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ELECTRON BEAMS IN THE GRADIENT MAGNETIC FIELD: CONTROL FOR CONVERTING LONGITUDINAL MOTION INTO TRANSVERSAL

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The motion of electrons in the cylindrical magnetic field of the magnetron gun with a gradient-type potential is considered. The formation of a beam with an energy of 55 keV in such the magnetic field has been studied. It is found that in the selected field, the initial motion of electrons along the longitudinal axis is converted into radial motion. It is determined that such the transformation is due to the influence of the solenoidal magnetic field with large longitudinal gradient. The transformation of the longitudinal direction of motion into the transverse one is stable in the energy range of 20...55 keV of electrons and in the range of 5...55 mm of radial dimensions of the particle beam. The modes of operation of the gun, in which the particle undergoes a stable transformation of the direction of motion, are studied numerically. It is shown that for the given electron energy and the fixed magnetic field, the parameter that determines the rotation of particles is the magnetic field gradient at the boundary of the entry region. It is found that the rotation effect takes place for the range of radial beam sizes, which leads to particle focusing. The possibility is shown to control the vertical coordinate of a focused beam on the basis of field adjustment as the whole. Based on the model of electron flow motion, the characteristics of the resulting electron beam are considered. It is shown that the beam, having radial dimensions of 5...55 mm, is focused vertically on the section of 1 mm.

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INTRODUCTION

Magnetron guns with cold secondary emission cathodes are promising for their use in the creation of high-power microwave devices, accelerator technology due to the high current density, structural simplicity, cathode emission stability, etc. [1 - 5]. As the object of research, the magnetron gun has the advantage that it can be modified to carry out experiments of various types. The use of intense magnetic fields with an increased gradient of their intensity makes it possible to consider new phenomena in the spatial picture of the evolution of electron beams. Despite the complexity of the analytical study, to obtain quantitative dependences, it is possible to use numerical methods and compare the calculation results with experimental data.

Earlier, in the course of numerical experiments [6 - 8], cases of transformation of the longitudinal motion of electrons into the radial one were revealed, which took place in the gradient magnetic field of the magnetron gun. Based on the Hamiltonian formalism of the motion of electrons in the magnetic field, the software tool [6, 7] was used to numerically simulate the dynamics of tubular electron flows in the cylindrical magnetic field. Together with the experimental data, the results of numerical simulation of the motion of the electron beam are presented. The obtained simulation results point to the phenomenon of controlled lateral movement.

Based on the magnetron gun, NSC KIPT created an electron accelerator that uses an axial electron beam to irradiate metal targets [4, 5] (Fig. 1).

As an object for research, the magnetron gun has the advantage that it can be modified to carry out experiments of various types. One of the possible directions is a combination of the magnetic field in the gun, created by solenoids, and the field of additional permanent magnets [6, 7].

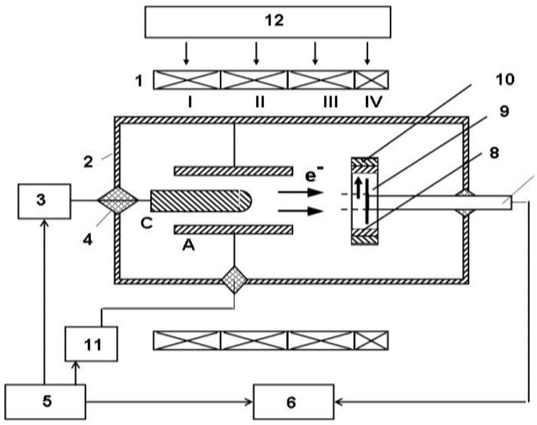

Fig. 1. Block diagram of the experimental setup.
1 – solenoid sections (I, II, III, IV); 2 – vacuum volume; 3 – high-voltage pulse generator; 4 – insulator; 5 – synchronization unit; 6 – measuring system; 7 – centering rod; 8 – copper insert; 9 – Faraday cup; 10 – permanent magnet; 11 – generator; 12 – current source for controlling the magnetic field of the solenoid; A – anode; C – cathode

The aim of the study is to build a model for the motion of an electron beam with energies of tens of kiloelectronvolt in the alternating gradient magnetic field, to study the formation of electron trajectories, the dependence of particle dynamics on initial conditions, and the distribution of the magnetic field along the axis of the system.

1. RESEARCH METHODOLOGY

A study was carried out on the formation of the electron beam by the magnetron gun (cathode diameter 40 mm, anode diameter 78 mm) and measurement of its parameters at a cathode voltage of 20...55 kV.

