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**RADIATION GENERATION**

# Generation of Narrow-Band THz Radiation by Collision of Laser Wake Waves with a Small-Scale Transverse Structure in a Plasma

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**Abstract**—A new method was proposed to generate high-power narrow-band terahertz radiation in the process of nonlinear interaction of counterpropagating laser wake waves, the potential profiles of which are modulated in the transverse direction and do not coincide locally with each other. It was shown that, to achieve a high efficiency of radiation at the doubled plasma frequency, the period of such modulation should coincide with the length of the generated electromagnetic wave. Each of the plasma waves with such a small-scale transverse structure was proposed to be created by a pair of interfering laser pulses propagating at a small angle to each other. Numerical simulation by the particle-in-cell method confirmed such a scheme can provide a narrow (2%) spectral emission line and a high energy conversion efficiency at a level of 1%. With the XCELS design parameters, the proposed method opens the way to achieving a record terawatt radiation power in the THz frequency range.

**Keywords:** terahertz radiation, plasma oscillations, laser pulse, XCELS project

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## 1. INTRODUCTION

Generation of high-power coherent terahertz (THz) radiation is important for new physics, which studies excitation of various collective degrees of freedom in solids, as well as for a number of chemical and biological sciences, for security sector, and for the development of alternative methods of electron acceleration [1–3]. Among many approaches [4–7] aimed at obtaining radiation pulses in the THz frequency range, plasma methods occupy a special place. Plasma as a nonlinear medium makes it possible to efficiently convert the energy of laser pulses and electron beams into the energy of electromagnetic radiation at the harmonics of the plasma frequency $\omega_p = \sqrt{4\pi ne^2/m_e}$, the value of which is determined by the plasma density $n$ ($e$ and $m_e$ are the electron charge and mass, respectively). The key advantage of this approach is the ability of plasma to maintain long-lived oscillations with electric field values that significantly exceed the material destruction thresholds, which opens up the possibility of generating intense narrow-band THz radiation of high peak power and energy. In addition, the dependence of the plasma frequency on the plasma density enables one to tune the radiation frequency over a wide range by changing the density of the working gas.

One of the methods to generate intense THz pulses with a narrow spectral line is the collision of counterpropagating wake waves excited in plasma by femtosecond laser pulses [8]. The nonlinear interaction of plasma waves with differing transverse profiles of the electrostatic potential leads to the excitation of electromagnetic radiation at the second harmonic of the plasma frequency. According to theoretical estimates, radiation is generated most efficiently if the size of focal spots of laser pulses in this scheme is comparable to the wavelength $c/\omega_p$ of plasma oscillations. Particle-in-cell (PIC) simulations showed that the efficiency of the conversion of laser pulse energy into THz radiation energy at such strong focusing reaches 0.02–0.03%. This idea is currently experimentally implemented at the Institute of Laser Physics, Siberian Branch (SB), Russian Academy of Sciences (RAS), Novosibirsk, Russia, using a multiterawatt laser system (830 nm, 0.2 J, more than 20 fs) [9, 10].

To obtain a narrow spectral line of radiation, it is necessary that the nonlinearity level of the plasma waves be low. This limits the intensity of the laser pulse, which is specified through the dimensionless vector potential of the laser field: $a_0 = eA_0/(m_ec^2) < 1$. As a result, while maintaining the optimal focal spot

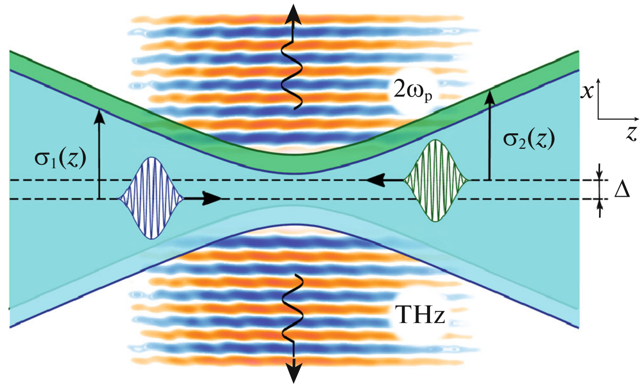


**Fig. 1.** Schematic formulation of the problem. Two counterpropagating laser pulses excite a pair of nonlinearly interacting waves. The asymmetry of the profiles is achieved by introducing impact parameter Δ relative to the propagation axis of one of the pulses. Both pulses are focused to the center of the system. The solid color represents the characteristic transverse size of the diffracting Gaussian pulses coming from the left (blue) and the right (green).

