The Effect of Nonuniform Illumination on the Shape of Deuterium Ice Layers

Michael Wozniak

The Effect of Nonuniform Illumination on the Shape of Deuterium Ice Layers

Michael Wozniak
Greece Athena High School
Rochester, NY

Advisors: R. Stephen Craxton, David Harding
Laboratory for Laser Energetics
University of Rochester
Rochester, NY

Michael Wozniak

The Effect of Nonuniform Illumination on the Shape of Deuterium Ice Layers

Abstract

Inertial confinement fusion requires the use of a uniformly thick target for best efficiency. Cryogenic targets are used in this process because deuterium ice has a higher density than deuterium gas, allowing more fuel in the target. These cryogenic targets are formed in a device called the layering sphere, which freezes the deuterium target to about 18 Kelvin, initially in a nonuniform layer. The target is then heated several millikelvin with a fiber-optic light source. This light is reflected throughout the layering sphere and deposited in the ice causing the thicker ice to vaporize and accumulate on the thinner parts. This process continues until the ice is uniformly thick with an isothermal inner surface. A problem associated with this layering process is that the illumination is not uniform because there is a "keyhole" in the layering sphere that is used to insert and extract the target. This nonuniformity in the illumination causes perturbations in the ice layer. The nonuniformities were modeled by first calculating the energy deposited in the ice due to a single beam of light using a PV-Wave code. The calculated energy deposition was then used in a computational fluid dynamics program called FLUENT, which was used to find the shape of the ice layer due to the keyhole. These perturbations due to the keyhole have been calculated to be about 5 μm (rms) in a 1-mm-diameter shell with an ice thickness of 100 μm.

1. Introduction

Fusion occurs when two atoms are compressed close enough together that their nuclei collide and combine to form a single atom.[1] This reaction releases energy, which is due to a conversion of mass into energy. The ideal fuel source for fusion is deuterium-tritium due to its high energy yield, but it is not used in most experiments because it is radioactive. Because of this, most fusion experiments use a deuterium-deuterium fuel source. Fusion is beneficial because the fuel source can be extracted from seawater, the product of the reaction is a nonradioactive inert gas, and fusion has the potential to produce a lot of energy.

One type of fusion is inertial confinement fusion, which uses an immense amount of power to rapidly heat a target to very high temperatures where fusion can occur. At the University of Rochester, this is done with the 60-beam Omega laser system. There are two types of targets that are used in this system: gas targets and cryogenic targets. The gas targets are easier to make, but they do not provide as much fuel and they are less dense. Cryogenic targets are deuterium-filled targets that have been frozen. Cryogenic targets are used in inertial confinement fusion because deuterium ice is a denser fuel source than deuterium gas. The fusion process is most efficient if the fuel source is compressed as much as possible, because the atoms are closer together and so more fusion collisions occur. The targets must be uniform to be compressed efficiently. The purpose of this research was to model one source of ice layer nonuniformity that had previously been ignored.

Cryogenic targets are created by filling a 3 micron thick plastic shell (1-mm diameter) with deuterium gas to several thousand atmospheres by permeating the gas through the shell. The temperature of the target is then dropped to about 18 Kelvin, which causes the deuterium gas to solidify.[2] The deuterium ice forms a layer, which is initially nonuniform due to gravity: the bottom of the target has a much thicker layer than the top. This nonuniform ice layer is then modified using a device called the layering sphere (see Fig.1). The layering sphere has a rough surface, which is gold plated so that it reflects the light very well. The layering sphere uses an infrared laser source aimed at the rough surface, which causes the light to be scattered throughout the layering sphere which allows the target to be illuminated from nearly all angles. This illumination heats the deuterium ice several millikelvin. The thicker portions of the deuterium ice become hotter than the thinner portions, and because the target is kept very close to the triple point of deuterium, the deuterium sublimates from the hotter (thicker) portions and deposits on the cooler (thinner) portions. With perfect illumination uniformity, this process will lead to a perfect cryogenic target, which will have a uniformly thick ice layer[3] (see Fig.2)

