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Longitudinal Magnetic Field Effect on Wave Dynamics in Multiharmonic Superheterodyne FEL of Dopplertron Type with Helical Electron Beam

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We performed the analysis of the longitudinal magnetic field influence on the amplification characteristics of the plasma-beam superheterodyne free-electron laser of dopplertron type with a helical relativistic electron beam in the framework of cubic nonlinear approximation. A right-polarized slow electromagnetic wave propagating towards the electron beam in the magnetized plasma-beam environment was used as pumping in the system under investigation. Based on the method of averaged characteristics, we acquired the system of differential equations describing the dynamics of harmonics of wave amplitudes. The saturation levels of electromagnetic waves were established. We took account of plural three-wave parametric resonant interactions of the space charge wave. We found out that such plural resonant interactions have a significant influence on the amplification properties of the investigated plasma-beam superheterodyne free-electron laser. In particular, they lead to the reduction of the saturation levels two times and more. We demonstrated that reduction of the longitudinal focusing magnetic field strength down to a certain critical value leads to the significant increase of the amplification rates along with the saturation levels of the electromagnetic signal wave (ten times and more). We have defined the minimal value of the magnetic field strength (critical value of the magnetic field strength) for the amplification regime in which the right-polarized electromagnetic wave is used as pumping. It is found that the investigated effect is related to the dependence of the conditions of the three-wave parametric resonance of the signal, pumping and the space charge wave on the longitudinal magnetic field strength. The growth rate related to the abovementioned three-wave resonant interaction depends substantially on the focusing magnetic field strength. We have demonstrated that plasma-beam superheterodyne free-electron laser of dopplertron type with a helical relativistic electron beam is able to form powerful coherent electromagnetic radiation in the millimeter wavelength band.

Keywords: Superheterodyne free-electron laser, Plasma-beam instability, Parametric resonance, Helical relativistic electron beam, Focusing magnetic field.

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1. INTRODUCTION

Sources of powerful electromagnetic radiation in millimeter-submillimeter wavebands constantly attract the attention of researchers. These devices can be applied in various fields of physics, chemistry, biology, medicine and defense technology [1-4]. Plasma-beam superheterodyne free-electron lasers (FELs) are such radiation sources [1, 5-11]. They stand out amongst the different types of devices operating in the same waveband due to high amplification rates achieved due to the additional amplification mechanism. This mechanism is based on plasma-beam instability.

Current work is aimed to find the optimal operation regimes of plasma-beam superheterodyne FELs (PBSFELs). One of the ways to increase the amplification rates in such devices is to use helical relativistic electron beams (REBs) [6]. This effect has the relativistic character. It is linked to the change in the longitudinal kinetic energy of electrons in the beam and hence to the increase of plasma-beam instability growth rate due to electron longitudinal velocity increase.

This paper continues the search for the ways to increase the amplification rates of waves in PBSFELs with helical electron beams. It is known that the longitudinal magnetic field can significantly affect the wave dynamics in FELs. In particular, it can enhance the device's effectiveness [7-11]. In current research we have found that this effect takes place in the studied PBSFEL. It turns out that significant increase of saturation levels (tens and more times!) and amplification rates occurs with the decrease of longitudinal magnetic field strength to a certain critical value.

2. MODEL

As a model of studied device we consider the plasma environment with plasma frequency ω_p which is passed through by helical relativistic electron beam with the Langmuir frequency ω_b ($\omega_b \ll \omega_p$). The velocity vector of the beam's electrons $\mathbf{\upsilon}_b$ is directed at an angle β with respect to the Z axis of the device in a way that $\mathrm{tg}\beta = \upsilon_{b\perp} / \upsilon_{bz}$, where $\upsilon_{b\perp}$ and υ_{bz} are the vector's longitudinal and transverse components. The focusing magnetic field with the strength H_0 is directed along the Z axis of the system. We select the system parameters in such a way that the cyclotron frequency ω_H of electrons rotating in the longitudinal magnetic field is much less than the plasma frequency ($\omega_H \ll \omega_p$).

We use powerful low-frequency circularly-polarized slow electromagnetic wave with frequency $\omega_{2,1}$ and wavenumber $k_{2,1}$ propagating along the Z axis towards the electron beam ($\omega_{2,1} \ll \omega_H$) as pumping. We also supply the high-frequency circularly-polarized electromagnetic signal wave with frequency $\omega_{1,1}$ and wave-

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number $k_{1,1}$. As a result of three-wave parametric resonance between electromagnetic waves of the signal and the pumping, a space charge wave (SCW) is excited in the plasma environment. The condition of parametric resonances between these waves is:

$$\omega_{3,1} = \omega_{1,1} - \omega_{2,1}\,,\ k_{3,1} = k_{1,1} + k_{2,1}\,, \qquad (1)$$

where $\omega_{3,1}$ and $k_{3,1}$ are the frequency and the wave-number of the first SCW harmonic.

