HEATING OF MATTER BY FOCUSED LASER RADIATION

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The heating of matter to high temperatures by laser radiation is analyzed. The emission spectrum of a solid lithium sample irradiated by a focused laser beam and the initial stages of an avalanche breakdown in air have both been investigated experimentally.

RECENT theoretical investigations[1-3] indicate that it may be possible to heat matter to high temperatures by focusing the radiation from a high-power laser on the surface of a solid. In particular,[2] it has been shown that a deuterium plasma bounded spatially by two parallel planes with an absorption coefficient $k = \alpha\rho^2 T^{-3/2}$ (the absorption is due to inverse bremsstrahlung), exhibits a self-regulating heating mode in which the plasma temperature and density increase in such a way as to satisfy the condition $kl \sim 1$ in all stages of the heating process; here l is the width of the region occupied by the plasma. The condition $kl \sim 1$ also holds when the irradiated plasma is not bounded in space and gas-dynamic motion can occur. In this case, starting from some general considerations[4] we can introduce the self-similar variable $\xi = \kappa t^{-9/8}$ into the system of hydrodynamic equations which describe the process; we then obtain the relation $T \sim q^{1/2} t^{1/4}$, $M \approx q^{1/2} t^{3/4}$ where T and M are the plasma temperature and mass respectively and q is the optical flux density.

Thus, the theoretical analysis of heating of the plasma formed by the evaporation of condensed matter indicates the possibility of obtaining high temperatures if a high-power laser is used.[1-3] However, it should be noted that a rather sharp focus obtains under most experimental conditions so that the considerations given above with respect to the self-similar solutions are violated; as a result the heating conditions are worsened because of the marked effect of gas-dynamic expansion. Another circumstance that must always be taken into account is the limitation on maximum temperature imposed by various loss mechanisms. In the present case the most important of these is evidently the electron thermal conductivity.

In contrast with the heating of solid targets, when radiation is focused in uniform media, for example in gases, the possibility of breakdown must be taken into account.[5-7] This factor is important because it sets a limit on the radiation energy that can be focused in a small volume: as the power is increased it simply means that breakdown occurs in new regions of the gas on the sides of the incident light beam. This process increases the effective volume in which the radiation energy is absorbed.

Let us consider qualitatively the motion of the breakdown boundary, assuming for simplicity that the time required for the development of the electron avalanche is less than the duration of the pulse (this point is discussed below). Let d_n be the diameter of the light beam at the focus of the objective (resulting from the divergence of the laser radiation), F the focal distance of the objective, and D the initial diameter of the beam (Fig. 1). The time dependence of the radiated power from a Q-switched laser is characteristically given by a bell-shaped curve (cf. for example, [8]). If breakdown at the focus occurs at a power I_n, breakdown at a distance l from the focus corresponds to a power $I = I_n S/S_n$, where S is the cross section of the beam at $S_n = \pi d_n^2/4$. Since $D \ll F$ and $d_n \ll D$ then $S \approx \pi(d_n + lD/F)^2/4$ and

