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Multiharmonic Interactions of Longitudinal Waves in Amplification Section of Superheterodyne Free Electron Laser

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We analyze multiharmonic interactions of space charge waves (SCWs) in the superheterodyne free electron laser (FEL) amplification section in the submillimeter wavelength range within the framework of the cubic nonlinear approximation. Amplification of electromagnetic waves in the studied parametric superheterodyne FEL is provided by a plural three-wave parametric resonance between fast and slow SCWs and a longitudinal periodic reverse pump electric field. We show that the presence of a monochromatic electric pump field is sufficient to amplify higher harmonics of multiharmonic SCWs. Also, we found that the growth increments of higher harmonics of SCWs do not depend on the harmonic number and are determined by the intensity of the pump electric field and the speed of the electron beam. This fact allows to amplify different higher harmonics equally. Using computer simulations, we show that in the studied system it is possible to amplify multiharmonic SCWs without distorting their amplitude spectrum. In the paper we also researched the effect of generating an additional periodic reverse pump electric field in the linear approximation. The electron beam generates this field and significantly affects the processes in the superheterodyne FEL. We show that such an additional electric field under the conditions of the studied system increases the pump electric field significantly (by 33 %). This leads to an increase in the resulting pump electric field in the system and, therefore, to a significant increase in the growth increments of all harmonics. We demonstrate that the saturation length of SCWs decreases because of generating an additional electric field, which allows engineers to reduce the device dimensions. We show that the effect of the generation of an additional electric field does not destroy the SCW's amplitude spectrum in the process of its amplification along the saturation length. Thus, we propose to use the studied systems for multiharmonic parametric superheterodyne FELs to amplify multiharmonic signals without distorting their amplitude spectra.

Keywords: Superheterodyne free electron lasers, Space charge waves, Three-wave parametric interactions, Mulriharmonic interactions, Plural resonances, Generation of an additional pump electric field.

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1. INTRODUCTION

The creation of new high-power terahertz radiation sources and their practical application is one of the basic directions of modern electronics [1-5]. Free electron lasers (FELs) are the most powerful devices in this frequency range [1, 2]. Therefore, the theoretical analysis of new schemes of such devices is an urgent task.

Among various types of FELs, superheterodyne FELs should be distinguished [1]. The main feature of superheterodyne FELs is the use of an additional wave amplification mechanism. In some cases, this allows to generate and amplify waves with a wide frequency spectrum in superheterodyne FELs, which can be useful in practice [1-5].

The purpose of this publication is to analyze multiharmonic interactions of longitudinal space charge waves (SCWs) in the amplification section of a parametric superheterodyne FEL [1, 6, 7], the scheme of which is shown in Fig. 1. A modulated electron beam is fed to the input of the amplification section, where its multiharmonic SCW is amplified and formed (position 1 of Fig. 1). To amplify SCWs we use a three-wave parametric resonance between slow and fast SCWs, and a longitudinal reverse electric field created by an electrostatic undulator [1, 6] (position 2 of Fig. 1). The designs of such an undulator can be different, including one that the electric field can be created by the effect of electromagnetic induction. After that, the electron beam enters the terminal section, where its kinetic energy is converted into a multiharmonic electromagnetic wave.

Further, we show that though the periodic reverse electric field of an electrostatic undulator is monochromatic, it is possible to amplify the multiharmonic SCW in the amplification section without its amplitude spectrum distortion. Another feature of the processes in this section is the generation of an additional periodic reverse electric field, which has a resonant character. This additional field can both weaken and strengthen the undulator's electric field. It also increases the resulting pump electric field significantly under the conditions of the parameters of the studied system. The reason is that the studied system is not in equilibrium, which leads to a general increase in the pump electric field.

2. MODEL

Let us analyze the physical processes in the amplification section qualitatively. Amplification of multiharmonic SCWs is possible using an undulator with a longitudinal electrostatic field [1, 6], the scheme of which is shown in Fig. 1. A pre-modulated relativistic electron beam (REB) 1 moves along the axis of the electrostatic undulator and passes through the region of a periodically reverse longitudinal electric field cre-

