J. Nano- Electron. Phys.
2 (2010) No2, P. 96-119

PACS number: 41.60.Cr

ACTIVE FEL-KLYSTRONS AS FORMERS OF FEMTOSECOND CLUSTERS OF ELECTROMAGNETIC FIELD. GENERAL DESCRIPTION

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A qualitative physical and technological substantiation of the creation possibility of a new class of Femtosecond Free Electron Lasers (FFELs) (active cluster FEL-klystrons) is given in the article. The concept of "electromagnetic field cluster" is introduced. Apart from that, the main difference between the concepts "the electromagnetic cluster" and "the radio-pulse" (which is well-known in radio-physics) is formulated. The concept of "cluster electromagnetic wave" is also discussed. A general approach to designing the proposed active cluster FEL-klystrons is formulated. The description of a principal design scheme of the active cluster FEL-klystrons and their key technological basis are discussed.

Keywords: *FREE ELECTRON LASERS, FEMTOSECOND CLUSTERS OF ELECTROMAGNETIC FIELD, ACTIVE KLYSTRONS.*

(Received 10 June 2010, in final form 16 July 2010)

1. INTRODUCTION

In the theory of free electron lasers (FEL) the pump field is often considered as a harmonic one (or quasi-harmonic if the transition regions at the system input-output are taken into account) [1-14]. In such models the appreciable multiharmonicity of the wave fields typical for nonlinear interaction stage becomes apparent only in the case of electron beam waves (spatial charge waves – SCW) [1, 10, 14]. As a rule, high harmonics of the signal and pump waves are neglected. First and foremost, their appearance in the spectrum of signal wave (and pump wave if it is a self-consistent electromagnetic one) is mostly conditioned only by the weak influence of non-resonance nonlinear effects [1].

However, in the experiment magnetic undulators (and, correspondingly, wigglers) are always characterized by the imperfectly sinusoidal magnetic or electromagnetic field, and, as a consequence, by the weakly expressed but appreciable multiharmonicity. This means that the additional conditions of the parametric coupling can be satisfied for some high harmonics of SCW and pump field harmonics. In this case, generation of the signal wave harmonics is found to be the resonance one, and, correspondingly, becomes much more intensive. And this, in turn, can have a great effect on the form of amplified (generated) electromagnetic signal.

Further, we have to note that in spite of the qualitative self-evidence of the above described resonance mechanism of high harmonic generation, in the theory of "usual" (i.e., parametric) FEL it was not formally studied. First of all, because such type of multi-harmonic interaction is not of a great practical interest in traditional statement of a question (when the main aim is to reach high amplification levels and efficiency at harmonic output signal [1, 10, 14]). In individual cases, when phenomena of the given class are of some interest, they are considered as parasitic effects, which realization is objectionable for practice.

However, situation was fundamentally changed with the appearance of the so-called superheterodyne FEL (SFEL). As known [15-33], the last ones are constructed based on the spatial superposition of some longitudinal beam instabilities (for example, two-stream [17] or plasma-beam [16]) with traditional for "usual" FEL parametric instability [1-14]. In contrast to "usual" parametric FEL [1-14], here (due to the specific properties of the pointed instabilities) multiharmonicity of SCW is found to be strongly expressed initially [34-38]. For example, in some special cases the maximum of harmonic amplitude in the SCW spectrum at the development of two-stream instability can fall at 15-th or 20-th harmonic, but not at the first one as usual. In this situation even the presence of the weakly expressed multiharmonicity of the pump field can lead to the generation of sufficiently intensive spectrum of high harmonics of electromagnetic signal. In this case, the form of the output signal can be radically changed. For example, as it is shown in particular in [39, 41], harmonic electromagnetic signal on the two-stream SFEL input during amplification can be transformed into the alternating sequence of super-power femtosecond clusters of electromagnetic field, i.e., cluster wave.

Half-qualitative analysis showed that femtosecond clusters as well as their more famous analogues, the femtosecond radio-pulses [43, 44], can have a number of unique physical properties. Among them, for example, ability to penetrate on the given depth in different dense material mediums (gaseous, solid, liquid) without damping. This, in turn, gives a possibility for practical realization of a number of absolutely new technologies both of the commercial and special purposes. However, we have to note that in such applications the main requirements to multi-harmonic FEL are substantially changed. Namely, the amplifying properties of FEL pale into insignificance, and the ability to operate as the shaper of short (including femtosecond) clusters of electromagnetic field becomes the main one. In other words, the system optimization problems in the amplification and efficiency maximum being still important become less relevant. System ability to effectively form the multiharmonic spectra of the output signal of a given form comes to the fore. And this, in turn, substantially changes both the ideology of FEL construction and the main accents of the theory while studying the basic physics of the processes proceeding here.

As the corresponding analysis showed, use, for example, of the two-stream superheterodyne FEL as femtosecond generator (SFEL-shapers) [39, 41] in practice was complicated by some purely technical problems. The main ones are closely connected with the tuning process of the output multiharmonic spectrum of the required form. Namely, with the presence of sufficiently convenient technical "free" setting parameters, varying which it is possible to achieve the optimal spectrum form of the output femtosecond signal. In the case of the models described, for example, in [39, 40], such relatively "free" parameters are the typical geometric size ratios for constructional elements of magnetic undulator, which, in turn, define the spectrum form of the pump field harmonics. However, we have to note that the possibility of real effective dynamic control over such "free" parameters nowadays belongs to unsolved technical problems. And this, in turn, essentially decreases the practical appeal of the idea of femtosecond systems of the given class.

Because of the aforesaid, the search of more perfect and, at the same time, more technically acceptable approaches to the construction of the femtosecond FEL models was undertaken. One of such most challenging, in our opinion, approaches is described and illustrated in the present work. The main idea here consists in the simultaneous use of two following basic techniques.

The first one is the spatial separation of two key basic mechanisms of femtosecond FEL. Namely, of the formation mechanism of multiharmonic SCW packet (regions of multiharmonic modulator and transit section) and the transformation mechanism of this SCW packet into electromagnetic wave packet of the signal (section of multiharmonic FEL-transformer). Such technological solutions in electronics are traditionally called the active klystrons [1, 22, 23] since an active amplifications of longitudinal SCW due to some external (additional) amplification mechanism occurs in the transit section. Thereupon in the present paper we use the following terminology: studied here design versions are called the active FEL-klystrons.

The second of the aforesaid techniques consists in the possibility to use the section of "usual" parametric high-current FEL with multiharmonic pump instead of the mentioned transformer "SCW-packet of clusters $\rightarrow$ electromagnetic packet of clusters". We have to remind that earlier we used the two-stream model of SFEL-klystron [39-42] as the basic one. However, as it will be shown below, it is not the only possible model for the discussed class of systems. Moreover, in the case, for example, when the parametric amplification mechanism of multiharmonic signal is realized in the end klystron section (i.e., when the parametric mechanism substantially prevails over the two-stream one), two-stream SFEL-klystron [1, 22, 23, 39-42], strictly speaking, cannot be interpreted as "purely superheterodyne" one any more. In accordance with the accepted here system of definitions, more correctly it should be considered as parametric (though two-stream) active FEL-klystron.

2. FEMTOSECOND PULSES AND FEMTOSECOND CLUSTERS

Before starting the study of the physics of femtosecond active FEL-klystrons we will briefly discuss both the femtosecond idea itself and some key problems typical for the given technology class.

Numerous theoretical and experimental publications at the end of the 70th – beginning of the 80th [43, 44] confirmed both the principal possibility of practical construction of femtosecond generators and the key physical features of femtosecond pulses, including their ability to propagate without damping over large distances in opaque mediums (gaseous, liquid, solid), presence of weak frequency dispersion (that, in turn, leads to the gradual increase in the pulse duration during its propagation), and some others. We also note that all, without exception, experimentally realized at that time femtosecond systems were constructed based on quantum lasers.

