The Generation of Fast Particles in Electrical Discharges

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Abstract – It has experimentally been studied that fast electrons and ions also have a radial component in the direction of propagation along with the component parallel to the discharge cell axis. The generation of fast particles correlates with generation of microwave radiation. Some theoretical background to the domain mechanism of the charged particle acceleration in plasma is given. The energy accumulation by electrons and ions occurs as a result of their interaction with the microwave radiation driven under separation of charges. The expressions for the waves frequencies of a space charge and for the transversal electromagnetic waves have been produced.

1. Introduction

The origin of the epithermal deuterons and electrons, detected in the experiments with high current discharges at the facilities of the Z-pinch type has been related with the presence of an acceleration mechanism in a plasma [1]. A number of the theoretical studies has been devoted to the attempts to explicate the essence of that mechanism. But they did not resolve the whole problem. One should note, that fast electrons which generating bremstrahlung, were dectered in diode of the accelerator of nanosecond duration [2]. Plasma fluxes, moving with the velosity $5 \cdot 10^7$ cm/s, were also observed. Such a flux velocity is characteristic for the systems with their own strong electric field – domains [3, 4]. Here and below a quasi-neutral system consisting of a layer or a region with the excessive negative charge and of a layer (zone) with an excessive positive charge is meant as an electric domain. The distance between the domain layers exceeds the Debye screening parameter. A strong electric field take place in the zone of charge separation under non significant voltage because of a short distance between the layers.

The fast charge particles and the microwave radiation were registered in the plasma opening switch (POS) [5], as well as in diodes with virtual cathodes [6, 7]. The fast electrons and ions were detected at a stage of the isolation violation in the magnetically-isolated diodes in a number of studies. The plasma at this stage of the diode operation the plasma is a source of the own microwave radiation, it abnormally diffuses across the longitudinal insolating magnetic field [8]. The multitude of the data produced for half-a-century period gives sufficient grounds for the assumption that the acceleration mechanism for electrons and ions in the plasma are the same. It is related with a drive of the strong fields and of the transversal electromagnetic waves which are produced under separation of the charges [9].

2. Experimental Results

The technique used in [10] has allowed one to find out that the fast particles in the Z-pinch have a near-axial nature. The fast electrons were observed in a spark discharge [11]. If one make orifice of a small diameter at the center of a passive semispherical electrode-transient into a cavity and locates the filter on the side opposite to the gap, one will detect the presence of a microbeam with the energy 100 keV under the applied voltage, $U = 23$ kV. The fast electrons accelerated in the radial direction in the spark discharge were observed by the author with the technique of filters and by the presence of imprints upon the metallic surfaces.

In the experiments on the breakdown near the dielectric surface, for which the discharge cell is given on Fig. 1, it has been found out that emergence of the near-electrode plasma – Fig. 2,a produced under explosion microspikes [12] and the presence of a current preceed the breakdown (see Fig. 2). Schematic of the diagnostics used in experiments is given on Fig. 3.

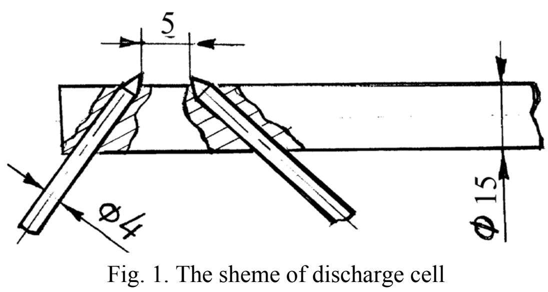

Fig. 1. The sheme of discharge cell

The fast electron microbeams were registered with the help of collector and with the Rogowski belt. In the near-electrode zone-bordering with one of electrodes, due to a non-equality of the directed drift fluxes the charge separation occurs and the flat domain emerges (see Fig. 2,a). It's birth is accompanied generation of the transversal electromagnetic wave by the help of which the charged particle acceleration occurs in the direction perpendicular to the discharge cell axis. The fast electron thermalization results in the emergence of a luminosity in the near-electrode space. In the breakdown phase the planar domain, which moves in toward to the passive electrode and is located in the head part of the current plasma sheath, transits in-to a stable state from an excited one, Fig. 4. The pulsed luminosity nature in the domain zone correlates with a change the electric field strength and with the fast electron microbeam emergence.

