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Debris Mitigation in Pinhole-Apertured Point-Projection Backlit Imaging

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Pinhole-apertured point-projection x-ray radiography is an important diagnostic technique for obtaining high resolution, high contrast, and large field-of-view images used to diagnose the hydrodynamic evolution of high energy density experiments. In this technique, a pinhole aperture is placed between a laser irradiated foil (x-ray source) and an imaging detector. In the present geometry, the x-rays that are not transmitted through the pinhole aperture, ablate the pinhole substrate's surface, and turn it into a flyer plate. The pinhole substrate then breaks apart into shrapnel, and that shrapnel can damage diagnostics inside the target chamber. In this letter, we present a technique on mitigating the debris by using a tilted pinhole.

I. Introduction

Pinhole-apertured point-projection x-ray radiography[1] is an important tool for diagnosing the hydrodynamic evolution of high energy density experiments[2-4]. The technique uses an x-ray source that is produced by illuminating a thin backlighter foil with high intensity laser beams. The x-ray source is then imaged onto a detector using a pinhole aperture. A sample to be radiographed is placed between the pinhole and the detector. This radiographic technique is advantageous to other techniques, such as area backlighters, in that it can produce a high resolution, high contrast, and large field-of-view image at a correspondingly lower laser intensity.[5]

Due to the close proximity of the pinhole substrate to the backlit x-ray source (<1mm), the x-ray intensity on the surface of the pinhole substrate (> GW/cm^2) is sufficient to drive ablation. This ablation results in two deleterious effects: pinhole closure[6] and shrapnel generation. In the first case of pinhole closure, the optically thick pinhole substrate material ablates, fills the pinhole aperture, and thus cuts off the pinhole transmission. This effect puts a limit on the temporal length of the pinhole imager, nominally 3 ns for an uncoated 10 μm pinhole. The second effect of ablation is when the x-ray intensity is sufficient to cause ablation over the whole surface of the pinhole substrate facing the x-ray source. The ablated material flows off of the pinhole, and due to conservation of momentum, accelerates the pinhole in the direction normal to the ablation surface.[7] Since the pinhole is not thin enough to vaporize $\left(t_{PH} < \dot{m}\tau_L\rho^{-1}\right)$, nor thick enough to remain intact, it fragments into several smaller pieces. Here t_{PH}, $\dot{m}$, τ_L, and ρ are the pinhole substrate thickness, mass ablation rate,[7] laser pulse length, and pinhole substrate density respectively. The shrapnel propagates ballistically and due to the vacuum inside the target chamber, it will not stop until it strikes the target, the detector, or the chamber wall. Figure 1 shows the backside of a 50 μm titanium filter located 360 mm from a 50 μm thick, backlit tantalum pinhole. The black dots on the foil are holes where the kinetic energy of individual shrapnel fragments (>200 mJ and >200 m/s) exceeded the penetration threshold of the filter foil (3 mJ for a 10 mg tantalum projectile)[8]. Furthermore, in the upper left corner of the foil, a fragment was energetic enough to tear through the foil and damage the detector.

Future experiments at the National Ignition Facility[9] and elsewhere will need to utilize pinhole-apertured point-projection backlighting due to their resolution and field of view requirements and their laser energy constraints.[5] The current method of protecting the diagnostic from shrapnel is to insert shielding, such as thick beryllium or titanium foils, in front of the diagnostic. Although this method will protect the diagnostic (with a sufficiently thick shield), it deleteriously affects the detector image quality in two ways. First, the shielding reduces the signal strength by a factor of $\exp\left(-n\mu_a d\right)$ where n, m_a, and d are the material atom density, photoabsorption cross-section, and shield thickness respectively. For example, one sixth of a 9 KeV zinc He_α x-ray signal will be lost when it passes through a 50 mil beryllium shield. The second deleterious affect of shielding is scattering of the x-rays as they propagate through the material.[10] This effect will increase the noise level of the image. The effects of increased shielding that lead to degradation of signal strength and increase of noise level, and thus lower signal-to-noise ratio, could be unacceptable for future experiments. To counteract these issues, we have developed a new tilted pinhole design that will direct the debris away from the diagnostic so that high signal-to-noise images can be acquired.

