Plasma propulsion using novel concepts

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The electric propulsion is intensively developing field, addressing new demands and challenges for the long term spacecrafts operation. The novel plasma propulsion concepts are aimed to find new acceleration principles, use alternative propellants, downscale thrusters for the small spacecrafts etc. In this work we consider neutralizer-free concepts, where both positive and negative particles are extracted from plasma and accelerated using the one acceleration system. As shown here, a recent Neptune concept seems to be one of the most prospective from novel EP concepts. This concept assumes using the plasma self-bias effect in the RF-powered gridded system, providing quasi-simultaneous ion-electron acceleration. First proof of concept is already achieved, demonstrating similar efficiency as for traditional gridded ion thrusters. The ion and electron fluxes emitted by the source are equal helping to achieve much better beam neutralization than in traditional system with neutralizer. The experiments demonstrate that emitted flow of electrons is highly directional, thus the thruster plume can be precisely localized. Strong advantage of this concept is significant technology heritage, because of similarity with the already operated ion thrusters.

1. Introduction

Since the early 1990s, broad-beam ion sources have been used as electric propulsion (EP) thrusters for commercial satellites and engines for scientific space missions. Using ion sources in space thrusters applications requires neutralization or compensation of both the ion positive space charge and the ion current [1]. Commonly, electrons are injected from an external neutralizer into the downstream beam. The neutralizer is a dedicated device based on thermo-electron emission or different kinds of gas discharges that usually needs additional power supplies and gas injection systems. Although much progress on neutralizer technology has been achieved over the last few years, it is still the part of the thruster with the shortest lifetime and is fragile during launch [1].

Most of the novel concepts of the plasma-based EP engines are aimed to be free from the neutralizing system, by achieving quasi-neutral accelerated beam at the exit [2-7]. In fact, simultaneous emission of oppositely charged particles from a single source may provide several advantages in space:

- The additional neutralizer is redundant.
- Space potential of the plume can be reduced
- Plume can be better localized due to co-directional extraction of oppositely charged particles
- The losses in power unit are reduced (there is no dedicated power system for a neutralizer).
- Decrease of the propellant consumption (no gas feed for the neutralizer).
- Total robustness of the system is increased due to reduced number of subsystems that can fault.

The simultaneous extraction concepts can be divided on the two main categories: plasma acceleration and beam acceleration concepts. In the first category, the magnetic nozzles or double layer structures formed at the plasma source output are used for the acceleration of a quasi-neutral plasma [2-4]. Although in principle these concepts provide long-life neutralizer-free operation, the achievable performances such as specific impulse and thrust efficiency are generally lower than the performances provided by the traditional electric propulsion concepts (ion and Hall thrusters [1]). For all these concepts the ion flux and energy cannot be controlled independently.

The second category of concepts consists from only few devices based on alternate or quasi-simultaneous acceleration of positive ions and electrons [7,8] or positive and negative ions [5,6] extracted from plasma using the biased grids. These devices may provide a time averagely quasi-neutral beam, while the ion flux and energy can much better be controlled, because gas ionization and acceleration are completely separated. Another strong advantage of these concepts is similarity with space-proven gridded thrusters allowing technology heritage.

One of such devices is the PEGASES thruster which is a gridded ion–ion plasma source that accelerates alternately positive and negative ions [5,6]. Operation of the source is possible only with highly electronegative gases, i.e. mainly with chemically-active halogens like iodine, operation with Xe or other inert gases is not possible.

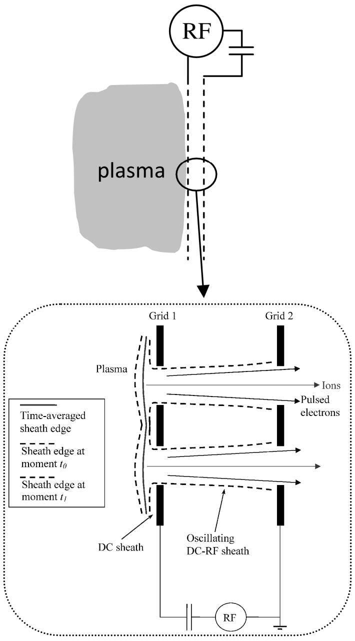

Fig. 1. Illustration of the Neptune propulsion concept. Time moments t_0 and t_1 corresponds to the minimum and maximum values of the instantaneous electrical field.

