Probe Measurements in the Channel of 1.5 kW Hall Thruster with Discharge Voltage up to 1000 V

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Abstract: Probe measurements of local plasma parameters in the channel of a 1.5 kW Hall thruster were carried out. The laboratory model of Hall thruster was used for experiments. Probe measurements of local parameters were carried out at voltage of 300-1000 Volts and at anode gas flow rate 1.5 - 3.5 mg /s. Moreover, measurements were carried out for two specially selected modes with significantly different voltage but at constant discharge power (300 V, 3.5 mg/s and 790 V, 1.5 mg/s accordingly). The received distributions of plasma potential, electric field strength, charge production rate and electron temperature for various operation modes are presented in this paper. Distribution of an ion birth rate was obtained with the help of one-dimensional semiempirical model of Hall thruster plasma with using experimental data on the ion energy distribution in plasma plume.

Nomenclature

E	=	electric field strength
I_d	=	discharge current
J_{ic}	=	ion current density at zero retarding potential on RPA
$J_i(\varphi)$	=	ion current density on RPA at retarding potential φ
J_{na}	=	equivalent neutral flow density in the entrance to the layer at the anode plane
$\dot{m}_a$	=	anode mass flow rate
N_d	=	discharge power
N_i	=	ion concentration
n_n	=	neutral concentration
T_e	=	electron temperature
U	=	probe potential
U_d	=	discharge voltage
U_{pl}	=	plasma potential

I. Introduction

NOWADAYS the development and testing of HET with increased discharge voltage (up to 1000 V) become of great importance in connection with spacecraft active life term increasing. Studying of local plasma parameters in a thruster channel and finding the dependences of these parameters on discharge characteristics (accelerating voltage and current) is one of the significant parts of this work.

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II. Experimental apparatus

A. Thruster

The laboratory model of 1.5 kW Hall thruster was used for experiments. The average diameter of discharge chamber equals to 88 mm. The BGP-10 ceramic was used as a material of walls for discharge chamber. The design of thruster was a little bit changed for accommodation with Langmuir probes in the channel of the thruster, however the geometry of the discharge chamber and magnetic circuit were not changed.

Appearance of the thruster equipped with near-wall probes, is shown in Fig. 1. The external wall of the discharge channel with the probes embedded in it is shown in Fig. 2. The total quantity of probes used in experiments was equal to 12: 9 in the channel and 3 outside of it near to the thruster channel exit. Inside the channel the probes were flush-mounted with a wall with step of 1 mm on an axis. The displacement on an azimuth was equal to 7.5 degrees from one probe to another, i.e. all 9 probes were placed within 60 degrees. External probes were located in one line along an axis of the channel and were distant from the thruster exit on 3, 9 and 15 mm. Internal probes were made of tungsten-rhenium wire with diameter 0.5 mm. External probes were made of tungsten wire with diameter 1 mm.

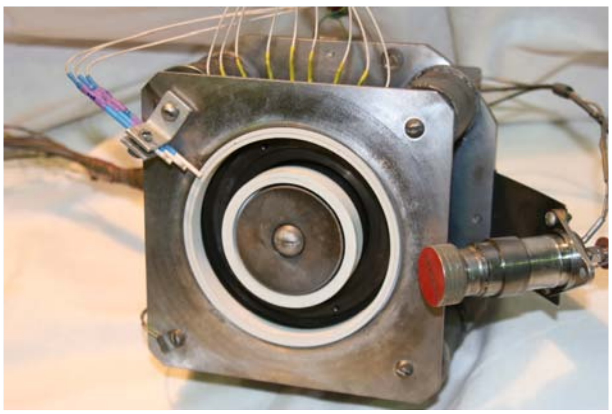


Figure 1. Appearance of 1.5 kW Hall thruster equipped with Langmuir near-wall probes.

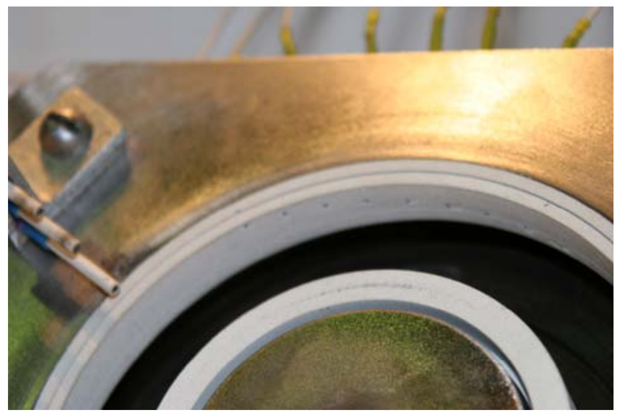


Figure 2. The discharge channel equipped with near-wall probes.

The basic thruster parameters (thrust, specific impulse) were in concordance with parameters of the thruster without probes during experiments.

B. Vacuum chamber and gaging equipment

The experimental investigations were carried out in vacuum chamber KVU-90 of Keldysh Research Centre[1]. The vacuum chamber has volume of 90 m^3 at diameter of 3.8 m. Total productivity of a cryogenic pumping is equal to 58 m^3/ s.

