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Active FEL-Klystrons as Formers of Femtosecond Clusters of Electromagnetic Field. Systems on the Basis of Two-Stream Instability

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A general analysis of the two-stream active FEL-klystrons, as a new high efficient class of electronic devices, intended for generation of femtosecond clusters of electromagnetic field has been performed. Three models are described firstly in the article. Detail weak-signal analysis of multi-harmonic processes within the FEL-klystron transit section is accomplished.

Keywords: Two-stream instability, Klystrons, Free-electron lasers, Femtosecond clusters of electromagnetic field.

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1. INTRODUCTION

The given work is the fourth part of the cycle of papers [1-3] which are devoted to the analysis of a new class of relativistic electronic devices – the active FEL-klystrons. The fact that all of them are intended for the formation of femtosecond clusters of electromagnetic field is an exclusive feature of such FEL.

General qualitative description of the active FEL-klystrons is carried out for the first time in [1]. Qualitative analysis, where the principal possibility of the formation of such devices on the basis of multiharmonic sections of "ordinary" (parametrical) FEL is demonstrated, is performed in [2, 3]. It is shown that, in principle, such devices can be created on the already existed technological basis. It is established that presence of a special external source of multiharmonic signal is the necessary condition for their practical realization. Such external source should generate multiharmonic electromagnetic signals of the specified shape that in the case, for example, of hundreds of harmonics is not a simple technical problem. Moreover, its feature is in the following: effective range of the input spectrum (at least, in the case of H-ubitron multiharmonic systems) should have pronounced "anomalous" behavior: higher spectral harmonics should have higher amplitude. This feature is conditioned by the fact that, as the analysis carried out in [2, 3] has shown, harmonics of the input signal with higher numbers are amplified less in such device than harmonics with lower numbers. Thus, mechanism of "ordinary" FEL used here as the basic operating one cannot, as the cluster signal synthesis principle earlier described in [1] requires, effectively generate higher harmonics of sufficient amplitude. This is explained, first of all, by pure parametrically-resonant nature of the specified basic mechanism. The latter, as known [4-9,] possesses a singular mechanism of "internal filter". As a result, higher harmonics of interacting signal waves are generated much less efficiently than lower ones.

Thus, class of active FEL-klystrons studied in [2, 3], at bottom, is only a power amplifier of multiple spectral harmonics of external cluster signals, but not a former of clusters.

In the given paper we analyze another type of the active FEL-klystrons which can form a power femtosecond electromagnetic cluster due to the effective generation of higher harmonics inside the system. As the basic one, in such devices one uses mechanism of multiharmonic generation of higher harmonics of the longitudinal spatial charge waves (SCW) because of two-stream instability [10, 11]. Feature of the two-stream mechanism consists in the fact that in contrast to the above discussed parametrical mechanism, it has a pronounced non-resonant nature [4-6]. As a result, it does not contain "internal filter" of higher harmonics which was mentioned above in connection with parametrical instability [4-6]. In the work, we consider two variants of such two-stream FEL-klystrons: the models in which moderately power monochromatic electromagnetic signal comes to the input and superpowerful cluster signal is taken from the output, and the models in which multiharmonic signal comes to the input.

2. SCHEMES OF THE FEL-KLYSTRONS, BASIC OPERATING PRINCIPLES, AND GENERALIZED THEORETICAL MODEL

Example of the design scheme where the idea of the synthesis of cluster electromagnetic wave is realized [1] at the harmonic (monochromatic) input electromagnetic signal is represented in Fig. 1.

Here monochromatic electromagnetic signal 1 (with frequency ω_1 and wave number k_1) comes into working volume of the first pump system 8. Two-speed electron beam 7, which is formed due to the coalescence of two single-speed beams 3 and 6 (accelerators 4 and 5 are the sources of these beams), also comes here.

According to the stated in [1], excitation in the volume of two-speed beam 7 of multiharmonic SCW is the main destination of the modulator section in the given cluster active klystron. Depending on the peculiarities of the modulator, namely, is it the resonant or non-re-

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sonant one (see [1] in detail), realization of some partial design variants of the studied two-stream FEL-klystrons is possible (see later Fig. 2-4).

