1. Introduction

Study of extreme physical processes in matter under intense pulsed actions 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, we used object back surface for opaque targets or directly shock wave front for transparent targets.

The paper presents laser velocimeter, designed for integration into the “Luch” laser facility [4] and other powerful lasers. The system is designed for the study of shock-wave processes occurring in the interaction of intense laser light with matter and is based on a line-imaging Velocity Interferometer System for Any Reflector (VISAR). 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 3 μm. The registration of probe light, reflected from the shock wave front or
back surface, allows to calculate the shock wave velocity, and the target luminescence detection gives the information about the shock wave exit time. Developed system provides to measure the inhomogeneity of shock wave velocity or time difference between shock wave exit times for complex targets with a one-dimensional spatial resolution (slit scanning mode). Also the system can be integrated into various laser setups with minimal changes and can be used for a wide range of another scientific problems related to the interaction of shock waves with condensed matter [5, 6].

Measuring system consists of five functional elements:

- Optical setup, which registers the motion parameters of the reflecting target surface.
- Laser light source with adjustable power. The laser light source has a wavelength of 660 nm.
- Adjustment and control system. Basic mechanical elements that provide adjustment of the optical scheme are equipped with motorized moving elements and controlled both remotely and directly.
- Recording system that records images, including interferometric, with a temporal resolution based on slit-scan streak cameras.
- Collection and processing system. The output data transport by a fiber-optic lines at a distance of at least 30 m. The angular and spatial position of the beam in the measuring system is monitored using digital cameras with a personal computer output.

2. Operating principle

A principle of the continuous velocity measurements is based on the Doppler interferometry. A wave of monochromatic radiation of a probe laser reflects from the moving sample and acquires Doppler frequency shift that can be analyzed by measuring system. The most widely used scheme in such measurements is a VISAR-type interferometers [7]. In different variations, this scheme is used in shock-wave experiments with light-gas guns [8], pulse electromagnetic generators [9], lasers [2, 10] etc.

Figure 1 shows a schematic layout of the line-imaging VISAR. The test target illuminates by probe light, which is scattered from a target and collected by a lens system. Further, the light enters a non-equable interferometer. For these experiments, it is most convenient to use Mach–Zehnder construction, since it allows aligning the arms length quite accurately. 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, the light scattered by the object at two different points in time interferes. The relation between phase and velocity has the form:

\[ V(t) = \frac{K}{2\pi} \varphi(t), \]

\[ K = \frac{\lambda_0 c}{4l(n - 1/n)(1 + \delta)}. \]

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.

Interference signal can be recorded by different types of recorders. The interference pattern is configured based on the selected recorder. For streak-camera it is preferably to obtain a set of 15–20 interference fringes. Streak cameras as a recording system allows getting time resolution 10 ps.

All the systems based on non-equable interferometers have a common disadvantage—the possibility that when recording a sharp front, the interference contrast will be temporarily lost, figure 2(a). In this case, one or more interference periods can be skipped during processing, which
Figure 1. Conceptual layout of a line-imaging VISAR: L1—lens; M1–4—mirrors; BS1–3—beamsplitters.

Figure 2. Relation between fringes form and surface velocity (a) and vernier interferometer system principle (b).

will lead to incorrect determination of the speed value and, although the temporal dynamics of velocity variation behind the shock front will be tracked, it will be shifted by a multiple of the constant of the interferometer K. In case of a loss of contrast, caused by insufficient time resolution of the photographic registration system, information about phase is lost, which causes ambiguity in velocity value determining. The solution to this problem is the realization
of a vernier circuit consisting of two interferometers with close non-multiple coefficients $K$, figure 2(b). The ambiguity of the velocity behind the shock front has a discrete form: the real velocity differs from the measured one by an integer number of interferometer constants $K$. This makes it possible to obtain a real value of velocity by selecting a number of missing periods for each of the interferometers so that the graphs behind the shock front, obtained for different interferometers, coincide. In addition, the reliability of the obtained values increases, because the experimental data are duplicated.

3. Optical layout
To measure the mass velocity in shock-wave experiments, we developed the vernier line-imaging VISAR. Because in laser shock-wave experiments usually used small, complex structure targets, requires receiving data on streak cameras with a spatial resolution. To obtain it, optical scheme is calculated in ZEMAX. 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 required magnification.

1-mm diameter test target illuminates by pulsed probe laser that mounted on the separate table. This table is connected to measuring system by 40 m 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. In additional, the adjusting continuous laser is mounted on the same table and provides to configure the system conveniently.

