DOI: 10.18721/JPM.14309
UDC 621.455.4; 621.455.34

A MODEL OF AN ION PLASMA ELECTRICALLY POWERED SPACECRAFT PROPULSION WITH A REMOTE MONITORING AND A CONTROL SYSTEM

D.B. Dyubo[1], **S.B. Makarov**[1], **Yu.V. Kuleshov**[2], **P.S. Goncharov**[2], **N.A. Shunevich**[2], **V.V. Martynov**[2], **O.Yu. Tsybin**[1]

[1] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation;

[2] Military Space Academy Named after A.F. Mozhaysky, St. Petersburg, Russian Federation

This paper continues the publication cycle on developing the ion plasma electrically powered spacecraft propulsion (EPSP) of the spacecraft. For monitoring and control of the EPSP operation, a feedback system based on a signal proportional to the EPSP plasma radiation intensity has been proposed to be used. It was assumed that the radiation intensity in the ultraviolet, visible and infrared ranges being proportional to the instantaneous thrust value of the EPSP. Accordingly, the introduction of a signal from the radiation registration detector into the feedback loop should allow to create an onboard closed system for monitoring and control of the EPSP operation. A photodetector based on a dynamic *pin*-diode integrator was considered for use in this system.

Keywords: ion plasma thruster, acceleration, neutralization, plasma radiation, photodetector, automatic control

Citation: Dyubo D.B., Makarov S.B., Kuleshov Yu.V., Goncharov P.S., Shunevich N.A., Martynov V.V., Tsybin O.Yu., A model of an ion plasma electrically powered spacecraft propulsion with a remote monitoring and a control system, St. Petersburg Polytechnical State University Journal. Physics and Mathematics. 14 (3) (2021) 116–125. DOI: 10.18721/JPM.14309

МОДЕЛЬ ИОННО-ПЛАЗМЕННОГО ЭЛЕКТРИЧЕСКОГО РАКЕТНОГО ДВИГАТЕЛЯ С СИСТЕМОЙ УДАЛЕННОГО КОНТРОЛЯ И УПРАВЛЕНИЯ

Д.Б. Дюбо[1], **С.Б. Макаров**[1], **Ю.В. Кулешов**[2], **П.С. Гончаров**[2], **Н.А. Шуневич**[2], **В.В. Мартынов**[2], **О.Ю. Цыбин**[1]

[1] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация;

[2] Военно-космическая академия имени А.Ф. Можайского, Санкт-Петербург, Российская Федерация

Данная статья продолжает цикл публикаций о создании ионно-плазменного электрического ракетного двигателя (ИЭРД) космического аппарата. С целью контроля и управления работой двигателя предлагается использовать систему с обратной связью, основанную на сигнале, пропорциональном интенсивности излучения плазмы ИЭРД. Предполагается, что интенсивность такого излучения в ультрафиолетовом, видимом и инфракрасном диапазонах пропорциональна мгновенной силе тяги ИЭРД. Соответственно, введение сигнала с датчика регистрации излучения в цепь обратной связи позволит создать бортовую замкнутую систему контроля и управления работой ИЭРД. Для использования в данной системе рассматривается фотоприемник на основе динамического *p*–*i*–*n*-диода-интегратора.

Ключевые слова: ионно-плазменный электрический ракетный двигатель, нейтрализация, излучение плазмы, фотоприемник, автоматическое управление

Ссылка при цитировании: Дюбо Д.Б., Макаров С.Б., Кулешов Ю.В., Гончаров П.С., Шуневич Н.А., Мартынов В.В., Цыбин О.Ю. Модель ионно-плазменного электрического ракетного двигателя с системой удаленного контроля и управления // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2021. Т. 14. № 3. С. 116–125. DOI: 10.18721/JPM.14309

Introduction

Space exploration has made great strides in recent years. Large spacecraft are increasingly constructed instead of small ones, with multiple rather than single spacecraft launched. The exploration of deep space, as well as interplanetary missions, also open vast new opportunities. New requirements are thus imposed on electrically powered propulsion systems (EPSs) in spacecraft, aimed at accelerating vehicles in outer space [1 – 4]. Particles are first ionized in propellant flow in such engines, with the resulting ions subsequently accelerated by an electric field. Accelerated ions are neutralized upon leaving the accelerating system in the EP; flow of the neutrals produced then expands freely into outer space. Electrical energy is consequently converted into kinetic energy of spacecraft motion. The efficiency of the engine can be characterized by a parameter determining the efficiency of converting electrical energy into kinetic energy of propellant flow [4]. The thrust generated by the electric prop system is fundamentally limited because, on the one hand, high values of electrical power are required to obtain large momenta, and, on the other hand, the power cannot exceed that of the solar arrays powering the spacecraft electrical system. Xenon is the most popular propellant for EPSs: its advantages are chemical inertness and a relatively large atomic mass. However, xenon has a high cost, its production is limited, and reserves on Earth are insufficient.

