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ON THE FEATURES OF OPEN MAGNETOACTIVE WAVEGUIDES EXCITATION

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It is shown that in the volume of an open waveguide, each electron – oscillator rotating in a constant magnetic field is capable of generating a TE wave, for which this waveguide is transparent. The generation efficiency is determined by the rate of electron injection and their longitudinal velocity along the waveguide axis. The field generation mode near the cutoff frequency with a low group velocity comparable with the longitudinal velocity of the injected electrons is selected. In this case, the transverse velocity of the electrons significantly exceeds their longitudinal velocity and the group velocity of the wave. In the absence of field reflection from the waveguide ends, each electron makes its contribution to the total radiation field, i.e. it can be considered that the field generation occurs in the superradiance mode. It is shown that the total field of the electron flow is capable of forming a resonator field consisting of two waves propagating towards each other due to even partial reflections from the waveguide ends. With a small reflection of the fields from the ends and a small drift velocity of the rotating electrons, the superradiance mode dominates, similar to the case of excitation of a completely open waveguide. In the case of a noticeable reflection of the fields from the ends of the system at a relatively high velocity of their longitudinal injection, the reflected fields significantly exceed the total field of the emitters and the traditional mode of waveguide resonator field generation is formed. The zones where either resonator field generation or generation under superradiance conditions dominate are presented on the plane "longitudinal motion velocity – reflection coefficient". Two cases are considered: when reflected waves are formed only due to reflection from the ends, and also when the effect of rotating electrons on reflected waves in the waveguide volume is taken into account. It is essential that the average amplitude of the total particle radiation field changes slightly for all considered generation modes. Resonance effects during reflection from the ends lead to a significant increase in the amplitude of the waveguide – resonator field.
Keywords: *Rotating electrons – oscillators, magnetoactive waveguide, resonator field generation, TE wave superradiance mode.*
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INTRODUCTION

The nature of excitation of oscillations in limited systems – waveguides and resonators – due to self-consistent [1] interaction with flows of charged particles and oscillators has been considered in a large number of different works (see, for example, [2 – 9]). Traditionally, problems of generation and amplification were solved in the paradigm of interaction of the field determined by the geometry of the waveguide or resonator with active particles according to the scheme proposed in [10]. In this approach to the description, there is no direct interaction between the active particles of the flow; each of them interacts only with the field of the waveguide.

On the other hand, each particle or oscillator in the active zone emits and it is possible to find the total field of these emitters. In the absence of a waveguide and a resonator at a low noise level [11-13], a system of such emitters under certain conditions is capable of generating radiation with a noticeable share of coherence, and such radiation is usually called superluminescence or superradiance mode. In the same way, in an open waveguide, in the absence of reflection from its ends or with a sufficiently small reflection, the superradiance mode can also be realized. In works [14-15] it is shown that the intensity of the eigenfield of particles in the modes of their arising synchronization is comparable with the intensity of traditional waveguide or resonator generation. Since the total field of the emitters (charged parts and oscillators) of the active zone in waveguide and resonator systems is always present and can be quite significant, it is rational to study the influence of this field on the formation of the resonator waveguide field under conditions of even partial reflection from the ends of the waveguide. This process of formation of the resonator waveguide field occurs due to the effects of reflection from the ends of the system and the interaction of the reflected waves with particles in the active zone. When the conditions of phase synchronization of particles and oscillators are met and the reflection of the field from the ends of the system increases, it is possible to observe the formation of a resonator waveguide field exceeding the total eigenfield of the active particles. At low reflection coefficients, the eigenfield of particles can dominate, which corresponds to the superradiance regime.

The aim of the work is to identify zones on the phase plane "injection velocity - reflection coefficient" where the conditions for generation in superradiance regimes are met and where the generation of a resonator waveguide field is realized.

1. PARTICLE OWN FIELD AND RESONATOR FIELD OF A WAVEGUIDE

Let us consider the excitation of a TE electromagnetic wave, the electric vector of which is perpendicular to the waveguide axis, with a frequency and a wave vector in a smooth metal cylindrical waveguide of radius by an electron

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beam in resonance cases, where is the cyclotron frequency of electron rotation. Generation is considered near the cutoff frequency, where the group velocity of the wave is small. Induction of a constant magnetic field. The electron beam occupies a cylindrical layer in the cross-section of the waveguide, which we will assume to be sufficiently thin. All centers of Larmor rotation of electrons with radius are at the same distance from the waveguide axis. Each such electron rotating in a constant magnetic field (actually an oscillator) is capable of generating a TE wave, for which this waveguide is transparent.

