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# STUDY OF DISCHARGE CHANNEL EROSION IN MULTI MODE ANODE LAYER THRUSTER

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## Abstract

Accelerated erosion tests of multi-mode D-80 anode layer thruster were carried out in three different modes. Tested modes differed from each other by using of one- or two-stage scheme where low or high summary voltage applied. Experimental data of erosion rate relation to a variation of summary voltage applied and at approximately same input power were obtained. With the help of consideration of simplified theoretical model of ion flux distribution in discharge channel, the thruster operating parameters influence on erosion characteristics was analyzed.

## NOMENCLATURE

| | |
|---|---|
| $V_d$ | Discharge voltage (1st Stage) |
| $I_d$ | Discharge current |
| $V_a$ | Acceleration voltage (2nd stage) |
| $I_a$ | Acceleration stage current |
| $\dot{m}_a$ | Anode mass flow (Xe) |
| N | Input power |
| $V_{sum}$ | Summary Voltage ($V_d + V_a$) |
| $I_{sp}$ | Specific impulse |
| F | Thrust |
| $\eta$ | Efficiency |
| $T_i$ | Chaotic ion temperature |
| $n_i$ | Ion concentration |
| $T_e$ | Chaotic electron temperature |
| $n_e$ | Electron concentration |
| $\tau$ | Ion travel time through the anode layer |
| B | Magnet induction |
| $M_i$ | Ion mass |
| $\alpha$ | Cathode sputtering coefficient |
| $\delta$ | Linear erosion value |
| $\dot{\delta}$ | Linear erosion rate |

## Introduction

The most perspective and interesting type of space EP missions, which are under consideration now, is a combination of orbit raising from some intermediate orbit to geo stationary one with consequent keeping of the S/C on GEO during several years.

To perform such a mission EP system has to satisfy specific and contradictory requirements:

- The first one comes from consideration of economical efficiency of orbit raising part of the mission: time for the maneuver should not exceed 3 months[1]. This limit, in turn, leads to idea to maximize thrust and use for it the most part of onboard electric power.
- The second requirement comes from consideration of the second part of the mission – orbit keeping. Level of thrust values required to maintain S/C in North/South and West/East directions are significantly lower than that for orbit raising maneuver. At the same time, while S/C is in working position, most of power has to go to a payload (radio transmitters, for example) and EP system has to consume significantly lower level of power. From the other hand, the mass of propulsion system and, in particular, the propellant mass for orbit keeping has to be minimized. Such a combination leads to necessity to have high specific impulse modes for this part of the mission.

Application of two different EPS one for orbit rising and another for the orbit keeping undoubtedly results in essential mission cost increasing. Therefore the idea of using one and the same EPS for both purposes looks very attractive.

In the frames of the program aimed at significant Hall type thrusters operating envelope expanding, in TsNIIMASH two-stage anode layer thruster D-80 had been developed[2]. Two-stage design allows to reach significantly higher specific impulses as compared with one-stage thrusters. From another side it allows to combine in one hardware one-stage modes with high thrust level and two-stage modes with high specific impulse.

D-80 design is shown in Figure 1.

