Computational and experimental investigation of a weakly diverging ion beam source

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Abstract. This paper presents the idea of space debris removal by the ion beam. The main part of this idea is the ion source on the board of the spacecraft. The ion beam should be narrow, with small half-angle of divergence - about 2°. Angle of divergence means that in there are 95% of ions in this angle. Authors show the concept of the slotted ion optic system. Based on calculation, the construction of the ion optic was designed and tested as part of the laboratory model of the ion source. The results obtained during the experimental testing verified the possibility of using an ion source of such type as an ion injector, which can be installed on board a next-generation spacecraft for the removal of space debris objects.

1. Introduction

The idea of active removal of large space debris objects (SDO) from the near-earth space gave rise to the design of weakly diverging ion beam technology. The essence of this idea is to impact of an intense ion beam on SDO (ion beam shepherd concept) [1-3]. The distance between an ion beam shepherd S/C and SDO in the process SDO transportation to the disposal orbit should exceed the sizes of both objects. This distance could be about 20 or 40 meters to exclude accidental collisions between S/C and SDO. However, because of the ion beam divergence [4, 5] only some part of the ion force created by the ion beam transfers to SDO and the transferred force depends on the operating distances. In fact, it is defining the demands to the ion source concerning a divergence angle of the beam on the ion source exit.

The problem of forming a weakly divergent beam of charged particles was considered in detail as applied to electronic tubes [6]. 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". Using the quasi-Pierce geometry of the ion-extraction system (IES), it was possible to obtain a ribbon beam of ions with energy of 45-60 KeV and a half-angle of divergence of about 1° [7].

The ion beam properties in the near field (at a distance of 5-6 source radii from the source exit) determine the initial conditions in the problem of its subsequent expansion and the beam parameters in the far field in the region of interaction with SDO. When analyzing the divergence of an ion beam upon expansion into outer space, the following factors must be taken into account: 1) the initial formation conditions, 2) the divergence under the influence of electron pressure and an ambipolar electric field, 3) scattering by atoms and ions of the environment. The initial conditions for beam formation in a slotted IOS are the subject of this article and will be discussed below. When a large-sized SDO is removed by an ion beam from the GSO region, where its application has the greatest prospects, the influence of the
ionosphere on ion beam propagation is negligible due to the low local density of the ionosphere. An analysis of various models of ion beam propagation taking into account the ambipolar electric field was carried out in [8]. In our estimates of the beam divergence under the action of an ambipolar electric field, we will rely on the data of [9], which gives the final expressions for calculating the ion beam streamtube containing 95% of the ion current using Parks and Katz self-similar model [9].

In the cited paper, a cone beam is considered. In the wedge-shaped beam formed by the slotted IES, the half-divergence angles in the transverse and longitudinal directions with respect to the slits are different. The half-divergence angle along the slits in the near field should be lower than the transverse one, that is determined by the ion’s temperature in the discharge plasma which is lower 0.5 eV. According to the results of the experiment with the source of the wedge-shaped ion beam [10], the following half-divergence angles can be accepted with some margin: transverse $4^\circ$, longitudinal $2^\circ$. The results of the model calculations for the cone beam can serve as an estimate for the wedge-shaped if, as the initial half-angle at the exit from the near field accept in the range of $2^\circ$-$4^\circ$.

Estimates will be carried out for the ion source design parameters, shown in table 1.

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Ion beam initial radii, $R_0$    | 0.1 m                  |
| Propellant                       | Xenon                  |
| Ion energy, $W_i$                | 4000 eV                |
| Ion beam current, $I_b$          | 0.5 A                  |
| Xenon flow rate (mass efficiency $\eta_m$ 0.8), $\dot{m}$ | 0.856 mg/s |
| Thrust, $F$                      | 0.52 N                 |
| Initial plasma plum number density, $n_0$ | $4 \cdot 10^{15}$ m$^{-3}$ |
| Initial ion’s velocity, $v_i$    | 76400 m/s              |
| Specific impulse, $I_{sp}$       | 61120 m/s              |
| Ion beam power, $N_b$            | 2 kW                   |
| Plasma plume Mach number, $M_i$  | 51.64                  |
| Initial divergence half-angle, $\alpha_0$: | $2^\circ$ |
| In transvers                      | $3^\circ$              |
| In longitudinal                  | $4^\circ$              |
| Distance between IS and SDO, $d$ | Up to 40 m             |
| Ratio $N_b/F$                    | 3.85 kW/N              |

