

Effect of Electron Beam Thickness Upon the Performance of a Resonant Type-O Carcinotron with a Tapered Magnetostatic Field

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Introduction.

Increasing the output power of vacuum electronic devices the millimeter waveband involves a series of technical problems, of which one is formation of compact electron beams with a high current density. The transverse dimensions of the beam are determined by the size of the electromagnetic system and the degree of microwave field localization near the surface of the slow wave structure (SWS).

At millimeter wavelengths an intense electron field interaction can be realized only within a narrow layer (less than the SWS-period) located close to the SWS-surface. This is the situation, where employment of more powerful (and, hence, thicker) beams to increase the efficiency of the electron-wave field interaction can only be advisable under the conditions of an intense energy exchange over the entire beam thickness. One of the possible ways for implementing such conditions is to taper the focusing field or change of its orientation [1-3]. In this connection, an analysis of the physical processes in the device, with several different beam thicknesses and a nonuniform magneto static field seems to be essential for working out practical recommendations that should allow increasing both the efficiency and out pup power of microwave generators and amplifiers.

In the present paper, we consider electronic devices employing strip beams, specifically, orotrons, diffracted radiation generators, resonant carcinotron, etc.

Initial relations.

The theoretical analysis proceeds from the nonlinear self-consistent set of equations to describe the electron wave field interaction within a two-dimensional model [4, 5]. The limiting cases are considered: these are the initial stage of self-excited oscillations and the steady-state generation which corresponds, respectively, to the maximum amplification and maximum power regimes. In the first case, the starting current of the generator, I_{st} , is the value to be calculated, while in the second it is the electron efficiency η . These parameters are connected to the slope of the amplitude of the generator oscillatory response as

$$I_{st} = (\alpha S_1(0))^{-1}; \quad \eta = F^2 S_1(F), \quad (1)$$

where F is the dimensionless oscillation amplitude and α a constant value associated with the interaction efficiency parameter [6].

The calculations were performed for spatial distributions of the focusing magnetic field of two kinds: first for the uniform field inclined to the SWS surface at an angle χ , and second for the non-uniform field with the components as follows:

$$B_y = 1 + A_m \exp\left[-((y - y_m)/(w_m L))^2\right], \quad (2)$$

$$B_z = \frac{2A_m}{(w_m L)^2} (y - y_m)(z - z_m) \exp\left[-((y - y_m)/(w_m L))^2\right]. \quad (3)$$

Here A_m, w_m, y_m are the amplitude, localization radius and coordinate of the magnetic nonuniformity center, respectively; the OY axis is parallel, while the OZ -axis perpendicular to the SWS surface; z_m is a constant magnitude characterizing the transverse distribution of the focusing field and L the length of the interaction space. The values B_y, B_z and A_m are normalized to the induction of the undisturbed magnetostatic field B_0 and w_m is normalized to the length L .

The structure of the spatial distribution of the focusing magnetic field is responsible for static electron trajectories and, thereby, can essentially affect the energy exchange process, both in the regime of maximum amplification and in the maximum power one. This fact is reflected in the oscillation characteristic $S_i(F)$ of the device, which has been calculated for two selected operation modes, i.e. linear and nonlinear.

Maximum amplification regime.

First, consider the starting characteristics, namely the starting current I_{st} , determining the electron-wave field interaction efficiency at the initial stage of the oscillation process for spatial distributions of the focusing field of two kinds. We assume the separation between the SWS surface and the beam to remain constant during variations of the electron beam thickness, Δ .

1. Tilted magnetic field [2]:

$$B_y = \cos \chi; \quad B_z = \sin \chi. \quad (4)$$

Fig.1 presents dependences of the dimensionless starting current, minimized over the generation band, upon the tilt angle χ of the uniform focusing field for several values of the parameter Δ/L ($\omega_c L/v_0 \gg 1$, where $\omega_c = eB_0/m$ is the cyclotron frequency and v_0 the initial longitudinal velocity of electrons). An increase of the beam thickness is accompanied by growth of the starting current, up to such values of the tilt angle χ for which the beam of thickness $\Delta/L = 0.005$ fully precipitates on the SWS. For thicker beams, precipitation of all the electrons on the SWS begins with greater tilt angles of the induction vector of the focusing field compared with the case $\Delta/L = 0.005$.

Thus, the familiar statement on the increase of the starting current with greater beam thicknesses is valid, in the case of a tilted focusing field, solely for that region of the angle χ where the electron precipitation at the SWS is absent or is inessential for relatively thin beams ($\Delta/L = 0.005$). In the case of $|\chi| > 40^\circ$ (Fig.1), the situation is possible where an increase of the beam thickness results in a reduced starting current of the generator. The cause for that is the electron precipitation which leads to shortening of the interaction length for thin beams and, as a result, to a considerable increase of their starting current at greater tilt angles of the focusing field, compared with the currents of thicker beams.