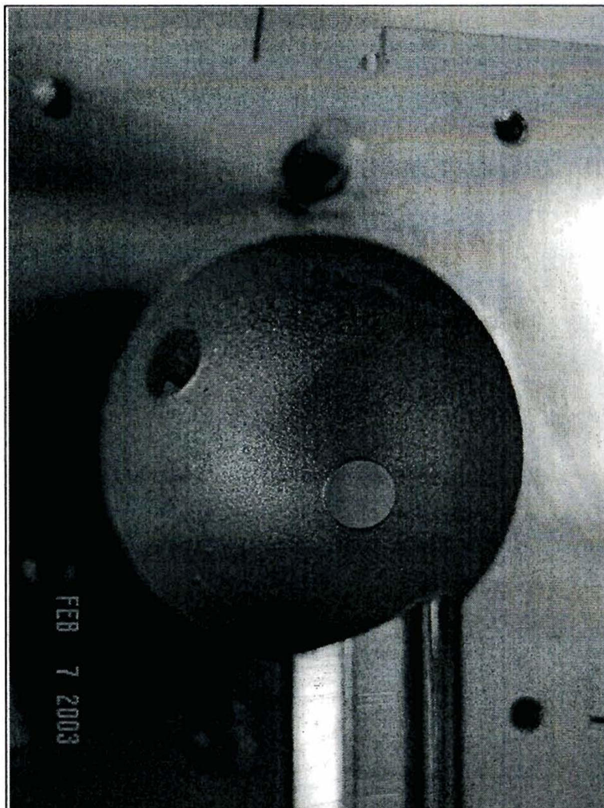

Figure 1: Picture of half of the layering sphere (diameter = 1 inch). The two holes are viewing windows. The keyhole is the shiny part at the bottom of the picture and the shadow created by x rays can be seen at the top of the picture.

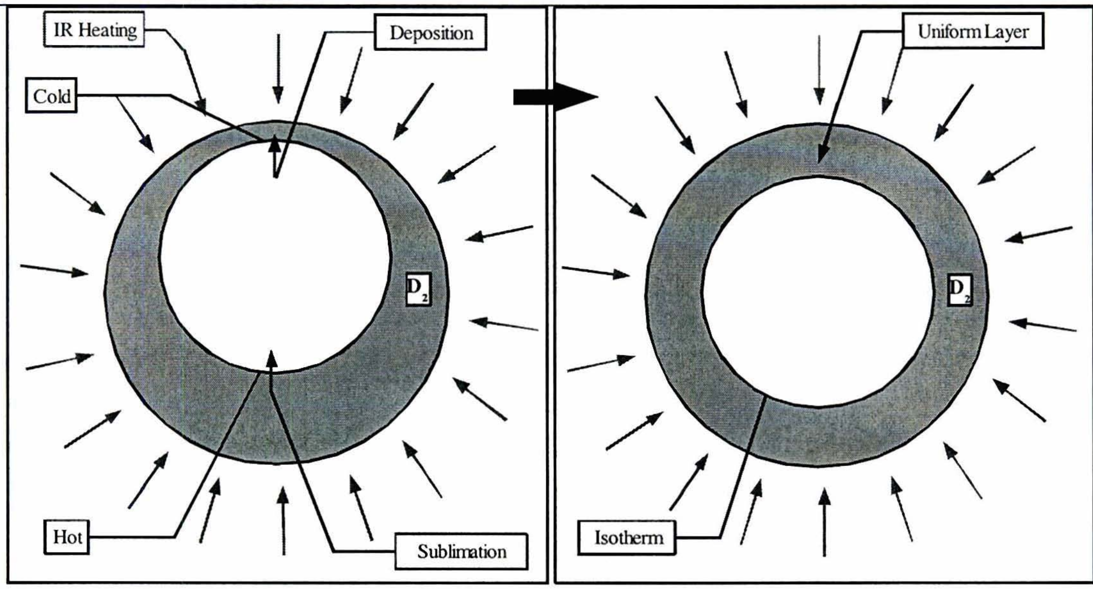

Figure 2: Uniform ice layers are formed using infrared heating. This infrared illumination is absorbed by the deuterium ice in the target. The thicker portions of the ice absorb more energy, creating a hotter surface. The thinner portions of the ice absorb less energy, creating a colder surface. The temperature difference between the hotter and colder portions of the ice is enough to cause the ice to sublimate from the hot portions and deposit on the cold portions. This process continues until the entire inner ice surface is an isotherm. With perfect illumination uniformity, the result is a perfect target.

