Development of a Standardized Saturn Ring for Proton Backlighting on the National Ignition Facility

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1. Abstract

Proton backlighter targets are of interest at the National Ignition Facility (NIF), where a small number of laser beams are pointed at a proton backlighter target filled with D^3He. The backlighter target produces a burst of protons upon implosion that irradiate a primary target. This provides a variety of diagnostics as the protons are either deflected or absorbed by the primary target while passing through it. Due to the small diameter of backlighter targets, unabsorbed light travels past the target and could potentially damage laser optics on the opposite side of the target chamber. Saturn rings have been proposed to be placed around the targets to minimize the effects of passing light. A Saturn ring has been developed, using the hydrodynamics simulation code SAGE, for a design on the NIF that will fit all backlighter target diameters from 440 to 1100 microns. Adjustments have been made to laser pointings where necessary to maintain a uniform implosion. This will allow for the manufacturing of a standardized Saturn ring that will prevent laser damage for a wide range of proton backlighter targets on the NIF while maintaining implosion uniformity.

2. Introduction

Nuclear fusion holds a promising future as a powerful, safe, and clean energy source. Instead of relying on natural gas or oil, fusion draws on the energy found in hydrogen atoms, specifically the deuterium and tritium isotopes. One method of achieving fusion involves using lasers to irradiate a spherical glass or plastic shell filled with cryogenic deuterium and tritium, as shown in Figure 1(a). As the shell heats and ablates outward, the hydrogen is compressed inward, experiencing a high temperature and density at peak compression. The resulting energy overcomes repulsive forces between the nuclei, and the deuterium and tritium fuse to form a helium nucleus and an energetic neutron. If the density and the radius of the fuel are great enough, the energy of the helium nucleus will also be redeposited in the fuel. This is known as ignition.[1] Ignition is the first step toward achieving breakeven, where the energy outputted by the fusion reactions exceeds the energy inputted by the laser. The approach shown in Figure 1(a) is known as direct drive, because laser beams are pointed directly at the target and their energy is directly deposited. This method is used at the University of Rochester Laboratory for Laser Energetics. Figure 1(b) depicts indirect drive, where laser beams are shot into the sides of a hohlraum, causing it to emit x rays. These x rays irradiate the target. Indirect drive is used at the National Ignition Facility (NIF). To enable the laser beams to enter the hohlraum, the NIF beams are located at angles 23.5 degrees to 50 degrees from the vertical. The lack of beams near the target's equator makes it difficult for direct drive targets to be imploded on the NIF. However, uniform implosions can be achieved using the NIF laser optics and repointing and defocusing the laser beam.[3]

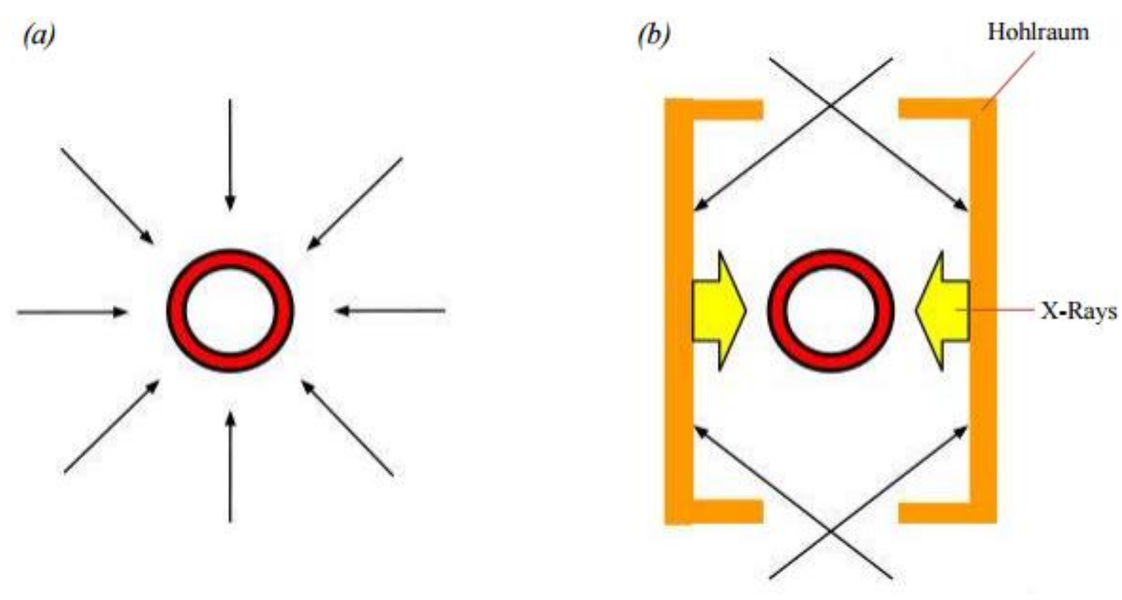

Figure 1. The two main approaches to laser-driven fusion: (a) direct drive and (b) indirect drive (Figure from reference 2).

