Cumulative phenomena due to the collision of laser-driven projectiles related to fast ignition and astrophysical applications.

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Abstract. The results of contemporary investigations of cumulative phenomena due to the collision of projectiles laser-accelerated up to the velocities significantly higher than the sound velocity in solids are reviewed. The discussion is focused on the applications directed on the development of a concept of fast ignition by projectile impact and the laboratory modeling of astrophysical phenomena. Low-entropy acceleration of a projectile in a dense state up to “thermonuclear” velocity of the order of 1000 km/s is grounded. The parameters of extreme matter state induced by laser-accelerated projectiles collision, namely, energy flows, pressure and temperature, spontaneous magnetic field and thermonuclear neutron yield are discussed. Astrophysical phenomena due to collision of cosmic objects such as a creation of a crater by meteorite's impact, as well as the emerging of a shock wave to a star surface, and formation of jets, ionization and emission waves are considered.

1. Introduction

The study of hydrodynamic phenomena due to laser-accelerated projectile impact is of fundamental importance for, at least, two basic fields of physics. The first one is astrophysics in the section of the phenomena associated with the collision of cosmic objects with relative velocities of several tens and hundred km/s. The second one is inertial confinement fusion (ICF). High-temperature plasma may be produced in the collisions of projectiles with relative velocities from several hundreds up to 1000 km/s. The latter has recently become of great interest in connection with fast ignition [1,2], a promising ICF-approach. An impact by accelerated projectile [3-6] is effective method to ignite the preliminarily compressed ICF-target, along with the action by fast electron or ion beams.

In the present are discussed the limits of laser-driven acceleration of the projectile in a dense state as well as an impact-produced energy cumulation. Laser and projectile parameters for impact fast ignition are concluded. Among astrophysical applications are considered the possibilities of laboratory modeling of crater creation and shock wave emerging at a star surface.

2. Laser-driven acceleration of a dense matter up to thermonuclear velocity.

To accelerate a projectile in a dense state the low-entropy regime should be applied, when $I\lambda^2$-parameter (product of laser radiation intensity and wavelength) does not exceed $5\times10^{14}$ W/cm$^2$. Such a regime corresponds to inverse Bremsstrahlung absorption of laser light, when the ablation density is close to the critical plasma density. Under this conditions, the rocket model gives the following solution for the final velocity of a plane foil $u$ (measured in the units of thermonuclear velocity, 1000 km/s) and thickness $\delta$ of unablated foil (normalized to initial foil thickness, $\Delta_0$):

$$u=0.83(I\lambda^2)^{1/3} \ln \delta^{-1}, \quad \delta=1-1.9\tau(I\lambda^2)^{1/3} \Delta_0^{-1} \rho_0^{-1} \lambda^{-2}$$

(1)
In Eqs. (1) are supposed that the blow off plasma is fully ionised, the adiabatic exponent is equal to 5/3 and intensity I, pulse duration \( \tau \), initial foil density \( \rho_0 \) and wavelength \( \lambda \), together with foil thickness \( \Delta_0 \) are measured in the units of 10^{14} \text{ W/cm}^2, \text{ ns}, \text{ g/cm}^3 and \text{ \mu m, respectively. The laser pulse and projectile parameters should meet the requirements that (i) an expansion of ablated projectile matter is close to a plane motion, \( \tau<\Delta/c_\gamma \), (ii) a foil density during the period of laser pulse exceeds initial density, \( \tau<\Delta/c_\gamma \), \( (c_\gamma \text{ and } c_\beta \text{ are the sound velocities in blow off plasma at the ablation boundary and in unablated foil, respectively) and (iii) a hydrodynamic instability influence on plane foil acceleration is insignificant } \tau<\Gamma^{-1} \text{ (}\Gamma \text{ is an increment of a perturbation growth).} \text{ The sound velocities are connected by the relation } \delta=[\gamma_\beta(\gamma_\beta+1)]^{1/2}(\rho_0/\rho_0^{1/2})c_\gamma \text{ and } \delta=[2(\gamma_\beta-1)/(\gamma_\beta+1)]^{1/2}/(1/\rho_0)^{1/3}, \text{ where } \rho_0 \text{ and } \rho_0 \text{ are the critical density and initial foil density, } \gamma_\beta \text{ and } \gamma_\beta \text{ are the adiabatic exponents in unablated foil and blow off plasma. The Rayleigh-Taylor instability increment is given by the well-known formula } [7]: \Gamma=\Gamma_0/\beta k_{\text{max}} D, \text{ where } \Gamma_0=[Ak_{\text{max}}g(1+\kappa_\Delta L_\Delta)]^{1/2}; \text{ } k_{\text{max}}=2\pi/\Delta \text{ for the most dangerous mode (with respect to foil destruction); } g=v/\tau \text{ is the acceleration; } L_\Delta=\delta \tau \text{ is the density gradient length at the ablation front; the Atwood number, } A=(\rho_0-\rho_\gamma)/(\rho_0+\rho_\gamma)=1, \text{ since } \rho_\gamma<<\rho_0; \text{ the evaporation wave rate, } D=\gamma_\alpha \rho_0/\tau_\beta \text{ and } \beta=3. \text{ So, the limitation requirement for laser pulse duration is}

