How Good is the Bright Ring Characterization for Uniformity of Deuterium Ice Layers within Cryogenic Nuclear Fusion Targets?

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Abstract:

Cryogenic targets, thin plastic shells surrounding thick cryogenic deuterium layers, are used to achieve nuclear fusion. These targets are irradiated by lasers causing the targets to implode and create fusion reactions by forcing the deuterium inside to fuse together. The cryogenic targets are pressurized with deuterium gas, and then the targets are chilled to about 20K to freeze an ice layer on the inside of the target. The ice layer needs to be as uniform as possible for the targets to implode correctly and thus create a successful fusion reaction.

Cryogenic targets have suffered from nonuniform deuterium ice coating. This nonuniformity causes irregular implosions and is the source of nuclear fusion reaction failure. The uniformity of the ice layer is measured by using the technique of shadowgraphy. A shadowgraphic target image exhibits a characteristic bright ring when viewed with a CCD camera. This bright ring can be used to estimate the ice thickness in the cryogenic targets. This method is based on the assumption that the bright ring radius uniquely determines the ice layer radius in the target. A computer program has been developed to test the shadowgraphic technique. The result is that the bright ring does not uniquely define the inner ice surface. When the experimental ring radius is compared with the radius predicted by the current model, significant inconsistencies (up to 1 micron) are observed. However, if two opposite views of the bright ring are averaged, then the inner ice layer can be measured to an accuracy of less than 0.2 microns. This is a five-fold increase in the accuracy of measuring the uniformity of the deuterium ice layer within a nuclear fusion target.

Introduction

The goal of the Laboratory for Laser Energetics (LLE) is to create fusion reactions and to make fusion a safe and viable source of energy. To achieve fusion the LLE has an array of 60 beams (called the OMEGA Laser System) that focus onto the target. The cryogenic targets are filled with pressurized deuterium gas and frozen to about 20K (see figure 1). The cryogenic targets need to have a consistent deuterium ice layer to produce high amounts of energy from fusion reactions. The cryogenic targets that the LLE uses consist of an outer shell, an inner layer of ice, and a gaseous center. The outer shell of the target is fabricated from hydrocarbon plastic (CH) that is approximately 3 microns thick. The inner ice layer consists of frozen deuterium (D2) gas (sometimes deuterium tritium (DT)), that is approximately 100 microns thick, cooled to about 20K. The ice layer must be uniform for a successful fusion reaction.

Cryogenic Target
Cross Section View

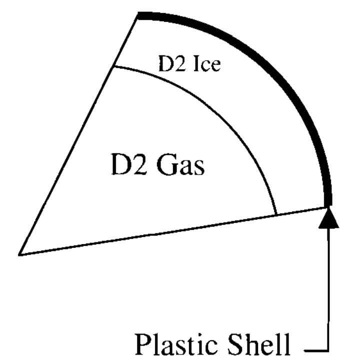

Figure 1. Target Cross-section

The OMEGA laser system focuses all of its 60 beams onto this small target and creates uniform pressure around the outside of the target. When the target implodes it generates massive amounts of heat and this heat is necessary to start a fusion reaction. Thus, you need uniform laser irradiation and a uniform thickness of the target. If part of the shell or ice is too thin, that part of the target will implode too fast and cause a nonuniform implosion, which will not create enough heat for a fusion reaction. Also for uniform irradiation, the target must be suspended. Spider silk is used to suspend the target and can be seen on Figure. 3.

Shadowgraphy is a technique used to look at the inner ice surface of a target. This technique requires that you backlight the target with a collimated light source.