One important diagnostic technique that can be used to diagnose target implosions and a variety of other laser-target experiments is proton backlighting.[4] In proton backlighting, a small number of laser beams are taken off the primary target and used to irradiate a small spherical shell filled with deuterium and helium-3. Upon implosion, the backlighter target emits protons that pass through the primary target. This allows for a variety of diagnostic possibilities, such as the shape of the primary target implosion and the deflection of protons in the electric and magnetic fields of the primary target. The first proton backlighting design for the NIF was developed by Kong[2] and the first proton backlighting shot on the NIF was reported by Rygg et al.[5]

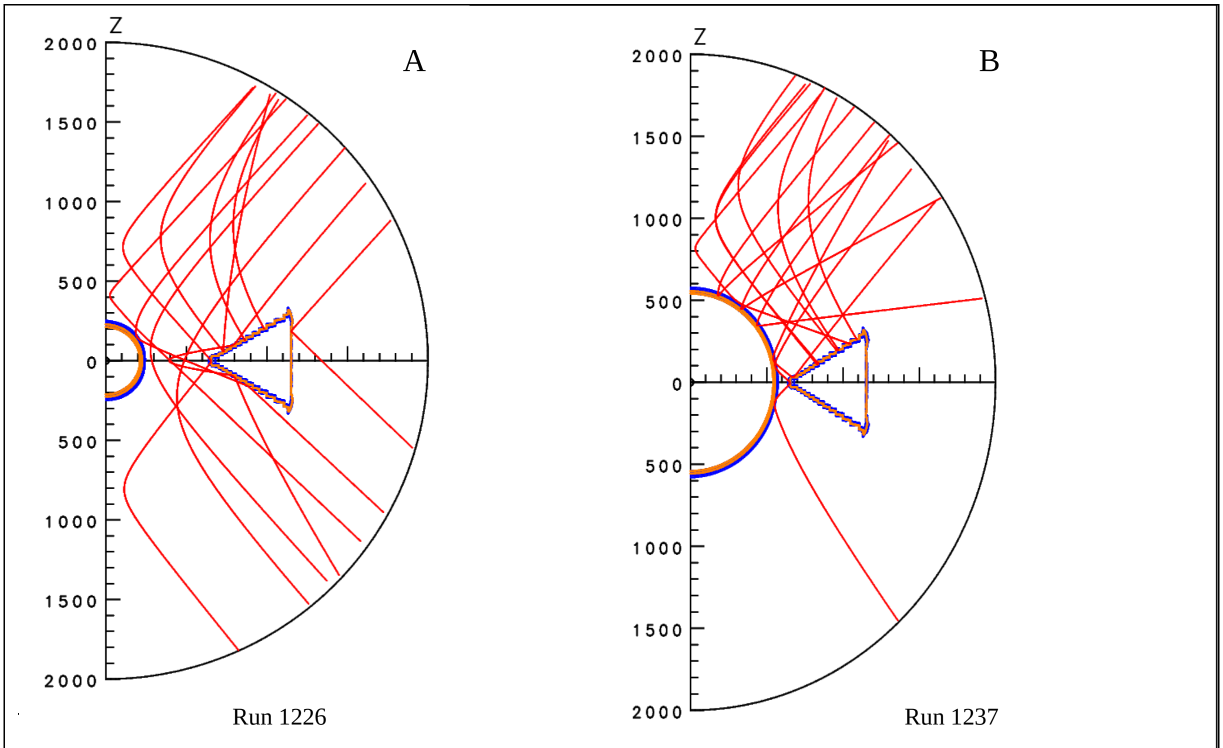

Figure 2. Ray-trace plots showing that a triangular Saturn ring can deflect the laser rays that would normally pass by the target and harm laser optics on the opposite side of the chamber for target diameters ranging from (a) 440 um to (b) 1100 um. All distances in this and similar plots are in um.

A significant problem with proton backlighter targets is that many applications require them to have a small size. They are so small that the laser beams are often wider than the target itself. As a result, portions of the laser beams pass by the target, directly into laser optics on the opposite side of the target chamber. This can cause severe damage to the laser optics due to the extremely high energy of the laser beams. Figure 2a shows a raytrace plot of laser rays (red lines) aimed at a small proton backlighter target, together with a solution to the scattered light problem, which is to place a Saturn ring[6] around the backlighter target. If the triangular ring circling around the target were not present, the laser rays would pass directly past the target without any deflection. Figure 2 is rotationally symmetric about the vertical (z) axis.