\[
2.210^{-7} \rho_0 A_0 \lambda^2 \left( \frac{\Delta_0^2}{\lambda^2} \right)^{-1/3} \leq \tau \leq \min \left( \frac{410^{-2} \Delta_0 \rho_0^{1/2} \lambda}{\rho_0 \lambda}, \frac{410^{-3} R_\lambda}{\lambda^2} \right)^{-1/3} \]

(2)

For the ratio } \delta=5, \text{ which corresponds to maximal hydrodynamic efficiency of the plane projectile acceleration the ultimate velocity achievable at low-entropy acceleration actually conforms to the thermonuclear velocity, and lies in the range of } (1.1-1.5) \times 10^7 \text{ km/s } (\lambda^2=1 \times 10^{14} \text{ Wcm}^{-2} \text{ pm}^2). \text{ Such a velocity corresponds to impact-produced temperature of deuterium-tritium fuel equal to } 10-20 \text{ keV. To reach the velocity of polystyrene foil of } 1000 \text{ km/s at the final density equal to initial value in the result of acceleration by the action of } 10^5 J \text{ pulse of the third Nd-laser harmonic radiation the laser pulse duration, beam radius and foil thickness should be chosen as } 1.2 \text{ ns, } 380 \mu \text{ m and } 27 \mu \text{ m.}

3. Impact-driven extreme state of matter

Inelastic collision of a projectile accelerated up to super sonic velocity with a massive wall initiates the strong shock waves propagating from the contact boundary in the both objects. The wave's velocities in projectile \( D_p \) and in wall \( D_w \), the pressure behind their fronts \( P_i \), the duration of impact \( t_i=\Delta/D_p \), which is the time of shock wave propagation through the projectile, and the impact efficiency, which is equal to the fraction of projectile energy transferred to the wall, are given by the solution [4]:

\[
\begin{align*}
D_p &= D_t (\tilde{\alpha} p + 1)/(\tilde{\alpha} t + 1) = \gamma p + 1, \quad P_i = (\gamma p + 1) \rho_p u_p^2 / (2(1+\alpha)^2), \quad \rho_p = \rho_0 \gamma p + 1, \quad \rho_p = m_n, \quad \rho_p = 0.1 \text{ g/cm}^3, \quad \gamma p = m_n/3k_B=0.75 \text{ keV (here } m_n \text{ is nucleon's mass, and } k_B \text{ is Boltzmann constant). The impact time } t_i \text{ is closed to } 0.03 \text{ ns. So, the impact-produced neutron yield } N \times \pi R_d \times (\rho_\alpha A)^2 < \gamma V >_{DD} |T=0.75 \text{ keV}/4u_p \text{ is estimated as } 10^6 \text{ neutronSHOT. The agreement with}
\end{align*}
\]


experimental results confirms the dynamics of inelastic impact given by Eqs. (3). At the projectile velocity \( u_p = 1000 \text{ km/s} \), the DD-neutron yield could be risen up to \( 10^8 - 10^9 \text{ neutron/shot} \).

