FORMATION OF THE ELECTRON BEAMIN A SECONDARY-EMISSION MAGNETRON GUN ITS STARTING BY ANODULUM HIGH-VOLTAGE PULSE

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The results of a study on the formation of an electron beam by a magnetron gun with a secondary-emission cathode (cathode diameter 36 mm, an anode 78 mm) in the voltage range 25...90 kV are presented. The secondary-emission process in the gun is triggered by a voltage pulse with an amplitude of up to 16 kV applied to its anode. The generation of an electron beam is investigated as a function of the voltage of the incoming pulse. The dependence of the onset of electron beam generation on the beginning of the decay of the triggering pulse with its positive and negative polarity is studied. The dependence of the formation of the electron beam on the time of the secondary emission on the flat part of the voltage pulse was investigated.

PACS: 29.27.Fh

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 accelerating technology and so on. [1, 2]. With the beam method of specimen processing, it is possible to create materials with improved characteristics, increased microhardness, corrosion resistance, etc. [3, 4]. These studies were carried out with an electron energy of 100...400 keV [5, 6].

The NSC KIPT conducts research with sources of electrons with cold metal cathodes operating in the secondary emission regime. The electron source is a magnetron gun. 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. On the basis of a magnetron gun with a secondary-emission cathode, an electron accelerator was created [7], in which an axial electron beam is used to irradiate metal targets [4]. The possibility of irradiating an inner cylindrical surface with a radial electron beam has been studied [8]. The electric field needed to generate the beam in the gun was created by a voltage pulse with an ejection at the top of two pulsed generators fed to the cathode of the gun. In this paper we present the results on the formation of an electron beam by a magnetron gun in which an electric field was created by summing the electric fields of two pulses: a long pulse with a flat apex fed to the cathode and a short pulse with a steep slope applied to the anode of the gun.

WAYS TO CREATE AN ELECTRIC FIELD IN THE INTERELECTRODE GAP OF THE MAGNETRON GUN

The electric and magnetic fields in the magnetron gun determine the development of secondary emission processes at its cathode and the generation of an electron beam. The electric field necessary for generating the beam in the gun in the anode-cathode gap must have two time intervals. The first is a section with a falling field, on which secondary emission multiplication occurs and the formation of a cloud of primary electrons around the cathode. The second is the share with a constant field, which provides the stationary stage of the secondary emission process and the formation of the beam. This can be obtained by several methods.

In the first method, secondary emission multiplication was initiated by a specially generated ejection at the apex of the plane part of the voltage pulse applied to the cathode of the gun [7].

The disadvantage of the first method is a sufficiently large amount of the duration of the emission drop. This is due to the influence of the parasitic parameters of the output circuit of the feeding pulse generator and the supply circuits, which does not allow having a large slope of the emission drop.

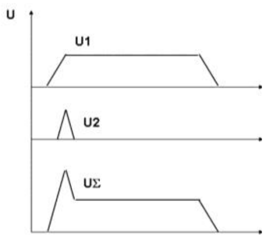


Fig. 1. Scheme of summation of electric fields of two pulses U1, U2

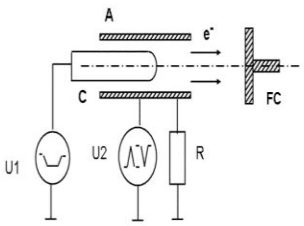


Fig. 2. Power plan magnetron gun with the summation of the fields of two pulses U1, U2: C – cathode; A – anode; R – load; FC – Faraday cylinder

The second method is the summation in the interelectrode gap of the magnetron gun of electric fields of two pulses: a long one with a flat top *U1* applied to the cathode and a short one with a steep *U2* drop applied to the anode of the gun. This allows us to obtain the necessary dependence of the total electric field on time (Fig. 1) to ensure secondary emission processes at the cathode and the formation of an electron beam.

Fig. 2 shows the power circuit of the magnetron gun in this way.

EXPERIMENTAL INSTALLATION AND RESEARCH TECHNIQUE

Experiments on the formation of an electron beam by a magnetron gun with a secondary-emission cathode and measurements of its parameters were carried out in an experimental setup, the block diagram of which is shown in Fig. 3. To power the magnetron gun, a pulse generator (1) was used with amplitude of the flat part of the pulse of 20...100 kV, with duration of 50...10 μs and a repetition rate of 3...10 Hz, which is fed to the cathode of the gun. In the pulse generator circuit, a full discharge of the storage capacitance was applied to the pulse transformer through a thyratron. The secondary emission in the gun is triggered by a voltage impulse with a steep recession that was created by an impulse generator (8) with voltage amplitude of up to 16 kV and applied to the anode of the gun.