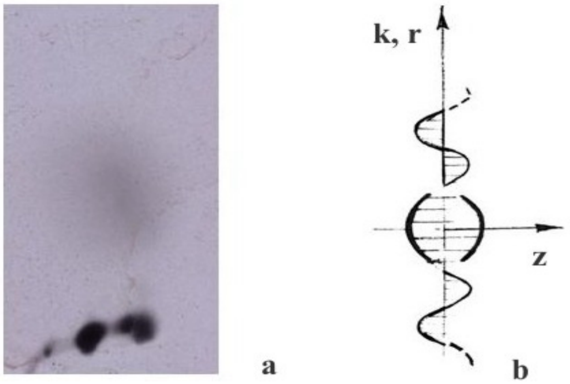

Fig. 2. Optical image at the time interval preceeding break-down – (a) and qualitative profile of the gene-rated transversal electromagnetic waves – (b)

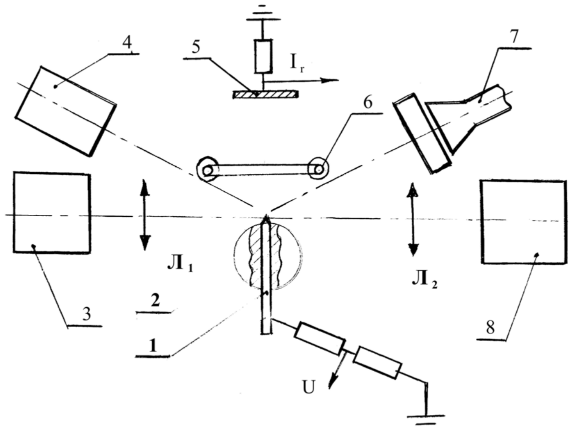

Fig. 3. Schematics of experiment. 1 – electrodes; 2 – cell body; 3 – electronic optical chamber FER-7; 4 – X-rays detector; 5 – collector; 6 – Rogowski belt; 7 – detector microwave radiation with phtoroplast absorber; 8 – electronic optical transformer; Л – lense

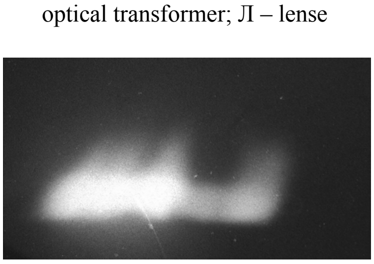

Fig. 4. Optical image when the planar domain passes between electrodes under breakdown

The potential oscillations also correlate with a signal at the output of the detector, measuring the microwave radiation, Fig. 5. Thus, a change in the space charge in the domain layers takes place under transition from the excited state into a stable one. The domain generation has a step-like character.

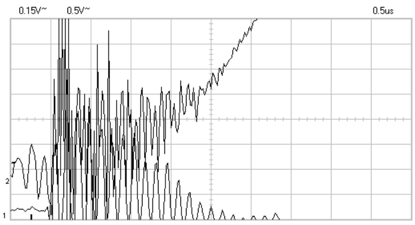

Fig. 5. Typical waveform of signals: microwave radiation (upper trace) and applied voltage (lower trace) at the initial phase of breakdown

A primary anomalous formations – spherical domain consisting of negatively charged nucleous and a positively charged external layer (see Fig. 6,a) – emerged in the near-electrode zone. A strong field presence between the nucleous and an external layer of the spherical domain results in the injection of the fast electron the thermalization of which gives birth to the secondary anomalous formation, Fig. 6,b.

