Investigation of the operation of a microwave autogenerator with emitters of various designs

I S Vavilov, P S Yachmenev, V V Fedyanin, K I Zharikov, P V Stepen' and A I Lukyanchik
Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia
E-mail: vava-igg@mail.ru

Abstract. This paper presents the results of experimental studies of 15 design versions of capacitive and induction type microwave antennas. As part of the work on the development of an accelerator ion thruster, 32 radiator designs were studied. The research was carried out in order to select the optimal design of a plasma-generating microwave antenna for installation in the discharge chamber of a prototype ion thruster. The volt-ampere characteristics (VAC) were obtained the microwave generator when working with each design of the radiator in a vacuum chamber. The VAC is obtained in the presence and absence of a high-frequency discharge.

1. Introduction

An important element of the ion thruster is the plasma source. Currently, there are ion thruster (IT) with a DC discharge, a high-frequency discharge (RF IT) and an ultrahigh-frequency discharge (microwave IT). In a DC IT, ionization of the atoms of the working medium occurs in the gas-discharge chamber due to the collision of atoms with electrons emitted by the cathode and gaining energy from a constant electric field. To prevent electrons from leaving the anode, a magnetic field is created in front of it [1]. In the RF IT, the ionization of the atoms of the working medium occurs due to the collision of atoms with electrons receiving energy from a time-varying electric field. Depending on the frequency of electromagnetic radiation and the presence or absence of an external magnetic field, various models of thruster can be implemented. The advantage of thruster with a discharge in an electromagnetic field is the absence of electrodes necessary to maintain a gas discharge. The type of emitter is induction. The emitter is presented in the form of a multi-turn antenna wrapped around a discharge chamber. The frequency of the RF field in various designs is 13.56 MHz [2-6]. The frequency of the induction antenna 5.25 MHz is implemented in the RF IT MiDGIT [7]. The paper [8] provides information on the development of the RF IT MRIT. The MRIT thruster has a ceramic conical discharge chamber with a diameter of 10 mm and a length of 10 mm. The frequency of the antenna operation was 1...1.5 MHz. The PEGASES IT [9, 10] generates plasma at a frequency of 4.2 MHz.

Further miniaturization of IT designs led to the development of microwave IT. By increasing the frequency of the radiating antenna, it is possible to reduce the overall dimensions of the antenna and the discharge chamber. The greatest development of microwave thruster was in Japan. Electron-cyclotron resonance (ECR) the microwave IT generates thrust by emitting ions in an ECR plasma with electrostatic grids. ECR plasma is produced by ionization of the working medium by electrons accelerated by ultrahigh-frequency radiation in a magnetic field created by permanent magnets. The thruster does not use a cathode to generate plasma. The source [11] shows a microwave IT with ionization of the working medium at a frequency of 2.45 GHz and a radiation power of 30-80 watts.
The microwave energy was supplied to the working chamber via a waveguide. The microwave IT \( \mu 10 \) [12] operates at a frequency of 4.25 GHz with a power of 34 watts. The energy is introduced into the discharge chamber by means of a pin antenna. The thruster \( \mu 1 \) [13] has a cylindrical discharge chamber with a diameter of 20 mm. The thruster antenna is represented as a waveguide segment. The frequency of the microwave is 4.2 GHz, the power of the microwave is 0.5-3 watts. The MMIT microwave IT [14] consists of a discharge chamber, a back panel on which the microwave input and gas supply are located, a clamp for supporting permanent magnets, a front panel for fixing the ion-optical system, a microwave antenna and permanent magnets.

From the above description, it can be seen that two types of antennas have been used in RF and microwave ion thruster: pin and spiral (induction).

As part of the design of the accelerator microwave IT, the authors of this article needed to investigate the operation of a microwave autogenerator with various antenna designs of two types: capacitive and induction emitters. In general, 32 designs of emitters were studied: logoperiodic, coaxial, biconic, induction-capacitive heliconic, spiral, horn emitters of biconic type, pin, ring, coaxial of different sizes, an emitter in the form of a chain link and a family of mesh capacitive emitters. For all the manufactured antenna-emitters, the volt-ampere characteristics (VAC) of the autogenerator operation in a vacuum chamber with supply and ionization (or lack thereof) of working bodies—nitrogen, argon, helium—were obtained.

