Modeling and experimental study of an ion source with a weakly diverging ion beam

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Abstract. An ion source was developed for transporting space debris to the disposal orbit by acting on such objects with an intense ion beam injected from a “service” spacecraft. The ion source differs by weakly diverging ion beam, radio-frequency inductive discharge, and a three-electrode slit ion-extraction system with quasi-Pierce geometry.

1. Introduction

For the first time, the problem of the electrostatic system (hereinafter, the ion-extraction system - IES) for the formation of a weakly divergent beam of charged particles was formulated by Pierce as applied to electronic tubes [1]. The analytically found geometry of an electrostatic system for obtaining a laminar weakly divergent electron beam for both the ribbon and axisymmetric cases has been called in publications as the "Pierce gun". A solid-state emitter (cathode) was considered as an electron source, the surface of which specifies the boundary condition for calculating the electrostatic system. Since the ion trajectories in the electrostatic system are independent of the particle mass, the conditions for the formation of a weakly diverging ion beam could be based on Pierce's results. However, to obtain an ion beam, one has to use not a solid-state, but a plasma emitter, the boundary of which is approximately stipulated by the condition of equality of electron and electrostatic pressures. From a mathematical point of view, the task of calculating the IES is transformed from a problem with a fixed boundary to a problem with a "self-consistent" boundary that complicating greatly both the calculation and the practical implementation of the ion beam formation system. However, Pierce's ideas are valid for this case as well.

The problem of developing an ion source with a small angle of divergence arose in thermonuclear studies with tokamaks, which required an ion source to introduce thermonuclear fuel (deuterium, tritium) into the volume of a magnetic trap. The development of the source, in which the plasma emitter was formed in a direct current discharge, was carried out with hydrogen. Using the quasi Pierce geometry of the ion-extraction system [2], it was possible to obtain a ribbon beam of hydrogen ions with an energy of 45-60 keV and a half-angle of divergence of about 1° [3].

Recently, interest in weakly diverging ion beams has been driven by the development of the idea of cleaning near-Earth space from large-sized objects of space debris (SDO) by acting on them by an ion beam injected from a “service” spacecraft (hereinafter - SSC). The distance between the service
spacecraft and the SDO in the process of transporting the SDO to the disposal orbit should exceed the sizes of both objects. This distance could be 30-60 meters that defining the required range of the ion beam [4].

It is planned to use an ion source forming a weakly diverging ion beam as an on-board source for influencing SDO. The development of such an ion source was the result of a calculation and experimental study presented in this paper. As a result of the calculations, an ion source with a radio-frequency induction discharge [5] and a three-electrode slit IES of quasi-Pierce geometry was selected. There is a strong dependence of the beam divergence angle on the normalized pervance with such geometry. It is necessary to rely on the calculations to determine such dependence for various electrode geometries during development of the ion source. The design should be developed on the basis of a computational study [6].

2. Experimental study of the ion source model
Before starting the process of developing a new source, it was necessary to study the operation of its subsystems using the model of an ion source with the diameter of the electrode of 100 mm. That is, to determine main characteristics and select a mode of operation, the experimental development of the ion source model was carried out.

The experiment was carried out as follows: a model of the ion source was mounted on the flange of the vacuum chamber opposite to the thrust measurement system frame (TMS); on the TSM frame, a screen was mounted perpendicularly to the axis of the ion source model and calibrated. During the experiment, the static pressure in the vacuum chamber was maintained at $4 \times 10^{-5}$ Torr (3.05x10⁻⁴ Pa), and the dynamic pressure during the ion source operation - at $1.5 \times 10^{-5}$ Torr (1.15x10⁻³ Pa).