The traditional description of the process of excitation of a resonator waveguide field (under conditions of field formation due to reflection from the boundaries - ends of the waveguide) assumes that the direct interaction of particles with each other in the active zone is neglected. Particles interact only with the waveguide field. It is obvious that in this traditional description the total field of particles – rotating electrons – during their interaction with each other is not taken into account at all. The equations for the longitudinal component of the magnetic field, electromagnetic waves propagating in both directions (the interference of which is the resonator waveguide field) have the form [16-17]

$$\frac{d\mathrm{B}_{wg\pm}}{d\tau}+\theta\cdot\mathrm{B}_{wg\pm}=\frac{i}{2}N^{-1}\cdot\sum_{j=1}^{N}a_j\cdot J_1^{'}(a_j)\cdot\exp(-2\pi\mathrm{i}\zeta_j\mp 2\pi\mathrm{i}Z_j)\,, \tag{1}$$

here $\mathrm{B}_{wg\pm}$ are the dimensionless amplitudes of the longitudinal magnetic field of counterpropagating waves, θ is the decrement of absorption due to radiation, a_j is the radius of Larmor rotation (in fact, the amplitude of the oscillator), N is the number of modeling particles, $2\pi\zeta_j$ is the phase of the oscillator, $Z_j = k_z z_j$ is the dimensionless longitudinal coordinate. If the condition $|\partial\mathrm{B}_{wg\pm}/\partial\tau| << \theta|\mathrm{B}_{wg\pm}|$ is met, equation (1) can be rewritten as

$$\mathrm{B}_{wg\pm}=\frac{i}{2N\theta\cdot}\cdot\sum_{j=1}^{N}a_j\cdot J_1^{'}(a_j)\cdot\exp(-2\pi\mathrm{i}\zeta_j\mp 2\pi\mathrm{i}Z_j)\,. \tag{2}$$

The resonator waveguide field can be represented in a simplified form using only the waves reflected from the ends of the system, which will be defined below

$$\mathrm{B}_{ref}(Z)=\mathrm{B}_{ref+}\exp(2\pi iZ)+\mathrm{B}_{ref-}\exp(-2\pi iZ)\,. \tag{3}$$

Then the resonator waveguide field can be written

$$\mathrm{B}_{wg+}=\mathrm{B}_{ref+},\quad \mathrm{B}_{wg-}=\mathrm{B}_{ref-}\,. \tag{4}$$

If we take into account the influence of particles in the volume on the reflected waves, then the resonant waveguide field can be approximated by two waves

$$\begin{gathered}\mathrm{B}_w(Z)=\mathrm{B}_{wg}(Z)+\mathrm{B}_{ref}(Z)=\mathrm{B}_{w+}\cdot e^{2\pi iZ}+B_{w-}\cdot e^{-2\pi iZ}\\ \mathrm{B}_{w+}=\mathrm{B}_{ref+}+0.5\,\mathrm{B}_{wg+},\quad \mathrm{B}_{w-}=\mathrm{B}_{ref-}+0.5\,\mathrm{B}_{wg-}\end{gathered} \tag{5}$$

and the fields are presented in complex form $B_\pm=|B_\pm|\exp\{i\varphi_\pm\}$. The equations of motion for electrons rotating in a constant magnetic field

$$2\pi\frac{d\zeta_i}{d\tau}=\eta_i(1-\alpha)+\mathrm{Re}\{J_1(a_i)\cdot[1-\frac{1}{a_i^2}]\cdot\exp(2\pi i\zeta_i)\cdot[\mathrm{B}(Z_i,\tau)]\}\,, \tag{6}$$

$$da_i/d\tau=\mathrm{Re}\{i\cdot J_1^{'}(a_i)\cdot\exp(2\pi i\zeta_i)\cdot[\mathrm{B}(Z_i,\tau)]\} \tag{7}$$

should be supplemented with two more equations that take into account the longitudinal motion of the oscillators

$$d\eta_i/d\tau=2\pi d^2Z_i/d\tau^2=\mathrm{Re}\{iR\cdot a_i\cdot J_1^{'}(a_i)\exp(2\pi i\zeta_i)\cdot[\mathrm{B}(Z_i,\tau)]\}\,, \tag{8}$$

$$2\pi dZ_i/d\tau=\eta_i\,, \tag{9}$$

here - α takes into account the relativism of the electron, η_i - is the dimensionless longitudinal velocity of the electron, $R_e=k_z^2\cdot\omega_B/k_{ms}^2\cdot\delta_e$ - is the quantity that determines the orientation of the wave vector of the wave.