Along with the starting current, it might be useful to employ in the two-dimensional theory such a characteristic as the specific starting current per unit beam thickness, $I_b = I_{st}/\Delta$. This permits analyzing current density variations in the electron-wave system which is important from the practical point of view.

Dependences of the specific starting current on the magnetic field tilt angle χ are presented in Fig.2 several values of the beam thickness. An increase of Δ/L results in reduced values of I_b over the entire range of variation of χ . Consequently, to excite oscillations in a generator with the thicker beam, electron guns with lower current densities can be used.

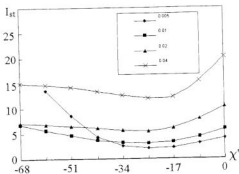


Fig.1. Dependences of the starting current upon magnetic field tilt angle for different magnitudes of the beam thickness.

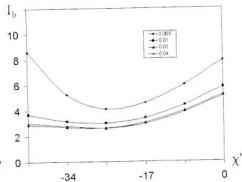


Fig.2. Dependences of the specific starting current upon the magnetic field tilt angle for the different values of the beam thickness.

The graphs of Fig.2 also suggest saturation of the specific starting current with the increase in the beam thickness. In the region of values $\Delta/L \geq 0.02$, the magnitude of I_b remains practically unchanged for all the angles χ considered (curves 3 and 4). This result follows from the inhomogeneity of the microwave field along the transverse (z) coordinate, as well as from the fact that further increase of the parameter Δ/L (above $\Delta/L = 0.02$) does not change the current distribution through the interaction space of the generator. It should be noted that, for the considered theoretical model of the device, the effect of specific starting current saturation permits determining the transverse dimensions of the beam-field interaction space beyond which the beam-field energy exchange can be neglected in the maximum amplification regime.

2. Nonuniform focusing field (2-3).

Fig.3 shows the $I_b(\xi_m)$ dependences for different values of the parameter A_m and $\Delta/L (A_m < 0)$. The specific starting current is saturated with increasing in the beam thickness in this case too, therefore the dependences have been constructed only for three values of $\Delta/L (\Delta/L = 0.005; 0.01; 0.02$ for curves 1, 2 and 3, respectively). When the magnetic inhomogeneity is weak (the electron precipitation is weak or absent, only quantitative variations in the dependences of the specific starting current upon the center coordinate of the magnetic inhomogeneity are observed (Fig.3.a). The major contribution to the electron-microwave field exchange is given by layers of the beam nearest to the SWS surface. In this situation, an increase of the parameter Δ/L can only result in changes in the number of charged particles within these layers through the length of the interaction space. In the case of a strong electron precipitation (Fig.3.b), an increase of the beam thickness is accompanied, along with a decrease of I_b , by an extended range of those values of ξ_m where the specific starting current of the generator with a nonuniform magnetic field is lower than in the generator with the conventional focusing (dotted lines, $A_m = 0$ and $\xi = 0$). Evidently, these features in the dependences upon ξ_m of the specific starting current are produced, in the case of a strongly inhomogeneous magnetic field, by changes in the current distribution in the interaction space. When a thin beam has precipitated nearly completely, an increase of the parameter Δ/L results in a growing fraction of the beam electrons participating in the interaction with the microwave field.

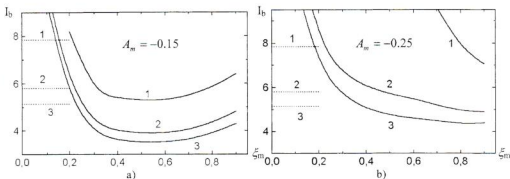


Fig.3. Dependences of the specific starting current on the center coordinate of the magnetic inhomogeneity.

As follows from numerical calculations, the mentioned effects of the electron beam thickness on the starting current of the generator remain with $A_m > 0$ too.

Maximum power regime.

In this case, the principal characteristic of the device is the electron efficiency, η , maximized over the generation zone. Fig.4 demonstrates the dependences of η on the central coordinate of the magnetic inhomogeneity for three values of the beam thickness, viz. $\Delta/L = 0.005$ (a); $\Delta/L = 0.01$ (b) and $\Delta/L = 0.02$ (c). The solid curves are for a fixed operating current-to-starting current ratio, and the dot lines are for a fixed value of the beam operating current. The dashed curves represent the electron efficiency for a uniform focusing field ($A_m = 0$ and $\xi = 0$).