In Reference 6, the Saturn ring was proposed to increase the equatorial drive on the NIF for direct-drive targets. Here, however, the primary purpose of the ring is to block or deflect laser rays away from the opposite laser ports in the target chamber. Figure 3 shows a cross section of a target with an elliptical Saturn ring. The design was proposed by Garcia.[7] It consists of a target 440 um in diameter and a ring with a diameter of 600 um, with the innermost edge placed 360 um away from the center of the target. The target is irradiated by four laser quads (one quad contains four beams) from the top at 45 degrees from the z axis and four quads from the bottom at 135 degrees. Garcia also designed a Saturn ring (of larger size) for an 860 um diameter target. Huang[8] showed that standard targets (i.e., targets without a Saturn ring) with diameter below 1000 um produce scattered light about the safety level of 60 kJ/sr.

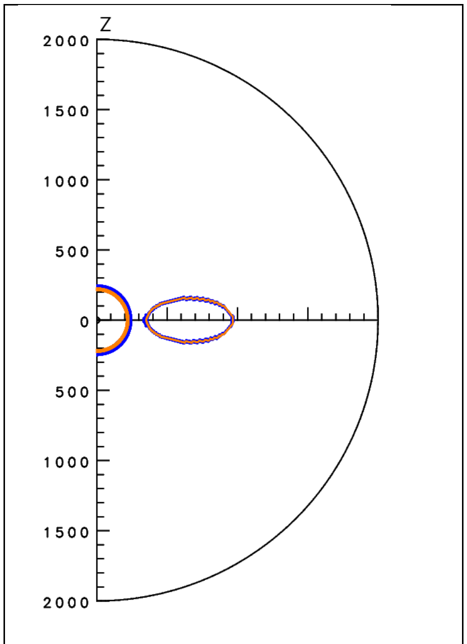

Figure 3. The initial ring set up, proposed by E. Garcia.[7] The ellipse is 600 um in diameter and 360 um away from the center of the target, whose radius is 220 um. (Distances in the figure are shown in um.) The figure shows one problem with the ring; it cannot accommodate larger target sizes.

The rings used by Garcia were successful in minimizing the scattered light to 30 kJ/sr, below the safety level. However, the ring for the 440 um target could not accommodate targets larger than 440 um because the inner edge of the ring would interfere with the implosion of the target. The purpose of this work was to develop a standardized ring that could fit all sizes of proton backlighter targets while maintaining a uniform target implosion and minimizing scattered light below 60 kJ/sr.

3. Designs

A design was developed wherein the cross-sectional shape of the ring was changed from an ellipse to a triangle. The idea was that the ring would better deflect laser beams towards the equator of the target, causing a more uniform implosion. A similar shaped ring was used in Reference 9 for a different application. After experimenting with triangle dimensions and sizes, it was determined that an equilateral triangle with a height of 500 um placed with its inner tip at a radius of 650 um was the most effective at blocking scattered light while allowing for uniform implosion. Figure 2 shows that this design blocks a significant number of laser rays for target diameters ranging from 440 um to 1100 um.

Figure 2 also demonstrates why the target size is limited from 440 um to 1100 um. The target diameter cannot be smaller than 440 um because otherwise too many laser rays (represented by the red lines) will pass through the gap between the ring and the target. Note that some of the rays in Figure 2a that go through the gap are actually close to straight (minimal deflection) because the figure plots the rays' projections in the (r,z) plane. Figure 2a shows the largest gap possible between the ring and the target without having too many undeflected laser rays. Figure 4 is the same as Figure 2 except that it is for a later time. Figure 4 shows that the target size cannot exceed 1100 um in diameter because the Saturn ring will interfere with the implosion uniformity of the target. Plasma ablated from the ring's inner tip will press into the equator of targets larger than 1100 um, resulting in an overdriven equator.

