Determination of the ion beam velocity of an accelerator two-gap ion thruster

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Abstract. The article is devoted to the measurement of the ion beam velocity of an accelerator two-gap ion thruster. A theoretical representation of the physical process of capturing charged particles using a cylindrical sensing element is given. A schematic diagram and a printed circuit board for detecting an accelerated ion beam have been developed. The expression for calculating the signal current of the sensing element is defined. A condition for capturing charged particles using the critical mobility of charges is formulated.

1. Introduction

A characteristic feature of scientific and technological progress is the research, development and implementation of ion thruster in small spacecraft weighing from 1 to 10 kg. Modern propulsion systems are widely used in the space industry. In [1], a detailed review of ion thrusters of various designs and methods of acceleration of charged particles was carried out. Promising developments of low-power ion thruster based on the Hall effect, electronic thruster based on cyclotron resonance, thruster using microwave discharge, etc. are given in [2-11]. Determining the energy characteristics of an thruster is a difficult task. The main parameters of the ion thruster are thrust, specific impulse and efficiency.

Researchers from the University of Sydney used torsion scales to determine the energy characteristics [12]. Mounted on a horizontal lever, the thruster and additional equipment were balanced by a counterweight. The assembled structure was suspended on a copper wire. The vibrations arising during the operation of the vacuum chamber were damped by a permanent magnet. To measure the movement of the balance lever, a differential sensor (transformer) of linear displacement was used. The developed design is quite simple, but it is worth paying attention to the influence of pulse interference during the operation of the magnetoplasmadynamic thruster. Steep current fronts can introduce distortions into the analog-to-digital converter circuit, which will lead to incorrect measurement of the lever movement.

The paper [13] shows the design of pendulum scales. Accelerometers and a capacitive lever position sensor are installed on the scales. With the help of the implemented design, thrust measurements were carried out from 0.02 to 1000 μN.

The determination of the ion flow rate in vacuum arc plasma is considered in [4]. The method is based on measuring the time delay between the arc current and the ion flow. The scheme of the experimental setup included a Faraday cylinder, the system of accelerating grids, a current sensor, a high-voltage pulse generator and an arc power source. The current sensor and the Faraday cylinder were connected to the channels of the recording oscilloscope. The accelerating system consisted of three acceleration-
deceleration grids. A voltage of -3 kV was applied to the central grid. The accelerating grid has a voltage of 30 kV. The method shown is well suited for measuring the speed of high-power ion thruster with a beam current from 10 mA to 70 mA. But to register currents in the microampere region, the presented method will give a large error due to the noise of the useful signal during the experiments. There are ways to determine the velocity of charged particles [14], including using mass spectrometers [15-18]. The advantage of time-of-flight mass spectrometers is high sensitivity. The ion beam almost always reaches the detector. Nevertheless, the complexity of the design, the complexity of the installation and the high price do not always allow the use of these devices in the process of experiments. Thus, the calculation of the magnitude of thrust, reactive power, specific impulse and efficiency of the ion thruster through direct measurement of the ion beam velocity rate is currently an urgent task.

2. Problem statement
To develop a design and consider the physical processes of particle capture, to measure the accelerated flow of charged particles.
To develop a schematic diagram for detecting an accelerated flow of charged particles. With the help of the created detectors to determine the speed of the ion beam of a two-gap thruster.

3. Theory
The design of the sensing element is similar to a capacitor. The outer plate is connected to positive or negative voltage, and the inner one to the input of the amplifier.
Let's consider the operation of such a sensitive element on the example of a cylindrical capacitor. Connect the outer plate of the diameter d2 to the positive potential, and the inner plate d1 to the negative (Fig. 1)

![Figure 1. Sensor element in the form of a cylindrical capacitor](image)

