SOVIET PHYSICS JETP VOLUME 32, NUMBER 6 JUNE, 1971

HIGH-PRESSURE LASER SPARK IGNITED BY AN EXTERNAL PLASMA SOURCE

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Submitted July 8, 1970

Zh. Eksp. Teor. Fiz. 59, 1975—1982 (December, 1970)

A laser spark in argon is ignited at high pressure reaching 80 atm by an external plasma source with the supporting radiation being considerably below the breakdown threshold. The threshold emission power of a ruby laser necessary to maintain plasma is found to range from 70 to 10 kW for a pressure interval from 16 to 80 atm. Plasma temperature of 18,000—33,000° and other parameters are measured. The results are in agreement with theory.

1. INTRODUCTION

ONE of the authors reported earlier[1] that the high laser emission powers used in experiments with laser sparks are necessary not so much to maintain the spark itself as to effect the gas breakdown, i.e., to generate the initial "igniting" plasma. If ignition is accomplished by an external plasma source, the propagation of the laser spark in the optical detonation regime can occur at emission powers that are two orders lower than those necessary for gas breakdown.

Experiments performed by Bunkin, Konov, and others[2] showed that laser spark can be maintained at still lower powers, even those inadequate to maintain the optical detonation regime. In these experiments a beam from a neodymium laser generating ~ 1000 J in the free-running mode was focused with a long-focus lens in atmospheric air. A slow propagation of the laser spark was observed after forced ignition by an ordinary electrode discharge. This effect was interpreted as a "slow burning" regime and combustion theory equations were used to justify the observed velocities of propagation of the order of several tens of m/sec. The threshold for generating spark in air at 1 atm was also measured and found equal to approximately 10 MW/cm^2 (730 J for a focal radius of ~ 0.15 cm; length ~ 1.5 msec).

The "slow burning" regime for the propagation of optical discharge was analyzed in greater detail in[3,4]. The theory developed there was analogous to the theory of a similar regime of propagation of high-frequency discharge[5]. The threshold for the experimental conditions in[2] was computed and found in good agreement with the measurements and computations were also made to determine the threshold for maintaining plasma by CO_2 laser emission and plasma temperature.

The fact that plasma can be maintained by infrared radiation at $\lambda = 10\ \mu$ and moderate power makes it possible to design an optical plasmotron using a cw CO_2 laser[3]. Along with the well-known arc and high-frequency (and also superhigh-frequency) plasmotrons this device can be used for continuous generation or maintenance of dense plasma and has a number of useful features. The theoretical feasibility of an optical plasmotron was confirmed by experiments[6] that produced a continuous optical discharge in xenon at several atmospheres and in argon at p ~ 10 atm; the discharge was maintained by a focused emission from a 150-W CO_2 laser. In a sense this effect is similar to the stationary-superhigh-frequency discharge in a resonator[7].

The present research was undertaken to determine the minimum emission power necessary to maintain plasma under various conditions, and to study some properties of the resulting plasma such as the plasma temperature. A pulse-type (ruby) laser was used in these experiments, as it was in[2].

According to computation[2,4], the minimum power necessary to maintain a discharge decreases at high pressure due to the increasing coefficient of absorption of laser light and, consequently, to the increasing energy emission rate in the gas. Therefore experiments can be performed even without a laser having a very high energy output per pulse, such as that used in[2]; a laser with a moderate power is adequate. In contrast to the ignition method used in[2] and based on a spark gap discharge, we used gas breakdown induced by another laser to generate the initial plasma. As a result the gas remains pure and without distortions caused by impurities from electrode damage and by energy input from the igniting discharge that in[2] was comparable to the laser energy. In these experiments we measured the threshold power required to produce a spark at various pressures and focal diameters, spark front velocities, plasma temperature, light absorption, etc., yielding a fairly detailed quantitative information about the process.