Total radiation fields of particles. Superradiance modes. However, in reality, first a total radiation field of electrons rotating in a constant magnetic field, actually oscillators, arises in the waveguide, and each such oscillator emits a TE wave in both directions. Because an oscillator is capable of emitting only waves that are in the transparency zone of the medium (or system - in this case, the waveguide). In this case, the field of this radiation will act on all particles of the oscillator ensemble. In other words, all oscillators interact with each other.

If all these rotating electrons were outside the waveguide, this process would be called the superradiance mode, if, of course, the oscillators are subsequently synchronized in phase, which is observed in the absence of noise [7]. But even in an open waveguide, without reflection or with insignificant reflection from the ends, this process is also no different from the superradiance mode and, in all likelihood, is it. Let us assume that the resonator waveguide field (2) is absent, and that there is only a superradiance field, i.e. a field that is determined only by the interaction of rotating electrons. To describe the magnetic field of the TE wave excited by this ensemble of rotating electrons, we can use the expression [13]

$$\mathrm{B}_{sr}(Z)=\frac{i}{2N\theta}\sum_{j=1}^{N}a_j J_1^{'}(a_j)\exp\{-2\pi i\zeta_j\}\cdot\exp\{2\pi i\left|Z-Z_j\right|\} \tag{10}$$

We write the total field acting on the particles as

$$\mathrm{B}(Z,\tau)=\mathrm{B}_{sr}(Z,\tau)+\mathrm{B}_w(Z,\tau) \tag{11}$$

Equations (2), (10), and (11) with the equations of motion (6) – (9) use the following variables
where $\tau=\delta_e t$, $\delta_e^2=4e^2\cdot\omega_B\cdot\mathrm{N}_{b0}\cdot[m_e\cdot c\cdot k_{ms}^2\cdot r_w\cdot J_m^2(x_{ms})\cdot(1-m^2/x_{ms}^2)\cdot D_\omega]^{-1}\cdot J_{m-n}^2(k_{ms}\cdot r_C)$, $D_\omega=\partial D/\partial\omega=\partial\{[\omega^2-(k_z^2+k_{ms}^2)c^2]/[\omega^2-k_z^2c^2]\}/\partial\omega|_{D=0}$, $B=e\cdot b_B\cdot J_{m+n}(k_{ms}\cdot r_C)/m_e\cdot c\cdot\delta_e$, $R_e=k_z^2\cdot\omega_B/k_{ms}^2\cdot\delta_e$, $Z_j=kz_j/2\pi$ is the position of the electron rotation center along the waveguide axis, $a=k_{ms}r_B=k_{ms}v_\Phi/\omega_B$, $\omega_B=eB_0/m_e c$, B_0 – is the constant magnetic field in the waveguide, N_{b0} – is the number of particles of the unperturbed beam per unit length. Here b_B is the wave amplitude, and t $B=B_z=b_B\cdot J_m(k_{ms}r)\cdot\exp\{-i\omega t+ik_z z+im\vartheta\}$ the longitudinal component of the magnetic field of the wave has the form in the cylindrical coordinate system (r, ϑ, z), m is an integer, and $J_m(x)$, $J_m^{'}(x)=dJ_m(x)/dx$ is the Bessel function and its derivative. The requirement that the tangential component of the field at the waveguide boundary vanishes determines the values of the transverse wave number $k_\perp=k_{ms}=x_{ms}/r_w$, where x_{ms} – is the root of the equation $dJ_m(x)/dx=0$.

Reflection conditions. The reflected field amplitudes $\mathrm{B}_{ref\pm}$ are obtained from the equations of the balance of the incident/reflected field at the boundaries

$$\begin{aligned}\mathrm{B}_{ref+}&=-r_L\cdot\left(\mathrm{B}_{sr-}+0.5\,\mathrm{B}_{wg-}+\mathrm{B}_{ref-}\right),\quad Z=0\\ \mathrm{B}_{ref-}&=-r_R\cdot\left(\mathrm{B}_{sr+}+0.5\,\mathrm{B}_{wg+}+\mathrm{B}_{ref+}\right),\quad Z=1\end{aligned}, \tag{12}$$

here $\mathrm{B}_{sr-}=\mathrm{B}_{sr}(0),\quad \mathrm{B}_{sr+}=\mathrm{B}_{sr}(1)$

$$\begin{aligned}\mathrm{B}_{ref+}&=\frac{r_l\left(r_r(\mathrm{B}_{sr+}+0.5\,\mathrm{B}_{wg+})-(\mathrm{B}_{sr-}+0.5\,\mathrm{B}_{wg-})\right)}{(1-r_l\cdot r_r)},\\ \mathrm{B}_{ref-}&=\frac{r_r\left(r_l(\mathrm{B}_{sr-}+0.5\,\mathrm{B}_{wg-})-(\mathrm{B}_{sr+}+0.5\,\mathrm{B}_{wg+})\right)}{(1-r_l\cdot r_r)}\end{aligned}, \tag{13}$$

