Generation of Laboratory Ball Lightning

A G Oreshko
Moscow Aviation Institute (State Technical University), Volokolamskoe shosse 4, 125871 Moscow, Russia
E-mail: Oreshko_Alex@mail.ru

Abstract The phenomenon of energy conversion in the streams of directed electrons and ions into electromagnetic radiation was found out experimentally and proved theoretically. The direct proofs of the domain mechanism of the charged particles acceleration and mechanism of ball lightning generation were obtained and the theoretical calculations were refined.

1. Introduction
The electric discharges in a gas under low and atmospheric pressures are of interest for solving a number of problems. Numerous papers are devoted to ball lightning (BL) phenomenon [1,2]. Knowledge, which is available in literature [1, 2], does not allow to explain the mechanism of ball lighting generation, structure and lifetime. The microball lighting was observed at the initial stage of discharge [3]. BL formation also was observed at initial stage of the capillary discharge [4]. This study represents continuation of experiments and is devoted to investigation of generation of laboratory BL near the dielectric surface [3].

2. Experimental setup
The experiments of the large scale BL generation were made on the facility “Prometheus - M”. It consists of the electric energy storage, rotating discharge cell and electronic system for the electric circuit commutation. The storing capacitors allowed accumulating the energy up to 10 kJ. The voltage pulse with amplitude up to 6 kV was applied to the discharge cell electrodes. Special design of the discharge cell allowed generating the BL of large diameter. It can be rotated during the experiments. The circuit commutation was realized with a special discharger unit. Initiation of the breakdown in the discharger was performed by injection of a fast electron microbeam into the interelectrode space at the atmosphere conditions. The voltage, current, luminosity of BL and its lifetime were registered. Special electrode spacing and the discharge geometry allow generating the intense beam of fast electrons at the initial stage of the time evolution of discharge plasma. The beam was injected into the water vapor, which continuously comes in near-electrode space. The initial stage of the discharge was characterized by maximum values of the voltage and current and was used for the effective BL generation.

3. On the physics of breakdown and structure of ball lightning
Figure 1a shows the typical integral images of BL luminosity of 20 cm in diameter. Luminosity intensity of BL ring layers enlarges with respect to that of BL kernel. BL was destroyed at the distance of 1 m from the place of its generation. It was associated with presence of high energy particle beam,
which is observed in Figure1 (in the top). BL velocity in vertical direction from the discharge cell exit coincided with the thermal velocity of ion component. The causal factors of BL destruction result from the presence of high charge ions ejected from electrode materials or force imbalance, which is available in lightning structure. In last experiments BL was destroyed after passage of 3 meters in the region of laboratory ceiling. Rotation of the cell after discharge period in “Prometheus - M” experiments gives the basis to assume that BL also rotates.

Figure1. Integral photos of the laboratory ball lightning of 20 cm in diameter – (a), optical image of BL luminosity in an initial stage of discharge breakdown – (b), the qualitative structure generated at the origin of the domain of a transverse electromagnetic waves – (c), and optical image, when flat domain passes between electrodes under breakdown – (d).

The experimental results [3, 4] and this study give the basis to consider the BL as an electric domain of spherical configuration. It consists of a kernel with surplus of negative charge and the ring external layers (REL) having surplus of positive charge. In the experiment on the breakdown near the dielectric surface, the scheme of which is given in [3], it was found that charge separation occurs and a flat domain is generated (see Figure 2 (b)) in the near-electrode zone (bordering with one of the electrodes). This process is caused by a non-equality of the directed fluxes of charged particles [5]. Domain’s origin is accompanied with generation of a transverse electromagnetic wave. It accelerates the charged particles in the direction perpendicular to the discharge cell axis. The fast electrons are thermalized. As a result, luminosity in the near-electrode space is observed (see Figure 2 (b)). In the breakdown phase the flat domain moves toward to the grounded electrode and is located in the head part of the current plasma sheath. It is transformed into a stable state from an excited one, Figure 2 (d). The luminosity in the domain zone correlates with a change of the electric field strength, with the fast electron microbeam occurrence, and with generation of X-rays and microwave radiation. Ambipolar and strong radial electrical fields occur between the rotating kernels and the REL. Electric field
intensity is sufficient for secondary generation of fast electron beam. Subsequent thermalization of the electrons in air leads to appearance of secondary plasma structure in the top (Figure 2). Large scale lifetime of BL is explained by rotating of charges in line of bearing. It produces azimuthal current, which generates a poloidal magnetic field (a magnetic dynamo). Such dynamo is present in the stars [6]. The magnetic field lines surround the REL from outside, and inside they are localized between the REL and the BL kernels. The spatial distribution of electrical charges and electric and magnetic fields occur in BL, under which the optimal magnetic insulation is realized. REL is magnetized under the conditions. Such distributions of charges and fields slow down the diffusion of ions across the magnetic field and markedly diminish process of charge recombination due to the lack of electrons in the ring layer and ions into the core. The resultant forces of coulomb interactions, Lorentz’s force, and forces due to gas kinetic pressure gradient and centripetal acceleration are equal to zero in BL observed in the Nature. Thus it is possible to explain the considerable lifetime of BL in the Nature.

