NONLINEAR THEORY OF RELATIVISTIC MICROWAVE ELECTRON DEVICES

V.Chursin, E. Odarenko, A. Shmat'ko
Dept. of Radiophysics, Kharkov State University,
Svobody Sq., 4, 310077, Kharkov, Ukraine

1. Introduction

The increase of output power is an important task of the theoretical and experimental research of resonant oscillators of millimeter and submillimeter waves (orotron, diffraction radiation generator, laddertron, ledatron, etc.). It is well known that the application of relativistic voltages for acceleration of electron beams in millimeter wave oscillators allows to obtain high levels of output power of radiation. Dynamic relativistic variation of the electron mass can considerably change the character of the electron-wave interaction process. This effect is essential if the magnetic guide field strength is limited or dc focusing field is nonuniform. In this case the transverse electron-wave interaction and to motion of electrons in the trnsverse direction should be taken into account, and for a theoretical description of the device a multi-dimensional model should be applied.

2. Theoretical model

We consider the following model of a resonant relativistic oscillator. A sheet electron beam is passing through the resonator (cavity or open one) near to the slow-wave structure surface. The electron beam is subjected to the dc longitudinal magnetic field applied in the y direction. The focusing field can be nonuniform in general case. The rf field is assumed to have fixed spatial structure and change slowly in the scale of the electron transit time through the resonator. This is justified if the oscillatory system has sufficiently large value of the quality factor.

For a self-consistent description of the electron-wave interaction process, we start from the Maxwell-Lorentz equations, which can be written assuming the ordinary for resonant devices approximations in the following form [1]:

$$-\frac{dC_S}{dt}+i(\omega-\omega_S)C_S=\frac{1}{2N_S\pi}\int\limits_V\int\limits_0^{2\pi}\vec{J}\vec{E}_S^*\exp(i\omega t)d(\omega t)dV; \qquad (1)$$

$$\frac{d\vec{v}}{dt}=-\frac{|e|}{m_0\gamma}\left\{\vec{E}+\vec{v}\times\vec{B}-\frac{\vec{v}}{c^2}(\vec{v}\vec{E})\right\}; \qquad (2)$$

where C_S is the complex amplitude of rf oscillations of the s-th resonator mode. The components of the electric field strength vector $\vec{E}=(0,E_y,E_z)$ are given by:

$$E_y=C_S f(y)\psi_y(z)\exp[i(\beta y-\omega t)],$$
$$E_z=iC_S f(y)\psi_z(z)\exp[i(\beta y-\omega t)]$$

The functions f and ψ_y,ψ_z define the longitudinal (along the coordinate y) and transverse (along the coordinate z) spatial distribution of the s-th resonator mode field, respectively; $N_S = \varepsilon_0 \int\limits_V \left|\vec{E}_S\right|^2 dV$ is the modal norm; $\dot{\omega}_S = \omega_S' + i\omega_S'/2Q_S$ is the fundamental complex frequency of the s-th mode; Q_S is the resonator quality factor; ω is the generation frequency; $\vec{J}$ is the convection current vector of the beam; e, m_0 are the electron charge and rest mass, respectively; $\vec{v}$ is the velocity vector of the electron; c is the light velocity; $\gamma = \left(1 - v^2/c^2\right)^{-1/2}$; $\vec{B}$ is the magnetic displacement vector; $\beta = \omega / v_P$; v_P is the phase velocity of the slow wave.

The equations set (1,2) is resolved numerically. Preliminary results are obtained for different values of magnetic displacement of uniform focusing field.