The layering sphere does not provide perfect illumination uniformity. The infrared radiation illuminates the target from all angles except from the points where there are nonuniformities in the layering sphere. These nonuniformities include four viewing windows, a keyhole, and the shadow of the keyhole. The viewing windows are used to monitor the progress of the layering of the deuterium ice in the target. The keyhole is a hole in the bottom of the layering sphere, which is used to extract the target just before it is shot by the Omega laser system. The shadow of the keyhole is created by x rays that are emitted during an Omega shot, go through the keyhole, and ablate the gold from the surface at the top of the layering sphere. This creates a region that does not reflect or scatter light as efficiently as other regions.

The effect of the keyhole on the ice thickness uniformity was modeled in two steps. First, a code that calculated the path of light rays through a target was modified to find the energy deposition in the target. Then, a computational fluid dynamics code called FLUENT was used to model the thermal conduction and calculate the final ice layer thickness nonuniformity. Previously, it was assumed that a perfect ice layer could be achieved if the target was placed in the layering sphere for a long enough time in the absence of other sources of nonuniformity. This model has shown that the best possible ice thickness uniformity is about 5 μm in a target with ice that is 100 μm thick and 1 mm in diameter.

2. Modeling the energy deposition

The effect of the keyhole was modeled by calculating the energy absorbed by the target for the case of uniform illumination and then subtracting the energy distribution due to a single ray trace (see Fig.3). The energy due to the ray trace was scaled to account for the size of the keyhole. This model assumed that the energy distributed into the target was axisymmetric and that the windows and shadow of the keyhole had no effect on the illumination uniformity. The keyhole represents the dominant nonuniformity in the layering sphere as its solid angle (2.141% of the total surface area) is approximately equal to the total solid angles of the four viewing windows. The model was based on a target that was 1 mm in diameter, had an ice thickness of 100 μm, and a shell thickness of 3 μm. The amount of energy absorbed by the target was assumed to be approximately the same as is produced through radioactive (beta) decay by a deuterium-tritium target of the same size (5×10^4 W/m^3).[4]

At each interface in the target, the light rays are refracted (see Fig.3). The light refraction was modeled with a computer program written in PV-Wave, based on the program described in Ref. 5. The model was based on a single beam of light aimed at the target. The beam was separated into many rays that were each calculated separately. The path of each ray of light was calculated using Snell's Law to find the angle through which the light was refracted. The program also calculated the reflection of some of the rays from the inner surface of the ice layer. These rays were reflected because when a