It is important to note that in spite of the achieved real fundamental success, such systems, however, did not have a wide practical application. First of all, because the most "interesting" among them demanded very high levels of average power (units-tens, and in some cases hundreds of kW), while really achieved levels of average power were much lower (as a rule, tens-hundreds of mW). This has stimulated the continuation of the financing of such studies and the search of more effective operational principles and physical mechanisms.

And such principles and mechanisms were finally found [39-42]. A new operational principle was formulated as an idea of synthesis (formation) of the electromagnetic field clusters of a signal from the field of many electromagnetic waves. A new physical mechanism was proposed as an effect of the multiple parallel three-wave parametric resonances in multiharmonic two-stream superheterodyne FEL (MTSFEL). As a result, the output electromagnetic signal was generated as a periodic alternating sequence of electromagnetic clusters, i.e., the cluster wave. Multiple harmonics of SCW excited in the same relativistic electron beam were used as the above mentioned "many harmonic sources". SCW in such multiharmonic system existed as a periodic alternating sequence of electron clusters. Correspondingly, the field of multiharmonic magnetic undulator is also considered as the given alternating sequence of specific magnetic clusters. Due to the effect of multiple three-wave parametric resonance of harmonics of these cluster waves the electron beam energy in the pump field through SCW harmonics is transformed into the energy of harmonics of electromagnetic cluster signal. As a consequence, at the system output we have a super-power electromagnetic signal in the form of the mentioned alternating sequence of narrow (including, femtosecond) clusters of electromagnetic field.

It was revealed afterwards that in addition to MTSFEL a number of other similar construction types, including active FEL-klystrons, is also possible. And they all can be successfully used as the sources of femtosecond cluster waves as well. Some of them are discussed both below in the present paper and in other (subsequent) parts of this work.

Thus, the key features of the proposed new approach [39-42] in contrast to the known before [43, 44] were the following:

a) classical (i.e., non-quantum) nature of the basic physical mechanisms;

b) transition from the femtosecond radio-pulses of a signal field to the femtosecond electromagnetic clusters.

The first of the pointed differences is self-evident enough since the effect of multiple parametric resonances in any FEL is fundamentally classical. As for the second difference, it does not look self-evident and banal. First of all, because the conception of electromagnetic field clusters was poorly studied and was not almost used in electrodynamics. As a result, it is not widely known as the conception of radio-pulse.

The essence of the main physical differences between definitions "femtosecond pulse" and "femtosecond cluster" is illustrated in Fig. 1 and Fig. 2. As known from standard course of radio engineering, electromagnetic pulse (radio-pulse) is not a "real" pulse. First of all, because this is a pulse of an envelope "filled" by oscillations of electromagnetic wave of a carrier frequency. The form of such pulse for the special case of femtosecond durations is shown in Fig. 1. Since the carrier frequency $\omega_1 = 2\pi/T_1$ (see Fig. 1) in this case belongs to the optical range, it is obvious that in the femtosecond case there are only some oscillation periods of the carrier in the interval of pulse duration, for example, of $\tau_{p2} \sim 5{\cdot}10^{-14}$ s. This implies about the second principal defect of the femtosecond technique based on the use of radio-pulses generated by quantum lasers [43, 44]. Namely, to obtain the pulse duration of the order of femtosecond and less, it is necessary to shift to the violet, and then to the ultraviolet and X-ray ranges of the carrier frequencies. At the same time, however, much more difficult technical problems, connected with the basic technique of laser radio-pulse pressure, arise [43, 44]. (We remind again that the first (and the main) among the principal defects is the deficient level of average power of such femtosecond generators).

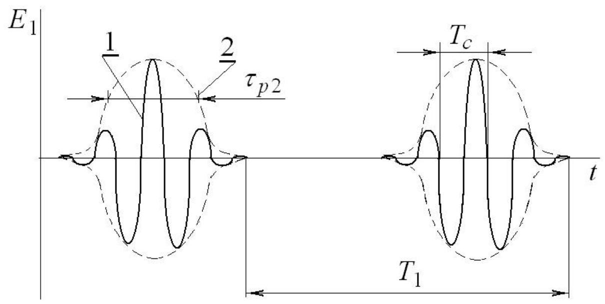


Fig. 1 *– Illustration of the conception of femtosecond electromagnetic pulse (radio-pulse). Here: 1 – instantaneous electric field intensity of radio-pulse; 2 – radio-pulse envelope;* τ_{p2} *is the radio-pulse duration;* T_1 *is the period of radio-pulses;* T_c *is the conditional period of the carrier (*$\omega_c = 2\pi/T_c$ *is the carrier frequency)*

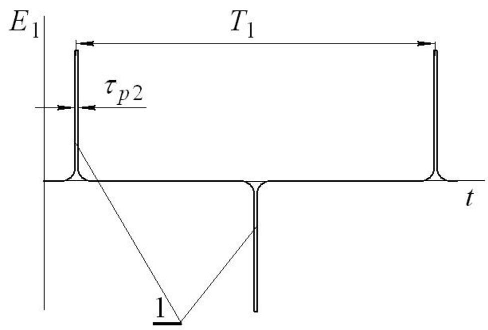


Fig. 2 *– Illustration of the concept of electromagnetic field femtosecond cluster. Here: 1 – clusters of electromagnetic field;* E_1 *is the instantaneous electric field intensity of electromagnetic signal wave;* T_1 *is the period of clusters;* τ_{p2} *is the cluster duration; t is the time coordinate. Instantaneous picture is observed in the output plane of the electromagnetic cluster wave source*

Electromagnetic field clusters (see Fig. 2) in contrast to the radio-pulse are the "real" pulses like current or voltage pulses studied, for example, in classical electrical engineering. Actually, in this case we have some periodic sequence of very dense and short bunch (clusters) of electric and magnetic fields propagating in the medium. Here it is principal that electromagnetic clusters do not connect with any carrier frequency and, correspondingly, their duration is not restricted by the reasons mentioned above with respect to radio-pulses. As the analysis shows, for the up-to-date level of technology development the formation of femtosecond clusters of the order and less (even substantially) of a femtosecond is possible in principle. Nevertheless the main advantage of femtosecond cluster technologies is a real prospect of the formation of periodic cluster series (cluster waves) with the average power of tens and even hundreds of kW and with the instantaneous power of 0,1-10 TW, respectively. This, in turn, offers the unique opportunity to create an absolutely new area of applied and theoretical femtocluster electrodynamics, and develop the commercial and special techniques based on this basis as well.

3. IDEA OF THE SYNTHESIS (FORMATION) METHOD OF ELECTROMAGNETIC FIELD CLUSTERS

In view of the abovementined we should clarify the only one "fine" question: how is it possible to form such femtosecond clusters in practice? This question, as it was pointed, was answered in publications [39-42]. Idea of the proposed method is illustrated in Fig. 3-5.