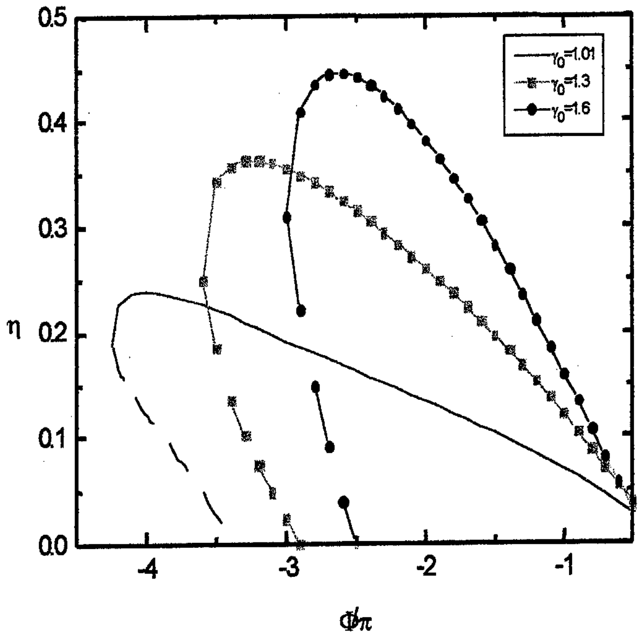

Fig. 1

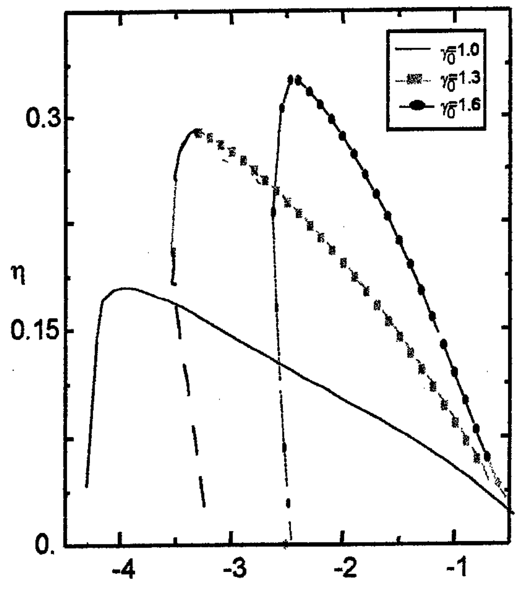

Fig. 2.

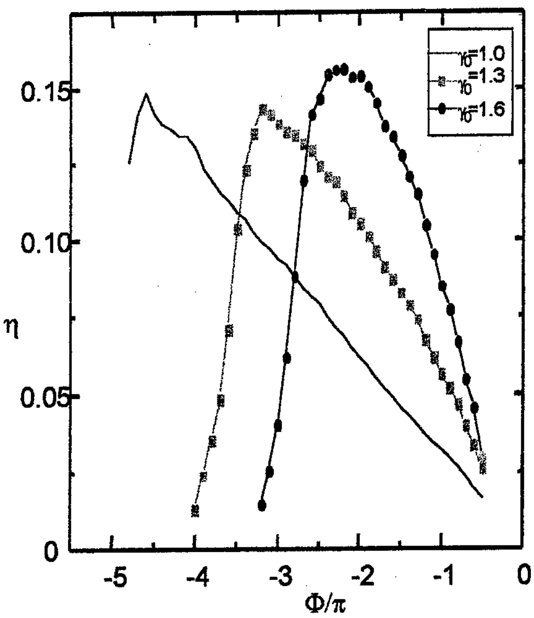

Fig.3.

Discussion

The efficiency dependences upon the parameter $\Phi = \left(1 - v_0/v_P\right)\omega L / v_0$ for the different values of γ_0 ($\gamma_0 = \gamma\big|_{v=v_0}$) and normalized cyclotron frequency $\omega_c/\omega = eB/m\omega$

are shown in Figs. 1, 2 and 3. Solid curves correspond to a drooping regime of the oscillations excitation and dotted curves correspond to a hard regime. All graphs are plotted for the fixed value of the beam current.

Dependences $\eta(\Phi)$ for the value $\omega_c / \omega = 0.4$ are shown in Fig.1. Electron trajectories can be assumed linear in this case. A relativistic factor increase results in the generation zone narrowing and efficiency enhancement. These results correspond to the one-dimensional theory of relativistic resonant oscillator. Hence, the longitudinal electron-wave interaction is the basic energy exchange mechanism between electrons and rf field in the case of $\omega_c / \omega = 0.4$. The cyclotron frequency decrease results in the narrowing of the hard excitation regime domain and efficiency reducing for all the values of relativistic factor (Fig.2, 3). Note that here $\omega_c / \omega = 0.15$ (Fig.2) and $\omega_c / \omega = 0.1$ (Fig.3).

It should also be noted that the maximum efficiency value almost does not depend upon the parameter γ_0 at $\omega_c / \omega = 0.1$ (Fig.3). Furthermore the electron hysteresis (especially nonlinear phenomenon) is absent in this case. The additional calculations showed that the focusing field displacement decrease results in the particles settling onto the slow-wave structure surface. The electrons which interact with the most intensive rf field are settling first. Therefore the settling of the electrons results in the change of relation between the electrons, which interact with damping, and the accelerating rf electric field of the slow wave. Conditions of the electron-wave interaction may be changed significantly in this case and efficiency changes as well. If the electrons interacting with the damping rf field are settling onto the grating, the efficiency decreases. On the other hand, the settling of the accelerated electrons may be a reason of the efficiency enhancement [2].

In the considered situation (uniform focusing field), the electron settling results in the efficiency decrease. To obtain the efficiency enhancement one should use a nonuniform dc magnetic field [2].

3. Conclusions

The efficiency of the relativistic resonant O-type oscillator depends upon the focusing field displacement value.

The settling onto the slow-wave structure surface results in the efficiency decrease. Moreover efficiency reduction is more significant in the relativistic case in comparison with nonrelativistic case.

4. References

1. L.A.Vaynshtein, V.A. Solntcev, Lections on Ultrahighfrequency Electronics, Moscow: Sov. Radio, 1973.
2. E.N.Odarenko, A.A. Shmat'ko, Nonlinear Theory of O-type Microwave Oscillators with Nonuniform Magnetostatic Field (Two-Dimensional Model), *J. of Communications Techn. and Electronics,* 1994, vol. 39, no 9, p.p. 1-8.