LONGITUDINAL-RADIAL MOTION OF
AN ELECTRON BEAM IN THE SOLENOIDAL FIELD
OF THE SECUNDARY-EMISSION MAGNETRON GUN

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The results of experimental studies and numerical calculations on the generation of an electron beam by a magnetron gun with a secondary-emission cathode are presented. With the aim of obtaining precision characteristics, the formation of a beam in the axial and radial directions was studied when transporting a solenoid in a magnetic field at energy of 55 keV. The dependence of the total vertical distribution on the inner wall of the cylindrical target and the Faraday cylinder on the distribution of the magnetic field along the axis of the system is studied. The results of numerical simulation on the motion of a tubular electron beam are given. It is shown that the obtained results of the simulation are consistent with experimental data. It is also shown that the electron flux falls on a vertical section, the length of which does not exceed 1 mm. The possibility of adjusting the location of a beam hit on a vertical wall is studied numerically with a variation in the amplitude of the control magnetic field.
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FORMULATION OF THE PROBLEM

Interest in the physics of processes with crossed electric and magnetic fields is due to their wide use in high-power vacuum electronics, accelerator technology, etc. It is of interest to use magnetron guns with cold secondary-emission cathodes in these regions as sources of electrons [1, 2]. The principle of operation of such guns is based on the secondary emission multiplication of electrons, the formation of an electron cloud and the formation of an electron beam in crossed electric and magnetic fields [3]. An electron accelerator based on a magnetron gun with a cold metallic secondary-emission cathode was created in the NSC KIPT [4]. In this paper, we present the results of studies on the formation of a radial electron beam by a magnetron gun with a secondary-emission cathode during its transportation in a decreasing magnetic field of a solenoid. The aim of this work is to study the precise characteristics of a beam formed in the axial and radial directions.

EXPERIMENTAL INSTALLATION
AND METHODOLOGY OF RESEARCH

Experiments were conducted on the formation of a radial electron beam by a magnetron gun in an installation which block diagram is shown in Fig. 1. To obtain the electron beam, a magnetron gun with an anode diameter of 78 mm and a cathode diameter of 36 mm was used. The main magnetic field for generating and transporting an electron beam is created by a solenoid consisting of 4 sections. By adjusting the current in the coils, it was possible to change the amplitude and longitudinal distribution of the magnetic field along the axis of the gun and the transporting channel of the beam, which made it possible to obtain various electron beam formation regimes. For a local change in the decay rate of the resultant magnetic field, a scattered field was used, which was created with a permanent magnet located on the axis of the system in the middle of the 6 ring. The main magnetic field was formed by varying the currents in the coils of the solenoid sections. The measurement of the total magnetic field of the solenoid and the scattered field of the ring magnet from the length z has shown that it is sharply nonuniform.
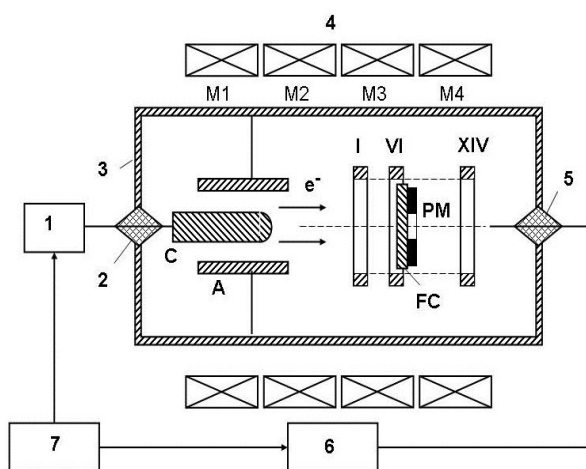

Fig. 1. Block diagram of the installation.
1 – pulse generator; 2, 5 – bushing insulators; 3 – vacuum chamber; 4 – solenoid; 6 – measuring system; 7 – synchronization unit; C – cathode; A – anode; FC – Faraday cylinder; PM – permanent magnet; I-XIV – metal rings measuring system (lamellas)

The measuring system for studying the distribution of current in the radial direction consists of 14 copper rings with an inner diameter of 66 mm and a width of 8 mm, which are isolated from each other and the earth. The distance between the rings is ~1.5 mm. Before the permanent magnet is located the Faraday FC cylinder, which serves to measure the current in the axial direction. The processing of the results of measuring the parameters of the voltage pulse, currents in the radial and axial directions was carried out using a recording system.

