coated on the inside with approximately 65 µm of deuterium-tritium (DT) ice, and filled with three atmospheres of DT. The laser is the 60 beam OMEGA laser system, one of the most powerful in the world. During inertial confinement fusion, the laser pulses partially ablate the surface of the capsule, causing it to rocket off, and compress the capsule. The deuterium and tritium are compressed together. On account of the large electrostatic repulsion between the two nuclei, a large amount of energy needs to be put into the fusion process. At a sufficiently high temperature, the deuterium and tritium combine to form helium, a neutron, and large amounts of energy.

The amount of energy produced by the inertial confinement fusion process can be measured by its neutron yield. LLE uses simulation programs, such as the one-dimensional hydrodynamics code LILAC, to predict such values. A major factor affecting inertial confinement fusion is opacity. Opacity is defined as a measure of impenetrability of electromagnetic or other kinds of radiation. The simulation program LILAC was modified to account for newer research revealing a more accurate measure of opacity. The method of calculating opacity currently employed by the LLE simulation programs uses the Los Alamos Astrophysics Opacity Table (AOT) [1]. The Quantum Molecular Dynamics (QMD) model [2] is a newer method of calculating opacity.

3. Differences Between QMD and AOT

The QMD approach is believed to be more accurate than the AOT approach because it takes into account many aspects neglected by the AOT approach for calculating the opacities. The QMD approach includes innately transient effects such as the association/dissociation of chemical bonds, and ionization/recombination. As a result, the pressure obtained by using the QMD model demonstrates not only the constituency of the fluid at the given temperature, but also density effects [3] . The AOT model also uses an equation of state model that that is based on the Saha equation. However, the Rydberg sequences are cut off by the plasma corrections. The QMD model uses a corrected version of the Saha equation which is solved iteratively to obtain a set of ion abundances, bound state occupancies, and free electrons. The AOT model doesn't fully account for molecular formation. As demonstrated in Figure 1, the QMD model's calculations result in much higher absorption values than those yielded by the AOT model. Despite the left half of the graph showing the QMD model having a lower absorption than the AOT model, that portion is insignificant because the photon energy is never that low during inertial confinement fusion implosions. This means that the DT shell is absorbing more electromagnetic radiation than previously assumed in the simulation programs and the final output will be different.

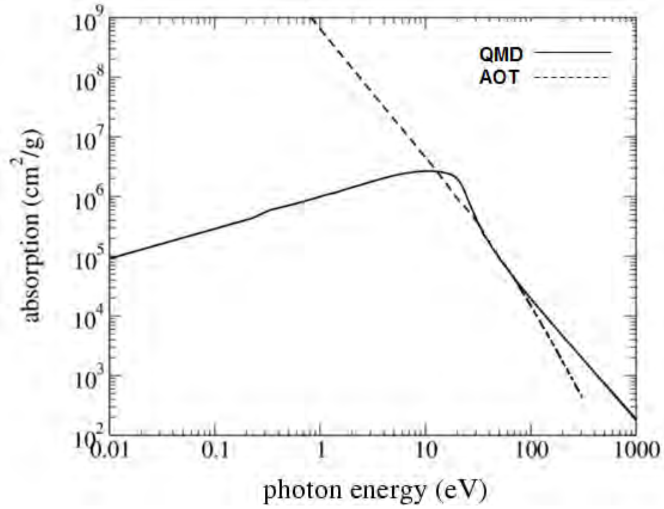

Figure 1: Graphical display of the absorption rates of the QMD model and the AOT model against various levels of photon energy at T=48000K and $\rho = 0.65\ g/cm^3$

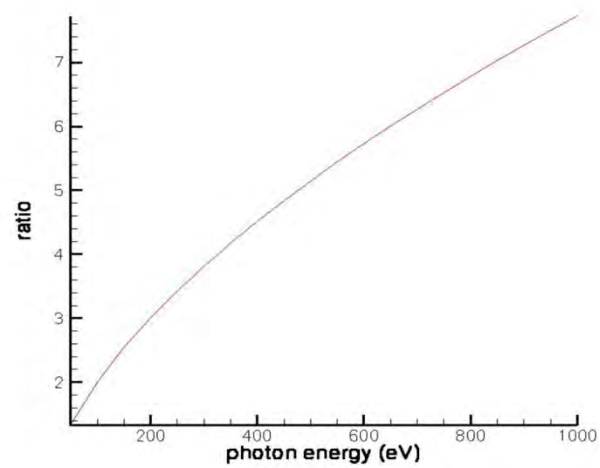

Figure 2: Graphical display of the ratio of the QMD to the AOT absorption rates. Conditions are the same as in figure 1.