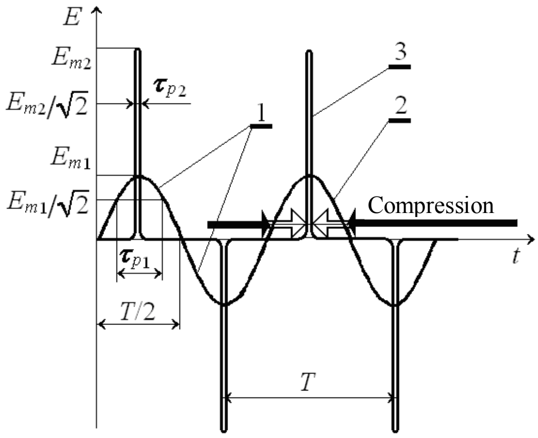


***Fig. 3** – Key idea of the synthesis (formation) method of femtosecond electromagnetic clusters. Here: 1 – initial harmonic signal; 2 – "half-sine pulse"; 3 – femtosecond cluster; E_{m1} is the harmonic signal 1 amplitude; E_{m2} is the electric field intensity of cluster wave 3; T is the period of clusters 3 which is equals to the period of harmonic signal 1; τ_{p1} is the half-width of "half-sine pulse" 2 of harmonic signal 1; τ_{p2} is the cluster 3 duration ("half-width"); t is the time coordinate*

We assume that we have initial harmonic (i.e., sinusoidal) electromagnetic wave shown in Fig. 3 by the curve 1. It is obvious that this curve can be mentally represented as a periodic alternating sequence (with the period T) of "half-sine pulses" 2. The main idea of the method consists in a strong compression (see Fig. 3) of every pulse 2 in time and space. It is obvious from Fig. 3 that such compression can be characterized, for example, by the compression coefficient f_{com}

$$f_{com} = \tau_{p1}/\tau_{p2} \approx T/4\tau_{p2} \, . \tag{1}$$

It is also obvious that each femtosecond cluster 3 can be considered as a peculiar wave packet. In the case when the conditions

$$f_{com} >> 1, \qquad \tau_{ch} < T/2 \tag{2}$$

hold, the each femtosecond cluster 3 is considered to be isolated if take into account the striking features of its propagation in the medium. Here τ_{ch} is the characteristic time interval where medium relaxation occurs after passing one cluster.

At first sight, the idea of the described method looks to be very simple. However, situation is changed if we ask the question: how to realize this experimentally? The answer proposed in [39-42] is not very simple. Because there was nothing in scientific publications before the appearance of the first systems with practical use of such approaches to the formation of narrow (including, femtosecond) clusters of electromagnetic field.

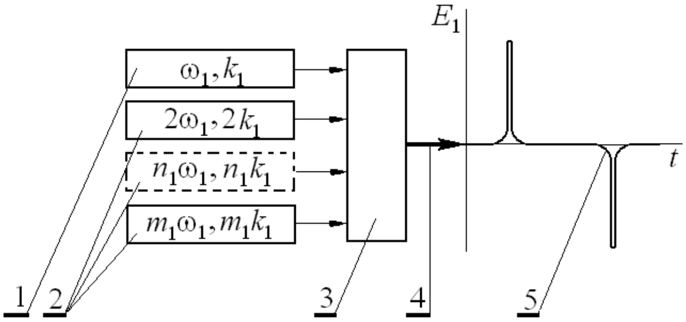


Fig. 4 *– The simplest design diagram of the device for the formation (synthesis) of femtosecond clusters by combination of many harmonics of a signal (synthesizer of cluster waves). Here: 1 – the first source of the initial harmonic signal (the first harmonic); 2 – sources of the second and other (up to the m-th) higher harmonics of a signal; 3 – combination system of signals of all harmonics* $n_1\omega_1$, n_1k_1; *4 – alternating sequence of multiharmonic wave packets of a signal 5 at the output of the combination system 3;* E_1 *is the instantaneous electric field of a signal cluster wave;* ω_1 *and* k_1 *are the cyclic frequency and the wave number of the first source 1 signal, respectively;* $n_1 = 1, 2, ..., m_1$ *are the numbers of harmonics of generator 1, 2 signal;* m_1 *is the maximum number of* n_1 *harmonics; t is the time coordinate*

The simplest design scheme of a possible device (femtosecond synthesizer-shaper) is illustrated in Fig. 4. Let us assume that we have a series of harmonic sources of electromagnetic signals 1, 2 of the frequency $n_1\omega_1$ and the wave numbers n_1k_1, which correlate as whole harmonics of the first source signal ω_1, k_1 (see Fig. 4). Ensemble of both the classical and quantum known devices can be used as such sources. Moreover, each of them can generate more than only one harmonic. However, for simplicity we suggest that each source generates the only one monochromatic signal.

We also assume that further all harmonic signals are input to the combination system 3. By a special adjustment of the amplitudes (and the initial oscillation phases as well) of the source 1, 2 signals at the output of the combination system 3, one can obtain (that is described mathematically by the inverse Fourier transformation) sequence of electromagnetic clusters of the given form, including femtosecond. In practice the last ones are conveniently described within the theory of the so-called “smear” Dirac delta function [45]. An example of the spectrum of periodic sequence of such clusters (i.e., as “smear” delta functions) is schematically shown in Fig. 5.

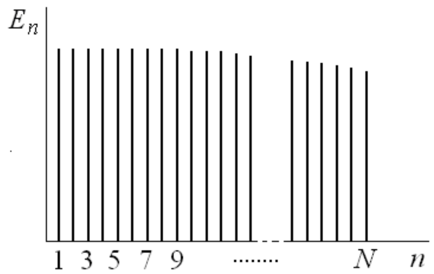


***Fig. 5** – Example of the spectrum of alternating periodic sequence of femtosecond clusters as "smear" Dirac delta functions. Here: E_n is the amplitude of the n-th harmonic of a signal; n is the sequential harmonic number; N is the upper number of the harmonic spectrum*

As the analysis shows, the illustrated in Fig. 4 and Fig. 5 the simplest design scheme of the electromagnetic cluster source can be realized experimentally without specific technical difficulties. However, we note that the field of possible practical applications of such shapers (especially femtosecond) is found to be sufficiently restricted in the given case. For example, these are the medicine systems for different types of radiation femtosecond therapy, research measuring complexes for different branches of physics, femtosecond sources for testing systems of the radio-electronic equipment, sources of the input cluster signal for femtosecond FEL, and others.

Nevertheless, the design solutions like those illustrated in Fig. 4 and Fig. 5 cannot solve the chief tasks. The main problem consists in the appearance of insurmountable technical difficulties if move to the region of high (starting from hundreds of watts and higher) levels of the average power of the output cluster signals. The corresponding analysis shows that in such situations as well as in the case of femtosecond quantum lasers it is necessary to use the design solutions based on multiharmonic FEL (MFEL). Also the analysis allows to clarify that in this case active MFEL-klystrons can have a number of important technical advantages.

According to the aforesaid we will perform a brief qualitative analysis of the most challenging design schemes and models of the given type.

4. ACTIVE MULTIHARMONIC FEL-KLYSTRONS: BASIC PRINCIPLES

Example of the block diagram of the proposed multiharmonic version of an active klystron is shown in Fig. 6. Its operation principle is the following.

Relativistic electron beam 3 (multispeed in the general case) is created by the source 2 (examples of the design schemes are represented below in Fig. 7-Fig. 11). Then beam 3 is input to the multiharmonic modulator 4 (see examples of the design schemes in Fig. 12 and Fig. 13). The input (multiharmonic in the general case) signal ($n_1\omega_1$, n_1k_1) formed by the source 1 is also input to the modulator input. The devices like those illustrated above in Fig. 4 or another multiharmonic FEL can be used as the source 1.

Interaction between the signal ($n_1\omega_1$, n_1k_1) and electron beam 3 occurs in the working volume of the modulator 4. As a simple analysis shows, the practical realization of a sufficiently large number of schematic versions of modulator design is possible in the given case. Thus, for example, in the previously studied models of active klystrons [39-41] it was planned to execute a modulator as an input harmonic (or multiharmonic in the general case) section of superheterodyne FEL (see caption to Fig. 13), i.e., fundamentally resonance systems. However, at high levels of amplification typical, for example, for two-stream and plasma-beam superheterodyne or "usual" modulator sections 4 [17-42], such solutions are found to be technically superfluous since much more simple non-resonance modulators can be used with the same success for sufficient modulation. One of such examples is shown in Fig. 13. In the general case we note that regardless of the form of the modulator 4, at the system output we always have the modulated (including multiharmonic) beam 5, which then passes to the active part of the middle section 6 where formation of an intensive cluster SCW of the electron beam 9 occurs. As it was mentioned above this cluster wave appears as the result of non-linear synthesis of many SCW harmonics 7 during the development of some additional amplification mechanism of longitudinal electron waves. Both quasi-liner (plasma-beam or two-stream) and parametric (electron-wave and others) beam instabilities [17-42] can be used as such mechanisms.