size on the order of $c/\omega_p$ and weak nonlinearity of the waves, this scheme is limited in terms of the allowable total energy of the laser system. The use of focusing laser pulses into a larger spot (tens or hundreds of plasma wavelengths) with a modulated transverse intensity profile on the $c/\omega_p$ scale was shown [11] to enable one to use higher-energy laser systems in this scheme and, consequently, to obtain THz pulses with much higher energy content. One of the ways to create a transversely modulated plasma wave can be the interference of a pair of laser pulses focused to one point with a small angle between the axes of their propagation. Owing to a significant weakening of the diffraction spreading of wider laser beams and an increase in the length of the emitting region, the energy conversion efficiency in such a scheme can be increased by more than an order of magnitude. The excitation of counterpropagating plasma waves using the promising XCELS laser system [12] will open the way to generating pulses of narrow-band THz radiation with record power and energy values.

## 2. THEORETICAL FORMULATION OF THE PROBLEM

Let us briefly describe the mechanism of radiation generation. Let us consider a homogeneous plasma, through which two potential plasma waves excited by laser pulses propagate toward each other along the $z$ axis (Fig. 1). The waves can be described in terms of the scalar electrostatic potential

$$\Phi_\Sigma = \frac{1}{2}\Phi_1(r_\perp)\exp(ikz - i\omega_p t) + \frac{1}{2}\Phi_2(r_\perp)\exp(-ikz - i\omega_p t) + \text{c.c.} \quad (1)$$

Mutual scattering of one wave by density perturbations created by another wave leads to the excitation of a nonlinear electric current capable of pumping electromagnetic radiation at the doubled plasma frequency. For identical waves excited by laser pulses and differing only in the transverse potential profile, the electric current responsible for the radiation can be expressed as

$$J = \frac{1}{4}[\Phi_1\Delta_\perp\Phi_2 - \Phi_2\Delta_\perp\Phi_1], \quad (2)$$

where $\Delta_\perp$ is the part of the Laplace operator that is transverse to the plasma wave propagation axis. The asymmetry of the transverse profiles is a necessary condition for the absence of complete compensation of the currents generated by each of the waves, and for absolutely symmetrical laser pulses, it can be implemented using a small impact parameter Δ between the axes of their propagation, as shown in Fig. 1.

The transition to wide transversely modulated plasma waves, while maintaining a low level of their nonlinearity, will increase the energy that can be introduced into the system and, consequently, will increase the energy of the generated radiation. As one of the ways to create such waves, we consider the interference of a pair of codirectional laser pulses focused to one point and propagating at a small angle to each other (Fig. 2a). A long-lived plasma wave is excited by the ponderomotive force $F_p$ of a laser pulse, which pushes plasma electrons out of the region occupied by the laser radiation wave packet and is deter-

