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GENERATION AND TRANSPORTATION OF LOW-ENERGY, HIGH-CURRENT ELECTRON BEAMS

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Abstract

Experimental data on the production of low-energy, high-current electron beams in a plasma-filled diode are presented. The highest beam energy density achieved is $\simeq$ 40 J/cm^2, which makes it possible to treat materials in the mode of intense evaporation of the surface layer. It has been shown that the use of a hollow cathode permits of improved beam homogeneity. The feasibility of the production of low-energy high-current electron beams in a gun with plasma anode based on the use of reflective discharge has been demonstrated.

Introduction

The low-energy (10–40 keV), high-current electron beams (LEHCEBs) of microsecond duration are of great interest of surface modification studies and applications [1, 2]. For the production of the LEHCEBs explosive-emission-cathode plasma-filled diodes hold much promise. The plasma-filled systems are distinguished, compared to vacuum systems, by the high perveance of the electron flow, by the feasibility of microsecond pulses of the electron beam, and by some technological advantages [3–5]. However, the techniques for the production of LEHCEBs of high current density ($10^2 - 10^3$ A/cm^2) especially for their generation and transportation, have not been adequately investigated, first of all, from the viewpoint of providing the electron beam homogeneity acceptable for technological use. The present study is an extension of our previous investigations in this area.

The experimental setup and results

We explain the principle of the LECHEB generation in a plasma-filled system by the example of an electron gun developed by us a few years ago [3–5].

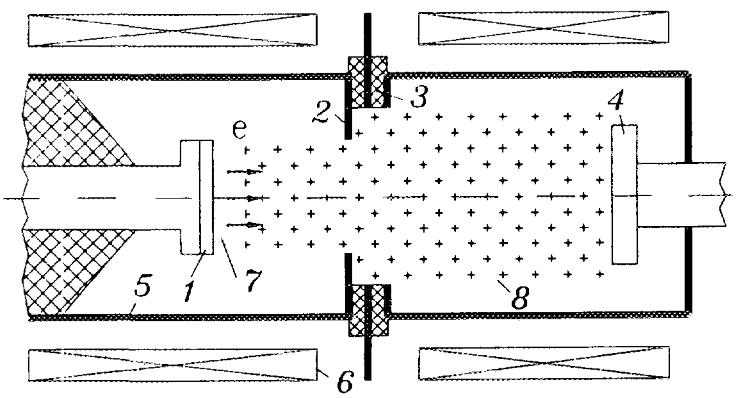

Fig. 1. Block diagram of the electron gun. 1 – cathode; 2 – anode; 3 – arc plasma sources; 4 – collector; 5 – vacuum chamber; 6 – solenoid; 7 – cathode plasma; 8 – anode plasma.

The block diagram of the electron gun is given in Fig. 1. The anode plasma generated by 12 arc sources arranged in a circle around the hole in the anode electrode preliminarily fills the acceleration gap and the beam drift space. The plasma density n_p, and the electron temperature are typically $10^{11} - 10^{12}$ cm^{-3} and $1 - 3$ eV, respectively [5]. After a time $t_d \simeq 2 - 5$ μs, an accelerating voltage pulse is applied to the cathode. Owing to its good conductivity, the anode plasma acquires the potential of the anode, and the effective gap in the diode shortens. Thus the electric field is localized in near-cathode layer of the ion space charge whose thickness ($\sim 1-2$ mm) is much smaller than the cathode and anode separation ($2-5$ cm). The explosive electron emission initiated at the cathode results in the formation of dense plasma blobs that coalesce (in 10^{-7} s) into a continuous emitting surface. The electron beam is generated in the double layer between the cathode and the anode plasmas across which the voltage applied to the diode is localized. Having passed through the hole in the anode electrode, the beam is transported in the plasma to the collector on which the specimen or workpiece to be irradiated can be placed. To prevent the beam from pinching, a guide magnetic field of strength up to 5 kOe is applied.

Increasing the beam energy content and improvement of the electron flow uniformity. Our former LEHCEBs [3–5] were capable of producing electron beams with an energy density W below 10 J/cm^2, which permitted treating materials in the mode of melting or initial evaporation of the surface layer. For the evaporation to be intense, it is necessary to increase W to $15-30$ J/cm^2 or even to higher values. To realize this mode, we have developed and built a higher-power voltage generator with a substantially lower impedance of the discharge circuit and a $1.5-2$ times higher density of the anode plasma. These and some other measures have enabled us to produce LEHCEBs with an energy density of up to 40 J/cm^2, a pulse duration of $2-4$ μs, and a beam current of up to 50 kA.

