Optimization of Cone-in-Shell Implosions

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Abstract

This report investigates the effectiveness of laser-driven fusion when cone-in-shell targets are used. Fast ignition, one method of laser-driven fusion, employs an energetic short pulse laser beam that irradiates an imploded target. Cone-in-shell targets, in which a gold cone is embedded in a shell of deuterium-tritium fuel, are one design proposed for fast ignition. Laser beams arrayed uniformly around the target implode the fuel to high densities. Energy from the short pulse laser is then funneled through the cone to ignite the dense fuel. Fast ignition is most effective when high fuel densities are achieved. The implosions of cone-in-shell targets that have been shot on OMEGA were simulated using the hydrodynamics code SAGE including laser ray tracing. It was found that portions of the shell near the cone were imploded with slower velocities, negatively impacting the uniformity of the implosion and the density of the fuel. By altering beam pointings and energies, improved implosions were found with somewhat higher peak fuel densities. Since there are many more combinations of pointing and energy adjustments than were explored, this technique opens the possibility of obtaining a near-uniform implosion even in the presence of the cone.

Introduction

Nuclear fusion is a promising way to provide fresh and plentiful energy in the future.[1] When two hydrogen nuclei are merged, it is called fusion, and this process can release large amounts of energy. Inertial confinement fusion is one approach to obtaining this energy. A target, a thin plastic shell containing fusion fuel, is irradiated from all directions by laser beams or x rays. The shell is ablated, causing the fuel inside to reach extremely high temperatures and densities. Because the fuel becomes so dense and hot, the atomic nuclei are able to fuse despite the electrostatic force that is driving them apart. Deuterium and tritium, both isotopes of hydrogen, combine to form a helium nucleus and an energetic neutron. Most of the fusion energy is carried away by the neutrons. If the target is large enough and compresses to a high density, the energy of the helium nucleus is deposited into the fuel, causing what is known as ignition. Ignition is required to achieve the condition (known as breakeven) where the energy released from the reaction is greater than the energy used to create the reaction. Fusion energy becomes a viable source of energy when the energy released is 100 times the input laser energy.

Direct drive[1] and indirect drive[2] are the two main methods of accomplishing laser fusion. The OMEGA laser at the University of Rochester's Laboratory for Laser Energetics is constructed to perform direct drive fusion, in which laser beams irradiate the target uniformly from all directions. However, with indirect drive fusion, a cylindrical gold hohlraum surrounds the target so that laser beams only enter through the top and the bottom of the cylinder. The energy that is needed for target compression with indirect drive fusion can be found in the x rays that are emitted from the hohlraum when the laser beams strike it. In this process, only about 20% of the initial energy from the laser is absorbed by the target. The rest of the energy is mainly absorbed by the gold hohlraum or lost through the openings of the hohlraum. While this may be seen as a disadvantage, the benefit is that the x rays irradiate the target more uniformly than the lasers alone. The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory has been configured to perform indirect drive fusion.

Fast Ignition

Fast ignition[3] is an important concept in inertial confinement fusion that is attracting a lot of attention worldwide[4]. After the target is imploded, a high-energy, high-intensity laser beam produces energetic electrons that heat the compressed fuel to even hotter temperatures. Using cone-in-shell targets is one method of bringing the short-pulse laser to the core of the target. For optimal fast-ignition energy gain, the short-pulse energy must be efficiently coupled to the compressed core by being focused through the cone at the optimum time. The hydrodynamics code SAGE[5] was used to simulate the use of cone-in-shell targets for fast ignition with OMEGA. Figure 1 shows a gold cone embedded in a target that is being imploded by laser beams. It displays the gold cone, one of the laser beams, and the plastic target with the different colors indicating different densities.

