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Amplification of short-wavelength subattopulses in a free-electron laser using electrons accelerated in a laser plasma

© A.A. Andreev[1,2], L.A. Litvinov[1,2], K.Yu. Platonov[3,¶]

[1] St. Petersburg State University,
199034 St. Petersburg, Russia
[2] Ioffe Institute,
194021 St. Petersburg, Russia
[3] Peter the Great Saint-Petersburg Polytechnic University,
195251 St. Petersburg, Russia
[¶]e-mail: konstantin_platonov@yahoo.com

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The amplification in a free-electron laser undulator of a short-wavelength subattosecond pulse formed in a laser plasma upon its interaction with a relativistic electron bunch produced by a petawatt laser is considered. The aim of this work is to find the parameters of the system at which it is possible to amplify ultrashort pulses with a duration of up to hundreds of zeptoseconds.

Keywords:: ultrashort pulses, free electron laser.

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Introduction

As known [1], ultrashort electromagnetic emission pulses are required for diagnostics of fast transient processes. For example, subfemtosecond pulses allow temporal resolution of the outermost electron shell behavior of atoms and molecules during chemical reactions and ionization processes, and attosecond pulses allow temporal resolution of inner electron shell transition behavior of atom [2]. Collective nuclear excitation energies are equal to keV, and the time of compound nucleus disintegration during nuclear reactions begins from hundreds of zeptoseconds [3,4]. Thus, ultrashort photon pulses allow to study both electron and nuclear phenomena, for example, such as resonant internal conversion (attosecond time scale) and compound nucleus evolution (zeptosecond time scale). It should be noted that quanta with energies in the range of units and tens of kilovolts correspond to subattosecond electromagnetic oscillation period. One of the methods of obtaining of such ultrashort pulse (USP) [3] includes reflection of relativistically intense optical laser pulse from a solid target. Numerical simulation of reflection process, including using EPOCH code [5], shows that, together with high-amplitude USP, a low-amplitude low-frequency (up to hundreds of eV) component of the reflected signal (substrate) [6] containing the major energy portion of the reflected radiation is generated. For practical applications, USP may be separated from the substrate with a filter cutting off the quanta with energy lower than several keV. After USP exit from the laser focal waist region and filtration, USP intensity becomes considerably lower resulting in the need for further pulse amplification. USP amplification using the same laser that was used for USP generation is studied herein by means of analytical and numerical simulations (PUFFIN code [7]). For this, a part of petawatt laser pulse is used for generation of GeV electron beam [8,9], which amplify USP when they are propagated together through a free-electron laser (FEL) undulator. A similar amplification procedure of longer pulses and in other quanta energy range was addressed in [10]. It should be noted that FEL amplification of a pulse with an amplitude exceeding the noise level by orders of magnitude is stable, and the use of the same petawatt laser pulse for USP generation and amplification simplifies time synchronization of the electronic beam and amplified pulse.

USP amplification according to FEL scheme

It will be shown below that the formed USP [6] may be amplified according to FEL scheme [11] using a fast electron beam generated in transparent plasma by petawatt laser pulse, when efficient electron acceleration is provided by various nonlinear mechanisms as a result of which electron energy achieves units of GeV [8,9,12]. As known from [13], the length of wave emitted by an electron in the undulator

$$\lambda_x = (1 + K_W^2/2)\lambda_W/2\gamma^2, \quad (1)$$

where λ_W is the undulator period, $K_W = eB_W\lambda_W/2\pi m_e c^2$ is the undulator constant, B_W is the magnetic field induction, γ is a relativistic factor, m_e is the electron mass, c is the speed of light. The electron deviation angle at undulator half-period is estimated as $\theta_e \approx \pi K_W/\gamma$.

Inherent hard quanta emission angle is $\theta_x \sim 1/\gamma$. For longitudinal electron grouping due to the action of the wave emitted (amplified) by them, the case $\theta_e \le \theta_x$, when $K_W \sim 1$ [13], is the most favorable. Equation (1) is satisfiable in keV range, since, for example, undulator with $\lambda_W = 1.7$ cm is resonant with wavelength $\lambda_x = 1.2$ nm at electron energy 1.5 GeV or $\gamma \approx 3000$. Such electrons may be produced in laser-plasma accelerator with inherent beam sizes $\sim 10^{-3}$ cm, charge $\sim 10^{-11}$ C, energy spread $\sim 0.1\%$ and angular divergence 0.2–0.3 mrad [12,14]. Small angle and energy spread has little effect on USP amplification factor. Due to interaction with the emitted wave, beam electrons in FEL are grouped into bunches with $L_x \sim \lambda_x$ [11]. To make the bunch electrons emit coherently a pulse with length $t_x \approx 0.3$ as, the bunch thickness should be $L_x \sim t_x c \approx 10^{-8}$ cm. If laser electron energy is $\varepsilon_e = 3$ GeV ($\gamma \approx 6000$), then, from (1), to achieve subattoseconds (nanometers) with optimum $K_W \sim 1$, the undulator period $\lambda_W \sim 1$ and magnetic field strength $B_W \sim 10$ kG are required. This is possible because the permanent Nd magnet field is equal to units of kG, and superconducting magnet field is equal to tens of kG [2]. In the approximation of weak FEL amplification in [13], dimensionless amplitude amplification factor a was defined for the wave field at undulator length (N periods λ_W)