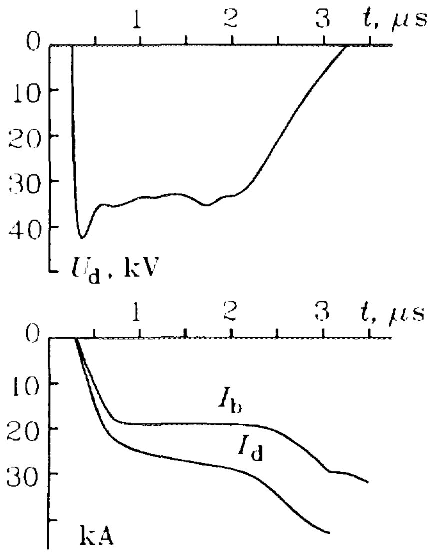

Fig 2. Typical waveforms of the diode voltage U_d, the diode current I_d, and the beam current I_b. Charge voltage of the pulse generator $U_c = 40$ kV; $H_z = 3$ kOe; cathode diameter – 6 cm.

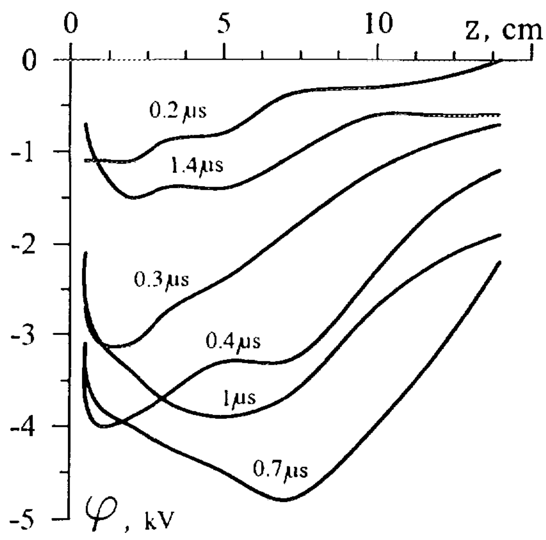

Fig. 3. Dynamics of potential "well" in the drift space. z – distance from the collector, $U_c = 20$ kV.

Figure 2 presents typical waveforms of the voltage across the diode, the diode current, and the beam current onto the collector. As can be seen from the waveforms, the density of the electrons injected into the anode plasma, n_b, increases in fact throughout the pulse. Starting from a certain point in time, n_b becomes higher than n_p, and in the drift space an unneutralized space charge of electrons appears that creates both an axial and a radial electric fields. We directly observed the presence of a potential "well" in the beam with the use of a floating probe introduced into the beam along its radius. The typical time behavior of the potential "well" is illustrated by Fig. 3. It should be noted that the reduction of the potential sag, starting from a certain point in time ($t > 0.7$ μs), promotes penetration of the collector plasma ions into the diode since for an ion decelerating electric field appears to be lower than the accelerating electric field. The ions of the anode plasma as well as of the collector plasma that appears after a time are accumulated within the pulse, under the action of the radial electric field in the near-axis region of the beam. With that, the collector plasma ions may penetrate into the diode thereby increasing the current density in the double layer. In the end, the energy (current) density in the near-axis region of the beam becomes higher than in the peripheral regions, even if the energy density distribution over the beam cross section was uniform energy early in the pulse.

The undesirable effect of the accumulation of ions in the center of the beam can be compensated by reducing artificially the electron current density in this region of the beam during its generation in the double layer. This can be done, for instance, by properly choosing the cathode shape. Figure 4 gives typical energy density distributions, $W(r)$, for a plane cathode and for a hollow cathode. It can clearly be seen that the $W(r)$ distribution for the hollow cathode is substantially more uniform than that for the plane cathode, although the pulse-integrated beam energy is somewhat lower. This difference in the form of the $W(r)$ curves is related, in our opinion, to the fact that the density of the anode plasma that preliminarily fills the diode falls with distance from the plane where the spark sources are placed [5]. Hence initially the current density will be lower in the near-axis region of the beam formed in the cathode cavity than in its peripheral regions and this in the end will reduce the density of the ion accumulated in the center of the beam. Curiously, in the experiment whose results are illustrated by Fig. 4 a decrease in n_p in the beam center only by 10–15 % compared to that in the peripheral regions results in a decrease in energy by a factor of 1.5 – 1.7.

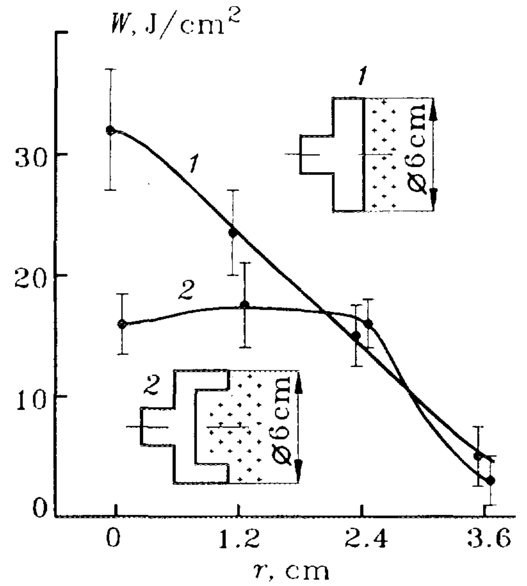

Fig. 4. Cross-sectional energy density distribution of the beam for two types of the cathode: 1 – plane cathode; 2 – hollow cathode.

