X-Ray Phase-Contrast Characterization of Cryogenic Targets

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Abstract

In order to obtain ignition and high gain in an implosion, a cryogenic target's ice layer must be almost perfectly spherically symmetric. The Cryogenic Fill-Tube-Target Test Facility (CFTF) can be used to create and characterize cryogenic target ice layers. X-ray phase contrast imaging on the CFTF uses a small-spot-size x-ray source to irradiate the target with x-rays that are recorded by an x-ray camera on the opposite side of the target. X-rays that pass through the ice layer at nearly tangential angles undergo strong refraction, resulting in light and dark rings in the camera image. Asymmetries and imperfections in the ice surface are characterized by analyzing these rings. To better understand the behavior of these rings, the ray-tracing code Icarus was used to simulate the rings. In particular, the effects of a finite spot size and the energy distribution of the x-ray source were studied and compared with experimental measurements of the rings.

Introduction

The OMEGA-60 laser[1] in the Laboratory for Laser Energetics is primarily used to conduct fusion reactions. To do this, it launches 60 laser beams at a suspended cryogenic target with enough concentrated heat to trigger an implosion. These cryogenic targets are made up of a very thin plastic shell surrounding a thin layer of DT ice. The central region contains some residual DT gas. The difficulty is that the slightest imperfections on the ice surfaces of these targets will cause a section to implode faster or slower than the rest of the layer, resulting in a failed implosion.

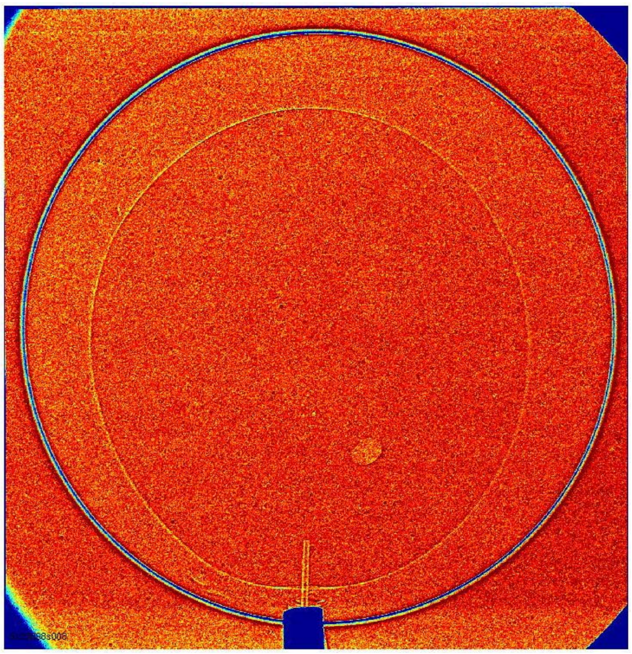

Figure 1: X-ray phase contrast image of a cryogenic target. The blue circle in the image is the outer edge of the target. The very asymmetric inner yellow "ring" is indicative of the shape of the inner ice layer. This image is of a very poor quality ice layer and is shown here to emphasize the usefulness of these images in diagnosing layer quality. Typical ice layers produced at LLE are much more symmetric.

In order to characterize the imperfections of the ice layer, a cryogenic target is observed through x-ray phase-contrast imaging[2] (Figure 1). Refraction of x-rays that strike the edge of the ice causes bright rings to appear in the image. It is the replication and study of these rings that is the focus of this project.

X-Ray Phase-Contrast Imaging

The new Cryogenic Fill-Tube-Target Test Facility (CFTF) shown in Figure 2 is specifically designed to test cryogenic targets for imperfections through backlit optical shadowgraphy and x-ray phase-contrast propagation imaging. A tungsten anode launches x-rays at a target suspended in a target chamber which are then received by a 1340 x 1300, 16 bit x-ray camera. The target can be rotated inside the chamber so that images can be recorded for many views and a 3D reconstruction of the target can be produced.

