A COMBINED SURFACE WAVE RELATIVISTIC GENERATOR

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The nature of energy exchange between a stream and a field in a surface wave generator is theoretically investigated in a high current relativistic electron stream with an electron energy of $\varepsilon_0 = 1$ MeV.

It is shown that in systems which consist of sectors of smooth waveguides with periodic heterogeneities and transverse dimensions much greater than the working wavelength with the use of interaction between the stream and a field with a lower axially symmetrical mode at frequencies near the boundary of the transparency band it is possible to acquire an effect of cyclotron power amplification and an electron efficiency of interaction greater than 40%.

Fundamental difficulties which lead to limitation of the size and duration of a radiation pulse arise in relativistic high current electronics with an increase in the power of relativistic generators with transverse dimensions of the electrodynamic structures on the order of the length of the generated wave. These difficulties are caused by the effect of different factors, including the effect of high frequency spark over [1] and disruption of the stream during generation [2]. Creation of devices with spatially developed periodic waveguides is a timely issue for a shift to less intensive modes of operation characterized by lower energy densities near the walls [3]. The operation of such devices may be based on interaction between a relativistic electron stream and a slow wave, including a surface wave. Such ultrasonic sources are called relativistic surface wave generators (RSWG). A single model RSWG which operates at beam intensities of $V_0 = 500$ kV and a current of $I_0 = 3$ kA may be cited as an example [4]. The problem of increasing the power of RSWG by shifting to higher voltages of $V_0 \sim 1$ MV and higher beam currents of $I_0 \sim 10$ kA is the current problem.

The power of relativistic Cherenkov single mode generators is a function of the power of the magnetic focusing field, where a cyclotron increase or reduction in the output signal may be observed [5]. In this regard, it is interesting to use the acquired results in investigating surface wave generators with high values of the accelerating voltage and beam current, in which additional characteristics caused by the different laws of radial change in the amplitudes of the spatial harmonics must be observed.

1. Interaction between a stream with a surface wave with a spatially developed electrodynamic structure, whose characteristic transverse dimension D (Fig. 1a) is much larger than the working wavelength ($D \gg \lambda$), is examined. Under such conditions the reduction in the amplitude of the surface wave in a direction

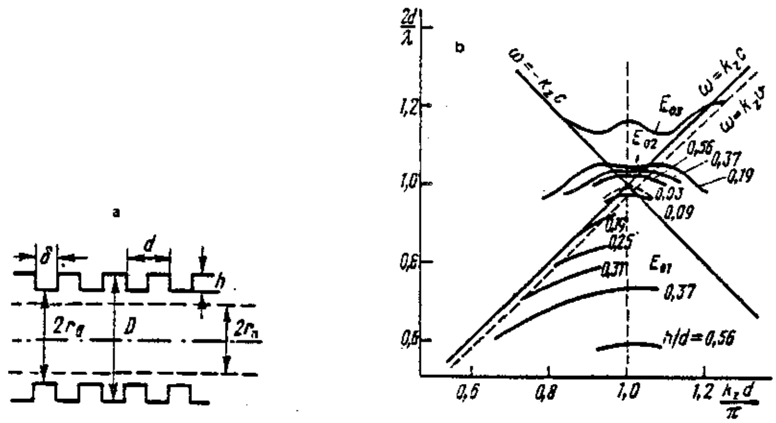

Fig. 1

perpendicular to the wall of the waveguide is approximately described by a formula from the theory of planar periodic lattices:

$$\frac{E_z(r)}{E_z(r_w)}=e^{-k_\perp \Delta r},\quad k_\perp=\sqrt{k_z^2-k^2}\simeq\frac{k_z}{\gamma_0},\quad \Delta r=r-r_w,$$

where $E_z(r)$ and $E_z(r_w)$ are the intensities of the longitudinal component of the electrical field at a radius of r and on the surface of the waveguide $r = r_w$, k_z and $k_\perp$ are the longitudinal and transverse wave numbers, γ_0 is a relativistic factor, $\gamma_0 = 1 + \varepsilon_0$ (MeV)/0.511, and ε_0 is the electron energy. A reduction by e times ($k_\perp \Delta r=1$) is reached at $\Delta r\sim\gamma_0/k_z$. The simplifying assumptions are valid at $\Delta r \ll D/2$, i.e., when $D\gg 2r=2\gamma_0/k_z$. With characteristic values of the relativistic correction γ_0 = 4-5 and interaction of the current and the field at frequencies near the "π"-type ($k_z d=\pi$), $D \gg \lambda$ is acquired, i.e., the diameter of the RSWG waveguide is $D \gtrsim 10$ cm for an operational wavelength of $\lambda \sim 3$.

