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ELECTRON BEAM FORMATION IN MAGNETRON GUNS WITH CATHODES OF MILLIMETER DIAMETERS: EXPERIMENT AND SIMULATION

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The characteristics of the electron beam generated by the magnetron gun are studied. The experiments were carried out with magnetron guns with secondary emission cathodes (cathode diameter 2 and 3 mm, anode diameter 15 and 50 mm) at the cathode voltage of 8...50 kV. The magnetic fields were created both by the solenoid and jointly by the solenoid and the permanent magnet. The possibility of controlling the beam diameter by varying the magnetic field is shown. Beam imprints were obtained on targets located at selected distances. The dependence of the transverse dimensions of the beam on the configuration of the magnetic field in the electron beam transport channel is numerically studied. It is shown that the experimental data are consistent with the results of numerical simulation.

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INTRODUCTION

The study of electron beams of various configurations and intensities is connected with their use in high-voltage pulsed microwave electronics, accelerator technology, etc. [1, 2]. Irradiation with electron beams with specified parameters makes it possible to control the structural and phase state in the surface layers and change the structural properties of materials [3, 4]. At the same time, the range of problems for the solution of which electron beams are used is constantly expands At the National Scientific Center KIPT, research is conducted with electron sources with cold metal cathodes, which work in the secondary emission mode, in crossed electric and magnetic fields. The magnetron gun is used as the source of electrons. The electron accelerator was built on the basis of this gun with the secondary emission cathode, which uses the axial electron beam to irradiate metal targets [5] with the prospect of irradiating the inner cylindrical surface with the help of the radial beam [6].

This paper presents the results of research into the parameters of the electron beam emitted by millimeter-diameter cathodes, and the results of numerical modeling of the movement of a tubular electron flow in the magnetic field and the gradient magnetic field.

EXPERIMENTAL INSTALLATION

Studies have been carried out on the transport of the tubular electron beam behind the anode cut of the magnetron gun in various configurations of the gradient magnetic field. The block diagram of the installation is shown in Fig. 1. To obtain the electron beam, magnetron guns with secondary emission cathodes are used. Gun sizes: cathode diameters 2 and 3 mm, anode inner diameters 16 and 50 mm, cathode length 130 mm, anode length 150 mm. The material of the cathode is copper, the anode is stainless steel. The magnetron gun is placed in the vacuum volume (2) (pressure 10^{-6} Torr).

Generator (11) with voltage amplitude up to 16 kV was used to start secondary emission multiplication in the gun. To power the magnetron gun, the pulsed generator (3) with the amplitude of the flat part of the pulse of 7...100 kV, the duration of 10...30 μs and the transmission frequency of 3...10 Hz was used, which is fed to the gun's cathode. In the generator circuit, the full discharge of the storage capacitance to the transformer through the thyratron was used. The electron source (A – anode, C – cathode) is placed in the vacuum volume (2). The Faraday cylinder (9) serves as the target and was placed at the distance of 3...6 cm from the anode cut.

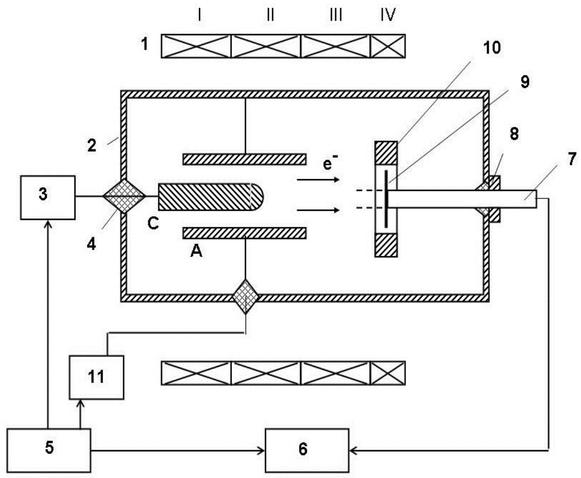


Fig. 1. Block diagram of the experimental setup: 1 – solenoid sections (I, II, III, IV); 2 – vacuum Volume; 3 – high-voltage pulse generator; 4 – isolator; 5 – synchronization block; 6 – measuring system; 7 – centering rod; 8 – vacuum seal; 9 – Faraday cylinder; 10 – permanent magnet; 11 – generator; A – anode, C – cathode

The magnetic field for generating and transporting the beam is created by the solenoid (1), which consists of 4 sections, which are powered by direct current sources. The amplitude and longitudinal distribution of the magnetic field can be adjusted by changing the magnitude of the currents in 4 coils of the solenoid. To create the additional magnetic field during focusing of the electron beam, one or two permanent ring magnets

(PM) made of NdFeB alloy with different field amplitudes were used. The transverse dimensions of the beam are measured by obtaining imprints on metal sensors. The results of measurements of the parameters of the beam current from the Faraday cup and the voltage pulse were processed using the measuring system (6).

