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Peculiarities of the propellant flow ionization in the Krypton Stationary Plasma Thrusters with the shifted out acceleration zone

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Given paper presents the results of the propellant flow ionization peculiarities study in the discharge with crossed electric and magnetic fields burning in the different scale stationary plasma thruster (SPT) models with the ionization and acceleration layer shifted out of thruster, namely: there were determined the integral characteristics and dependences of the total current of the exhausting ions from thruster operating with Krypton under different operation modes. It is shown that the mentioned ion current and its ratio to the discharge current are typically reduced with increase of the discharge voltage and these trends are different from that ones for the standard SPT's. As result they cause the notable change of the thrust efficiency dependence on the discharge voltage.

Keywords: Stationary Plasma Thruster, propellant flow ionization, gas discharge, crossed electric and magnetic fields.

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Morozov Stationary Plasma Thrusters (SPTs) are the most widely used electric thrusters in current space technology, and their scales of application is getting wider [1,2]. Active development and application of SPT's utilizing other propellants than the originally used xenon is already underway [2–6]. Krypton, which is significantly cheaper than xenon and is produced in significantly larger quantities, attracts much interest as an alternative option. The transition to krypton helps to solve the problem of supplying of large amounts of propellant needed for propulsion systems of certain spacecraft (such as the Starlink constellation that consists of several thousands of satellites [6]. However, it is rather hard to design krypton SPT's with a high thrust efficiency and a large lifetime. The problem is that operating modes with elevated discharge powers and krypton consumption densities in the ionization and acceleration layer (IAL) need to be used in order to ensure efficient ionization of the krypton flow in the electrical SPT discharge [3,7]. This makes it difficult to construct a thruster with large lifetime. In view of the above, the SPT thruster design with an IAL, where the main part of the potential drop is realized, shifted out of a thruster (further SPT-B) appears to be the most promising layout option for a krypton SPT. The transition to this design provides an opportunity to reduce the loss of accelerated ions on the discharge chamber walls and prolong the service life of SPT's in operating modes with elevated propellant consumption densities in an IAL and in the accelerating channel. The available research (including the research performed by the authors of the present study) data suggest that competitive thrusters of this design may well be constructed [3,8]. However, this transition also affects the conditions of ionization of atoms in an IAL, since the flow of atoms and ions expands stronger in SPT-B than in thrusters of the traditional design, and the plasma concentration in an IAL decreases. With this in mind, the aim of the present study is to reveal the specifics of ionization of the krypton flow in SPT-B thrusters.

The dependence of current I_i of accelerated ions exhausted from SPT-50B, SPT-70B, and SPT-140B thrusters of the SPT-B design (with external diameters of the acceleration channel in the magnetic inter pole gap being equal to 50, 70, and 140,mm, respectively) on their operating mode was examined in order to achieve this goal. The first method of I_i determination consists of the measurement of the spatial distribution of the current density of the accelerated ions exhausted from a thruster and integrating this distribution over a surface covering the exit hemisphere into which the jet is exhausted [9]. The second estimation technique involves the measuring the current in the ion collector (target) circuit connected to the emitter of the thruster cathode. The potential of the thruster discharge circuit, which loses ions that reach the collector, is maintained by removal electrons to the collector from the emitter of the cathode (negative terminal of the discharge power supply) along a conductor connecting the cathode emitter to the ion collector. Electrons from the cathode emitter may also be dumped through the discharge plasma in it and the jet plasma, but the resistance along this trajectory for electrons is significantly higher. According to estimates, the corresponding current should be considerably lower than the current along the conductor between the cathode emitter and the ion collector. This is confirmed

