EXPERIMENTAL INVESTIGATION OF PECULIARITIES OF THE BEAM-PLASMA DISCHARGE INITIAL STAGE

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It was shown experimentally that beam-plasma discharge (BPD) in the system of electron beam plus plasma (created by the beam) does not "wait" the condition $n_p >> n_b$, that connected with the instability increment usually used in that case (n_p and n_b are electron concentrations of plasma and beam). Instead, BPD starts at $n_p \approx n_b$ with another increment that was received in this work with help of the corresponding dispersion equation.

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As it is known, in case of electron beam propagating through a rarefied gas of some critical pressure, the beam-plasma instability starts and drives to the high-frequency break-down of gas, that is, to the beam-plasma discharge (BPD) (e.g., see [1] and references there). BPD used in many fields of science and technology (plasma electronics, plasma chemistry, plasma sources, etc.).

Practically all experimental and theoretical works devoted to BPD (e.g., see references in [1]) do not deal with collective effects at the initial stage of BPD where plasma density (n_p) is less or equal to beam density (n_b). Usually, it was supposed that an electron beam firstly prepared (by impact ionization of neutrals) the plasma density that is much grater than the beam density. Afterwards, the beam-plasma instability begins with the increment [2-4]:

$$\gamma = \frac{\sqrt{3}}{2^{4/3}}\,\omega_p \left(n_b / n_p\right)^{1/3} \qquad (1)$$

and drives the beam-plasma discharge.

We have investigated the BPD initial stage (i. e., at $n_p \sim n_b$) in two experiments: 1) in case of pulse electron beam, and 2) in case of CW (continuous in time) electron beam. In both experiments the beams running along a uniform magnetic field (with intensity up to 1 kOe) in air at pressure $p=10^{-6}$–10^{-3} Torr. Summary electron linear concentration (electron number per cm) of the beam and plasma (N_b+N_p) was determined by measuring frequency shift (Δf) of an UHF cavity of the 10-cm range: $N_b+N_p=\Delta f/A$, where the coefficient A was determined experimentally at $p=10^{-6}$ Torr, $N_p=0$, $N_b=6\cdot 10^{18}$ I/V_b, were I is electron beam current in Amperes, V is beam electron velocity. (On increasing accuracy of measuring small electron concentration see [5,6]).

At $p \sim 10^{-6}$ Torr the frequency shift was conditioned by the beam electrons only ($N_b=6\cdot 10^{18}$ I/V_b). In the interval $p=3\cdot 10^{-5}$–$8\cdot 10^{-5}$ Torr the frequency shift slowly rose with plasma electron concentration due to impact ionization of neutrals. At $p \approx 1\cdot 10^{-4}$ Torr the temp of plasma electron concentration rising essentially increased. Simultaneously, burning of the BPD could be visually observed.

Parameters of our first installation (see Fig. 1) are: a pulsed axial electron beam of 0-12 keV, 0-3 A, 10 mm diameter; pulse duration 25 μs, a longitudinal magnetic field up to 1 kOe. The electron beam was passed through a multi-mode 10-cm cavity that was used for the electron and plasma density measurements.

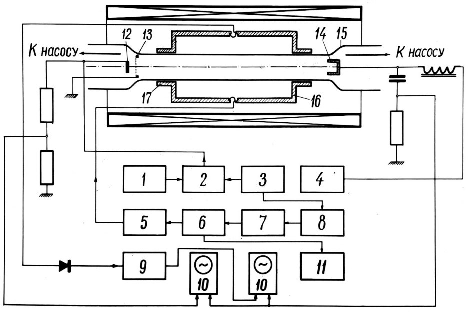

Fig. 1. 1-15 kV rectifier, 2-pulse forming line, 3-trigger device, 4-400 V rectifier, 5–attenuator 10 dB, 6–power distributor, 7–UHF oscillator, 8–delay line, 9–amplifier, 10–oscillоscopes, 11–frequency meter; 12, 13-cathode and anode of electron gun, 14- electron beam collector, 15-quartz tube, 16-UHF cavity, 17–cutoff waveguides

In case of increasing gas pressure (air) up to 10^{-4} Torr, the BPD starts, and the electron linear density quickly rises from $2.3\cdot 10^9$ cm^{-1} to $8.6\cdot 10^9$ cm^{-1} (Fig. 2).

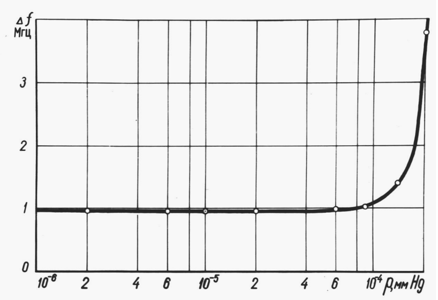

Fig. 2. Resonance frequency shift of the UHF cavity vs. gas pressure in case of 2.3 A, 10 keV electron beam that initiates the plasma-beam discharge at $p \approx 1.5\cdot 10^{-4}$ Torr and $n_p \sim n_b$ (here Δf=1 MHz corresponds to electron beam linear density $N_b=2.3\cdot 10^9$ cm^{-1})

It was determined that, in case of the pulse electron beam, the BPD started at $p \approx 1.5\cdot 10^{-4}$ Torr and $N_p/N_b \approx 0.5$ (but not $N_p >> N_b$, as it was supposed in formula (1)). The measuring accuracy of N_b/N_p was less than 10 %.

