# Experimental Investigations of Component Determining CAMILA Hall Thruster Performance

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M. Rubanovich[1], V. Balabanov[2], A. Kapulkin[3], E. Behar[4]
*Asher Space Research Institute, Technion-Israel Institute of Technology, Haifa, 32000, Israel*

**Abstract: The paper is devoted to further experimental investigations of a new version of Hall thruster (HT) for small powers – CAMILA Hall thruster. This new version of HT showed itself previously as an effective engine for powers of 100 – 300 W. At expected lifetime of approximately 4000 h, its anode efficiency is ≈ 45 % at power of 200 W. However, this value is still noticeably lower than at large powers. Therefore, clarifying where the efficiency is lost is of prime importance. The carried out experiments, the results of which are presented in the paper, revealed that the propellant usage efficiency and fraction of the ion current in the discharge current are quite acceptable. The problem is to increase the discharge voltage usage efficiency.**

## I. Introduction

MUCH attention is presently being focused on the development of small power Hall thrusters (HT) for applications on micro-satellites. The creation of such the thrusters faces significant obstacles due to the necessary to provide the compatibility of the high thrust efficiency and acceptable lifetime. One of the possible ways to solve this problem was development of CAMILA Hall thruster[1] (CAMILA – Co-Axial Magneto-Isolated Longitudinal Anode.)

The CAMILA Hall thruster showed itself as an effective engine for powers of 100 – 300 W[1,2]. At expected lifetime of approximately 4000 h, its anode efficiency is ≈ 45 % at power of 200 W. However, this value is still noticeably lower than at large powers. Therefore, clarifying where the efficiency is lost is of prime importance.

Some data concerning the sources of the anode efficiency losses were obtained in Ref. 3, 4 as a side result of the experimental investigations of physical processes inside the anode cavity and acceleration channel of the CAMILA Hall thruster. These investigations were performed with the use of electrical probes under one mass flow rate and discharge voltage. However, taking into account the importance of the problem, it was necessary to carry out the targeted research of the sources of the anode efficiency losses with needed accuracy and completeness, and with an obligatory study of the trends at changing the input parameters of the thruster. This is a topic of the paper.

## II. Components Determining Hall Thruster Anode Efficiency

In this Section, we consider components on which anode efficiency depends. The anode efficiency of Hall thrusters is defined by the following expression

$$\eta_a = \frac{F^2}{2\dot{m}P} \qquad (1)$$

Where $F = \dot{m} < V > -$ the thrust,
$\dot{m}$ – the mass flow rate of propellant,

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[1] Engineer, Electric Propulsion Lab, aerrumax@tx.technion.ac.il.
[2] Leading Researcher, Head of Mechanic Group, balaban@tx.technion.ac.il.
[3] Leading Researcher, Head of Electric Propulsion Lab, kapulkin@tx.technion.ac.il.
[4] Director of Institute, Professor of Physical Department of Technion, behar@physics.technion.ac.il.

$< V >$ – the average value of ion and atom velocity component directed along the thruster axis in the cathode placement plane,

$P = I_d U_d$ – the power of discharge,

$I_d$ – the discharge current,

$U_d$ – the discharge voltage.

Because the average velocity of the atoms is significantly less than the velocity of the ions, one can neglect the contribution of the atoms in the thrust, as first approximation. Then

$$F \cong \dot{m}_i < V_i > \tag{2}$$

Where $< V_i >$ – the average of ion velocity component directed along the thruster axis in the cathode placement plane,

$\dot{m}_i$ – the mass flow rate of ions.

We introduce the following quantities.

$\mu_1 = \frac{\dot{m}_{i(1)}}{\dot{m}_i}$ – the fraction of single charged ions in mass flow rate of ions,

$\mu_2 = \frac{\dot{m}_{i(2)}}{\dot{m}_i}$ – the fraction of double charged ions in mass flow rate of ions.