Expressions (13) take into account the effect of particles - electrons in the waveguide volume on the reflected waves. In the case where the effect of particles in the volume on the reflected waves is not taken into account, for the reflected field amplitudes determined only by the reflection processes at the ends of the system we obtain (see (5)).

$$\mathrm{B}_{ref+}=\frac{r_l\left(r_r\,\mathrm{B}_{sr+}-\mathrm{B}_{sr-}\right)}{(1-r_l\cdot r_r)},\quad \mathrm{B}_{ref-}=\frac{r_r\left(r_l\,\mathrm{B}_{sr-}-\mathrm{B}_{sr+}\right)}{(1-r_l\cdot r_r)}. \tag{14}$$

2. NUMERICAL SOLUTION OF THE PROBLEM

A waveguide contains a given number of particles simulating an ensemble of electrons – N. At the initial moment, all particles have a given amplitude, velocity, and random phase $a_i(0)=a_0=1,\quad \eta_i(0)=\eta_0,\quad \zeta_j\in(0,2\pi)$.

Particles are injected into the beginning of the waveguide in such a way that their total number in the waveguide remains constant. Here is the oscillator amplitude, velocity, and phase of the new (replacement) particles are the same as those of the particles at the initial moment: $a_{new}=a_0=1,\quad \eta_{new}=\eta_0,\quad \zeta_{new}\in(0,2\pi)$.

Constant parameters $N = 500$, $\theta = 1$, $\alpha = 0.5$, $a_0 = 1$, $R = 0.1$, $r_L = 1$ (total reflection at the left edge) were used in the calculations. The velocity of the incoming particles and the reflection coefficient at the right edge η_0, r_L were changed. Particles with a random phase were injected in the region of the left end. Here a_i, ζ_i, η_i, Z_i is the amplitude (radius of rotation), phase, longitudinal velocity, and coordinate of the i-th particle. $\mathrm{B}(Z_i)$ is the field acting on the particle at the point with coordinate Z_i. In the absence of reflection at the two ends of the waveguide, the ensemble of rotating electrons generates only their total radiation field, which can be considered a superradiance field (see Fig. 1).

It is worth noting that in the absence of reflection there is no wave field; only the presence of reflection effects allows the formation of a waveguide field.

Phase synchronization and formation of noticeable coherence of radiation of an ensemble of particles in the active zone of an open waveguide in superradiance mode with a large dispersion (scattering) of the initial amplitudes of the oscillators (here these are the Larmor rotation radii of the electrons) generally require an initiating external field and noise attenuation [9] to accelerate the generation process. It turned out that in the absence of a spread of the initial amplitudes of the oscillators, an external field is not required, the development of the generation process (see Fig. 1) occurs noticeably faster. Under the considered conditions, the proper field of rotating particles-electrons turns out to be large enough and can effectively form reflected waves of noticeable amplitude due to reflection from the ends. Reflection from the ends of the resonator leads to the appearance of reflected waves traveling in the opposite direction. Reflected waves can be formed due to reflections of the field from the ends according to (14). But, generally speaking, these waves can change when passing through the active zone under the influence of the fields of moving oscillators in the volume of the active zone. Therefore, it is useful to take into account the influence of the oscillators in the active zone on these reflected waves. And then the resonator field will consist of two waves traveling in different directions, where the amplitude of the reflected waves at the boundary is supplemented by a term that qualitatively takes into account the influence of the oscillators in the resonator volume on these waves (13).

