Design, assembly, and testing of a high-resolution relay lens used for holography with operation at both doubled and tripled Nd:YAG laser wavelengths

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ABSTRACT

The design and assembly of a nine-element lens that achieves >2000 lp/mm resolution at a 355-nm wavelength (ultraviolet) has been completed. By adding a doublet to this lens system, operation at a 532-nm wavelength (green) with >1100 lp/mm resolution is achieved. This lens is used with high-power laser light to record holograms of fast-moving ejecta particles from a shocked metal surface located inside a test package. Part of the lens and the entire test package are under vacuum with a 1-cm air gap separation. Holograms have been recorded with both doubled and tripled Nd:YAG laser light. The UV operation is very sensitive to the package window's tilt. If this window is tilted by more than 0.1 degrees, the green operation performs with better resolution than that of the UV operation. The setup and alignment are performed with green light, but the dynamic recording can be done with either UV light or green light. A resolution plate can be temporarily placed inside the test package so that a television microscope located beyond the hologram position can archive images of resolution patterns that prove that the calibration wires, interference filter, holographic plate, and relay lenses are in their correct positions. Part of this lens is under vacuum, at the point where the laser illumination passes through a focus. Alignment and tolerancing of this high-resolution lens are presented. Resolution variation across the 12-mm field of view and throughout the 5-mm depth of field is discussed for both wavelengths.

Keywords: UV optical relay, holography, submicron optical resolution, ejecta, particle size distribution

1. INTRODUCTION

As a shock wave interacts at a metal-vacuum (or gas) interface, metal particulates are produced and are emitted at velocities faster than the metal free surface velocity. These particles are referred to as ejecta. Depending on the properties of the metal and the initial shock conditions, the ejecta particle size, velocity and mass distributions may vary.

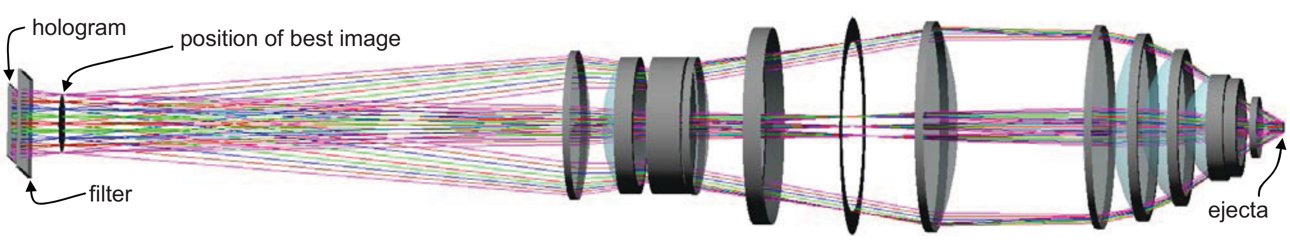

Fig.1. High-resolution lens used to record holograms with tripled Nd:YAG laser. Laser light travels from right to left.

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We measure the microjet production from several grooves that are machined into the surface of a metal. The particle size distributions in the microjets will depend on the initial groove angles that are machined into the target material. Figure 1 shows the design of a new high-resolution lens, which relays images of ejecta particles to be recorded by a hologram. One benefit of holography is that with a short-pulse laser, it can freeze the motion of a three-dimensional (3-D) image of high-speed ejecta.

To measure ejecta particle size distributions, an in-line Fraunhofer holography[1] technique was developed. This experimental technique was implemented on a variety of hydrodynamic experiments at the Pegasus facility located at the Los Alamos National Laboratory (LANL).[2, 3] This technique uses only one laser beam with the unscattered light serving as the reference beam. Greater than 90 percent transmission through the ejecta volume is required. Holography offers the unique capability to record distributions of ejecta particles over a 3-D volume. The earlier work used an optical relay lens with 1000 lp/mm resolution and a doubled Nd:YAG laser. This system allowed particles close to 2.0 microns in diameter to be measured. After the hologram is recorded, the particles are re-created in space by illuminating the hologram with laser light. The particles are then imaged using a CCD and effectively digitized. These images are analyzed as described in reference 4.

Holography records particle size distributions by using a high-power, short-pulse laser to freeze particle motion. A new high-resolution lens (>2000 lp/mm resolution, operating at f/0.89) has been designed to relay the holographic interference fringes out of an energetic environment and into a protected holographic film can.[5] Particle sizes within a 12-mm-diameter, 5-mm-thick volume are recorded onto the holographic film. To achieve resolution down to 0.5 µm in diameter, both UV laser light and a high-resolution optical relay system has been implemented. To set up this lens system, a doublet lens is temporarily attached that enables operation with 532-nm laser light. Part of this lens is under vacuum, at the point where the laser illumination passes through a focus. Figure 2 shows how the lens is mated to a