Suppose that the area of the considered area is much smaller than the area of the capacitor. Due to symmetry, the electric field vector \( \vec{E} \) must have a radial component \( E_r \) and lie in a plane perpendicular to the axis. Then the magnitude of the vector should depend only on \( r \).
Using the Gauss theorem and obtain the following relations for the flow of the electric field intensity vector

\[
\Phi_E = \int \vec{E} \cdot \hat{n} \, dA, \tag{1}
\]

where \( \hat{n} \) is the unit vector of the normal, \( dA \) is the area of the plot in question.
Let's determine the radial component of the electric field. At the ends of the inner cylinder, the electric field \( \vec{E} \) is perpendicular to the normal \( \hat{n} \), so the scalar product \( \vec{E} \cdot \hat{n} = 0 \). On the side surface of the cylinder, the electric field \( \vec{E} \) is parallel to the normal \( \hat{n} \), then
\[ \oint \vec{E} \cdot \hat{n} \, dA = \int \vec{dA} = 2\pi r L E_r = \frac{\lambda \cdot L}{\varepsilon_0}, \quad (2) \]

where \( \lambda \) is the linear charge density, \( \varepsilon_0 \) is an electrical constant, and \( L \) is the length of the cylinder.

From where the radial component of the electric field is equal to

\[ E_r = \frac{\lambda}{2\pi \varepsilon_0 r}. \quad (3) \]

Let's find expressions for the electric field in terms of the potential difference between the cylinders

\[ \begin{align*}
    \int \vec{E} \cdot d\vec{r} &= -\int V \Phi \cdot d\vec{r} = -\int d\Phi, \\
    \Phi &= \begin{cases} 
        V & \text{for } r = r_2/2, \\
        0 & \text{for } r = r_1/2.
    \end{cases}
\end{align*} \quad (4) \]

Substituting the radial component \( E_r \) in the expression (4), we determine the potential difference

\[ V_1 - V_2 = -\frac{\lambda}{2\pi \varepsilon_0} \ln \left( \frac{d_2}{d_1} \right). \quad (5) \]

From which

\[ E_r = \frac{-V_{1,2} \cdot \hat{r}}{r \ln \left( \frac{d_2}{d_1} \right)}. \quad (6) \]

Thus, to calculate the capacitance of a sensitive element, we have the following expressions:

\[ \begin{align*}
    Q &= C \cdot V; \\
    L\lambda &= Q = \frac{2\pi \varepsilon_0 L V}{\ln \left( \frac{d_2}{d_1} \right)} = C \cdot V; \\
    C &= \frac{2\pi \varepsilon_0 L}{\ln \left( \frac{d_2}{d_1} \right)}. \quad (7)
\end{align*} \]

If the outer cylinder is connected to the positive pole of the source, a negative charge is induced on the inner cylinder.

Suppose that a directed beam of positively charged ions enters the electric field of the considered cylindrical capacitor. Charged particles drift towards the inner cylinder at a drift velocity \( \vec{v}_d \). During the time interval, the \( dt \) ion will be moved to \( dr \)

\[ dr = \vec{v}_d \cdot dt. \quad (8) \]

Figure 2 shows the process of capturing accelerated ionized gas by a sensing element.
If we assume that the drift velocity in the cavity is equal to the electric mobility $\mu$ of the charge carriers multiplied by the electric field $E$, then

$$\frac{dr}{\mu \cdot E} = \frac{dr}{d\nu}; \quad \int \frac{dr}{\mu \cdot E} = \int dt.$$  \hspace{1cm} (9)

Let us determine the time $T$ during which the ion drifts from the outer cylinder of the sensing element to the inner one by the expression

$$T = \int_0^T \left( \frac{d_1^2 - d_2^2}{4} \right)^2 \frac{\ln \left( \frac{d_2}{d_1} \right)}{2\mu \cdot V} dt.$$  \hspace{1cm} (10)

The time of passage of the particle $T$ should be less than the time of passage of the particles through the sensing element. Then the ions are more likely to fall on the inner cylinder. Consider this from the point of view of the critical mobility of charge carriers

$$\mu_c = \left( \frac{d_2^2 - d_1^2}{4} \right)^2 \frac{\ln \left( \frac{d_2}{d_1} \right)}{2\nu \cdot L \cdot V}.$$  \hspace{1cm} (11)

where $\nu'$ is the velocity of the ion beam.

