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Power of Microwave Generation in an Ultrarelativistic Electron Beam in the Regime of Virtual Cathode Formation in an Externally Applied Magnetic Field

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Abstract—A numerical study of the output power characteristics of microwave radiation from a relativistic electron beam (REB) with a virtual cathode in the presence of externally applied longitudinal magnetic field is performed. Typical dependences of the output microwave power of the relativistic vircator system on the external magnetic field strength are obtained, showing a number of local maxima. It is found that the characteristic behavior of the radiation power is determined by the conditions and mechanisms of virtual cathode formation in the presence of external longitudinal magnetic field and a self-magnetic REB field.

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INTRODUCTION

Recent investigations of the progression of nonlinear microwave oscillations, the formation of structures, and the establishing of complex generation regimes in active electron-wave systems with intense relativistic electron beams under regimes of virtual cathode formation have attracted much attention in the scientific community [1–3]. On the one hand, this attention is explained by the fundamental significance of such investigations [4]. On the other hand, intense relativistic electron beams are widely used in a number of practical applications, e.g., in plasma heating, in nuclear synthesis with inertial plasma containment, in ion acceleration systems, and in the generation of high-power microwave radiation. Generators employing relativistic electron beams with VCs (virtual cathodes) hold particular promise as devices for high-power microwave electronics, due to their unique properties (high output radiation power, simple design, ease of frequency, and generation regime tuning) [1, 2].

It was shown in a number of studies [5–11] that the dependence of vircator output power on different system parameters (particularly its external magnetic field (MF)) displays complex behavior. In [6], an experimental investigation of vircator microwave radiation output power as a function of external MF revealed oscillating behavior with 2–3 peaks in amplitude that diminished with the MF. It was also shown that at high strengths of an external MF, the output power of the relativistic vircator asymptotically approaches a relatively low constant value. Similar results were obtained in other studies [5–8, 10]. However, the physical influences behind vircator output power are remain unknown; an important problem in researching systems with VC is therefore analyzing the behavior of output power generated by relativistic vircators as a function of and external MF and investigating the underlying physical processes.

Note that in researching systems with REB, it is necessary to consider effects that are unimportant with respect to weak relativistic beams. In particular, the self-magnetic fields in REBs cannot be ignored, as they greatly influence the processes in the system. Considering self-magnetic fields requires the use of essentially three-dimensional self-consistent electromagnetic models of REB dynamics at supercritical currents. This work is a numerical, three-dimensional, completely electromagnetic study of the output microwave radiation from a relativistic system with a pipe-shaped REB in an externally applied uniform longitudinal MF of finite strength. We also analyze the physical causes of its observed behavior.

INVESTIGATED SYSTEM AND NUMERICAL MODEL

The investigated system was a classical model used in studies of VC dynamics [3]. The electron beam drift space is a closed section of a cylindrical waveguide with length L and radius R, closed at the ends with net-shaped electrodes. An axially symmetric pipe-shaped relativistic mono-energetic electron beam (radius, R_b; thickness, d; energy W_e; current upon entry, I) is injected into an interaction space through the left (input) net and let out through the right (output) net and can also be deposited on the lateral walls of the interaction space. The geometric parameters used in

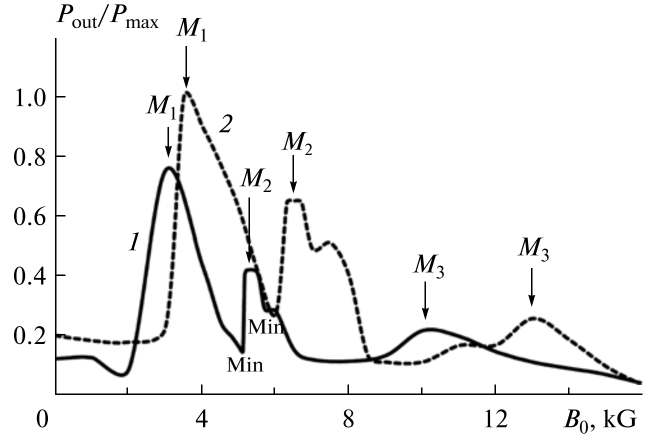


Fig. 1. Dependences of the normalized output power of radiation from REBs with VCs on the induction of external magnetic field B_0 at the following values of initial beam energy W_e: 600 keV (curve *1*) and 850 keV (curve *2*). Beam current, I = 20 kA; symbols M_1, M_2, and M_3 denote the local maxima of the dependences.