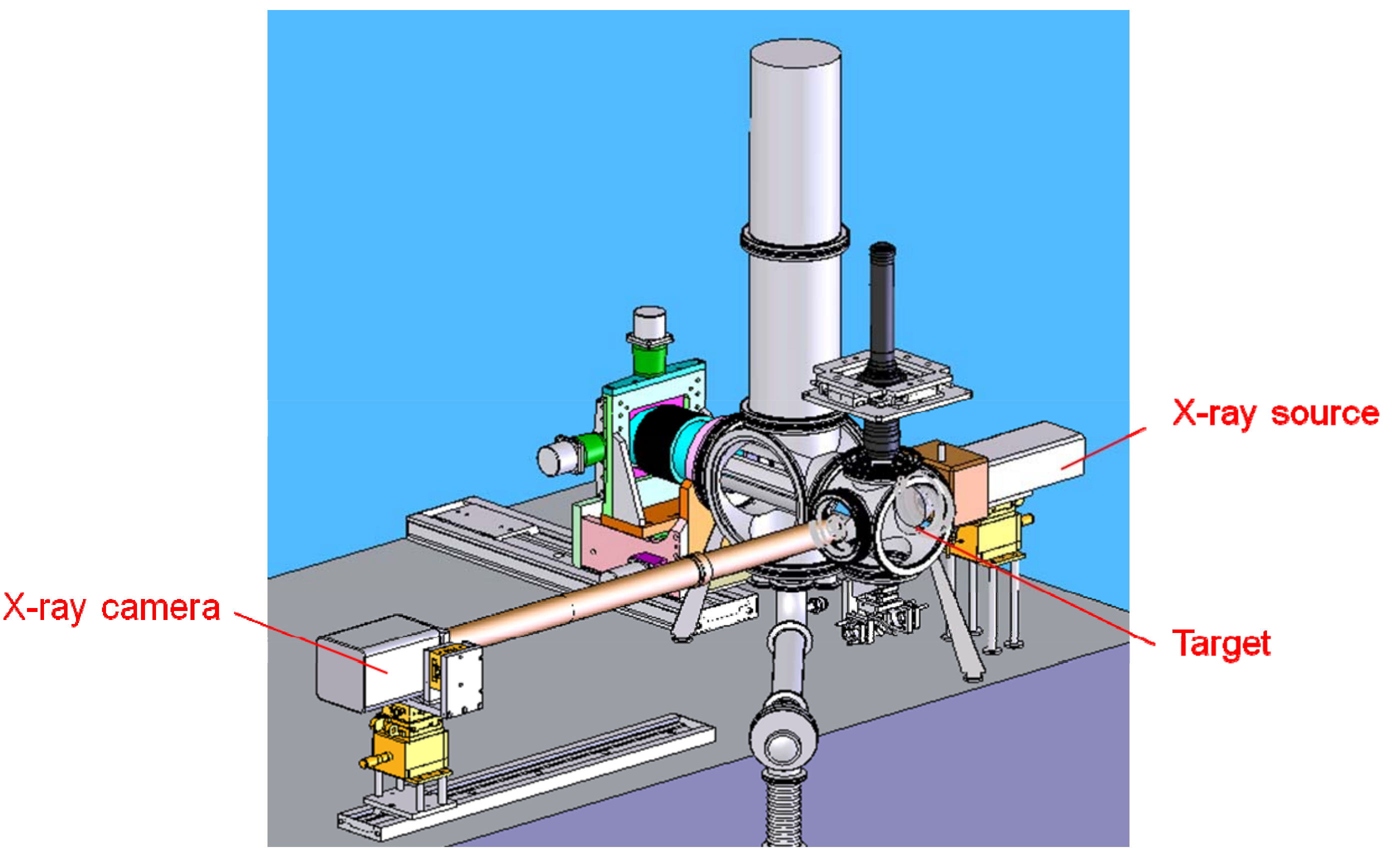

Figure 2: The Cryogenic Fill-Tube-Target Test Facility

The x-rays pass through the target with almost no deflection from a straight line as shown in Figure 3.

