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Beam and Sector Modes of Electron Fluxes in Cylindrical Magnetic Field of Magnetron Gun

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The results of the study on the formation of a radial electron beam by a magnetron gun with a secondary emission cathode are presented. The aim of the work was to create a mathematical model of the formation of a radial electron beam with energy of tens of keV in a magnetic field of a solenoid, to study the dependence of the beam current characteristics on the amplitude and distribution of the magnetic field along the axis of the system, the collimation of electronic fluxes and to study the possibility of irradiation of the surface of the tubular products. In the work, on the basis of the Hamiltonian formalism of electron motion in a magnetic field, a software tool has been synthesized that allows performing numerical simulations of the dynamics of tubular electron fluxes in a falling magnetic field of a solenoid. An algorithm is constructed for converting an array of magnetic field values along the axis of particle transport into an analytic differentiable function, which, based on an array of experimental data on the axis, made it possible to restore the amplitude of the magnetic field and its derivative as analytic functions of the longitudinal coordinate. The results of numerical simulations of the motion of a tubular electron flux are presented. The formation of the electron flux distribution during transport in a solenoid falling magnetic field is studied. Experimental data on sectoral and multi-beam collimation of an electron beam and registration of particle flux at metal targets in a gun chamber are also given. The possibility of regulating the beam diameter by variation of a magnetic field is shown. Based on the results obtained, the possibility of irradiating the outer surfaces of cylindrical samples at different distances from the cut of the anode is shown. The results of numerical simulations and experimental data on the motion and collimation of a tubular electron flux are compared.

Keywords: Magnetron gun, Secondary emission cathode, Magnetic field distribution, Electron beam collimation, Mathematical modeling, Histogram.

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1. INTRODUCTION

The study of electron beams of various configurations and intensities is associated with their use in high-voltage pulsed microwave electronics, electron beam technologies of accelerator technology, etc. [1, 2]. Using the beam method of sample processing, the creation of materials with improved characteristics, increased microhardness, corrosion resistance, etc. is achieved [3, 4]. To solve these problems, accelerators of intense electron beams with electron energies of 100...400 keV are widely used [5]. The NSC KIPT conducts research with electron sources with cold metal cathodes operating in the secondary emission mode. A magnetron gun is used as an electron source. The principle of operation of such guns is based on the reverse bombardment of the cathode by electrons returned by the magnetic field, the formation of an electromagnetic cloud near the cathode and the formation of a beam in crossed electric and magnetic fields. An electron accelerator was created on the basis of a magnetron gun with a secondary emission cathode, in which an axial electron beam is used to irradiate metal targets [4]. The possibility of irradiating the inner cylindrical surface using a radial electron beam was studied [6].

We present the results of a study of the dynamics of an electron beam in a transport channel and the results of numerical simulation of the motion of a tubular beam. The possibility of controlling the transverse dimensions of a beam using a gradient magnetic field was studied, and experiments were carried out to transport the beam in an increasing magnetic field.

2. MAGNETIC FIELD MODELING TECHNIQUE

In the experimental setup, there is a cylindrical magnetic field, the values of which are given by the data array. This array must be associated with an analytic differentiable function whose values coincide with the experimental field array at given nodes. Let an electron with energy E moving parallel to (or at an angle) the axis at a certain distance r_0 from it flies into a magnetic field. It is required to construct the equation of motion of a particle in a magnetic field and, based on the solution of the equation of motion for the selected time instants, determine the coordinates of the electron.

To build a mathematical model of the solution, we use the axial symmetry of the problem. Therefore, we will work in the polar coordinate system (r, z, ϑ). In it, the Hamiltonian has the form

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

where e_0 and m are the charge and rest mass of the electron, p_r, p_z, p_ϑ are the canonical moments, and A is the magnetic potential. Based on azimuthal symmetry, we can write it in the form $A(r, z) = Brf(z)$, where $f(z)$ is the function of the longitudinal coordinate, which we shall control below, B is the magnetic field strength at the point under consideration. In the Hamiltonian form, the equations of motion for coordinates and moments have a general form