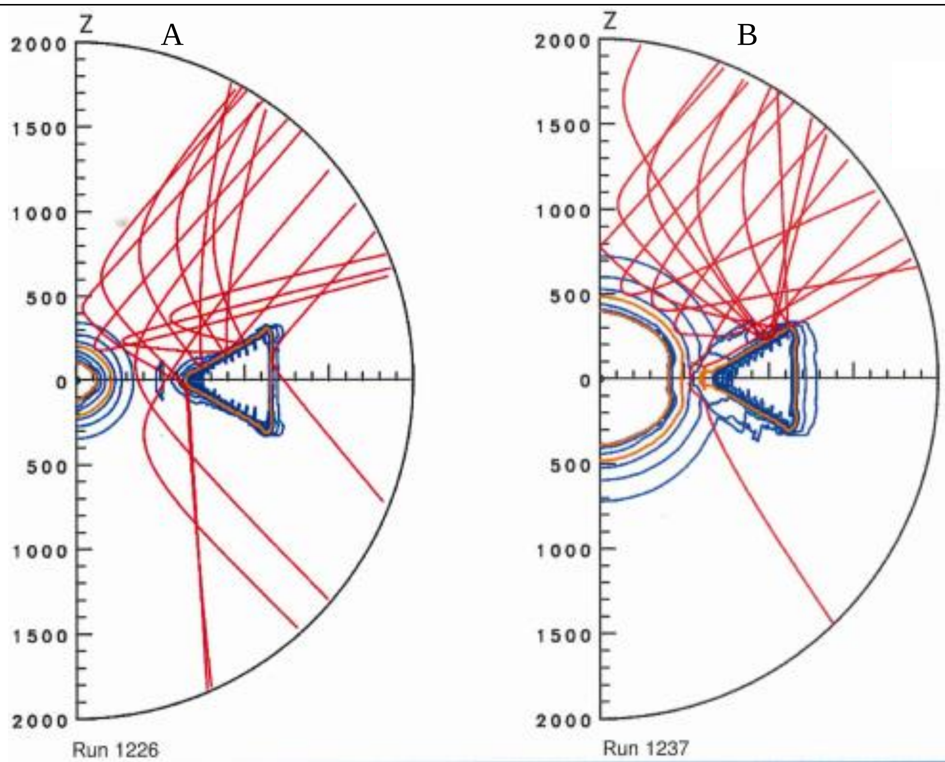

Figure 4. The same two runs as Figure 2, except at a later time in the implosion (500 ps). (a) shows the plasma on the ring expanding to further deflect laser rays. (b) shows how the expanding plasma of the ring interferes with target implosion at the equator. The ring blocks rays from reaching the equator, but plasma from the ring pushes the equator inward, causing a slightly overdriven equator.