This paper presents the results of a study of the operation of several types of emitters with a microwave autogenerator. The power consumption of the autogenerator did not exceed 10 watts.

2. Problem statement
The authors solved the problem of choosing the optimal design of the plasma generator antenna for the development of a prototype of an accelerating microwave ion thruster (UMD) with an energy consumption of less than 10 watts. The prototype implements the concept of stepwise acceleration of an ionized gas in the high-frequency gaps of a plasma generator and a toroidal resonator. To excite the toroidal resonator, electromagnetic energy is taken from the microwave generator.

The main task of all the authors work is to study the high-frequency low-temperature ionization of gaseous working bodies in reactors based on solid-state RF and microwave elements and to study the gas-dynamic, electrical and thermal parameters of the plasma jet.

In this part of the work, the authors investigated the operation of a microwave autogenerator together with radiating antennas of various designs.

The following tasks were solved:
1. Production of two types of antennas: capacitive and induction. The antennas are made in various design versions;
2. Study of the operation of a microwave generator together with antennas in a vacuum chamber in a low-pressure nitrogen environment-up to 30 Pa. Here the power consumption of the autogenerator is estimated with a step-by-step voltage rise, the visual definition of the discharge and the power consumption with a step-by-step voltage decrease under the condition of the existence of a discharge. Thus, the area of the existence of a discharge on the antenna structure under study is determined;
3. Construction of the VAC of the autogenerator in the absence and presence of a discharge.

3. Theory
The source of microwave radiation is an autogenerator on a microwave transistor (Fig. 1), weighing no more than 40 g. Characteristics when tested in an atmosphere with a two-wire emitter, 15 cm long:
1. The supply voltage is 6-20 V. The starting voltage is 6 V with the possibility of reducing the supply voltage to 4 V.
2. The current consumption depends on the operating mode of the generator:
   – when an arc (microwave torch) occurs-the current is 1 A or more,
   – simple generation mode - from 0.1 A.
3. The current consumption (radiated power) is regulated by changing the current-limiting resistor – from 0.2 to 10 ohms.

The technical characteristics of the MOSFET transistor that are of interest in the context of the study:
   1. The frequency of 2 GHz at 26 V;
   2. EFFICIENCY up to 45 %;
   3. The operating temperature of the housing is 150 °C;
   4. The operating temperature of the connection is 200 °C;
   5. Thermal resistance of 2 °C/W.

During tests in vacuum, the antenna design under study was connected to the microwave generator through a detachable connection. A stepwise voltage rise was performed (ΔU=0.2-0.5 V), the consumption current readings were recorded, the discharge voltage was recorded. Then the voltage gradually decreased. The consumption current was fixed. As a result, the direct and reverse branches of the VAC of the autogenerator were built.

4. Results experiments
As a result of the tests, capacitive and induction antennas were manufactured and the VAC of a microwave autogenerator was obtained.

1. Capacitive mesh antenna (grids with a diameter of 8 mm, the distance between the grids is 0.5 mm) with focusing bushings and an electron removal grid

The antenna is installed in a polymer housing. The grids are installed parallel to each other at a distance of 0.5 mm. Each grid is equipped with a focusing copper bushing with an outer diameter of 10 mm, an inner diameter of 8 mm and a height of 3.6 mm (Fig. 2). Side A-to the output of the engine (in the ion optics of the acceleration system), side B-to the feed section of the working substance.

The VAC of a microwave autogenerator was obtained (Fig. 3) under the conditions of a vacuum chamber with nitrogen as the working medium.
Figure 3. VAC of a microwave autogenerator with a capacitive mesh emitter-a plasma generator, the working medium is nitrogen, the pressure in the vacuum chamber is -17 Pa

2. Capacitive mesh antenna (grids with a diameter of 6-22 mm, the distance between the grids is 1 mm)

In continuation of the topic of capacitive mesh emitters, a series of mesh emitters of various diameters without focusing bushings was manufactured and considered in work with an autogenerator (Fig. 4).