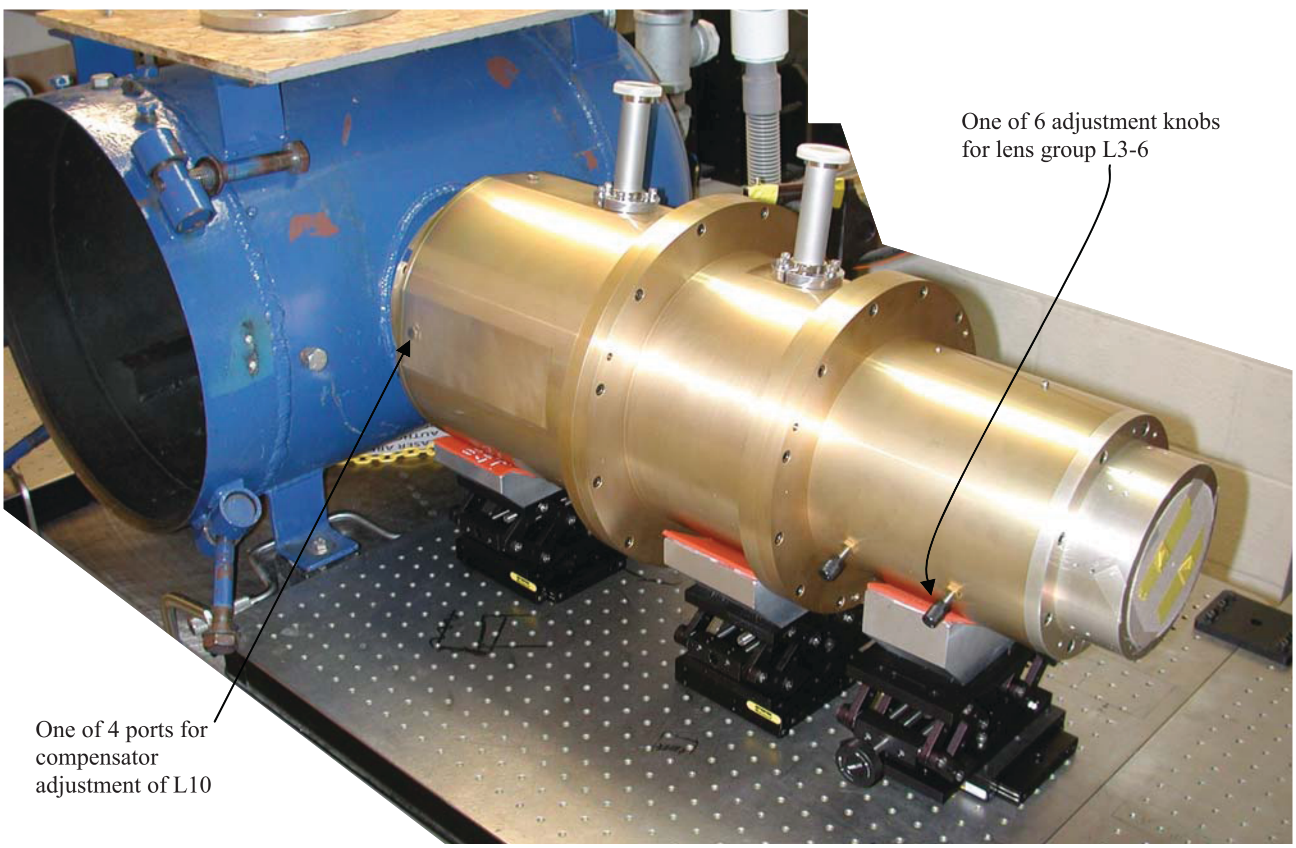


Fig. 2. UV lens housing mated up to containment vessel. Hologram holder is to the right of the lens (not shown). Laser light travels from left to right. The lens housing (shown in gold) is 31 inches long. The 2 pipes at the top of the lens are for the vacuum system.

containment vessel to conduct measurements on ejecta. The holographic film can and interference filter are to the right of the lens and are not shown. Part of the lens also extends inside the vessel. The lab jacks allow for tilting the lens. The lab jacks are mounted onto glide rails to easily detach the lens from the containment vessel. The entire lens system is slid away from the vessel and back towards the wall to check the optical axis which is established with two counter-propagating alignment lasers (one red and one green).

2. OPTICAL DESIGN

The in-line holographic technique dictates that the object and reference beams use the same path to the holographic plate. One constraint is that there is >95% transmission through the region to be recorded. There must be enough unscattered, undiffracted light for the reference beam to make good interference fringes with the ejecta particles. Immediately outside the ejecta region, these two beams form interference fringes. However, we cannot put the holographic plate in this destructive environment. Therefore, a high-resolution relay system transfers the interference fringes to a safe environment.

High-resolution holographic film (3-in square) is not very light-sensitive. The hologram exposure requires >20 mJ of energy from the 150-ps pulse duration laser sources, at 354.7 nm. The holographic emulsion is more sensitive in the UV than at green wavelengths (>50 mJ of energy is required for 532 nm exposure onto the hologram). The laser light is collimated when passing through the ejecta region. This collimated light will focus at the stop position located in the middle of the lens system. Unless this location is under vacuum, the air will break down and destroy the reference beam wave front. A $>10^{-4}$ Torr vacuum at this location will preserve reference beam quality.

Earlier attempts at collecting particle size distributions onto holograms used a different high-resolution lens with 1000 lp/mm resolution.[3] A 532-nm pulsed laser exposed the hologram with 50 mJ of energy in 80 ps. This high-resolution lens consisted of two lens groups, each with five elements that required precision alignment. A 15-mm-diameter by 6-mm-thick cylindrical volume of ejecta was recorded onto 62-mm-square holographic film. This lens had a magnification of 4X and collected light at f/1.21. Requirements for future dynamic shock experiments called for 2000 lp/mm resolution to measure down to a 0.5-µm particle size. This resolution required use of a tripled Nd:YAG laser and a much lower f/#.

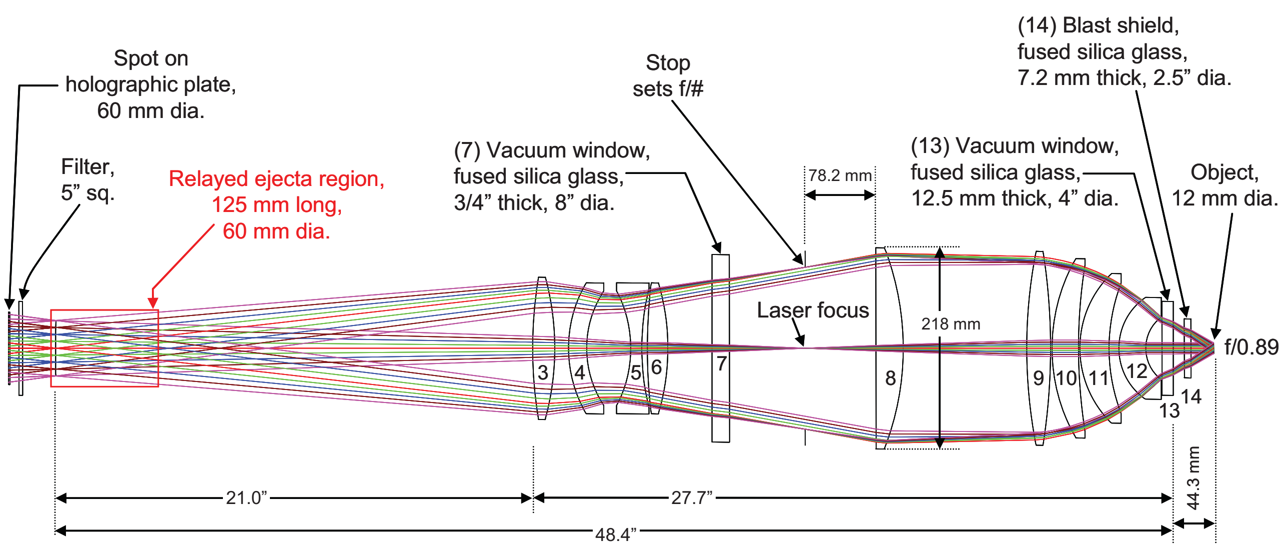


Fig. 3. The holographic lens for recording with 354.7-nm laser light uses nine lenses, providing 5X magnification. Laser light travels from right to left.