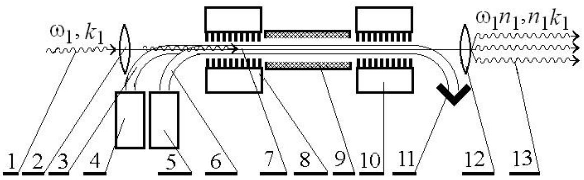

Fig. 1 – Structural scheme of two-stream cluster FEL-klystron with resonant modulator 8 and monochromatic input signal 1

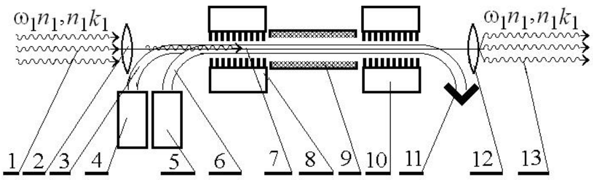

Fig. 2 – Structural scheme of two-stream cluster FEL-klystron with resonant modulator 8 and multiharmonic input signal 1

Comparing the presented schemes we can see that resonant arrangement of the modulator is the feature of the schemes illustrated in Fig. 1 and Fig. 2 [1]. Physical analysis shows (see below in this work) that in spite of the external similarity, the schemes considerably differ in the physics of the development scenarios of the basic excitation processes of multiharmonic SCW in an electron beam. In turn, the scheme presented in Fig. 1 also can have two modifications, namely, the cases when pump system 8 is realized as the harmonic ("monochromatic") and multiharmonic one, respectively. This also significantly influences both the physics of processes in the modulator 8 and operation of the device in whole.

Thus, for the first of possible modifications represented in Fig. 1 not only signal 1, but also pump system 8 are monochromatic. Because of the realization of the parametric resonance effect, monochromatic signal 1 and pump 8 waves excite monochromatic SCW in an electron beam 7. Then in the transit section 9 due to the effect of two-stream instability in beam 7 higher harmonics are generated, i.e. multiharmonic SCW is generated which in the terminal FEL-section 10 is transformed into femtosecond cluster electromagnetic wave 13. The key physical peculiarities of such processes are discussed further in the present paper. Here we continue to discuss the technical features of the schemes of other design versions of such devices.

Scheme of the two-stream cluster FEL-klystron with multiharmonic input signal is represented in Fig. 2. The key distinction between schemes in Fig. 1 and Fig. 2 consists in the fact that here the use of initially multiharmonic input signal 1 is provided. Therefore, the first pump system 8 also should be a multiharmonic one. As a result, multiharmonic SCW is formed not in the transit section 9, but in the region of the first pump system 8. Changing the shape of the input multiharmonic signal 1, we can influence the spectrum shape of multiharmonic SCW, and so, we obtain one more possibility for optimization of the output signal spectrum 13.

Structural schemes illustrated in Fig. 3 and Fig. 4 represent another production branch in the field of two-stream cluster active FEL-klystrons. Their key feature is the choice of non-resonant design for the modulation section of a two-speed electron beam. The main idea of such engineering solution consists in the following: non-resonant modulators (see in detail Fig. 13 in work [1]) are structurally much simpler than the resonant ones discussed above. On the other hand, when two-stream instability (which is known in electrodynamics by the extremely high amplification levels [4-6, 12-14]) is the basic operating mechanism of the transit section 7 (see Fig. 3 and Fig. 4), necessity of application of the exactly resonant modulation sections ceases to be self-evident. As it will be shown further and in the subsequent parts of the present work, the use of non-resonant modulators in many practically interest cases is found to be much more interest from the applied point of view.

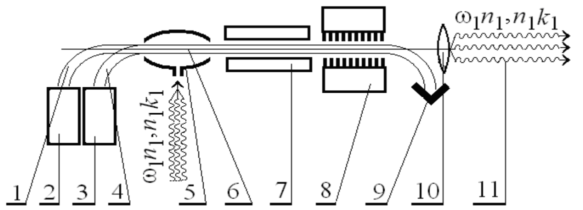

Fig. 3 – Structural scheme of two-stream cluster FEL-klystron with non-resonant modulator 5 and multiharmonic (cluster) input signal

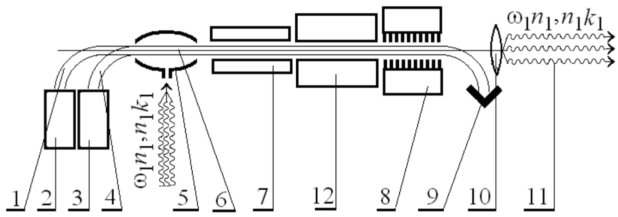

Fig. 4 – Structural scheme of two-stream cluster FEL-klystron with non-resonant modulator 7 and system of intermediate acceleration of an electron beam 12

