Operation of Two-stage Thruster with Anode Layer in "Floating Electrode" scheme

IEPC-2005-145

Presented at the 29th International Electric Propulsion Conference, Princeton University,
October 31 – November 4, 2005

Alexander E. Solodukhin* and Alexander V. Semenkin†
Central Research Institute of Machine Building (TSNIIMASH),
Pionerskaya 4, Korolev, Moscow region, 141070, Russia

Two-stage scheme provides unique operation range for Hall thrusters with anode layer (TAL). But in comparison with one stage Hall thrusters applied up to the present, two stage scheme operating requires more complicated power supply system. It should include two discharge supplies for the first and for the second stages correspondingly. Potential possibility of two stage thruster with anode layer to operate in two stage mode with single power supply was demonstrated earlier. In this case intermediate electrode – first stage cathode – is floating, so that the scheme was called "Floating Electrode" (FE) scheme. Voltage distribution at the discharge channel at FE scheme is self established, and it is determined by balance between flows of electrons and ions on the electrode. Simplicity of the power supply system is one of critical criteria to select the thruster for practical application, so that FE scheme is considered as an attractive solution for high I_{sp} and multimode Hall thrusters. However, previously this solution was never studied in relation to whole set of characteristics of the certain hardware (efficiency, operating envelope, lifetime etc).

Nomenclature

V_d	=	Discharge voltage (1st Stage)
I_d	=	Discharge current
V_a	=	Acceleration voltage (2nd stage)
I_d	=	Acceleration stage current
m_a	=	Anode mass flow (Xe)
N	=	Input power
V_{sum}	=	Summary Voltage (V_d + V_a)
I_{sp}	=	Specific impulse
F	=	Thrust
η	=	Efficiency

* Group Leader, Electric Propulsion Laboratory, asolodukhin@mtu-net.ru
† Head of Laboratory, Electric Propulsion Laboratory, avs@tse.ru

I. Introduction

Modern trends in development of new generation Hall thrusters are closely connected with requirements to a new spacecrafts (SC) being developed with electric propulsion systems (EPS). Typical requirements are: design lifetime 15-20 years and design total power 15-30 kW. As an example *Express-2000* NPO PM Platform[1] and *@bus* – platform of Alcatel-Astrium JPT[2] can be considered.

@bus EPS requirements are as follows:

1. $1500<I_{sp}<2500$ for transfer mission (orbit raising)
2. $2500<I_{sp}<4000$ for orbit station keeping

However the most preferable is a mission scenario with I_{sp} variation during the orbit raising[3]. It leads to significant SC mass saving in comparison with constant I_{sp} mission scenario. Hence new PPU which can provide a possibility to regulate discharge voltage like the SMART1 PPU[4] is also needed.

In case of using one and the same thruster for orbit raising and station keeping it can be concluded:

1. High I_{sp} thruster mode is required: currently used Hall thrusters has $I_{sp} \sim 1700$ s. I_{sp} value up to 4000 s is needed.
2. Multimode is required. Multimode is an ability to operate in a several modes with variable main parameters (Thrust, I_{sp}, Power). As a particular case two modes with very distinctive parameters are needed.

Scientific and engineering efforts aimed on new generation Hall thruster research and developments involves study of stationary plasma thruster (SPT) and thruster with anode layer (TAL) technology. Option with TAL application was considered below.

TAL history started from physical concept research, theoretical model of working process development and experimental study of laboratory hardware characteristics. This activity resulted in two TAL modifications development: at first two-stage modification (Figure 1) was created, one-stage thruster modification (Figure 2) was the next[5,6]. Two-stage TAL has the first (discharge) and the second (acceleration) stages. Ionization mainly takes place at the first stage while ion acceleration happens at the second. Laboratory samples were created operating with