The obtained experimental data are shown in table 1.

| Mode | $m$, mg/s | Supplied power, W | SG Voltage, V | AG Voltage, V | AG Current, mA | SG Current, mA | Thrust, mN |
|------|-----------|-------------------|--------------|--------------|----------------|----------------|-----------|
| 1    | 0.4       | 110               | 1060         | 100          | 95.0           | 4.0            | 4.1       |
| 2    | 0.4       | 120               | 1000         | 100          | -              | -              | 4.3       |
| 3    | 0.4       | 130               | 1000         | 100          | -              | -              | 4.5       |
| 4    | 0.4       | 140               | 1000         | 100          | 108.5          | 17.0           | 4.6       |
| 5    | 0.4       | 140               | 1000         | 100          | 119.5          | 14.0           | 4.3       |
| 6    | 0.4       | 140               | 1200         | 120          | 128.5          | 4.0            | 5.2       |
| 7    | 0.4       | 140               | 1200         | 160          | -              | -              | 5.4       |
| 8    | 0.4       | 140               | 1200         | 160          | 120.0          | 4.0            | 5.4       |
| 9    | 0.4       | 140               | 1200         | 180          | 123.0          | 3.5            | -         |
| 10   | 0.4       | 140               | 1200         | 150          | 119.5          | 4.0            | 5.3       |
| 11   | 0.4       | 140               | 1400         | 160          | 131.5          | 3.0            | 6.0       |
| 12   | 0.4       | 140               | 1600         | 180          | 117.0          | 2.5            | 6.5       |
| 13   | 0.4       | 140               | 1700         | 180          | 134.0          | 2.5            | 7.0       |
| 14   | 0.4       | 140               | 1830         | 180          | 132.5          | 2.5            | 7.1       |
| 15   | 0.4       | 140               | 2000         | 200          | 154.5          | 2.5            | 7.6       |
| 16   | 0.4       | 140               | 2500         | 180          | 160.0          | 4.0            | 9.1       |
| 17   | 0.4       | 140               | 3000         | 180          | 200.0          | 8.0            | 10.2      |
| 18   | 0.4       | 100               | 3180         | 180          | 160.0          | 11.0           | 7.5       |
| 19   | 0.4       | 100               | 3400         | 180          | 150.0          | -              | 8.0       |
| 20   | 0.4       | 100               | 3600         | 150          | 150.0          | 15.0           | 8.0       |
| 21   | 0.4       | 100               | 4000         | 160          | 164.5          | 18.5           | 8.2       |
| 22   | 0.4       | 100               | 2000         | 200          | 110.0          | 3.5            | 6.0       |
| 23   | 0.4       | 100               | 4000         | 180          | 167.0          | 18.0           | 8.0       |
The main point of this work was the implementation of the required mode of ion source operation and the registration of the impact pulse on the target (sensor) simulating a SDO. The pulse measurement task was performed by a thrust measurement system comprising a double pendulum with force compensation and a capacitive displacement sensor. A tracking system based on the principle of proportional integro-differential regulation with first-order astatism was integrated in the device for displacement measurement. Such solution made it possible to realize full compensation of the force in the system without a static error and, therefore, to completely eliminate the deviation of the pendulum from the zero point during the measurement process.

A scheme of the thrust measurement system is shown in figure 1.

![Figure 1. Thrust measurement system.](image)

The thrust measurement system allowed making pulsed measurements during stable operation of the ion source.

3. Ion source modernization

Based on the experimental data obtained with the prototype of an ion source with the electrode diameter of 100 mm, a limiting value of ion current of 0.220 A was obtained to provide the values of specific impulse and thrust required for the usage of this source onboard the service spacecraft for SDO removal. It was decided to increase the diameter of the ion-extraction system, which entailed a change in the design of the ion source.

The development of a new ion source began with the adaptation of an ion source prototype system with an electrode diameter of 100 mm to a laboratory model of an ion thruster with an electrode diameter of 160 mm.

3.1 The gas discharge chamber modernization

The unit of the gas discharge chamber (GDC) represents a propellant ionization volume. The GDC is made of the ceramic material that is radio-transparent for magnetic and electric fields, quartz glass or polymer-ceramic materials. The inductor is a spiral, which is located on the GDC outer surface, and is designed to generate electromagnetic field and for the ignition of the discharge. The shape of the GDC can be cylindrical, hemispherical, or conical, depending on the design of the source. After the modernization of the unit, the gas supply tube became an integral part of GDC.

