PHYSICAL ELECTRONICS

Original article
DOI: https://doi.org/10.18721/JPM.17107

CURRENT AND SPEED CHARACTERISTICS OF ELECTRON FLOWS FORMED BY THE ELECTRON-OPTICAL SYSTEM WITH A MULTI-TIP FIELD EMITTER

E. P. Taradaev✉, *G. G. Sominskii*, *S. P. Taradaev*

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

✉ evgeny_tar@hotmail.com

Abstract. The article presents the results of studies of the characteristics of electron flows generated by an electron-optical system with a multi-tip field emitter. Information has been obtained on important beam parameters: the beam current, electron velocity spectrum, pitch factor. The spread in transverse velocity did not exceed 50% in the studied modes. The shape of the spectra did not depend on the magnitude of the magnetic field and did only weakly on the current in the beam.

Keywords: field emission, multi-tip field emitter, electron flow, velocity spread

Funding: The reported study was funded by Russian Science Foundation (Grant No. 23-29-00224).

Citation: Taradaev E. P., Sominskii G. G., Taradaev S. P., Current and speed characteristics of electron flows formed by the electron-optical system with a multi-tip field emitter, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 17 (1) (2024) 64–70. DOI: https://doi.org/10.18721/JPM.17107

Научная статья
УДК 537.533
DOI: https://doi.org/10.18721/JPM.17107

ТОКОВЫЕ И СКОРОСТНЫЕ ХАРАКТЕРИСТИКИ ЭЛЕКТРОННЫХ ПОТОКОВ, ФОРМИРУЕМЫХ ЭЛЕКТРОННО-ОПТИЧЕСКОЙ СИСТЕМОЙ С МНОГООСТРИЙНЫМ ПОЛЕВЫМ ЭМИТТЕРОМ

Е. П. Тарадаев✉, *Г. Г. Соминский*, *С. П. Тарадаев*

Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия

✉ evgeny_tar@hotmail.com

Аннотация. В статье представлены результаты исследований характеристик электронных потоков, формируемых электронно-оптической системой с многоострийным полевым эмиттером. Была получена информация о важных параметрах пучка: токе в пучке, спектре скоростей электронов, питч-факторе. Разброс по поперечной скорости не превышал 50% в исследованных режимах. Форма спектров не зависела от величины магнитного поля и проявляла лишь слабую зависимость от тока в пучке.

Ключевые слова: полевая эмиссия, многоострийный полевой эмиттер, электронный поток, скоростной разброс

Финансирование: Работа выполнена при финансовой поддержке гранта Российского научного фонда № 23-29-00224.

Ссылка для цитирования: Тарадаев Е. П., Соминский Г. Г., Тарадаев С. П. Токовые и скоростные характеристики электронных потоков, формируемых электронно-оптической системой с многоострийным полевым эмиттером // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2024. Т. 17. № 1. С. 64–70. DOI: https://doi.org/10.18721/JPM.17107

Introduction

One of the practically important directions in the development of modern microwave electronics is the creation and improvement of subterahertz radiation sources driven by electron beams (see, for example, [1–3]). In this paper, we consider the possibilities of using field emitters to form electron flows with annular cross-section, necessary for miniature but high-voltage devices of this frequency range. The field emitters developed [4–9] have obvious advantages over hot cathodes, since they do not require heating and provide rapid (practically inertialess) on/off switching of the electron source.

However, the development of electron-optical systems (EOS) with field emitters is difficult due to the lack of information about the characteristics of electron flows that they generate. We previously conducted an experimental study of the spatiotemporal and velocity characteristics of electron flows in EOS with field emitters whose electrode configuration is typical for gyrotron-type devices [10]. However, the measurements were performed only at low magnetic fields not exceeding 0.1 T.

In this paper, we investigate the characteristics of electron flows generated in the EOS with multi-tip field emitters in significantly higher magnetic fields (approximately up to 2.5 T), typical for gyrotron devices of the sub-THz range.

Experimental procedure and instrumentation

The cross-sectional view of the EOS used to measure the characteristics of electron flows is shown schematically in Fig. 1.