$$l = (d_n F / D)\left[(I / I_n)^{1/2} - 1\right]. \quad (1)$$

The displacement velocity of the breakdown boun-

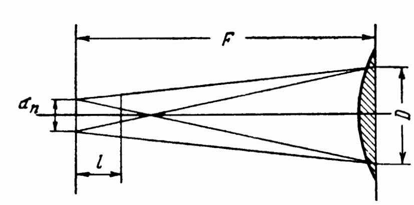

FIG. 1

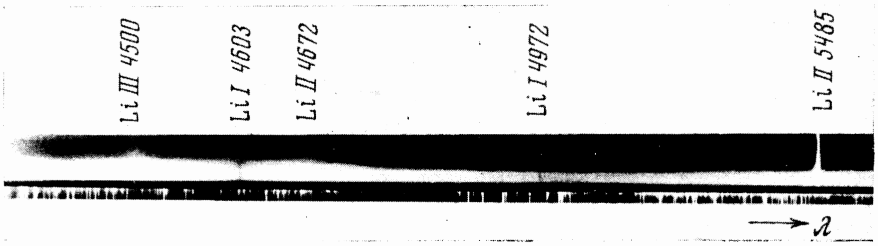

FIG. 2

dary is

$$dl / dt = (d_n F / 2DI_n^{1/2} I^{1/2}) \, dI / dt. \tag{2}$$

Let us assume that the threshold power density required for breakdown is 2×10^{11} W/cm^2. For a divergence angle $1/350$ and a focal distance 7 cm the diameter of the focal spot is 2×10^{-2} cm and the breakdown power I_n is 60 MW. For a peak power I of 180 MW that is to say, $I/I_n = 3$, the quantity l computed from (1) is 0.2 cm and the velocity $dl/dt = 2 \times 10^7$ cm/sec for a pulse length of 20 nsec.

We note that the surface S essentially defines a surface of constant energy flux density that limits the temperature rise of the gas beyond it. If the velocity of the breakdown boundary exceeds the other characteristic velocity in the problem—the velocity of the heating boundary, the total energy of the mass $dm = \pi\rho D^2 l^2 dl / 4F^2$ is $E = Idt = Idl/(dl/dt)$, where ρ is the density; this is the case since absorption occurs in a thin layer beyond the breakdown surface. Thus

$$E = \frac{8DdmI_n^{1/2}I^{3/2}}{\pi\rho d_n^3 F\,[(I/I_n)^{1/2} - 1]^2 \, dI/dt}, \tag{3}$$

and the temperature can be found from the relation $E = \epsilon(\rho, T)\,dm$ where $\epsilon(\rho, T)$ is the specific energy. We note that the relation given above $E = Idl/v$ determines the gas temperature for any mechanism of motion of the boundary of the heating region so long as the energy losses due to thermal conductivity, radiation, and gas-dynamic motion can be neglected.

Zeldovich and Raĭzer[9] have considered processes which occur in breakdown in gases and have computed the time required for the development of the electron avalanche. In this case the threshold value for the power corresponds to a field at the focus such that an electron avalanche can develop during the pulse ($\sim 10^{-8}$ sec). This shows that the formulas given above are only approximate and do not take account of the lag in the development of the avalanche. In particular, it follows that the quantity l given by (1) is somewhat higher than the true value, that the boundary of the breakdown region cannot be sharply defined in the direction of the incident beam (in contrast with the transverse direction), and that it must be characterized by appreciable large-scale fluctuations in electron density.

Thus, focusing of laser radiation on the surface of a condensed medium located in a vacuum is evidently the most promising method of obtaining a high-temperature plasma. In this case the most convenient mode of operation is the one in which one-dimensional motion of the plasma occurs; three-dimensional motion leads to a rapid reduction in density and a decrease in the relative fraction of the laser radiation absorbed in the plasma. Under these conditions the maximum achievable temperature is determined by the energy loss due to radiation and thermal conductivity. When radiation is focused in uniform media (for example, gases) the maximum temperature is limited by breakdown, which leads to an increase in the volume which absorbs the laser radiation.

We have carried out a spectral analysis of the emission from a plasma produced by focusing the radiation from a neodymium-glass Q-switched laser on the surface of a solid sample containing lithium located in a vacuum. The laser radiation[10] consisted of two pulses, each of which contained an energy of approximately 3 joules and each of which was approximately 40 nsec in length. In the spectrum shown in Fig. 2 it is possible to distinguish lines of singly ionized lithium against the background of uniform plasma emission; (the ionization potential of LiI is 5.39 eV): 4671 Å, which corresponds to the 4f – 3d transition (excitation potential approximately 73 eV) and 5484 Å, which corresponds to the 2p – 2s transition (excitation potential approximately 62 eV). In addition one sees the line of doubly ionized lithium (the ionization potential of LiII is 75.6 eV), 4510 Å (excitation potential approximately 118 eV) which corresponds to the 4.05 μ transition in the Brackett series of hydrogen G → F. The lines are broadened appreciably, evidently as a result of the Stark effect.