If the mobility of the charge carriers $\mu > \mu_c$, then the ions will fall on the inner cylinder. Otherwise, the capture will not happen. The lower the flow rate and the longer the length of the cylinders, the probability of capture increases. An increase in the potential difference between the cylinders will lead to an increase in the electric field strength and increase the drift velocity of the particles.

Let's determine the output signal current of the sensing element. The magnitude of the current will depend on the concentration of charged particles $N_i$.

$$I_s = \frac{N_i \cdot \mu \cdot V \cdot C}{\varepsilon_0}.$$  \hspace{1cm} (12)

The measurements carried out using the Faraday cylinder showed that the accelerated ion currents are in the region of microamperes. Therefore, when developing a circuit, it is necessary to provide shielding from electromagnetic interference of the network and other interference.

The circuit of the created detector consists of a signal current amplifier, a Schmitt trigger, an RS-trigger and a high-speed optocoupler with a logical output voltage level. The schematic diagram of the detector is shown in
A high-speed operational amplifier was used to design the detection unit. The minimum input bias current of the operational amplifier is 5 pA. The detector is assembled according to a non-inverting circuit with a gain of 3.5. The gain was calculated by the expression

\[ G_A = \frac{R_1}{R_2} + 1. \]  

(13)

The input resistance is provided by resistors R8-R17. A sensor element is connected to the detector input via the XP2 connector. The design of the sensing element is shown in Figure 4.

The accelerated ion beam hits the sensing element and creates a current in the resistances R8-R17. The resulting voltage is amplified by a non-inverting amplifier.
The signal received from the output of the amplifier through the voltage divider R3, R4 enters the input of the Schmitt trigger. The hysteresis of the trigger prevents the "rattling" of the detected signal. In this way, interference is filtered and a true signal is generated at the output. The true output signal of the Schmitt trigger goes to the high-speed optocoupler. The optocoupler is designed for galvanic isolation of the measuring and recording parts of the detector. The optocoupler has an open collector. The maximum input current of 5 mA provides a minimum output current of 13 mA, and the internal screen guarantees protection against pulse interference.

There are two measurement methods implemented in the detector:

1. Multiple measurement.
2. Single measurement.

When measured multiple, "bundles" of pulses caused by the flow of ions are recorded on the oscilloscope screen. To make multiple measurements, the oscilloscope channel must be connected to the XW1 connector.

With a single measurement, a step signal is recorded on the oscilloscope screen. This indicates that the detector is triggered. Schematically, a single measurement is performed on an RS-trigger. The trigger circuit is shown in Figure 5.

The trigger circuit is implemented on two logic elements OR-NOT D2 chips. A non-locking button is connected to input S via the XP3 connector. The button is designed to set the detector output signal to the zero state. Input R receives a signal from the output of the VO1 optocoupler. At the zero moment of time, the direct output \( Q = 0 \), and the inverse \( \overline{Q} = 1 \). The inverse trigger output generates a single measurement signal. If voltage is applied to the input S through the button, the output will change its value by 0. Information will be recorded in the trigger and the detector will be set to zero. Accordingly, when an ion beam appears, a logical unit will arrive at the input R and a high-level step signal will be formed at the detector output. The operation of the trigger is shown in Figure 6.
The detector is assembled on a double-sided printed circuit board made of fiberglass. A three-dimensional model of the board is shown in Figure 7.

![Figure 7. Printed circuit board with installed components](image)

When designing a printed circuit board, it is necessary to reduce the parasitic capacitance at the inputs and outputs of the chips, minimize the capacitance between the common wire and any of the signal conductors. Figure 8 shows photos of the detector board installed in the housing and detectors with a fixed time-of-flight channel.

![Figure 8. Photo of the sensor installed in the housing (a) and detectors with a time-of-flight channel (b)](image)

The polygons of the ground and the power supply of the printed circuit board should not be located close to the signal terminals. It is necessary to exclude narrow power and ground conductors, to minimize parasitic inductance between the terminals and decoupling capacitors. All microcircuits and stabilizers must be shunted by capacitors. Measuring resistors must be selected with a low transit resistance. Place the signal conductors as close to the operational amplifier as possible.