Optical layout shown in figure 3 is conditionally divided into sections bounded by intermediate images. This solution allows adjusting the various parts of the optical path independently. The first part of the system transmits the probe light into the scheme, collects scattered light from the target and makes the first intermediate image; the second part of the light passes through the interferometer, 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 required magnification on the streak cameras slits. Maximum field of view of the imaging system is 1.6 mm in the target plane. The overall magnification of the optical system is 13.6–27.3 for the target sizes of 1.0–0.3 mm and a resolution in the target plane is about $3 \mu m$. The depth of field on the cameras is estimated to be $\sim 100 \text{mm}$, which does not create obstacles to the focus and does not reduce the resolution of the system.

Besides VISAR-type interferometers, the measuring system includes a target luminescence diagnostic. Its optical scheme is integrated into the overall system and works in parallel with VISAR. The 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 forwards to the lower part of the layout and images the target on the streak camera slit. Resolution and an overall magnification of the system do not differ from those of the VISAR system.

In more detail this optical layout is described in the article [11].

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 $\approx 1–2 \mu m$.

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 $8^\circ$. All the elements are mounted on the gimbal mounts that provides easy interferometer adjustment. The system is designed for getting accurate time
Figure 3. General view of the line-imaging shock breakout diagnostic system layout: L—lenses; M—mirrors; BS—beamsplitters.

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

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

where $h$ is etalon length, $n$ is etalon index of refraction, $c$ is speed of light.

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.

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. Figure 4 shows the typical white light fringe pattern. 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, which consequently displace the interference fringes pattern. Turning the output beamsplitter adjust the interference fringes incline and quantity.

5. Spatial resolution measuring
One of the most important parameters determining the measuring accuracy is the optical system resolution. This feature is decisive for obtaining a spatial velocity profile. To assess the spatial resolution of the system, test measurements were carried out. Target was replaced by the USAF-51 test target, figure 5.

Behind the test target, a red LED at a wavelength of 660 nm with a power of 1 W was placed. Beam configuration completely corresponds to the scattered light obtained during the experiments. The location of the test target is shown in figure 5. A ToupCam digital camera with a detached lens was used as a registration system. The images of test bars of an optical system corresponding of 0.3 to 1.0 mm target sizes were obtained. One of this test images is shown in figure 6. It is clearly seen that allows to resolve the 4-th element of the 7-th group of strokes, which corresponds to a resolution of $\approx 3 \, \mu m$ ($\approx 200$ stroke/mm).

6. 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. Laser system is designed under Master Oscillator Power Amplifier (MOPA) scheme and includes pulsed Q-switched Nd:YAG laser at a wavelength 1319 nm, CW seed laser at same wavelength, two-pass amplifier and second-harmonic generator.

For correct working of interferometers with time delay between arms it is necessary to use a light with coherence length more then arms optical length difference. For a pulsed Nd:YAG
lasers is achieved with single-frequency operation mode. This mode is hard to reach for pulsed solid-state lasers with long cavity (more than 1.5 m) and special steps requires. In this scheme single-frequency light from a 1319-nm CW seed laser injected into the cavity. The injection laser light wavelength tuned to one of the longitudinal modes of the pulsed laser near the center of the luminescence line. This makes it possible to increase the ratio of the gain to the losses of the cavity for this separate mode and gives it an advantage over the other longitudinal modes. The single-frequency light is a smooth pulse of $\approx 50$ ns duration, which can be amplified up to 30 mJ per pulse. For holding the single-frequency operation mode, position of longitudinal

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**Figure 5.** Position of optical elements for resolution tests.

**Figure 6.** Test target image of 0.6 mm target size configuration.
modes is stabilized by displacement of the cavity 99.9%-reflective mirror. The feedback signal is formed on the basis of interferometric signal from cavity between the pulses, the source of light for which is the seed laser. Pulse duration certainly exceeds the time of processes in target, and the intensity is sufficiently low to make no damage the target. Figure 7 shows the examples of multifrequency and single-frequency generation modes. Single-frequency pulses are smooth pulses with duration about 50 ns and jitter about 5–8 ns.

7. Conclusions
For laser-driven equation-of-state experiments on the “Luch” laser facility, we have developed a diagnostic system consisting of the VISAR-based vernier velocimeter, the target luminescence registration system and the target illumination system. All components of the diagnostic system have the potential for modification and can be adapted for various powerful laser setups. Optical layout is calculated in ZEMAX, which made it possible to reduce aberration and to obtain diffraction-limited target image with a resolution of 3 \( \mu \)m for the target size of 0.3–1.0 mm. The system measures velocity in the range of 5–50 km/s.

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