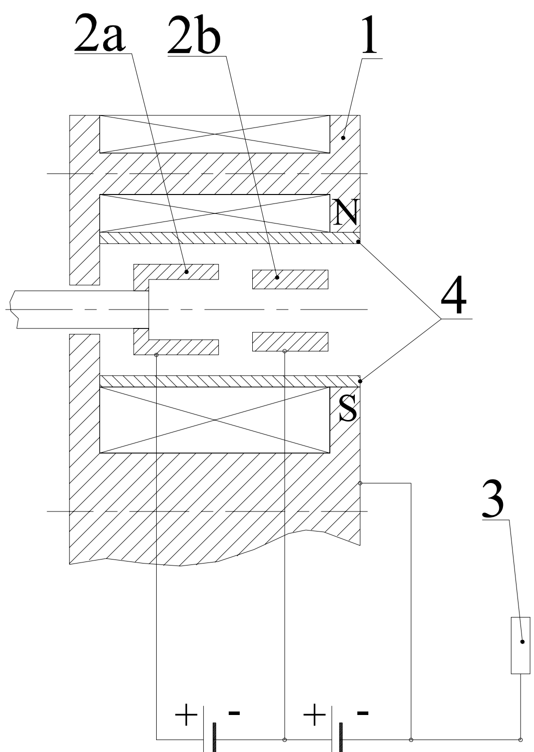

Figure 1. Two-stage TAL modification. *1 – Pole piece outer; 2a –The first stage anode; 2b – The first stage cathode; 3 – Cathode-neutralizer; 4 – Guard rings.*

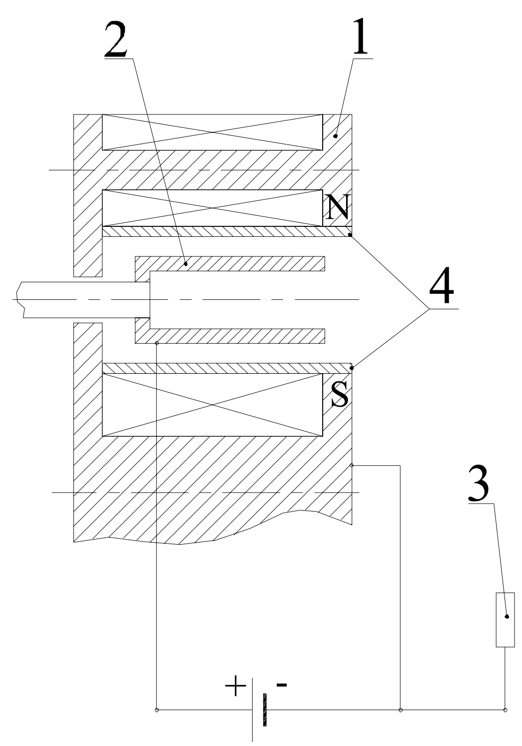

Figure 2. One-stage TAL modification.

1 – Pole piece outer; 2 Anode; 3 – Cathode-neutralizer; 4 – Guard rings.

different propellants: Bi, Cs, Xe etc. I_{sp} ~ 8000 seconds and efficiency up to 0.8 with N~150 kW were reached. One-stage TAL has only one stage and discharge where ionization and acceleration processes occur. It has more simple construction than two-stage one as well as power supply system. One-stage laboratory samples with different propellants operating were created also. Experiments showed typical characteristics: I_{sp} up to 3000 seconds and efficiency up to 0.7.

Both TAL modifications supplement each other – one stage TAL can be operated at the specific impulse range 1000-3000 seconds. At the I_{sp} value more than 3000 seconds one-stage TAL encounters difficulties connected with discharge instabilities and construction elements overheating. When higher I_{sp} is needed two-stage TAL can be used.

Moreover a possibility of the one and the same hardware (two-stage TAL modification) operating at both one-stage and two-stage connection schemes was shown. Switch between the schemes is realized with only power supply scheme changing and without any construction elements modifying. So two-stage TAL can provide I_{sp} regulating at the very wide range. This feature is inherent for all two-stage TALs.

As one can see TAL based EPS meets the modern SC requirements which relate high I_{sp} modes obtaining and I_{sp} variation possibility.