Due to these drawbacks of xenon, new EP engines running on alternative propellants need to be constructed. Novel EPSs should be simple, fuel-efficient, stable, easy to control, reliable and durable at an acceptable cost. The EPS should be designed to endure multiple switching cycles and pauses in operation. Besides, as EPSs are installed in an increasing number of spacecraft, the motion control systems should be improved. Modern EPSs in spacecraft include an onboard power supply/control (PSC) unit. The system of telemetric control (STC) sends the data on the operation of the EPS to the mission control center of the spacecraft, which processes the data and sends control signals to the spacecraft (via the onboard controller integrated in the PSC unit).

The set of basic operating parameters of the EPS includes the thrust F, the mass flow rate $\dot{m}_p$ of the propellant, the ion beam current I_i, the velocity v_i of accelerated ions at the exit from the accelerator, the acceleration voltage U_k of each k^{th} electrode, the velocity v_{ex} of accelerated neutrals in the beam, the neutral flux $\dot{m}_{ex}$ in the exiting beam, and some others. Since each individual parameter does not completely describe the operation of the EPSP, all parameters must be measured simultaneously and logically combined in commands. The latter involves a fairly complicated step-by-step procedure where errors and false signals can be generated.

Assuming that the plume is a mono-velocity flux of neutral particles, the thrust can be found from the simplified formulation of the momentum conservation law [1 – 4]:

$$F = \frac{d\left(mv\right)_{ex}}{dt} = \dot{m}_{ex}v_{ex}, \dot{v}_{ex} = 0, \tag{1}$$

where $\dot{m}_{ex}$ is the mass flow rate of propellant, v_{ex} is the outflow velocity of propellant particles.

The parameters $\dot{m}_{ex}$, v_{ex} in Eq. (1) correspond only to the ejected neutral plume. Because a magnetic mirror is produced in the spacecraft as charged particles escape, ions cannot completely leave, generating thrust. It is typically impossible to simply measure the parameters $\dot{m}_{ex}$, v_{ex} on board. The simplified theory assumes that the parameter $\dot{m}_{ex}$ is equal to the flow rate of the propellant, the velocity v_{ex} corresponds to the potential difference passed by the ion U from the injection plane to the equipotential region where neutralization occurs. An ideal EPS in this representation provides the thrust F created by the ion beam current I_i of singly charged ions accelerated by the electric voltage U [4]:

$$F = I_i\sqrt{\frac{2\mu_i U}{e}}, \tag{2}$$

where μ_i is the ion mass, e is the elementary ion charge. Eq. (2) is derived for the ideal case, when each ion must be instantly neutralized in the plane where it is ejected from the accelerator. The correction can be introduced with two additional parameters η_m, η_n that the thrust $F(t)$ depends on:

$$F(t) = \eta_m \eta_n I_i(t)\sqrt{\frac{2\mu_i U}{e}}. \tag{3}$$

The conversion efficiency η_m of propellant mass is the ratio used to measure the ionization efficiency of the neutral propellant flow. The mass conversion efficiency η_n is the ratio used to measure the neutralization efficiency of the ionized propellant flow. Moreover, each parameter in relation (3) can be unstable, depending on time. In addition, a fraction of the electrical power of the ion flux is spent on electromagnetic radiation. Apparently, the relationship between plasma electromagnetic radiation and the thrust and jet power of the EPSP has not been described in literature. The goal of our study is to formulate a model for a plasma ion electrically powered spacecraft propulsion with a remote monitoring and control system, using plasma radiation from the EPSP to generate signal and transmit it to the onboard control system and telemetrically to the mission control center.

Plasma radiation in EPS

We suggest to monitor and control the EPS, in particular, to stabilize the thrust, by measuring the integral control the signal from the sensor recording the intensity of plasma radiation in the system and using it to automatically regulate the feedback loop. The control signal is proportional to the thrust F.