3.1 Quantitative difference between QMD and AOT

As a direct result of these and other factors, the QMD model has shown that the actual DT absorption can be many times higher than the DT absorption value obtained by using the AOT model for photon energies above 200 eV. The photon energies important to OMEGA laser implosions range from 100 eV to 5000 eV. As demonstrated in figure 2, the ratio of the QMD prediction to the AOT prediction increases significantly with the photon energy in the hv<1-keV range.

4. Modification to the LILAC simulation program, and results of the simulation

The LILAC program was modified to test what happens if the overall opacity value is multiplied by a factor of 2. The value of 2 was chosen to test the sensitivity of the simulation to changes in the opacity variable. The simulation led to significant changes in the results for the neutron yield when compared to an original run without the modifier in place. As seen in figures 3 and 4, the original run's DD and DT neutron yields are almost twice as high as those of the run with the modifier implemented. The decrease in the neutron yield shows that not as much of the deuterium reacted with the tritium, which results in less energy being produced. The high sensitivity suggests that making the switch from the AOT model to the QMD model will significantly alter the results.

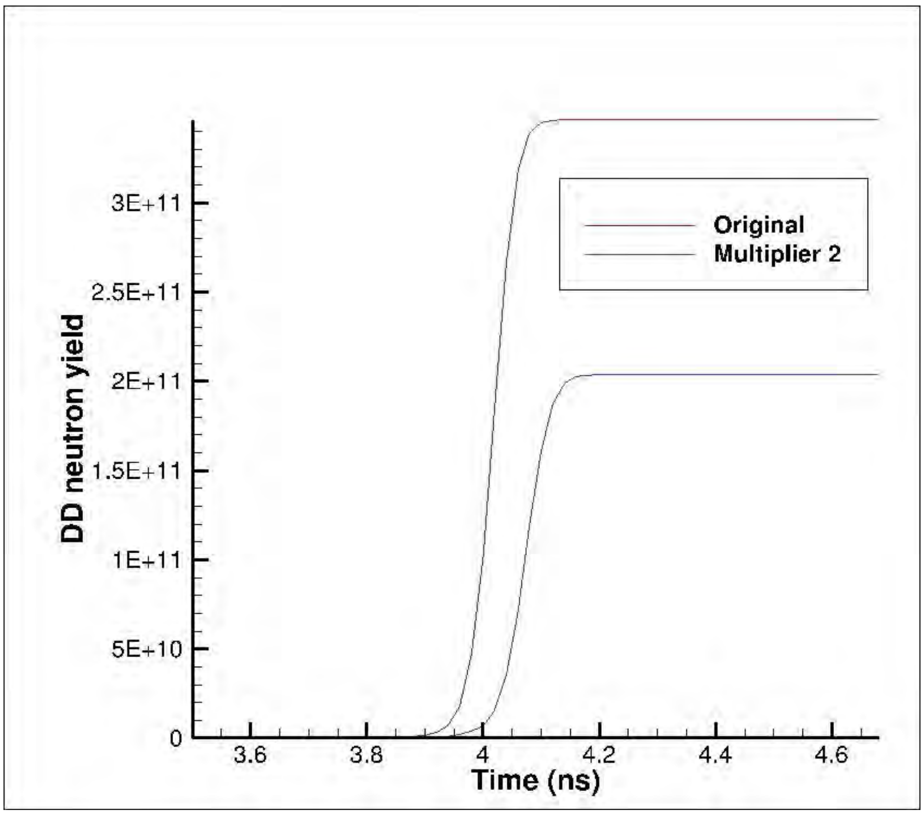

Figure 3: Cumulative DD neutron yield against time for the original run and the modified run