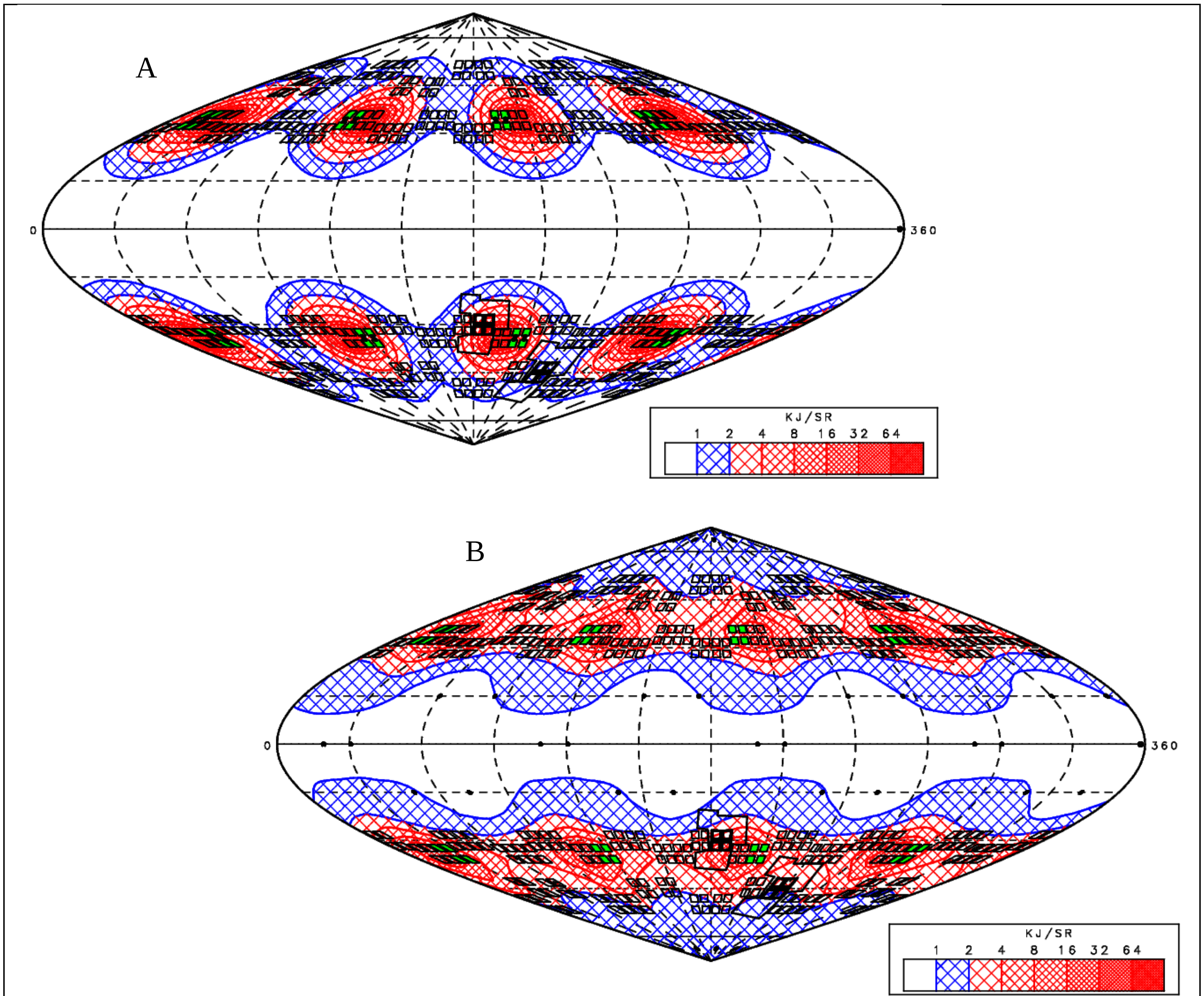

Figure 5. (a) A contour plot of scattered light around the target chamber for a target of 440 um diameter. The small green squares represent the quads of laser beams that are used to irradiate the target. The adjacent squares indicate the projections of beams (coming from the opposite hemisphere) through the center of the chamber. High concentrations of scattered light focused on these adjacent squares indicate light that has passed through the center of the chamber with minimal deflection.
(b) Same as (a) except that a Saturn ring of inner radius 650 um was placed around the target. The scattered light is much more dispersed and less focused on the laser quads.

Figure 5 shows contour plots of scattered light around the target chamber for a target of 440 um diameter. Figure 5a shows the scattered light around the chamber without a Saturn ring. The light is concentrated directly on squares representing laser optics on the opposite side of the target chamber. The maximum scattered light intensity on the laser optics is higher than 64 kJ/sr, exceeding the safety limit. Figure 5b shows the same 440 um target, except with a Saturn ring. The ring has deflected the laser rays, diffusing the scattered light away from the laser optics and reducing the maximum scattered light to less than 32 kJ/sr, well below the safety limit.