Figure 4. Capacitive mesh antennas: grid № 3-external ø14 mm, internal ø6 mm; grid № 1 –external ø15 mm, internal ø8 mm; grid № 6-external ø19 mm, internal ø10 mm; grid № 2 –external ø22 mm, internal ø12 mm; grid № 5 –external ø24 mm, internal ø15 mm; grid № 4-external ø30 mm, internal ø22 mm

The antennas shown in Fig. 4 did not allow creating a stable discharge in a low-pressure nitrogen environment. The tests were carried out at a pressure of 30 Pa. The VAC is shown in Fig. 5.

Figure 5. VAC of an auto generator with mesh antennas: a) – grid № 1; b) – grid № 2; c) – grid № 3; d) – grid № 4; e) – grid № 5; f) – grid № 6
The discharge occurs when the grids are blown with nitrogen and the power consumption of the autogenerator is 20 watts. The discharge is maintained with a gradual decrease in power to 0.45 W (Fig. 5 c).

3. Capacitive mesh emitter in a polymer housing with grids, with an external \( \varnothing 18 \) mm, internal-\( \varnothing 12 \) mm

The antenna is installed in a polymer housing. The grids are installed parallel to each other at a distance of 1 mm. The grids are not equipped with focusing bushings, the outer diameter of the grids is 18 mm, the inner diameter is 12 mm (Fig. 6). Side A to the exit from the engine (in the ion optics of the acceleration system), side B to the feed section of the working substance, a sealed cavity.

![Figure 6. Capacitive mesh emitter in the housing and its operation in the vacuum chamber: 1 – mesh \( \varnothing 12 \) mm (internal); 2 – gas supply; 3 – contacts to the microwave generator; 4 – electron removal wire; 5 – organic glass housing; 6 – copper electrode for electron removal (square \( \sim 1 \) cm\(^2\))](image_url)

Figure 7 shows the VAC of an autogenerator equipped with this emitter.

![Figure 7. VAC of an autogenerator with an emitter according to fig. 6, the working medium is nitrogen, the pressure in the vacuum chamber is -30 Pa (the sign ( \( < \) ) indicates the VAC branch obtained when the voltage is reduced)](image_url)

It can be seen that with a gradual increase in the voltage on the generator, the gas breakdown occurs in the region of 13.4-13.6 V. At the same time, the current consumption increases by 0.2 A. With a further decrease in the voltage (the reverse branch of the VAC), the discharge is maintained to a supply voltage of 2.6 V.

Figure 6 shows a photo of the emitter’s operation during the generation of nitrogen plasma. You can see the glow on the bare section of the electron removal wire.
4. Two-pin antenna
The two-pin emitter is presented in the form of two segments of nichrome wire arranged collinearly in a ceramic insulator. The distance between the pins is 0.8 mm. The pins protrude beyond the insulator to a height of 2 mm (Fig. 8).

![Figure 8. Two-pin emitter and its operation in a vacuum chamber: 1-nichrome pins; 2-ceramic insulator; 3-contacts to the microwave generator](image)

Figure 8. Two-pin emitter and its operation in a vacuum chamber: 1-nichrome pins; 2-ceramic insulator; 3-contacts to the microwave generator

Figure 9 shows the VAC of an autogenerator equipped with a two-pin emitter.

![Figure 9. VAC of an autogenerator with a two-pin emitter, the working medium is nitrogen, the pressure in the vacuum chamber is -20 Pa](image)

Figure 9. VAC of an autogenerator with a two-pin emitter, the working medium is nitrogen, the pressure in the vacuum chamber is -20 Pa

The emitter was placed in a transparent glass flask, in which gas was supplied to the emitter and gas was discharged from the flask into the vacuum space. In the microwave field, the ceramic insulator acted as a load and its temperature reached more than 100 °C, as evidenced by the melting of the polyethylene elements in contact with it.