<u>**Use of a reflective discharge to create a plasma anode.**</u> To produce a plasma anode in the electron guns developed up to now, the erosion plasma of a vacuum arc was used. Obviously, this plasma used for the above purpose has some disadvantages. The erosion products may pollute the surface layer of the material under treatment. The parameters of erosion plasmas are not so reproducible as those of gas-discharge plasmas because of the non-steady-state nature of the electrode erosion in arc. When there is a need to produce a long plasma channel, it is necessary to place additional arc plasma sources in the drift space, which reduces the reliability of operation and complicates the design of the electron gun. Furthermore, the energy required to generate the anode plasma is rather high since the total current the arc plasma sources is generally comparable to the diode current [4, 5], although only the ion component of the anode plasma is used in the beam generation. It is also important that for a plasma column produced in a reflective discharge the plasma density distribution in radius can be made highly uniform [6].

We pioneered in developing an electron gun with the anode plasma generated by a pulse reflective (Penning) discharge (Fig. 5). The cathodes of the Penning discharge are the beam collector and the explosive-emission cathode of the gun. The gas (argon) pressure was $(4 - 10) \times 10^{-4}$ Torr. The discharge was powered from a 0.5 μF capacitor charged to 4 – 5 kV. The discharge current was 40 – 80 A.

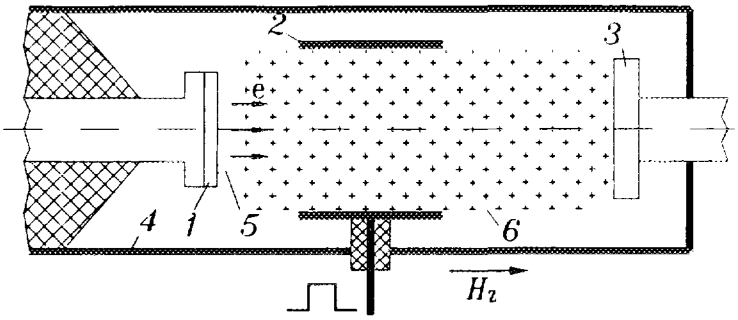

Fig. 5. Block diagram of the electron gun. 1 – cathode; 2 – Penning anode; 3 – collector; 4 – vacuum chamber; 5 – cathode plasma; 6 – anode plasma.

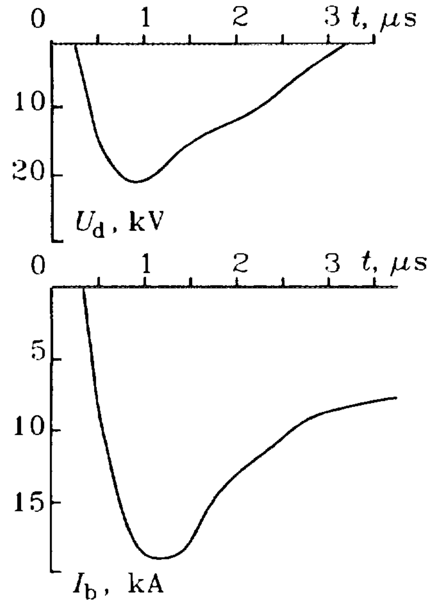

Fig. 6. Typical waveforms of the diode voltage U_d and the beam current I_b (U_c = 30 kV, H_z = 2.4 kOe).

From the waveforms of the discharge current and the discharge gap voltage we found the time delay to the initiation of the discharge as a function of gas pressure. The values of this time were then used to bring the instant of application of the acceleration voltage to the cathode into step with the discharge operation. Figure 6 gives typical waveforms of the diode voltage and the beam current onto collector. It can be seen that the current onto collector reached 19 kA. The total beam energy was about 200 J for a beam diameter of 8 cm.

Summary

1. The LEHCEB parameters achieved ($\sim$ 40 J/cm^2) make it possible to treat materials not only in the surface melting mode but also in the mode of intense evaporation of the surface layer.

2. The unneutralized negative space charge appearing in the drift space gives rise to accumulation of ions in the near-axis region of the beam. This in turn causes an increase in beam energy density in this region. Using a hollow cathode improves the uniformity of the beam energy density cross-sectional distribution.

3. It has been demonstrated that the generation of an LEHCEB in a plasma-anode system whose operation is based on a reflective discharge is quite feasible.

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