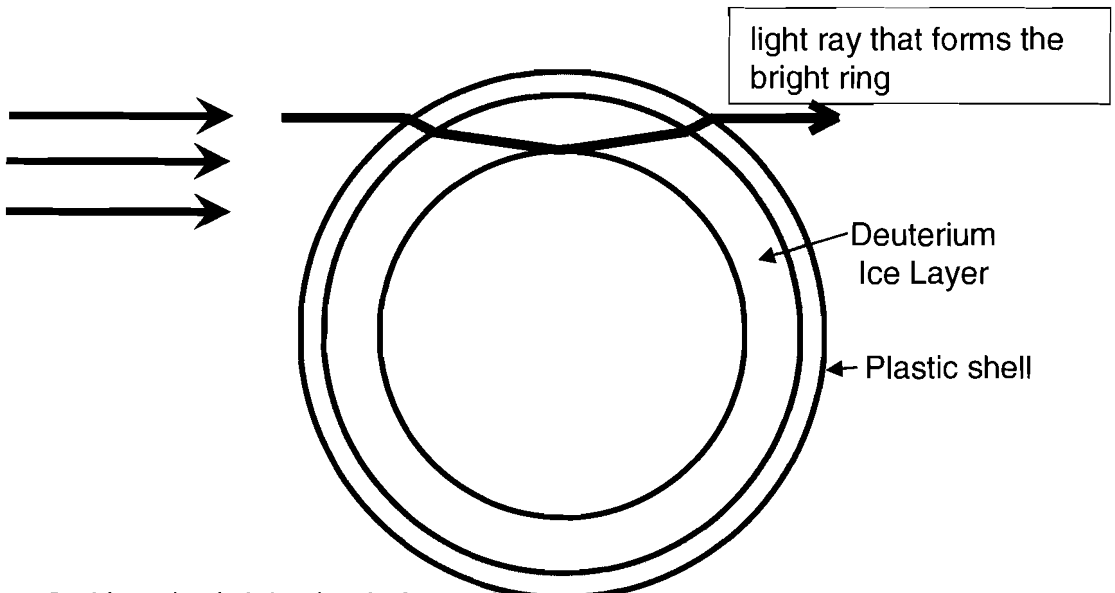

Figure 2. How the bright ring is formed

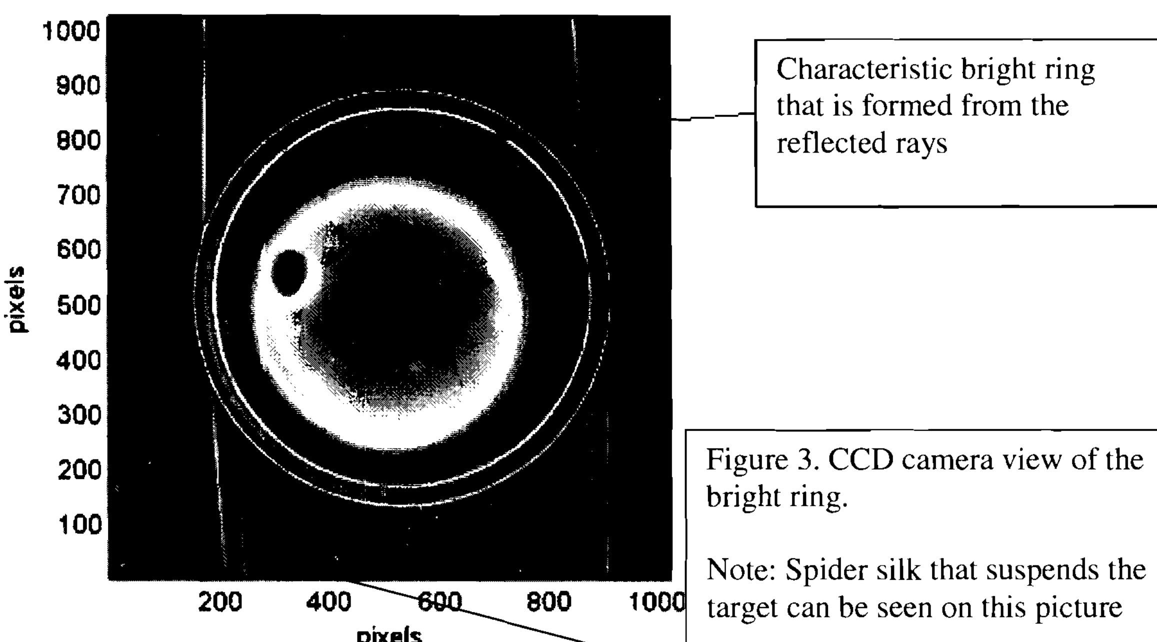

Figure 3. CCD camera view of the bright ring.

