

## Gas-dynamic stage of laser plasma evolution: 2D simulation

V. MAZHUKIN, I. SMUROV\* and G. FLAMANT\*\*

*Institute of Mathematical Modeling, Russian Academy of Sciences, Miusskaya Square 4, 125047 Moscow, Russia*

*\* Ecole Nationale d'Ingénieurs de Saint-Etienne, 58 rue Jean Parot, 42023 Saint-Etienne cedex, France*

*\*\* Institut de Science et de Génie des Matériaux et Procédés, CNRS, BP. 5, 66125 Font-Romeu cedex, France*

### I. INTRODUCTION

The evolution of laser plasma about the threshold values (for plasma formation) of radiation intensity ( $q_0 = 5 \cdot 10^7 - 5 \cdot 10^8$  W/cm<sup>2</sup>; laser wavelength  $\lambda = 1.06$   $\mu\text{m}$ ) in nitrogen with pressure variation in the range of 3-10 MPa, is analyzed. The specific point of the process under consideration is that along with the hydrodynamic mechanism of energy transfer, the mechanism of radiative transport is essential; heat conduction processes are of little consequence. Besides, if the laser pulse is comparatively long (about 0.5  $\mu\text{s}$ ), and the radius  $r_f$  of the focal spot is comparatively small (about 300  $\mu\text{s}$ ), the radial expansion of laser induced plasma need to be taken into account, that leads to 2D problem. It is assumed that the condition of local thermodynamic equilibrium takes place in laser produced plasma.

### II. RESULTS AND DISCUSSION.

The mathematical model of the process comprises the system of 2D axisymmetric equations of radiative gas dynamics. Laser radiation is incident along the  $z$  axis; laser pulse has a rectangular time-profile and Gaussian spatial distribution. It is assumed that the preliminary specified hot region located along the specimen surface is 15  $\mu\text{m}$  thick, and its temperature is 1.8 eV. At the beginning of the pulse, intense absorption of laser radiation occurs only in the hot region and causes a strong gas dynamic expansion of the material, therewith entailing the excitation of a shock wave in a cold gas.

A. HIGH PRESSURE OF AMBIENT ATMOSPHERE ( $P_0 = 10$  MPa). Laser radiation (power density  $5 \cdot 10^7$  W/cm<sup>2</sup>) rapidly raises the temperature and pressure in the hot region. By the time  $t = 5$  ns, the pressure reaches a maximum of  $6 \cdot 10^2$  MPa. Later, despite the temperature growth, the pressure in the hot region falls down because the intensive gas dynamic expansion reduces the material density. The shock wave excited in these conditions reaches a maximum velocity  $v = 1.3$  km/s at time  $t \approx 10$  ns (Figure 1). The maximum temperature  $T_{sw}$  of the gas of the shock wave reaches 0.36 eV, which is insufficient to initiate intensive absorption of laser radiation. The shock wave is in fact transparent to laser beam, so the conditions are unfavourable for the generation of a laser-supported detonation wave that could effectively shield the target. Since the shock wave velocity  $v_{sw}$  is higher than the velocity of the plasma front,  $v_{pf}$ , the shock wave breaks away from the hot region. The absorption of radiation occurs near the hot region at about 50  $\mu\text{m}$  from the target. The shock wave decoupled from the energy source begins to decay, its speed and temperature fall rapidly, and by the time  $t = 0.533$   $\mu\text{s}$  the shock wave dissipates, leaving behind a subsonic perturbation site. Conditionally, the stage of plasma formation terminates at  $t = 0.533$   $\mu\text{s}$ , when the gas dynamic velocity becomes lower than the sound velocity.

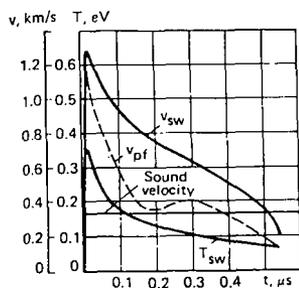


Fig.1. Maximum temperature and speed of a shock wave in gas versus time.

