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Using a pulsed radio-frequency discharge to increase the efficiency of a gridded ion thruster

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The paper presents the results of experimental study of a laboratory gridded ion thruster during its operation on a pulsed inductive radio-frequency discharge and various working gases: argon, oxygen and nitrogen. It is shown that the use of such a discharge leads to an increase in the extracted ion current compared to that in continuous operation modes.

Keywords: ion thruster, radio-frequency discharge, pulsed discharge.

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A gridded ion thruster (IT) based on radio-frequency (RF) discharge is one of the most actively exploited spacecraft electric rocket engines. Their design and operating principle are described in detail in [1–6]. At the moment, RF ITs used in the space industry are devices deeply optimized in terms of their design and basic processes: injection of RF power into the discharge plasma and extraction of ions through the ion-optical system (IOS). However, the process of IT scaling towards small sizes and powers, which is associated with exploring low Earth orbits and developing small spacecraft, is accompanied by deterioration in their efficiency parameters [6–8]; therefore, it is necessary to search for new, not yet exhausted ways to improve the RF IT parameters. This work considers the case of using a pulsed inductive RF discharge to increase the ion current extracted from RF IT (the possibility of this was demonstrated in our previous publications devoted to the same problem [9,10]). This paper supplements the results of previous publications and is focused on specific values of the ion current increment for the working gases (oxygen and nitrogen) which are residual atmospheric gases in low Earth orbits (~ 200 km).

As the laboratory RF IT under study, there was used a gridded ion source with a cylindrical gas-discharge chamber (GDC) 10 cm in diameter and 7.5 cm in length with a three-electrode IOS. The time-average RF power of up to 300 W (the incident one minus the reflected one) was considered; the pulse-mode reflected RF power was greater than the continuous-mode one, but did not exceed 10% of the incident power. The operating frequency was 13.56 MHz, while the pulsation frequency was 5 or 10 kHz with the duty factor of 40 to 100%. As working gases, argon, oxygen and nitrogen were used. The working gas flow rates ranged from 12 to 36 sccm. GDC was installed in the longitudinal external magnetic field with induction of 0 to 72 G. The magnetic field range was chosen based on presented in [2] considerations of optimizing the RF power injection into the discharge. In the experiment, RF currents through the antenna were measured with the Rogowski coil, while time dependences of current in the IOS emission electrode circuit and parameters of the particle flow from IT were measured with a four-grid energy analyzer.

The shape of envelope of the RF current signal through the antenna and ion-beam current I_b are shown in Fig. 1. The front and rear edges of the RF current pulse are sharp, ion current after the pulse start reaches the stationary value at the time moment of about $20\,\mu$s and after the end of the pulse has not enough time to drop to zero until the start of the next pulse; however, the main current decrease occurs also in approximately $20\,\mu$s.

Due to the presence of significant current I_b after the end of the RF current pulse, there appears a gain in the time-average beam current (relative to that in the continuous operating mode) at the same values of the time-average RF power supplied to the discharge; this was considered in more detail in [9]. This gain varies with the duty factor and is maximal in the duty factor range of 40 to 70% at the selected pulsation frequencies (5 and 10 kHz). For all the considered working gases (argon, oxygen, nitrogen), the absolute value of the ion current gain caused by transition to the pulse mode was up to 30 mA and depended on the RF power. Fig. 2 presents a typical view of this dependence. As the time-average RF power supplied to the discharge increases, the gain due to transition to the pulse mode decreases. However, the RF generator used in this study failed to exceed the 500 W instantaneous RF power in the pulse, which, hence, limited the average RF power range under study depending on the duty factor (see, e. g. curve *2* in Fig. 2). The described ion current gain depends also on the working gas flow rate (see in Fig. 3). As the plots show, the pulse operating mode is most efficient at low working gas flow rates and low RF powers (below 200 W).

No magnetic field effect on the rate of decrease in the ion current after the RF pulse end was detected in the

