Discharge features in crossed electric and magnetic fields

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Abstract. The article discusses the study of a self-sustained discharge in the plasma accelerator with closed electron drift and the anode layer. Dependencies of the density and the average energy of ions on the magnitude and direction of the magnetic field induction vector \( n = f(B_rA) \), \( W_{av} = f(B_rA) \) characterized by minimum and maximum values of \( n \) and \( W_{av} \) have been discovered. It has been determined that the most efficient and optimal modes of discharge combustion are achieved when \( n \) and \( W_{av} \) reach the maximum. The density rose to \( n_{opt} / n \approx 5.5 \), and the average ion energy increased by 1.6 times. The evidence of “breakdowns” of density upon the change in the magnetic field is provided. The concept of isomagnetic jumps for the energy spectra of ions is introduced; their evolution is traced upon the change in discharge parameters. A theoretical model establishing the mechanisms of energy gain and loss by electrons has been proposed. It determines the formation of the ion energy distribution function as well as the ion density in the discharge gap. Likewise, the model explains various dependencies of the ion density upon the growth of the magnetic field and the “breakdown effect” of the ion density.

1. Introduction

In this work, we studied a self-sustained \( E \times B \) discharge in the plasma accelerator with closed electron drift (magnetized electrons, unmagnetized ions) and the anode layer (TAL) at the low plasma density, when the discharge current is proportional to the pressure of the plasma-forming gas.

Many researchers have examined the principles of TAL operation as well as the macroscopic characteristics of the discharge. We will review [1–3], which contains the data directly related to the topic of our article.

Robinson R.S. [1] studied TAL where the accelerator channel was coated by the grounded walls. Argon was used as a plasma-forming gas; discharge voltage: \( U_d \approx 125 \) V, discharge current: \( I_d \approx 800 \) mA. The induction of the radial electric field at the anode: \( B_{rA} \approx 0.013 \) T, at the cathode: \( B_{rC} \approx 0.025 \) T. The direction of the magnetic field was not strictly radial: it changed in the anode-cathode interval. The deviation was minimal in the center of the discharge interval (about 9°) while at the anode it was maximum (18°). An external cathode-compensator which emitted the current 0.5–2 A greater than the discharge current was used.

The growth of the magnetic field in the discharge channel resulted in the increase in electrical resistance and a corresponding jump in the potential across the magnetic field as well as the rise in the average ion energy \( W_{av} \) with \( \approx 60 \) eV (the current in the coil of the electromagnet \( I_{em} \approx 0.2 \) A) up to the maximum value of \( W_{av} \approx 97 \) eV (0.82 A). At \( I_{em} > 0.82 \) A, the average ion energy decreased. The
increase in argon inlet velocity from $Q \approx 35$ sccm to $Q \approx 80$ sccm resulted in the reduction of $W_{av}$ from 100 to 38 eV.

In [2], it was concluded that the generation of ions and their acceleration in TAL occurs in the anode layer (AL) whose width $L$ exceeds Larmor radius of electrons $r_{Be,d}$ determined by its drift velocity: $L > r_{Be,d} = (2eV_d/m)^{1/2}/\omega_{Be}$ (where $e$ stands for the electron charge, $V_d$ is the drift velocity of the electron, $m$ is the electron mass, $\omega_{Be}$ is the electron cyclotron frequency). The areas of ionization and electron temperature gradient almost completely overlap. The average energy of ions in TAL corresponds to 70–90% of $eU_d$. The acceleration process in TAL is determined by the potential distribution, which is set by electrons diffusing from the cathode to the anode. The diffusion is due to two gradients: potential gradient and electron temperature gradient. The electrons gain directed energy upon the movement from the cathode to the anode in the anode-cathode electric field. The energy is randomized by electron collisions as well as the influence of electrostatic fluctuations that exist in the plasma.