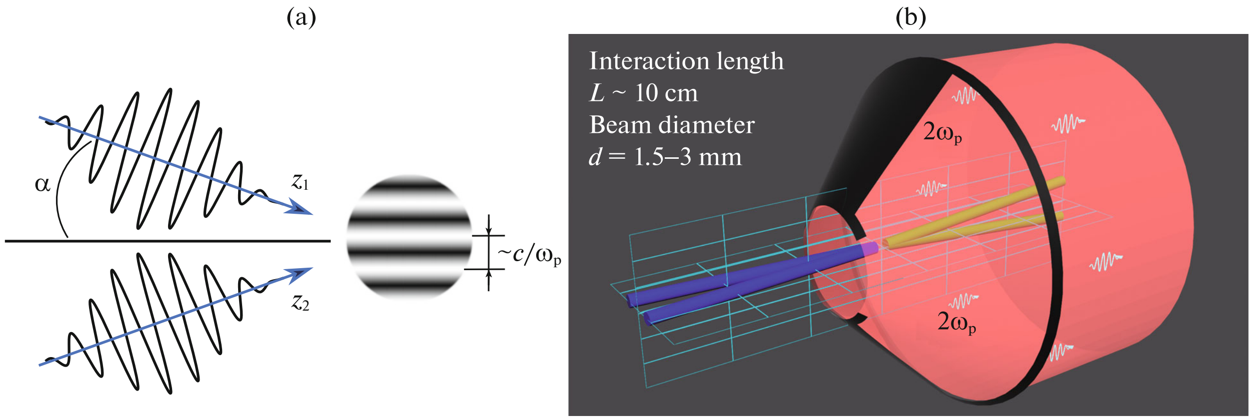


**Fig. 2.** (a) Two codirectional laser pulses focused to one point at a small angle $2\alpha$ with respect to each other, as a result of interference, excite a transversely modulated plasma wave, the modulation period of which is determined by the $\alpha$ value; and (b) the interaction of two such modulated waves, each of which is created by a pair of laser pulses (shown in blue and yellow), leads to the generation of radiation at a frequency of $2\omega_p$.

mined by the gradient of the pulse envelope. The interference of laser fields leads to modulation of the ponderomotive force

$$F_p = -\nabla\left[\frac{a_1^2}{4} + \frac{a_2^2}{4} + \frac{a_1 a_2}{2}\cos(qx)\right], \tag{3}$$

where $a_{1,2}$ is the dimensionless vector potential of the laser pulse field. Consequently, the resulting plasma wave will also have an inhomogeneous transverse structure

$$\Phi(r,t) = \int_0^t dt' \sin(t-t')\left[\frac{a_1^2(r,t')}{4} + \frac{a_2^2(r,t')}{4} + \frac{a_1(r,t')a_2(r,t')}{2}\cos(qx)\right] \tag{4}$$

with the wavenumber $q = 2\omega_0 \sin\alpha$ depending on the angle $\alpha$. Let us consider the interaction of a pair of such waves, each of which is excited by two laser pulses (Fig. 2b). We assume that the envelope of each of the pulses with center frequency $\omega_0$, duration $\tau$, and amplitude $a_0$ is described by the following expression:

$$a_s(r,t) = a_0\sqrt{\frac{\sigma_0}{\sigma_s(z_s)}}\exp\left(\frac{-x_s^2}{\sigma_s^2(z_s)}\right)\sin^2\left(\frac{\pi(t-z_s)}{2\tau}\right), \tag{5}$$

where $\sigma_0$ is the size of the focal spot and diffraction effects are taken into account by the dependences $\sigma_s(z_s) = \sigma_0\sqrt{1 + (z_s - z_0)^2/R^2}$ ($R = \omega_0\sigma_0^2/2$ is the Rayleigh length). All expressions given here are written in dimensionless units: the potentials of electric and magnetic fields are expressed in units of $m_e c^2/e$; and spatial and temporal dimensions, in $c/\omega_p$ and $\omega_p^{-1}$, respectively.

## 3. NUMERICAL SIMULATION

Let us perform numerical simulation of the problem described above using the particle-in-cell method. For this purpose, we will use the original relativistic electromagnetic 2D3V code, in which the plasma is described by a set of parabolic macroparticles moving under the action of electromagnetic fields [13] calculated on a grid [14, 15]. In the central part of the simulation area, there is a plasma column, along which laser pulses propagate. The radiation generated by them leaves the plasma in the transverse direction and is absorbed in the walls of the computational region. Two approaches are used to describe the excitation of a modulated plasma wave. In the first one, realistic self-consistently evolving laser fields with envelope (5) are specified; in the second, the effect of laser radiation on plasma is described by adding ponderomotive force (3) to the equations of motion (model of a virtual laser pulse).

