SEMI-SELF-MAINTAINED DISCHARGE IN E ⊥ H FIELDS WITH OPEN ELECTRON DRIFT

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Powerful gas-discharge devices controlled by a small signal are of considerable interest in connection with problems of high-current electronics and high-voltage switching technology. In the present paper we study the semi-self-maintained discharge in the rarefied gas between coaxial cylindrical electrodes in an external azimuthal magnetic field. We demonstrate that under specific conditions the discharge will be maintained only in the presence of an external triggering current or where the discharge current is considerably greater than the triggering current.

The majority of papers in which a gas discharge in E ⊥ H fields has been studied is devoted to the self-maintained discharge with closed electron drift. Such a discharge is utilized in plasma accelerators [1] for the formation of ion bundles [2] and may be employed for purposes of magnetic insulation [3] and the generation of high-voltage pulses [4]. An experimental study was undertaken in [5] of the self-maintained discharge with an open electron drift whose cathode and anode were coaxial cylinders of radii R_c and R_a ($R_c < R_a$) and length $L \gg R_a$. The external magnetic field was generated by an axial current flowing through the internal cylinder. The electrons in this case drift in the radial electric E and azimuthal magnetic H_θ fields along the x axis of the system, multiplying as a consequence of ionization and the ion-electron γ emission from the cathode. The self-maintained discharge is generated to have the x-ray quanta flowing in primarily from the end electrode under an anode potential and positioned so that x = L (where the Hall current is at its maximum) will knock out the photoelectrons from the cathode in the region x = 0. In the absence of an x-ray stream from the region $x \approx L$ (which is achieved with a corresponding change in the geometry of the electrodes in this region) no discharge was ignited. We did not examine the characteristics of the semi-self-maintained discharge.

The present study is devoted to a study of the semi-self-maintained discharge of low pressure in such a system, achieved on application of a small triggering current I_0. We have demonstrated the possibility of regimes in which the discharge current considerably exceeds I_0. When the triggering current I_0 is "switched off" we should expect extinction of the discharge. Such a discharge is of interest as a basis for the solution of a broad range of problems in high-current electronics, associated with the powerful current accelerators and switching devices controlled with a low signal.

For the sake of simplicity let us examine the case in which $d = R_a - R_c \ll R_a$ (see Fig. 1). The collision-free ions generated through ionization move in the direction of the cathode and, on reaching it, knock out the γ electrons. Under conditions typical of the experiment (a voltage of $\varphi_0 \sim 1$ kV, pressure $p \sim 0.1$-1 Pa, $H_\theta \sim 10^2$-10^3 Oe) the electron magnetization parameter $\omega\tau \equiv \kappa \gg 1$. The electron motion represents the superposition of axial drift at a velocity $v_{ex} = cE/H_\theta$ and movement toward the anode in a regime of magnetized mobility at a velocity $v_{ey} = -b_\perp E$. The semi-self-maintained discharge is achieved as a consequence of the fact that the ion reaches the cathode to the right of the point from which the electron ionization event began. Thus, in the absence of a stream of x rays to the cathode in the

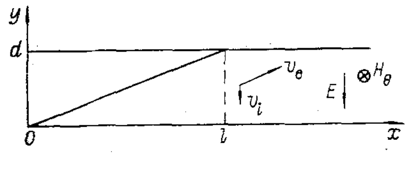

Fig. 1

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region x = 0 a positive feedback is developed, which ensures the self-maintained discharge (the absence of such feedback may serve as a stabilizing factor relative to the development of certain discharge instabilities).