EXPERIMENTAL RESULTS AND DISCUSSION

Experimental studies on the formation of the electron beam by the magnetron guns with secondary emission cathodes and the measurement of its parameters were carried out at the cathode voltage in the range of 8...50 kV. On Fig. 2 shows the distributions of the solenoidal magnetic field along the axis of the magnetron gun and the beam transport channel, in which experiments and numerical simulations of the motion of electrons emitted by cathodes of millimeter diameters were carried out during their transportation along the system.

Secondary emission multiplication of electrons at the gun cathode was triggered by nanosecond pulses with an amplitude of up to U_z~16 kV, applied to the gun anode [7] with the decay steepness of more than 300 kV/μs.

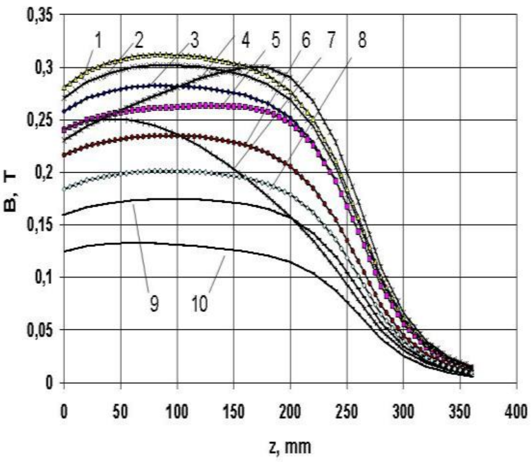


Fig. 2. Magnetic distribution field B along the axis of the magnetron gun and beam transportation channels (curves 1–10)

The dependence of the electron beam current on the Faraday cup on the voltage amplitude at the cathode and on the geometrical dimensions of the gun (cathode diameter D_C=2…3 mm and anode diameter D_A=15…50 mm) was studied. The studies were carried out for different distributions of the magnetic field on the cathode and in the channel for transporting the electron beam.

The measurement results are shown in Fig. 3. As you can see, the resulting dependences of the beam current on the cathode voltage are consistent with the "3/2" law.

It is shown that the minimum voltage amplitude at the cathode, at which the formation of the beam in the magnetron gun with cathode diameters D_C=2 mm and 3 mm and anode diameter D_A=15 mm, is 8 kV.

In the gun with the cathode diameter D_C=2 mm and the anode D_A=15 mm in the uniform magnetic field (see Fig. 2, curve 9) at the minimum voltage U=8 kV, the electron beam with the current I=1.2 A was obtained. At the voltage U=22 kV at the cathode in the uniform magnetic field (see Fig. 2, curve 2) the electron beam was obtained with the current I=5.0 A and perveance P=2μA/V$^{3/2}$.

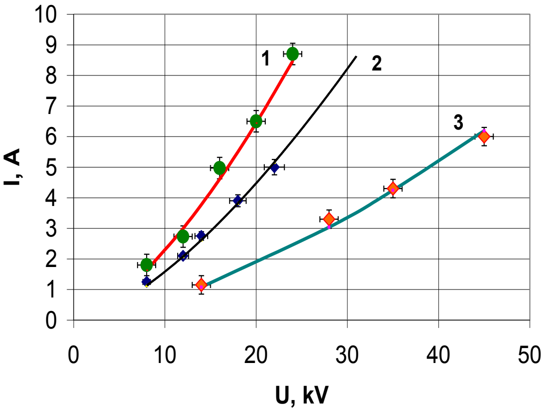


Fig. 3. Dependences of beam current I on voltage U on cathode for magnetron guns with different diameters of cathodes D_C and anodes D_A: 1 – D_C=3 mm, D_A=15 mm; 2 – D_C=2 mm, D_A=15 mm; 3 – D_C=3 mm, D_A=50 mm