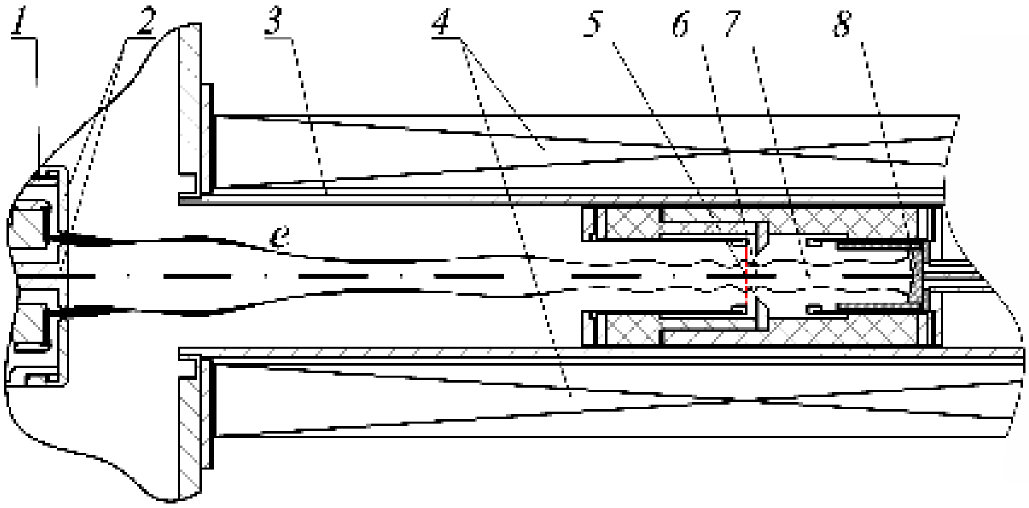

Fig. 1. Schematic of electron-optical system (EOS) with a retarding field analyzer (installed in the center of the solenoid):
cathode system *1*; control electrode with annular aperture *2*; channel *3* for electron beam transport (*e*); solenoid *4*; protective grids *5*, *7*; retarding grid *6*; electron collector *8*

The dimensions of the main parts of the EOS and the analyzer are shown in Table. Magnetic field pulses with a duration of 10 ms were generated using a solenoid to compress and confine the electron flow. To ensure field emission, a pulse of negative (relative to the grounded control electrode) voltage U with an amplitude up to 15 kV was applied to the cathode. The pulse duration was varied from 10 to 100 μs.

Table

Main geometric parameters of electron-optical system (see Fig. 1)

Element	Parameter	Size, mm
Cathode system *1*	Distance between control electrode *2* and cathode *1*	2.00
	Aperture width in control electrode *2*	2.00
	Average diameter of field emitter	14.0
	Width of field emitter	0.65
	Tip height and distance between tips	0.03
Solenoid *4*	Coil diameter:	
	external	42
	internal	30
	Length of solenoid *4*	200
Electron velocity analyzer	Distance between protective (*5*) and retarding (*6*) grids	2

A magnetic field was applied, increasing from a minimum B_c at the cathode to a maximum B_m in the center of the solenoid. The maximum value of the magnetic flux density B_m varied from 0.1 to 2.5 T. The magnetization reversal coefficient $k = B_m/B_c$ could be adjusted by moving the solenoid along the axis. The current I of electrons in the beam and the longitudinal component of the electron velocity $V_{||}$ (directed along the magnetic field lines) were experimentally measured; the transverse component of the velocity $V_{\perp}$ (directed perpendicular to the field lines) was calculated using a previously developed technique [10].

The electron velocities were determined by the retarding field method using the analyzer (see Fig. 1 and Table). The analyzer was placed in the region of magnetic field uniform along the axis, near the central plane of the solenoid section. The delay curves (dependences of the current I of the electrons passing to collector 8 of the analyzer on the magnitude of the retarding negative (relative to the ground) voltage U_r, applied to grid *6*) were measured. Since electrons with the velocity $V_{||} < (2eU_r/m_e)^{1/2}$ do not fall into collector 8, the resulting delay curve $I(U_r)$ was reconstructed in the coordinates $I(V_{||})$.