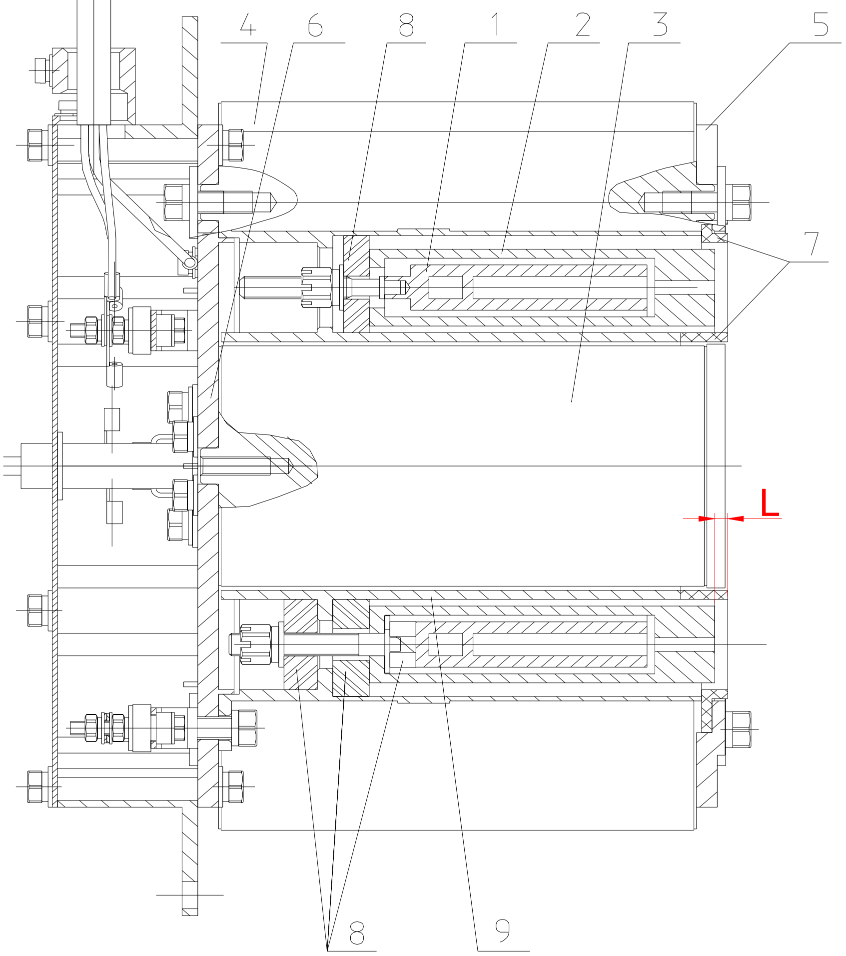

Figure 1. D-80 design.

The thruster consists of two main parts:

1. Magnet system.
2. Anode unit.

Magnet system, in turns, consists of following main components:

- mounting flange (#6);
- inner coil with magnetic pole (#3);
- outer coils (#4);
- outer pole piece (#5).

The anode unit is mounted on magnet mounting flange. It includes gas distributing anode (#1), first stage cathode (#2), guard rings (#7), insulators (#8), screen (#9). Anode unit components which are under different potential are isolated from each other with the help of insulators (#8). Magnet system poles are protected from ion sputtering by using the guard rings (#7).

Mainly radial magnet field is formed between magnet system poles. Voltages from power supplies are applied between the anode, the first stage cathode and channel walls (guard rings), the latter electrically connected with the cathode-neutralizer. Thus discharge with closed drift of electrons in crossed electric and magnet fields is appeared. Propellant entering into the discharge is ionized and accelerated.While operating in two-stage scheme ionization and consequent acceleration are realized in two separate discharges: in the discharge stage (first discharge) almost full propellant ionization occurs, and ions acceleration takes place in the acceleration stage (second discharge).While operating in one-stage scheme voltage is applied only to the second stage, thus ionization and acceleration happen in one discharge.

The thruster characteristics detailed study confirmed that the thruster can operate as well in one-stage scheme typical for modern Hall thrusters as in two-stage scheme. The change from one scheme to another does not require the thruster design modification and can be accomplished by power supply scheme change.

Areas of preferable one-stage and two-stage schemes using are shown in Figure 2. High thrust level is provided in one-stage scheme and in low voltage modes (less than 400 V). High specific impulse is provided in two-stage scheme in high voltage modes (up to 1000 V)[3].

