Characteristics of Radio-Frequency Ion Thruster with an Additional Magnetic Field in the Ionization Area

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Abstract: We investigate experimentally how additional external magnetic field in the ionization area influences onto radio-frequency ion thruster's performances and we reveal that in some cases it is possible to increase its efficiency. The additional magnetic field decreases the required flow rate and input high-frequency power under the same ion beam current. That generally enhances thruster's propellant utilization efficiency. We investigate three modes of thruster operation and we obtain how electrons concentration and energy are distributed along the discharge chamber's radius for the current in an additional coil of 0, 3, 6, and 9 A. For all examined modes of thruster operation the additional permanent magnetic field equalizes electrons energy over radius and increases greatly its concentration that improves the integral performances of the thruster. We also investigate performances of RIT laboratory model on the base of pole-free configuration with permanent magnet.

Nomenclature

e	=	elementary charge
f_{rf}	=	frequency
I_i	=	ion current
I_{mf}	=	current in the winding
I_{rf}	=	current in the inductor
$\dot{m}$	=	mass flow
M_{Xe}	=	xenon ion mass
T_e	=	electron temperature
β	=	propellant utilization efficiency
R_{Le}	=	electron Larmor radius

I.Introduction

THE ion engine is one of the most promising types of electric propulsion. Its specific impulse can reach hundreds of kilometers per second[1]. Recently the radio-frequency ion thrusters (RIT)[2,3] are arousing interest. The ionization of the propellant in this type of thruster is due to the high-frequency electromagnetic field. Despite several advantages RIT has the worse energy characteristics, in comparison with the ion thrusters of the "Kaufman" type. This is due to the large share of the power of the high-frequency radiation which go to heating of the thruster construction elements and with large losses for the recombination of ions on the walls of the discharge chamber[4].

Different ways were researched to improve the RITs' energy efficiency such as: geometry and materials of the discharge chamber; and characteristics and materials of the electrodes of the grid system and inductor. These

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researches have significantly improved the characteristics of radio-frequency thrusters. However, the RIT's power consumption for ionization is all the same higher than for the "Kaufman's" type ion thrusters. Experiments made at Moscow State University[5] on high-frequency ion sources showed that the imposition of an external magnetostatic axial field in the area of the high-frequency discharge leads to the increase of plasma density. This phenomenon was used to research the possibility of improving the energy characteristics of the RIT.

II.Plasma local parameters measurements

All the studies presented were conducted with the use of the laboratory model of RIT with the 8 cm beam diameter (Fig. 1).

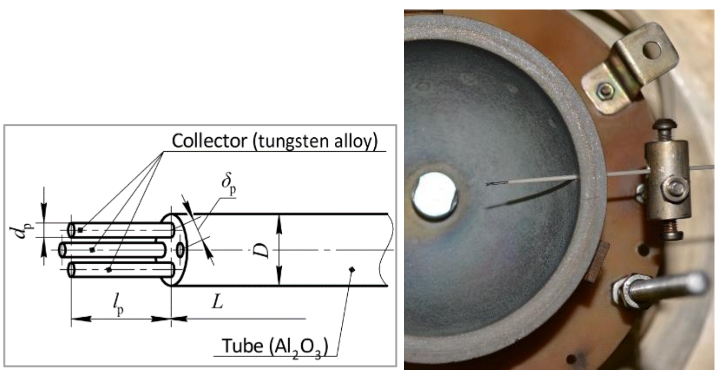
Figure 1. Laboratory model of RIT.

A. Experimental method

To solve the problems of obtaining local plasma parameters, it is necessary to choose a proper diagnostic technique. In our work we focused on the method using the Langmuir probe. This probe includes use of a cylindrical wire — collector placed in the plasma. With change of the voltage at the collector it is possible to measure current-voltage characteristic (i.e. the particles current on the probe).

The application of the classical single Langmuir probe diagnostic technique[6] is difficult in the RIT plasma due to induction discharge. The high-frequency field interferes with the collector of the probe which distorts the actual probe characteristic causing its broadening. It leads to underestimation of the electron temperature T_e and the shift of the probe floating potential towards more negative values[7].

During the study such interference on the collector should be compensated. Existing methods of compensation (both active and passive) reduce the accuracy of measurements, while they require additional hardware and mathematical tools of correcting measurement results.



a) **b)**

Figure 2. Triple Langmuir probe geometry (a). Probe installed in the laboratory model of RIT (b).

Based on the known techniques the simplest method for plasma diagnostics in the RF discharge conditions are measurements' with a triple Langmuir probe[8,9]. Such probe consists of three closely spaced cylindrical collectors (Fig. 2a). Electron temperature estimation can be obtained using a probe without additional interference from the compensation elements[10,11].