The fraction of third charged ions is neglected. Then

$$\dot{m}_i = \frac{MI_i}{(1+\mu_2)e} \tag{3}$$

Where $I_i$ – the ion current in the cathode placement plane,

$e$ – the unit positive charge,

$M$ – the mass of ion.

In this case, for the propellant usage efficiency, we have

$$\eta_m = \frac{\dot{m}_i}{\dot{m}} = \frac{MI_i}{\dot{m}(1+\mu_2)e} \tag{4}$$

We will also use the following quantity

$$\eta_m^* = \frac{MI_i}{\dot{m}e} \tag{5}$$

This is, in some sense, the "conditional" propellant usage efficiency. As distinct from $\eta_m$, the conditional propellant usage efficiency can take values exciding 1 if there are double charged ions in the ion flux. Unfortunately, in the carried out experiments, the value of $\mu_2$ was not known. Therefore, the following model was used. It was assumed that if $\eta_m^* \le 1$, then $\mu_2 = 0$ and $\eta_m = \eta_m^*$, if $\eta_m^* > 1$, then $\mu_2 = \eta_m^* - 1$ and $\eta_m = 1$. Given model means that never the double charged ions appear until all atoms of Xenon are transformed into the single charged ions. Strongly speaking, it is not correct, but taking account that difference between an energy of ionization of the single charged ion and energy of ionization of the atom is not too small, the error, probably, is not great.

Substituting in Eq. 1 the expression for the thrust from Eq. 2 and after that substituting instead of the first ions mass flow rate its expression from Eq. 4 and instead of the second ions mass flow rate Eq. 3, we obtain for the anode efficiency of the thruster the following equation

$$\eta_a = \eta_m \eta_i \eta_{dv} \tag{6}$$

Where $\eta_i = \dfrac{I_i}{I_d}$ – the fraction of the ion current in the discharge current (7)

$$\eta_{dv} = \frac{M < V_i >^2}{2ZeU_d} \quad \text{– the discharge voltage usage efficiency} \tag{8}$$

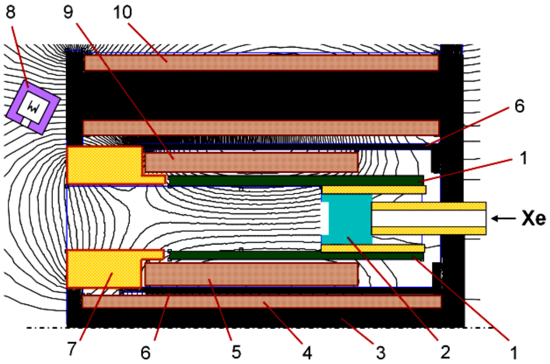
$$Z = 1 + \mu_2$$

The product $Ze$ is the average charge of the ion.

The discharge voltage usage efficiency takes into account the losses due to ionization of atoms in the area where the potential is less than anode one, the fall of the potential near the cathode, the divergence of the ion flux, and the dispersion of the ion velocities.

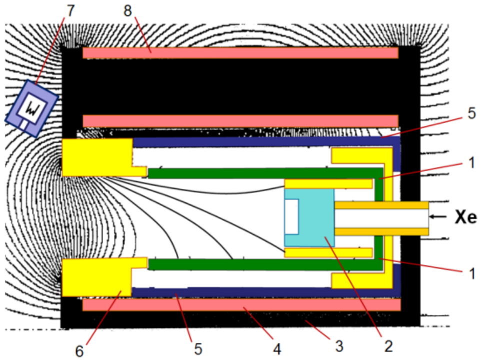
It is possible to represent $\eta_{dv}$ as a product of terms defining the noted above losses[5,6], which, in turn, require conducting the corresponding measurements. In this stage of the investigations, we restricted our consideration to the integrated parameter.

## III. Experimental Setup



1 – Anode, 2 – Gas-distributor, 3 – Magnetic circuit, 4 – Central magnetic coil, 5 – Inner anode coil, 6 – Magnetic screens, 7 – Acceleration channel wall, 8 – Cathode-neutralizer, 9 – Outer anode coil, 10 – Outer magnetic coils.

