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GLOW DISCHARGE IN HELIUM AND NITROGEN ATMOSPHERES AT STELLARATOR URAGAN-2M

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Investigations of glow discharge on the Uragan-2M stellarator in helium and nitrogen atmospheres have been carried out. Studies were made in the range of discharge currents from 0.05 to 1 A and working gas pressure from 0.284 to 14.93 Pa. The current-voltage characteristics of the glow discharge were measured. The floating potential along the minor radius was measured using a single probe. In the optical emission spectrum of the plasma, spectral lines of excited He I atoms in the He atmosphere were observed. In the N_2 atmosphere, spectral lines of excited molecules N_2^* and molecular ions N_2^{+*} were also registered.

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INTRODUCTION

In the preparation and research of high-temperature plasma for magnetic confinement fusion, wall conditioning is an important and necessary procedure. The use of such a procedure can reduce the amount of impurities (C, O_2, C_nH_n, etc.) arrived into the plasma from the walls of the vacuum chamber. Accordingly, it reduces the power of radiation losses from the plasma and improving the plasma parameters. In modern magnetic confinement toroidal facilities such as tokamaks and stellarators various wall conditioning procedures are used. These include those based on the interaction of the plasma with the inner surface of vacuum chambers and the equipment installed in it. There are various wall conditioning methods: baking, boronization, glow discharge, radio frequency discharges in different frequency ranges [1-3]. Glow discharge is one of the commonly used for cleaning vacuum surfaces in tokamaks and stellarators see, e.g.: EAST [4], ADITYA [5], Wendelstein 7-X [6], LHD [7]. The working gas in a glow discharge is usually used as H_2 [4-6], He [4, 6], Ar [7], and mixtures of Ag+H_2 [8].

The wall conditioning using glow discharge plasma has its advantages. Firstly, it is technically simple, where a power source, cathode and anode (anodes) are necessary. Secondly, this method can be very effective. Each glow discharge (GD) system used in modern tokamaks and stellarators has its own peculiarities. Since the volume of the facilities can be from ≈ 1 m^3 at TOMAS [9] to ≈ 1400 m^3 at ITER [10], the number of electrodes used as anode varies from 2 [5] to 10 [6].

A glow discharge cleaning (GDC) system was developed and used in the Uragan-2M (U-2M) stellarator [11]. The first experiments were carried out in the Argon atmosphere [12, 13].

The sputtering coefficient of materials with argon ions is higher than for lighter ions such as hydrogen, helium or nitrogen [14]. Helium, like argon, is a chemically inert gas. Helium is one of the main gases in thermonuclear research along with hydrogen and its isotopes. In contrast to the inert gases He and Ar, nitrogen as well as hydrogen are chemically active gases. When these gases are used, the process of chemical sputtering, e.g. of carbon and carbon-containing films, is observed [14]. The glow discharge cleaning efficiency depend on the gas sort [15]. And new studies are always required when the basic gas is changed in the glow discharge. Therefore, it is of interest to investigate the glow discharge in the atmosphere of light gases such as helium [4, 6] and nitrogen [16, 17]. This paper presents the results of the first experiments of glow discharge on U-2M in the atmosphere of helium and nitrogen.

1. EXPERIMENTAL SETUP AND DIAGNOSTICS

1.1. STELLARATOR URAGAN-2M

The Uragan-2M stellarator is a medium-sized torsatron-type stellarator with a major radius of 1.7 m, minor radius of the toroidal vacuum chamber 0.34 m, inner volume 3.879 m^3 and inner surface area S ≈ 23 m^2 [11, 12]. The vacuum chamber is pumped out by 3 turbomolecular pumps of TMN-500 type. In the forevacuum part of the vacuum system, a mechanical pump AVZ-63D is used. The working gas was injected and controlled using a two-channel gas puffing system SNA-2-01 [18]. Discharge current and voltage were measured using an ammeter and voltmeters. A single probe was used to measure the floating potential along the radius of the vacuum chamber. Using a SOLAR TII SL-40-2-3648 USB optical spectrometer, the discharge is characterized [19].