The facility is equipped with completely automated system of data recording on basis of an industrial computer. All parameters necessary for measuring of a thruster integral parameters, such as thrust, I_d, U_d are gained with the help of gauge system and through L-card modular system of data gathering are entered in a computer.

The parameters of a thruster plasma plume were measured on distance of 1500 mm from the thruster exit plane and registered with the help of widely known tools: retarding potential analyzer (RPA) and emission probes similar to that described in Ref. 2. Probes are placed on the coordinate system providing their necessary moving in space. Full processing of these data is conducted also automatically.

Flat electrostatic probes were used for studying plasma inside the accelerating channel and in immediate vicinity of the channel exit. The method of their introduction inside of the thruster was similar to that used in Ref. 3. The voltage on probes was feed between probes and ground level for decreasing of noise level. Volt-ampere characteristic of probes and their floating potential was registered by the two-channel digital oscillograph Tektronix TDS3012B working in a XY-mode with averaging of a final signal by several curves (up to 32). The potential of the cathode concerning the ground was measured separately, also with the help of the oscillograph. The oscillograph has connection with a computer via Ethernet line that considerably accelerates inquiry of all probes system. The scheme of measurements and electric potential supply to the probes is shown in Fig. 3. Sinusoidal scanning voltage with frequency 50 Hz and amplitude up to 1500 V was feed to the probes.

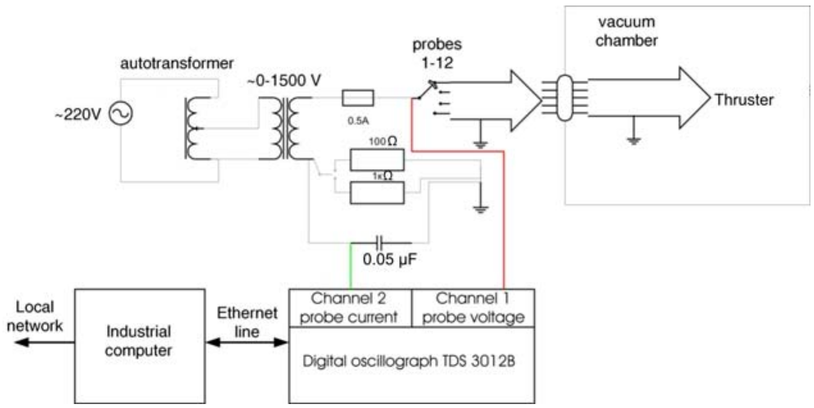


Figure 3. The scheme of local plasma parameters measurements with help of Langmuir probes in HET discharge channel.

III. Results and discussion

C. Plasma potential and electron temperature

The data from Langmuir probes were processed with the help of the special software. The typical volt-ampere characteristic of a probe is presented in Fig. 4. Probe measurements of local parameters were carried out at discharge voltage 300-1000 V and anode gas flow rate 1.5-3.5 mg /s.

The potential of plasma was determined by location of volt-ampere curve inflection which was found by the first derivative of this curve. At that the point of first derivative maximum achievement was supposed to be a plasma potential value. In some cases the derivative does not fall after maximum achievement and leaves at constant level. In this case the point of achievement of this constant value was supposed to be the plasma potential[4].

Usually the same part of the volt-ampere characteristic is used for the definition of an electron temperature; however it can result in serious errors. The matter is that when the electron current to a probe is big, the probe can warm up and that lead to the distortion of received results. In this case it is more convenient to use a part of the volt-ampere characteristic near the floating potential for the definition of the electron temperature. The following formula was used to find the electron temperature[5]:

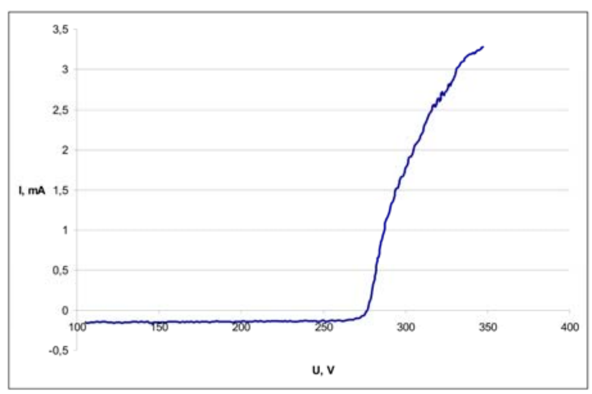
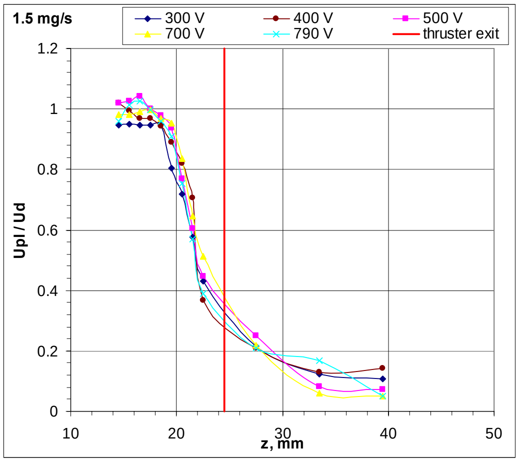


