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LOW-TEMPERATURE PLASMA

Macroscopic Separation of Charges in a Pulsed Electric Discharge

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Abstract—The possibility of separating charges in an ordinary electric discharge is demonstrated. The luminous object formed after the end of the discharge is found to exist over a few hundred milliseconds, which is six orders of magnitude longer than the lifetime of an ideal plasma of the same volume. It is shown that the luminous object has a negative electric charge and has no free charged particles of opposite sign. *© 2005 Pleiades Publishing, Inc.*

1. INTRODUCTION

A new type of electric discharge excited in air over the water surface was discovered at the Konstantinov Institute of Nuclear Physics (Gatchina) [1–3]. In such a discharge, two phases can be distinguished: a discharge that is initially produced around a negative electrode (a jet ejected from the water) and a long-lived autonomous luminous object (LO) into which the discharge transforms thereafter. The LO exists over a few hundred milliseconds without external energy supply. In [2], it was supposed that the LO had an unneutralized electric charge localized in the thin LO shell. Studies of the electric characteristics of such discharges [4–6] confirmed the presence of an unneutralized electric charge in the LO. It was also hypothesized that the LO was a one-component plasma consisting of only negative charged particles [5]. An anomalously strong response of this unneutralized system (both the jet and the LO) to a weak harmonic action (laser radiation with a power as low as 10^{-3} W) allowed the authors of [4] to suggest that the leader of a streak lightning could be controlled by a low-power laser. The problem of controlling lightnings by lasers was investigated in [7–9]. Two basic methods of laser control are usually considered: (i) the generation of a laser spark at the top of a lightning rod (in this case, the spark serves as an extension of the rod) and (ii) the generation of a laser spark at a large altitude, in the region where the thundercloud field is maximum. Moreover, in [9], an interesting hypothesis was put forward that “a cloud of charged aerosol is a self-organizing system.”

2. EXPERIMENT

The results obtained in this paper, which continues the studies [1–6], may be of interest in developing new methods for the laser control of lightning. For this purpose, it is necessary to gain a better insight into the structure of LOs and the nature of electric charge carriers in them. We believe that the leader of streak lightning is best modeled by the discharge investigated in our study. When performing probe measurements, it is necessary to have a certain, even if rough, model of the object under study. Among the LO models considered in [2, 3], the most preferable is that proposed in [2]. In that model, the LO was treated as a shell structure formed of a highly nonideal plasma.

The concept of a device for generating LOs is outlined in [1, 2], and its design is described in [3–4]. The basic component of the device is a 0.6-mF capacitor bank, which is charged to 5.5–6.0 kV. A discharge is excited by switching the capacitor bank to a 6-mm-diameter graphite electrode (cathode), which projects over 2–3 mm from the water surface. The side surface of the electrode is insulated from the water by a quartz tube. The annular positive electrode (anode) is immersed in water at a depth of 15 cm. After the high voltage is applied to the discharge gap, a slipping discharge propagates over the water surface and a water jet is ejected upward from the negative electrode. After 80 ms, the capacitor bank is disconnected (the residual voltage being 3 kV) and the jet separates from the electrode to form a LO. The LO evolution is described in [3]. At 60–100 ms, the LO usually appears as a jellylike body (see Fig. 1); sometimes the LO is shaped as a perfect sphere. If the discharge is interrupted at early times (<80 ms), the second LO appears near the switching rod (Fig. 2). Figure 2 shows a photograph of the first (greater) LO, which forms near the graphite electrode, and the second LO, which is located near the copper rod. The emission intensities and colors of both LOs are almost the same. The LO formed near the graphite electrode exists over a longer time, and the LO colors in the decay stage are somewhat different. This indicates that, in essence, water plays the role of a variable resistance. We positioned detectors near the LO, at a height of 25–45 cm above the electrode. The minimum height of the

Fig. 1. Photograph of an LO. The inset at the top left of the figure shows a slipping discharge that preceded the appearance of a jet and its subsequent transformation into the LO.

detector was chosen with account of the time during which the LO propagates to the detector: about 100 ms after the end of the discharge. The LO rises at a velocity of about 1 m/s, approaches the detector at 100 ms, and leaves it at about 200 ms. When investigating the LO, we used a Langmuir probe, a double probe, a dipole antenna, and their various combinations.

