IGNITION AND BREAK-DOWN OF THE GAS DISCHARGE IN MAGNETIC FIELD

A.V. Zykov, N.A. Azarenkov
V.N. Karazin Kharkiv National University, Department of Physical Technologies, Kharkov, Ukraine
E-mail: zykov@karazin.ua

The characteristics of the low pressure discharge in crossed electric and magnetic fields in the cases of magnetically insulated diode and electron anode layer with free cathode boundary are described. The phenomenal theory of the gas discharge switch-on was developed. The theory is based on Townsend ionization approach, adapted to the gas discharge in magnetic field. Also the mechanism of discharge initiation based on combined ionization of gas by electron avalanches and high energy γ-electrons is considered. The theory was compared with experimental characteristics breakdown and ignition curves of Hall-type ion source "Radical".

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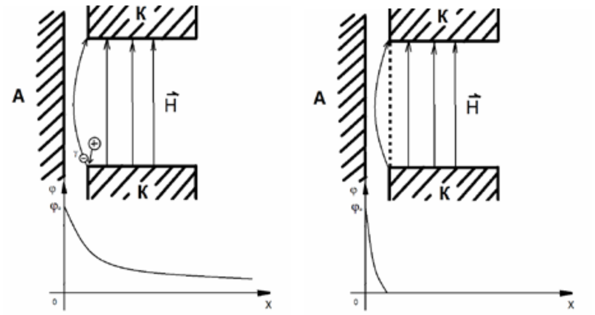
INTRODUCTION

The interest to the gas discharge in magnetic field is grown last decades thanks to many practical applications. The pressure gauge, high vacuum pumps, ion sources, plasma accelerators, sputtering systems for plasma technology and space thrusters were investigated and introduced into industry [1 - 3]. At the same time the gas discharge and plasma physics fundamental questions, such as ignition and break-down of discharge in magnetic field, current voltage characteristics and transition from accelerated to plasma regime are the actual problems.

The present study continues the research of the gas discharge in magnetically insulated diode (MID) which are presented in our previous works [4, 5]. The aim of the study is development of the analytic model of the gas discharge switch-on in magnetic field. Two cases of the discharge with different boundary conditions are considerated (Fig. 1,a,b).



a *b*

Fig. 1. Schematic model of "Radical"ion source discharge cell: the electron anode layer with free cathode boundary (non uniform vacuum electric field) (a); the cathode boundary is fixed by the conductive grid with transparency of 50% (the case of magnetically insulated diode with homogeneous electric field) (b)

In these discharge types two groups of electrons are responsible for working gas ionization: primary high energy electrons, emitted from the cathode, and secondary electrons, born in anode layer. Therefore the variation of boundary condition is changed the balance of electrons in anode layer and the mechanism of discharge.

1. IONIZATION PROCESS PARAMETERS IN CROSSED EH FIELDS

The parameters introduced by Townsend for creation phenomenon theory of the gas discharge in uniform electric field were used for characterization of the atom ionization process in crossed electric (E) and magnetic (H) fields .

Ionization coefficient α is the number of the ion-electron pairs, that creates a primary electron drifting along E $\alpha = \nu_i/\upsilon_D \sim 1/l_i$, where the ν_i, l_i are the ionization frequency and length consequently, υ_d – drift velocity. The empirical formula for α (the first Townsend coefficient) was introduced by Townsend [6]:

$$\alpha = \frac{1}{l_i} \cdot \exp\left(-\frac{I}{eEl_i}\right), \qquad (1)$$

where I is the ionization potential of atoms.

Total ion energy cost η (IEC) is related with α by equation:

$$\eta = \frac{eE}{\alpha} = eEl_i \cdot \exp\left(\frac{I}{eEl_i}\right) = \varepsilon \cdot \exp\left(\frac{I}{\varepsilon}\right), \qquad (2)$$

where $\varepsilon = eEl_i$. η is the sum of elastic and inelastic losses of the energy ε_c and kinetic energy ε for creation ion-electron pair $\eta = \varepsilon_c + \varepsilon$. Formula (2) is valid at the *strong electric field* strength, when the electron energy distribution function (EEDF) is not equilibrium and isotropic.

