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THE WAVE GENERATION MODES IN AN OPEN WAVEGUIDE

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The excitation of a TE cyclotron wave at the waveguide cutoff frequency by a cylindrical beam of continuously injected electrons whose transverse rotation velocity exceeds their longitudinal velocity in the direction of a constant magnetic field is considered. It is shown that the beam particles initially generate a self-field – the sum of the radiation fields of individual electrons in the waveguide transparency region – which, due to reflection effects from the output end, is capable of shaping the waveguide field in the form of a standing wave. Regions of priority self-field excitation – essentially, superradiance fields – and regions where waveguide field generation dominates are presented (on the "reflection coefficient–longitudinal electron drift velocity" phase plane). The intensity of the induced self-field significantly exceeds the spontaneous emission level of the particle ensemble and remains virtually unchanged for all generation modes, reaching a maximum near the waveguide output end. The amplitude of the waveguide field increases with increasing reflection coefficient and electron drift velocity and then significantly exceeds the amplitude of the particle self-radiation field.

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INTRODUCTION

In [1–4], waveguide modes of TE cyclotron wave generation at the cutoff frequency of a partially open metal waveguide by a thin cylindrical beam of electrons whose transverse velocity exceeds their longitudinal velocity in the direction of a constant magnetic field were considered. However, in the present work, it is shown that the beam particles initially create a self-field – the sum of their radiation fields in the transparency region of the waveguide – which, due to the effects of reflection from the output end, is capable of forming a waveguide field in the form of a standing wave. In the present work, the influence of this self-field of continuously injected electrons on the formation of a waveguide field under conditions of partial reflection from the output end of the waveguide is investigated for different values of the reflection coefficient and depending on the longitudinal drift velocity of the rotating electron beam. This process of waveguide field formation occurs due to the effects of reflection from the ends of the system and the interaction of reflected waves with particles in the active zone. At low reflection coefficients, the self-field of the particles dominates, which is analogous to the superradiance regime. With increasing reflection coefficient and beam drift velocity, the formation of a waveguide field is observed, significantly exceeding the total eigenfield of the active particles.

The aim of this work is to study the excitation of oscillations in the superradiance mode in an open waveguide and the formation of a waveguide field under various reflection conditions from the waveguide output end and depending on the beam particle drift velocity.

1. PARTICLE OWN FIELD AND WAVEGUIDE FIELD

Let us consider the excitation of a TE electromagnetic wave, whose electric vector is perpendicular to the waveguide axis, with a frequency ω and wave vector $\vec{k} = (k_{ms}, 0, k_z)$ in a smooth metal cylindrical waveguide of radius r_w, by an electron beam in resonance cases $\omega \approx \omega_B$, where ω_B is the cyclotron frequency of electron rotation. Generation is considered near the cutoff frequency, where the group velocity of the wave is small, $v_g \ll c$. Induction of a constant magnetic field $\vec{B} = (0, 0, B)$. The electron beam occupies a cylindrical layer in the waveguide cross section, which we will assume to be sufficiently thin. All centers of Larmor rotation of electrons with radius r_B are located at the same distance from the waveguide axis r_C. Each such electron rotating in a constant magnetic field (effectively an oscillator) is capable of generating a TE wave, for which this waveguide is transparent.

The traditional description of the waveguide field excitation process (under conditions of significant reflection from the waveguide ends) assumes that direct interactions between particles in the active zone are neglected. In this generation model, particles interact only with the waveguide field. The equations for the longitudinal component of the magnetic field, electromagnetic waves propagating in both directions (the interference of which constitutes the waveguide field), are as follows [5]:

$$\mathrm{B}_{wg}(Z) = \frac{1}{2}[\mathrm{B}_{wg+}\,\mathrm{e}^{2\pi iZ} + \mathrm{B}_{wg-}\,\mathrm{e}^{-2\pi iZ}], \qquad (1)$$

where the complex amplitudes of running waves $\mathrm{B}_{wg+}, \mathrm{B}_{wg-}$ are found from equations

