Research on a wide-angle diagnostic method for shock wave velocity at SG-III prototype facility

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Abstract
A wide-angle diagnostic method for shock wave velocity is proposed in this paper. An ellipsoidal equation deduced for wide-angle diagnosis by using geometrical optical laws is presented. The combination of an ellipsoidal mirror and a traditional velocity interferometer system for any reflector (VISAR) forms a wide-angle VISAR. Several fundamental problems such as assembly, imaging, and interference in the wide-angle VISAR are discussed. The method is proven to be feasible based on the results of an eight-beam laser direct drive experiment at SG-III prototype facility. The diagnostic method is expected to be usable in a wide variety of experiments, especially those related to implosion compression, including high-pressure equation of state experiments, materials characterization experiments, shock characterization for Rayleigh–Taylor experiments, and shock timing experiments for inertial confinement fusion research.

Keywords: shock wave measurement, implosion compression, optical design, velocimetry, inertial confinement fusion

(Some figures may appear in colour only in the online journal)
is valuable to know 3D information about the shock wave [17–27].

This paper introduces an emerging system for realizing spherical shock wave measurement, which could be called a wide-angle VISAR. To achieve wide-angle diagnosis, a theoretical model for an imaging system and a diagnostic target is proposed. The imaging and interference performance of the model was simulated using optical design software. Furthermore, a target for wide-angle VISAR was designed and tested in an eight-beam laser direct drive experiment at SG-III prototype facility with reference to the theoretical calculations. The results show that the technique can be employed for spherical shock wave velocity diagnosis in implosion research.

2. Theory

The classic line-VISAR structure is shown in figure 1(a). When the target is shocked, a convergent probe beam is incident on the shock wave interface through the imaging system. The probe beam reflected from the shock wave interface carries the shock wave velocity information because of the optical Doppler effect, is collected by the imaging system, and enters a pair of interferometers. Doppler shifts in the reflected probe are manifested as fringe shifts at the interferometer outputs. The streak cameras record the central chord of the field of view and sweep this signal across the output detector. Further, the shock wave speed is obtained by observing the fringe shifts.

In ICF research, a spherical capsule is typically used as the target for implosion experiments because of its high symmetry. The shape of the spherical shock wave during ablation is considered to be an important factor affecting the subsequent compression results [28]. When a conical Au tube enters the interior of the capsule, providing optical access to the propagating shocks as they break out of the ablator, the shape of the central cross-section of the target is like that of a traditional keyhole; hence, it is called a ‘keyhole target’. A keyhole target has an ablation progress similar to that of a conventional spherical capsule when it has the same geometrical design, so such targets are often used to diagnose shock wave evolution in the ablation process [29]. In this study, a mirror was designed in the keyhole target. After entering the capsule, a convergent probe beam is scattered by the mirror and interacts with the whole spherical detection surface, then returns to the interferometers through the imaging system. If each ray of the scattered beam, which carries the velocity information of a unique position on the capsule, is traced by performing calculations and recorded by a streak camera, wide-angle diagnosis of a spherical shock wave is achievable. Because of the requirement of tracing every ray, the above model, which is depicted in figure 1(b), is called a ‘tracing model’.

In the tracing model, it is assumed that the convergent probe beam, mirror, and shock wave interface are ideal, and the rays in the y-z plane are studied first. The center of the capsule is located at O, the beam focus is at O’, and the distance between O’ and O is k (a constant). In addition, the radius of the detection surface is r, P is an arbitrary point on the mirror, θ is the angle between a ray incident upon the mirror and the y axis, and φ is the angle between a ray emerging from the mirror and the y axis. If the probe beam can return along the incident direction and the track of P(y, z) is continuous and differentiable, then

$$\frac{z'}{y'} = \frac{1}{\tan \frac{\varphi - \pi}{2}}. \tag{1}$$

Furthermore, there is a geometric equation for P(y, z):

$$\begin{cases} y(\varphi) = -k \cdot \frac{\sin \theta(\varphi)}{\sin(\theta(\varphi) + \varphi)} \cos \varphi \\ z(\varphi) = k \cdot \frac{\sin \theta(\varphi)}{\sin(\theta(\varphi) + \varphi)} \sin \varphi \end{cases}. \tag{2}$$

Solving (1) and (2) by using trigonometric formulas to divide the parts into $\tan \frac{\theta}{2}$ and $\frac{\varphi}{2}$ forms, we obtain

$$\tan \frac{\theta}{2} \cdot \tan \frac{\varphi}{2} = m, \quad (m = \text{const} \in (0, 1)). \tag{3}$$