1.2. GLOW DISCHARGE SYSTEM

In the discharge, the U-2M vacuum chamber was the cathode, and 4 identical electrodes were used as anodes [12]. The electrodes are ≈ 59 cm long and 2 cm in diameter, they are mounted symmetrically along the length of the vacuum chamber. The cathode and anode are made of stainless steel. The surface area of the cathode is ≈ 23 m^2, and the collecting the electric current surface area of the 4 electrodes is ≈ 1568 cm^2. The general scheme of the glow discharge is shown in Fig. 1. The power supply has a maximum power up to 8.5 kW, voltage up to 1.7 kV and current up to 5 A.

2. EXPERIMENTAL RESULTS AN DISCUSSION

The experiments were carried out in He and N_2 atmospheres, in the range of discharge currents from 0.05 to 1 A and working gas pressure from 0.284 to 14.93 Pa. Before the experiments, the vacuum chamber was evacuated, then the working gas was injected. In these experiments 3 of 4 anodes were used (electrodes E1, E2, E3), see Fig.1.

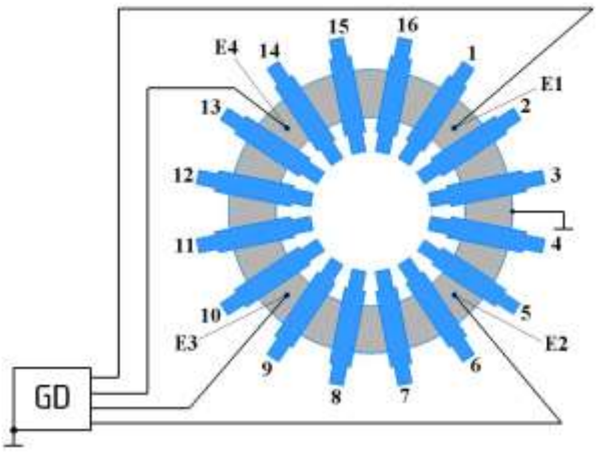

Fig. 1. The scheme of glow discharge on Uragan-2M: E1-E4 electrodes (anodes); GD is glow discharge system power supply; 1–16 toroidal field coils

2.1. GLOW DISCHARGE IN HELIUM ATMOSPHERE

Within these conditions, the breakdown of the vacuum gap and ignition of glow discharge between the cathode (vacuum chamber) and anodes (electrodes) are realized sequentially. Such a glow discharge can be classified as a self-sustaining discharge with a cold cathode [15, 20]. In previous experiments, the measured breakdown voltage in the pressure range of 0.6…13.1 Pa of argon was between 253 and 564 V [12]. In these experiments, the dependence of the breakdown voltage in He atmosphere, in the pressure range of 2.09 to 14.93 Pa, was measured. Fig. 2 presents the dependence of the breakdown voltage on the helium pressure. In this case, the minimum breakdown voltage was 242 V at 14.93 Pa and the maximum was 782 V at 2.09 Pa. As it can be seen from Fig. 2, the breakdown voltage is observed to be higher in helium than in argon up to a pressure of 11 Pa. At pressures above 11 Pa, the breakdown voltage is higher in argon than in helium. Thus, for example, the breakdown voltage at a pressure of 3.4 Pa in helium is 469 V, while in the case of argon at the same pressure it is 269 V.

In the case of a homogeneous constant electric field, the breakdown voltage can be estimated from the relation [15, 20]:

$$\alpha d = \ln\left(1+\frac{1}{\gamma_{se}}\right), \quad (1)$$

where the α – first Townsend coefficient; d – distance between cathode and anode; γ_{se} – coefficient of secondary electronic emissions. The coefficient α depends on the type of gas and its pressure (concentration of neutral particles) as well as on the value of electric field strength. The secondary ion electron emission coefficient depends on the type of ion, its energy and the cathode material. Coefficients α and γ_{se} are different for helium and argon [15, 20]. Higher breakdown voltage in helium than in argon was observed earlier in many experiments, see, e.g. [15, 20].