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ated by electrodes 2. Electrodes 2 are connected to high voltage sources in such a way that electric fields 3 between any electrode and its neighbors on the right and left are collinear to the beam axis and mutually opposite. Multiharmonic slow (index α) and fast (index β) SCWs propagating in this REB have the following forms:

$$\mathbf{E}_\alpha = \sum_{m=1}^{N} \left[E_{\alpha,m} \exp(ip_{\alpha,m}) + c.c. \right] \mathbf{e}_z , \qquad (1)$$

$$\mathbf{E}_\beta = \sum_{m=1}^{N} \left[E_{\beta,m} \exp(ip_{\beta,m}) + c.c. \right] \mathbf{e}_z , \qquad (2)$$

where $E_{\alpha,m}$ and $E_{\beta,m}$ are the complex amplitudes of the electrostatic field strengths of m-th harmonics of the slow (α) and fast (β) SCWs, $m = 1, 2, \ldots, N$ are the ordinal numbers of SCW harmonics, $p_{\alpha,m} = m\omega t - k_{\alpha,m} z$ and $p_{\beta,m} = m\omega t - k_{\beta,m} z$ are the phases of the m-th harmonic of the slow and fast SCWs, $k_{\alpha,m}$ and $k_{\beta,m}$ are the m-th harmonic wave numbers of the slow and fast SCWs, ω is the frequency of the fundamental (first) harmonic, $\boldsymbol{e}_z$ is the unit vector Z.

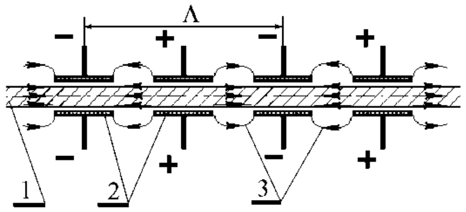

Fig. 1 – Scheme of the amplification section for SCWs: 1 – REB; 2 – undulator's electrodes; 3 – periodic reverse electric field of pumping

The undulator's (pump) electric field has the following form:

$$\mathbf{E}_{20} = \left[E_{20} \exp(ip_2) + c.c. \right] \mathbf{e}_z , \qquad (3)$$

where E_{20} is the complex amplitude of the electric field of the undulator in the vacuum, $p_2 = k_2 z$ is its phase, $k_2 = 2\pi/\Lambda$ is its wave number, Λ is the undulation period. The electron beam is modulated by the undulator field, and hence this creates an additional periodic reverse electric field of the phase p_2:

$$\mathbf{E}_2^d = \left[E_2^d \exp(ip_2) + c.c. \right] \mathbf{e}_z . \qquad (4)$$

The resulting electrostatic field of the phase p_2 has the mathematical form:

$$\mathbf{E}_2 = \mathbf{E}_{20} + \mathbf{E}_2^d = \left[E_2 \exp(ip_2) + c.c. \right] \mathbf{e}_z . \qquad (5)$$

In formula (5), E_2 is the complex amplitude of the resulting pump electric field.

We consider the case when the Raman interaction mode is released in the system, and the following conditions of the three-wave parametric resonance are satisfied for each triple of harmonics:

$$p_{\alpha,m} = p_{\beta,m} - p_2 \text{ or}$$
$$k_{\alpha,m} = k_{\beta,m} + k_2 . \qquad (6)$$

The wave numbers of slow and fast SCWs have the form [1, 2]:

$$k_{\alpha,m} = m \cdot \omega / \upsilon_0 + \omega_p / \left(\gamma_0^{3/2} \upsilon_0 \right),$$
$$k_{\beta,m} = m \cdot \omega / \upsilon_0 - \omega_p / \left(\gamma_0^{3/2} \upsilon_0 \right), \qquad (7)$$

where υ_0 is the constant component of the electron beam velocity, γ_0 is its relativistic factor, ω_p is the Langmuir or plasma frequency. Substituting (7) into (6), we obtain the undulation period of the electrostatic field that satisfies parametric resonances (6):

$$\Lambda = \pi \gamma_0^{3/2} \upsilon_0 / \omega_p . \qquad (8)$$

Analyzing condition (8), it is easy to see that the undulation period does not depend on the harmonic. That is, if the parametric resonance condition (6) is satisfied for the first harmonic, then it is also true for all the others. Note that in this publication we consider cases where only the fundamental harmonic of the electrostatic undulator field $\mathbf{E}_2$ participates in all resonant processes.

Thus, in the SCW amplification section, many three-wave parametric resonances simultaneously arise between the N harmonics of the fast and slow SCWs and the first harmonic of the electrostatic undulator field. We call such interactions plural parametric resonances [1, 7, 8].