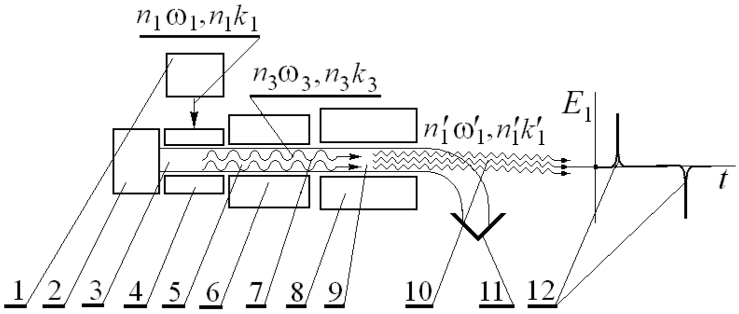


***Fig. 6** – Example of general block diagram of an active multiharmonic FEL-klystron. Here: 1 – source of multiharmonic input signal $n_1\omega_1$, n_1k_1 (where ω_1 is the cyclic frequency; k_1 is the wave vector; n_1 are the numbers of harmonics); 2 – source of relativistic electron beam; 3 – electron beam formed by the source 2; 4 – multiharmonic modulator; 5 – relativistic multiharmonic modulated electron beam; 6 – middle section, which consists, in the general case, of active and passive parts; 7 – SCW harmonics of the beam 5; 8 – pump system of the end FEL-section; 9 – electron beam 5 in the interaction region of the FEL-section 8; 10 – generated by the FEL-section multiharmonic output signal as a sequence of femtosecond electromagnetic clusters (cluster wave of a signal) 12; 11 – recuperation system and collector of the spent electron beam 5; 12 –cluster wave of a signal; $n_3\omega_3$, n_3k_3 is the multiharmonic wave packet of SCW (where ω_3 is the frequency; k_3 is the SCW wave vector; n_3 are the numbers of harmonics); $n_1'\omega_1', n_1'k_1'$ is the multiharmonic wave packet of the output signal (where ω_1' is the cyclic frequency of the first harmonic; k_1' is the wave number; n_1' is the number of harmonic); in the general case the output signal frequency ω_1' is considered to be shifted with regard to the input signal ω_1*

After passing the middle section 6 the modulated beam is directed to the interaction region of multiharmonic FEL-section 8. Here, as well as in the case of modulator, a sufficient variety of partial schematic versions is also possible. However, the general operational principle is found to be the same: for each harmonic of multiharmonic cluster SCW ($n_3\omega_3$, n_3k_3) the condition of the parametric resonance with similar harmonics of cluster pump waves

($n_2\omega_2$, n_2k_2) and electromagnetic signal ($n_1'\omega_1', n_1'k_1'$) holds. Thus, non-traditional physical effect called as multiple three-wave parametric resonance [39-42] is at the basis of the discussed electron systems. Adjusting the form of the cluster SCW spectrum at the modulator 4 output, we have the possibility to control the parameters of electromagnetic clusters at the FEL-section 8 output. As seen, the main principal difference between the multiresonant FEL-section and the "usual" one [1-17] in the given case consists only in the use of multiharmonic, i.e., cluster (instead of harmonic) pump system. Moreover, in the form of both the magnetic undulator (wiggler, see the example in Fig. 15) and the intensive electromagnetic wave (dopplertron pump, see the example in Fig. 16).

As the design analysis shows, the most interesting (for practice) versions of femtosecond active klystrons can be constructed based on the sources of high-current and very high-current relativistic beams. As such, later we consider some examples of such design sources.

5. SOURCES OF RELATIVISTIC ELECTRON BEAMS

Sources of the relativistic electron beam 2 (see Fig. 6) can be performed as both the relatively low-voltage (up to ~ 1-5 MeV) electron injectors and the high-current electron accelerators. The analysis shows that use of linear and undulator induction accelerators [46-54] is the most challenging by the set of operating characteristics. Moreover, both the single-beam and the single-channel and the multibeam and the multichannel, in the general case.

The simplest example of the single-beam electron induction injector [49, 50] is illustrated in Fig. 7.

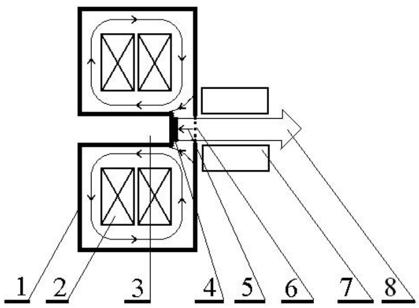


***Fig. 7** – Example of the design scheme of the single-beam induction electron injector. Here: 1 – electric screen; 2 – magnetic inductor; 3 – central electrode; 4 – cathode; 5 – force line of the internal part of the electric field, which is directly used for the beam 8 acceleration; 6 – transparent (for the beam 8) part of the electric screen 1 (anode, for example, is grid or foil); 7 – system of the electron beam 8 formation; 8 – output high-current electron beam*

Injector consists of the electric screen 1, inside which there are magnetic inductors supplied from the external high-current pulsed power source. Time-dependent magnetic flux in inductors 2 generates the vortex electric field 5. As a result, a high voltage (as a rule, ~ 1-2 MeV or more) appears in the gap between the central bar 3 and the earthed part of the screen 1 realized in the form of a grid (or thin foil) 6. Cathode 4 (based on thermo-, photo- or autoemission, for example) is placed into this gap. Generated ("extracted") high-current electron beam 8 is caught by the system of the electron beam formation 7. The last one can be realized in the form of a section of both the direct solenoid (as in the example in Fig. 7) and the toroidal solenoid (turning system [48, 49]).

We note that, as the simplest, the design version shown in Fig. 7 is not the most perfect one. It has defects, among them the short lifetime of the cathodes 4 that leads to the appearance of a number of technical problems. Therefore injectors based on plasma ("eternal") cathodes (see, for example, design versions presented in [54]) look more attractive in practice.

Example of a high-current single-beam undulator electron accelerator based on the injector shown in Fig. 7 is presented in Fig. 8 [50].

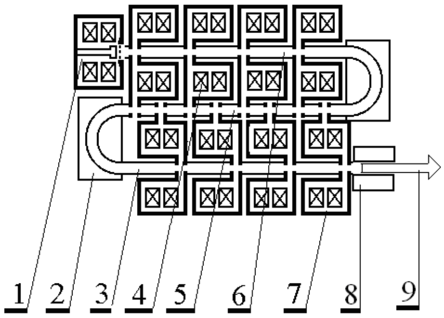


***Fig. 8** – Design diagram of the single-beam undulator induction electron accelerator with two internal and one external accelerating channels. Here: 1 – injector; 2 – turning systems; 3 – first internal accelerating channel; 4 – first linear accelerating unit; 5 – doubled external accelerating channel; 6 – second internal accelerating channel; 7 – second linear accelerating unit; 8 – output unit of the electron beam 9 formation*

Accelerator consists of five main units: two turning systems 2, injector 1 and two linear accelerating units 4, 7. The last ones, in turn, contain the kits of accelerating sections connected in such a way that linear parts of internal accelerating channels 3, 6 were formed in the range of each unit 4, 7. Moreover, one more external doubled accelerating channel 5 is formed here. Its accelerating gaps are formed by the electrodes coupled with special slits in external electric screens of accelerating sections of the units 4, 7. And if in the accelerating gaps of internal channels 3, 6 the accelerating voltage is formed due to internal regions of the inductor force lines (see, for example, the force lines in Fig. 7), in the external channel – due to their external regions. The key technical element here is a special form of the screens made as the concentrators of external parts of the electric field force lines. As a result, in each accelerating gap of the external accelerating channel 3 it is possible to accumulate up to 60% and more force lines with regard to a number internal force lines penetrating internal gaps. And since the electrodes of both accelerating units output to the external accelerating channel, the acceleration rate is fond to be at least 1,2 times more than in internal cannels 3, 6.