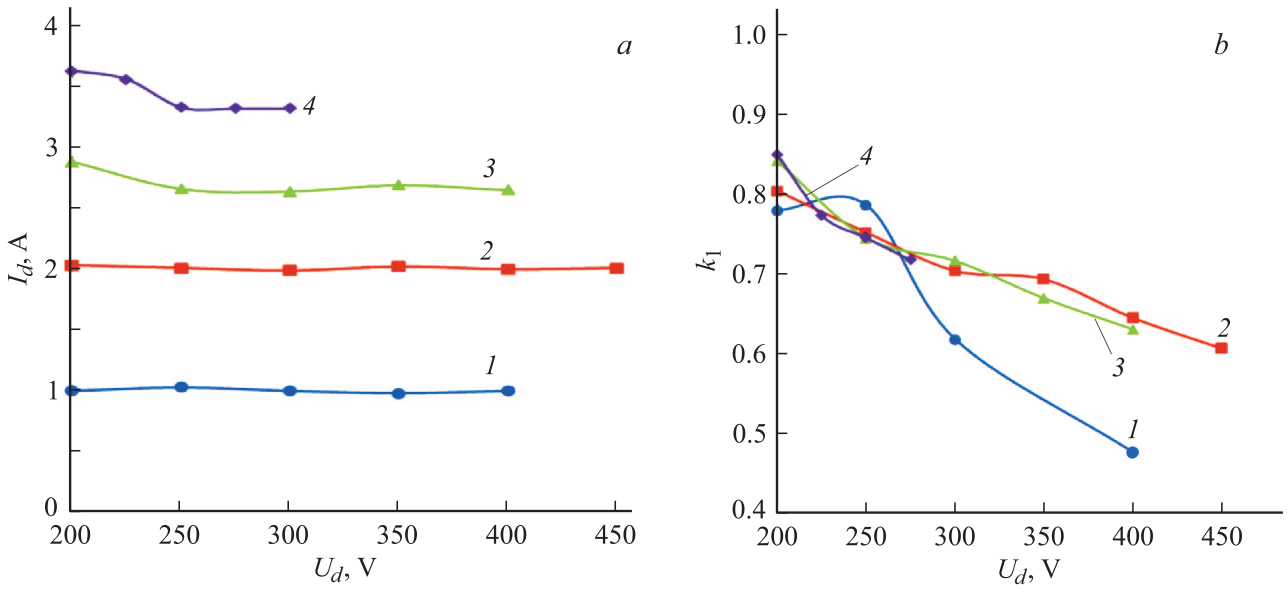

Figure 1. Voltage-current characteristics (a) and dependence of ratio $k_1 = I_i/I_d$ of the ion current to the discharge one on discharge voltage U_d (b) for SPT-50V. $\dot{m}_a = 1.07$ (*1*), 1.80 (*2*), 2.34 (*3*), and 2.81 mg/s (*4*).

by the fact that the results of measurements performed in accordance with these two methods are close. In view of the above, the easier (second) method was used in the present study to measure I_i. These measurements were performed in a vacuum chamber of 1.5 m in diameter with a working volume of approximately 12 m^3 for SPT-50V and SPT-70V and in a chamber of 2 m in diameter with a working volume of approximately 18 m^3 for SPT-140V. Cryogenic pumps were used for high-vacuum pumping. The pressure in the chamber did not exceed $7 \cdot 10^{-5}$ mm Hg in the case of thruster operation.

Figure 1 presents the results of measurement of the voltage-current characteristics and the dependences of ratio $k_1 = I_i/I_d$ of current I_i of ions exhausted from an SPT-50V thruster to discharge current I_d, which was obtained by optimizing the currents in magnetization coils for the minimum discharge current optimal for an SPT, on discharge voltage U_d.

It is evident that this ratio tends to decrease as discharge voltage U_d increases. This trend differs from the one typical for xenon thrusters of the traditional design, where k_1 values reach a plateau of ~ 0.8 at a certain discharge voltage and vary only slightly as U_d increases further [9]. The k_1 reduction is less pronounced in larger SPT-70V and SPT-140V thrusters, but the overall trend persists (Fig. 2). The mentioned trend is an important feature of SPT−V operation and is indicative of an enhancement of the electron component of the discharge current (and the corresponding losses) in optimized operating modes. It provides an explanation for the fact that the thrust efficiency of SPT-V thrusters increases less markedly at higher discharge voltages (Fig. 3) than the efficiency of thrusters of the traditional design. This efficiency η_a was determined using the measured values of reactive thrust F of thrusters, mass-flow rate $\dot{m}_a$ of krypton through their accelerator channel, and discharge power $N_d = U_d I_d$ in accordance with the following relation: $\eta_a = \dot{m}_a \langle V_z \rangle^2 / 2N_d = F^2/2\dot{m}_a N_d$, where $\langle V_z \rangle = F/\dot{m}_a$ is the longitudinal component of the mass-averaged exhaust velocity of the flow of krypton atoms and ions. The obtained data did also indicate that ratio $k_2 = I_i/I_m$ of the ion current to „flow“ current $I_m = \dot{m}_a e/M$, where e and M are the electron charge and the krypton atom (ion) mass, exceeds unity at elevated voltages (Fig. 2). This provides evidence of the presence of multicharged ions in the thruster jet. A similar result was obtained in experiments with a traditional xenon SPT [9].

Secondary electron emission also affects the results of measurements of the ion current. However, measurements performed using probes with grids in front of the collector, which are biased negatively relative to it, demonstrate that the secondary electron emission does not exceed 3−5% at typical ion energies if the surface of a stainless steel collector is clean.