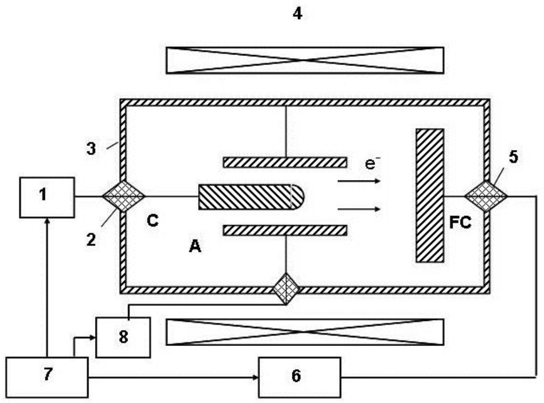


Fig. 3. Block diagram of the experimental setup: 1 – high voltage pulse generator; 2, 5 – insulators; 3 – vacuum chamber; 4 – solenoid; 6 – measuring system; 7 – synchronization unit; 8 – trigger pulse generator; C – cathode; A – anode; FC – Faraday cylinder

A magnetic field for the generation and transport of an electron beam is created by a solenoid (4) consisting of 4 sections, powered by direct current sources. The amplitude and longitudinal distribution of the magnetic field could be controlled by varying the current in the sections of the solenoid, which made it possible to obtain various modes of electron beam formation.

Measurements of the electron beam current were made with the help of an 8-section Faraday cylinder FC. The processing of the results of measurements of the beam currents and the voltage pulse was carried out using a computer measuring system (6). The measurement error is 1...2%. The transverse dimensions of the beam were measured by obtaining a print on a copper disk. During the research, a digital oscilloscope with the Tektronix TDS-2012 memory with a bandwidth of 100 MHz was used.

EXPERIMENTAL RESULTS AND THEIR DISCUSSION

Experimental studies on the formation of an electron beam and measurement of its parameters on the voltage at the cathode in the range 20...90 kV have been carried out.

Fig. 4 shows the distributions of the magnetic field along the axis of the magnetron gun and the beam transport channel at which the experiments were performed, and it shows the arrangement of the elements of the gun and the Faraday cylinder.

The secondary-emission multiplication of electrons at the cathode of the gun was triggered by pulses of nanosecond duration with an amplitude decay up to ~16 kV applied to the anode of the gun. The formation of the electron beam was carried out with a pulse of triggering a positive and negative polarity in the voltage range 7.5...16 kV, which is shown in Fig. 5.

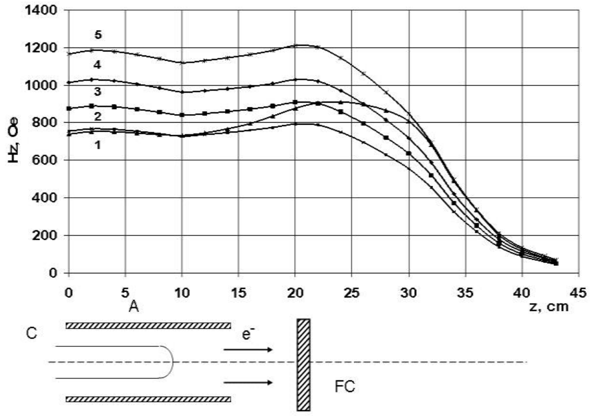
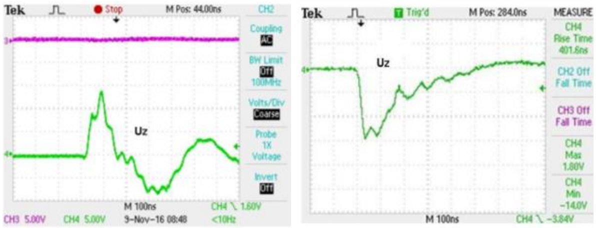


Fig. 4. Distributions of the magnetic field along the axis of the magnetron gun (curves 1-5) and the transporting channel of the beam and the arrangement of the elements of the gun and the Faraday cylinder FC. A – anode; C – cathode

The dependence of the onset of beam generation on the voltage of the trigger pulse U_z is studied. Experiments have shown that this dependence has a threshold character of triggering secondary emission electron multiplication and beam generation, both for positive and negative polarities of the trigger pulse.



a *b*

Fig. 5. Voltage pulses at the anode of the magnetron gun, a – positive polarity; b – negative polarity, vertical scale 5 kV/div

Fig. 6 shows the dependence of the beam current I6, taken from the 6[th] segment of the Faraday cylinder, with negative (curve 1) and positive (curve 2) polarity of the triggering pulse U_z (50 kV cathode voltage). It can be seen that the steady generation of the electron beam occurs at amplitude of the triggering pulse of ~7 kV.