The authors [2] introduced the concept of “optimal magnetic field” which corresponds to minimum discharge current $I_{d,min}$ is considered optimal since the discharge current consists of the ion current which is almost completely constant in case the gas flow is constant as well, and the electron current $I_e$ at the anode which leads to energy loss. Efficiency of TAL is maximal when $I_{eA}$ is minimized. The dependence $B_{opt}$ upon the change $U_d$ can be expressed as $(U_d)^{1/2}$.

In a number of works by Japanese scientists, a non-self-sustained discharge in crossed electric and magnetic fields (in an external hollow cathode compensator) was studied as well. The growth of $B_A$ from 17.1 to 27 mT led to the decrease in the width of AL, determined by the gradient of the plasma potential and its localization within the discharge channel. As the magnetic flux density increases, the AL position moves towards the anode, as does the ionization zone.

2. Experimental results

The plasma accelerator used to obtain the results is a part of a system for the formation of a compensated multicomponent ion beam in the layout of the POMS-E-3 plasma-optical mass separator [4–6]. The axial interelectrode line of TAL has a radius $R = 90$ mm; the slit radii in the cathode $R_{min} = 87.5$ mm, $R_{max} = 92.5$ mm; the anode-cathode distance $\Delta = 8$ mm. The cathode as well as the shell-type magnetic core is made of soft magnetic steel, the anode is non-magnetic (made of stainless steel). Radial component of the magnetic field induction at the anode $B_{A}$ varied in the range from $10^{-2}$ to 0.12 T; at the cathode $B_{C} = 0.045–0.515$ T; $dB/dz > 0$.

The magnetic field was created by the currents from two independent coils – the internal (current $I_1$) and external ($I_2$) ones. The discharge voltage $U_d$ varied from 200 to 1800 V, the discharge current equalled $I_d \leq 0.3$ A. 1–V curve of the discharge (VAC) is monotonic and is increasing linearly; no dependence on the density of neutrals is observed. The accelerator was docked to a vacuum tank (volume about 1 m$^3$). Pumping to the residual pressure $P \approx 10^{-5}$ Torr was performed by a cryogenic pump. Argon, nitrogen, neon are used as working gases; the pressure of the working gas at the outlet of the TAL varied in the range of $4 \cdot 10^{-5}–3 \cdot 10^{-4}$ Torr, at which the anomalous $E \times B$ discharge was ignited and combusted steadily.

The ions generated by TAL have a wide energy spectrum. Ion energy distributions were measured by a retarding field analyzer (RFA). The hardware-software complex [7] was used to register the delay curve. The hardware consists of a personal computer NI PXIe-8115, ADC and DAC, combined in a complex device NI PXIe-6361 and an adjustable voltage source 0–4 kV. Communication between the computer and the ADC/DAC was conducted via PXI interface in NI PXIe-1078 chassis.

Figure 1 demonstrates the evolution of the ion density and average ion energy upon the change in the induction of the radial magnetic field on the anode. The density of plasma and the average energy of the ion spectrum were determined, respectively, as:

$$n = \int_{W_1}^{W_2} f(W) dW, \quad W_{av} = \int_{W_1}^{W_2} Wf(W) dW,$$

where $f(W) = -\frac{1}{qA} \left( \frac{M}{2W} \right)^{1/2} \frac{dI(W)}{dW}$,
and $q$ stands for the ion charge (the value of 1 was considered), $M$ – the mass of the ion, $A$ – the relative mass of the ion, and $I$ is the current from the collector of the RFA. As shown in figure 1a and 1b, $n$ and $W_{av}$ behave in two ways: curves characterized by the minimum (1) and the maximum (2). The dependence 1 for the density is known provided that the density “follows” the discharge current; the minimum value is explained by a significant increase in the oscillations of the discharge current at the magnetic field corresponding to the extremum [4, 8]. Curves of type 2 constitute a new experimental result.

![Figure 1.](image)

**Figure 1.** Neon; $U_d = 1100$ V; $P = 9 \cdot 10^{-5}$ Torr. (a) – Dependence of the ion density at the TAL output on the magnetic field induction at the anode: curve 1 – $B_z/B_r \leq 0.05$ ($I_1 = I_2$); 2 – $B_z/B_r > 0.05$ ($I_1 \neq I_2$). (b) – The average ion energy as a function of magnetic field induction at the anode: curve 1 – $B_z/B_r \leq 0.05$; 2 – “optimal” mode, $B_z/B_r > 0.05$.