The upgraded gas discharge chamber unit is shown in figure 2.
The main advantage of the model shown in Figure 2 is a fundamentally new approach to the design of the gas supply tube and the gas isolation unit. To prevent surface breakdown from the plasma side to structural elements that are under the ground potential, gas is supplied through a ceramic channel made of dielectric material – silicon nitride, i.e. without the use of conductive material. This leads to the fact that the heating of the gas distributor becomes more uniform due to the lack of the possibility of a glow discharge origination.

The problem of possible penetration of the charged particles inside and breakdown of the discharge on the grounded structural elements was solved by introducing a complex dielectric labyrinth into the channel of the gas line, which increased the probability of charged particles neutralization on the extended surface of the dielectric labyrinth.

3.2 Ion extraction system modernization

The main task of the ion source modernization was to determine the geometry of the IES electrodes. Slotted IES forms a wedge-shaped weakly divergent ion beam; the beam divergence along the slot is defined by the thermal spread of ion velocities only. The divergence in the transverse direction depends primarily on the IES electrodes geometry perfection. It was shown in publications of various authors, a generalized analysis of which is given in [3], that the ion beam focusing depends strongly on the profile of the aperture in the screen grid (SG) where the plasma boundary is established. This was experimentally verified when developing a source of hydrogen ions for thermonuclear research [2]. Figure 3 shows the geometry of the unit cell of the slotted electrode of the IES. Taking into account the focusing conditions, the profile shape in the SG (on the left in the figure) is formed by two surfaces and has the appearance of a chamfer. The geometric parameters of the IES cell are as follows: the width of the slot in the SG is 2.5 mm; SG thickness - 1.0 mm; interelectrode gap - 1.75mm; width of slot in AG - 2.0 mm; AG thickness - 1.0 mm. For the IES geometry shown in figure 3, the dependence of the half-angle of beam divergence on the reduced perveance is obtained.

Figure 2. The gas discharge chamber.

Figure 3. Elementary cell.
The ion beam divergence half-angle and the perveance depend on the following plasma parameters: plasma density and ion current density. Table 2 shows the results of calculations, and the selected optimal mode is shown in figure 4.

Table 2 presents the results of numerical simulations in the Igun software environment.

**Table 2.** Numerical simulations in the Igun software environment.

| No. | Electron density n10^{11}, 1/cm^3 | Ion beam divergence angle, Δϕ^0 | Ion current density, j, mA/cm^2 | Perveance Π\cdot10^{-8}, A/(cm^2\cdotB^{3/2}) |
|-----|----------------------------------|----------------------------------|---------------------------------|-----------------------------------------------|
| 1   | 1.70                             | 4.150                            | 4.40                            | 1.245                                         |
| 2   | 1.75                             | 2.960                            | 4.52                            | 1.278                                         |
| 3   | 1.80                             | 1.950                            | 4.68                            | 1.324                                         |
| 4   | 1.85                             | 2.150                            | 4.80                            | 1.358                                         |
| 5   | 1.90                             | 2.580                            | 4.92                            | 1.392                                         |
| 6   | 1.95                             | 2.895                            | 5.04                            | 1.426                                         |
| 7   | **2.00**                         | **3.280**                        | **5.20**                        | **1.471**                                     |
| 8   | 2.02                             | 3.450                            | 5.24                            | 1.482                                         |

Figure 4 shows data from the Igun software environment: plasma meniscus boundaries, distribution of ion flow lines, equipotential lines and voltage values associated with the selected electrode geometry. Software modeling is based on solving an axisymmetric problem (shown in figure 4). But in accordance with the experimental study [4], round holes in the developed model of the ion source are replaced by slotted apertures.

**Figure 4.** Equipotential streamlines of the ion beam.

As a result of IES modeling, three types of electrode design were developed: two sets of slotted profiled electrodes and one set of electrodes with round apertures. Electrodes are planned to be manufactured from carbon material and kovar.
4. Conclusion
Based on the experimental data and the simulation, an ion source was developed with a slotted ion-extraction system providing a half-angle divergence of up to 1.95 °, increased working area of the electrodes, and a modernized propellant feed system that eliminates breakdowns in the propellant supply path.

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