Study of extreme states of matter at high energy densities and high strain rates with powerful lasers

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Abstract
In this paper, a review of the most important results of the experimental studies of thermonuclear plasma in conical targets, the generation of shock waves and of spallation phenomena in different materials is presented, all of which have been carried out at the laser facilities of the A M Prokhorov General Physics Institute RAS since 1977.

Keywords: thermonuclear plasma, strong shock waves, conical targets

1. Introduction
The investigation of the properties of matter under extreme conditions (high temperatures, high pressures, high strain rates) has been carried out at the A M Prokhorov General Physics Institute (GPI) RAS, in collaboration with other institutes of the Russian Academy of Sciences (the Joint Institute for High Temperatures (JIHT) RAS, the Institute of Problems of Chemical Physics (IPCP) RAS, the A A Dorodnitsyn Computing Center RAS, and the L D Landau Institute of Theoretical Physics RAS) as well as the Moscow Institute of Physics and Technology since 1977 [1–30]. To this end, the unique laser facilities based on neodymium glass (wavelength $\lambda = 1.06 \mu m$, pulse duration $\tau = 20$ ns, energy up to 100 J per pulse, and laser irradiation intensity up to $10^{11}$ W cm$^{-2}$). An encouraging result was obtained immediately: the neutron yield of the DD reaction in every experiment exceeded $10^4$ particles per pulse [1, 2]. A photograph of a microsection of the target after laser action is shown in figure 1. A spherical cavity in the vertex of the cone appeared as a result of the expansion of gas compressed at pressures of up to 2 TPa when the generated shock wave had converged at the vertex (a zone of cumulative explosion is shown schematically at the cavity center). During this investigation, the following values were measured: the velocity of the target envelope, the part of the laser energy deposited into the target, the envelope evaporation rate, the ablation pressure acting on the envelope, and the neutron yield as a function of the initial conditions over a wide range of its variation.

The large number of experiments enabled statistical treatment to be carried out, and meant that important conclusions could be made about the heating process of thermonuclear plasma in a target [9, 10]. It was ascertained that the amount of thermonuclear fuel heated up to temperatures of 10 keV comes to 0.15% of the total mass of the initial filling of the target. It was supposed that in conical targets, cumulative phenomena in the central part of the cone played a crucial role

2. The generation of thermonuclear plasma in conical targets
2.1. Laser action on conical targets
Experiments on the generation of thermonuclear plasma in conical targets have been carried out at the laser facility ‘Phoenix’ based on neodymium glass (wavelength $\lambda = 1.06 \mu m$, pulse duration $\tau = 20$ ns, energy up to 100 J per pulse, and laser irradiation intensity up to $10^{11}$ W cm$^{-2}$). An encouraging result was obtained immediately: the neutron yield of the DD reaction in every experiment exceeded $10^4$ particles per pulse [1, 2]. A photograph of a microsection of the target after laser action is shown in figure 1. A spherical cavity in the vertex of the cone appeared as a result of the expansion of gas compressed at pressures of up to 2 TPa when the generated shock wave had converged at the vertex (a zone of cumulative explosion is shown schematically at the cavity center). During this investigation, the following values were measured: the velocity of the target envelope, the part of the laser energy deposited into the target, the envelope evaporation rate, the ablation pressure acting on the envelope, and the neutron yield as a function of the initial conditions over a wide range of its variation.

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Subsequent theoretical investigation using two-dimensional numerical simulations [13, 15] has validated this supposition. As the simulations show, the main neutron yield happens during the stage when the shock wave, which is generated in deuterium with the target envelope movement, converges at the vertex of the cone cavity (figure 2).

2.2. Explosive action on conical targets

After successful experiments with laser action on conical targets, the idea was suggested to use such targets for the quasi-spherical shock compression of thermonuclear plasma. New experiments were carried out by collaborators from GPI RAS and IPCP RAS [3]. For the experiments, traditional explosive planar-projectile systems were used at aluminum flyer plate velocities of up to 5.4 km s$^{-1}$ with a simple scheme and up to 18 km s$^{-1}$ with the use of a layer system. A stable yield of up to $10^7$ neutrons per shot was measured. For an understanding of the possible mechanisms of deuterium-gas heating, both analytical calculations and numerical simulations were performed for the processes being studied. The problem is sufficiently complex; it has not been fully solved up to now. An analytical evaluation gives 6 TPa for the maximum value of deuterium pressure in the vertex of the cone, as well as a compression ratio of 3400 (the ratio of density to its initial value), a temperature of 0.24 keV and a neutron yield of $10^5$. It seems that the discrepancy in the neutron yield and the experimental value is connected to the complex structure of real hydrodynamic flow in the cone, for example, with Mach waves or jet streams. The possibility of jet stream formation is confirmed by the two-dimensional simulations of hydrodynamic processes in the conical targets (without gas filling) [7] at the flyer plate with a velocity of 5.4 km s$^{-1}$ and two thicknesses (2 and 0.25 mm). In both cases, the plate is made of aluminum, the target is lead, the cone base diameter is 2 mm, and the cone angle is $28^\circ$. The results of the simulations are shown in figure 3.