The mode of the ion source operation with a high ion energy of 4 keV is accompanied by high specific costs of electric power per unit of force (thrust) created by the beam 3.85 kW/N. However, such a regime, in comparison with regimes with a lower ion energy, can give a lower beam divergence in the far field due to the high Mach number ($M_i \approx 51.64$), higher momentum transfer efficiency and a high specific impulse of 61120 m/s, which gives savings in xenon consumption. Keep in mind that Xenon stock is a non-renewable resource aboard SSC.

The divergences of the ion beam in the far field were calculated using the formula obtained for the cone beam [9].

$$\frac{dh}{dz} = \sqrt{\tan^2 (\alpha_0) + \frac{12 \ln h}{M_i^2}}$$

where $\bar{z} = z/R_0$, is the normalized axial coordinate; h is the dimensionless quantity associated with the beam radii $R(z)$ by the ratio $R(z) = R_0 \cdot h$.

The boundary condition for (1) is: $h(0) = 1$. The calculation results are shown in figure 1 for three values of $\alpha_0$. On the graph as well as the limiting case, the dependence $h(\bar{z})$ for $M_i \rightarrow \infty$ is shown, which follows from (1):

$$h(\bar{z}) = 1 + \tan \alpha_0.$$
Figure 1. Calculation results.

According to the calculation, at a distance from the ion source \( d = R_0 \overline{z} = 20 \) m, the beam radii can be between 2 and 2.5 m. In conclusion, it seen that small initial divergency angle is the major factor that increases the momentum transfer efficiency to SDO, and the development an ion source of weekly diverging ion beam is actual.

2. Calculation

2.1. Simulation of the cell of the ion-extraction system

Taking as a basis a three-grid slotted IES, the authors stated the problem of investigating the potential possibilities of such scheme by numerical modeling. The development of the geometry that provides the smallest angle of divergence for the ion beam at a given diameter of the IES (100 mm) is the main task of simulation of the unit cell of the ion-extraction system. The aim was to determine the electrode cell profile, which influences on a plasma meniscus shape. Preferred shape is a convex surface toward plasma boundary for, to focus ion streamlines. Sharp edge of a slit provides the most focused streamlines.

As a result of the simulation by the software IGUN–8.022©, the geometry of IES grids was defined (figure 1) with the following parameters: the width of slit in the screen grid (SG) is 2.5 mm, the SG thickness is 1.0 mm, distance between two grids is 1.7±0.05 mm; the width of slit in the accelerating grid (AG) is 2.0 mm, AG thickness is 1.0 mm. Here is a short description of IGUN–8.022© computations. This program considers a multiple particle tracing method, in terms of solving Laplace’s and Poisson’s equation. For simplicity lets focus on two particle tracing, at a first step the result of Laplace’s equation shows a charged particle parameter, at a second step Poisson’s equation result shows a trajectory of a charged particle. These iterations continue until given values of current density. Ion beam divergence is calculated as a geometrical value based on borders of streamlines.

Figure 2 shows the dependence of the half-angle of divergence of the ion beam in the slotted IES of the aforementioned geometry on the normalized perveance. The normalized perveance for the given geometry was determined by the following relationship:

\[
P_i = j_i \cdot U_{\Sigma}^{-1.5} = (0.9 \pm 0.05) \times 10^{-8} \text{ A} \cdot \text{cm}^{-2} \cdot \text{V}^{-1.5}
\]

Here \( j_i \) is the ion current density, \( U_{\Sigma} \) is the total accelerating potential.
Thus, the simulation showed the possibility of creating an IES that provides a minimum beam divergence angle of about 4° (shown in the figure 3).