The discharge occurs at a voltage of 13.2 V with a current jump from 0.55 to 0.59 A. On the reverse branch of the VAC, the discharge is kept up to a voltage of 3.8 V (0.22 A).

5. Capacitive multi-gap emitter
The emitter is a structure of six plates forming five capacitive gaps (Fig. 10).

![Figure 10. Multi-gap capacitive emitter and VAC of a microwave generator, the working medium is nitrogen, the pressure in the vacuum chamber is -30 Pa](image)

Figure 10. Multi-gap capacitive emitter and VAC of a microwave generator, the working medium is nitrogen, the pressure in the vacuum chamber is -30 Pa
In Fig. 10, the electrodes indicated by position 1 are connected by a common bus suitable for one of the contacts (pos. 3) of the emitter. Position 2 indicates the electrodes connected by a common bus that supplies microwave energy through the contact (pos. 3) from the microwave generator to the electrodes.

6. Capacitive emitter with intersecting rings «Link»

The antenna, called the «Link», is an intersecting rings such as a chain link (Fig. 11).

![Figure 11. The «Link» emitter:](image)

- a) - design: 1-copper rings (diameter 9 mm, tape width 5 mm); 2-contacts to the microwave generator
- b) - low voltage discharge («Discharge A»);
- c) - discharge after the breakdown of the direct and reverse branches of the VAC

The VAC of an autogenerator with an emitter is shown in Figure 12. On a direct VAC, the discharge begins with a voltage of 6.8 V (0.11 A) (the «Discharge A» zone), a breakdown occurs at 7 V with a sharp increase in current above 1 A, the peak current values fall by 14 V (0.42 A), the discharge changes color and lasts up to 17 V (0.51 A). The reverse branch of the VAC without breakdowns, the plasma exists up to 6.4 V (0.1 A).

![Figure 12. VAC of an autogenerator with an antenna «Link»](image)

7. Capacitive emitter «Petals»

A capacitive type emitter with four lobes is shown in Fig. 13. A photographic image of the discharge is also presented here.

On the direct branch of the VAC, the discharge is ignited at a section of 14-14. 2 V, the current increases from 0.22 A to 0.36 A. On the reverse branch of the VAC, the discharge lasts up to 13 V.

![Figure 13. Emitter "Petals": 1-capacitive gap; 2-electrodes; 3-contacts to the microwave generator](image)
The VAC of an autogenerator with an emitter is shown in Fig. 14.

![Graph of VAC](image)

**Figure 14.** VAC of a microwave generator with a «Petals» emitter, the working medium is nitrogen, the pressure in the vacuum chamber is -30 Pa.

8. **Bispherical emitter**

Conical type antennas (emitters) belong to simple emitters [15]. In shape, conical emitters are capacitive systems, since there is no conductor between the electrodes.

A biconic type emitter with electrodes whose working surface has a radius of curvature (Fig. 15 a). The discharge in the emitter is shown in Fig. 15 b.

![Image of a bispherical emitter](image)

**Figure 15.** Image of a bispherical emitter, its operation in a vacuum chamber and a VAC microwave autogenerator with a bispherical emitter: 1 – upper hemisphere; 2 – lower hemisphere; 3 – coaxial waveguide rack; 4 – contacts to the microwave autogenerator.

The VAC of an autogenerator with a bispherical emitter is shown in Figure 15 c. The working substance is nitrogen, the pressure in the vacuum chamber is -30 Pa.

From Figure 15 c, it can be seen that a gas breakdown occurs at the transition of 4.6-4.8 V with a current jump from 0.23 to 0.46 A. Further, energy consumption increases along the parabolets. On the reverse branch of the VAC, the discharge is maintained to a voltage of 3.2 V (0.15 A). The reverse branch coincides with the direct branch of the VAC, except for the gas breakdown section. The smoothness of the change in the geometry of the gap affects the smoothness of the ignition of the discharge, its maintenance and eliminates the errors of the installation of the electrodes.