**Figure 1.** Schematic of Full CAMILA HT.



1 – Anode, 2 – Gas-distributor, 3 – Magnetic circuit, 4 – Central magnetic coil, 5 – Magnetic screens, 6 – Acceleration channel wall, 7 – Cathode-neutralizer, 8 – Outer magnetic coils.

**Figure 2.** Schematic of Simplified CAMILA HT.

### A. Experimental model

A schematic of the CAMILA Hall thruster with simulated magnetic field is shown in Fig.1. The ionization of propellant should be produced mainly in the anode cavity that is formed by two co-axial metallic cylinders, which are kept under the anode potential, and an end face of the gas-distributor which is under a floating potential. In the anode cavity, the longitudinal magnetic field is applied. It is produced by outer and inner anode magnetic coils with electric currents in opposite directions and the magnetic screens. The propellant, entering the cavity through the gas distributor, is ionized by electrons, which oscillate between the end face of the gas-distributor and the exit of the cavity. At a sufficiently strong magnetic field in the cavity, it is possible to form a radial electric field, directed to the middle surface of the cavity, in spite of the radial gradient of electron pressure[7]. This radial electric field keeps ions from colliding with the cylindrical walls of the cavity. (The length of the cavity can be varied to obtain a high degree of propellant ionization.) After leaving the anode cavity, the ions are accelerated by a longitudinal electric field in the acceleration channel.

The experimental investigations showed that rather high anode efficiency can be obtained, even in the simplified version of the CAMILA Hall thruster (Fig. 2), where a longitudinal component of the magnetic field in the anode cavity is created with only basic magnetic coils (outer and central), that is, without using the anode coils. In this case, a magnetic system is lesser complex and consumes less power.

The experiments were performed with CAMILA HT-55 model (Fig.3), having the acceleration channel outer diameter of 55 mm and the width of the channel of 12 mm. This is 200 W-class model. In the thickness of the acceleration channel walls and density of the mass flow rate, the model belongs to the category of the thrusters, having a large lifetime (> 4000 h).

The model allows for many different experimental set ups, which are defined, in particular, by availability of two mutually-replaceable pairs of anode coils, distinguished in length, discrete control of the anode coil position, discrete control of the length of the anode cavity by means of installation of the special dielectric spacers between the gas-distributer and back plate, separate connections of the outer and inner anode rings to the power supply.

**Figure 3.** Experimental model of CAMILA Hall thruster (CAMILA-HT-55).

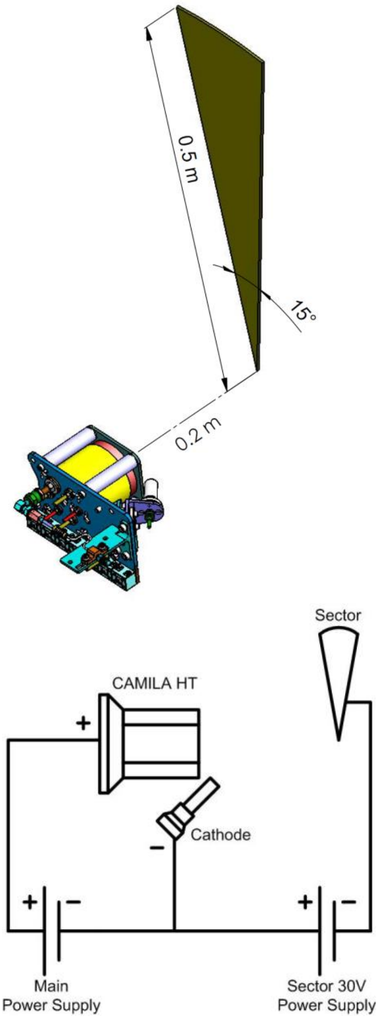


**Figure 4.** System for measurements of ion current.

### B. Facility for Experiments

The experiments were carried out in the facility at Asher Space research Institute of the Technion. The vacuum chamber, where the experiments were carried out, has a volume of $\approx 3\ \mathrm{m}^3$. The cryogenic pumping system provided the residual gas pressure not exceeding $6 \cdot 10^{-8}$ mBar and the Xenon pressure not exceeding $2.5 \cdot 10^{-5}$ mBar at a total mass flow rate of 1 mg/s.