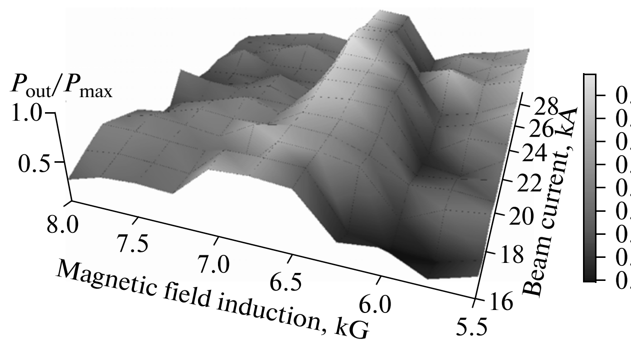


Fig. 2. Dependences of the normalized output power of radiation from REBs with VCs on the induction of an external magnetic field and beam current. W_e = 850 keV.

this work were L = 40 mm, R = 10 mm, R_b = 5 mm, and d = 2 mm. A uniform external focusing MF of induction B_0 is applied along the system axis. Energy is put out from the region of REB and VC interaction with a coaxial line. A three-dimensional model based on numerical solutions for a self-consistent system of Maxwell's equations and equations for charged particle movement was used for numerical modeling of the nonstationary processes in a relativistic beam of charged particles [3, 12].

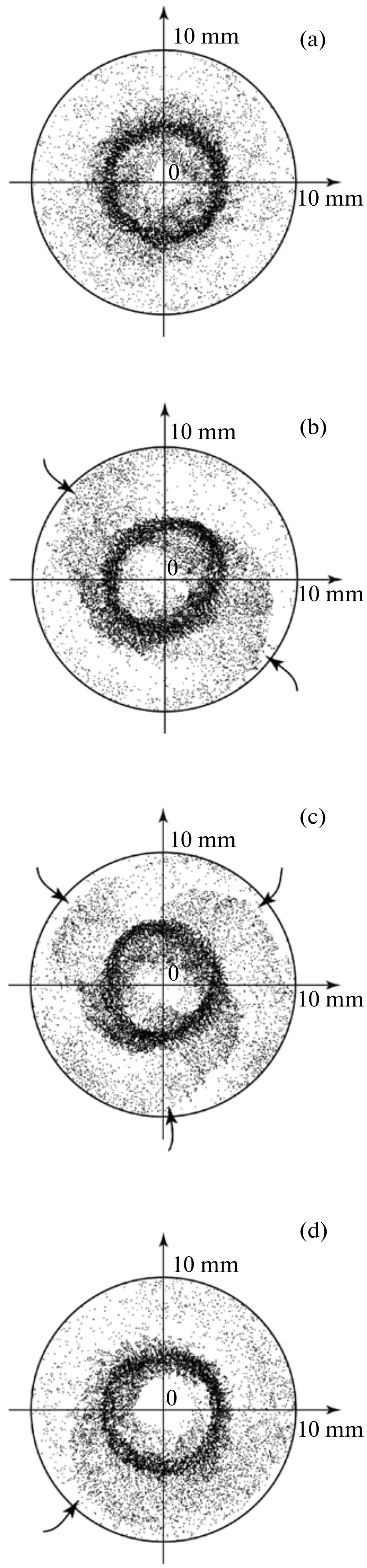
SYSTEM DYNAMICS

Figure 1 shows the dependences of the normalized output power of radiation from an REB with VC on external MF induction $P_{out}(B_0)$, obtained by numerical modeling for two values of initial beam energy W_e. It can be seen that the curves in this figure have similar characteristic features: the presence of three local maxima (denoted M_1, M_2, and M_3 in Fig. 1) against backgrounds of monotonically decreasing output power with increasing MF.

The physical process responsible for this behavior of the output power were analyzed using the results from studies in [3] of the conditions of VC formation (critical beam current values) as a function of the external MF strength. We recall that a nonstationary VC forms in a beam when its current exceeds a critical value [1–4]. In [3], it was established that the dependence of the critical REB current on the induction of external longitudinal MF $I_{cr}(B_0)$ has a characteristic shape with a maximum and several local minima, attributed to the formation of turbulent electron structures in REBs due to the so-called azimuthal instability of a beam under the influence of external and self-magnetic fields [3]. A comparison of dependences $I_{cr}(B_0)$ and $P_{out}(B_0)$ showed that the behavior of REB radiation output power is determined by the complex behavior of the critical beam currents upon variation in the external MF, and by features of VC formation in a system at different external MF intensities.