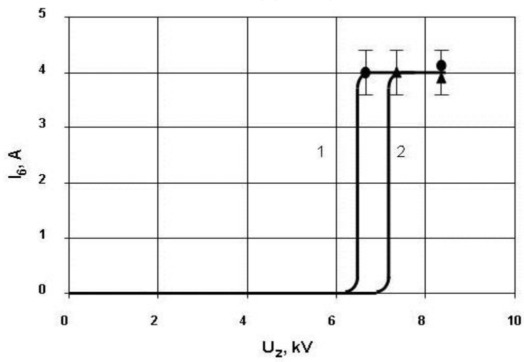


Fig. 6. Dependence of the beam current on the 6[th] segment of the Faraday cylinder from the polarity of the trigger pulse voltage U_z: 1 – negative polarity; 2 – positive polarity

Investigations were conducted on the formation of an electron beam and measurement of its parameters with negative polarity of the triggering pulse U_z~15 kV. The experiments were carried out with a voltage on the cathode of 56 kV and the distribution of the magnetic field shown in Fig. 4 (curve 2). Fig. 7 shows oscillograms of voltage pulses and beam currents *I5, I6, I7* taken from three segments (5, 6, and 7) of the Faraday cylinder. The above oscillograms of currents indicate that the shapes of the pulses practically coincide, and during the pulse the ratio of currents from different segments in time is constant. This suggests that the process of the secondary emission multiplication of electrons is stable during the duration of the voltage pulse across the entire surface of the cathode.

From Fig. 7 it can be seen that at the moment of beam generation at the voltage pulse drop *U* there appears a "gain" of the amplitude, which is connected with the "loading" of the pulse generator by the beam current. In this case, the law of increase in the beam current for all oscillograms coincides. Thus, in the process of secondary emission multiplication, the entire surface of the cathode is used, which can occur when the primary electrons are equidistantly distributed along the azimuth in the cathode-anode gap. It follows that a fairly well-formed cloud of primary electrons has been created which bombard the cathode. With a positive polarity of the trigger pulse, a similar picture is observed.

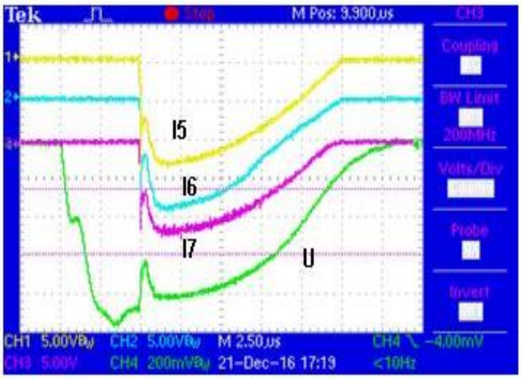


Fig. 7. Oscillograms of voltage pulses at the cathode (U) and currents from three segments of the Faraday cylinder (I5, I6, I7). U – 14 kV/div; I5, I6, I7 – 2 A/div

With a uniform distribution of the magnetic field at the cathode of the magnetron gun and in the beam transport region (see Fig. 4, curve 2), the coefficient of azimuthally homogeneity beam $k=I_{max}/I_{min}$ was of the ~1.12, where I_{max} and I_{min}, respectively, the maximum and the minimum value of the currents from the Faraday cylinder segment.

The dependence of the beginning of electron beam generation on the instant of voltage drop of the starting pulse U_z with positive and negative polarity is investigated. Fig. 8 shows the oscillograms of the trigger pulse U_z and the beam current *I6* taken from the 6th segment of the Faraday cylinder (Fig. 8,a – positive polarity) and the current *I6, I7* taken from the 6th and 7th segments (Fig. 8,b,c – negative polarity) at a voltage of 70 kV on the cathode.

