Study of two Different Discharge Modes in Hall Thruster

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Abstract: In the article, two stable discharge modes of a Hall thruster, which significantly differ from each other in anode efficiency, were experimentally investigated. The most striking distinguishing features of the observed discharge modes are the shape of the plasma plume and the value of the discharge current at almost identical input parameters (gas flow rate, discharge voltage, magnetic field). The main integral and local parameters in two discharge modes was investigated. High frequency waves with azimuthal component in the range of 5-150 MHz were detected. The intensity of the waves differs significantly between modes. The paper suggests that transition is associated with a change in electron conductivity due to non-classical transport mechanisms. In particular, we have indirectly confirmed that the waves with azimuthal component influence on anomalous part of the electron conductivity.

Nomenclature

B/B_0	=	relative value of the magnetic field
R	=	thrust
I_d	=	discharge current
I_e	=	electron current
η	=	anode efficiency
η_m	=	the propellant utilization factor
η_I	=	ratio of the ion current to discharge current
γ	=	ions' velocity distribution factor
γ_θ	=	angular distribution factor
γ_E	=	energy deviation factor
λ	=	wavelength
m	=	mode number
f	=	frequency
S	=	signal from the probe
φ_ω	=	Fourier spectrum of azimuthal perturbations in the plasma
$\hat{f}(S)$	=	Fourier spectrum of the signals from the probe
I	=	intensity of the azimuthal waves
I_s	=	intensity of signals from the probe

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n_0	=	plasma concentration
ω_c	=	electron cyclotron frequency

I. Introduction

Hall thruster (HT) is electrically-powered spacecraft propulsion system, which has been developed since the middle of the 20th century and is used to correct the orbit and orientation of spacecraft. A detailed description and principle of operation of the thruster can be found in Ref. 1-2.

The development trends of modern spacecraft are associated with an increase in the duration of their lifetime and an increase in the relative share of the payload, which leads to develop thrusters with an increased specific impulse (over 2000 s). It is usually achieved by increasing the discharge voltage. Ensuring lifetime and stable operation is a key issue to produce the thrusters.

Hall thruster can be operated in several discharge modes[3-12]. The authors of this work experimentally confirmed the existence of two different discharge modes with almost identical input parameters (discharge voltage, gas flow rate, magnetic field). These modes were studied in Ref. 3-4. Two modes differ from each other in the shape of the plasma plume and anode efficiency. The optimal mode in terms of anode efficiency is called the “jet”, and the non-optimal mode is called the “bell”[3-4]. The names of the modes are chosen associatively with the shape of the plasma plume.

Similar discharge modes were observed in Ref. 5–9. Hall thruster BHT-1500 was turned from the “jet” mode to the “collimated” (similar to the “bell”) mode at a voltage of more than 400 V after the thruster was heated for more than one hour[5]. The temperature of the output rings of the thruster increased by approximately 20% after transition. Also similar discharge modes are observed for low power thrusters (<500 W)[6–9]. In the “diffuse” mode (“bell”)[6], the anode efficiency decreases, the thruster’s temperature grows, the shape of the plasma plume changes. The transition into the “bell” mode leads to an increase in the thermal stress on the construction and a reduction in the lifetime. In addition, transitions can occur when the output part of the discharge channel of the thruster expands due to erosion of the walls[7]. Thus, Hall thrusters with different types and sizes can be operated in “jet” and “bell” modes, so this investigation is relevant. We note that in this paper only two modes is considered, but there are more different modes for HT[10-12].

It is known that the classical types of conductivity, which based on electron collisions with heavy particles (neutral atoms and ions) or with the walls of the discharge channel, do not fully describe the observed value of the electron current[13]. According to Ref. 14 the oscillations and waves influence on the electron conductivity. In the HT plasma oscillations and waves are observed within the range from several kHz to several GHz[15-16]. Among all instabilities, the high-frequency waves in the megahertz range is associated with the drift motion of electrons. Their properties were studied theoretically[14, 16-18] and experimentally[19-24]. One of the most interesting features of these waves is that they have a phase velocity close to the electron drift velocity and the azimuthal component of the electric field, which gives freedom for oscillatory drift motions of electrons along the thruster’s axis, i.e. azimuthal waves can affect the electron conductivity process in the discharge channel of HT. In addition, the thruster can transit between modes because of some type of the instability arises.

The aim of this work was an experimental study of the integral (discharge current, thrust, specific impulse, and efficiency) and local (measurement of floating potential oscillations) parameters of HT in two stable discharge modes — “jet” and “bell”.

II. Experimental setup and test conditions

The experiments were carried out at Keldysh Research Centre in a vacuum chamber KVU-90 with a diameter of 3.8 m and a length of 8.0 m. The pressure in the chamber during the tests was maintained as high as $5 \cdot 10^{-3}$ Pa. The vacuum unit is equipped with a probe diagnostics system, which includes retarded potential analyzer probes to measure the angular divergence and energy distribution of the ion stream. The set up provides collection all the thruster’s parameters by an automated control system (currents, potentials, gas flow rate, temperatures of the thruster’s elements and thrust).

There were two series of the experiments. In the first series of experiments, the integral parameters of the operation were studied, including the parameters of efficiency. In the second series, oscillations of the floating potential were measured using Langmuir probes installed in an external ring of the thruster.

III. Integral parameters in two discharge modes

Hall thruster with the middle line diameter equal to 77 mm with an external layer and power as high as 2.5 kW was used for the research. The acceleration zone of this thruster is located at the construction exit section, which leads to a reduction in ion flow to the channel walls and prolongs the lifetime. The thruster was additionally equipped with a set of thermocouples on all the main structural units, including the internal and external output insulators, which are in direct contact with the plasma.

