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A SOURCE OF INTENSE HELIUM ION FLOW BASED ON AN ARC DISCHARGE IN A MAGNETIC FIELD

S.M. Gubarev, V.O. Khomych, A.V. Ryabtsev

Institute of Physics NAS of Ukraine, Kyiv, Ukraine

E-mail: gubarev@iop.kiev.ua, ryabtsev@iop.kiev.us, khomich@iop.kiev.ua

The work is dedicated to the investigation of a source of intense ion flow based on a low-pressure arc discharge in a longitudinal magnetic field. The obtained helium ion flows are characterized by a total current of up to 0.75 A, a current density of up to 10 A/cm², and a specific power at the collector of up to 6.4 kW/cm². The dependence of the ion flow on experimental parameters and conditions was studied. This ion flow source can be applied in ion-plasma technology processes.

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INTRODUCTION

Intense ion flows are widely used in modern plasma technologies. Arc discharge plasma with a thermionic cathode in a strong longitudinal magnetic field is commonly used to generate ion flows. Numerous studies have investigated arc discharges in magnetic fields [1, 2]. In such discharges, charged particles are confined by the external magnetic field, while neutral gas is pumped out of the discharge region.

Particularly attractive is the arc discharge with electron oscillation in a magnetic field [3, 4]. Compared to the two-electrode discharge, the three-electrode discharge configuration with a reflecting electrode is more energy efficient. Primary electrons emitted by the thermionic cathode oscillate at low gas pressure in the longitudinal magnetic field between the thermionic cathode and the reflecting electrode, which optimizes the ionization of the gas. This discharge is highly efficient in plasma generation across a wide range of electrical parameters, allowing for almost complete gas ionization even at relatively low discharge currents. Additionally, a significant portion of multi-charged ions is present in the plasma composition [4].

The high degree of ionization in the arc plasma allows for magnetic field control of the plasma flow: it can be transported, focused, or deflected within specified ranges. By adjusting the negative bias voltage of the collector (U_{bias}), the energy of the ion flow extracted from the plasma can be regulated.

This work is a continuation of our previous studies on arc discharge plasma in a longitudinal magnetic field both in gases and metal vapors [5, 6]. The goal of this study is to experimentally achieve conditions that enable the most efficient generation of an intense helium ion flow directed at a target. The data obtained on the parameters of the ion flow extracted from the arc plasma source along the magnetic field to the collector in steady-state mode will provide detailed insights into the effects of discharge parameters on the characteristics of the ion flow and help optimize the operation of the ion source.

1. EXPERIMENTAL SETUP AND METHODS

Fig. 1 shows a schematic diagram of the experimental setup for the low-pressure plasma generator with a longitudinal magnetic field, which provides the extraction of intense ion flows along the magnetic field onto the collector (processed target).

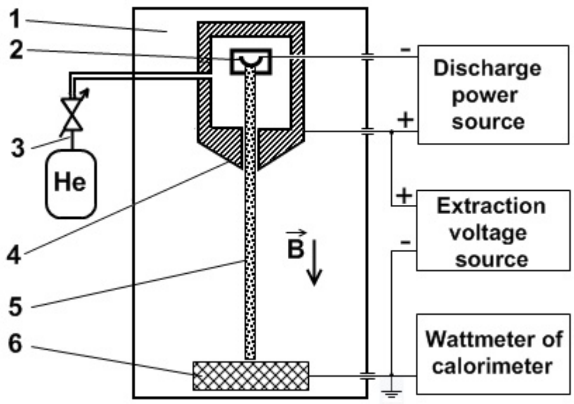

Fig. 1. Experimental setup: 1 – vacuum chamber; 2 – thermionic cathode; 3 – gas supply system; 4 – anode chamber; 5 – plasma column; 6 – collector