Substituting (3) into (2) yields

$$\left(\frac{y + \frac{k}{2}}{k(1+m)}\right)^2 + \left(\frac{z}{k/m}\right)^2 = 1. \tag{4}$$

Due to the rotational symmetry, the trajectory of P(x, y, z) in the whole space is

$$\left(\frac{x + \frac{k}{2}}{k(1+m)}\right)^2 + \left(\frac{y}{k/m}\right)^2 + \left(\frac{z}{k/m}\right)^2 = 1. \tag{5}$$
Thus, $P(x, y, z)$ is an ellipsoid with its center at $(-k/2, 0, 0)$ and focal points at $(0, 0, 0)$ and $(-k, 0, 0)$. The left focus coincides with the beam focus, and the right focus coincides with the center of the capsule. It can be shown that the distance each ray travels to reach the detection surface is equal. That is, for any two different ray paths $L$ and $L'$,

$$L - L' = r - \frac{k(\sin \varphi + \sin \theta)}{\sin(\theta + \varphi)} = r - \frac{k(\sin \varphi' + \sin \theta')}{\sin(\theta' + \varphi')} = 0.$$  \tag{6}$$

According to the above theory, the size of the ellipsoid is mainly determined by $k$ and its shape is mainly determined by $m$, so a spherical shock wave can be diagnosed by designing a suitable ellipsoidal mirror combined with the keyhole target.

In a real case, with the ellipsoidal mirror completely illuminated by the probe beam, its size is considered to be sufficiently large to facilitate machining and assembly. The upper limit of $k$ is determined by the size of the diagnostic hole and the opening angle of the probe beam. The $F$-number of the receiving system of the VISAR for SG-III prototype facility is 4.5, and the diameter of the diagnostic tip on the keyhole target is 620 $\mu$m, so $k$ can be designed to be 2000 $\mu$m. When $k$ has been defined, the diagnostic angle increases with $m$, but the transverse length of the ellipsoidal mirror decreases. When $m$ is optimized to 0.016, the ellipsoidal mirror has a transverse length of 260 $\mu$m, and the theoretical range of $\varphi$ that satisfies the wide-angle diagnostic requirement is from 40° to 140°. These $k$ and $m$ values were used in the following simulation and experiment.

### 3. Simulation

A simplified wide-angle VISAR model similar to the classic VISAR was built using optical design software. This model contains an imaging system, an interferometer, and two detectors, as shown in figure 2(a). The imaging system contains two beam splitters, several imaging lenses, and light barriers. The lenses used in imaging system have been corrected for axial aberrations. The beam splitter in front of the interferometer is used to import the probe beam reflected from the target into the interferometer, and the beam splitter in front of the target is used for probe beam transmission between the imaging system and target. They also have functions in a debugging imaging system. As described in the previous section, there is a strict positional relationship between each ray and the target surface in the tracing model. Therefore, a light barrier near the beam splitter can be used to observe the shapes of the beams entering and leaving the beam splitter. The debugging process is not the focus of this paper, so the details of this process have been omitted.

In the simulation, detector 1 was used to observe the output of the tracing model. In an ideal case, the output of detector 1 is a ring with interference fringes, and each position on the ring corresponds to a position on the detection surface. However, once assembly error and the light source size are accounted for, the quality of the ring decreases significantly. For example, when spherical aberration makes the focal spot radius exceed 20 $\mu$m, the assembly error exceeds 1 $\mu$m, or...
the diameter of the ray source exceeds 5 µm, it is difficult to obtain utilizable interference fringes. Figure 2(b) shows the output generated under the above conditions. This phenomenon can be explained by the rays from different positions on the detection surface being superimposed at the same output position under non-ideal conditions. Although spherical aberration can be eliminated by designing a composite lens, the engineering requirements are too high to be achieved experimentally for this assembly error and light source size.

