

High-current electron gun with a planar magnetron integrated with an explosive-emission cathode

P P Kiziridi and G E Ozur

Institute of High-Current Electronics, SB RAS, Tomsk, 634055, Russia

E-mail: ozur@lve.hcei.tsc.ru

Abstract. A new high-current electron gun with plasma anode and explosive-emission cathode integrated with planar pulsed powered magnetron is described. Five hundred twelve copper wires 1 mm in diameter and 15 mm in height serve as emitters. These emitters are installed on stainless steel disc (substrate) with 3-mm distance between them. Magnetron discharge plasma provides increased ion density on the periphery of plasma anode formed by high-current Penning discharge ignited within several milliseconds after starting of the magnetron discharge. The increased on the periphery ion density improves the uniformity of high-current electron beam produced in such an electron gun.

1. Introduction

Low-energy (10-30 keV), high-current (10-25 kA) electron beams (LEHCEBs) are of great interest for material surface treatment and found already rather wide application in practice: increasing the corrosion resistance of metals and alloys, smoothing (polishing) of the surface, improvement the electric strength of vacuum insulation and so on [1, 2].

To produce LEHCEBs, the axis-symmetric electron guns with an explosive-emission cathode and plasma anode based on high-current Penning discharge are generally used [1-3]. One of the key parameter of LEHCEBs is their uniformity of energy density distribution via cross section and the requirements to the beam uniformity grow constantly. Multiple experiments have shown that to improve LEHCEB it is needed to increase ion density on the periphery of plasma anode in comparison with its near-axis region.

We suggest a new method for producing of plasma anode with such profile of ion density. For this purpose, we install a planar magnetron inside the cathode assembly. Planar magnetron produces an annular plasma column as well as a flux of neutrals due to cathode sputtering. At further ignition of high-current Penning discharge, the ion density at the periphery of plasma anode becomes higher than in the central region. Besides, we expected that magnetron discharge plasma will improve the stability of cathode emission. The present paper describes the developed high-current electron gun with explosive-emission cathode integrated with planar pulsed powered magnetron.

2. Description of electron gun

Principal design of electron gun is given in Fig. 1. Planar magnetron consists of two permanent magnets (disc 1 and ring 2) and magnetic circuit 3 and is placed just behind the cathode substrate 5. Magnets produce an arched magnetic field 4 over the cathode surface. Such magnetic field localize plasma of magnetron discharge mainly in the vicinity of magnetic field maximum. Thus, plasma cloud



acquires a ring shape occupying the periphery region over the cathode surface. The cathode disc substrate 5 is manufactured from stainless steel, on which the emitters 3 made of copper wires with 1 mm diameter and 15 mm height are regularly installed with the step of 3 mm.

The principal problem of the operability of the suggested scheme is the difference in working gas (argon) pressure required for magnetron discharge operation and for production of LEHCEB. For ignition of the magnetron discharge, the pressure of 1.5×10^{-3} Torr or higher is required (at the 1-kV of triggering pulse and 500–600 Gs of magnetic field induction on the cathode surface). But for LEHCEB production, the pressure should be about three times lower. The are, at least, two ways how to solve this problem:

1. It is possible to decrease the working gas pressure threshold needed for magnetron discharge ignition if increase the magnetic field induction near the cathode surface. In our case, it was provided by decreasing of the cathode substrate to 1–2 mm instead of standard 4–5 mm. The pulsed mode of magnetron discharge excludes water cooling of the cathode substrate and allows one to decrease its thickness.

