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ADP015036

TITLE: Formation of an Electron Beam in Helium at Elevated Pressure

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TITLE: International Conference on Phenomena in Ionized Gases [26th] Held in Greifswald, Germany on 15-20 July 2003. Proceedings, Volume 4

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Formation of an electron beam in helium at elevated pressure

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1. Introduction

There exist many papers devoted to investigations of X-ray radiation and electron beams formed in gases at elevated pressures (see [1], and references to this paper). However, electron beams with high current density and efficiency is actually achieved at relatively small gas pressures [2,3]. A number of papers report on accelerated electrons obtained at pressure of about 1 atm, still there are either small current and e-beam densities realized [1]. This work was aimed at theoretical and experimental study of the probability to obtain high e-beam current at elevated pressure values of helium.

2. Theory

A theoretical examination and simulation of multiplication process of electrons in discharge gap was done in order to recognize the conditions for running electrons. The main results obtained are as follows: Some part of electrons (~1%) start to run away when the electron accumulates the energy $\varepsilon \equiv m_e v^2/2 = eEl$ of about two energy orders of atom ionization on the free path $l = 1/\sigma_i N$. Here σ_i is cross section of ionization; N is density of neutral atoms; v, m_e are velocity and mass of an electron; E is strength of electrical field. Correspondingly, the condition for the voltage U between anode and cathode when electrons appear has the following form: $U > U_{cr1} \equiv NL\sigma_0\varepsilon_0/e$, where L is distance between planes; σ_0 is cross section of ionization with energy of an electron as $\varepsilon \sim \varepsilon_0 \sim 2J$. The fair quantity of electrons (~50%) run away at the condition realized $\frac{m_e N}{eE}\int_0^{\sqrt{2U/m_e}} \sigma_i(v) v dv > 1$. If in the range of energies $\varepsilon_1 < \varepsilon < eU$, most significant for integration, the cross section of ionization may be approximated by dependence inversely proportional to the energy $\sigma_i(\varepsilon) = \sigma_1\varepsilon_1/\varepsilon$, one might write the condition of running away electrons in the following way:

$$U > U_{cr2} \equiv NL\sigma_1\varepsilon_1 \ln(eU/\varepsilon_1)/e.$$

We may set for helium $\sigma_1 \approx 4\cdot10^{-17}$ cm^2, $\varepsilon_1 \approx 500$ eV. Being headed for $U \sim 100$ kV, for the presented critical field strength we will have $E_{cr2}/N \equiv U_{cr2}/LN = \sigma_1\varepsilon_1\ln(eU/\varepsilon_1)/e \approx 10^{-13}$ cm^3·V/cm or $E_{cr2}/p \equiv U_{cr2}/Lp = (N/p)\cdot\sigma_0\varepsilon_1\ln(eU/\varepsilon_1)/e \approx 3.4$ kV/Torr·cm. Here p is pressure of gas at room temperature.

Numerical simulation of the processes of electron multiplication and running away between two planes at distance L and voltage U was performed using one of particle method modifications. The results of modeling are in accord with presented estimation. For example, for the pressure values of 13.5 Torr and 25 Torr corresponding to the part η = 50 % of accelerated electrons (from the total number of the electrons reached the anode) at E = 62.5 kV/cm and E = 125 kV/cm, we have accordingly E/p = 4.6 kV/Torr·cm and E/p = 5 kV/Torr·cm. Notice that with $E < E_{cr2}$ at intensive multiplication of electrons the beam current occurs to be much higher than with $E > E_{cr2}$, though the part η of running away electrons with $E < E_{cr2}$ is less than with $E > E_{cr2}$. In other words, at the given electrodes voltage, the beam current may increase both with pressure and distance between electrode increase. It should be noted, by the way, that the mentioned above takes place only in the case if the field strength in plasma is not yet dropped due to screening by free charges.

3. Experiment

The pulsed generator earlier used for e-beam formation in vacuum [4] was taken for experiments. The generator had 30-Ohm impedance and formed with matched load an impulse with voltage of 200 kV and duration at FWHM 4 ns at voltage leading edge of about 1 ns. The diode used in experiments was filled in with helium at pressure from 0.1 up to 760 Torr. Two cathodes were used in experiments. The cathode №1 constituted a set of three coaxial cylinders (12, 22, and 30 mm in diameter) made from 50-μm Ti foil, inserted one into other and fixed on duralumin substrate 36-mm in diameter. Height of rings decreased by 2 mm from the smaller to the greater. The cathode №2 was made from graphite in the form of a tablet of 29-mm in diameter with rounded edges being convex in the foil direction with 10-cm radius of curvature. The graphite cathode was placed on a copper holder of 30-mm in diameter. E-beam extraction was realized through 45-μm thick AlBe foil mounted at the end flange. The beam current was measured using graphite electrode mounted at the distance of 10 mm from the foil and connected by low-value shunt with the case of accelerator. Besides that, at the same time, the total diode current on the end flange was measured too, the end flange being connected with cylindrical case of vacuum diode through the second shunt.

