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# Optimizing the parameters of a diode-based plasma voltage stabilizer

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An experimental study was conducted to analyze the effect of side screen geometry in a diode-based voltage stabilizer on plasma-beam electron energy relaxation. The results demonstrate that using a conical screen configuration provides for a gradual increase in energy relaxation length and a multi-fold increase in current density. Parameters such as helium pressure, interelectrode gap, and electrokinetic characteristics were optimized. Effective voltage stabilization was achieved within the range of 20 to 65 V at current densities of approximately 2 A/cm$^2$.

**Keywords:** low-voltage beam discharge, electron beam, anisotropic plasma, plasma instabilities, stabilized voltage.

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Recent research [1–3] has demonstrated that the design of devices based on a low-voltage beam discharge (LVBD) in inert gases is a promising trend in the plasma energy industry. Regimes of highly anisotropic plasma with an electron velocity distribution function (EVDF) containing several groups of fast electrons of high concentrations were found to be efficient [4].

On the one hand, this non-equilibrium EVDF structure complicates significantly the process of anisotropic plasma diagnostics. In addition, significant increases in current density lead to instabilities and oscillations, which exert a negative influence on the electrokinetic characteristics of plasma devices [1].

On the other hand, a non-equilibrium EVDF in an LVBD opens up the possibility of control over different groups of fast electrons with the use of active plasma boundaries [3] for optimization of the electrokinetic characteristics of devices. Such studies for plasma triodes were performed in [1].

The examination of diode voltage stabilizers based on an LVBD in helium, neon, and argon [2] has demonstrated that the LVBD voltage decreases down to the excitation potential of the metastable level of plasma-forming gas as the gas pressure rises. The use of inert gases with different ionization potentials made it possible to obtain stabilized voltage within the range of 9–50 V; however, when the voltage rose above 30 V, the stabilization coefficient decreased.

In the present study, the electrokinetic parameters of a diode device of classical design (Fig. 1, $a$) with electrodes 10 mm in diameter were examined experimentally. To increase the discharge current density, a conical screen for the plasma channel of the device was constructed (Fig. 1, $b$). The anode of this device has a diameter of 30 mm and is mounted at a distance of 8 mm from the cathode. Helium was chosen as a plasma-forming medium for the fact that it has the highest excitation and ionization potentials among other inert gases. This provides an opportunity to maximize the magnitude of non-local effects for the purpose of optimizing the electrokinetic characteristics of gas-discharge devices.

Cylindrical probes 1 mm in length and 0.07 mm in diameter were used to study plasma. This particular design was chosen for the ease of fabrication and use of probes for LVBD plasma diagnostics. Note that the modern mathematical apparatus of the cylindrical probe method allows one to determine both even and odd EVDF components in anisotropic plasma [5]. Factors introducing experimental distortions into the results of probe measurements were taken into account [6]. The phase detection method was used to record the second derivative ($I''_U$) values [7].

Fundamental theoretical and experimental studies of an LVBD were carried out by the authors of [4,8,9]; their most important findings are listed below.

— LVBD plasma is characterized by a strongly non-equilibrium EVDF: it consists of several groups of electrons of different energies. A heated cathode emits electrons in the process of thermionic emission. Following this, they form a dense beam due to acceleration at the near-cathode potential jump to an energy on the order of the ionization energy of filler gas (24.6 eV for helium). As they move toward the anode, beam (fast) electrons excite and ionize atoms, producing slow (thermal) electrons with an energy of approximately 2 eV.

— Fast electrons drive current transfer in plasma, while slow electrons are trapped in a potential well between the cathode and the anode and are virtually excluded from current transfer.

— The recombination of charged particles proceeds primarily near the walls of the plasma volume.

— The beam-plasma instability, which leads to complete energy relaxation of electron beams and current interruption [8,9], is likely to develop in LVBD plasma.

Let us use these results to optimize the electrokinetic characteristics of the voltage stabilizer. It was demonstrated in [9] that a threshold-type beam-plasma instability is