The special diagnostics included:

1) The device for measurements of thrust;
2) The receiver for measurements of ion current at a distance of 0.2 m from the thruster. The receiver has the shape of a sector with the radius of 0.5 m and arc of $15^0$ (Fig.4). It is manufactured from stainless steel. The large radius of the receiver and a small value of the arc allowed on the one hand gathering ions going even under very large angles with respect to the axis of the thruster, and on the other hand to provide the absent of the noticeable influence of the ion receiver on the thruster parameters. At the measurements of the ion currents, an ion-electron emission from the receiver was taken into account. At measurements, the potential of the sector was biased by -30 V with respect to the cathode. At such the bias, the current in the circuit of the sector ceased to depend on the potential of biasing. The value of the full ion current is determined by the following expression

$$I_i = 24 \cdot I_s \qquad (9)$$

Where $I_s$ – the current to sector.

## IV. Results of Experimental Investigations and Discussion

The experiments carried out at the following discharge voltages: 250 V, 275 V, 300 V, and 330 V. The mass flow rate was varied from 0.680 to 1.2 mg/s. At these input parameters, the discharge power was varied from 140 to 390 W.

In the experiments, two different cathodes were applied: 1) KhAI' cathode, which operated in a self-sustained mode. The mass flow rate through the cathode was 0.15 mg/s; 2) the commercial cathode HWPES-250. The latter could not operate in self-sustained mode at a discharge current of less than 1 A. Therefore in the experiments, additional heating of the cathode emitter was performed by the use of an auxiliary discharge between it and a cathode keeper. The voltage between the keeper and emitter was kept at a level of 14 – 17 V. The mass flow rate through the cathode was 0.25 mg/s. The current in the circuit of the keeper was artificially restricted to 0.9 A.

In the course of the experiments, the thrust of the thruster and ion current to the sector were measured. Using equations 1, 9, 7, 5, 4, the anode efficiency, the fraction of the ion current in the discharge current, the condition propellant usage efficiency, and the propellant usage efficiency were determined. As for the discharge voltage efficiency, independent methods for its determination were not applied. It was evaluated according to the principle: all remaining losses are contained in the discharge voltage usage efficiency, that is, $\eta_{dv}$ was evaluated from Eq. 6 for the anode efficiency

$$\eta_{dv} = \frac{\eta_a}{\eta_m \eta_i} . \qquad (10)$$

The results of the experimental investigations of $\eta_m^*$, $\eta_i$, and $\eta_{dv}$ are presented in Fig. 5 – 8 for the simplified CAMILA Hall thruster and full CAMILA Hall thruster. First of all, one can see that the condition propellant usage efficiency exceeds 93 % at the power of 200 W for all discharge voltages used in the experiments. In the case if the discharge voltage is equal to 250 V, the condition propellant usage efficiency is equal to 100 % for the simplified CAMILA HT and exceeds 100 % for the full CAMILA HT. At almost all discharge powers and all discharges voltages in the full CAMILA HT, the higher level of the condition propellant usage efficiency is provided in comparison with the simplified CAMILA HT, where a magnetization of the anode is worse. Thus, we have the direct confirmation of the validity of the principles lying in the basis of the CAMILA HT design, namely, for an essential improvement of ionization of the propellant in the thruster, it is necessary to have a co-axial anode and well fitted longitudinal magnetic field in the anode cavity.