It can also be noted that the increase in $B_{zA}$ leads to the increase in the floating potential of the plasma $U_{fl}$ (proportional to the plasma potential). For example, when discharge is observed in argon ($U_d = 1100$ V, $P = 9 \cdot 10^{-5}$ Torr), $U_{fl}$ grows from 280 to 470 V when the $B_{zA}$ changes from 0.02 to 0.115 T. If $B_{zA} \approx 0.097$ T is fixed while the pressure of the plasma gas (Ar) changes, $U_{fl}$ decreases from 370 to 200 V and the pressure grows from $4 \cdot 10^{-5}$ to $18 \cdot 10^{-5}$ Torr.

The ratio of the longitudinal and radial components of the magnetic field in the discharge gap is emphasized in the caption to figure 1. Likewise, we also introduce the concept of the “optimal” mode. It means that when the value $B_z/B_r$ is determined in the process of adjusting the discharge mode, the ion current observed at the RFA collector is the maximum. Figure 2 illustrates the increase in the ion density in the optimal mode (upon optimal magnetic field induction). At the maximum, $n_{opt}/n \approx 5.05$. The highest values of $\Delta B = \Delta B_{max} = B_{zA} - B_{zA,opt} \approx 0.017$ T and $(B_z/B_r)_{max} \approx 0.2$ were recorded. The “jump” (5.5 in figure 2) are seen to be considerably higher than shown in figure 1a.

![Figure 2.](image)

**Figure 2.** Density jump at optimal magnetic field (at maximum ion current at the RFA collector).
The behavior of the ion energy spectra in the area of “optimal density jump” is shown in figure 3. Along with the apparent increase in density, the shift of the distribution function as a whole to the high energy area is also observed (the increase in $W_{av}$). Figure 4 illustrates two cases of abrupt curves $n = f(B_{cr})$ with a slight change in the magnetic field.

**Figure 3.** Ion spectra by energy: curve 1 – $B_{RA} = 0.083$ T; $B_{ZA} = 0.0087$ T; $B_z/B_r \approx 0.1$; curve 2 – “optimal” mode: $B_{RA} = 0.066$ T; $B_{ZA} = 0.013$ T; $B_z/B_r \approx 0.2$; $n_{opt}/n \approx 5.05$.

**Figure 4.** Dependence of the ion density at the TAL output on the magnetic field induction at the anode: argon; $U_d = 1100$ V; $P = 9 \times 10^{-5}$ Torr; curve 1 – $B_z/B_r \leq 0.05$; 2 – $B_z/B_r > 0.05$.

**Figure 5.** Evolution of spectra and isomagnetic jumps upon the growth of the magnetic field induction. Neon: $P = 9 \times 10^{-5}$ Torr; $U_d = 1100$ V. (a) $B_z/B_r \leq 0.05$, curve 1 – $B_{RA} = 0.074$ T; 2 – 0.09 T; 3 – 0.099 T; 4 – 0.106 T; 5 – 0.12 T. We left only isomagnetic jumps on spectra 2–4. (b): $B_z/B_r > 0.05$; curve 1 – $B_{RA} = 0.038$ T; 2 – 0.044 T; 3 – 0.66 T; 4 – 0.8 T; 5 – 0.87 T; 6 – 0.1 T. We left only isomagnetic jumps on spectra 4, 5.
Another type of data concerns the fine structure of the ion energy spectra. In experiments, when the change in the magnitude of the magnetic field induction was noted, a narrow area of the energy spectrum was discovered near the area of the most probable energy allowing for the sharp growth of the density of ions (up to 10 times) – figure 5. Moreover, this selected section of the spectrum – the isomagnetic jump – can be observed in the entire range of the changing magnetic field (figure 5a; $B_z/B_x \leq 0.05$) as well as only at the highest values of $B_x$ (figure 5b; $B_z/B_x > 0.05$).