A calculation of the equilibrium ionization shows that at a temperature of 8.6 eV (10^5 degrees) the ratio of the number of Li III ions to the initial number of atoms is approximately 0.32 and 0.66 for an initial density of 10^{20} or 10^{19} cm^{-3}. On the other hand, if it is assumed that the continuous plasma emission approximates that of a black body a comparison of the line intensities and the corresponding spectral portion of a continuous background indicates roughly that the temperature is $\frac{1}{5}$—$\frac{1}{7}$ of the excitation potential of the line at a density 10^{20} – 10^{19} cm^{-3}; thus it reaches values of the order of 20 eV (2.3×10^5 degrees). It should be noted that we are making a very rough estimate in determining the temperature in this way since the plasma density and radiation lifetime of the excited states are not known accurately.

In Fig. 3 we show a photograph of the development of a breakdown in air of normal density by focused radiation from a Q-switched ruby laser.[8] The pulse energy is approximately 3 joules. The focal distance of the objective is 5 cm, the initial laser beam diameter is 1 cm, and the divergence is 10′. The photographs were taken with a scanning camera.[11] The diameter of the image of the scanning point is 0.035 mm in the plane of the film and the distance between scan points (the step length h) is 0.3 mm. The velocity of the scanning points on the film is 4 km/sec. Since the linear dimensions on the photograph can be determined to within the step accuracy, that is to say 0.3 mm, and the accuracy of the time measurements is equal to the step length divided by the velocity of the beam, the time measurements are accurate to 0.9×10^{-8} sec. The time interval between individual frames is 4.4 nsec. (The image on the photograph is a negative.) The time dependence of the laser radiation intensity can be determined from the degree of blackening of the spot located in the right part of each frame which is a photograph of the face of a light pipe which transmitted part of the laser radiation. The light pipe delays the pulse by approximately 6 nsec and causes some spreading (within these limits) of the pulse. The shape of the radiation pulse has been described in an earlier work[8].

The pulse length between levels equal to half the peak level is approximately 11 nsec. About $\frac{1}{25}$ of the maximum power is achieved approximately 15 nsec before the maximum.[8] The ratio I/I_n in this experiment is greater than 25.

The series of frames before No. 8 indicate that breakdown occurs in a conical region of 4 ± 0.1 mm in length and 1 ± 0.1 mm on the base. The volume of the region in which breakdown occurs is 1 ± 0.2 mm^3. The vertex of the cone is at the focus of the lens. The peak power of the laser pulse is reached at a time corresponding to frame No. 8. At this point the energy of the pulse from a generator is 36—40 percent of the total energy in the pulse, that is to say, 1.1—1.2 joules; this result follows from an analysis of the laser pulse shape[8]. If it is assumed that this energy goes