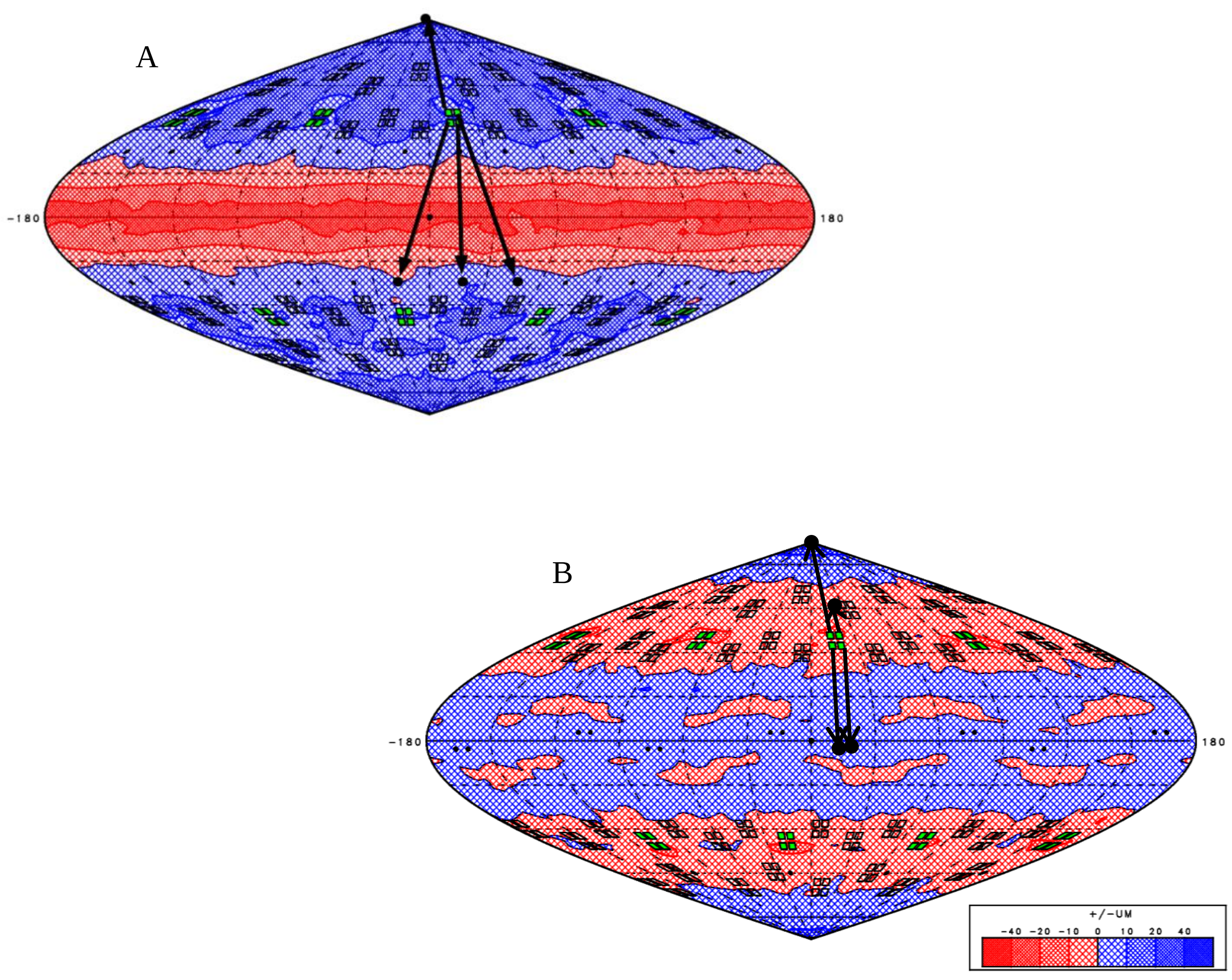

Figure 6. Center of mass plots for the implosion of a 860 um diameter target with a triangular ring of inner radius 650 um. Red represents an over driven area of the target and blue represents under driven. (a) original beam pointings, (b) amended pointings.

After finding the optimal ring size for targets 440 um to 1100 um in diameter, it was noticed that at target diameter 620 um there was a jump in nonuniformity. The cause of the jump was determined to be laser beam pointings. Targets smaller than 620 um were so small that laser pointings made no significant difference to the implosion uniformity, but larger targets were impacted by laser pointings because the beam was no longer wider than the target itself. Figure 6a shows the initial top four laser beam pointings for targets 620 um and larger. One beam is pointed at the pole and the other three are spread along the 120 degree line. The deep red at the equator shows that the equator is severely overdriven, resulting in a high RMS of 3.12%. Figure 6b shows the corrected laser beam pointings. One beam is pointed at the pole, a second at the 45 degree mark, and two beams at the equator. This resulted in a much more uniform implosion with an RMS of 1.43%.

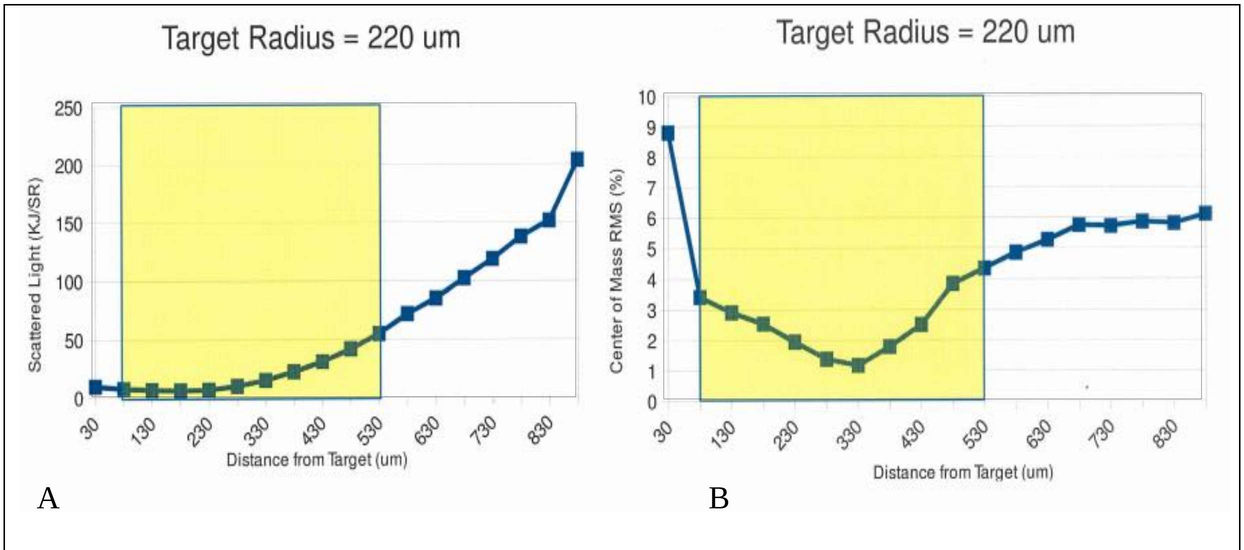

Figure 7. (a) Scattered light intensity and (b) center of mass implosion uniformity as functions of the distance of the ring from the target for a target radius of 220 um. The ring separation from the center of the target must lie in a range (shaded in yellow) determined by a tradeoff between scattered light and uniformity. The scattered light must stay below the safety limit of 60 kJ/sr and the implosion nonuniformity must not exceed a few percent.

The distance the ring is from the target has a profound effect on scattered light intensity and target implosion uniformity. Figure 7 shows how ring separation affects both scattered light and implosion uniformity. When the ring is moved very close to the target (Figure 7a), essentially no scattered light is detectable. However, when the ring is moved too far away, it allows laser rays to pass between the target and ring, resulting in high intensities of scattered light. Regarding implosion uniformity (Figure 7b), moving the ring too close causes it to interfere with target implosion, resulting in high nonuniformity. As the ring moves too far away, it no longer deflects laser rays into the equator of the target. This causes the target equator to be underdriven, and the implosion has a higher nonuniformity. Thus a tradeoff between scattered light and uniformity determines the range of distances the ring can be placed from the target. Figure 7 shows that for a 220 um radius target, the tradeoff range (shaded in yellow) is between 80 um and 530 um from the target. The ranges were determined for targets from 440 um to 1100 um in diameter, and compared to find a ring distance that reduced scattered light and maintained uniformity for all target sizes in the range.