It is easy to see comparing the structural schemes illustrated in Fig. 3 and Fig. 4 that their distinction consists in the introduction into second device (Fig. 4) of the system of intermediate acceleration of modulated electron beam 12. Remember, we have discussed earlier the same technique in the theory of single-stream active FEL-klystrons constructed on the basis of "ordinary" FEL [2, 3]. Change in the beam energy significantly influences the spectrum of the output multiharmonic signal 11. As for the rest, operating principles of the devices shown in Fig. 3 and Fig. 4 are sufficiently self-evident and do not require additional explanations.

Generalized theoretical model of two-stream cluster FEL-klystron for the devices illustrated in Fig. 1-Fig. 4 is represented in Fig. 5. Here, the unified interaction region is divided into four parts, each of which corresponds to the certain section of the devices, whose structural schemes are shown in Fig. 1-Fig. 4.

It follows from Fig. 5 that electron two-speed beam with velocities $\boldsymbol{v}_1$ and $\boldsymbol{v}_2$ of partial beams directed into the interaction region of cluster FEL-klystron meets firstly the modulation section I (region of resonant or non-resonant modulator), then it sequentially passes the active II and passive III parts of the transit section.

Then it moves toward the terminal section IV. A number of structural schemes which are different in the combinations of sections can be sufficiently large, while variety of their different theoretical models is found to be much less. This fact gives the possibility to consider the generalized theoretical model represented in Fig. 5 as that which includes the majority of variants.

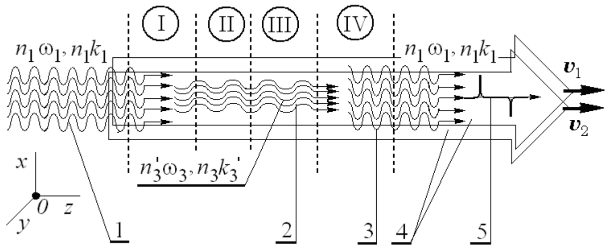

Fig. 5 – Generalized theoretical model of two-stream cluster FEL-klystron for the devices shown in Fig. 1-Fig. 4

3. ANALYSIS OF TWO-STREAM INSTABILITY IN THE TRANSIT SECTION

Before we start the analysis of the physical processes in resonant modulators or terminal sections of the model (Fig. 5), we firstly consider the peculiarities of the physics of two-stream instability. Such order of investigation we motivate, first of all, by the fact that two-stream instability is actually present in each section of each cluster FEL-klystron, whose structural schemes are illustrated above in Fig. 1-Fig. 4.

Further analysis of the cluster FEL-klystron, whose generalized model is represented in Fig. 5, will be the following. Firstly, we consider the physics of the basic processes in the transit section (region III in Fig. 5) which are determined by two-stream instability solely. Physics of the processes in other sections will be considered in subsequent parts of the given work.

So, unperturbed beam is considered to be uniform, two-speed (Fig. 5), relativistic, and wide, and therefore, we can neglect the influence of the boundaries on the processes of wave interaction far from them. We also neglect thermal velocity spread of electrons. Quasi-hydrodynamic equation and continuity equation are taken as the initial ones. We assume that the beam, as whole, moves along the z-axis in weak focusing magnetic field (see classification of the longitudinal magnetic fields in FEL in [4-6] in detail).

In the given item we confine ourselves by the weak signal analysis only, in the frame of which we suggest that SCW amplitudes are small. We consider two variants of the two-stream instability development. In the first one (standard) weak monochromatic signal of the SCW shape comes to the input, then it is amplified in the system due to the effect of two-stream instability [4-6, 12-14]. Within the second (non-standard) one we assume that weak multiharmonic SCW comes to the input, and then each spectral component of this SCW interacts with plasma of two-speed high-current beam irrespective of other components. That is, a parallel simultaneous and independent amplification of many spectral components of the input signal is expected within the second variant.