To eliminate the influences of non-ideal factors, the incident angle limit was discarded, and the incident rays were only used to illuminate the detection surface. Thus, development based on the tracing model was performed. A set of imaging lenses was arranged after the interferometer, and the target was imaged around detector 2, creating what is herein called the imaging model. In this model, the presence of interference is independent of the light source size, and the assembly error only affects the location of the final image, not its quality. Detector 2 is used to observe the output of the imaging model, indicating that the opening angle on the detection surface is very small (less than 4°) due to the existence of the ellipsoidal mirror and diagnostic hole and thereby controlling the spherical aberration to be within a certain range. The simulation results indicate that the detection surface is imaged on a streak camera in the form of a ‘ring’, as shown in figure 2(c). As in the tracing model, the image is a ring, where each position on the ring corresponds to a position on the detection surface and the interference fringes still appear, because the imaging system has a certain depth of field. As can be seen from the imaging of the feature location, the inner and outer boundaries of the ring correspond to the vicinities of the diagnostic hole and capsule bottom, respectively. The differences between the images are bending and lower quality. It is considered that a set of image correction lenses can be designed as in panoramic imaging to improve the image quality in the future.

The simulation results and analysis indicate that the imaging model increases the assembly tolerance and is not limited by the size of the light source, greatly improving the utility of the wide-angle VISAR.

4. Experiment

To verify the feasibility of the wide-angle diagnostic method for shock waves, an eight-beam laser direct drive experiment was performed at SG-III prototype facility. A diagram of the shooting target is provided in figure 3(a), and the target parameters are listed in table 1. An Al–W–Al–CH multishell was adopted for the target, where the outer Al shell not only could block the initial optical interference, but also had good ablation efficiency. Meanwhile, the W shell could reduce the influence of preheating on the elliptical mirror, the inner Al shell was used for VISAR static debugging, and the CH shell was initially transparent and could form a highly reflective surface when the shock wave arrived. To acquire more compression information in the experiment, the two streak camera slits of the VISAR were set at different positions to detect different areas so as to observe the 3D compression situation as much as possible and prevent incomplete collection of information.
Table 1. Parameters used in 20170712059 shooting of wide-angle VISAR.

| Parameter               | Details                                                                 |
|-------------------------|-------------------------------------------------------------------------|
| Diagnostic cone         | Au, solid angle ~20°, tip diameter ~620 µm                              |
| Capsule                 | Inner diameter ~1000 µm, composition from outside to inside: 5 µm Al/2 µm W/1 µm Al/80 µm CH |
| Ellipsoidal mirror      | Al, semi-long axis ~1032 µm, semi-short axis ~254 µm                   |
| Terminal shield         | Au, diameter 996 µm                                                    |
| Drive laser             | Laser energy 8 × 350 J, symmetrical drive, wavelength 351 nm, square wave, pulse time 1.5 ns, focal spot radius 500 µm |
| Probe laser             | Wavelength 532 nm, square wave                                         |
| Etalon                  | Length: left 4 cm, right 7 cm                                          |
| Gear of streak camera   | 10 ns                                                                   |

Theoretically, the shock wave enters CH shell 0.7 ns after the driven laser arrives at target surface.

\begin{align*}
\text{t} &= 1.8\ \text{ns, probe signal record starts.} \\
\text{t} &= 3.5\ \text{ns, driven laser arrives at the target surface.} \\
\text{t} &= 4.2\ \text{ns, shock wave enters the CH shell in the theory.} \\
\text{t} &= 5\ \text{ns, shock wave of top region enters the CH shell in the experiment} \\
\text{t} &= 6\ \text{ns, shock wave of bottom region enters the CH shell in the experiment}
\end{align*}

Figure 4. (a) Evolution of the material density of each shell in the ablation process in the Multi1D simulation. (b) Results of 20170712059 wide-angle VISAR shooting. The black lines indicate the time and space coordinates of the fringe patterns, and the blue lines indicate $\varphi$ corresponding to what is shown in figure 3(c).
that could have been caused by acquisition location factors, as shown in figure 3(c).

The static image of the target is composed of two concentric rings, where the inner ring corresponds to the image of the detection surface, which is the same as the simulation result. The outer ring corresponds to the image of the illuminated part of the diagnostic cone, as shown in figure 3(b). It should be noted that this experiment was performed to verify the wide-angle VISAR theory and technology described above and that no correction for the curved image surface was performed because the static fringes appeared and could be distinguished by the streak camera. In future experiments, we will design correction lenses to improve the image quality.

Before the experiment, a simulation was performed using a 1D sphere fluid model to calculate the shock wave propagation in the capsule. Figure 4(a) shows the evolution of the material density of each shell, demonstrating that after the driven laser arrives at the target surface, the shock wave enters the CH shell in 0.7 ns and the interference fringes begin to move.