When starting the magnetron gun with the cathode diameter D_C=3 mm and the anode D_A=15 mm and the minimum cathode voltage U=8 kV in the uniform magnetic field (see Fig. 2, curve 8), the beam is formed and current I=1.8 A. At the cathode voltage of 24 kV in the uniform magnetic field (see Fig. 2, curve 3), the electron beam was obtained with the current I=8.5 A and perveance P=1.35 μA/V$^{3/2}$. As can be seen from Fig. 3, in the gun with the cathode diameter D_C=3 mm and the anode D_A=50 mm at the cathode voltage U=45 kV in the uniform magnetic field (see Fig. 2, curve 10), the electron beam with the current I=6 A and perveance P=0.42 μA/V$^{3/2}$. The pulse power in the beam is 270 kW. Thus, with the large aspect ratio, intense electron beams can be obtained. It follows from the results obtained that with the increase in the anode diameter D_A, the beam perveance decreases. The observational data are consistent with the dependence of perveance on anode diameters as 2/(D_A-D_C).

The dependence of the formation of the electron beam on the moment of applying the triggering pulse U_z to the flat part of the voltage pulse in the magnetron gun with the cathode diameter of 3 mm and the anode of 15 mm at the cathode voltage of 24 kV has been studied. On Fig. 4 shows the oscillograms of voltage U pulses at the cathode and beam current I for different times t_1, t_2, t_3 when the trigger pulse is applied to the gun anode. From Fig. 4 it can be seen that the generation of the electron beam is carried out at the moments of time on the flat part of the voltage pulse at the cathode of the gun, which correspond to the moment the trigger pulse is applied to its anode.

The dependence of the beam current amplitude on the magnetic field strength at the cathode voltage of 24 kV has been studied. The results of the study showed that the dependence of the beam current amplitude has the threshold character for the appearance and decay of the beam current (Fig. 5). The beam is generated at the magnetic field of 0.265 T, which is 1.8 times higher than the Hull field, and the current decline occurs at the magnetic field of 0.310 T. In this case, the amplitude and shape of the beam current pulse within the boundaries of the generation zone changes insignificantly – by 3...4 %. The region of the optimal magnetic field is located in the beam formation zone, at which the beam current amplitude is maximum (see Fig. 2, curve 3).

The width of the electron beam formation zone was measured by the magnetic field ΔB (where $\Delta B=B_{max}-B_{min}$, B_{max} and B_{min} – are the maximum and minimum values of the magnetic field for beam generation, respectively) at the cathode voltage of 24 kV (magnetron gun D_C=3 mm, D_A=15 mm). The measurement results show that the width of the formation zone ΔB in the uniform magnetic field (see Fig. 2, curves 1 and 5) is ΔB=0.45 T (see Fig. 5). With the decrease in the amplitude of the magnetic field from the boundary ΔB from below or increase from above, the shape of the beam current pulse first changes, then the conditions for secondary emission multiplication are violated and the beam generation process is disrupted. A similar picture takes place for the gun D_C=2 mm, D_A=15 mm.

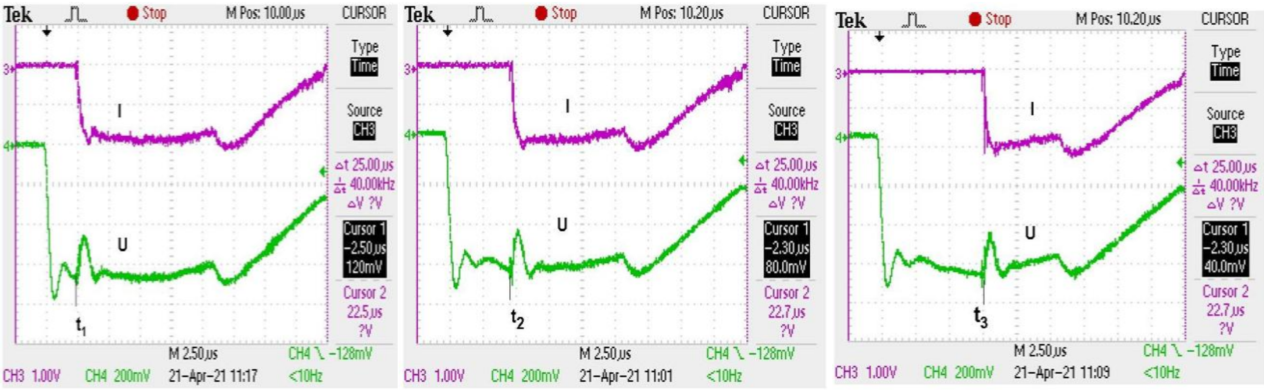


Fig. 4. Oscillogramms of voltage pulses on the cathode U and beam currents I for three moments of time t_1, $t_2=t_1+2{,}5$ μs, $t_3= t_1+5$ μs of the start pulse. The horizontal scale is 2.5 μs/del, the vertical scale is relative units