From Fig. 8,a it can be seen that the generation of the electron beam occurs in 60 ns from the beginning of the decay of the triggering pulse at a slope of 250 kV/µs. From Fig. 8,b it follows that the beam generation occurs in 27 ns with a drop slope of ~550 kV/µs. From Fig. 8,c it follows that there is practically no scatter in the amplitudes of the beam current *I6* and *I7* from the 6th and 7th segments of the Faraday cylinder for 15 consecutive pulses.

The rise time of the electron beam current is investigated. By the magnitude of the onset time, one can judge the processes of formation of an electron cloud around the cathode. In Fig. 8,b,c shows the beam current *I6* and *I7* from 6th and 7th segments of the Faraday cylinder. It is seen that the rise time of the beam current is ~7 ns at the level of 0.1...0.9.

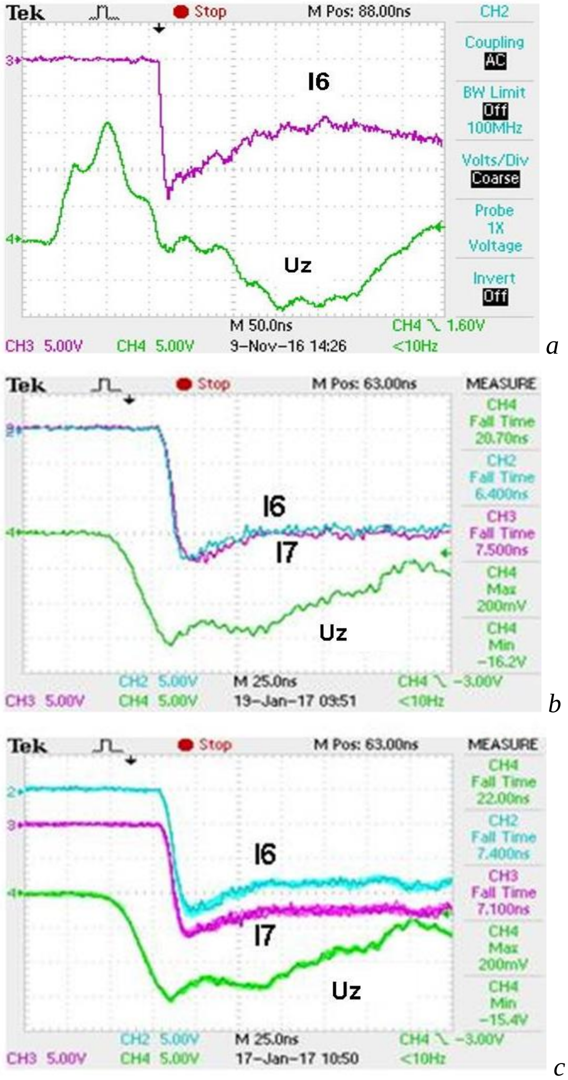


Fig. 8. Oscillograms of the onset of pulses of currents I6, I7 on the 6th and 7th segments of the Faraday cylinder and the voltage of the trigger pulse U_z; a – positive polarity; b and c – negative polarity; c – 15 consecutive pulses. U_z – 5 kV/div; I6, I7 – 2 A/div

This indicates that in a short time (a few nanoseconds) the number of secondary electron multiplication acts was sufficient to achieve the space charge density necessary for self-sustaining secondary emission in a magnetron gun with a cold secondary-emission cathode.

The minimum time for the initiation of the generation of the electron beam from the decay of the trigger pulse, with its negative polarity, was ~20 ns (the

750 kV/μs), and with a positive ~55 ns (the slope of the decay was ~270 kV/μs).

The dependence of the beginning of the time of electron beam generation on the voltage of triggering secondary emission of U_z in the voltage range 7.5...16 kV for positive and negative polarity was studied (Fig. 9).