The final lens configuration was achieved with the aid of the CodeV[6] lens design program. The CodeV global optimization feature was used extensively to develop the lens system design. We started with a seven-element lens and gradually increased the number of lenses and their diameters until the required resolution was achieved. When selecting the best lens form factor after each global optimization run, we were diligent in achieving minimum ray bending at each lens surface. Minimum ray bending between these surfaces relaxes the tolerance requirements.

The final UV lens system, shown in Figure 3, uses nine elements. Only after allowing both the image and the object planes to be curved were we able to get to the desired resolution. It is more important to achieve high resolution than it is to know the exact position of the ejecta particle. So, the object and image planes were allowed to be curved. This is unusual because most imaging applications require flat image planes.

This optical design is a one-sided telecentric system, leaving the holographic plate side non-telecentric. The traditional approach to correcting 1st order longitudinal chromatic aberration is to use crown glass for the positive elements and flint glass for negative ones. However, for this design, using a higher index flint glass for one of the positive lenses reduced the largest lens's diameter.

The ejecta particle volume measures 12 mm in diameter by 5 mm thick. Because of the lens magnification, the image of these particles (relayed ejecta region) measures 60 mm in diameter by 125 mm thick. The laser focus is protected inside a vacuum chamber. Because the sticky holographic emulsion can attract dirt particles, the relayed ejecta data region must be positioned well away from any contaminants. An interference filter is also placed outside the relayed ejecta region. This filter blocks white light from the detonator that accelerates the target material. Even though the filter has two polished surfaces, pits in its polished surface show up as micron sized particles. To prevent contamination of ejecta data, the filter must be located outside the ejecta data region.

It is difficult to work with UV light during lens system setup. To address the fact that UV light poses an eye hazard, a doublet lens was designed to be mounted to the UV lens system. This configuration allows alignment work to be performed at 532 nm (green); see Figure 4. The doublet is pinned to the larger lens housing to allow for repeatable alignment. One constraint is that the position of the hologram is fixed with or without this doublet lens. The result causes a shift in the object plane where the ejecta volume is located. We compensate by shifting the calibration resolution target. We will only measure 1100 lp/mm resolution with this green laser mode, but experiment set up and documentation are easily facilitated.

All lens and window surfaces have a double V-coating at both 354 and 532 nm, except for two lenses (elements 1 and 2) that only require a V-coating at 532 nm on their surfaces. All coatings are <0.1% reflective at the 0-degree angle of incidence. The laser damage threshold for these coatings is 0.2 J/sq. cm with a 5-ns laser pulse at 354 nm. All coatings are for random polarizations.

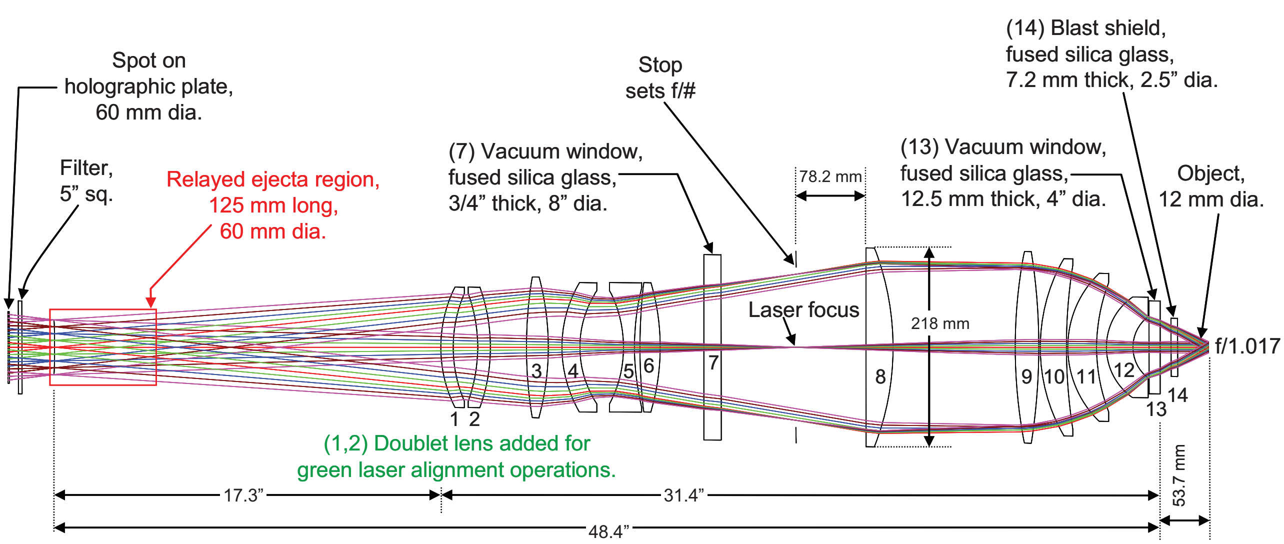


Fig. 4. The holographic lens for recording with 532-nm laser light uses eleven lenses, providing 5X magnification.

The resolution performance of the dual modes is shown in Figure 5. The UV mode is very nearly diffraction limited over the full field of view. The holographic film has better than 3000 lp/mm resolution. With the 5X magnification, the film needs to record at only 400 lp/mm resolution.