Mechanical thrust is generated based on the principle that charges induced on the surfaces of the surfaces of accelerator electrodes produce the force of attraction between the electrodes and the accelerated ions. Induced charges are created by the electric field of external sources together with the intrinsic electric field of the accelerated ions. Ions can produce positive traction on a given electrode during the period they spend in the accelerating electric field from the side of this electrode. The traction produced by an ion becomes zero immediately after this ion is neutralized, since the neutralized particles do not interact with the EPS electrodes.

The voltage U in Eqs. (2, 3) is the potential difference between point where the ion is injected from the ionizer into the interelectrode gap of the accelerator and the accelerating electrode (the ejection plane of the ion from the accelerator). If an ion settles on any electrode of the accelerator before neutralization, its overall contribution to the thrust vanishes. Moreover, the thrust decreases if the ions are not neutralized completely. Thus, the ion current I in Eqs. (2, 3) neither has a measurable magnitude nor is exactly related to the thrust F. The value of the thrust can be estimated more correctly by measuring the parameters of the plasma generated in the neutralizer.

Intense ultraviolet, visible, infrared and microwave radiation is generated from a flux of accelerated ions during operation [7 – 10]. EPS plasma provides high radiative luminosity at the stage of neutralization, allowing diagnostics by optical and microwave spectroscopy [7 – 9]. Photographs of the bright luminous flux accompanying the operation of the EPS are given in many studies, in particular, [10].

The plasma plume starts to glow, mainly due to recombination resulting from neutralization of the ion charge, collisions and resonant charge exchange, spontaneous relaxation of excitation. The predominant mechanisms governing radiation depend on both the individual properties of charged and neutral particles contained in the plasma and by its collective properties, primarily bearing a vibration-wave nature. The radiation of individual particles is generated by electron transitions in atoms or ions between discrete energy levels; electron deceleration in an ion cloud; cyclotron radiation of electrons in a magnetic field.

Structure of onboard remote monitoring/control system

Remote monitoring and control of the EPS should be carried out via a photodetector recording the luminous intensity of plasma [11, 12]. Accordingly, the electromagnetic radiation intensity of the plasma can serve as a parameter for rapid monitoring of the EPS parameters during operation. The intensity of ultraviolet, visible and infrared radiation I_{rad} (ω, t) can be represented as following integral parameter:

$$I_{rad}(\omega,t)=\eta_{rad}(\omega)I_i(t). \tag{4}$$

Relation (4) contains the generation efficiency of frequency-dependent radiation η_{rad} (ω), which is smaller than unity, η_{rad} (ω) < 1. When the onboard detector receives radiation I_{rad} (ω, t) emanating from the neutralizer, the parameter η_{rad} (ω) indicates the neutralization efficiency of the operating ion current I_i (t) as the main source of radiation. The radiation intensity I_{rad} (ω, t) can be represented by a time-dependent signal S(ω, t), accounting for the fluctuations in all parameter values: vacuum conditions and temperature, power source, propellant flow, ionizer, particle losses in the accelerator, instability of ion flux neutralization.

The signal $S(\omega, t) = kI_{rad}$ (ω, t) can also be used as a complex signal for monitoring and control of the EPS. Accordingly, Eqs. (2, 4) prove that the signal S(ω, t) is proportional to the thrust F(t):

$$S(\omega,t)=\left[\left(k\cdot\eta_{rad}/\eta_n\eta_m\right)\left(e/2\mu_iU\right)^{1/2}\right]\cdot F(t)=\mathrm{const}(\omega)F(t), \tag{5}$$

and can be used to control the magnitude of thrust F(t) in the onboard monitoring system.

Fig. 1 shows a simplified block diagram describing the operation of the EPS with a closed system for remote monitoring and control. The design of the EPS, the spatial characteristics of ion and electron beams in an independent electric field, and the induced surface electric charge were calculated using the Computer Science Technology (CST) Particle Studio package [5, 6].

The block diagram shows the propellant flow, the accelerated ion and electron fluxes combined inside the neutralizer, and a neutral exhaust plume.

This layout is commonly used for ion-electron neutralization in widespread grid and Hall-effect EPSP.

