Line-imaging VISAR for laser-driven equations of state experiments

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Abstract. The paper presents the diagnostic system for velocity measurements in laser-driven equations of state experiments. Two Mach–Zehnder line-imaging VISAR-type (velocity interferometer system for any reflector) interferometers form a vernier measuring system and can measure velocity in the interval of 5 to 50 km/s. Also, the system includes a passive channel that records target luminescence in the shock wave front. Spatial resolution of the optical layout is about 5 \( \mu \)m.

1. Introduction
Study of unsteady physical processes and extreme states of matter under intense pulsed action is one of the most pressing fundamental problems of high energy physics [1]. The important scientific problem in this area, which is of great practical importance, is to study the physical and mechanical properties of materials exposed to intensive shocks. Analysis of pressure and velocity at the shock-wave experiments provides the basis for determining the kinetics of elastic-plastic deformation processes, destruction, chemical and phase transformations, study dynamic strength and fracture of materials.

One of the few methods that provide information about events related to the passage of powerful shock waves through matter is the Doppler interferometry [2]. This method is non-contact and provides information about the object with a high spatial and temporal resolution [3]. As the reflecting surface in such experiments usually one may use back surface of the object, moving under the action of the outgoing shock wave. Furthermore, under the action of passing through an intense shock wave, material of a transparent target can acquire reflective properties and reflect a probe light.

One of few material parameters available for measuring in the course of these experiments is the surface velocity (for opaque target) or shock wave velocity in the matter (for transparent target). Information about the temporal dynamics and spatial variations of this parameter allows exploring the fundamental phenomena and processes occurring in the material under extreme pressures and temperatures.

The paper presents the laser velocimeter, designed for integration into the “Luch” laser facility (VNIIEF) [4] and other powerful lasers. The system is designed for the study of shock-wave processes occurring in the interaction of intense laser radiation with matter and is based on a line-imaging VISAR (Velocity Interferometer System for Any Reflector). The system allows for remote non-contact measurements of the shock wave velocity in the range of 5–50 km/s with a
spatial resolution of about 5 microns. The developed diagnostic system can be used for a wide range of basic and applied scientific problems related to the interaction of shock waves with condensed matter.

2. Operating principle

The principle of continuous velocity measurements based on the Doppler frequency shift analysis of a probe monochromatic wave reflected by the moving surface of the sample. The most widely used scheme in such measurements is a VISAR-type interferometers [5]. In different variations this scheme used in shock-wave experiments with light-gas guns [6], pulse electromagnetic generators [7], lasers [2, 8] etc.

Figure 1 shows a schematic diagram of the line-imaging VISAR. Probe light scattered by the object is inserted into the optical system by the beamsplitter BS1. Beamsplitter BS2 splits the light between two interferometers formed by mirrors M2, M3 and beamsplitters BS3, BS4. The delay etalon provides a time shift between the interfering waves, and its size is determined by the conditions of the experiment. Thus, on the interferometer beamsplitters interferes the light scattered by the object at two different points in time. The relation between phase and speed has the form:

\[ V(t) = \frac{K}{2\pi} \phi(t), \]  
\[ K = \frac{\lambda_0 c}{4l(n - 1/n)(1 + \delta)}, \]  

where \( V \) is velocity, \( K \) is interferometer constant, \( n \) is refraction index of the etalon, \( l \) is etalon length, \( c \) is speed of light, \( \delta \) is dispersion correction in the etalon, \( \lambda_0 \) is initial wavelength of laser light.

With regards to using lasers in equation of state (EOS) experiments integrated collection of scattered radiation from the target has become irrelevant. The small size of the targets, their complex structure requires receiving data with a spatial resolution. This is achieved by
using streak cameras as registration systems in experiments and imaging target on cameras photodetectors with a predetermined magnification.

The interference pattern is configured to obtain a set of 15–20 interference fringes. Using a streak camera as a recording system allows getting time resolution of about 10 ps.

All the systems based on VISAR-type interferometers have common drawback—the possibility that the interference contrast is temporarily lost when registering a shock front. In this case, the calculating may skip one or more periods of interference, resulting in incorrect calculation of the velocity. In the case of the interferometer contrast loss caused by insufficient speed photographic system, the phase information is lost, causing ambiguity in the definition of velocity values. The solution to this problem is the implementation of vernier system consisting of two interferometers with similar interferometer coefficients \( K \). The ambiguity of the shock front velocity has a discrete form and different from the actual speed by an integer number of interferometer constants \( K \). It allows you to get the actual speed value by adjusting the amount of missed periods for each of the interferometers that graphics of velocity behind the shock front, obtained for the different interferometers, coincide. In addition, increases the reliability of the values, because experimental data are duplicated.