Note: Spider silk that suspends the target can be seen on this picture

Some of the rays of light from the source will reflect off the inner ice surface (figure. 2) and will form a bright ring on an opposing CCD camera (figure 3.). Since these rays reflect off the inner ice surface you can use them to measure the inner ice surface. A simple theory valid for spherical surfaces has been used to calculate the relationship between the inner ice layer radius and the bright ring radius. Thus, by measuring the nonuniformities in the radius of the bright ring it should be possible to measure the nonunformities of the inner ice radius as well. Looking at many different views (two cameras, 25 each) of the target a 3-D model can be created using spherical harmonics. The radius R is given as a function of direction (theta, phi) as

$$R(\Theta,\Phi)= \sum_{L=0}^{Lmax} \sum_{M=0}^{L} [Ac(l,m)Clm(\Theta,\Phi)+As(l,m)Slm(\Theta,\Phi)]$$

Equation. 1

where Clm's and Slm's are standard spherical harmonic functions, Ac's and As's are coefficients predetermined for this particular model [1], and Lmax is typically 11.

A computer program has been developed to trace rays though a target with such a reconstructed ice layer that can calculate the actual bright ring radius that the target will produce. The recreated bright ring can be compared with the experimental ring radius and the radius predicted by the simple model. While all three radii generally agree quite closely, significant inconsistencies (up to 1 micron) are observed. This indicates that there are limitations to the accuracy with which the 3-D ice thickness can be reconstructed and that the bright ring radius does not uniquely define the inner ice radius. This problem has been solved by tracing rays from a directly opposite view creating another bright ring. By averaging these two views together the inner ice radius can be determined to an accuracy of less than 0.2 microns.

Ray Tracing Program

The research project involved creating a computer code to calculate the bright ring radius as a function of angle based upon the spherical harmonic representation (Equation 1) of the thickness of the plastic shell and the inner ice layer of the target. This representation was obtained on the basis of many different views of the target [1]. The program started by using some existing programs that traced rays through a target. Pieces of the code *Pegasus* written by Sharon Jin [2] were used. *Pegasus* traces light rays through an ideal target and provides information on the position and intensity of the expected bright ring. Other subroutines were also used that had been written by Dr. Craxton. These included a routine to find the exact intersection of a ray with the interface between two layers (such as the plastic and the ice).

First the computer program starts out by setting up a cube in three-dimensional space with grids on each side so that, if given a line passing through the origin with a given direction (in the form phi and theta), you can find the intersection point of that line with one of the six grids. Given any formula such as Equation 1 that expresses the radius of a surface in terms of phi and theta it is possible to set the radius at each point on each grid. This also allows for this program to be used to trace rays through any other type of perturbed surface as long as the radius can be expressed in terms of phi and theta.

Once the grids are set up, the program uses the spherical harmonic formula for each point on the six grids and stores three quantities: R1 for the plastic radius, R2 for the plastic-ice interface, and R3 for the ice-gas interface. Once these quantities are stored they can be recalled at any time when the program needs it. This is done to avoid computing Equation 1 many times and thus saving time.

A small iterative procedure was written to find the side on which the ray hit and exactly where it hit on the grids. This is done by taking the unit vector of the ray and breaking it up into x, y, and z components. Once this is done the sign and value of the largest component will determine what side the ray intersects. For example, if the vector is proportional to (1,y, z) where y and z are smaller in magnitude than 1, it is on the first side of the cube, if it's proportional to (-1,y, z) it is on the second side, if it's proportional to (x, 1,z) where x and z are smaller in magnitude than 1, it is on the third face, and so on. When the side the ray intersects is found, simple two-dimensional interpolation can be used to find the radius where it hit.

Tracing Rays

A program was put together to find the true paths of the rays. Many factors had to be taken into account since the tilts of the surfaces caused the rays to be deflected out of the plane in which they would otherwise have propagated. The simple ray tracing methods used in Reference 2 could not be used, so a ray tracing step program was created.

The program starts by launching rays from the plane on the left of figure 4 towards the reconstructed target. The first ray is launched from a predetermined radius that is below the starting radius of the bright ring rays and emerges with a positive angle to the vertical (the dashed ray). Successive rays are launched higher with the goal of finding the "bright ring ray" (see figure 2) that emerges parallel to the incoming ray (i.e. horizontal). Once a ray is launched, the program makes the ray travel a certain distance, usually less than the distance to the next interface. As the program continues to "step" the ray this distance is allowed to increase until the new point is the other side of the next interface determined by interpolation from the grids. Once this occurs, the program uses an iterative algorithm, reducing the space step size by a carefully chosen factor to find the exact point where the ray crosses the new interface. The point at which the ray intersects the new interface is calculated to an accuracy of $1x10^{-5}$ micron (smaller than an atom).