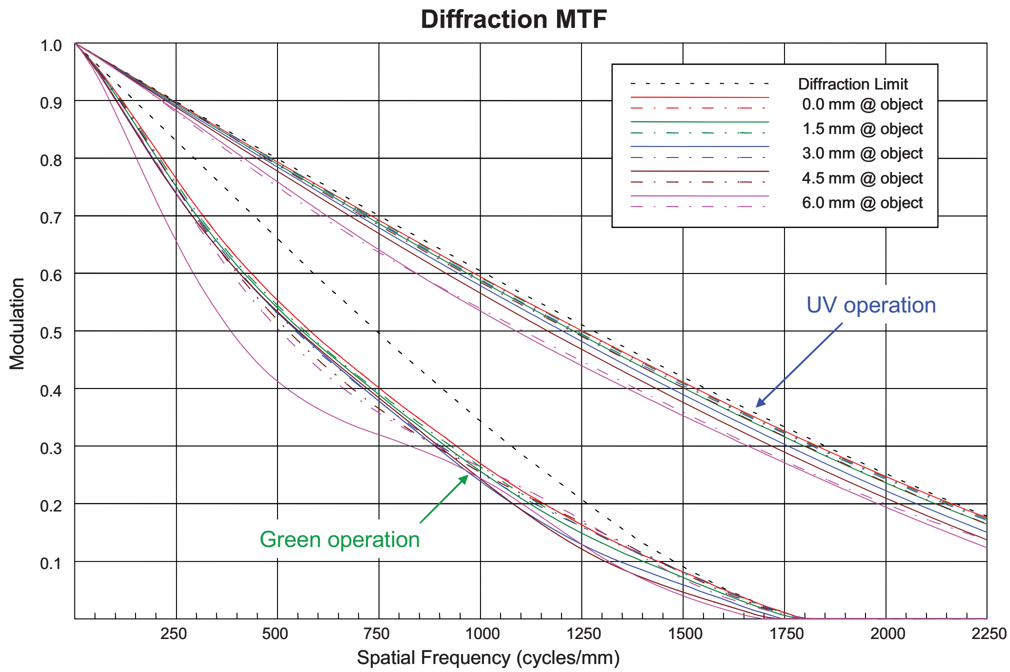


Fig. 5. Resolution performance with and without the doublet lens. This resolution is measured at the object plane where the ejecta are created.

Because chromatic aberrations do not exist for the single-wavelength lasers used, only a few glass types are needed. The glasses used for the UV system were SBSL7 and PBM18Y from Ohara. These glasses were selected because of their transmission properties and cost. The UV lens was optimized by systematically testing only these two glasses at each lens position. The glasses used for the green doublet were NBK7 and SF11 from Schott. The air spacings for the lens housing were recomputed after melt data, radius of curvature data, and lens element thickness were measured following the lens element fabrications.

3. OPTICAL SETUP

Earlier holographic work required taking multiple holographic exposures to align two lens relay groups and correctly position the ejecta region (including calibration wires and pegs) relative to the holographic film. This earlier procedure was very time consuming and increased the cost of fielding holographic experiments. Now, a 6.6-megapixel CCD camera views data presented to the holographic plate. In Figure 6, a TV camera’s zoom lens is looking through the hologram plate and is focused on the image of a calibration wire located inside the test package. The image and its micrometer position are archived on this computer. This camera has a 16X optical zoom lens with a 190-mm standoff distance. This CCD camera system is mounted on tip/tilt and translation stages. The translation stage allows focus shifts of 200 mm along the optical axis. We focus on the emulsion of the holographic plate and measure its position. We then shift the focus and measure the positions of calibration wires that are positioned within the test package. This arrangement allows us to document the performance of the optical setup prior to the dynamic experiment.

The light source for the CCD camera system is a low-power continuous wave (CW) doubled Nd:YAG laser. It is difficult to view the small features of the resolution target with this laser light because of laser speckle. Therefore, we place a spinning diffuser in front of the optical system, about 1 meter before laser light enters into the containment vessel. The diffuser has about a 5-degree spread and completely averages out the laser speckle during the integration

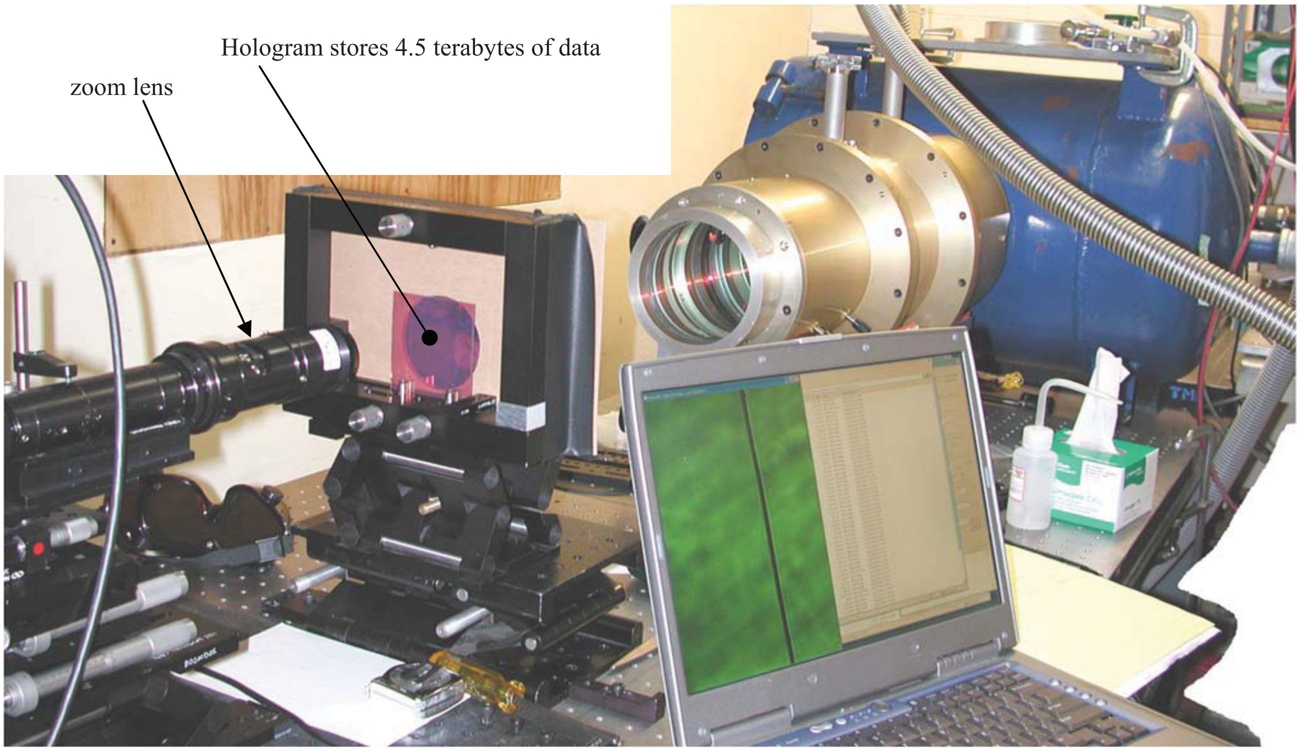


Fig. 6. Laptop computer archives resolution measurements from CCD alignment camera. The CCD camera is to the left of the zoom lens and is not shown.

time of the CCD camera. It allows us to find the best focus of the resolution target and the calibration wires. The spin rate is not critical.