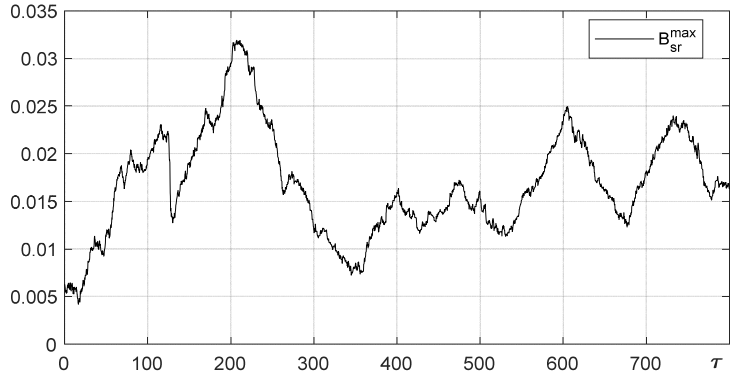

Figure 1. Time dependence of the particle field maximum for each moment of time at zero reflection coefficients

$$r_L = 0,\ r_R = 0$$

In the general case, $\mathrm{B}_{sr}(Z)$ this field consists of the total field of the particles and $\mathrm{B}_w(Z)$ the resonator (waveguide) field. Below, two mechanisms for the formation of reflected waves that make up the waveguide field are considered. The first is due only to reflections from the ends of the waveguide according to (14) and the second, where the influence of particles in the active zone volume on the reflected waves is additionally taken into account, that is, taking into account the corrections after formula (13).

The process of the emergence of a waveguide resonator field is associated with the formation of reflected waves at the boundaries. When reflecting from the ends of the resonator, reflected waves appear, running in the opposite direction: from the end Z=0, a reflected wave running to the right with the amplitude at the boundary B_{ref+} (Z=0), from the end Z=1, a wave running to the left with the amplitude at the other boundary B_{ref-} (Z=1). Generally speaking, these waves change under the influence of the fields of moving oscillators when passing through the active zone. Therefore, the effect of oscillators in the active zone on these reflected waves should be taken into account $\mathrm{B}_{wg}(Z,\tau)$. And then the resonator field will consist of two waves running in different directions, where a term is added to the amplitude of the reflected waves at the boundary, qualitatively taking into account the influence of oscillators in the resonator volume on these waves.

After a certain period of establishing the generation in the waveguide, a quasi-stationary mode is formed, on which chaotic oscillations are superimposed due to incoming particles with a random phase. Therefore, after establishing this mode, the values of the squares of the resonator waveguide field and the total particle field, as well as their ratio K, averaged over the waveguide volume and time are calculated.

$$\mathrm{E}_{sr}{}^{2} = <(E_{sr}{}^{2})_{av}>_{t}, \quad \mathrm{E}_{w}{}^{2} = <(E_{w}{}^{2})_{av}>_{t}, \quad K = \mathrm{E}_{w}{}^{2}/\mathrm{E}_{sr}{}^{2} \tag{15}$$

Calculations show that for given reflection coefficients and an increase in the particle input velocity, both the total proper field of the particles and the waveguide field grow, but the waveguide field grows somewhat faster. Thus, the following operating modes can be observed: 1 – dominance of the generation of the proper field of the oscillators - the superradiance mode ($K < 1$), 2 – generation of the resonator field ($K > 1$). Fig. 2 shows the boundaries between the modes depending on the parameters changed in the calculations: the injection velocity and the reflection coefficient at the right edge of the waveguide.

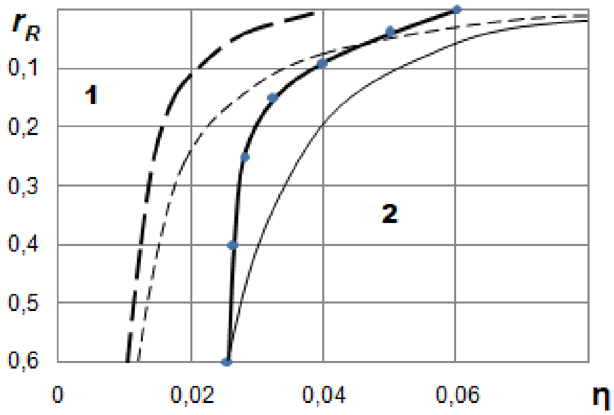

Figure 2. Boundaries between generation modes during correction of reflected waves, according to the conditions of taking into account the influence of particles in the active zone volume on reflected waves (13) (bold line), the thin line indicates the boundary of the regions in the absence of such consideration, according to conditions (14).

The dotted lines correspond to the boundary of the regions in the case when the average particle velocity in the waveguide volume is used, and not the initial velocity of the injected particles. In region 1, the generation of the intrinsic particle field dominates (in fact, the superradiance mode), in region 2 - the generation of a resonator waveguide field of the traditional type, caused by reflection processes from the ends.

In the developed mode 1 - dominance of superradiance - the intensity of the total particle field exceeds the intensity of the resonator waveguide field.