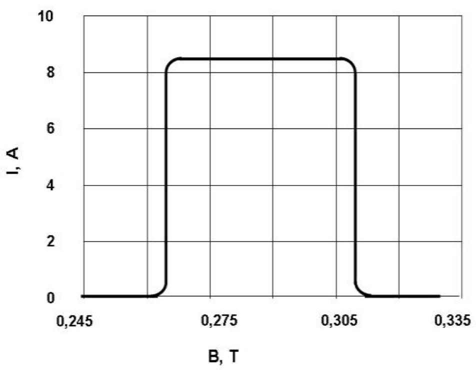


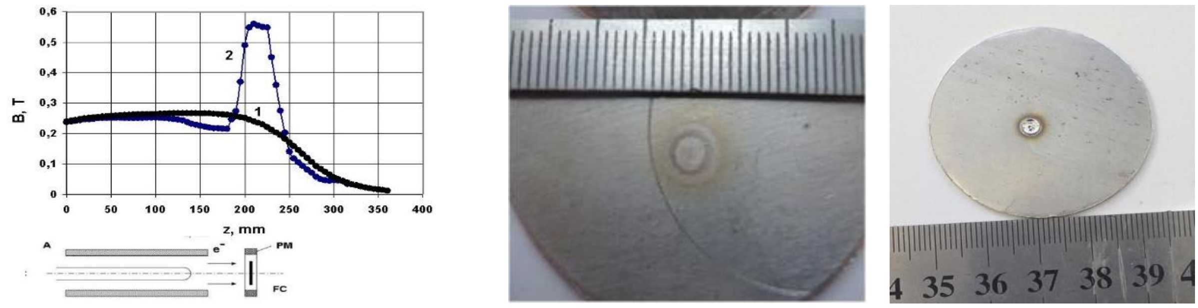
Fig. 5. Dependence of the current I of the beam on the Faraday cylinder on the strength of the magnetic field B

The dependence of the beam current to the Faraday cup, which is located at the distance of 30 mm from the anode cut, on the distribution of the magnetic field along the axis of the magnetron gun (D_C=3 mm, D_A=15 mm) is studied.

It can be seen from the observation results that in the uniform magnetic field (see Fig. 2, curve 3) the magnetron gun generates the electron beam with the current 15…20 % higher than in the case of the growing magnetic field (see Fig. 2 , curve 4) at the cathode and in the transport region. The decrease in current in the growing case is associated with the influence of the radial component $B_r \sim dB_z/dz$ of the field.

The dependence of the transverse dimensions of the electron beam formed by the magnetron gun with the cathode diameter D_C=3 mm and anode diameter D_A=15 mm was studied during its transportation in the magnetic field *B*s, which was created by the solenoid, and the magnetic field *B*sм, which was created by the solenoid together with two permanent magnets. The results of the observations were recorded on metal targets at the distance of 30 mm and 60 mm from the gun anode cut (z=180 mm and z=210 mm), which made it possible to interpret the dynamics of the electron beam. As can be seen from the imprint (Fig. 6,b), in the uniform magnetic field at the distance of z=180 mm, the magnetron gun (voltage at the cathode 24 V) forms the beam with outer diameter *D*=6.4 mm.

During the movement of the electron beam in a growing magnetic field with the gradient of 0.135 T/cm and the amplitude of 0.57 T at the distance of z=205 mm, there is the noticeable decrease in the beam diameter to *D*=4.2 mm (see Fig. 6,c), which is determined by focusing of the electron beam.



a *b* *c*

Fig. 6. Distribution of magnetic fields (curves 1, 2) along the axis of the magnetron gun and the beam transportation channel and placement of the gun elements; A – anode, C – cathode, FC – Faraday cylinder, PM – permanent magnet. a – distribution of magnetic fields; b – imprint of the beam on the aluminum target, the outer diameter of the beam is 4.3 mm; c – imprint of the beam on the aluminum target, outer diameter of the beam D=4,2 mm, B=0.57 T, increasing magnetic field with the gradient of 0.135 T/cm

NUMERICAL MODELING

Mathematical modeling of beam dynamics was carried out and its results were compared with observed data. A software tool based on the analytical model of the distribution of the magnetic field along the axis of the system has been developed. This made it possible, based on the array of experimental data on the axes of electron transport, to restore the magnetic field amplitude $f(z)$ and its derivative $df(z)/dz$ as analytical functions of the longitudinal coordinate using the method of least squares. On the basis of the restored field functions, numerical modeling calculations were carried out on the dynamics of the electron beam in the considered magnetic fields. The numerical Monte-Carlo method and the Runge-Kutta method were used in the built software environment [6, 8].