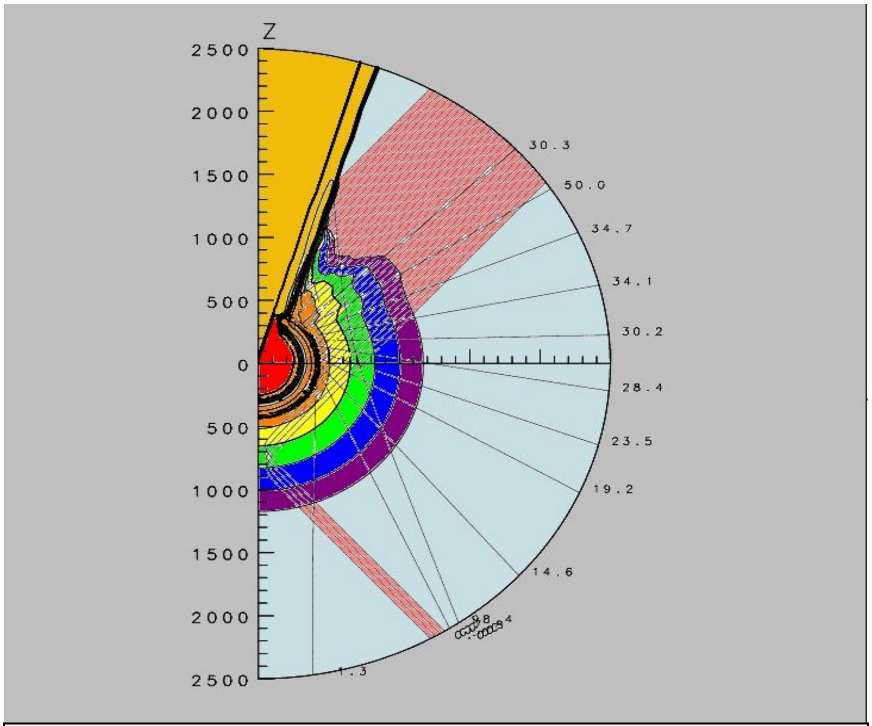


Figure 1. Simulation of a cone-in-shell target using the hydrodynamics code SAGE, showing the gold cone (yellow), laser rays (orange), and density contours (colored bands). In this and similar figures, the target is rotationally symmetric about the vertical (z) axis and distances are labeled in microns (μm).

The OMEGA Laser

The OMEGA laser at the University of Rochester's LLE is based on the structure of a soccer ball. The laser has eight rings containing a total of 60 beams. Each beam would be the equivalent of a corner of a black pentagon on the ball. There are five beams in the first ring, and they are configured at an angle of 21 degrees to the vertical. The first ring is situated at what would be the top of the soccer ball. The second ring contains five beams at a 42-degree angle. Table 1 illustrates the configurations of the eight rings on OMEGA. The first ring of beams is not used in the cone-in-shell simulations due to the position of the cone. Rays from the second ring (shown in Figure 1) strike the gold cone as well as the plastic shell.

Ring	Angle	Number of Beams
1	21˚	5
2	42˚	5
3	59˚	10
4	81˚	10
5	99˚	10
6	121˚	10
7	138˚	5
8	159˚	5

Table 1. Arrangement of the 60 beams on LLE's OMEGA laser system. They are organized in 8 rings with varying angles.

Parameters for Optimization

The parameters available for use include shifting the beam pointings and adjusting the energies of the beams. Rings of beams can be shifted up or down, can have their energies changed, and can even be turned off completely. Simulations were run with various combinations of parameters to determine which configuration would yield the most uniform implosion of the target.

The Cone-in-Shell Target

Cone-in-shell targets are spherical plastic (CH) shells with a gold cone embedded in the wall. Targets may vary in size, but the shell wall is typically ~24 μm thick, while the cone opens at either a 35° or 70° full angle. The shell is filled with deuterium-tritium fuel that is heated and ignited by the short-pulse laser. When cone-in-shell targets are used for fast ignition, they present the problem of an implosion that is not uniform. With decreased uniformity also comes lower temperatures and decreased density of the fuel.

Implosions of Cone-in-Shell Targets

The decreased uniformity of cone-in-shell targets is caused by the presence of the gold cone in the shell's wall. Laser beams cannot irradiate the target from all directions at equal angles since the cone prevents the use of the first ring of beams. Because of this, the parts of the shell closest to the cone often implode at a slower rate than the rest of the shell. Figure 2 shows the peak density of the initial design as a function of time, which at its peak reaches 34 g/cm^3. In this design, the sections of the shell that were touching the cone fell behind the rest of the shell in the implosion, reducing the compression of the fuel in the center.