The Fig. 3a shows the placement of the investigative cross section of the discharge chamber with probe positions at which the local plasma parameters were obtained.

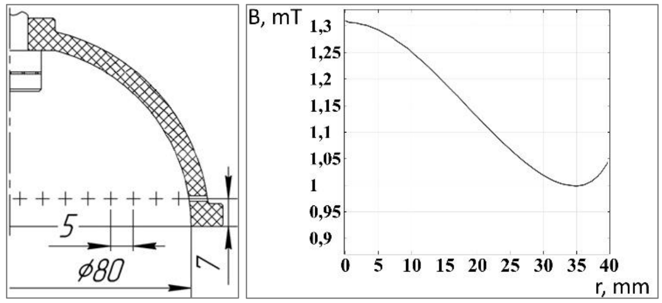
The Fig. 3b presents the result of numerical calculation of the total magnetic field induction in the investigative cross section of the discharge chamber (both current values in the inductor I_{rf} and in the additional winding I_{mf} reach 10 A)[12,13].

A preliminary calculation of the geometry of the probe collectors also considers the use of the probe in the radio-frequency discharge f_{rf} = 1.94 MHz.

The main criteria for the applicability of the triple probe were follows[6]:

- the absence of recombination and ionization in the layer at the collector of the probe (the mean free path of particles is larger than the dimensions of the probe);

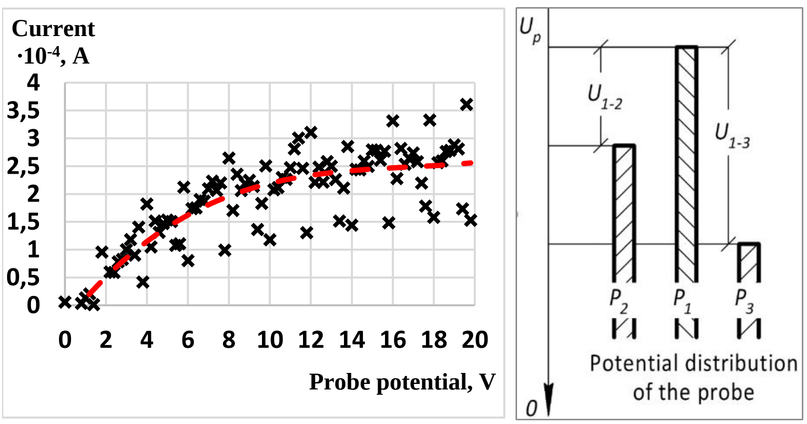
- the absence of overlapping of the particles current collecting zones (Debye layer thickness is less than the ion mean free path);
- the minimum effect of the magnetic field on the collected current (the probe length is comparable to the Larmor radius).



a) b)

Figure 3. The placement of the investigative cross section of the discharge chamber for the measurements of local plasma parameters (a). The calculation of magnetic fields in the investigative cross section (b).

The magnetic field prevents collection of electrons on the probe, so the length of the cylindrical probe has been chosen comparable to the Larmor radius for the electron in plasma $R_{Le} \approx l_p = 5$ mm. As a result, the collecting surface of the cylindrical Langmuir probe used in the experiments is a thin collector of tungsten alloy wire ($d_p = 0.2$ mm). Three collectors are placed into the tube insulator (diameter $D = 1.2$ mm, length $L = 80$ mm), made of Al_2O_3. Each collector is fixed in the tube with a compound based on Al_2O_3 powder, spacing between collectors is $\delta_p = 0.4$ mm.



a) b)

Figure 4. Probe characteristic for the single collector use (a). Potential distribution between probe collectors for triple collector mode (b).

The Fig. 4b shows the distribution of the voltages in the system of a triple probe and its circut. In the measurement mode on the collectors of the triple probe constant external potential was fixed. All potentials remain close to the floating potential in the plasma, therefore large currents are not drawn to the probe. The existence of such currents can distort the plasma formation or even destroy the probe. The probe is insensitive to plasma oscillations since each collector have simultaneous identical disturbances.

The calculation of the local parameters of the plasma for each point position in the volume of the discharge chamber is carried out according to known formulas[8]:

$$\frac{1-\exp\left(\frac{-eU_{1-2}}{kT_e}\right)}{1-\exp\left(\frac{-eU_{1-3}}{kT_e}\right)} = \frac{1}{2};\ n_e = \sqrt{\frac{m_i}{kT_e}} \cdot \frac{I \cdot \exp\left(\frac{1}{2}\right)}{eS\left(\exp\left(\frac{eU_{1-2}}{kT_e}\right)-1\right)}.$$

So the main advantages of the triple probe are following:

1. reduction of the measurement time down to microseconds due to the absence of monotonically varying voltage at the probe collectors;
2. reliable data in the RF discharge without additional filter elements;
3. simplicity of the plasma parameters calculation.