With the lens system in place, there is considerable focus shift when viewing with 532-nm or 354.7-nm laser light. The position of the holographic film is fixed relative to the lens housing and the position of the resolution pattern placed in the ejecta region will shift by 9.4 mm depending on the wavelength used, as shown in Figure 7. The thickness of the ejecta region is 5 mm. Therefore, a resolution target can be placed outside the delicate calibration wires and alignment pegs that define the ejecta region. We can document the image quality and alignment with the 532-nm laser and have confidence that the UV laser operation will function properly. The resolution target is removed before the dynamic event.

Counter-propagating CW alignment lasers (green and red) are used to set up the optical system. The red laser is centered on the green laser's output mirror and vice versa. We view both retro-reflections and steering of these two laser beams. Apertures are also mounted to the front and back lens-housing flanges to establish the optical axis. Floating apertures are used several feet before and after the lens system to precisely detect alignment errors demonstrated by the laser spot groupings. Each aperture will show a grouping of spots in two colors, the result of either steering or retroflection errors. Great care is taken to keep the green and red lasers collinear to each other.

Even though this high-resolution lens has near zero depth of field, the CCD camera system can view the full 5 mm depth of field to search for calibration wires and a resolution plate. This is because the alignment laser even after passing through the spinning diffuser propagates laser light a very high f/#. In this backlit shadowgraph mode, accurate simulation of the hologram's depth of field is be archived.

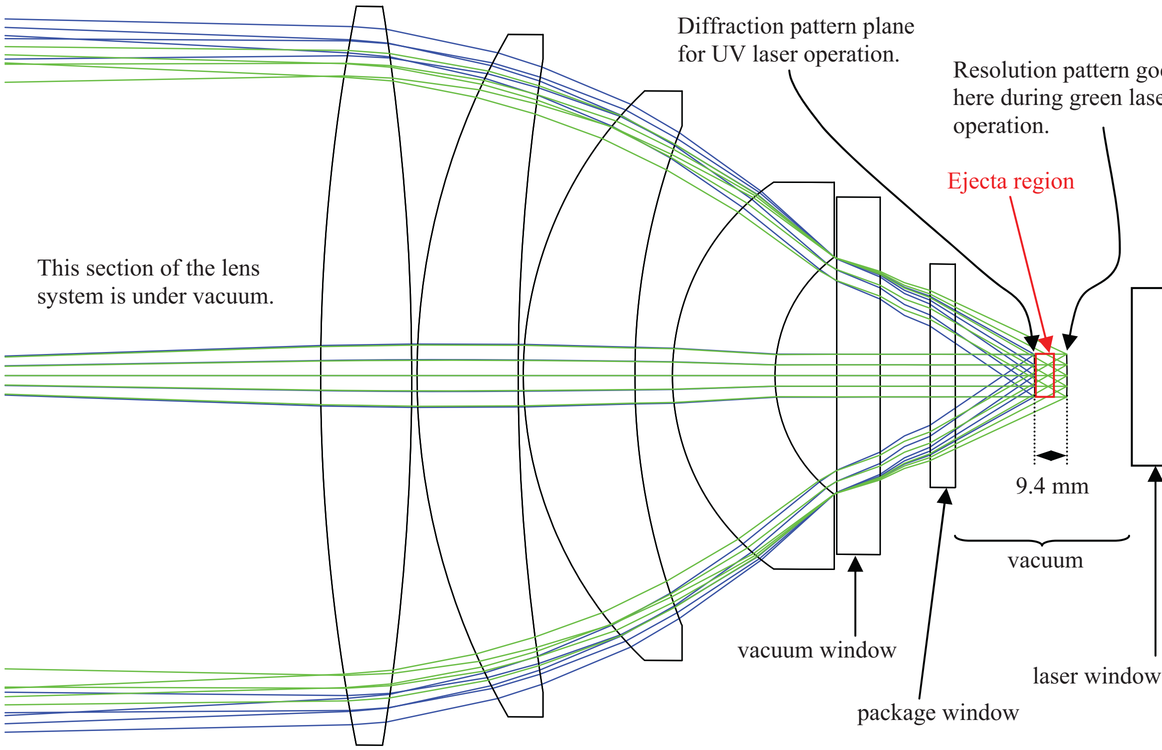


Fig. 7. The diffraction pattern plane contains the interference patterns produced inside the ejecta region using the 354.7-nm laser light. This plane is relayed with the optical system to a position 35 mm from the holographic emulsion. When operating with 532-nm laser light, a resolution target can be placed outside the ejecta region and simulate what the diffraction pattern plane would present to the hologram emulsion.

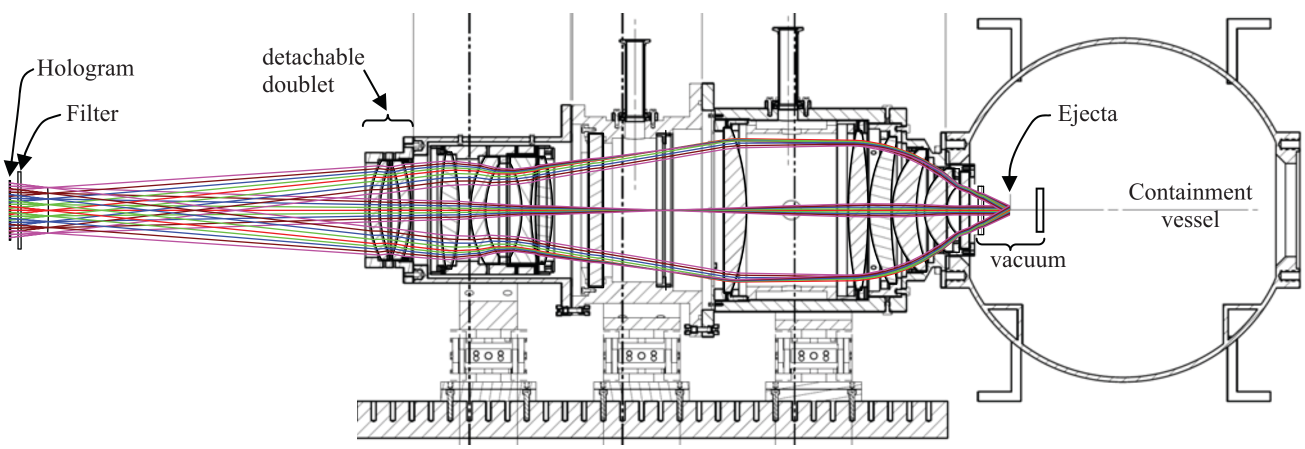


Fig. 8. The lens housing is mated up to the containment vessel. Laser light travels from right to left. The ejecta transits through an evacuated test package (not shown). The containment vessel is at ambient pressure.