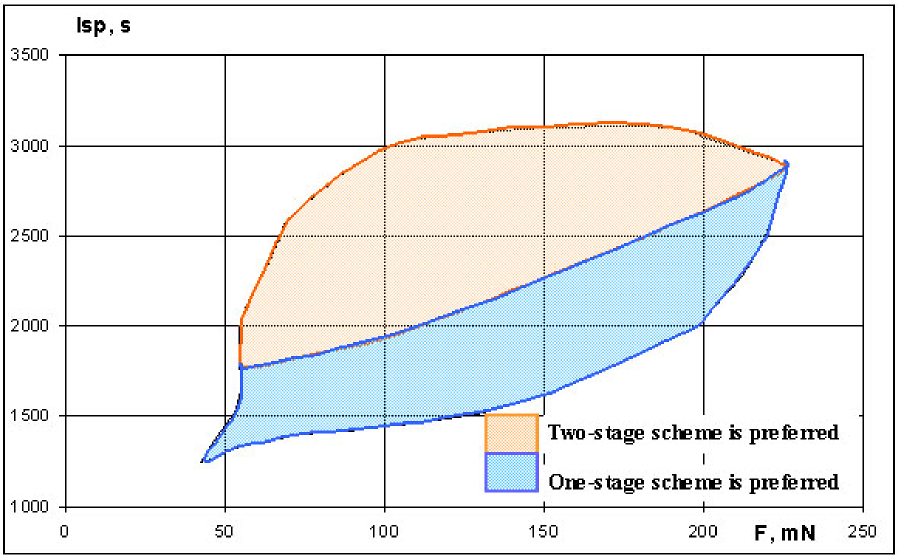

Figure 2. D-80 Operating envelope.

After detailed study of the thruster operating envelope, the next phase of the thruster development was consideration of lifetime providing. Sputtering of the surfaces exposed to the plasma discharge is the main life-limiting factor of any Hall thruster operation. To protect the structure from erosion the thruster employs a special guard rings that are located adjacent to the magnetic pole pieces and are made from the sputter-resistant conductive material (Figure 1 #7). At the operating in two-stage scheme the first stage cathode erosion can be expected, however the sputtering should be less intensive in comparison with the guard rings sputtering, since the discharge voltage applied to the first stage cathode is lesser than acceleration voltage applied to the guard rings.

There are several ways to provide the thruster lifetime required:

1. Very sputter-resistant materials utilization.
2. The guard rings thickness increasing.
3. The discharge channel length (L, see Figure 1) reducing.

The last way is the most efficient, it potentially allows to exclude construction elements direct bombardment by accelerated ions flux. This way is demonstrated in the TAL-WSF (D-55)[4] and in TAL-110[5] design and D-80 design allows to vary discharge channel length and to implement scheme with external anode layer. Though discharge channel length reducing requires magnet system mass increasing and additional magnet coils power, therefore it is reasonable to determine maximum discharge channel length corresponding to the lifetime required thus minimizing magnet system mass and magnet coils power.

To determine acceptable discharge channel length it is necessary to estimate erosion rate in chosen operating mode. There are available experimental data obtained after TAL lifetime tests carrying out in steady modes for discharge voltages range 150…350 volts. TAL high voltage modes erosion characteristics were not studied yet. Due to this uncertainty D-80 initial discharge channel length was chosen as a reference value equal to 3 mm, since this discharge chamber geometry provides reliable and efficient operating in wide range of working parameters.

The first erosion D-80 tests were carried out at NASA Glenn Research Center[6] in one-stage scheme high voltage mode ($V_d$=700 V, $I_d$=4 A) and the first erosion characteristics were obtained. However, for multi-mode concept realizing, it is needed to determine erosion rate relation to a variation of operating mode.

Therefore the aim of the current research was to study erosion characteristics in one- and two-stage schemes in different voltage modes.

**Erosion tests procedure and results**

In comparison with the thruster tested at NASA GRC the next version of D-80 thruster was modified using the previous experimental experience and results of the first erosion tests[6]. The main difference between them is the discharge channel length. The length was reduced from 3 mm down to 1.8 mm to prove the feasibility erosion rate decreasing in comparison with base design. Another difference is the material of guard rings. For erosion tests acceleration guard rings made of stainless steel were used. Stainless steel erosion rate is significantly higher than erosion rate of pyrolitic graphite, which is utilized for guard rings of the thruster tested at NASA GRC. The guard ring material replacement was repeatedly proved before for the erosion test acceleration[4,7]. Stainless steel erosion rate can be converted to pyrolitic graphite erosion rate with the help of experimental coefficients obtained for this pair of materials and energy of xenon ions corresponding to the thruster operating modes. Ratio between the erosion rates of stainless steel and graphite is usually in the range of 5…7.