The dynamics of the motion of electrons for a number of particles equal to 500 in a total magnetic field has been numerically studied. In the work, the final histogram of the vertical distribution of the particles was used as the result of the calculation, determined from the fulfillment of the predetermined condition-the achievement by the radial component of the trajectory of particles of a given value r_U=33 mm. In turn, the generated histogram should be compared with the distribution of currents on the measuring lamellae.

EXPERIMENTAL DATA AND RESULTS
OF NUMERICAL SIMULATION

Research has been carried out on the formation of an electron beam in the radial direction when it is transported in the total magnetic field produced by a solenoid and a magnet. When performing modeling calculations, the coefficient of variation k of the magnetic field of the solenoid varied in the range from 0.6 to 1.2.

Fig. 2 shows the main characteristics of the magnetic system: the distribution of the total longitudinal magnetic field for two values of the coefficient of variation of k along the axis of the system at which experiments were carried out.
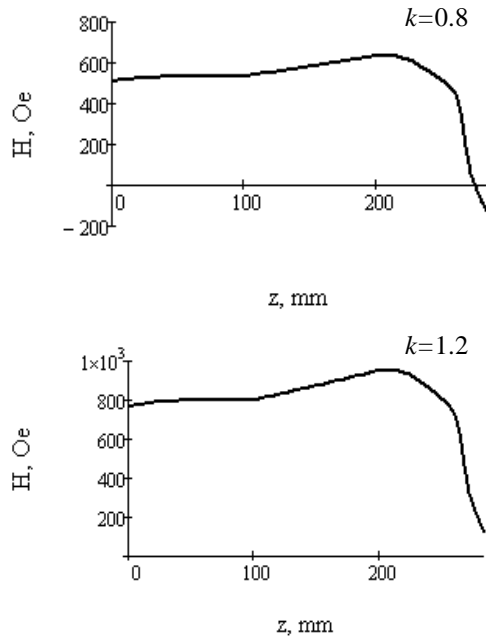

Fig. 2. Distribution of magnetic fields. Specified coefficient of variation k of the magnetic field of the solenoid

Experimental studies on the formation of an electron beam in the radial direction in a decreasing magnetic field of a solenoid and a permanent magnet have been carried out. In studies in the energy range of 35…55 keV, it was found that the beam current in the radial and axial directions depends on the amplitude and distribution of the magnetic field along the axis of the system.

Fig. 3 shows the arrays of experimental data on the distribution of the amplitude of the magnetic field along the axis of the magnetron gun (squares) and the result of its approximation.

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The initial conditions for the electron beam were taken: initial radius r_0=18 mm (average radius of the emission ring); z_0=13 mm (place of emission vertically); the coordinate was determined by the particle energy (in the dependences obtained, the energy E of the particles

was equal to 55 keV). In this case, the initial distribution in the azimuth ϑ_0 was set uniformly on $(0, \pi)$, and the spread of the particle deviation along the radius from r_0 was subject to the normal law with a standard deviation Δr_0=1 mm.
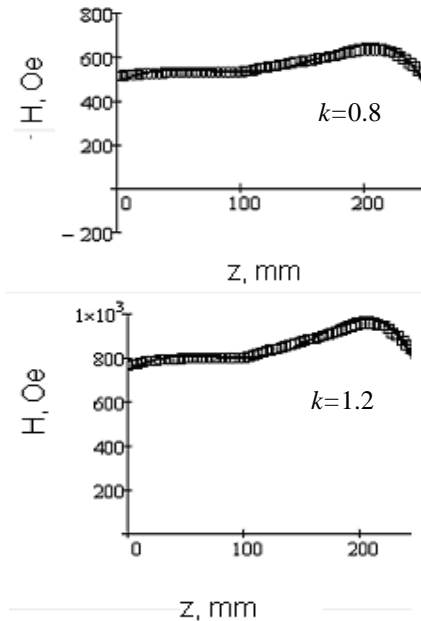