In the simulation, laser pulses with a dimensionless amplitude of $a_0 = 0.3$ were considered; the focal spot size $\sigma_0$ was varied from $10c/\omega_p$ to $30c/\omega_p$. The grid size for setting real lasers was $\Delta_x = \Delta_z = 0.025c/\omega_p$

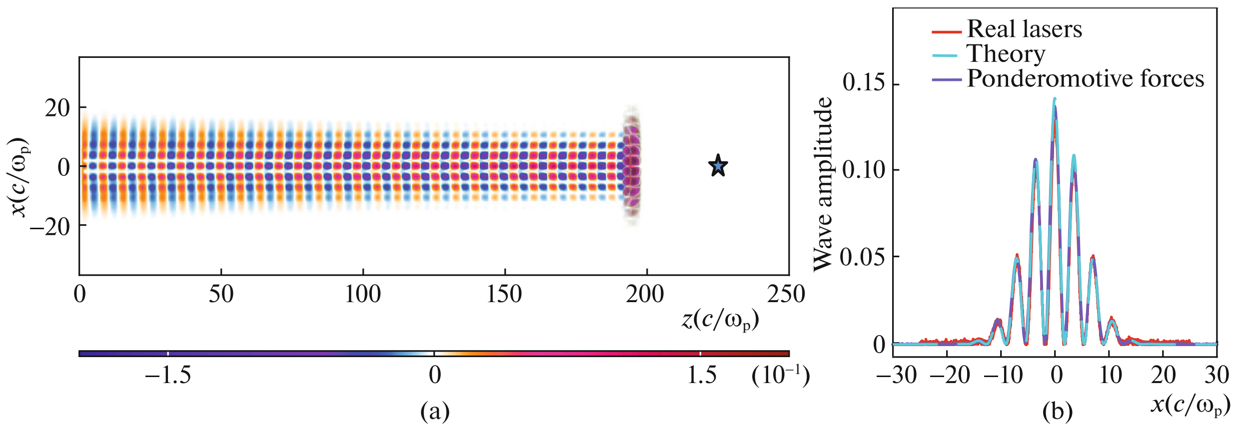


**Fig. 3.** Results of numerical simulation of the excitation of a modulated wake wave in plasma: (a) the map of the longitudinal fields $E_z$ at the time $187.5\omega_p^{-1}$: the wave is excited by real laser fields (the focus point of laser pulses is indicated by the blue star); (b) comparison of the transverse profiles of the wave near the focus in theory (dashed blue curve), when simulating real laser fields (red curve), and when using a virtual laser pulse (purple curve) (b).

at a time step of $\Delta_t = 0.0125\omega_p^{-1}$. In calculations with a virtual laser pulse, the grid size was $\Delta_x = \Delta_z = 0.05c/\omega_p$ and $\Delta_t = 0.025\omega_p^{-1}$. At these parameters of the system, oscillations at the plasma frequency and its second harmonic can be well resolved.

## 4. SIMULATION RESULTS

Figure 3 illustrates the results of numerical simulation of the excitation of a transversely profiled wake wave by a pair of interfering laser pulses. For comparison, the calculations were carried out using two approaches: using real laser pulses and with the addition of ponderomotive force. Figure 3b shows that, using both approaches, the transverse profile of the plasma wave is reproduced reliably, in good agreement with theoretical dependence (4), taking into account expression (5). Thus, the simulation confirmed that the use of a pair of codirectional laser pulses focused to one point at a small angle with respect to each other indeed makes it possible to excite a long-lived (hundreds of $\omega_p^{-1}$) plasma wake wave with a modulated transverse profile, the amplitude and modulation period of which coincide with the predictions of linear theory. Despite some excess of the threshold power at the chosen parameters, relativistic self-focusing does not have a noticeable effect on the shape and characteristics of the wake wave, which is confirmed by the results of numerical simulation with self-consistently evolving laser pulses (Fig. 3). Whether this is a consequence of the two-dimensional nature of the calculations remains to be seen in the future. Later, to model much more extended spatial scales, which include a significant part of the radiation generation area, a more economical model of a virtual laser pulse was used.