In principle we might imagine a semi-self-maintained discharge with a large amplification factor $k = j_a/j_0$ (j_a is the density of the discharge current to the anode when y = d, j_0 is the density of the external bare current to the cathode when y = 0) in a system with a closed Hall current (where the magnetic field is directed along the axis) and in the gas-filled diode without an external magnetic field. From the Townsend discharge theory it follows that for each of these cases

$$k = \frac{e^{\alpha d}}{1-\Gamma(e^{\alpha d}-1)} = \frac{1}{\delta} + \frac{1}{\Gamma}\left(\frac{1}{\delta}-1\right). \quad (1)$$

Here $\alpha = \nu_i/v_{ey}$ = const is the first Townsend coefficient; ν_i is the ionization frequency; Γ is the effective coefficient of ion-electron emission (with consideration of the action of the magnetic field); $\delta = 1 - \Gamma[\exp(\alpha d) - 1]$. When $\delta = 0$ the discharge becomes self-maintained. We can see from (1) that the large amplification factors ($k \approx 10^3$) can be achieved either with a small δ or with a small Γ.

The requirement that $0 < \delta \ll 1$ imposes very rigid limitations on the operating parameters of the system (voltage, pressure). With a slight change in these the discharge becomes self-maintained and it is not extinguished when the current I_0 is "switched off." Small values of Γ are realized with a rather strong magnetic field ($H \gtrsim 10^3$ Oe), since in this case the majority of the γ electrons bunch up under the action of the magnetic field and return to the cathode, having failed to collide with the neutral ($\Gamma \sim \gamma_0 h/\lambda$, γ_0 is the coefficient of the ion-electron emission, without consideration of the magnetic field, h is the length of the cycloid described by the electron knocked out from the cathode in the absence of collisions, λ is the mean free path of the electron relative to collisions with the neutrals).

It would seem that in order to achieve a semi-self-maintained discharge with a high amplification factor it would be preferable to have a system with an open Hall current. First of all, in this case, given corresponding means to suppress the flow of x rays from the anode, the discharge will always be semi-self-maintained, and consequently, we will have no rigid limitations on the tolerances to the parameters, associated with the need to prevent the transition of the discharge to the self-maintained form. Second, the volume multiplication of the electrons and their entry into the discharge as a result of the γ processes at the cathode take place at each x cross section. The current amplification factor therefore increases with an increase both in αd and in Γ, and there is no need for any small values of Γ and, consequently, for any large magnetic fields.

Let us find the relationship of the discharge current to the parameters of the system and we will demonstrate the possibility for the existence of a high-current regime with a large amplification factor. Without imposing the problem of a precise description of the structure of the two-dimensional discharge layer on ourselves, we will use the simplifying assumption to the effect that the electric field is uniform along the x axis (see Fig. 1). When $\kappa \gg 1$, $v_{ex} = \kappa v_{ey}$, $j_e = n_e v_e = n_e v_{ex}\sqrt{1 + 1/\kappa^2} \approx n_e v_{ex}$ and from the continuity equation for the ions we have

$$\operatorname{div} j_i = \frac{\partial j_i}{\partial y} = -\nu_i n_e = -\frac{\nu_i}{v_{ey}} v_{ey} n_e = -\alpha j_{ey} \equiv -\alpha_0 f\left(\frac{y}{d}\right) j_{ey},$$
$$j_i(x, y=0) = -\alpha_0 \int_0^{y_0(x)} f\left(\frac{y}{d}\right) j_{ey}\, dy = -\frac{\alpha_0}{\varkappa} \int_0^{y_0(x)} f\left(\frac{y}{d}\right) j_e(x, y)\, dy. \quad (2)$$

The subscripts i, e denote quantities pertaining to the ions and electrons; n is the concentration; j is the density of the flow; ν_i is the electron ionization frequency; $\alpha_0 = \nu_i d/b_\perp \varphi_0$.