Table shows the parameters of the electron beam depending on the configuration of the magnetic field. It can be seen from it that, under certain conditions, the 55 keV energy beam as the whole moved along the axis of the system and was recorded on the Faraday cup. Under other conditions, the beam on the Faraday cup was not registered, because, moving in the radial direction, it hit the copper insert. In this case, cases were observed when the change in the direction of the beam and the place of registration had an abrupt character.

Types of magnetic field, directions of beam motion

Magnetic field (Fig. 2)	Current along axes	Current in radial direction	Current in 4 sections of the solenoid, A
B_1	30 A	0	35, 0, 27, 0
B_2	0	18 A	-33, 0, -16, -54
B_3	0	17 A	-33, 0, -21, -54

On Fig. 2 shows the distribution of the field B_1 (triangles). The configuration of this field, being quite smooth, ensures the passage of the beam along the vertical axis and registration on the Faraday cup.

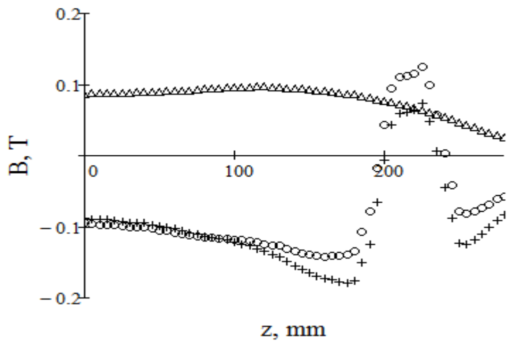

Fig. 2. Three magnetic fields B; triangles – field B_1, circles and crosses – fields B_2 and B_3

On Fig. 2 also shows the configurations of fields B_2 (circles) and B_3 (crosses), in which the intensity (in modulus) does not exceed 0.18 T, while the field gradient reaches 9 T/m. When synthesizing these fields in the scheme of Fig. 1, the permanent annular magnet with the strength of 0.21 T was additionally used, the direction of the field of which was opposite to the direction of the field of the solenoids. As a result, the configuration of the magnetic field was sign-variable and had areas with the large gradient. The motion of particles in fields of such configurations was qualitatively different. In particular, the electron beam as the whole turned by 90^0 and moved in the radial direction, and the beam current on the Faraday cup vanished in the threshold manner.

Thus, the problem arises of studying the properties of the electron beam during its transportation in the intense magnetic gradient field and constructing the computational model for the motion of the electron beam in the gradient region of the field.

2. NUMERICAL SIMULATION

The configurations of the fields B_2 and B_3 differ from the field B_1 by the pronounced gradient property in the range from 170 to 210 mm. After emission, the particle beam, moving along the axis of the system, flies into the region with the large field gradient, the interaction with which determines the trajectory of each particle.

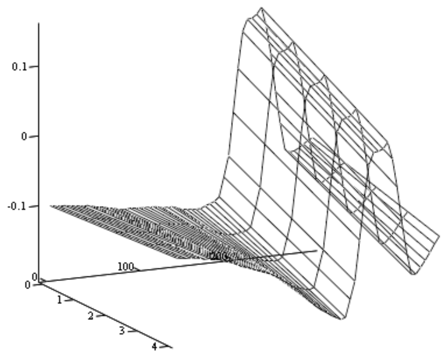

Fig. 3. Set of 5 magnetic fields A_0,..., A_4 in the area with the large gradient

Since the fields B_2 and B_3 are formed by selected sets of current options on the windings of the solenoid sections (I, II, III, IV), the digitized arrays of these fields were taken as the basis for further modeling. The software tool [6] was used to numerically simulate the dynamics of tubular electron flows in the cylindrical magnetic field with a large gradient. For this purpose, numerical arrays A_0,..., A_4 were created from 5 additional magnetic fields:

$$A_k = B_2 + \frac{k-1}{2}\left(B_3 - B_2\right). \quad (1)$$

Thus, for k=1 we get the field A_1=B_2, and for k=3 we get A_3=B_3 (Fig. 4).