Figure 4(b) is the result of 20170712059 wide-angle VISAR shooting. The characteristics of the experimental process are marked, where the black horizontal axis represents space, the blue horizontal axis corresponds to , and the vertical axis is time. Based on the one-to-one relationship between the imaging and target points, the measurement range of is actually from 80° to 135°. It seems difficult to detect the information in the range from 40° to 80° because of angular resolution degradation caused by the imaging quality. The fringes quickly disappear when the shock wave reaches the CH shell, which may be due to blindness or the shock wave interface being too tilted. The fringe shifts in the outer boundary of the ring of the right arm are detectable, which indicates that this method may be suitable for spherical shock wave detection. The area of fringe shifts is blurred, which reveals compression inhomogeneity. In the results for the left arm, the shock wave in the region irradiated by the lower four driven laser beams, reaches the CH shell ahead of the shock wave in the region irradiated by the upper four driven laser beams by nearly 1 ns, which may be one of the main reasons for the driving asymmetry. On the other hand, the shock wave enters the CH shell nearly 1 ns later than the Multi1D calculations indicate; thus, the 1D model can provide a reference on the time scale, but may not fully reflect the true 3D compression. Other factors such as insufficient injection of the main laser energy may have led to this difference.

There is no doubt that this wide-angle diagnostic method will provide a powerful experimental tool for further experimental research of such physical processes.

5. Discussion

The streaked data reveal significant asymmetry and blindness in the drive in the top-to-bottom direction. This phenomenon is acceptable. On the one hand, the eight-beam laser focal spot size is 500 μm, which is equal to the radius of the target and illuminates the target symmetrically, rather than spherically; therefore, there is asymmetry in the geometric distribution of the driving laser energy on the outer surface of the target. On the other hand, due to the different angles of the driving laser injection on the outer surface of the target and the uneven distribution of the energy density of the focal spot, energy absorption asymmetry occurs on the outer surface of the target. As a result, the driving energy density on the outer surface of the target is non-uniform. These asymmetric factors form a shock wave with an initial non-uniform velocity. The asymmetry increases with the propagation of the shock wave [18]. The shielding of the W shell may be affected, resulting in shear damage of the W shell, high-energy laser or x-ray transmission through the W shell gap, and direct preheating of the Al ellipsoidal mirror, causing VISAR blindness. In addition, the asymmetry could cause the shock wave surface to be too tilted for the probe beam to return to the VISAR imaging system. Consequently, the fringe pattern shows asymmetry and blindness. The focal spot size or number of driving lasers could be increased in future experiments to test or compensate for these effects on the drive symmetry.

Although it has been proven that a keyhole target can replace fuel pellets in diagnostic ICF experiments, it is necessary to study whether the ellipsoidal mirror and terminal shield affect the compression symmetry when assembled in the capsule and how the reflectivity of the ellipsoidal mirror is affected during implosion compression. In future experiments, we will test additional methods of improving the capsule composition, reducing blindness, and optimizing the target structure to improve the reliability of the wide-angle VISAR for laser tuning.

As with the previous tracing model, it is necessary to perform accurate calibration between the imaging and detection surfaces. However, the detection cross-section is in a plane in the tracing model, while the imaging surface is a curved ring in the imaging model. Combined with imaging correction technology, it may be possible for the inner and outer boundaries of the ring to be imaged perfectly in a plane and for more spatial information to be detected, including that corresponding to from 40° to 80°.

In optical design, more devices can be loaded to achieve spherical shock wave diagnosis in a wider region in a single shooting experiment. In addition, 2D-VISAR insertion into the wide-angle VISAR can be considered, depending on the specific needs.

6. Conclusion

Because of the need for diagnosis in ICF, a means of recording shock velocity data over a wide range of angles for shock fronts directed into a spherical capsule was developed in this study. The wide-angle recording is achieved by placing an ellipsoidal reflective optic in the central region of the capsule and directing a probe beam from a line-imaging VISAR diagnostic through an aperture in the capsule along the major axis of the ellipsoidal optic.

Parametric equations were derived, and the use of this optic to provide angularly resolved information was demonstrated. Then, two modes of operation were described in optical software: the tracing model and the imaging model, which differ in the way the optical beam emerging from the target is relayed.
to the detector. The former model represents an idealized picture in which there is a one-to-one relationship between the angles of rays returning through the collection lens and points of reflection on the interior of the sphere. However, this configuration suffers from severe sensitivity to deviations from the ideal geometry and is therefore impractical. The second model operates by relaying an image of the ellipsoid surface to the detector, with the object plane placed near the midplane of the ellipsoid surface. The second model is more robust against alignment errors, assembly errors, and variations in the illumination beam, at the expense of some angular resolution degradation. Last, the paper provides practical demonstrations of both a static image returned in an assembled target and streaked VISAR data (including fringe shifts) from an implosion experiment performed at SG-III prototype facility.