Recently, a new plasma propulsion concept called "Neptune" is proposed where ions and electrons are co-extracted from a double-grid source where the grids are biased with RF frequency (see Fig. 1) [7,8]. In this case, a so-called RF plasma self-bias effect is used to convert applied RF voltage by plasma into the combination of RF and DC voltages, allowing continuous acceleration of ions between the grids and frequent periodical co-extraction of electrons [8]. The proof-of-concept has recently been achieved with Ar and N gases, where it was found that the RF ion acceleration has the same efficiency as traditional DC acceleration [8]. The floating potential of the beam is found to be lower than in the case of DC acceleration with neutralizer, which can be explained by highly directional extraction of electrons with RF acceleration scheme. The Neptune source provides a separate control of the ion energy and flux of the broad quasi-neutral beam, and the average fluxes of emitted ions and electrons are absolutely equal [8]. The working gas ionization, ion acceleration and neutralization is supplied by only one RF generator without any additional power supplies. Taking all of this into account, the Neptune thruster seems to be one of the most prospective from novel EP concepts. This paper presents recent results of the plume investigation in the medium-size test facility equipped with Neptune thruster. This research is mainly focused on the electron flow directionality measurements.

2. Experiments with a Neptune thruster

In this work, the experimental investigation of the plasma and beam properties of the Neptune thruster has been performed on the setup schematically shown on the Fig. 2. The Neptune prototype is made as a metallic rectangular parallelepiped with size 8 × 12 × 12 cm. The plasma is generated using an RF antenna supplied by a 4 MHz 200 W RF power. A set of two grids is placed at the source exit. Both grids are made of stainless steel and have an optical transparency of 0.6 and an aperture diameter of 2.5 mm; the intergrid distance is 2 mm. The extraction system is a rectangle with dimensions 65 × 105 mm. An RF distribution and matching system is introduced to allow matching of the RF generator with the plasma load and to distribute the RF power between the ICP antenna and extraction grid system. The first grid in contact with the plasma is biased with RF voltage via a blocking capacitor and the applied RF voltage amplitude is controlled in the range 0–600 Vp–p. The second grid is grounded.

The Neptune prototype is attached to 1 m long cylindrical test chamber, where the propagating beam is analyzed. The main diagnostics consists of a rotating RF-compensated double grid RFEA, the beam target, Langmuir and planar probes. The Ar gas is used here, the pressure in prototype is about 2 mTorr, and in test chamber is 0.2 mTorr.

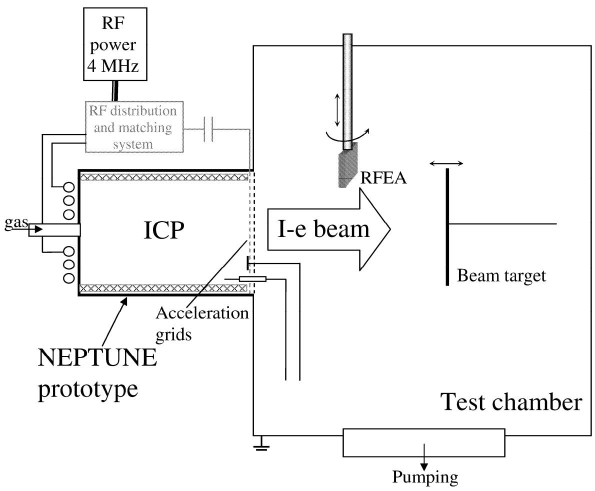

Fig. 2. Schematic view on the experimental setup.

As mentioned in Introduction, when only the RF voltage is applied to the acceleration grids a plasma self-bias effect leads to the DC voltage generation. The reason is that the effective area of the second grid is much smaller than area of the first grid, due to partial screening of the second grid from plasma. The very asymmetric "capacitive divider" formed by a space charge sheathes in front of each grid leads to dropping almost the all applied RF voltage over the oscillating space charge sheath between the second grid and plasma. Difference between the ion and electron response time to the electrical field cause charging up the plasma, thruster walls and first grid to averagely positive DC potential (if measured versus the second grid). This effect is demonstrated on the Fig. 3, where the experimentally measured voltage waveform is plotted for the case when 600 V p-p RF voltage is applied between the grids through the blocking capacitor (the second grid is grounded).

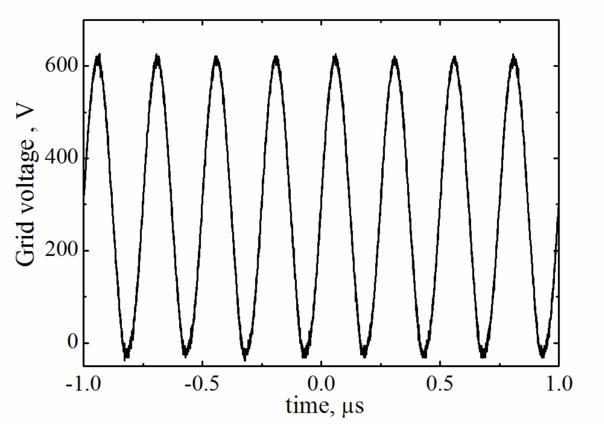

Fig. 3. Voltage waveform of the first grid when 600 V p-p RF voltage is applied.