II. Experimental Setup

The experiment was performed at the OMEGA Laser Facility.[11] Five 500 J, 1 ns, 351 nm laser beams were used to illuminate a 5 μm thick zinc backlighter foil. The laser spot size of 500 μm corresponded to an intensity of $1\text{x}10^{15}$ W/cm2. Two different pinhole geometries were tested. In the first, the pinhole was oriented so that it's surface normal pointed towards the diagnostic location. This setup, detailed in Fig. 2a, consisted of a 5 μm zinc backlighter foil placed 1.5 mm away from a 4 mm x 4mm x 50 μm tantalum pinhole. The second setup utilized the tilted pinhole design. It consisted of a 5 μm zinc backlighter foil placed 400 μm away from a 5 mm x 4mm x 50 μm tantalum pinhole. The pinhole was rotated 37 degrees off parallel so that the surface normal of the pinhole pointed away from the diagnostic location. The rectangular shape of the pinhole was used so that when it was tilted 37 degrees it would appear to be a 4 mm x 4 mm square as viewed from the diagnostic. This setup is detailed in Fig. 2b. The pinhole apertures were made by laser cutting a 10 μm hole into the tantalum substrate. The tilted pinhole apertures were drilled at a 37 degree angle so that the axis of the aperture was oriented towards the diagnostic. Both pinholes were coated in 4 μm of parylene to reduce fluorescence from the pinhole substrate.

Two target chamber setups were used in our experiment. The first setup was designed to measure the debris generated by the different pinhole geometries. It consisted of two debris catchers[12]: one at the detector location, and the other positioned 37 degrees away such that the normal of the tilted pinhole would point towards it. The analysis of the debris measured by the catchers is ongoing; however, visible inspection gave us a "yes or no" answer as to whether debris was directed in the direction of the catcher. The second target chamber setup involved removing the debris catchers and inserting a gated imaging detector. For both setups, the main debris diagnostic used for this analysis was the Kowaluk camera.[13] This camera captured a visible image of the shrapnel and plasma ejected by the pinhole. This allowed us to determine the direction in which the shrapnel was ejected as well as the interaction of the shrapnel with the target chamber diagnostics.

III. Experimental Results

Figure 3 shows the Kowaluk visible camera images from the debris test shots. In these images, the target (not visible) is located at the central white spot of the image. The detector location is at 4 o'clock and the normal to the tilted pinhole points towards 2 o'clock. The plasma and shrapnel flow appear in these images as a solid or diffuse white trace originating from the center of the image. Figure 3a shows the first pinhole configuration in which the pinhole is parallel to the detector location. In the detector location is a round aerogel debris catcher. The image shows a white streak of shrapnel being directed into the detector. This was confirmed by visible inspection of the aerogel that showed significant debris impacts. The square glass debris catcher located 37 degrees away at 2 o'clock, did not show any debris impact.

Figure 3b shows the debris ejection results with a tilted pinhole. The square glass debris catcher is now in the detector location and the round aerogel debris catcher is located normal to the tilted pinhole. The image shows a white streak being directed away from the detector location. This was confirmed by inspection of the debris catchers that showed significant debris impact damage to the aerogel at the 2 o'clock position, while the glass slide at the detector location did not show any debris impact damage. Therefore, by tilting the pinhole, we were able to direct the debris away from detector.