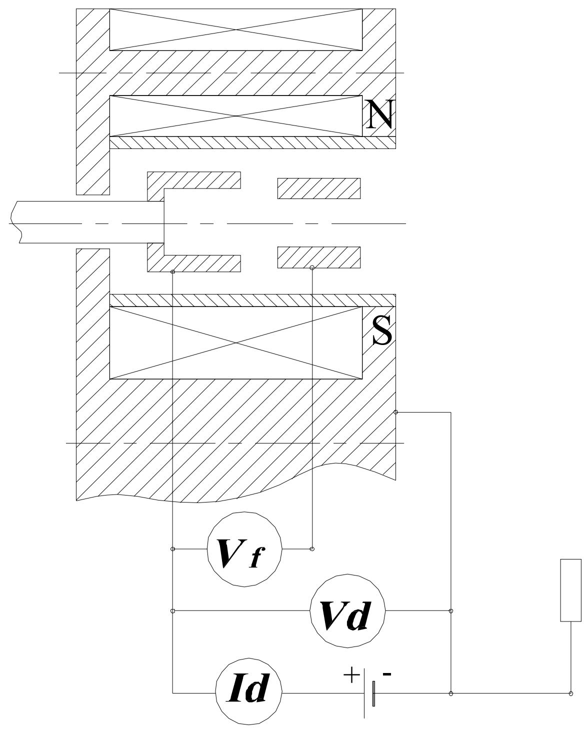

Figure 3. Floating Electrode connection scheme.

Along with advantages two-stage connection scheme has drawback – it needs more complex power supply system. For the both stages two discharge supplies are needed. Due to power supply system complexity increasing EPS reliability is decreased, so additional elements reserving is needed and it results in additional power losses and total mass growing. This also leads to EPS cost raising and total testing time increasing.

However operation of the first and the second stages can be coordinated with help only one discharge power supply. As it was shown previously[7,8] two-stage TAL can operate at so called "Floating Electrode" (FE) connection scheme (Figure 3). As one can see intermediate electrode – first stage cathode – is floating. Its potential is determined discharge channel plasma. At this scheme with help only one discharge power supply parameters analogous for two-stage scheme can be provided. FE scheme allows using advantages of the two stage connection scheme without complicating of the power supply system. Application of such engineering solution is significant; however it was never studied in detail relative to the certain hardware.

II. Goals and Objectives

One of the new generation Hall thrusters is multimode two-stage TAL D-80 Figure 4. The thruster testing and verifying is being carried out since 1999[9,10,11,12]. Rich experimental data base is obtained for the thruster. Results are quite promising:

- One-stage and two-stage schemes operating ability was proven.
- A unique operating envelope of parameters was determined.
- Areas of preferable one-stage and two-stage schemes within the envelope were found out (Figure 5).
- Erosion tests were carried out at different schemes

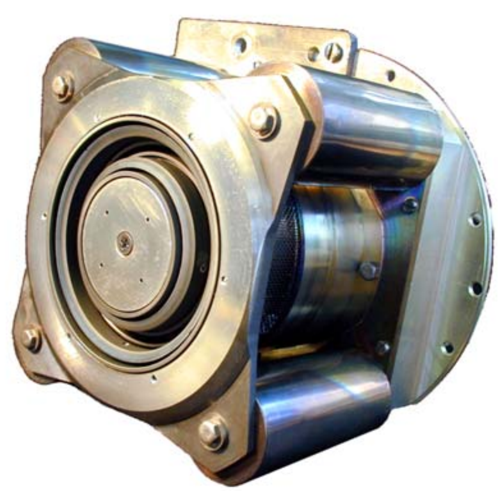

Figure 4. D-80 Photo.