Design of each accelerating section of accelerating units is similar to the injector presented in Fig. 7. The difference consists in the following: instead of the cathode 4 (Fig. 7) transparent part of the electric screen (for example, in the form of a grid) is placed here in such a way that accelerating gaps for the beam are formed in the channel. In other respects, the operation principle of accelerating section does not differ from the described above for injector shown in Fig. 7.

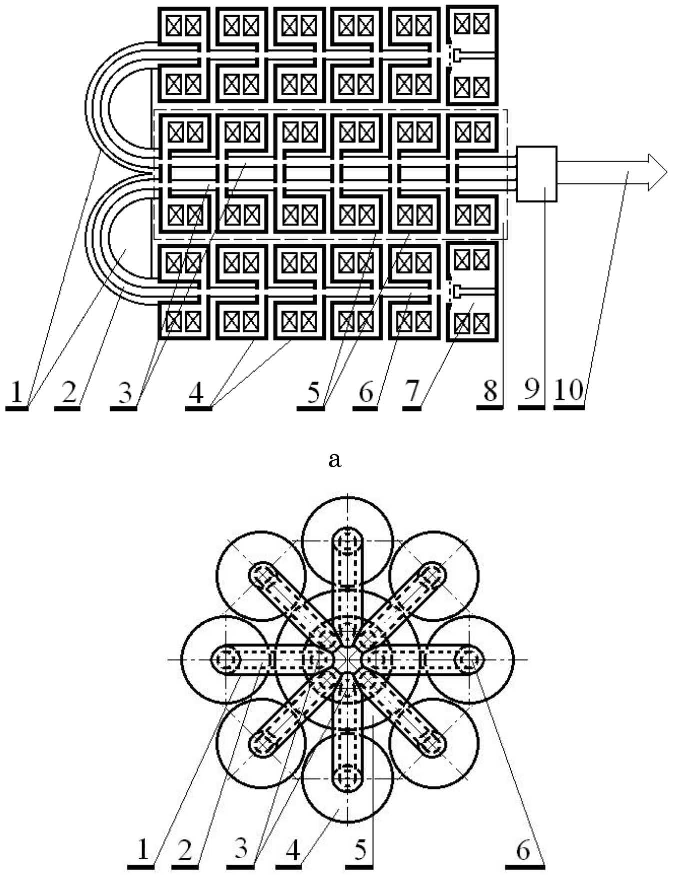
As in the previous case, the turning systems 2 can be realized as sections (or a set of sections) of toroidal solenoids [48, 49], which are similar to those used, for example, in TOKAMAKs [55].

Thus, the one of the main features of the illustrated in Fig. 8 undulator construction is the use of the turning systems 2. This allowed to essentially (some times) decrease the total longitudinal dimension of the accelerator. In this case, and it is very important, in linear parts of the accelerating channel we have the same acceleration rate that in the chosen for the comparison equivalent linear (much longer) accelerator. The second innovation consists in the use of the so-called doubled external channel 5 which was mentioned above. Due to this paradoxical design solution in the presence of two linear accelerating units 4, 7 we obtain three linear accelerating channels 3, 4, and 6. As a result, at the equal acceleration rate in the channels we have three-fold decrease in the longitudinal dimension. As an example we remind that the length of the known accelerator ATA [3] is about 75 m. Transition to the undulator layout of the system (of the same type that is presented in Fig. 8) allows to decrease it down to ~ 25 m. This means that the equal total acceleration is obtained not in the system of the length of 75 m (as in the case of ATA), but in the accelerator of the length of "only" ~ 25 m. It is possible to achieve more decrease in the total longitudinal dimension of the accelerator if use the construction with larger number of turns and external channels. The last circumstance is of a great importance while constructing the compact femtosecond systems since in the FEL engineering the accelerator occupies up to 80% of the total longitudinal dimension of the experimental unit.

We note that in the case of two-stream multiharmonic SFEL (or multi-stream, the theory of which is not still constructed) use of two-channel (or multi-channel, respectively) structural designs of undulator accelerators is found to be the optimal. Efficiency of such solutions increases if there is a task, for example, to form a very high-current (super power) active femtosecond MFEL-klystron. Example of the structural design of the induction accelerator intended for use in such systems is shown in Fig. 9 [48, 49].

Here eight single-channel linear accelerating units with injectors (which are similar to the units 5, 6 in Fig. 8) are placed on the generatrices of an imaginary cylinder which is formed by the construction of the central eight-channel linear accelerating unit 8 (see Fig. 9). Single-channel units in this case are coupled by the turning systems 1, each one with its own channel of this central unit 8.

As known, the problem of formation and transportation of very high-current (with the current of tens-hundreds kA) is still very sharp. For example, formation of super power special systems of the type of the discussed here femtosecond FEL is determined in many respects by success in engineering of very high-current accelerators. Unfortunately, effective practically realized design solutions have not been still demonstrated in many technical aspects of the plan. The main technical obstacles here are connected, first of all, with the features of the "extraction" process of such strong beams from the cathode region, and with their further transportation in the working channels as well. In the first case, the main obstacle is the necessity of use of unreal high accelerating voltages in the cathode-anode regions. In the second case, the key aspect is that the maximum possible current of the transported beam in the channel with conducting walls is found to be restricted by the so-called critical current [56]. The last one, as known, at the given density is proportional to the beam energy. In physical meaning this is the largest (i.e., the maximum possible) current which can be transported in such accelerating channel.



b

Fig. 9– *Structural design of multi-channel induction eight-beam accelerator-former of a very high-current electron beam (frontal (a) and cross (b) projections). Here: 1 – turning systems; 2 – curvilinear channels of the electron beam transportation in the turning systems 1; 3 – internal straight channels of central eight-channel accelerating unit; 4 – peripheral single-channel accelerating sections; 5 – accelerating sections of the central eight-channel linear accelerating unit; 6 – linear channels of peripheral accelerating units; 7 – single-beam partial electron injectors; 8 – central eight-channel linear accelerating unit; 9 – combining system of eight high-current electron beams to the one very high current beam 10*

In connection with the aforesaid, a lot of active attempts of the search of new nonstandard approaches to the projecting of such accelerating systems were undertaken. The most interesting from both the technical and physical points of view were the design solutions based on the idea of the synthesis of a single very high-current electron beam from some weaker partial high-current beams [48, 49]. In this case each partial beam is injected and further accelerated independently. On the certain stage of acceleration some of them are combined to "more high-current" beam, and then these "more high-current" beams are combined to a smaller number of "more high-current" beams, etc. Thus, on the last stage the formation of only one (or two of different velocity, if it is provided by the statement of the problem) relativistic very high-current beam is performed. Based on the state-of-the-art of high-current induction accelerators one can conclude that it is possible to create the accelerating systems for the formation of fabulous (from the modern point of view) beams with the current of units MA. Both the level of their technical complexity and amount of financing, which is necessary for the practical realization of such systems, inspire a profound respect.

To the authors' opinion, the significance level of special problems, which can be solved by the systems based on super power femtosecond (cluster) FEL can sufficiently motivate both the overcoming of the expected technical difficulties and doubt removal regarding the appropriateness of financial expenditure. Among such FEL the most challenging are the following:

1. two-stream quasi-linear and parametric active FEL-klystrons [23, 36-42];
2. multi-beam active FEL-klystrons (the theory of which, as it was mentioned, has not still developed);
3. plasma-beam quasi-linear and parametric single-beam active FEL-klystrons;
4. parametric active FEL-klystrons, both the "classical" electron-wave [24-27] and those where the middle section is fulfilled in the form of longitudinal electric undulator [33].

Physics of the processes in active femtosecond MFEL-klystron versions of the listed systems will be discussed in other papers of the given series.

Note that the main physical idea built into the described above method of the beam synthesis is based on the mentioned proportionality of the critical current to the beam energy. This means that due to the sufficiently strong acceleration of each partial beam the critical current of every beam substantially increases. The system parameters in the considered case are chosen in such a way that the critical current on every stage of combining of each partial beam exceeds some threshold value necessary for further acceleration of the combined resulting beam.