Figure 4. Typical volt-ampere characteristic of Langmuir probe.

$$\ln(\partial I / \partial U) = const + (eU)/(kT_e) \qquad (1)$$

Thus, the current derivative diagram inclination in a half-logarithmic scale allows determining electron temperature. It is necessary to note, that the gained value depict energy of electron component only qualitatively. The matter is that such features as e.g. the deviation of the electron energy distribution function from maxwellian one and the influence of the magnetic field on the electron component are not taken into account during the processing of the results. The influence of the given factors can deform received results essentially, therefore all diagrams brought in the given section should be considered rather as qualitative results, than as exact digital values.

Probe measurements results viz. dimensionless potential distribution along the channel U_{pl}/U_d, electric field strengh E, charge production rate and electron temperature T_e are presented in Fig. 5-10. For the convenience of the analysis diagrams on figures were grouped to allow separating influences of discharge voltage changes and gas flow rate.



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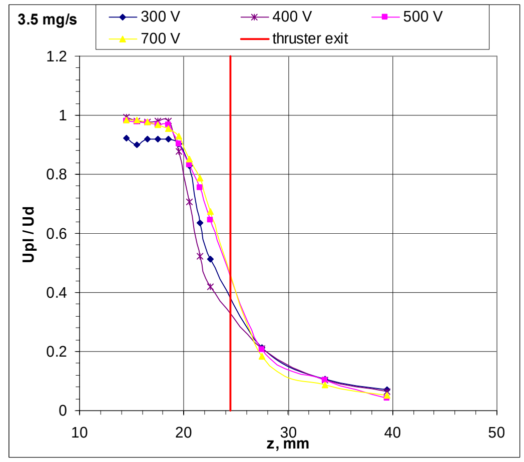

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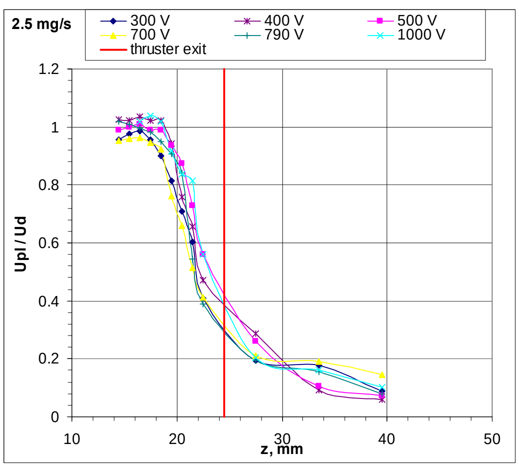

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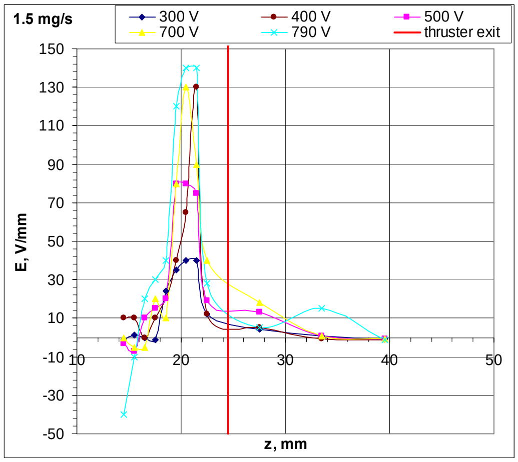
Figure. 5. Dimensionless plasma potential changing along discharge channel depending on discharge voltage at constant $\dot{m}_a$ for anode gas low rate 1.5 mg/s (a), 2.5 mg/s (b) and 3.5 mg/s (c).

As it is seen U_{pl}/U_d is rising with the increase of the discharge voltage at constant gas flow rate (Fig. 5). An area on the diagram with a maximum of the potential distribution starts to form at U_d ~790-1000 V. Maximum value of E is increasing and an area with a significant electric intensity (acceleration layer) spreads both in the direction of the cathode and anode plasma (Fig. 6). The axial position of the electric field maximum remains nearly constant except for the operation mode with a 3.5 mg/s gas flow rate, when with the increase of U_d from 300 to 500 V E_{max} position moves on 4-5 mm towards the thruster exit that is possibly connected to the alteration of the thruster operation mode.