The program also deciphers which rays will actually make up the bright ring. These rays must follow the path through five interfaces: air-plastic, plastic-ice, reflect off inner ice surface, ice-plastic, and plastic-air. The modified program *Pegasus,* is used to sift through the rays to find only those that met the determined path.

Once a good ray is found it is tagged and stored. The first such ray has a positive angle to the vertical when leaving the target. As the new rays are launched successively higher, their angle leaving the target becomes smaller and then becomes negative (see the solid black ray in figure 4).

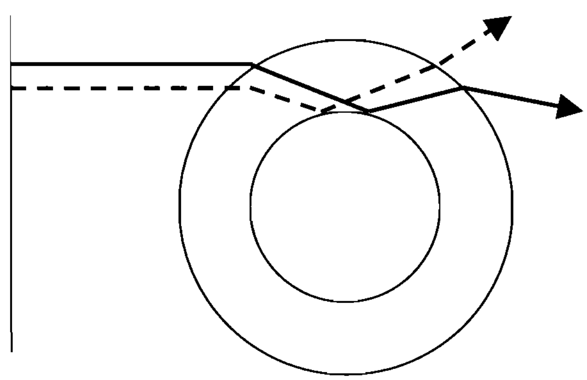

Figure 4. First rays launched (Dashed) have positive angle and further rays have negative angles (solid black).

Once a ray is found to have a negative angle the program stops tracing rays. It interpolates to find the parallel ray exiting the target based upon the final ray and the ray before it. This parallel ray gives the radius of the bright ring at that point. This is done 360 times, as the rays are moved 360 degrees around the target, one degree at a time. This is all repeated 50 times for the 50 different views. A typical graph giving the bright ring radius as a function of angle for one of the views is shown in figure 5 as the Dashed Curve #3 ("Actual Bright Ring").

