Laser shock tube for the study of supersonic gas flows and the development of hydrodynamic instabilities in layered media.

Lebo I.G.[1),2)], Zvorykin V.D.[2)]

[1)] Technical University-MIREA, Russia, Moscow, Vernadsky prospect, 78,
[2)] Lebedev Physical Institute, Russia, Moscow, Leninsky prospect, 53,
Fax: (095)- 132-11-96, e-mail: lebo@sci.lebedev.ru

Abstract.

The design of miniature laser shock tube for the study of a wide range of hydrodynamic phenomena in liquids at pressures greater than 10 kbar and supersonic flows in gases with large Mach numbers(greater than 10) is discussed. A substance filling a chamber of quadratic cross section, with a characteristic size of several centimeters, is compressed and accelerated due to local absorption of 100-ns, 100-J KrF laser pulses ("GARPUN" installation, Lebedev Phys. Institute, Moscow) near the entrance window. It is proposed to focus a laser beam by a prism raster, which provides a uniform intensity distribution over the tube cross section. The system used to study the hypersonic flow past objects of complex shape and the development of hydrodynamic instabilities in the case of a passage of a shock wave or a compression wave through the interfaces between different media. The numerical simulations are used to model the laser shock tube experiments.

1. Introduction.

The stability of an interface between two media found in the field of constant or pulsed acceleration is a fundamental problem of fluid and gas mechanics.

In the first case, the contact surface is unstable if the gradients of pressure and density have opposite directions (Rayleigh-Taylor instability) /1/.

In the case of pulsed acceleration caused by the passage of a shock wave through a contact surface between two liquids or gases or a sharp deceleration of a substance, which previously moved, the interface is unstable for any arrangement of layers (Richtmyer-Meshkov instability-RMI) /2,3/.

The study of the evolution of hydrodynamic instabilities is a problem of great importance in inertial fusion, physics of high energy densities, cosmology and astrophysics. The passage of strong shock waves through contact surfaces of two gases with different densities causes the formation and development of complex vortex structures, which are of interest for present-day nonlinear hydrodynamics and for studying the problem of a change from an order state to chaos. Another problem, which is important for the development of modern aerospace engineering and protecting the Earth from collisions with space objects, is the study of supersonic flow past bodies of complex shape at large Mach numbers. The problems mentioned above are studied by numerical methods using 2D and 3D codes, in laboratory experiments with shock tubes /3-5/, special rocket and gun facilities /6,7/ using high -power lasers /8,9/ and explosions /10,11/.

Lasers are used to study hydrodynamic flows and instabilities in plane, cylindrical, and spherical geometries, both in the case of direct target heating and in the case of converting laser radiation to x-rays. However, the multichannel and multielement laser facilities used for this

purpose, such as ISKRA-5 (Russia), VULCAN (Great Britain), GEKKO-XII (Japan),
NIKE, NOVA and OMEGA (USA) with radiation energy of order of 10 kJ are extremely expensive. In typical laser experiments, the radiation intensity q in focal spot of size *(0.1-1) mm* is 10^{13}-10^{15} W/cm^2 and the pulse duration is of order of *1-10 ns*. In this time, a shock wave travels in a solid path *1-10* μm long, which determines the characteristic scale of a phenomenon being studied, because the unloading wave rapidly weakens the shock wave after the termination of a laser pulse. The development of instability in condensed media, as a rule, is studied with complex and expensive x-ray techniques, which often give only time- and space integrated information.

We propose a new technique for exciting shock waves in gases and compression waves in liquids by a pulsed KrF-laser with considerably lower radiation energy *(~100 J)* for modelling a wide range of hydrodynamic phenomena mentioned above at a spatial scale of *1-10 mm* in a range of microsecond duration. The idea is based on two known facts:

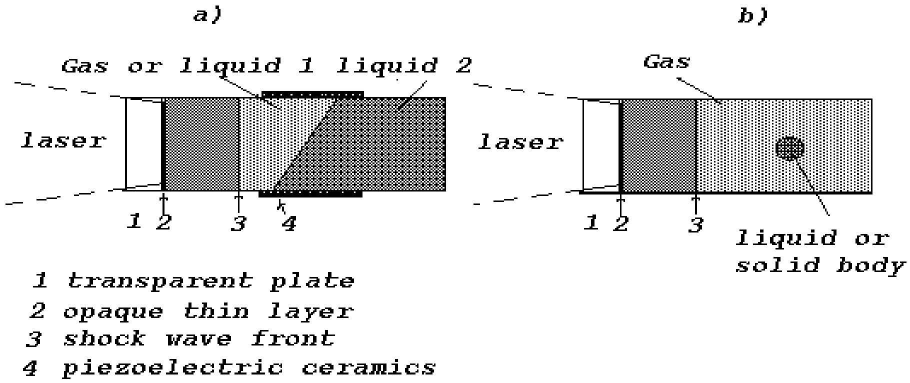
(1) lasers with pulse duration of *10-100 ns*, when irradiating the surface of a solid coated with a thin transparent layer, which hampers a rapid unload of the evaporated substance, produce pressure jumps with amplitudes more then 10 kbar at moderate radiation intensities 10^8-10^9 W/cm^2;