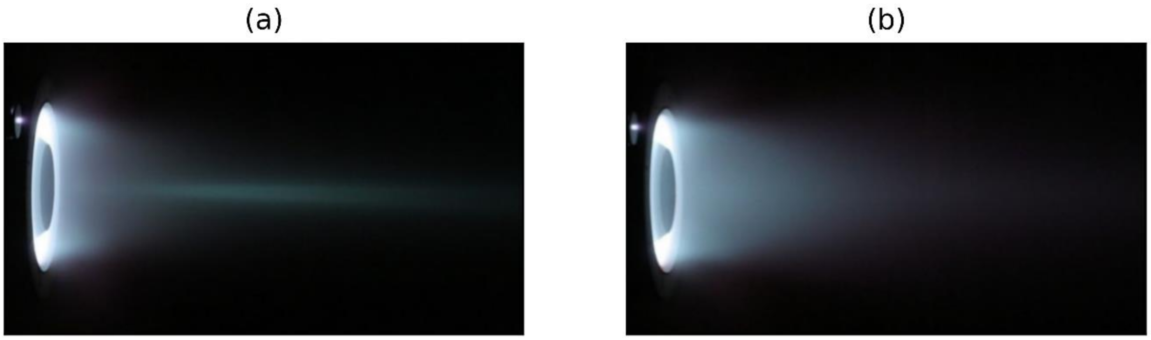

Figure 1. Appearance of the plasma plume in the "jet" mode (a) and the "bell" mode (b).

The gas consumption in the experiment was changed within the range from 2.0 to 4.0 mg/s with a step 0.5 mg/s, the discharge voltage was varied in the range from 500 to 900 V with a step 100 V. For each value of the gas flow rate and discharge voltage was searched for the transition point from the “jet” mode to the “bell” mode by changing the magnetic the field. Then the thruster’s parameters (including plume characteristics) were measured in both modes near this point by a slight change in the magnetic field. During measurements the thruster work stable in one discharge mode. Turning from the “jet” mode to the “bell” mode was achieved by increasing the magnetic field. Also the reverse transition was achieved by decreasing it relative to the transition point. We note that the transition occurred with a certain “hysteresis” in the magnetic field, i.e. the turning from the “jet” to the “bell” occurred at a slightly higher field value than the reverse transition. Initially, the study was conducted within the range from 300 to 1000 V, but it was not possible to provoke a transition below 500 V, and the thruster worked all the time in the “jet” mode. Over 900 V overheating of the thruster in the “bell” mode became so significant that it was not possible to achieve stable work. Therefore, further results are mainly given only for the voltage range 500-900 V.

Figure 1 shows the appearance of the plasma plume in the “jet” and “bell” modes. The “jet” mode looks like a pronounced plasma “needle” with green and white shades, which is located on the thruster’s axis. The plasma “needle” disappears in the “bell” mode, and the shape of the plume resembles a trumpet or bell with red and white shades.

Figure 2 shows the dependence of the transition point by the magnetic field from the discharge voltage; different curves correspond to different values of the gas flow rate. Each curve divides the area into two parts: all points above the curve correspond to the "bell" mode, all points below the curve - to the "jet" mode. It will be shown later, such a division is equivalent to indicating the operating range of the thruster, because of the long-term operation in the “bell” mode is unacceptable, especially at a high discharge voltage.

Two distinct trends can be identified from Fig. 2: the operating range of the magnetic field in the “jet” mode expands with increasing gas flow rate and narrows with increasing discharge voltage. We note that the bottom border of the operating range by magnetic field is also present, however, it practically does not depend on the gas flow rate and increases slightly with increasing discharge voltage.

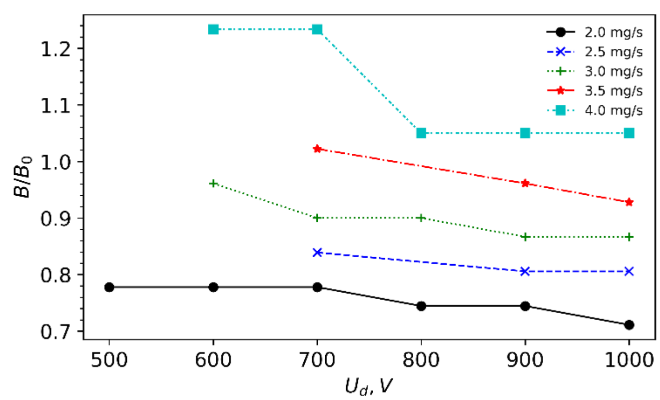

Figure 2. Relative magnitude of the magnetic field, at which a change from one mode to another occurs, depending on the discharge voltage for different values of the gas flow.

Next, we compare the main characteristics of the thruster in the “jet” and “bell” mode. Data is given only for a gas flow rate equal to 2 mg/s. If we look at higher gas flow rates, all trends will be qualitatively preserved. Figure 3 contains the main parameters of the operation. When HT turns from the “jet” mode to the “bell” mode with a constant value of gas flow rate and discharge voltage, the discharge current increases by 10-30% (Fig. 3a) with a simultaneous decrease in thrust by 5-15% (Fig. 3c), the anode efficiency decreases by 20-40% in relative units (Fig. 3d). The negative consequences of the transition become more critical with an increase in the discharge voltage: the difference in the discharge current, thrust and the efficiency between the “jet” mode and the “bell” mode increases.