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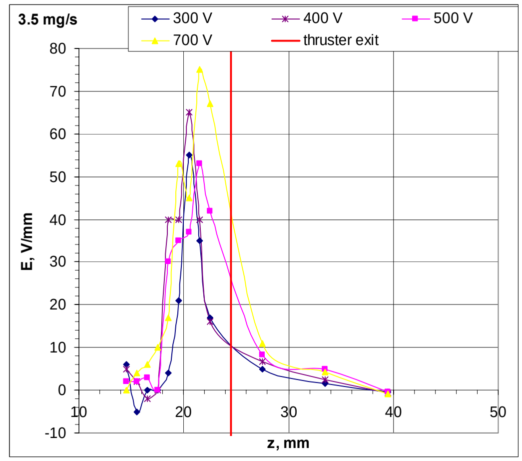

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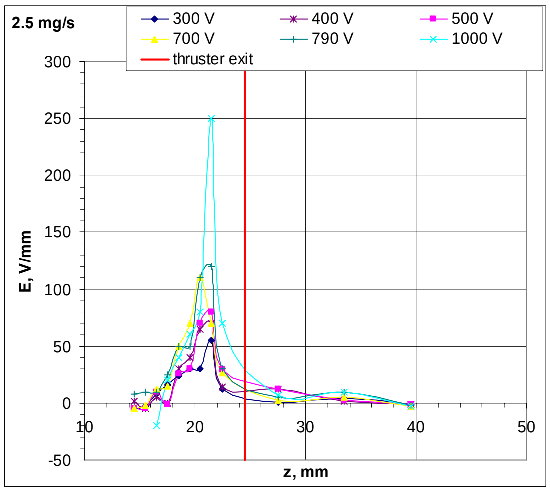


b)

Figure. 6. Electric field intensity changing along discharge channel depending on discharge voltage at constant $\dot{m}_a$ for anode gas low rate 1.5 mg/s (a), 2.5 mg/s (b) and 3.5 mg/s (c).

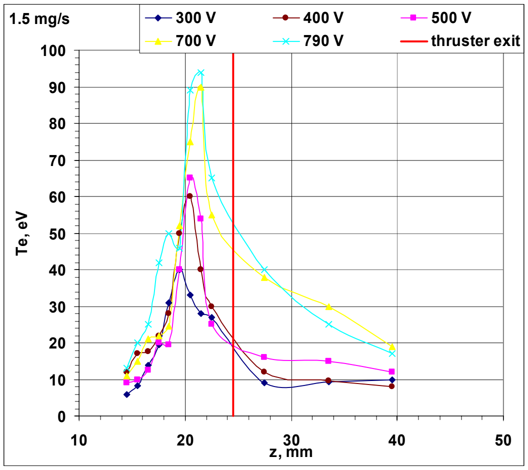
The electron temperature (Fig. 7) increases almost linearly (Fig. 8) in accordance with the expression:

$$T_e[eV] \sim 0.1eU_d[V] + 12 . \qquad (2)$$

Deviations from this pattern appear due to the lowering of the T_e increase rate with increase of U_d in the range 400-500 V ($\dot{m}_a$=1.5 and 2.5 mg/s) at 55-60 eV and also in the range $U_d \geq 700$ V at 100-110 eV. At that the area with a significant T_e value spreads with some displacement of axial position of $T_{e\ max}$ towards the thruster exit at low gas flow rate (1.5 mg/s) and towards the anode at larger flow rate (3.5 mg/s). At the same time at $\dot{m}_a$ = 2,5 mg/s this area spreads in both directions while $T_{e\ max}$ axial position remain almost unchangeable.

The value of E_{max} changes insignificantly with growth of anode gas flow rate from 1.5 to 3.5 mg/s at constant voltage (Fig. 9). The shift of E_{max} location along axis on 5-7 mm towards thruster exit is observed for some regimes (e.g. for U_d ~500, 700 V). The size of zone with significant electric field strength is not changing.

The maximum value of T_e weakly depends on anode gas flow rate (Fig. 10).



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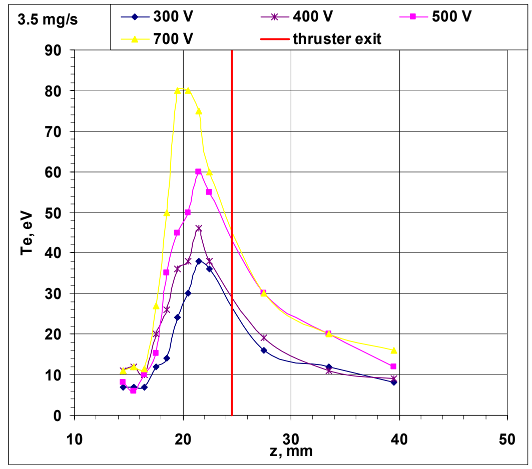

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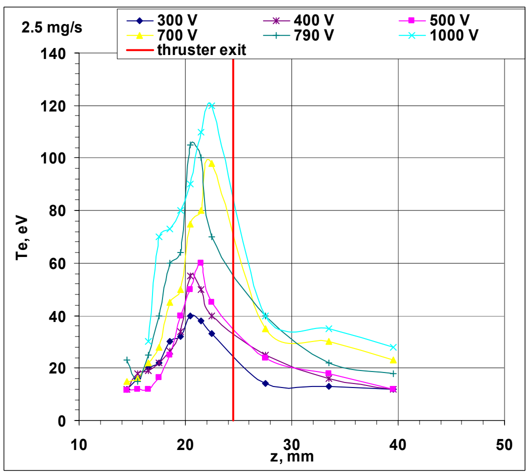

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Figure. 7. Electron temperature changing along discharge channel depending on discharge voltage at constant $\dot{m}_a$ for anode gas flow rate 1.5 mg/s (a), 2.5 mg/s (b) and 3.5 mg/s (c).

