MECHANISM OF GAS IONIZATION BY AN INTENSE ELECTRON BEAM

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Ionization of the gas in a drift chamber has been studied on injection of an electron beam of energy 660 keV, current 10–20 kA, and duration 4×10^{-8} sec. The value of the return current was measured as a function of pressure in the range from 10 Torr to 1 atm for air and helium. The results obtained agree satisfactorily with a calculation carried out in the approximation of the Townsend ionization mechanism.

THE formation of a plasma on injection of a beam into a neutral gas is determined not only by the ionization by particles of the beam but also by the electric fields produced by the beam. It has been shown[1,2] that at a pressure $p < 10$ Torr the ionization of the gas is due mainly to electric breakdown in the induced field of the total current, since the breakdown time t_{br} is less than the time of injection of the beam τ. With increasing pressure τ_{br} becomes greater than τ, and therefore breakdown can occur only as a result of increase in the electric field as the result of instability of the beam in a dense gas.

In the present work we have studied experimentally the dependence of the plasma concentration and value of the return current on the gas pressure in a drift chamber for $p \geq 10$ Torr. In order to explain the results obtained, we carried out a calculation of the ionization in the approximation of the Townsend mechanism. In the calculation it was assumed that the electric field is induced by the total current of the plasma and of a homogeneous beam. The coefficient of ionization by secondary electrons under the influence of the electric field α_i^E was taken from the empirical dependence

$$\alpha_i^E = \alpha_T v_{dr}, \quad \alpha_T = Ap\exp(-Bp/|E|),$$

where α_T is the Townsend ionization coefficient and $v_{dr} = k|E|/p$ is the plasma electron drift velocity. The constants A, B, and k in the calculations either were chosen from the experimental curves or were taken from the tables given by Brown[3].

The possibility of using the ionization coefficients for a static field in our case is due to the fact that the characteristic time of acquisition by the electrons of an energy of the order of the ionization potential in the pressure region considered is less than the characteristic time τ of the problem.

1. EXPERIMENTAL ARRANGEMENT

Figure 1 shows the experimental arrangement. A beam of electrons from the Neptune accelerator[4] was transmitted through an anode foil of thickness 100 μ into a dielectric chamber of diameter 18 cm and length 80 cm. The experiments were carried out for an electron energy of 0.66 MeV and a beam current 10–20 kA with a duration 40 nsec. The diameter of the electron beam at the entrance to the chamber was 4–5 cm. An

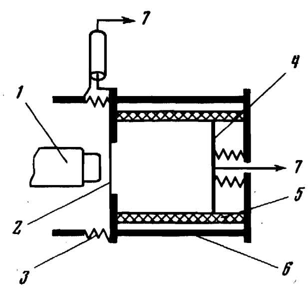

FIG. 1

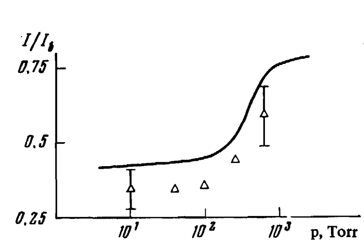

FIG. 2

FIG. 1. Experimental arrangement: 1–cathode, 2–exit foil, 3–shunt, 4–collector, 5–drift chamber, 6–pins, 7–to oscilloscope.

FIG. 2. Ratio of maxima of the total current I and beam current I_b as a function of helium pressure; Δ–experimental points.

oscillogram of the electron beam current pulse recorded by a shunt located along the perimeter of the anode flange of the accelerator tube, with a time resolution ≤2 nsec, is shown below in Fig. 5b. The relation between the shunt reading and the tube current was established by means of a Faraday cup installed in the chamber directly beyond the exit foil for a neutral gas pressure in the chamber of not more than 5×10^{-2} Torr. The beam current and the electron energy, evaluated by means of a capacitance divider mounted in the accelerator tube, corresponded within 20% to the total beam energy recorded by a calorimeter. The total current arriving at the end of the drift chamber was conducted to the exit foil through six metallic pins equally spaced around the chamber perimeter. The total current was measured by a shunt placed at the chamber end.

The behavior of the electron beam in the drift chamber, which was filled with a neutral gas, is determined by the self-consistent electric and magnetic fields of the beam and by the concentration of the plasma produced by the beam. For air pressures $p \leq 10^{-2}$ Torr the time of ionization by relativistic electrons is greater than the beam injection time τ, and the plasma concentration is insufficient to compensate the space charge. Therefore the beam is scattered at the entrance to the drift chamber.