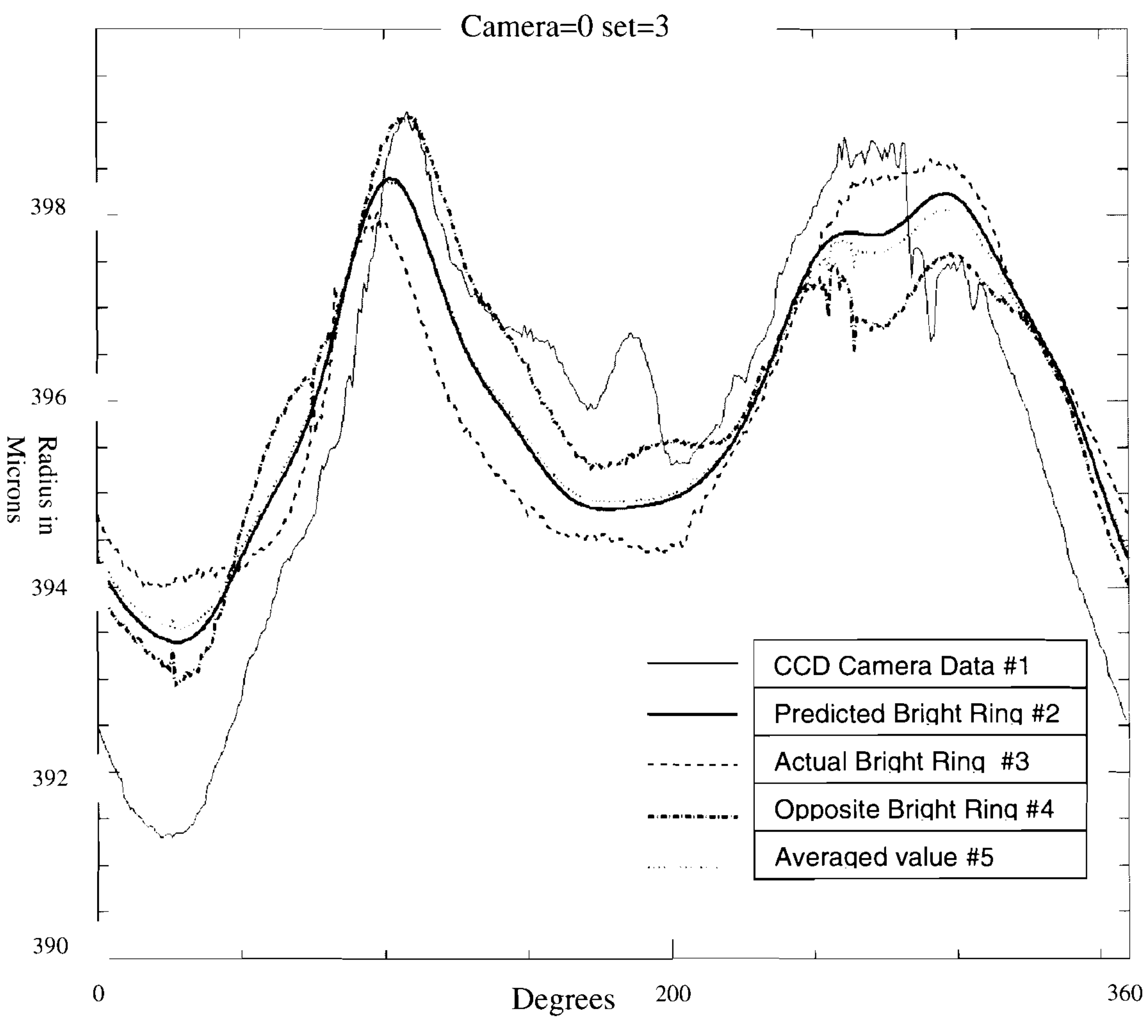

Figure 5: Radius vs. Degrees

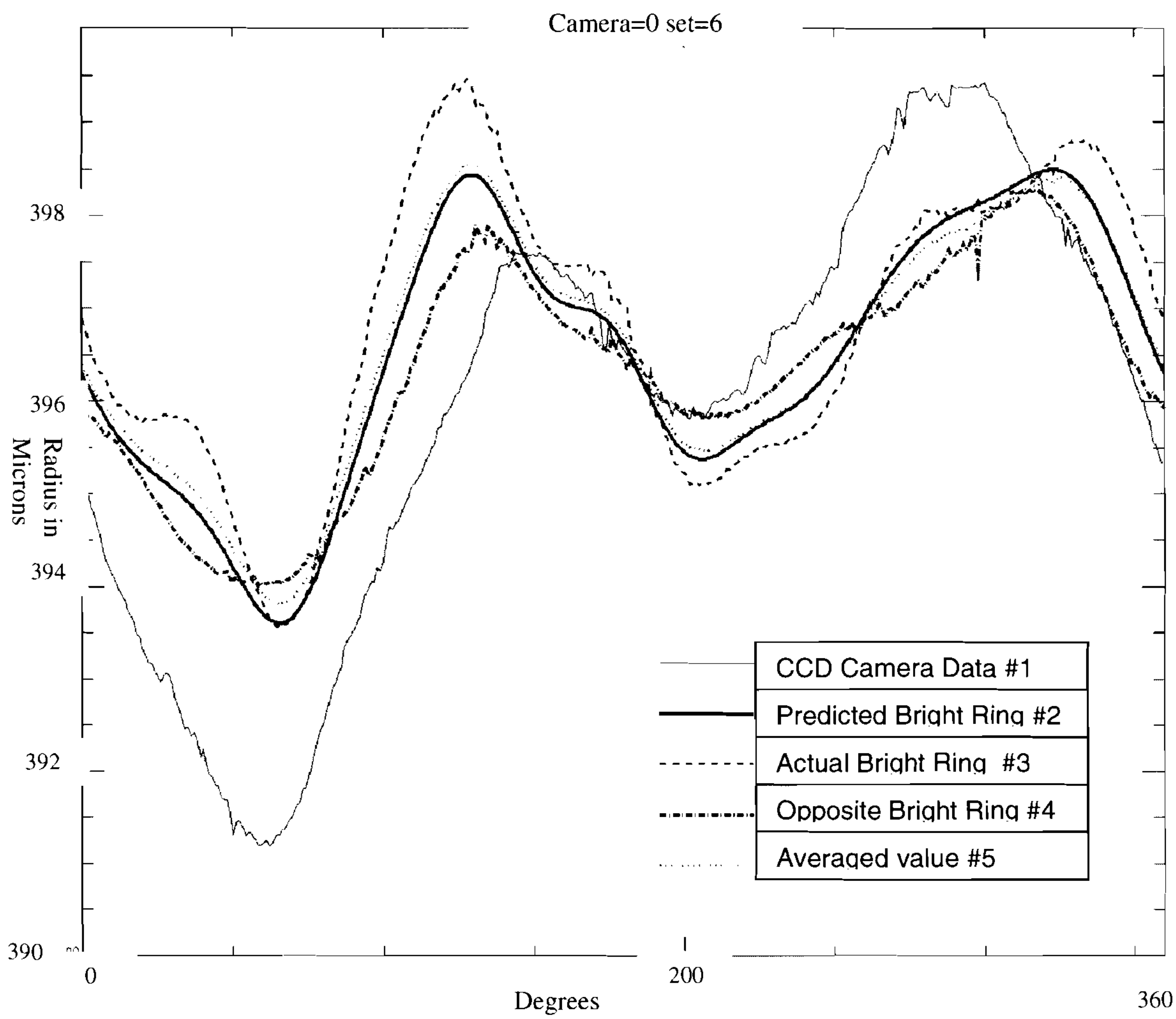

Figure 6: Radius vs. Degrees for a different view

Results

Figure 5 also shows several other curves. Curve #1 gives the original experimental data for this target (obtained from the CCD camera). Curve #2 ("Predicted Bright Ring") is derived from the spherical harmonic model (based on the CCD data from all 50 different views) under the simple assumption that the ice thickness and bright ring radius are under a direct relationship. The first two curves do not match exactly because the model was made from a best-fit interpolation from the 50 images. The third curve, the bright ring produced by the exact ray-tracing calculation based on the spherical harmonic model, doesn't correlate very well with the second curve. It typically has an error of plus or minus 0.75 microns. A possible explanation for this error lies in the ice layer itself. The ice layer is assumed to be spherical in nature in the simple interpretation that the bright ring radius uniquely gives the ice thickness. However, if the ice layer is tipped in a certain direction it can affect the position of the bright ring even though the ice thickness is unchanged (Figure 7). This tipped ice layer can explain the difference between curves two and three.

To correct this problem of the ice layer being tipped, it is proposed that two opposite views should be used. This was tested by tracing rays in both directions. The opposite view is graphed as curve four.

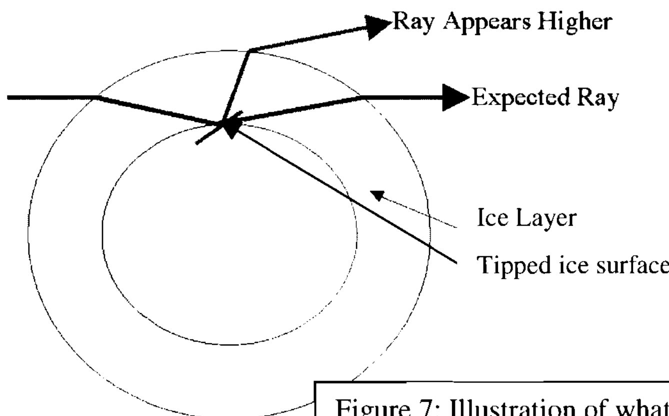

Figure 7: Illustration of what a tipped surface will do to the expected bright ring ray.