Fig. 3 shows the time dependence of the average particle field squared over the waveguide volume (solid lines) and the resonator waveguide field (dotted lines) in mode 1 ($\eta_0 = 0.02$, $r_R = 0.2$), taking into account the influence of particles in the waveguide volume on reflected waves, and in the absence of such an influence.

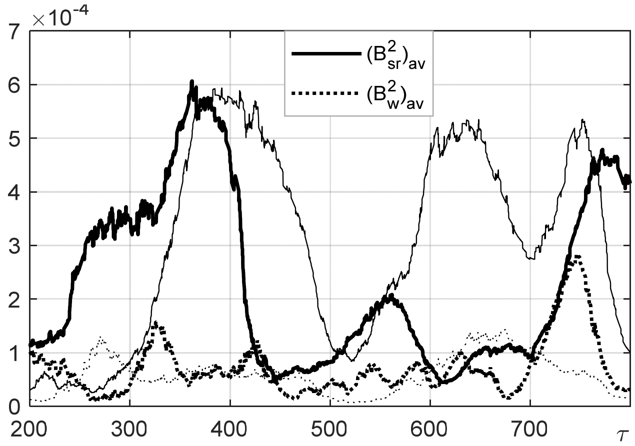

Figure 3. Time dependence of the averaged over the waveguide volume squares of the particle field (dotted line) and the resonator waveguide field (solid line) in mode 1 ($\eta_0 = 0.02$, $r_R = 0.2$) bold lines in the case of taking into account the influence of particles in the waveguide volume on the reflected waves, according to conditions (13). Thin lines are the particle field and the reflected field in the absence of such an influence of particles in the volume on the reflected waves according to conditions (14).

A decrease in the drift velocity of electrons along the system in developed generation modes is characteristic. For mode 1 - superradiation: $\eta_0 = 0.02$, $r_R = 0.2$, Fig. 4 demonstrates the time dependence of the average particle velocity over the waveguide volume in mode 1, taking into account the influence of particles in the waveguide volume on reflected waves, and in the absence of such influence,

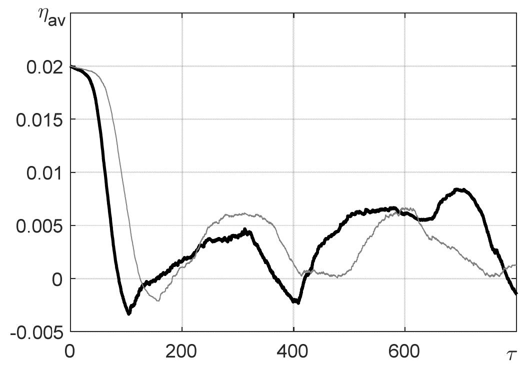

Figure 4. Time dependence of the average particle velocity over the waveguide volume in mode 1, $(\eta_0 = 0.02, r_R = 0.2)$ the thick line in the case of taking into account the influence of particles in the waveguide volume on the reflected waves, according to conditions (13). The thin line - in the absence of such influence, according to conditions (13).

We can give the form of the fields for this mode. It is seen that the resonant waveguide field retains the sinusoidal shape of the standing wave, the field of particles increases towards the left end of the system. The resonator waveguide field in this mode is less than the total field of particles, the attenuation coefficient is $K = 0.32$.

From Fig. 5 it is seen that if the waveguide field is distributed approximately uniformly along the length of the system, then the total electron field (superradiation field) increases significantly along the system. When generating a waveguide field, the contribution of each electron to the field amplitude is determined by its position in the active zone. However, it is important that the distribution of oscillators in the active zone and their phase synchronization do not change the spatial structure of the waveguide field. The growth of the particle field (superradiation) is associated with an increase in the fraction of rotating electrons locally synchronized with the total field along the length of the system. Thus, the advantage of generation in the radiation mode is an increase in the field amplitude at the end of the system in the direction of electron drift, which greatly simplifies energy extraction and increases the generation efficiency.

In the mode of traditional waveguide generation 2 ($\eta_0 = 0.06, r_R = 0.6$), the radiation field of particles changes weakly in relation to the field of the same type in the superradiance mode 1. However, due to the increase in reflection and acceleration of injection, the amplitudes of the resonator waveguide field increase noticeably. Below in Fig. 6 the dependence on time of the square of the particle field averaged over the waveguide volume (solid lines) and the waveguide field is shown with and without taking into account the influence of particles in the waveguide volume on reflected waves.