2. EXPERIMENT

The experimental setup is shown in Fig. 1. High-pressure chamber 1 can be filled with various gases up to 200—250 atm (the majority of experiments were performed with argon). The ignition plasma was generated by gas breakdown induced by a pulse from ruby laser 3 operating in a free-running spiking mode. The pulse of 1.5—2 J and 0.3—0.4 msec long was focused by an f = 2.5 cm lens approximately in the center of the volume. Plasma was maintained by another ruby laser 2 operating in a quasi-continuous spikeless mode and producing a smooth pulse up to 50 J, 1.5 msec long (see Fig. 2b below). This laser was specially built for such experiments in which the disordered random structure of the spiking millisecond pulse does not allow for definite quantitative conclusions. In particular, the time-

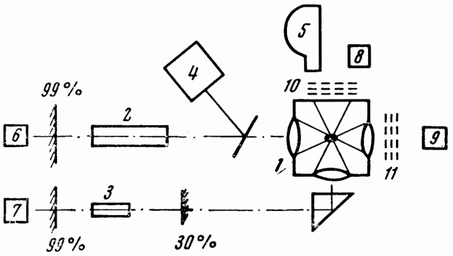

FIG. 1. Experimental setup: 1–high-pressure chamber; 2–ruby, PO 16 X 240 (cw generation); 3–ruby, PO 7 X 120 (spiking generation, ignition); 4–calorimetric energy meter; 5–high-speed camera; 6–9–F-5 photocells; 10, 11–optical filters.

scan photographs showing a plasma generated by the smooth and spiking pulses (see Figs. 3 and 5 below) indicate the homogeneous nature of plasma in the first case and its space and time inhomogeneity in the second. The "spikeless" laser was described in detail in[8]. The emission of laser 2 was focused by an f = 2.5 cm lens at a right angle to the ignition laser beam and the foci of both lenses were brought into coincidence.

The length and shape of pulses from both lasers were monitored with photocells 6 and 7; photocell 8 recorded the spark brightness and photocell 9 recorded the emission of the spark maintaining laser passing through the plasma. The velocity of the plasma front moving toward the maintaining beam was determined from a time scan photograph made by superfast camera (SFR) 5. The recorded plasma luminescence was first allowed to pass through an SZS-21 optical filter (10) to eliminate the laser light. Plasma temperature was determined by comparing photographic film density with that of a standard source[9]. The methodology used was described in detail in[8]. Since the maximum measured temperature reached 33,000° while the standard source was represented by the IFK-50 lamp whose brightness temperature is only 6500°, a special verification of the method was performed by measuring a known temperature of 40,000° of an ÉV-45 calibrated source. The measurement error did not exceed 5% even for these temperatures.

We note that we did not succeed in igniting a spark by gas breakdown from a giant pulse of a ruby laser. While the breakdown was normal there was no ignition. This is apparently due to the very short duration of plasma from a giant pulse breakdown; such a plasma is fairly quickly dissipated after the termination of the pulse. The igniting spark must be sufficiently long-lived to produce "ignition."

It is worth noting that in the spiking mode the breakdown occurs at medium power that is much lower than that necessary for the Q-switched mode. Thus a ruby pulse of 2 J, 0.4 msec long and of 5 kW mean power breaks down argon at 10 atm; a giant pulse would require ~ 800 kW for the same pressure and approximately the same focusing. This is also shown by the results of experiments[10] with air breakdown by a millisecond pulse from a ~ 1400-J neodymium laser. The cause of this effect is the fact that the power in individual spikes that produce the breakdown is much higher than average power. Furthermore the length of the spikes is greater than that of ordinary giant pulses and thus facilitates the breakdown. The assumption that it is these particularly strong spikes that break down the gas is also supported by the fact that a prolonged smooth pulse of a spikeless laser generation capable of maintaining the discharge failed to break down argon independently even at very high pressures of ~ 150 atm, although the maximum pulse power reached 90 kW.

The pulses of the igniting and maintaining lasers (the first up to 0.4 msec long, the second 1.5 msec long) were synchronized so as to produce a partial overlap. In order to determine plasma maintenance thresholds the emission of laser 2 was attenuated until "ignition" ceased.