(2) unloading target excites strong shock waves with Mach number more then 10 in the atmospheric air surrounding it.

2. Design of laser shock tube.

The design of such a laser shock tube is based on the use of following basic components: a miniature shock tube chamber, a powerful KrF laser, a laser focusing system and 2D numerical codes. The shock tube chamber is shown in **Fig.1a,b.**

Figure 1. Schematic of laser shock tube for investigation of RMI (a) and hypersonic flow past objects of complex shape (b).



Laser radiation enters through a transparent window (1) inside a chamber, which is filled with a liquid or gas. Radiation is absorbed in a thin layer (2) adjacent to the window, resulting in a compression wave travelling in both directions from the energy release region.

Initial perturbations on the contact surface between two liquids or a liquid and gas can be produced by a piezoceramic transducer (4) attached to the chamber wall or with help of a thin shaped film. One can place liquid drops or solid particles of different shape inside the chamber which is filled with a gas (see **Fig.1b**). Because the liquids and gases under study are transparent to probing visible radiation, one can use conventional high-speed shadow and schlieren photography. In detail it is possible to find the description of laser shock tube in /12/.

3. Numerical simulation of the propagation of pressure waves in laser shock tube.

The numerical calculations modeling the formation and propagation of a pressure wave were made using 2D Lagragian code "ATLANT" /13/ and 2D Euler code "NUTCY" /14/ in cylindrical geometry. A laser beam traveled along z-axis. Laser shock tube has length of 12 cm and contains three (or four) subregions: transparent layer of silica glass with density $2.5\ g/cm^3$, aluminium foil with thickness of 2 μm and *Xe*-gas filled chamber with initial density $5.4\ mg/cm^3$. Laser radiation was incident from the right, passed through a transparent layer, and was totally absorbed in aluminium layer. A KrF laser pulse had a trapezoidal form, with leading and trailing edges 20 ns long and a region of constant intensity $3.1x10^8\ W/cm^2$ 60 ns long. Because of heating and evaporation of a thin Al-foil, a pressure jump with the amplitude about 10 kbar occurred and compression wave in glass and shock wave in gas was produced. **Fig.2** shows the results of calculation modeling the propagation of a shock wave in Xe-gas filled chamber. The sound speed in xenon and glass was *174 m/s* and *3.7 km/s*, respectively. One can see that strong shock wave with Mach numbers M~40 is formed in gas, and this wave gradually damps during its position. By a moment of *700* ns, it travels a *4 mm* path, but its velocity remains rather high and corresponds to *M≥20*.