In the next section, we will explain obtained experimental data in greater detail.

3. Discussion

In the experiments, the density $n$ of the charged particles in the $E \times B$ discharge is $n \leq 5 \cdot 10^{13}$ m$^{-3}$, so one can conclude that almost linear distribution of the electric potential will remain between the anode and the cathode. Indeed, the density of charged particles of any sign $n_ε$ at which the spatial charge will significantly affect the potential distribution, can be estimated as follows:

$$n_ε = \frac{ε_0 φ_A}{eΔ}, \quad (1)$$

where $φ_A$ is the anode potential; $ε_0$ is the electric constant; and $e$ is the elementary charge. For the experimental conditions, $n_ε = 5 \cdot 10^{14}$ m$^{-3}$ at $Δ = 1$ cm, $φ_A = 1$ kV, and the experimentally measured ion density at the output of the discharge gap is $n_i = 5 \cdot 10^{13}$ m$^{-3} < n_ε$. Therefore, we assume that the electric field $E_0$ between the anode and the cathode is vacuum $E_0 = φ_A/Δ$, and the electrons and ions will move within the given constant fields $E_x(x) = E_0$ and $B_z(x) = B$ (one-dimensional consideration; coordinate $x$ is directed along the electric field).

The discharge current along the $x$ axis remains constant:

$$j_i + j_e = const, \quad (2)$$

where $j_e = -en_εu_{ε}$ stand for the electron current; $n_ε(x)$ is electron density; $u_{ε}(x)$ stands for the component of the directed velocity of electrons along the $x$ axis; $j_i$ is the ion current. The current density of electrons across the magnetic field is determined by $j_e = σ_ε E_0$, where

$$σ_ε = \frac{σ_||}{ω_n τ_a},$$

stands for the conductivity across the magnetic field; $τ_a = (n_n σ_|| u_{ε})^{-1}$ is the time between collisions of electrons; $u_{ε}(x)$ is thermal velocity of electrons; $n_n$ stands the density of neutrals; $σ_||$ is the cross section of electron scattering at neutrals; and $σ_ε = (ε^2 n_n τ_a)m^{-1}$ is the conductivity along the magnetic field. The equation of the directed velocity of electrons is:

$$u_{ε}(x) = -\frac{en_ε σ_ε E_0 u_{ε}(x)}{mω_n^2}. \quad (3)$$

Using (2), we obtain

$$1 \frac{d}{dx} = \frac{d(n_ε u_{ε})}{dx} = n_ε ν_i, \quad (4)$$

where $ν_i = n_n σ_|| u_{ε}$ is the collision frequency of ionized electrons; $σ_i = f(r_e)$ is cross-section of the ionization with regard to the electron temperature. Based on (4) and (3), we obtain:

$$\frac{d}{dx} \ln(n_ε u_{ε}) = -\frac{σ_i mω_n^2 Δ}{σ_ε eφ_A}. \quad (5)$$
Let us analyze the process of the ion generation. Ions appear at some point with coordinate \( x \) at the velocity of \( u_{ix} = 0 \) and distribution function \( f_i(u_{ix}=0, x) \), and then accelerate in the electric field \( E_0 \). The ion flow at point \( x \) can be illustrated as follows:

\[
Q_i(x) = \int_{0}^{[2e/M(\phi_0 - \phi)]^{1/2}} f_i(u_{ix}, x) u_{ix} du_{ix} .
\]  

(6)

Let us analyze the variable \( \phi = \phi(x) \). Then the ion distribution function at point \( x \) at zero velocity \( u_{ix} \) is expressed as follows: \( f_i(u_{ix}=0, x) = f(\phi) \). For non-zero ion velocity \( f_i(u_{ix}, x) = f(\xi) \) where

\[
\xi = \phi + Mu_{ix}^2 / 2 .
\]