It is possible to evaluate the resistance of the coupling between the surface wave and the stream using simplified formulas for a planar system in a single wave approximation [6]:

$$R_{e_1}=\frac{cW(k_\perp)^2 e^{-2k_\perp \Delta r}}{(k_z)^2 v_{gr} k^2 \pi r_w},$$

where W is the wave resistance of free space, v_{gr} is the group speed of the basic wave in the structure and c is the speed of light. The greatest coupling between the stream and the field will be at a frequency of the "π"-type, when $v_{gr} \to 0$. However, under actual conditions, the single wave approximation is invalid and one time interaction with direct and reverse waves should be examined.

A more precise calculation requires a multimode examination, but it is possible to remain limited to a single mode approximation for a sufficiently long system matched on the input and output [7].

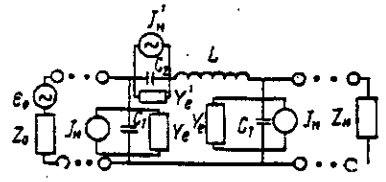

Fig. 2

2. In examining surface waves, the wavelength exceeds twice the period of corrugation of the structure. Under these conditions for specific calculation of the dispersion characteristics of a waveguide, it is possible to shift to an equivalent system with rectangular corrugation (see Fig. 1a). Such a waveguide is characterized by the following parameters: D) the diameter of the smooth part of the waveguide, d) the period of the structure, h) the height of the corrugation, and δ) the thickness of the corrugations. The shift from the actual corrugation of complex form to a rectangular structure may be accomplished by a variety of methods, including with preservation of the volume of the perturbating bodies. Calculations of a waveguide with rectangular corrugation were performed using a specially developed program based on joining the fields in the centers of the channels using a technique from [6].

The constants of distribution were calculated in dimensionless parameters: $D/\lambda = 2$–3; $d/\lambda \simeq 0{,}5$; $h/d \simeq 0$–$0{,}6$. The specific results, presented in Fig. 1b, deal with a range of centimetric waves (3 cm), but they may be used for a qualitative analysis of the processes in other ranges and for waveguides with different corrugation. The change in the depth of the corrugation changes the form of the dispersion characteristics primarily in a frequency range close to the "π" type. An increase in the corrugation (an increase in h) leads to a substantial drop in the lines which relate to the lower type, E_{01} mode. A corrugation with $h/d \approx \approx 0.25$ should be considered quite severe and provides a synchronism of the current and field at a distance from the "π" type boundary of the transparency band; the resistance of the stream and field coupling is quite high. In the case of slight corrugation $h/d < 0.25$, the dispersion curves of the E_{01} mode are adjacent to the $\omega = \pm k_z c$ lines and the interaction of the stream and the field occurs near the "π" type band boundary.

Figure 1b presents the points of intersection of the dispersion curves of the E_{01} mode and the kinematic straight lines which relate to the stream. At accelerating voltages of 1-2 MV, the slow down in the electrons is characterized by values of $v/c = 0.94$–0.98. The points of intersection lie near the "π" type band boundary. Such a condition of synchronism of the stream and the field determines the complex mode of operation of the device - amplification of the travelling wave tube (TWT) type in the presence of an internal feedback of the backward wave tube (BWT) type coupling, while the resulting process is a TWT-BWT type process [7].

3. A vortex field of a surface wave in the structure is described by an equivalent system presented in Fig. 2. The electron stream is examined in a weak signal approximation using slow and fast spatial charge waves (SSCW and FSCW) and cyclotron waves (SCW and FCW). Description of the self-consistent interaction of the stream and the field is performed using an approach based on separation of the fields and currents into vortex and potential parts [8]. The loading of the waveguide on the input Z_0 and the output Z_o is taken into consideration.

The parameters of the equivalent system are determined from a system of equations which includes the frequencies ω_0 and ω_π which correspond to "0" ($k_z d = 0$) and the "π" type of oscillations, and the group speed v_{gr} at the point $k_\perp \to 0$:

$$\frac{C_1}{C_2} - \omega_0^2 L C_1 = 0, \quad \frac{C_1}{C_2} - \omega_\pi^2 L C_1 = -2, \quad C_2 = \frac{0.4\pi}{16W} \frac{\omega_0^2 (r_w)^4}{dv_{gr} c^2}.$$

The first and second equations from these systems follow from the dispersion equation of the equivalent chain $(1 + C_1/C_2 - \omega^2 L C_1)$ which is written for frequencies of $\omega = \omega_0$ and $\omega = \omega_\pi$, and the third equation reflects the condition of equality of the resistance of the R^e_{co}, expressed through the parameters of the equivalent system, to the resistance R_{co}, found using a technique from [6] for a low wave slowing.