4. OPTOMECHANICAL DESIGN

The housing shows two pump-out vacuum ports for faster pump out, but they are tied to only one vacuum pump. Only the stop aperture was black anodized with a vacuum-compatible inorganic black dye. To prevent corrosion to the aluminum, a chromate conversion coating was applied to all other metal surfaces. Nonfunctional threads are used on two of the air spacers to reduce unwanted light scatter. However, because the threads do not catch the light as well as expected, other techniques should be considered.

An extra-thick (0.5-inch) vacuum window is mounted to the front of the lens housing to protect the lens elements from possible damage by flying shrapnel during the dynamic event. The vacuum window is replaced after every event.

The lens housing, shown in Figure 8, is mated to the containment vessel with a thick flat gasket. The containment vessel is not under vacuum; only the dynamic test package (not shown), where the ejecta are produced, and the lens housing are under vacuum. Shock generated during a dynamic event is a concern, as it may affect the lens system. The lens support consists of three lab jacks mounted to dovetail rails. The lab jacks tilt the lens relative to the containment vessel. During a dynamic event, the rails allow the lens housing to move with the shock wave.

For shock mitigation, the retaining rings have rounded edges where they encounter a glass surface. An analysis of stresses on the metal-to-glass interface was done for up to 20 G shock loading. We found that a 20-G quasi-static load results in less than 1000 psi of stress on the glass near the rounded metal edges.

To enhance the center-to-center alignment of this lens system, most of the lenses are mounted into subcells as shown in Figure 9. Care must be taken to not over tighten the centering screws on the lens cells before the glue operation. Over tightening these screws will make the lens cell out of round. The five different sections have match drilled holes and used tapered pins for precision mating.

The total weight of the 14 elements used for the 532-nm alignment mode is 36 lbs. The total weight of the metal housing is 80 lbs.

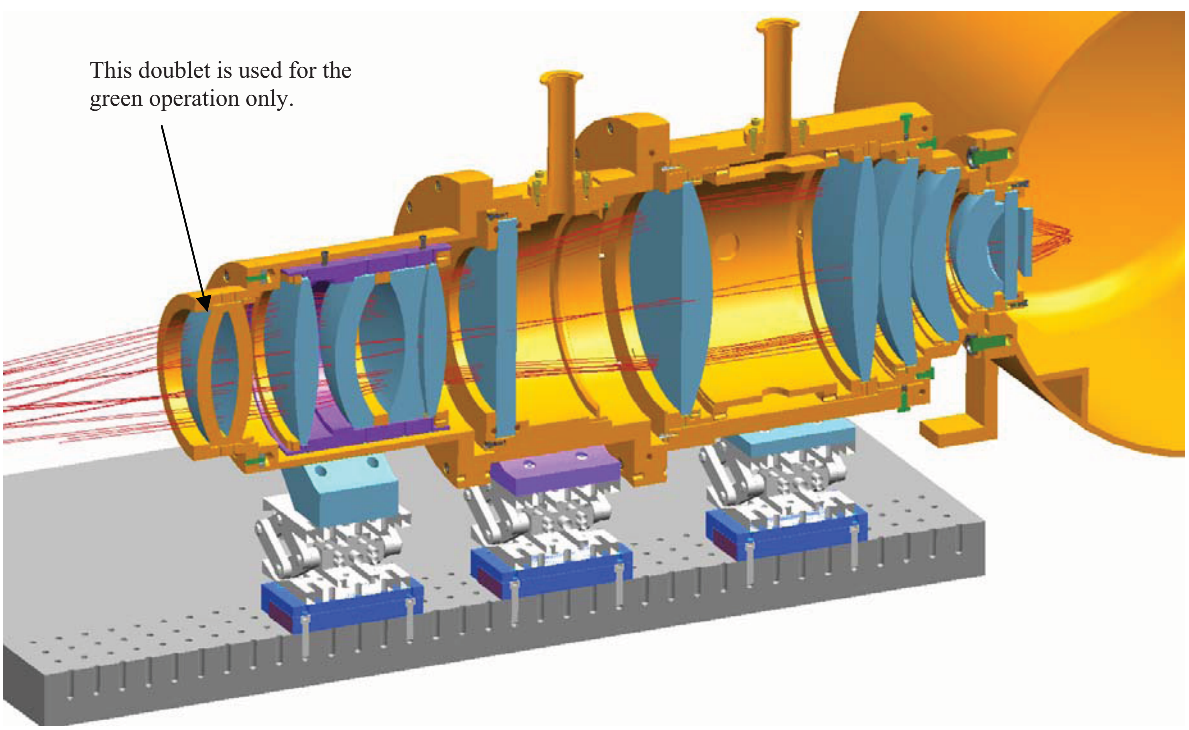


Fig. 9. Model of the lens housing. Laser light travels from right to left. The red rays represent the scattered light from ejecta particles.

5. TOLERANCING OF THE LENS SYSTEM

Initially the lens tolerances were very tight until we found the best set of compensators. After starting with all lenses inside the vacuum, we moved the lens subcell that contains elements 3, 4, 5, and 6 outside the vacuum where we could easily decenter and tilt them. We then found the lens element that was the most sensitive to decenter and made this a compensator. This lens (element 10) is inside the vacuum. Allowing this lens to decenter in X and Y relaxed the tolerancing of the first group of four lens elements by almost a factor of 10X. So, after a one-time, single decentering is completed on this lens, its access holes is sealed off with a pressure port O-ring screw. All other lenses were mounted with machine tolerances. Figure 10 shows the location and values for the final compensators. We used the root sum of the squares (RSS) method to add up the most probable mechanical tolerance buildup. In most cases the RSS error buildup was <75% of the error budget that was determined from a CodeV Monte Carlo error analysis for decentrations. Even though this lens system provides 2000 lp/mm resolution, whereas the earlier design provided 1000 lp/mm, the housing tolerances were a factor of 5 looser.

