Technical Physics, Vol. 50, No. 3, 2005, pp. 380–383. Translated from Zhurnal Tekhnicheskoĭ Fiziki, Vol. 75, No. 3, 2005, pp. 98–101.

BRIEF COMMUNICATIONS

Generation of Autonomous Long-Lived Plasma Objects in Free Atmosphere

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Received October 23, 2003; in final form, June 16, 2004

Abstract—Results are presented from experimental studies of autonomous long-lived plasma objects in free atmosphere with a visible afterglow lasting 2 s. The experimental setup is described, and the energy conditions ensuring the generation of such plasma objects are determined. *© 2005 Pleiades Publishing, Inc.*

INTRODUCTION

Studies of long-lived plasma objects (LPOs) are mainly related to the problem of ball lightning (BL). This problem has been actively studied over a long time both theoretically and experimentally [1–12].

Studies of LPOs that are remote from both the discharge chamber wall and energy sources are important for understanding the nature of BL, testing lightning protection systems, plasma chemistry, creating high-power pulsed open sources of optical radiation, and accumulation and transportation of electromagnetic energy.

Experimental studies aimed at generating plasma objets possessing some properties of BL (shape, size, color, velocity, lifetime, and decay) under laboratory conditions are reviewed in [13]. There are various means for generating LPOs: an erosion discharge [14, 15], a capillary discharge [16, 17], a microwave discharge and its modifications [18], etc. Since natural BLs occur in free atmosphere, most of the experiments were performed with atmospheric air.

Experiments in which the working medium is air saturated with water vapor seem to be the most promising, because such a medium most closely models natural conditions for the origin of BL. Using an erosion discharge, one can produce glowing objects with a diameter of 7–19 cm and lifetime of 0.5–1.0 s [19, 20]. It is shown experimentally that LPO lifetime depends on many parameters: the size and shape of the central electrode, the discharge voltage, the amplitude and duration of the current pulse, and the temperature and conductivity of the water deposited on the electrode [21].

In most experiments, a capacitor bank was used as a power supply (e.g., in [14], the capacitance was varied from 650 μF to 5 mF and the stored energy was varied from 50 to 200 J, while in [15], these quantities were 216 μF and 100 kJ, respectively) and the current pulse duration was a few microseconds. Over such a short time, an LPO decays before it transforms into a stable structure.

The aim of this study was to produce LPOs with an afterglow time of up to 2 s in free atmosphere at normal pressure. For this purpose, an inductive energy storage unit with a current pulse duration of ~100 ms and high stored energy (of about 500 kJ) was used. No additives to the discharge plasma other than the products of electrode material erosion were used.

EXPERIMENTAL FACILITY FOR GENERATING LPOs

The experimental setup for producing and studying LPOs consisted of four main parts: a power supply, switches, a generator, and a system for monitoring the LPO parameters [12, 22, 23]. A schematic of the experimental setup is shown in Fig. 1. The storage inductance was fed from nine VAKG-12/6-3200 rectifiers connected in parallel. The parameters of the power supply were as follows: the input circuit voltage was 380 ± 38 V, the circuit frequency was 50 Hz, the rated output power was 38.4 kW, the rated rectified current was 3200 A, and the rated rectified voltage was 12 V (mode I)

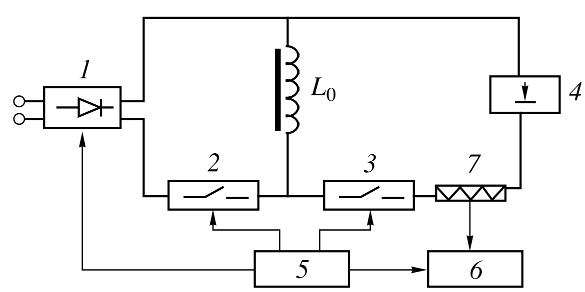

Fig. 1. Schematic of the experimental setup: (*1*) block of nine VAKG-12/6-3200 rectifiers, (*2*) MGG-10-U3 switch, (*3*) VMG-10 switch, (*4*) plasma gun, (*5*) program mechanism, (*6*) recording system, (*7*) 75ShSMUZ shunt, and (L_0) storage inductance.

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or 6 V (mode II). Electric energy (about 500 kJ at a feeding current of 3000 A) was stored in the inductive storage with a total mass of 4000 kg. The power circuit was switched by an MGG-10-U3 switch (with a breaking current of 45 kA, turn-on time of ≤0.4 s, and clearing time up to arc extinction of 0.14 s) and a VMG-10 switch. LPOs were produced using a plasma gun made of nonmagnetic materials.