Two operation modes were investigated for comprehension of physical processes changing in plasma for different accelerating voltages at constant discharge power. The first operation mode: U_d=300 V, $\dot{m}_a$= 3.5 mg/s and the second one: U_d=790 V, $\dot{m}_a$= 1.5 mg/s. The discharge power for both modes was equal to 885 W.

The results of this operation modes investigation are presented in Fig. 11. The values of electron temperature and electric field strength are normalized to maximum values which correspond to operation mode with larger discharge voltage. Plasma potential is normalized to discharge voltage.

As it can be seen the dimensionless potential is growing significantly on the anode border of accelerating layer at higher U_d. Also the maximum of plasma potential distribution is arising with

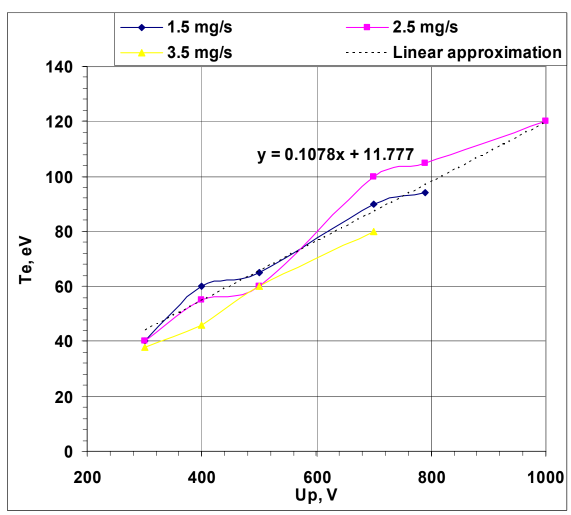
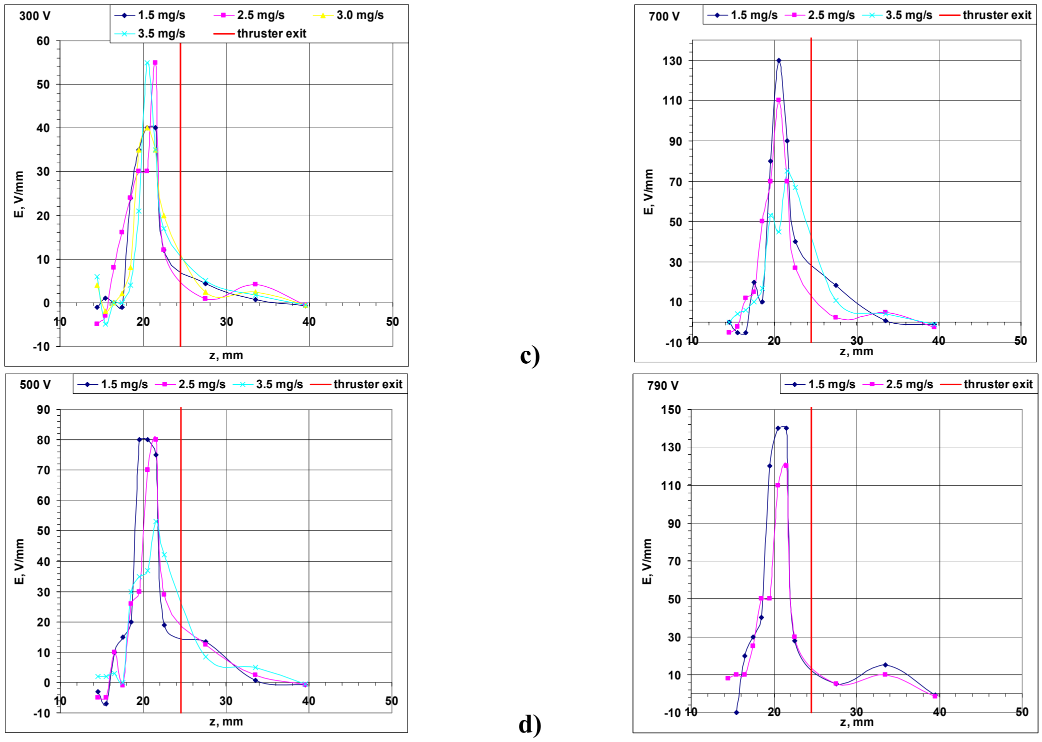
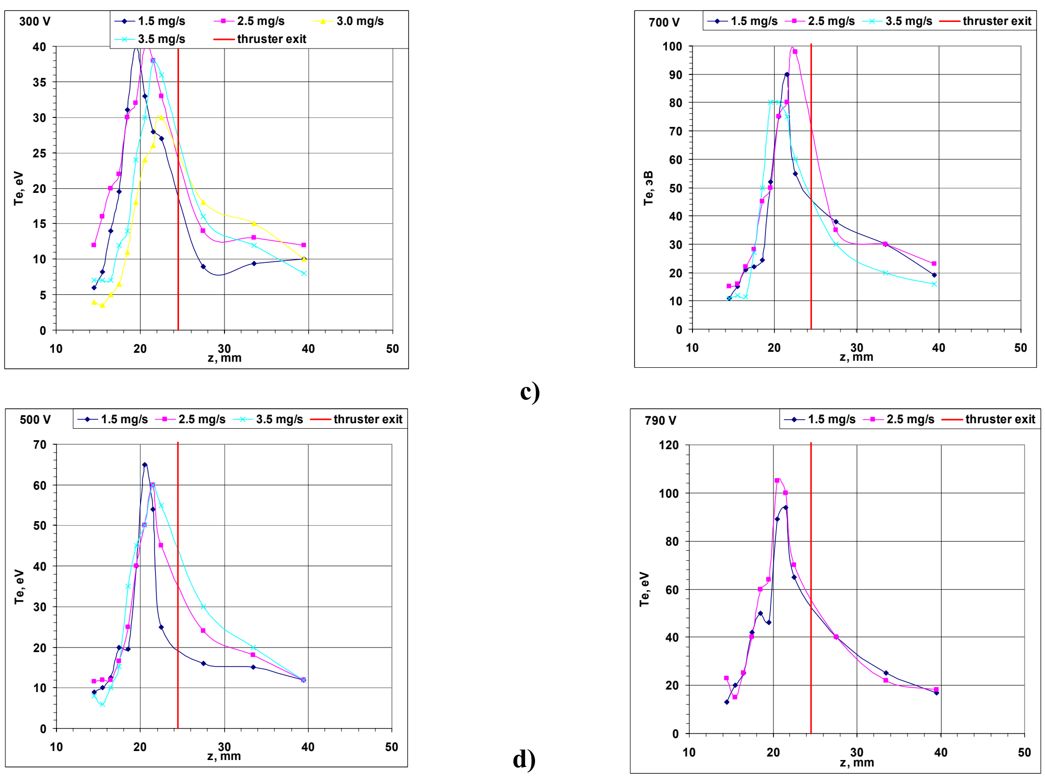