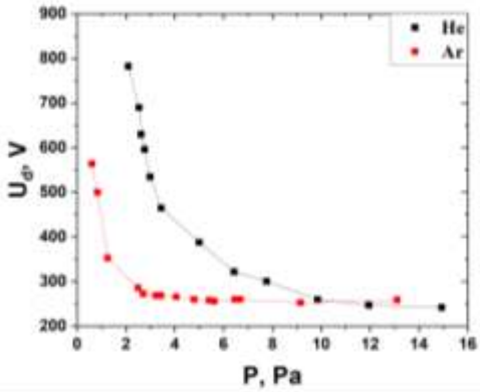

Fig. 2. Dependence of breakdown voltage on the gas pressure: Ar data taken from [12]

Eq. (1) is obtained for the case of plane electrodes with infinitely large radius. The modified equation (1) taking into account the cylindrical geometry was obtained in [21]. In the case of a non-uniform electric field along one coordinate (1D), expression (1) can be written in a different form, see equation 2 [15].

$$\int_0^d \alpha(z)\,dz = \ln\left(1+\frac{1}{\gamma_{se}}\right). \quad (2)$$

However, in the case of these experimental conditions, the electric field is inhomogeneous in at least two coordinates (2D). The calculation of the electric field, taking into account the geometry of electrodes and their dimensions used in these experiments, were carried out using the FEMM code [22]. The calculation results at a voltage of 300 V are presented in Fig. 3.

The picture in Fig. 3 is idealized. Since it does not take into account the real geometry of the vacuum chamber, which has a more sophisticated geometry (vacuum ports, equipment installed inside, etc.) and a finite length of electrodes (anodes) that will affect the electric field distribution. Naturally, in this case eg. (2)

can be used only for rough estimates of the breakdown voltage. Taking in calculations one of the distances from cathode to anode. And it will not accurately describe the complexity real dependence of the breakdown voltage on pressure.

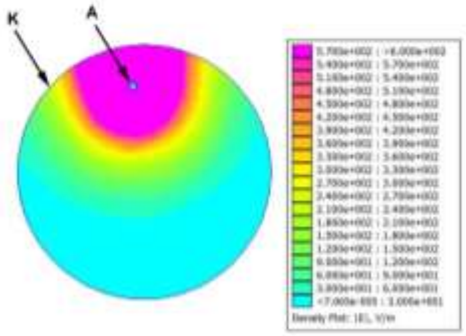

Fig. 3. Electric field strength between electrodes for 2D electrode geometry at U-2M. K – cathode, A – anode

In self-sustaining discharges with a cold cathode, ionisation of neutral gas molecules (atoms) is mainly due to electrons emitted from the cathode surface and accelerated in the cathode layer. The production of primary electrons is mainly due to the process of secondary ion-electron emission during the interaction of ions with the cathode surface. As a result, the discharge voltage is maintained so that the energy of the secondary electrons is sufficient to ionization the required number of ions to maintain a self-sustaining discharge [15, 20].

A current-voltage (I–V) characteristics of the discharge is shown in Fig. 4, at a pressure of 1.11 Pa. The figure shows that the increase in voltage by ≈ 1.14 times leads to an increase in discharge current in 5. It is also seen that the voltages at the electrodes are different. The maximum voltage is observed at the second electrode – E2 (246 V), at a current of 1 A, with a voltage difference of 15 V the electrodes E2 and E3 (231 V). At a current of 0.2 A, the voltage difference was 6 V. The smallest voltage difference was 2 V between E1 (211 V) and E2 (213 V), at a current of 0.2 A. This may be due to the inhomogeneity of the plasma parameters. The difference of voltages at the electrodes was also observed earlier in the glow discharge in argon at U-2M [12, 13]. The plasma inhomogeneity was also pointed out in [23, 24]. Note that the observed I–V characteristics of the discharge with a hollow cathode [25-27]. Since the cathode is a toroidal vacuum chamber U-2M, it is topologically similar to a hollow cathode.

Fig. 5 shows the voltage dependence on He pressure, at a current of 0.2 A. The difference in the voltages at the electrodes is also observed. The maximum voltage difference was 58 V between E3 electrode (382 V) and E2 electrode (324 V) at a pressure of 0.284 Pa. At a pressure of 1.786 Pa, the voltage difference was 43 V for E2 electrode (235 V), and E3 electrode (192 V). From the data obtained, it can be seen that the voltage across the electrodes decreases with increasing He pressure.

The optical emission spectrum of the glow discharge plasma in the range 210…670 nm in helium atmosphere at a pressure of 6.97 Pa was measured. The most intense lines of excited He I (He^*) atoms are observed, see Fig. 6.