3. THE RESULTS

Figure 2a shows a signal of the igniting pulse recorded by a photocell; Fig. 2b shows a signal of a maintaining pulse, Fig. 2c the luminescence of plasma, and Fig. 2d the maintaining emission that passed through plasma.

Figure 3 shows a typical time scan of the process. The tiny bright dashes following each other along the time axis represent the breakdown plasma created by the most powerful spikes, which subsequently decays, is recreated, etc. The linear dimensions of these plasma foci are fairly small, approximately 0.04 cm. Several tens of microseconds after the beginning of the maintaining pulse the forward plasma front is detached from the "ignition" site and propagates opposite the beam (downwards on the time scan). The front covers a distance of ~ 0.5 cm and stops in the cross section of the light cone where the intensity is no longer strong enough. At the end of the pulse the front recedes. It is apparent that the "burning" plasma is generally detached from the focal region which is the site of the ignition. The focal region becomes transparent and breakdown centers that continue to flash are visible. The picture is further explained in Fig. 4.

Figure 5 shows a time scan photograph analogous to Fig. 3 for the case of laser 2 operating in a spiking mode rather than in a quasi-continuous mode and generating 25 J. Ignition was not necessary in this case since the pulse was sufficient to break down the gas. The in-

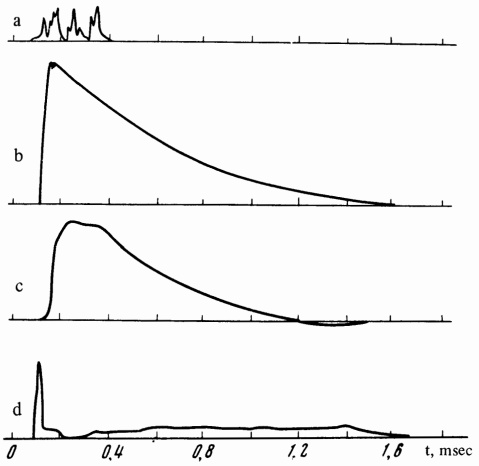

FIG. 2. a–pulse of spiking generation responsible for primary breakdown (1.5 j); b–pulse of spikeless generation (40 j); c–plasma luminescence; d–signal of spikeless generation that passed through plasma at p = 80 atm.

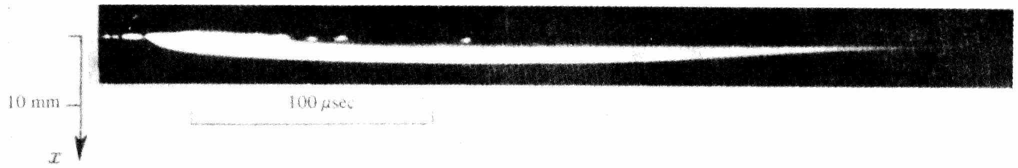

FIG. 3. Time scan of smooth generation spark taken with high-speed camera (time reckoned from left to right, laser beam directed upwards).

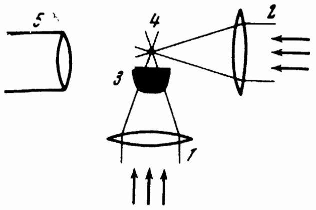

FIG. 4. Process geometry at the point of detachment of plasma from focus. 1—laser beam maintaining plasma; 2—penetrating beam; 3—burning plasma; 4—breakdown plasma; 5—scanning camera.

homogeneity of plasma in comparison to that derived from a smooth pulse is apparent.

Figure 6 shows the threshold value of emission power necessary to produce "burning" in argon as a function of pressure. The focal spot diameter was 0.042 cm. The adjacent axis carries the corresponding values of intensity. There was no ignition at pressures below 16 atm since the power of our laser was insufficient. For the sake of comparison we note that according to[2] the threshold power is approximately 900 kW for air at 1 atm and neodymium laser wavelength. The sharp decrease of threshold at high pressures is evident even if we take the difference in air and argon properties and the different wavelengths into account. This is also indicated by Fig. 6 illustrating the increasing steepness of the curve with dropping pressure.