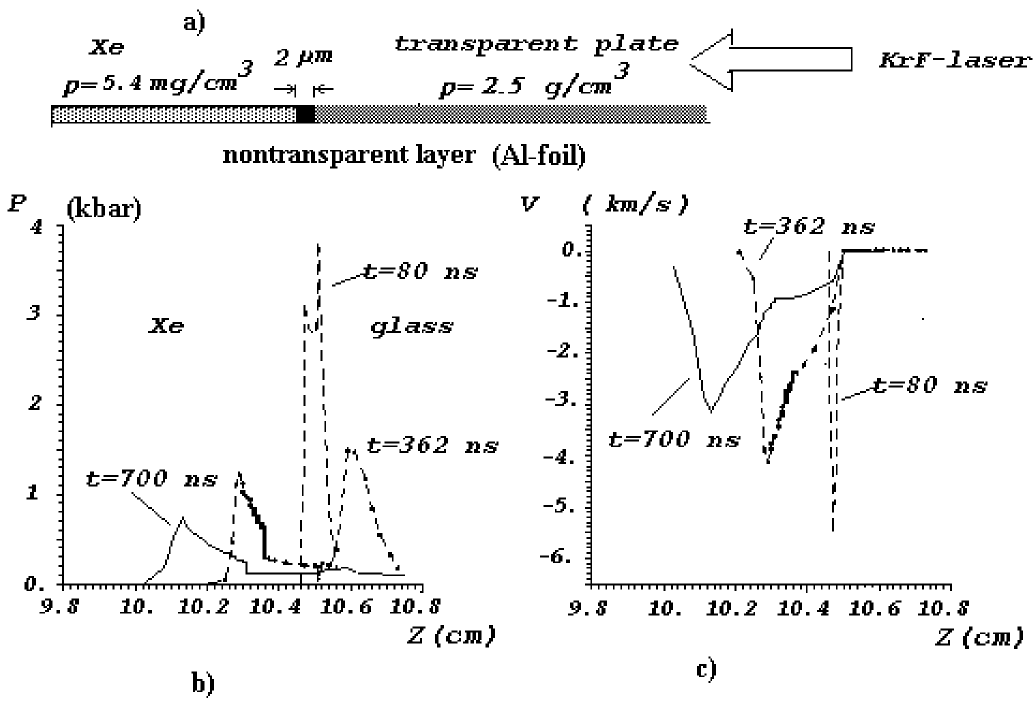


Figure 2. Results of calculation. Schematic of the experiment (a); the distributions of pressure (b), and velocity (c) along the z-axis at the moments of time t=80 (1), 362(2), and 700 (3) ns.

4. Preliminary experiments.

The experiments have been performed at GARPUN electron-beam pumped KrF laser installation in Lebedev Physical Institute (Moscow) /15/. Laser beam was focused on the targets by an optical system consisting of the prism raster and the lens. Overlapping of 25 individual beamlets provided non-uniformity less then few percents across the square spot. By moving the lens we could vary a spot size from *20x20* to several mm. For a fixed 7x7 mm focal spot laser intensities were changed in the range of $0.1\text{-}1\ GW/cm^2$ by attenuating incident laser energy. The targets were set inside an evacuated chamber filled with an air, which pressure being varied in the range of $p_0=0.0001\text{-}1\ bar$. Gasdynamic processes that developed under laser-target interaction were studied with the help of high-speed optomecanical camera in combination with schlieren or shadow technique /16/. Slit scanning images of the self-luminescence laser-produced plasma were combined with images of flying foil targets and shock wave (SW) propagating in surrounding air.

It was observed that during laser pulse action plasma front propagated towards an incident radiation together with the SW front. The velocities in dependence on laser intensity (**Fig.3**) and air pressure (**Fig.4**) are shown. Solid lines in Fig.3 correspond to calculated velocities of laser-supported detonation wave (LSDW) /17/, dashed lines are the results of numerical simulations using "ATLANT_C"-code /18/.

The most part of laser radiation (up to 90%) penetrated to the target. At lower air pressures $p_0<0.1$ *bar* (Fig.4) the absorption in air reduced and did not influence on SW velocity ($\cong$ *30 km/s*).

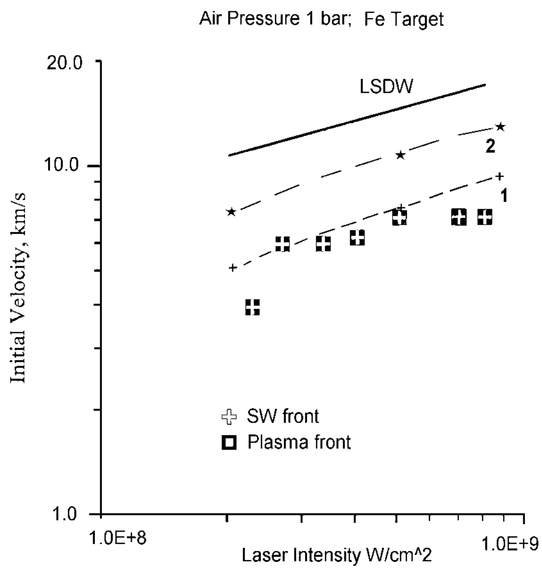


Fig.3. The dependence of plasma front velocity from laser intensity. Dashed lines – the results of numerical simulations with allowance for ionization processes (1) and when Z=const (2).