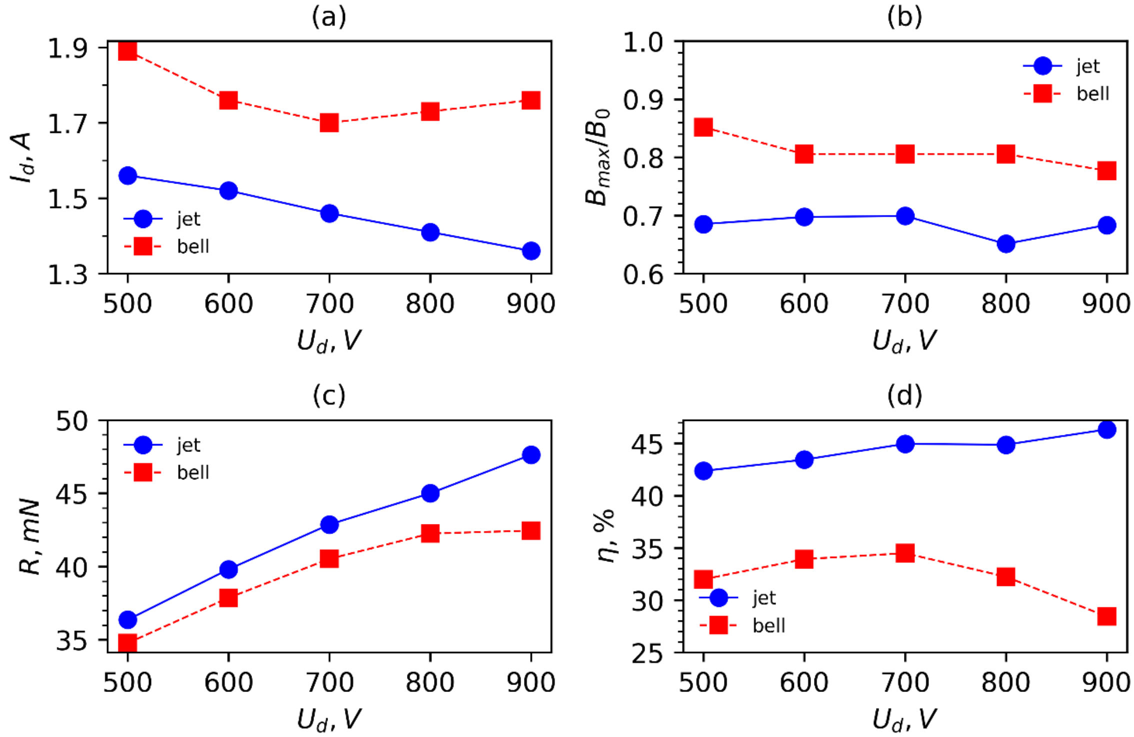

Figure 3. Basic parameters of operation in the “jet” and “bell” modes: a) discharge current b) relative magnetic field c) thrust d) anode efficiency,%.

Figure 4 shows the behavior of the temperatures of the internal and external insulators that are in direct contact with the plasma layer, so they undergo maximum thermal stress. The temperature of the rings in two modes differs by approximately 100-150°. Therefore, the heat flux to the output rings in the “bell” mode is significantly higher than in the “jet” mode. The discharge power in the “bell” mode is higher, so these differences leads to a strong overheating of the thruster’s components. Based on the analysis of the operating parameters, it can be clearly stated that the optimal mode of operation is the “jet” mode, and operation in the “bell” mode is unacceptable.

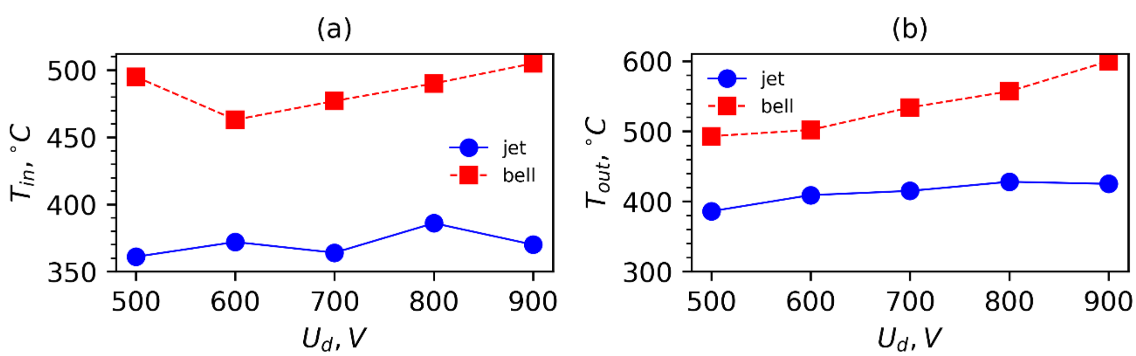

Figure 4. The temperature of the internal (a) and external (b) ceramic insulators of the thruster in the "jet" and "bell" modes.

To analyze the processes occurring in either mode in more detail, the structure of the anode efficiency of the thruster was investigated using the technique described in Ref. 25. The methodology is based on the representation of the main integral parameters of operation as a multiplication of a efficiency coefficients' set: $R = \eta_m \gamma \sqrt{\frac{2m_e U_d}{e}}$, $\eta = \eta_m \eta_I \gamma$, where η_m is the propellant utilization factor (ratio of the ion current to the mass flow), η_I is ratio of the ion current to discharge current, $\gamma = \gamma_E \gamma_\theta$, where γ_θ describes the angular divergence of the beam, γ_E is the factor, which describes losses caused by the scatter of ion energies. The calculation of these coefficients requires knowledge of the energy and angular distributions in the ion flux, so a probe diagnostic system based on a retarded potential analyzer probes was used.

An example of the angular and energy distributions for both discharge modes at 600 V and 2 mg/s is shown in Fig. 5. Figure 6a-6c shows the efficiency parameters depending on the discharge voltage in two modes, and Fig. 6d contains the electron current addition (the difference between the discharge current and the ion current).