In this case, \( \phi(x) \leq \xi \leq \phi_A \). It is worth noting that

\[
\frac{\partial f_i(u_{ix}, x)}{\partial x} = \frac{\partial f_i}{\partial \xi} \frac{d(\phi)}{dx} .
\]

Using (6), we arrive at the rate of the flow change:

\[
\frac{dQ_i}{dx} = -e \frac{d\phi}{M} f_i(u_{ix} = 0, x) = -e \frac{d\phi}{M} = f[\phi(x)].
\]

(7)

According to (4), we obtain:

\[
f_i(u_{ix} = 0, x) = f(\phi) = n_a M n_e(\phi) \sigma_i(\phi) u_{te}(\phi) .
\]

In our case \( E(\phi) = E_0 \) and \( \phi(x) = \phi_A - (\phi_A/\Delta)x \).

The equation of the ion density at point \( x \):

\[
n_i(x) = n_a \left( \frac{M \Delta}{2e\phi_A} \right)^{1/2} \int_0^{\Delta} n_e(\Delta - x + t)u_{te}(\Delta - x + t)\sigma_i(\Delta - x + t) dt .
\]

(8)

For \( x = \Delta \), the ion density is as follows:

\[
n_i(\Delta) = n_a \left( \frac{M \Delta}{2e\phi_A} \right)^{1/2} \int_0^{\Delta} n_e(t)u_{te}(t)\sigma_i(t) dt .
\]

(9)

The ratios (5), (8) and (9) have distributions of \( n_e(x) \) and \( n_i(x) \), which demonstrate dependence on the electron temperature determining cross section of ionization. We will not discuss the equation of electron energy balance while consider it only qualitatively.

If you do not take into account the cooling of electrons due to their removal with thermal velocity along the magnetic field on the walls of the discharge channel, the electrons will acquire energy \( \Delta \xi = \phi_A \Delta x/\Delta \) at a distance of \( \Delta x \). To gain energy \( \xi \), sufficient for ionization, the electrons must travel a distance \( \Delta x_i = \xi e / \phi_A \). The time in which they will pass this distance equals:

\[
t_{\Delta x_i} = \Delta x_i / u_{ex} = \xi e / \phi_A e n_a \sigma_i u_{te} .
\]

The cooling time of electrons \( t_C \approx \Delta r/u_{te} \), where \( \Delta r \) stands for the distance to the walls of the discharge channel. If \( t_C < t_{\Delta x_i} \), the electrons cannot acquire energy that is sufficient for the ionization, and \( \sigma_i \) will have a small value. The condition \( t_C < t_{\Delta x_i} \) is satisfied if
Using inequality (10), we can explain the effect of a sharp decrease in the density of ions at the cathode upon the increase in the magnetic field, when the density of neutrals is fixed (see figure 4). If combustion of the discharge occurred at the parameters when the condition (10) is not satisfied, the electron temperature will exceed the ionization energy near the cathode; the electron energy will be sufficient for the ionization of neutrals in almost entire discharge interval. A large number of the low-energy ions, appearing near the cathode, will be observed in the ion energy spectrum at the cathode, and the ion density at the cathode will be large due to the intensive process of ionization. Further, if the magnetic field is increased at a fixed \( n_a \) or the concentration of neutrals is reduced at a fixed magnetic field, inequality (10) will more likely be solved. At the same time ionization stops near the cathode. If the magnetic field decreases (or the distance to the walls \( \Delta r \) increases) when approaching the anode, the condition (10) ceases to be met and ionization near the anode becomes possible. The ionization layer moves towards the anode, and the energy distribution of the ions shifts towards high energies. The density of ions near the cathode decreases remarkably due to the absence of the ionization process on the main part of the discharge gap.