Figure 3. The ion beam divergence half-angle as a function of the normalized perveance.

3. Experimental setup
Based on the results of the simulation, a model of a laboratory prototype of an ion source was developed. The slit ion-extraction system with a diameter of 100 mm (figure 4) was made of Kovar; it comprised two grids – a screen one and an accelerating one. The laboratory prototype, model of the prototype is shown in the figure 5, was developed on the basis of a previously created prototype [10]. As in the prototype, the inductor was located at the top part of the discharge chamber and was surrounded by ferrite to increase the inductive coupling of inductor and plasma. The discharge chamber was made of quartz glass.
In order to verify the modeling results, the experiments were conducted to determine:

1. The ion beam current with the ion energy of 1000-4000 eV;
2. The ion current density;
3. The normalized perveance in the indicated ranges of ion energy and ion current density;
4. Impulse transfer by the ion beam to the plate-sensor mounted on the thrust meter.

The experiments were carried out at the test facility comprising vacuum chamber, designed for the investigation of integral characteristics of electric propulsion and of the parameters of plumes of the thrusters with the power of up to 1.5 kW in continuous mode and of up to 4 kW for short-term operation. In addition, the facility comprised the thrust meter for the thrust level determination, the power supply units, and the propellant feed system. The target of thrust meter was mounted normal to a plume at the distance $\pm 600$ mm. Target was made from a titanium alloy with a surface of 0.3 m$^2$. The lowest pressure during experiments was about $10^{-4}$ Pa.
4. Results and discussion

Experimental work with laboratory prototype included measurements at 24 modes, which differed in the total RF-power, the potentials on the screen grid and accelerating grid. The xenon flow rate remained constant during the experiment. At each mode, the following parameters were measured: the current of the ion beam, the current on the accelerating grid and the thrust $F$ on the plate sensor mounted on the thrust meter. The data obtained during the specified modes of operation of the laboratory prototype is shown in table 2.

| Mode | Flow rate, mg/sec | RF-power, W | SG potential, V | AG potential, V | Ion beam, mA | Accel. current, mA | Thrust, mN |
|------|------------------|-------------|----------------|----------------|--------------|-------------------|------------|
| 1    | 110              | 1060        | 100            | 95             | 4            | 4.1               |
| 2    | 120              | 1000        | 100            | -              | -            | 4.3               |
| 3    | 130              | 1000        | 100            | -              | -            | 4.5               |
| 4    | 140              | 1000        | 100            | 108.5          | 17           | 4.6               |
| 5    | 140              | 1000        | 100            | 119.5          | 14           | 4.3               |
| 6    | 140              | 1200        | 120            | 128.5          | 4            | 5.2               |
| 7    | 140              | 1200        | 160            | -              | -            | 5.4               |
| 8    | 140              | 1200        | 160            | 120            | 4            | 5.4               |
| 9    | 140              | 1200        | 180            | 123            | 3.5          | -                 |
| 10   | 140              | 1200        | 150            | 119.5          | 4            | 5.3               |
| 11   | 140              | 1400        | 160            | 131.5          | 3            | 6.0               |
| 12   | 140              | 1600        | 180            | 117            | 2.5          | 6.5               |
| 13   | 140              | 1700        | 180            | 134            | 2.5          | 7.0               |
| 14   | 140              | 1830        | 180            | 132.5          | 2.5          | 7.1               |
| 15   | 140              | 2000        | 200            | 154.5          | 2.5          | 7.6               |
| 16   | 140              | 2500        | 180            | 160            | 4            | 9.1               |
| 17   | 140              | 3000        | 180            | 200            | 8            | 10.2              |
| 18   | 100              | 3180        | 180            | 160            | 11           | 7.5               |
| 19   | 100              | 3400        | 180            | 150            | -            | 8.0               |
| 20   | 100              | 3600        | 150            | 150            | 15           | 8.0               |
| 21   | 100              | 4000        | 160            | 164.5          | 18.5         | 8.2               |
| 22   | 100              | 2000        | 200            | 110            | 3.5          | 6.0               |
| 23   | 100              | 4000        | 180            | 167            | 18           | 8.0               |