The solution to the direct problem of modeling electron trajectories for given initial conditions and parameters of the system has been obtained.

Calculated dependences of the distribution of the electron beam (sample size up to 500 particles) in the target plane are given.

The dependence of the radial dimensions of the electron beam, which is formed by the magnetron gun in the transportation channel under the uniform, decreasing and increasing magnetic field, was numerically investigated (see Fig. 2, curves 3, 7 and Fig. 6,a, curve 2).

On Fig. 7,a shows the calculated cross-sections of the electron beam distribution in the uniform magnetic field, and Fig. 8,b shows the calculated dependence of the mean radius **r** of the beam on the coordinate z. Calculations were made for the field shown in Fig. 2, curve 1. It can be seen from the figures that as the amplitude of the magnetic field decreases, the average radius of the beam increases.

On Fig. 9,a shows the distribution of the gradient magnetic field along the axis of the gun, created jointly by the solenoid and two permanent magnets. The corresponding calculated cross sections of the beam particles are shown in Fig. 9,b, from which it can be seen how the minimum and maximum transverse dimensions of the beam track the longitudinal distribution of the gradient magnetic field along the axis of the gun.

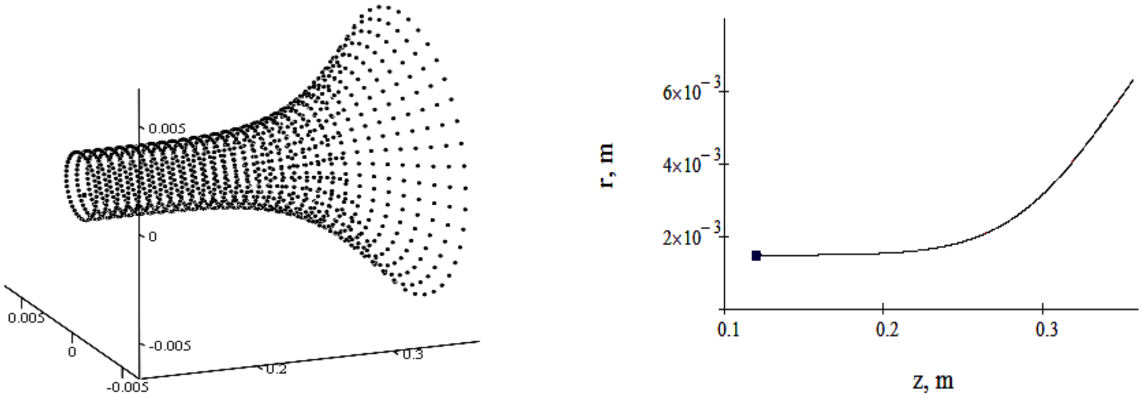
Numerical simulation was carried out for the case of two configurations of the magnetic field, with which the radial dimensions of the electron beam generated by the magnetron gun were studied (D_C=3 mm, 8 mm, D_A=50 mm). Numerical calculations were carried out in order to simulate the movement of particles in the interval from z_0=160 mm at the start to z=285 mm at the finish at different maximum amplitudes (0.27 T and 0.37 T) of the growing magnetic field in the electron transport channel.

On Fig. 10,a shows the initial distributions of electron beam particles with the diameter D_C=3 mm, which were chosen to be the same for both fields. The first of them was formed by the set of currents in the solenoid coils together with the permanent magnet PM. The second magnetic field was formed using the same set of currents in the solenoid coils, but together with two permanent magnets PM + PM.

On Fig. 10,b shows the cross sections of the beam particles for two cases of the field at the beginning of the motion.