Thus, due to the energy accumulation by the electrons of partial beams the formed total beam 10 ceases to be the overcritical one.

Designs of accelerators presented in Fig. 8 and Fig. 9 obtain many supplementary design versions under the transition from the use of single-beam injectors (of the type presented in Fig. 2) to their multi-beam analo-gues. An example of such two-beam (or four-beam and more – in the given projection their schemes look similar) injector is presented in Fig. 10. Comparing the structural designs of Fig. 7 and Fig. 10 it is possible to see that the main modernization consists in the presence of the cathode assembly. Namely, in the case presented in Fig. 10 it is fulfilled in the form of two (or four and more, respectively) isolated cathodes.

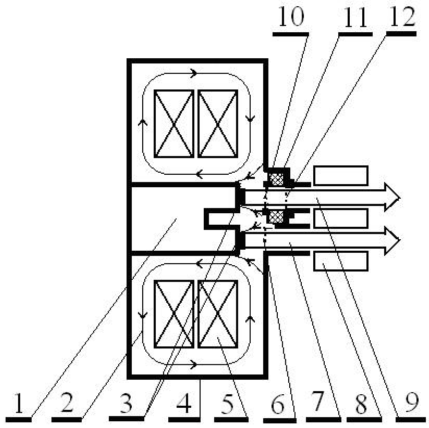


Fig. 10 *– Structural design of the induction injector of two high-current electron beams with different velocities. Here: 1 – central electrode; 2 – force lines of the vortex electric field; 3 – cathodes; 4 – electric screen; 5 – magnetic inductors; 6 – anode grid (or foil) of the beam 7; 7 – the first electron beam; 8 – system of the beam 7 formation; 9 – the second electron beam; 10 – the first anode grid (foil) of the second electron beam 9; 11 – insulator; 12 – the second anode grid (foil) of the second electron beam 9*

If it is necessary to form two beams with different velocities (that is typical, for example, for two-beam systems), one more (relatively low-voltage) accelerating interval for the second beam (the anode grids (foils) 10, 12 as it is proposed in the version shown in Fig. 10) should be additionally placed into the injector construction. It is obvious, that presented structural idea can be relatively easy generalized for the case of many (i.e., more than two) beams with different velocities.

An example of undulator two-channel induction accelerator based on the shown in Fig. 10 two-beam injector is represented in Fig. 11. As seen, along with the number of beams (there are two of them here) in comparison with the versions of undulator accelerators presented in Fig. 8 and Fig. 9, the principle of double (multiple, in the general case) transmission of the beams through the same linear accelerating units, but through different channels is also used here. Because of this at the same (in comparison, for example, with the systems of the type shown in Fig. 8) linear accelerating units we have two-fold (multiple, in the general case) increase in the energy of the accelerated beams 6.

In contrast to the accelerating systems of the type presented in Fig. 9, the systems of the type shown in Fig. 11 [49, 50] are intended for use in the moderately power femtosecond FEL. The known to date magnetic materials which are the basis of inductors of modern linear (and undulator) accelerators have appreciable level of energy loss. This leads to the fact that high values of the electron efficiency of acceleration can be obtained only at sufficiently high levels of the beam current. Typical values of the threshold currents, i.e., such currents which give acceptable values of the electron efficiency, are the currents not less than ~ 1-2 kA. In the case of the scheme presented in Fig. 11 the practical sharpness of the problem can be substantially softened. First of all, because the same beam during acceleration passes the same accelerating unit, at least, doubly. This means that each linear accelerating unit simultaneously accelerates the electron beam with the twice total current. As a result, the electron efficiency is found to be appreciably higher.

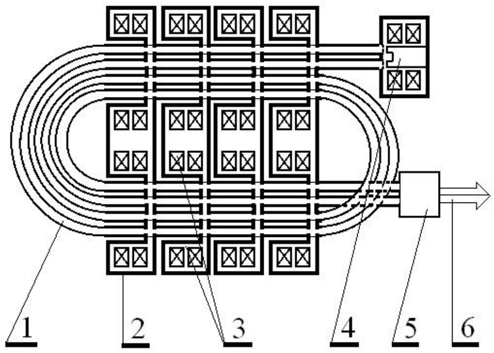


Fig. 11 *– Example of the structural design of two-beam induction accelerator-shaper of two-beam electron beam. Here: 1 – curvilinear channels in the turning systems (which for simplicity are not shown here); 2 – doubled eight-channel linear accelerating section; 3 – elliptic inductors of linear accelerating sections 2; 4 – two-beam injector; 5 – system of the double-speed beam 6 formation*

6. MODULATORS

As it was mentioned above, in the considered here active FEL-klystrons it is possible to use two fundamentally different classes of the electron beam modulators: resonance and nonresonance ones. A whole set of possible structural solutions based on the principles of resonance interaction between the input electromagnetic signal and the relativistic electron beam is ascribed to the resonance modulators. Examples of such design solutions are numerous, and it seems they can be taken from the classical microwave electronics, plasma electronics, etc. In principle, this could be sections of the TWT (traveling-wave tube), klystrons and cyclotron systems, or other similar devices for the excitation of intrinsic beam instabilities.

However, the more detailed design analysis shows that this visible variety means little for practice of the discussed here relativistic electronics. First of all, because relativistic systems of the type, for example, of FEL are characterized by the sufficiently specific technical and physical features. Therefore the more complete analysis concludes that the only one type of technically acceptable resonance systems, which satisfy the all aforesaid specific features, exists, and this is the sections of different FEL. This could be both the sections of "usual" parametric FEL and superheterodyne two-stream and plasma-beam FEL.

Example of the structural design of such modulators is shown in Fig. 12. Here multiharmonic electromagnetic signal 1 (cluster signal wave with the frequency spectrum $n_1\omega_1$, n_1k_1) inputs to the volume of the multiharmonic undulator 3. The initially nonmodulated electron beam 2 is directed here as well. As a result of the effect of multiple three-wave parametric resonance [39, 42] the cluster SCW characterized by the frequency spectrum $n_3\omega_3$, n_3k_3 is generated in the beam. Then this packet proceeds to the working volume of the next (middle) section (see Fig. 12).

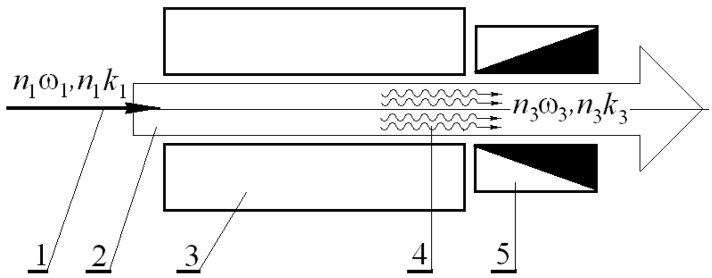


***Fig. 12** – Structural design of the resonance (parametric) modulator of the electron beam. Here: 1 – multiharmonic input signal (cluster signal wave with the frequency spectrum $n_1\omega_1$, n_1k_1); 2 – nonmodulated electron beam; 3 – transverse undulator; 4 – modulated electron beam with the SCW packet (cluster SCW with the frequency spectrum $n_3\omega_3$, n_3k_3); 5 – energy absorber of the cluster signal wave 1*

Note that for the above stated aim of multiharmonic modulation it is possible to use the FEL section with monochromatic input signal and pump [39, 42]. Appearance of multiharmonicity in the SCW spectrum in this case is conditioned by non-linear nature of the basic working mechanism of FEL. It is especially brightly exhibited if use “quasi-monochromatic” resonance modulators based on superheterodyne two-stream [15-21] and plasma-beam [30-32] FEL.