For $p > 0.1$ Torr, compensation of the beam space charge occurs, but the plasma concentration is still insufficient to transport the return current, which is equal to the beam current. Calorimetric measurements show that passage of the beam through the drift tube is improved on changing the pressure from 5×10^{-2} to 10^{-1} Torr. Photographs of the luminescence of the plasma produced by the beam, and the dependence of the diameter of the beam spot on the target on its distance from the exit foil, indicate radial oscillations of the beam, which have been noted by Graybill and Nablo[5]. The minimum diameter of the main zone struck by the beam was ~1.5 mm, which agrees with the optical measurements.

Further increase of the gas pressure leads to a sharp rise in ionization by secondary electrons, and a return current is excited in the dense plasma produced. Figure 2 shows the dependence of the total current amplitude on pressure for a drift gap of length 80 cm for $p \gtrsim 1$ Torr. The diameter of the collector which recorded the beam was ~8 cm. The decrease in current for $p \geq 0.2$ Torr is due to the increase of the beam diameter and its passage around the collector. In order to avoid these effects the collector was placed at a distance of 4 cm from the exit foil. The dependence of the total current on pressure did not change qualitatively.

On increase of the air pressure in the chamber above 300 Torr in the path length of the beam was shortened to 10—20 cm. Therefore, for comparison of the theoretical and experimental values of the total current in the chamber, a collector of diameter 17 cm was placed 20 cm from the exit foil. The main experiments were carried in air and helium at pressures from 10 Torr to 1.6 atm.

2. THEORY AND CALCULATIONS

The dynamics of gas ionization and the induced electric field are described by the system of equations:

$$\frac{1}{r}\frac{\partial}{\partial r}(rH_\varphi)=\frac{4\pi}{c}(j_b+\sigma E_z), \quad (1)$$

$$\frac{\partial E_z}{\partial r}=-\frac{1}{c}\frac{\partial H_\varphi}{\partial t}, \quad (2)$$

$$\frac{\partial n_e}{\partial t}=\alpha_i^E n_e+\alpha_i^b n_b'-\beta_r n_e^2. \quad (3)$$

Here $j_b = en_b'v_b$ is the beam current density, α_i^b is the coefficient for ionization of the gas by electrons of the beam, and β_r is the recombination coefficient.

We note that for a cylindrically symmetric system in the case in which recombination can be neglected, Eqs. (1)—(3) are invariant with respect to the substitution

$$n_e\to n_e/b^2,\quad n_b\to n_b/b^2,\quad r\to rb,\quad H_\varphi\to H_\varphi/b$$

(b is the beam radius). This means that, for given values of the beam current I_b and gas pressure p, the ratio of concentrations of the beam and plasma n_b/n_e and the electric field E_z as a function of the variables r/b and t do not depend on the beam radius. Consequently, the neutralization of the beam current also does not depend on radius. These scaling relations permit us to extend the data obtained below to beams with variable radius under conditions in which the recombination is greater than the characteristic time of the problem. Eliminating H_φ from Eqs. (1) and (2) we obtain the equation of the electric field $E \equiv E_z$:

$$\sigma\frac{\partial E}{\partial t}=-\frac{4\pi}{c^2}E\frac{\partial\sigma}{\partial t}-\frac{4\pi}{c^2}\frac{\partial j_b}{\partial t}-\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial E}{\partial r}. \quad (4)$$

For numerical calculation we took for the electron density of the beam n_b' the function

$$n_b'=n_b\exp\left\{-\left(\frac{t-z/\beta c}{\tau}\right)^2\right\},$$

where τ is the duration of the pulse of fast electrons and $\beta = v_b/c$ is the ratio of the axial electron velocity of the beam to the velocity of light. The value of n_b was assumed constant inside the beam radius b and equal to zero beyond its limits. The last term in Eq. (4) was replaced by the quantity E/b^2. Equation (4) was solved numerically simultaneously with Eq. (3) for a beam with the parameters $n_b = 10^{12}$ cm^{-3}, $\tau = 10^{-8}$ sec, $(1 - \beta^2)^{-1/2} = 2$, b = 1 cm, which corresponds to a beam current $I \approx 13$ kA.