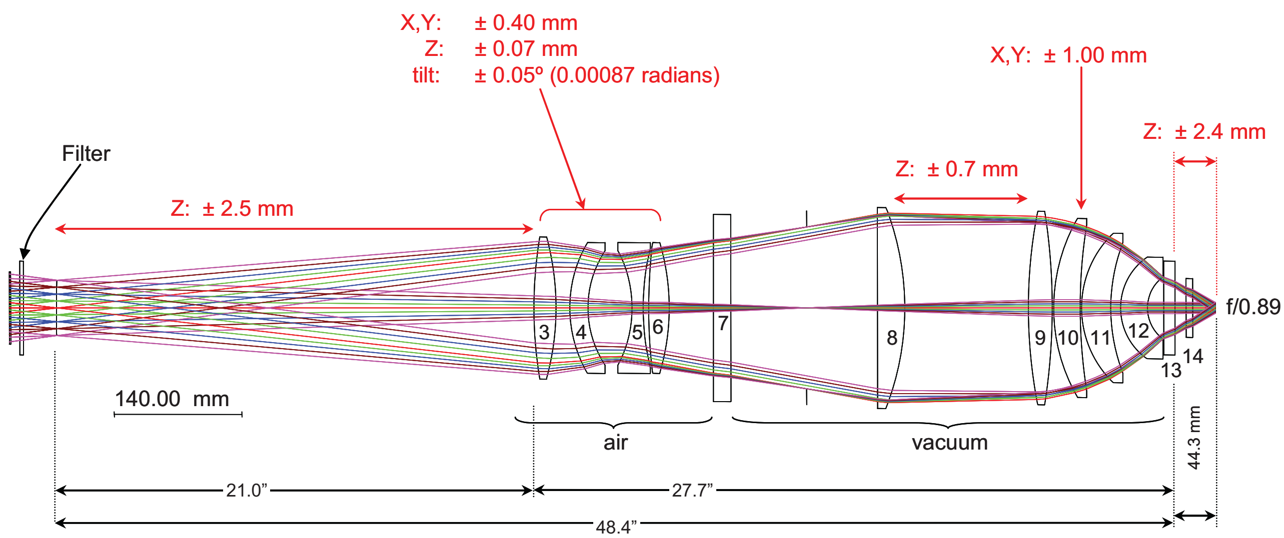
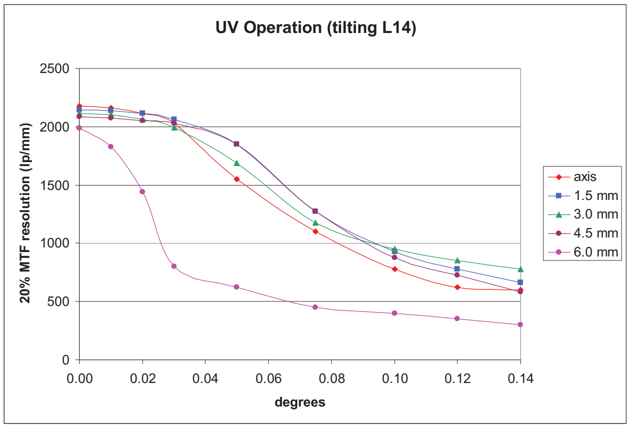


Fig. 10. Probable change of compensators (Monte Carlo analysis). Laser light travels from right to left. These compensator values were built into the metal housing adjustments. The tilt tolerance of L14, which is a vacuum window of the test package, is ± 0.01 degrees for UV operation.

Initial setup and alignment of the test package to the lens was done with the green laser. Images of resolution patterns placed at the ejecta plane were archived with the TV recording system. The contrast of the dot patterns was found to be insensitive to the care taken in aligning the test package to the lens. However, the contrast of the dots reconstructed from an exposed hologram using the UV laser showed that we were not achieving the required resolution. After careful analysis, using the lens design software we found that tilting of the test package window to be much more sensitive for the UV wavelength than for the green wavelength. Figure 11 shows just how much more sensitive the alignment with UV light can be. If the test package window is tilted by more than 0.10 degrees, then higher resolution holograms will be taken with the green laser. The position of this package window relative to the lens elements is shown in Figure 7. Careful, patient attention with the retro reflections from the two counter propagating laser beams was used to verify that this package window had no tilt.



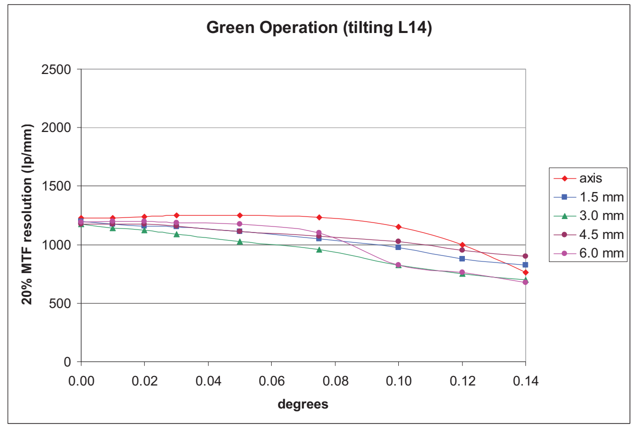


Fig. 11. Resolution of this lens varies with the tilt of the test package window. If the window tilt is more than 0.10 degrees, then better resolution is obtained with the green laser.

6. DYNAMIC TESTING OF THE LENS

Using two grams of high explosives during the first dynamic test caused the L12 lens to crack. This was the amount of energy needed to accelerate the ejecta to desired velocities. The damage to lens element 12 is shown is Figure 12. What looks like a double crack is actually only one crack with a ghost image of the crack photographed under these lighting conditions. We used as much hard rubber as possible to cushion the shock. The crack was initiated in the sharp edge cutout of the lens shown in Figure 13.