Obviously, formally the first of two variants can be considered as the particular case of the second one. Real distinctions between them are purely technological and reflect some peculiarities of the considered here designs of the studied cluster FEL or other. Therefore, we take the second variant as the basic one for further analysis in the weak signal approximation. The first variant will be taken into account only in the discussion of the physical features of any design of the transit section.

Following the well-known algorithm of the theory of weak signal approximation, it is not difficult to obtain the known dispersion correlations for the longitudinal electron waves in two-speed beam [4-6]. Partially some peculiarities of these solutions are illustrated in Fig. 6. The above mentioned characteristic of the two-stream instability development is taken into account here. More specifically, in the region of the transit section, except the first one, higher harmonics can be present as well. Generalizing the known dispersion correlations [4-6, 12-14], we can obtain the following expression:

$$k_3(n_3\omega_{31}) = \frac{n_3\omega_{31}}{v_0} \pm \Gamma'(n_3\omega_{31}), \qquad (1)$$

where ω_{31} is the cyclic frequency of the first harmonic of SCW; $n_3 = 1, 2, \ldots, N'$ is the current number of SCW harmonic; N' is the maximum harmonic number taken into account; $v_0 = (v_{01} + v_{02})/2$ is the average velocity of two-speed system; v_{01} and v_{02} are the initial longitudinal velocities of partial beams at the input; Γ' is the correction to the linear part of the dispersion law (complex correction, in the general case).

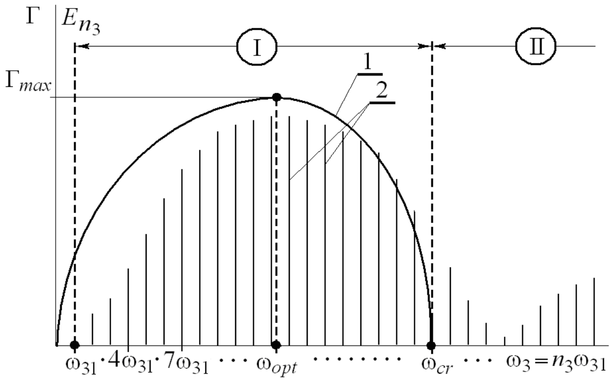

Fig. 6 – Dependence of the increment of SCW rise (curve 1) on the SCW frequency, and typical for cluster FEL spectrum 2 of higher SCW harmonics in two-stream high-current relativistic beam

Simple analysis allows to establish that in the case of SCW, which is initially monochromatic on the input, within the weak signal approximation stated here, generation effect of higher harmonics (starting from $n_3 = 2$), as it was assumed above, does not take place. Similarly, each of spectral components in the case of the initially multiharmonic spectrum on the input into transit section, as it was also mentioned above, is amplified irrespective of other components. Example of such linearly multiharmonic spectrum is shown in Fig. 6.

Further, we note that significant interconnection between harmonics appears only on the system lengths larger than it is permitted by the corresponding criteria of the weak signal theory [4-6]. Such effects should be exhibited within the theories of higher approximations over chosen small parameter of the problem [4-6].

The mere fact of SCW amplification is interpreted as the initiation of two-stream instability in the studied quasi-linear system. As the elementary analysis shows, the result of amplification of each spectral component of SCW significantly depends on both the number of harmonic n and correlations of the type ω_{31}/ω_{opt}, ω_{31}/ω_{cr} (the corresponding determinations for the values ω_{opt} and ω_{cr} are given below; see also Fig. 6).

At the fulfillment of the condition

$$\left|\Gamma'(\upsilon_{01}-\upsilon_{02})/\omega_p << 1\right| \qquad (2)$$

which, as a rule, is true in the case of high-current relativistic beams (because of the fact that at $\upsilon_{01}, \upsilon_{02} \to c$, correlation $(\upsilon_{01}-\upsilon_{02}) \to 0$ takes place), explicit expression for the correction Γ' can be represented in a relatively simple analytical form [4-6]

$$\Gamma' \cong \pm\left(\frac{\omega_p}{\upsilon_0\gamma^{3/2}}\right)\left\{\left(\frac{\omega_3\delta}{\omega_p}\right)^2\gamma_0^3+1\pm\left[4\left(\frac{\omega_3\delta}{\omega_p}\right)^2\gamma_0^3+1\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}}, \qquad (3)$$

where ω_p is the plasma frequency of each partial electron beam; $\delta = (\upsilon_{01}-\upsilon_{02})/\upsilon_0$ is the normalized separation of their velocities; $\gamma_0 = (1 - (\upsilon_0/c)^2)^{-1/2}$ is the average relativistic factor of two-stream system; c is the speed of light in vacuum; $\omega_3 = n_3\omega_{31}$.