The signals of the current of negative charge carriers to an unbiased Langmuir probe and to a probe biased by +300 V are shown in Figs. 3a and 3b, respectively. In the probe signals, peaks of the probe current are clearly seen when the leading and trailing edges of the LO cross the probe (Fig. 3a). In Fig. 3b, the signal from the trailing edge is less pronounced, but there is a sharp spike of opposite (positive) polarity. Starting from a bias of +600 V, this peak somewhat broadens, but the shape of the signal generally remains the same. The probe theory does not suggest the appearance of the current of positive ions to the probe as the positive bias increases. Estimates show that, at a bias of +300 V, the electric field at the probe amounts to 14 kV/cm. The observed behavior of the probe current may be attributed to electron emission; this is also evidenced by the probe glow that is seen with the naked eye [10]. The results obtained in [11] and probe measurements with a

Fig. 2. Generation of two LOs in the same discharge. The second LO (on the right) is located near the copper rod.

negative bias down to –600 V allow us to conclude that there are no positive ions in the LO.

Figure 4 shows a signal from a high-resistance double probe electrically insulated from the measurement facility. The shape of this signal shows the presence of an electric field inside the LO; this means that the LO interior is spatially charged. Figure 4 does not demonstrate the presence of a shell; however, as the input resistance of the probe is decreased, the probe signal shows sharp jumps in the electric field [11], which indicate the presence of a shell.[1] In an ordinary plasma, a double probe introduces minimal perturbations. In our case, however, the double probe with a low input resistance destroyed the LO when it contacted the shell. The data presented in Fig. 4 were not processed with a computer. Since probe measurements are hart to interpret, we also used a dipole antenna, which only slightly interacts with the LO.

The dipole antenna and its measurement circuit were specially designed by S.I. Stepanov, E.A. Drobchenko, G.D. Shabanov, and A.I. Egorov for studying LOs. Structurally, the dipole antenna is a double probe with an electrode distance of 3 mm; however, in contrast to an ordinary double probe, the electrodes of the dipole antenna are insulated from one another. We used two versions of the dipole antenna: with and without a reference electrode. In some measurements, the refer-

[1] These measurements confirmed the presence of a nonluminous layer between the shell and the interior of the LO. The nonluminous layer is free of charged particles. A similar layer with a thickness of 0.1–0.2 mm was also detected in Avramenko's jet. Such a layer arises due to Coulomb repulsion between like charges that are present in the shell and the interior of the object [2]. In the LO, this layer is 2–3 mm thick in its upper part and ~20 mm thick in its lower part. For the lower part of the LO, this can be seen from the probe signal shown in Fig. 3a. In the upper part of the LO, the probe did not show the presence of this layer because the probe size was too large. We could not use a smaller probe because the probe conductors were melted when interacting with the LO, no matter whether the conductor was grounded or not.