9. **Biconic horn-type emitter**

The emitter is made in a polymer case with a transparent lid. Electrodes are metal strips mounted on the rounded surface of the housing in such a way that a horn is obtained. The gas is supplied to the narrowest place between the electrodes (Fig. 16).
Figure 16. Biconic horn-type emitter and its operation in a vacuum chamber: 1-electrodes; 2-gas input; 3-housing; 4-contacts to the microwave generator

The VAC of the autogenerator when working with the emitter is shown in Fig. 17.

Figure 17. VAC of an autogenerator with a horn emitter, the working medium is nitrogen, the pressure in the vacuum chamber is ~30 Pa

The power growth line is almost straight, the gas breakdown occurs without a sharp increase in current at a voltage of 10.2 V (0.16 A). On the reverse branch of the VAC, the discharge goes out at a voltage below 9.4 V.

10. X-shaped emitter

The emitter is made in a polymer case with a transparent lid. Electrodes are metal strips mounted on the body surfaces made with an angle of 90° in such a way that the «hourglass» shape (or the letter «X») is obtained. The gas is supplied to the lower part of the funnel, passes through a narrow place and exits from the upper part of the funnel formed by the electrodes (Fig. 18). The VAC of an autogenerator with an X-shaped radiator is also presented here. The working substance is nitrogen, the pressure in the vacuum chamber is ~30 Pa.

An arc-type breakdown occurs at the narrowest point of a pair of electrodes at high voltages (above 13 V) and is accompanied by a sharp increase in the current level. The discharge is unstable. At the slightest decrease in voltage, the discharge disappears.

Figure 18. X-shaped biconic emitter: 1-electrodes; 2-polymer housing; 3-upper funnel; 4-lower funnel; 5-gas supply
11. Y-shaped emitter

The antenna is made in a polymer case with a transparent cover. Electrodes are metal strips installed on the surfaces of the upper part of the body made with an angle of 90° in such a way that the shape of the letter «Y» is obtained. The gas is supplied to the lower part (the leg of the letter «Y»), passes through a narrow channel and exits from the upper part of the funnel formed by the electrodes (Fig. 19).

![Figure 19. Y-shaped radiator and its operation in a vacuum chamber: 1-electrodes; 2-polymer housing; 3-funnel; 4-lower gap; 5-gas supply](image)

The VAC of the autogenerator when working with a Y-shaped emitter is shown in Figure 20.

![Figure 20. VAC of an autogenerator with a Y-shaped emitter, the working medium is nitrogen, the pressure in the vacuum chamber is -30](image)

A gas breakdown occurs on a straight branch of the VAC at a voltage of 8.4 V without a current jump, the discharge develops evenly to voltages of 13.2-13.3 V, followed by an arc-type breakdown. On the reverse branch of the VAC, the discharge exists up to a supply voltage of 7.8 V (0.13 A).

13. Coaxial emitter with a short central electrode

The emitter is made of two cylindrical electrodes: covering (inner diameter of 8 mm) and covered (outer diameter of 3 mm). The covered electrode is shortened and is located inside the space of the covering electrode (Fig. 21). The electrodes are separated by a dielectric washer. The cut of each electrode, by means of soldering, is equipped with a metal grid. The gas is fed into the cavity through a metal gas pipeline.

The discharge occurs when the voltage changes from 3.8 V to 4 V and is accompanied by a current jump from 0.08 A to 0.27 A. Then the VAC line goes straight with a large angle of inclination. The reverse branch of the VAC is identical to the direct one, the discharge goes out at a voltage of 3.8 V (0.25 A).

It can be seen that the plasma is localized in the annular gap formed by the enclosing and enveloped electrodes and does not go beyond the section of the inner electrode.