In Fig.3 the second installation is presented. The electron beam was created by a gun consisting of LaB_6 cathode (11) and a mesh anode (12), with the following parameters: DC beam voltage U=10-1000 V, current I=1-100 mA, beam diameter 2a=10 mm, magnetic field H variable between 100 and 1 kOe , magnetic field inhomogenity 1 %. The beam was shot down the axis of a quartz tube 30 mm in diameter, which was evacuated down to pressures of the order of 10^{-6} Torr.

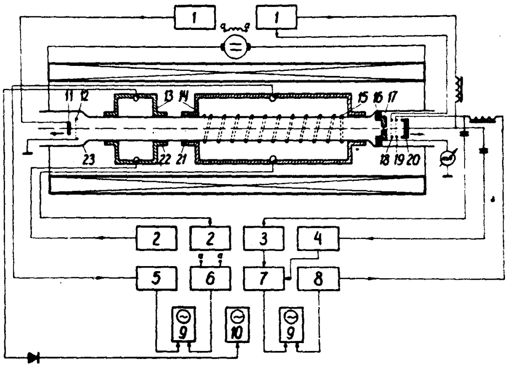

Fig. 3. Setup of 2-nd installation. Main parts: electronic equipment (1-10), electron gun (11, 12), magnetic solenoid, cavity for electron density measurements (13), spiral resonator for measurements of the electron distribution function over axial velocities (15), beam collector (17), multi-electrode probe to measure the electron energy distribution by means of the retarding potential method (18-20)

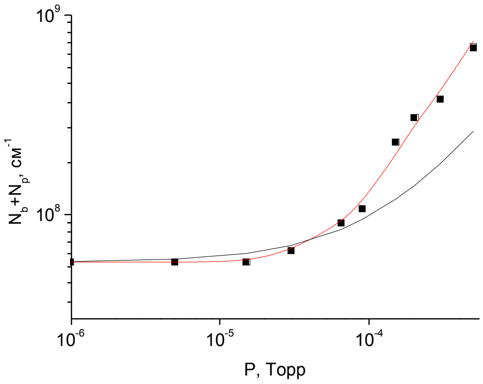

Fig. 4. Measuring electron linear density versus gas pressure in case of 10 mA, 300 eV electron beam that initiates the plasma-beam discharge at $p \approx 9 \cdot 10^{-5}$ Torr

Magnetic field intensity H=1 kOe. The origin of coordinates corresponds to $N = N_b + N_p = 2 \cdot 10^7$ cm^{-1}, p=10^{-6} Torr.

At p~10^{-6} Torr the plasma density $N_p=0$, and the beam one $N_b=5.8 \cdot 10^7$ cm^{-1}. In Fig. 4 a solid curve corresponds to calculation of (N_b+N_p) for case of impact ionization of neutrals by the electron beam. In this experiment the BPD started at $p \approx 9 \cdot 10^{-5}$ Torr and $N_p/N_b \approx 0.8$, but not $N_p >> N_b$, as it was supposed in formula (1). The measuring accuracy of N_b/N_p was less than 10 %.

Both experiments show that the BPD in the system of beam plus plasma (created by beam) do not "wait" the condition $n_p >> n_b$, connected with the increment (1). Instead, the BPD starts at $n_p \approx n_b$ with another increment (see below). So, we made calculation of the instability increment at the condition $n_b=n_p$.

Firstly the two electron beam instability at equal electron concentration $n_{b1}=n_{b2}$ had investigated A.V. Haeff [7], theoretically and experimentally. In that case, Haeff's dispersion equation was as it follows:

$$\frac{\omega_b^2}{(\omega - k_z V_1)^2} + \frac{\omega_b^2}{(\omega - k_z V_2)^2} = 1 , \qquad (2)$$

where ω_b is Langmuir frequency of each beam, k_z is the wave number, V_1 and V_2 are the beams' velocities. By method of successive substitutions, Haeff reduced (2) to the biquadrate equation and solved the problem. However, it was declared in [8] that Haeff's results "were vitiated by the omission of certain terms". Actually, Haeff neglected the difference of beam velocities in comparison with their summary. That action is admissible to his two-beam electron-wave tube but not right to the plasma-beam instability at $\omega_b=\omega_p$, where beam velocity is much high than plasma one ($V_b>>V_p$).

Let us get back to the BPD. Firstly, at the very initial stage of the BPD, where $n_p<<n_b$, the increment of the beam-plasma instability, in accordance with a remark in [9, §1.5], can take the following form:

$$\gamma = \frac{\sqrt{3}}{2^{4/3}} \omega_b \left(n_p / n_b\right)^{1/3} , \qquad (3)$$

where n_p and n_b change over. In case of increasing plasma density up to beam density, $n_p=n_b$, the dispersion equation takes the form of (2), where $V_1 \equiv V_b$, $V_2 \equiv V_p$ ($V_p<<V_b$).