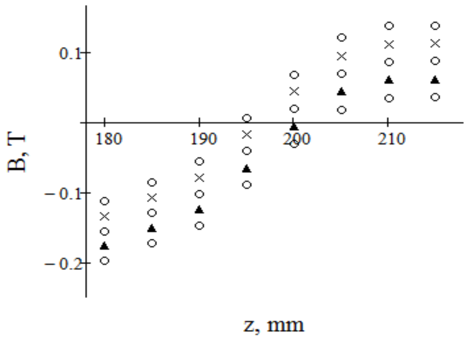

Fig. 4. Set of 5 magnetic fields A_0,..., A_4 in the area with the large gradient, crosses – field A_1, triangles – field A_3

For modeling, the beam of 9 particles was chosen, for which the initial conditions at the start were $\mathbf{z_0}$=120 mm, as well as the uniform distribution in $\mathbf{x_0}$ in the interval of 15...55 mm and in y_0 in the interval of 15...55 mm in the plane ($\mathbf{x_0}$, y_0).

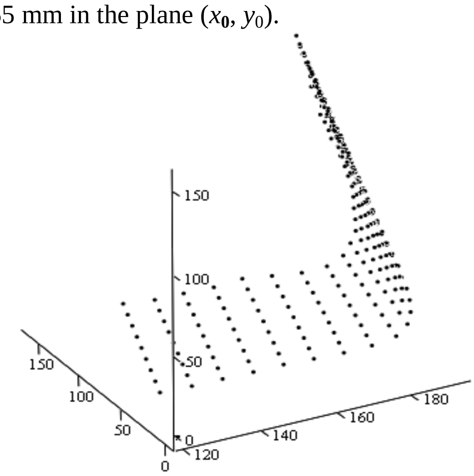

Fig. 5. Beam dynamics (example with 9 particles)

Typical examples of the dynamics of 9-particle beam are shown in Fig. 5. It can be seen that for all initial radii r_0, the electron trajectories are of the same type, namely, in the gradient region, their motion is transformed from longitudinal to transverse. Such a change takes place for all considered initial radii r_0. In this case, the focusing of particles along the vertical axis ***z*** of the system is carried out.

To refine the type of motion and the accompanying rotation and focusing, the series of numerical experiments was performed in which both the fields $A_0,\ldots, A_4$ and the initial conditions on the plane $(\boldsymbol{x_0,y_0})$ were changed. The conversion stability of motion was also tested by varying the particle energy E, as well as the initial conditions along the vertical $\mathbf{z_0}$.

On Fig. 6 shows the particle trajectories for two gradient-type fields A_1 and A_3 as well as the field B_1 from Fig. 2 with a weakly pronounced gradient property. It can be seen that the trajectory of particles in the field B_1 is regular with the slight change in the current radius $r=r(z)$ in the flight interval from 180 to 210 mm. In the same gradient region, the trajectory rotates with subsequent focusing, which was registered for all five fields $A_0,\ldots, A_4$.

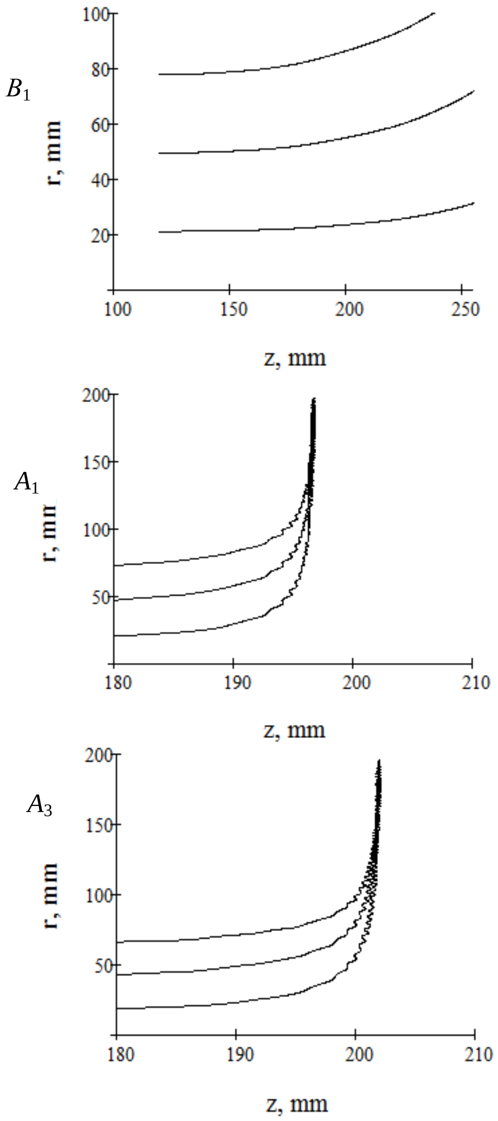

Fig. 6. Examples of particle trajectories

The shift Δz of the focus point is shown in Fig. 7. When changing the control parameter k in the range of the parameter 0...4, it amounted to $195 \le \Delta z \le 205$ millimeters.