Discrete interaction between the i-th wave of the stream and the field in the cells is described using the coefficients of longitudinal and transverse interaction

$$M_i = \mu_{ri}\mu_{zi}, \quad \mu_{zi} = \frac{\sin(\beta_i t_i/2)}{\beta_i t_i/2}, \quad i = 1 \div 4,$$

$\mu_{ri} = I_0(k_\perp r_s)/I_0(k_\perp r_w)$, i = 1 (SSCW), i = 2 (FSWC), $\mu_{ri} = I_1(k_\perp r_s)/I_1(k_\perp r_w)$, i = 3 (SCW), and i = 4 (FCW), β_i are the constants of propagation of the waves of the beam, t_i is the length of the equivalent field of interaction between the field and the i-th wave of the stream, r_s is the radius of the stream, and $I_0(x)$ and $I_1(x)$ are the modified Bessel functions. The induced points $J'_H = \sqrt{G_{0q}}(M_2 a_2 - M_1 a_1)$, $J_H = \sqrt{G_{0H}}(M_4 a_4 - M_3 a_3)$ (a_i is the amplitude of the i-th perpendicular wave in the stream in the range of interaction) and the electron conductivities Y_e and Y'_e, determined by the change in the amplitudes of the waves in the beam in the range of the interaction space:

$$Y'_e = \left\{\frac{G_{0q}}{8}(M_2^2 - M_1^2) + i\frac{G_{0q}}{4}\left[\frac{\varphi_2 - \sin\varphi_2}{\varphi_2^2} - \frac{\varphi_1 - \sin\varphi_1}{\varphi_1^2}\right]\right\},$$

$$Y_e = \left\{\frac{G_{0H}}{8}(M_4^2 - M_3^2) + i\frac{G_{0H}}{4}\left[\frac{\varphi_4 - \sin\varphi_4}{\varphi_4^2} - \frac{\varphi_3 - \sin\varphi_3}{\varphi_3^2}\right]\right\}.$$

where $\varphi_i = \beta_i t_i$, $G_{0H} = 2\frac{\omega_H}{\omega}\frac{I_0}{V_0}$, $G_{0q} = 2\frac{\omega_q}{\omega}\frac{I_0}{V_0}$, $\omega_H = \frac{\omega_{H0}}{\gamma}$ is the relativistic cyclotron frequency and ω_q is the reduced relativistic plasma frequency, are included in the equivalent system.

4. The work examines RSWG which consist of two sections V_0 = 1 MB and I_0 = 7 kA. The typical geometry of the device has the appearance presented in Fig. 1a. Investigation of surface wave generators shows that in the field of interaction between the stream and the field there is a distortion in the dispersion characteristics. Without consideration of the transverse interaction between them, the appearance is analogous to the dispersion characteristics acquired in work [7] with investigation of a relativistic TWT-BWT in a corrugated waveguide. The effect of the structure leads to an active coupling of the fast and slow waves in the beam and to a shift of the line of the complex root into the range

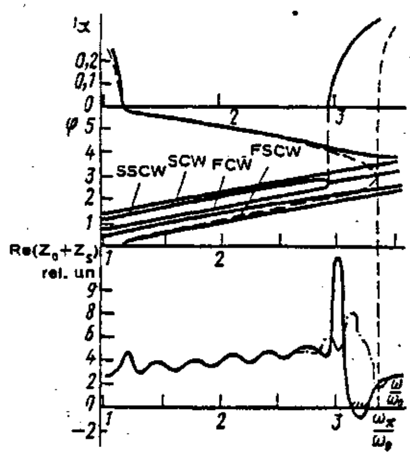

Fig. 3

of the transparency band. The dispersion characteristics of the system with consideration of transverse interaction are presented in Fig. 3 (ϕ is the shift of the wave phase to the cell and α is the constant rise or fading; the dotted line indicates the characteristics of the "cold" system). There is a substantial shift of the line of the complex root inside the band. This shift is increased due to the effect of the transverse interaction and the passive couplings of the cyclotron waves with the field of the structure may lead to internal reverse couplings and facilitate autoexcitation of oscillations in the system, or the opposite, hinder it. It is noted that the position of the lines of the cyclotron waves is determined by the induction of the focusing magnetic field B_0. At the examined values of the magnetic field, the fast cyclotron wave interacts with the field of the structure in a range of $\varphi=\beta_4 d \simeq -\pi$, while the slow wave interacts in the field of $\phi \approx 3\pi$. In light of the possibility of transfer of the curves to 2π, a wave pattern is acquired which is shown in Fig. 3. A small change in B_0 near resonance leads to a great change in the type of dispersion characteristics - a shift from a passive coupling to an active and the reverse.