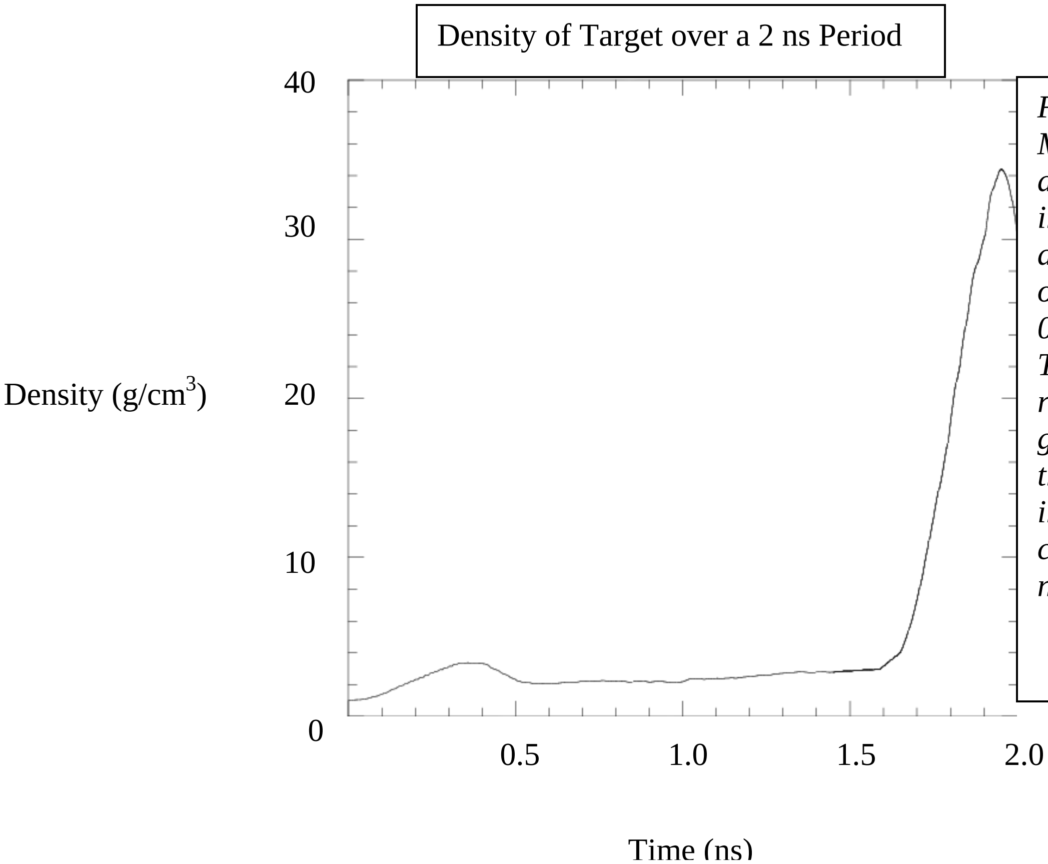


Figure 2. Maximum density of the initial design as a function of time from 0 to 2.0 ns. The density reaches 34 g/cm^3 near the end of the implosion, close to 2.0 ns.

Improved uniformity was achieved by shifting the second ring of beams up 12 µm toward the cone, and decreasing the energy of the third ring to 70%. Making these changes focused more energy on the section of the shell that was imploding too slowly, and took some energy from other areas. The series of plots, shown below in Figure 3, shows the uniformity of the implosion and the approximately circular shape the shell takes on as it implodes. The shell, colored red, becomes thicker as time passes from 1 nanosecond to 1.6 nanoseconds. The outside of the shell ablates because of the extensive amount of heat that the beams irradiate it with.

Figure 3. Density contours of a cone-in-shell target of initial radius 400 μm at four successive times. The plastic shell is shown in red and the gold cone in yellow. (a) The implosion of the target has already commenced by 1.0 ns.

(a)

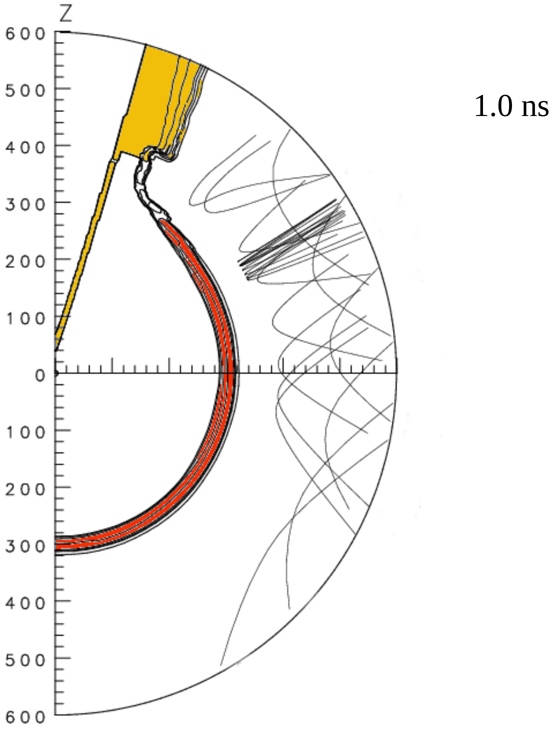


Figure 3. (b) At 1.2 ns, the shell has grown thicker as it becomes hotter.