The impact-generated spontaneous magnetic field is an interesting phenomenon. The magnitude of magnetic field due to excitation of thermo-current is estimated on the base of following relations

\[
B = \frac{c}{e} \frac{\partial T_e}{\partial t} \ln n_e = t_i C_T e / c L_T L_n - \frac{1}{2} A (\gamma - 1) u_p / Z (\gamma + 1) \Delta, \text{ MGs (4)}
\]

Here \( c \) and \( e \) are the light speed and electron charge; electron temperature, \( T_e \) is proposed as equal to ion one since in considered conditions the energy relaxation time \( \tau_{\text{nr}} \approx 10^{12} \text{ s} \) is less than the duration of impact \( t_i = 10^{-11} \text{ s} \); \( n_e \) is electron density, \( L_T \) and \( L_n \) are the size scales, which define the plasma temperature and density gradients, \( L_T \sim L_n \sim A_m \); \( A \) and \( Z \) are the atomic number and charge of plasma ions; \( u_p \) and \( \Delta \) are measured in 1000 km/s and \( \mu m \). So, the magnetic field of several hundred MGs may be generated at the impact of the heavy metal projectile accelerated up to thermonuclear velocity.

4. Impact fast ignition

Igniting projectile parameters could be obtained from the analysis of impact-produced shock wave dynamics given by Eqs. (3). The first requirement is the energy equation which means that during the period of impact the shock wave heats the wall's layer up to ignition temperature, \( T_{\text{ig}} = 10 \text{ keV} \) and the second one is the equality of shock-heated wall mass to \( (\rho \Delta)_{\text{ig}} \) – parameter which is equal to 0.3 g/cm\(^2\):

\[
\rho_p u_p^2 \Delta t_i / 2 = c_v T_{\text{ig}} \gamma T_{\text{ig}} / t_i, \quad \rho_p D T_{\text{ig}} = (\rho \Delta)_{\text{ig}} \text{ (5)}
\]

Here \( c_v \) is specific heat of deuterium-tritium plasma. Substitution of (3) in (5) gives the velocity and mass of projectile which ignites the deuterium-tritium fuel with density \( \rho_f \) (\( \rho_f > \rho_p \), \( \gamma_f = \gamma_p = 5/3 \))

\[
u_{\text{ig}} = 10^3 \left( \rho_f / \rho_p \right)^{1/2} \text{ km/s,} \quad \rho_p \Delta t_{\text{ig}} = 0.3 (\rho_p / \rho_f t_i)^{1/2} \text{ g/cm}^2 \text{ (6)}
\]

For DT-fuel density, \( \rho_f = 200 \text{ g/cm}^3 \); \( u_{\text{ig}} = 30000 \text{ km/s,} \Delta_{\text{ig}} = 450 \mu m, \quad \eta_{\text{imp}} = 0.06 \text{ at } \rho_f = 0.2 \text{ g/cm}^3 \) (DT-ice); \( u_{\text{ig}} = 3000 \text{ km/s,} \Delta_{\text{ig}} = 60 \mu m, \eta = 0.31 \text{ at } \rho_f = 10 \text{ g/cm}^2 \) (Au). In the case of heavy-material projectile the radiative processes should be studied to take into account corresponding energy losses.

To provide an acceptable impact efficiency, 0.3–0.4, the projectile density must be close to 10–20 g/cm\(^3\). There are several approaches to go to this goal. As a "freely accelerated projectile" may be considered [4]: 1) heavy-material or composite projectile consisting of heavy-material impactor and light-material ablator, 2) compressed-in-flight projectile accelerated by a time-profiled pulse. The main directions of research here are two-dimensional effects of laser-driven acceleration, impact-initiated emission, compression-in-flight effectiveness. Another approach is a "cone-guided projectile" [5,6]. The main unclear problems are the effectiveness of a cone-guided compression and energy losses in a cone wall. The cone-guided acceleration by profiled laser pulse looks quite attractive.

At the fuel density of 200 g/cm\(^3\) the expressions (1) and (6) give the following results for matched parameters of the third Nd-laser harmonic pulse and composite igniting projectile (beryllium ablator and gold impactor): pulse energy, 120 kJ; intensity, \( 510^{14} \text{ W/cm}^2 \); duration, 70 ns; thickness of Be-layer, 1600 \( \mu m \) (totally evaporated before impact); thickness of Au-layer, 30 \( \mu m \) (non-evaporated before impact); ratio of Be-layer and Au-layer masses, 7.8; projectile radius, 40 \( \mu m \).

