Role of self-focusing of laser radiation on breakdown in liquid He^4

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The conditions for optical breakdown in liquid and gaseous helium are studied experimentally. A weak diffuse track of a laser beam focused by a lens is observed in pure helium. A bright glow with a frequency close to that of the exciting line is observed in the focus region in helium which was not subjected to special purification. This glow exhibits the field structure in the focus region and as a rule is accompanied by a plasma glow at that part which faces the lens. It is suggested that self-focusing has a decisive role in breakdown phenomena and from the experiments it follows that beam collapse is connected with the appearance of inhomogeneities in the medium, most likely of microscopic particles suspended in helium.

The results of investigations of laser breakdown in low-temperature helium vapor and in liquid helium have been presented in a number of papers[1-6]. It has been shown[1,2,5] that breakdown of liquid helium simulates breakdown of gaseous helium of the same density (pressure ~ 10^3 atm at room temperature). It was suggested that breakdown in helium begins as a result of thermal- or photoemission from solid submicroscopic impurity particles, very small amounts of which can exist in the helium in a suspended state[2]. Subsequently, this conclusion concerning the origin of the electrons that initiate the development of the cascade ionization[7] was confirmed in experiments in which liquid helium was subjected to special purification by low-temperature aerosol filters (Petryanov filters)[5,8].

The growth of the breakdown threshold observed in unpurified helium on going to He II was attributed in[2,5] to coagulation and rapid settling of the impurities in superfluid helium[9]. Winterling, Heinicke, and Dransfeld[3] had noted an increase, by one order of magnitude, of the threshold intensity on going from T_λ to 1.5° K, and attribute this increase to a decrease in the frequency of collisions between the electrons and the thermal excitations with decreasing temperature of the superfluid helium. Silver et al.[4] have indicated that this explanation contradicts experimental data on the injection of hot electrons into liquid helium, and discussed the possible role of electronic bubbles in breakdown of liquid He^4 by a laser beam. The latest experiments[6] have again confirmed the influence of impurities on the breakdown of liquid helium under the influence of optical radiation.

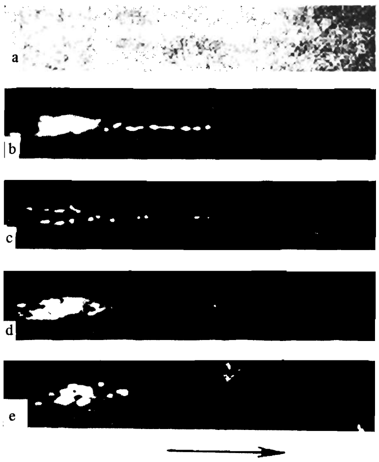
In the present study we investigated effects that arise in the action of the emission of a ruby laser operating in the multimode regime on liquid helium. The following observations can be noted.

1. In purified liquid helium, optical breakdown is not excited at the maximum laser power (20 MW), at a pulse duration of 30 nsec and a lens focal length 4.5 cm. In directions perpendicular to the propagation of the laser beam, the photograph (KN-4S film) shows a weak diffuse glow near the focus of the lens (Fig. a). The dependence of the glow intensity on the helium temperature and on the orientation of the polarization vector of the exciting light indicates that the geometry of the beam in the region of the focus can be seen in the photograph, apparently as a result of molecular scattering.

2. When a repeated pulse is used, the picture changes rapidly. In the focal region facing the lens one observes a bright white spark, meaning that breakdown takes place (Fig. b). To reconstruct the pre-breakdown strength, it is necessary either to use the Petryanov filters, or to left a half-hour interval elapse between flashes.

Hunklinger and Leiderer[6] have noted an appreciable decrease of the threshold power after the first breakdown, and have therefore verified the assumption that the first breakdown leaves behind it electrons that initiate the breakdown in the following flahses. Hunklinger and Leiderer performed experiments on the introduction of charges into the focal region prior to turning on the laser, a procedure that does not influence in any way the threshold intensities. It is interesting that for a noticeable decrease in the threshold fields in the second and succeeding pulses, there is no need at all to produce a breakdown with the aid of large intensities during the first flash. A light pulse that passes through purified helium without producing breakdown changes the state of the medium in such a way that breakdown can be excited in succeeding flashes at lower intensities.

It is difficult to accept the idea that such a weak interaction is capable of producing the appearance of free electrons. It is most likely that in the first pulse, when



Illumination from the focal region at right angle to the direction of laser-beam propagation: a – scattering in purified liquid helium, b – laser spark, c – bright red glow, d – two-color spark, e – photograph with SZS-10 filter in front of the camera. The arrow shows the direction of laser-beam propagation.

the light passes through the walls of the vessel, submicroscopic solid particles break away from the walls and subsequently initiate the breakdown. The appearance of a strong perturbation in the medium was registered with the aid of a piezoceramic pickup placed in a Dewar with helium, and a light pulse was also noted when the light passed through the instrument without focusing. It should be noted that by "contamination" of the helium we do not have in mind the appearance of any noticeable turbidity. This was verified visually with the aid of a bright gas-laser beam.

The decreased breakdown strength is probably not connected with any direct action of the light on the helium in the region of the focus, for example with the production of free charges or long-lived excited states. Two pulses spaced approximately 10^{-4} sec apart produced no breakdown in carefully purified helium, although the power in each pulse was large enough.

3. When the helium is of sufficiently high degree of purity, one can sometimes see in the repeated pulse not a spark but strong scattering of the laser emission, in the form of bright red glow that duplicates fully the discrete structure of the breakdown spark (Fig. c). A two-color spark is more frequently obtained (Fig. d). The photograph e was obtained with an SZS-10 filter in front of the camera. The red part of the glow was completely cut off.