The facility operated as follows: After switch *2* was turned on, the storage inductance $L_0 = 6.5 \times 10^{-4}$ H was connected to rectifier bank *1*. When the stored magnetic energy reached a necessary value, the storage inductance was switched to load *4* (plasma gun) by switch *3*. After 0.07 s, switch *2* was turned off and the diaphragm of the plasma gun exploded under the action of the break induced current. The 0.07-s time interval was chosen in order for the diaphragm to remain undestroyed at a feeding voltage of 4 V and, at the same time, for switch *2* to provide a quite reliable contact. The switches, rectifiers, and recording system *6* were controlled by program mechanism *5*. The current in the discharge circuit was measured using shunt *7*.

The main component of the facility was a plasma gun used to generate autonomous LPOs in free atmosphere with an afterglow time of up to 2 s. A schematic of the plasma gun is shown in Fig. 2. The discharge was initiated with the help of 100-mm-diameter conducting diaphragm *4* composed of seven 8-μm Al foils. This number of foils was experimentally shown to be optimal. The diaphragm was placed on dielectric plate *3* (textolite, Plexiglas, cardboard, etc.), to which it was pressed by ring electrode *2*, made of a nonmagnetic material (stainless steel or brass). Electrode *1*, made of two to eight (depending on the experimental conditions) stranded wires with diameters of 1.0–2.4 mm, was connected to the diaphragm center. The opposite ends of the wires were connected (over a circle) to electrode *6*. To reduce the effect of the magnetic field generated by electrode *6* on the formation of LPOs, electrode *6* was placed below the discharge gap, whereas the current was supplied to electrode *5* via guide racks *7*. All the elements were made of nonmagnetic materials and set on support *8*. It was shown experimentally that the use of magnetic materials hindered the formation of stable LPOs; this was indicated by the fact that, in this case, the afterglow time was as short as a few tenths of a second. The design of the gun was rather compact and allowed one to vary the LPO size by changing the inner diameter *D* of the ring electrode from 60 to 150 mm.

The parameters of the experimental setup and LPO were simultaneously recorded on a UF-67-135 photo paper using a K-115 oscilloscope. Figure 3 shows typical waveforms of the current *I*, voltage *U*, and visible radiation intensity *P* recorded with the K-115 loop oscilloscope. The discharge current was recorded by the oscilloscope indirectly, using the voltage drop across the 75ShSMUZ shunt. The discharge voltage, including the electrode voltage drops, was measured

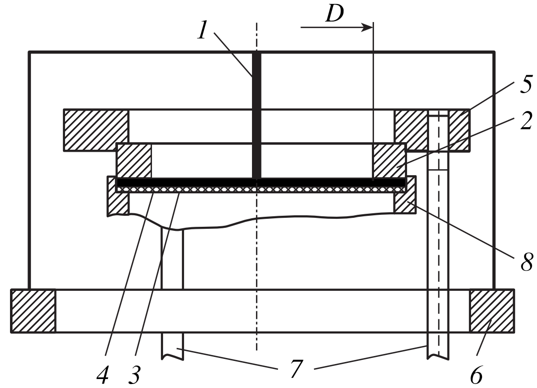

Fig. 2. Plasma gun: (*1*) central electrode, (*2*) ring electrode, (*3*) dielectric plate, (*4*) conducting diaphragm, (*5*, *6*) electrodes, (*7*) guide racks, (*8*) support.

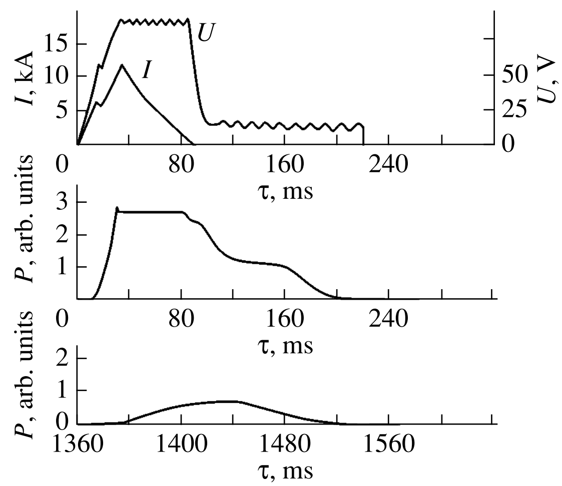

Fig. 3. Waveforms of the discharge current *I*, voltage *U*, and radiation intensity *P*.

between the axial and ring electrodes. The discharge current and voltage were recorded by the oscilloscope with the help of MO14-1200 galvanometers with an accuracy of 5%. The optical characteristics of LPOs were recorded using an AIETs2-S photometer with an F-2 vacuum photodetector. The operating spectral range of the photocathode (at a half-maximum level) was 320–600 nm. Special measurements showed that the time constant of the photometer was no more than 5 ms.