Fig. 3. Distribution of the magnetic field (squares) and the result of approximating the experimental data

The cross sections of the particle beam are numerically studied for their propagation along the axis in a magnetic field (coefficient of variation k=1.0), as well as the starting and finishing histograms of the number of particles in the (x, y)-plane at a sample size N=300. It is shown that when the particle is propagated, the azimuthally rotation is also tested along with the radial motion.

A sketch of the normal distribution density of emitted particles in the cathode plane with parameters r_0=18 mm and Δr_0= 1 mm and uniform density on $(0, \pi)$ in azimuth ϑ_0 is shown in Fig. 4.
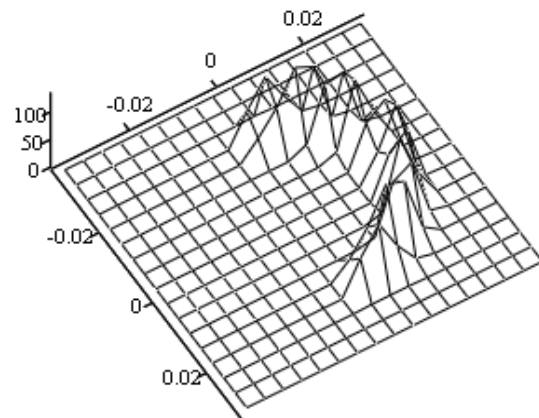

Fig. 4. Density of electron distribution in the (x,y)-plane of the cathode of the gun

Fig. 5 shows the cross sections of the beam of particles corresponding to the value r_0=18 mm at the time of emission and the value at the time of reaching the target wall r_U=33 mm. Together with the radial motion, the particles undergo a rotation along the azimuth, which can also be seen in Fig. 7.
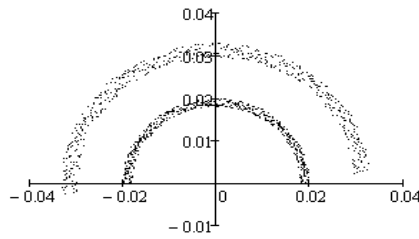
Fig. 5. Cross sections of the original (r_U=18 mm)
an array of particles at the start
and at the finish (r_U=33 mm)

A further increase in the solenoid magnetic field (k>1.1) leads to the fact that practically the entire electron flux hits the Faraday cylinder (z_{CF}=283 mm), with only a small part falling on the lamellae of the 6th ring and did not exceed ~5% of the beam current. This mode of beam formation was carried out with a magnetic field in the region of the arrangement of 650 Oe rings and with a field drop gradient of 350 Oe/cm.
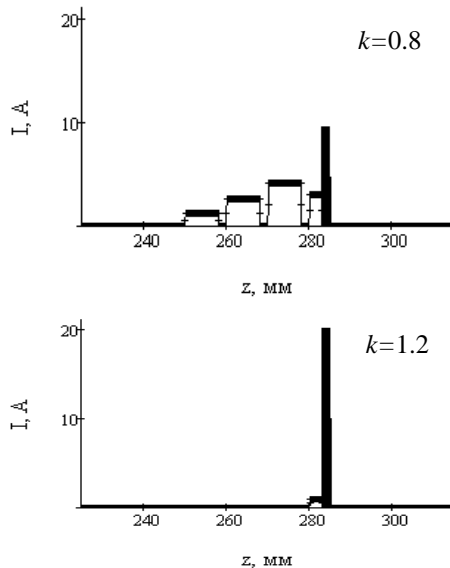

Fig. 6. Distribution of currents on lamellae
and Faraday cylinder. The black color indicates
the hit on the cylinder

Fig. 6 shows the relative intensities of the fluxes of particles falling on the Faraday cup and on the target wall, depending on the coefficient of variation k of the magnetic field. It was found that for k=0.6 half of all particles hit the target wall.