The spectrum of longitudinal electron velocities $V_{||}$ was obtained by differentiating the curve $I(V_{||})$. The transverse velocity spectrum $V_{\perp}$ was determined taking into account the information about the total energy eU of electrons in the beam and the data obtained on the distribution of electron velocities in the longitudinal direction.

Before taking measurements, the cathode was trained with current sampling up to 20–25 mA for a time of up to ten hours. The operation of the electronic flow generation system was stabilized.

Results and discussion

The electron source operated stably under technical vacuum in the entire studied range of beam currents (the pressure was approximately 10^{-7} Torr). After the training was completed, the variation in the beam current in a single pulse did not exceed 1%.

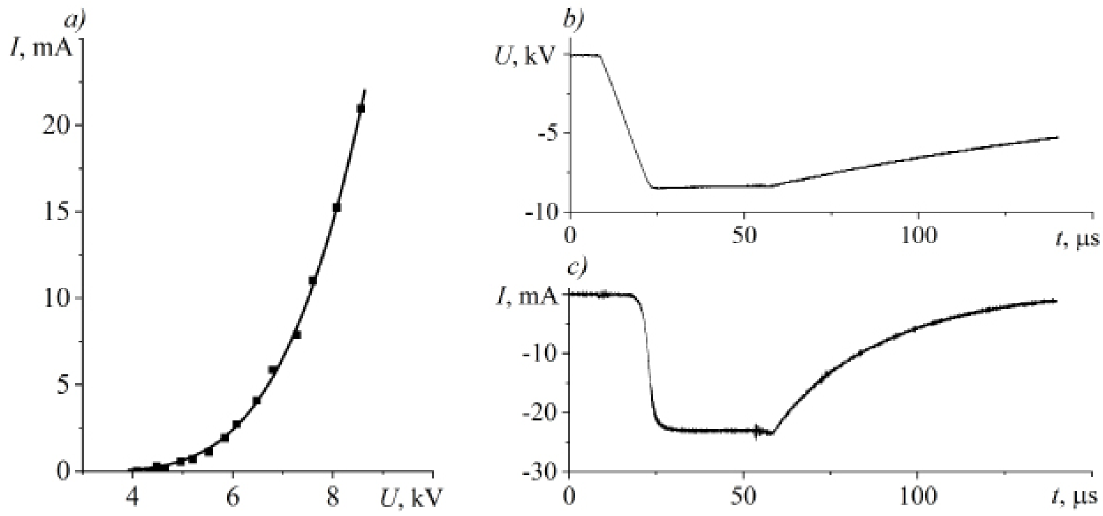

Fig. 2. Measured characteristics of the EOS: voltage characteristic (*a*); waveforms of cathode voltage and the current in the collector, respectively (*b*, *c*)

Fig. 2 shows the current–voltage characteristic of the studied EOS as well as waveforms of voltage pulses and electron current to the analyzer collector. The EOS made it possible to obtain beam currents over 20 mA in the modes considered.

Figs. 3 and 4 illustrate the main results of the analysis of electron velocity spectra in the flow generated by the electron gun with the multi-tip field emitter. Fig. 3 shows experimentally measured spectra of longitudinal and transverse velocities in electron flow at different values of the beam current. Fig. 4 shows the transformation of the spectra with a change in the magnetization reversal coefficient and the maximum magnetic flux density B_m for fixed current in the beam.