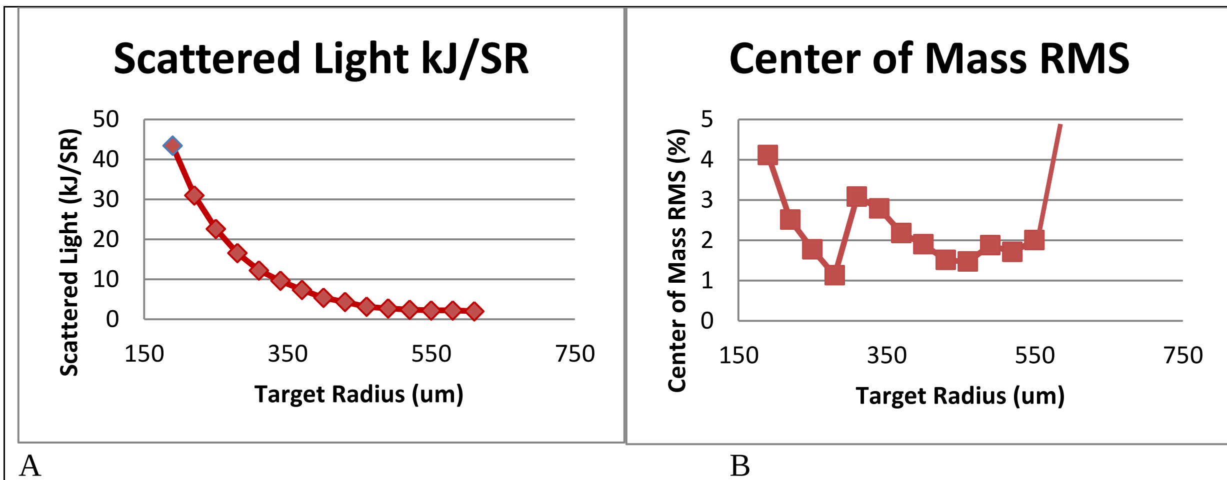

Figure 8. (a) A graph of scattered light vs. target radius for a triangular ring of inner radius 650 um. For targets 190-610 um in radius, the scattered light stays below the safety limit of 60 kJ/sr. (b) Graph of uniformity vs. target radius. The nonuniformity remains reasonable for targets 550 um radius and below, but jumps to extremely high values for larger targets.

It was determined that an equilateral triangular ring with a diameter of 500 um and placed 650 um from the center of the target effectively reduced scattered light to below 30 kJ/sr while maintaining a uniform implosion for all proton backlighter targets sized from 440 um to 1100 um in diameter. Figure 8 shows the scattered light and nonuniformity values obtained using this ring for target diameters 380 um to 1220 um at 60 um increments. At the smallest targets, the scattered light becomes too high for safety, and at the largest targets the nonuniformity becomes too high, for the same reasons that the ring can only lie in a certain range of distances from the target. Thus, there is another tradeoff between scattered light and nonuniformity that determines the range of targets for which the ring is effective.

4. Comparison between Triangular and Elliptical Saturn Rings

Comparisons were made between triangular and elliptical rings. The elliptical ring was set to have a 600 um diameter in the horizontal direction and 300 um diameter along the z axis, as in Garcia's design[7]. The inner edge of the ring was set to be 650 um from the center of the target, as for the triangular ring. Several simulations were run using targets in the range effective with the triangular ring.