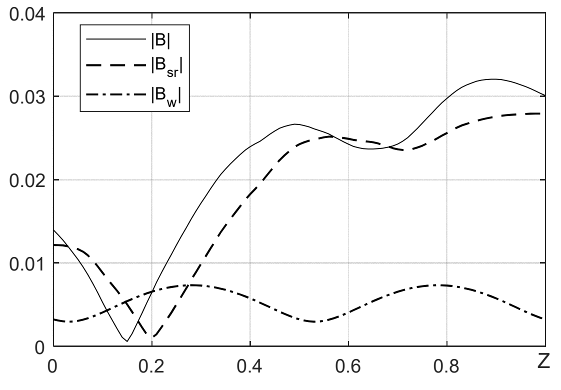

Figure 5. Distributions along the waveguide length of the amplitude modulus of the total field, the particle field, and the waveguide field in mode 1 at the moment τ=800 for the parameters in the case of the influence of particles in the waveguide volume on the reflected waves, according to conditions (13)

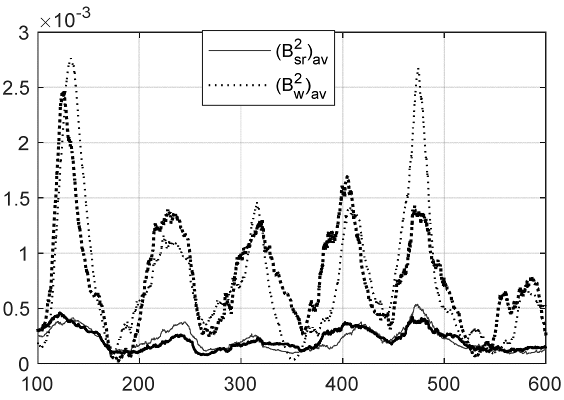

Figure 6. Time dependence of the averaged over the waveguide volume squares of the particle field (solid lines) and the waveguide field (dotted lines) in the waveguide generation mode 2 $(\eta_0 = 0.06, r_R = 0.2)$, thick lines in the case of the influence of particles in the waveguide volume on the reflected waves, according to conditions (13). Thin lines are the particle field and the reflected field in the absence of such influence according to conditions (14)

In the waveguide generation mode, i.e. in mode 2, the longitudinal velocity of electrons also decreases noticeably. In Fig. 7 it is not difficult to see the dependence on time of the average particle velocity over the volume of the waveguide in mode 2 ($\eta_0 = 0.06, r_R = 0.6$) the bold line in the case of taking into account the influence of particles on reflected waves, the thin line in the absence of such influence.

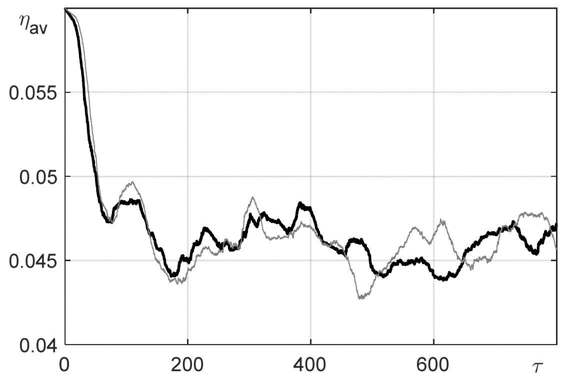

Figure 7. Time dependence of the average particle velocity over the waveguide volume in mode 2 ($\eta_0 = 0.06, r_R = 0.6$) the bold line in the case of taking into account the influence of particles on reflected waves, according to conditions (13). The thin line – in the absence of such influence, according to conditions (14).

Distributions of the amplitude moduli of the total field, particle field and waveguide field for mode 2, in particular, in the case of the influence of particles in the waveguide volume on reflected waves (see Fig. 8).

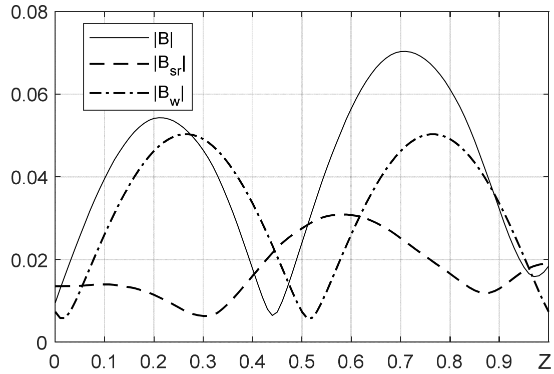

Figure 8. Distributions of the amplitude moduli of the total field, particle field and waveguide field in mode 2 at the moment τ=800 along the waveguide length for the parameters in the case of the influence of particles in the waveguide volume on the reflected waves, according to conditions (13)

The waveguide-resonator field in this case is greater than the total particle field, the excess factor is $K = 2.77$.