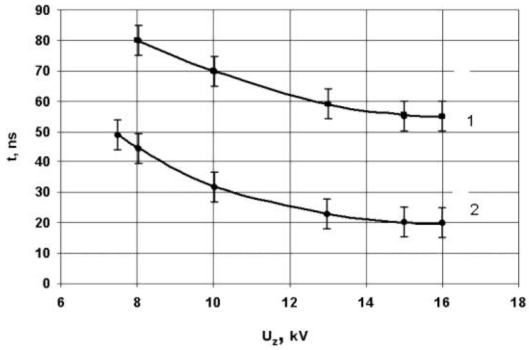


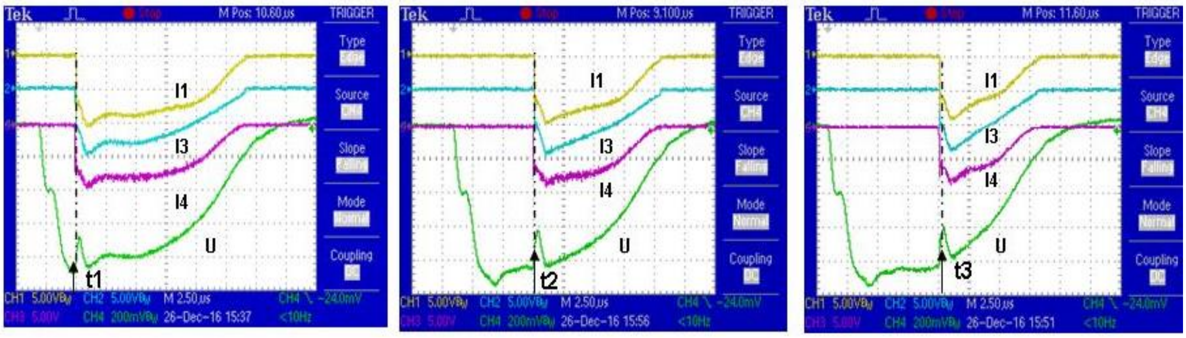
Fig. 9. Dependence of the onset of beam current generation on the Faraday cylinder from the voltage of the trigger pulse U_z: 1 – positive polarity; 2 – negative polarity

Measurements of the dimensions of the electron beam on a copper target located in the region of the Faraday cylinder at electron energy of ~50 keV are carried out. In Fig. 10 the beam imprint at a distance of ~60 mm from the cut of the magnetron gun is shown. As it can be seen, the magnetron gun forms a tubular electron beam with an outer diameter of ~42 mm and wall thickness ~3 mm.

The dependence of the formation of an electron beam on the moment of the secondary emission pulse is applied to the flat part of the voltage pulse. Fig. 11 shows the oscillograms of the voltage pulses at the cathode and the beam current for different instants of time t_1, t_2, t_3 of the triggering pulse U_z~15 kV. In the case of negative polarity, the beam currents (*I1*, *I3, I4*) taken from 1st, 3rd and 4th segments of the Faraday cylinder (see Fig. 11,a,b,c) at a cathode voltage of 56 kV. From Fig. 11 it can be seen that the generation of the electron beam occurs at instants of time on the plane part of the voltage pulse at the cathode of the gun, corresponding to the moment the trigger pulse is applied to its anode.

Fig. 10. Imprint of the beam on a copper target

The width of the formation zone of the electron beam is measured from the magnetic field $\Delta H=H_{max}-H_{min}$, where H_{max} and H_{min} are the maximum and minimum values of the magnetic field, respectively, for a cathode voltage of 75 kV.



a *b* *c*

Fig. 11. Oscillograms of voltage pulses at the cathode U and beam current I for three time instants; a – t_1; b – t_2; c – t_3 of the trigger pulse. The horizontal scale is 2.5 μs/div: U ~ 14 kV/div; I1, I3, I4 – 3 A/div

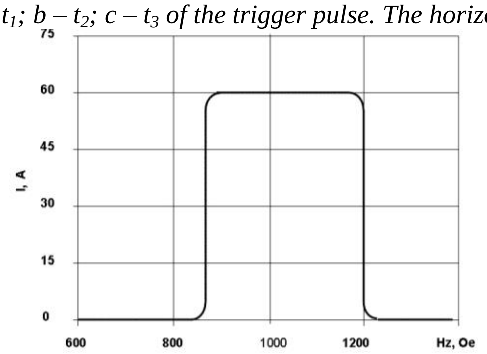


Fig. 12. The dependence of the beam current on the Faraday cylinder on the strength of the magnetic field

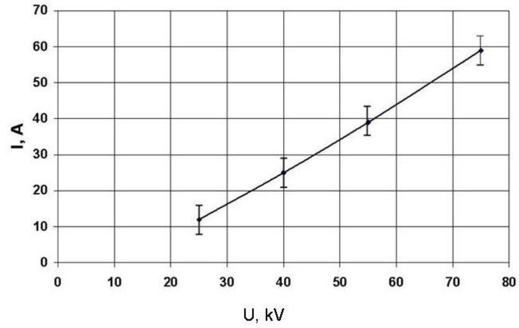


Fig. 13. Dependence of the beam current I on the Faraday cylinder on the voltage U on the cathode

As can be seen from Fig. 12, the formation of the beam begins at a magnetic field at the cathode of 860 Oe (see the lower boundary Fig. 4, curve 3), with the Hall cutoff field of 610 Oe. The beam generation continues with an increase in the magnetic field amplitude up to 1200 Oe (the upper border, see Fig. 4, curve 5). Thus, in this experiment, the formation zone of the magnetic field is 350 Oe.

