action, in which both absorption and appreciable amplification of the signal took place, did not exceed 10 V. The largest gain obtained by us (without allowance for loss due to the mismatch between the sample and the microwave channel) was 15 dB at 10 GHz, T = 120°K, H = 11 kOe, and V = 1.2 kV.

Estimates have shown that under the given conditions the beam velocity was approximately equal to the phase velocity of the helicons, so that the synchronism condition was satisfied for the helicons and the slow wave of the space charge. This means that the electron beam interacted with the longitudinal component of the electric field of the slow electromagnetic wave produced by the helicons in the inner cavity of the sample. Such an interaction is analogous to the interaction between an electron beam and the field of the slow-wave system in an ordinary traveling-wave tube, which leads, as is well known, to the occurrence of convective instability. This apparently was indeed observed in experiment.

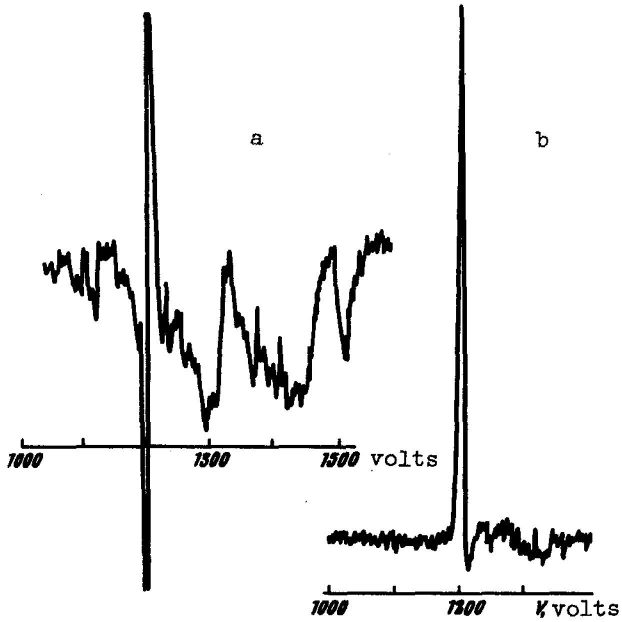

Fig. 2. Microwave power passing through the plasma-beam system as a function of the accelerating voltage of the beam; a - modulated microwave power compensated for, b - no compensation. The receiver gain has been decreased by several times.

In conclusion, we thank D. N. Astrov for useful advice and a discussion of the results.

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THE FEASIBILITY OF AN OPTICAL PLASMOTRON AND ITS POWER REQUIREMENTS

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High-frequency plasmotrons have found important applications in physical research and in engineering. In these devices, gas is blown along a tube through a solenoid in which a stationary inductive discharge is produced. A jet of dense plasma at atmospheric pressure flows out of the tube. There exist also microwave plasmotrons. This raises the question whether a CO_2 laser can be used to produce or to maintain continuously a dense plasma.

Let us determine the minimum required light power and the plasma temperature. Assume that a plasma initially produced by an external source is situated in the path of a parallel light beam of radius R, intensity S, and power $S\pi R^2$. The light intensity is too low to produce "optical detonation," which has a relatively high threshold [1], but is sufficient to maintain "slow combustion," i.e., subsonic propagation of the discharge against the beam by the heat-conduction mechanism (and by transport of the thermal radiation of the plasma). The analogy between slow propagation of a discharge maintained by absorption of electromagnetic energy, on the one hand, and combustion on the other, was established in [2], where the theory of a high-frequency plasmotron was developed on this basis. The analogy was also used by the authors of [3] to estimate the observed rate of slow propagation of a laser spark maintained by a millisecond pulse from a neodymium laser.

The axial length of the zone responsible for the maintenance of the plasma front does not exceed R. A wave that is stationary in the coordinate frame in which the front is at rest is therefore possible, and will now be considered. Cold gas of density ρ_0 and velocity u flows into the wave, becomes heated, and expands at constant pressure (see Fig. 1.). We shall consider a simplified one-dimensional problem, as if the light channel were to be contained in a tube. The equation for the temperature T takes the form