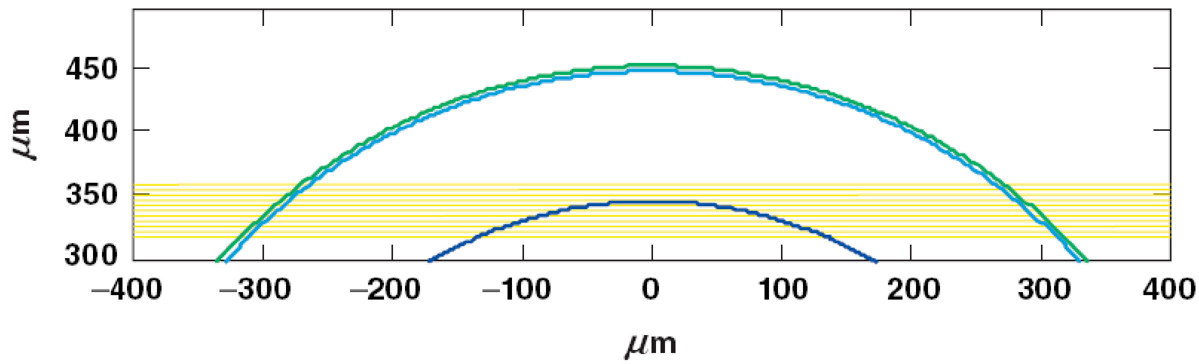

Figure 3: Ray trace of x-ray paths through a cryogenic target.
The dark blue circle is the inside surface of the ice layer.

However, when the rays are allowed to travel the distance to the camera (about 1m) a deflection due to refraction becomes noticeable for those rays that are nearly tangential to the inner ice surface as shown in Figure 4.

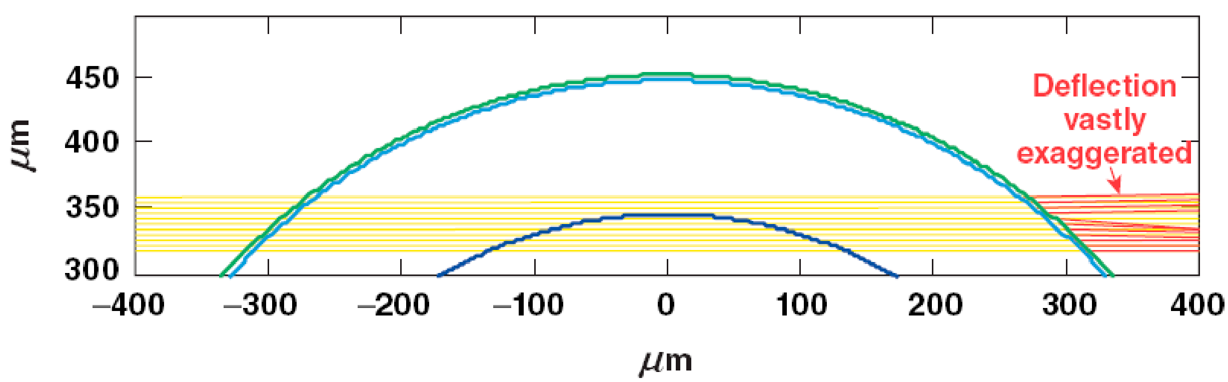

Figure 4: Same as Figure 3 except that the emerging ray deflections have been greatly exaggerated. The small deflection due to refraction of those rays that are nearly tangential to the inner ice surface becomes apparent when the camera is placed a meter away from the target.

The variation in x-ray intensity due to the deflection of the x-rays results in a ring appearing in the phase-contrast image (the blue/orange ring in Figure 5).

To determine where the actual ice layer is, the position of the ring relative to the ice surface must be calculated.