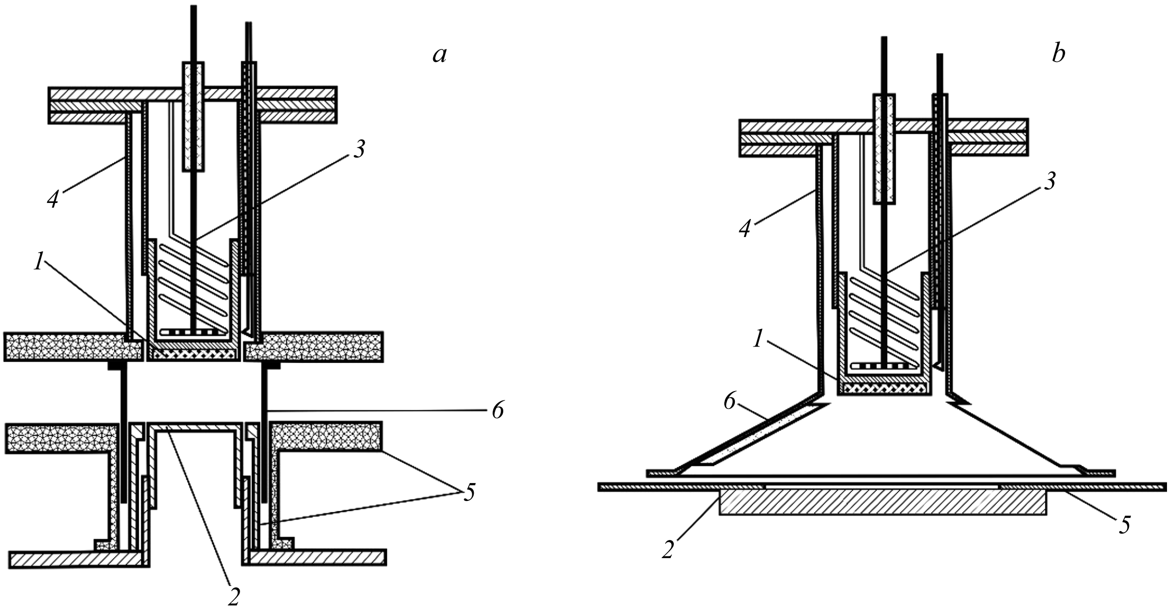

**Figure 1.** Schematic diagrams of experimental diode devices with cylindrical (*a*) and conical (*b*) side screens. *1* — cathode, *2* — anode, *3* — cathode heater, *4* — heat screen, *5* — alundum insulators, and *6* — side metal screen.

observed in an LVBD only if the following condition is satisfied:

$$\frac{\lambda_{ea}}{\lambda_0} \geqslant 5, \tag{1}$$

where $\lambda_{ea}$ is the electron transport path length and $\lambda_0$ is the Langmuir wavelength. When criterion (1) is fulfilled, the discharge becomes unstable, and the beam loses energy quickly and does not reach the anode. Notably, the following equality holds true in this case:

$$\frac{L_E}{\lambda_0} \approx 5, \qquad L_E = l_i + l_\varepsilon \cong \lambda_{ea}, \tag{2}$$

where $L_E$ is the length of complete relaxation of an electron beam, $l_i$ is the relaxation length in the velocity direction, and $l_\varepsilon$ is the energy relaxation length.

In turn, Langmuir wavelength $\lambda_0$ depends on beam electrons velocity $v_0$ and oscillation frequency $\omega_e$:

$$\lambda_0 = \frac{2\pi v_0}{\omega_e}, \tag{3}$$

where Langmuir frequency $\omega_e$ is given by

$$\omega_e = \sqrt{\frac{4\pi n_t e^2}{m_e}}, \tag{4}$$

where $n_t$ is the concentration of slow electrons.

It has been established experimentally [9] that an increase in discharge current density is accompanied by an increase in concentration $n_t$ of slow electrons, and expression (1) may be rewritten for $n_t$ as

$$n_t \geqslant 1.7 \cdot 10^8 \varepsilon_0 \sigma_{ea}^t N_A^2, \tag{5}$$

where $\varepsilon_0$ is the electron beam energy, $\sigma_{ea}^t$ is the transport cross section, and $N_A$ is the concentration of filler gas atoms.

Thus, when threshold concentration $n_t$ is reached at fixed values of helium pressure and interelectrode gap width, criterion (1) for excitation of beam-plasma instability is fulfilled. The beam then loses energy completely, and ionization and current transfer processes are disrupted. This is an important factor limiting the possibilities of improving the energy parameters of plasma stabilizers. At helium pressures $P_{\mathrm{He}}$ on the order of 1 Torr, the beam-plasma instability is excited when the discharge current density exceeds 1 A/cm$^2$.

We attempted to increase the discharge current density of the plasma stabilizer by reducing concentration $n_t$ of slow electrons on the discharge axis.

Let us consider the features of beam motion from the cathode to the anode. Colliding with atoms, beam electrons lose their directionality (isotropize) over a travel distance equal to transport length $\lambda_{ea}$. This is accompanied by gradual broadening of the beam, which is associated with the diffusion of charged particles in the radial direction [10]:

$$|r| = \sqrt{2D_0\tau_0}, \tag{6}$$

where parameter $D_0$ characterizes the dynamics of beam electrons in the radial direction and $\tau_0$ is the time of their propagation from the cathode to the anode. Under typical LVBD conditions (at helium pressure $P_{\mathrm{He}} = 1$ Torr, discharge current density $j = 1$ A/cm$^2$, and longitudinal field strength $E_z$ on the order of $5\,\mathrm{V}\cdot\mathrm{cm}^{-1}$), we obtain $D_0 = 1.3 \cdot 10^7\,\mathrm{cm}^2 \cdot \mathrm{s}^{-1}$ and $\tau_0 \approx 1.8 \cdot 10^{-8}$ s. Formula (6) yields the end result: $|r| \approx 1$ cm, which is approximately equal to the anode diameter of the device with a cylindrical side screen.