In the absence of electron precipitation at the SWS surface (curves 1 in Fig.4), an enhancement of the electron beam thickness practically has no effect on the run of the $\eta(\xi_{sm})$ dependences. It is only the magnitude of the electron efficiency that changes. A similar result has been obtained heretofore for the maximum amplification regime (Fig.3,a).

The graphs of Fig.4 indicate that the growth of the beam thickness is followed by reduction in the efficiency of the electron-wave field interaction. This effect owes to the decrease of the specific-starting current, which is equivalent, in the case considered, to reduction of the specific operating current (per unit beam thickness). Hence, within the model under investigation, fixing the operating-to-starting current ratio leads to reduction of the beam current density and, as a result, to a lower electron efficiency when the Δ/L parameter is increased. To maintain the current density at a fixed level, the operating-to-starting current ratio should be raised, while the beam thickness is increased.

In the regime of strong electron precipitation (curves 2 in Fig.4), a twofold increase of the beam thickness from $\Delta/L = 0.005$ (Fig.4,a) to $\Delta/L = 0.01$ (Fig.4,b) at a fixed operating current results in a growth of the electron efficiency over the whole range of variations of the parameter ξ_{sm} . High values of η for a fixed operating-to-starting current ratio (the solid curves) and $\Delta/L = 0.005$ can only occur with forbiddingly high currents. The enhanced electron efficiency mentioned for the fixed operating current in the device with a thicker beam is associated, first of all, with the changed current density distribution and the high-frequency layering of the electron beam. If, in some case, the thin beam ($\Delta/L = 0.005$) precipitates completely at the SWS, then the precipitation would be only partial for $\Delta/L = 0.01$, with

the beam layers to remain in the interaction space being those which are farthest from the SWS. Prior to the start of the precipitation, the electrons from these layers are under the action of a weaker microwave field compared with the electrons precipitating at the SWS. Therefore, upon precipitation of the lower layers where electrons have changed from the decelerating to the accelerating phase of the microwave field (the maximum efficiency mode with the use of a nonuniform focusing field [3]), the electrons staying in the interaction space are those which are decelerated by the field giving up their energy.

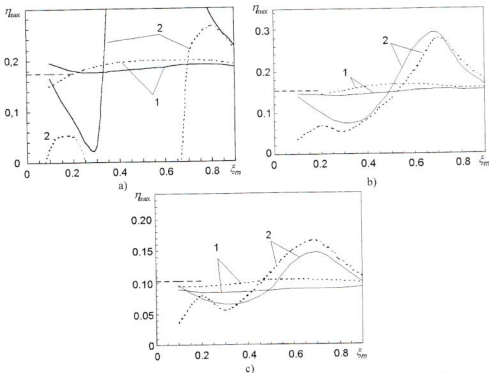


Fig.4. Dependences of the electron efficiency on the coordinate of the magnetic inhomogeneity center.

Further increase of the beam thickness, from $\Delta/L = 0.01$ to $\Delta/L = 0.02$ (Fig.4,c) results in a reduced interaction efficiency, both for the fixed operating current and for the fixed operating-to-starting current ratio. Apparently, the nature of the noted efficiency reduction is the same as in the case of absence of the electron precipitation, since the fraction of the beam electrons precipitating on the SWS decreases with greater thicknesses.

Proceeding from the analysis of the curves of Fig.4, we can conclude that the basic regularities of the electron efficiency dependence upon the location of the magnetic inhomogeneity center are retained as Δ/L is increased at $A_m = -0.25$. The reason is splitting of the electron beam into layers owing to the microwave field inhomogeneity in the transverse direction (along the oZ axis). In the thick beam, the major contribution to the energy exchange with the microwave field is given by the layers closest to the SWS surface that precipitate independently of the beam thickness. The farther layers bring about just

quantitative corrections to the ξ_m dependences of the efficiency. Within the device model considered, these layers do not precipitate, and hence travel a greater length through the interaction space.

Conclusions.

1. In the generator with a tilted focusing field, the increase of the electron beam thickness results in a greater starting current only in the case of partial beam precipitation on the SWS surface. With a complete current precipitation, the starting current is reduced.
2. In the device with either a nonuniform, or tilted magnetostatic field, the specific starting current first decreases and then is saturated as the beam thickness is increased.
3. In the absence of current precipitation, the electron efficiency of the generator with a nonuniform focusing field is reduced as the beam thickness is increased. The efficiency dependence on the central coordinate of the magnetic inhomogeneity remains unchanged.
4. In the case of strong electron precipitation, an optimum value of the beam thickness exists for which the highest efficiency occurs in the fixed operating current mode irrespective of the location of the magnetic inhomogeneity center.

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