Comparison of experimental data (currents on lamellas and Faraday cup) and numerical results (histograms of the vertical values z_U particles when they reach a given radial level r_U=33 mm) indicates a fairly good agreement. It follows from simulating calculations that for both variants of the magnetic field the electron flux falls on a vertical section, the length of which Δz is equal to fractions of millimeters. This concentration is due to the decreasing nature of the magnetic field of the solenoid and the initial distribution of particles along the radial coordinate r_0.

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Fig. 7 shows the calculated cross sections of the particle beam as they propagate along the axis in a magnetic field (coefficient of variation k =1.0), as well as the starting and finishing histograms of the number of particles in the (x,y)-plane at a sample volume of N=300. It can be seen that during the propagation of the particle, the azimuthally rotation is also tested along with the radial motion.

Fig. 8 (on the left) shows the distributions of the amplitude of the field H (z), in which the beam particles, propagating along the axis z in a decreasing magnetic field, undergo a radial-azimuthally motion. On the right Fig. 8 also shows the final histograms $G(z)$ of the vertical coordinate values when the hit condition r=r_U=33 mm on the target wall (sample size N=500).

In the paper, the dependence of the midpoint Zsr and the root-mean-square size of the beam distribution on the target wall on the coefficient of variation k of the magnetic field was studied.

Fig. 9 shows that the displacement of particles along the vertical coordinate on the target wall is caused by the rate of decrease of the amplitude of the total field H(z) in the region of the permanent magnet. Thus, an increase in the coefficient of variation k of the magnetic field of the solenoid causes an increase in the vertical coordinate of the particle beam incident on the target wall. From Fig. 9, it can be seen that the desired dependence Zsr = Zsr(k) is monotonic and almost linear, which indicates the possibility of adjusting the beam hit on the target.

From Fig. 10 it follows that, for given initial conditions of simulation, the dimensions of the Ssr of the electron beam on the target wall do not exceed 1 mm for the selected values of the magnetic field variation parameter k.

Thus, it is fixed that for the accepted initial particles and the considered simulation regime, the change in the configuration of the magnetic field affects only the total displacement of the electron beam, but does not lead to a noticeable broadening of the type of the final particle flux distribution at the target wall along the coordinate z_U.

When considering the fluxes of particles with a phase volume of initial magnitudes of increased size, in particular, with a large spread in pulses, we can expect an increase in the vertical section Δz_U at which the hit condition is realized. The calculations also considered a variant of the initial conditions with an increased value of the media-non-quadratic deviation of the beam during emission (Δr_0=3 mm). For it, the effect of an increase in the scatter at the start was manifested only in the corresponding broadening of the calculated histogram of the impact of particles on the target wall (Δr_0=15 mm).