In the *weak electric field* strength the EEDF is equilibrium and anisotropic. So ε_c for creation ion-electron pair accordingly to Lieberman [7] is

$$\varepsilon_{cp} = \frac{K_i I + K_{ea}\varepsilon_{ea} + K_{ee}T_e 3m/M}{K_i}, \qquad (3)$$

where K_i, K_{ea}, K_{ee} are the reaction rates of ionization, excitation and elastic losses; I and ε_{ea} – potentials of atom ionization and excitation; m, M – the mass of electrons and ions.

For γ-electrons, injected into MID along the magnetic field lines, the EEDF is monoenergetic and $\varepsilon_{c\gamma}$ determined by [8]:

$$\varepsilon_{c\gamma} = \frac{I\sigma_i(\varepsilon) + \varepsilon_{ea}\sigma_{ea}(\varepsilon_{ea})}{\sigma_i(\varepsilon_e)}, \qquad (4)$$

where σ_i, σ_{ea} are cross-sections of ionization and excitation processes.

The dependence of dimensionless η' on dimensionless energy $\varepsilon'=\varepsilon/I$ for electrons in strong E (s-electrons) can be presented from (2) by such empirical formula:

$$\eta'_s = \frac{\eta}{I} = \varepsilon' e^{1/\varepsilon'} . \qquad (5)$$

The value for η_p' for electrons in weak E (p-electrons) and argon atoms (I=15.8 eV, ε_{ea}=11.5 eV) can be calculated from (3) and presented by such empirical formula [9]:

$$\eta'_p = \frac{\eta}{I} = \varepsilon' + 1.73\exp\left(\frac{0.19}{\varepsilon'}\right). \qquad (6)$$

The value for η_{os}' for high energy γ-electrons trapped due to collisions with atoms (os-electrons) and argon atoms (I=15.8 eV, ε_{ea}=11.5 eV) can be calculated from (4) and presented by such empirical formula [9]:

$$\eta'_{os} = \frac{\eta}{I} = \varepsilon' + 1.73. \qquad (7)$$

The graphs for different η' from (5), (6), (7) are presented on Fig. 2.

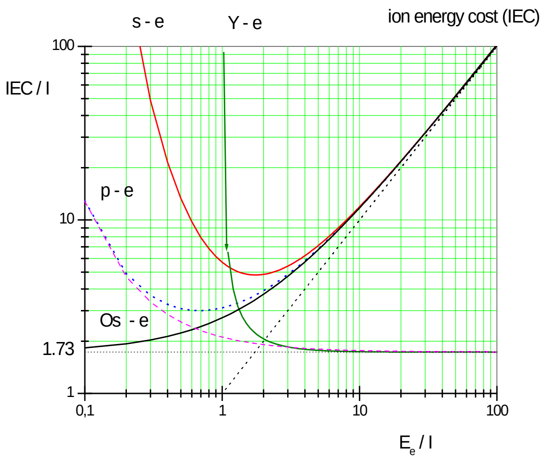


Fig. 2. The dependences of total ion energy cost η/I (IEC) for p-, s-, os-electrons and the inelastic energy losses for γ-electrons (monoenergetic EEDF) on dimensionless energy ε/I

In crossed EH fields the relation between ε and E is

$$\varepsilon_e = eE \cdot l_i = eE \cdot \frac{\upsilon_D}{\nu_i} = I\left(\frac{E}{E_0}\right)^2 , \qquad (8)$$

where $\upsilon_D=\mu_{He}E$ – drift velocity; $\mu_{He} = e\nu_c / m\omega_{He}^2$ – coefficient of classic mobility; $\omega_{He} = eH/mc$ – electron cyclotron frequency; ν_c – the frequency of electron-atom elastic collision. $E_0{}^2 = \nu_i I / e\mu_{He}$ is a normalizing value of $E=I/el_i$, corresponding the energy $\varepsilon=I$ that the electrons accumulate on the length l_i. The next equations $\alpha(E/E_0)=eE/\eta(E/E_0)$ for s-, os- and p-electrons are followed from (5)-(8):