The ion density according to (5) and (9) is determined by the electron density in the near-cathode layer, which can be estimated as follows. We assume that the electron flux is formed by the emission from the cathode. This flow will be considered constant and equal to \( Q \) despite the change in the wide range of discharge parameters. We assume that the electrons fly from the cathode at low velocity. Then they turn back at a distance of the magnetron surface from the cathode:

\[
x_c = \frac{2eE_0}{B\omega_m} = \frac{2e\varphi_d}{m\omega_m^2}.
\]

(11)

Electrons pass this distance in time \( \Delta t \approx 1/\omega_m \). The average electron density \( n_{e\Delta} \) in the “magnetron” layer can be determined as follows:

\[
n_{e\Delta} = \frac{Q\Delta t}{x_c} = Q \frac{\omega_m \Delta m}{2e\varphi_d}.
\]

(12)

According to (12), electron density in the near-cathode layer grows with an increase in \( B \). Hence, experimental dependence of the ion density at the cathode upon the change in the magnetic field can be explained (see figure 1a). The ion density at the cathode is determined by two opposite effects. The first effect leads to the increase in ions density \( n_i(\Delta) \) as the electron density \( n_{e\Delta} \) rises upon the growth of the magnetic field. The second effect leads to a decrease in \( n_i(\Delta) \) due to a fall in the temperature of the electrons upon the growth of the magnetic field.

The experiment proved that if there is an external longitudinal component of the magnetic field (along the \( x \) axis) in the area of the \( E \times B \) discharge, the nature of the dependence of the ion density of the cathode on the magnetic field changes (see figure 1b). Now the distance of “removal” of electron energy along the magnetic field increases. This causes the energy of electrons to change slightly upon the increase in the magnetic field. Likewise, the density of ions \( n_i(\Delta) \) rises due to the growth of the electron density \( n_{e\Delta} \) in accordance with (9). With a further increase in the magnetic field, the energy of electrons begins to fall faster, which leads to a decrease in \( n_i(\Delta) \).

If the longitudinal component of the magnetic field is absent, the increase in the magnetic field leads to a decrease in the energy of electrons, and the effect of reducing the ion density \( n_i(\Delta) \) is more predominant. At some value \( B \), the energy of electrons stops decreasing and remains at a constant level; and upon the further increase in \( B \), the density of ions \( n_i(\Delta) \) grows due to the rise increase in the density of electrons \( n_{e\Delta} \).
4. Conclusion

The article discusses new experimental data obtained in the study of the self-sustained plasma discharge in crossed electric and magnetic fields. Dependencies \( n = f(B_{rA}) \) characterized by the minimum were supplemented by the modes of the discharge, where maximum values of \( n \) and \( W_{av} \) (figure 1) were observed in the graphs \( n = f(B_{rA}) \) and \( W_{av} = f(B_{rA}) \).

We expanded and refined the concept of the optimal magnetic field – as the field where the maximum values of the ion density and average ion energy are achieved. It is under such conditions that the efficiency of the plasma accelerator will be the greatest. We managed to reach the optimal values in the process of changing the ratio \( B_{z}/B_{r} \) (figure 2). The maximum increase in the density amounted to \( n_{opt}/n \approx 5.5 \) which is considered to be a significant value for plasma accelerators with closed electron drift. Likewise, the average energy of ions (spectrum) increased by approximately 1.6 times (figure 3). In total, the energy of the compensated ion beam rose by about an order of magnitude.

The data set which reflects the unsteadiness of the discharge upon the change of the magnetic field is defined as follows: “breakdowns” of density upon the change of the magnetic field (figure 4) and the evolution of isomagnetic ion density jumps (figure 5). Such effects can be a consequence of rapid changes in the macroscopic parameters of the discharge as well as the generation of electrostatic oscillations the ions are sensitive to, in the process of pumping instability in the \( E \times B \) plasma discharge.

A pilot theoretical model has been developed to explain some experimental results. The model takes into account the effect of scattering and collisions of electrons with ionized neutral as well as diffusion of electrons along and across the magnetic field. The found mechanisms of the gain and the loss of the electron energy provided for determination of the mechanism of formation of the ion energy distribution function and the ion density in the discharge interval. This, in turn, explained various dependencies of the ion density upon the growth of the magnetic field (figure 1) and the effect of disruption of ion density (figure 4).

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