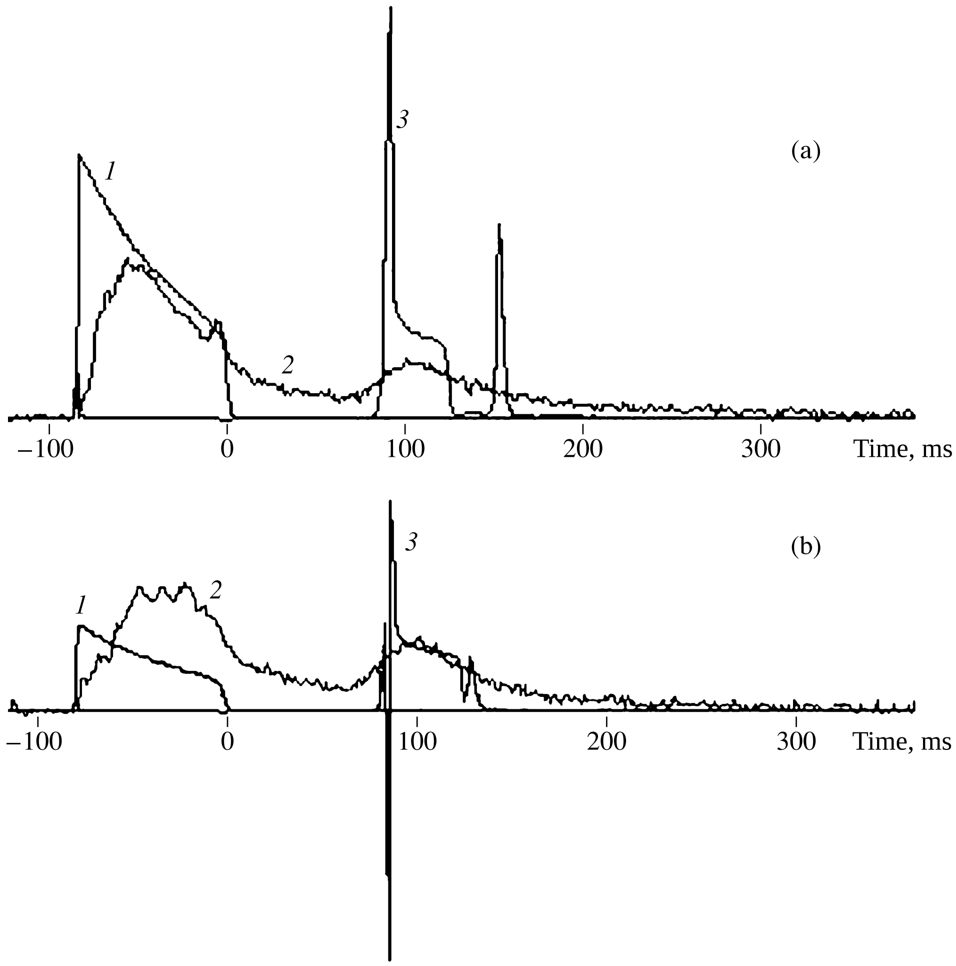

Fig. 3. Experiment with (a) a 0.45-mm-diameter unbiased Langmuir probe and (b) a probe biased by +300 V: the time evolution of (*1*) the voltage across the discharge gap (the maximum voltage is 5.5 kV), (*2*) the LO intensity (arb. units), and (*3*) the current of negatively charged particles to the probe. The peaks of the probe current correspond to the leading (5 μA) and trailing edges of the LO.