Figure. 8. The dependence of maximum electron temperature value on discharge voltage at different gas flow rates.



a) b) c) d)

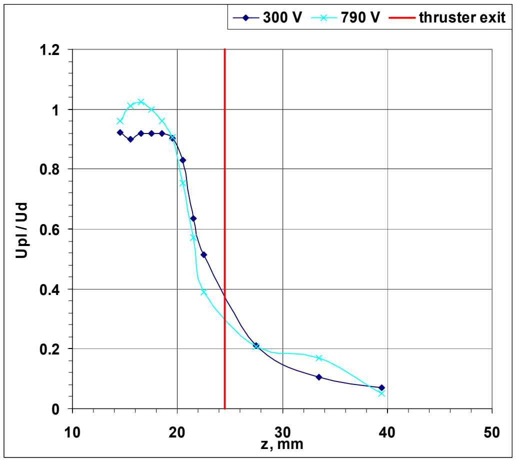
Figure 9. The electric field strength changing along discharge channel depending on gas flow rate at constant discharge voltage for U_d 300 V (a), 400 V (b), 700 V (c) and 790 V (d).



a) b) c) d)

Figure 10. The electron temperature changing along discharge channel depending on gas flow rate at constant discharge voltage for U_d 300 V (a), 400 V (b), 700 V (c) and 790 V (d).

value U_{pl}/U_d>1. The maximum value of electric field strength is growing significantly (more than 3 times). The location of E_{max} is in the same place and region with significant E is spreading mainly towards anode. The maximum value of electron temperature is growing in concordance with linear law and region with significant T_e value is spreading in both directions (as anode and cathode plasma).



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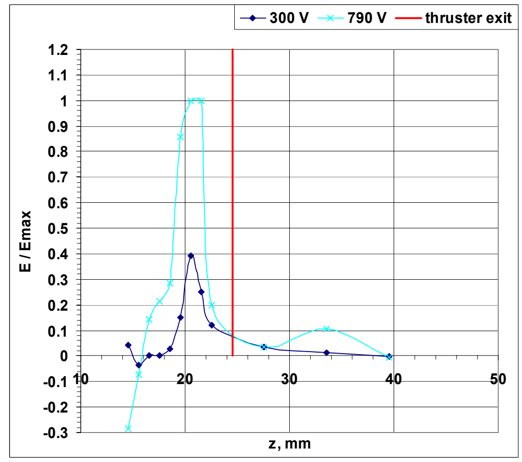