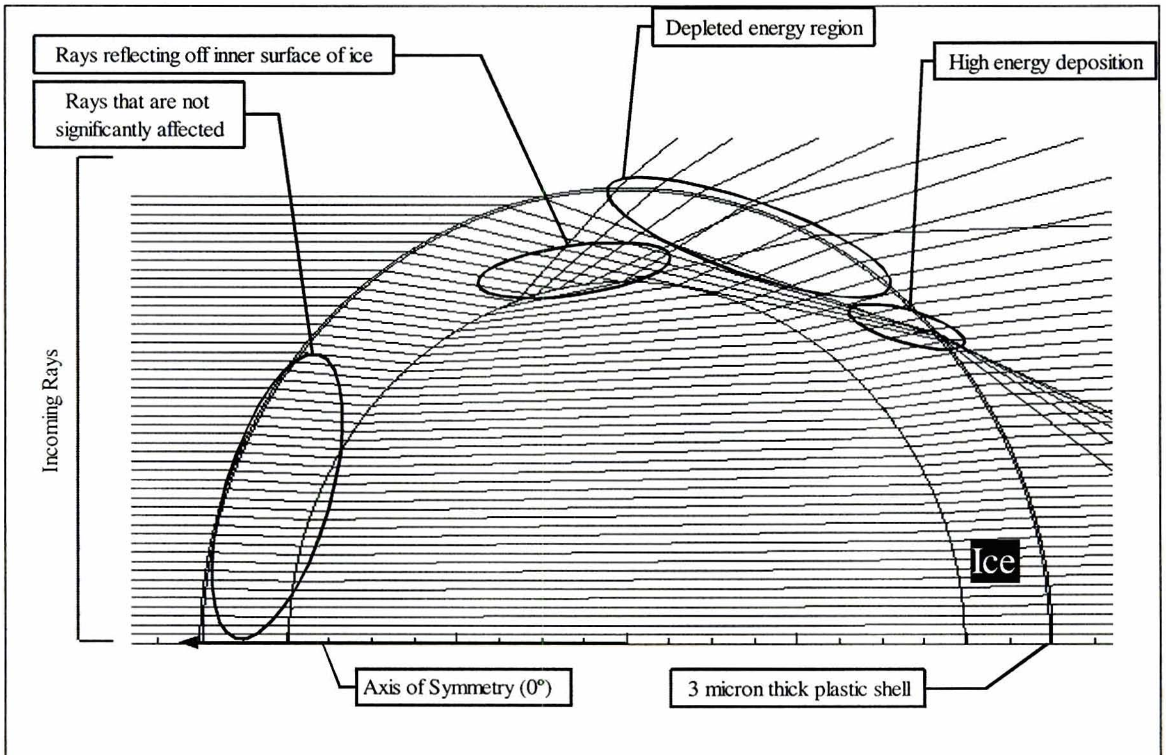

Figure 3: Ray trajectories through a cryogenic target (100 μm of deuterium ice inside a 3-μm plastic shell of diameter 1 mm). (Specific features that give rise to nonuniform heating are labeled.)

ray strikes the inner surface of the ice at an angle close to that which would cause the ray to be totally internally reflected, the Fresnel coefficients show that the majority of the energy of the light ray is reflected.[5]

From Fig. 3 it is seen that the energy from a single beam of light is not deposited uniformly throughout the ice layer. Three regions of nonuniform energy deposition are indicated in Fig. 3: a region where rays reflect off the inner surface of the ice, a depleted energy region, and a region where there is focusing of the light rays. The rays that reflect off the surface of the ice cause a higher energy deposition in that region of the ice because it is being heated from two separate sets of rays. The depleted energy region only receives energy from a few rays that are reflected off the inner surface of the ice; these rays are spaced out, which causes less energy to be deposited. The region where light rays are focused has rays that overlap and cause a high energy deposition.

A calculation of the energy deposited by the light rays was added to the ray-trace program. Each ray that was traced was assigned an extra parameter, which holds the amount of energy that the ray represents. Each ray represents an area of the light beam, and carries an amount of energy proportional to this area. The energy that is deposited in the ice by each ray is then calculated based on the absorption coefficient of deuterium ice, which is 4 cm^{-1} for the wavelength of the light source (3.16 μm) used in the layering sphere. The energy from each ray is then added to a grid that represents the ice layer. Since each cell on the grid does not represent the same volume, the energy at each point on the grid is divided by the cell volume to give the absorbed energy per unit volume (see Fig.4). The labeled regions from Fig. 3 are labeled again in Fig. 4 to show the effects each feature had on the energy distribution: the focused light rays caused high energy deposition and the depleted energy region had very low energy deposition as expected based on Fig. 3.

The large number of grid cells are then divided into a smaller number of zones by averaging cells whose energy per unit volume differ by less than 10% (see Fig.5). The absorbed energy in these zones formed the basis for the next stage of modeling.