The basic experimental results are as follows. There were four typical modes of diode operation. The first mode was observed at small helium pressure in the diode (0.1÷1 Torr, E/p > 70 kV/Torr·cm) for the cathode №1 which provided additional electrical field acceleration on the foil selvages. With this well-known mode of accelerator operation, the highest beam current values behind the foil (> 1 kA) were registered. With further decrease of residual pressure of helium in the diode (>0.01 Torr) the diode beam current was equal by amplitude to the "total" diode current.

The second mode was observed at average pressures of helium (1÷10 Torr, E/p > 7 kV/Torr·cm) being different by high instability from pulse-to-pulse due to helium breakdown with low voltage values. In this mode, beam current was registered only in separate pulses for the cathode №1 made from foil. As for the cathode №2 made from graphite, it was not possible to register the beam current in the first and second modes.

The third mode was observed with helium pressure values 10-40 Torr (E/p > 1.5 kV/Torr·cm) also for the cathode №1 made from foil. Increase of helium pressure leaded as compared with the second mode to increasing of the time of breakdown delay, voltage increase at the gap, and appearance of beam current comprising behind the foil of up to 30 % as compared to the bean current of the mode 1.

At helium pressures above 100 Torr for the graphite cathodes №1 and №2, there was observed the fourth mode. This mode is characteristic for low values of E/p < 0.7 kV/(Torr·cm).

It is necessary to note that with the use of this generator with the pulse of 4-ns duration, a short-circuit discharge and (or) the discharge between anode (foil) and cathode was observed in the diode resulting in diode short-circuit to voltage pulse end, correspondingly, the total diode current was close to short-circuit current, and beam current pulse was shorter than the voltage pulse on the matched load.

Increase of the beam current extracted behind the foil was recorded with increasing of the cathode-anode gap from 7.5 to 28 mm. The electron energy estimation show that the half current is being transferred by the electrons possessing energy above 100 keV (the current beam behind two foils) and the part of such electrons is proportional to the total current of the beam. For the graphite cathode №2, the maximum of beam electron distribution by energy was corresponded to the energy of ~150 keV. Let us note that similarly to [1], we registered electrons with abnormally high energy exceeding the value of eU.

The form of the gas-filled diode discharge during the fourth mode essentially differed for the cases of cathodes №1 and №2. With the foil cathode №1, there were observed single channels, and with the graphite cathode №2, the discharge was more uniform, similar form of discharges was earlier observed in [1].

In our opinion, most important is the experimental result obtained with the use of the graphite cathode №2, when essentially higher beam current (up to 140 A, current density above 10 A/cm^2) was increased. In these conditions, in contrast to [1], the beam electrons reached anode either with greater gaps. Diameter of the electron beam trace of the foil in the case of the cathode was ~40 mm, and uniform change of foil color along the beam aperture was registered.

4. Discussion

Numerical analysis of theoretical and experimental results is difficult due to the circumstance that there are no yet means to take into account shielding of electrical field correctly. Really, plasma is formed during breakdown having high conductivity as compared with the rest part of the discharge gap, and within fractions-units of nanoseconds it bridges the gap. The plasma may serve, in particular, as a source of electrons, i.e. to be plasma cathode. Nevertheless, some qualitative conclusions may be drawn.

It is possible to determine the value of the parameter E/p > 3 kV/cm×Torr with which an essential rise of beam current was observed. This value of E/p is in accord with calculated value of E/p, when the part of running away electrons increases (the mode 3). Some difference is connected with change of voltage value at the gap in experimental conditions. Duration of voltage pulse of 4 ns was sufficient for gap short-circuiting in all modes with which e-beam was stably registered.

The beam current behind the foil was registered with both cathodes cases at E/p < 0.7 kV/cm×Torr when the part of beam electrons is small. As for the cathode №1 made from the foil, the beam current value increased with pressure from 150 to 760 Torr, with that the value of the parameter E/p decreased from 0.5 to 0.1 kV/cm×Torr. It may be connected with the results of calculations, demonstrating the rise of beam current with decrease of E/p.

5. Conclusion

Thus the experimental and theoretical investigations performed with the aim to study conditions for obtain of running away electrons in helium show that the accelerated electrons are being formed both at the values of E/p above 3 kV/cm×Torr (in these conditions a high e-beam efficiency may be reached) and at the comparatively low values of the parameter E/p = 0.1-0.5 kV/cm×Torr. An electron beam has been obtained in atmospheric helium with amplitude of 140 A (beam current density is above 10 A/cm^2) with electron energy of ~150 keV.

The authors express there thanks to Sergey Korovin for provision of a pulsed generator used in experiments. The works were performed under the financial support of ISTC grant No. 1270.

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