Structurally, the plasma source is designed as an axisymmetric system. The gas from the vacuum chamber 1 was evacuated by a diffusion oil vapor pump with a capacity of 1200 l/s to a residual pressure of $7\cdot10^{-4}$ Pa. A copper water-cooled chamber 4, which serves as the anode, is installed in the upper part of the vacuum chamber. Inside the anode chamber, there is a tungsten thermionic cathode 2 of direct heating, placed inside a molybdenum screen with an emission aperture. The anode chamber has a long aperture with a diameter of 3 mm for transporting the plasma flow to the collector 6. The plasma-forming gas is fed directly into the anode chamber, and its flow is regulated by a valve in the range of 1 to 13 Pa. At the same time, the pressure in the vacuum chamber varies within $7\cdot10^{-3}$ to $7\cdot10^{-2}$ Pa, meaning the gas pressure drop at the anode aperture is 2 to 3 orders of magnitude. Technically pure helium was used as the working gas. The anode chamber 4, like the entire vacuum chamber 1, is positioned between the poles of an electromagnet, with the magnetic field strength being smoothly adjustable. In our experiments, the induction of the constant magnetic field was set to 0.34 T. The magnetic field's inhomogeneity in the working area is less than 1%. Under such conditions, the plasma electrons are magnetized, and their Larmor radius is significantly smaller than the diameter of the plasma column 5 (see Fig. 1).

At the beginning of the operation, the temperature of the thermionic cathode was gradually increased to thermionic emission values, after which the discharge DC power supply with an open-circuit voltage of 250 V was turned on. When the plasma-forming gas was introduced into the anode chamber, the electric arc was ignited. By adjusting the internal reactive resistance of the discharge power supply, the discharge current could be smoothly varied from a minimum of 3 to 16 A. The dense primary plasma generated in the anode chamber [6] diffuses through the anode aperture along the magnetic field into the main volume of the vacuum chamber. The effective diameter of the plasma column practically coincides with the size of the exit aperture of the anode chamber and is 3 mm.

In the lower part of the vacuum chamber, coaxial with the anode chamber, a copper water-cooled collector 6 is located. The distance between the thermionic cathode and the collector is 12 cm. The collector's plane is perpendicular to the plasma flow direction. The bias voltage on the collector relative to the anode chamber can be smoothly adjusted from zero to -600 V using a separate power supply, while the collector is grounded. Plasma electrons, oscillating along the magnetic field between the cathode and the collector, significantly increase the degree of ionization of the plasma-forming gas. Depending on the discharge parameters, the degree of gas ionization ranges from 50 to 100%, and the plasma electron concentration n_e reaches 10^{12} to 10^{14} cm^{-3}. By increasing the negative bias on the collector, an ion flow with a current density of about 10 A/cm² can be extracted from the plasma. At a fixed discharge current, the ion saturation current extracted from the plasma onto the collector exhibits a maximum depending on the gas pressure, which is achieved by adjusting the plasma-forming gas flow rate to its optimal value. Almost all of the energy of the charged particle flow incident on the collector is dissipated as heat and is measured by a calorimetric method (absorbed power wattmeter). The measurement error of the calorimeter is 2%.

2. EXPERIMENTAL DATA AND DISCUSSION

At a magnetic field induction of 0.34 T in the working area of the vacuum chamber and a discharge current $I_d = 10$ A, the maximum ion saturation current on the collector is achieved at a pressure of $4 \cdot 10^{-2}$ Pa in the vacuum chamber. In this case, the discharge burning voltage is approximately $U_d \approx 100$ V. Fig. 2 shows the dependence of the experimentally measured current I_m on the collector as a function of the bias voltage U_{bias}. Simultaneously, the power dissipated by the collector P_{cal} was recorded using a calorimetric wattmeter (Fig. 3). When the bias of the collector U_{bias} reaches the value of -150 V, almost all plasma electrons are reflected back into the plasma, and only helium ions with energy around $q \cdot U_{bias}$, where q is the ion charge, reach the collector.

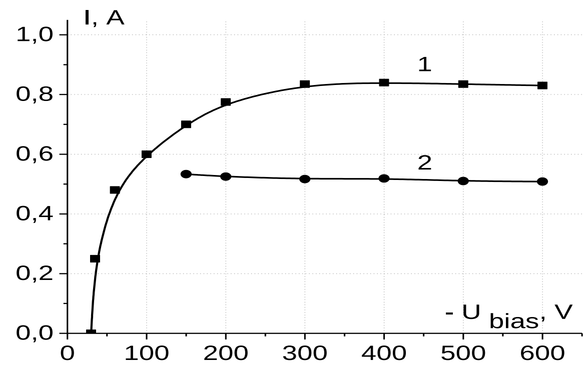

Fig. 2. Currents to the collector depending on the collector bias voltage: 1 – measured current I_m; 2 – calculated actual ion current I_i. Discharge current I_d = 10 A; discharge voltage U_d = 100 V; pressure in the vacuum chamber $P = 4 \cdot 10^{-2}$ Pa