Guard rings material does not influence on the other thruster characteristics, that was repeatedly proved by dedicated experiments on D-80.

As it was mentioned above erosion characteristics in one- and two-stage schemes low and high voltage modes were compared:

1. One-stage scheme, High voltage mode.
2. Two-stage scheme, High voltage mode.
3. One-stage scheme, Low voltage mode.

Concrete operating parameters for every mode were chosen in accordance with the following conditions:

- To make easier results comparison input power should be equal in all modes.
- The thruster steady state with safe thermal condition should be maintained.
- At high voltage modes summary voltage applied should be at least twice as much voltage applied at low voltage mode.

Selected parameters are given in (Table 1).

Table 1. Tested modes operating parameters.

| **MODE/ PARAMETER** | Two-stage, High voltage | One-stage, High voltage | One-stage, Low voltage |
|---|---|---|---|
| $m_a$, mg/s | 4.7 ± 0.1 | 4.7 ± 0.1 | 7.95 ± 0.1 |
| $V_d$, V | 705 ± 5 | 125 ± 5 | 355 ± 5 |
| $I_d$, A | 4.1 ± 0.1 | 4.4 ± 0.1 | 7.8 ± 0.1 |
| $V_a$, V | —//— | 575 ± 5 | —//— |
| $I_a$, A | —//— | 4.0 ± 0.1 | —//— |
| N, W | 2891 ± 91 | 2851 ± 112 | 2770 ± 75 |
| F, mN | 114…123 | 124…128 | 161…169 |

Test run duration was chosen to provide reliable erosion profile measurement. It was equal to 28…100 hours in every mode. During the tests the thrust value was measured every hour. Cathode-neutralizer mass flow rate value did not change and was equal to 0.4 mg/s. Residual pressure did not exceed $2.5 \cdot 10^{-4}$ torr. Operating parameters during the every run were within the range predetermined (see Table 1), i.e. we can state that in every run stable mode was kept.

After every run completion the vacuum chamber was opened, the thruster was dismounted and the guard rings used were replaced by new ones. There were no other replacements in the thruster construction.

Used guard rings were measured with the help of profilometer, which allows to measure the erosion along the channel axis at several azimuth sections. Discharge channel erosion profiles obtained after 30 hours of tests duration in every run are shown in Figure 3. Each erosion profile point is averaged by 12 measurements made with 30° step around the channel.