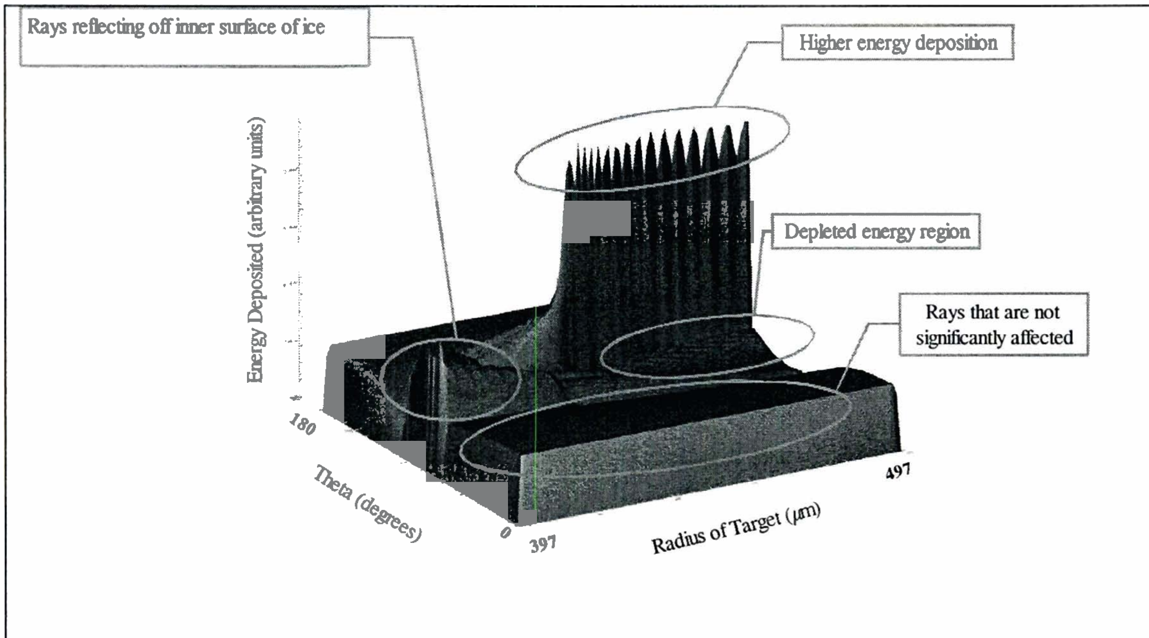

Figure 4: Energy per unit volume deposited in the ice of the target due to the ray trace. As in Fig. 3, the regions experiencing nonuniform heating are labeled.