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$$\dot{r} = \partial H / \partial p_r, \quad \dot{z} = \partial H / \partial p_z, \quad \dot{\vartheta} = \partial H / \partial p_\vartheta,$$
$$\dot{p}_r = -\partial H / \partial r, \quad \dot{p}_z = -\partial H / \partial z, \quad \dot{p}_\vartheta = -\partial H / \partial \vartheta.$$

As a result of finding the partial derivatives, we obtain a system of 6 equations. In it, we pass, using the speed of light c, from the current time t to a variable $s = ct$, the derivative of which will be denoted by a prime. For canonical impulses, we replace $p_r = e_0Bq_r$, $p_z = e_0Bq_z$, $p_\vartheta = e_0Bq_\vartheta$. After transformations we arrive at a system of equations

$$\begin{cases} r' = \mu q_r, \ q_r' = \mu r\left(q_\vartheta / r^2 - f(z)\right)\left(q_\vartheta / r^2 + f(z)\right), \\ z' = \mu q_z, \ q_z' = \mu r^2\left(q_\vartheta / r^2 - f(z)\right) df(z)/dz, \\ \vartheta' = \mu\left(q_\vartheta / r^2 - f(z)\right), \ q_\vartheta' = 0, \end{cases} \quad (2)$$

in which $f(z)$ is the field function of the longitudinal coordinate, $df(z)/dz$ is the derivative of the function.

In equations (2), $\mu = e_0B/mc$, $Bf(z)$ is a function that describes the magnetic field along the axis z. We select the amplitude B so that you can use the function $Bf(z)$ over the entire range of possible values z. To equations (1), it is necessary to add the initial conditions for r_0, z_0, ϑ_0, and also q_{r0}, q_{z0}, $q_{\vartheta 0}$. The stability of the solution algorithm is related to the solution step Δs and parameter μ. Then the condition will be satisfied if $\Delta s \ll 0.0001$ m. So, from a computational point of view, the problem can be formulated as the problem of finding a solution to a system of ordinary differential equations with given initial conditions. The formulated problem can be solved, provided that it is possible at each step of the integration of equations (1) to use functions $f(z)$ and $df(z)/dz$ as analytic functions.

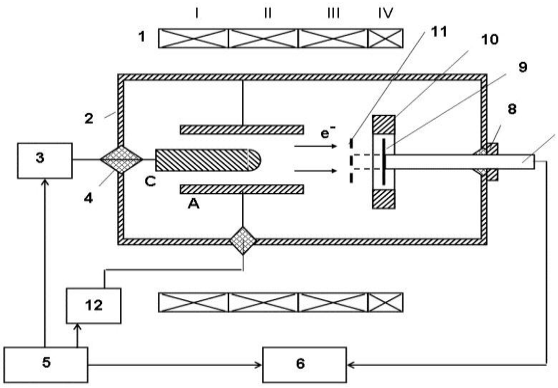

Fig. 1 – The block diagram of the experimental setup: 1 – sections of the solenoid (I, II, III, IV), 2 – vacuum volume, 3 – high-voltage generator, 4 – insulator, 5 – synchronization unit, 6 – measuring system, 7 – centering rod, 8 – seal, 9 – Faraday cylinder (metal target), 10 – ring magnet, 11 – replaceable collimator, 12 – generator, A – anode, C – cathode

The block diagram of the installation is shown in Fig. 1. When electrons move, it is important that the magnetic field in the gun (Fig. 2) has cylindrical symmetry. This allows the use of system (2) for analysis and numerical simulation.

Let the longitudinal distribution of the magnetic field be given along the axis z. The experimental data were obtained as a result of measurements, according

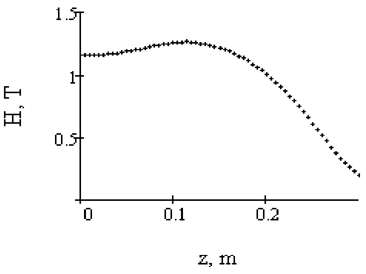

Fig. 2 – Typical longitudinal magnetic field distribution

to which a table $\{z_n, H_n\}$, where $n = 0, 1,\ldots, N$. Suppose now that this magnetic field is created by a sequential set of M virtual solenoids with a set of known geometric characteristics $\{R_m, Z_{1,m}, Z_{2,m}\}$, where $m = 1,\ldots, M$ and R_m, $Z_{1,m}$, $Z_{2,m}$ are the radius, left and right boundaries of the m^{th} solenoid along the axis z, respectively. It is necessary to restore (estimate) the values $\{h_m\}$, $m = 1,\ldots, M$ tensions in each solenoid and, based on them, construct a function $f(z)$ of the magnetic field configuration.