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

When the condition $|\partial \mathrm{B}_{wg\pm}/\partial\tau| < \theta|\mathrm{B}_{wg\pm}|$, is satisfied (where $\theta = 2v_g/d \cdot \delta_e$ – is the ratio the attention decrement $2v_g/d$ to the maximum increment δ_e, and d is the waveguide size, chosen for simplicity of description to be equal to the wavelength of the excited wave), equation (2) can be rewritten as

$$\mathrm{B}_{wg\pm} = \frac{i}{2N\theta}\cdot\sum_{j=1}^{N} a_j\cdot J_1^{'}(a_j)\cdot \mathrm{e}^{-2\pi i\zeta_j \mp 2\pi i Z_j} \qquad (3)$$

we will also take into account the waves reflected from the ends of the system, which will be defined below

$$\mathrm{B}_{ref}(Z) = \mathrm{B}_{ref+}\,\mathrm{e}^{2\pi iZ} + \mathrm{B}_{ref-}\,\mathrm{e}^{-2\pi iZ}. \qquad (4)$$

Then, if we take into account the influence of particles in the volume and reflected waves, the waveguide field can be represented as follows

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

Equations of motion for electrons rotating in a constant magnetic field

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

$$\frac{da_i}{d\tau} = \mathrm{Re}\{i\cdot J_1^{'}(a_i)\cdot \mathrm{e}^{2\pi i\zeta_i}\cdot \mathrm{B}(Z_i,\tau)\}, \qquad (7)$$

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

$$\frac{d\eta_i}{d\tau} = 2\pi\frac{d^2Z_i}{d\tau^2} = \mathrm{Re}\{iR\cdot a_i\cdot J_1^{'}(a_i)\,\mathrm{e}^{2\pi i\zeta_i}\cdot \mathrm{B}(Z_i,\tau)\}, \qquad (8)$$

$$2\pi dZ_i/d\tau = \eta_i, \qquad (9)$$

where $i\in[1\div N]$, N – the number of large particles, that model the beam.

The proper radiation field of particles. Superradiance modes. However, in reality, initially, a combined radiation 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. This is because an oscillator is capable of emitting only waves located 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 of radiation by the particle ensemble would be called the superradiance mode, provided, of course, that phase synchronization of the oscillators subsequently occurs, which is observed after overcoming the threshold caused by noise. 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 what it is (see, for example, [6]). Phase synchronization and the formation of a noticeable coherence of the self-radiation field of a particle ensemble in the active zone of an open waveguide with a large dispersion (scattering) of the initial oscillator amplitudes (here, the Larmor radii of rotation of the electrons) generally requires an initiating external field and noise attenuation to accelerate the generation process [7]. However, it turned out that in the absence of dispersion of the initial oscillator amplitudes and the absence of noise, an external field is not required; the development of the generation process and the phase synchronization of the waves emitted by each electron in the superradiance mode occur significantly faster.

We assume that the waveguide field (2) is absent in the absence of reflections, and there is only a superradiance field, that is, a field determined solely by the interaction of rotating electrons. To describe the magnetic field of TE waves excited by this ensemble of rotating electrons, we can use the expression [4, 8]

$$\mathrm{B}_{sr}(Z) = \frac{i}{2N\theta}\sum_{j=1}^{N} a_j J_1^{'}(a_j)\,\mathrm{e}^{-2\pi i\zeta_j}\cdot \mathrm{e}^{2\pi i|Z-Z_j|}. \qquad (10)$$

The total field (component of the magnetic field of radiation) acting on the beam electrons is written as