Our measurements showed that the debris was directed in the direction normal to the pinhole and was contained inside a 10 degree full cone angle. This angle meant that the detector would have greater than a 20 degree clearance from ejected debris and would be safe from debris damage. Therefore, the next step was to demonstrate the ability to acquire an image using the titled pinhole. To do this, we switched to the second target chamber configuration in which the debris catchers were removed and a gated imaging detector was inserted. Figure 4 shows the results where a 400-mesh gold grid (21.5 μm thick grid wires separated by 63.5 μm) placed 10 mm away from the pinhole, was imaged with a magnification of 22.7. Figure 4a is a visible camera image that shows the inserted detector at 4 o'clock. This reconfirmed that by using the tilted pinhole, the debris was directed away from the detector in the 2 o'clock direction. Figure 4b shows a sample of the image captured on the detector. The dark horizontal and vertical lines are the grid wire shadows while the lighter squares are the regions where the x-rays passed through the grid. Figure 4c shows a horizontal lineout from the grid image. The signal strength of 0.1 ergs/cm^2 corresponded to a signal-to-background ratio of 14 (the background was ~0.007 erg/cm^2). The measured contrast of 6 between the apertures of the 21.5 μm grid wires was limited by the 10 μm spatial resolution of the pinhole.

IV. Summary

Damage to diagnostics from debris is expensive in terms of both detector replacement and loss of data. The ejection of debris from pinholes used in pinhole-apertured point-projection backlighters has been qualitatively measured using visible camera images of the debris tracks inside the target chamber. The directionality of the debris ejection was measured to be contained inside a 10 degree full-angle cone centered on the normal to the pinhole. Therefore, tilting the pinhole mitigated damage to the diagnostic by diverting the debris away from the diagnostic. Furthermore, a pinhole spatially resolution limited image was acquired using the titled pinhole technique.

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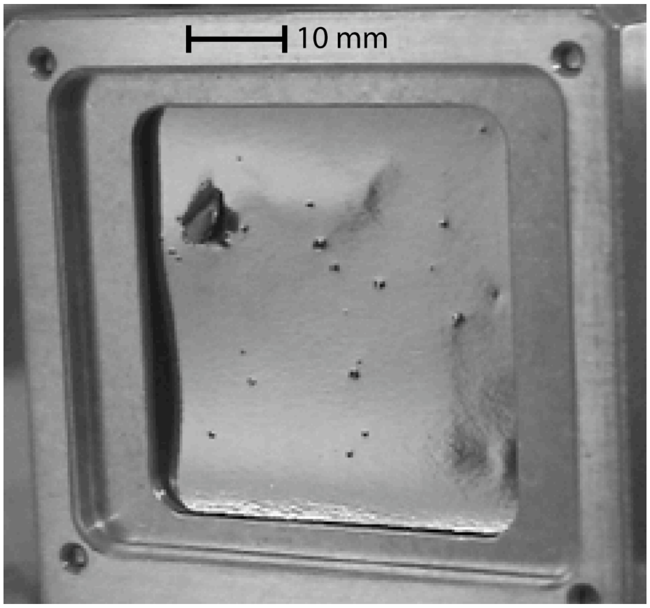

Figure 1. Shrapnel damage as seen in a filter foil from a point-projection backlighter in which the normal to the pinhole faced the gated imaging detector. The 50 μm thick Titanium foil shows puncture marks (dark spots) where shrapnel from the pinhole was launched towards the diagnostic. The large hole in the upper left corner is from a large fragment that penetrated the foil and seriously damaged the diagnostic.