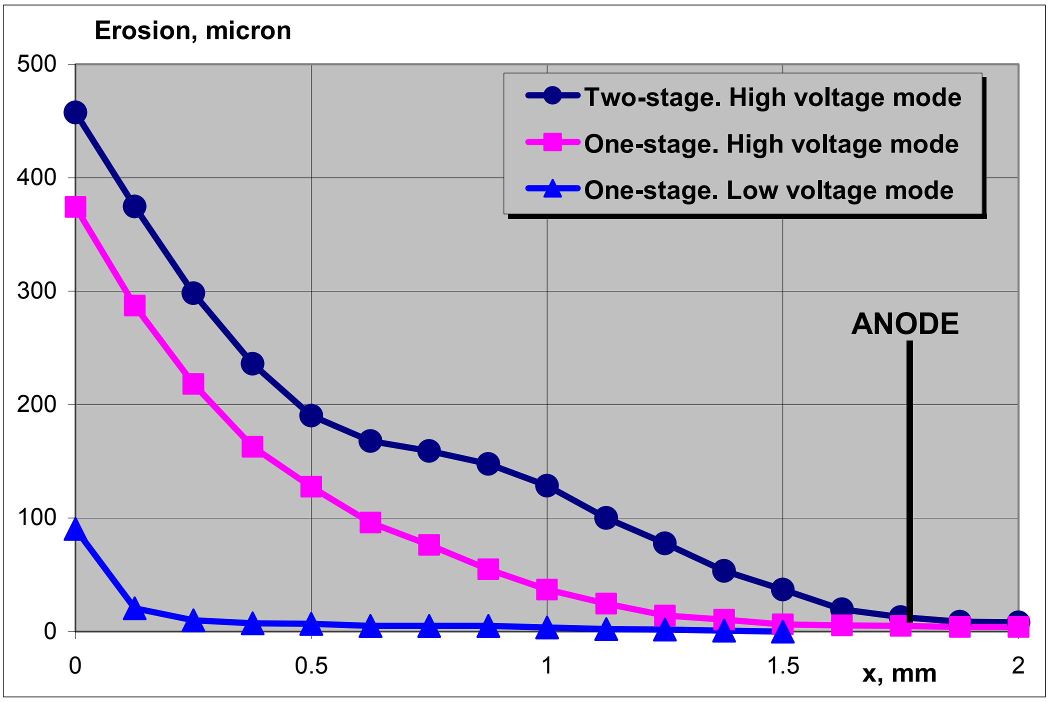

Figure 3. Erosion profiles obtained in different modes.

The discharge channel length is on abscissa axis, X = 0 corresponds to the thruster exit plane and $X_A$=1.8 mm corresponds to the second stage anode position (first stage cathode). Erosion rates measured at X=0 position are given in Table 2 where NASA GRC result is also shown for comparison. It was obtained by measuring discharge channel profile published in paper[6] after 300 hours duration run. TsNIIMASH experimental data of stainless steel guard ring erosion rates are recalculated for pyrolitic graphite.

Table 2. Guard rings erosion rate obtained in different modes.

| **Site of Erosion Tests carrying out** | **Mode** | **$V_{sum}$, V** | **N, W** | **$\dot{\delta}$, µm/h** |
|---|---|---|---|---|
| **NASA GRC** | One-stage, High voltage, L=3 mm | 700 | 2800 | 3.3 |
| **TsNIIMASH** | One-stage, High voltage, L=1.8 mm | 700 | 2800 | 2.4 |
| | Two-stage, High voltage, L=1.8 mm | 700 | 2800 | 3.2 |
| | One-stage, Low voltage, L=1.8 mm | 350 | 2800 | 0.54 |

In two-stage scheme high voltage mode the first stage cathode erosion was not identified. At least the erosion was lesser than sensitivity of the used measuring device.

### The results discussion

Obtained data show two main facts:

1. Erosion characteristics in one-stage scheme in low voltage mode accurate within to measurement error coincided with ones of D-55 and TAL-110 in comparable modes.
2. Erosion rate in high voltage modes significantly exceeded one in low voltage in spite of the fact that the input power was the same in all modes.

Since D-80 erosion rate in low voltage mode coincides with erosion rates of D-55[4] and TAL-110[5] thrusters in comparable modes all previous experience of one-stage thruster lifetime providing is also fully applicable for D-80. It means that the D-80 lifetime equal to 5000…10000 hours in low voltage mode can be provided.

The same order of erosion rate magnitude obtained at NASA GRC and at TsNIIMASH data proves its significant growing due to voltage doubling, i.e. the growing can not be explained by specific character of the tests. On the other hand, the discharge channel length reducing allowed to decrease erosion rate as compared with the previous thruster version. There is a possibility of further design optimization to provide required lifetime in high voltage modes.

In two-stage scheme the first stage cathode erosion absence can be explained by lesser discharge voltage and sputter-resistant first stage cathode material. The first stage cathode erosion rate is lesser than guard rings erosion rate, but the effect shall be investigated further in detail for required lifetime providing.

The most interesting result of the performed erosion tests is nonlinear dependence between erosion rate and applied voltage. Therefore it is reasonable to consider possible processes which can lead to nonlinear erosion rate behavior due to the thruster operating mode variation. This phenomenon is of great importance because for Hall type thruster lifetime forecasting the assumption is used, that the erosion rate is directly proportional to input power[4], i.e. erosion rate in operating modes with different discharge current and voltage may be the same if the discharge power is equal. The assumption is right if ionization zone location relative to the thruster construction elements and ion flux focusing remain unchangeable. It was experimentally proved for TAL mass flow variation at constant voltage and for relatively narrow voltage range 150…350 V. Tested high voltage modes are well over this range and detail consideration of physical model of ion flux distribution in discharge channel is needed.

