CURRENT CONTROL OF THE ELECTRON BEAM FORMED IN THE MAGNETRON GUN WITH A SECONDARY-EMISSION CATHODE

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Data are reported on electron beam generation and beam current control in two types of secondary-emission cathode magnetron guns. The influence of the magnetic field value and field distribution on the formation of the beam and its parameters has been investigated in the electron energy range between 20 and 150 keV. The influence of local magnetic field variations on the cathode and the electron beam characteristics has been studied. The possibility to control the electron beam current in various ways has been demonstrated.

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INTRODUCTION

Magnetron guns with cold secondary-emission cathodes show promise for use in creation of powerful microwave devices, electron-beam technologies, accelerator facilities, etc. The operation of these guns is based on secondary-emission multiplication of electrons, electron cloud production and electron beam formation [1, 2] in crossed electric and magnetic fields. The advantage of secondary-emission guns lies in the absence of incandescence and in their simple design. Furthermore, the cathodes are capable of emitting after multiple inlets of air and keep their emission properties for a long time (up to ~ 100000 hours).

Using the secondary-emission magnetron gun as the base, the electron accelerator has been created, which is employed for irradiating metal targets [3]. The electron beam has the following maximum parameters: electron energy ~ 100 keV, beam current ~ 100 A. However, to increase the electron beam current, and hence, the specific power on the target, it is necessary either to increase the cathode voltage (this being restricted by the electric strength of the interelectrode gap) or to seek other ways to solve the problem. In ref. [2], the electron beam current was increased through electron accumulation and confinement in the magnetron diode. To that effect, inhomogeneous electric or magnetic fields were used to create the axially decelerating force and to provide conditions for axial oscillations of electrons, thereby increasing their kinetic energy.

The present paper reports the data on electron beam formation in two types of secondary-emission magnetron guns and discusses a possibility of controlling the beam current by different methods.

1. EXPERIMENTAL SETUP AND RESEARCH TECHNIQUE

Experiments on electron beam formation and current control were performed at the electron accelerator at voltage ranging from 20 to 150 kV. The block diagram of the accelerator is shown in Fig. 1. For feeding the secondary-emission system, an impulse generator 1 was used, which provided the voltage pulse with a pulse spike amplitude of 200 kV and the time of spike droop of ~ 0.6 μs. The amplitude and duration of the flat part of the pulse were ~ 150 kV and ~ 10 μs, respectively; and the pulse repetition frequency was ~ 3 Hz.

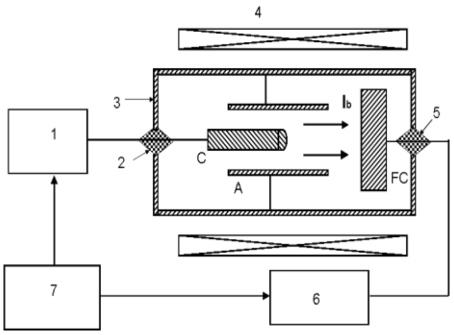

Fig. 1. Block diagram of the accelerator. 1 – impulse generator; 2, 5 – passed insulators; 3 – vacuum chamber; 4 – solenoid; 6 – computer-aided measuring system; 7 – control unit. C – cathode; A – anode; FC – Faraday cup

The electron source (C – cathode, A – anode) is located in the vacuum volume 3, where the pressure was ~ 10^{-6} Torr. For electron beam generation, two magnetron guns were used, having the following dimensions: cathode diameter – 40 mm, cathode length – 90 mm, anode diameter – 78 mm (Type 1 gun); and cathode diameter – 50 mm, cathode length – 90 mm, anode diameter – 78 mm, anode length 140 mm (Type 2 gun). The cathode was made from copper, while the anode was made from stainless steel. To provide a local short-length magnetic field variation on the cathode, a scattered magnetic field was used from a thin NdFeB magnetic ring (~ 3 mm in thickness and 31 mm in diameter) placed inside the cathode. If the magnetic field of the ring was coincident in direction with the solenoid field, then the magnetic field distribution showed the field spike, and if the directions of the solenoid field and the ring field were opposite, then the field distribution curve showed a dip (see Fig. 7).

The magnetic field for electron beam generation and transport was generated by the solenoid 4, which consisted of four sections energized by dc sources. The magnetic field amplitude and longitudinal distribution could be controlled by varying the current value in the solenoid sections.