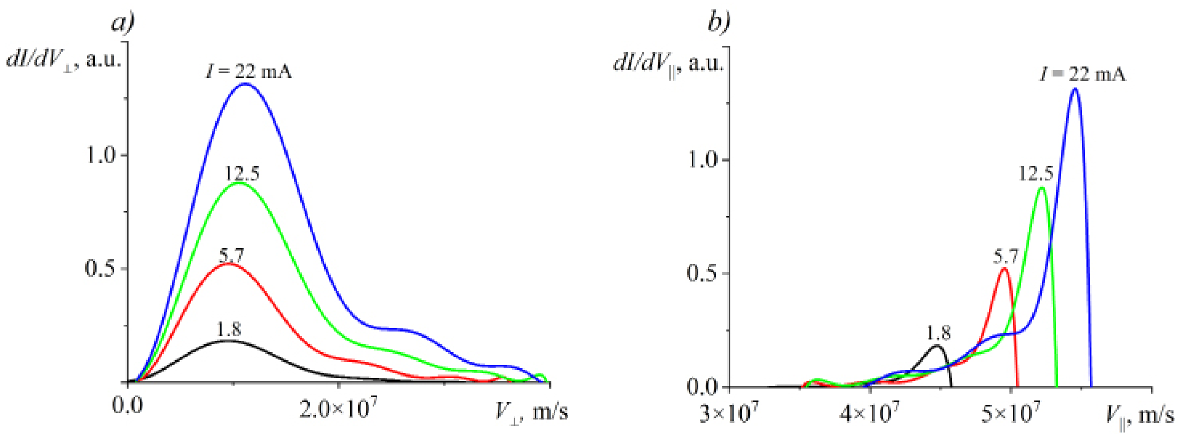

Fig. 3. Spectra of transverse (*a*) and longitudinal (*b*) electron velocities in the electron beam in EOS at different currents; maximum magnetic flux density $B_m = 2.5$ T, magnetization reversal coefficient $k = 13$

The RMS spread of electrons over the transverse velocity reached about 50% for the entire electron flow. The data obtained indicate that the shape of the transverse velocity distribution was practically unchanged with the beam current varying over a wide range (from 0.1 to 25 mA). The pitch factor averaged over the entire electron flow increased from 0.26 to 0.30 with an increase in current.

The variation in the magnetic field in the cathode with a fixed magnetization reversal coefficient has practically no effect on the electron velocity spread. An increase in the magnetization reversal coefficient from 13 to 28 at constant voltage U and magnetic flux density B_m leads to a decrease in the beam current. The average pitch factor increases markedly from 0.24 to 0.38.