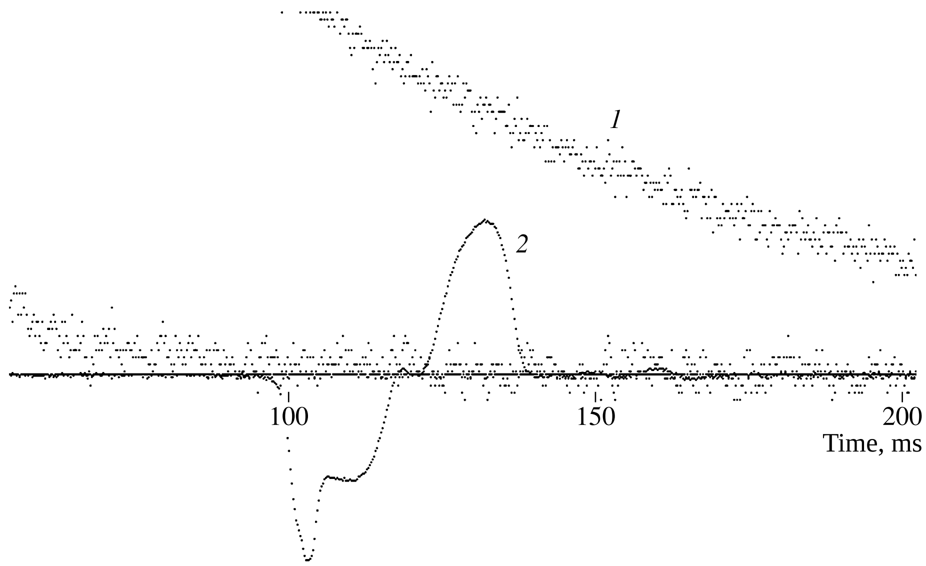

Fig. 4. Experiment with a double probe: (*1*) the time evolution of the LO intensity (arb. units) and (*2*) the double-probe signal.

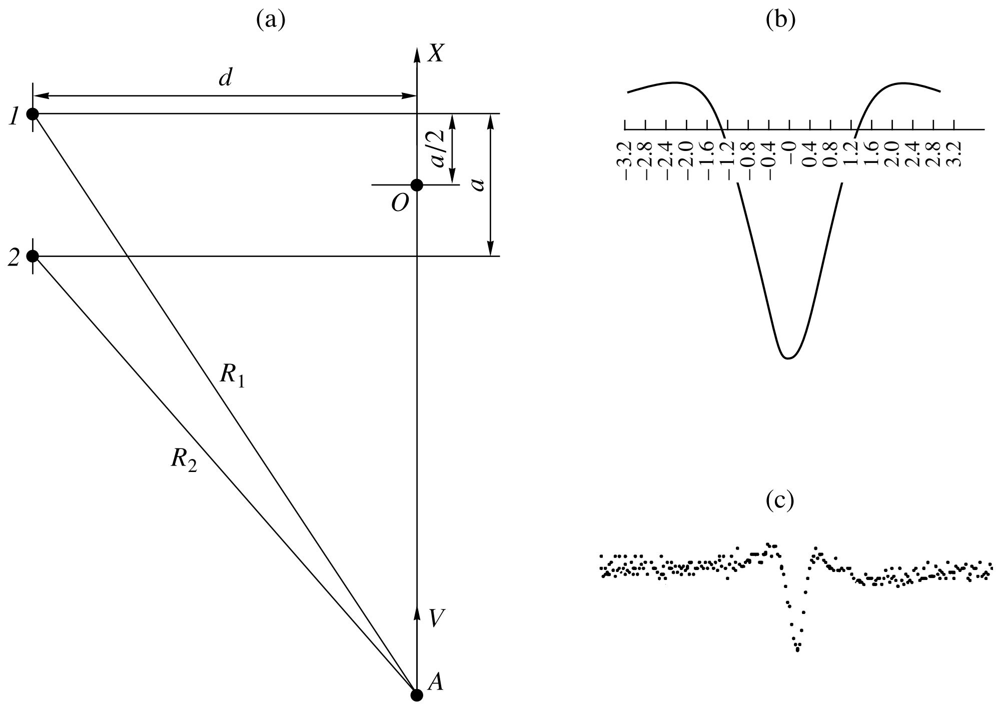

Fig. 5. (a) Scheme of calibrating the dipole antenna: the tips of the dipole antenna are at points *1* and *2*, *A* is a point source, and *d* is the minimal distance between the source and the dipole antenna; (b) dipole-antenna signal calculated by formula (2); and (c) dipole-antenna signal measured during the passage of a 2-cm-diameter source, to which a potential of 5.5 kV was applied.

ence electrode was used as a Langmuir probe. The dipole antenna was calibrated in a uniform capacitor field (in various media) and under conditions similar to our experimental conditions. Figure 5a shows the scheme of calibrating the dipole antenna by point source *A* (the tips of the dipole antenna are at points *1* and *2*). The 2-cm-diameter source, to which a voltage of 5.5 kV was applied, was carried near the dipole antenna along the *x* axis, the minimal distance *d* between the source and the dipole antenna being 1 cm.

