The influences of reflected electrons on the REB potential and on the energy distribution function of the REB electrons

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Abstract. In plasma microwave oscillators, electrons fall onto the surface of a collector, which leads to the generation of secondary electrons. The influence of the electrons reflected from the collector on the parameters of a high-current relativistic electron beam propagating in a strong longitudinal magnetic field was studied experimentally. It is shown that the penetration of the reflected electrons into the drift space can lead to a substantial increase in the depth of the potential well in the drift space, a decrease in the velocity of the beam electrons and a broadening of the electron energy distribution function.

INTRODUCTION

The efficiency of a microwave device depends largely on the quality of an electron beam. The high efficiency can be achieved by using a monoenergetic beam with a small angular spread in velocity space. It is also important that the beam potential related to the beam space charge be low. For this reason, thin-walled annular high-current relativistic electron beams (REBs) in a strong uniform magnetic field are usually used in relativistic microwave electronics. It is well known that, when the beam electrons fall onto the collector, they cause secondary electron emission. Since the beam potential in all relativistic microwave electronics devices is higher than 1 kV, original secondary electrons (with energies lower than 50 eV) do not affect the REB parameters. In contrast, the electrons that undergo elastic or inelastic reflections can penetrate into the drift space of the beam. The influence of the reflected electrons on the parameters of a high-current REB was studied in [1, 2, 3]. In [2], an REB was investigated in the absence of a magnetic field.

In the present study, the influence of the reflected electrons on the beam parameters is investigated at beam currents from I_0 to $0.45I_0$ (fixed current $0.65I_0$ in [1]), were I_0 is the limiting current in a vacuum [4]. It is shown that the influence of the reflected electrons is higher at low beam currents. The experimental results are compared with numerical simulations.

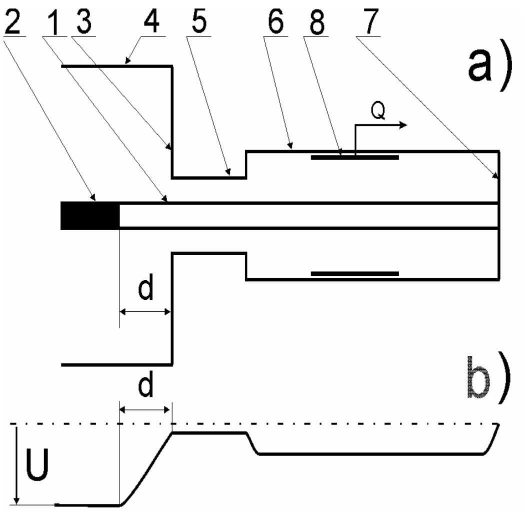

FIGURE 1 (a) Schematic of the experimental setup: (1) REB, (2) cathode, (3) anode plane, (4) anode tube, (5) transition tube, (6) drift tube, (7) collector, and (8) beam space charge meter, and (b) the REB potential profile along the system axis.

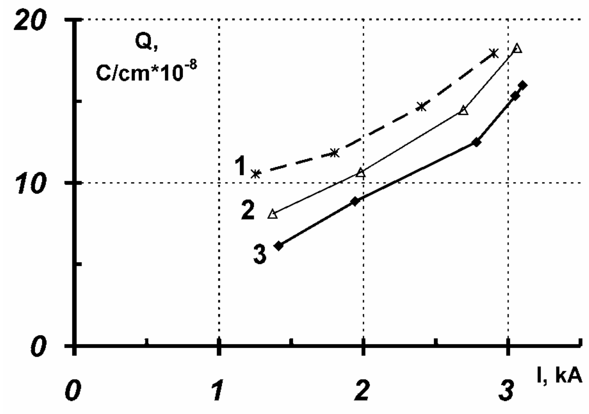

FIGURE 2 Measured dependences of the beam space charge per unit length on the beam current for different collector materials: 1— tungsten, 2— stainless steel, and 3— graphite.

EXPERIMENT

A schematic of the experimental setup is shown in Fig. 1. Thin-walled electron beam 1 was formed at cylindrical explosive-emission cathode 2 with a radius of $r_2 = 0.5$ cm and propagated in a uniform magnetic field of B = 1.5 T along the axis of the vacuum chamber. The metal vacuum chamber consisted of anode tube 4, transition tube 5, and drift tube 6, whose radii satisfied the inequalities $r_4 > r_6 > r_5$ ($r_4 = 5.6$ cm, $r_5 = 0.7$ cm, and $r_6 = 1$ cm). The beam electrons arrived at collector 7. The experiments were performed with three types of collectors made of different materials: graphite, stainless steel, and tungsten. The voltage pulse with an amplitude of 540 kV and a full width at half-maximum of 35 ns was applied to the accelerator cathode. The beam current was varied by varying the distance d between cathode 2 and anode plane 3. When the condition $d \gg r_4 - r_2$ is satisfied, the beam current is limited by the beam space charge in tube 4. It is usually referred to as the limiting current of a coaxial magnetically insulated diode I_m [5]. In tubes 5 and 6, the external electric field is low (Figure 1b); therefore, the beam potential is primarily determined by the field of the beam space charge. As the gap d decreases, the current injected in tube 5 increases; however, the current cannot exceed the vacuum limiting current I_0 [4] for drift tube 6.