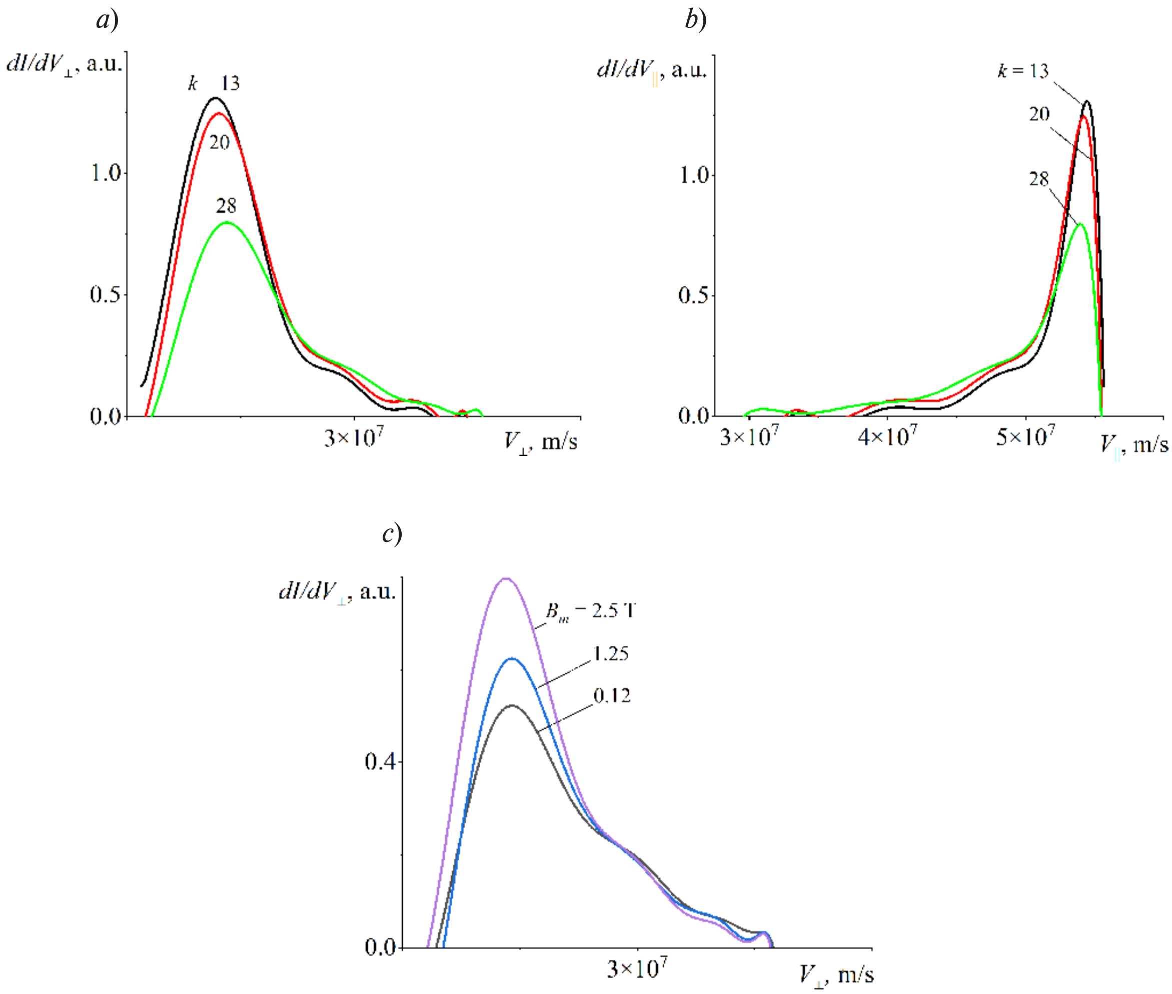

Fig. 4. Spectra of transverse (*a*) and longitudinal (*b*) electron velocities in electron beam in EOS at different magnetization reversal coefficients *k* and maximum magnetic flux densities B_m (*c*). Current in the electron beam I = 22 mA

Conclusion

Let us overview our main findings. We obtained data on the values of currents as well as electron velocity spectra observed in an EOS with a multi-tip field emitter. In our opinion, these results might prove indispensable for developers of subterahertz microwave devices.

In the future, it is planned to study the characteristics of flows in electron-optical systems with multi-tip and multilayer emitters [9].

REFERENCES

1. **Litvak A. G., Denisov G. G., Glyavin M. Y.,** Russian gyrotrons: Achievements and trends, IEEE J. Microw. 1 (1) (2021) 260–268.

2. **Idehara T., Sabchevski S. P., Glyavin M., Mitsudo S.,** The gyrotrons as promising radiation sources for THz sensing and imaging, Appl. Sci. 10 (3) (2020) 980.

3. **Thumm M. K. A., Denisov G. G., Sakamoto K., Tran M. Q.,** High-power gyrotrons for electron cyclotron heating and current drive, Nucl. Fusion. 59 (7) (2019) 073001.

4. **Li J., Zhang Y., Ke Y., et al.,** A cold cathode electron gun using convex carbon nanotube emitter, IEEE Trans. Electron Devices, 69 (3) (2022) 1457–1460.

5. **Chen Q., Yuan X., Xu X., et al.,** Development of a high-beam-transparency gridded electron gun based on a carbon nanotube cold cathode, IEEE Electron Device Lett. 43 (4) (2020) 615–618.

6. **Whaley D. R., Duggal R., Armstrong C. M., et al.,** 100 W operation of a cold cathode TWT, IEEE Trans. Electron Devices. 56 (5) (2009) 896–905.
7. **Yuan X., Zhu W., Zhang Y., et al.,** A fully-sealed carbon-nanotube cold-cathode terahertz gyrotron, Sci. Rep. 6 (09 Sept) (2016) 32936.
8. **Sominskii G. G., Tumareva T. A., Taradaev E. P., et al.,** Annular multi-tip field emitters with metal-fullerene protective coatings, Techn. Phys. 64 (2) (2019) 270–273.
9. **Sominskii G. G., Sezonov V. E., Taradaev S. P., Vdovichev S. N.,** Multilayer field emitters made of contacting hafnium and platinum nanolayers, Techn. Phys. 64 (1) (2019) 116–120.
10. **Taradaev E. P., Sominskii G. G.,** Characteristics of an annular electron flow formed by an electron gun with a field emitter, IEEE Trans. Electron Devices. 69 (5) (2022) 2675–2679.