For diagnostics a data acquisition system was created that includes: a source-meter unit, an oscilloscope, a program for collecting data and a program for processing and visualizing local plasma parameters[11]. To set the Langmuir probes voltage programmable source-meter were used. Source-meter unit allows setting the voltage between two collectors and immediate measuring its currents. In the pulse mode 40 measurements are made for each position in the chamber volume and for each operating mode. The total time of the single measurement series is 150 ms. The entire measuring system is galvanically isolated from the power units of the RIT via an isolation transformer.

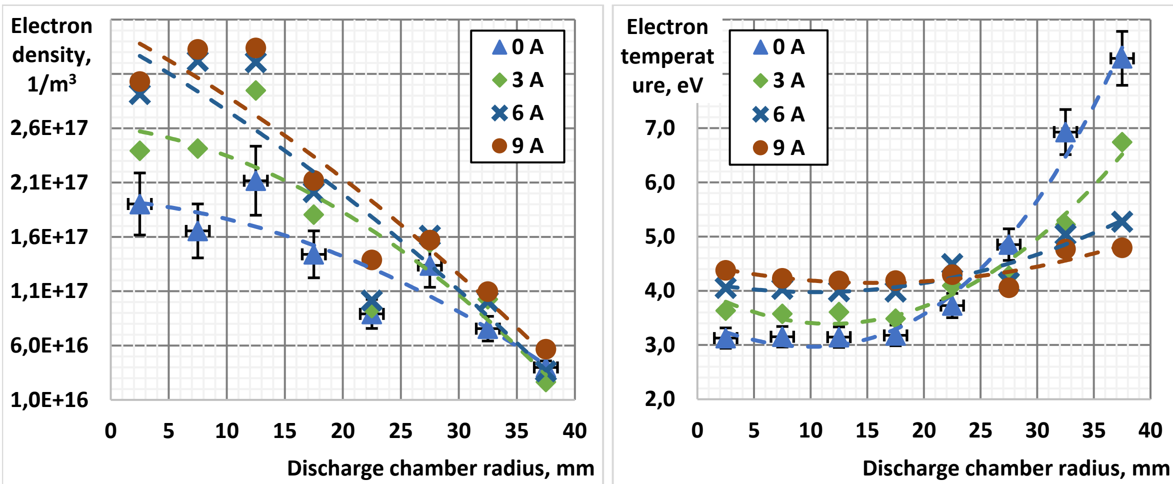
B. Experimental results

During the study, three modes of engine operation were considered:

- RF power: 60 W, flow rate: 2.24 sccm, emission grid potential: 550 V, accelerating grids potential: – 100 V;

- RF power: 82 W, flow rate: 2.87 sccm, emission grid potential: 650 V, accelerating grids potential: – 200 V;
- RF power: 98 W, flow rate: 3.98 sccm, emission grid potential: 750 V, accelerating grids potential: – 200 V.

The probe parameters for each of these modes were taken at different currents in the additional winding. The results of measurements of the local plasma parameters along the radius of the discharge chamber are presented for most typical second mode (RF power: 82 W) in the Fig. 5. As can be seen from the presented results, the additional magnetic field in the region of the RF discharge leads to a noticeable increase in the electron concentration, especially in the center of the discharge chamber, where the induction of the additional constant magnetic field is maximum. In this case, alignment of the electron temperature profile along the radius of the discharge chamber is also observed.



a) **b)**

Figure 5. Distributions of the local plasma parameters (electron number density n_e (a), electron temperature T_e (b)) along the discharge chamber radius with 82 W of RF power, 2.87 sccm of Xe, 650 V potential on the emission grid and – 200 V potential on the accelerating grid.

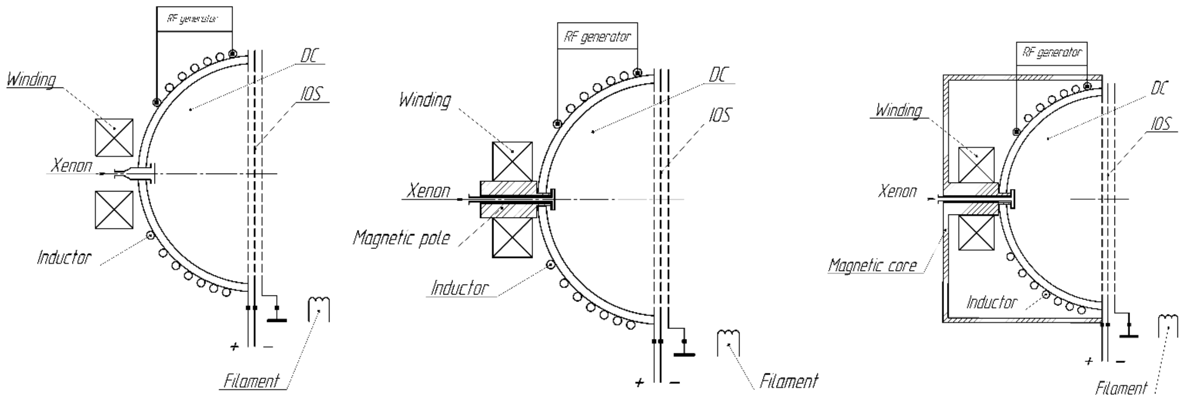
The obtained distributions of the local plasma parameters are in good agreement with the previously presented results of the study of the influence of the additional magnetic field on the integrated characteristics of the RIT[14,11]. The greatest positive effect in both cases is observed when the current strength in the winding is increased to 6 A. When switching to 9 A, the positive effect becomes less obvious.