The gas dynamic problem initially is practically one-dimensional, but after a time of about  $0.1 \mu\text{s}$  the plume extends radially at a rather high speed, and the motion becomes two-dimensional. Since hot layers of nitrogen shield laser radiation from the target, near surface there forms a plasma layer whose temperature is much lower than that of the adjacent upper layer. Two factors are responsible for the shape of the hot region as well as for the shape of the cold region adjacent to the surface: (a) gas dynamic motion; (b) almost complete absorption of laser radiation. The temperature of the region adjacent to the surface gradually falls from  $1.8$  to  $1.1 \text{ eV}$  due to shielding of laser radiation and gas dynamic expansion. Starting from  $t \approx 15 \text{ ns}$ , plasma products become almost transparent to laser radiation; it is mainly the flux of laser radiation alone (whose incident power density  $q_e$  reaches  $10^5 \text{ W/cm}^2$ ) that interacts with the target surface. The maximum temperature of the hot region comes to  $3.6 \text{ eV}$  and does not exceed this limit because the hot region begins to emit radiation much more intensely.

The calculated data show that the area of heat affected zone on the target's surface is a few times larger than the size of focal spot of incident radiation. As follows from the simulation, the process of propagation of plasma products at the initial stage of interaction is transient in character: it progresses from excitation of laser-supported detonation to slow burning. Although the laser-supported detonation process does not influence on, gas dynamic forces contribute markedly to the plasma wave excitation (Figure 2). The amount of energy emitted from the hot region and absorbed by cold nitrogen grows with time, while the amount of energy that goes into gas heating through gas dynamic compression decreases.

**B. DECREASE OF PRESSURE OF AMBIENT ATMOSPHERE ( $P_0=3\text{MPa}$ ).** Initially the process of plasma excitation is similar to that observed at  $10 \text{ MPa}$ . Incident laser radiation, mainly absorbed in the hot zone, leads to an intensive dissipation of the hot plume, followed by the generation of a supersonic wave in time  $t \approx 10 \text{ ns}$ , which propagates into the cold gas. The velocity  $v_{sw}^{\text{max}}$  of the shock wave along the  $z$  axis at  $r=0$ , temperature  $T_{sw}^{\text{max}}$ , and density  $\rho_{sw}$  are  $1.9 \text{ km/s}$ ,  $0.36 \text{ eV}$ , and  $6.1 \cdot 10^{-2} \text{ g/cm}^3$ , respectively.

The profiles of  $T$ ,  $p$ , and  $\rho$  of the plasma cloud at  $t=0.1; 0.2; 0.3;$  and  $0.4 \mu\text{s}$ , with the shock wave bounded by dash lines, are shown in Figure 3. The hot plume first extends upward along the  $z$  axis. As in the case of laser interaction in nitrogen at  $10 \text{ MPa}$ , here too the thickness  $\Delta z$  of the hot zone becomes much larger than the absorption length  $l$  of a laser light quantum because of the expansion of this zone (Figure 3a). As a result, a major fraction of laser radiation is absorbed in the upper

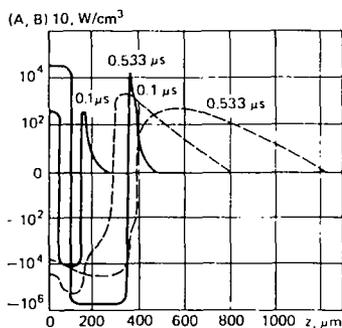


Fig.2. Spatial-temporal distribution of power components in gas due to gas dynamic forces (dashed curves) and radiation transfer (full curves) at  $r=0$ .

region of the hot zone (region II), while region I adjacent to the target surface is in fact decoupled from laser radiation and at time  $t = 0.1 \mu\text{s}$  its temperature  $T_I$  is much lower than  $T_{II}$ , as seen from Figure 3a. At  $t = 0.1 \mu\text{s}$ , the plume extends radially at appreciable velocities. The effect of gas dynamic expansion of region II at  $t = 0.1 \mu\text{s}$  is quite apparent. From this time on, the process of plasma formation at 3 and 10 MPa are no longer similar. In view of a lower gas density at 3 MPa, the hot plume in region II dissipates at  $t > 0.1 \mu\text{s}$  to such an extent that it becomes transparent to laser radiation. The laser pulse now efficiently couples the region I where the nitrogen density  $\rho_I$  is higher than  $\rho_{II}$  and, hence, the absorptivity is higher too. The rate of expansion of region I grows fast. The profiles of velocities  $v(z)$  at  $r = 0$  are shown in Figure 4, where the region of plume dissipation exhibits a second peak; the first one corresponds to the speed of the shock wave.