The dispersion dependences of the fast and slow SCWs are linear and shifted relative to each other by a constant value (see relations (7)). Therefore, plural parametric resonant interactions of the second type can be also realized between their harmonics:

$$k_{\alpha,n-m+l}\Big|_{n-m+l>0} = k_{\beta,n} - k_{\beta,m} + k_{\alpha,l} ,$$
$$k_{\alpha,n-m+l}\Big|_{n-m+l>0} = k_{\alpha,n} - k_{\alpha,m} + k_{\alpha,l} ,$$
$$k_{\alpha,n+m+l} = k_{\alpha,n} + k_{\beta,m} + k_{\alpha,l} ,$$
$$k_{\beta,n-m+l}\Big|_{n-m+l>0} = k_{\alpha,n} - k_{\alpha,m} + k_{\beta,l} , \qquad (9)$$
$$k_{\beta,n-m+l}\Big|_{n-m+l>0} = k_{\beta,n} - k_{\beta,m} + k_{\beta,l} ,$$
$$k_{\beta,n+m+l} = k_{\beta,n} + k_{\alpha,m} + k_{\beta,k} .$$

Here n, m, and l are integers.

As is known, a slow SCW is characterized by negative energy, while a fast SCW is characterized by positive energy [1, 8]. Therefore, plural parametric wave resonances amplify both fast and slow multiharmonic SCWs simultaneously due to the REB deceleration.

3. BASIC EQUATIONS

To study an FEL with a longitudinal electrostatic undulator, we use the relativistic quasi-hydrodynamic equation [1], the continuity equation, and Maxwell's equations as initial ones. We apply the hierarchical asymptotic approach to the theory of oscillations and waves [1], and the method of slowly varying amplitudes. As a result, we obtain a system of differential equations for SCWs' electric field strength amplitudes that participate in parametric resonances in a cubic-nonlinear approximation:

$$C_{2,\alpha,m}\frac{d^2E_{\alpha,m}}{dz^2}+C_{1,\alpha,m}\frac{dE_{\alpha,m}}{dz}+D_{\alpha,m}E_{\alpha,m}= \\ =C_{3,\alpha,m}E_{\beta,m}E_2^*+F_{\alpha,m}\,,$$

$$C_{2,\beta,m}\frac{d^2E_{\beta,m}}{dz^2}+C_{1,\beta,m}\frac{dE_{\beta,m}}{dz}+D_{\beta,m}E_{\beta,m}= \\ =C_{3,\beta,m}E_{\alpha,m}E_2+F_{\beta,m}\,. \qquad (10)$$

The coefficients of this equation are determined only by the parameters of the system:

$$D_{\chi,m}=-ik_{\chi,m}\left(1-\frac{\omega_p^2}{(m\omega_\chi-k_{\chi,m}\upsilon_0)^2\gamma_0^3}\right), \qquad (11)$$

$$C_{1,\chi,m}=\partial D_{\chi,m}/\partial(-ik_{\chi,m})\,,$$

$$C_{2,\chi,m}=\partial^2 D_{\chi,m}/\partial(-ik_{\chi,m})^2/2\,,$$

$$C_{3,\alpha,m}=\frac{k_{\alpha,m}\cdot\omega_p^2 e/m_e}{\Omega_{\alpha,m}\Omega_{\beta,m}k_2\upsilon_0\gamma_0^6}\times$$

$$\times\left(\frac{k_{\alpha,m}}{\Omega_{\alpha,m}}+\frac{k_{\beta,m}}{\Omega_{\beta,m}}-\frac{k_2}{k_2\upsilon_0}-\frac{3\upsilon_0\gamma_0^2}{c^2}\right),$$

$$C_{3,\beta,m}=-k_{\beta,m}C_{3,\alpha,m}/k_{\alpha,m}\,,\ \Omega_{\chi,m}=m\omega_\chi-k_{\chi,m}\upsilon_0\,,$$

where index χ indicates the type of SCW (α or β); e and m_e are the values of the electron charge and mass; $F_{\chi,m}=F_{\chi,m}(\mathbf{E}_\alpha,\mathbf{E}_\beta,\mathbf{E}_2)$ are functions containing cubic nonlinear terms, including those associated with plural parametric resonant interactions.

The system of differential equations (10) shows plural parametric resonant interactions of SCWs of two types: three-wave parametric resonance (6) and plural parametric resonances (9). This allows us to study a wide range of nonlinear processes in REB plasma, passing through a periodically reverse longitudinal electric field in the cubic approximation.