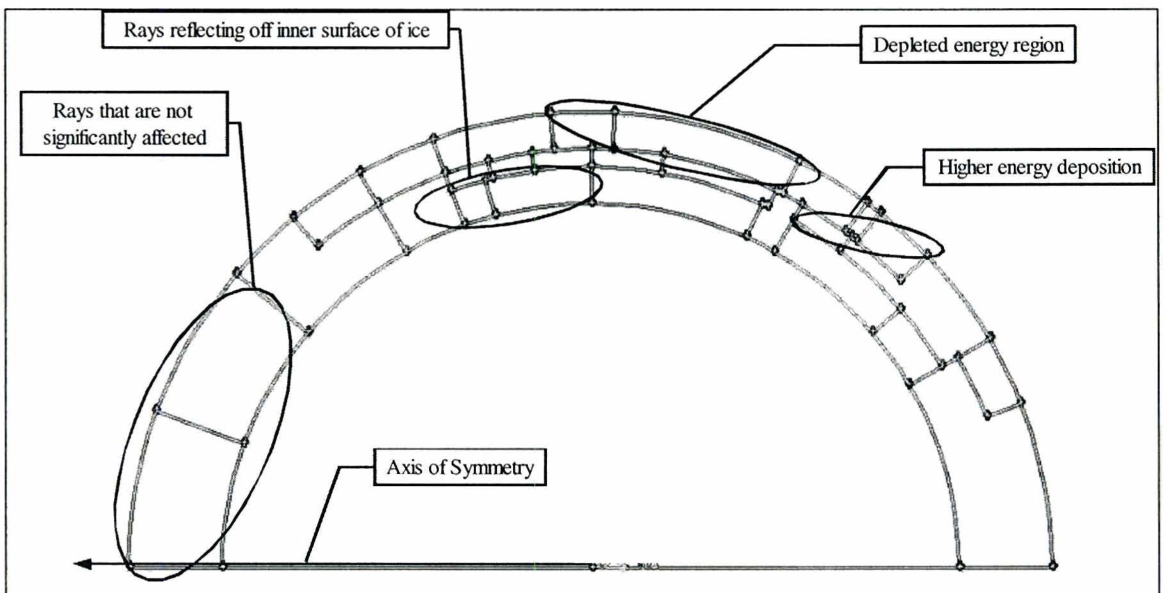

Figure 5: Wireframe created in GAMBIT corresponding to Fig. 3. The zones were created by averaging cells from the energy distribution grid that differed by less than 10%.

3. Modeling the Ice Layer Thickness

In order to determine the shape of the deuterium ice layer due to the energy absorbed in the layering process, an iterative process is used. This process begins with a uniformly thick ice layer, for which the temperature contours resulting from the given absorbed energy are calculated. The temperature along the inner ice surface is then analyzed; the portions of the ice that are relatively hotter are modified to be thinner and the portions of the ice that are relatively colder are modified to be thicker. The relationship between ice thickness and temperature is based on the results of Ref. 6. The temperature contours are recalculated and the process begins again with a new ice shape. When the inner ice surface becomes an isotherm after several iterations, the final ice shape has been achieved. This is because when the ice surface is an isotherm, if any parts of the ice layer sublimate or if there is any deposition, then it will be uniform throughout the target and will not affect the shape.

This process is done manually with the aid of two software packages. GAMBIT[7], a wireframe mesh generator, was used to create a mesh to represent the cryogenic target. This mesh was exported to FLUENT[8], a computational fluid dynamics code. FLUENT was used to calculate heat transfer through the cryogenic target and thus the temperature contours.

First, GAMBIT is used to create a wireframe mesh that represents a target with a uniformly thick ice layer and zones that correspond to those that were calculated from the energy deposition. GAMBIT then fills in the large zones with small meshes that help FLUENT perform calculations. The mesh that represents the target is then exported to FLUENT where the values for the energy deposited into the ice are entered. The boundary conditions also have to be entered into the program. These boundary conditions include an isothermal outer layer on the target, which is set at 18K. The inner ice surface is coupled to the outer surface of the deuterium gas on the inside of the target. There is some deuterium gas inside the ice layer because some of the solid deuterium vaporizes. The deuterium gas is given an energy value of 50 W/m^3, which is the amount of energy that was assumed to be absorbed by the deuterium gas in the target. The physical constants of deuterium ice and deuterium gas are entered into the materials section of FLUENT (see Table 1).

FLUENT first solves (by iterating 500 times) for the temperature contours that result from a uniform ice layer. FLUENT displays the temperature contours and the temperature along the inner surface of the ice with respect to its position along the z axis, the axis of symmetry (see Fig. 6). The graph of the temperature along the inner surface of the ice is used to determine how the shape of the ice layer should be changed. This process is done manually by trial and error. The areas on the inner ice surface that are hotter are modified to be thinner and the colder areas are modified to be thicker. Using the new ice surface, the wireframe mesh in GAMBIT is changed. It takes about ten iterations of calculating the temperature contours to achieve a nearly isothermal inner ice surface. The temperature of the inner ice surface was considered to be isothermal when it was within a range of 15 to 20 microkelvin. This is illustrated in the right hand portion of Fig. 6.