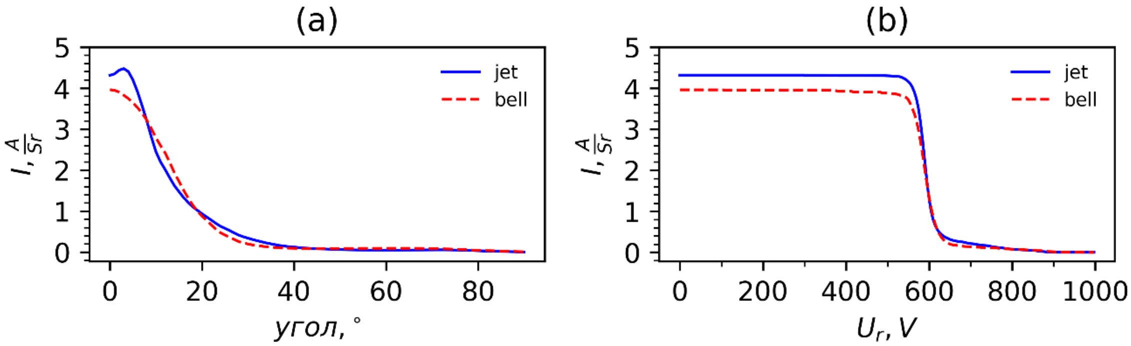

Figure 5. Angular and energy distributions in the "jet" and "bell" modes at 600 V and 2 mg/s.

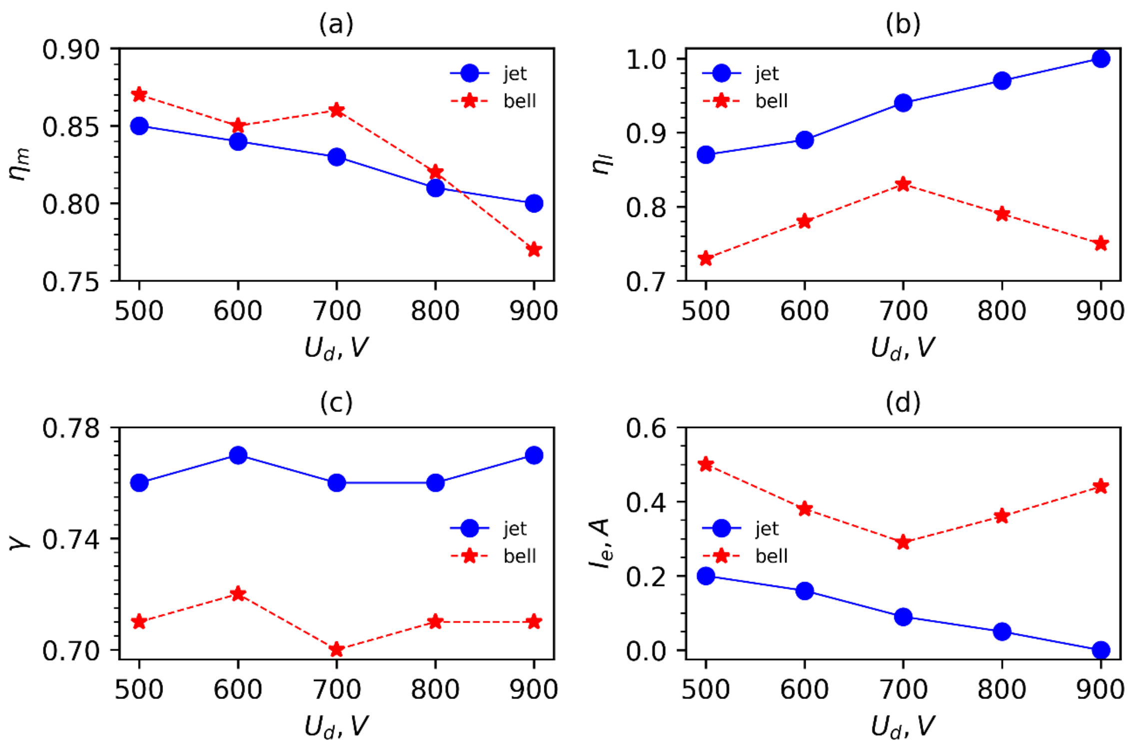

Figure 6. Efficiency parameters in the "jet" and "bell" modes: a) η_m, b) η_I, c) γ, d) - electronic current addition.

From the analysis of the graphs in Fig. 6, we can conclude that difference of the propellant utilization factor in both modes is only a few percent, while the ratio of the ion current to discharge current in the "jet" mode is more than

10% higher. Also in this mode the angular and energy distribution is approximately in 5-6% higher. A small difference the propellant utilization factor and a strong difference in the ratio of the ion current to discharge current suggests that the discharge current in the “bell” mode is growing mainly due to the electronic component of the current. From Fig. 6d it can be seen that the electronic additive current for discharge voltages in the range of 500-700 V is in ~ 1.5 times higher in the "bell" mode, and for 800-900 V, it is more than in 5 times higher than the similar value in “jet”.

IV. High frequency oscillations in two discharge modes

The experiment was conducted on a laboratory model of a Hall thruster with the middle line diameter equal to 88 mm. The thruster was equipped with Langmuir probes mounted into an external ceramic insulator at a distance of 1-2 mm from each other in the axial direction and located at different angles in the azimuthal direction. It is better suited for measurements of the local plasma parameters then the thruster, which we use in previous section. The schematic representation of the thruster is shown in Fig. 7. The positions of the probes in the axial and azimuthal directions are specified in Table 1 (the 0 ° axis in azimuth is chosen in the direction of probe No. 1).

Table 1. Location of the Langmuir probes in outer insulator.