EXPERIMENT

Figures 4 and 5 show photographs of the experimentally obtained autonomous LPOs. The photographs were taken manually from a distance of 4 m on the Kodak-400 color film using a Zenit ET photo camera equipped with an MIR-1V lens (with a relative aperture of 8 and an exposure of 1/125 s). At the bottom of the photographs, parts of the plasma gun can be seen. In the

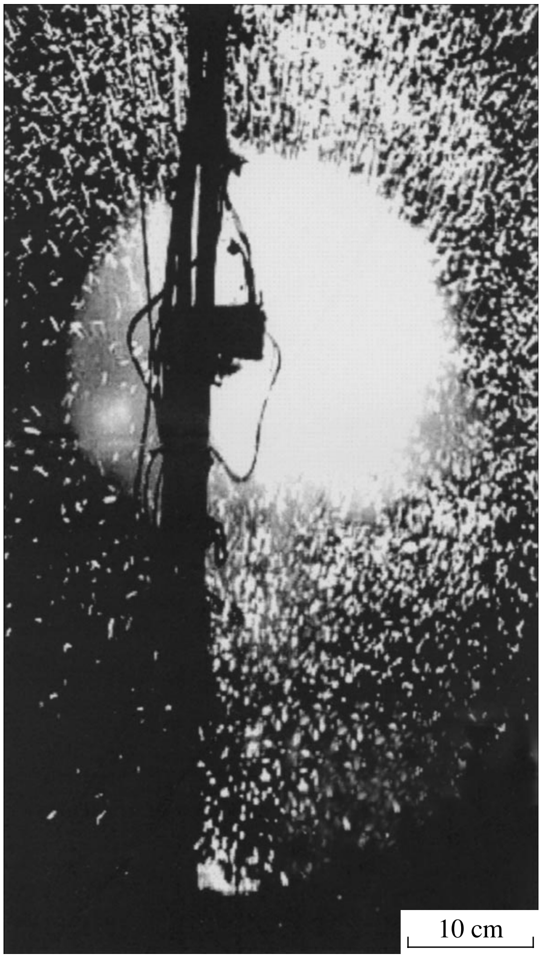

Fig. 4. LPO in the initial stage of formation.

initial stage, the LPO has a mushroom shape (Fig. 4), and by the end of the formation process, it transforms into a sphere (Fig. 5) with a diameter of 35–40 cm. It should be noted that the above photographs present the results obtained in different discharges. The dark vertical structure overlapping the periphery of the sphere is the holder of the measurement system. One second after the termination of the energy supply, the distance from the center of the sphere to the plasma gun was 70 cm. In the case at hand, the current amplitude was 10.2 kA and the current pulse duration was 100 ms.

Revealing physical processes responsible for the prolonged afterglow of the observed LPOs is beyond the scope of this study. Note, however, that photometric measurements of the LPO glow showed that the total radiation energy emitted by an LPO exceeds the sum of the thermal energy of particles, the ionization energy, and the energy of phase transformations in the condensed disperse phase. Depending on the experimental conditions, the radiated energy varied from 1.6 ± 0.7 to 10.8 ± 4.4 kJ. Hence, a fraction of the energy might be stored in, e.g., an electromagnetic field; i.e., an autonomous LPO can be regarded as a mirrorless photon trap.

Fig. 5. LPO at the end of the formation stage.

This is confirmed by the fact that, in about one-tenth of the experiments, the LPO glow intensity somewhat increased prior to its decay (a “hump” in the radiation intensity in Fig. 3). Such behavior cannot be explained using a cooling plasma concept.

Experiments showed that there were certain threshold parameters (or critical experimental conditions) under which LPOs arose in free atmosphere and existed for a rather long time. It was found in [19] that the duration of the LPO afterglow depended nonlinearly on the discharge energy (as well as on the discharge current). As a first approximation, the duration of the LPO afterglow on the discharge energy was assumed to be linear and was determined by the least squares method. The intersection of this linear dependence with the abscissa (where the lifetime is zero) gave an energy of 40 kJ, which corresponded to the discharge energy at a current of 10.4 kA. However, there is no sufficient reason to seek for the dependence of the LPO lifetime on the discharge energy in such a form. The actual behavior is more complicated, and the criterion for the formation of LPOs is still unknown. The observed statistical relationship between the LPO lifetime and the deposited electric energy can be regarded as fairly appropriate (the correlation factor is 0.32 for a significance of $\chi^2 = 0.1$). This means that the statistical relationship is determined by a more complicated combination of the parameters, which has yet to be found.

CONCLUSIONS

Experiments on the generation of autonomous LPOs with energy densities comparable to those typical of natural ball lightnings have been carried out. For autonomous LPPs with a diameter of 30 cm and stored energy of 10 kJ, the calculated energy density is ~0.7 J/cm^3, which agrees with the data for BLs [9]. In BLs, the energy density varies from 2×10^{-3} to 2×10^2 J/cm^3, the average energy density being relatively low, on the order of 1 J/cm^3.

An analysis of the video and photo information, as well as the waveforms of the glow intensity, shows that it is possible to obtain autonomous LPOs with a diameter of 30–35 cm and a visible afterglow lasting 2 s. Depending on the experimental conditions, the radiated energy varies from 1.6 ± 0.7 to 10.8 ± 4.4 kJ.

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Translated by N. Ustinovskiĭ