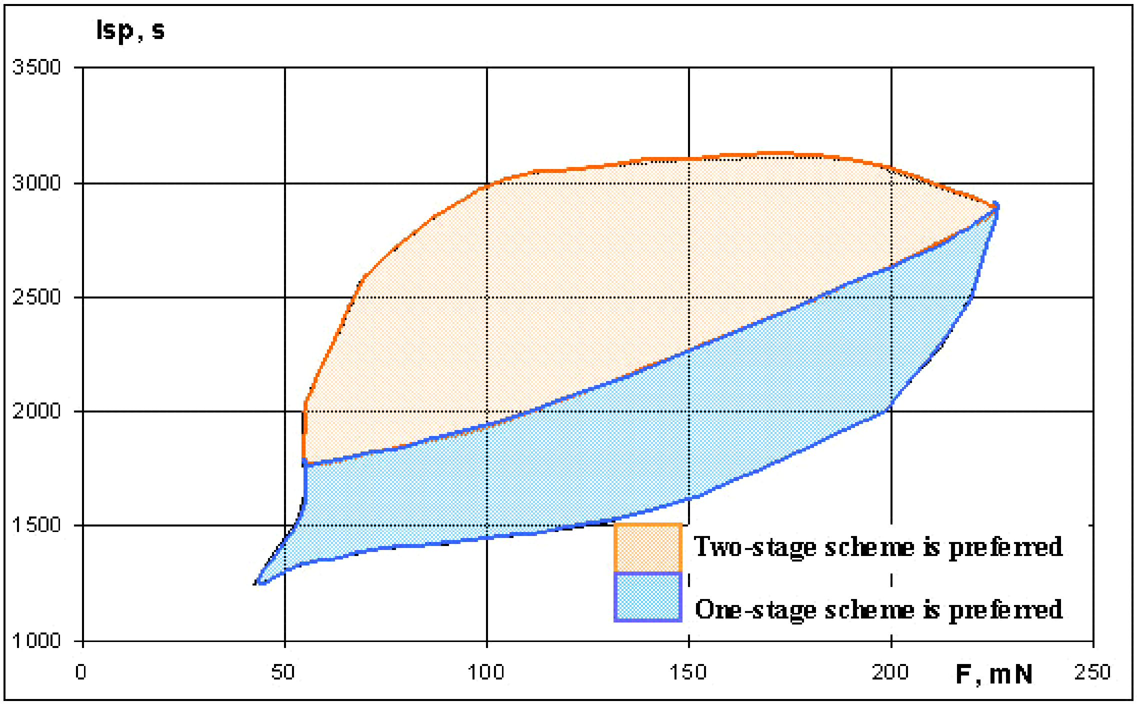

Figure 5. D-80 Operating envelope.

and modes.

Obtained erosion tests results[11,12] allows to do optimistic estimation for the thruster lifetime. Moreover the thruster design can be optimized for further erosion rate decreasing.

Thus the thruster operating envelope includes the appropriate modes for the modern SC. It was decided to study in detail D-80 at FE scheme and to compare its characteristics with ones obtained at one- and two-stage schemes.

The FE detail study includes obtaining:

1. Realization of FE scheme for given hardware;
2. Volt-ampere characteristics
3. F, I_{sp} and efficiency;
4. Oscillations, ion beam divergence, ion spectra...
5. Lifetime characteristics.

The paper presents the first test series at FE scheme which was dedicated to 1-3 positions (see above).

Physical idea of FE scheme arises from the two-stage scheme. At two-stage scheme discharge channel potential distribution is mainly determined by power supplies. Electric potential of the first stage cathode is determined by balance of the plasma currents (electrons and ions) and power supply current. There are some conditions at two-stage connection scheme when the summary current to the first stage cathode is practically absent. The conditions are realized at the first stage and the second stage currents equality. It provides a potential possibility to exclude the connection of the electrode with power supply system – the first stage cathode becomes floating. The cathode potential in this case is determined by the balance between electron and ion currents from the discharge plasma.

III. Test Procedure

TsNIIMASH vacuum chambers of 5 cubic meters equipped with 5 oil diffusion pumps and with forvacuum mechanical pumps was used to run the thruster. The general view of the test facility with measuring equipment is shown in Figure 6. Vacuum tank is equipped with power supply and xenon management systems and measurement equipment. Vacuum system had provided tank pressure no more than 0.00025 torr (not corrected for Xe) for all tested D-80 modes. TsNIIMASH laboratory multi-purpose cathode-neutralizer was used for the thruster tests. The cathode-neutralizer was not optimized for any specific thruster and provided electron current in a range 0…10 A with cathode mass flow rate about 0.4 mg/sec.

D-80 multimode two-stage thruster was tested at one-stage, two-stage and FE connection schemes. Three distinctive mass flow rates of the thruster operating envelope were chosen: ~3.5 mg/s (relatively low mass flow rate value); ~4.7 mg/s (average value) and 6.3 mg/s (large value). Maximal summary voltage was limited by stationary modes at one-stage scheme. Maximal D-80 summary voltage obtained for one-stage scheme is about 800 V. D-80 at two-stage scheme and FE scheme can be stationary operated up to 1000 V.