Thus, as it follows from (3), four types of proper SCW can propagate in a two-speed beam. It is important to note that physical features of these waves are considerably different. Critical frequency [4-6]

$$\omega_{cr} = \omega_p/(\sqrt{2}\delta\gamma_0^{3/2})$$

is the physical boundary between these sets of waves. Starting from this frequency, conditions for the realization of two-stream instability are not fulfilled any more, and, correspondingly, all roots of (3) are real. During this investigation phase, we pay special attention to the study of the region I (Fig. 6), where the opposite case is realized and growing, damped, fast, and slow waves exist.

At $\omega_3 < \omega_{cr}$ we obtain from (3) two complex conjugate solutions. These solutions correspond to the growing ($\Gamma' = +i\,|\,\Gamma'\,|$) and damped ($\Gamma' = -\,i\,|\,\Gamma'\,|$) waves. Simple analysis of the expression (3) for the presence of extremes of function $\Gamma'(\omega_3)$ allows to determine that the value of imaginary addition Γ' in (2) ($Re\{\Gamma'\} = 0$ in this case) reaches a maximum for the growing wave

$$\Gamma_{\max} = \omega_p/\left(2\upsilon_0\gamma_0^{3/2}\right) \qquad (4)$$

on the frequency

$$\omega_{opt} = \sqrt{3}\omega_p\gamma_0^{3/2}\left(1-\gamma_0^{-2}\right)/\Delta\gamma_0\,, \qquad (5)$$

where $\Delta\gamma_0 = \gamma_{01}-\gamma_{02} \approx 2(\upsilon_0/c)^2\gamma_0\delta$; $\gamma_i = (1 - (\upsilon_i/c)^2)^{-1/2}$ is the relativistic factor of the i-th partial beam.

Comparing expressions (4) and (5) with analogues which are well-known non-relativistic variants of these formulas [12], we can make two important conclusions.

The first one consists in the fact that, as it follows from (4), increase in the beam relativism (described by the relativistic factor γ_0) leads to the decrease in the maximum increment of growth $\Gamma_{\max}$. In practice, negative influence of relativism can be appreciably soften by the circumstance that relativistic beams, as a rule, are more high-current and dense (i.e. they are characterized by large values of partial plasma frequency ω_p) than non-relativistic ones. However, in any case this means that use of essentially relativistic beams in two-stream systems is found to be non-reasonable.

The second conclusion is also concerned about relativism, however, in this case – its positive influence. It is easy to see that mentioned relativism, as it follows from (5), allows to considerably increase the optimal frequency ω_{opt} up to the visible frequency range. In this case, the fact that with the increase in γ_0 the value of relativistic separation $\Delta\gamma_0$ also decreases (since, as it was stated above, at $\upsilon_{01}, \upsilon_{02} \to c$ correlation $(\upsilon_{01}-\upsilon_{02}) \to 0$ takes place) is of a great importance. Exactly this feature of the two-stream instability makes it promising for the practical applications nowadays.

Now we remember that besides of the growing and damped waves, the slow and fast SCW are also excited in the region I (see Fig. 6) for each electron harmonic

$$\Gamma' = \pm\Gamma_{1,2} = \pm\frac{\sqrt{15}}{2}\frac{\omega_p}{\upsilon_0\gamma_0^{3/2}}. \qquad (6)$$

Moreover, analyzing (3) it is easy to make sure that at $\omega_3 > \omega_{cr}$, i.e. at numbers of harmonics $n > \omega_{cr}/\omega_{31}$, two-stream instability does not take place anymore. In this case, for each harmonic of SCW instead of the four waves discussed above, four the so-called supercritical electron waves are excited, which are, in contrast to the case of the waves in the region I, not growing

$$k_3^{(1,2)} = \frac{\omega_3}{\upsilon_{01}} \pm \frac{\omega_p}{\upsilon_0\gamma^{3/2}}, \quad k_3^{(3,4)} = \frac{\omega_3}{\upsilon_{02}} \pm \frac{\omega_p}{\upsilon_0\gamma^{3/2}}. \qquad (7)$$

The above described set of SCW exhausts all types of proper waves of the simplest relativistic two-stream system which can be described within the used weak-signal theory. At the transition to the following (quadratic and higher) approximations dispersion laws of the mentioned waves obtain the corresponding non-linear additions, which, as we will make sure, considerably complicate the general evolution of the two-stream system. However, it is more important that there appear other types of instabilities, mainly, of the resonant type, including wave parametric resonances between specified types of the longitudinal waves.