Let us consider the generation of electromagnetic radiation at a frequency of $2\omega_p$ by counterpropagating transversely modulated wake waves in a plasma. As an example, Fig. 4 shows the simulation results in the case of $\sigma_0 = 10c/\omega_p$. Collision of plasma waves generates intense coherent radiation from the region of the overlap of diffracting laser pulses. The generation occurs at the second harmonic of the plasma frequency, which is confirmed by the Fourier spectrum (see Fig. 4b): the width of the emission spectral line is only ~2%. A weak peak is also observed in the vicinity of the third harmonic of $\omega_p$, which is related to subsequent nonlinear decay processes—the coalescence of the original wave and nonradiating harmonics, but the contribution of these processes is small. Radiation occurs in the transverse direction, as predicted by theory.

Let us consider how the radiation generation efficiency $\eta$, defined as the ratio of the radiation energy at the frequency $2\omega_p$ to the total laser pulse energy

$$E_{las} = \frac{3}{2}\sqrt{\frac{\pi}{2}}a_0^2\omega_0^2\tau\sigma_0, \tag{6}$$

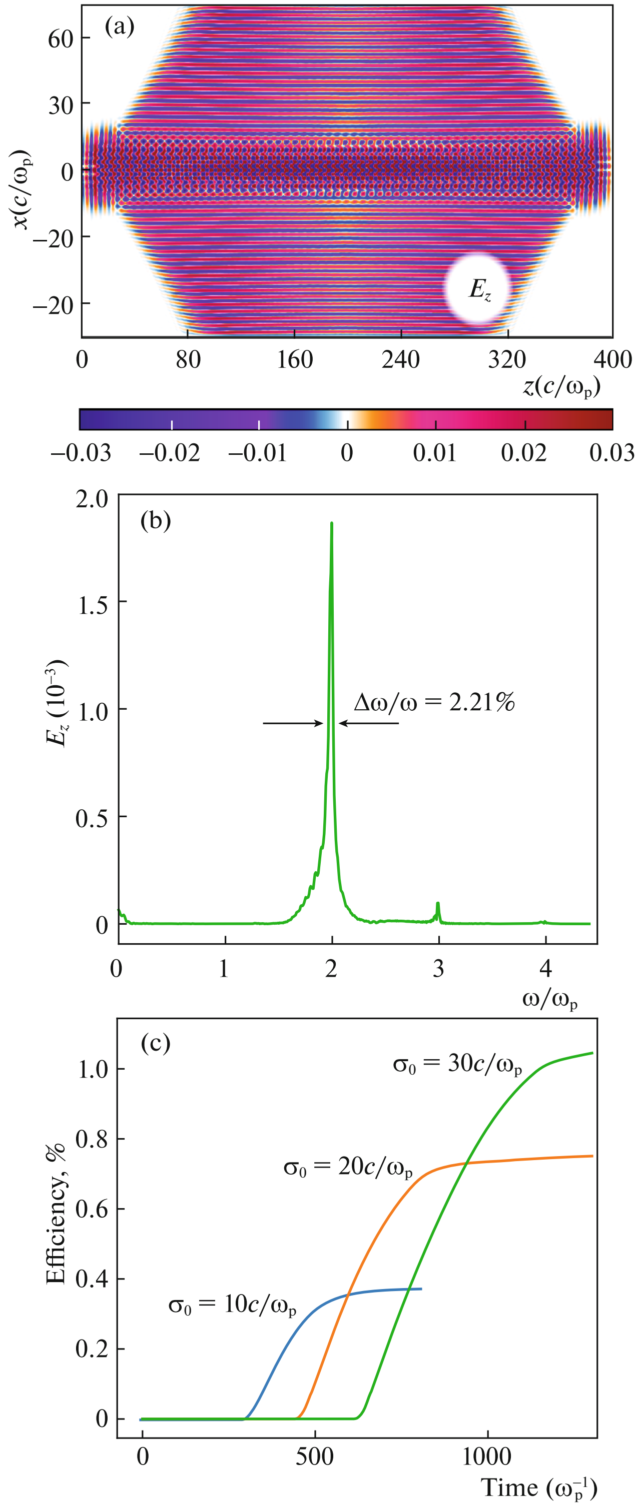


**Fig. 4.** Results of the numerical simulation of the radiation generation by counterpropagating transversely modulated wake waves in a plasma: (a) the map of longitudinal fields $E_z$ at $\sigma_0 = 10c/\omega_p$ (laser pulses propagating towards each other are focused to the center of the system); (b) the Fourier spectrum of radiation for the case shown in Fig. 4a, recorded at the center of the system near the boundary of the absorbing layer; and (c) the time dependence of the efficiency of conversion of laser pulse energy into radiation energy at various sizes of focal spots of $\sigma_0 = 10c/\omega_p$, $20c/\omega_p$, and $30c/\omega_p$.