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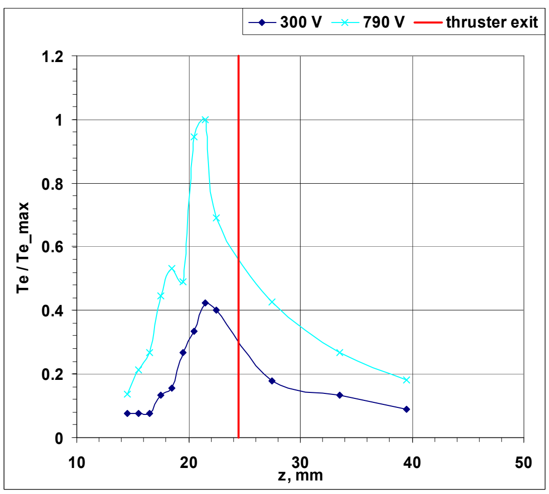


b)

Figure 11. Plasma parameters changing (dimensionless potential (a), electron temperature (b) and electric field strength (c)) for two operation modes with the same Nd but different Ud.

D. Charge production rate

The semi-empirical model[6] was used for definition of charge production rate. This model allows to use an ion energy distribution in plasma plume for this purpose. It is necessary to note, that this plasma characteristic cannot be gained by means of traditional probe diagnostics as for this purpose the information on distribution of neutral particles concentration along the channel is required. Data about neutral component cannot be found from probe measurements, but it can be restored by means of the semi-empirical computation model. Distribution of charge production rate in a discharge channel of thruster is extremely important as it is directly connected with parameters of an ionization zone (an axial location in the channel, linear size and the maximal value of ion birth rate). Joint use of computation model of plasma with probe experimental data (in particular, electron temperature) allows to define axial distribution of ionization zone unequivocally.

According to this model the potential can be restored by means of integration of the following equation:

$$\frac{d\varphi}{dx} = -\sqrt{\frac{m_i}{2e^3}} \cdot \frac{\beta_{ion} \cdot J_{na}}{V_n} \cdot \frac{1-\eta_g \cdot F}{F'} \cdot \int_{\varphi}^{\varphi_a} \frac{F'(\psi)}{\sqrt{\psi - \varphi}} d\psi \,, \tag{3}$$

where φ is an electric potential, x is an axial coordinate, m_i and e are electron mass and charge correspondingly, β_{ion} is ionization coefficient, J_{na} and V_n are flow and velocity of neutrals, η_g is thruster gas efficiency,

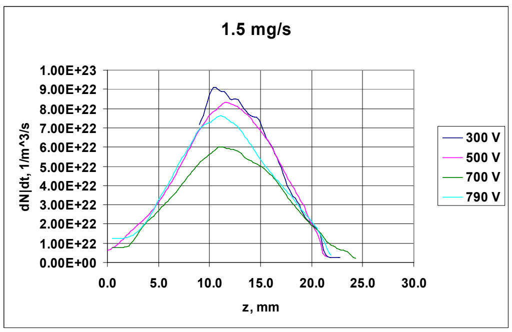
$$F(\varphi_\kappa)=J_i(\varphi_\kappa)/J_{ic}, \tag{4}$$

where $J_i(\varphi_r)$ is ion current density on RPA probe at retarding potential φ_r, J_{ic} is ion current density at zero retarding potential, $F`$ is derivative of F by potential. Densities of neutrals and ions in discharge channel of HET can be found with help of the following expressions:

$$n_n(x) = \frac{J_{na} - J_{ic} \cdot F(\varphi(x))}{e \cdot V_n(x)} , \tag{5}$$

$$n_i = -\sqrt{\frac{m_i}{2e^3}} J_{ic} \cdot \int_{\varphi}^{\varphi_a} \frac{F'(\psi)}{\sqrt{\psi - \varphi}} d\psi . \tag{6}$$

Using the expressions for neutral and charged particles densities it is possible to find charge production rate. The received results are presented in Fig. 12,13.



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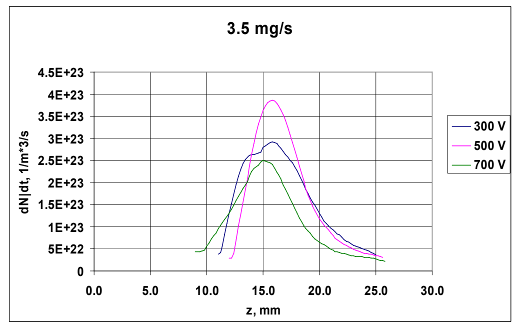