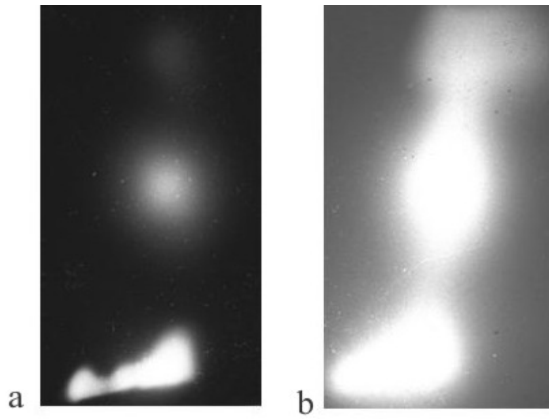

Fig. 6. The generation of anomalous formations in space under breakdown near surface of dielectric

The presence of axial and radial components in the spread direction of the fast charged particle microbeams, as well as the microwave radiation drive allow one to explain the accumulation of energies by the particles as a result of their interaction with the transversal electromagnetic waves driven under the charge separation.

3. Theoretical Background

For the emergence of domains in a plasma, it is necessary to have a strong electric field. A high voltage at the outputs of the power supply sources and presence of peaks or triple points provide the electric field strength value, exceeding the critical Dreiser one, $\vec{E}_c$. When $\vec{E} > \vec{E}_c$, electrons, as known, make transition into the mode "of running away" from collisions. At some value of $\vec{E}$, the directed velocity of electrons exceeds a thermal one. In the presence of a magnetic field, when $\vec{E} > \vec{B}$, particles also make transition into the acceleration mode. The fields and density gradients give birth in a plasma of directed electron and ion drift the flows, which given in next form [13]:

$$\vec{\Gamma}_e = -n_e \vec{u}_e(\vec{E}) - D_e \nabla n_e \,, \qquad (1)$$

$$\vec{\Gamma}_i = n_i \vec{u}_i(\vec{E}) - D_i \nabla n_i \,, \qquad (2)$$

where n is the density; $\vec{u}$ is the directed velocity; D is the diffusion coefficient. An inequality of the directed drift flows, i.e. $\vec{\Gamma}_e \neq \vec{\Gamma}_i$, takes place in the charge separation zone. In a strong longitudinal electric field $\vec{\Gamma}_e > \vec{\Gamma}_i$. Neglecting the ionization, recombination and collision effects, the continuity equation for electrons and ions can be written in the form

$$\frac{\partial n_e}{\partial t} = -\nabla \cdot \vec{\Gamma}_e \,, \qquad (3)$$

$$\frac{\partial n_i}{\partial t} = -\nabla \cdot \vec{\Gamma}_i \,. \qquad (4)$$

The electric field strength distribution for the plasma with the dielectric permittivity, ε, is given by the Poisson equation

$$\nabla \cdot (\varepsilon \vec{E}) = 4\pi \rho_e \,, \qquad (5)$$

where ρ_e is the space charge determine by the expression

$$\rho_e = e(n_i - n_e) \,. \qquad (6)$$

The component density expressions included into the right-hand side of the expression (6), are excessive ones. The dependence between a rotor of an induction of magnetic field and dencities of currents bias and conduction is given by Maxwell equation

$$\nabla \times \vec{B} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \frac{4\pi}{c}\vec{J} \,. \qquad (7)$$

In the process of the domain generation, the conduction current in the zone of charge separation drops to zero. According to Maxwell, a change in the electric field strength results in that of the magnetic field induction. The domain generation is accompanied by a change energies of a particles group. The charge separation in a plasma for a very short time accompanied by a change in the energy, should give birth to waves. For a weakly-ionized plasma in the presence of the electric field, the strength of which exceeds the critical Dreiser value, the equation of motion for electrons and ions can be written, respectively, in the form

$$m_e\left(\frac{\partial}{\partial t} + \vec{u}_e \cdot \nabla\right)\vec{u}_e = -e\vec{E} - m_e \nu_{ea}\left(\vec{E}\right)\vec{u}_e \,, \qquad (8)$$

$$m_i\left(\frac{\partial}{\partial t} + \vec{u}_i \cdot \nabla\right)\vec{u}_i = e\vec{E} \,. \qquad (9)$$