Probe №	1	2	3	4	5	6
Distance from the exit plane, mm	-9	-8	-7	-5	-3	-1
Azimuthal angle, °	0.0°	7.5°	15.0°	30.0°	45.0°	60.0°

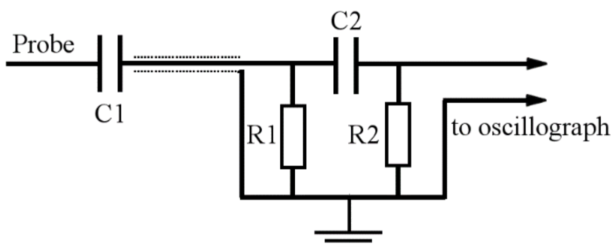

Figure 8. Electrical circuit for measuring signal from the Langmuir probe.

The oscillations of the floating potential of the plasma were measured using the electrical circuit shown in Fig. 8[26-27]. The floating potential oscillations differ from the plasma potential oscillations in amplitude by an amount corresponding to the resistance of the boundary layer. Thus, the main phase relasions between probes remain undistorted. The capacitors and resistors were selected: C1 = 1000 pF, C2 = 330 pF, R1 = R2 = 2 kΩ. The capacitor C1 allows us to measure only the variable part of the floating potential, and the capacitor C2 and the resistors R1 and R2 form a high-pass filter. A digital storage oscilloscope was used to record measurements.

The transition between modes was initiated by a change in the magnetic field at a constant value of the discharge voltage and gas flow rate. The discharge voltage was varied from 400 to 600 V with step 100 V. The thruster was working stably in one of two discharge modes during the measurements. The operating parameters (discharge voltage, discharge current, gas flow rate) are shown in Table 2.

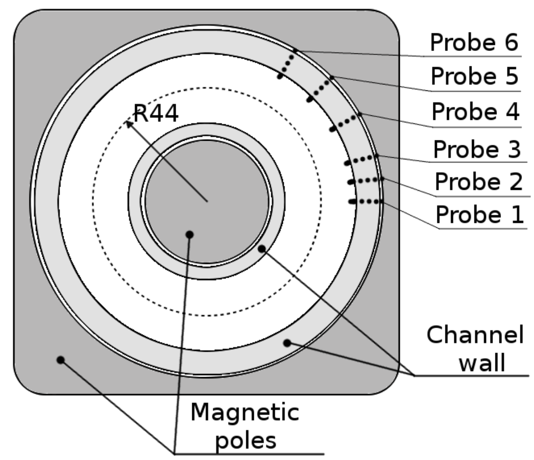

Figure 7. The schematic representation of the thruster with probes mounted in the outer insulator.

Table 2. The main parameters of the operation

Discharge voltage, V	Discharge mode	Discharge current, A	Gas flow rate, mg/s
400	“jet”	1.90	2.1
400	“bell”	2.01	2.1
500	“jet”	2.17	2.2
500	“bell”	2.25	2.2
600	“jet”	2.26	2.3
600	“bell”	2.40	2.3

Figure 9 shows examples of signals at a discharge voltage of 400 V for probe No. 6 (the probe that is closest to the thrusters exit plane) in the “jet” (Fig. 9a) and “bell” (Fig. 9b) mode. We note that the oscillations differ significantly in amplitudes. The Fourier spectra of oscillations for probe No. 6 in two modes are shown in Fig. 10 for discharge voltages: 400 V (Fig. 10a), 500 V (Fig. 10b) and 600 V (Fig. 10c). The spectra in all operation modes represents a set of equidistant resonances with a frequency difference about ~ 9-11 MHz. The oscillation amplitude in the “bell” mode within the range of 30-150 MHz is significantly higher than in the “jet” mode.

To analyze the obtained data in more detail, wavelet analysis of signals with the Morlet mother function[20, 21, 24] was used. Also the cross-correlation function of signals for different probes depending on frequency (spectral density of phase delays between probes) were calculated.

The spectral density of phase delays in the "jet" mode is shown in Fig. 11a, 11c, 11e and in the "bell" mode in Fig. 11b, 11d, 11f. The abscissa corresponds to the delay between the signals, the ordinate axis - to the frequencies. The graphs represent the spectral density of the phase delays between probes No. 4 and No. 5. Plots (a) and (b) were obtained at 400 V, (c) and (d) - at 500 V, (e) and (f) – at 600 V. The first maximums of phase delays between probes for all frequencies within the investigated range is located approximately at the same region (about 4-6 ns) regardless of the operational parameters, so the dispersion law of the observed waves is close to linear. The observed waves have the azimuthal component of velocity. The estimation of the azimuthal velocity component gives us the value about $(2-3)\cdot 10^6$ m/s.