2. The amplitude of the triggering voltage pulse was increased from standard 800–1000 V to 3 kV.

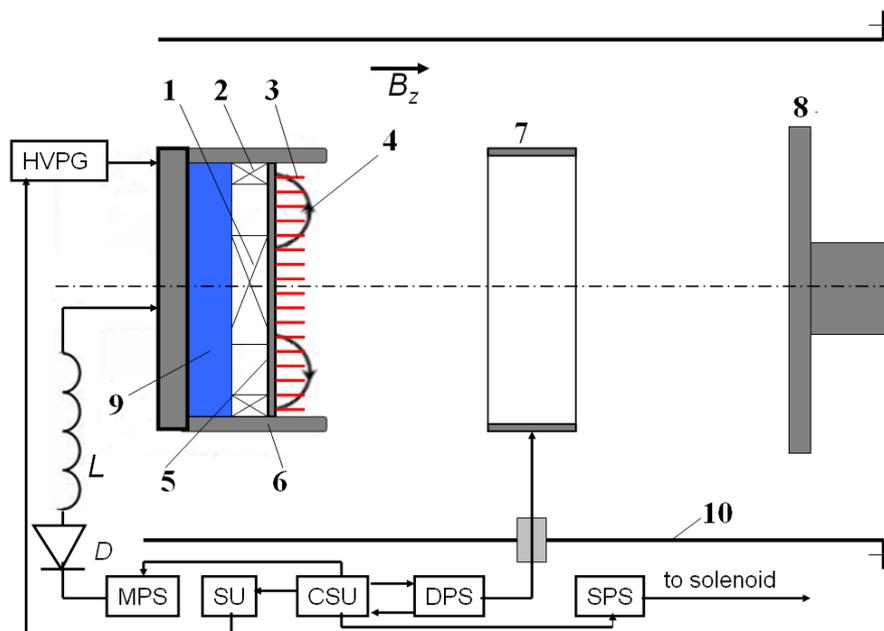


Figure 1. The block-diagram of LEHCEB source. 1 and 2 – permanent magnets; 3 – copper emitters; 4 – magnetic field lines B_z ; 5 – cathode substrate; 6 – body of the cathode assembly; 7 – anode of reflective discharge; 8 – collector of electron beam; 9 – magnetic circuit; 10 – body of electron gun; HVPG – high-voltage pulsed generator; MPS – magnetron power supply; SU – starting unit of HVPG; CSU – control and synchronization unit; DPS – discharge (reflective) power supply; SPS – solenoid power supply; D – diode assembly; L – protective inductance.

After several milliseconds from the starting of magnetron discharge with the current of 1–5 A, the processes in electron gun will develop in traditional way [1]. Pulsed powered solenoid produces longitudinal guide (for further produced LEHCEB) magnetic field B_z , and then with the delay of several milliseconds else (when it reaches the value of $B_z \approx 500\text{--}1500$ Gs), 5-kV positive voltage pulse is applied to the anode 7 and Penning (reflective) discharge starts. The grounded collector 8 and explosive-emissive cathode serve as the cathodes of reflective discharge (RD). After RD transits to high-current stage (discharge current up to 200 A), a cylindrical column with characteristic density of $(2\text{--}5) \times 10^{12} \text{ cm}^{-3}$ is formed between the cathode and collector. After formation of this column (plasma

anode), an acceleration voltage pulse with an amplitude of 15–30 kV and 10–50 ns rise time is applied to the cathode. Electric field is concentrated in a narrow near-cathode layer and achieves significant values (up to 300–400 kV/cm). The electric field is amplified on the tips of emitters, and explosive-emission centers (dense plasma clouds or cathode spots) appear quickly (within several ns or tens of ns). Plasma anode ions bombardment of the emitters stimulate their operation. After the cathode spots appeared, acceleration voltage is concentrated in a double layer between the cathode and anode plasmas. Electrons emitted by cathode plasma are accelerated in double layer and transported through anode plasma onto the collector in a guide magnetic field B_z . Due to charge neutralization of the beam, it is transported practically without the loss of current. The loss of kinetic energy of the beam electrons is also negligible [4].

The time of RD transition into high-current stage makes up usually tens of microseconds, but at the presence of magnetron discharge plasma this time decreases several times because of quick inclusion of the electrons of this plasma into the process of ionization of the working gas. Since these electrons are located in the peripheral part of plasma column, so the degree of ionization and ion density are expected to be higher just in this region. Finally, just such an increase of the ion density is desirable for improvement the LEHCEB uniformity [4].

In order to transverse magnetic field of the permanent magnets do not hinder RD operation as well as LEHCEB formation, the emitters have the height of 15 mm. Since the induction B_r falls dramatically with the distance from the cathode surface, so at the tips of emitters B_r does not exceed 50–70 Gs and does not distort the guide magnetic field B_z , therefore RD and beam formation are running without problem.

To prevent MPS from over voltage, the inductance coil $L \approx 500 \mu\text{H}$ is installed (Fig. 1). An additional and very important protection is provided by the diode assembly D , consisting of 50 diodes HER308 (1000 V, 3 A, time of recovery 100 ns) connected in series.

Acceleration voltage pulse is measured by resistive divider, cathode current and beam current onto collector are measured by wide-band Rogowsky coils.

LEHCEB's energy density is measured with the use of thermal imager TESTO 875-1. At these measurements, 200- μm stainless steel foil serves as the beam collector. At energy density of 3–10 J/cm², such a foil is heated by tens of degree Centigrade per pulse and this heating which reflects beam energy density distribution is panoramically measured through an infrared window. Characteristic spatial resolution of such a method is defined by the pause between the beam pulse and the moment of thermogram fixing. This time makes up about 1 s which corresponds to spatial resolution about 2–3 mm.