Now we change the laboratory coordinate system to another one, moving with (non relativistic) velocity

$$V_m=(V_1+V_2)/2 \qquad (4)$$

In this system the beam velocity is $V_{bm} \equiv V_{1m}=(V_1-V_2)/2$, and the plasma velocity (or 2-nd beam one) is $V_{pm} \equiv V_{2m}= - (V_1-V_2)/2$. Then, the dispersion equation takes the form:

$$\frac{\omega_b^2}{\left[\omega - \frac{1}{2} k_z (V_1 - V_2)\right]^2} + \frac{\omega_b^2}{\left[\omega + \frac{1}{2} k_z (V_1 - V_2)\right]^2} = 1 \qquad (5)$$

The solution of this biquadrate equation concerning to the complex frequency ω takes the form:

$$\omega^2 = \omega_b^2 + \frac{1}{4} k_z^2 \left(V_1 - V_2\right)^2 \pm \omega_b \left[\omega_b^2 + k_z^2 \left(V_1 - V_2\right)^2\right]^{1/2} \qquad (6)$$

Instability will take place at $\omega^2 < 0$, that, as it appears from (6), at the choice of sign of "–" before a square root, and $k_z<k_{z1}$, where:

$$k_{z1} = 2\sqrt{2}\omega_b / \left(V_1 - V_2\right) . \qquad (7)$$

From (6) we will find also, that at an optimum value of the wave number:

$$k_{z2} = \sqrt{3}\omega_b / \left(V_1 - V_2\right) \qquad (8)$$

the maximum value of increment of instability takes place

$$\Gamma_{\max} \equiv \mathrm{Im}\,\omega = 0.5\omega_b \qquad (9)$$

(in this case $\mathrm{Re}\,\omega = 0$). At the transition to the laboratory coordinate system the oscillation frequency, having greatest increment, in accordance with Doppler transformation, takes on a value:

$$\mathrm{Re}\,\omega_{lab.\max} = \mathrm{Re}\,\omega + k_{z2} V_m = \frac{\sqrt{3}}{2} \omega_b \frac{V_1 + V_2}{V_1 - V_2} . \qquad (10)$$

In our experiments $V_1 >> V_2$ and

$$\mathrm{Re}\,\omega_{lab.\max} = \frac{\sqrt{3}}{2}\omega_b . \qquad (11)$$

Thus, accordingly to the formulas (6-11) the branches of oscillations in the plasma-beam system in case of $n_p = n_b$ look like the following (Fig. 5).

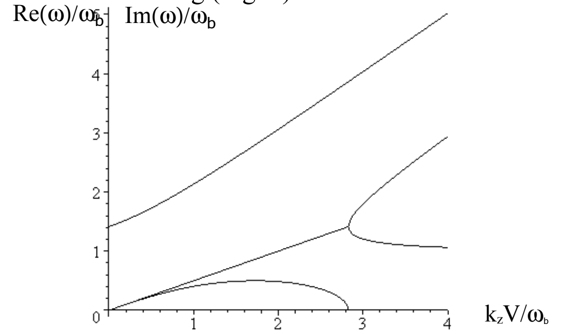

Fig. 5. The branches of oscillations in the plasma-beam system at $N_b = N_p$

In Fig. 5 the relative instability increment $\mathrm{Im}\omega/\omega_b$ is presented by the bottom curve. Upper branches present dispersion of waves $\mathrm{Re}\omega(k_z)$ in this system.

At further growth of the plasma density and fulfillment of the condition $n_p >> n_b$ the evolution of BPD is possible accordingly to the increment (1).

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ОСОБЕННОСТЕЙ НАЧАЛЬНОЙ СТАДИИ ПУЧКОВО-ПЛАЗМЕННОГО РАЗРЯДА

Б.И. Иванов, В.И. Бутенко, В.П. Прищепов

Результаты приведенных экспериментов показывают, что пучково-плазменный разряд (ППР) в системе электронный пучок плюс плазма, создаваемая пучком, не «ждет» выполнения условия $n_p >> n_b$ (n_p и n_b–плотности плазмы и пучка), связанного с инкрементом неустойчивости, обычно используемом в данном случае. Вместо этого ППР начинается при $n_p \approx n_b$ с другим инкрементом, значение которого получено в данной работе.

ЭКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ОСОБЛИВОСТЕЙ ПОЧАТКОВОЇ СТАДІЇ ПУЧКОВО-ПЛАЗМОВОГО РОЗРЯДУ

Б.І. Іванов, В.І. Бутенко, В.П. Прищепов

Результати наведених експериментів показують, що пучково-плазмовий розряд (ППР) в системі електронний пучок плюс плазма, що створюється пучком, не «чекає» виконання умови $n_p >> n_b$ (n_p и n_b–густини плазми й пучка), пов’язаної з інкрементом нестійкості, що зазвичай використовується в даному випадку. Замість цього ППР починається при $n_p \approx n_b$ з іншим інкрементом, значення якого отримано в даній роботі.