To reduce the concentration of slow electrons, the diode device design was modified in such a way that the anode

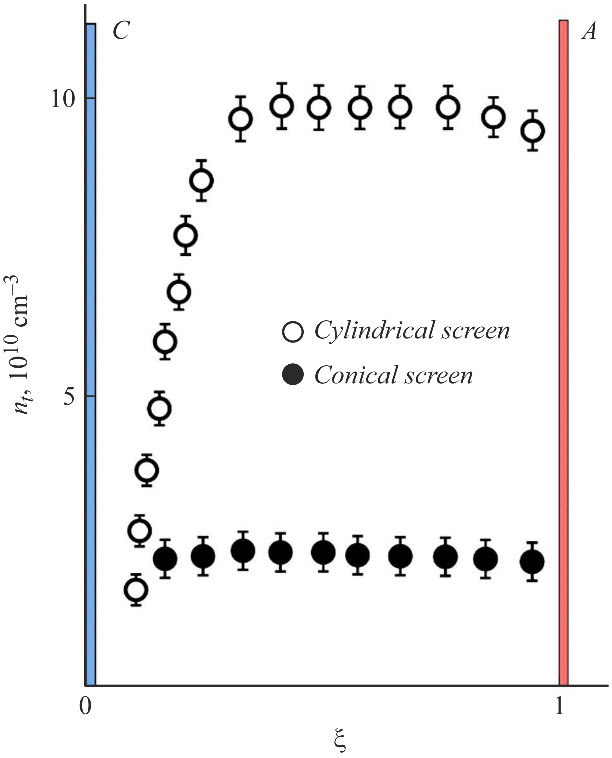

**Figure 2.** Distribution of the concentration of slow electrons in the interelectrode gaps of devices with cylindrical and conical side screens. $P_{\mathrm{He}} = 0.8$ Torr, $d = 8$ mm, and $j = 1$ A/cm$^2$.

diameter was increased to $d_a \approx d_k + 2|r|$ ($d_k$ is the cathode diameter) and the interelectrode gap was surrounded by a conical conductive screen with the cathode potential applied to it. This helped reduce the concentration of slow electrons on the device axis by a factor of 4, which was confirmed by experimental data. Figure 2 presents the axial dependences of $n_t$ recorded in devices with different designs of the side screen ($\xi$ is the dimensionless interelectrode gap width). The 4-fold reduction in concentration of slow electrons induced by the introduction of the conical screen is seen clearly. According to formulae (2)–(4), this provides an opportunity to increase the beam energy relaxation length by a factor of 2 and raise the discharge current density to 2 A/cm$^2$.

Let us now consider the possibility of increasing stabilized voltage $U_{st}$. Since the current–voltage curve (CVC) of plasma stabilizers is shaped by the filler pressure and interelectrode gap width $d$, it is possible to increase $U_{st}$ by optimizing the values of $P_{\mathrm{He}}$ and $d$. Figure 3, *a* shows that, under the discussed conditions, the beam of fast electrons loses energy almost completely over a distance of approximately 4 mm. Therefore, optimal values should be chosen at $d < 4$ mm. Figure 3, *b* presents the dependences of $U_{st}$ on $d$ for two values of helium pressure. It can be seen that $U_{st}$ reaches its maximum at $P_{\mathrm{He}} = 0.5$ Torr and $d$ on the order of 2–3 mm. These values are taken to be the optimal ones.

Let us consider the influence of helium pressure on the device CVC. Figure 4 shows the stabilizer CVCs recorded at $d = 3$ mm and different pressures.

As expected, a change in $P_{\mathrm{He}}$ allows one to vary the value of stabilized voltage within a wider range. An increase in pressure leads to a gradual reduction of stabilized voltage to a value on the order of the helium excitation potential (19.8 V) [2], while the maximum values ($U_{st} \approx 65$ V) are achieved at $P_{\mathrm{He}} = 0.2$ Torr. A further pressure relief leads to CVC deformation and a reduction of the stabilization coefficient. Apparently, this is attributable to a disbalance between the processes of production and annihilation of charged particles in LVBD plasma [1].