We can easily obtain an expression for the additional pump electric field in the linear approximation using the hierarchical asymptotic approach to the theory of oscillations and waves [1], and the method of slowly varying amplitudes:

$$\mathbf{E}_2^d=\mathbf{E}_{20}/\left(\left(k_2^2\upsilon_0^2\gamma_0^3/\omega_p^2\right)-1\right). \qquad (12)$$

Analyzing this expression, we can see that this additional electric field can not only enhance the undulator field but also weaken it (5) in general. Furthermore, when $\left(k_2^2\upsilon_0^2\gamma_0^3/\omega_p^2\right)-1=0$ the electric field strength value tends to infinity, that formally indicates its resonant nature, which we can explain as follows. Let us move to a reference frame in which REB is motionless. In this case, the reverse electric field $\mathbf{E}_{20}$ that is periodic in the coordinate with respect to the device becomes a field $\mathbf{E}'_{20}$, which is periodic in time with respect to the electron beam. The resonance will arise if the oscillation frequency of the field $\mathbf{E}'_{20}$ approaches to the frequency of natural oscillations of the beam electrons, determined by the plasma frequency of the beam. However, in this publication we choose specific values of Λ (or k_2) satisfying conditions of three-wave parametric resonance (6) and (8), which lead to the following equalities:

$$\left(k_2^2\upsilon_0^2\gamma_0^3/\omega_p^2\right)=4\ \rightarrow\ \mathbf{E}_2^d=\mathbf{E}_{20}/3\,. \qquad (13)$$

4. ANALYSIS

Let us consider the dynamics of SCWs in the weak-signal approximation. Equations describing the dynamics of waves in this approximation can be easily obtained from the system (10) by removing cubic terms from it. As a result, we get:

$$C_{1,\alpha,m}\frac{dE_{\alpha,m}}{dz}=C_{3,\alpha,m}E_{\beta,m}E_2^*\,,$$

$$C_{1,\beta,m}\frac{dE_{\beta,m}}{dz}=C_{3,\beta,m}E_{\alpha,m}E_2\,. \qquad (14)$$

Here we consider $D_{\chi,m}=0$. From the resulting system (13), it is easy to determine the growth increments of wave harmonics at the initial stage of the waves interaction:

$$\Gamma=|E_2|\sqrt{\frac{C_{3,\alpha,m}C_{3,\beta,m}}{C_{1,\alpha,m}C_{1,\beta,m}}}=\frac{3|eE_2|}{4m_e\gamma_0\upsilon_0^2}\,. \qquad (15)$$

Analyzing the obtained expression (15), we see that the growth increments of different harmonics of SCWs depend only on the amplitude of the first harmonic of the resulting pump electric field strength and the constant component of the REB velocity. They do not depend on the frequency or wave number of a specific harmonic, i.e., the growth increment of different harmonics is the same. Thus, in an electrostatic undulator with a monochromatic field (5), it is possible to implement plural three-wave parametric resonant interactions (6) between harmonics of SCWs without distorting their amplitude spectrum.

Using the system of cubic-nonlinear equations (10), we can determine the levels and saturation lengths z_{sat} of SCWs, the domain and the nature of the dynamics of various harmonics of SCWs. We also analyzed the effect of the generation of an additional pump electric field on the process of enhancing multiharmonic SCWs.

Fig. 2 shows the dependence of electric field strength harmonic amplitudes of the slow SCW $E_{\alpha,m}$ on the longitudinal coordinate z for two cases: without the influence of an additional generated pump electric field (position 1) and with such influence (position 2). To demonstrate that the studied system can amplify a multiharmonic wave without distorting its amplitude spectrum, we consider the following case. We have done the calculation for the case when the slow SCW has 10 harmonics with the same magnitudes in the submillimeter wavelength range at the input of the amplification section ($\lambda_{31,1}=3$ mm, …, $\lambda_{31,10}=0.3$ mm), and without an initial fast SCW. The plasma frequency of the beam is $\omega_p=3.6\cdot10^{11}$ s^{-1}, the relativistic factor is $\gamma=3.0$. In this case, as follows from (8), the undulation period of the electrostatic field is equal to $\Lambda=1.3$ cm.