$$\alpha_s = \frac{eE_0}{I} \cdot \frac{E_0}{E} \cdot e^{-\left(E_0/E\right)^2} , \qquad (9)$$

$$\alpha_{os} = \frac{(eE_0/I)\cdot(E/E_0)}{1.73 + (E/E_0)^2} , \qquad (10)$$

$$\alpha_p = \frac{(eE_0/I)\cdot(E/E_0)}{1.73\cdot\exp\left(0.19(E_0/E)^2\right) + (E/E_0)^2} . \qquad (11)$$

The dependences (9)-(11) are presented on Fig. 3. Also the Townsend coefficient
$\alpha_T=(eE_0/I)\cdot exp(-E/E_0)$ is presented for comparison.

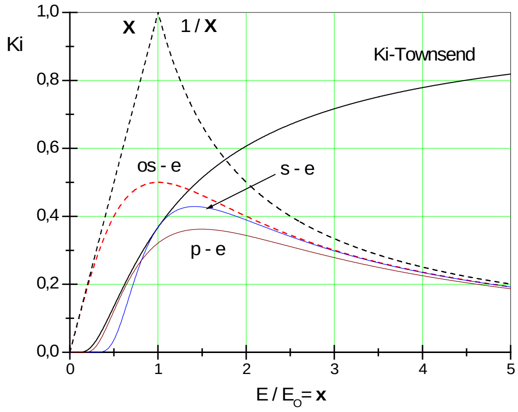


Fig. 3. Dependence of the ionization coefficient Ki=α for s-, os- and p-electrons from the normalized electric field E/E_0

As it follows from the picture, the E_0 is not only the normalization parameter for electric field, but also is a value criterion of the strong and weak E. In *the weak electric field* (E/E_0)<1: $\alpha_s\to0$, $\alpha_p\to0$, $\alpha_\gamma\to (eE_0/I)\cdot(E/E_0)$ and so only ionization by primary electrons with large energy ε>2I is important. In *the strong electric field* (E/E_0)>1 $\alpha_s\approx\alpha_p\approx\alpha_\gamma\approx(eE_0/I)\cdot(E_0/E)$ and so the ionization coefficient α does not depend on the initial velocity EEDF.

2. IGNITION AND BREAK-DOWN OF THE GAS DISCHARGE IN MID

The equation of electron current density conservation for MID model on Fig. 1 is [1]:

$$\frac{dj_{ex}}{dx} = e\nu_i n_e = \alpha \cdot j_{ex} , \qquad (12)$$

where $j_{ex} = en_e\mu_{He}E_x$ the electron current density determined by classic mobility μ_{He}. In *uniform electric field eE=U/d* (*U, d* – the voltage and distance between anode and cathode) the relation E/E_0 in equation (9)-(11) is:

$$\frac{E}{E_0} = \frac{eU}{I} \cdot \frac{r_0}{d} = \left(\frac{\varepsilon}{I}\right)^{\frac{1}{2}} , \qquad (13)$$

where $r_0 = \left(\nu_c I / \nu_i m\omega_H{}^2\right)^{1/2}$ – space scale along E ($E_0r_0=I$). The equation (12) has solution for two cases: in strong electric field E/E_0>1, when the electron avalanches take place, and in weak electric field E/E_0<1, when only the primary os-electrons with high energy can ionize. For the first case the solution of (12) is:

$$j = j_0 \cdot \exp(\alpha_s x), \qquad (14)$$

and for second case

$$j(x) = (\alpha_{os} x + 1) \cdot j_0 , \qquad (15)$$

where j_0 is the primary os-electrons current density. In summary the Townsend *break-down condition* for electron avalanches in MID can be written:

$$\alpha_s \cdot d = \ln\left(1+\frac{1}{\gamma}\right), \quad \frac{U}{I} > \frac{d}{r_0}, \tag{16}$$

and *condition for ignition* of discharge by os-electrons is:

$$\alpha_{os} \cdot d = \frac{1}{\gamma}, \quad \frac{U}{I} < \frac{d}{r_0}, \tag{17}$$

where γ is the ion-electron secondary emission coefficient (the third Townsend coefficient). The break-down curves *φ'=f(d'), (d'~H)* for s-electrons in parametrical form are followed from (9), (16):

$$\varphi_s' = \frac{eU}{I} = x^2 e^{1/x^2} \cdot \ln\left(1+\frac{1}{\gamma}\right),$$

$$d_s' = \frac{d}{r_0} = x e^{1/x^2} \cdot \ln\left(1+\frac{1}{\gamma}\right), \tag{18}$$

and for os-electrons the ignition curves from (10), (17):

$$\varphi_{os}' = \frac{eU}{I} = \left(1{,}73+x^2\right)\cdot\frac{1}{\gamma},$$

$$d_{os}' = \frac{d}{r_0} = \frac{1{,}73+x^2}{x}\cdot\frac{1}{\gamma}. \tag{19}$$

As it follows from (18), (19) the parameters *ln*(1+1/*γ*) and 1/*γ* have no effect to the shape of the curve and only move curves along axes.

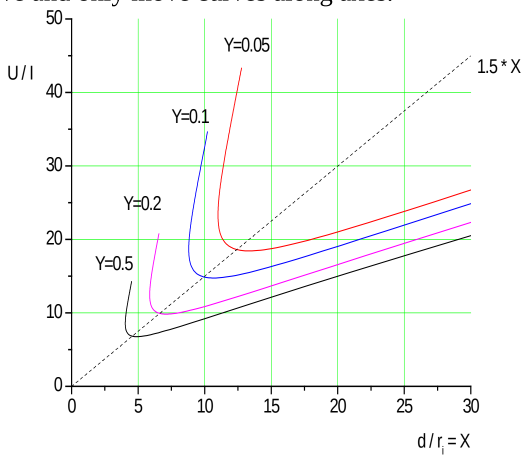


Fig. 4. Break-down discharge curves for s-electrons at different values of coefficient γ

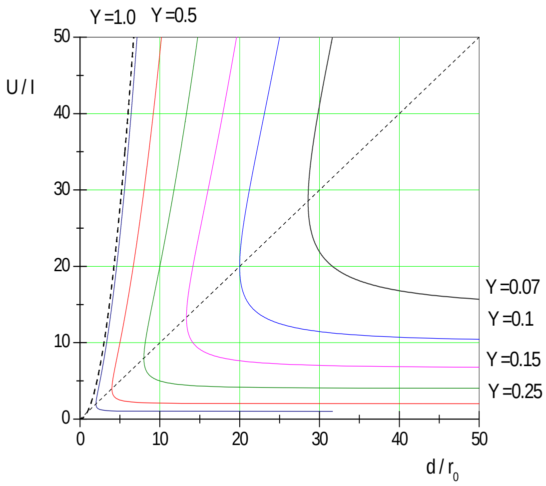


Fig. 5. Break-down discharge curves for os-electrons at different values of coefficient γ

So, the values *eU/I* and *d/r₀~d·H* are the parameters of similarity for the gas discharge in magnetic field with different gases, materials and configuration of electrodes. Series of ignition and break-down curves for different values of similarity parameters are presented on the Figs. 4, 5.