EPS with the closed system for remote monitoring and control includes a photodetector, a modulator, a power supply/control unit (PSCU), a power source and a propellant flow controller. The PSCU-controlled power source supplying electric energy generates the voltage applied to the electrodes. Plasma radiation, photodetector, modulator, PSCU, power source and flow controller comprise a closed loop providing automated control of the EPSP. The photodetector generates instanta-

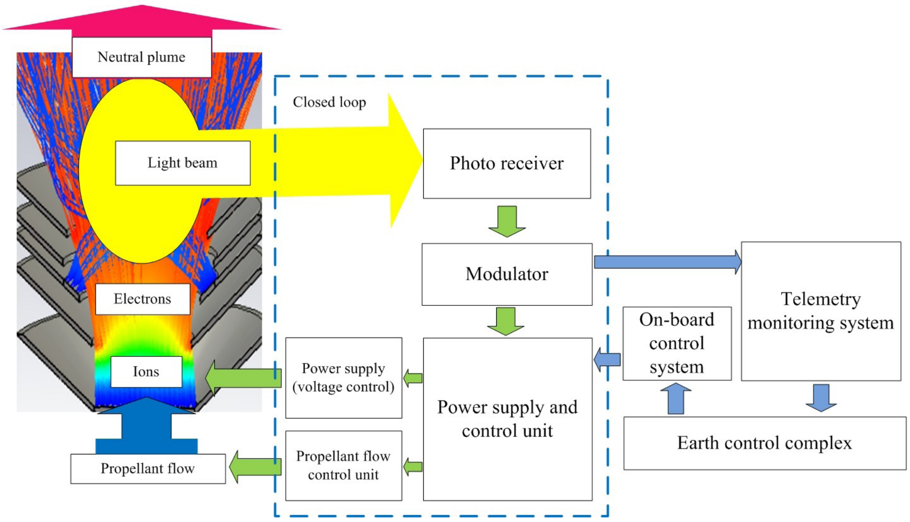

Fig. 1. Block diagram for EPS with closed loop for remote monitoring and control

neous control signal directed to the modulator. Signal from the modulator is transmitted to the PSCU and the telemetric system, which then sends data about the EPS to the mission control center. After the data about the EPS are processed, the mission control center sends control signals to the spacecraft (to the onboard system) whenever necessary. If thrust is unstable and the respective correlated changes occur in plasma radiation, the closed loop for remote monitoring and control provides rapid stabilization by correcting the voltages on the electrodes of the accelerator.

The photodetector has to satisfy several requirements for the EPS to function correctly [13, 14]: it should have small weight and overall dimensions, be reliable, have a long service life, high sensitivity, low noise figure and be equipped with noise protection. The well-known photodiodes do not actually integrate the amplitude-time characteristics of noise and signals, so additional external units with wide dynamic and frequency ranges are required for them to operate as part of the EPS, including preamplifiers, integrators, comparators, etc.

The photodetectors meeting these requirements include the recently developed novel integrated photodetector based on a dynamic *pin* diode-triode, offering several of the necessary functions in a single device [15]. The dynamic *pin* diode-triode with trapped charge carriers and built-in potential barrier generated in the gate is a device with a signal-to-noise ratio $SNR > 1$ and high sensitivity in the wavelength range from 400 to 700 nm. Experimental measurements have shown that the characteristics of the device are satisfactory for using it in an onboard system for remote monitoring and control of the EPS [16, 17]. The output analog signal is proportional to the absorbed energy dose of plasma radiation. Thus, the photodetector serves as a charge integrator/comparator, acting as a dose-to-time converter. Measuring the time delay of the photocurrent, rather than its magnitude, provides a new efficient method for detecting plasma radiation. Noise and other spurious signals are reduced by the averaging effect in the device itself. The magnitude of forward current is controlled only by the forward voltage and does not depend on the radiation intensity.

Conclusions

The closed system for remote control of electrically powered propulsion in spacecraft uses plasma radiation in the ultraviolet, visible and infrared ranges as signal characterizing the operation mode of the EPS. The system must measure the EPS thrust, accurately adjust it and transmit telemetric data to the mission control center. Assuming that the signal $S(\omega, t)$ is proportional to the thrust $F(t)$ of the

EPSP in accordance with relation (5) allows designing a new EPSP with a closed system of remote control, planned to be tested experimentally.

A photodetector based on a pin diode-triode, operating in dynamic mode with the respective properties and parameters, is proposed as a device for obtaining and collecting the initial data. The photodetector developed should make it possible to set the parameters required for the operation of the EPS in remote and automated modes, ensure more precise maneuvering in space, quickly identify errors and malfunctions, control and optimize the consumption of the propellant.