4. SOME KEY FEATURES OF THE SYSTEMS ON THE BASIS OF TWO-STREAM INSTABILITY

Two-stream instability in high-current relativistic beams has two key features [10, 11, 14-18] which, basically, make it so interest for use in two-stream cluster FEL-klystrons. Now we will briefly discuss these features having performed simplest numerical estimations which illustrate some of the above described properties of two-stream systems.

We assume, for example, that $\omega_p \sim 2\cdot10^{11}$ s^{-1} (that is real for high-current electron beams), $\gamma_0 \sim 10$ (that corresponds to the energy of electrons of ~ 5 MeV; in this case, average velocity of beams approaches to the speed of light: $v_0 \sim c$). Then, using expression (4), for the maximum increment of growth it is not difficult to obtain that $\Gamma_{\max} \sim 0{,}1$ cm. The latter means that at the length of the interaction region, for example, of three meters (that, in principle, can be easily provided for high-current FEL) linear amplification coefficient of the weak input monochromatic SCW can achieve fabulous values of ~ exp(30)! That is why two-stream instability is considered to be one of the strongest in electrodynamics.

It is important to note here that in practice linear amplifications of such level cannot be realized. First of all, because of the fact that different non-linear effects, which appear at much less lengths L (see below in this paper), prevent amplification. Including those, for example, as the active generation of SCW multiharmonics [10, 11]. In this case, however, the latter is not very important. Numerical estimation carried out above has demonstrated the point, namely, potentially high amplification abilities of two-stream (as a result, plasma-beam ones as the particular case) systems. Exactly this circumstance has historically stimulated the appearance of the first publications on the two-stream plasma-beam FEL.

We will continue numerical estimations. Let us to discuss the frequency features of two-stream instability have taken formula for the optimal frequency ω_{opt} (5) as the basic one. Namely, at the same (as in the first case) values of the parameters ω_p and γ_0 and assuming, moreover, that $\Delta\gamma_0 \sim 0{,}1\div0{,}01$ (that corresponds to the separations of partial beams in the energies 50÷5 keV), for the optimal frequency ω_{opt} we obtain $\omega_{opt} \sim 10^{14}\div10^{15}$ s^{-1}. Or, in other words, we can conclude that in the case of sufficiently high-current, qualitative relativistic beams the following situation is possible: optimal frequency of SCW of two-beam system belongs to the optical range. Obviously, transformation of energy of such longitudinal SCW into the energy of the transverse electromagnetic waves is not a problem currently. First of all, due to the achievements of modern engineering of high-current FEL produced on the physical mechanisms of mutual transformation of the transverse electromagnetic waves and longitudinal SCW. Therefore, we can say that exactly this unique feature of relativistic version of two-stream instability (to operate in the visible range) makes it promising physic-technological basis for the creation of a number of two-stream FEL of different applications including cluster femtosecond active FEL-klystrons discussed here.

Thus, as it follows from the consideration carried out above (and illustrated in Fig. 6), two-stream instability is realized in the frequency range I (i.e. at $\omega_3 \le \omega_{cr}$). This means that weak input SCW signal with frequency ω_{31} is amplified always if it gets to the region of two-stream instability I (see Fig. 5). In monochromatic two-stream FEL [4-6, 14-18] frequency of the first SCW harmonic ω_{31} is chosen to be close to the optimal one ω_{opt}, since in this case, according to (4), one can expect the maximum of amplification. It is natural, since achievement of maximum amplification at minimum length is one of the main aims during creation of any monochromatic amplifier or generator.

Another situation takes place in the case of multiharmonic two-stream FEL [10, 11]. Here different SCW harmonics correspond to different values of the increment Γ' (Fig. 6), i.e. all harmonics are amplified differently. In the case of cluster FEL this circumstance plays the key role, since formation of narrow beams of multiharmonic transverse clusters of electromagnetic field is the main problem here. Because of the basic physics of the process of transformation of the longitudinal SCW to the electromagnetic signal, performance of the stated problem is found to be possible technically only in the case when sufficiently long "anomalous" region is present in the SCW spectrum. Namely, the region, where spectral components with large numbers of harmonics have large amplitudes. Example of such anomalous region is qualitatively represented in Fig. 6 (see frequency range from ω_{31} to about ω_{opt}).