Table 1: Physical Constants of Deuterium

	D_2 ice	D_2 gas
Density (kg/m^3)	195	0.452
Heat capacity C_p (J/kg K)	2950	5200
Thermal conductivity k (W/m K)	0.38	0.009

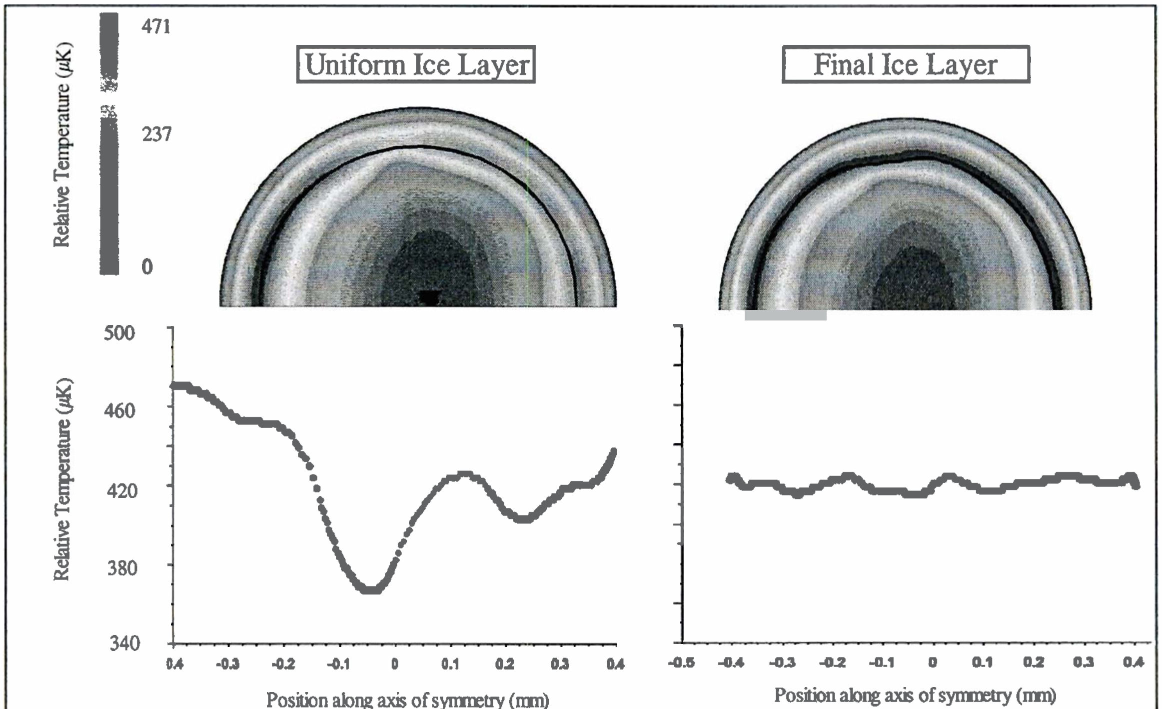

Figure 6: The temperature contours are shown for the given energy distribution. The black line in the temperature contours shows the shape of the deuterium ice in the target. The graphs below the temperature contours display the temperature along the inner ice surface of the target (black line in temperature contours) with respect to the axis of symmetry (z axis).

4. Discussion

The final shape of the ice layer in the cryogenic target (see Fig.7) reveals that the nonuniform illumination of the layering sphere has a significant effect on the uniformity of the ice thickness in the target. The effect of the keyhole in the layering sphere induces a 5 μm rms ice roughness in the final shape of the ice. This is comparable to the experimentally measured roughness (2-3 μm rms) of the best targets that have been created to date.

The main feature seen in Fig. 7 is a large increase in the ice thickness (smaller inner radius), which occurs near 1.5 radians. The cause of this feature is most likely due to the area shown in Fig. 3 that is heated by two sets of rays, one set that goes through the area directly, and another set that reflects off the inner surface of the ice. This causes an increase in ice thickness, because the calculated energy distribution was subtracted due to the lack of heating from the keyhole.