It is seen from the Fig. 3 that the self-generated DC component of the grid voltage is similar to the amplitude of the RF voltage applied. As a result, heavy ions are continuously accelerated by this field, while electrons can still periodically escape plasma toward the thruster exit when the plasma potential reaches minima. The ion and electron energy distribution functions (EDF) measured by a RFEA are shown on the Fig. 4. It is seen that the ion EDF is multi-peaked in the range 70-250 eV, while the electron EDF is situated at low energy.

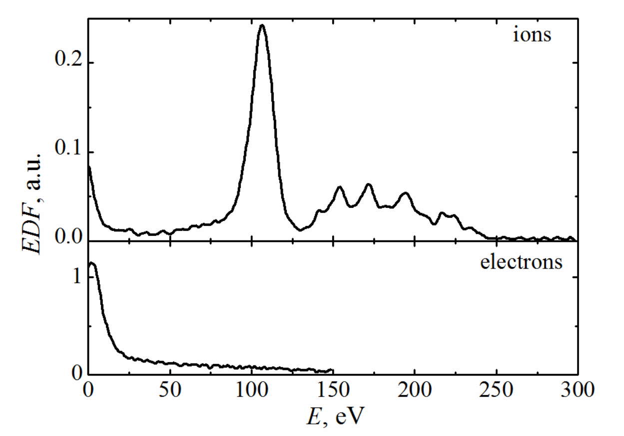

Fig. 4. Ion and electron EDFs measured simultaneously in the downstream of the Neptune thruster with 200 V p-p RF acceleration voltage.

As a result of the electron extraction a plume generated by the Neptune thruster is optically bright (see Fig. 5). The strong optical emission results from the inelastic collisions of co-extracted electrons with residual gas atoms.

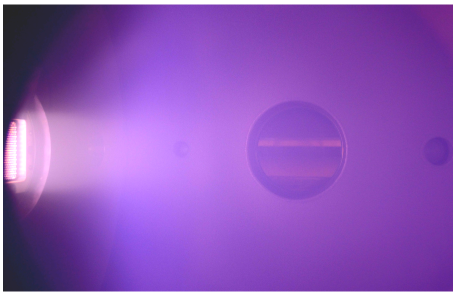

Fig. 5. View on a plume of the Neptune thruster.

However, the main question for a future Neptune thruster operation in space is: if the extracted electron flow is co-directional with the ion beam? If answer is yes, then plume localization in space can be significantly improved (comparing to existing thrusters), while if not – then the electron collection-drain downstream processes between the electron extraction phases can play such an important role, that some charging and oscillation effects could not be easily simulated in the ground experiments and may be observed only during the space flight tests.

To answer this question, the electron EDFs have been measured in the beam downstream at different radial positions of RFEA and with different angular orientation of RFEA with respect to the beam direction (0 and 90 degrees). Fig. 6 (a) presents radial distribution of the electron fluxes measured along the beam direction, and perpendicular to it (the RF voltage amplitude is 200 V). The electron flux has been deduced by integrating electron EDFs. For comparison, Fig. 6 (b) shows the measured radial ion flux profile. As follows from the figure 6 (a), the electron flux is highly anisotropic in the ion beam region, and is equal in both directions (isotropic) at the beam periphery. Therefore, the electrons are directionally co-extracted along with ions from the Neptune thruster. The weak isotropic plasma is only observed outside the beam region.

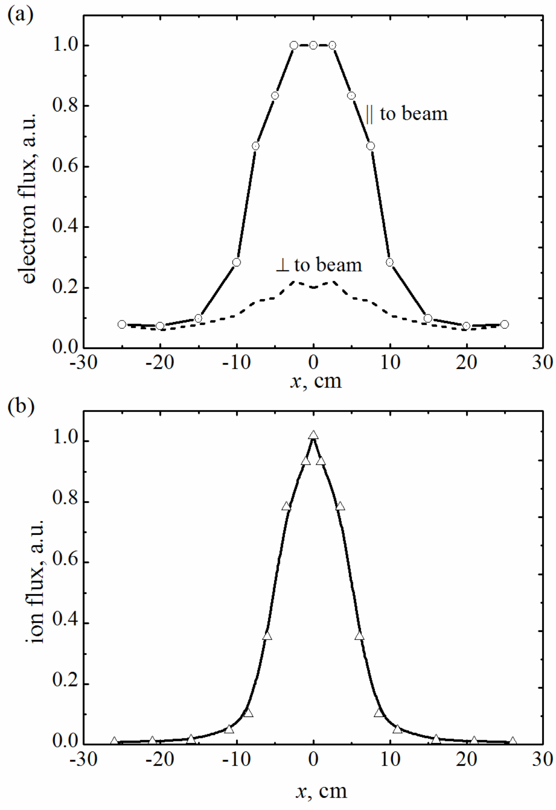

Fig. 6. Radial distribution of the (a) electron fluxes measured along the beam direction and perpendicular to it; (b) ion flux.

3. Conclusions

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Acknowledgments

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