The dependence of amplification in the system on the value of the magnetic field is presented in Fig. 4. It is characterized by a resonance amplification in the output power at values of $B_0 \approx$ 17-21 kG which is in accordance with the conclusions drawn from analysis of the dispersion characteristics.

Analysis of the conditions for autoexcitation may be conveniently performed using a conventional approach in analyzing electronic devices: autoexcitation arises when the total value of the equivalent resistances of the input device Z_0 and the structure associated with the electron beam Z_s becomes less than one. The dependences of $Re(Z_0 + Z_s)$ on frequency are presented in Fig. 3. In the absence of transverse interaction, the beam current is less than the starting value (in the entire frequency band $Re(Z_0 + Z_s) > 0$ - as depicted by the dashed-dotted line). The introduction of transverse interaction in the system increases the feedback which leads to autoexcitation of the device ($Re(Z_0 + Z_s) < 0$ at $3.1 < \omega/\omega_0 < 3.25$), where the autoexcitation is observed primarily at frequencies in direct proximity to the boundary of the band of transparency.

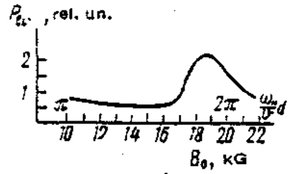

Fig. 4

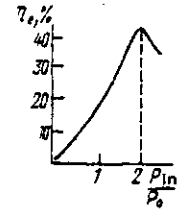

Fig. 5

5. An RSWG in its operational principle is suitable for realizing highly effective interaction, especially with the use of a sectional periodic waveguide. In fact, in an RSWG, in principle, it is possible to acquire a field distribution which rises in terms of the coordinate according to a required law. Initial analysis of the corresponding modes of the RSWG may be conveniently performed in an approximation of induced radiation of a stream of charged particles in a field with an assigned distribution of the vortex field along the structure. The longitudinal distribution of the field, for instance, may be approximately found based on data from a linear self-consistent theory.

In investigating the energy exchange of a particle which flies through the interaction clearance, the change in the relativistic correction

$$\Delta\gamma_{s,i} = \gamma_{s,i} - \gamma_{s-1,i} = M(\gamma_0 - 1)(V_s/V_0)\cos(\omega t_{i_s} + \varphi_i + \psi_s)$$

is found. Here, V_s is the voltage in the s-th clearance, ψ_s is the stationary phase of the s-th resonator, ϕ_i is the entry phase of the i-th particle, ω is the operational frequency, and M is the interaction coefficient.

Figure 5 presents the results of a calculation of the efficiency for different levels of the input signal. The distribution of the field along the section and the modulation of the stream on the input of the section were taken from data from the linear theory. The electronic efficiency was calculated using formula

$$\eta_e = \frac{\sum_{i=1}^{I} (\gamma_{s,i} - \gamma_0)}{I(\gamma_0 - 1)},$$

where $\gamma_{s,i}$ is the value of the relativistic correction for the i-th particle on the output from a section and I is the number of particles per electron wavelength (I = 16). The calculations showed that a high level of nonlinearity is achieved in the stream in the second section or in the output sector of a two-section system and electron beams are formed. With a braking of the beams in a sequence of clearances, it is possible to realize a mode of highly effective interaction with an efficiency of $\eta > 40\%$.

CONCLUSION

In multimode electrodynamic structures, it is possible to achieve conditions for existence of a surface wave through selection of the type of periodic heterogeneities. With interaction between a slightly slowed surface wave and a relativistic electron beam near the boundary of the transparency band its power may be distributed throughout the volume of the structure, which may reduce the high frequency spark over.

By changing the diameter of the stream and the value of the magnetic field, it is possible to change the conditions for interaction between the stream and the field of the structure and to change the relation between the longitudinal and transverse interactions. With specific values of the magnetic field, the transverse interaction may have a resonant nature, which facilitates autoexcitation of oscillations in an RSWG.

Quite high electronic efficiency reaching 40% may be reached in a two-section RSWG.

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