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

The equations for fields (2), (10) and (11) with the equations of motion (6) – (9) use the following variables:

$$\tau = \delta_e t, \quad \delta_e^2 = \frac{4e^2\cdot\omega_B\cdot \mathrm{N}_{b0}\cdot J_{m-n}^2(k_{ms}\cdot r_C)}{m_e\cdot c\cdot k_{ms}^2\cdot r_w\cdot J_m^2(x_{ms})\cdot\left(1-\frac{m^2}{x_{ms}^2}\right)\cdot D_\omega},$$

$$D_\omega = \frac{\partial D}{\partial\omega} = \frac{\partial}{\partial\omega}\left(\frac{\omega^2-(k_z^2+k_{ms}^2)c^2}{\omega^2-k_z^2c^2}\right)\Bigg|_{D=0}, \quad R_e = \frac{k_z^2\cdot\omega_B}{k_{ms}^2\cdot\delta_e},$$

$B = e\cdot b_B\cdot J_{m+n}(k_{ms}\cdot r_C)/m_e\cdot c\cdot\delta_e$, $Z_j = kz_j/2\pi$ – the position of the electron's center of rotation along the waveguide axis, $a = k_{ms}r_B = k_{ms}v_\Phi/\omega_B$, $\omega_B = eB_0/m_e c$, B_0 – constant magnetic field in the waveguide; N_{b0} – the number of particles (electrons) of the undisturbed beam per unit length. Here b_B – the amplitude of the wave, where the longitudinal component of the magnetic field of the wave has the form $B = B_z = b_B\cdot J_m(k_{ms}r)\cdot\exp\{-i\omega t + ik_z z + im\vartheta\}$ in a cylindrical coordinate system (r, ϑ, z), m – integer, $J_m(x)$ и $J_m^{'}(x) = dJ_m(x)/dx$ – Bessel function and its derivative. The requirement that the tangential component of the field vanishes at the walls of the waveguide determines the values of the transverse wave number $k_\perp = k_{ms} = x_{ms}/r_w$, and x_{ms} – s – root of the equation $dJ_m(x)/dx = 0$, $\theta = 2v_g/d\cdot\delta_e$ – maximum increment ratio δ_e to the attenuation decrement here due to radiation from the ends of the system $2v_g/d$.

Reflection conditions. The reflected field amplitudes are obtained from the incident/reflected field balance equations at the boundaries

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

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

Finally

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

$$\mathrm{B}_{ref-} = \frac{r_r\left(r_l(\mathrm{B}_{sr-}+0.5\,\mathrm{B}_{wg-}) - (\mathrm{B}_{sr+}+0.5\,\mathrm{B}_{wg+})\right)}{(1-r_l\cdot r_r)}. \qquad (13)$$

2. NUMERICAL SOLUTION OF THE PROBLEM

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

Instead of the particles, leaving the waveguide, electrons are introduced at its beginning, so that the total number of particles in the waveguide remains constant. The amplitude, velocity, and phase of the new (replacement) particles are the same as those of the particles at the initial instant:

$a_{new} = a_0 = 1, \quad \eta_{new} = \eta_0, \quad \zeta_{new} \in (0, 2\pi)$.

Constant parameters were used in the calculations $N = 500, \ \theta = 1, \ \alpha = 0.5, \ a_0 = 1, \ R = 0.1, \ r_L = 1$ (total reflection on the left edge).

The calculations change r_R – output reflection coefficient (right edge) and η – longitudinal velocity of incoming particles.

Previously [8], a graph of the separation of generation modes was obtained: on the left is the region of dominance of generation in the superradiance mode, on the right is the region of dominance of the generation of waveguide modes (Fig. 1).

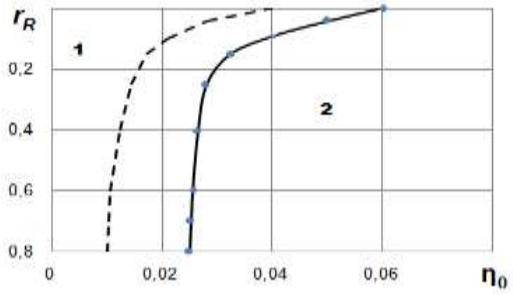


Fig. 1. Boundaries between generation modes on the plane "reflection coefficient at the right edge – particle injection velocity (thick solid line)". The dotted line corresponds to the boundary of the regions in the case where the average particle velocity in the waveguide volume is used, rather than the initial velocity of the injected particles

In region 1, the generation of the particle's own field dominates (in fact, the superradiance mode), while in region 2, the generation of a resonator waveguide field of the traditional type, caused by reflection processes from the ends, dominates [9].