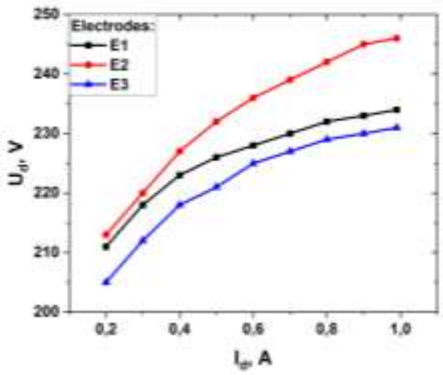

Fig. 4. I–V characteristics. Gas is He, P = 1.11 Pa

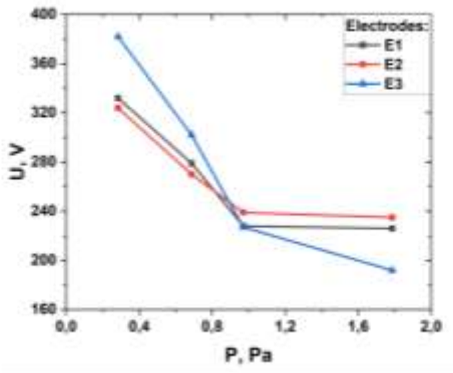

Fig. 5. Voltage dependence on pressure at three electrodes, at I = 0.2 A. The gas is He

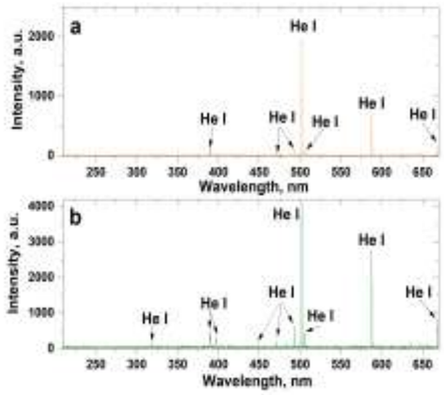

Fig. 6. Emission spectra of glow discharge in helium, at P = 6.97 Pa. I = 0.1 A, U = 201 V (a); I = 0.4 A, U = 238 V(b)

An increase in the intensity of He I spectral lines with increasing discharge current is observed (Fig. 7). To analyze the intensity of He I spectral lines from the discharge current, we selected a number of lines presented in Table. Dependence of the intensity of these spectral lines, in the range of currents 0.1 and 0.4 A, are presented in Fig. 7. It can be seen that the dependences of the intensity of spectral lines do not increase linearly with increasing discharge current.

Data characterizing the selected optical emission lines. Here, λ_{air} is the line wavelength in air, E_i and E_k are the excitation energies of its lower and upper level, respectively and A_{ki} is the transition probability [28]

	λ_{air}, nm	Lower Level	Upper Level	E_i(eV)- E_k, eV	A_{ki}, (10^7 s^{-1})
He I	471.3	1*s*2*p*(^{3}P°)1	1*s*4*s*(^{3}S)1	20.96…23.59	0.31736
He I	492.19	1*s*2*p*(^{1}P°)1	1*s*4d(^{1}D)2	21.218…23.736	1.9863
He I	504.77	1*s*2*p*(^{1}P°)1	1*s*4s(^{1}S)0	21.218…23.674	0.67712

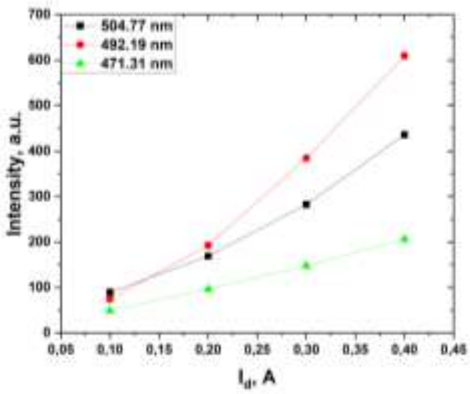

Fig. 7. Dependence of the intensity of spectral lines on discharge current, P = 6.97 Pa

This is due to the increase of adsorbed power in the discharge from 20 to ≈ 95 W resulting in changes in plasma parameters such as electron density and temperature. Accordingly, the probability of collisions of electrons with atoms leading to processes of excitation of atoms increases. The intensity of emission of spectral lines from the plasma increases.