$$a_N = a_0 \exp(\kappa/2) \approx a_0(1 + \kappa/2),$$

and with $\kappa < 1$, the following was obtained:

$$\kappa \approx 20\pi K_W^2 \left(\frac{\lambda_x}{\Lambda_L}\right)^2 \frac{n_e}{n_{cr}} \gamma N^3. \qquad (2)$$

For ~ 10 fs petawatt laser pulse generating the electronic beam with charge 10 pC, initial diameter 33 μm and concentration $n_e \sim 10^3 n_{cr}$ [9,12], from (2) we obtain that for initial emission of $\lambda_x \approx 10^{-8}$ cm (0.3 as), the condition $\kappa \sim 1$ or undulator with $N \sim 70$ periods is required. With $N > 70$, for the considered parameters in the finite part of the undulator, developed amplification mode is implemented, which is described by self-consistent solution of equations of field and electron motion [13]. There are no analytical solutions of such system in nonlinear interaction mode, however, ultimate energy of the amplified pulse may be estimated as follows. With amplitude filtration, USP is presented as a single oscillation period of λ_x wavelength (Fig. 1, *b*) and occupies a small part of electron beam length L_e. Beam electron velocity $\upsilon_e \sim c$, and during electron motion time L_W/υ_e in undulator with length $L_W = N\lambda_W$, it will fall behind the amplified pulse at $\Delta x = \upsilon_e(L_w\upsilon_e - L_w/c) \approx L_w/2\gamma^2$. Thus, electrons from a spatial region with $\sim (\lambda_x + L_w/2\gamma^2)$ will be involved in amplification of single pulse. For the parameters used by us, condition $\lambda_x \ll L_W/2\gamma^2 < L_e$ is met. Suppose electron energy fraction η from $L_W.2\gamma^2$ region flows into USP, then the energy conservation law of the field–electrons system for amplified pulse intensity I_a in saturation mode will be $I_a S\lambda_x/c = \eta\varepsilon_e n_e S L_W/2\gamma^2$, where S is the transverse area of field-electrons interaction, $\varepsilon_e = (\gamma - 1)m_e c^2 \approx \gamma m_e c^2$ is the electron energy, n_e is the electron concentration in the beam. Therefore, intensity I_a in saturation mode will not exceed the upper limit of $I_a \le \eta n_e \varepsilon_e L_w c/2\gamma^2\lambda_x = \eta n_e \varepsilon_e c N/(1 + K_W^2/2)$, which allows to assess the dimensionless vector potential of USP:

$$a_a \approx (\eta n_e \gamma N/(1 + K_W^2/2)n_{cr})^{1/2}, \quad N < 2\gamma^2 L_e/\lambda_W, \quad (3)$$

where $n_{cr} = m_e\omega_L^2/4\pi e^2$ is the critical concentration corresponding to laser frequency ω_L. In case of laser-plasma accelerator (electron bunch charge 10 pQ, density $n_e \sim 10^{18}$ cm^{-3}, energy $\gamma = 3000$) and undulator with $N = 150$, $\eta = 0.1$, $K_W = 0.75$, estimation from (3) is $a_a = 0.15$. It should be emphasized that, in this case,