### 3. Optical layout

To measure the mass velocity of matter in shock-wave experiments vernier measuring system has been developed. Since it is necessary to obtain the target image on streak cameras with spatial resolution, optical scheme is implemented in Zemax optical design program. The tasks assigned to the optical system include: target illumination by the probe laser beam, collecting and collimating scattered light and passing it through the interferometers, followed by the target imaging on the streak cameras with a predetermined magnification.
Optical layout shown in figure 2 is conditionally divided into several sections, limited by intermediate images. This solution makes it possible to adjust the various parts of the optical path independently. The first part of the system input the probe light into the scheme, collects scattered light from the target and makes the first intermediate image; the second part passes the light through the interferometers, followed by making a second intermediate image. The third part of the system, including the zoom lens, is designed for imaging the target with a predetermined magnification on the streak cameras.

Inserting probe light into the chamber and target illumination is performed by 75 mm lens L6, beamsplitter BS2, narrowband mirror BS1, aluminum-coated mirror M1 and 125 mm f/1.5 L1 main lens. Probe and adjusting lasers are mounted on the separate table and connected with measuring system by 40 meters of 1-mm core fiber with numerical aperture 0.22. Considerable length and diameter of the fiber allow getting a flat intensity profile at the fiber output and, as a consequence, to provide uniform target illumination. Also, this scheme reduces speckles on the image. Probe and adjustment light is collimated by a 75 mm lens L6, inserted into the scheme via 50% BS2 splitter and focused by the 125 mm main lens in the target plane with a magnification of 0.4. Defocusing control allows adjusting the diameter of the beam spot and analyzing targets of various sizes and shapes. Half of the probe light, reflected on BS2, is removed from the system to the absorber (not shown in the figure).

The first part of the registration system consists of 125 mm f/1.5 lens, narrowband mirror BS1, beamsplitter BS2 and mirrors M1, M2, M3. Sonnar 125 mm lens with a relative aperture of f/1.3 collects the scattered light. This prevents aberrations, inherent in the single and glued lens while maintaining high light collection. L1 lens is located in the diagnostic pipe in 66.5 mm from the target and form target image at the 1.3 m distance with magnification of 13. Glass window at the end of the diagnostic pipe protects the lens from the target destruction products. Iris diaphragm present in the lens design allows adjusting the incoming light in the event of excess.

Collected light leaves the pipe and is turned by M1 mirror to the plane of the optical layout. Narrow-band dielectric mirror BS1 reflects light at a wavelength of 660 nm and passes the target luminescence for registration in the passive channel. Beamsplitter BS2 and 70 mm diameter M2 and M3 mirrors direct light into a long (85 cm) free arm, where the adjustment irises are located. First image plane IP1 is located between the splitter BS3 and mirror M3.

The second part of the layout consists of 50% beamsplitter BS3, two Mach–Zehnder interferometers (BS4, BS5, M6), four 300-mm achromatic doublets L2, L3, 50 mm mirrors M4-M8 and a pair of CCD cameras. BS3 splits the light into two equal intensity beams. 300-mm achromates L2a and L2b, spaced about 400 mm from the first intermediate image IP1, collimate beams and passed them through the interferometers. Their location and parameters are selected so that the beams passing through the interferometers have a minimum aperture. This simplifies the design and allows using small diameter interferometer mirrors (1 inch). Thus, beam diameters on the splitters BS4 and BS5 are respectively 15 mm and 20 mm. Placed symmetrically L2 300 mm achromates L3 form a second intermediate image (IP2) after turning mirrors M7 and M8, in 5 cm from the latter. The magnification generated by the optics on the second section of the system is 1.4, the total magnification of the image relative to the target size is 18.2.

Installed in the layout CCD cameras can focus on the various elements of interferometers, previous part of the optical system, intermediate image in IP1 and they are a necessary and useful tool for the imaging system adjusting and the interference fringes visualization.

The third part of the optical path formed by the 55–200 mm f/4–5.6 zoom lenses L4 and 50 mm mirrors M9. Zoom lenses L4 intended for the forming of the final image on the streak-cameras slits. Variation of the L4 focal length provides a large range of possible magnifications and allows the most efficient using of the streak camera photocathode by selecting the image size.
to the height of the slit. Focusing is performed by moving the lens along the optical axis in the range of 100 mm, it is possible to fine-tune with the lens own mechanism. The range of possible magnifications in the third section is 0.75–1.5 and can be extended if necessary. Maximum field of view of the imaging system is 1.6 mm in the plane of the target.

Thus, the overall magnification of the optical system is 13.6–27.3 for the target sizes of 0.6–0.3 mm and a resolution in the target plane is about 5 microns. The depth of field on the cameras is estimated to be 100 mm, which does not create obstacles to the focus and does not reduce the resolution of the system.