Thus, the area that contains the place of controlled focusing has a longitudinal dimension of ≈11 mm along the vertical axis ***z***. The beam particle focusing area itself, in turn, has the size $\delta z \approx 1$ mm, which is formed by Larmor oscillations of electrons in the cylindrical magnetic field, whose amplitude is determined by the initial radius r_0.

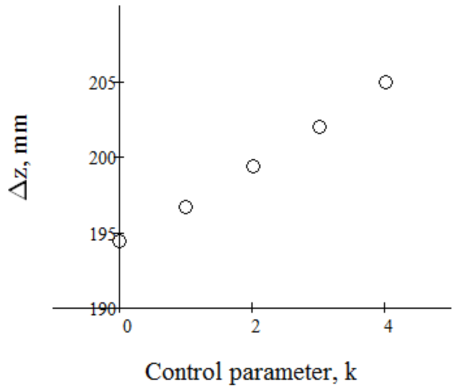

Fig. 7. Dependence of the regulated displacement Δz vertically from the field selection parameter k

3. MATHEMATICAL MODEL AND DISCUSSION OF RESULTS

On the basis of the Hamiltonian formalism of the motion of electrons in the magnetic field, the software tool was built for numerical simulation of the dynamics of electron flows in the gradient magnetic field [6, 7].

We use the polar coordinate system (r, z, θ) and write down the Hamiltonian of the electron in the magnetic field in a cylindrical system

$$H = \frac{p_r^2 + p_z^2}{2m} + \frac{1}{2m}\left(\frac{p_\vartheta}{r} - e_0 A\right)^2, \qquad (2)$$

where e_0, m are the electron charge and rest mass, p_r, p_z, p_θ are the canonical momenta, A is the magnetic potential. Taking into account the azimuthally symmetry, we write it in the form $A(r,z)=rB(z)$, where $B(z)$ is the magnetic field strength at the point.

The equations of motion for coordinates and momenta have the general form

$$\begin{cases} \dot{r} = \dfrac{p_r}{m}, \\ \dot{z} = \dfrac{p_z}{m}, \\ \dot{\vartheta} = \dfrac{1}{m}\left(\dfrac{p_\vartheta}{r} - e_0 r B(z)\right)\dfrac{1}{r}, \\ \dot{p}_r = \dfrac{1}{m}\left(\dfrac{p_\vartheta}{r} - e_0 r B(z)\right)\left(\dfrac{p_\vartheta}{r^2} + e_0 B(z)\right), \\ \dot{p}_z = \dfrac{1}{m}\left(\dfrac{p_\vartheta}{r} - e_0 r B(z)\right)\left(e_0 r \dfrac{\partial}{\partial z} B(z)\right), \\ \dot{p}_\vartheta = 0. \end{cases} \qquad (3)$$

As can be seen from equations (3), both the distribution of the magnetic field B along the z axis and its derivative affect the formation of the particle trajectory.

In system (3) of 6 equations, consider the second equation for z and the fifth for the canonical momentum p_z. From these equations it follows that the derivative dp_z/dt can vanish if

$$\left(p_{\vartheta} - e_0 r^2 B(z)\right)\frac{\partial}{\partial z}B(z) = 0. \qquad (4)$$

In the gradient region, the derivative $\partial B(z)/\partial z$ does not vanish anywhere (see Figs. 2 and 3). At $z=z_0$, the momentum p_θ is proportional to the canonical momentum p_z, i.e. $(2E/E_0)^{1/2}$, where E is the energy of the electron, E_0=511 keV is the rest energy of the electron. At the beginning of the movement, the momentum p_θ changes slightly. In the process of moving along the longitudinal axis, the electron approaches the gradient region from the left, in which the function $B(z)$ increases rapidly. For the sufficiently large value of $B(z_F)$ at some point $z=z_F$, the value of the expression in the round bracket in (4) vanishes. The approach of the particle to this point z, however, has an asymptotic character of motion in the radial direction. The coordinate z_F itself on the z axis depends on the selected magnetic field (Fig. 3) and for the fields A_0,...,A_4 described above, it shifted from z_F=195 mm at k=0 to z_F =205 mm at k=4 (see Fig. 7).