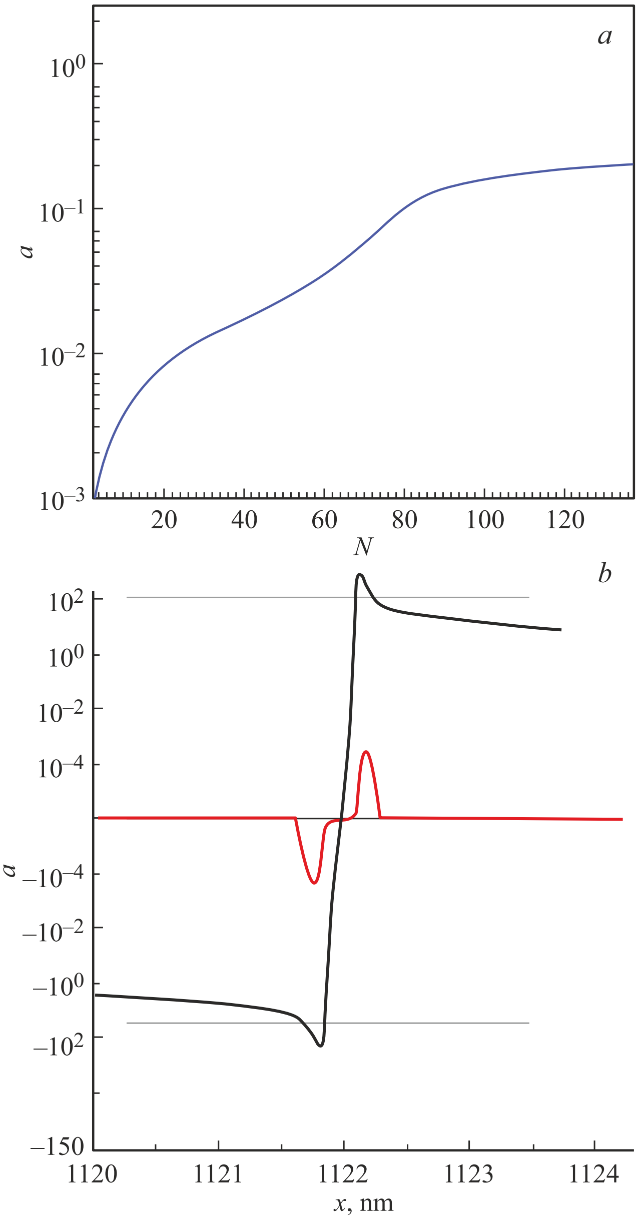

Fig. 1, (*a*) USP amplitude as function of the number of undulator periods N. Initial amplitude $a_0 = 10^{-3}$. Electron energy $\gamma = 3000$, current 180 kA, undulator period length $\lambda_W = 17$ cm, $N = 200$. (*b*) Spatial field distribution $a(x)$ of USP: black line with substrate and red line with substrate cut off by frequency or amplitude filter.

electromagnetic pulse amplification takes place from the specified initial value at the undulator inlet, and in „regular" FEL, it takes place from the noise level. The noise level is estimated from spontaneous emission intensity in the undulator. It is known from [13] that emission intensity of one electron in the undulator field is $I = 2e^2cK_W^2\gamma^2/3\lambda_W^2$. The beam contains N_e electrons and the emission is directed forward in the beam movement direction. Then noise level E_s is estimated as

$$cE_s^2S/4\pi \approx N_eI = 2N_ee^2cK_W^2\gamma^2/3\lambda_W^2$$

or

$$a_s = \frac{eE_s}{m_e\omega_Lc} \approx K_W\gamma\sqrt{\frac{2n_ee^2L_e}{3n_{cr}\lambda_W^2m_ec^2}}. \quad (4)$$

Estimate in equation (4) for the parameters listed above, gives $a_s \sim 10^{-8}$. Thus, initial value a_0 of the amplified field should fall into the interval $a_s \ll a_0 < a_a$. In our case, the USP filtration procedure (selection of pulse top with length $t_x \sim 0.3$ as) and transportation to the point of amplification results in $a_0 \sim 10^{-3}$. It should be noted that, to achieve saturation with amplification from initial value $a_0 = 10^{-3} \gg a_s$, a shorter undulator is required than for FEL operation with generation from the spontaneous level, and the amplified noises will not introduce interference in the amplified USP. The given estimates are true up to a multiplier about unity and we confirm them by means of numeri calculation of the amplification process. Fig. $1, a$ shows 1D calculation by PUFFIN code [7] for amplification of a single subattopulse (red curve, Fig. $1, b$) with initial amplitude $a_0 = 10^{-3}$ calculated by EPOCH code [5]. Electron energy in the beam was $\gamma = 3000$, current was 180 kA, undulator period length was $\lambda_W = 1.7$ cm, $N = 200$. It can be seen that, when $N = 120$, amplitude saturation is achieved at level $a \approx 0.2$, and the total amplification achieves two orders of magnitude by amplitude.

Finally, it should be noted that the provided research uses analytical and numerical simulation to investigate whether it is possible to achieve photon USP with multi-keV-energy using petawatt laser pulse and subsequent USP amplification by a portion of the same laser pulse according to FEL scheme. The research should be considered as a preliminary stage (appropriateness estimate) of the ultrashort pulse amplification investigations. A more detailed consideration planned for the future study will take into account 3D effects, electron bunch parameter spread, presence of focusing electronic lens in FEL, nonideality of the undulator magnetic field and a set of other effects of FEL physics.

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