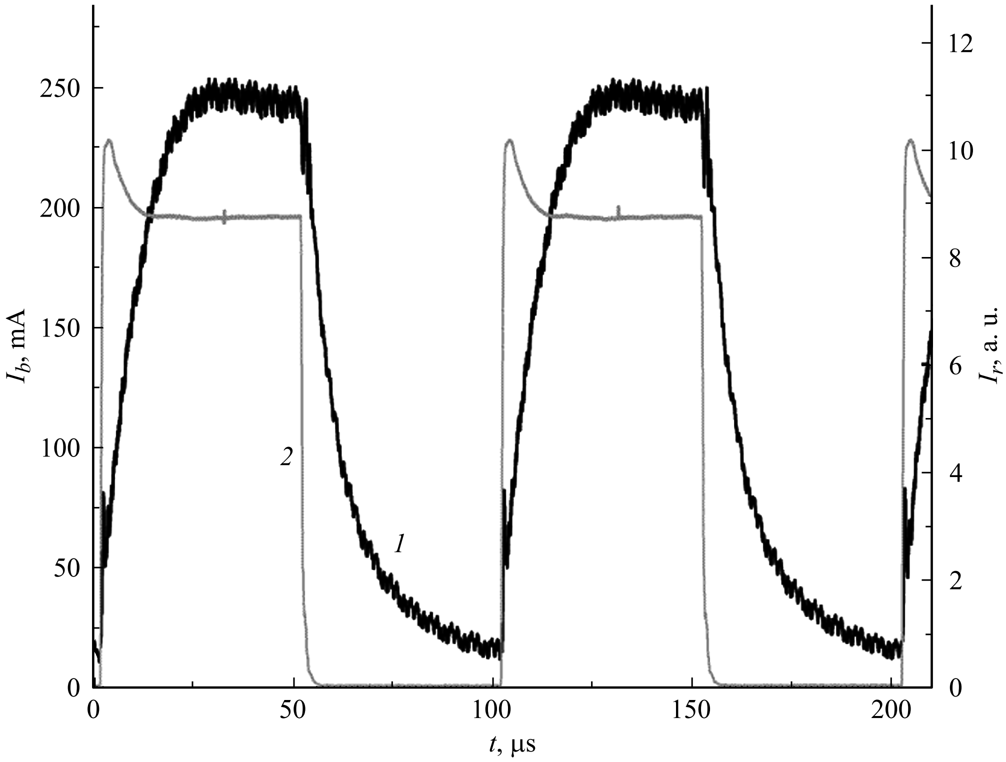

Figure 1. Time dependence of extracted ion current I_b (1) and amplitude of the RF current through the antenna I_r (2). The working gas (argon) flow rate is 24 sccm, RF power is 140 W, pulsation frequency is10 kHz, no external magnetic field.

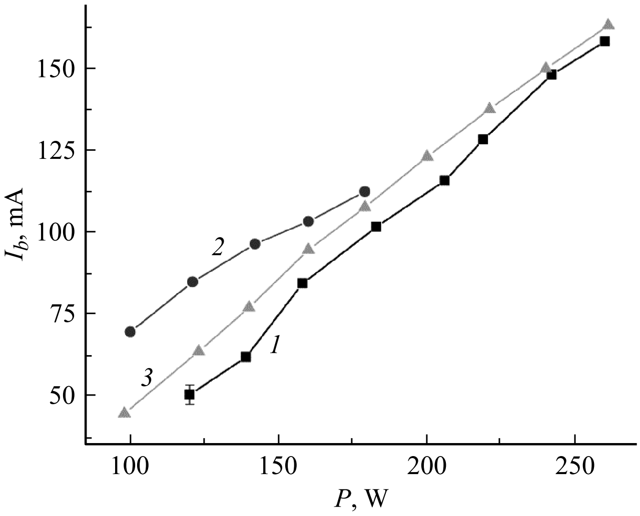

Figure 2. Extracted ion current I_b versus time-average RF power for the continuous mode (1) and pulse modes with duty factors of 40 (2) and 70% (3). The working gas (nitrogen) flow rate is 24 sccm, external magnetic field induction is 19 G, pulsation frequency is 10 kHz.

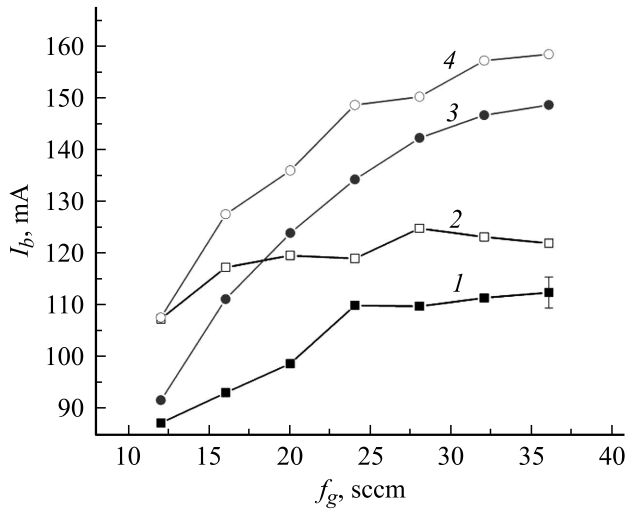

Figure 3. Extracted ion current I_b versus working gas flow rate for nitrogen (1, 2) and oxygen (3, 4). Curves 1 and 3 correspond to the continuous operating mode, while curves 2 and 4 are for the pulse mode with the pulsation frequency of 10 kHz and duty factor of 70%. RF power is 200 W, external magnetic field induction is 19 G.

considered range of its induction. This is, probably, due to the role of IOS and electric fields it creates in plasma at the deionization phase. However, notice that, when the laboratory IT operates on oxygen, the pulse mode is possible only in the presence of magnetic field (in the absence of magnetic field, the discharge gets extinguished).

In this study, the possibility was considered of extracting electrons through IOS at the emission-electrode voltage of

-100 V. Time dependence of the extracted electron current is completely similar to that for ions at the same external discharge parameters but at the electron current approximately 2 times higher than the ion current. For instance, the maximum of the ion current curve (Fig. 1) takes place at 245 mA; the relevant electron current curve has a maximum at 460 mA. The electron current magnitude is apparently limited by the maximal ion current fed from the GDC plasma to the emission electrode. When IT operated on oxygen, no extraction of negative ions was detected. The obtained electron currents allow considering the possibility of using a gridded RF ion source as a compensator cathode in the cases when conventional compensator cathodes can hardly operate because of the presence of residual upper-atmosphere gases.

The possibility of increasing the extracted ion current in RF IT operating on argon, oxygen and nitrogen by up to 30 mA due to transition to the pulsed RF discharge in GDC has been experimentally demonstrated. In relative units, the current gain was about 15, 10 and 25%, respectively. This relative ion-current gain decreases with increasing RF power and working gas flow rate. The possibility of extracting electrons through IOS has been demonstrated. In the considered range of discharge parameters, the extracted electron current exceeds the ion current approximately twice.

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Conflict of interests

The authors declare that they have no conflict of interests.

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