The measured data on the voltage pulse, beam current on the Faraday cup and the parameter stability were processed by means of the computer measurement system 6. The obtained data were displayed on the computer screen. The measurement error was within 1 to 2%. A digital data-storage oscilloscope Tektronix TDS-2014 was also used in the studies. The cross-sectional size of the beam was determined from its prints on the targets.

2. EXPERIMENTAL RESULTS AND THEIR DISCUSSION

Experimental studies were made into steady operation adjustment and electron beam current generation in the accelerator constructed around the magnetron gun with a secondary-emission cathode. The beam current on the Faraday cup was investigated as a function of the magnetic field distribution along the axis of the system up to the Faraday cup in the Type 1 magnetron gun. The experiments have shown that in the uniform magnetic field (Fig. 2, curve 2) the magnetron gun forms a tubular electron beam with a current of 140 A at a particle energy of ~ 125 keV and with energy density on the target of ~ 40 J/cm^2 at a pulse length of ~ 10 µs. The azimuthal uniformity factor of the beam is ~ 1.2.

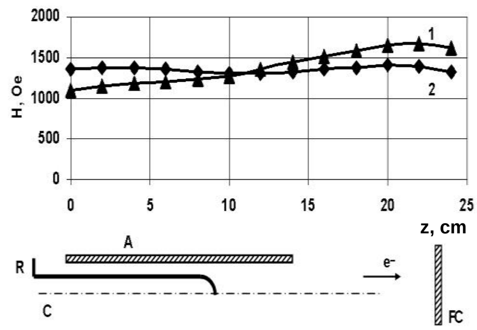

Fig. 2. Magnetic field distribution (curves 1, 2) and the arrangement of the setup components: A – anode, C – cathode, R – reflector, FC – Faraday cup

Typical oscillograms of cathode voltage, beam current and anode current pulses are shown in Fig. 3. In this case, to attain the maximum beam current, it is necessary to choose the optimum distribution of the magnetic field by varying its amplitude and distribution along the system axis.

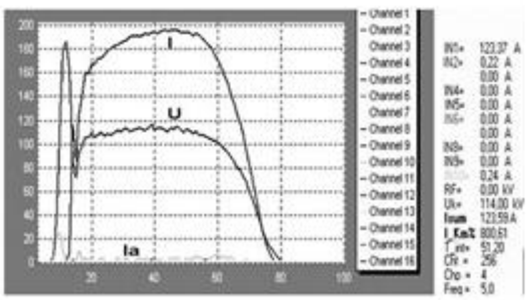

Fig. 3. Oscillograms of cathode voltage (U), current to the Faraday cup (I), and anode current pulses (I_a)

The experiments have demonstrated that the stability of the total beam current, and also, of the current from each of the eight segments of the Faraday cup in the course of 8 successive voltage pulses, varied within ~ 2…3 %. It has been shown that at a cathode voltage of ~ 125 kV, the beam formation starts at the magnetic field of ~ 1450 Oe, and continues with an increase in the magnetic field amplitude up to 1750 Oe. In other words, the zone of beam formation in accordance with the magnetic field (where $\Delta H = H_{max} - H_{min}$, H_{max} and H_{min} being, respectively, the maximum and minimum magnetic field values for beam generation) amounts to ~ 300 Oe. At that, the amplitude and shape of the beam current pulse at the zone boundaries vary only slightly (by 2…4 %).

So, a considerable width of the zone of beam formation and generation, ΔH, is very important in technological studies of the magnetron gun-based accelerator. Note that with a decrease in the magnetic field amplitude from the lower boundary of ΔH or with an increase from the upper boundary, it is the pulse form of the beam current that first changes, and then the conditions of secondary-emission multiplication are violated, and the process of electron beam generation comes off.

Fig. 4 shows the annular beam print obtained on the Faraday cup at a cathode voltage of ~ 125 kV. As is seen from the figure, the magnetron gun forms the beam having an external diameter of ~ 39 mm and a wall thickness of ~ 1 mm. The beam has a rather high azimuthal uniformity.

The working range of the accelerator at a given magnetic field value has been investigated versus the cathode voltage amplitude. It is shown that at a constant magnetic field, the electron beam formation persists with the voltage amplitude variation by ± 10 % of the optimum value.