IV. Results and Discussion

Firstly for the two-stage connection scheme the thruster parameters at the currents (I_a, I_d) equality

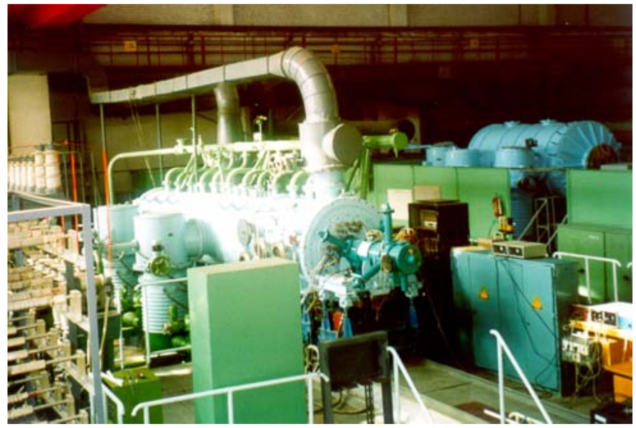

Figure 6. TsNIIMASH vacuum chamber.

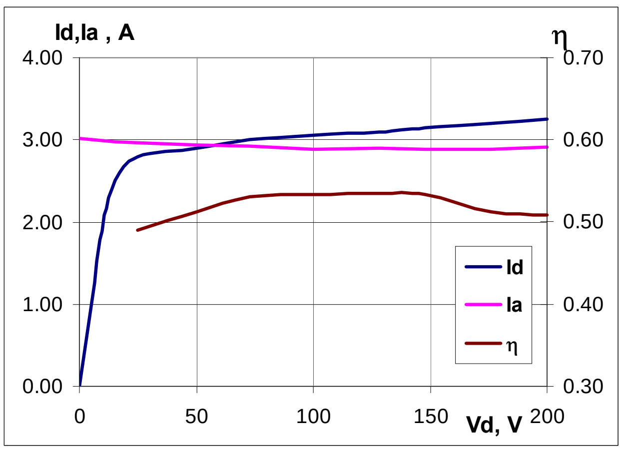

Figure 7. Two-stage scheme. *m_a~3.5 mg/s, Vsum~700 V.*

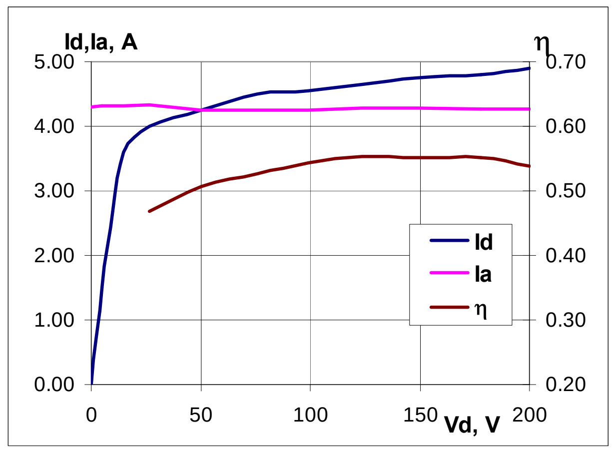

Figure 9. Two-stage scheme. *m_a~4.7 mg/s, Vsum~700 V.*

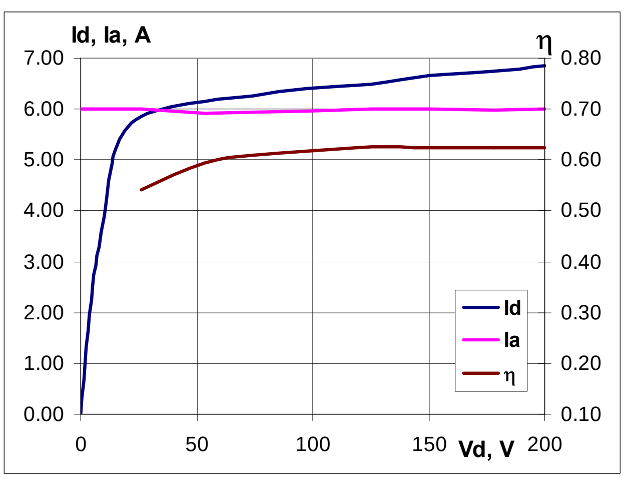

Figure 8. Two-stage scheme. *m_a~6.3 mg/s, Vsum~700 V.*

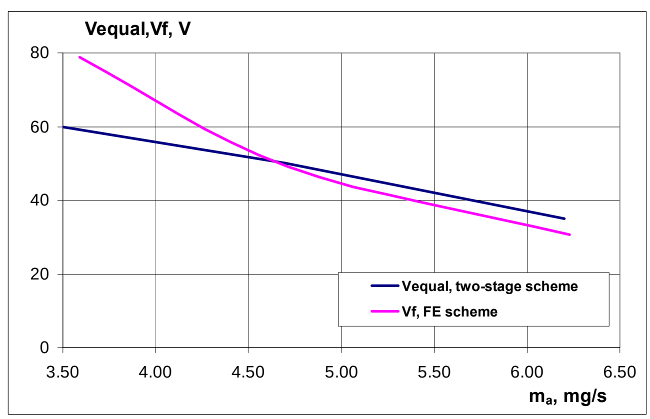

Figure 10. Two-stage and FE schemes. *Vsum~700 V.*

conditions were studied. Figure 7-Figure 8 present the first stage current, the second stage current and efficiency as functions of the first stage voltage. As one can see mentioned above condition exists. There is the first stage (discharge) voltage value at which the currents are equal: $I_a = I_d$. This voltage value was called V_{equal}. For tested modes V_{equal} value varied in range 30-70 V, and it is reducing with mass flow rate value increasing. It is important that thruster efficiency at V_{equal} is close to the maximum value. V_{equal} as a function of the mass flow rate is given in Figure 10. Approximate FE scheme efficiency also can be estimated from the figures.

Blue curve corresponds to the two-stage scheme (V_{equal}) and pink one to the FE scheme (V_f). As one can see general trends of both dependencies are similar, but at the same time there is the significant difference between