changes with increasing focal spot size. Figure 4c shows that the maximum radiation efficiency increases linearly with increasing $\sigma_0$ and, hence, with increasing total energy (6) introduced into the system by laser pulses. In the above calculations, the width of the beams at the focus was varied from $10c/\omega_p$ to $30c/\omega_p$.

The efficiency of energy conversion in this case increased from about 0.35 to 1%. We also note that, in comparison with the original scheme, where the colliding Gaussian beams were focused to spots of a small size of ~$c/\omega_p$, the radiation generation efficiency increased by a factor of more than 30.

## 5. RESULTS AND DISCUSSION

The increase in the efficiency of radiation generation with an increase in the width of laser beams is due to the fact that wide beams diffract weakly; therefore, the length of the region of efficient interaction of wake waves turns out to be much larger than that for narrow ($\sigma_0 \sim c/\omega_p$) laser beams and increases linearly with increasing focal spot size $\sigma_0$. Such an increase is indeed observed in the virtual laser model, but in reality, it cannot last indefinitely long, since at sufficiently large lengths, it is necessary to take into account the energy depletion of the laser driver. The reliability of the trend $\eta \propto \sigma_0$ observed in the simulation and the feasibility of achievement of the efficiency of radiation generation at the level of 1% in the proposed scheme are justified by the fact that, in all the cases discussed here, the energy content of plasma waves did not exceed a tenth of laser energy (6).

The experimental implementation of this mechanism involves the injection of laser radiation into a homogeneous gas, which can be helium. The influence of inhomogeneity effects, which naturally arise during gas ionization at the periphery of the plasma channel, was studied under similar conditions previously [10]. It was shown that such effects do not significantly influence the parameters of the wake wave in the region of electromagnetic emission. The radiation at the second harmonic of the plasma frequency can freely leave the plasma without experiencing its screening effect; therefore, the presence of the surrounding plasma does not affect the radiation output. However, for efficient excitation of a plasma wake wave with a small-scale modulation of the profile, the question of the homogeneity of the gas and subsequent plasma is very important. To implement the discussed mechanism, it is required to create a region of homogeneous gas with a length of ~10 cm and a radius of 1 mm, which can be done in a gas cell preliminarily filled with a gas. The radiation of the laser system should be divided into four channels and focused in pairs to the center of the gas cell at the angle $\alpha = \arcsin(\sqrt{3}\omega_p/2\omega_0)$ to the axis of the system (Fig. 2b). This angle is determined by the equality of the modulation period of the wake wave profile and the wavelength of the generated radiation. At a constant $\omega_0$, the optimal convergence angle and the allowable deviation from this value (~10–14%) increase with an increase in the density and, accordingly, the radiation frequency (Fig. 5). To prevent the return of laser radiation to the amplification system, each pair of laser beams can be brought together in mutually perpendicular planes. Since the radiation frequency $2\omega_p$ is determined by the plasma density, $\propto\sqrt{n}$, by changing the gas density, one can cover almost the entire terahertz spectrum, while adjusting the duration of laser pulses and the angle of convergence. Wake wave excitation is most efficient when the size of the laser pulse wave packet is approximately half the plasma wave length, i.e., $\tau \sim \pi/\omega_p$. Thus, for a laser pulse of a certain duration, there is an optimal density value. For example, to generate radiation in the range 5–30 THz, the duration of laser pulses, determined at half the height of the intensity profile, should vary in the range $\tau_{FWHM}$ = 140–25 fs. Since the efficiency of excitation of the wake wave also depends on the ratio $\omega_p/\omega_0$, the radiation efficiency is higher at higher plasma density and longer wavelength laser radiation [8].