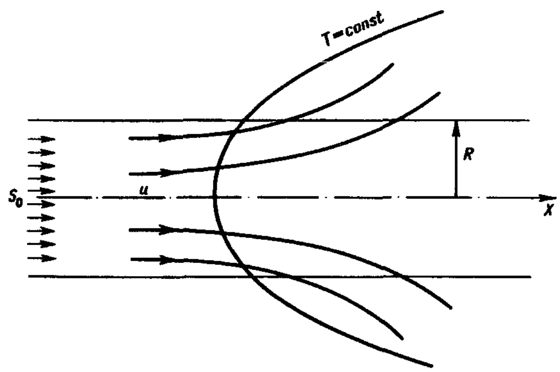

Fig. 1

$$\rho_0 u c_p \frac{dT}{dx} = -\frac{dJ}{dx} + F,$$

$$J = -\lambda\frac{dT}{dx}, \quad F = F_+ - F_-, \tag{1}$$

$$F_+ = S\kappa_\nu, \quad F_- = A\theta/P^2 + \Phi, \quad \theta = \int_0^T \lambda(T)dt .$$

Here c_p is the specific heat, $\lambda(T)$ the thermal-conductivity coefficient, and (T) the light-absorption coefficient corrected for the stimulated emission. The term $A\theta/R^2$ describes the loss connected with the thermal conduction of the heat through the lateral surface of the channel, and the number A depends only on the raidal temperature profile; $\Phi(T)$ is the loss to thermal radiation (at p = 1 atm, the plasma is strongly transparent to thermal radiation).

The absorption of neodymium light laser ($h\nu$ = 1.17 eV) in the first-ionization region can be calculated from the formula of [4]. For a CO_2 laser $h\nu = 0.124$ eV << kT, we have

$$\kappa_\nu = 10{,}4\, p^2_{atm}\, x_e^2\, (T°/10^4)^{-7/2} g \ \text{cm}^{-1},$$

where x_e is the molar fraction of the electrons, determined by Saha's formula, and g is the Gaunt factor (g ≈ 2.5). Plots of $\varkappa_\nu$ for air at p = 1 atm are shown in Fig. 2. The maximum values of $\varkappa_\nu$ are 0.006 cm^{-1} for $h\nu$ = 1.17 eV (T ≈ 16000°) and 0.85 cm^{-1} at $h\nu$ = 0.85 cm^{-1} (T ≈ 17000°). When R ∿ 1 mm we have $\varkappa_\nu R \ll 1$, i.e., the beam experiences little attenuation in the wave: S(x) ≈ const. We have obtained the approximate function $\phi(T)$ of the average volume of loss at p = 1 atm for cylinders several millimeters in diameter by combining the data of [5, 6]. This function can be determined from Fig. 2.

Since S(x) ≈ const, the final temperature of the wave (the maximal plasma temperature) T_f is determined directly from the condition F = 0, with T_f corresponding to the upper point of

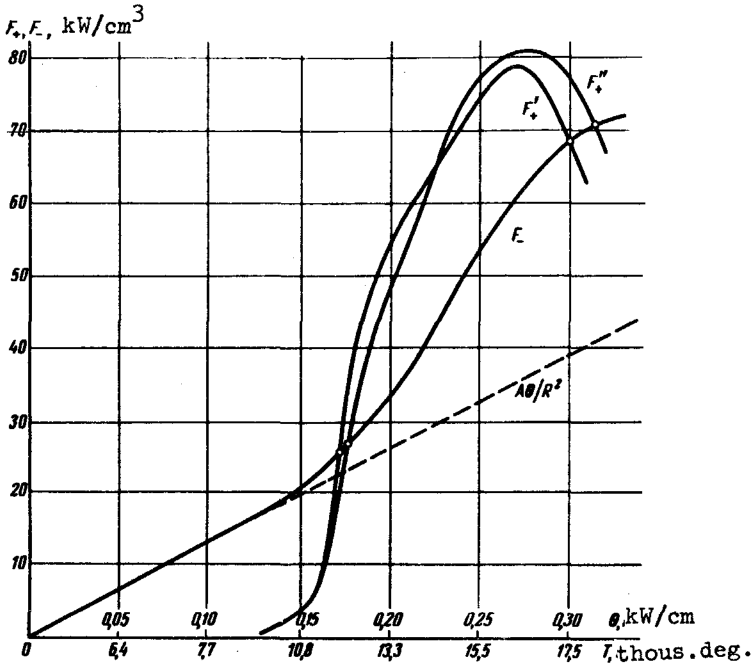

Fig. 2. Heat release and loss curves: $F_+' = 1.3 \times 10^4$ kW/cm^2 × κ_ν cm^{-1} (neodymium laser); $F_+'' = 10^2$ kW/cm^2 × κ_ν cm^{-1} (CO_2 laser). The difference between F_- and the dashed line determines half the radiation loss: $\Phi = \phi/2$. The lower scale is the temperature scale, i.e., the connection between T and θ.

intersection of the F_+ and F_- curves (Fig. 2), at which the state is stable. Equation (1) can be reduced in order. Two conditions, namely T = 0, J = 0 and $T = T_f$, J = 0, are added to the obtained first-order equation for J(T). The problem is overdefined, and this yields the unknown wave velocity u.