Fig. 2 presents typical waveforms of the pulses, and Fig. 3 presents a temporal diagram of the processes. The consequence of the processes in time and time delays t_1 , t_2 , t_3 are regulated by control and synchronization unit.

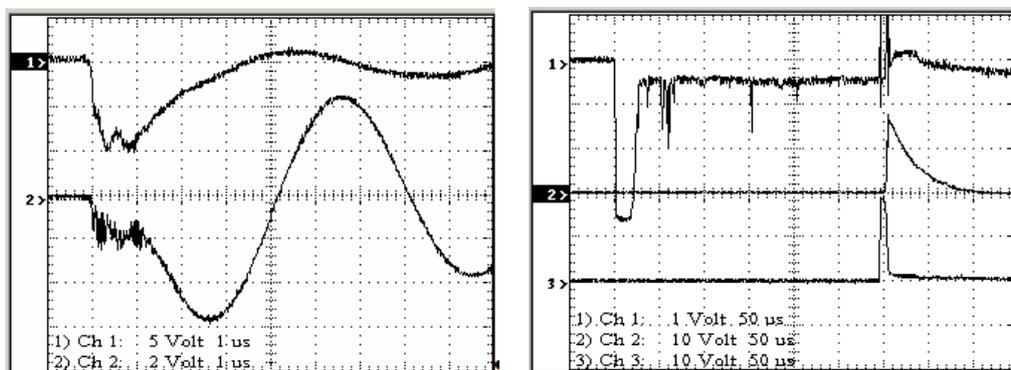


Figure 2. Typical waveforms. (a): acceleration voltage (Ch1, 10 kV/div); cathode current (Ch2, 12 kA/div); (b): magnetron discharge burning voltage (Ch1, 320 V/div), RD current (Ch2, 80 A/div); RD burning voltage (Ch3, 2 kV/div).

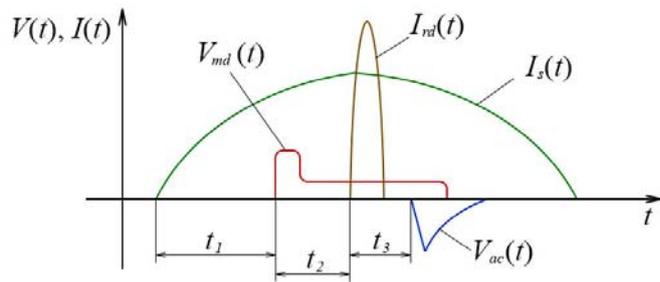


Figure 3. Temporal diagram of the processes in electron gun. $I_s(t)$ is solenoid current, $I_{rd}(t)$ is RD current, $V_{md}(t)$ is magnetron discharge burning voltage, $V_{ac}(t)$ is acceleration voltage of electron gun.

Fig.4 presents a thermogram and corresponding energy density distribution via beam cross section. It can be seen that non-uniformity in the central part of 4.5 cm in diameter does not exceed $\pm 10\%$.

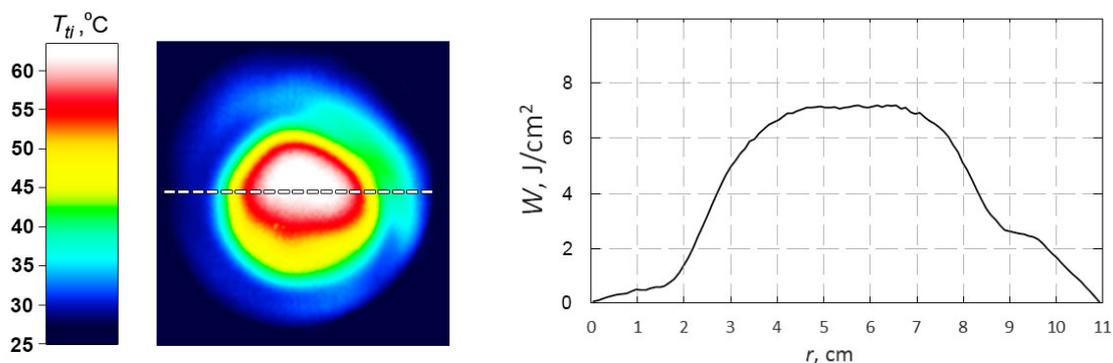


Figure 4. Thermogram and corresponding energy density distribution via beam cross section (along the dashed line). Charge voltage of HVPG is 25 kV, the distance between the cathode and the collector is 20 cm, argon pressure is 0.5 mTorr.

3. Summary

The new high-current electron gun, in which plasma anode is formed with the use of hybrid discharge matching pulsed magnetron and reflective (Penning) discharge, has been developed and tested. The suggested scheme of high-current electron beam production looks promising from the point of view of the beam uniformity and stability.

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