The design presented in Fig. 12 can have two main design versions. The first one proposes the amplifying composition of FEL as a modulator when the signal 1 (Fig. 12) passes the region of section interaction only once. In this case the “spent” input signal after passing the section is absorbed by the absorber 5. In the second case the open resonator for the signal 1 is additionally introduced into the design.

In the general case different design modifications of resonance modulators can also differ in the structure of an electron beam, type of the pump field in undulator, etc. As for the beam structure one can say that in the well-known publications both the one-velocity and two-velocity straight beams are often used. As the primary analysis shows it is possible to use three- and more velocity beams. However, nowadays such versions of femtosecond FEL have not been still studied, though the corresponding half-qualitative analysis shows their potentially great practical availability. As for the design versions of the undulator 3 (Fig. 12), there are much more possible structural realizations here. Among them can be magnetic (H-ubitron) undulators [1-17], undulators with crossed magnetic and electric fields (EH-undulators) [1], undulators based on intensive electromagnetic waves (dopplertron systems) [1], etc. Moreover, all this devices can be both of the quasi-harmonic and multiharmonic realization. Two examples of such multiharmonic pumps of FEL are represented below in Fig. 15 and Fig. 16.

In the case of nonresonance undulators a somewhat different principle of SCW excitation is used. It is known that under periodic disturbance of the electron velocities, the eigenwaves, including longitudinal, are excited in the beam. The real effectiveness of the transformation “electromagnetic signal wave – SCW” is quite low in comparison with the resonance case. However, in practice this circumstance not always plays the core role. For example, in structural designs of active FEL-klystrons with high amplification of SCW in the middle section (for example, due to two-stream or plasma-beam instabilities) use of nonresonance modulators is technically preferred. First of all, because such systems are always structurally simpler than their resonance analogues.

Design example of the optical (quasi-optical) nonresonance modulator of the electron beam is shown in Fig. 13. The electron beam 1 enters the interaction region of the resonator 2, where the field of multiharmonic cluster signal with the frequency spectrum $n_1\omega_1$, n_1k_1 is excited. Beam modulation occurs under the action of the longitudinal field component. This modulated beam 4 is further directed to the middle section (see Fig. 6).

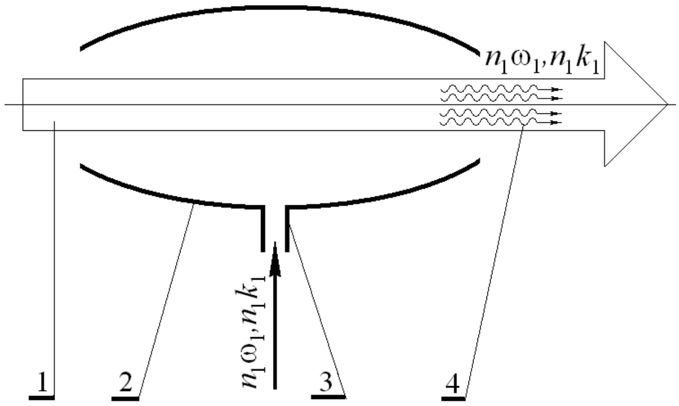


Fig. 13 *– Structural design of the optical (quasi-optical) modulator of the electron beam. Here: 1 – nonmodulated input signal; 2 – barrel-shaped multiharmonic optical (or quasi-optical) resonator; 3 – the resonator 2 input for a cluster electromagnetic signal with the frequency spectrum $n_1\omega_1$, n_1k_1; 4 – modulated electron beam at the system output, i.e., the excited cluster SCW with the same (as signal) frequency spectrum $n_1\omega_1$, n_1k_1*

7. MIDDLE SECTIONS

In the general case the middle section of active FEL-klystron (see Fig. 6), as it was mentioned above, can contain both the active 3 and passive 5 parts (see Fig. 14). In turn, analysis shows that the most challenging from the technical point of view are the versions where the active part is done based on two-stream [38-42], plasma-beam [29-32], and parametric electron-wave systems (including systems with longitudinal electric pump undulator) [33].

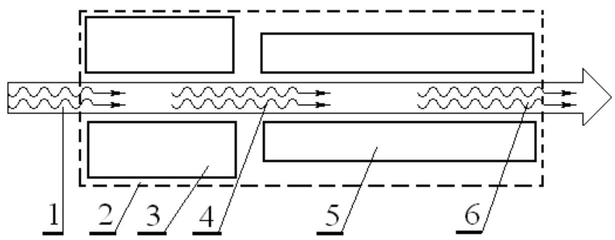


Fig. 14 *– Block diagram of the middle section in general case. Here: 1 – modulated electron beam coming from the modulator; 2 – middle section; 3 – active part of the middle section 2; 4 – multiharmonic modulated electron beam 2; 5 – passive part of the middle section 2; 6 – output multiharmonic modulated electron beam*

In the active part of the middle section two key physical processes occur simultaneously. The first process is the amplification of electron harmonics of the beam 5 (SCW), and thus the formation of multiharmonic SCW spectrum. The second one is the process of shaping of the cluster SCW spectrum. The last one is carried out due to additional generation (amplification) of high harmonics of SCW. We have to note that if use quasiharmonic (i.e., single-frequency) modulators (as, for example, in the model studied in [38-42]) both processes are found to be physically very different. It is well seen while making the corresponding analysis. If use the "initially multiharmonic" modulators (as those, for example, shown in Fig. 12 and Fig. 13) the second effect is proved to be like "puttied" effect of multiharmonic amplification, though, in fact, the observed amplification of harmonics is only the one aspect of the generation process.

The passive part of the middle section 5 can be realized in the form of the magnetic compression system (decompression) or as the intermediate accelerating unit for the electron beam 4. Technical meaning of the introduction of the middle section passive part into the design consists, first of all, in the achievement of the optimal configuration of the beam 6 before its introduction into the next (end) FEL-section. In the last one, as it was mentioned, the transformation of the electron-wave (beam) clusters to the electromagnetic signal clusters occurs. The fact is that the optimum conditions for the realization, for example, two-stream or plasma-beam instabilities, as a rule, substantially differ from the optimal operating conditions of the next end FEL-section. Correspondingly, in the general case, in systems without such passive part quite often there is a design contradiction in the optimal settings of the middle and the end sections. Thus, introduction of the passive part allows to remove such contradictions.

From the variety of the analyzed versions of possible design solutions of the section active parts 3 we can separate three the most interesting from the applied point of view. In the systems of the first type the possibility of variation of the beam parameters, such as the plasma frequency, the wave parameters (for example, moderation retarding factor of the extraordinary pump wave in plasma-beam systems [29]), etc is provided. Technically it can be achieved due to the compression (or decompression) of the beam when it moves in the focused magnetic field. Physically such situation is realized, for example, if use it for the amplification of longitudinal SCW of the effects of plasma-beam, two-stream, longitudinal parametric (including application of longitudinal electric pump undulator) and other similar instabilities. At the same time, as it was mentioned, the beam parameters within the active part of the middle section are chosen to be the optimal for the mechanisms of the SCW-cluster formation, while within the passive part the adjustment of these parameters to the optimum for the end FEL-section takes place.

In the systems of the second type, in addition, change in the beam energy is provided that is achieved by the beam acceleration or deceleration. The fact is that the increments of growth of the above mentioned longitudinal instabilities, as a rule, are found to be much more sensitive to the degree of relativism of an electron beam than traditional longitudinal-transverse parametric FEL-mechanism. As a result, in a number of practically important cases a strict design constraint on the beam energy in the middle section appears. At the same time, such criteria for the end FEL-section require the use of much more relativistic beams. Introduction of the intermediate acceleration allows to substantially soften the described conflict of requirements. Namely, there is a technical possibility to form SCW-clusters on the relatively low (units MeV) levels of the beam energy, while the energy extraction and formation of electromagnetic clusters are performed at appreciably higher energies.

And, finally, the structural designs of the third type are characterized by the simultaneous application of both the above described technical methods, i.e., the simultaneous change in the parameters such as, for example, plasma beam frequency and its energy. Such situations appear, for example, in two-stream active FEL-klystrons when during the acceleration it is reasonable to continue simultaneously the process of two-stream amplification of the beam longitudinal SCW as well.