From experimental data and modeling results it follows that for the selected initial conditions of the particles and the transport regime, the change in the configuration of the magnetic field affects the total displacement of the electron beam, without leading to a noticeable broadening of the form of the final distribution of the particle flux on the target wall.
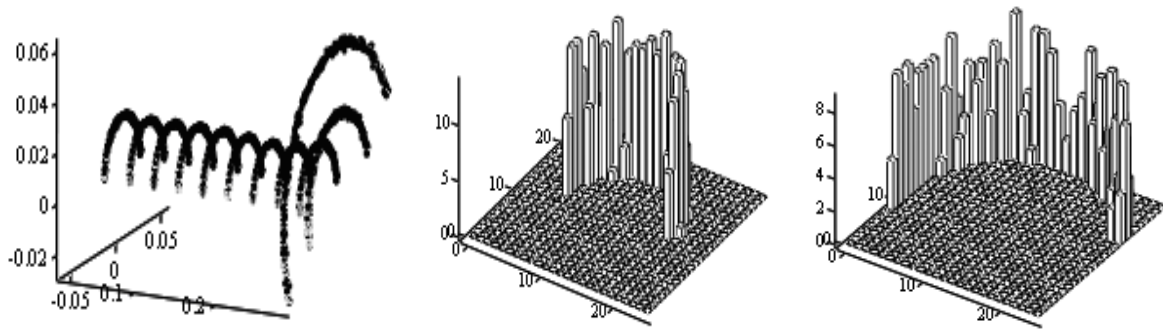
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*Fig. 7. Cross sections of the particle beam (left), starting (in the middle)
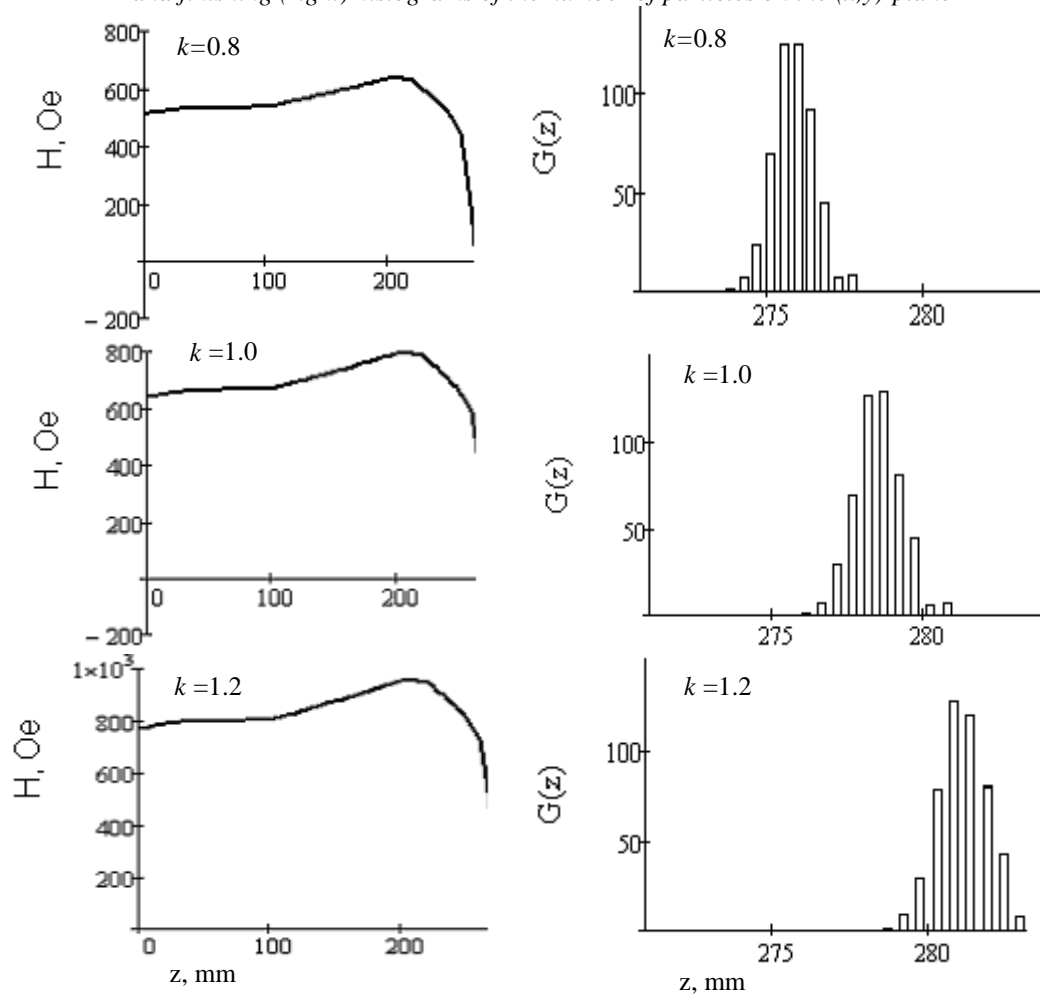and finishing (right) histograms of the number of particles on the (x,y)-plane*