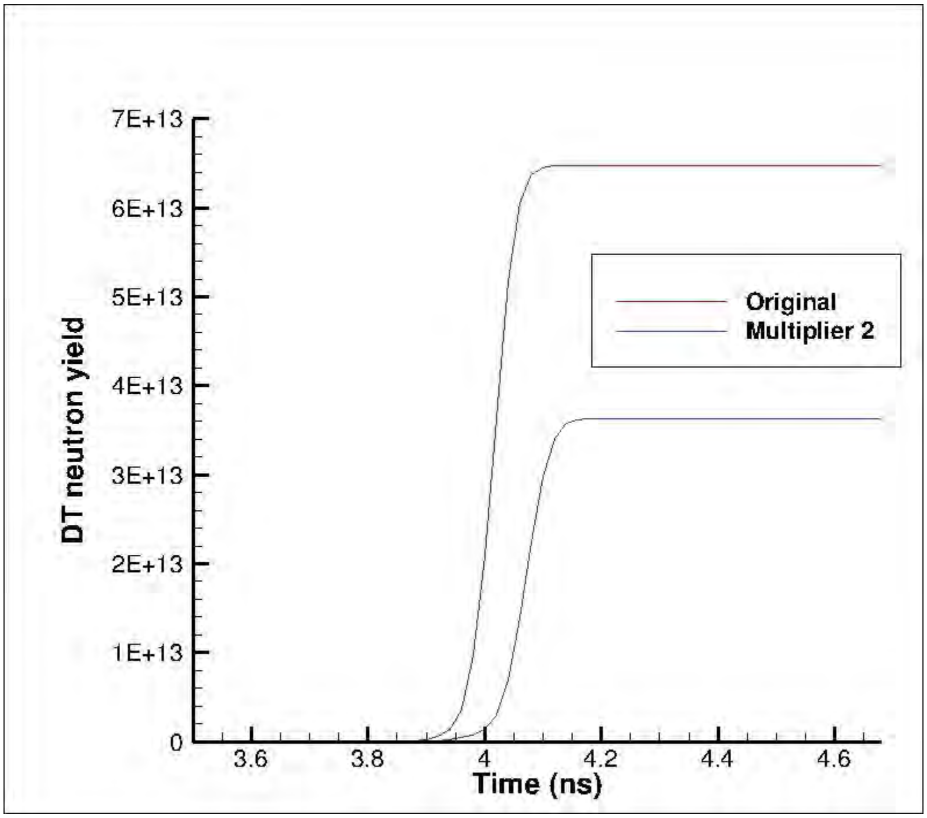

Figure 4: Cumulative DT neutron yield against time for the modified run and the original run

As seen from figure 5, a drop in density between the original run and the run with the multiplier of 2 was observed. This is due to an increase in absorption of radiation in the shell of the deuterium tritium capsule. The radiation converts to heat, making the capsule more difficult to compress, effectively dropping the density. Areal density, defined as the integral of the mass density with respect to radius from the center of the target to infinity, is an important measurement in inertial confinement fusion because energy from fusion reactions is redeposited in the fuel, initiating thermonuclear ignition if the areal density is high enough. As demonstrated by figure 6, the areal density also drops significantly. This occurs for the same reason that the mass density dropped. The peak areal density dropped 10% from 0.32 g/cm^2 to 0.29 g/cm^2. The peak mass density dropped 20% from 254 g/cm^3 to 204 g/cm^3. The modified simulation also produces a 40% drop in both DD neutron yield and DT neutron yield. The DD neutron yield dropped from 3.5×10^{11} to 2.0×10^{11}. The DT neutron yield dropped from 6.5×10^{13} to 3.6×10^{13}. From the equation for the dominant fusion reaction, ${}_{1}^{2}H + {}_{1}^{3}H \rightarrow {}_{2}^{4}He + {}_{0}^{1}n$, a neutron is produced whenever a deuterium molecule and a tritium molecule react, along with a large quantity of energy. The decline in the neutron yield therefore shows that fewer reactions are taking place and that the energy output from the inertial confinement fusion implosion is smaller.