Fig. 2 shows the similar behavior of harmonics for both cases of their amplification with the effect of generating an additional electric pump field (position 2) and without it (position 1). Indeed, we see that at the initial stage of interactions all harmonics are amplified equally. Amplitudes of all harmonics have close values up to the length coordinate 0.8 z_{sat}. When amplitudes of all harmonics are saturated, the electric field strengths of the slow SCW appear to be comparable and have values in the range 5-9 MV/m.

Also, you can notice that, because of the generation of an additional electric field, the growth increments go up faster, and, consequently, the saturation lengths of these harmonics decrease ($z_{sat2} < z_{sat1}$).

Fig. 3 shows the dependences of the electric field strength harmonic initial phases of the slow SCW $\Phi_{\alpha,m}$ on the coordinate z. As in the case of amplitudes (Fig. 2), the behavior of harmonics both in the case of amplification with the effect of generating an additional electric pump field (position 2) and without this effect (position 1) is similar. Also, the difference in the initial phases between the harmonics changes insignificantly to saturation processes for both cases as well as amplification of harmonic amplitudes (Fig. 2).

Thus, the amplification section, the length of which is determined by the coordinate range $0 < z < 0.8\ z_{sat}$, allows amplifying a multiharmonic SCW with no distortion.

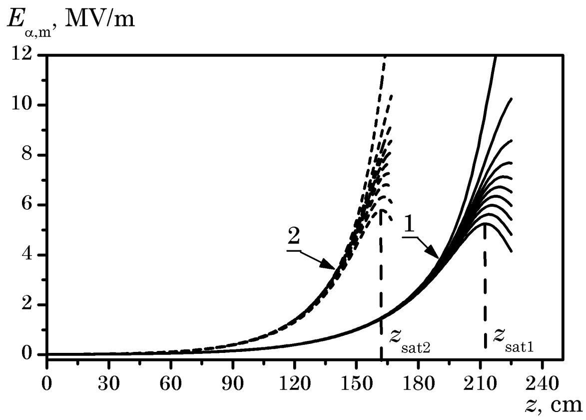

Fig. 2 – Dependences of the amplitudes $E_{\alpha,m}$ of electric field strength harmonics of the slow SCW on the longitudinal coordinate z in two cases: 1 – without the effect of generation of an additional pump electric field; 2 – with it

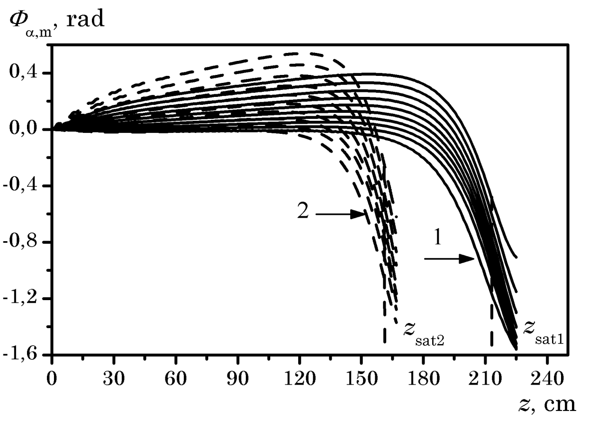

Fig. 3 – Dependences of the initial phases $\Phi_{\alpha,m}$ of electric field strength harmonics of the slow SCW on the longitudinal coordinate z in two cases: 1 – without the effect of generation of an additional pump electric field; 2 – with this effect