In our experiments three parameters were measured: the beam space charge in the central part of the drift tube (measured by capacitive divider 8 (see Fig. 1), the REB current to the collector 7, the cathode 2 potential.

RESULTS AND ITS COMPARISON WITH SIMULATIONS

Figure 2 shows the beam space charge as a function of beam current at the collector. One can see that, when graphite is replaced with tungsten, the increase in the flux of reflected electrons leads to an increase in the beam space charge. This effect is the most pronounced at low currents, then Q_w exceeds Q_c by 45%. When the current is close to the limiting value then the difference is 25%. Here Q_w and Q_c are the beam charge densities per unit length for collectors made of tungsten and graphite, respectively.

The electrons reflected from the collector can penetrate into the diode; as a result, the beam space charge increases. The influence of the reflected electrons on the beam space charge should be more pronounced at low beam currents. The point is that, at a high beam current equal to I_0, the beam potential in the drift tube Φ_0 is close to the cathode potential. According to $\Phi_0 = -511(\gamma - \gamma^{1/3})$, this potential is equal to –400 kV when the cathode potential is –540 kV. Therefore, only a small fraction of the reflected electrons (with energies above 400 keV and escape from the collector at small angles to the tube axis) can enter the drift tube. When the beam current is low, the potential in the drift tube is low and the fraction of the reflected electrons that can enter the drift tube increases. Figure 2 shows the results obtained with a stain-less-steel collector. Since the reflection coefficient for iron is smaller than for tungsten and is larger than for carbon, the curves for stainless steel lie between the curves for tungsten and graphite.

Let us compare the experimental dependences of the beam current to those calculated for graphite and tungsten (see Fig. 3) [6]. Numerical simulations were performed using KARAT particle-in-cell electromagnetic code [7]. For graphite, the measured and calculated values of the space charge are different by 10% (Fig. 3), for tungsten the difference is up to 20%. Thus, the simulations agree with the experimental dependences of the beam space charge on beam current and on the collector material.

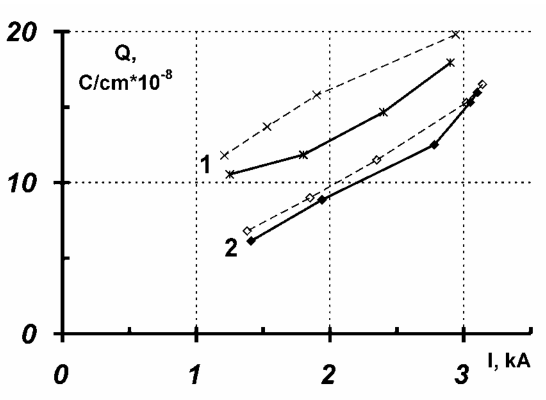

FIGURE 3 Comparison of the measured (solid lines) and calculated (dashed lines) dependences: 1— tungsten, 2— graphite

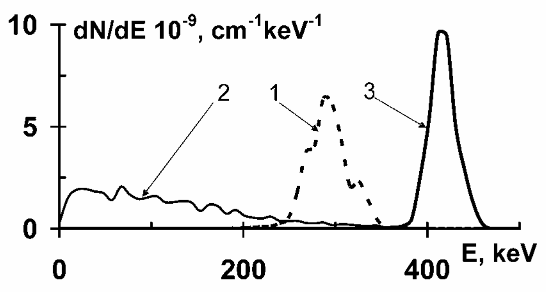

FIGURE 4 Calculated energy distribution functions of the electron density per unit length for a tungsten collector: (1) primary electrons and (2) reflected electrons. curves (3) show the electron energy distribution functions in the absence of reflected electrons.

The penetration of the reflected electrons to the drift space leads not only to a decrease in the average kinetic energy of the beam electrons, but also to a significant broadening of their energy distribution function (Fig. 4). The broadening of the energy distribution function in the presence of reflected electrons can be attributed to the onset of electron two-stream instability.

The present study has demonstrated that, in principle, the reflected electrons can catastrophically deteriorate the beam parameters. The adverse effect of the reflected electrons on the operation of relativistic microwave devices was described, e.g., in [8, 9]. Note that, in [8], a method for completely eliminating the penetration of the electrons actual microwave devices significantly complicates their design. For this reason, in existing vacuum microwave sources, the side wall of the metal cylindrical chamber that is situated in a weaker magnetic field serves as a beam collector. In plasma microwave oscillators [10], electrons are incident normally onto the graphite collector surface. Therefore, measurements and simulations similar to those described in our paper would be of interest for any study on relativistic microwave electronics.

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