Acknowledgment

The authors are grateful to ActLight SA, Switzerland, for providing a sample pin-diode for the study. This work was supported by State Assignment of the Russian Federation for Basic Research (Project No. FSEG-2020-0024).

REFERENCES

1. **Nauschütt M., Kiefer B., Kunze F., et al.,** Ion thrusters for electric propulsion: Scientific issues developing a niche technology into a game changer, Rev. Sci. Instrum. 91 (6) (2020) 061101.

2. **Levchenko I., Xu S., Mazouffre S., et al.,** Perspectives, frontiers, and new horizons for plasma-based space electric propulsion, Physics of Plasmas. 27 (2) (2020) 020601.

3. **Levchenko I., Bazaka K., Ding Y., et al.,** Space micropropulsion systems for Cubesats and small satellites: From proximate targets to furthermost frontiers, Appl. Phys. Rev. 5 (1) (2018) 011104.

4. **Goebel D.M., Katz I.,** Fundamentals of electric propulsion: Ion and Hall thrusters, John Wiley & Sons, Hoboken, New Jersey, USA (2008) 1–507.

5. **Kurushin A.,** Basic course of design of microwave devices using CST Studio Suite, One-Book, Moscow, 2014.

6. **Dyubo D.B., Tsybin O.Yu.,** A computer model of the contact ionization ion accelerator for the electrically powered spacecraft propulsion, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 13 (1) (2020) 78–91.

7. **Holste K., Dietz P., Scharmann S., et al.,** Use of emission spectroscopy for real-time assessment of relative wall erosion rate of BHT-200 hall thruster for various regimes of operation, Vacuum. 84 (9) (2010) 1085–1091.

8. **Ferreira J.L., Souza J.H.C., Rego I.S., Ferreira I.S.,** Plasma diagnostics and performance of a permanent magnet Hall thruster, 2004. Access mode: https://hal.archives-ouvertes.fr/hal-00003100

9. **Nishiyama K., Shimizu Y., Funaki I., et al.,** Measurements of the electromagnetic emissions from the MUSES-C ion engine system, Proceedings of the 27th International Electric Propulsion Conference, 15–19 October, 2001, Pasadena, CA. 2001. Paper IEPC-01-112.

10. **Tsybin O.Yu., Makarov S.B., Dyubo D.B., et al.,** An electrically powered ion accelerator with contact ionization for perspective electrically powered thrusters, St. Petersburg Polytechnical State University Journal. Physics and Mathematics. 13 (2) (2020) 99–115.

11. **Penkov M.M., Goncharov P.S., Martynov V.V., Tsybin O.Yu.,** Elektroraketnyy dvigatel [Electrically powered spacecraft propulsion]. Pat. No. 2726152, Russian Federation, MPK H05H 1/54 (2006.01) F03H1/00 (2006.01) B64G 1/54 (2006.01). Mozhaisky Military Space Academy is a declarant and patentee. No. 2019140727; declar. 09.12.2019; publ. 09.07.2020. Bull. No. 19.

12. **Goncharov P.S., Martynov V.V., Shunevich N.A., Tsybin O.Y.,** Use of plasma electromagnetic radiation of an electric rocket thruster, Izvestiya Tula State University. (11) (2020) 197–202.

13. **Kawabata Y., Kawakatsu Y.,** On-board orbit determination using sun sensor and optical navigation camera for deep-space missions, Transactions of the Japan Society for Aeronautical and Space Sciences. 15 (2017) 13–19.

14. **Hufenbach B., Habinc S., Vuilleumier P.,** Space applications for smart sensors, European Space Agency, European Space Research and Technology Centre (1999) 9–16. Access mode: http://microelectronics.esa.int/vhdl/doc/Smart Sensor. pdf.

15. **Okhonin S., Gureev M., Sallin, D., et al.,** A dynamic operation of a *pin* photodiode, Appl. Phys. Lett. 106 (3) (2015) 031115.

16. **Dyubo D.B., Tsybin O.Yu.,** A novel photodiode in on-board micro receiver in 400–800 nm range, Proceedings of the First Joint International Conference on Astrophysics for Young Scientists, Peter the Great St. Petersburg Polytechnic University, Higher School of Applied Physics and Space Technologies (2017) 53–57.