In the formation zone, there is an area of the optimal magnetic field (see Fig. 4, curve 4), in which the amplitude of the beam current is maximal. In this case, the ratio of the value of the optimal magnetic field to the Hall field is ~1.7, which agrees with the data of the work.

As the amplitude of the magnetic field decreases from the boundary of ΔH from below or from above, the conditions for the secondary-emission multiplication of electrons are violated, and the process of generation of the electron beam is disrupted. The amplitude and shape of the current pulse of the electron beam in the generation zone vary insignificantly – by 3...4%.

The dependence of the beam current *I* on the Faraday cylinder on the voltage at the cathode in the range 25...75 kV was studied. The results of the measurements are shown in Fig. 13. It can be seen that the beam current *I* obeys the law "3/2". In the process of measuring, each value of the voltage corresponded to the value of the magnetic field at which the amplitude of the beam current was maximum.

CONCLUSIONS

1. Studies have shown the possibility of a stable formation of an electron beam by a magnetron gun at the start of secondary emission multiplication at its cathode by a high-voltage voltage pulse applied to the anode.

2. It is shown that the beam generation in the magnetron gun occurs only when the threshold value of the trigger pulse is exceeded for its positive and negative polarity.

3. It has been shown that the formation of an electron beam in a magnetron gun with a secondary-emission cathode occurs within ~20 ns with negative polarity and ~55 ns with positive polarity from the onset of the decay of the trigger pulse and a drop steepness of ~750 kV/μs and ~270 kV/μs, respectively.

4. It is shown that the generation of the electron beam occurs at the instants of time on the plane part of the voltage pulse at the cathode of the gun, corresponding to the moment the triggering pulse is applied to its anode.

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Article received 13.02.2018

ФОРМИРОВАНИЕ ЭЛЕКТРОННОГО ПУЧКА ВО ВТОРИЧНО-ЭМИССИОННОЙ МАГНЕТРОННОЙ ПУШКЕ ПРИ ЕЁ ЗАПУСКЕ АНОДНЫМ ВЫСОКОВОЛЬТНЫМ ИМПУЛЬСОМ

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Представлены результаты исследования по формированию электронного пучка магнетронной пушкой с вторично-эмиссионным катодом (диаметр катода 36 мм, анода 78 мм) в диапазоне напряжений 25..90 кВ. Запуск вторично-эмиссионного процесса в пушке осуществляется импульсом напряжения амплитудой до 16 кВ, подаваемым на её анод. Проведено исследование генерации электронного пучка в зависимости от напряжения запускающего импульса. Исследована зависимость начала генерации электронного пучка от начала спада запускающего импульса при его положительной и отрицательной полярностях. Исследована зависимость формирования электронного пучка от времени подачи импульса запуска вторичной эмиссии на плоскую часть импульса напряжения.

ФОРМУВАННЯ ЕЛЕКТРОННОГО ПУЧКА У ВТОРИННО-ЕМІСІЙНІЙ МАГНЕТРОННІЙ ГАРМАТІ ПРИ ЇЇ ЗАПУСКУ АНОДНИМ ВИСОКОВОЛЬТНИМ ІМПУЛЬСОМ

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Представлені результати дослідження щодо формування електронного пучка магнетронною гарматою з вторинно-емісійним катодом (діаметр катода 36 мм, анода 78 мм) у діапазоні напруг 25...90 кВ. Запуск вторинно-емісійного процесу в гарматі здійснюється імпульсом напруги амплітудою до 16 кВ, що подається на її анод. Проведено дослідження генерації електронного пучка в залежності від напруги запускаючого імпульсу. Досліджена залежність початку генерації електронного пучка від початку спаду запускаючого імпульсу при його позитивній і негативній полярностях. Досліджена залежність формування електронного пучка від часу подачі імпульсу запуску вторинної емісії на плоску частину імпульсу напруги.