In the first case (thicker flyer plate), one can suppose that the gaseous deuterium placed in the target will be compressed and heated quasi-adiabatically. In the second case (thinner flyer plate), a cumulative effect becomes apparent. It seems that the junction of jet streams initiates a shock wave in the gas, and the collapse of the wave leads to plasma formation with thermonuclear synthesis conditions.

2.3. Resuming remarks

More details regarding the use of conical targets in the investigation of inertial thermonuclear synthesis can be found elsewhere [12, 20].

Recently, interest in conical targets has been renewed in connection with the idea of using miniature versions for the fast ignition of laser thermonuclear spherical targets [31].

The use of conical targets for graphite-to-diamond transformation in a convergent shock wave was proposed in [32], investigated with numerical simulations in [33, 34] and with explosive experiments in [35]. As a result of the simulations, an unexpected feature of convergent shock waves in porous media was discovered [36–38], the like of which was particularly revealed in the threefold increase of maximum pressure in the target following a decrease of the initial density of the graphite cone from 2.26 to 1.7 g cm$^{-2}$.

Conical targets are complex objects for experimental study because the diagnostics of hydrodynamic processes within them is difficult. However, the current development of numerical methods allows the modeling of physical processes in conical targets over a wide range of initial conditions for the
3. The laser generation of strong shock waves

One more direction in the investigation at GPI RAS is in the purpose of the realizing of the required characteristics of thermonuclear plasma in experimental conditions.

3.1. The dependence of ablation pressure upon the intensity of laser irradiation

The problem of determining the ablation pressure on an irradiated surface as a function of the intensity of laser irradiation has been solved experimentally [11]. This function is widely used in experiments on the laser generation of shock waves. In order to do so, different methods were applied such as the measurement of the arrival time of the shock wave on the rear surface of the target, interference and the Doppler registration of the movement of foils in cylindrical and conical channels [8]. As a result, a dependence of ablation pressure $P_a$ (TPa) with a laser intensity of $I_l$ (TW cm$^{-2}$) was proposed over the range from 0.04 to 1000 TW cm$^{-2}$:

$$
P_a = \begin{cases} 
1.2 \times 10^{-2} I_l^{1/3} \lambda^{-2/3} & \text{at } 4.3 < I_l \leq 1000, \\
[12 A/(2 Z)]^{1/16} & \\
1.62 \times 10^{-1} I_l^{1/2} \lambda^{-3/4} & \text{at } 0.8 < I_l < 4.3, \\
1.7 \times 10^{-1} I_l^{1/2} \lambda^{-3/4} & \text{at } 0.04 < I_l \leq 0.8,
\end{cases} \quad (1)$$

where $\lambda$ is the laser irradiation wavelength ($\mu$m), and $A$ and $Z$ are the atomic mass ($u$) and the atomic number of the target material respectively.

3.2. The use of lasers in the study of spallation phenomena in matter

At GPI RAS, an experimental study of spallation phenomena in different materials was started from an investigation of the possibilities of using the aluminum–magnesium alloy AMg6M for the counter-meteor defense of the spacecraft Vega-1 and Vega-2. At that time, the laser facilities ‘Kamerton’ and ‘Sirius’ were used for the purpose. Today, using the laser ‘Kamerton-T’, spallation phenomena are studied for aluminum, tantalum, copper, tungsten, palladium, lead, silicon, graphite, synthetic diamond and polymethylmethacrylate [16, 17, 19, 21–30]. Photographs of the rear sides of the targets of some materials after laser action are shown in figure 4.

3.3. The method for determining the spall strength and strain rate at negative pressures

To determine the spall (tensile) strength $\sigma_{sp}$ of a material at a strain rate $V/V_0 = d(V/V_0)/dt$ ($V_0$ is the initial specific volume, $V$ is the rate of specific volume $V$ change with time $t$), an approach has been used based on measuring the depth of the spall cavity $h$ after laser pulse action and a subsequent modeling of the shock wave process in the sample under study. To calculate the values $\sigma_{sp}$ and $V/V_0$, a one-dimensional computational code based on the Courant–Isaacson–Rees scheme for hydrodynamic equations [40, 41] was used. The code is supplemented with wide-range equations of state for the materials in question [42–47]. In the calculations, it was suggested that the time profile of the ablation pressure pulse on the irradiated surface of the target...
replicates the profile of the laser pulse intensity. The relation between the ablation pressure amplitude $P_a$ and the maximum intensity of the laser irradiation $I_l$ is determined by equation (1).