3. DISCUSSION OF GENERATION MODES

The injected particles have an initial amplitude $a^2 = 1$.

The average amplitude of particles exiting the waveguide is less than unity $< a_{ex}{}^2 > < 1$ and characterizes the efficiency of energy transfer from the particles to the generated field. Table 1 shows the value $< a_{ex}{}^2 >$ for each calculation (average value of the squared amplitudes of the outgoing particles for the case of the total field = the sum of the waveguide field in the active zone and the field reflected from the ends of the waveguide (5)). Averaging is performed over the range $\tau = 200\ldots800$, $(1 - < a_{ex}{}^2 >)$ is the particle energy retained in the waveguide.

Table 1

Average particle energy at the system exit $< a_{ex}{}^2 >$

r_R	η			
	0.03	**0.06**	**0.1**	**0.15**
0.0	0.773	0.737	0.937	0.973
0.2	0.781	0.791	0.718	0.944
0.4	0.789	0.820	0.751	0.851
0.6	0.822	0.871	0.807	0.801
0.8	0.908	0.890	0.864	0.861

It can be shown that if all particles are localized at one point in space, the field will be absolutely coherent, and the maximum proper field of the particles (the superradiance field) can reach the value

$$| B_{sr} |_{\max} = \frac{1}{2N\theta} \sum_{j=1}^{N} 1 \cdot J_1'(1) = \frac{J_1'(1)}{2\theta} \approx \frac{0.325}{2\theta} \approx 0.16 \cdot \theta^{-1}. \quad (14)$$

With the number of modeling particles N=500, the random (spontaneous) field of particles in the system can have an amplitude $0.16 \cdot 1/\sqrt{N}$ = 0.008. The intensity of the particles' intrinsic field is more than an order of magnitude greater than the intensity of the spontaneous level (Table 2), meaning that the particles' intrinsic field can be considered an induced field.

Table 2

Ratio of averaged values of the field amplitude maxima envelope $< (B_w)_{\max} > / < (B_{sr})_{\max} >$

r_R	η			
	0.03	**0.06**	**0.1**	**0.15**
0.0	0.00835 0.01075	0.0141 0.0219	0.02175 0.01583	0.01639 0.01221
0.2	0.0108 0.0115	0.01951 0.0213	0.04043 0.02555	0.02932 0.01451
0.4	0.0099 0.0122	0.0309 0.0206	0.05441 0.02231	0.05754 0.01899
0.6	0.0146 0.0161	0.03313 0.02189	0.06915 0.02066	0.09552 0.01884
0.8	0.0168 0.0155	0.04011 0.02565	0.09144 0.02310	0.1284 0.01738

In Table 2 $< (B_w)_{\max} >$, $< (B_{sr})_{\max} >$ – averaged values of the envelope of the maximum amplitude of the corresponding fields (averaging over the time range $\tau = 200\ldots800$).

Table 3

Ratio of maximum amplitude values $(B_w)_{\max} / (B_{sr})_{\max}$

r_R	η			
	0.03	**0.06**	**0.1**	**0.15**
0.0	0.016 0.028	0.029 0.038	0.042 0.025	0.035 0.023
0.2	0.020 0.019	0.036 0.040	0.069 0.035	0.059 0.025
0.4	0.023 0.027	0.054 0.032	0.101 0.034	0.101 0.032
0.6	0.030 0.027	0.058 0.034	0.109 0.029	0.148 0.030
0.8	0.037 0.031	0.067 0.038	0.158 0.037	0.201 0.029

In Table 3 $(B_{sr})_{\max} = \max_{Z\in[0,1],\,\tau\in[200,800]} B_{sr}(Z,\tau)$, $(B_w)_{\max} = \max_{Z\in[0,1],\,\tau\in[200,800]} B_w(Z,\tau)$ – the maximum values of the amplitudes of the corresponding fields in the time range τ = 200…800.