The necessity of the presence of "anomalous" region is explained by the fact that spectrum of magnetic undulators, which are most often used for the pumping in cluster FEL, as a rule, is found to be evidently decaying [1]. Further we take into account that, as it is shown in the following parts of the given work, quadratic terms of the shortened equations proportional to $\sim E_{3m}H_{2m}$ (where E_{3m} and H_{2m} are the amplitudes of m-*th* harmonics of the electric signal field and magnetic pump field) give the main contribution to the formation of each m-*th* spectral component of the signal E_{1m} (far from saturation). In this connection it is evident that only in the case of "anomalous" dependence $E_{3m}(m)$ at decaying similar dependence $H_{2m}(m)$ one can obtain a sufficiently long spectral region with almost same spectral amplitudes E_{1m}. We remember that such behavior of the spectrum is proper to the femtosecond cluster electromagnetic waves [1].

As it was noted before in the work [1], on the basis of some systems with Doppler pumping, in principle, one can create cluster cascade FEL, in which the requirement to the "anomality" of SCW spectrum is not so rigid. Unfortunately, currently such models are not practically studied. Therefore, as the performed analysis of the majority of the most interest special models of the H-ubitron type has shown, the longer "anomalous" spectral region is, the narrow clusters are and more "interest" practical problems, which can be solved by the studied systems, are.

However, in the light of the above stated it is not completely clear: how and due to what peculiarities of the discussed physical mechanisms this problem can be really solved. An appropriate physical answer was proposed in works [5, 10]. Namely, one should pass on the models where frequency of the first SCW harmonic ω_{31} is found much less than the optimal frequency ω_{opt}. In this case, as it is illustrated in Fig. 6, each subsequent harmonic (up to the harmonic $n_3 \approx \omega_{opt}/\omega_{31}$) is amplified with larger amplification increment Γ than the previous one. Taking as the basis, for example, the above discussed variant of numerical estimations of formulas (4) and (5) ($\omega_{opt} \sim 10^{15}$ s^{-1}), it is easy to see that at the choice of the frequency of the first harmonic, let us say, "anomalous" part of the cluster SCW spectrum can contain ~ 100 harmonics in the submillimeter-wave region (ω_{31} ~ 10^{13} s^{-1}). In this case, for the half-width of cluster $\tau_{p2} \approx \pi/(n_3\omega_{31}) \sim \pi/\omega_{opt}$ (see [1] in detail) one can obtain numerical estimation exactly in the femtosecond range we are interested in: $\tau_{p2} \sim \pi \cdot 10^{15}$ s^{-1} (for the period of cluster wave $T_{31} \sim 2\pi \cdot 10^{-13}$ s). Compression coefficient f_{com} (see expression (1) in work [1]) in the given case achieves the values of f_{com} ~ 50.

Thus, the performed estimations illustrate two key features of two-stream instability in high-current relativistic electron beams. The first one consists in the ability of two-stream FEL operate in the visible spectrum ($\omega_{opt} \sim 10^{14} - 10^{15}$ s^{-1}). The second feature is exhibited in the explicitly expressed tendency to the generation of the large number of higher SCW harmonics. On the one hand, the performed conclusions clarify the physical meaning of the basic principles of construction of cluster FEL discussed earlier in the work [1]. On the other hand, they demonstrate the circumstance that even within such simplest (weak-signal) theory of two-stream high-current systems, physics of the basic processes is found to be not very simple. Obviously, therefore, further development of the theory toward more complete accounting of the influence of different nonlinearities of higher order should lead to a larger complication of both the physical picture of interaction and the theory itself.

5. CONCLUSIONS

In the given work, analysis of two-stream cluster FEL-klystrons as a new class of devices is carried out. Three of four structural designs and their theoretical models (systems with multiharmonic input signal, with non-resonant modulator and intermediate acceleration) are considered for the first time. Multiharmonic processes in the transit section of two-stream cluster FEL-klystron are analyzed in detail in the weak-signal approximation.

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