A task of this kind, in the general case, is one of incorrect tasks. Therefore, below we restrict ourselves to the task of estimating the required amplitudes $\{h_m\}$. When solving, we will use the well-known (exact) expression for the amplitude $\phi(z)$ of the magnetic field with the amplitude h on the axis of one solenoid of radius R having left Z_1 and right Z_2 boundaries and, accordingly

$$f(z,h,R,Z_1,Z_2) = h\phi(z) \equiv$$
$$\equiv \frac{h}{4}\left[\frac{z-Z_2}{\sqrt{(z-Z_2)^2+R^2}} - \frac{z-Z_1}{\sqrt{(z-Z_1)^2+R^2}}\right]. \quad (3)$$

Denote by $\phi_m(z) = \phi_m(z, R_m, Z_{1,m}, Z_{2,m})$, and $\{h_m, R_m, Z_{1,m}, Z_{2,m}\}$ are the field amplitude, the radius, the left and right boundaries of the m^{th} solenoid along the axis z. Then, the magnetic field $f(z)$ formed by the totality of such solenoids can be described by the expression

$$f(z) = \sum_{m=1}^{M} h_m \phi_m(z) =$$
$$= \sum_{m=1}^{M} \frac{h_m}{4}\left[\frac{z-Z_{2,m}}{\sqrt{(z-Z_{2,m})^2+R_m^2}} - \frac{z-Z_{1,m}}{\sqrt{(z-Z_{1,m})^2+R_m^2}}\right], \quad (4)$$

from which the analytic expression for $df(z)/dz$ follows.

Let the registration data be given in the form of a table $\{z_n, H_n\}$, where $n = 0, 1,\ldots, N$ (Fig. 2). It is necessary, on the basis of the data presented, to find an array of field amplitudes $\{h_m\}$, where $m = 1,\ldots, M$ with which you can synthesize a field $f(z)$ with the properties of continuity and differentiability. Comparing the two groups of data used, we write the equations for the amplitudes of the magnetic field $\{h_m\}$ for each measurement point along the axis z:

$$\textstyle\sum_{m=1}^{M} h_m \phi_m(z_n) = H_n, \quad n = 0,\ldots,N. \quad (5)$$

These equations are a system of $(N + 1)$ linear inhomogeneous equations with respect to the M sought quantities $\{h_m\}$. Depending on the values of $(N + 1)$ and

M, such a system can also be joint, overfilled or under filled. In this regard, we will consider the estimation of the values of quantities $\{h_m\}$ as a solution. We apply the well-known method of least squares, on the basis of which as a solution we take the one that best approaches the exact solution in the sense of its least mean square deviation.

We build the functional

$$Q(h_1, h_2, ..., h_M) = \sum_{n=0}^{N}\left[\sum_{m=1}^{M} h_m \phi_m(z_n) - H_n\right]^2 \qquad (6)$$

and require that the functional Q reaches a minimum,

$$Q(h_1, h_2, ..., h_M) \underset{h}{\rightarrow} \min ,$$

in the space of variables $\{h_m\}$. The minimum condition leads to a system of equations

$$\partial Q(h_1, h_2, ..., h_M) / \partial h_m = 0 , \quad m = 1, ..., M. \qquad (7)$$

In this system, after differentiation with respect to each of them $\{h_m\}$, we obtain a set of linear equations for the components of the desired vector h_V, which we write in the form

$$Ah_V = B . \qquad (8)$$

Here A is a matrix with elements

$$A_{n,m} = \sum_{k=0}^{N} \phi_m(z_k)\phi_n(z_k) , \qquad (9)$$

B is the vector of the right side with components

$$B_n = \sum_{k=0}^{N} H_k f_n(z_k) . \qquad (10)$$

As a result, we obtain the desired solution

$$h_V = A^{-1}B . \qquad (11)$$

The found solution of the obtained system of equations will be taken for the required set of amplitudes $\{h_m\}$.