8. PUMP SYSTEMS OF THE END FEL-SECTION

As the analysis shows, one of the key technical problems of the femtosecond FEL engineering is the practical realization of multiharmonic (cluster) pump. By analogy with "usual" FEL it is possible to create here a long series of possible design versions. Among them are H-ubitron, crossed EH-ubitron, dopplertron, etc [1-17] multiharmonic versions of the well-known in the FEL engineering pump systems. Two examples of such type are illustrated in Fig. 15 and Fig. 16.

Example shown in Fig. 15 represents the version of a cluster (multiharmonic) H-ubitron pump. The idea of periodically reversing sequence of the so-called magnetic clusters is realized here. Such clusters are formed in the gaps between very narrow (in comparison with the undulation period λ_2) magnetic tips 1 structurally connected with the magnetic poles 2 (Fig. 15). It is obvious that expanding the vector of magnetic field induction $\vec{B}_2$ of such cluster pump wave into the Fourier series, it is not difficult to obtain the sufficiently pronounced multiharmonic spectrum over the wave numbers $k_2 = 2\pi/\lambda_2$. And the most typical physical feature of the formed wave is its static (magnetostatic in the given case) nature. Moreover, the pump field is found to be improper for the working region of the pump system.

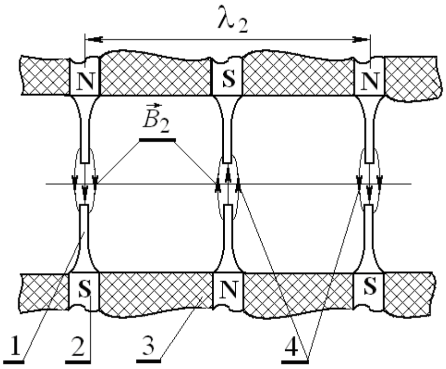


Fig. 15 *– Design of multiharmonic (cluster) magnetic undulator. Here: 1 – narrow magnetic tips; 2 – magnetic poles; 3 – magnetic insulator; 4 – force lines of the magnetic field of multiharmonic pump (magnetostatic clusters);* λ_2 *is the undulation period (period of the first harmonic); N is the north magnetic pole; S is the south magnetic pole;* $\vec{B}_2$ *is the vector of magnetic field induction*

Versions of a dopplertron pump are based on the phenomena of fundamentally different physical nature. As a result the pump fields here, as a rule, are proper and non-static. Example of multiharmonic dopplertron pump illustrated in Fig. 16 is ascribed to the class of the so-called cascade systems. The cascade nature in the given case consists in the following: the same electromagnetic cluster wave at the same time is a signal for the lower (first) cascade 6 and a multiharmonic (cluster) pump in the second (upper) cascade of the given MDFEL-klystron.

The key structural element of the represented in Fig. 16 design is the ring resonator 1. Generator 6 of multiharmonic (cluster) wave 4 (with the frequency spectrum $n_1\omega_1$, n_1k_1) and the shaper of the output femtosecond cluster signal wave 10 (with the frequency spectrum $n'\omega'_1$, $n'k'_1$) formed by the structural elements 2, 3, 5, 7 and 8 are placed, respectively, on two different optical axes of the generator. The pump system operates as follows. Generator 6 generates multiharmonic (cluster) electromagnetic wave 4, which circulates in the ring resonator 1. As it was mentioned above, this wave acts as multiharmonic (cluster) signal of the first cascade. On one of the optical axes of the resonator 1 this wave propagates towards two-velocity electron beam 7. And it penetrates the working volumes of the beam transportation system 8 and modulator 5. In this case it acts as the counter multiharmonic dopplertron pump for the second cascade of the given FEL. As a result of realization of multiharmonic version of the superheterodyne acceleration mechanism the desired output cluster signal 10 is finally generated (formed).

As it is known, the main advantage of cascade FEL is a possibility of obtaining sufficiently high-frequency signals using relatively low-voltage electron beams. It can be easily illustrated if, for example, use the well-known correlation of the dopplertron FEL theory [1-17]

$$\omega_1' \approx 4\gamma_0^2\omega_1 >> \omega_1 , \tag{3}$$

where γ_0 is the mean relativistic factor of two-stream electron system; other designations are represented in Fig. 16. We assume, for example, $\gamma_0 \sim 10$ (the average energy of the beams 2, 3 in Fig. 16 is ~ 5 MeV), the cyclic frequency of the first signal harmonic generated by the first cascade $\omega_1 \sim 4{\cdot}10^{12}$ s^{-1} (the wavelength is ~ 0,5 mm), we obtain $\omega'_1 \approx 1{,}6{\cdot}10^{15}$ s^{-1} (i.e., the generated signal belongs to the optical range). In the case of the equivalent in scale one-stage transformation (assuming, for example, that the generator 6 in Fig. 16 is also produced based on the one of cluster FEL designs) we find that to obtain the same transformation coefficient it is necessary to use beams with the energy of ~ 50 MeV that is much more difficult technically. Based on this, we suggest that using the cluster versions of two- and more cascade designs it will be possible in future to create the sources of “sub-femtosecond” clusters in the visible-ultraviolet and even in more shortwave ranges of the wavelengths. Moreover, while using the relatively moderate relativistic accelerating systems.

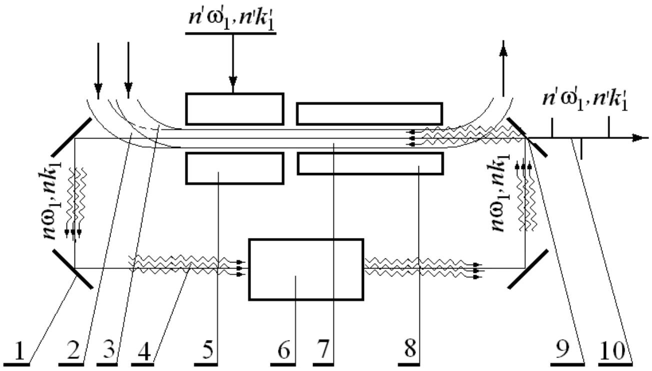


Fig. 16 *– Design example of two-cascade dopplertron multiharmonic pump in femtosecond active MDFEL-klystron based on ring resonator. Here: 1 – mirrors of the ring resonator of multiharmonic pump; 2, 3 – two one-velocity relativistic electron beams; 4 – electromagnetic cluster wave, which is at the same time the signal (with the frequency spectrum $n_1\omega_1$, n_1k_1) for the lower cascade 6 and the pump wave in the second cascade of MDFEL-klystron; 5 – modulator of the two-velocity electron beam 7; 6 – generator of the wave signal of cluster pump (the first cascade of MDFEL-klystron); 7 – two-velocity electron beam; 8 – middle section of the second cascade of MDFEL-klystron (the beam transportation system); 9 – output window for the generated (formed) cluster signal wave; 10 – generated (formed) cluster electromagnetic signal; $n'\omega_1$, $n'k'_1$ is the frequency spectrum of the generated output femtosecond signal*

9. CONCLUSIONS

Thus, a qualitative physical and technological substantiation of the possibility of practical implementation of a new wide class of femtosecond FEL, which were called the active FEL-klystrons, is carried out in the present work. We have to note that only the single-section (i.e., monotron) versions of femtosecond two-stream FEL were studied earlier in the well-known literature. Or, in other words, majority of the above stated ideas and klystron principles of FEL designing are sufficiently new. Therefore the demonstrated possible exceptionally rich variety of the proposed new design solutions is surprised, on the one hand, and states the problem of carrying out the equivalent quantitative analysis, on the other hand. Since only the quantitative analysis, finally, can answer the questions like: which of the above described design solutions are challenging and which of them not? All subsequent parts of the given work are devoted to the elucidation of these questions.

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