The VAC of the autogenerator is shown in the diagram (Fig. 22).
Figure 21. Coaxial emitter with a shortened internal electrode and its operation in vacuum conditions: 1-external (enclosing electrode); 2-internal (enveloped electrode); 3, 4-external electrode grid; 5-internal electrode grid; 6-gas supply; 7-contacts to the microwave generator; 8-dielectric ring

Figure 22. VAC of an autogenerator with an emitter, the working substance is nitrogen, the pressure in the vacuum chamber is \(-30\) Pa

14. Annular coaxial emitter
A simple but very interesting capacitive emitter is a coaxial ring emitter with large-area electrodes and a very narrow gap between the rings (no more than 0.7-0.8 mm). Two rings of the same thickness are concentrically fixed on the dielectric base (Fig. 23). The gas moves along the coaxial transmission line and flows out through the hole in the center of the ring pair.

Figure 23. Annular coaxial emitter and its operation in a vacuum chamber (photos at different shutter speeds of the camera matrix): 1-enclosing electrode; 2-enveloped electrode; 3-gas input; 4-polymer base with a coaxial transmission line; 5-textolite washer; 6-contacts to the microwave generator

The VAC of an autogenerator with an annular emitter is shown in Fig. 24. When the voltage rises, the discharge occurs at the transition of 10.6 V -10.8 V and a current jump of 0.27 A-0.37 A. When the voltage at the 10 V -9.8 V junction decreases, the current increases from 0.38 A to 1 A, then goes beyond the permissible level. Only with 6.2 V the current comes to values of 1 A and below. The discharge over the entire area of the covering ring exists up to 5 V (0.46 A), then there is a fragmentary pulsating glow up to 4.2 V (0.26 A).
Figure 2. VAC of an autogenerator with an annular coaxial emitter, the working substance is nitrogen, the pressure in the vacuum chamber is -30 Pa.

15. Induction spiral cylindrical antenna with tight coils
The emitter is a dense cylindrical spiral of seven turns with an internal diameter of 17 mm, a wire diameter of -1.4 mm.

The VAC of the autogenerator is shown in Fig. 25.

Figure 25. VAC of a microwave generator with a spiral emitter and a photographic image of the emitter and the discharge, the working substance is nitrogen, the pressure in the vacuum chamber is -25 Pa.

The discharge occurs on the direct branch of the VAC at a voltage of 3.1 V with a small current jump from 0.37 A to 0.47 A. On the reverse branch of the VAC, the discharge is kept up to 2.5 V (0.25 A).

It can be seen that the localization of the discharge is limited by the internal volume of the cylinder. The emitter is interesting in the context of the convenience of installing ion optics elements, an electron extraction electrode from a plasma and a low level of power consumption of an autogenerator.

5. Discussion of results
As part of the project to develop an accelerator ion thruster with microwave plasma generation, experimental studies of the operation of 32 structures of capacitive and induction type antennas were carried out. This paper presents 15 design versions of plasma generator antennas. The VAC of the operation of the microwave autogenerator in conditions of low pressure of the working gas was obtained. The power consumption of the autogenerator in the tests did not exceed 10 W in the stationary operation mode. The lower limit of the existence of the discharge was 0.6 watts. From the point of view of the smooth start of the discharge, we can distinguish a bispherical capacitive antenna and a spiral induction antenna. The advantage of mesh capacitive antennas is the diffusion of ions from the discharge as their primary acceleration to the ion-optical system and the high-frequency gap of the toroidal resonator. The disadvantage of mesh emitters is the shock ignition of the discharge with a jump in the current strength, which is unfavorable for the microwave transistor.
6. Conclusion
The article presents the results of the authors’ work in the field of studying the structures of radiating antennas in order to choose the optimal plasma generator for an experimental prototype of an accelerator ion thruster [16]. The authors conducted vacuum tests with the registration of voltages and currents of consumption of the microwave generator. According to the results of the measurements, the VAC of the microwave autogenerator was obtained. For further development, based on the results of experiments, a mesh capacitive emitter was selected for the discharge chamber of the UMD prototype. This type of antenna allows us to obtain the primary axisymmetric movement of ions towards the grids of the ion-optical system.

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