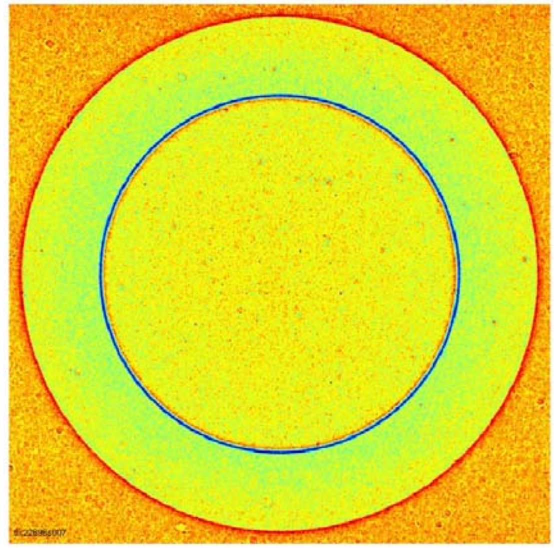

Figure 5: Experimental x-ray phase contrast image of a thick walled plastic shell used for calibration purposes. The deflection of the x-rays creates a ring in the image. The dark blue ring (low intensity) indicates where the rays have been deflected from. The fainter orange ring (higher intensity) inside the blue ring is where the rays have been deflected to.

The Icarus Program

Developed to model actual x-ray paths, Icarus is a comprehensive program that simulates the CFTF. It launches rays according to the x-ray's source position and energy, follows these ray paths using Snell's law, and then calculates final ray positions at the x-ray camera. Great care was taken to make sure the model geometry is an accurate representation of the CFTF. By varying the parameters of both the x-rays and the target, we can determine the exact location of the ice layer. The bright ring created by refraction in the simulation is compared to the actual bright ring location in the x-ray image and the ray-trace model target parameters are adjusted until the simulations match the recorded image. By applying the model to real experimental runs, in this way, the ice thicknesses of real cryogenic targets can be determined. As such, much time was taken to fine tune this program to produce results as similar to actual experimental data as possible.

The first main task was creating a finite source spot. At first the program used a single point source for the x-rays. In this construction, every ray originates from a single, microscopic point as shown in Figure 6. Obviously, this is not a realistic technique as the CFTF x-ray source has a finite spot size. As such, the program was modified to reflect this by using an entire conglomeration of these point sources in a pattern similar to that shown in Figure 7. This single point turned into many rings of multiple points, launching an array of x-rays. To produce quicker runs, a limited number of points in each ring were used (about 8). Nevertheless, this final finite spot used in Icarus resulted in a much more precise simulation of the CFTF.

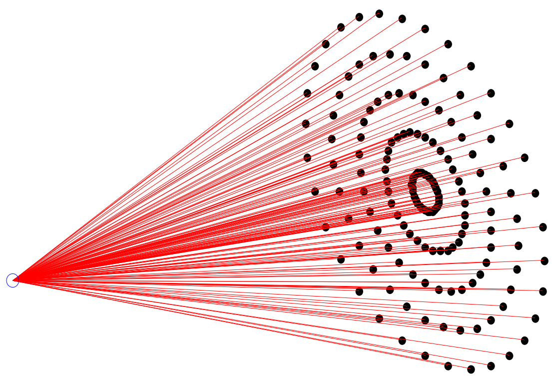

Figure 6: In the ray trace point source all rays in the model are launched in a cone from a single point. Only a limited number of rays are shown in this image for clarity. In an actual ray trace run, many more rays would be used

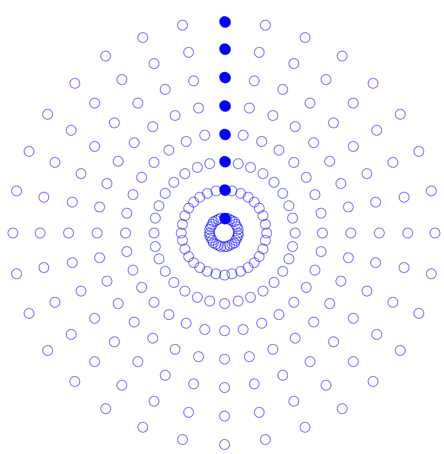

Figure 7: In the ray trace finite spot size model, many separate point sources are spread over the appropriate spot area to simulate the finite source size. Each circle in this figure represents a separate point source.