*Fig. 8. To the left: the distribution of the field amplitude H(z), in which the beam particles experience motion.
Right: the final histograms G(z) of the values of the vertical coordinates $z=z_U$ when condition hit (r= r_U=33 mm)
on the target wall. The sample size is N = 500. The coefficient of variation of the magnetic field k = 0.8, 1.0,
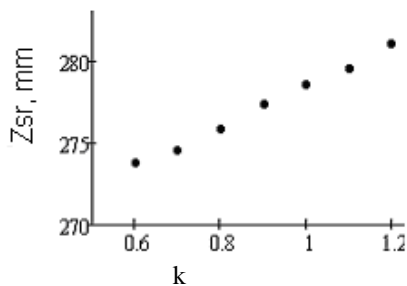and 1.2 is indicated*

*Fig. 9. Dependence of the average point Zsr
of the electron beam distribution on the target wall
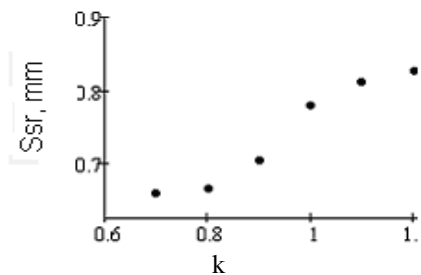on the coefficient of variation k of the magnetic field*

*Fig. 10. Dependence of root-mean-square size Ssr
of the electron beam distribution on the target wall
from the coefficient of variation k of the magnetic field*

CONCLUSIONS

From the conducted research it follows that it is possible to form a stable electron beam in the radial and axial directions when transporting a solenoid in a magnetic field. The solutions of the direct problem of simulation of electron trajectories for given initial conditions and parameters of the system are obtained. It is shown that the electron flux falls on a vertical section, the length of which does not exceed 1 mm. The numerical dependences found agree with the experimental results. The possibility of adjusting the location of the beam hit on a vertical wall is shown with the variation of the amplitude of the control magnetic field.

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ПРОДОЛЬНО-РАДИАЛЬНОЕ ДВИЖЕНИЕ ЭЛЕКТРОННОГО ПУЧКА В СОЛЕНОИДАЛЬНОМ ПОЛЕ ВТОРИЧНО-ЭМИССИОННОЙ МАГНЕТРОННОЙ ПУШКИ

А.Н. Довбня, Н.А. Довбня, А.С. Мазманишвили, Н.Г. Решетняк

Представлены результаты экспериментальных исследований и численных расчетов по генерации электронного пучка магнетронной пушкой с вторично-эмиссионным катодом. Изучено формирование пучка в осевом и радиальном направлениях при транспортировке в магнитном поле соленоида при энергии 55 кэВ. Исследована зависимость итогового вертикального распределения на внутренней стенке цилиндрической мишени и цилиндре Фарадея от распределения магнитного поля вдоль оси системы. Показано, что полученные результаты моделирования согласуются с данными эксперимента. Показано также, что поток электронов попадает на вертикальный участок, длина которого не превышает 1 мм. Численно изучена возможность регулировки места попадания пучка на вертикальную стенку при вариации амплитуды управляющего магнитного поля.

ПОЗДОВЖНЬО-РАДІАЛЬНИЙ РУХ ЕЛЕКТРОННОГО ПУЧКА В СОЛЕНОЇДАЛЬНОМУ ПОЛІ ВТОРИННО-ЕМІСІЙНОЇ МАГНЕТРОННОЇ ГАРМАТИ

А.М. Довбня, Н.А. Довбня, О.С. Мазманішвілі, М.Г. Решетняк

Представлено результати експериментальних досліджень і чисельних розрахунків по генерації електронного пучка магнетронною гарматою з вторинно-емісійним катодом. Вивчено формування пучка в осьовому і радіальному напрямках при транспортуванні в магнітному полі соленоїда при енергії 55 кеВ. Вивчено залежність підсумкового вертикального розподілу на внутрішній стінці циліндричної мішені і циліндрі Фарадея від розподілу магнітного поля уздовж осі системи. Показано, що отримані результати моделювання узгоджуються з даними експерименту. Показано також, що потік електронів потрапляє на вертикальну ділянку, довжина якої не перевищує 1 мм. Чисельно вивчена можливість регулювання місця попадання пучка на вертикальну стінку при варіації амплітуди керуючого магнітного поля.