PBSFEL uses the effect of superheterodyne amplification [1, 5, 6]. Its essence is in use of an additional amplification mechanism for one of three waves interacting in three-wave parametric resonance. The amplification of SCW due to the plasma-beam instability is used as such mechanism in the FEL under study [1, 3, 12]. We choose the device parameters in order to achieve maximum SCW gain due to plasma-beam instability. It is known that the growth rates of the plasma-beam instability are extremely high [1, 3, 12]. Thus, the resulting amplification rate of the electromagnetic wave in the FEL under study also appears to be high. So, PBSFELs have better amplification characteristics than any other FELs exactly due to the additional amplification mechanism.

Another feature of such devices is the fact that the SCW growing due to the plasma-beam instability is characterized by the quasilinear dispersion dependence [1, 5, 6]:

$$k_{3,m} \approx \omega_{3,m} / \upsilon_{bz}\,, \qquad (2)$$

where m stands for the harmonic number, $k_{3,1}$ and $\omega_{3,m} = \omega_{3,1}\cdot m$ are the wavenumber and the frequency of the m^{th} harmonic respectively. It means that the frequencies and wavenumbers of m^{th} harmonic are proportional to the harmonic number m. Therefore, a number of three-wave parametric resonances occur between SCW harmonics

$$\omega_{3,m_1} = \omega_{3,m_2} + \omega_{3,m_3}\,,\ k_{3,m_1} = k_{3,m_2} + k_{3,m_3}\,, \qquad (3)$$

where m_1, m_2, m_3 are the numbers of the interacting harmonics. Considering (2), equations (3) reduce to the relation

$$m_1 = m_2 + m_3\,. \qquad (4)$$

Note that m_1, m_2, m_3 are integers. Thus, the condition (4) can be fulfilled in a lot of ways, e.g. $2 = 1 + 1$, $3 = 2 + 1$, etc. Such three-wave interactions lead to the excitation of higher SCW harmonics. Plural three-wave resonant interactions of SCW harmonics that satisfy conditions (3) are considered during the analysis of wave dynamics in PBSFEL.

3. BASIC EQUATIONS

To achieve the equations describing the dynamics of wave amplitudes in the investigated device, we apply the quazihydrodynamic equation [1, 3], the continuity equation and Maxwell's equations. The quazihydrodynamic equation is solved by means of the averaged characteristics method [1], the continuity equation and Maxwell's equations – by slowly varying amplitudes method.

We neglect the electron velocity spread and their collisions. According to the method of averaged characteristics, we pass to the characteristics of the quazihydrodynamic equation. In the achieved equations we represent the beam electron velocity components υ_{bx} and υ_{by} through the perpendicular velocity component $\upsilon_{b\perp} = \sqrt{\upsilon_{bx}^2 + \upsilon_{by}^2}$ and the electron rotation phase p_{b0}: $\upsilon_{bx} = \upsilon_{b\perp} \cos p_{b0}$, $\upsilon_{by} = \upsilon_{b\perp} \sin p_{b0}$. Such transition is explained by the fact that electrons move along the circle in the longitudinal focusing magnetic field. Then the initial movement equations take the form:

$$\frac{d\upsilon_{b\perp}}{dt} = \frac{e}{m_e\gamma_b}\left[\cos p_{b0}\left(E_x - \frac{\upsilon_{bz}}{c}B_y\right) + \right.$$
$$\left. + \sin p_{b0}\left(E_y + \frac{\upsilon_{bz}}{c}B_x\right) - \frac{\upsilon_{b\perp}(\mathbf{E}\boldsymbol{\upsilon})}{c^2}\right], \qquad (5)$$

$$\frac{dp_{b0}}{dt} = -\frac{\omega_H}{\gamma_b} + \frac{e}{m_e\gamma_b\upsilon_{b\perp}}\left[\cos p_{b0}\left(E_y + \frac{\upsilon_{bz}}{c}B_x\right) - \right.$$
$$\left. - \sin p_{b0}\left(E_x - \frac{\upsilon_{bz}}{c}B_y\right)\right], \qquad (6)$$