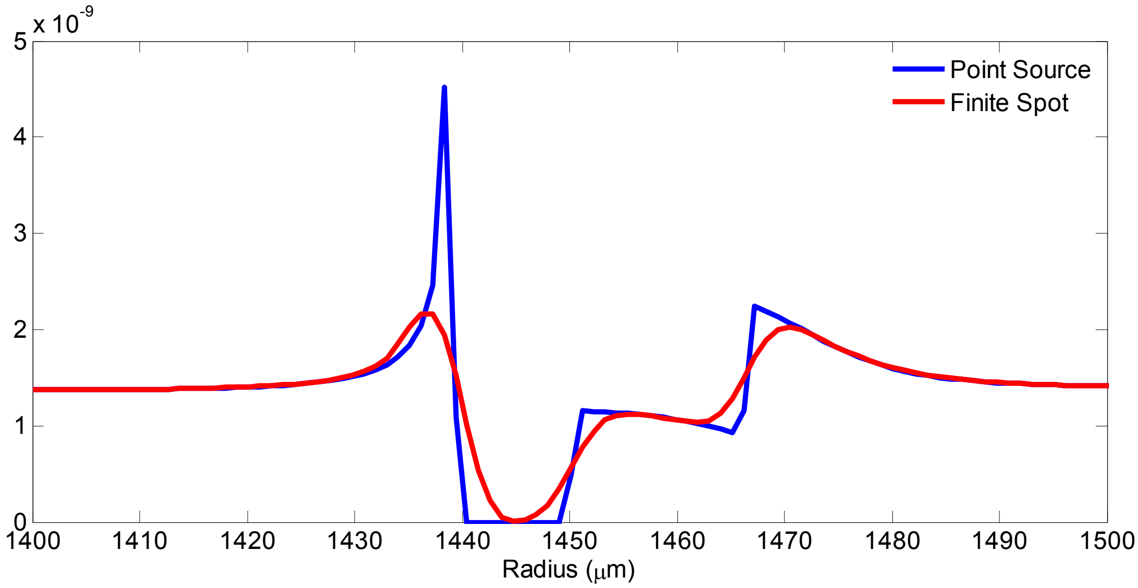

Figure 8: A comparison of the ray-trace predictions of the outer region of a cryogenic target for the point source (blue) and the finite spot size source (red). The target comprised a DT layer inside a plastic shell of inner and outer radii 1447 and 1467μm.

Simulations were performed for a target with an ice layer of inner radius 1151 μm on the inside of a plastic shell of outer radius 1467 μm and thickness 20 μm. Results are shown in Figure 8 for both a point source and a finite source. It can be seen that the spot produced much smoother results than the jagged, abrupt variations of the point source. The intensity of 0 from about 1440 μm to 1450 μm corresponds to the discontinuity in emerging ray directions seen in Figure 4. Then from about 1450 μm to 1465 μm the x-rays appear to be passing through the inside of the plastic layer. The x-rays have a higher intensity level from 1465 μm on, passing through the outside of the plastic layer. One of the major points of this work is to determine from the lineout where the actual interface is located. Producing results that more accurately match experimental data will facilitate this process.