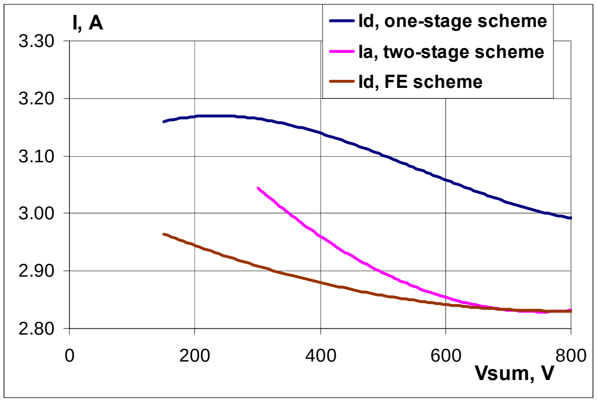

Figure 11.Volt-ampere characteristics. *m_a~3.5 mg/s.*

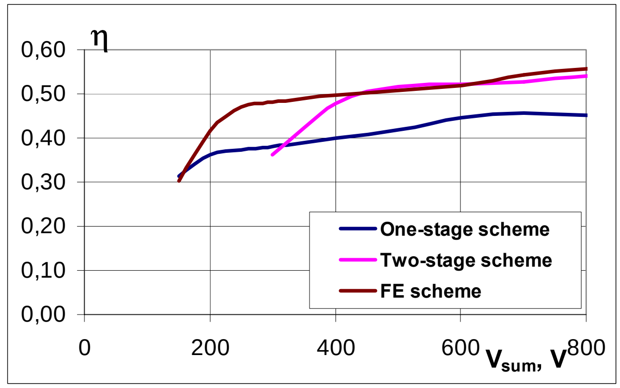

Figure 16. Efficiency. *m_a~3.5 mg/s.*

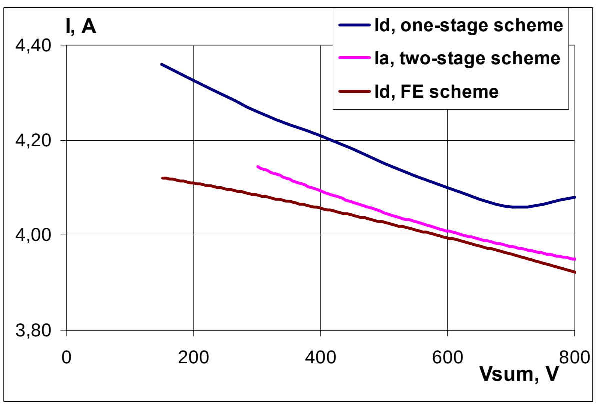

Figure 12. Volt-ampere characteristics. *m_a~4.7 mg/s.*

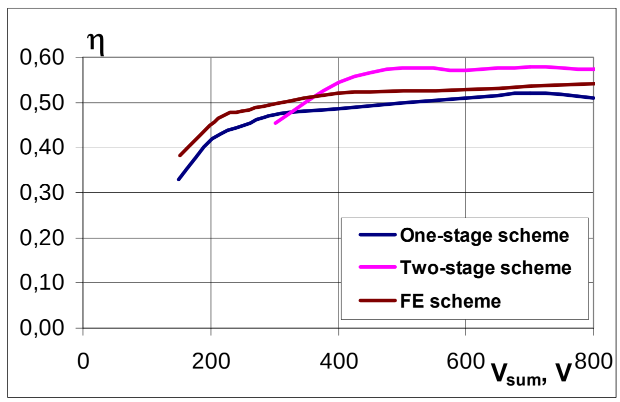

Figure 14. Efficiency. *m_a~4.7 mg/s.*

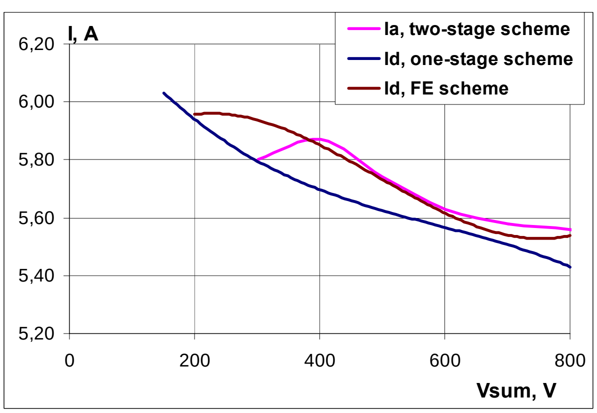

Figure 13. Volt-ampere characteristics. *m_a~6.3 mg/s.*

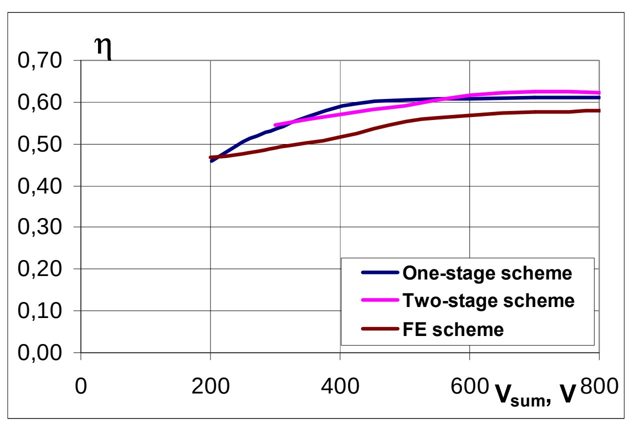

Figure 15. Efficiency. *m_a~6.3 mg/s.*

predicted floating electrode potential values and real one at low mass flow rates values.

This difference indicates that FE scheme operation has essential differences in comparison with two-stage scheme.

So the FE feasibility of realization for the D-80 was identified. Approximate FE scheme efficiency also can be estimated from the figures.

Volt-ampere and efficiency characteristics at different connection schemes are given in Figure 11-Figure 16 at different mass flow rate values. At two-stage scheme the second stage current is shown.

It can be seen that FE scheme as well two-stage scheme for low (3.5 mg/s) and average (4.7 mg/s) mass flow rates allows reducing discharge current. It leads to efficiency growth as compared with one-stage scheme efficiency. Two-stage scheme efficiency grows at high voltage (400 V and higher), and at FE scheme thruster efficiency higher than at one-stage scheme starting from 150-200 V.