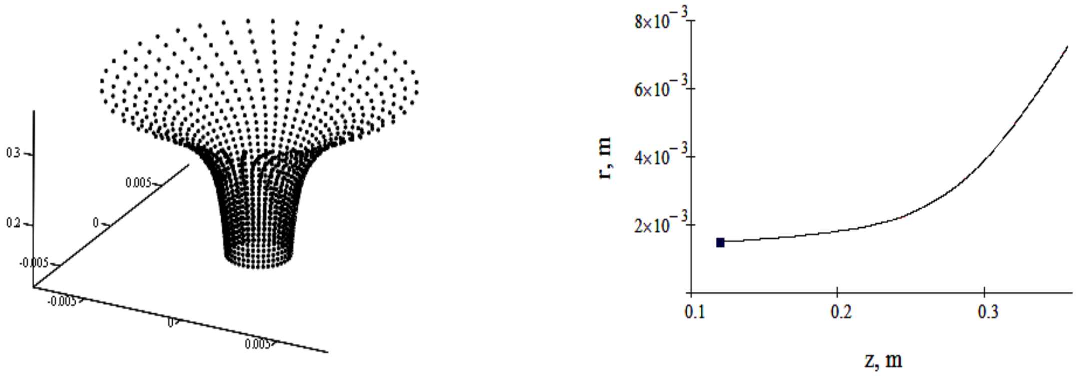
From Fig. 10,c, it can be seen that the beam profiles track the distributions of magnetic fields along the *z* axis of the system. One can see the significant decrease in the size of the beam in the region in which the amplitude of the magnetic field is increased. Thus, with the increase in the maximum amplitude and/or field gradient, the effect of radial beam focusing becomes more pronounced. From Fig. 10,c, it can be seen that the beam profiles track the distributions of magnetic fields along the *z* axis of the system.

On Fig. 10,d shows the dependences of the average beam radius **r**=*r(z)* for both fields on the longitudinal coordinate *z*. One can see the significant decrease in the size of the beam in the region in which the amplitude of the magnetic field is increased. Thus, with the increase in the maximum amplitude and/or field gradient, the effect of radial beam focusing becomes more pronounced.



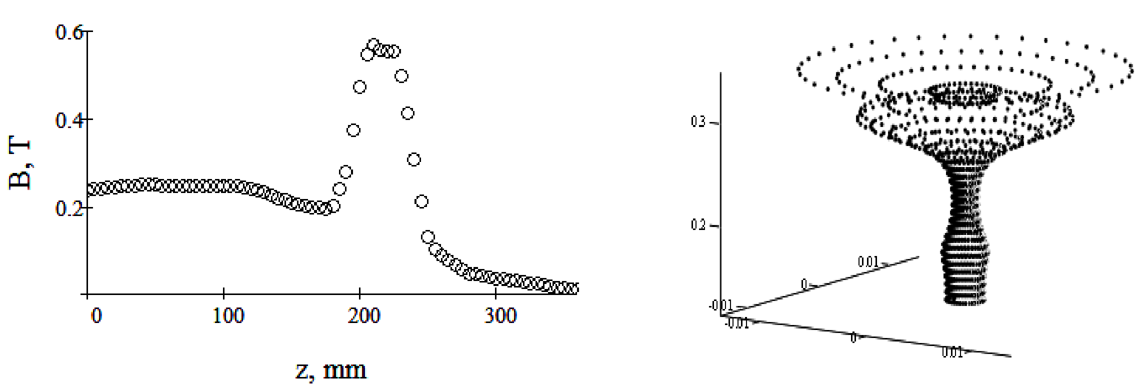
a *b*

Fig. 7. Calculated characteristics of the distribution of beam electrons in the uniform magnetic field: a – calculated cross-sections of the beam electron distribution in the uniform magnetic field; cathode diameter D_C=3 mm, anode diameter D_A=15 mm, B=0.265 T); b – calculated dependence of the mean radius r of the beam on the coordinate z



a *b*

Fig. 8. Calculated characteristics of the distribution of beam particles in the falling magnetic field. a – calculated cross sections of the distribution of beam particles in the descending magnetic field, cathode diameter D_C=3 mm, anode diameter D_A=15 mm; b – calculated dependence of the average radius r of the beam on the coordinate z



a *b*

Fig. 9. Distribution of the gradient magnetic field along the axis of the gun and properties of the electron beam. a – the increasing magnetic field created together with the solenoid and two permanent magnets, B=0,57 T; b – calculated cross-sections of beam particles