Two gases were considered; nitrogen and helium in the pressure range from 10 to 10^3 Torr. The following values of the constants were used in the calculation:

	Nitrogen	Helium
A, cm^{-1} X Torr^{-1}:	1.66	3
B, V X cm^{-1} X Torr^{-1}:	121	25
k, cm^2 X Torr X V^{-1} X sec^{-1}:	3.9 X 10^5	7.6 X 10^5
$\alpha_i^b/v_b n$, cm^2 X sec^{-1}:	1.79 X 10^{-18}	2.36 X 10^{-19}
β_{0r}, cm^3 X sec^{-1}	10^{-7}	10^{-8}

Here n is the gas density and β_{0r} is the recombination coefficient at room temperature.

The coefficient of ionization by beam particles α_i^b was calculated from the equation for the energy loss by a fast particle with incorporation of the experimentally known ionization values[6]. The dependence of the recombination coefficient for nitrogen on the mean electron velocity of the plasma was taken as $\beta_r \sim T_e^{-1/3}$.[7] The average energy T_e as a function of E/p was calculated according to Nighan[8]. The comparatively strong dependence of the recombination coefficient on E/p for helium ($\beta_r \sim T_e^{-3/2}$) for electron temperatures characteristic of helium discharges permitted recombination in this gas to be neglected in our calculations.

As a result of the calculations we obtained the dependence of the plasma electron concentration, electric field, return plasma current density σE, and total current $(j_b + \sigma E)$ on time for various pressures of nitrogen and helium.

3. EXPERIMENTAL AND THEORETICAL RESULTS

In Fig. 3[1)] we have shown the dependence of the plasma concentration on time for helium and neon, calculated by the method described above. In the same figure we have shown curves of ionization by beam electrons in the absence of an electric field. It is evident from the figure that the role of the field induced by the beam in the ionization process increases with decreasing pressure. In helium at pressure of 10 Torr the secondary electron concentration produced by the

[1] The zero time in all the theoretical curves coincides with passage of the peak of the bean concentration through the point considered.

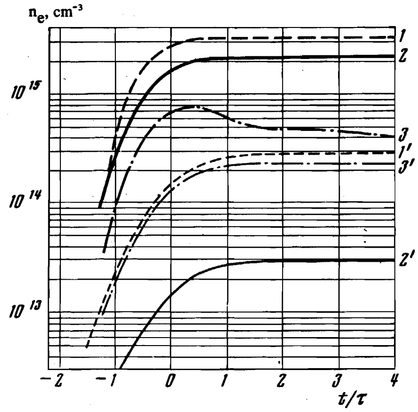

FIG. 3. Secondary electron concentration as a function of time ($\tau = 10^{-8}$ sec). Curves 1 and 1′ are the concentration in helium for a pressure 10^{-1} atm respectively with and without inclusion of ionization under the influence of the electric field; 2 and 2′ are the same for helium at $p = 10^{-2}$ atm, 3 and 3′ are the same for nitrogen for $p = 10^{-2}$ atm.

field exceeds by two orders of magnitude the concentration from fast beam electrons. From Eq. (3), on comparing the first two terms of the right-hand side, we can find the limiting pressure below which the role of the field in production of secondary electrons becomes appreciable. For a beam with current $I_b \approx 13$ kA and duration $\tau = 10^{-8}$ sec this value is ~ 1.5 atm for helium and 0.3 atm for nitrogen. These numbers are in good agreement with the experiments and theory on passage of a beam through a gas[9]. As can be seen from Fig. 3, for the same pressure the role of the field in ionization of nitrogen is less than in ionization of helium. This, like the difference in the limiting pressure, is explained by the smaller value of the ionization coefficient in nitrogen for a given E/p. In the cases calculated the maximum plasma concentration reaches values of the order $\sim 10^{15}$ cm^{-3} and depends only weakly on gas pressure. The plasma concentration in helium can be compared with that calculated from an experiment on the characteristic time for decay of the total current, which in helium is much smaller than the recombination time. This comparison gives satisfactory agreement of theory and experiment. For nitrogen the reverse relation exists between the decay time of the field and the recombination time.

The dependence obtained in the calculation for the electric field as a function of time is shown in Fig. 4.