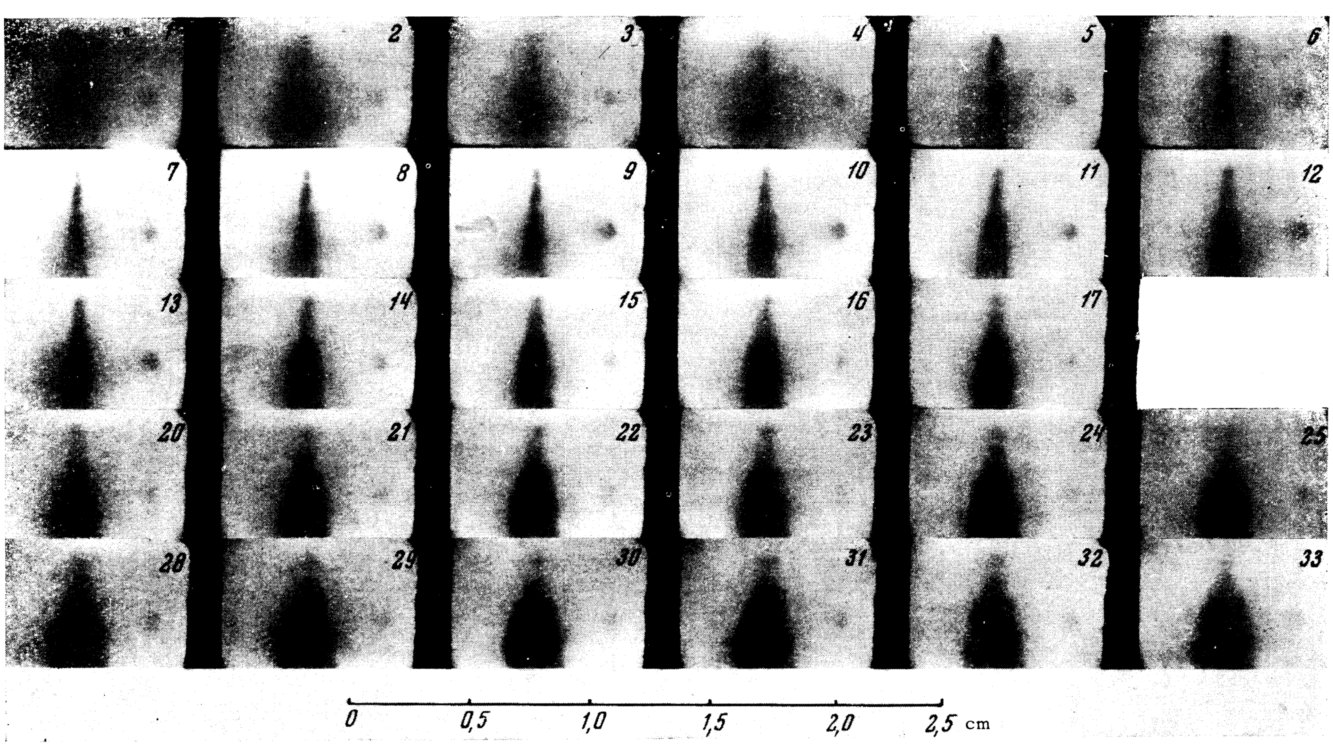

FIG. 3

completely into heating of the air the energy per molecule is less than 370 eV and the corresponding temperature cannot be greater than 10.5 eV.

It is evident from the photograph that the breakdown occurs very nonuniformly in space; this is evidently a result of the fact that the characteristic time for the development of breakdown is comparable with the rise time of the laser pulse, as has been discussed above. Hence, the determination of the velocity of the breakdown boundary must be very approximate. The photograph does show, however, that the breakdown propagates very rapidly in the direction of the lens, the effective "velocity" being at least 10^7 cm/sec.

The vertex angle of the emission cone in frame No. 8 agrees with the angle of convergence of the rays at the output from the lens. On this basis we may state that gas-dynamic expansion of the heated volume in the transverse direction is not important before frame No. 8. This expansion is obvious in the subsequent frames, however. The time for the development of the gas-dynamic motion and the formation of a shock wave in the direction perpendicular to the beam is of order $\tau \approx r\sqrt{\rho/P}$, where r is the radius, ρ is the density and P the pressure. With r = 0.5 mm, $\rho = 1.29 \times 10^{-3}$ g/cm^3, T = 10 eV (P = 3800 atm[11]), the quantity $\tau \approx 3.0 \times 10^{-8}$ sec. The transverse transit time to a distance 4 mm from the focal point as computed from the motion of the boundary on the photographs 9–14 of Fig. 3 is 1.4×10^6 cm/sec. According to photographs 14–20 the motion in these cross sections proceeds with a velocity 10^6 cm/sec.

The velocity of the shock wave in air is 1.4×10^6 cm/sec corresponding to a temperature beyond the front somewhat lower than 3 eV.[12] The pressure beyond the front computed from the formula for a shock wave of limiting strength is $P = 2[\gamma + 1]^{-1}D^2\rho$ where D is the wave velocity, γ is the adiabaticity index and ρ is the initial density of the air, 1.29×10^{-3} g/cm^3. Thus $P = 2.3 \times 10^9$ erg/cm^3 = 2350 atm for $\gamma = 1.2$, corresponding to a temperature of the order of 0.9×10^5 degrees (approximately 8 eV) in the uncompressed air. This value of the temperature is close to that in the central region of the heated air, where the density change at the beginning of the gas-dynamic motion is small.

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