The threshold of the regime corresponds to zero velocity u: the amount of heat released suffices only to offset the losses, but not to advance the wave. We put in (1) u = 0, multiply the equation by λ, and integrate with respect to T from 0 to T_f, with allowance for the boundary conditions. We then obtain the equation

$$\int_0^{\theta_k} F(\theta)\, d\theta = 0,$$

which expresses the condition for the equality of the areas enclosed between the $F_+(\theta)$ and $F_-(\theta)$ curves (Fig.2) and enables us to find the threshold intensity S_t.

In the absence of axial gradients of heat release, decreasing along the radius r like the bessel function $J_0(2.4r/R)$, and T(r = R) = 0, $\theta(r) \sim J_0(2.4r/R)$ and $A = 2.4^2 = 4.8$. Actually, the gas outside the light channel is also heated, and the temperature T(R) is quite high (see Fig. 1), so that the losses are smaller. We put

$$A = 0.5A_{max} \approx 2,9.$$

Further, the plasma emits mainly ultraviolet radiation. the part of the plasma emerging in a direction opposite to the beam is absorbed ahead of the wave, i.e., just like the axial heat flux, it is not a "loss." The radiation through the lateral surface of the channel is also absorbed, contributing to an increase of T(R) and to a decrease of the heat-conduction losses. These favorable effects will be taken into account approximately by decreasing the radiation loss to one-half its value: $\Phi = 0.5\phi$. Figure 2 was plotted for the indicated values of A and Φ for air at p = 1 atm and R = 0.15 cm, just as in the experiments of [3]; λ(T) was taken from [7].

As a result, we obtained for the neodymium laser $S_t = 1.3 \times 10^4$ kW/cm^2, in splendid agreement with experiment [3]; T_f = 17000 °K. For a CO_2 laser at the same R = 0.15 cm we have T_f = 18000°, $S_t = 10^2$ kW/cm^2, and $P_t \approx 7$ kW. When R decreases, the heat-conduction losses prevail, $S_t \sim R^{-2}$, and the power decreases, but little. Increasing the radius is not useful:

the radiation losses prevail, S_t = const, and $P_t \sim R^2$.

Thus, to maintain the plasma continuously in atmospheric air by means of a CO_2 laser, the required power is about 7 kW. This is an imposing figure, but not unrealistic. The discharge can be ignited practically anywhere, using mirrors and lenses to feed the energy. It is also easy to localize (to "stabilize the flame") by focusing the beam. At high pressures, the power required is much lower (it can be varied also by choosing different gases), but the construction of the "plasmotron" is in this case obviously more complicated. The complete solution of the problem of subsonic propagation of a light discharge will be published in Zh. Eksp. Teor. Fiz. (Sov. Phys.-JETP).

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OSCILLATORY APPROACH TO SINGULAR POINT IN THE OPEN COSMOLOGICAL MODEL

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It was shown in earlier communications [1, 2] that in the general cosmological solution of Einstein's equation there exists a singularity having a complicated oscillatory character. There was also considered a particular example of a homogeneous closed model (a world with homogeneous space of type IX after Bianchi), admitting of a more complete analysis [2] (this model was considered also by Misner [3]). We wish to report in this paper another similar example, which not only confirms once more the qualitative analysis of the general case, but casts additional light on certain aspects of the problem. We refer here to a model with homogeneous space of type VIII after Bianchi.

Let again $\vec{l}$, $\vec{m}$, and $\vec{n}$ be reference vector defining the coordinate dependence of the space metric, and let a(t), b(t), and c(t) be functions of the synchronous world time t, defining the scales of the spatial distances in the directions $\vec{l}$, $\vec{m}$, and $\vec{n}$, respectively. Homogeneous spaces of types VIII and IX correspond to constant values (independent of the coordinates) of the quantities

$$\lambda = (\vec{l}\cdot \mathrm{curl}\ \vec{l})/v, \quad \mu = (\vec{m}\cdot \mathrm{curl}\ \vec{m})/v, \quad \nu = (\vec{n}\ \mathrm{curl}\ \vec{n})/v, \quad v = \vec{l}\cdot\vec{m}\times\vec{n},$$

(the products $\vec{m}\cdot\mathrm{curl}\ \vec{l}$, $\vec{n}\cdot\mathrm{curl}\ \vec{l}$, etc. vanish). If the signs of these constants are all the same we have space of type IX, and if the sign of one of them is the opposite of the other two we have space of type VIII. In the former case we can put $\lambda = \mu = \nu = 1$, and in the