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* Here $c = \hbar = 1$ and $\alpha \simeq 1/137$.

POSSIBILITY OF IGNITING A TRAVELING LASER SPARK AT BEAM INTENSITIES MUCH BELOW THE BREAKDOWN THRESHOLD

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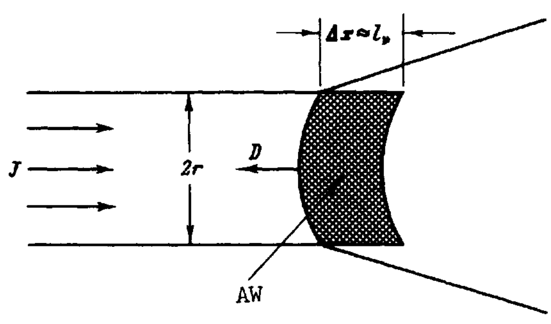
Experimental investigations of the laser spark [1,2] have shown that the boundary of the plasma initially produced in the focus of the lens moves in an optical channel in a direction opposite to that of the laser beam at a velocity ~100 km/sec. The light-absorbing plasma is heated to a temperature higher than half a million degrees [2]. The plasma boundary moving counter to the beam can be regarded as a wave of light absorption and gas heating (AW), which is similar in many respects to the detonation wave in an explosive [3,4].

We wish to emphasize here the circumstance that the tremendous light intensities, approximately 10^5 MW/cm^2, which are produced in the experiments, are not needed at all to maintain the AW, and are required only to produce the initial breakdown in the air. The plasma front absorbing the parallel light beam can propagate without attenuation even at much lower light intensities, far from those needed for breakdown - all that is necessary is to "ignite the detonation," by creating in the light channel an absorbing plasma focus (for example, with the aid of another breakdown-producing laser pulse, a discharge, or some other way).

Let us estimate the lowest limiting intensity J capable of maintaining an undamped AW in a light channel of radius r. The leading front of the AW is a strong shock wave, which ionizes the gas, creating conditions for the absorption of the light. The energy released in the gas, in turn, contributes to the progress of the shock wave. *



The AW width Δx is of the same order of magnitude as the range of the light for absorption in heated gas: $\Delta x = \ell_\nu$. The shock wave is attenuated by energy lost to lateral expansion of the gas in the AW zone (see the figure). The energy loss is very small if $\Delta x \ll r$, but when $\Delta x > r$ it is so large that a self-maintaining AW is impossible in this case. Yet at temperatures $T \approx 10\ 000 - 20\ 000°$, corresponding to weak ionization of the atoms, $\ell_\nu(T)$ increases rapidly with decreasing T. Thus, the condition $\ell_\nu(T_{min}) \sim r$ characterizes the limiting AW temperature, just as the condition $\Delta x \sim r$ (if Δx is the width of the chemical reaction zone) determines the detonation limits of cylindrical charges of small diameter.

According to [4], in the "detonation" mode the AW velocity D and the specific energy of the heated gas ϵ are given by

$$D = [2(\gamma^2 - 1)J\delta/\rho_0]^{1/3}, \tag{1}$$

$$\epsilon = \frac{\gamma}{(\gamma^2 - 1)(\gamma + 1)} D^2 = \frac{2^{2/3}\gamma}{(\gamma^2 - 1)^{1/3}(\gamma + 1)} \left(\frac{J\delta}{\rho_0}\right)^{2/3}. \tag{2}$$

Here ρ_0 is the initial density, γ the effective adiabatic exponent, and $\delta \approx (1 + \ell_\nu/r)^{-1} < 1$ is a coefficient that takes into account, in rough approximation, the decrease of the "effective" intensity as a result of energy loss to lateral expansion. The density behind the AW is $\rho = [(\gamma + 1)/\gamma]\rho_0$. In the case of weak ionization and of quanta with $h\nu \ll I$ (I is the ionization potential of the atoms), the light absorption coefficient, corrected for stimulated emission, is given by the Kramers-Unsold formula [5]:

$$\kappa_\nu = 1/\ell_\nu = 6{,}2\cdot 10^{-20}\, n\, T_{deg}\, (h\nu_{eV})^{-3} \exp(-I - h\nu/kT)(1 - \exp(-h\nu/kT)), \tag{3}$$

where n is the number of atoms per cm^3. ** Formulas (2) and (3), together with the thermodynamic interpolation relation $\epsilon \sim T^{\alpha}$ ($\alpha \approx 1.5$ [5]) define the function $J(T)$, which has a sharp maximum. The minimum condition $dJ/dT = 0$ yields the approximate equation

$$\ell_\nu(T_{min}) \approx r/\left(\frac{2}{3\alpha}\frac{I - h\nu}{kT_{min}} - 1\right), \tag{4}$$

which is a refinement of the qualitative condition $\ell_\nu(T_{min}) \sim r$. In practice $\ell_\nu(T_{min}) \approx 0.4r$.