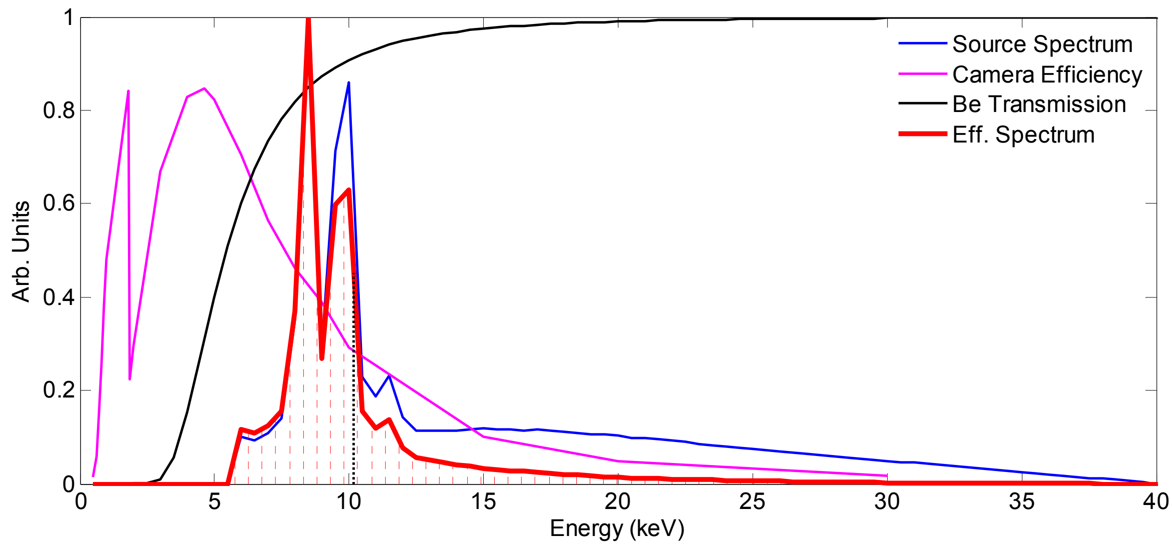

Figure 9: An effective x-ray energy spectrum (red) was produced by multiplying the actual source spectrum (blue) with the camera efficiency (pink) and the beryllium window transmission (black). The effective spectrum was normalized to have a maximum of 1.0.

An equally important task was incorporating a realistic x-ray energy spectrum for the CFTF system into the Icarus program rather than assuming that all the x-rays had the same energy as originally done in Icarus. The first factor to be accounted for was the spectrum of x-rays produced by the source (see the blue curve of Figure 9). These x-rays are mostly around 8 or 9 keV but many x-rays have higher energies. Since these high energy x-rays refract less and blur the image, it is vital that their effect is minimized. Next, the camera's variation in efficiency based on the x-rays' energies was accounted for (see the thin pink curve of Figure 9). The camera was extremely efficient at detecting the lower energy x-rays, but it had difficulty recording the more energetic x-rays. At 10 keV the camera was operating at less than 50% efficiency. The last factor that had to be taken into account was the several beryllium windows within the CFTF (see the black curve of Figure 9). In order to pass through these barriers, the rays needed to have a minimum amount of energy. Those at lower energy levels were

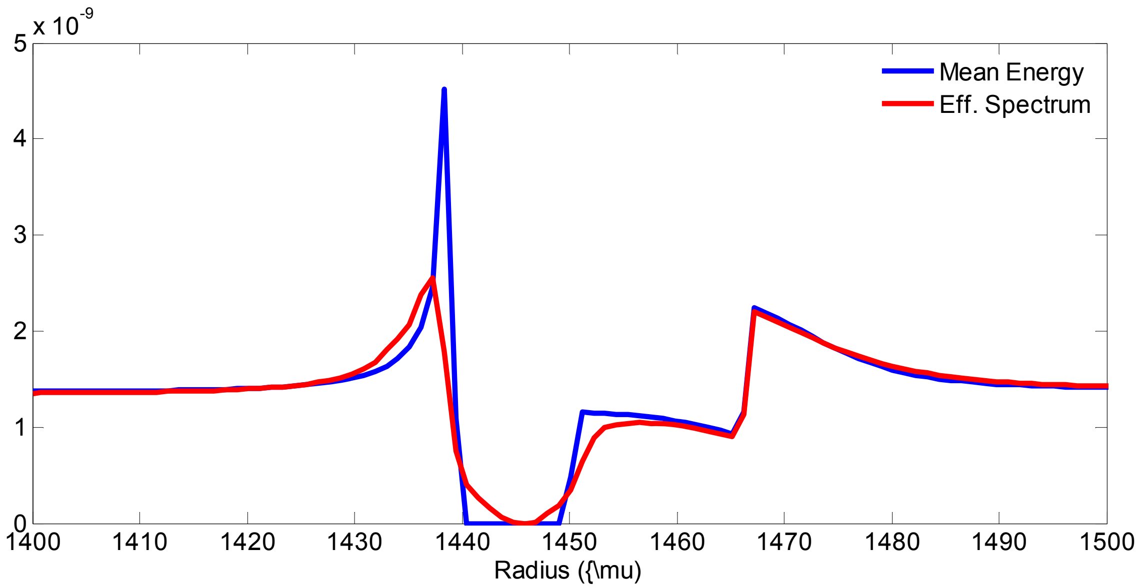

Figure 10: A comparison of the ray-trace predictions for the target of Figure 8 for the single x-ray energy case (blue) and the effective energy spectrum case (red). In both cases a point source is used.

completely blocked. Multiplying these three factors together, an effective energy spectrum was produced, as shown in Figure 9 (the thick red curve).