(b)

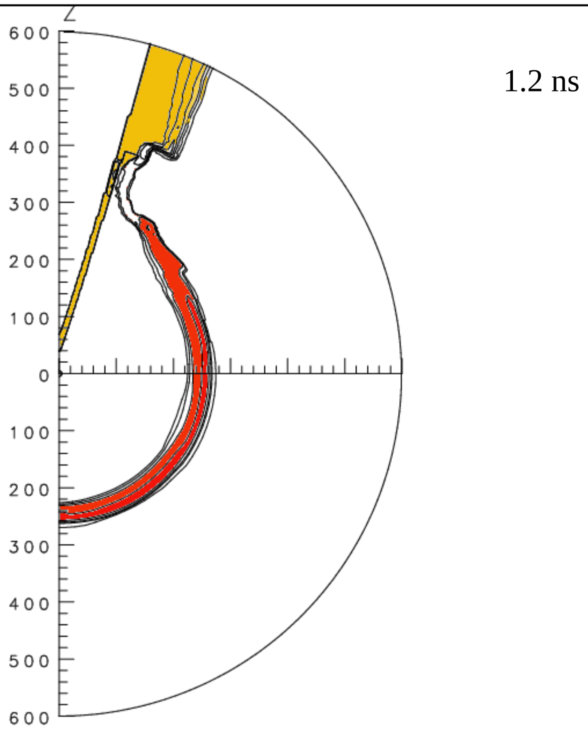


Figure 3. (c) By 1.4 ns, the shell has ablated a great amount, and has a significantly smaller diameter than before.

(c)

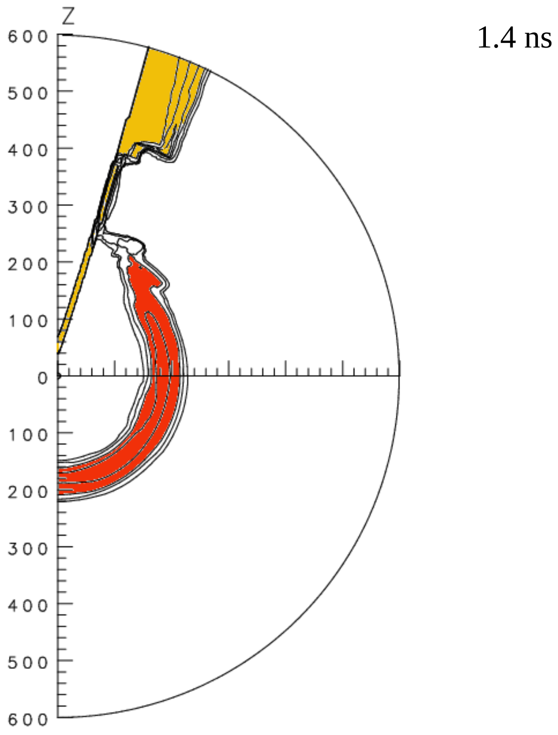
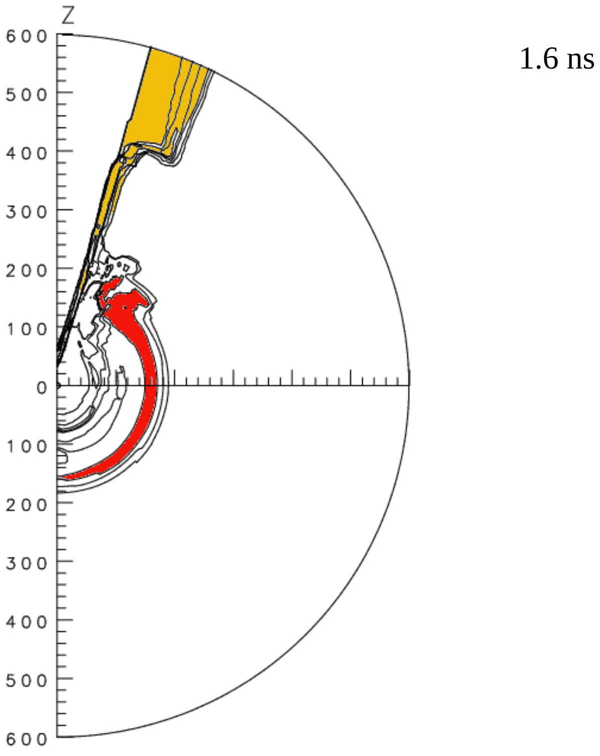


Figure 3. (d) The target reaches its densest and hottest point so far at 1.6 ns. The uniformity of the shell is generally good.