1. The amplitudes of the particles own field, when averaging the envelope of its maximum values with increasing velocity and for different reflection coefficients, change only slightly, since reflection does not act directly on them, but only very indirectly through the waveguide field, which acts on the particles.

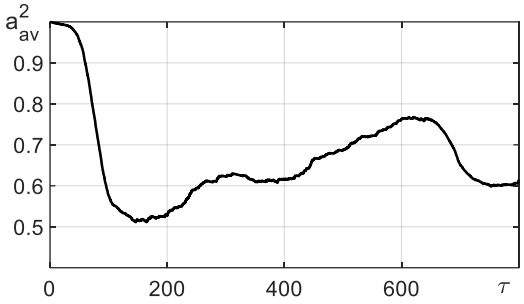


Fig. 2. Time dependence of the volume-averaged square of particle amplitudes. $N = 500,\ \theta = 1,\ \alpha = 0.5,$ $a_0 = 1,\ R = 0.1,\ r_L = 1,\ r_R = 0,\ \eta_0 = 0.03$

At a speed of 0.03, the particle travels the wavelength = the size of the waveguide in τ = 210 (Figs. 2, 3). The first group of particles passes the waveguide during this time and gives half of their energy to the fields (at zero reflection) to the particle field, that is, the superradiance field), then an exchange of energy is observed between the field and the particles.

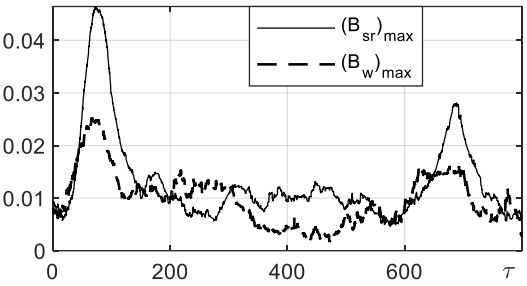


Fig. 3. Time dependence of the maximum amplitudes of the waveguide field $(B_w)_{\max}$ *and the particle field* $(B_{sr})_{\max}$ *in the waveguide volume.* $N = 500,\ \theta = 1,$ $\alpha = 0.5,\ a_0 = 1,\ R = 0.1,\ r_L = 1,\ r_R = 0,\ \eta_0 = 0.03$

At high speeds, the maximum energy extraction occurs during the flight of the first batch of particles (at a speed of 0.06 for a time of about τ = 100) and then an exchange of energy between the field and the particles is observed (Fig. 4).

At even higher velocities, for example, 0.15, the particles do not have time to transfer energy to the field, and the efficiency of particle interaction with their self-field decreases significantly, regardless of reflection conditions, which generally has only a weak effect on the generation of the self-field.

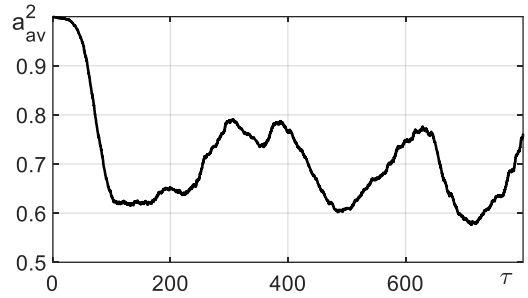


Fig. 4. Time dependence of the volume-averaged square of particle amplitudes. $N = 500,\ \theta = 1,\ \alpha = 0.5,$ $a_0 = 1,\ R = 0.1,\ r_L = 1,\ r_R = 0,\ \eta_0 = 0.06$

2. The waveguide field at low velocities is smaller than or comparable to the particle's self-field, but with increasing particle drift velocity, it exhibits an increase, which significantly increases with increasing reflection coefficient. At high reflection coefficients, the intensity of the waveguide field is already one to two orders of magnitude greater than the intensity of the particle's self-field, and increasing drift velocity even significantly increases this ratio.