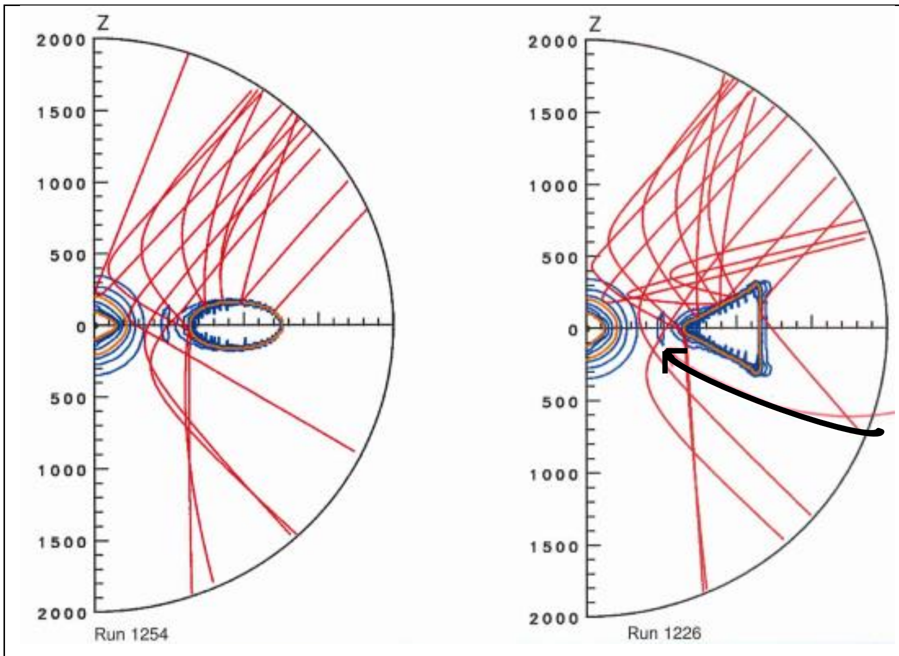

Figure 9. (a) A raytrace plot of a 650 um elliptical ring vs. (b) a raytrace plot of a 650 um triangular ring. For a 440 um diameter target, the elliptical and triangular rings deflect rays with similar effectiveness. The arrow indicates the "bow shock" formed by the collision of the target and ring plasmas.

Raytrace plots of both the elliptical ring and triangular ring were compared, as shown in Figure 9. The elliptical ring deflected rays less toward the equator of the target, resulting in a slightly underdriven equator. Otherwise, the 650 um elliptical ring had similar effectiveness to the triangular ring in minimizing scattered light while maintaining implosion uniformity. An interesting feature seen between the target and the ring in both cases (shown by the arrow in Figure 9) is a contour of higher density known as the "bow shock." The bow shock is formed by the collision of the expanding plasmas from the target and the ring. The plasmas collide, and produce a higher density area.

It was determined that the elliptical ring had a similar effectiveness to the triangular ring, as shown in Figure 10. The elliptical ring did not block as much scattered light as the triangular ring for target radii above 310 um radius, but this was irrelevant because the scattered light was still well below the 60 kJ/sr limit for all target sizes. This may have occurred because the laser beam pointings used were the optimal pointings for the triangular ring. In addition, the uniformity of implosion was similar to that for the triangular ring.

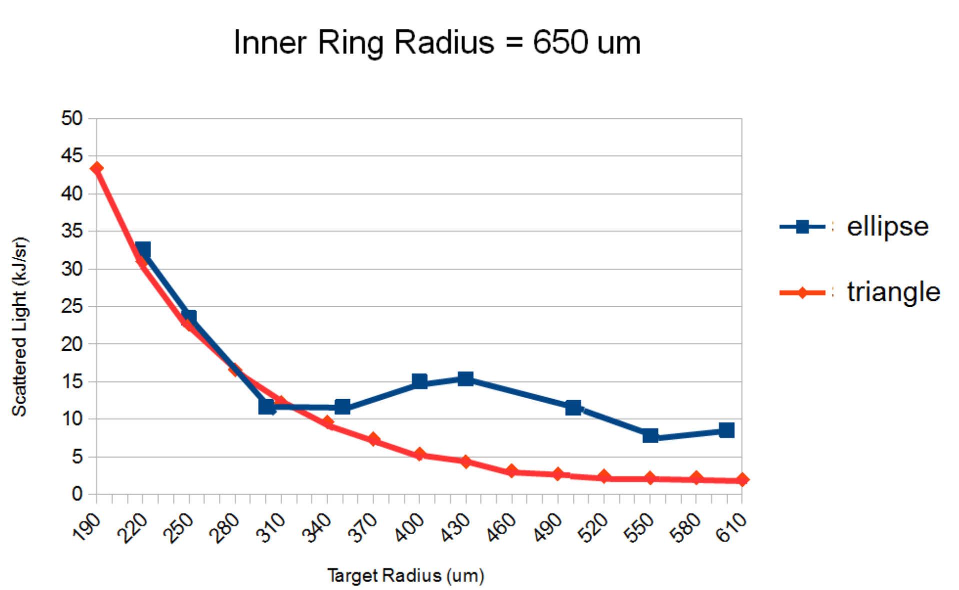

Figure 10. Graphs of scattered light vs. target radius for the elliptical and triangular rings. The red triangle data are the same as those plotted in Figure 8 (a). Both rings are equally effective at minimizing scattered light below 60 kJ/sr.

5. Conclusion

The purpose of this work was to develop a standardized ring that could be used with all sizes of proton backlighter targets while maintaining a uniform target implosion and minimizing scattered light below 60 kJ/sr. A triangular ring with an inner radius of 650 um was developed that effectively worked with all target diameters from 440 um to 1100 um. An elliptical ring was found to be equally effective in blocking scattered light and maintaining implosion uniformity for this range of target diameters.

6. Acknowledgements

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