**4. Results experiments**

In the prototype radiator, the spiral resonators end in two span bushings. The bushings are installed at a small distance from each other. Span bushings and grids provide primary acceleration and stretch the plasma boundary to the electrodes of the accelerating system. Nitrogen was chosen as the working gas.
The thruster shown uses the concept of an isolated microwave module located in a cylindrical resonator. The advantages of the induction-capacitive circuit in the prototype micro-thruster are the smooth start of plasma generation.

The ionized gas flow velocity was measured using a designed circuit (Fig. 10.)

With the help of a switch, the accelerating voltage is applied to the grids of the ion thruster. The ion beam initiated by the accelerating voltage flies between the metal grids of the sensors S1 and S2. The sensors are located at a known distance L. Accelerated positive ions arrive at the sensors at different times, and are recorded by the x and y channels of the oscilloscope. The calculation of the speed was carried out by the expression

$$v_i = \frac{L}{\Delta t},$$

where $\Delta t$ is the time of flight of the ion beam.

During the experiment, the accelerating voltage varied from 350 V to 1200 V. For each voltage value, 3 measurements of the time of flight of the ion beam $\Delta t$ were performed. Table 1 shows the values
obtained. The distance between the grids and the cathode of the two-gap ion thruster during the measurements was 2 mm.

| Accelerating voltage, V | Δt₁, s | Δt₂, s | Δt₃, s | Δt_avg, s | v₁, m/s | v₂, m/s | v₃, m/s | v_avg, m/s | vᵢ, m/s |
|------------------------|--------|--------|--------|------------|--------|--------|--------|-----------|--------|
| 350                    | 2.35×10⁻¹ | 3.56×10⁻¹ | 3.56×10⁻¹ | 3.16×10⁻¹ | 42.6   | 28.1   | 28.1   | 31.7      | 4.90×10⁻² |
| 400                    | 1.85×10⁻¹ | 2.16×10⁻¹ | 3.08×10⁻¹ | 2.36×10⁻¹ | 54.1   | 46.3   | 32.5   | 42.3      | 5.24×10⁻² |
| 450                    | 1.66×10⁻¹ | 1.90×10⁻¹ | 0.029  | 1.09×10⁻¹ | 60.2   | 52.6   | 3.45   | 9.21      | 5.55×10⁻² |
| 500                    | 0.012   | 0.012  | 1.68×10⁻¹ | 8.56×10⁻¹ | 8.33   | 8.33   | 59.5   | 11.7      | 5.85×10⁻² |
| 550                    | 1.46×10⁻¹ | 1.3010⁻¹ | 1.220⁻¹ | 1.3310⁻¹ | 68.5   | 76.9   | 82     | 75.4      | 6.14×10⁻² |
| 600                    | 7.92×10⁻¹ | 9.59×10⁻¹ | 8.79×10⁻¹ | 8.77×10⁻¹ | 126    | 104    | 114    | 114       | 6.41×10⁻² |
| 650                    | 7.75×10⁻¹ | 6.87×10⁻¹ | 7.59×10⁻¹ | 7.4×10⁻¹   | 129    | 146    | 132    | 135       | 6.67×10⁻² |
| 700                    | 1.72×10⁻¹ | 1.17×10⁻¹ | 1.54×10⁻¹ | 1.48×10⁻¹ | 5.810  | 8550   | 6490   | 6770      | 6.93×10⁻² |
| 750                    | 6.68×10⁻¹ | 7.08×10⁻¹ | 7.68×10⁻¹ | 7.15×10⁻¹ | 1.50×10⁻¹ | 1.41×10⁻¹ | 1.30×10⁻¹ | 1.40×10⁻¹ | 7.17×10⁻² |
| 800                    | 3.76×10⁻¹ | 5.36×10⁻¹ | 4.48×10⁻¹ | 4.53×10⁻¹ | 2.66×10⁻¹ | 1.87×10⁻¹ | 2.23×10⁻¹ | 2.21×10⁻¹ | 7.40×10⁻² |
| 850                    | 2.41×10⁻¹ | 3.04×10⁻¹ | 3.04×10⁻¹ | 2.83×10⁻¹ | 4.17×10⁻¹ | 3.29×10⁻¹ | 3.29×10⁻¹ | 3.54×10⁻¹ | 7.63×10⁻² |
| 900                    | 1.61×10⁻¹ | 2.28×10⁻¹ | 1.60×10⁻¹ | 1.83×10⁻¹ | 6.25×10⁻¹ | 4.39×10⁻¹ | 6.25×10⁻¹ | 5.47×10⁻¹ | 7.85×10⁻² |
| 950                    | 1.44×10⁻¹ | 1.44×10⁻¹ | 2.42×10⁻¹ | 1.77×10⁻¹ | 6.94×10⁻¹ | 6.94×10⁻¹ | 4.13×10⁻¹ | 5.66×10⁻¹ | 8.07×10⁻² |
| 1000                   | 1.5×10⁻¹ | 8.96×10⁻⁷ | 9.76×10⁻⁷ | 1.12×10⁻⁶ | 6.67×10⁻⁷ | 1.12×10⁻⁶ | 1.02×10⁻⁶ | 8.90×10⁻⁷ | 8.28×10⁻³ |
| 1050                   | 7.96×10⁻¹ | 8.96×10⁻⁷ | 1.50×10⁻⁶ | 1.06×10⁻⁶ | 1.26×10⁻⁶ | 1.12×10⁻⁶ | 6.67×10⁻⁷ | 9.4×10⁻⁷  | 8.48×10⁻³ |
| 1100                   | 1×10⁻⁶   | 1×10⁻⁶   | 1×10⁻⁶   | 1×10⁻⁶     | 1×10⁻⁶   | 1×10⁻⁶   | 1×10⁻⁶   | 1×10⁻⁶     | 8.68×10⁻⁴ |
| 1150                   | 8.16×10⁻⁷ | 9.16×10⁻⁷ | 9.16×10⁻⁷ | 8.3×10⁻⁷   | 1.23×10⁻⁶ | 1.09×10⁻⁶ | 1.09×10⁻⁶ | 1.13×10⁻⁶ | 8.88×10⁻⁷ |
| 1200                   | 2.8×10⁻⁷  | 5.2×10⁻⁷  | 5.2×10⁻⁷  | 4.4×10⁻⁷   | 3.57×10⁻⁷ | 1.92×10⁻⁷ | 1.92×10⁻⁷ | 2.27×10⁻⁷ | 9.07×10⁻⁸ |