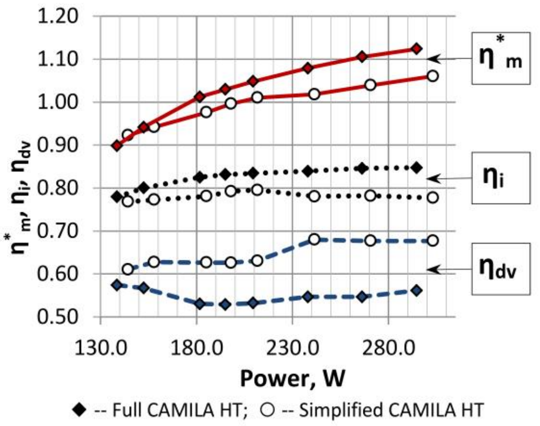


**Figure 5.** Efficiencies vs. Power (Discharge Voltage - 250V).

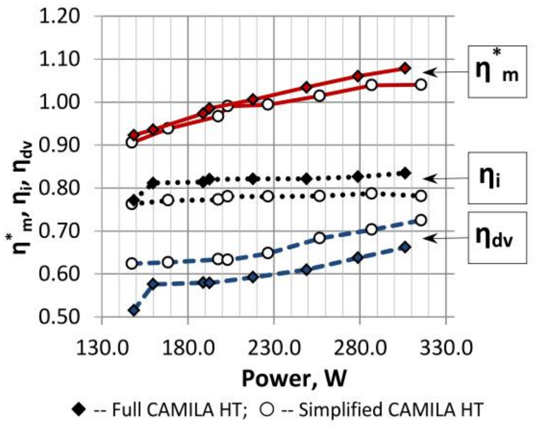


**Figure 6.** Efficiencies vs. Power (Discharge Voltage - 275V).

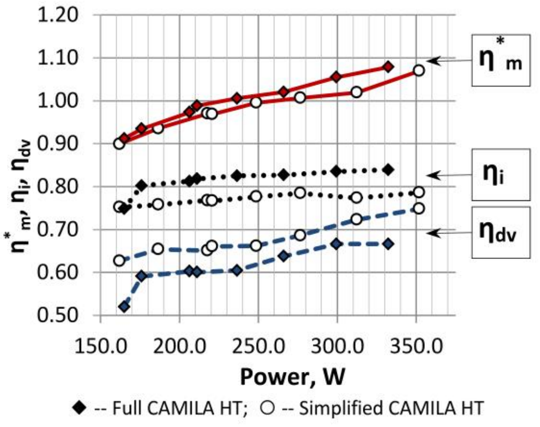


**Figure 7.** Efficiencies vs. Power (Discharge Voltage - 300V).

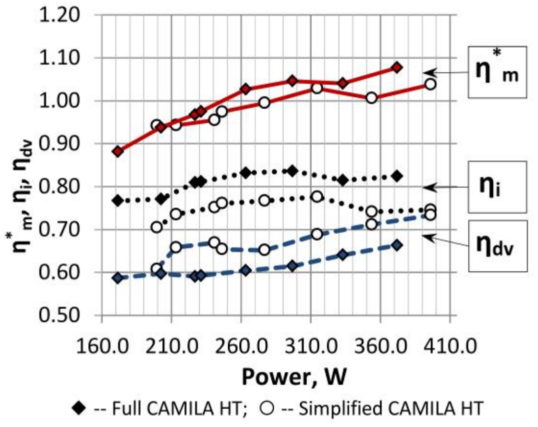


**Figure 8.** Efficiencies vs. Power (Discharge Voltage - 330V).

The higher magnetic isolation which is provided in the full CAMILA HT in comparison with the simplified one leads to another important effect. As is seen from Fig. 5 – 8, in the full CAMILA HT, the fraction of the ion current in the discharge is essentially higher than in simplified CAMILA HT. At the discharge voltage of 250 V and powers exceeding 250 W, it attains 84 – 85 %, while in the simplified CAMILA HT, it equals 78 %. Thus, the fraction of the electron current in the discharge current $\eta_e = 1 - \eta_i$ in the full CAMILA almost by a factor of 1.5 lower than in simplified one. Taking into account the fact that the condition propellant usage efficiency is also essentially higher in the case of the full CAMILA HT, probably, besides, noted above, influence of the better magnetization of the anode on the fraction of the electron current, in the full CAMILA HT, a death of the ions on walls of the acceleration channel is also less than in the simplified CAMILA HT. This circumstance should reduce the electron fraction in the discharge current because, when the ion emerges in the area of the ionization, for example, in the anode cavity, the electron, arising together with it, is captured by the anode. If this ion collides with the wall of the acceleration channel, it recombines there with an electron. The electron for the recombination comes from the cathode. Therefore, the electrical field in the acceleration channel redistributes in such manner in order to provide an additional electron current from the cathode.