The bold-type data were chosen for the comparison with the simulation. The thrust $F$ was determined by the following relationship:

$$F = \frac{m v^2}{e M_i} \sqrt{\frac{2 e U_{EE}}{M_i} EE \times K(\alpha)}$$  \hspace{1cm} (3)

Here $m$ is the xenon flow rate, $v$ is the ion velocity, $e$ is the elementary charge, $M_i$ is the xenon ion mass, and $K(\alpha)$ is the coefficient depending on the angle of ion beam divergence in near field. Coefficient $K(\alpha)$ was defined as:

$$K(\alpha) = 0.5 \left(1 + \cos \alpha \right)$$  \hspace{1cm} (4)

here $\alpha$ is the half-angle of ion beam divergence.

When obtaining the calculated values, it was assumed that the accelerating potential was 10% of the screen grid potential, which differed from the experimental values. In the experiment, the accelerating electrode potential was selected based on the minimum value of the accelerating grid current. Therefore, the calculated values of the normalized perveance differ slightly from the experimental values. The results of comparison of experiments with simulation are shown in table 3.
Table 3. Experimental data analysis.

| Parameter                  | \(U_{SG} = 1200\) V | \(U_{SG} = 2000\) V | \(U_{SG} = 3000\) V | \(U_{SG} = 4000\) V | \(U_{SG} = 4000\) V |
|----------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Ion current density, A/m² | 34.7                 | 34.7                 | 41.8                 | 41.8                 | 45                   | 45                   |
| Ion beam, mA              | 128.5                | 128.5                | 154.5                | 154.5                | 167                  | 167                  |
| Thrust, mN                | 5.2                  | 7.18                 | 7.6                  | 11.4                 | 8                    | 16.9                 |
| Perveance, \(10^{-8}\) A/cm²·V\(^{-1.5}\) | 7.2                   | 7.2                  | 4.05                 | 4.05                 | 1.6                  | 1.5                  |

The value \(U_{Σ}\), indicated in the table, is equal to the sum of screen grid potential and accelerating grid potential. The total potential defines the value of the normalized perveance in the gap between two grids.

The last column of table 2 contains calculated parameters of the laboratory prototype corresponding to the minimum beam divergence at the perveance of \(1.9 \times 10^{-8}\) A/cm²·V\(^{-1.5}\). As can be seen from table 2, the perveance experimental values differ from the optimal value. At that, the lower is the \(U_{Σ}\) value, the stronger is this difference. The experiment, in which \(U_{Σ}\) was 4180 V, corresponded to the perveance of \(1.6 \times 10^{-8}\) A/cm²·V\(^{-1.5}\), i.e. less than the optimal.

The conducted experimental and computational study allowed us to outline the main design characteristics of the ion source and the ion-extraction system with an increased diameter of 160 mm, which had improved characteristics compared to the previously developed models. Figure 6 shows the calculation result for the new geometry of the ion-extraction system. The screen grid potential is 4500 V, the accelerating grid potential is minus 500 V, the decelerating grid (the case of the model) has a potential equal to zero. This calculation, provided by the software IGUN–8.022©, showed that the best half-angle of divergence equal to 1.95° is achieved at the current density of 48.6 mA/cm², the normalized perveance is equal to \(1.32 \times 10^{-8}\) A/cm²·V\(^{-1.5}\). This geometry of the IES will provide the thrust of the order of 15-40 mN with ion energy of 2-4 KeV and an ion beam current of 200-300 mA.

Figure 6. Geometry of the IES elementary slit cell.
5. Conclusion
The paper considers a full cycle of research for the sources of weakly divergent ion beams, including numerical simulation of the ion-extraction system, laboratory testing of models and determination of their optimal parameters.

It is shown that it is possible to develop an IES with the half-angle of beam divergence of 1.95°, ion beam current of 200-300 mA, thrust from 15 mN to 40 mN, and the ion energy of up to 4 KeV. Such parameters of the ion source are within the range of operating values required as applied to the designed spacecraft.

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