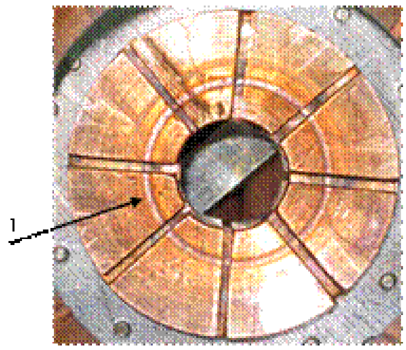

Fig. 4. Beam print 1 on the Faraday cup

The undertaken studies have demonstrated that at a constant cathode voltage the amplitude and distribution variations in the magnetic field lead to variations in the electron beam current. In this way we could increase the beam current (Fig. 5) from 40…45 A at a cathode voltage of 138±12 kV and with an increasing magnetic field (see Fig. 2, curve 1) up to 140 A (the magnetic field being uniform, see Fig. 2, curve 2).

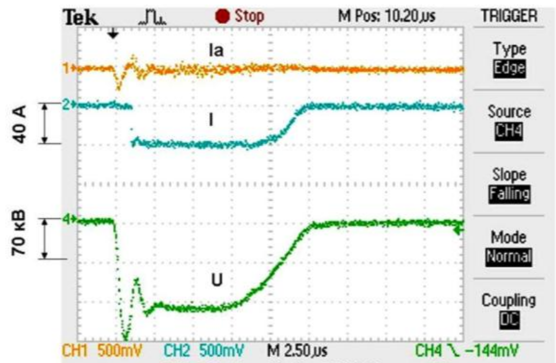

Fig. 5. Oscillograms of cathode voltage (U), Faraday-cup axial current (I) and anode current (I_a) pulses

In the course of the studies various modes of electron beam formation on targets were realized, thereby proving the possibility of current control in a wide range.

Electron beam control (increase/decrease) experiments have been performed in the accelerator, where the Type 2 magnetron gun (Fig. 6) was used as an electron source. Inside the gun cathode, there was an annular NdFeB magnet, placed at different distances (L_1 ~ 20 mm, L_2 ~ 65 mm, L_3 ~ 82 mm) from the cathode end. The gun anode had the diameter 70 mm. The voltage ranged from 20 to 50 kV. The annular magnet provided local variations in the magnetic field on the cathode surface. The experiments were performed for three cases: 1) the magnetic field shows a spike (Fig. 7, curve 1, the field directions of both the ring and the solenoid are coincident); 2) the magnetic field shows a dip (Fig. 7, curve 2, the ring and solenoid fields are opposite in the direction); 3) the magnetic field is uniform (there is no ring).

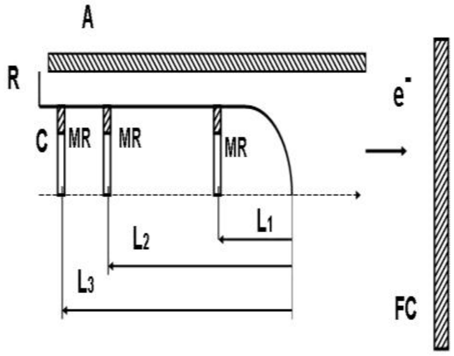

Fig. 6. Arrangement of magnetron gun components and magnetic ring locations (L1= 2 cm, L2 = 6.5 cm, L3 =8.2 cm from the cathode end). A – anode, C – cathode, R – reflector

Fig. 7 shows the total distribution of the longitudinal magnetic field along the gun axis and along the beam transport channel up to the Faraday cup (curves 1, 2).

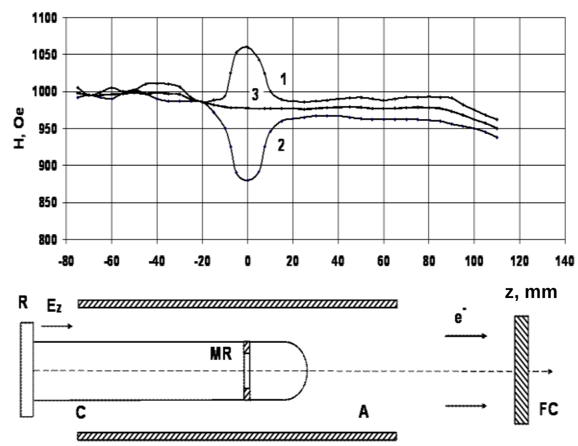

Fig. 7. Arrangement of magnetron gun elements and the magnetic field distribution along the axis of the system. Curve: 1 – field directions of the ring and solenoid are the same; 2 – the ring field is opposite to the solenoid field; 3 – the magnetic field is uniform. C – cathode, A – anode, MR – annular magnet arranged at 2 cm from the cathode end, FC – Faraday cup, R – reflector