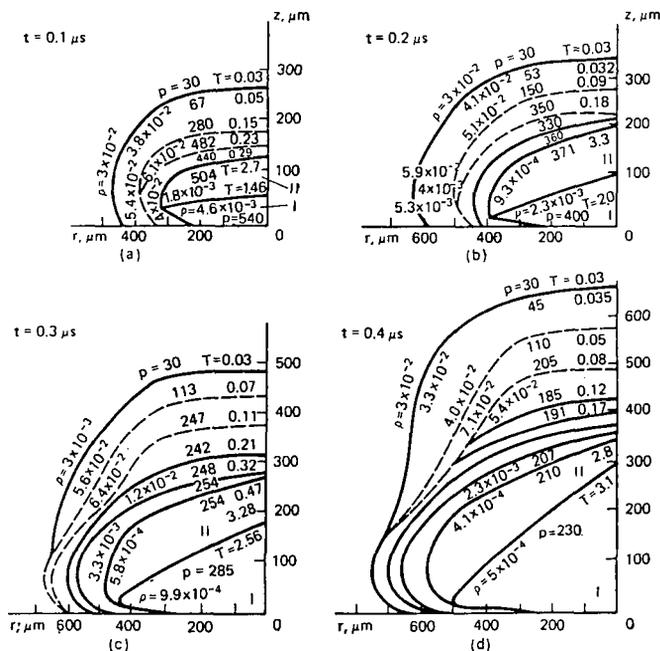


Fig.3. Profiles of temperature, density, and pressure of plasma at  $t = 0.1; 0.2; 0.3; 0.4 \mu\text{s}$ .

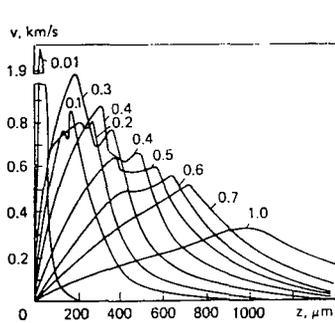


Fig.4. Velocity profiles  $v(z)$  at  $r = 0$  with time ( $\mu\text{s}$ ) as parameter.

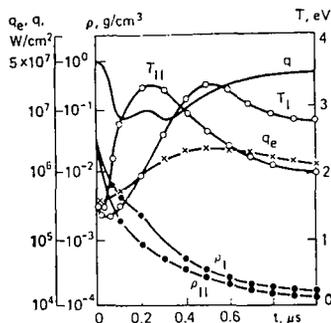


Fig.5. Time dependence of temperatures  $T_I$  and  $T_{II}$ , plasma densities  $\rho_I$  and  $\rho_{II}$ , total power density  $q$ , and incident irradiance  $q_e$  at the target surface.

By the time of the order of  $0.3 \mu\text{s}$ , the spread velocity  $v$  of the hot zone approaches a maximum of  $1.1 \text{ km/s}$  and exceeds the shock wave velocity  $v_{\text{sw}}$ , which is around  $0.75 \text{ km/s}$  (Figure 3c). Nevertheless, the second shock under the first does not appear since the plume in region I disperses into region II where the density is lower. The density of the gas within the confines of the shock wave grows from  $0.59 \text{ g/cm}^3$  at  $t=0.2 \mu\text{s}$  to  $0.71 \text{ g/cm}^3$  at  $t=0.4 \mu\text{s}$  (Figure 3d).