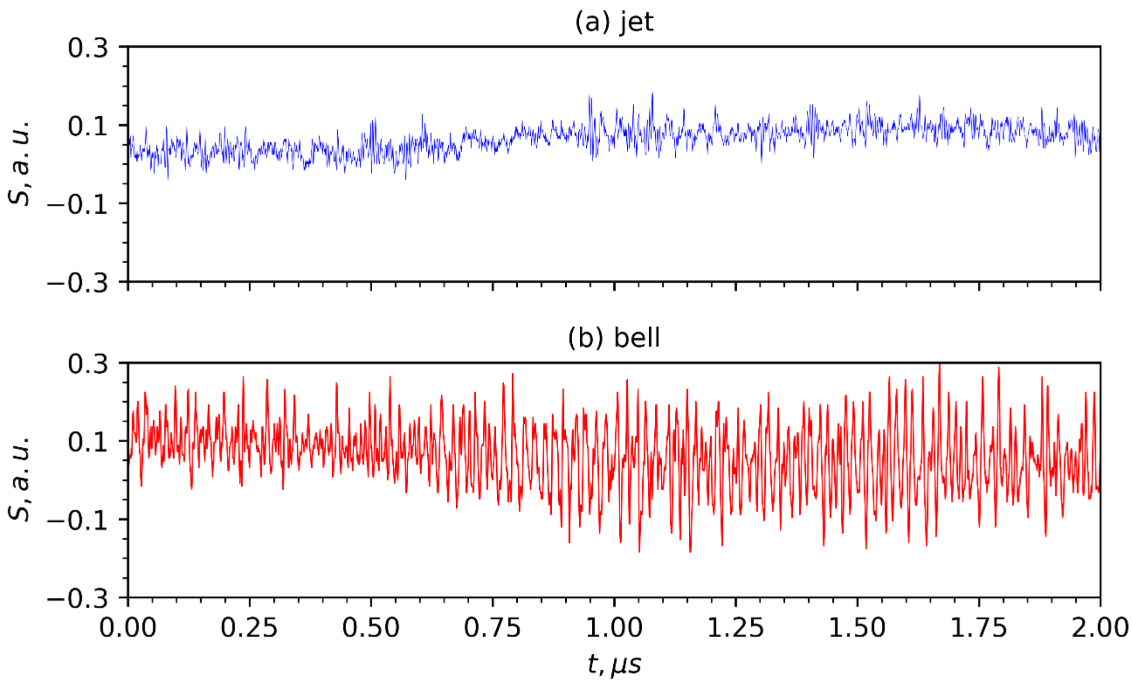

Figure 9. Examples of signals from probe No. 6 with a discharge voltage of 400 V in the "jet" (a) and "bell" (b) modes

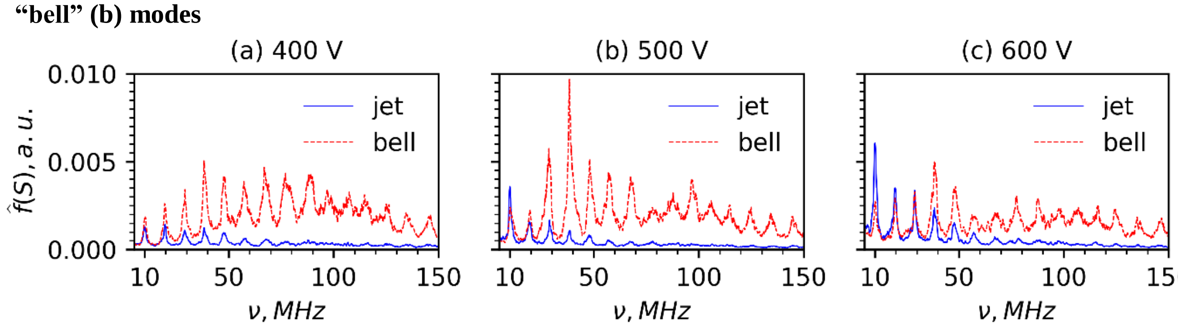

Figure 10. Fourier spectra of signals at the discharge voltage: a) 400 V, b) 500 V, c) 600 V in the "jet" and "bell" mode.

From the characteristic values of the phase velocity of the waves and frequencies, it is possible to estimate the characteristic values of the wavelengths in the azimuthal direction: from ~ 20 to ~ 300 mm. The waves rotation direction coincides with the electron drift direction. The wavelength in the azimuthal direction of the HT must take on discrete values, which are determined according to the formula $\lambda = 2\pi \cdot r/m$, where m is the mode number, r is the Langmuir probes radius. In this way, the equidistant resonances on the Fourier spectra of signals (Fig. 10) can be associated with azimuthal harmonics of the waves with a sequential change in the mode number, which starts from 10 MHz (m=1) up to 146 MHz (m = 15).

Table 3. Main properties of the observed waves.

m	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
f, MHz	10	20	29	39	48	58	68	77	88	97	107	115	125	135	146
λ, mm	320	160	107	80	64	53	46	40	36	32	29	27	25	23	21