It should also be noted that this mechanism allows one to generate both narrow-band radiation (~2%) while maintaining low nonlinearity, and broadband radiation ($\Delta\omega/\omega \sim 1$), when $a_0 \sim 1$ is reached. The width of the radiation spectrum is determined by the lifetime of the wake wave. Higher peak power can be achieved for waves with higher nonlinearity, but the lifetime of such waves decreases with increasing their amplitude, leading to a significant broadening of the emission spectral line. Narrow-band terahertz radiation with a large electric field amplitude is more difficult to generate by other methods; therefore, this mechanism is proposed to be used primarily for this problem. In this case, the allowable laser radiation intensity is limited by the requirement that the wake wave nonlinearity should be low: $a_0 < 1$. Nevertheless, even in this case, the electric field amplitude can reach tens of GV/cm.

Let us estimate the THz radiation parameters that can be obtained using four beams of the XCELS laser system [16] with a total energy of 1.5 kJ as plasma wave drivers. To generate radiation in a plasma with a density of $10^{17}$ cm$^{-3}$, the optimal beam duration calculated at half the height of the intensity profile should be 140 fs. The central frequency of the generated radiation at this plasma density is 5.7 THz. To obtain a THz pulse with a narrow spectral line (with a frequency spectrum width of 2%), the diameter of the focal spot of each laser beam, determined at the half-height of the intensity profile, should be equal to 1.4 mm. The optimal angle between the axes of the laser beams in this case is ~1°. The energy in a radiation pulse at a conversion efficiency of ~1% will reach 15 J at a duration of 3–5 ps. As shown in Fig. 2b,

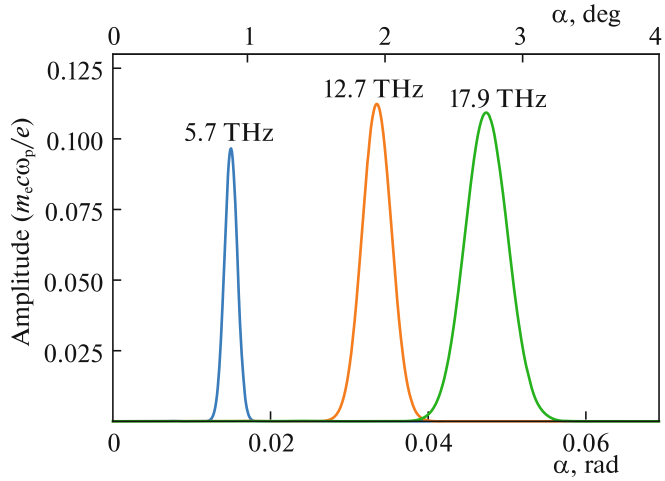


**Fig. 5.** Dependence of the maximum radiation amplitude on the angle of pairwise convergence of laser pulses at $\sigma_0 = 30c/\omega_p$, $a_0 = 0.3$, and various plasma concentrations $n = 10^{17}$ cm$^{-3}$ (radiation frequency 5.7 THz), $n = 5 \times 10^{17}$ cm$^{-3}$ (12.7 THz), and $n = 10^{18}$ cm$^{-3}$ (17.9 THz).

the radially divergent radiation can be transformed using a conical mirror into a beam, which then propagates along the axis of the system and can be efficiently focused to obtain high electric field strengths.

## 6. CONCLUSIONS

A new method was proposed to generate radiation in the terahertz frequency range by the interaction of counterpropagating plasma wake waves, each of which is created by a pair of interfering laser pulses and has a small-scale transverse structure. The key properties of this scheme are the possibility of obtaining THz pulses with a narrow spectral line and its scalability to the world's most powerful laser systems. The PIC simulation showed the possibility of achieving a high efficiency of laser energy conversion into THz radiation energy (at a level of 1%) in such a scheme. Successful implementation of the proposed scheme on the XCELS infrastructure is expected to significantly exceed the record parameters of narrowband THz pulses obtained using free-electron lasers and will open the way to the generation of THz radiation at a terawatt power level.

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## CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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