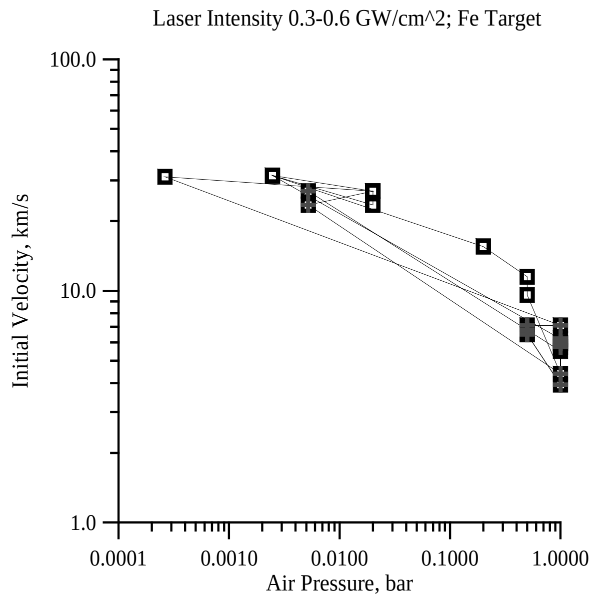


Fig.4. The dependence of plasma front velocity from gas pressure. Laser intensity is 0.3-0.6 GW/cm^2.

5. Conclusions.

The technique proposed here for exiting shock waves in gases and compression waves in liquids by KrF laser radiation has some advantages in comparison with the conventional technique used in experiments with nanosecond laser pulses. The typical scale of gas-dynamic flow is of the order of 1 mm, and the duration of processes reaches several microseconds. This enables one to use conventional optical techniques to observe the spatial and time evolution of instabilities at the interfaces between different media and to study the supersonic gas flow past objects of complex shape. One can also study the effect of a repeated initiation of acceleration by several shock waves, which are produced by a tandem of laser pulses.

The advantages of laser shock tube in comparison of ordinary shock tube are

1) the generation of large pressure pulse (as a result high Mach number ≥ 20 shock wave) and

2) the economy of noble gases and other supplies.

The preliminary experiments show that in contrast of CO_2 laser-plasma experiments the radiation of UV KrF laser comes through atmosphere and reach condense target. It allows to carry out experiments with solid targets and background gases with the initial pressure is about 1 bar.

Acknowledgments.

We are grateful to Prof.V.F.Tishkin and Dr.A.B.Iskakov for help of numerical modeling of laser plasma jet formation and shock wave expansion in Air (see Fig.3).

This work was supported by the Russian Foundation for Basic Research, project N 01-01-00023.

References.

[1] G.Taylor Proc. Roy. Soc., A201, 192, (1950)

[2] R.D.Richtmyer, Commun. Pure Appl. Math.,13, 297, (1960)

[3] E.E.Meshkov, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gasa, 5, 151, (1969)

[4] J.Haas, B.J.Sturtevant. Fluid Mech., 1281, 41, (1987)

[5] A.N. Aleshin, E.V.Lazareva, S.G.Zaytsev et al. Dokladi Akademii Nauk SSSR, 310, 1105, (1990)

[6] K.I.Read, Physica D, 12, 45, (1984)

[7] Yu.A. Kucherenko et al., In: Proc. of 3rd International Workshop on Physics of Compressible Turbulent Mixing at Royaumont, France, 1991, p.427

[8] C.J.Pawlew et al. Phys. Plasmas, 4, 1969, (1997)

[9] D.H.Kalantar et al., Phys. Plasmas, {4}, 1985, (1997)

[10] R.F.Benjamin. In: Proc. of 3rd International Workshop on Physics of Compressible Turbulent Mixing at Royaumont, France, (1991)

[11] A.Lebedev et al., In: Proc. of 5th International Workshop on Physics of Compressible Turbulent Mixing at Stony Brook, USA, 1995, p.213

[12] V.D.Zvorykin, I.G.Lebo Quantum Electronics, 30, 540, (2000)

[13] I.G.Lebo et al. J. Russ. Laser Research, 15, 136, (1993)

[14] I.G. Lebo et al., In: Proc. of 6th International Workshop on Physics of Compressible Turbulent Mixing at Marcellie, France, 1997, Institute Universitaire des Systemes Thermiques Industriels 1997, p.312

[15] V.D.Zvorykin, I.G.Lebo, Laser and Particle Beams, 17, 69, (1999)

[16]. V.A.Danilychev, V.D.Zvorykin. In: Trudi Fiz. Insit. P.N.Lebedeva Akad. Nauk SSSR, {142}, 117, (1983)

[17] Yu.P.Raizer Sov. Phys.-JETP, 21,1009, (1965)

[18] A.B.Iskakov, I.G.Lebo, V.F.Tishkin. J. Russ. Laser Research, 21,247, (2000)