For air at atmospheric pressure with $h\nu = 1.7$ eV ($\lambda = 1.06\ \mu$) and $r = 0.1$ cm we get $T_{min} = 19\ 000°K$, $\epsilon_{min} = 6.7 \times 10^{11}$ erg/g, and $\gamma = 1.17$ [5]. The limiting light intensity and the AW velocity are $J_{min} = 82\ MW/cm^2$ and $D_{min} = 8.5$ km/sec. The limiting values T_{min} and J_{min} depend weakly (logarithmically) on the radius of the channel; T_{min} is furthermore practically insensitive to the degrees of the approximations. The limiting intensity decreases with decreasing gas density (provided only the rarefaction is not too high). Thus, in air at 0.1 atm and with other conditions equal, we have $T_{min} = 26\ 000°$, $\epsilon_{min} = 1.1 \times 10^{12}$ erg/g, $I_{min} = 19\ MW/cm^2$, and $D_{min} = 11$ km/sec. At the assumed radius, 0.1 cm, the total limiting beam powers $P = J_{min}\pi r^2$ are respectively 2.6 and 0.6 MW for 1 and 0.1 atm.

It is meaningful to observe the effect only in the case of a sufficiently prolonged light pulse, when the AW has a chance to cover an appreciable distance, i.e., the laser should operate in the free-running mode ($t \approx 10^{-3}$ sec; in the ideal case $L \approx 8$ km/sec $\times 10^{-3}$ sec $= 8$ m). *** The required power is not fantastic, although it is at the limit of the present-day capabilities: a neodymium-glass laser ($\lambda = 1.06\ \mu$) with a pulse energy ~1500 J produces an average power ~1.5 MW. Great difficulties are encountered here in producing (with the aid of a telescopic system) a long and very thin beam with a diameter on the order of a millimeter - too high powers are required for a larger diameter. It is, of course, possible to use a lens of sufficiently long focus; then the AW will cover a shorter distance - from the focus, where it is natural to produce the ignition, to that section of the conical light channel at which J drops below J_{min}.

An important factor is that the required average power is somewhat higher than the calculated value as a result of the spiked nature of the lasing, so that it is necessary to decrease to a minimum the off-duty cycle of the light beam. A harmful effect is exerted by the pauses during which the wave attenuates. In order for the AW to continue to move it is necessary that the plasma, which expands adiabatically and cools during the pause, retain its absorptivity, i.e., a temperature not lower than ~20 000°, at the instant when the spike begins. It turns out that the additional energy acquired during the time of the spike, when the power is accordingly larger than the mean value $\bar{J}$, is insufficient when $\bar{J} = J_{min}$. An estimate shows that for typical conditions (spike period ~1 μsec, spike duration ~1/3 of the period) and r = 0.1 cm the limiting average intensity is about double than in the case of a continuous light flux. The average AW velocity decreases somewhat. It is clear from the foregoing that in order to "ignite the detonation" it is necessary that a plasma with a temperature higher than approximately 25 000° overlap the light channel over a length on the order of one millimeter.

The author is grateful to V. L. Tal'roze for stimulating discussions.

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* The radiative mechanism of maintaining the AW [4], which is effective at large values of J, is much inferior to the "detonation" mechanism considered here for small J.

** Estimates show that ionization, excitation, and the equalization of the electron and atomic temperatures are much faster, so that the use of formulas based on the assumed thermodynamic equilibrium in the gas is justified.

*** We note that this phenomenon has nothing in common with the "long spark" [6] produced as a result of gas breakdown by laser light over the entire length.

ELASTIC NONLINEARITY IN STIMULATED MANDEL'SHTAM-BRILLOUIN SCATTERING

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Stimulated Mandel'shtam-Brillouin scattering (SMBS) which is produced when a powerful laser light wave is focused, is accompanied by intensification of the particular sound wave