3. DISCUSSION OF RESULTS

In this work, an array of magnetic field data of volume $N = 73$ points was considered. In numerical calculations, a set of $M = 20$ virtual solenoids was used. Fig. 3 shows the initial data on the amplitudes of the magnetic field (squares) and the result of reconstructing the distribution of the magnetic field $f(z)$. The result of calculating the longitudinal derivative $df(z)/dz$ of function $f(z)$ is shown in Fig. 4.

Studies on the formation of an electron beam at various configurations of the magnetic field at the cathode and in the beam transport channel were carried out. The experiments were conducted at a cathode voltage of 20...80 kV. The dependence of the transverse dimensions of the electron beam on the configuration of the magnetic field is investigated. Three-sector and 8-point collimation of electron fluxes was used in the work. The research results were recorded on metal targets, which made it possible to interpret the dynamics of electron fluxes. For a magnetic field with a maximum amplitude of 0.15 T, the calculated dependences (two-dimensional histograms, fission price 12 mm/div) of the 8-beam distribution of the electron beam (sample size of 600 particles) and the imprints of the beam in the target plane are shown in Fig. 5.

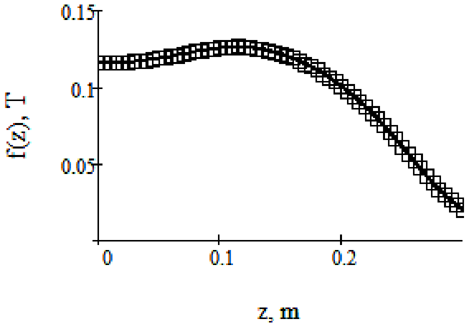

Fig. 3 – Data of the magnetic field (squares) and function $f(z)$ (line) of the coordinate z

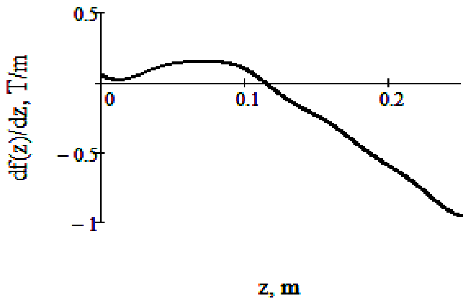

Fig. 4 – The dependence of the constructed derivative $df(z)/dz$ on the longitudinal coordinate z

From Fig. 5, one can see an increase in the size of the beam with a decrease in the amplitude of the magnetic field. The outer diameter of the beam D in a decreasing magnetic field with a gradient of 0.01 T/cm and an amplitude of 0.07 T near the target at a cathode voltage of 60 kV was 44 mm. The beam imprint on target was $z = 270$ mm.

In Fig. 6, for a magnetic field with a maximum amplitude of 0.45 T are similarly shown: calculated dependences (two-dimensional histograms, fission price 12 mm/div) of the 8-beam distribution of the electron beam (sample size of 600 particles). The beam imprint on target was $z = 205$ mm. When the electron beam moved in an increasing magnetic field with a gradient of 0.1 T/cm and an amplitude of 0.42 T, the beam diameter D was 22 mm.

Characteristics of the sector flux of electrons were similarly obtained for a magnetic field with a maximum amplitude of 0.45 T. The beam imprint on target was $z = 270$ mm.

From the figures, one can see a decrease in the beam size in the region of the maximum amplitude of the magnetic field. It was found that with increasing maximum amplitude and/or field gradient, the effect of radial beam compression is more pronounced.

From the totality of the results that describe the dynamics of radial dimensions, we can conclude that it is possible to irradiate external cylindrical products placed in the region of increasing magnetic field. This follows from the calculated histograms and target prints illustrated in Fig. 6, which show the effect of radial compression of the electron beam.