The temperature  $T_{\text{II}}$  (Figure 3) climbs to a maximum of  $3.6 \text{ eV}$  at  $t=0.18 \mu\text{s}$  and then drops to  $2.0 \text{ eV}$  at  $t=1 \mu\text{s}$  as the plume releases the absorbed energy and attenuates the laser beam to a less extent. The temperature  $T_{\text{I}}$  first decreases at  $t=0.1 \mu\text{s}$  because of the gas dynamic dissipation, but later, as region II gets more transparent and region I absorbs more laser energy, this temperature increases (at  $t=0.2, 0.3$  and  $0.4 \mu\text{s}$ ) and reaches a maximum of  $3.6 \text{ eV}$  at  $t=0.49 \mu\text{s}$ . Late in the pulse, as the gas density decreases, the hot zone becomes more transparent, its temperature and pressure fall down, so that the amount of laser energy coupled to the target increases.

The analysis of the contributions of gas dynamic and radiative mechanisms of energy transfer on plasma formation discloses that the first one dominates at the initial stage,  $t < 0.2 \mu\text{s}$ . At  $t = 0.1 \mu\text{s}$ , the pulse energy proper that goes into gas heating is merely one tenth that resulting from the work done by the compressive forces. The energy spent on gas dynamic expansion and the plasma-released energy are approximately equal. Even at  $t = 0.3 \mu\text{s}$  this ratio changes markedly:  $50/1$  - becomes the ratio of the energies spent on heating and compression of gas; while the radiation loss becomes 4 times the loss due to expansion. At  $t > 0.8 \mu\text{s}$ , gas dynamic processes are practically negligible. However, the radiant flux delivered to the target decreases with time because of a temperature decrease in region II, as it apparent from Figure 5. The power density of laser beam leaving the region II is  $q_c \approx 10^6 \text{ W/cm}^2$ , which is almost an order of magnitude higher than that attainable at  $p=10 \text{ MPa}$ .

It is certainly of importance for laser material processing to know the estimates of laser power density  $q_e$  and and the total power density  $q(t)$  delivered to the target surface. The  $q_e$  coupled to the target surface amounts to  $3 \cdot 10^6 \text{ W/cm}^2$  and then drops to  $1.6 \cdot 10^6 \text{ W/cm}^2$ . The radius of the focal area at  $t = 1 \mu\text{s}$  is  $r_f \approx 600 \mu\text{m}$ . At  $r_f = 250 \mu\text{m}$ , the curve of  $q$  versus time has two clearly defined minima. The first one at  $t \approx 0.01 \mu\text{s}$  ( $q = 6.5 \cdot 10^6 \text{ W/cm}^2$ ) is indicative of the intensive absorption of laser radiation in region II ( $q_p \approx 0.9q$ ). The second minimum at  $t=0.3 \mu\text{s}$  ( $q = 6 \cdot 10^6 \text{ W/cm}^2$ ) results from absorption of laser radiation in region I. Later, as the hot zone becomes transparent due to a decrease in  $\rho_{\text{I}}$  and  $\rho_{\text{II}}$  to  $0.14$  and  $0.13 \text{ g/m}^3$ , respectively, the laser power density delivered to the target surface rises to  $3.9 \cdot 10^7 \text{ W/cm}^2$ . So,  $1 \mu\text{s}$  after the start of laser pulse, the laser power density delivered to the focal spot reaches about 80% and the plasma cloud does not shield the target surface at an initial nitrogen pressure of  $3 \text{ MPa}$ .

Calculations show that laser power required to sustain the plasma discharge is practically independent of pressure. The threshold value of power both at  $10$  and  $3b \text{ MPa}$  is equal to  $q = 4.4 \cdot 10^7 \text{ W/cm}^2$ .

### III. CONCLUSION.

The utilized approach describes the gas-dynamic stage of laser plasma evolution in a wide range of pressure of ambient atmosphere, and near the threshold values (for plasma formation) of intensity of laser radiation; only some illustrations were presented here. It is possible to determine : different mechanisms of plasma pattern propagation (from laser-supported detonation to slow burning); the total energy flux (including radiative component) reaching the target's surface, etc.