(d)



These results, obtained with the modified beam arrangements, suggest that adding more energy near the cone is beneficial to the uniformity of the implosion. However, adding too much heat to the volume surrounding the cone can cause a large amount of erosion of the gold cone. This in turn can cause the nearby shell to decrease in velocity as it implodes. It is important to add an amount of energy that improves the uniformity of the implosion, but does not interfere with the cone. The improved design proves that this is a possibility with cone-in-shell targets. The density as a function of time for the new design, shown in Figure 4, has a peak value of 51 g/cm^3, which is a 50 percent increase from the original. However, it should be cautioned that the maximum density is often found in a small portion of the compressed fuel and thus may not always be representative of the overall compressed fuel density.

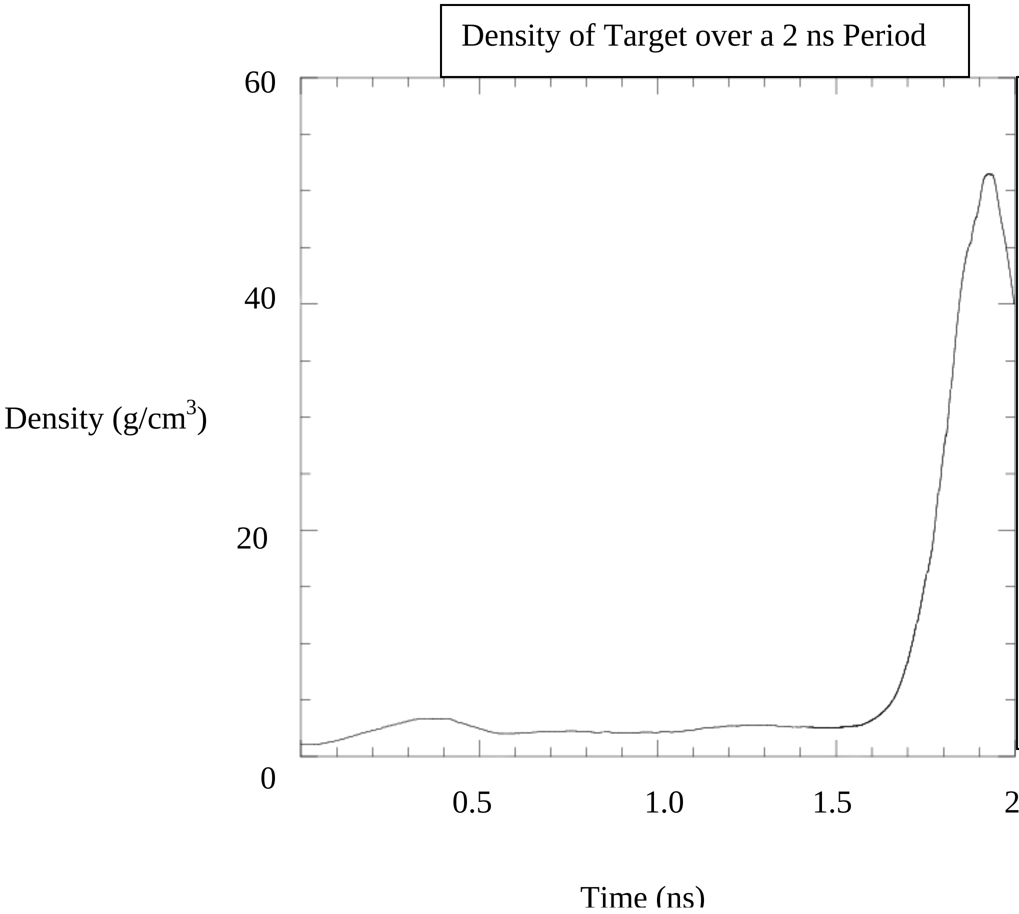


Figure 4. Maximum density of the imploding target as a function of time after adjustments in beam pointings and intensities. The density reaches its peak value of 51 g/cm^3 at a time close to 2 ns

Conclusion

Through the use of the hydrodynamics code SAGE, it can be seen that the implosion of the target is fairly uniform in spite of the presence of the cone in the target. Since both the beam pointings and beam energies can be changed on seven of the eight rings of beams, there are many more possible combinations for changing these parameters than have been investigated in the present work. There is thus room for future improvement.

The amended design suggests that adding more laser energy to the areas of the shell closest to the cone will increase the implosion velocity in this area, leading to a higher fuel density in the center of the target, but more simulations are needed to confirm this. The combination of a high fuel density with the extremely hot temperature expected from the short-pulse laser will hopefully cause a large improvement in the fusion energy output from the center of the target. Experiments will soon be done on OMEGA to test this. The simulations done with SAGE suggest that cone-in-shell targets have the potential to produce implosions that are nearly as uniform as for targets without cones. Because of this, cone-in-shell targets are a promising method to achieve fast ignition.

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