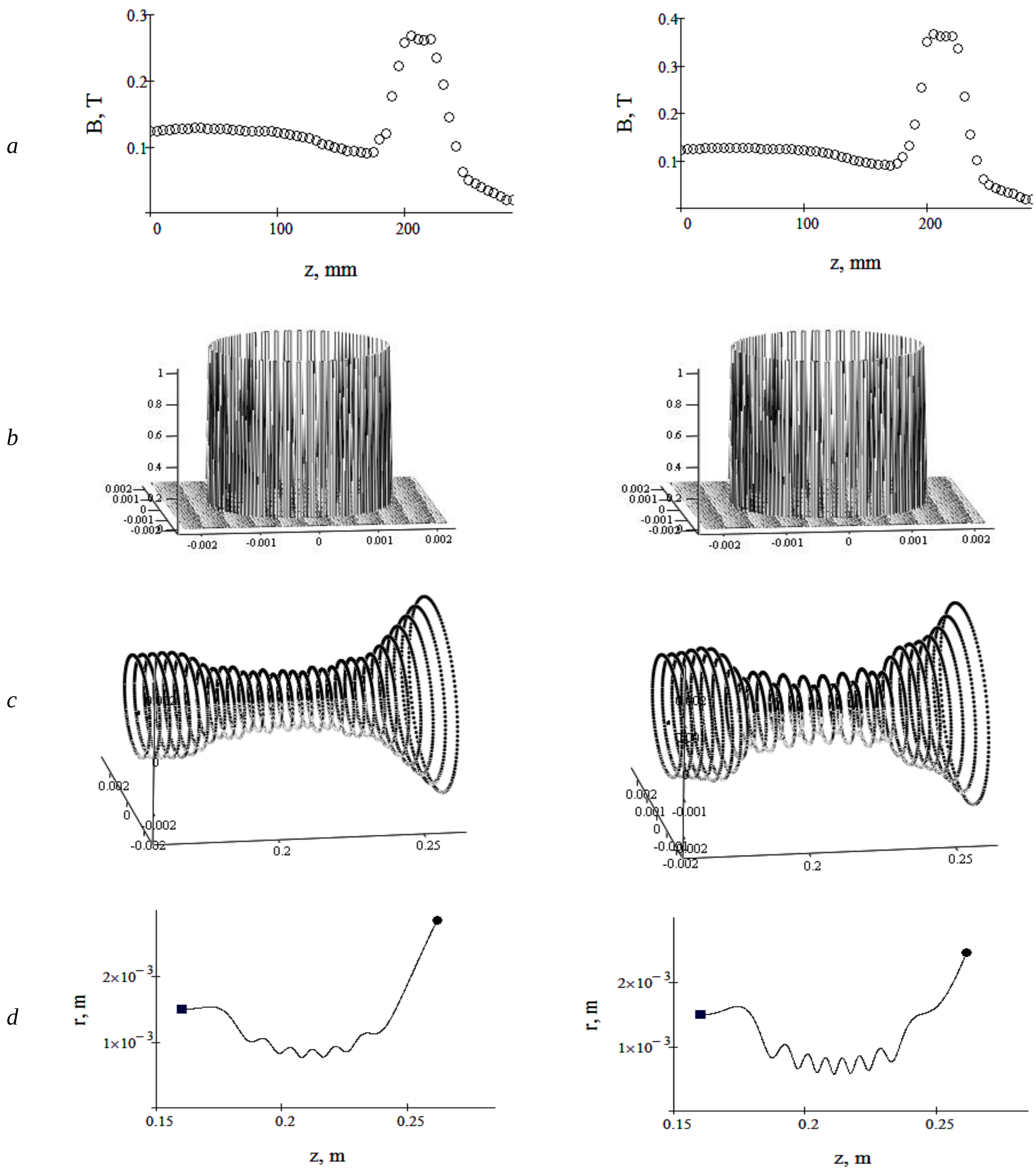


Fig. 10. Distribution of the gradient magnetic field along the gun axis and properties of the beam:
a – the growing magnetic field is created jointly by the solenoid and the permanent magnet (left),
the growing field is created jointly by the solenoid and two permanent magnets (right);
b – the initial distributions of beam particles;
c – the cross sections of the distribution of beam particles;
d – the calculated dependences of the average radius r of the beam on the coordinate z