17. **Dyubo D.B., Tsybin O.Yu.,** The relation of volume and surface effects with a charge barrier height in a dynamic *p–i–n*-photodyode, St. Petersburg Polytechnical State University Journal. Physics and Mathematics. 11 (2) (2018) 16–25.

Received 15.06.2021, accepted 06.07.2021.

THE AUTHORS

DYUBO Dmitry B.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
dyubo_db@spbstu.ru

MAKAROV Sergey B.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
makarov@cee.spbstu.ru vka@mil.ru

KULESHOV Yuri V.
A.F. Mozhaysky Military-Space Academy
13 Zhdanovskaya St., St. Petersburg, 197198, Russian Federation
vka@mil.ru

GONCHAROV Pavel S.
A.F. Mozhaysky Military-Space Academy
13 Zhdanovskaya St., St. Petersburg, 197198, Russian Federation
vka@mil.ru

SHUNEVICH Nikolay A.
A.F. Mozhaysky Military-Space Academy
13 Zhdanovskaya St., St. Petersburg, 197198, Russian Federation
vka@mil.ru

MARTYNOV Viktor V.
A.F. Mozhaysky Military-Space Academy
13 Zhdanovskaya St., St. Petersburg, 197198, Russian Federation
vka@mil.ru

TSYBIN Oleg Yu.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
otsybin@rphf.spbstu.ru

СПИСОК ЛИТЕРАТУРЫ

1. **Nauschütt M., Kiefer B., Kunze F., et al.** Ion thrusters for electric propulsion: Scientific issues developing a niche technology into a game changer // Review of Scientific Instruments. 2020. Vol. 91. No. 6. P. 061101.

2. **Levchenko I., Xu S., Mazouffre S., Lev D., Pedrini D., Goebel D., Garrigues L., Taccogna F., Bazaka K.** Perspectives, frontiers, and new horizons for plasma-based space electric propulsion // Physics of Plasmas. 2020. Vol. 27. No. 2. P. 020601.

3. **Levchenko I., Bazaka K., Ding Y., et al.** Space micropropulsion systems for Cubesats and small satellites: From proximate targets to furthermost frontiers // Applied Physics Reviews. 2018. Vol. 5. No. 1. P. 011104.

4. **Goebel D.M., Katz I.** Fundamentals of electric propulsion ion and Hall thrusters. Hoboken, New Jersey, USA: John Wiley & Sons, 2008. Pp. 1–507.

5. **Kurushin A.** Basic course of design of microwave devices using CST Studio Suite. Moscow: One-Book, 2014. 433 p.

6. **Дюбо Д.Б., Цыбин О.Ю.** Компьютерная модель ускорителя ионов с контактной ионизацией для электроракетных двигателей космических летательных аппаратов // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2020. Т. 13. № 1. С. 78–91.

7. **Holste K., Dietz P., Scharmann S., Keil K., Henning T., Zschätzsch D., Reitemeyer C.M., Batishchev O., Martinez-Sanchez M.** Use of emission spectroscopy for real-time assessment of relative wall erosion rate of BHT-200 hall thruster for various regimes of operation // Vacuum. 2010. Vol. 84. No. 9. Pp. 1085–1091.

8. **Ferreira J.L., Souza J.H.C., Rego I.S., Ferreira I.S.** Plasma diagnostic and performance of a permanent magnet Hall thruster. 2004. Режим доступа: https://hal.archives-ouvertes.fr/hal-00003100.

9. **Nishiyama K., Shimizu Y., Funaki I., Kuninaka H., Toki K.** Measurements of the electromagnetic emissions from the MUSES-C ion engine system // Proceedings of the 27th International Electric Propulsion Conference, 15–19 October, 2001, Pasadena, CA. 2001. Paper IEPC-01-112.

10. **Цыбин О.Ю., Макаров С.Б., Дюбо Д.Б., Кулешов Ю.В., Гончаров П.С., Мартынов В.В., Шуневич Н.А.** Электростатический ионный ускоритель с контактной ионизацией для перспективных электрических ракетных двигателей // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2020. Т. 13. № 2. С. 99–115.

11. **Пеньков М.М., Гончаров П.С., Мартынов В.В., Цыбин О.Ю.** Электроракетный двигатель. Патент 2726152 МПК H05H 1/54 (2006.01) F03H 1/00 (2006.01) B64G 1/54 (2006.01). Заявитель и патентообладатель: Федеральное государственное бюджетное военное образовательное учреждение высшего образования «Военно-космическая академия имени А.Ф. Можайского» Министерства обороны Российской Федерации (RU). № 2019140727; заявл. 9.12.2019; опубл. 09.07.2020, Бюлл. № 19.