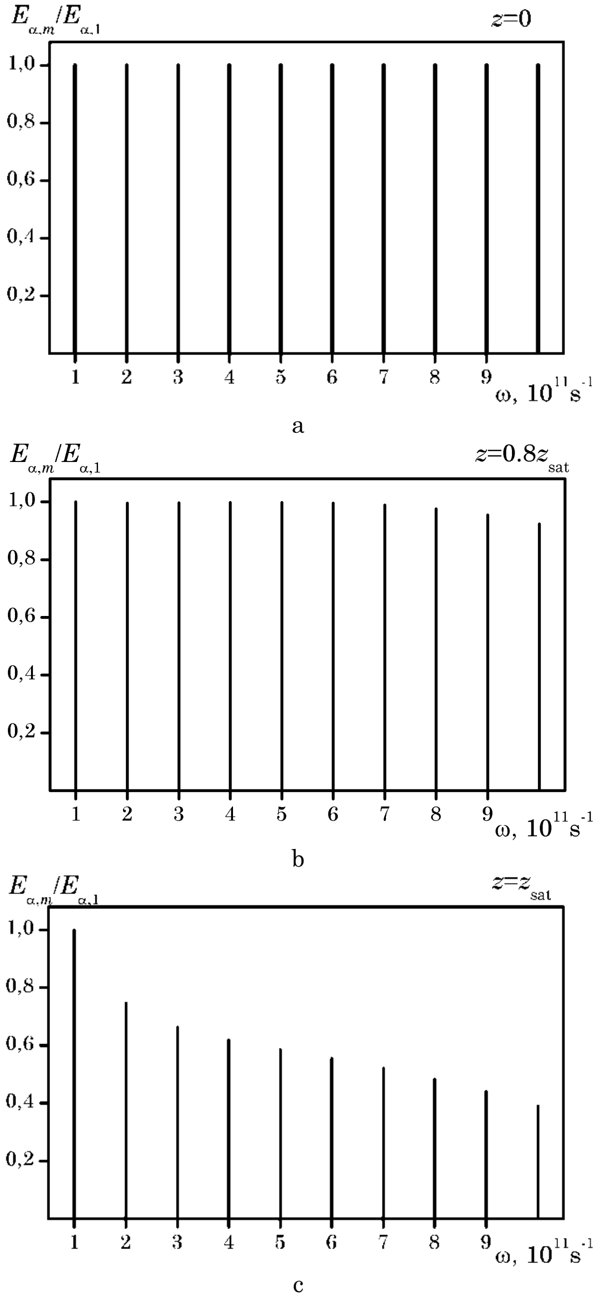

Fig. 4 – Normalized amplitude spectra of each harmonic at the input of the amplification system with the effect of generation of an additional pump electric field ($z = 0$) (a); at the length 80 % of the saturation length ($z = 0.8z_{sat}$) (b); at the end of the saturation length ($z = z_{sat}$) (c)

Let us consider the amplitude spectrum amplification in more detail. Fig. 4 shows the normalized amplitude spectra of each harmonic at the input of the amplification system with the effect of generation of an additional pump electric field (a); at the length 80 % of the saturation length z_{sat} (b); and at the end of the saturation length z_{sat} (c). These plots are consistent with our assumption that the input signal is amplified almost without distortion of its amplitude spectrum up to 80 % of the laser saturation length. To be precise, you can see that the harmonics are amplified a little differently. If the amplitudes of all harmonics are the same at the input, then the amplitude of the 10-th harmonics at 80 % of the saturation length is 7.6 % less, and at 100 % of this length is more than 60 % less than the amplitude of the first harmonic.

We noticed that plural parametric resonant interactions excite a fast SCW β. Dependences of the amplitudes and initial phases of the harmonics of the SCW-β on the longitudinal coordinate z are close enough to the dependences of the slow SCW-α, which are shown in Fig. 2 and Fig. 3.

Fig. 5 shows the dependence of the harmonic amplitudes of the electric field strength of the fast SCW $E_{\beta,m}$ on the longitudinal coordinate z for two cases: amplification without the effect of generating an additional pump field (position 1) and with this effect (position 2). Note that the saturation level of the fast SCW is the same as for the slow SCW and is in the range of 5-9 MV/m. It should also be noted that the saturation level in the case of amplification with the generation of an additional electric field is higher than without it.

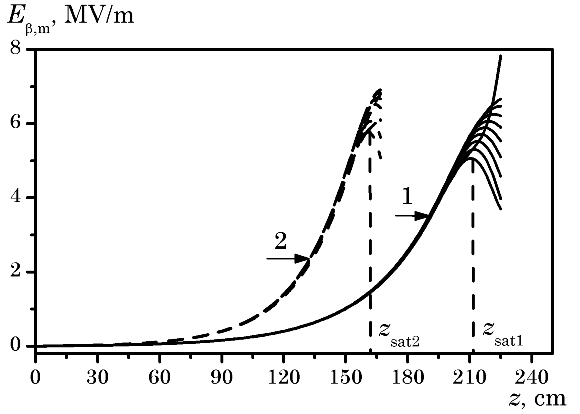

Fig. 5 – Dependences of the amplitudes $E_{\beta,m}$ of electric field strength harmonics of the fast SCW on the longitudinal coordinate z in two cases: 1 – without the effect of generation of an additional pump electric field; 2 – with this effect