In the *inhomogeneous electric field* the equation of electron conservation is:

$$\frac{dj}{dx} = j\cdot\alpha(x) = j\cdot\frac{E(x)}{\eta_{os}(E(x))}, \tag{20}$$

and for os-electrons can be written in form:

$$\frac{j}{j_0} = \frac{1}{\gamma} = \int_0^{d_s}\frac{E(x)dx}{I\left(1{,}73+\left(E(x)/E_0\right)^2\right)}. \tag{21}$$

The equation (19) can be solved numerically or approximately analytically, if we introduce the average electric field along layer thickness d_s: $E(x)\approx\overline{E}=U/ed_s$. Then the equation (19) can be integrated and final solution is:

$$\frac{U}{\eta_{os}} = \frac{d_s}{r_0}\cdot tg\left(\frac{r_0}{\gamma\cdot d_s}\right). \tag{22}$$

The graphs of the function (22) and the break-down curves for os-electrons calculated accordingly to (20) for *γ*=0.1 are presented on Fig. 6.

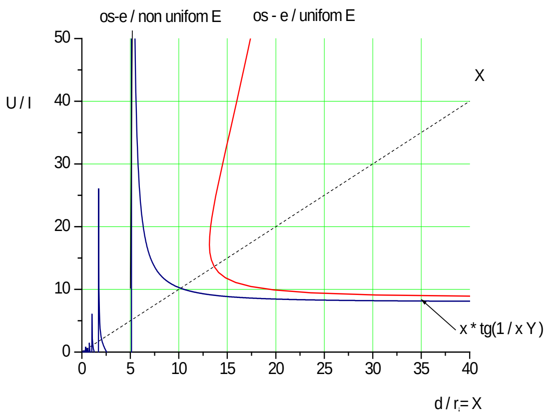


Fig. 6. The ignition curves in the inhomogeneous electric field, calculated accordingly to (22) and the break-down curves for os-electrons calculated accordingly to (20) for coefficient γ=0,1

3. COMPARISON OF THEORETIC RESULTS AND EXPERIMENTAL DATA

The experiments were carried out at the ion source "Radical" with electrons close drift in anode layer, described in details in [4, 5]. Two series of discharge switch-on measurements were performed: with the free cathode boundary (the discharge cell without the grid, Fig. 1,a) and with the fixed cathode boundary (the cause of MID, Fig. 1,b). The results of experiments are presented on Fig. 7. As follows from the figure, qualitative difference of breakdown character takes place. It can be seen, that the discharge switch-off at high anode voltage appears in magnetically insulated diode.

In Figs. 7-9 the anode current dependences of the ion source with different boundary conditions on the magnetic fields strength are presented. It can be see from the figures, that qualitative differences of dependences also take place. The initial part of characteristics at magnetic fields strength *H* = 0.5…1 kOe demonstrates continuous growth in the ion source without the grid. On the contrary, the abrupt switch-on of the discharge take place in magnetically insulated diode.

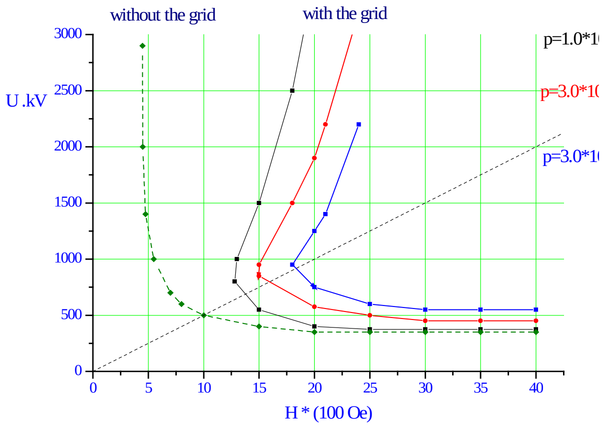


Fig. 7. The ignition curves of the discharge at different boundary conditions

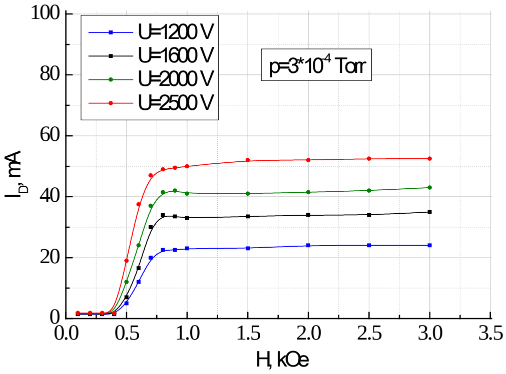


Fig. 8. The anode current dependences of the ion source without the grid on the magnetic fields strength at pressure $p=3\cdot10^{-4}$ Torr