The reduction of the ratio of the exhaust ion current to the discharge current at higher discharge voltages is indicative of an enhancement of electron component I_e of the discharge current and the corresponding energy losses. As the discharge voltage increases, this enhancement induces first a weaker (relative to thrusters of the traditional design) increase in the thrust efficiency, and then the efficiency stabilizes or starts decreasing at a voltage level that is lower than the one typical of traditional thrusters (Fig. 3).

The enhancement of electron component I_e of the discharge current may be attributed to the IAL narrowing in SPT-B thrusters and to an increase in the mean-square amplitude of oscillations of the discharge current at higher

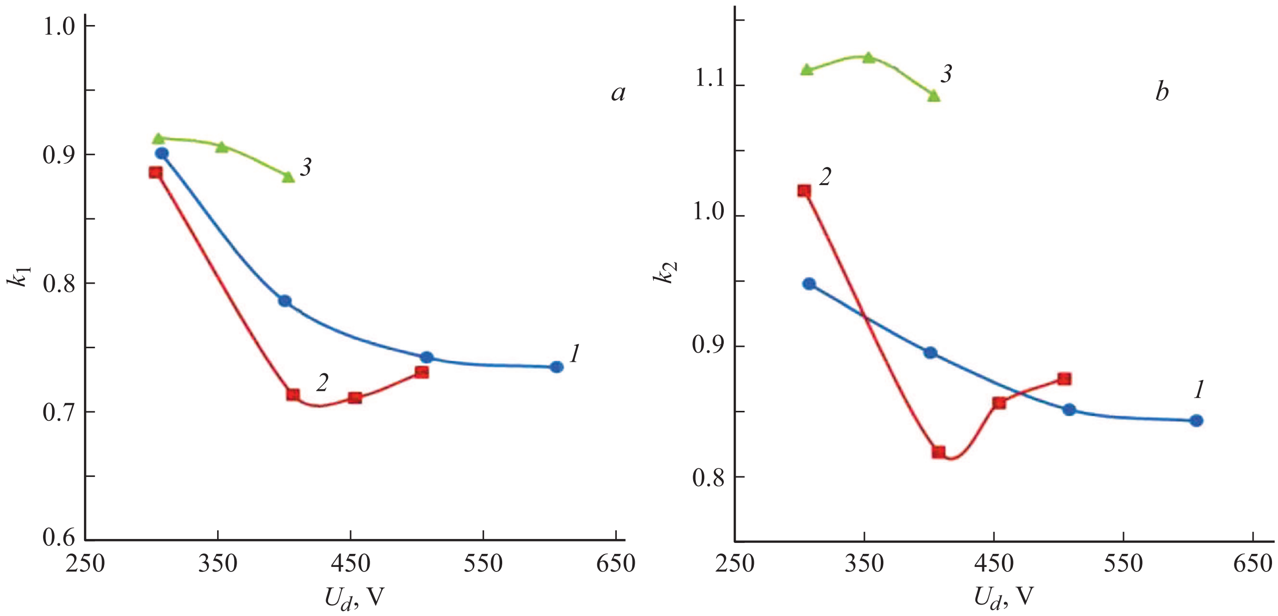

Figure 2. Dependences of ratios $k_1 = I_i/I_d$ (*a*) and $k_2 = I_i/I_m$ (*b*) for SPT-140V on the operating mode. $\dot{m}_a = 10$ (*1*), 14 (*2*), and 18 mg/s (*3*).