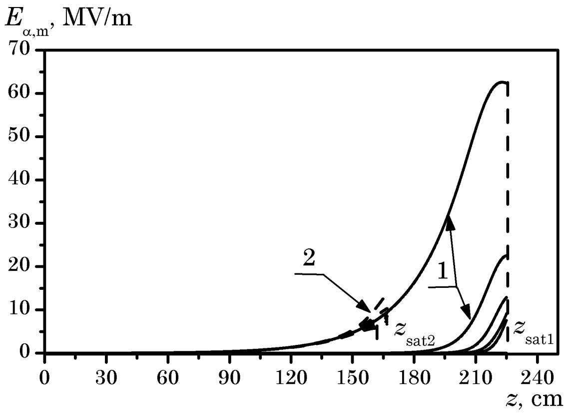

Fig. 6 – Dependences of the amplitudes $E_{\alpha,m}$ of electric field strength harmonics of the slow SCW on the longitudinal coordinate z in two cases: 1 – slow SCW has only one harmonic at the input of the amplification section; 2 – slow SCW has 10 equal harmonic amplitudes at the input of the amplification section

In Fig. 2-Fig. 4, we consider the case when a multiharmonic slow SCW with 10 equal harmonic amplitudes is applied to the input of the amplification section. Computer simulation based on equations (10) demonstrated an interesting feature of the studied system: all harmonics have the same growth increments. Therefore, in this system, it is possible to implement the amplification of multiharmonic SCWs without distorting their amplitude spectrum.

Now let us consider another case when a slow single harmonic SCW is applied to the input of the amplification section. Fig. 6 shows the dependence of the first harmonic amplitude of the electric field of the slow SCW $E_{\alpha,1}$ on the longitudinal coordinate z, with the effect of the generation of an additional pump field (position 1). For comparison, we also plotted the longitudinal distribution of the electric field strength harmonic amplitudes of the slow multiharmonic SCW with 10 equal harmonic amplitudes at the input (the identical dependence is plotted in Fig. 2, position 2) (Fig. 5, position 2).

We noticed that the growth increments for multiharmonic (position 2) and single-harmonic (position 1) input signals are the same. However, saturation levels and saturation lengths are significantly different. We see that the saturation level of the slow SCW in the case when only one harmonic is fed to the amplification section exceeds by up to 7 times compared to the case when 10 identical harmonics are fed to the input. In this case, the saturation length increases from $z_{sat2} \approx 167$ cm to $z_{sat1} \approx 220$ cm. We also see that when saturation occurs and only one harmonic is fed to the input of the amplification section (position 1); then due to the resonance effect (9) higher harmonics are generated, though they were absent at the beginning of the system.

Such a significant increase in the saturation level of the first harmonic (up to 7 times) can be explained easily. In this case, the saturation process is associated with a nonlinear frequency shift [1, 8]. Its reason is the destruction of the conditions of parametric resonance due to the deceleration of REB according to (8). And deceleration, in turn, is a consequence of the energy transfer from REB to the harmonics of SCWs. Therefore, when 10 harmonics are fed to the input and immediately amplified, the deceleration of REB occurs more intensively than in the case when one harmonic is fed to the input of the system. And when SCW's harmonics are saturated, the energy of their electric field turns out to be comparable with the energy of the first harmonic's field.

5. CONCLUSIONS

So, in this publication within the framework of the cubic nonlinear approximation, we carried out the analysis of the amplification of multiharmonic SCWs in the amplification section of a superheterodyne FEL with a longitudinal electrostatic undulator. In this section, a three-wave parametric resonance between fast and slow SCWs and a longitudinal periodic reverse pump electric field was used for the multiharmonic SCW amplification.

In the publication we showed that the presence of a monochromatic pump electric field is sufficient to generate and amplify the higher harmonics of multiharmonic SCWs. Theoretically we found that the growth increments of the higher harmonics of the SCW do not depend on the harmonic number. It is determined only by the intensity of the pumping electric field and the REB speed. This fact allows to amplify different higher harmonics equally. Using computer simulation, we found the lengths of amplification of multiharmonic SCWs' amplitude spectrum with no distortion.