In spite of the fact that the full CAMILA demonstrates the higher level of the ionization of the propellant and the smaller fraction of the electron current in the discharge current, the anode efficiency of the full CAMILA HT at the discharge voltage of 250 V is lower than the simplified CAMILA has (Fig.9). This means that the discharge voltage usage efficiency in the case of the full CAMILA HT is essentially lower than in the case of the simplified CAMILA HT. The reason of this is, in our opinion, as follows. In the modernized full CAMILA HT, the radial drop of a potential in the anode cavity and the radial and longitudinal drop of a potential in the area of an influence of the co-axial anode, probably higher than in the former experiments[2-4], where was used the full CAMILA HT with symmetric currents in the anode coils. This led to the improvement of the ionization of the propellant and reducing the fraction of the electron current in the discharge current. However, increasing the fall of the potential in the area of the ionization simultaneously brought about reducing the fall of a potential in the area of the ion acceleration. As a result, the velocity of the ions reduced and possible the divergence of the ion flux increased. The dependence of the anode efficiency on the discharge voltage (Fig. 10 – 12) confirms the suggested explanation. At the discharge voltage of 275 V, the difference between the anode efficiencies for two versions of the CAMILA HT is less than at 250 V. At the discharge voltage of 300 V, the anode efficiencies coincide almost for all investigated powers. At increasing the discharge voltage till 330 V, there are areas of the powers, where the anode efficiency of the full CAMILA HT slightly exceeds the anode efficiency of the simplified HT. The given dependence of the anode efficiencies on the discharge voltages, in turn, is due to the fact that the fall of the potential in the area of the ionization depends weakly on the discharge voltage.