Excited helium ions He II (He^{+*}) were not registered in the entire range of the measured current. This is probably due to the excitation energy of ions being much higher than in the case of neutral He atoms. For example, as can be seen from Table, the excitation energy of He atoms is ~ 24 eV, while the excitation energy of He^+ ions is ~ 51…53 eV [28]. Apparently, the energy of electrons is enough for the effective process of excitation and ionization of neutral He atoms, but not enough for excitation of ions. Note that the ionisation energy of a neutral He atom (He I) is 24.6 eV, for He ions (He II) is 54.4 eV [28].

The floating potential, radial distribution was measured with the probe and is shown in Fig. 8. The floating potential at the centre of the vacuum chamber was 123 and 120 V, respectively, at P = 1.79 Pa and P = 0.896 Pa. The minimum values of the floating potential were observed at the edge of the vacuum chamber wall U_f = 10 V at P = 1.79 Pa and U_f = 9.2 V at P = 0.896 Pa. A similar picture was observed in [12, 13]. Fig. 9 shows the dependence of the floating potential on the discharge current for two coordinates: r=34 cm (at the edge of the vacuum chamber wall) and r=0 cm (centre of the vacuum chamber). It can be seen that the floating potential increases from 4.6 to 18 V at the edge of the wall in the range of discharge current 0.2…1 A (see Fig. 9,a). A similar picture is observed in the centre of the vacuum chamber, where the floating potential increases from 82 V to 154 V (see Fig. 9,b).

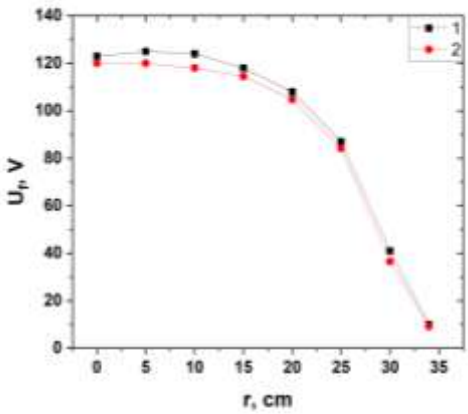

Fig. 8. Floating potential at I=0.5 A, P=1.79 Pa (1); P=0.896 Pa (2)

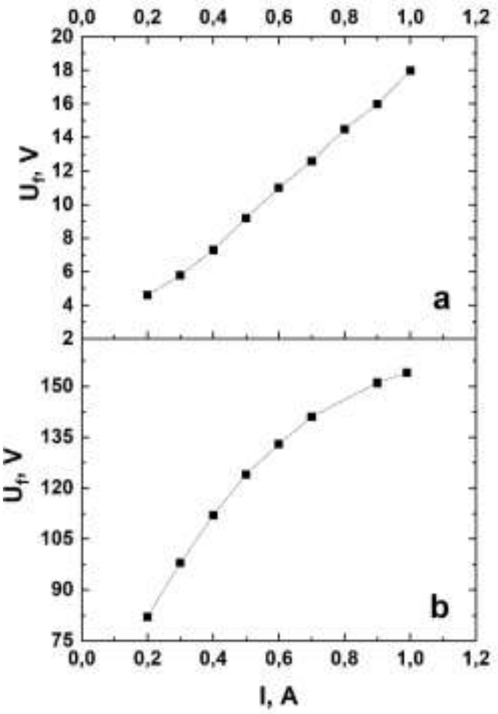

Fig. 9. Floating potential: P=0.896 Pa, r=34 cm (a); P=1.79 Pa, r=0 cm (b)

2.2. GLOW DISCHARGE IN NITROGEN ATMOSPHERE

The experimentally measured I–V characteristics of glow discharge, in N_2 atmosphere, is shown in Fig. 10. The maximum voltage is observed at the third electrode (E3), see Fig. 10, which is 492 V at a current of 1 A. It is different from the voltage at electrodes E1 and E2 (488 V). It differs from the voltage at electrodes E1 and

E2 (488 V) by 4 V. At a current of 0.5 A, the voltage at electrode E3 was 455 V, which is 7 V higher than at electrodes E1 and E2 (455 V). In the whole range of discharge current, the voltage at electrodes E1 and E2 was the same. Fig. 10 shows that the increase in discharge current by a factor of 2 with increasing voltage in ≈ 1.09. A similar pattern of voltage-current dependence was observed in He and Ar at U-2M [12, 13].