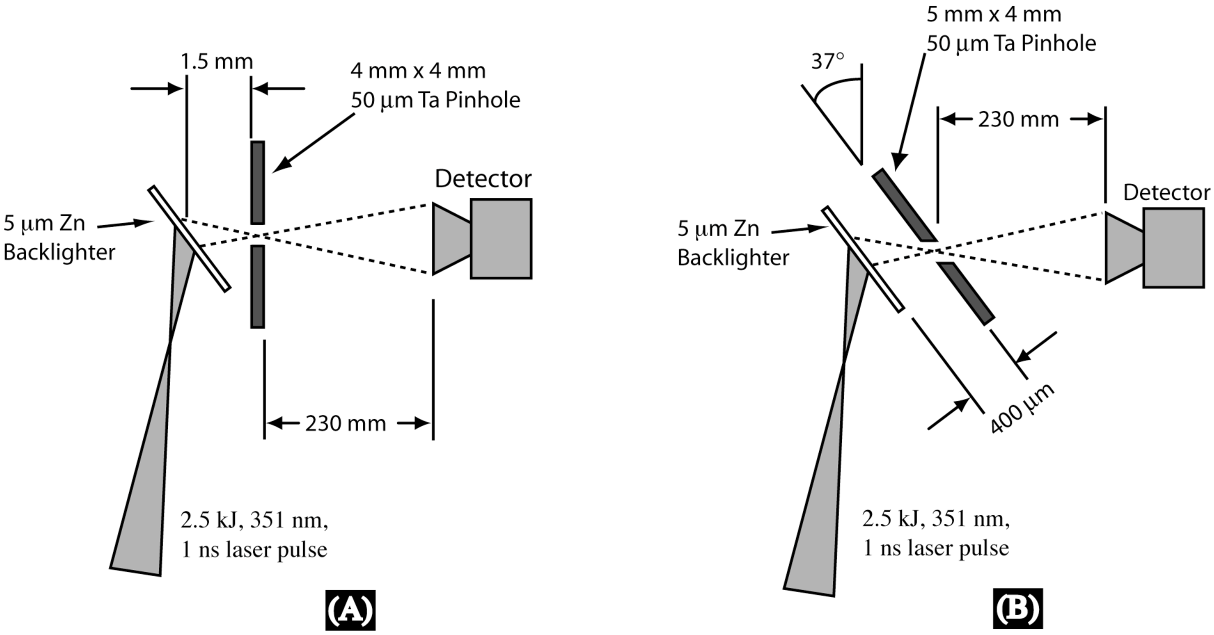

Figure 2. Schematics of backlighter designs used in the experiment. The traditional design is shown in part (a) in which the normal to the pinhole substrate is pointed towards the diagnostic. The laser pulse illuminates a thin backlighter foil to generate an x-ray source that radiates in all directions. A pinhole collimator is used to image those x-rays onto a detector (dashed lines). The tilted pinhole design is shown in part (b). The pinhole substrate has been tilted by an angle of 37 degrees but the pinhole aperture was drilled such that its axis is aligned with the detector. (The figures are not drawn to scale.)