According to the table, diagrams were constructed for direct measurement of the ion beam velocity and velocity (Fig.11). The determination of the ion flow velocity was performed by the expression

\[ v_1 = \sqrt{2q_e \cdot V_{nom} / m_i} \]  

(15)

where \( q_e \) is the amount of charge, \( V_{nom} \) is the nominal accelerating voltage, \( m_i \) is the mass of an ion.

![Figure 11](image_url)

Figure 11. The velocity value obtained by direct measurement of the ion beam flow rate (a), the indirectly calculated value of the ion beam flow rate (b)
5. Discussion of results

The presented method showed an interesting feature of the ionized gas velocity set when the voltage on the electrodes rises. At the level of 500 V and 1000 V, there is a point of "rattling" of speed. The speed does not grow linearly, but exponentially. At a voltage of 1200 V, the speed reached 200 km/s. This is due to the level of alternating voltage in the gap of the toroidal resonator and the rate of ion entry into this gap (the number of accelerations and decelerations of the particle changes when crossing the gap). It can be seen from the figures that when measuring the flow of ionized gas, the shape of the curve differs from the values calculated by expression (15) for similar values of the accelerating voltage.

Conclusion

The article presents the intermediate results of the authors' work in the field of direct measurement of the velocity of charged particles of an ion thruster. The design and technical embodiment of a two-gap ion thruster is presented. Based on theoretical considerations, a technique and an installation for measuring the flight time of an ion beam have been developed.

The experiments were carried out in a vacuum chamber. The mass gas consumption was 0.828 mg/s. The measurements were carried out at a distance of 10 cm from the nozzle cutoff. The distance between the sensitive elements was 10 cm.

The method of direct measurement of the ionized gas velocity is of great practical interest for determining the characteristics of an ion thruster.

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