Detail physical model consideration is too difficult task, which is not fully solved up to now. Calculation methods are hardly compatible for engineering approach and design analysis. Therefore we will consider simplified models allowing to get rough (approximate) analytic dependencies for the phenomenon observed.

Depending on discharge chamber geometry two typical flow modes can be marked:

- one-dimensional flow model, i.e. plasma parameters are homogeneous across the velocity vector;
- two-dimensional flow model, plasma parameters are inhomogeneous across the velocity vector.

Both flow modes are illustrated in Figure 4.

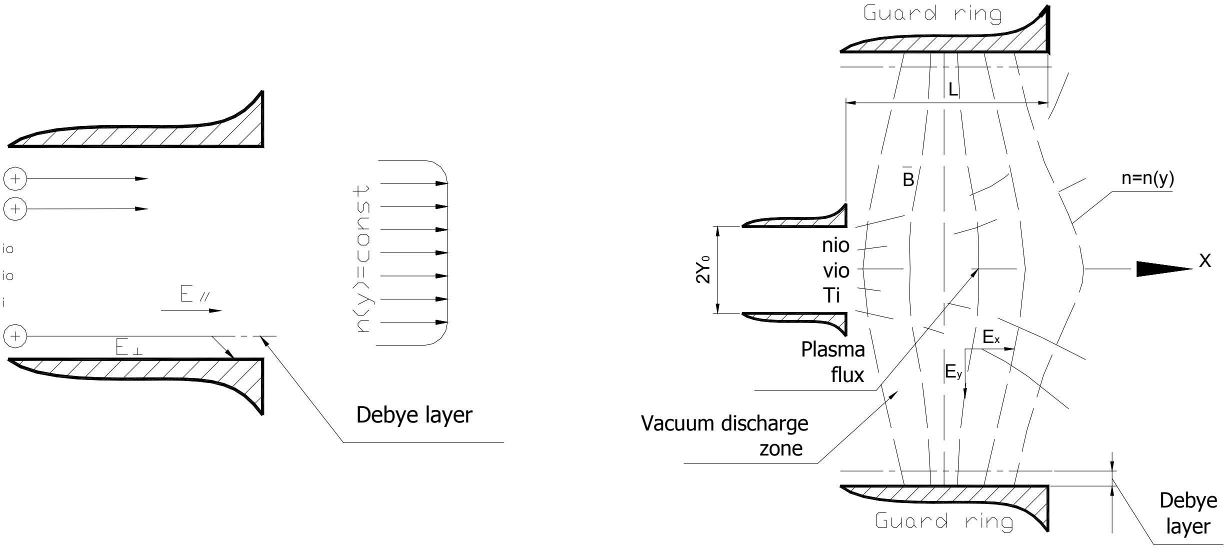

Figure 4. One- and two- dimensional flow models.

Let us assume that the propellant ionization happens just at the anode gas-distributor. It assumption has a physical meaning for both one-stage and two-stage schemes, because in the two-stage scheme fully ionized propellant comes to the second stage from the first stage and modern one-stage design implements the hollow anode gas-distributor where the propellant ionization takes place.

One-dimensional flow approach is applicable in case when the discharge chamber width is much less than the discharge chamber length. For one-dimensional flow intensity of ion bombardment flux is determined by ion temperature and ion acceleration zone length. To a first approximation the acceleration zone length can be assumed as anode layer thickness:

$$L_a \sim \frac{\sqrt{V_d}}{B}. \qquad (1)$$

For the range of ion energies up to 1000 V the cathode sputtering coefficient can be described as:

$$\alpha \sim V_d.$$

With those assumption quantity of sputtered guard rings material can be described by the following expression:

$$Q \sim \alpha \cdot n_i \cdot \tau \cdot \sqrt{T_i} \sim \alpha \cdot \dot{m}_a \cdot \frac{\sqrt{T_i \cdot V_d}}{B} \sim \frac{\dot{m}_a \cdot V_d^{3/2} \cdot \sqrt{T_i}}{B} \sim \frac{(I_d \cdot V_d) \cdot \sqrt{V_d \cdot T_i}}{B} \qquad (2)$$

One can see, that according to the expression erosion rate is nonlinear function of voltage applied and also it is in inverse proportion to magnetic induction.