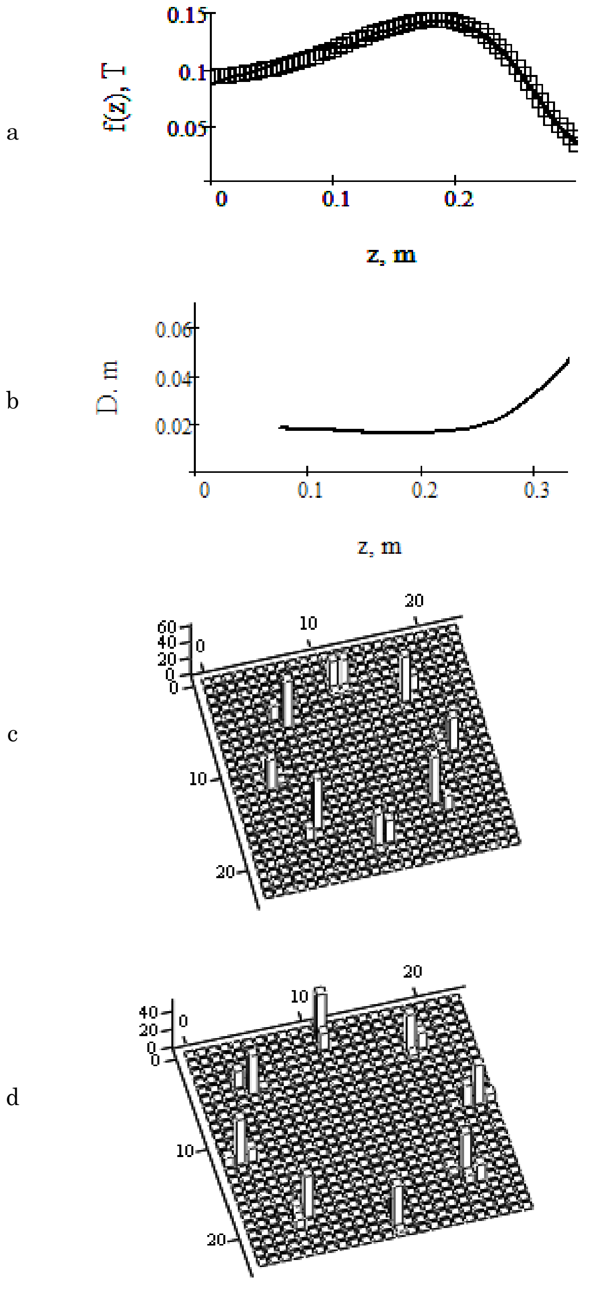

Fig. 5 – Characteristics of 8-beam flux: the amplitude of the magnetic field (a), the dependence of the average beam diameter *D(z)* on the longitudinal coordinate *z* (b), the histogram of the beam distribution at the start (z = 75 mm) (c), the calculated distribution of particles (z = 270 mm) (d)