Besides VISAR-type interferometers measuring system includes a target luminescence diagnostic. Its optical scheme is integrated into the overall system and works in parallel with VISAR. Elements such as L1 lens, M1 mirror, BS1 narrowband mirror, are also parts of the SOP scheme. After passing through the L1 and M1, light collected from the target reaches the narrowband mirror BS1. Here, light at a wavelength of 660 nm is separated and sent to VISAR system. The remainder of the beam is forwarded by the mirrors M10 and M11 to the lower part of the layout form the similar image with magnification 13. Zoom lens L5, identical lenses L4a L4b, and mirror M12 image the target on the streak camera slit with a magnification of 1–2. Zoom and focus are made similar to L4a and L4b. Resolution and an overall magnification of the system do not differ from those of the VISAR system.

Figure 3 shows a 3D-model of the measuring system mounted in the operative position near the target chamber. Integrated PC is used to display CCD cameras images and to control shutters and interferometers linear translators.

4. Interferometers
In shock-wave experiments velocity measurement precision of 1% is sufficient. To ensure the specified precision it is very important to maintain alignment of the beam optical axis passing through the interferometer and to ensure the precision of etalon setting 2 microns.

The interferometers are made under the Mach–Zehnder scheme. Two 50% splitters and two mirrors have a diameter of 1 inch and are arranged in the form of a rhombus with diagonals of 500 and 35 mm and the angle of about 8°. All the elements are mounted on the gimbal mounts.
that provides easy interferometer adjustment. The system is designed for getting accurate time delay in one of the interferometer arms. For this purpose, the delay etalon is mounted in one of the arms. Together with one of the reflective mirrors, etalon is mounted on motorized translator. The stepper motor provides translation of these elements along the axis perpendicular to the surface of the mirror with micrometer accuracy. The required optical delay is achieved by the combination of etalon and translation delays. This combination is necessary, as such methods individually lead to a parallel displacement of the beam and, as a result, misalignment of the interferometer. The mirror displacement value \( d = h(1 - 1/n) \) is calculated to make the beams come out of the delay etalon at the same point and at the same angle, that in the absence of etalon. As well as increasing the optical path of the reference is \( \Delta l = h(n - 1) \), the resulting optical delay is:

\[
\tau = \frac{2h}{c} \left( n - \frac{1}{n} \right),
\]

where \( h \) is etalon length, \( n \) is etalon index of refraction, \( c \) is speed of light.

Interferometers adjustment is performed in two stages. The first stage includes the mounting the interferometer mirrors, setting the equal length of interferometer arms by the white light source, exposure amount and direction of the interference fringes. The second stage is an optical delay setting by mounting a delay etalon and moving M6 mirror by the motorized linear translator.

Arms length is fine-tuned by moving the rear mirror by the linear translator. The correct alignment criterion of the interferometer arms optical lengths is to obtain interference fringes with the incoherent light source; the alignment accuracy is corresponding to coherence length of the white light. In the line-imaging scheme 15–20 fringes are obtained by a small tilt of the interferometer output beamsplitter. Doppler shifts in an optical signal lead to a change of phase at the output, that consequently displace the interference fringes pattern. Turning the output beamsplitter adjust the interference fringes incline and quantity.

Delay etalons are fused silica cylinders with a diameter of 1 inch, coated for 660 nm wavelength transmission. Etalons having length 1–10 mm provide a range of measured velocities of 5–50 km/s.

5. Probe laser

Probe laser system is designed for the target illumination during an experiment. Its wavelength must be out of spectral intervals of the main laser harmonics (532 and 1064 nm), that allows separating probe and main light simply. Probe laser power should be sufficient to illuminate the target, but should not damage it. To ensure the interferometers operability width of the laser spectral line should not exceed 1 MHz. Probe pulse duration must exceed the typical duration of the interaction of the target with the shock wave.

As the probe laser system we used frequency-doubled Nd:YAG laser operating at a wavelength 659.5 nm. Its operating principle is injecting 1319 nm CW seed laser light into the pulsed laser with adjustment and stabilization of its cavity. After amplification form probe laser pulses with energy of 30 mJ and 100 ns duration and allows using targets thickness up to 1 mm at a typical speed of 5–50 km/s.

6. Summary

For the laser-driven EOS experiments on the “Luch” laser facility we have developed a diagnostic system consisting of VISAR-based vernier velocimeter and target luminescence registration system. Optical layout is calculated in Zemax, which made it possible to reduce aberration and to obtain diffraction-limited target image with a resolution of 5 \( \mu \)m for the target size of 0.3–0.6 mm. The system measures velocity in the range of 5–50 km/s.
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