5. Astrophysical phenomena modeling

The physics of cosmic objects collision may be studied in experiments on laser-driven projectile impact. That fact illustrated by the results of recent experiments [9] on laser-accelerated projectile collision with massive target performed on the PALS/Asterix iodine-laser (the energy, 100-500 J; pulse duration, 0.4 ns; beam radius, 100–1200 \( \mu m \)). The features of crater creation were discovered such as the dependence of crater longitudinal and transverse sizes as well as energy transmitted from projectile to the wall on the projectile sizes, density, composition (aluminum, copper, plastic, lead and others), form (disk and cone) and projectile velocity. Projectile velocity varied in the range of 50 – 150
km/s. Measurements together with numerical simulation results defined the impact efficiency of the collision of Al-disk with Al-wall as 17-22 % at the projectile velocity of 60-100 km/s.

Another interesting phenomenon investigated in PALS/Asterix impact-experiments is the impact-produced jet on the rear side of a impacting disk projectile. The existence of such a jet with a longitudinal size of a several nm significantly larger than transverse size of 100-200 µm was observed during the period of a several tens of nanoseconds significantly longer than impact time (several fraction of nanosecond). Generation of such a jet could be associated with the astrophysical phenomenon of a shock wave emerging at star surface. Laser-driven impact introduces the new cumulation features due to opposite directions of density and velocity gradients of blow off plasma of impacting projectile. At the initial stage, a high-speed shock wave from dense projectile propagates on a low-speed blow off plasma. Shock wave cumulation due to density decreasing leads to acceleration of wave up to the velocity $D_f$ which is close to the utmost velocity of shock wave emerging to vacuum

$$D_f = D_p \left( \frac{2 \gamma_p}{(\gamma_p - 1)} \right)^{1/2} \left[ \frac{(\gamma_f + 1)}{(\gamma_p + 1)} \right]$$

Here $P_f$ is the pressure in the emerging shock wave, the velocity of impact-produced shock wave in projectile $D_p$ is given by Eq. (3), $\rho_p$ and $\gamma_p$ are the density and adiabatic exponent in blow off plasma. Thereon as the shock wave reaches the region of blow off plasma where the velocity is close to shock wave velocity $D_s$ the character of the motion changes. The front of shock wave transforms to the front of quasi-stationary motion of matter of heightened density. Such a motion actually corresponds to jet propagation observed in the experiments. At the measured velocity of disk-projectile $u_p=610^6$ cm/s, Eq. (7) gives the utmost velocity as $D_s \approx 8.210^6$ cm/s that is close to the velocity of jet front registered in the experiments. At the measured electron density of jet plasma $(1-2)10^{10}$ cm$^{-3}$, Eqs. (7), give the pressure and temperature of jet plasma close to $15-20$ Mbar and $100-200$ eV. So, the cumulation of shock wave in blow off plasma could initiate the secondary ionization process in impact-produced jet. Jet area mass is, approximately, $310^4$ g/cm$^2$ that is close to the mass of unablated part of projectile.

6. Conclusion

The experiments with Gekko/HIPER laser on the record-breaking foil acceleration and impact-produced neutron generation, as well as the experiments with PULS/Asterix laser on a demonstration of high efficiency of impact energy transfer emphasize the development of impact fast ignition.

An extreme state of matter could be reached as a result of laser-accelerated projectile collision. The pressure of more than 1 Gbar and spontaneous magnetic fields of more than 100 MGs of amplitude could be obtained under the laboratory conditions. DD-neutron yield of the order of $10^3 - 10^4$ could be generated in the result of impact by (CD), disk accelerated by laser pulse with the energy of $10^3$ J.

The astrophysical phenomena due to the collision of cosmic objects could be modeled in the laboratory experiment with the using of laser-accelerated projectile. Among them there are the crater creation due to impact of meteorite, as well as the emerging of a shock wave on a surface of star, and the formation of jets, ionization and emission waves produced by such a shock wave.

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