At moderate pressures of 16—17 atm thresholds were measured also for other focal diameters: 0.1 and 0.18 cm, with the threshold power remaining the same. For a diameter of 0.3 cm the threshold was higher and ignition failed to occur since the threshold exceeded the power of our laser. At lower pressures of 16—20 atm up to 70% of emission passed through the plasma; the transmission fell with increased pressure and amounted to less than 10% at 80 atm.

Figure 7 shows the results of measuring plasma temperature at various pressures, times, and distances x from the focal point. As noted before, the temperature was determined by a photometric method based on film density on the time scan. According to Fig. 7 the maximum temperature increases with increasing pressure and equals approximately 18,000° at p ~ 17 atm, and 33,000° at p ~ 80 atm. The temperature curve shifts towards the beam (curves 1—3, 4 and 5) in accordance with the propagation of the combustion front.

The propagation velocities were measured from the slope of the luminescence boundary on the time scan. The maximum velocities (near the focus in the spiking power period, i.e., at the highest emission intensities) reached 250 m/sec.

4. DISCUSSION

Plasma temperature is determined mainly by its capacity to absorb laser emission. Argon coefficients of absorption of ruby laser light corrected for stimulated emission in the region of primary ionization can be computed from the formula derived approximately from the Biberman-Norman theory[11] (p in atm and T in °K):

$$\varkappa = \frac{0.05 p^2 \chi_e{}^2 (e^{20800/T} - 1)}{(T/10^4)^{5/2}} \ [\mathrm{cm}^{-1}]$$

representing an improvement of the Unsoldt-Kramers formula (the theoretical formula is treated in greater detail in[4]). Here $\chi_e = p_e/p$ is the molar fraction of electrons determined from the Saha equation. Taking the depressed ionization potential into account we have for argon

$$\frac{\chi_e{}^2}{1 - 2\chi_e} = \frac{3.6 \cdot 10^4 (T/10^4)^{5/2}}{p e^{172000/T}}.$$

Figure 8 shows curves $\kappa(T)$ for the pressure range under consideration. Since the characteristic dimensions of plasma are of the order of 0.3 cm, plasma is still fairly transparent to radiation at the lowest pressures of ~ 16 atm (in terms of maximum κ) and it is weakly transparent at high pressures of p ~ 80 atm, which is in qualitative agreement with the measurements of transmitted radiation. According to[3,4] if plasma is transparent its temperature is beyond the maximum of the $\kappa(T)$ curve under near-threshold conditions (which was the case with our low-pressure experiments). Plasma temperature is determined from the condition of equality of areas bounded by the thermal emission curve $\kappa(T)$ and the thermal loss curve that roughly speaking can be considered close to a straight line drawn from the origin of coordinates in Fig. 8. The temperature corresponds to the upper point of intersection of these curves. An elementary construction shows

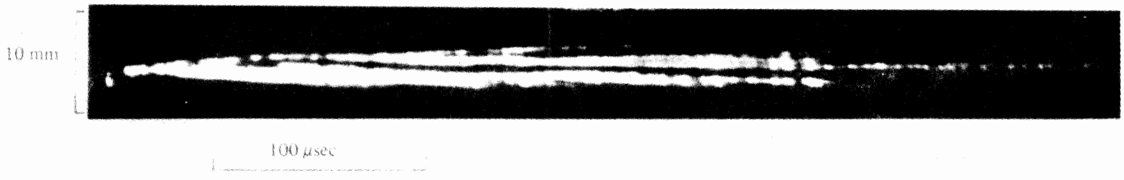

FIG. 5. High-speed scan of a spark due to a spiking generation pulse at p - 80 atm and 20—25 J (scan from left to right, laser beam pointing upwards).

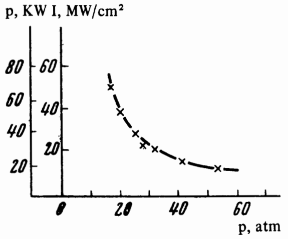

FIG. 6. Plasma maintenance threshold as a function of pressure.