As experiments have shown, in the presence of the magnetic field spike by 5…10% (see Fig. 7, curve 1), at different distances L_1, L_2, L_3 along the cathode, a combined electromagnetic trap for electrons is created due to a joint action of electric and magnetic fields. From the side of cathode entrance into the anode, the generated reflecting electric field E_z, while from the side of the beam outlet of a magnetic field spike is creatid.

Fig. 8 (curve 1) shows the Faraday-cup current ratio $K_1 = I_1/I_2$ obtained at the magnetic field spike (I_1) and dip (I_2) with the annular magnet arranged at different distances (L_1, L_2, L_3) from the cathode end. It can be seen from the curve that if the magnetic ring is located at the beginning of the cathode entrance into the anode (L_3 ~ 82 mm), the beam current amplitudes differ insignificantly (by ~ 15 %).

However, with an increasing length of the trap, when the ring is at L_1, the beam current amplitude is 2.5…2.7 times higher in the case of the magnetic field spike than in the case of the field dip, the experimental conditions remaining the same.

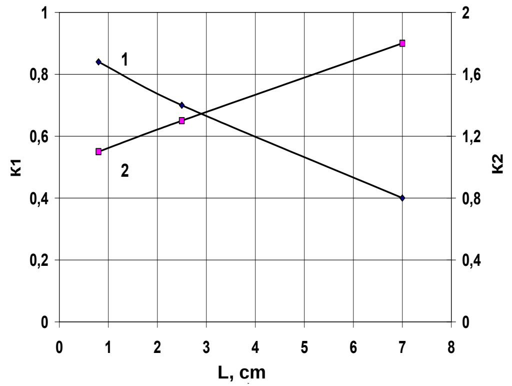

Fig. 8. The Faraday-cup current ratios $K_1=I_1/I_2$ and $K_2=I_1/I_0$, obtained with the magnetic field rise (I_1), dip (I_2), and the magnetic field being uniform (I_0)

Fig. 8 (curve 2) shows the $K_2 = I_1/I_0$ ratio of the Faraday cup current measured at the magnetic field spike (I_1) to the current I_0 measured at a uniform magnetic field (the cathode has no magnetic ring inside). From curve 2 it is evident that if the magnetic ring is located at the beginning of the cathode at point L_3, then the beam current amplitude increases by 12…15% with magnetic field spike formation, and if the ring is at point L_1, then we have a considerable increase in the electron beam current amplitude (by 80…85%) as compared with the magnetron gun experiments performed at the same conditions but with the uniform magnetic field.

The experiments have shown that at the magnetic field dip by 5…10% the beam current amplitude was lower in comparison with the experiments carried out at a uniform magnetic field.

The present experiments have also shown that the most optimum location of the magnetic ring was at point L_1, therefore, further experiments with the ring were performed at this location only.

Fig. 9 shows the total magnetic field distribution along the gun axis and along the beam transport channel up to the Faraday cup (curves 1 - 4). This distribution and the arrangement of the setup elements were kept the same in our further experiments.

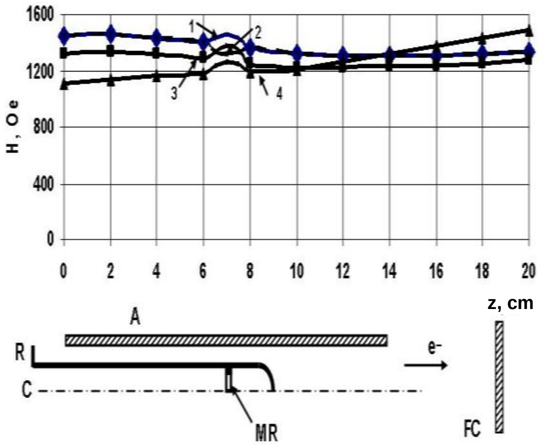

Fig. 9. Total magnetic field distribution (curves 1-4) and the arrangement of the gun elements. A – anode; C – cathode; R – reflector; MR – magnetic ring; FC – Faraday cup