The presence of contamination changes most strongly the character of the interaction of the liquid helium with a powerful laser radiation. Instead of a weak scattering (Fig. a) in the focal region facing the lens, bright radiation from individual zones is produced. The geometry of the laser beam focused into the liquid helium becomes entirely different. Thus, the structure of the emission in the focus can be observed separately from the breakdown. The high concentration of light in such a structure apparently determines the development of the laser spark.

A thorough experimental investigation of this effect revealed the following regularities. Since the laser operated with many transverse modes, the radiation profile was spotty and this determined the shapes of the sparks. For each individual spot (the remaining spots were covered) we obtained a clear-cut regularity, namely a strong dependence of the character of the interaction on the purity of the helium. Along the axis of each beam, bright points were produced, apparently by regions of large field amplitude. The sharp boundaries of the bright region and the structure offer evidence that this is not scattering of light by very small impurity formations, but more readily intensity spikes.

Breakdown is observed, as a rule, at the ends of filaments facing the focusing lens. In the region of the largest light concentration, inside the caustic of the lens, no breakdown develops, and only glowing red points can be observed. It is possible that energy is being transferred here in the SMBS process, and there is no time for breakdown to develop. Experiments also confirmed the following assumption: a correlation was observed between the SMBS intensity and the character of the glow in the indicated part of the focal region. The large backscattering intensity (almost equal to that obtained in purified helium when there is no breakdown at all) corresponds to the red rather than the white plasma glow.

When the beam power is altered (the radiation was weakened with neutral filters), we observed a change in the length of the section subject to the strong interaction, and a simultaneously shortening (or lengthening) of the part located at the entrance of the focal region of the lens (almost always subject to breakdown), and the part of the caustic consisting of red zones. At a constant radiation power and a constant helium density (in a gas above the liquid, the dimension of the bright region becomes shorter with increasing distance from the surface of the liquid), succeeding pulses or other methods of contamination only increase the fraction of the breakdown points; the dimension of the interaction zone does not change noticeably.

The observed effect has a clearly pronounced threshold. Whereas in pure helium one can see at the focus of the lens only a weak trace, in the succeeding pulse an entire chain of light points appears immediately even at threshold power. The red glow reveals regions of light concentration in which no breakdown develops, and these regions, like the breakdown ones, are clearly localized. Regardless of the appearance of plasma clusters, once the region becomes even insignificantly contaminated, it is capable of changing the structure of the beam in the focal region. The noted features of the phenomenon make it possible, in our opinion, to suggest that we are dealing here with a collapse of the beam and with the appearance of additional contraction of each beam, corresponding to the bright spots in the section of the laser beam. Thus, breakdown in liquid helium is due to collapse of the beam; estimates of the intensity at the focus on the basis of geometrical optics are not suitable, and the conditions for the breakdown are determined by the conditions for self-focusing.

It is known that investigations of gas breakdown by a laser beam have revealed a number of effects that are frequently associated with self-focusing of the beam[10–18] 1). Filamentary structure of a laser beam scattered by a spark at an angle 90° was observed in the breakdown of gases by a beam of either a single-mode[10–12] or a multimode[12,13] laser, and also by a laser beam operating in the mode-locking regime[14]. The distribution of the intensity and the changes in the spectrum of the laser beam scattered during breakdown in the beam direction are regarded as proofs of self-focusing[12,14]. Interference patterns of the spark in inert gases, obtained with high spatial and temporal resolution[15], have shown that even prior to formation of the main region of the plasma there appears a plasma filament, the diameter of which is much smaller than the transverse dimension of the beam at the focus of the lens. The development of the plasma filament is regarded as a result of self-focusing of the beam. Similar filaments were observed in breakdown in argon by the shadow method of photography[16]. The structure of the laser spark and the dynamics of the development of the breakdown points due to picosecond pulses in nitrogen, air, and argon[17] also point to the possible occurrence of self-focusing in breakdown of gases. Bunkin et al.[17] note that near the breakdown threshold (at a peak power 1.5×10^9 W and at a gas pressure 1 atm), a strong nonlinear scattering occurs at the points.

Distinguishing features of experiments with helium are, first, the clear-cut dependence of the effect on the purity of the medium and, second, the possibility of directly observing the structure in the focus as a result of intense scattering with frequency close to the frequency of the incident wave.

From the foregoing observations it is difficult to draw any conclusion with respect to the mechanism whereby a structure is produced in the focus in helium in the presence of inhomogeneities connected with impurity particles. The very fact that impurities exert an influence (as possible sources of the first electrons) and the proximity of the conditions for collapse and for breakdown (there are almost always white breakdown points, see Fig. d), indicate that ionizing action can play a role. It is known, in particular, from the paper of Naiman et al.[21] that ions appear in the focal region at prethreshold power, but their number is insufficient to develop breakdown within a time equal to the duration of the light pulse. It is possible that during the very initial stage of the ionization process the neutral atoms in the excited state can alter the refractive index of the medium. The influence of the population of the excited levels on the self-focusing process was considered by Askar'yan[22].

We can also propose another mechanism, for example, the medium may become nonlinear as a result of the change of the polarizability of the particles suspended in it when the field is turned on[23]. One cannot exclude, however, the possibility of nonlinear scattering by the inhomogeneities and this, in turn, would stimulate self-focusing.

[1)] In liquids with high anisotropy of the polarizability, for example carbon disulfide or nitrobenzene, the processes of self-focusing and breakdown can be distinctly separated[19, 20], whereas in liquid helium the conditions for the collapse of the beam practically coincides with the conditions for breakdown.

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