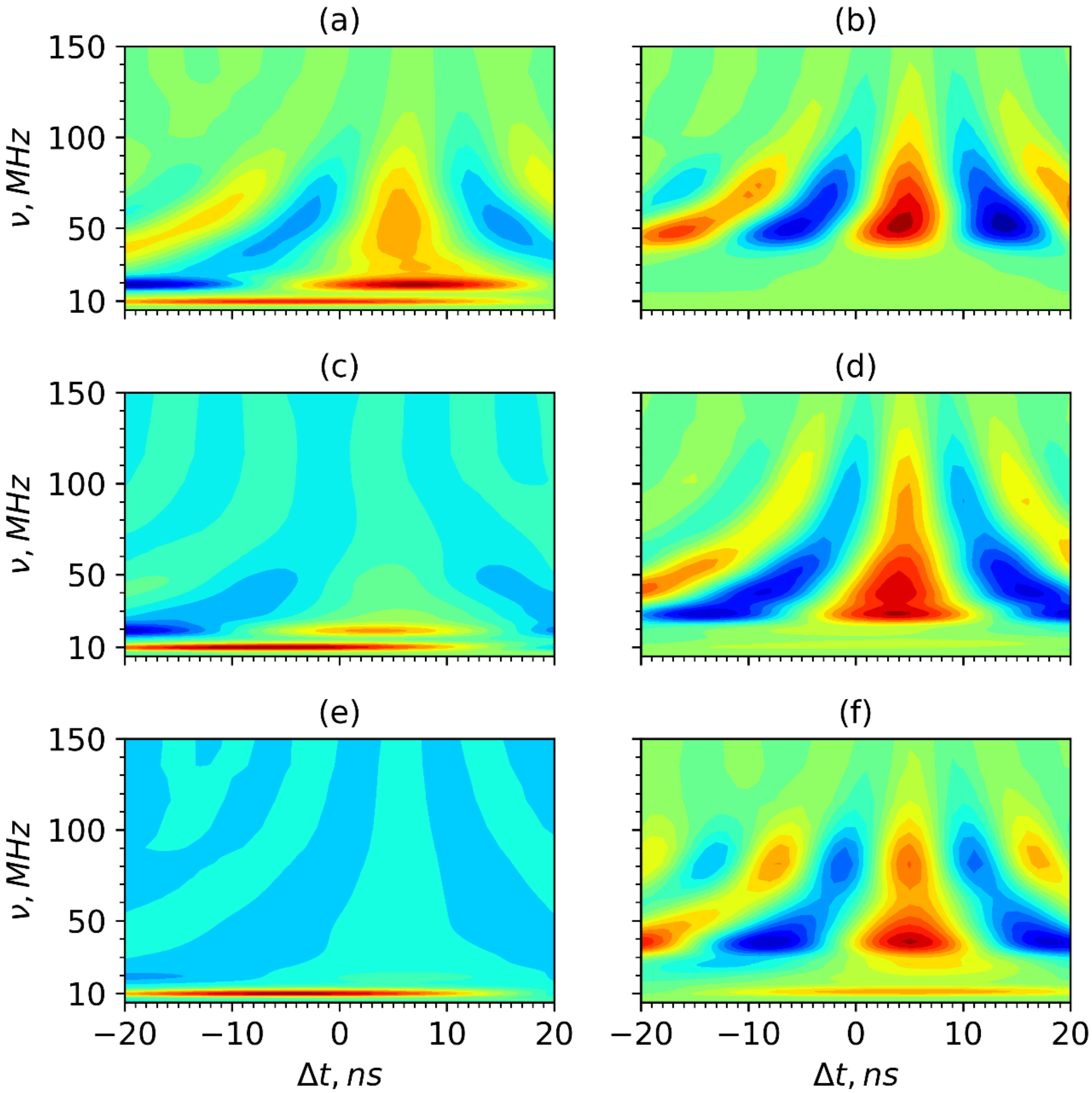

Figure 11. Spectral densities of phase delays between probes No. 4 and 5 in the "jet" mode (a, c, e) and in the "bell" mode (b, d, f) at discharge voltages 400 V(a and b), 500 V (c and d) and 600 V (e and f).

Table 3 contains the main wave properties: mode number, frequency, wavelength estimation. Fifteen azimuthal harmonics in the range from 10 to 146 MHz are observed in the experiments. The wavelength of the azimuthal harmonics is much greater than the characteristic scale of the cyclotron radius of electrons and the frequency of the waves is much less than the electron cyclotron frequency, so the electrons in the wave make drift oscillatory motions. According to theoretical studies[14, 16-17], the azimuthal waves can propagate in HT plasma. The observed waves are in the frequency range from 5 to 150 MHz, propagate with velocity in order 10^6 m/s in the azimuthal direction; the velocity direction of the waves coincides with the direction of the electron drift, the wavelengths in the azimuthal direction are discrete and approximately correspond to the condition $\lambda = 2\pi \cdot r/m$. The dispersion law of the observed waves is close to linear. Thus, it can be assumed that the detected waves belong to gradient-drift instabilities.

HF waves and, in particular, gradient-drift instabilities are often associated with an anomalous electron current. According to Ref. 14, the azimuthal component of the perturbation electric field affects the electron flux according to the following law:

$$\Gamma \sim \frac{I}{\omega_c^2} \frac{\partial}{\partial x}\left(\frac{n_0}{\omega_c}\right),$$

where Γ is the electron flux, $I \sim \sum_k k^2 \varphi_\omega \tilde{\varphi}_\omega$ is the intensity of the azimuthal component of the electric field of the wave, φ_ω is the Fourier spectrum of azimuthal perturbations in the plasma, ω_c is the cyclotron frequency, n_0 is the plasma concentration.

Thus, we determine the intensity of the observed waves by the equation:

$$I_s \sim \sum_k k^2 \hat{f}(S)\tilde{\hat{f}}(S),$$

where $\hat{f}(S)$ is the Fourier spectrum of the measured signals from the probe. The dispersion law of the waves is close to linear, thereby the intensity can be represented as $I_s \sim \sum_\omega \omega^2 \hat{f}(S)\tilde{\hat{f}}(S)$, i.e. we go away from spatial dependence to temporal in the intensity expression. Estimation of the intensity in the "jet" and "bell" modes discharge is presented respectively in Fig. 12a and Fig. 12b (0 mm on the x-axis corresponds to the exit plane of the thruster). The intensity near the exit plane of the thruster is significantly higher in compare with its values inside the discharge gap in all modes of operation. The intensity in the "jet" mode grows with increasing discharge voltage, and in the "bell" mode it drops. For all discharge voltages, the intensity near the exit plane of the thruster in the "bell" mode is in 10–60 times higher than in the "jet" mode.