During the experiments, the value of the laser pulse intensity at which the spallation takes place is registered. Then, a numerical simulation of the propagation of the shock wave through the target is carried out. The results of a variant of the simulation are shown in figure 5. The moment of spallation $t_{sp}$ is determined by measuring the velocity of the spall layer using an electric contact gauge. The spall strength is determined as $\sigma_{sp} = -P(t_{sp})$ on a calculated graph of the pressure at the spall plane as a function of time (see figure 5(a)) taking into account the value $t_{sp}$. The strain rate is determined from the graph of density as a function of time (see figure 5(b)) by a derivation of $\rho(t)$ with respect to time: $V/V_0 \approx \rho(t_{sp})/\rho_0$, where $\rho_0 = 1/V_0$, $\rho$ is the rate of density change with time.

Figure 4. Photographs of the rear sides of the targets obtained using a scanning electron microscope: (a) aluminum–magnesium alloy AMg6M, (b) aluminum, (c) tungsten, (d) silicon, (e) synthetic diamond, (f) graphite.
3.4. The spall strength of aluminum targets

The results of the measurements of spall strength as a function of strain rate for aluminum and the aluminum–magnesium alloy AMg6M [25] are shown in figure 6. One can see that at a strain rate of 56 $\mu s^{-1}$, the dynamic strength of both materials achieves an ultimate value of about 10.5 GPa according to the equation-of-state model [42]. The theoretical estimations of the full-potential linearized muffin-tin orbital method [48] give the ultimate strength of aluminum as 11.7 GPa. So, the experimental value of the ultimate strength of aluminum is 11% less than the theoretical evaluation [48]. In figure 6, the previous data [49, 50] for the two materials is also presented.

In experiments with aluminum targets, besides direct laser action, irradiation by the 2.5 ns pulses was used for the acceleration of flyer plates (Al) with a thickness of 8 and 15 $\mu m$ to impact the targets [21, 22]. This allowed the shortening of the shock wave pulse down to 1.4 ns as well as advancement to the higher strain rate domain.

3.5. The spallation of carbon modifications

The results of investigation about the spall strength upon the strain rate for diamond [26–28] and graphite [29, 30] are presented in figure 7. In experiments with synthetic diamonds, the value $\sigma_{sp} \approx 16.5$ GPa at a strain rate of 70 $\mu s^{-1}$ is achieved, which is 24% of the theoretical evaluation of the ultimate strength 69.5 GPa according to the equation of state [43]. In the case of graphite, at the strain rate of 10 $\mu s^{-1}$, a spall strength of $\sigma_{sp} \approx 2.1$ GPa is obtained, which is 64% of the ultimate theoretical value 3.27 GPa from the equation of state for graphite [43].

3.6. The polymorphic transformations of diamond and graphite

The phase composition of carbon near the spall region in targets of graphite [29] and synthetic diamond [27] was studied with the Raman spectroscopy method using the spectrometer LabRam HR (Horiba) with a spectral resolution of 0.5 cm$^{-1}$. Evidence was shown that near the spall region of
the polycrystalline diamond targets, part of the material transforms into a disordered graphite-like phase at the deformation and spallation of the diamond layer.

The Raman spectra in the spall region of the graphite targets indicate the well-re-crystallized structure of the graphite with small amounts of disordering and a higher degree of crystallinity than displayed initially.

3.7 The spall strength of polymethylmethacrylate targets

Direct laser interaction and laser-driven thin foils (shock impact) were used for the investigation of spallation phenomena in polymethylmethacrylate (PMMA) targets in cases with high strain rates [23]. Aluminum foils with a thickness of 8 and 15 μm were used for the impact. The mass and velocity of the laser-driven foils after laser ablation and acceleration were determined by the method of measuring the foil deceleration in a gas atmosphere. Based on the experimental data, we determined the spallation plane position (figure 8) and the time taken for the spall layer to arrive at an additional electric-contact gauge located next to the rear side of the target. Then, the spall strength and strain rate were calculated numerically using a hydrodynamic code with a wide-range semi-empirical equation of state for PMMA [43]. The results of the experiments are shown in figure 9.

It is shown that the ultimate spall strength of PMMA has been reached. The ultimate strength value obtained in our experiments appears to be slightly below the theoretical estimation of 1.06 GPa from the used equation of state.

As a result of the experiments, we have shown for the first time that the ultimate spall strength of PMMA (about 1 GPa) is achieved in the case of a 3 μs⁻¹ strain rate.

4. Conclusion

Experimental studies at the laser facilities of the A M Prokhorov General Physics Institute RAS have made an essential contribution to high-energy-density physics and shown the possibilities of astrophysical phenomena modeling under laboratory conditions. The studies result in new data on the thermophysical and mechanical properties of some materials in laser-generated shock waves and reveal the prospects of achieving thermonuclear temperatures in conical targets [51].

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Figure 8. A PMMA target section after shock wave action (the face of the target is on the left-hand side).

Figure 9. The spall strength of PMMA versus strain rate: circles correspond to data [23]; the solid line represents a function of the spall strength of PMMA upon the strain rate σsp = 0.38(V/V0)²⁴ according to previous data [49]. The dotted line corresponds to the ultimate spall strength σm = 1.06 GPa according to the equation of state [43] for PMMA.