If $\frac{\sqrt{V_d}}{B}$ criterion remains constant while the thruster operating mode varying, then the erosion rate is direct proportional to input power ($I_d \cdot V_d$) as it was observed before[4].

One-dimensional flow model is the most simplified approach. Real ion flux distribution pattern in discharge channel is rather adequate to two-dimensional flow model. For two-dimensional approach three zones in the discharge channel can be marked:

- Main plasma flux in the center of the discharge channel.
- Vacuum discharge zone formed at the periphery of the plasma flux.
- Near wall Debye layer.

It is too difficult to find evident analytic solution for the thruster discharge channel erosion rate because of two- dimensional system complexity. However the displacement of some distinctive zones/points of erosion profile can be evaluated. Let us consider threshold position of the dependence $\delta = f(x)$ as a distinctive point. This point bounds two typical erosion profile zones:

- The first zone is located closer to the anode and characterized by relatively small erosion rate.
- The second zone is located at the exit plane of the thruster and characterized by dramatic erosion rate increasing.

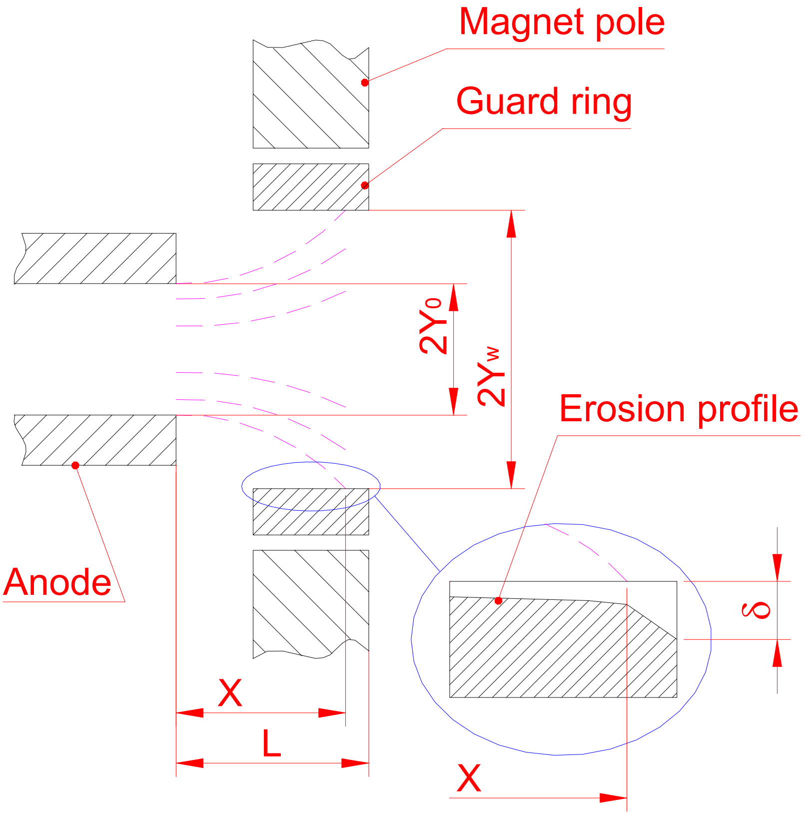

Figure 5. Discharge channel schematic.