Fig. 10 shows the beam current as a function of the cathode voltage in the voltage range from 20 to 35 kV. Curves 1 and 2 were obtained at the magnetic field spike and dip, respectively. As is seen from the figure, the Faraday-cup beam current curve obeys the 3/2 law. So, at a cathode voltage of ~ 35 kV, the magnetron gun forms a tubular electron beam of current ~ 105 A. In this case, during the measurements, the optimum magnetic field value, at which the beam current amplitude was maximal, corresponded to each fixed voltage value. Thus, by creating the spike or dip in the magnetic field distribution, we could vary the beam current amplitude from 38 up to 105 A at a cathode voltage of 35 kV (see Fig. 10, curves 1, 2).

Besides, the undertaken experiments have proved that the electron beam current could be regulated through the control of the voltage spike amplitude. Experiments were made for three cases of voltage spike amplitude variations: 82, 66 and 59 kV at a constant amplitude of the generator no-load voltage, U_{nl}~45 kV (no beam).

The experiments have shown that to attain a stable electron beam generation with voltage spike amplitude variation, it was necessary to vary both the amplitude and distribution of the magnetic field (see Fig. 9, curves 1, 3, 4).

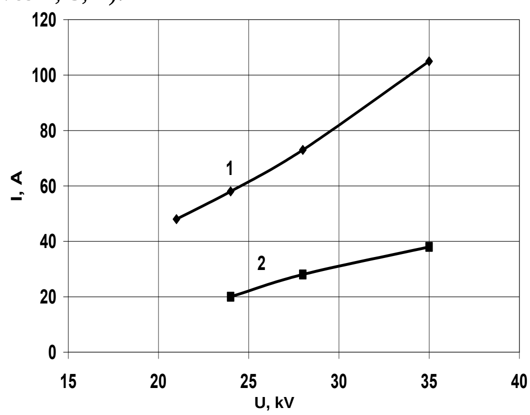

Fig. 10. Current versus cathode voltage. The magnetic ring is at ~ 20 mm from the cathode end. Curve 1 – magnetic field spike, curve 2 – magnetic field dip

Fig. 11 shows the Faraday-cup electron-beam current as a function of the ratio of the spike amplitude to the flat part of the voltage impulse, K = U_{spike}/U_{nl}, The curve was obtained at the no-load voltage U_{nl} ~ 45 kV.

It is obvious from Fig. 11 that at K = U_{spike}/U_{nl}> 1.6 and at the magnetic field distribution shown in Fig. 9 (curve 1), a stable electron beam generation with peak performance takes place (U_b~35 kV, I_b~105 A). With a decrease in the ratio down to K = U_{spike}/U_{bnl} ~1.42 the beam current amplitude decreases down to 80 A. In this case, to support stable generation, it was necessary to vary the magnetic field amplitude and the field distribution along the system axis (see Fig. 9, curve 3).

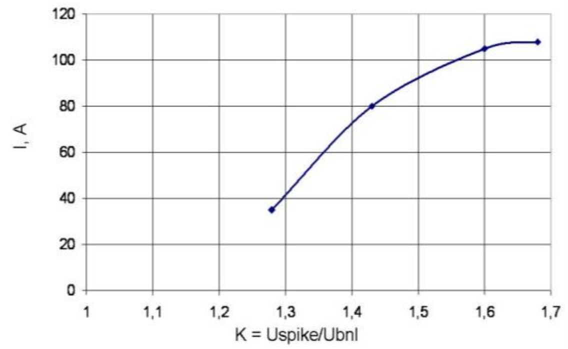

Fig. 11. Beam current versus the ratio of the voltage spike amplitude to the flat part of the voltage impulse $K=U_{spike}/U_{bnl}$

As the K=U_{spike}/U_{bnl} ratio decreased down to 1.28, the beam current went to ~ 36 A. In this case, the magnetic field amplitude and the field distribution have essentially changed (see Fig. 9, curve 4) as compared to the first and second cases, while the magnetic field on the cathode and in the beam transport region, which is required for stable electron beam generation, has become growing with gradients of ~ 15 and 21.4 Oe/cm, respectively.