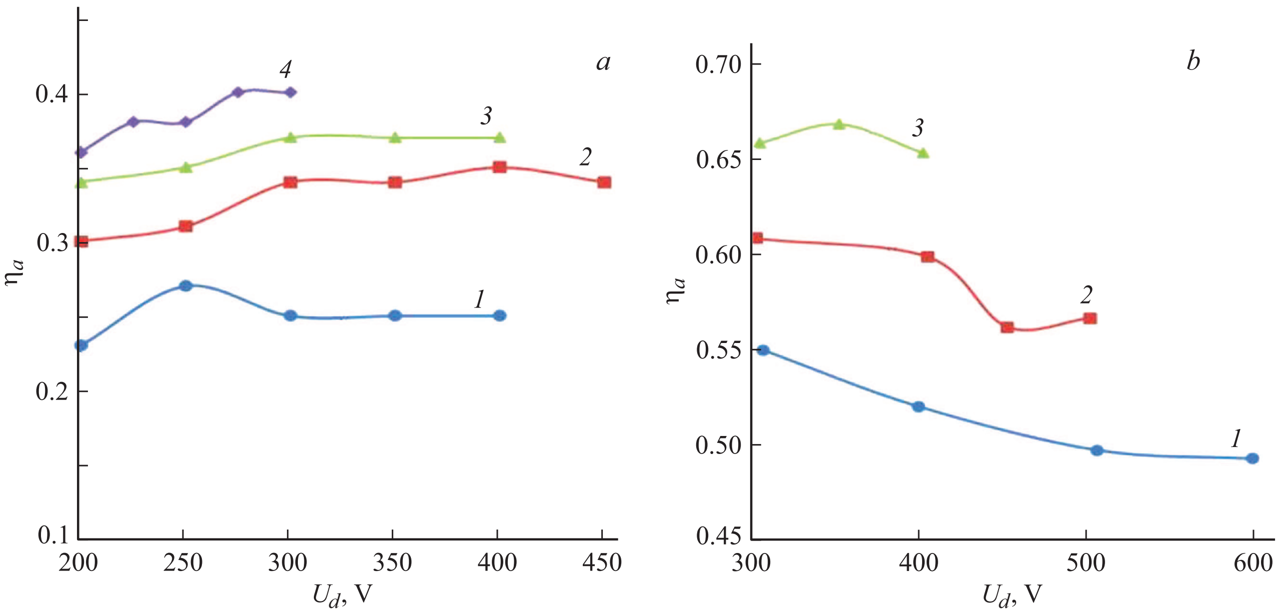

Figure 3. Dependences of the thrust efficiency on the operating mode of SPT-50V (*a*) and SPT-140V (*b*) thrusters. $\dot{m}_a$, mg/s: *a*) *1* — 1.07, *2* — 1.80, *3* — 2.34, *4* — 2.81; *b*) *1* — 10, *2* — 14, *3* — 18.

discharge voltages. The physical reasons behind this require further study.

Thus, the key feature of discharge ionization processes in an SPT with an ionization and acceleration layer shifted out of it is the reduction of the total exhaust ion current and the ratio of this current to the discharge current. This feature is indicative of an enhancement of the electron component of the discharge current in operating modes with the minimum discharge current, which are the optimum ones for an SPT, and warrants further study.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] D. Lev, R.M. Myers, K.M. Lemmer, J. Kolbeck, M. Keidar, H. Koizumi, H. Liang, D. Yu, T. Schönherr, J. Gonzalez Del Amo, W. Choe, R. Albertoni, A. Hoskins, S. Yan, W. Hart, R. Hofer, I. Funaki, A. Lovtsov, K. Polzin, A. Olshanskii, O. Duchemin, in *Proc. 35th Int. Electric Propulsion Conf.* (Georgia Institute of Technology, Atlanta, USA, 2017), paper IEPC-2017-242.

[2] P. Hruby, N. Demmons, D. Courtney, M. Tsay, J. Szabo, V. Hruby, in *Proc. 36th Int. Electric Propulsion Conf.* (University of Vienna, Austria, 2019), paper IEPC-2019-926.

[3] V.P. Kim, V.S. Zakharchenko, D.V. Merkur'ev, P.G. Smirnov, E.A. Shilov, Plasma Phys. Rep., **45** (1), 11 (2019). DOI: 10.1134/S1063780X19010082.

[4] C. Ducci, T. Andreussi, A. Arkhipov, A. Passaro, M. Andrenucci, A. Bulit, C. Edwards, in *Proc. 34th Int. Electric Propulsion Conf.* (Kobe, Hyogo, Japan, 2015), paper IEPC-2015-126.

[5] J. Kurzyna, M. Jakubczak, A. Szelecka, A. Riazantsev, in *Proc. 36th Int. Electric Propulsion Conf.* (University of Vienna, Austria, 2019), paper IEPC-2019-591.

[6] *Space X reveals more Starlink info after launch of first 60 satellites* [Electronic source]. https://techcrunch.com/2019/05/24/spacex-reveals-more-starlink-info-after-launch-of-first-60-satellites

[7] A.I. Morozov, I.V. Melikov, Zh. Tekh. Fiz., **44** (3), 544 (1974) (in Russian).

[8] V.P. Kim, R.Yu. Gnizdor, D.P. Grdlichko, V.S. Zakharchenko, D.V. Merkur'ev, O.A. Mitrofanova, P.G. Smirnov, E.A. Shilov, Tech. Phys. Lett., **44** (12), 1108 (2018). DOI: 10.1134/S1063785018120271.

[9] A.S. Arkhipov, V. Kim, E.K. Sidorenko, Tech. Phys., **57** (5), 621 (2012). DOI: 10.1134/S1063784212050040.