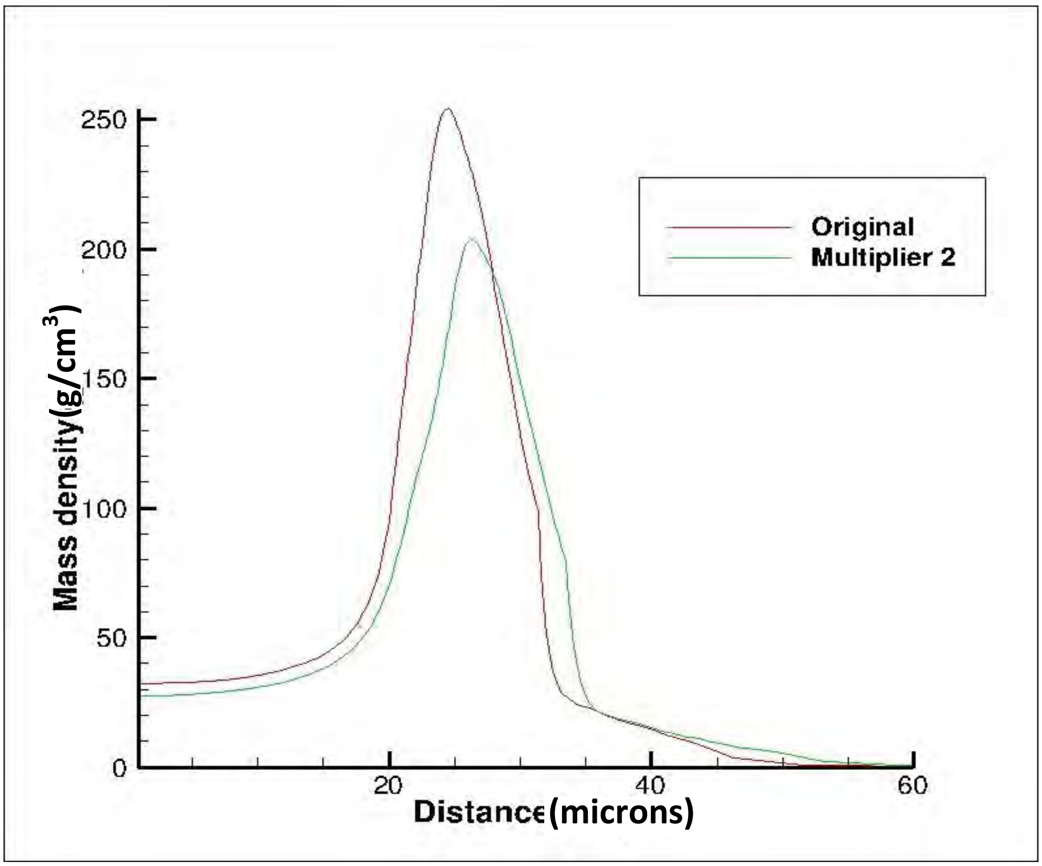

Figure 5: Mass density against the radius in the original run and the modified run.