Let us derive the expressions for the potential difference between the tips of the dipole antenna $\varphi_1 - \varphi_2$ and for the observed signal $\Phi(x) = \frac{d(\varphi_1 - \varphi_2)}{dt}$. The distances from the source to the antenna tips are

$$R_1^2 = d^2 + \left(x + \frac{a}{2}\right)^2, \quad R_2^2 = d^2 + \left(x - \frac{a}{2}\right)^2,$$

From this, we obtain

$$\varphi_1 - \varphi_2 = Q\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

$$= Q\left(\frac{1}{\left(d^2 + x^2 + ax + \frac{a^2}{4}\right)^{\frac{1}{2}}} - \frac{1}{\left(d^2 + x^2 - ax + \frac{a^2}{4}\right)^{\frac{1}{2}}}\right).$$

For $a \ll d$, we can ignore the term $\frac{a^2}{4}$ in the radicand and to factor $\frac{Q}{(d^2 + x^2)^{\frac{1}{2}}}$ out. We then find

$$\varphi_1 - \varphi_2 = -aQ\frac{x}{(d^2 + x^2)^{\frac{3}{2}}} \qquad (1)$$

and

$$\Phi(x) = \frac{d(\varphi_1 - \varphi_2)}{dt} = \frac{d(\varphi_1 - \varphi_2)}{dx}\frac{dx}{dt}$$

$$= -aVQ\left[\frac{1}{(x^2 + d^2)^{\frac{3}{2}}} - \frac{3x^2}{(x^2 + d^2)^{\frac{5}{2}}}\right]$$

or

$$\Phi(x) = A\frac{d^2 - 2x^2}{(x^2 + d^2)^{\frac{5}{2}}}, \qquad (2)$$

where $A = -aVQ$ and $V = \frac{dx}{dt}$ is the velocity of the source.

The curve in Fig. 5b corresponds to expression (2) at $d = 2$ cm. Figure 5c shows an experimental curve obtained for the above parameters of the antenna and

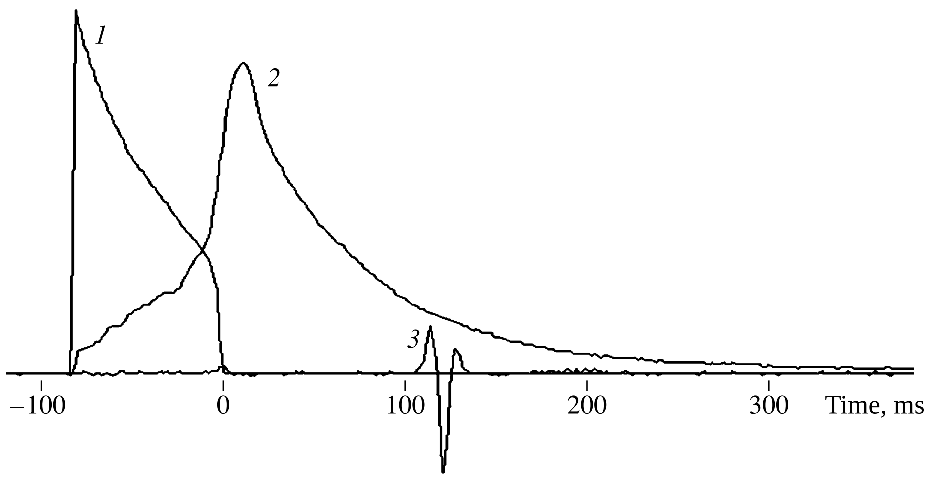

Fig. 6. Experiment on the propagation of a LO near the dipole antenna: the time evolution of (*1*) the voltage across the discharge gap, (*2*) the LO intensity (arb. units), and (*3*) the dipole-antenna signal.