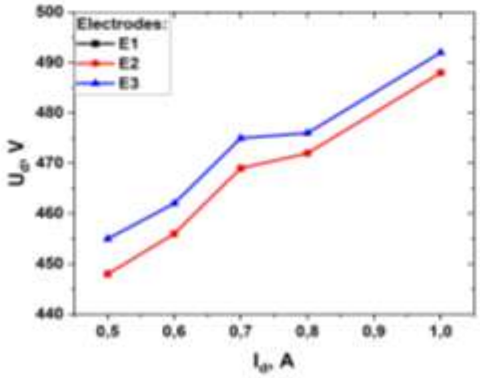

Fig. 10. I–V characteristics. Gas is N_2, P=0.333 Pa

The optical spectrum of the glow discharge plasma in nitrogen is shown in Fig. 11. In the optical spectrum, intense lines 337.13, 357.69, 315.9 nm of the second positive system of the neutral molecule N_2^* are observed. And also the first negative system (391.44, 427.81 nm) of molecular ions N_2^{+*}. The ionisation potential of N_2 molecules is smaller than for He. And also the excitation potential, for example, for the spectral line 504.7 nm He I excitation energy is 23.674 eV, see Table, and for the line 337.13 nm N_2 is 11.032 eV [29]. In this case of ion excitation for He^+ the excitation energy is ~ 51…53 eV, and for N_2^+ for example for the 391.44 nm line is 18.751 eV [28, 29]. Accordingly, at lower electron energies, excitation of molecular ions in N_2 is possible than that of He ions. Since the excitation process is threshold, below the excitation energy the process is impossible.

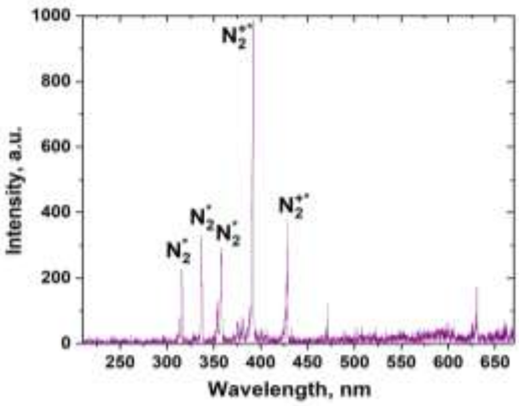

Fig. 11. Emission spectra of glow discharge in nitrogen, at P=0.333 Pa, I=0.5 A, U = 461 V

CONCLUSIONS

The measured volt-ampere characteristics of the glow discharge in the atmosphere of He showed that an increase in voltage by a factor of ≈ 1.14 results to an increase in discharge current by a factor of 5, from 0.2 to 1 A. In the N_2 atmosphere, an increase in voltage by a factor of ≈ 1.09 results to an increase in discharge current by a factor of 2, from 0.5 to 1 A. In both cases, the difference of voltages on anodes is observed, which can be connected with inhomogeneity of plasma in the volume of the vacuum chamber. The obtained I–V characteristics are similar with the characteristic of discharges with a hollow cathode.

Measurements of the radial distribution of the floating potential, in the atmosphere of He, showed its increase along the radius from the wall to the centre of the vacuum chamber. Also the floating potential increases with increasing discharge current.

In the optical emission spectrum of the He plasma, spectral lines of excited He I atoms are observed. Excited helium ions He II (He^{+*}) were not registered in over the entire range of the measured current. Apparently, the electron energy is enough for efficient excitation and ionization of neutral He atoms, but not enough for excitation of ions.

In the optical spectrum of the n_2 glow discharge plasma, spectral lines of excited N_2^* molecules and N_2^{+*} molecular ions are observed.

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ЖЕВРІЮЧИЙ РОЗРЯД В АТМОСФЕРІ ГЕЛІЮ ТА АЗОТУ НА СТЕЛАРАТОРІ УРАГАН-2М

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Проведено дослідження жевріючого розряду в стеларaторі Ураган-2М в атмосферах гелію та азоту. Дослідження проводилися в діапазоні розрядних струмів від 0.05 до 1 А і тиску робочого газу від 0.284 до 14.93 Па. Виміряно вольт-амперні характеристики жевріючого розряду. За допомогою зонда виміряно плаваючий потенціал уздовж малого радіуса. В оптичному емісійному спектрі плазми спостерігалися спектральні лінії збуджених атомів He I в атмосфері He. В атмосфері N_2 реєструвалися спектральні лінії збуджених молекул N_2^* і молекулярних іонів N_2^{+*}.