The reason for this, of course, is that reflection from the ends of both the self-field and the waveguide field amplifies only the reflected component of the waveguide field, which is a standing wave. Therefore, only the energy of the waveguide field accumulates in the generation mode with noticeable reflection from the ends (Fig. 5).

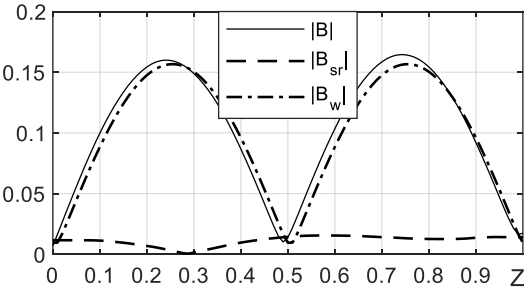


Fig. 5. The amplitudes of the waveguide field B_w*, the particle field* B_{sr} *and the total field* $B = B_w + B_{sr}$ *at* $N = 500,\ \theta = 1,\ \alpha = 0.5,\ a_0 = 1,\ R = 0.1,\ r_L = 1,\ r_R = 0.8,$ $\eta_0 = 0.15,\ \tau = 800$

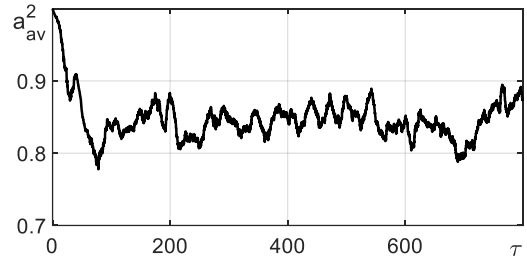


Fig. 6. Time dependence of the volume-averaged square of the particle amplitudes at $N = 500,\ \theta = 1,\ \alpha = 0.5,$ $a_0 = 1,\ R = 0.1,\ r_L = 1,\ r_R = 0.8,\ \eta_0 = 0.15$

It should be noted that in the superradiance mode, energy extraction from beam particles exceeds energy extraction during dominant waveguide field generation.

The relatively low efficiency of energy extraction from particles in the waveguide mode is compensated for by the accumulation of energy from this field due to reflection effects from the ends (Fig. 6).

3. The characteristics of the superradiance mode at low particle drift velocities and low reflection from the system's output end include the highest values of the particles own field at the waveguide's output end, while the waveguide field (which is formed due to reflection effects from the system's input end) is significantly weaker (Fig. 7). This generation mode may prove preferable if the highest field amplitude at the system's output is achieved.

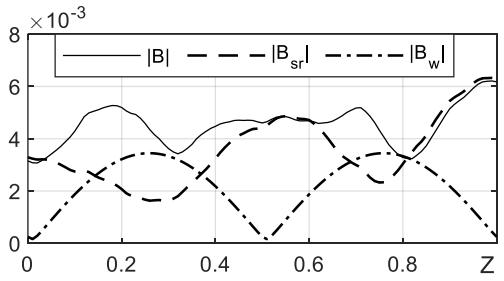


Fig. 7. Amplitudes of the waveguide field B_w *, particle field* B_{sr} *and total field* $B = B_w + B_{sr}$ $B = B_w + B_{sr}$ *at* $N = 500,\ \theta = 1,\ \alpha = 0.5,\ a_0 = 1,\ R = 0.1,\ r_L = 1,\ r_R = 0,$ $\eta_0 = 0.03,\ \tau = 800$

It is also important to note that the efficiency of particle phase synchronization near the output end of the system, as shown in Part 3 of the review [8], significantly increases, promising noticeable radiation coherence. This also explains the increase in the amplitude of the particle's self-field at the output end of the waveguide

4. In all waveguide modes, the maximum amplitude of the waveguide field is most often observed in the depth of the waveguide. The fact that the waveguide field turns out to be unexpectedly large at high reflection coefficients is due to the process of field accumulation in the waveguide resonator due to reflections from the ends of the system.