Figure 2. The generation of anomalous formations looks like the microball lightning in the space under breakdown near the dielectric surface for four intervals of time (framing mode). Exposure time was 20 ns.

4. Conversion of the energy in a plasma

The fields and density gradients generate the flows of directed electron and ion in a plasma, which are given in the next form [7]

$$\Gamma_e = -n_e \vec{u}_e (\vec{E}) - D_e \nabla n_e, \quad (1)$$
$$\Gamma_i = n_i \vec{u}_i (\vec{E}) - D_i \nabla n_i, \quad (2)$$

Here, $n$ is the density, $\vec{u}$ is the directed velocity, $D$ is the diffusion coefficient. An inequality of the directed drift flows, i.e. $\Gamma_e \neq \Gamma_i$, leads to the charge separation. At strong longitudinal electric field $\Gamma_e > \Gamma_i$. Neglecting the ionization, recombination and collision effects, the continuity equations for electrons and ions can be written in the form

$$\frac{\partial n_e}{\partial t} = -\nabla \cdot \Gamma_e, \quad (3)$$
$$\frac{\partial n_i}{\partial t} = -\nabla \cdot \Gamma_i. \quad (4)$$

The electric field strength distribution is given by the Poisson equation
\[ \nabla \cdot (\varepsilon \vec{E}) = 4\pi \rho_e, \]  
where \( \varepsilon \) is the dielectric permittivity of the plasma, \( \rho_e \) is the space charge, which is determined by the expression

\[ \rho_e = e(n_i - n_e). \]  

The component density expressions included in the right-hand side of the expression (6) are excessive ones. The dependence between a rotor of magnetic field induction, current density and electric field is given by Maxwell equation

\[ \nabla \times \vec{B} = \frac{1}{c} \frac{d\vec{E}}{dt} + \frac{4\pi}{c} \vec{j}. \]  

In the process of the domain generation, the conduction current drops to zero in the zone of charge separation. According to Maxwell equations, the change in the electric field strength results in that of the magnetic field induction. The domain generation is accompanied by change of the energies of a particle group. The charge separation in a plasma accompanied with a change in the energy for a very short time. It should generate the microwaves. 

For weakly-ionized plasma, when the electric field strength exceeds the critical Dreiser value, the equations of motion for electrons and ions can be written in the form, respectively:

\[ m_e \left( \frac{\partial \vec{u}_e}{\partial t} + \vec{u}_e \cdot \nabla \right) \vec{u}_e = -e\vec{E} - m_e \nu_e \left( \frac{\vec{E}}{e} \right) \vec{u}_e, \]  
\[ m_i \left( \frac{\partial \vec{u}_i}{\partial t} + \vec{u}_i \cdot \nabla \right) \vec{u}_i = e\vec{E}. \]  

Since the directed drift velocity of electrons in a strong field exceeds the thermal one, the dependent on the energy frequency of collisions can be written in the form:

\[ V_{ea} = \frac{e \left( du / dt \right)^{-1}}{m_e \mu_d} = \frac{1}{m_e \mu_d}, \]  

where \( \mu_d \) is the differential mobility. The linearization of a set of equations, including the equations of the motion, the continuity and the Poisson ones for the perturbations of particle velocity \( u = u_0 + u_i e^{i(kz-\omega t)} \), their density, \( n = n_0 + n_i e^{i(kz-\omega t)} \) and field strength, \( \vec{E} = \vec{E}_i e^{i(kz-\omega t)} \) allow us to obtain the expression for the space charge waves in a weakly-ionized plasma in the presence of a strong field,

\[ \vec{k} \vec{E}_i \left( 1 - \frac{\omega_p^2}{(\omega - ku_{e,0})^2} \right) - \frac{\omega_p^2}{\omega - ku_{e,0} - \frac{e}{im_e \mu_d}} = 0. \]  

Since the drift velocities are established for a time between collisions, then, neglecting the low frequency components, the expression for a dielectric plasma permittivity in a strong field can be written in the form:

\[ \varepsilon = 1 - \frac{\omega_p^2}{\omega} - \frac{\omega_p^2}{\omega^2 - \omega - \omega - \frac{e}{im_e \mu_d}}, \]  

from which an equation follows for the space charge waves:

\[ \omega^3 - \frac{e}{im_e \mu_d} \omega - (\omega_p^2 + \omega_p^2) \omega + \frac{e\omega_p^2}{im_e \mu_d} = 0. \]
One of the solutions of equation (13) is the expression \( \omega = 0 \). It is probable, that such solution corresponds to the case of absence of the strong field in plasma. In result of solution of the cubic equation by Karman’s method and taking into account of dominating parts only for the case of high frequency waves of the space charge one can get one negative and two equal positive roots

\[
\omega_{asc} = \omega_{pe} + \frac{e}{3im_e \mu_d} = \omega_{pe} - \frac{\omega_{pe}^2}{12\pi \sigma_d} i. \tag{14}
\]