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

$$\nu_{ea} = \frac{e}{m_e}\left(\frac{du}{dt}\right)^{-1} = \frac{e}{m_e}\frac{1}{\mu_d} \,, \qquad (10)$$

where μ_d is differential mobility. The linearization of a set of equations, consisting of the equations of motion, continuity and the Poisson ones for the perturbations particle velocity $u = u_0 + u_1 e^{i(kz-\omega t)}$, their density, $n = n_0 + n_1 e^{i(kz-\omega t)}$ and field strength, $\vec{E} = \vec{E}_1 e^{i(kz-\omega t)}$ allow one to obtain an expression for the space charge waves in a weakly-ionized plasma in the presence of a strong field,

$$\vec{k}\vec{E}_1\left(1 - \frac{\omega_{pi}^2}{\left(\omega - ku_{i,0}\right)^2} - \frac{\omega_{pe}^2}{\left(\omega - ku_{e,0}\right)\left(\omega - ku_{e,0} - \frac{e}{im_e\mu_d}\right)}\right) = 0. \qquad (11)$$

Since the drift velocities are installed 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

$$\varepsilon = 1 - \frac{\omega_{pi}^2}{\omega} - \frac{\omega_{pe}^2}{\omega^2 - \omega\frac{e}{im_e\mu_d}} \,, \qquad (12)$$

from which an equation follows for the space charge waves:

$$\omega\left(\omega^3 - \frac{e}{im_e\mu_d}\omega^2 - (\omega_{pi}^2 + \omega_{pe}^2)\omega + \frac{e\omega_{pi}^2}{im_e\mu_d}\right) = 0 \,. \qquad (13)$$

One of the equation (13) solution is 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 keeping dominating members only for the high frequency waves of the space charge one can get one negative and two equal positive roots

$$\omega_{wsc} = \omega_{pe} + \frac{e}{3im_e\mu_d} = \omega_{pe} - \frac{\omega_{pe}^2}{12\pi\sigma_d}i \,. \qquad (14)$$

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 conduction of plasma a differential $\sigma_d = en\mu_d$. Linearization of the equations of motion, continuity and of the Maxwell ones (7) allow one to obtain the equation

$$\nabla\times\vec{B} = -\frac{i\omega}{c}\varepsilon\hat{E}_1 . \quad (15)$$

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

$$\frac{c^2}{\omega^2}\nabla\times\nabla\times\hat{E}_1 = \left(1-\frac{\omega_{pe}^2}{\omega^2-\omega\frac{e}{im_e\mu_d}}\right)\hat{E}_1 . \quad (16)$$

As a result of scalar or vector multiplication of Eq. (16) by a wave vector $\vec{k}$ one can produce the equations for the spatial charge waves (electrostatic waves) and for the electromagnetics ones, respectively. According to the approach [14], let find the solutions Eq. (16) as a plane homogeneous wave under conduction that the electric field strength is perpendicular to the wave propagation direction. Thus one has the following set of equations [14]:

$$\hat{E}_1(\omega,\vec{z}) = \tilde{E}_1\exp(i\vec{k}\cdot\vec{z});$$
$$\vec{k}\cdot\hat{E}_1 = 0. \quad (17)$$

The set of equations (17) allows one to reduce Eq. (16) to the form

$$\omega(\omega^3 - \frac{e}{im_e\mu_d}\omega^2 - (k^2c^2+\omega_{pe}^2)\omega +$$
$$+k^2c^2\frac{e}{im_e\mu_d})\vec{k}\times\tilde{E}_1 = 0. \quad (18)$$

The condition for the existence of a non-zero solution to Eq. (18) $\left(\hat{E}_1 \neq 0\right)$, allows one to write the dispersion equation for the driven transversal electromagnetic waves in plasma

$$\omega_{shf}^2 = k^2c^2 + \omega_{wsc}^2 , \quad (19)$$

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 in the equatorial domain plane.

The qualitative profile generated at the birth of the domain of the transversal axis-symmetrical electromagnetic wave is given on Fig. 2,b. Induction lines of the azymuth magnetic field in wave are located in a plane containing 0r-axis and perpendicular to the plane of Fig. 2. In result motion in the field of the propagating transversal electromagnetic wave the captured charged particle accumulate energy, which significant exceeds the value corresponding to the applied voltage. Therefore, in the process of its birth 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. In this work the direct experimental proofs of the domain mechanism of acceleration were obtained and the theoretical calculations were refined. On the basis of the obtained results two types the source of fast particles – collapsotrons and the source of microwave radiation – domaintron have been developed.

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