12. **Гончаров П.С., Мартынов В.В., Шуневич Н.А., Цыбин О.Ю.** Использование электромагнитного излучения плазмы электрического ракетного двигателя // Известия Тульского государственного университета. Технические науки. 2020. № 11. С. 197–202.

13. **Kawabata Y., Kawakatsu Y.** On-board orbit determination using sun sensor and optical navigation camera for deep-space missions // Transactions of the Japan Society for Aeronautical and Space Sciences. 2017. Vol. 15. Pp. 13–19.

14. **Hufenbach B., Habinc S., Vuilleumier P.** Space applications for smart sensors // European Space Agency. European Space Research and Technology Centre. 1999. Pp. 9–16. Режим доступа: http://microelectronics. esa.int/vhdl/doc/ SmartSensor.pdf

15. **Okhonin S., Gureev M., Sallin, D., et al.** A dynamic operation of a *pin* photodiode // Applied Physics Letters. 2015. Vol. 106. No. 3. P. 031115.

16. **Dyubo D., Tsybin O.Yu.** A novel photodiode in on-board micro receiver in 400–800 nm range // Proceedings of the First Joint International Conference on Astrophysics for Young Scientists. Peter the Great St. Petersburg Polytechnic University. Higher school of Applied Physics and Space Technologies. St. Petersburg, 2017. Pp. 53–57.

17. **Дюбо Д.Б., Цыбин О.Ю.** Связь объемных и поверхностных эффектов с высотой зарядового барьера в динамическом *p*–*i*–*n*-фотодиоде // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2018. Т. 11. № 2. С. 16–25.

Статья поступила в редакцию 15.06.2021, принята к публикации 06.07.2021.

СВЕДЕНИЯ ОБ АВТОРАХ

ДЮБО Дмитрий Борисович – *инженер Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Российская Федерация.*

195251, Российская Федерация, г. Санкт-Петербург, Политехническая ул., 29

dyubo_db@spbstu.ru

МАКАРОВ Сергей Борисович – *доктор технических наук, профессор Высшей школы прикладной физики и космических технологий Санкт-Петербургского политехнического университета Петра Великого, главный научный сотрудник научной лаборатории «Космические телекоммуникационные системы» того же университета, Санкт-Петербург, Российская Федерация.*

195251, Российская Федерация, г. Санкт-Петербург, Политехническая ул., 29

makarov@cee.spbstu.ru

КУЛЕШОВ Юрий Владимирович – *доктор технических наук, профессор, заместитель начальника Военно-космической академии имени А.Ф. Можайского по учебной и научной работе Военно-космической академии имени А.Ф. Можайского, Санкт-Петербург, Российская Федерация.*

197198, Российская Федерация, г. Санкт-Петербург, Ждановская ул., 13

vka@mil.ru

ГОНЧАРОВ Павел Сергеевич – *кандидат технических наук, начальник 12-го отдела Военного института (научно-исследовательского) Военно-космической академии имени А.Ф. Можайского, Санкт-Петербург, Российская Федерация.*

197198, Российская Федерация, г. Санкт-Петербург, Ждановская ул., 13

vka@mil.ru

ШУНЕВИЧ Николай Александрович – *кандидат технических наук, начальник лаборатории, старший научный сотрудник 122-й лаборатории 12-го отдела Военного института (научно-исследовательского) Военно-космической академии имени А.Ф. Можайского, Санкт-Петербург, Российская Федерация.*

197198, Российская Федерация, г. Санкт-Петербург, Ждановская ул., 13

vka@mil.ru

МАРТЫНОВ Виктор Васильевич – *старший научный сотрудник 121-й лаборатории 12-го отдела Военного института (научно-исследовательского) Военно-космической академии имени А.Ф. Можайского, Санкт-Петербург, Российская Федерация.*

197198, Российская Федерация, г. Санкт-Петербург, Ждановская ул., 13

vka@mil.ru

ЦЫБИН Олег Юрьевич – *доктор физико-математических наук, профессор Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Российская Федерация.*

195251, Российская Федерация, г. Санкт-Петербург, Политехническая ул., 29

otsybin@rphf.spbstu.ru