3. CONCLUSIONS

In this paper, the generation process in a short cylindrical magnetoactive waveguide is considered. It is shown that even in the absence of reflection from the ends, a total radiation field of TM waves is formed in the waveguide by an ensemble of particles - rotating electrons, which corresponds to the superradiance mode. The possibility of generating a TM wave in a waveguide of the type under consideration - in a gyrotron in the superradiance mode was considered in [18-19]. However, a more general problem of forming a waveguide-resonance field, which is initiated by the field of an ensemble of particles - rotating electrons, is of interest. The appearance of a waveguide resonant field occurs due to reflection from the ends of the waveguide, taking into account the interaction of such reflected waves with particles in the volume of the active zone. It is these reflected waves that form a standing wave - a resonant waveguide field.

If the reflection coefficients from the waveguide ends are small and the particle injection rate is low, then the conditions for the dominant excitation of the total eigenfield of the particles are realized, which corresponds to the superradiance modes. The amplitudes of the resonator waveguide field are small. With increasing reflection from the ends and at a higher injection rate, the resonator waveguide field exceeds the total eigenfield of the electron oscillators in the active zone. That is, the traditional mode of generation of the resonator waveguide field is realized. Fig. 2 shows the zones of occurrence of the superradiance mode and excitation of the resonator waveguide field. The waveguide resonator field can be supported by particles in the waveguide volume, or it can be formed only due to reflection effects. It is important to note that the zones of dominance of superradiance and traditional resonator generation are always formed under different conditions of energy exchange between reflected waves and oscillators in the waveguide volume, described by conditions (13) and (14). Note that even with a decrease in the direct effect of oscillators in the volume on reflected waves, which meets conditions (14), the zones of different types of generation shift slightly. This is due to the presence of a total field of oscillators, which is capable of acting as an intermediary between the oscillators in the active zone and the waves reflected from the ends of the resonator, forming the waveguide resonator field. It is noted that the amplitudes of the eigenfields of electron oscillators in different modes differ slightly. The advantage of generation in the radiation mode is an increase in the field amplitude at the end of the system in the direction of electron drift, which greatly simplifies energy extraction and increases the generation efficiency.

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ПРО ОСОБЛИВОСТІ ЗБУДЖЕННЯ ВІДКРИТИХ МАГНІТОАКТИВНИХ ХВИЛЕВОДІВ

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Показано, що в об'ємі відкритого хвилеводу кожен електрон-осцилятор, що обертається в постійному магнітному полі, здатний генерувати хвилю ТЕ, для якої цей хвилевід прозорий. Ефективність генерації визначається швидкістю інжекції електронів і їх поздовжньою швидкістю вздовж осі хвилеводу. Вибрано режим генерації поля поблизу частоти відсічення з низькою груповою швидкістю, порівнянною з поздовжньою швидкістю інжектованих електронів. При цьому поперечна швидкість електронів значно перевищує їх поздовжню швидкість і групову швидкість хвилі. За відсутності відбиття поля від кінців хвилеводу кожен електрон вносить свій внесок у сумарне поле випромінювання, тобто можна вважати, що генерація поля відбувається в режимі надвипромінювання. Показано, що сумарне поле електронного потоку здатне утворювати резонаторне поле, яке складається з двох хвиль, що поширюються назустріч одна одній за рахунок навіть часткового відбиття від кінців хвилеводу. При малому відбитті полів від торців і малій дрейфовій швидкості електронів, що обертаються, домінує режим надвипромінювання, подібно до випадку збудження повністю відкритого хвилеводу. У разі помітного відбиття полів від торців системи при відносно високій швидкості їх поздовжньої інжекції відбиті поля значно перевищують сумарне поле випромінювачів і формується традиційний режим генерації поля хвилевідного резонатора. На площині «поздовжня швидкість руху – коефіцієнт відбиття» представлені зони, де домінує генерація резонаторного поля або генерація в умовах надвипромінювання. Розглянуто два випадки: коли відбиті хвилі утворюються тільки за рахунок відбиття від торців, а також коли враховується вплив активної зони електронів на відбиті хвилі в об'ємі хвилеводу. Суттєво, що середня амплітуда сумарного поля випромінювання частинок змінюється незначно для всіх розглянутих типів генерації. Резонансні ефекти при відбиванні від торців призводять до значного збільшення амплітуди поля хвилеводу.

Ключові слова: *електрони-осцилятори, що обертаються; магнітоактивний хвилевід; резонаторна генерація поля; режим надвипромінювання ТЕ хвилі.*