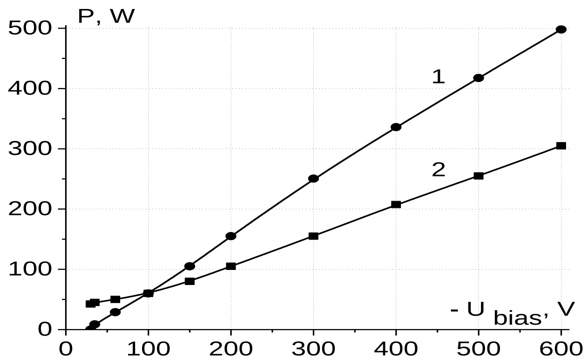

Fig. 3. Electrical and calorimetrically measured plasma flux power to the collector: 1 – electrical power P_{el}; 2 – calorimetrically measured power P_{cal}. Discharge current I_d = 10 A; discharge voltage U_d = 100 V; pressure in the vacuum chamber $P = 4 \cdot 10^{-2}$ Pa

Fig. 2 also shows the actual ion current on the collector, which is determined as $I_i = P_{cal}/U_{bias}$ at values of U_{bias} where nearly all electrons are reflected from the collector back into the plasma. From the difference between the measured current on the collector I_m and the actual ion current I_i, the value of the secondary ion-electron emission current from the collector can be obtained: $I_e = I_m - I_i$.

Fig. 3 also presents the dependence of the electric power of the plasma flow on the collector, calculated as $P_{el} = U_{bias} \cdot I_m$.

The electron temperature T_e and the electron concentration n_e are the main characteristics that determine plasma properties. Measuring the ion saturation current on the collector is a simple method for determining n_e. For plasma in a magnetic field, n_e can be estimated from Bohm's formula for the ion saturation current density on a negatively biased collector:

$$j_{i\,sat} = 0.5 e n_e \sqrt{kT_e / m_i}\,, \qquad (1)$$

where $j_{i\,sat}$ is the ion saturation current density; m_i is the mass of the ion of the studied gas, and k is Boltzmann's constant; e is an elementary charge; T_e is the electron temperature of the plasma, and n_e is the plasma electron concentration.

As analysis [2] showed, using the probe method to determine the electron temperature of plasma under strong magnetic fields is inaccurate. Estimates of the electron temperature [7] obtained by spectroscopic methods for conditions close to ours yielded a value of 5 eV.

Thus, from equation (1) and considering the measured value of $j_{i\,sat}$, the plasma concentration in our experiment is $n_e \approx 10^{14}$ cm^{-3}.

From Fig. 2, it can be seen that with a significant negative bias on the collector (U_{bias} = -150…-600 V), only the ion saturation current of approximately 0.5 A reaches the collector. This corresponds to an ion current density on the collector of $j_i \approx 7.2$ A/cm².

As the negative bias of the collector decreases to U_{bias} = −100 V, the ion current on the collector begins to be partially compensated by the electron current (see Fig. 3). It can be seen that the graphs of the electric and calorimetrically measured power of the charged particle flow from the plasma to the collector intersect at U_{bias} = -100 V, when the potential on the collector becomes equal to the cathode potential, making the discharge cell symmetric (potential-wise, not geometrically). At this point, the electron current from the plasma to the collector approximately equals the electron current of the secondary ion-electron emission I_e from the collector. In other words, the electron component in the collector current balance disappears, leaving practically only the ion current on the collector.

At U_{bias} = -100 V, the slope of the P_{cal} curve changes due to the appearance of electron current from the plasma to the collector. When the collector bias potential reaches the floating potential ($U_{fl} \approx$ -30 V), the total current on the collector is zero (see Fig. 2).

It is possible to estimate the thickness of the space charge layer created by helium ions near the surface of the negatively biased collector:

$$x_s = \left(\frac{4\varepsilon_0}{9}\sqrt{\frac{2e}{m_i}}\frac{U^{3/2}}{j_i}\right)^{1/2}, \qquad (2)$$

where m_i is the ion mass; U is the voltage between electrodes; ε_0 is vacuum permittivity, and x_s is the space charge layer thickness.

For our conditions (helium, U_{bias} = -600 V, j_i = 10 A/cm²), calculations using equation (2) give $x_s \le 1.6$ mm. This means that the ion extraction and flow formation occur within a thin space charge layer near the collector surface, where almost all the externally applied bias voltage is concentrated.