When this effective energy spectrum was incorporated into Icarus, the new results also became much smoother, more accurately reflecting the CFTF (Figure 10).

To compare with experiment, predictions were made that included both the finite spot size and integration over the energy spectrum. The results are shown in Figure 11, where the red curves indicate the predictions and the blue dots the experimental measurements. For both the inner and outer surfaces the agreement is very close. These results provide confidence that the interface locations can be accurately identified.

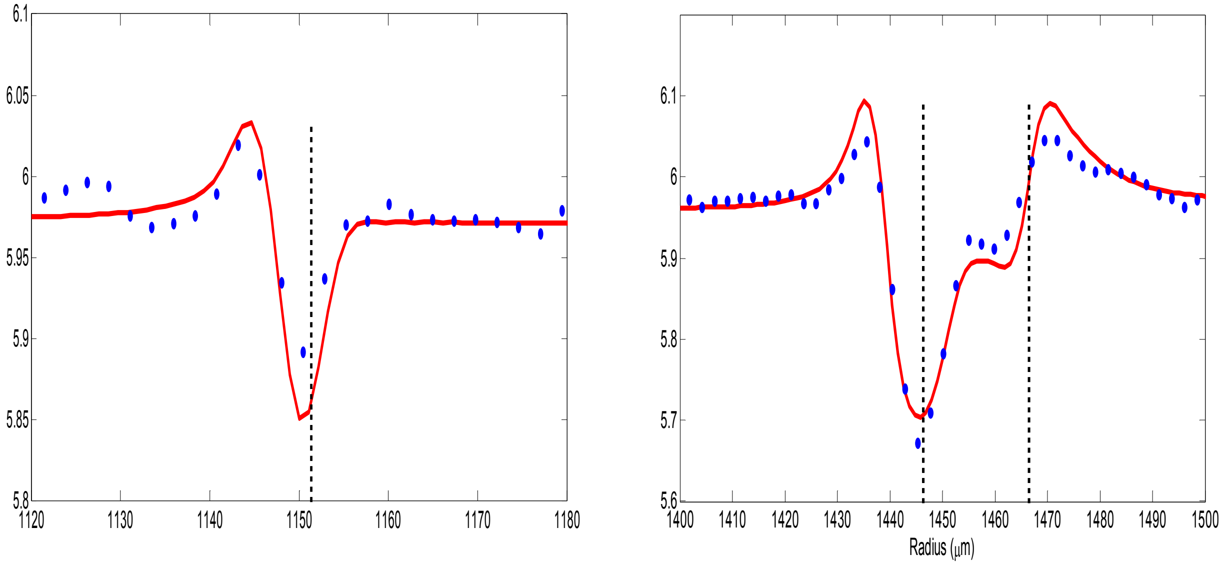

Figure 11: A comparison of experimentally measured x-ray intensities (dots) with the Icarus ray trace predictions when both the finite spot size and effective energy spectrum are accounted for. a) The rings produced by the inner ice surface ; b) the rings produced at the shell surfaces. The actual surface locations are indicated by the vertical dotted lines.

Conclusion

The Icarus program was greatly refined in order to produce a more accurate representation of experimental runs. It was found that a finite spot size and energy spectrum incorporating the source energies, camera sensitivity, and beryllium window produced an excellent match to runs conducted by the CFTF. These results can hopefully be used to more accurately characterize the thickness of ice layers and to pinpoint deviations from uniformity on cryogenic target ice layers.

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[2] B.J. Kozioziemski, et al., “Quantitative characterization of inertial confinement fusionj capsules usingphase contrast enhanced x-ray imaging”, J. Appl. Phys., 99, 063103 (2005).