$$\frac{d\upsilon_{bz}}{dt} = \frac{e}{m_e\gamma_b}\left[E_z + \frac{\upsilon_{b\perp}}{c}\times \right.$$
$$\left. \times\left(B_y \cos p_{b0} - B_x \sin p_{b0}\right) - \frac{\upsilon_{bz}(\mathbf{E}\boldsymbol{\upsilon})}{c^2}\right], \qquad (7)$$

$$\frac{d\gamma_b}{dt} = \frac{e}{m_e c^2}\left[E_x\upsilon_{b\perp}\cos p_{b0} + E_y\upsilon_{b\perp}\sin p_{b0} + E_z\upsilon_{bz}\right]. \qquad (8)$$

In equations (5)-(8), E_x, E_y, E_z are the components of the electric field strength of the signal, pumping and SCW, B_x, B_y are the components of the magnetic field induction of the signal and pumping, $\omega_H = eB_0/(m_e c)$ is the cyclotron frequency of the electrons rotating in the longitudinal magnetic field, c is the light speed; $\gamma_b = 1/\sqrt{1-(\upsilon_{bz}^2 + \upsilon_{b\perp}^2)/c^2}$ is the relativistic factor; e and m_e are the electrons charge and mass respectively. We apply the asymptotic integration procedure to this equation system according to the method of averaged characteristics [1]. We acquire velocities as functions of the electric and magnetic fields. After that, we substitute the achieved solutions into the continuity equation and Maxwell's equations, to which we apply the slowly varying amplitude method.

As a result, we get the differential equation system in cubic nonlinear approximation for the complex amplitudes of x and y components of the signal electric field strength (E_{1x}, E_{1y}), of x and y components of the pumping electric field strength (E_{2x}, E_{2y}) and of m^{th} SCW harmonic electric field strength ($E_{3z,m}$):

$$K_2\frac{d^2E_{1x}}{dt^2} + K_1\frac{dE_{1x}}{dt} = K_3E_{3z}E_{2x} + F_{1x}\,, \qquad (9)$$

$$K_2\frac{d^2E_{1y}}{dt^2} + K_1\frac{dE_{1y}}{dt} = K_3\eta_1\eta_2E_{3z}E_{2y} + F_{1y}\,, \qquad (10)$$

$$M_2 \frac{d^2E_{2x}}{dt^2} + M_1 \frac{dE_{2x}}{dt} = M_3 E^*_{3z} E_{1x} + F_{2x}, \quad (11)$$

$$M_2 \frac{d^2E_{2y}}{dt^2} + M_1 \frac{dE_{2y}}{dt} = M_3 \eta_1 \eta_2 E^*_{3z} E_{1y} + F_{2y}, \quad (12)$$

$$C_{2,m} \frac{d^2E_{3z,m}}{dt^2} + C_{1,m} \frac{dE_{3z,m}}{dt} + D_{3m} E_{3z,m} =$$
$$= C_{3,m}(E_{1x,m} E^*_{2x,m} + E_{1y,m} E^*_{2y,m}) + F_{3z,m}. \quad (13)$$

It follows from (9)-(13) that circularly-polarized electromagnetic waves are the eigenwaves for the device under study. In these equations, $K_2 = 0,5 \cdot \partial^2 D_1 / \partial(i\omega_1)^2$; $K_1 = \partial D_1 / \partial(i\omega_1)$; $M_2 = 0,5 \cdot \partial^2 D_2 / \partial(i\omega_2)^2$; $M_1 = \partial D_2 / \partial(i\omega_2)$, where $D_1 = D(\omega_1, k_1)$, $D_2 = D(\omega_2, k_2)$ are the dispersion functions of electromagnetic waves of signal ($\omega_{1,1}$, $k_{1,1}$) and pumping ($\omega_{2,1}$, $k_{2,1}$)

$$D(\omega,k) = \frac{i}{c\omega}\left\{k^2c^2 - \omega^2 + \sum_{\alpha}^{b,p}\left[\frac{\omega_\alpha^2}{\gamma_\alpha\left(\Omega_\alpha + \eta\omega_H/\gamma_\alpha\right)^2} \times \right.\right.$$
$$\left.\left. \times\left(\Omega_\alpha\left(\Omega_\alpha + \eta\omega_H/\gamma_\alpha\right) - \frac{\upsilon^2_{\alpha\perp}}{2c^2}\left(\omega^2 - k^2c^2\right)\right)\right]\right\}. \quad (14)$$