Fig. 4 shows the dependence of the ion saturation current extracted from the plasma to the collector at a negative bias of 600 V on the discharge current. The actual ion current on the collector (see Fig. 4) is almost 1.5 times less than the measured collector current and constitutes approximately 5…10% of the discharge current.

The total calorimetric power of the ion flow on the collector (at U_{bias} = -600 V, I_d = 16 A, $I_i \approx 0.75$ A) reaches 450 W, corresponding to a specific power density of 6.4 kW/cm² (see Fig. 4).

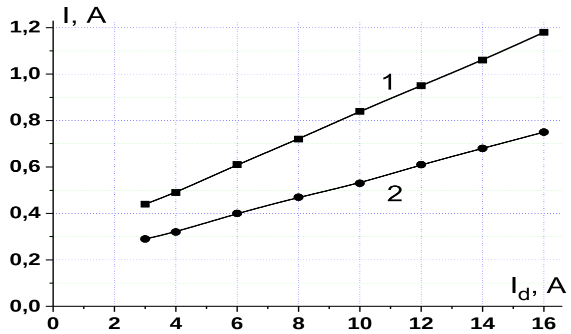

Fig. 4. Dependence of the current from the plasma to the collector on the value of the discharge current I_d: 1 – measured current I_m; 2 – actual ion current I_i

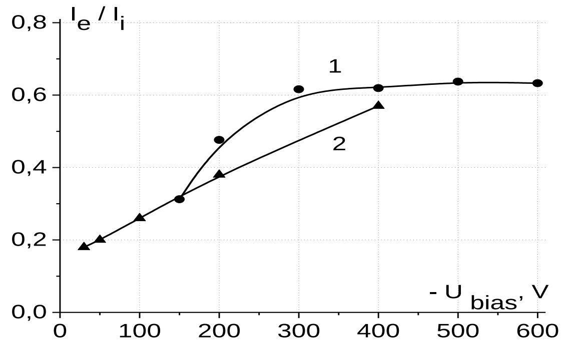

Fig. 5. Ratio of secondary ion-electron emission currents I_e from the collector and ion flux to the collector I_i depending on the bias voltage U_{bias}. 1 – our experiment (I_d = 10 A; U_d = 100 V); 2 – from the work of Rostagni [8]

Fig. 5 presents the dependence, obtained from our experiments, of the ratio I_e/I_i of the secondary ion-electron emission current to the actual ion current on the collector as a function of the negative bias voltage U_{bias}, which corresponds to the averaged ion-electron emission coefficient γ for both single-charged and double-charged helium ions (since we may have a mixture of both single- and double-charged ions). For comparison, the same figure also shows the curve of this coefficient for He^+ ions bombarding a copper target, taken from Rostagni's work [8], in which only singly charged helium ions were reported.

The secondary ion-electron emission coefficients measured by different authors [8, 9] can vary significantly, as the presence of gas and other contaminants greatly affects the γ coefficients [10]. The slightly higher γ coefficient (see Fig. 5) obtained in our experiment, compared to [8], may be due to the presence of doubly charged ions He^{2+} in the ion flow, which have a higher secondary ion-electron emission coefficient than singly charged ions [11].

CONCLUSIONS

The design and main characteristics of a source of intense helium ion flux based on a non-self-assisted low-pressure arc discharge with electrons oscillating in a strong longitudinal magnetic field are presented.

A helium ion flux to the collector with a total current of up to 0.75 A and a current density of up to ≈ 10 A/cm^2 and a specific power of up to 6.4 kW/cm^2 was obtained.

The high specific power and the geometry of the discharge (the presence of electron oscillations) contribute to the formation of multi-charge ions, which is indirectly confirmed by our observations.

This source of ion flux can be used in the processes of ion-plasma technologies.

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ДЖЕРЕЛО ІНТЕНСИВНОГО ПОТОКУ ІОНІВ ГЕЛІЮ НА ОСНОВІ ДУГОВОГО РОЗРЯДУ В МАГНІТНОМУ ПОЛІ

С.М. Губарєв, В.О. Хомич, А.В. Рябцев

Досліджено джерела інтенсивного іонного потоку на основі дугового розряду низького тиску в поздовжньому магнітному полі. Отримані потоки іонів гелію характеризуються загальним струмом до 0,75 А, густиною струму до 10 А/см^2 та питомою потужністю на колекторі до 6,4 кВт/см^2. Досліджено залежність іонного потоку від експериментальних параметрів та умов. Дане джерело іонного потоку може бути використане в процесах іонно-плазмових технологій.