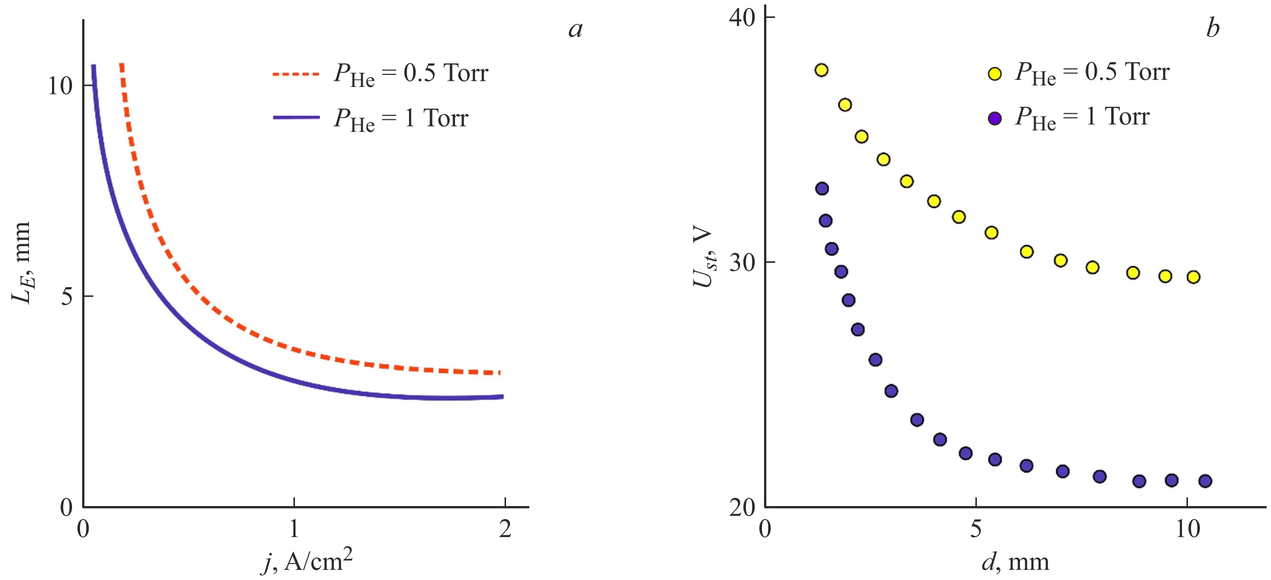

**Figure 3.** Dependences of the length of complete relaxation of beam electrons on the discharge current density (*a*) and the stabilized voltage on the interelectrode gap width (*b*) at different helium pressures.

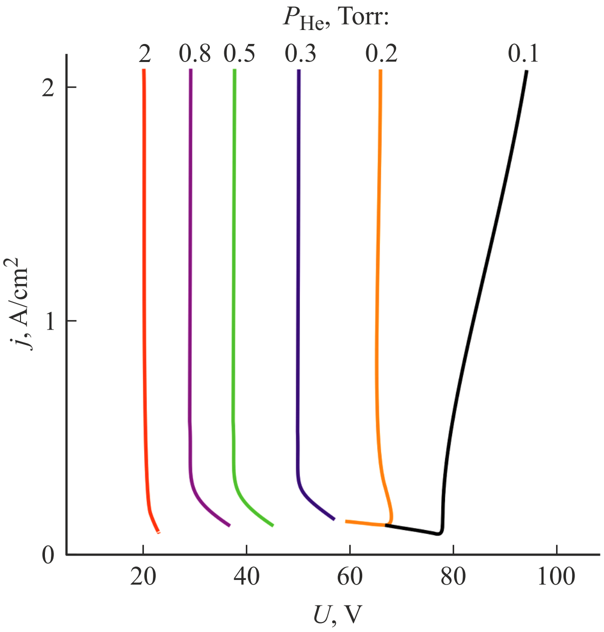

**Figure 4.** Discharge CVCs at different values of $P_{He}$ and $d = 3$ mm.

New data on the properties of LVBD plasma are of fundamental interest in themselves and may be used in the design of plasma energy sources [11], methods for nanomaterial synthesis [12,13], renewable energy components [14], etc.

Thus, the influence of the plasma channel geometry on the threshold of beam-plasma instability development was investigated. It was found that a conical screen allows one to increase the energy relaxation length of an electron beam and the operating current density by a factor of 2. The influence of the interelectrode distance and helium pressure on discharge CVCs was analyzed. Optimal LVBD regimes, which allow for a several-fold increase in $U_{st}$ and current density (relative to similar characteristics of a diode device [2]), were identified as a result. Importantly, $U_{st}$ values within the range from 20 to 65 V are achieved by varying the helium pressure from 2 to 0.2 Torr without the need to fill the device with various inert gases.

## Conflict of interest

The authors declare that they have no conflict of interest.

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