The wide-angle diagnostic method can be further enhanced in target fabrication and optical design in the future and would be an effective method of implosion diagnosis. The experimental wide-angle VISAR data can be used to study drive laser tuning for fusion, the equation of state of the material under the implosion conditions, the laser–plasma interaction, the Rayleigh–Taylor instability, and so on, thereby contributing to the creation of preparatory conditions for the final ignition. The wide-angle diagnostic method can even be extended for use in aspheric surface compression measurements and will play a role in high-energy-density physics and astrophysical radiation research.

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References

[1] Nuckolls J., Wood L., Thiessen A. and Zimmerman G. 1972 Nature 239 139
[2] Lindl J. 1995 Phys. Plasmas 2 3933
[3] Craxton R.S. et al 2015 Phys. Plasmas 22 110501
[4] Atzeni S., Ribeyre X., Schurtz G., Schmitt A.J., Canaud B., Betti R. and Perkins L.J. 2014 Nucl. Fusion 54 054008
[5] Landen O.L. et al 2011 Phys. Plasmas 18 051102
[6] Munro D.H., Celliers P.M., Collins G.W., Gold D.M., Da Silva L.B., Haan S.W., Cauble R.C., Hammel B.A. and Hsing W.W. 2001 Phys. Plasmas 8 5
[7] Robey H.F., Boehly T.R., Olson R.E., Nikroo A., Celliers P.M., Landen O.L. and Meyerhofer D.D. 2010 Phys. Plasmas 17 012703
[8] Barker L.M. and Hollenbach R.E. 1972 J. Appl. Phys. 43 4669
[9] Malone R.M. et al 2004 Proc. SPIE 5523 148
[10] Vogler T.J., Trott W.M., Reinhart W.D., Alexander C.S., Furnish M.D., Knudson M.D. and Chhabildas L.C. 2008 Int. J. Impact Eng. 35 1844
[11] Celliers P.M., Bradley D.K., Collins G.W., Hicks D.G., Boehly T.R. and Armstrong W.J. 2004 Rev. Sci. Instrum. 75 11
[12] Celliers P.M., Erskine D.J., Sorce C.M., Braun D.G., Landen O.L. and Collins G.W. 2010 Rev. Sci. Instrum. 81 035101
[13] Philpott M.K., George A., Whiteman G., De ‘Ath J. and Millett J.C.F. 2015 Meas. Sci. Technol. 26 12
[14] Moody J.D. et al 2014 Phys. Plasmas 21 092702
[15] Erskine D.J., Smith R.F., Bolme C.A., Celliers P.M. and Collins G.W. 2012 Rev. Sci. Instrum. 83 043116
[16] Smith R.F. et al 2013 J. Appl. Phys. 114 133504
[17] Piriz A.R. 1996 Nucl. Fusion 36 10
[18] Petrasov R.D. 1994 Nature 367 20
[19] Batani D. 2014 Nucl. Fusion 54 054009
[20] Tikhonchuk V.T. et al 2015 Plasma Phys. Control. Fusion 58 014018
[21] Soubiran F., Mazevet S., Winisdoerffer C. and Chabrier G. 2013 Phys. Rev. B 87 165114
[22] Callahan D.A. et al 2012 Phys. Plasmas 19 056305
[23] Hicks D.G., Boehly T.R., Celliers P.M., Eggert J.H., Vianello E., Meyerhofer D.D. and Collins G.W. 2005 Phys. Plasmas 12 082702
[24] Hicks D.G., Boehly T.R., Eggert J.H., Miller J.E., Celliers P.M. and Collins G.W. 2006 Phys. Rev. Lett. 97 025502
[25] Edwards J. et al 2004 Phys. Rev. Lett. 92 075002
[26] Murakami M. et al 2014 Nucl. Fusion 54 054007
[27] McWilliams R.S., Eggert J.H., Hicks D.G., Bradley D.K., Celliers P.M., Spaulding D.K., Boehly T.R., Collins G.W. and Jeanloz R. 2010 Phys. Rev. B 81 014111
[28] Haan S.W. et al 1995 Phys. Plasmas 2 6
[29] Robey H.F. 2013 Phys. Rev. Lett. 111 6