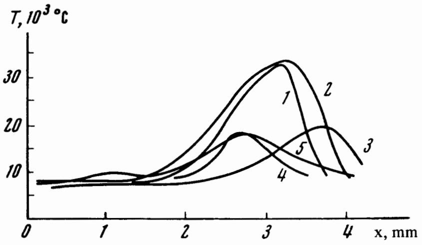

FIG. 7. Spark temperature as a function of spark coordinates at various times reckoned from the start of the maintaining pulse. Curves 1–3: p = 80 atm, peak power P = 70 kW; Curve–t - 50 μsec; 2–t = 100 μsec; 3–t = 500 μsec; Curves 4, 5: p = 17 atm, P = 70 kW (near threshold); curve 4–t = 50 μsec, 5–t = 100 μsec.

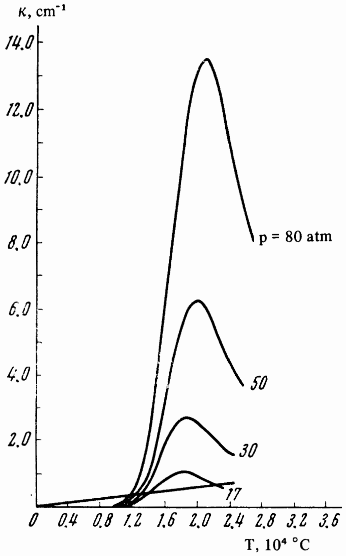

FIG. 8. Absorption coefficient of ruby line in argon.

that for p ~ 16 atm the computed plasma temperature amounts to about 22,000° and is in good agreement with the measured maximum value of 18,000°. A similar construction for p ~ 80 atm yields T ~ 25,000° which is below the measured value of 33,000°. In this case however plasma is not transparent, the theory developed in[3,4] is not applicable, and in accordance with the results of[5] pertaining to the case of absorption of electromagnetic energy flow (i.e., opacity), the temperature should be higher in this case (losses are relatively less important).

Furthermore both the plasma temperature, in the case of plasma transparency, and the threshold power necessary for plasma maintenance are determined according to[3,4] by the condition of balance of energy emission due to laser light absorption and losses. The latter consist of thermal conduction losses (energy leakage from the emission region beyond the light channel boundaries due to the conduction mechanism) and radiative losses. Conduction losses are weakly dependent on pressure, while radiative losses in plasma that is transparent to thermal radiation depend on pressure in the same manner as energy emission, i.e., roughly speaking as $\kappa_{\max}$ or p^2. The fact that under low pressures threshold power drops sharply with increasing pressure indicates the insignificant role of radiative losses. According to[4] the same conclusion can be drawn from the fact that threshold power is independent of focal diameter within a considerable range of diameters, as determined in experiments with pressures of 16–17 atm. At the highest pressures radiation losses also seem to be due to conduction since plasma is opaque and radiant heat exchange is described by an approximation to radiant conductivity.

The threshold value of ruby laser power obtained above and necessary to maintain plasma in argon, say, at ≈ 16 atm and focal diameter less than 0.1 cm, amounts to 70 kW; this permits us to make a rough estimate of the power required for prolonged maintenance of plasma under analogous conditions using a cw CO_2 laser. In fact the threshold power is inversely proportional to the coefficient of absorption of light. The light from a CO_2 laser at $\lambda_1 = 10.6\ \mu$ is absorbed roughly speaking $(\lambda_1/\lambda_2)^2$ 200 (more precisely 250) times stronger than the light from a ruby laser at $\lambda_2 = 0.7\ \mu$. Consequently the threshold power is ~ 300 W. The experiments described in[6] confirmed this evaluation and showed that even 150 W is sufficient with a very sharp focusing.1)

The authors thank A. K. Fannibo for his kind cooperation in presenting the method of achieving a smooth generation mode, and V. I. Suponin for help with the experiments.

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1) This paper was written earlier than [6] and the calculation given together with purely theoretical considerations of the kind discussed in [4] made it possible to predict the threshold conditions necessary to maintain plasma with CO_2 laser radiation.

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Translated by S. Kassel
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