However at the large mass flow rates one-stage scheme is preferred than FE. It is connected with low value of floating electrode potential (see Figure 10). At the large mass flow V_f is about 30 volts, it is not enough for efficient ionization.

Summarizing the volt-ampere and efficiency experimentally obtained data for the different schemes it can be said:

Low mass flow rate (3.5 mg/s). There is highest efficiency and lowest current at FE scheme, though parameters at two-stage are close to ones at FE scheme.

Average mass flow (4.7 mg/s). Again current at FE scheme is minimal, but at two-stage there is highest efficiency. Efficiency at FE scheme higher than at one-stage.

Large mass flow (6.3 mg/s). Minimal discharge current is at one-stage scheme. Efficiency at FE scheme is lowest.

V. Conclusion

1. Feasibility of the D-80 operating at FE scheme was demonstrated. Volt-ampere and efficiency characteristics at FE scheme were obtained. Floating electrode potential can reach value of 100 V at low mass flow rates and it reduces down to 30 V at large mass flow rates.
2. There is a significant difference between predicted and measured floating electrode potential value. This matter needs further studying.
3. Preferable range of mass flow rate values for FE scheme application is identified.
4. For certain mass flow rate values EF scheme provides a unique ability to regulate the thruster parameters in wide range.
5. Proposed operating algorithm of D-80 operating with help only one power supply is the following:
    - FE connection scheme application for low and average mass flow rates.
    - One-stage connection scheme for large mass flow rate.

Such algorithm allows obtaining parameters at FE scheme throughout all the range determined earlier (see Figure 5) with help only one discharge power supply.

FE scheme will be researched further. Studying of discharge oscillations, lifetime characteristics and magnetic field influence on floating electrode potential at FE scheme is planned.

References

[1] "Express-2000 platform technical characteristics", http://www.npopm.ru/e/produkt/platforms/e2000.htm.

[2] Michel LYSZYK et al, "Electric Propulsion on @BUS Platform", IEPC 2003-170, 28th International Electric Propulsion Conference. Toulouse, France, March 17-21, 2003.

[3] D.Y. Oh, G. Santiago, "Analytic Optimization of Mixed Chemical-Electric Orbit Raising Missions", IEPC-2001-173, 27th International Electric Propulsion Conference Pasadena, CA, October 2001.

[4] "SMART-1 Primary Electric Propulsion Sub-System The Flight Model", Christophe R. Koppel et al, IEPC-2003-205, 28th International Electric Propulsion Conference. Toulouse, France, March 17-21, 2003.

[5] Grishin S.D. et al, "Electric Propulsion", Mashinostroenie, Moscow, 1975 (in Russian).

[6] Grishin S.D., V.S., Leskov L.V. "Spacecrafts electric thrusters" Mashinostroenie, Moscow 1989 (in Russian).

[7] Kovrizhko A.F., Safronov I.N., Semenkin A.V., Study of two-stage thruster with anode layer and one power source Sov. Journal of Appl. Mech. & Tech. Phys., № 6, 1981 (in Russian).

[8] Ageev V.P., Safronov I.N., Tverdokhlebov S.O., "Operating Mode Characteristics and Performance of Two-Stage Anode Layer Accelerator with Low Voltage and Magnetic Field", Sov. Journal of Appl. Mech. & Tech. Phys., № 6, 1987 (in Russian).

[9] S. Tverdokhlebov, A. Semenkin and A. Solodukhin, "Current Status of Multi Mode TAL Development and Areas of Potential Application.", AIAA 2001-3779, Joint Propulsion Conference.

[10] A. E. Solodukhin, A. V. Semenkin, S. O. Tverdokhlebov and A. V. Kochergin, " Parameters of D-80 anode layer thruster in one- and two- stage operation modes", IEPC-2001-032.

[11] D. Jacobson, "High Voltage TAL Erosion Characterization.", AIAA-2002-4257.

[12] Solodukhin A.E., Semenkin A.V. "Study of Discharge Channel Erosion in Multi Mode Anode Layer Thruster", IEPC 2003-0204, 28th International Electric Propulsion Conference, March 17-21, Toulouse, France.