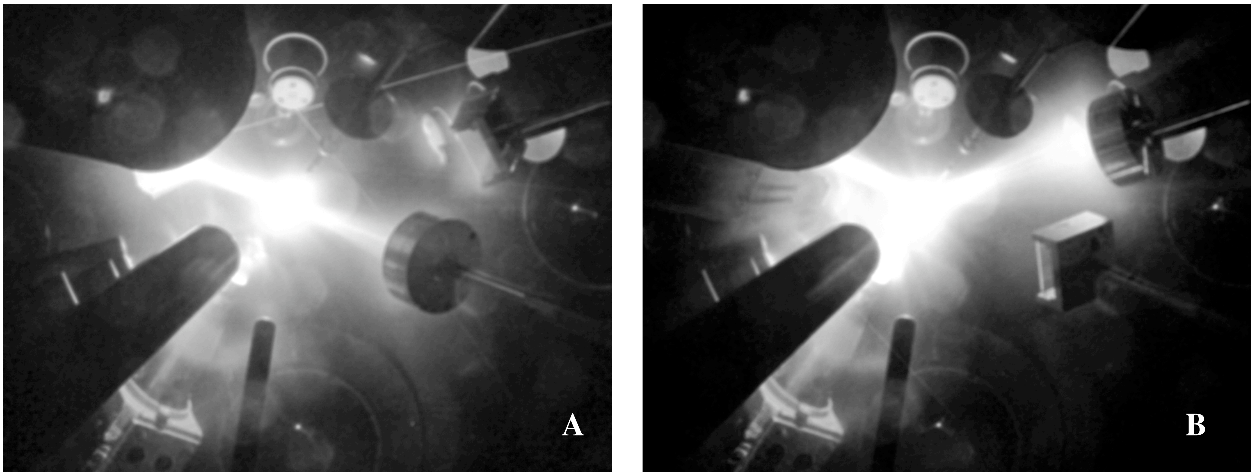

Figure 3. Directionality measurements of backlit pinhole debris. The orientation of both images is the same. The pinhole was located inside the white sphere in the center of the image.   The detector location is at the 4 o'clock position and the normal to the tilted geometry points towards 2 o'clock. The debris tracks shows up as the white streaks in the images. Image (a) shows the debris ejected from the traditional pinhole geometry (Fig 2a). A cone of debris is observed to be directed towards the detector location (round debris catcher). Image (b) shows the debris results using the tilted pinhole geometry of Fig 2b. The cone of debris is now directed away from the detector location (square debris catcher). It is now directed 37 degrees away towards the round debris catcher.

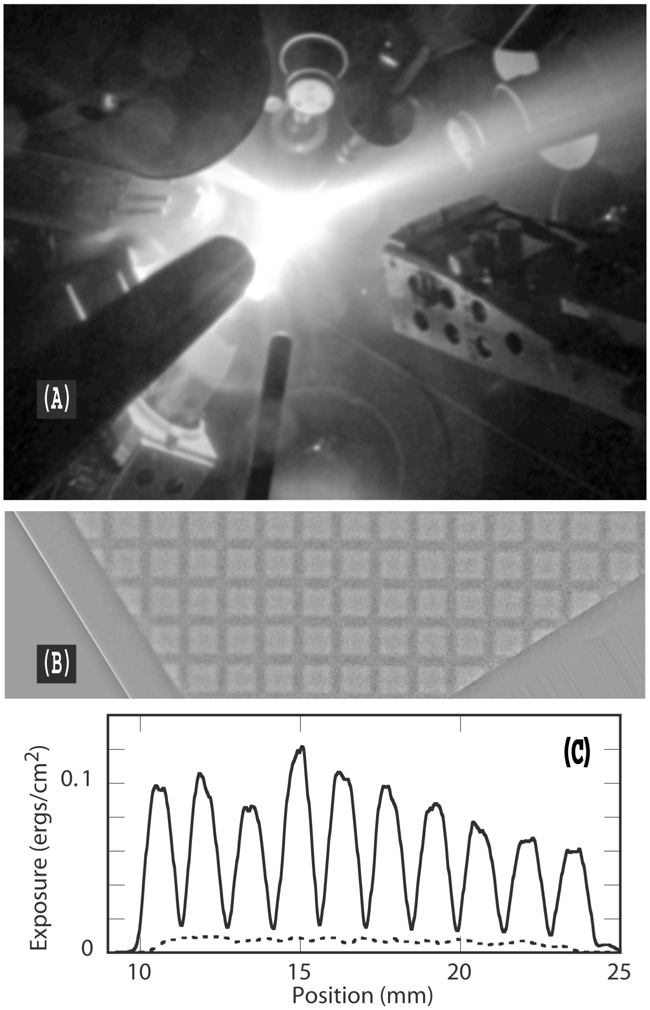

Figure 4. Use of a tilted pinhole to acquire an image of a 400-mesh grid using a gated imaging detector. With a gated imaging detector inserted at the 4 o'clock position, the debris cone (white cone) was directed safely away by utilizing the tilted pinhole as seen in part (a). The acquired pinhole-apertured point-projection backlit image of a 400-mesh grid with a magnification of 22.7 is shown in part (b). Figure 4c shows a horizontal lineout of the grid image (solid line) and the background level (dashed line). A signal-to-background ratio of 14 and a spatially resolution limited contrast of greater than 6 were both measured with the tilted pinhole.