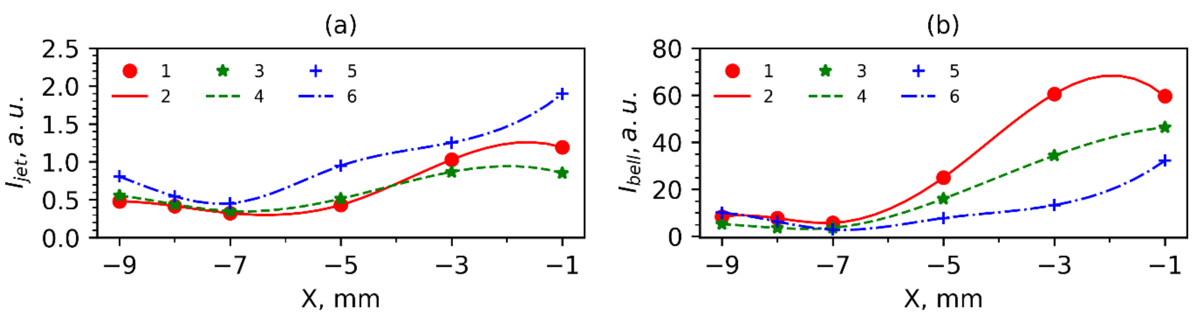

Figure 12. Intensity of the high-frequency waves in the "jet" (a) and "bell" (b) modes. 0 mm corresponds to the exit plane of the thruster, the X axis is located in the direction of the thruster's plume. Designations: 1 - 400 V, 3 - 500 V, 5 - 600 V; curves 2, 4, 6 - cubic interpolation of points at respectively 400 V, 500 V, 600 V.

V. Discussions

The experiments have shown that the discharge mode can undergo an abrupt change at the high enough discharge voltage (above 400-500 V), relatively low gas flow rate and a sufficiently high magnetic field. When the transition occur, the discharge current at a constant gas flow rate increases by 10-30%, which leads to a significant drop in the efficiency. The temperature of the thruster's components increases by 20-40%. Previous studies[3-4] show that the plasma layer in the "bell" mode is located closer to the anode in compare to the "jet" mode, so the heat flux on the working surfaces of the thruster increases and explains the sharp rise in temperature of the insulators. This process leads to an increase in thermal stress of the thruster's construction and a reduction in the operational lifetime of structural elements. In particular, this concerns the magnetic coils, because of the it's operation lifetime depends on the thermal state. Thereby, we can make an obvious conclusion that the "bell" mode is unacceptable for HT operation.

However, it can be argued that the transition from the "jet" to the "bell" mode can be compensated either by increasing the gas flow rate (the discharge power) or by decreasing the magnetic field. In modern methods of scaling HT[28] usually operate only with the discharge power, without taking into the account the discharge voltage corresponding to this power. In this work, it was shown that the range of stable and efficient operation by the magnetic field at constant power with the discharge voltage rapidly shrinking due to the transition between discharge modes. Thus, the choice of voltage at a given power and fixed thruster's geometry cannot be arbitrary.

The observed transitions take place on the thrusters with different sizes and constructions, so it can be assumed that some fundamental physical process causes the conversion. This process shouldn't be associated with the design features of the specific device and operating conditions. The reason for the conversion from the "jet" to the "bell" qualitatively may be the level of electronic conductivity necessary to maintain a steady discharge in the "jet" mode. The change from the "jet" to the "bell" mode occurs either with an increase in the magnetic field or with a decrease in the gas flow at a constant discharge voltage. In this way, the conductivity in the entire plasma volume decreases, but the electronic current addition shoots up (Fig. 6d). The reverse process can be triggered by either a decrease in the magnetic field or an increase in the flow rate with a slight "hysteresis". In this case the electronic conductivity in the entire plasma increases in the channel. Thus, it can be supposed that the transition is associated with the development of some process that seeks to maintain the continuity of the electronic current component.

The problem of the electronic conductivity in the HT discharge remains open: the classical collisional mechanism with heavy particles and the near-wall conductivity are not enough to describe the experimental value of the electron current. The so-called anomalous conductivity, which is often associated with oscillations and waves in the HT discharge, has a significant effect[14]. The gas flow rate was constant in these experiments and the magnetic field differed slightly, so we can assume that the classical electron conductivity was approximately the same in both modes. Thus, the increase in electronic conductivity in the "bell" can occur due to either the abrupt growth of anomalous transport, or near-wall conductivity, or their complex combination.

Several harmonics of gradient-drift waves in the range of 5-150 MHz were observed in both modes. The observed waves are in the frequency range from 5 to 150 MHz, propagate with velocity in order 10^6 m/s in the azimuthal direction, which coincides with the direction of the electron drift. The dispersion law of the observed waves is close to linear. The wavelength of the azimuthal harmonics is much greater than the characteristic scale of the cyclotron radius of electrons and the frequency of the waves is much less than the electron cyclotron frequency, so the electrons in the wave make drift oscillatory motions. In the "bell" mode (with higher electron current) the intensity of these waves is more than 10 times higher than in the "jet" mode. As a result of the study, we can conclude that when the thruster transit between modes, the anomalous part of electronic conductivity changes due to the gradient-drift waves. In addition, this fact indirectly confirms the relationship between the intensity of the gradient-drift waves and the anomalous electron transport in the discharge.

VI. Conclusion

An experimental study of two discharge modes was carried out at Keldysh Research Centre. First, the comparative study of the main integral parameters of the thruster in both modes including the structure of the anodic efficiency was made. Two modes differ from each other in the discharge current and anode efficiency: the discharge current increased by 10-30% and the anode efficiency dropped by 20-40% in relatives unit at a constant discharge voltage and gas flow rate. From the point of view of the degradation of the integral parameters and the rise in temperature of thruster's structural elements the transition from the "jet" to the "bell" can be called catastrophic. Also the electron current in the "bell" mode is significantly higher than in the "jet" mode. Secondly, the floating potential oscillations were measured using Langmuir probes. The harmonics of waves with azimuthal component of velocity were detected in both modes. The dispersion law of this waves is closed to linear. According to the characteristics these waves can be attributed to gradient-drift instabilities. The intensity of the waves is more than ten times higher in the "bell" than in the "jet" mode. This fact indirectly confirms the sharp growth of the electron current in the "bell" mode: it can be assumed, that the anomalous component of the electron current arises in the "bell" due to the increasing of the intensity of gradient-drift waves with azimuthal component.

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