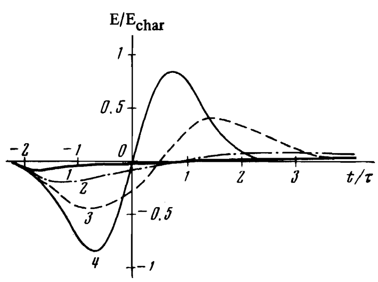

FIG. 4. Electric field induced by the beam as a function of time. $E_{char} = 4I_b/c^2\tau$; $I_b \approx 13$ kA, $\tau = 10^{-8}$ sec. Curve 1—Electric field in helium for $p = 10^{-2}$ atm; 2— in nitrogen for $p = 10^{-2}$ atm, 3—in nitrogen for $p = 10^{-1}$ atm, 4—the axial field of the beam in the absence of return current.

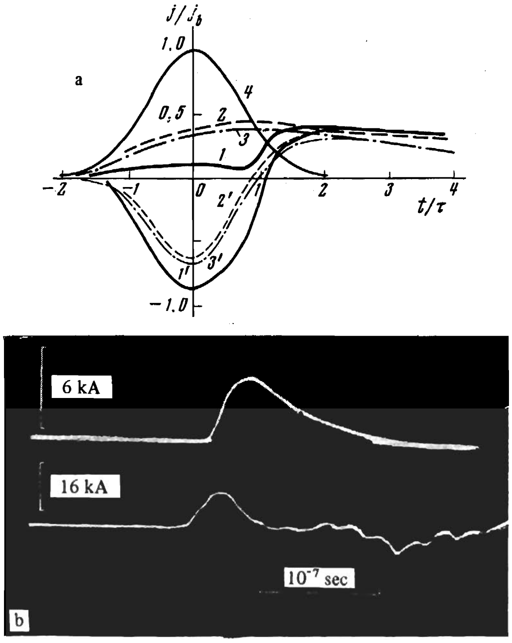

FIG. 5. a—Time dependence of total current density (curves 1 and 2—helium at $p = 10^{-2}$ and 10^{-1} atm, 3—nitrogen at $p = 10^{-2}$ atm), and return current density (curves 1′, 2′, 3′ correspond to the same gases and pressures as curves 1, 2, and 3). Curve 4—the dependence of beam current on time assumed in the calculations. b—Oscillograms of the total current—upper curve—and beam current—lower curve—in helium at $p = 0.1$ atm.

The maximum electric field increases with increasing gas pressure. This is explained by the rise in amplitude of the total current $I \propto (j_b + \sigma E)$, this change being responsible for appearance of the induced field. We note, however, that with reduction of the pressure the quantity E/p rises, which explains the increase in the degree of ionization.

Figure 5a shows the calculated densities of the return and total currents as a function of time, the heavy line representing the beam current. The results of the calculation are in good agreement with the experimental total-current curves and their relative location with respect to the beam current (Fig. 5b). A characteristic feature of the return current is the presence of a spike in the fall of the beam current. The height of this spike is almost independent of pressures, which is explained by the weak dependence of the maximum total current on pressure for $p < 10^2$ Torr (Fig. 2). For high pressures the total current maximum is less shifted relative to the beam current, the degree of neutralization of the current decreases, and the dependence of the total current amplitude on pressure becomes more rapid. which is qualitatively confirmed experimentally. We note that the ratio of the return current to the beam current at the maximum of the latter increases with decreasing pressure and for $p \approx 10$ Torr reaches a value 0.85 for helium and 0.6 for nitrogen.

In comparison of the theoretical and experimental results, it is necessary to take into account the fact that the calculation was carried out approximately (the effect of external inductance was neglected, the radial dependence was taken into account crudely, the calculation for nitrogen is compared with an experiment in air, and so forth). Therefore the most important result of the work is the qualitative agreement of the experimental and theoretical functions. The satisfactory agreement of the theoretical and observed values of the concentration and the currents (Figs. 2, 3, 5) gives a basis for asserting that the mechanism considered by us for ionization of a gas by secondary electrons under the influence of the electric field induced by the beam is, at sufficiently low pressures, stronger than the ionization by the fast electrons of the beam. In this case for an easily ionized gas, for example, helium, this mechanism plays a role up to higher pressures than for nitrogen, which is ionized with relative difficulty.

In conclusion the authors thank G. P. Maksimov for assistance in carrying out the experiment, and A. N. Starostin and S. S. Krasil'nikov for their interest in this work and for helpful discussions.

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