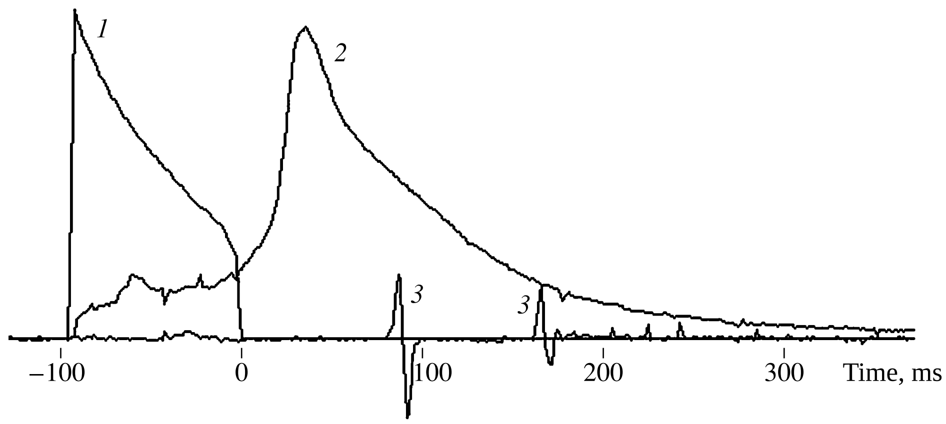

Fig. 7. Passage of the dipole antenna through the center of the LO: the time evolution of (*1*) the voltage across the discharge gap, (*2*) the LO intensity (arb. units), and (*3*) the dipole-antenna signal.

the source and for a source velocity of higher than 2 m/s. The curve corresponding to expression (1) is obtained by integrating the curve in Fig. 5b. An analysis of expression (2) shows that the dipole-antenna signal depends crucially on the parameter d; this agrees with the experimental results.

Figure 6 shows the antenna signal for an experiment in which a compact LO about 8 cm in diameter passed by the dipole antenna with a velocity of higher than 2 m/s, the minimal distance between the LO surface and the antenna being 2 cm. When the antenna fell into the LO interior, the signal corresponded to the passage of the detector through a charged plane (Fig. 7). In Fig. 7, this corresponds to curve *3* with two oscillations, which appear when the detector passed through the front and rear walls of the LO shell.

3. DISCUSSION

In the electric discharge under study [1–3], the macroscopic separation of charges results in the generation of a negatively charged LO. From the measurement results, it is rather difficult to determine the absolute values of the electric charge, field, and temperature of the LO, even though we calibrated the detectors and modeled different regimes of interaction between the LO and detectors. Thus, according to calibration in air, the shell field in some experiments was found to be 7 kV/cm, whereas the calibration in a conducting medium (e.g., in a liquid) gave a field lower by a factor of 2 to 3. It follows from probe measurements that the LO has a thin shell in which the electric parameters change by a jump and that the shell consists of negatively charged particles with a high density or high

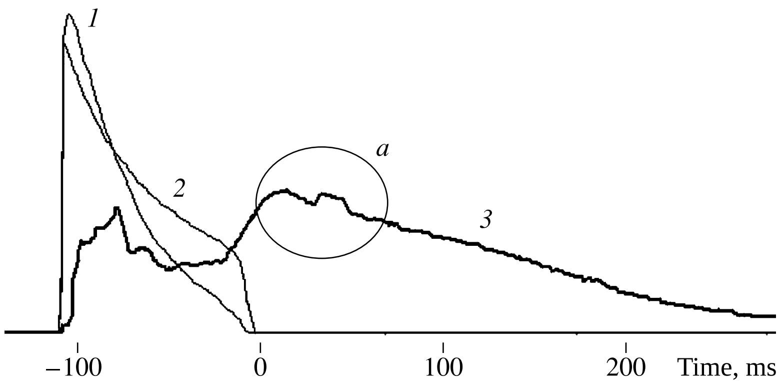

Fig. 8. Experiment on the interaction of a propagating LO with a 0.08-mm wire: the time evolution of (*1*) the discharge current (the maximum current is 52 A); (*2*) the voltage across the discharge gap, and (*3*) the LO intensity (arb. units). The plateau with an enhanced intensity in region *a* corresponds to the interaction between the wire and the LO. In the course of interaction, the end of the wire was melted to form a sphere 0.2 mm in diameter