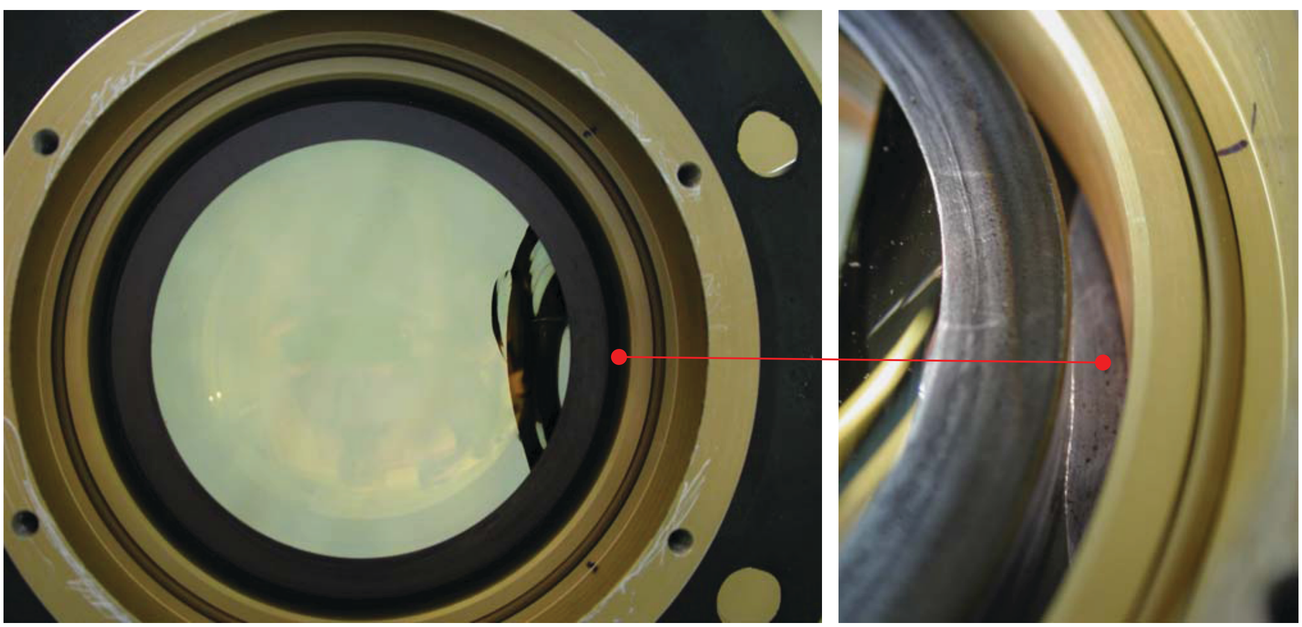


Fig. 12. Damage to the L12 lens caused by the dynamic experiment is shown in the left photo. A close up of the damage is shown in a tilted photo on the right.

The reason for the unusual edge for lens element 12 was due to the porthole of the containment vessel, which constrained the diameter of this first collecting lens. In order to get this lens mounted as far inside the containment vessel, a double shelf was used. As shown in the drawing of Figure 13, there was a sharp 90-degree cutout made to this lens and this is where the crack was initiated.

7. LENS REDESIGN

Replacement lenses for L12 will put a 2 mm curvature on the stepped edge where the crack was initiated. Additionally, all edge surfaces will be polished instead of rough ground. A thin Teflon spacer will be placed on the reference surface to help mitigate shock pressures.

We attempted to redesign the 12.5-mm-thick fused silica vacuum window by replacing it with a suitable sapphire window. A sapphire window has more shock strength and it would better protect the lens elements. However, the as-built lens system was designed to compensate the astigmatism produced by the fused silica window. The already designed system would not compensate the astigmatism of the sapphire window even after allowing all lens air spacings to vary. The use of sapphire would never allow us to achieve the required 2000 lp/mm resolution.

The 12.5 mm fused silica vacuum window (L13) is currently being replaced with two fused silica windows, each half as thick. A Teflon shim will be used to keep the windows from touching each other. The edges outside the clear aperture will also be cushioned so that no metal encounters any window surfaces.

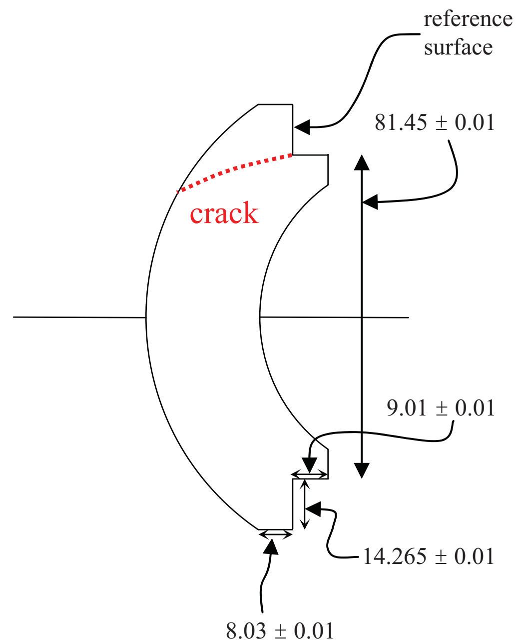


Fig. 13. Edge around the L12 lens had a double level allowing closer insertion of the lens system into the containment vessel.

8. CONCLUSION

An optical relay system that can resolve 2000 lp/mm resolution has been designed for holography using a tripled Nd:YAG laser. To achieve this resolution requires both a low f/# lens and the use of UV light. To get this resolution, the image plane is allowed to be curved. For particle size distributions, the actual position of the ejecta particles is not critical. However, we will apply image curvature corrections to the positions of the measured ejecta particles. By adding a doublet lens to the system, holograms can be recorded with 1100 lp/mm resolution using a doubled Nd:YAG laser. However, the use of a green laser is used mainly for setup alignment and documentation of resolution.

Use of a CCD camera alignment system reduces the number of holograms that have to be taken before a dynamic event. We are able to document the optical system performance with digitized resolution patterns. Use of the CCD camera allows us to set up the optics more efficiently, which reduces fielding costs. Being able to set up with green laser light simplifies laser safety issues.

The amount of data recorded by the hologram is enormous: recording 2000 lp/mm over a cylinder that measures 12 mm in diameter by 5 mm thick collects 4.5 terabytes of resolvable data. An existing automated reconstruction system can process and store this data.[4]

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REFERENCES

[1] Vikram, C. S., *Particle Field Holography*, Cambridge Studies in Modern Optics (1992).

[2] Sorenson, D. S., Malone, R. M., Frogget, B. C., Ciarcia, C. A., Tunnell, T. W., Flurer, R. L., "Particle distribution measurements using in-line Fraunhofer holography," Proc. SPIE **2869**, 206–213 (1997).

[3] Sorenson, D. S., Minich, R. W., Romero, J. L., Tunnell, T. W., Malone, R. M., "Ejecta particle size distributions for shock loaded Sn and Al metals," Journal of Applied Physics, **92**, 5830–5836 (2002).

[4] Tunnell, T. W., Malone, R. M., Fredrickson, R. H., Delanoy, A. D., Johnson, D. E., Ciarcia, C. A., Sorenson, D. S., "Deriving particle distributions from in-line Fraunhofer holographic data," Proc. SPIE **3163**, 558–569 (1997).

[5] Malone, R. M., Capelle, G. A., Cox, B. C., Frogget, B. C., Grover, M., Kaufman, M. I., Pazuchanics, P., Sorenson, D. S., Stevens, G. D., Tibbitts, A., Turley, W. D., "High-resolution UV relay lens for particle size distribution measurements using holography," SPIE Optics & Photonics Conference, Proc. SPIE **7060**, 70600A (2008).

[6] CodeV is licensed software from Optical Research Associates, Pasadena, CA.