In (9)-(14),

$$\eta_1 = E_{1y,1}/(iE_{1x,1}) = \pm 1, \qquad \eta_2 = E_{2y,1}/(iE_{2x,1}) = \pm 1 \quad (15)$$

are the sign functions characterizing the rotation of the transverse electric field strength vector; $\Omega_\alpha = \omega - k\upsilon_{\alpha z}$. α index takes values b and p; index b stands for the beam parameters, index p – for plasma parameters. In equation (13),

$$D_{3m} = \frac{-im\omega_3}{c}\left(1 - \sum_{\alpha}^{b,p} \frac{\omega_\alpha^2(1 - \upsilon_{\alpha z}{}^2/c^2)}{(m\omega_3 - k_{3,m}\upsilon_{\alpha z})^2 \gamma_\alpha}\right) \quad (16)$$

is the SCW dispersion function, $C_{1,m} = \partial D_{3m} / \partial(i\omega_{3,m})$; $C_{2,m} = 0,5 \cdot \partial^2 D_{3m} / \partial(i\omega_{3,m})^2$, K_3, M_3, $C_{3,m}$ are the differential equation coefficients depending on frequencies, wavenumbers and on the parameters of the investigated system. Functions F_{1y}, F_{2x}, F_{2y}, F_{1x}, $F_{3z,m}$, are the components of the corresponding equations that consider cubic nonlinear components.

The system (9)-(13) should be also supplemented by the equations for the constant components of the velocity and concentration

$$d\upsilon_{b\perp}/dt = V_{b\perp}, \; d\upsilon_{bz}/dt = V_{bz},$$
$$dn_b/dt = N_b, \; dn_p/dt = N_p, \quad (17)$$

where the functions $V_{b\perp}$, V_{bz}, N_b, N_p consider cubic nonlinear components depending on wavenumbers, frequencies, field amplitudes, constant components of velocities and concentrations.

4. ANALYSIS

We perform the analysis of the wave dynamics in PBSFEL in cubic nonlinear approximation using the equation systems (9)-(13), (17). Equation systems (9)-(13), (17) are solved numerically with the following device parameters: plasma frequency is $\omega_p = 1 \cdot 10^{12}$ s^{-1}, beam's Langmuir frequency is $\omega_b = 2 \cdot 10^9$ s^{-1}, beam's relativistic factor is $\gamma = 2$, focusing magnetic field strength is $H_0 = 1.8 \cdot 10^5$ A/m ($\omega_H = 4 \cdot 10^{10}$ s^{-1}), pumping electric field first harmonic is $E_2 = 2.8 \cdot 10^5$ V/m, beam injection angle is $\beta = 20°$.

As follows from [6], this device has four operation regimes. Two of them use right-polarized electromagnetic waves of the signal and pumping, two other use left-polarized waves. Paper [6] demonstrates that the most effective interaction regime is the one with right-polarized waves. Therefore, the further research is conducted for the right-polarized signal and pumping wave interaction regime.

Let us now find out how the plural three-wave parametric resonant interactions (3) of SCW harmonics affect the dynamics of the high-frequency electromagnetic signal wave. Fig. 1 represents the dependences of the signal wave electric field strength first harmonic amplitude on the normalized time $\tau = t \cdot \delta\omega_0$ where $\delta\omega_0$ is the growth rate of plasma-beam instability for the input angle $\beta = 0°$. Here curve 1 represents the calculation results considering interactions of only the first wave harmonic. Curve 2 is acquired considering plural parametric resonances of the first ten SCW harmonics. Comparing curves 1 and 2 in Fig. 1 we can conclude that higher SCW harmonics influence leads to the reduction of the saturation levels more than two times (curve 2). It means that plural resonant interactions between SCW harmonics significantly affect the nonlinear processes in PBSFELs. That is why consideration of such interactions is necessary for the achievement of better quality analysis of wave dynamics in superheterodyne FELs. Further, all calculations are performed considering plural interactions between SCW harmonics.