Also, in our work we clarified and investigated the effect of generating an additional periodic reverse pump electric field in a linear approximation. This field is generated by the REB. We showed that such an additional electric field under the conditions of the studied system significantly increases the pumping electric field (by 33 %). It affects the processes in the superheterodyne FEL significantly, which leads to a significant increase in the growth increments of all harmonics. We demonstrated that because of generating an additional pump electric field, the saturation lengths of the SCW were reduced, which made it possible to reduce the device dimensions. We showed that the effect of the generation of an additional electric field does not destroy the SCW's amplitude spectrum in the process of its amplification along the saturation length. Thus, we propose to use the studied systems for multiharmonic parametric superheterodyne FELs for amplification of multiharmonic signals without distorting their amplitude spectra.

REFERENCES

1. V.V. Kulish, *Hierarchic Electrodynamics and Free Electron Lasers: Concepts, Calculations, and Practical Applications* (CRC Press: 2011).
2. Y.U. Jeong, K.-H. Jang, S. Bae, V. Pathania, J. Mun, K. Lee, *J. Korean Phys. Soc.* **80**, 367 (2022).
3. A. Fisher, Y. Park, M. Lenz, A. Ody, R. Agustsson, T. Hodgetts, A. Murokh, P. Musumeci, *Nat. Photon.* **16**, 441 (2022).
4. N. Sei, T. Sakai, Y. Hayakawa, Y. Sumitomo, K. Nogami, T. Tanaka, K. Hayakawa, *Sci. Rep.* **11**, 3433 (2021).
5. K. Kawase, M. Nagai, K. Furukawa, M. Fujimoto, R. Kato, Y. Honda, G. Isoyama, *Nucl. Instrum. Meth. Phys. Res. A* **960**, 163582 (2020).
6. V.V. Kulish, A.V. Lysenko, I.V. Gubanov, A.Yu. Brusnik, Pat. 87750, Ukraine, MPK (2009): H05H 9/00, publ. 10.08.2009, bull. No 15/2009.
7. A.V. Lysenko, A.Yu. Brusnik, I.I. Volk, M.A. Korovai, S.S. Ilin, O.L. Bunetskyi, *J. Nano- Electron. Phys.* **12** No 4, 04037 (2020).
8. H.P. Freund, *Principles of Free Electron Lasers* (Springer: 2018).

Множинні трихвильові резонансні взаємодії в пролітній секції двопотокового супергетеродинного ЛВЕ з поздовжнім електричним полем

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У рамках кубічного нелінійного наближення проведено аналіз підсилення мультигармонічної хвилі просторового заряду (ХПЗ) в секції підсилення параметричного супергетеродинного лазера на вільних електронах (ЛВЕ). Підсилення мультигармонічної ХПЗ у досліджуваному пристрої забезпечується трихвильовим параметричним резонансом між швидкою та повільною ХПЗ та поздовжнім періодичним реверсивним електричним полем накачки. Показано, що для підсилення вищих гармонік мультигармонічних ХПЗ достатньо наявності монохроматичного електричного поля накачки. Також з'ясовано що інкременти зростання вищих гармонік ХПЗ не залежать від номера гармоніки і визначаються напруженістю електричного поля накачки та швидкістю електронного пучка. Ця обставина відкриває можливість підсилювати усі вищі гармоніки однаково. Використовуючи комп'ютерне моделювання визначено довжини, на яких можливо підсилювати мультигармонічні ХПЗ з амплітудним спектром без спотворень. У роботі також з'ясовано та досліджено в лінійному наближенні ефект генерації додаткового періодичного реверсивного електричного поля накачки. Це поле генерується електронним пучком та суттєво впливає на процеси у супергетеродинному ЛВЕ. Показано, що таке додаткове електричне поле в умовах досліджуваної системи суттєво підсилює електричне поле накачки (на 33 %) Це призводить до збільшення результуючого електричного поля в системі, а значить і до суттєвого збільшення інкрементів зростання усіх гармонік. Продемонстровано, що завдяки ефекту генерації додаткового електричного поля довжини насичення хвиль просторового заряду зменшуються, що дозволяє зменшити габарити пристрою. Показано, що ефект генерації додаткового електричного поля не руйнує амплітудний спектр ХПЗ у процесі його підсилення вздовж довжини насичення. Запропоновано використовувати досліджувані системи в мультигармонічних параметричних супергетеродинних ЛВЕ для підсилення мультигармонічних сигналів без спотворення їх амплітудних спектрів.

Ключові слова: Супергетеродинний лазер на вільних електронах, Хвилі просторового заряду, Трихвильовий параметричний резонанс, Мультигармонічні взаємодії, Множинні резонанси, Генерація додаткового електричного поля накачки.