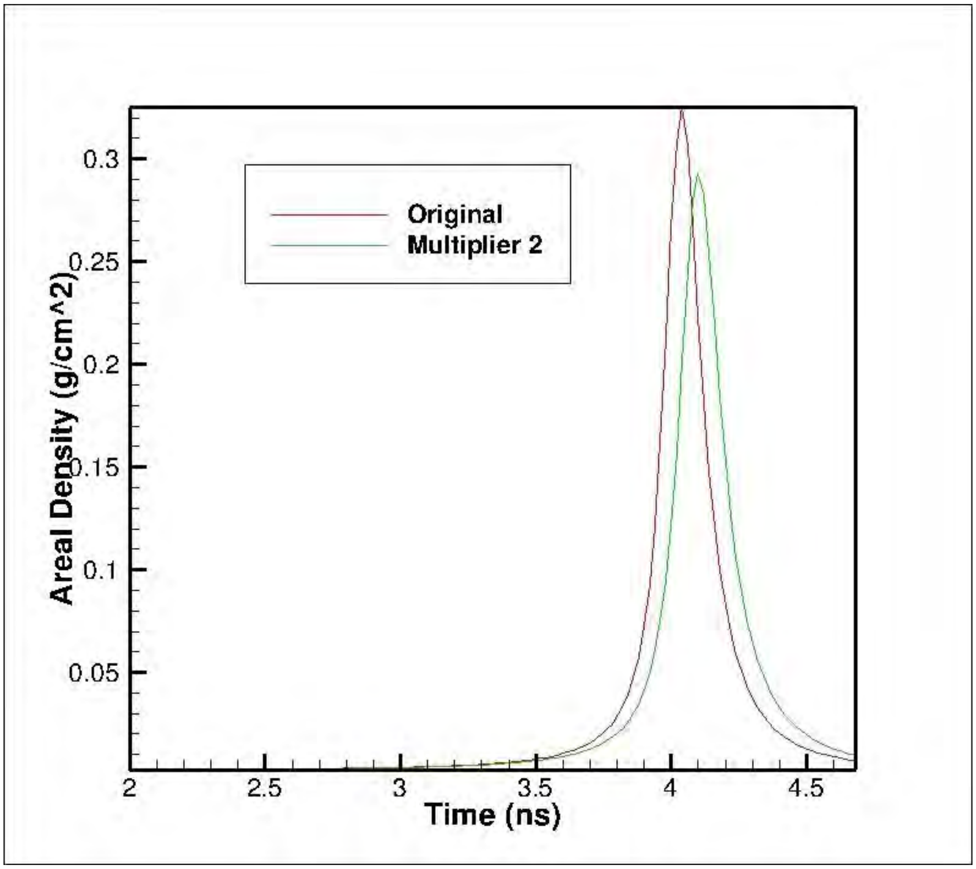

Figure 6: Graphical display of areal density against time for the original run and the modified run

5. Conclusion

The newer QMD model for calculating opacity should be implemented in LLE's simulation programs. It takes many factors into account that the original AOT model did not consider and should provide more accurate results. The ratio between the QMD opacity and the AOT opacity increases significantly as the photon energy increases. The sensitivity of the simulation to opacity was proven to be high, which means that getting more accurate opacity calculations will greatly improve simulation accuracy. Changes to the target design should be explored to compensate for the opacity effects.

6. Future work

This project paves the way for much future work. It is clear that more emphasis should be placed on researching opacity values. The significance of having accurate opacity values has been demonstrated, so more accurate simulations require more accurate opacity values. Also, the program was only modified with a multiplier of 2. The realistic QMD predicted values should be implemented. This is expected to lead to significant changes in the predicted neutron yield. Finally, the modifications should be implemented in all of LLE's hydrodynamic simulation programs, and not only LILAC.

7. Acknowledgements

I could not have completed my project without the help of my peers. I'd like to thanks my supervisor, Suxing Hu, most of all for his abundance of advice throughout the project. I'd also like to thank R. Stephen Craxton for having this program and giving high school students a wonderful opportunity to apply their knowledge by doing real research. I'd also like to thank my fellow high school interns for their occasional advice throughout the program and help with minor setbacks.

References

1. W. F. Huebner, A. L. Merts, N. H. Magee, Jr., and M. F. Argo, Astrophysical Opacity Library, Los Alamos National Laboratory, Los Alamos, NM, Report LA-6760-M (1977)

2. S. Mazevet, L. A. Collins, N.H. Magee, J.D. Kress, J.J. Keady, “Quantum Molecular Dynamics calculations of radiative opacities,” Astronomy & Astrophysics, **405**, L5, 2003

3. S.X. Hu, B. Militzer, V.N. Goncharov, S. Skupsky, “First principles equation-of-state table of deuterium for inertial confinement fusion applications,” Physical Review B **84**, 224109, 2011