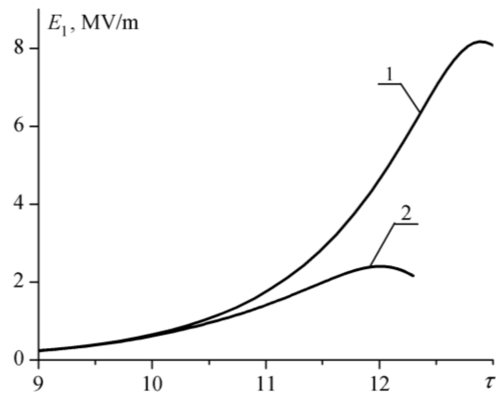

Fig. 1 – Dependence of the signal wave electric field strength E_1 first harmonic amplitude on the normalized time $\tau = t\,\delta\omega_0$ for the input angle $\beta = 0°$. Curve 2 is calculated considering plural parametric resonances of the first ten SCW harmonics, curve 1 is for the case when only one SCW harmonic is considered

Fig. 2 represents the dependences of the signal wave electromagnetic field strength first harmonic amplitudes on normalized times with different field strengths of the longitudinal magnetic field H_0. Curve 1 corresponds to the value $H_0 = 1.8 \cdot 10^5$ A/m ($\omega_H = 4 \cdot 10^{10}$ s^{-1}), curve 2 – to $H_0 = 0.41 \cdot 10^5$ A/m ($\omega_H = 9 \cdot 10^9$ s^{-1}), and curve 3 – to $H_0 = 0.18 \cdot 10^5$ A/m ($\omega_H = 4 \cdot 10^9$ s^{-1}). As follows from Fig. 2, the saturation level of curve 3 exceeds the level of curve 1 more than ten times. At that, in case of curve 1, the magnetic field strength is more than ten times higher than in case of curve 3. Therefore, the reduction of the longitudinal magnetic field leads to the significant increase in both saturation levels and amplification rates of the electromagnetic signal wave. Note that the magnetic field strength can only be reduced to certain critical value H_{0cr}. Further reduction leads to the violation of the three-wave parametric resonance conditions and investigated device becomes unable to operate. We should also note that the electric field strength reaches magnitudes of ~ 2.4 MV/m in the saturation region. Signal wavelength is $\lambda_1 = 2\pi c/\omega_1 \approx 1.9$ mm. Thus, PBSFEL can operate as the powerful source of the electromagnetic radiation in the millimeter waveband.

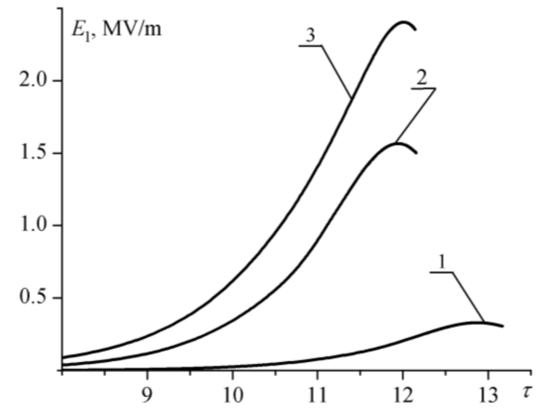

Fig. 2 – Dependence of the signal wave electric field strength E_1 first harmonic amplitude on the normalized time $\tau = t\,\delta\omega_0$ for the input angle $\beta = 20°$ Curve 1 is calculated at the longitudinal magnetic field strength $H_0 = 1.8 \cdot 10^5$ A/m, curve 2 – at $H_0 = 0.41 \cdot 10^5$ A/m, curve 3 – at $H_0 = 0.18 \cdot 10^5$ A/m

In order to understand the wave dynamics represented in Fig. 2, we analyze the influence of the longitudinal magnetic field on the parametric growth rate α_{par} of the waves in the device under study. Parametric growth rate can be found from the system (9)-(13), where we neglect cubic components. As a result, we get

$$\alpha_{par} = \sqrt{\frac{K_{3,1}C_{3,1}(1+\eta_1\eta_2)}{K_{1,1}C_{1,1}} \, | E_{2x,1} |^2} \,, \qquad (18)$$

where $K_{1,1}$, $K_{3,1}$, $C_{1,1}$, $C_{3,1}$ depend on the magnetic field strength H_0. Fig. 3 demonstrates the parametric growth rate α_{par} normalized on plasma-beam instability growth rate $\delta\omega_0$ depending on the cyclotron frequency $\omega_H(H_0)$. It follows from Fig. 3 that the parametric growth rate increases with the decrease of the cyclotron frequency up to the critical value ω_{Hcr}. Signal wave amplification rates, in their turn, are defined by the total growth rate depending on both the plasma-beam and parametric growth rates. Thus, the reduction of the longitudinal magnetic field strength leads to the increase of the total amplification rates. Therefore, the signal wave in case of curve 3 in Fig. 2 grows faster than in case of curves 1 and 2. So, the reduction of magnetic field strength to the critical value H_{0cr} significantly (more than ten times) enhances amplification characteristics of PBSFEL of dopplertron type with helical REB.