It can be seen that the first pronounced local minimum in the $P_{out}(B_0)$ dependence (minima are denoted as "Min" in Fig. 1) appears at induction values of the external MF where the corresponding $I_{cr}(B_0)$ dependence has its maximum. When the critical beam current attains its maximum value, the supercriticality of the considered system in terms of current $(I - I_{cr}(B_0))$ at fixed REB current I = 20 kA turns out to be minimal; the output power, which is proportional to supercriticality, consequently has a minimum value as well. Similarly, the maxima of the $P_{out}(B_0)$ dependence coincide with the minima of $I_{cr}(B_0)$. The current and induction of an external MF at which dependence $I_{cr}(B_0)$ attains its first local minimum, correspond to coordinates of first maximum M_1 in dependence $P_{out}(B_0)$ (Fig. 1). The VC structure is most developed at this value of MF induction. The external MF strength at which the critical current dependence reaches saturation is determined by the position of M_3, the third maximum in the dependence of output power on MF induction (Fig. 1). The output power's tendency to fall with rising external MF strength (leading in particular to the formation of third maximum M_3) is due to limiting the electron beam transverse dynamics by raising the external MF's strength, lowering the intensity of BC interaction with electromagnetic fields [13].

To find the reasons for the emergence of second maximum M_2 in dependence $P_{out}(B_0)$ (Fig. 1), we consider a typical dependence of REB output radiation on external MF induction and beam current $P_{out}(B_0, I)$ (Fig. 2) at a beam energy of W_e = 850 keV. It can be seen that the surface in Fig. 2 has a peak region extending along the current axis (the light grey area in Fig. 2), where the output power reaches its maximum values. The coordinate of this region along the MF induction axis ($B_0 \sim 6$–7 kG) is virtually independent



of the beam current and corresponds to the optimum external MF strength at which an REB with BC radiates a microwave signal of locally maximum power. The coordinate of second maximum M_2 in dependence $P_{out}(B_0)$ at energy W_e =850 keV (Fig. 2, curve *2*) corresponds to the optimum external MF strength, so the output power has a local maximum at this MF.

Let us consider the evolution of REB dynamics in the regime of VC formation in a changing external MF and establish its relationship to characteristics of the output power's behavior. Figures 3a–3d show the characteristic phase patterns of an electron beam as projections of the instantaneous positions of large beam particles (black dots in the figures) on cutting transverse plane (r, θ) at a beam current of I = 20 kA and different characteristic values of external MF induction B_0. Figure 3a corresponding to a weak external MF shows the virtually uniform distribution of the beam in the azimuthal direction. As MF induction rises, turbulent electron structures begin to form in the REB, due to the development of azimuthal beam instability [3]. Double (Fig. 3b), triple (Fig. 3c), or single (Fig. 3d) turbulent electron structures thus form in an REB with an external MF lower than a certain threshold value (9 kG for the case shown in Fig. 3). The azimuthal instability and transverse dynamics of an REB are suppressed by a strong external MF, $B_0 > 9$ kG; therefore, turbulent electron structures do not form in a system in such an MF.

From our analysis of Fig. 3, it follows that an external MF in the range of 0 to 9 kG determines the structure of the electron turbulence in the structure (compare Figs. 3a–3d). This could explain the existence of an optimum external MF value at which the output power assumes a local maximum value (peak M_2 in Fig. 1). It was found that the efficiency of REB and VC interaction with electromagnetic fields and thus the output power is higher when an electron beam is not heterogeneous in the azimuthal direction. Indeed, the case in Fig. 3a, where the REB has the most homogeneous structure in the azimuthal direction, corresponds to the maximum output power (peak M_1 in Fig. 1, curve *2*). Peak M_2 is observed at the external MF strength at which a triple turbulent electron structure forms in the system (Fig. 3c). This system is less homogeneous in the azimuthal direction than the one presented in Fig. 3a; therefore, peak M_2 is lower than M_1. The least homogeneous dynamics in the azimuthal direction are observed with the external magnetic fields corresponding to Figs. 3b and 3d displaying

Fig. 3. Projections of the instantaneous positions of large particles of the electron beam on cutting plane (r, θ) at B_0 = 3.5 kG (a), B_0 = 6 kG (b), B_0 = 6.5 kG (c), and B_0 = 9 kG (d); I = 20 kA; W_e = 850 keV; the longitudinal coordinate of the cutting plane z_s = 7 mm. Only those particles located beyond the cutting plane (with coordinates $z < z_s$) are shown; the arrows show the ends of turbulent electron structures forming in the REB.

double and single turbulent electron structures, respectively. As a result, the output power assumes minimum values that correspond to the local minima of dependence $P_{out}(B_0)$ to the left and right of peak M_2. Raising external MF $B_0 > 13$ kG does not increase the output power despite the suppression of azimuthal structure nonhomogeneity. This is a consequence of the reduced efficiency of interaction between the VC and electromagnetic fields in the electron beam, due to the restraining effect on REB transverse dynamics by the stronger external MF [13].

CONCLUSIONS

We have shown that in a relativistic vircator, the dependence of output power on the induction of a homogeneous longitudinal external magnetic field has a number of maxima. Characteristic features of output power behavior are determined by the conditions under which a virtual cathode forms under the effect of external and self-magnetic fields. Our results explain earlier experimental dependences of the output power generated by relativistic vircators on external magnetic field strength [6].

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