The electron starting out from the cathode at point x = 0 reaches the anode when $x = \ell = \kappa d$. Let us subdivide the discharge interval into region I ($x \leq \ell$) and region II ($x > \ell$). The function $y_0(x)$ in region I defines the boundary of the electron stream $y_0(x) = x/\kappa$, while in region II we have $y_0 = d$. Let us assume that in region II the lateral dimension of the discharge layer is equal to d. Directing the vector s along v_e ($|ds| = \sqrt{dx^2 + dy^2} = dx\sqrt{1 + 1/\kappa^2} \approx dx$), from the continuity equation for the electrons we find

$$\operatorname{div} j_e(x, y) = \frac{dj_e}{ds} = \nu_i n_e = \frac{\nu_i}{v_{ey}} v_{ey} n_e = \frac{\alpha}{\varkappa} j_e(x, y),$$
$$j_e(x, y) = j_e(s=0) \exp\left[\frac{\alpha_0}{\varkappa}\int_0^s f\left(\frac{y}{d}\right) ds\right] = \varkappa j_\text{к}(x - \varkappa y) \exp\left[\alpha_0 \int_0^y f\left(\frac{y}{d}\right) dy\right], \tag{3}$$

where j_c is the electron flux density in the cathode plane when $y = 0$; it is made up of the stream of γ emissions and the flow $j_{0c}(x)$, which is determined by the external bare current:

$$j_c(x) = -\Gamma j_i(x, y=0) + j_{0c}(x) \tag{4}$$

(Γ is the effective coefficient of the ion-electron γ emission). We will assume that $\Gamma = \Gamma_0\gamma(y/d)$, $\Gamma_0 = \Gamma(e\varphi_0)$. The function γ describes Γ as a function of the ion energy. Denoting $\xi = x/\ell$, from (2)-(4) we obtain

$$j_c(\xi) = \Gamma_0\alpha_0 d \int_0^{\min(\xi,1)} j_c(\xi - t)\,\Psi(t)\,dt + j_{0c}(\xi)$$
$$\left(\Psi(t) = f(t)\,\gamma(t) \exp\left[\alpha_0 d \int_0^t f(t')\,dt'\right]\right). \tag{5}$$

We will show that Eq. (5) has solutions that correspond both to the ascending and descending functions $j_c(\xi)$ when $\xi > 1$:

$$j_c(\xi) = j_0 \exp(\beta\xi),\ j_0 = \text{const},\ \beta = \text{const}.$$

In this case the value of β is determined from the condition

$$\Gamma_0\alpha_0 d \int_0^1 \exp(-\beta t)\,\Psi(t)\,dt = 1, \tag{6}$$

while the triggering current from the cathode

$$j_{0c}(\xi) = j_0 \exp(\beta\xi)\left[1 - \frac{\int_0^{\min(\xi,1)} \exp(-\beta t)\,\Psi(t)\,dt}{\int_0^1 \exp(-\beta t)\,\Psi(t)\,dt}\right]. \tag{7}$$

We can see from (7) that $j_{0c}(\xi \geq 1) = 0$. In region I the density of the cathode current after subtraction of the bare current $j_c(\xi) - j_{0c}(\xi)$ increases from zero to $j_0 \exp(\beta)$. In region II the behavior of $j_c(\xi)$ depends on the values of Γ_0, αd. If

$$\Gamma = \Gamma^* = \left[\alpha_0 d \int_0^1 \Psi(t)\,dt\right]^{-1}, \tag{8}$$

then $\beta = 0$, $j_c(\xi) = \text{const}$. The discharge current to the anode in the segment [1, ξ]

$$I_d(\xi) = 2\pi R_a \int_1^\xi j_a(\xi)\,d\xi \approx 2\pi R_a \int_1^\xi j_c(\xi - 1) \exp(\alpha_0 d)\,d\xi$$

(j_a is the current density at the anode) in this case increases linearly over the length. With $\Gamma_0 < \Gamma^*(\beta < 0) j_c(\xi)$ the drop is exponential and the discharge current is limited. When $\Gamma_0 > \Gamma^*(\beta > 0)$ the discharge current increases exponentially. It is precisely this regime that is of interest for purposes of amplifying the current and for the switching of large currents. Let us note that the value of I_d and, consequently, the amplification factor for the discharge under consideration can be substantially elevated through a simple increase in the length L of the discharge chamber.