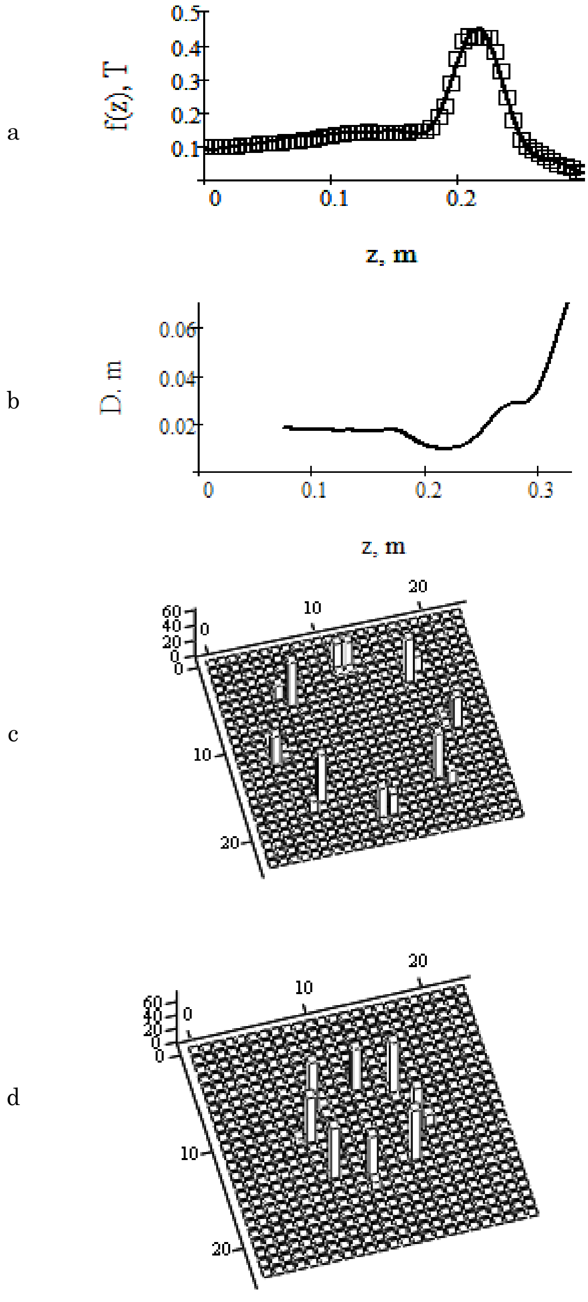

Fig. 6 – Characteristics of 8-beam flux: the amplitude of the gradient magnetic field (a), the dependence of the average beam diameter $D(z)$ on the longitudinal coordinate z (b), the distribution of the beam at the start (z = 75 mm) (c), the calculated distribution of particles (z = 205 mm) (d)

4. CONCLUSIONS

The use of the developed software based on an analytical model of the magnetic field distribution along the axis of the solenoid made it possible, based on an array of experimental data on the axis of electron transport, to restore the amplitude $f(z)$ of the magnetic field and its derivative $df(z)/dz$ as analytic functions of the longitudinal coordinate z. Solutions of the direct problem of modeling electron trajectories for given conditions are obtained. The calculated dependences of the distribution of the electron beam in the target plane are presented. It follows from the studies that stable formation of an electron beam in the radial and axial directions during its transportation is possible. Fingerprints of a collimated electron beam were experimentally obtained on metal targets located at various selected distances. The found numerical dependences are consistent with experimental results. Based on the constructed software, a number of inverse problems can be considered, including such tasks, the purpose of which is to find the parameters of the system and the operating mode to obtain the vertical distribution of the beam in a given place and with given properties.

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Пучкові та секторні режими електронних потоків у циліндричному магнітному полі магнетронної гармати

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Представлені результати досліджень з формування радіального електронного пучка магнетронною пушкою із вторинно-емісійним катодом. Метою роботи було створення математичної моделі формування радіального електронного пучка з енергією в десятки кеВ в магнітному полі соленоїда, дослідження залежності характеристик струму пучка від амплітуди та розподілу магнітного поля вдовж осі соленоїда, колімуванні електронних потоків і вивченні можливостей опромінювання зовнішньої поверхні трубчастих виробів. У роботі на основі гамільтонового формалізму руху електронів у магнітному полі синтезовано програмний засіб, що дозволяє провести чисельне моделювання динаміки трубчастих електронних потоків у магнітному полі соленоїда. Побудовано алгоритм перетворення масиву значень магнітного поля вдовж осі транспортування в аналітичну диференційовану функцію, що дало можливість, спираючись на масив дослідних даних на осі, відновити амплітуду магнітного поля та її похідну як аналітичні функції повздовжньої координати. Приводяться результати чисельного моделювання руху трубчастого електронного потоку. Досліджено формування розподілених електронних потоків при транспортуванні в магнітному полі соленоїда. Приводяться також експериментальні дані по секторній і багатопучковій колімації пучка електронів і реєстрації потоку часток на металевих мішенях у камері пушки. Показана можливість регулювання діаметра пучка шляхом варіації магнітного поля. На підставі отриманих результатів показана можливість опромінювання зовнішніх поверхонь циліндричних зразків на різних відстанях від зрізу анода. Проведено порівняння результатів численного моделювання та дослідних даних в експериментах по руху та колімації трубчастого електронного потоку.

Ключові слова: Магнетронна гармата, Вторинно-емісійний катод, Електронний пучок, Математичне моделювання, Гістограма, Розподіл магнітного поля, Колімація пучка.