mobility. Signals from the dipole antenna show that an unneutralized electric charge is mainly localized in the shell (Fig. 7). From the experimental results presented in Fig. 6, it follows (with allowance for the modeling and calibration measurements) that the LO electric charge is larger than -10^{-7} C. In [11], the authors refined the model of the LO shell proposed in [2], where it was assumed that the unneutralized electric charge was concentrated in the shell and the charge carriers had short-range order. This is possible if the potential energy of Coulomb interaction between particles exceeds their thermal kinetic energy. Shell and stratified charged particle systems with both short- and long-range orders were studied experimentally in [12, 13]. In this context, data on the interaction of lightning with copper rods [14] may be interpreted (using results of measurements with Langmuir probes biased from –600 to +600 V) as the appearance of several closely spaced (by 4 μm) layers of likely charged particles in the LO shell [11].

Strong Coulomb interaction between particles in nonideal systems causes gas–liquid–solid phase transitions. This may be sufficient for the system to be displaced as a whole in response to a weak external action [15]. Taking this into account, the authors of [4, 5] proposed that streak lightning be controlled with the help of a low-power laser. In [9], a system of charged particles was considered as being self-regulating. According to our estimates, the coupling parameter Γ of the system considered in [9] with parameters reported in [16] is larger than unity; i.e., the system is nonideal. It follows from this that the potential energy of the system is larger than its kinetic energy; therefore, the cloud may be self-regulated.[2]

As was noted in [9], a laser spark extending a grounded electrode is unable to initiate lightning when the thundercloud electric field is too low; this is a serious disadvantage of this method of lightning protection. This method is efficient only when the electric field is high enough to initiate an upward leader even in the absence of a laser spark [9]. The same disadvantage is peculiar to the method proposed in [4, 5], where it was suggested that the leader be subject to an external action in the final (rather than initial) stage of its formation.

Fig. 9. Interaction between the jet and the laser beam. The laser beam propagates from right to left perpendicular to the discharge axis at a height of 22 cm above the electrode. The formation of the LO begins after the jet has traversed a distance of 8.5 cm across the laser beam.

[2] Many examples of self-regulation of LOs were given in [2, 11], in particular, the recovery of the LO shell after its damage (see Fig. 8).

Therefore, the most promising method of lightning protection is to initiate lightning at a large altitude, where the field is sufficiently high [7, 8]. This will allow one to discharge thunderclouds in sparsely populated regions [7], far from the protected objects. To guide the formed leader to a desired point, the method proposed in [4, 5] can be used. The results of investigations of the action of a low-intensity laser with a power lower than 10^{-3} W (see Fig. 9) on a nonideal Coulomb system of charged particles (as well as other relevant effects [2, 11, 15]) allow us to hope that a detailed study of the processes that occur in such systems will help to solve the problem of lightning protection.

4. CONCLUSIONS

It has been shown that a pulsed electric discharge produced in air over the water surface can initiate a LO, which is a one-component plasma with no neutralizing positive background. The LO can exist over a few hundred milliseconds without external energy supply. The LO has a rather complicated structure: it consists of a shell formed by negative charged particles with a high density or high mobility and the internal space filled with negative atomic and molecular ions. Between the shell and the internal space, there is a nonradiative layer free of charged particles. This layer forms due to the Coulomb repulsion between the shell and the internal region.

The self-organization of natural Coulomb systems (such as thunderclouds and lightning) and artificial ones (such as charged aerosols and LOs) can be attributed to the fact that these systems are far from being ideal [9]. Studies in this field can lead to the development of new methods for protecting vulnerable and important objects from lightning strikes.

Among possible methods for the laser control of lightning, the most promising is to initiate lightning by a laser spark in the region where the thundercloud field is maximum [7, 8] and then to guide the lightning by a low-intensity laser to the required point [4, 5].

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