СПИСОК ЛИТЕРАТУРЫ

1. **Litvak A. G., Denisov G. G., Glyavin M. Y.** Russian gyrotrons: Achievements and trends // IEEE Journal of Microwaves. 2021. Vol. 1. No. 1. Pp. 260–268.
2. **Idehara T., Sabchevski S. P., Glyavin M., Mitsudo S.** The gyrotrons as promising radiation sources for THz sensing and imaging // Applied Sciences. 2020. Vol. 10. No. 3. P. 980.
3. **Thumm M. K. A., Denisov G. G., Sakamoto K., Tran M. Q.** High-power gyrotrons for electron cyclotron heating and current drive // Nuclear Fusion. 2019. Vol. 59. No. 7. P. 073001.
4. **Li J., Zhang Y., Ke Y., Li B., Deng S.** A cold cathode electron gun using convex carbon nanotube emitter // IEEE Transactions on Electron Devices. 2022. Vol. 69. No. 3. Pp. 1457–1460.
5. **Chen Q., Yuan X., Xu X., Zhang Y., Cole M. T., Zu Y., Yan Y.** Development of a high-beam-transparency gridded electron gun based on a carbon nanotube cold cathode // IEEE Electron Device Letters. 2020. Vol. 43. No. 4. Pp. 615–618.
6. **Whaley D. R., Duggal R., Armstrong C. M., Bellew C. L., Holland C. E., Spindt C. A.** 100 W operation of a cold cathode TWT // IEEE Transactions on Electron Devices. 2009. Vol. 56. No. 5. Pp. 896–905.
7. **Yuan X., Zhu W., Zhang Y., Xu N., Yan Y., Wu J., Shen Y., Chen J., She J., Deng S.** A fully-sealed carbon-nanotube cold-cathode terahertz gyrotron // Scientific Reports. 2016. Vol. 6. 09 September. P. 32936.
8. **Соминский Г. Г., Тумарева Т. А., Тарадаев Е. П., Рукавицына А. А., Степанова А. Н.** Многострийные кольцевые полевые эмиттеры с защитными металл-фуллереновыми покрытиями // Журнал технической физики. 2019. Т. 89. № 2. С. 302–305.
9. **Соминский Г. Г., Сезонов В. Е., Тарадаев С. П., Вдовичев С. Н.** Многослойные полевые эмиттеры, изготовленные из приведенных в контакт нанослоев гафния и платины // Журнал технической физики. 2019. Т. 89. № 1. С. 142–146.
10. **Taradaev E. P., Sominskii G. G.** Characteristics of an annular electron flow formed by an electron gun with a field emitter // IEEE Transactions on Electron Devices. 2022. Vol. 69. No. 5. Pp. 2675–2679.

THE AUTHORS

TARADAEV Evgeny P.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
evgeny_tar@hotmail.com
ORCID: 0000-0001-5219-6744

SOMINSKII Gennadii G.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
sominski@rphf.spbstu.ru
ORCID: 0000-0001-7945-7238

TARADAEV Sergei P.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
sergio.rumos@mail.ru
ORCID: 0000-0001-5548-7379

СВЕДЕНИЯ ОБ АВТОРАХ

ТАРАДАЕВ Евгений Петрович – *кандидат физико-математических наук, доцент Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Россия.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
evgeny_tar@hotmail.com
ORCID: 0000-0001-5219-6744

СОМИНСКИЙ Геннадий Гиршевич – *доктор физико-математических наук, профессор Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Россия.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
sominski@rphf.spbstu.ru
ORCID: 0000-0001-7945-7238

ТАРАДАЕВ Сергей Петрович – *аспирант Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Россия.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
sergio.rumos@mail.ru
ORCID: 0000-0001-5548-7379

Статья поступила в редакцию 23.11.2023. Одобрена после рецензирования 08.12.2023. Принята 11.12.2023.
Received 23.11.2023. Approved after reviewing 08.12.2023. Accepted 11.12.2023.