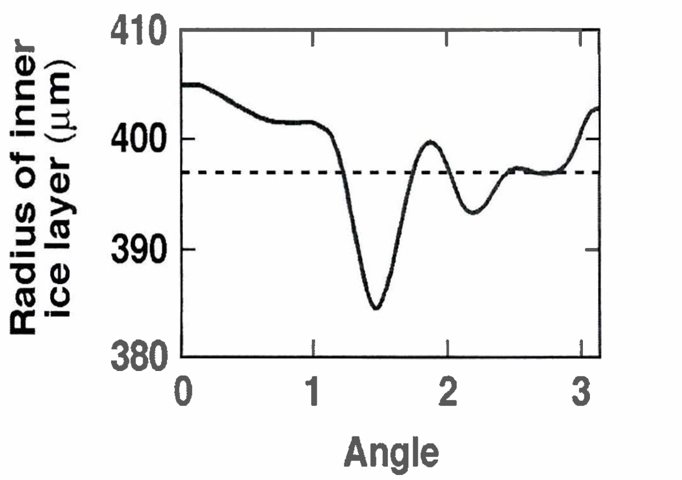

Figure 7: The angular variation of the radius of the inner ice surface (μm from center of target) as a function of angle (radians from the axis of symmetry).

The difference between modeled and experimental results is most likely due to the assumptions that were made for this model. One possible explanation is that the energy that would come from the keyhole has a larger angular spread than the calculations assumed. However, this is unlikely to have much of an effect on the uniformity. Alternatively, the viewing windows and the shadow of the keyhole may have some effects that counteract the effects of the keyhole. This is also unlikely because these other features would probably contribute to more nonuniformities in different positions. To model these, a more extensive three-dimensional model must be created that can account for all the nonuniformities of the layering sphere. Also, the empirical results of 2-3 μm rms could be low because the measurement technique does not sample all parts of the target. The empirical measurements may not detect the largest feature shown in Fig. 7. Finally, inaccuracies may be introduced through the way that information is transfered to

FLUENT. The energy values that are imported to FLUENT have a low resolution; a model using a finer wireframe than shown in Fig. 5 would show if this affects the results significantly.

5. Conclusion

The effect of the keyhole in the layering sphere on the ice thickness uniformity of cryogenic targets has been modeled for the first time. The energy that is deposited due to a single beam of light was calculated using a PV-Wave code. The output of this code was then exported to FLUENT, which was used to find the shape of the ice layer due to the keyhole. The model predicted thickness nonuniformities of 5 μm rms that are consistent with empirical data considering the assumptions that were made. This shows that there is a limit to the thickness uniformity of a cryogenic target produced in the layering sphere. Because of the importance of uniform targets to inertial confinement fusion, more accurate calculations and further experiments must be done in the future.

6. Acknowledgements

I would like to thank Dr. Craxton for providing me with the opportunity to participate in the University of Rochester's Summer Research Program. I would like to thank my advisors, Dr. Craxton and Dr. Harding for assisting me with my research throughout the summer. Also, I would like to thank the other students in the research program for being so supportive and making the entire summer enjoyable.

7. References

1. Craxton, R. Stephen, Robert L. McCrory, and John M. Soures, Scientific American, Volume 225, pp. 68-79, "Progress in Laser Fusion (August 1986)."
2. Laboratory for Laser Energetics Report LLE-02422, October 2001, Section 2.8, "Target Development and Production."
3. Laboratory for Laser Energy Report LLE-02422, October 2001, Section 2.9, "Cryogenic Target Handling System."
4. J. K. Hoffer and L. R. Foreman, Phys. Rev. Lett. **60**, 1310 (1988).
5. Sharon Jin, "A Ray-Tracing Model for Cryogenic Target Uniformity Characterization," 2002 Summer High School Research Program for High School Juniors, Laboratory for Laser Energetics Report 329 (2003).
6. E. L. Alfonso, I. Antemy, and D. R. Harding, LLE Review, Volume 81, pp.12-20, "Modeling the Temperature and Ice-Thickness Profiles Within OMEGA Cryogenic Targets" (1999).
7. Gambit Version 2.0, produced by Fluent Inc., Lebanon, NH.
8. Version 6.0, Fluent, Inc., Lebanon, NH.