So, with a decrease in the ratio of the voltage spike amplitude to the flat part of the voltage impulse by 30…35% of the optimum value, the beam current decreased by factors of 2.5…3. At that, the type of magnetic field distribution along the system axis changed from falling to rising, and this permitted the beam current control.

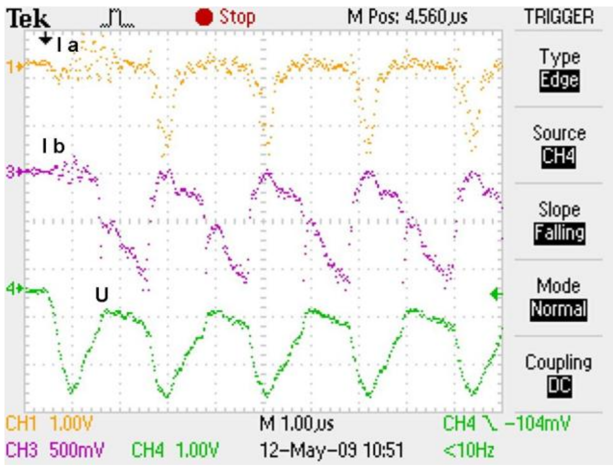

Fig. 12. Pulse oscillograms of cathode voltage U, axial current to the Faraday cup I_b, and the radial current I_a

It has been shown experimentally that the formation of the magnetic field spike and the type of magnetic field distribution, close to that of Fig. 8, (curve 1), but of lower amplitude, in the vicinity of the bottom boundary of electron beam formation, led to electron bunch generation in both axial and radial directions. This mode of operation is characterized by the fact that the current micropulse first goes in the axial direction, and then, during the voltage spike, the current pulse changes its direction for radial one. As is seen from Fig. 12, the pulse peak has close to sine modulation, and the beam current has the form of bunches time-spaced at the sites, where the sine curve shows the dip. The bunch current amplitude was found to be ~ 70 A, and the bunch repetition rate was 2 μs. The anode current bunches arose at the sites, where the sine curve showed the rise. The anode current bunch amplitude was about 30 A, the bunch duration being between 300 and 400 ns.

Thus, by controlling the magnetic field amplitude it appears possible to form separate bunches of axial and radial currents.

CONCLUSIONS

1. The investigation of the electron beam formation with the secondary-emission magnetron gun as the basis has resulted in attaining the maximum operational mode, at which the beam current comes to 140 A at a particle energy of 125 keV, the beam energy density on the target reaches ~ 40 J/cm^2. The possibility of controlling the beam current in the range from 40 to 140 A by varying the magnetic field amplitude and distribution has been demonstrated.

2. The undertaken studies have shown that in the accelerator, in the presence of the magnetic trap on the magnetron gun cathode, the increase in the beam current by 80…85% takes place. It has been shown that the beam current can be varied in a wide range by different methods, namely, by creating the magnetic field spike or a dip, and also, by varying the voltage spike amplitude.

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УПРАВЛЕНИЕ ТОКОМ ЭЛЕКТРОННОГО ПУЧКА, ФОРМИРУЕМОГО В МАГНЕТРОННОЙ ПУШКЕ С ВТОРИЧНО-ЭМИССИОННЫМ КАТОДОМ

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Приведены результаты по формированию и управлению током электронного пучка в двух типах магнетронных пушек с вторично-эмиссионными катодами. Исследовано влияние величины и распределения магнитного поля на формирование пучка и его параметры в диапазоне энергий электронов 20…150 кэВ. Изучено влияние локального изменения магнитного поля на катоде на характеристики электронного пучка. Показана возможность управления током электронного пучка различными способами.

КЕРУВАННЯ СТРУМОМ ЕЛЕКТРОННОГО ПУЧКА, ЩО ФОРМУЄТЬСЯ В МАГНЕТРОННІЙ ГАРМАТІ З ВТОРИННО-ЕМІСІЙНИМ КАТОДОМ

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Приведено результати з формування та управління струмом електронного пучка в двох типах магнетронних гармат з вторинно-емісійними катодами. Досліджено вплив розміру та розподілу магнітного поля на формування пучка та його параметри в діапазоні енергій електронів 20…150 кеВ. Вивчено вплив локальної зміни магнітного поля на катоді на характеристики електронного пучка. Показано можливість управління струмом електронного пучка різними засобами.