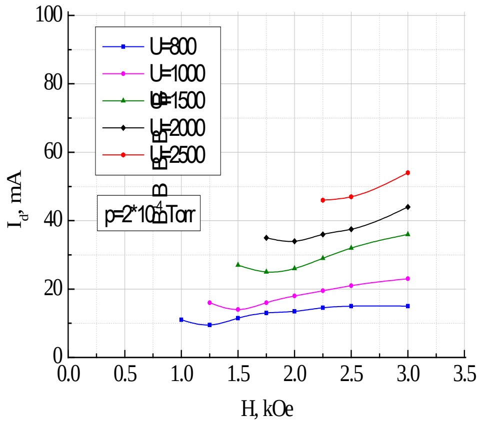


Fig. 9. The anode current dependences of the ion source with the grid on the magnetic fields strength at pressure $p=2\cdot10^{-4}$ Torr

From comparison of theoretical results (see Fig. 6) with experimental data (see Fig. 7) we can determine the parameters C, D:

$$C_1 = I\ln\left(1+\frac{1}{\gamma_{ýô}}\right),\ D_1 = r_0\ln\left(1+\frac{1}{\gamma_{ýô}}\right), \quad (23)$$

$$C_2 = \frac{I}{\gamma_{ýô}},\ D_2 = \frac{r_0}{\gamma_{ýô}}. \quad (24)$$

Parameters C, D are the analogies in magnetic field of the constant A, B for ionization coefficient α, introduced by Townsend $\alpha/p = A\cdot\exp(-B/(E/p))$. The values of C, D can be determined by the approximation of switch-on experimental data for the specific experimental device. In our case C_1=300 V, $D_1=3\cdot10^{-2}$ cm (H=1000 Oe).

CONCLUSIONS

The main results of present work are:

- The phenomenal theory of the gas discharge switch-on in MID was developed. The theory is based on Townsend ionization approach, adapted to the gas discharge in magnetic field.
- The theory demonstrated the ability of two mechanism of discharge switch-on: the break-down by electron avalanches in the strong electric field and the ignition of discharge in weak electric field by high energy primary electrons, oscillating in electromagnetic trap.
- The analytic equations for ionization coefficient, ion energy cost and switch-on curves for primary and secondary electrons were obtained.
- Two cases of uniform and non uniform electric field were considered.
- The good agreement of theoretic results and experimental data has been demonstrated.

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ЗАЖИГАНИЕ И ПРОБОЙ ГАЗОВОГО РАЗРЯДА В МАГНИТНОМ ПОЛЕ

А.В. Зыков, Н.А. Азаренков

Представлены характеристики разряда низкого давления в скрещенных электрическом и магнитном полях со свободной и фиксированной катодными границами. Развита феноменологическая теория зажигания газового разряда на основе теории Таунсенда, адаптированной к разряду в магнитном поле. Также рассмотрены механизмы пробоя разряда электронными лавинами и зажигания высокоэнергетичными γ-электронами. Проведено сравнение теории с кривыми пробоя и зажигания разряда в источнике ионов холловского типа «Радикал».

ЗАПАЛЮВАННЯ ТА ПРОБІЙ ГАЗОВОГО РОЗРЯДУ В МАГНІТНОМУ ПОЛІ

О.В. Зиков, М.О. Азаренков

Представлено характеристики розряду низького тиску в схрещених електричному і магнітному полях з вільною і фіксованою катодними межами. Розвинена феноменологічна теорія запалювання газового розряду на основі теорії Таунсенда, яка адаптована до розряду в магнітному полі. Також розглянуто механізми пробою розряду електронними лавинами і запалювання високоенергетичними γ-електронами. Проведено порівняння теорії з кривими пробою й запалювання розряду в джерелі іонів холлівського типу «Радикал».