CONCLUSIONS

This paper investigates the excitation of TE cyclotron electromagnetic oscillations at the waveguide cutoff frequency by a thin cylindrical beam of electrons rotating in a constant magnetic field. Initially, a net radiation field of interacting beam electrons arises at the waveguide transparency frequency. In the absence of reflections from the waveguide ends, this field can be considered a superradiance field. In the case of non-zero reflection coefficients from the waveguide ends, the effect of this field on the generation of waveguide modes is demonstrated.

This net beam electron eigenfield is the sum of the radiation emitted by each particle in the transparency region of the waveguide medium. Note that, for a small spread of the initial electron energy and a low noise level, the intensity of the particle eigenfield significantly exceeds the spontaneous level and represents induced radiation [7]. In the absence of reflections from the ends, such eigenradiation of the beam electrons at the waveguide transparency frequency has all the characteristics of superradiance. It has been shown that at low field reflection coefficients from the ends and low electron drift velocities in the longitudinal direction, the self-radiation field of the particles dominates, corresponding to the superradiance regime. The superradiance field amplitude near the waveguide output end is greatest, in part due to the increasing number of active particles along the waveguide, whose phases are synchronized with the phase of the total field. This generation regime may prove preferable if the highest field amplitude at the system output is achieved.

It has been shown that this self-radiation of the beam electrons can form a waveguide field (representing a standing wave) due to reflection from the system ends and the interaction of the reflected waves with particles in the active zone. With increasing reflection from the system ends and with increasing longitudinal drift velocity of the beam particles, the amplitude of the waveguide field can exceed the amplitude of the total self-radiation field of the active particles. Moreover, the maximum amplitude of the waveguide field is most often observed deep in the waveguide. It is important to note that the intensity of the particle's self-radiation field remains virtually unchanged across different generation modes (although it significantly exceeds the spontaneous level and represents induced emission).

At high reflection coefficients, due to the accumulation of field energy in the waveguide resonator due to reflections from the system's ends, the intensity of the waveguide field can significantly exceed the intensity of the particle's self-radiation field, i.e., the traditional description, where beam particles interact only with the waveguide mode, is justified to a certain extent. Thus, at high reflection coefficients from the system's ends, the waveguide field dominates, and the total self-radiation field of the electrons can be neglected in this case. This, to some extent, clarifies previous approaches to describing the processes of generation and amplification by charged particles in high-Q waveguides with high field reflection coefficients from the ends.

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РЕЖИМИ ГЕНЕРАЦІЇ ТЕ ХВИЛІ У ВІДКРИТОМУ ХВИЛЬОВОДІ

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Розглянуто збудження ТЕ циклотронної хвилі на частоті відсічення хвилеводу циліндричним пучком електронів, що постійно інжектуються, поперечна швидкість обертання яких перевищує їх поздовжню швидкість у напрямку постійного магнітного поля. Показано, що частинки пучка спочатку створюють власне поле – суму полів випромінювання у галузі прозорості хвилеводу окремими електронами, – яке за рахунок ефектів відбиття від вихідного торця здатне формувати поле хвилеводу в вигляді стоячої хвилі. Представлено (на фазовій площині «коефіцієнт відбиття – швидкість поздовжнього дрейфу електронів») області пріоритетного порушення власного поля – фактично поля надвипромінювання та області, де домінує генерація хвилеводного поля. Інтенсивність власного індукованого поля значно перевищує спонтанний рівень випромінювання ансамблю частинок і практично не змінюється для всіх режимів генерації, досягаючи максимуму поблизу вихідного торця хвилеводу. Амплітуда хвилеводного поля зі збільшенням коефіцієнта відбиття та швидкості дрейфу електронів зростає і помітно перевищує амплітуду власного поля випромінювання частинок.