Thus, an increase in the control parameter k corresponds to the general decrease in the field amplitude A according to (1) and, therefore, to the larger particle falling into the gradient region (see Fig. 6) at the larger coordinate $z=z_F$. We can say that there is the "bulldozer" effect.

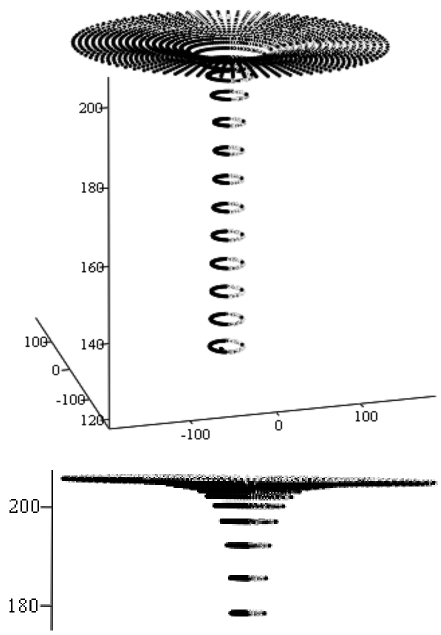

Fig. 8. Example (100 particles) transformation direction of travel (top) and fragment of the rotation area (bottom)

On Fig. 8 shows the typical example. Initial conditions: z_0=120 mm, in the plane (x_0,y_0) particles are located on a circle with center x_0=0, y_0=0 and initial radius r_0=20 mm. The area of rotation and focusing starts around the point z_F=185 mm.

CONCLUSIONS

The motion of electrons in the cylindrical magnetic field with the gradient-type potential is considered. The formation of the beam with the energy of 55 keV in such the magnetic field has been studied. It is found that in the chosen field the initial motion of electrons along the longitudinal axis is converted into radial motion. It is determined that such the transformation is due to the influence of the solenoidal magnetic field with the large longitudinal gradient. The transformation of the longitudinal direction of motion into the transverse one turned out to be stable in the energy range of 20...55 keV of electrons and in the interval of 5...50 mm of the radial dimensions of the particle beam. For the given electron energy and the fixed magnetic field, the parameter that determines the rotation of particles is the magnetic field gradient at the boundary of the entry region. It is found that the rotation effect takes place for the range of radial beam sizes, which leads to particle focusing.

The possibility of controlling the vertical coordinate of the focused beam on the basis of the field control as the whole is shown, thereby giving the interpretation of the threshold dependence of the registration of electrons on the detector. On the basis of the numerical model of the motion of the electron beam, the characteristics of the resulting electron beam are considered. It is shown that the beam, which has initial radial dimensions of 5...55 mm, is focused vertically onto the section of 1 mm in size.

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ЕЛЕКТРОННІ ПУЧКИ В ГРАДІЄНТНОМУ МАГНІТНОМУ ПОЛІ: КЕРУВАННЯ ПЕРЕТВОРЕННЯМ ПОЗДОВЖНЬОГО РУХУ НА ПОПЕРЕЧНИЙ

О.С. Мазманішвілі, М.Г. Решетняк, І.А. Чертищев

Розглянуто рух електронів у циліндричному магнітному полі магнетронної гармати з потенціалом градієнтного вигляду. Вивчено формування пучка з енергією 55 кеВ у такому магнітному полі. Отримано, що у вибраному полі вихідний рух електронів уздовж поздовжньої осі перетворюється на радіальний рух. Визначено, що таке перетворення обумовлено впливом соленоїдального магнітного поля з великим поздовжнім градієнтом. Перетворення поздовжнього напрямку руху на поперечне виявилося стійким у діапазоні енергій 20...55 кеВ електронів та інтервалі 5...55 мм радіальних розмірів пучка частинок. Чисельно вивчені режими роботи гармати, у яких частка відчуває стійке перетворення напряму руху. Показано, що при заданій енергії електрона та фіксованому магнітному полі параметром, що визначає поворот частинок, є градієнт магнітного поля на межі ділянки вльоту. Отримано, що ефект повороту має місце для інтервалу радіальних розмірів пучка, що призводить до фокусування частинок. Показана можливість на основі регулювання поля, як загалом управляти вертикальною координатою сфокусованого пучка. На основі моделі руху електронного потоку розглянуто характеристики результуючого електронного пучка. Показано, що пучок, який має радіальні розміри 5...55 мм, фокусується по вертикалі на ділянку розміром 1 мм.