From (14) it follows that the spatial charge wave frequency and the time constant of rising or of damping the fluctuations amplitude in a weakly-ionized plasma with a strong electric field is determined by the differential conduction of plasma \( \sigma_d = e n \mu_d \). Linearization of the equations of motion, continuity and Maxwell’s (7) allow us to obtain

\[
\nabla \times \vec{B} = -\frac{i\omega}{c} \varepsilon \vec{E}_1. \tag{15}
\]

By using the equation \( \nabla \times \vec{E}_i = i\omega \vec{B}_i \), determining \( \nabla \times \vec{B}_1 \) from it and then, substituting the produced value into (15), it can be transformed into the following form:

\[
\frac{c^2}{\omega^2} \nabla \times \nabla \times \vec{E}_1 = -\left(1 - \frac{\omega_{pe}^2}{\omega^2 - \omega} \right) \vec{E}_1. \tag{16}
\]

As a result of scalar or vector multiplication of Equation (16) by a wave vector \( \vec{k} \) one can produce the equations for the spatial charge waves (electrostatic waves) and for the electromagnetic ones, respectively. According to the approach of [8], let us find the solutions Equation (16) as a plane homogeneous wave at which the electric field strength is perpendicular to the wave propagation direction. Thus one has the following set of equations [8]

\[
\vec{E}_1(\omega, \vec{z}) = \vec{E}_i \exp(i\vec{k} \cdot \vec{z})
\]

\[
\vec{k} \cdot \vec{E}_i = 0
\]

The set of equations (17) allows us to reduce Equation (16) to the next form

\[
\omega(\omega^3 - \frac{e}{im_e \mu_d} \omega^2 - (k^2 c^2 + \omega_{pe}^2)\omega + k^2 c^2 \frac{e}{im_e \mu_d})\vec{k} \times \vec{E}_i = 0 \tag{18}
\]

The condition for the existence of a non-zero solution to Equation (18) \( \vec{E}_1 \neq 0 \), allows us to write the dispersion equation for the driven transverse electromagnetic waves in plasma

\[
\omega^2_{def} = k^2 c^2 + \omega_{asc}^2, \tag{19}
\]

which emerge in the process of charge separation and transit into the waves of light, in the absence of plasma, for which \( \omega = kc \). Since the electric and magnetic fields of driven waves are characterized by the Pointing vector, the separation of charges is characterized by radiation of the electromagnetic energy. A maximum of the radiated energy is placed in the equatorial plane domain.

The qualitative profile of generated transversal electromagnetic wave at the occurrence of the domain is given on Figure 1 (c). Induction lines of the azimuth magnetic field of the wave are located in a plane containing \( 0 \)-axis and perpendicular to the plane of Figure 1. As a result of the motion of the captured charged particle in the field of the propagating transverse electromagnetic wave they accumulate the energy, which significant exceeds the energy corresponding to voltage on the domain. It is evident that there are the particles with the energy, which is sufficient for phase matching condition performing in the region of the flat domain. Therefore, in the process of its occurrence the electric domain performs as the “built in the plasma” accelerator. Generation of the microwave radiation proves for the presence of energy conversion phenomena in plasma.
5. Theoretical background of the mechanism generation of a ball lightning

Data are available in the literature [3, 4] allow proposing model of BL generation in the presence of electrical discharge. Its occurrence is related with generation of the first electric domain. The fist flat domain is generated at the initial stage of the electric discharge because of higher of electron mobility with respect to the mobility of ions, $\mu_e >\mu_i$. Such domain probably appears at break or branching of line lighting in atmospheric discharges at the presence of run away electrons in the lidar channel. It is occurred in the initial stage of the breakdown. Ions and electrons emerge in the near electrode zone under the field strength growth. A break in the continuity occurs because of high electron mobility in comparison with the mobility of ions. The departure or a displacement of the group electrons by a characteristic size exceeding the length of screening results in the generation of a “near-electrode” flat domain [3]. Its occurrence is accompanied with generation of a transverse electromagnetic wave with assistance of which the captured electrons and ions acquire energy which exceeds the value corresponding to the voltage on the domain. The dissipation of their energy occurs under interaction of fast electrons in air. The ionization cross-section achieves a maximum at some values of energy and consequently, the fast electrons are thermalized. The thermalization zone is the kernel of BL. Besides, it is the zone with the surplus negative charge. Since the kernel production time is less than the time during which the system is able to neutralize, the surplus negative spatial charge appears on some distance from electrodes. The ring external layer is the zone with the surplus positive charge. It practically simultaneously rounds the kernel due to a photoionization. The step-like character of the domain generation is experimentally confirmed in [9].

6. Conclusion

It is shown, that the ball lightning is the electric domain of a spherical forms. Significant lifetime of such system is determined by magnetizing of ring external layer. The domain mechanism of generation ball lightning is developed. In this paper the direct experimental proofs of the domain mechanism of acceleration were obtained and the theoretical calculations were refined. It is necessary to note, that the structure of a ball lightning is to similar structure of stars in Universe. There is a common mechanism of generation ball lightnings at electric discharges in atmosphere and stars in Big Bang in the Universe.

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