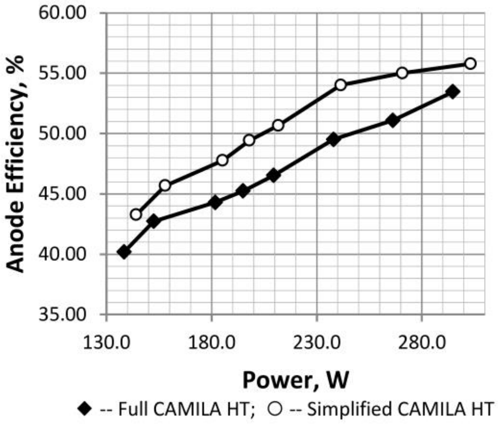


**Figure 9.** Anode Efficiency for Discharge Voltage - 250V.

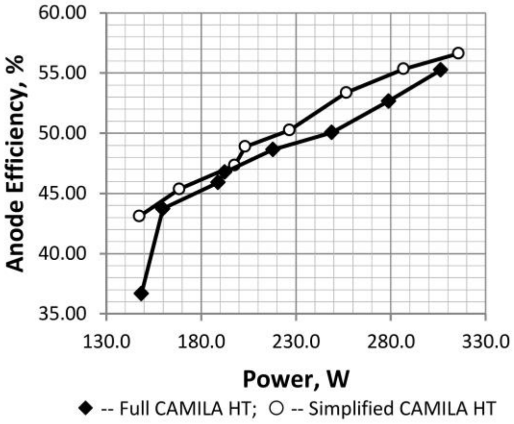


**Figure 10.** Anode Efficiency for Discharge Voltage - 275V.

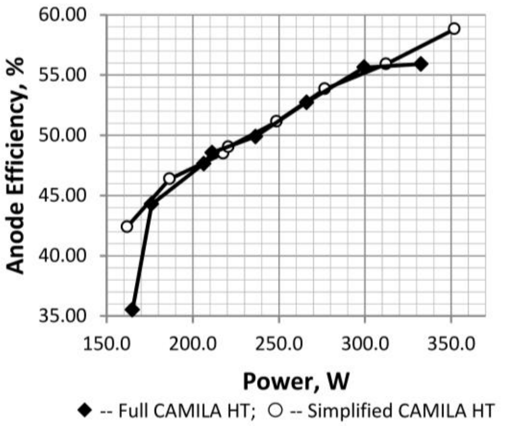


**Figure 11.** Anode Efficiency for Discharge Voltage - 300V.

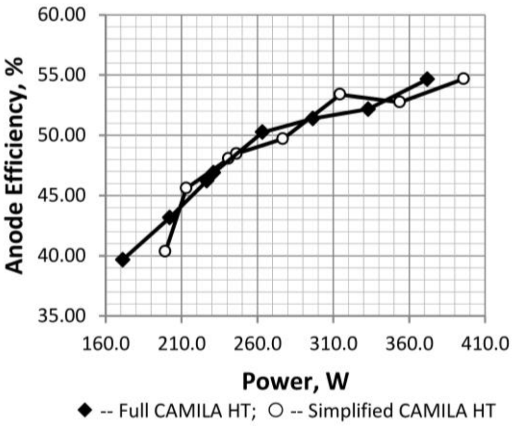


**Figure 12.** Anode Efficiency for Discharge Voltage - 330V.

It is necessary also note that the additional reason of lowering the discharge voltage usage efficiency in the full CAMILA HT in comparison with the simplified one is the higher fraction of two charged ions in the ion flux. The indicator of latter is exceeding 1 by the condition propellant usage efficiency. The increase of the average charge of the ions is not compensated by the adequate growth of the average ion velocity component along the thruster axis.

Thus, in order to attain the maximal anode efficiency at the same basic geometrical sizes of the CAMILA HT, it is necessary to strive for the optimal values of the propellant usage efficiency and fraction of the ion current in the discharge current at which the drop of the potential in the area of the ionization is not too large.

## V. Conclusion

1. The experimental investigations of ion currents beyond the acceleration channel were carried out for two versions of the CAMILA Hall thruster: a) the simplified version; b) the modernized full version. The investigations were conducted for a wide enough field of powers (140 – 390 W) and four discharge voltages.
2. The investigations of the ion currents were conducted with the use of the special receiver having the shape of a sector with the radius of 0.5 m and arc of $15^0$, which allowed gathering ions going even under large angles (up to $68^0$) with respect to the axis of the thruster.
3. It was revealed that in all investigated area of input parameters, the propellant usage efficiency was large enough. At power of 200 W, it exceeded 93 % for both versions of the CAMILA Hall thruster and for all investigated voltages.
4. The propellant usage efficiency in the case of the full CAMILA Hall thruster almost at all input parameters was higher than in the case of the simplified one.
5. The fraction of the ion current in the discharge current is moderate (73 – 78 %) in the simplified CAMILA Hall thruster and high (82 – 84 %) in the modernized full CAMILA Hall thruster.
6. The comparison of the propellant usage efficiency and the fraction of the ion current in the discharge current with the values of the anode efficiencies for two versions of the CAMILA Hall thruster shows that the higher values of the first two quantities, inherent in the full CAMILA Hall thruster is not yet an assurance of the higher anode efficiency. The reason of this is the higher discharge voltage efficiency in the case of the simplified CAMILA Hall thruster. This is probably due to the larger fall of a potential in the area of ionization in the full CAMILA Hall thruster. Besides, in the full CAMILA Hall thruster, the fraction of two charged ions is higher as well.
7. In order to attain a maximum of the anode efficiency at the same basic geometrical sizes of the full CAMILA Hall thruster, it is necessary to strive for the optimal values of the propellant usage efficiency and fraction of the ion current in the discharge current at which the drop of a potential in the area of ionization is not too large.

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