CONCLUSIONS

It follows from the study that the electron flow at the exit of the magnetron gun undergoes the rearrangement of the radial distribution, which is determined by the type of magnetic field and its gradient in the beam transport channel. The possibility of controlling the beam diameter by varying the magnetic field in the electron beam transport channel has been experimentally shown. The dependence of the transverse dimensions of the electron beam formed by the magnetron gun on the configuration of the magnetic field in the particle transport channel is numerically studied. It is found that the experimental data are consistent with the results of numerical simulation. It is shown that with the increase in the maximum amplitude and/or field gradient, the effect of radial beam focusing is more pronounced. It has been found that the minimum voltage amplitude at the cathode, at which beam formation in magnetron guns with cathode diameters D_C=2 mm, D_C=3 mm and anode diameter D_A=15 mm, is maintained, is 8 kV. The results presented indicate the possibility of focusing, as well as defocusing, of the electron beam emitted by cathodes of millimeter diameters, which can be used when irradiating the surfaces of cylindrical samples.

REFERENCES

1. V.I. Engelko, G. Mueller, A. Andreev, et al. Pulsed Electron Beam Facilities (GESA) for Surface Treatment // *Proc. of 10th International Conf. on Applied Charged Particle Accelerators in Medicine and Industry*. St.-Petersburg, Russia. 2001, p. 412-417.
2. M.F. Vorogushin, V.A. Glukhikh, G.S. Manu-kyan, D.A. Karpov, Svin'in, V.I. Engelko, B.P. Yatsenko. Beam and ion-plasma technologies // *Problems of Atomic Science and Technology. Series "Physics of Radiation Effect and Radiation Materials Science"*. 2002, N 3, p. 101-109.
3. V.A. Glukhikh, O.P. Pechersky, V.I. Engelko, B.P. Yatsenko. Modification of the surface properties of materials using high-power pulsed electron beams // *Collection of reports of the tenth international meeting on the use of particle accelerators in industry and medicine*. M.: "CNIIatominform", 2001, p. 445-447.
4. A.N. Dovbnya, S.D. Lavrinenko, V.V. Zakutin, et al. Surface modification of zirconium and Zr1%Nb alloy by the electron beam of the magnetron gun-based accelerator // *Problems of Atomic Science and Technology. Series "Physics of Radiation Effect and Radiation Materials Science"*. 2011, N 2, p. 39-45.
5. A.N. Dovbnya, V.V. Zakutin, N.G. Reshetnyak, et al. Investigation of beam formation in an electron acceleration with a secondary-emission source // *Visnik Kharkivskogo University. Series "Nuclei, particles, fields"*. 2006, N 732, vyp. 2(30), p. 96-100.
6. M.I. Ayzatsky, A.N. Dovbnya, A.S. Mazma-nishvili, N.G. Reshetnyak, V.P. Romasko, I.A. Chertishchev. Studies on formation of the radially-directed electron beam generated by the magnetron gun with a secondary emission cathode // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations" (66)*. 2016, N 3(103), p. 11-16.
7. N.G. Reshetnyak, V.P. Romasko, I.A. Chertish-chev. Development of a pulse solenoid of magnitude field amplitude up to 0.5 T and a pulse sinusoidal current generator for its power supply // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations" (73)*. 2020, N 3(127), p. 19-22.
8. I.V. Barsuk, G.S. Vorobyev, A.A. Ponamareva. Numerical modeling of electron beam formation processes in axially symmetric systems // *Journal of Nano- and Electron Physics*. 2014, v. 6, N 2, p. 02012-1.

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ФОРМУВАННЯ ЕЛЕКТРОННИХ ПУЧКІВ У МАГНЕТРОННИХ ГАРМАТАХ З КАТОДАМИ МІЛІМЕТРОВИХ ДІАМЕТРІВ: ЕКСПЕРИМЕНТ І МОДЕЛЮВАННЯ

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

Досліджено характеристики електронного пучка, що генерується магнетронною гарматою. Експерименти проводилися з магнетронними гарматами з вторинноемісійними катодами (діаметр катодів 2 і 3 мм, діаметр анодів 15 і 50 мм) при напрузі на катоді 8…50 кВ. Магнітні поля створювалися як соленоїдом, а також спільно соленоїдом і постійним магнітом. Показано можливість регулювання діаметра пучка шляхом варіації магнітного поля. Одержано відбитки пучків на мішенях, які розташовані на вибраних відстанях. Чисельно досліджено залежність поперечних розмірів пучка від конфігурації магнітного поля в каналі транспортування електронного потоку. Показано, що експериментальні дані відповідають результатам чисельного моделювання.