III.Experimental comparison of magnetic systems

For a more convenient analysis[15] of the gain of an arrangement of the magnetic field, it is convenient to carry out a comparative study of the propellant utilization efficiency (P.U.E.) in the presence of a field (β_{MF}) and without it (β_0):

$$\beta = \frac{I_i M_{Xe}}{e\dot{m}}; \Delta\beta = \beta_{MF} - \beta_0.$$

Possible active pole configurations of magnetic system for the laboratory model of the RIT considered in the experiment are shown on the Fig. 6. A permanent magnet system (with single cylindrical Alnico alloy magnet) was also considered. It was similar in magnetic field parameters to the magnetic system from the Fig. 6a.



a) **b)** **c)**

Figure 6. Configurations of magnetic system for the laboratory model of the RIT: without active pole (a), with one active pole (b), with two active pole (c).

At optimal RF power values, the average *Δβ* gain due to the permanent magnet was compared with the results demonstrated by a magnetic system based on a DC winding. The histogram obtained from experimental data is shown in the Fig. 7. With the same RF input power, *Δβ* increases by 5 ... 6%, which is observed both at 50 mA and at 100 mA of the ion beam current.

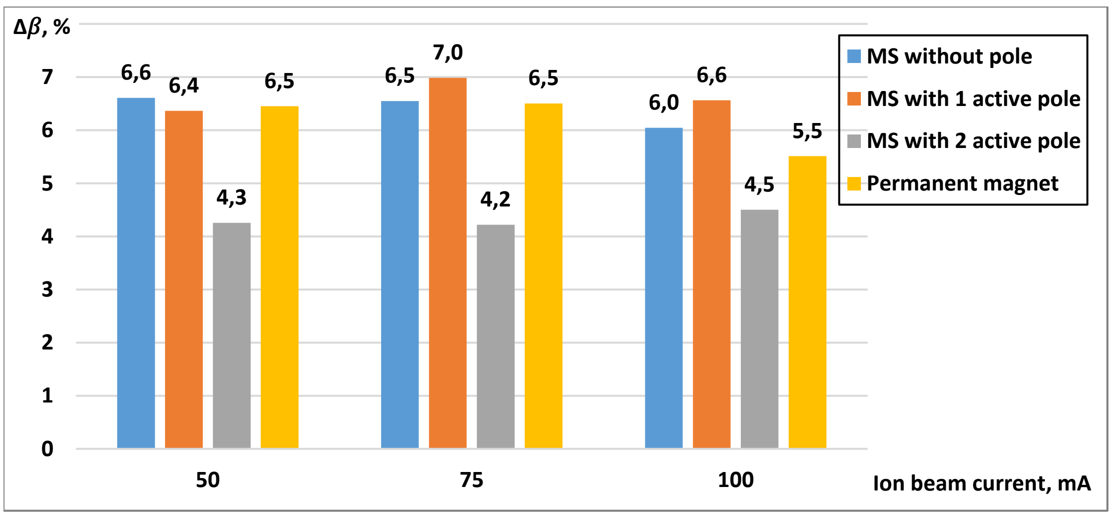


Figure 7. The average value of the increase of propellant utilization efficiency.

IV.Conclusion

Distributions of electrons concentration and temperature along the discharge chamber's radius of high-frequency ion thruster with and without additional magnetic field presence in the discharge area were obtained.

For all examined modes of thruster operation the additional permanent magnetic field equalizes electrons energy over radius and increases greatly its concentration that improves the integral performances of the thruster.

Experimental comparison shows nearly equal advantage of pole-free and one pole configurations with respect to two-pole configuration.

According to the results of the comparison, the laboratory model of RIT with a permanent magnet was prepared and tested. This engine showed stable operation in all investigated modes of operation, while ensuring the increase in propellant utilization efficiency almost at the same level of the previously considered pole-free configuration with DC winding.

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