Let us now limit ourselves to the case in which $f = \gamma = 1$. Relationships (6) and (8) will then assume the form

$$1 - \exp(\alpha d - \beta) = (\beta - \alpha d)/\Gamma\alpha d, \quad \Gamma^*[\exp(\alpha d) - 1] = 1. \tag{9}$$

For the amplification factor when $\Gamma \neq \Gamma^*$ we find from (7) and (9) [compare to (1)]

$$K = \frac{I_d(\xi)}{2\pi R_c \int_0^1 j_{0c}(\xi)\, d\xi} = \frac{\exp(\alpha d)}{\Gamma[\exp(\alpha d) - 1] - 1}\{\exp[\beta(\xi - 1)] - 1\}. \tag{10}$$

Here β is determined from (9). When $\Gamma > \Gamma^*$ the denominator in the right-hand side of (10) and β are positive, while when $\Gamma < \Gamma^*$ they are negative. With $\Gamma = \Gamma^*$, $\beta = 0$,

$$K = \frac{\alpha d \exp(\alpha d)}{\Gamma\alpha d \exp(\alpha d) - 1}(\xi - 1). \tag{11}$$

For example, when $\Gamma = 1/\alpha d$, $\beta = \alpha d$, assuming $\alpha d \gg 1$ for $\xi = 2$, from (10) we find that $K = \alpha d \exp(\alpha d) \gg 1$. With $\Gamma = \Gamma^*$ in this case we find $K \approx \exp(\alpha d) \gg 1$ from (11).

Formally, the equality $\Gamma = \Gamma^*$ coincides with the Townsend condition for ignition of a self-maintained discharge [see (1)]. In our case Γ affects only the amplification factor.

It was earlier assumed that the triggering current $j_{0c}(\xi)$ is described by relationship (7). With $\alpha = \gamma = 1$ it is not difficult to find $j_c(\xi)$ for any arbitrary form of $j_{0c}(\xi)$. Assuming $u(\xi) \equiv j_c(\xi)\exp(-\alpha d\xi)$, $u_0(\xi) \equiv j_{0c}(\xi)\exp(-\alpha d\xi)$, from (5) we obtain

$$u(\xi) = \Gamma\alpha d \int_{\max(0,\xi-1)}^{\xi} u(t)\,dt + u_0(\xi),$$

from which

$$[u(\xi) - u_0(\xi)]' = \Gamma\alpha d u(\xi), \quad \xi \leqslant 1,$$
$$[u(\xi) - u_0(\xi)]' = \Gamma\alpha d[u(\xi) - u(\xi - 1)], \quad \xi > 1 \tag{12}$$

(the prime denotes differentiation with respect to ξ). Equations (12) are solved analytically for any form of $u_0(\xi)$. In each subsequent segment $[\xi, \xi + 1]$ the solution is obtained with consideration of the solution in the previous segment $[\xi - 1, \xi]$. It can be demonstrated that for various forms of $j_{0c}(\xi)$ (concentrated in the segment $0 < \xi < \varepsilon \ll 1$ the current, the uniform current density j_{0c} = const, etc.) there exist rapid-growth regimes for $j_c(\xi)$ for which $K(\xi \geq 2) \gg 1$.

In the experiments described in [5] the length $L \approx 2$ m. The discharge current in this case amounted to several kiloamperes. With reduced dimensions for the discharge chamber it becomes possible to apply an external longitudinal magnetic field H_x. The electrons will then move along a helical line and with the same discharge current the length of the system can be reduced by a factor of $\sqrt{1 + H_x^2/H_\theta^2}$ (in the assumption that $d \ll R_c$ and without consideration of the effects associated with the shear of the magnetic field force lines).

When we examine the polarity of the applied voltage φ_0 the discharge layer is diamagnetic. If the internal electrode is subjected to an anodic potential a new mechanism for an increase in the Hall current along x appears, and this is associated with the paramagnetism of the electron stream. However, this effect appears only in the case of very large current (with a large length L) and is limited by the process of gas exhaustion.

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