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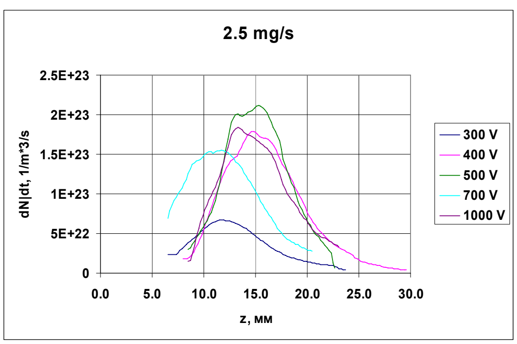
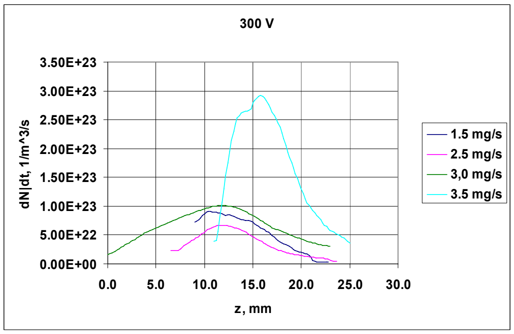


b)

Figure 12. Charge production rate along discharge channel depending on accelerating voltage at constant $\dot{m}_a$ for gas flow rate 1.5 mg/s (a), 2.5 mg/s (b) and 3.5 mg/s (c).

As it can be seen in Fig. 12, the ionization zone at the constant gas flow rate practically does not shift (except for modes with the flow rate 2.5 mg/s and discharge voltage 300 and 1000 V where the ionization zone noticeably shifts to the anode).

At constant voltage and increase of gas flow rate the maximal value of charge production rate grows approximately as square of the gas flow rate. At that the ionization zone shrinks and shifts to the thruster exit. These results are presented in Fig. 13.



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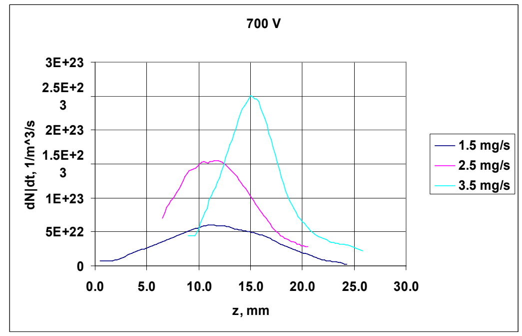

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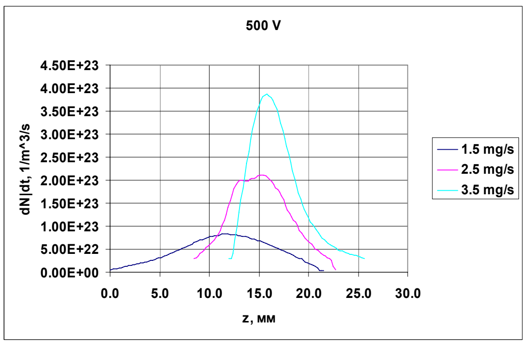

b)

Figure 13. Charge production rate changing along discharge chamber depending on anode gas flow rate at constant V_d for discharge voltage 300 V (a), 500 V (b), 700 V (c).

Comparison of ion birth rate for modes with equal power, but essentially different discharge voltage is presented in Fig. 14. It is visible in the figure, that ion birth rate decreases approximately proportionally to $\dot{m}_a$, the zone of ionization enlarges in both directions, and position of the maximal ion birth rate value shifts to the anode on 5 mm.

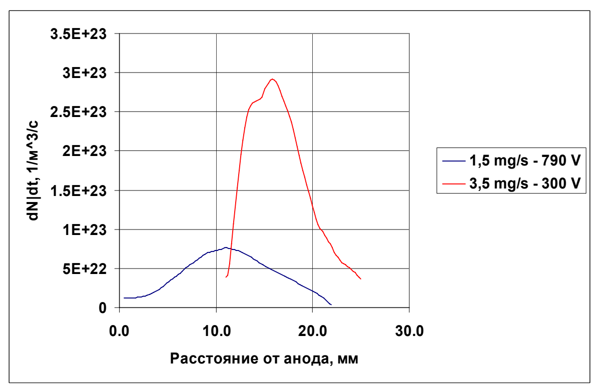

Figure 14. Ion birth rate for two operation modes with different U_d and constant N_d.

Conclusion

The results of probe measurements in the channel of 1.5 kW HET are presented in this paper. Measurements are carried out for anode flow rates 1.5-3.5 mg/s and discharge voltages 300-1000 V. The semi-empirical model was used for calculation of charge production rate.

It is observed, that with growth of the discharge voltage from 300 to 1000 V at the constant gas flow rate the temperature of electrons grows practically linearly. The acceleration layer extends both to the anode, and to exit of thruster, the maximal value of electric field strength in layer grows. At the same time the axial position of E_{max} practically does not vary. The ionization zone practically does not change.

The electron temperature does not change with growing of gas flow rate at constant discharge voltage. At the same time accelerating layer shifts towards thruster exit, its length and E_{max} does not change. The ionization zone shrinks and shifts to the thruster exit, the maximum value of charge production rate growth approximately as square of the gas flow rate.

With growth of discharge voltage from 300 to 790 V at constant discharge power 885 W (the gas flow rate decreases) the electron temperature grows proportionally to U_d, the acceleration layer extends basically towards the anode. At that E_{max} value increases more, than in 3 times, the ionization zone extends in both sides and shifts towards the anode.

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