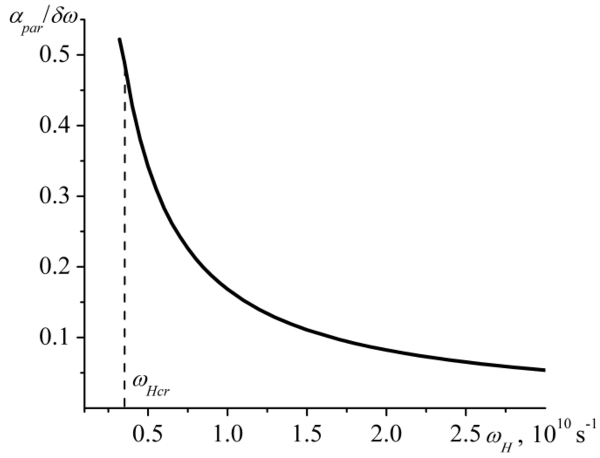

Fig. 3 – Dependence of the parametric growth rate $\alpha_{par}/\delta\omega$ normalized on plasma-beam instability growth rate $\delta\omega$ on the cyclotron frequency ω_H

5. CONCLUSIONS

We performed a cubic-nonlinear analysis of the longitudinal magnetic field influence on the wave dynamics in PBSFEL of dopplertron type with helical REB. The right-polarized slow electromagnetic wave propagating in magnetized plasma-beam system towards electron beam was used as pumping in the device under study. We accounted plural parametric resonant interactions of the SCW harmonics. It was found that plural resonant interactions lead to the reduction of the signal saturation length twice and more.

We demonstrated that the decrease of the longitudinal magnetic field to the critical value leads to the significant increase of both amplification rate and saturation length (tens and more times). This effect is related to the dependence of parametric growth rate on longitudinal magnetic field strength. We found out that investigated system is able to generate and amplify powerful electromagnetic radiation in millimeter waveband.

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Вплив поздовжнього магнітного поля на динаміку хвиль у мультигармонічному супергетеродинному ЛВЕ доплертронного типу з гвинтовим електронним пучком

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В рамках кубічно-нелінійного наближення проведено аналіз впливу поздовжнього фокусувального магнітного поля на підсилювальні характеристики плазмово-пучкового супергетеродинного лазера на вільних електронах доплертронного типу з гвинтовим релятивістським електронним пучком. В досліджуваному лазері на вільних електронах як накачка використана правополярізована уповільнена електромагнітна хвиля, що розповсюджується назустріч електронному пучку в замагніченій плазмово-пучковій системі. На основі методу усереднених характеристик отримано систему диференціальних рівнянь, які описують динаміку амплітуд гармонік хвиль. Знайдено рівні насичення електромагнітних хвиль. Проведено урахування множинних трихвильових параметричних резонансних взаємодій гармонік хвилі просторового заряду. З'ясовано, що такі множинні резонансні взаємодії істотно впливають на підсилювальні характеристики досліджуваного лазеру на вільних електронах, зокрема, призводять до зменшення рівня насичення сигналу в два і більше разів. Продемонстровано, що зменшення напруженості поздовжнього фокусувального магнітного поля до деякого критичного значення призводить до значного збільшення як темпів підсилення, так і рівнів насичення електромагнітної хвилі сигналу (в десять і більше разів). Визначене мінімальне значення напруженості магнітного поля (критичне значення напруженості магнітного поля) для режиму підсилення, у якому як накачка використовується правополяризована електромагнітна хвиля. З'ясовано, що досліджуваний ефект пов'язаний із залежністю умов трихвильового параметричного резонансу хвилі сигналу накачки та просторового заряду від напруженості поздовжнього магнітного поля. Інкремент зростання, що пов'язаний з вищевказаною трихвильовою резонансною взаємодією, суттєво залежить від напруженості фокусувального магнітного поля. Продемонстровано, що плазмово-пучковий супергетеродинний лазера на вільних електронах доплертронного типу з гвинтовим релятивістським електронним пучком здатний формувати потужне когерентне електромагнітне випромінювання в міліметровому діапазоні довжин хвиль.

Ключові слова: Супергетеродинний лазер на вільних електронах, Плазмово-пучкова нестійкість, Параметричний резонанс, Гвинтовий релятивістський електронний пучок, Фокусувальне магнітне поле.