This curve is also different from curve three. Thus, if the simple relationship between the bright ring and ice thickness were true, the thickness would depend on which way the target is viewed. However, when the actual bright ring curve (number three) is averaged together with the opposite-traced bright ring curve (number four), the resulting curve (number five) matches quite closely with the predicted bright ring (number two) with deviations from that curve less than 0.2 microns. This holds up for all of the views of the target (see figure 6 for another example). The main result is that if the average of two opposite views is taken, an accurate reproduction of the ice layer is possible.

Conclusion

A ray-tracing program has been developed to calculate the bright ring for a cryogenic target with non-spherical surfaces. This program allows for exact ray tracing through the target and can trace rays through a variety of perturbed surfaces as long as their radii are expressed as functions of phi and theta. It has been found that, from a single view of the target, the shadowgraphic technique is limited because the expected ring position and the actual ring position do not correlate exactly; i.e., the bright ring does not uniquely define the ice thickness. This is believed to be due to ice surface tipping. However, by finding the averaged value of two opposite views, it can be seen that the predicted bright ring and the averaged value only differ by about 0.2 microns. Using this method it is possible to accurately measure the ice thickness.

Acknowledgements

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References

[1] Edgell, Dana, private communication (2004).

[2] Jin, Sharon. "A Ray-Tracing Model for Cryogenic Target Uniformity Characterization," 2002 Summer High School Research Program at the University of Rochester's Laboratory for Laser Energetics.