This approach is illustrated in Figure 5. The closer the point is located to the anode, the higher total thruster construction elements erosion is. The position of the point is physically connected with guard ring bombardment by defocused part of the ion flux. It is possible to calculate this point position using ion-optical approach and considering system of equations describing ion motion.

$$M_i \frac{d^2x}{dt^2} = e \cdot E_x$$

$$M_i \frac{d^2y}{dt^2} = e \cdot E_y = f(T_e) \tag{3}$$

Let us make several assumption to solve the system of equations:

- Discharge voltage is considered to be applied at the length $L_a$ which is equal to anode layer thickness described in equation *(1).* $E_x = V_d/L$.
- Electric field cross component is constant and $E_y \sim T_e/y_0$.
- Initial ion velocities are equal to zero ($v_{ix0}=v_{iy0}=0$).
- Ion flux width variation is much less than the width itself, so it is possible to neglect the electron temperature variation during the ion flux widening.
- The electron temperature is constant along the flux and is direct proportional to the voltage applied ($T_e \sim V_d$).

Solving the system we obtain the following expression for the threshold point position:

$$X_A - X \sim \frac{(Y_w - Y_0) \cdot Y_0 \cdot B}{\sqrt{V_d}}, \tag{4}$$

where $(X_A - X)$ is the distance between anode and the threshold point location,
$Y_w$, $Y_0$ are the coordinates of discharge channel wall and initial boundary of ion flux correspondingly (see Figure 5). Values $Y_w$, $Y_0$ for the given design remain unchanged.

Assuming that, it is easy to see that when magnet induction is decreased and discharge voltage increased threshold point location is approached to the anode, and hence growing of erosion rate value at thruster exit plane should be expected.

Using the expression *(4)* relative change of threshold point location can be obtained for D-80 erosion profiles in tested low voltage and high voltage modes. In the low voltage mode the voltage applied is twice lower than in high voltage mode. While the magnet induction in the low voltage mode is in two times more than one in the high voltage mode. The expression *(4)* gives that the ratio of $(X_A - X)$ for the low and high voltage modes is equal to 3.2.

As it follows from experimental data Figure 3 $(X_A - X) = 1.8 - 0.125 = 1.675$ mm for the low voltage mode.

If the same erosion rate value will be taken as threshold point location for high voltage mode the value $(X_A - X) = 1.8 - 1.25 = 0.55$ mm will be obtained.

One can see that theoretical estimation and experimental data are in a close fit with each other. So that proposed simplified model can be considered for description of the ion flux in the discharge channel.

Solving the system of equation *(3)* angle of divergence of ion flux can also be obtained:

$$\Theta \sim arctg(k \cdot \sqrt{V_d} / (B \cdot y_0),$$

where k = constant is a proportional coefficient.

Angle of divergence is increased with voltage increasing and reduced with magnet induction increasing. It is obvious that with angle of divergence increasing discharge channel erosion grows.

So, it can be underlined that two dimensional approach consideration also gives nonlinear dependence between erosion and working parameters of the thruster.

While considering one-dimensional and two-dimensional flow models it is supposed that ionization zone location at the discharge channel is one and the same despite on variation of the operating modes. In practice the ionization zone location can be shifted due to change of the operating scheme, voltage and/or magnet induction variation. This effect can cause additional shift of distinctive zones of erosion profiles. It allows to explain the observed difference between erosion value in one- and two-stage schemes. Corresponding profiles are similar, but in two stage scheme erosion is displaced inside the discharge channel. This displacement corresponds to the ionization zone shifting into the first stage of the thruster. So, for the same angle of divergence erosion rate is larger in two-stage scheme (see Figure 3).

As a whole, consideration of D-80 operating modes allows to state, that for varying voltages and magnetic field values the change of discharge ion-optical conditions takes place. This change can be the cause of nonlinear dependence between erosion rate and thruster input power and it has to be taken into account for correct consideration of the erosion processes.

Obtained D-80 erosion characteristics are the initial experimental data, which are needed for further thruster design adjustment. It is important that in spite of various absolute erosion values in different modes, erosion profiles behavior is not changed, i.e. minimal erosion value is at near anode zone and maximal erosion value is at the thruster exit. It allows to use further discharge channel length reducing for required lifetime providing.

## Conclusion

Accelerated erosion tests of multi-mode D-80 anode layer thruster were carried out in three different modes. The significant nonlinear dependence between erosion rate and the thruster operating parameters was revealed. Erosion data necessary for further thruster design adjustment are obtained.

## Acknowledgement

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