

PACS numbers: 41.75.Ht; 41.75.Jv; 52.25.Dg
DOI: 10.1070/QE2015v045n06ABEH015734

Laser vacuum acceleration of a relativistic electron bunch

I.V. Glazyrin, A.V. Karpeev, O.G. Kotova, K.S. Nazarov, V.Yu. Bychenkov

***Abstract*.** **With regard to the problem of laser acceleration of a relativistic electron bunch we present a scheme of its vacuum acceleration directly by a relativistic intensity laser pulse. The energy of the electron bunch injected into the laser pulse leading edge increases during its coaxial movement to a thin, pulse-reflecting target. The laser-accelerated electrons continue to move free forward, passing through the target. The study of this acceleration scheme in the three-dimensional geometry is verified in a numerical simulation by the particle-in-cell method, which showed that the energy of a part of the electrons can increase significantly compared to the initial one. Restrictions are discussed, which impose limiting values of energy and total charge of accelerated electrons.**

Keywords: *laser pulse, electrons, vacuum acceleration, spectrum of particles, ponderomotive scattering.*

1. Introduction

Recent studies on electron acceleration by short, relativistically strong laser pulses have demonstrated the ability to produce high-energy particle beams. The most impressive results have been achieved in wakefield acceleration of particles by laser pulses propagating in a gas plasma or capillary under conditions of a sufficiently large (over 10 μm) focal spot. The corresponding energies of accelerated electron beams have substantially exceeded 1 GeV [1–4], reaching a record-high value of 4.2 GeV [5]. Along with this, an alternative approach has been developed to accelerate electrons using solid state density plasma upon tight focusing of laser radiation which is capable of providing a maximum intensity on the target. Due to a higher density of the solid target one can expect a larger number of accelerated particles (although with a lower energy) as compared with a case of wakefield acceleration in a rarefied plasma. Application of tight focusing that is close to the diffraction limit has already made it possible to develop an efficient source of collimated quasi-monoenergetic electrons with energies ~1 MeV, emitted in the backward direction (from the target) at a laser energy of 3 mJ and a pulse repetition rate of 0.5 kHz [6]. Similar beams of accelerated electrons in the regime of single shots, but with a substantially higher energy (~30 MeV) in the forward direction, were observed in experiments with a more powerful laser irradiating ultrathin foils [7].

If till now experiments on generation of high-energy electrons have been performed mainly at laser intensities less than 10^{20} W cm^{-2}, it is now possible to think of experiments with a greater intensity. Thus, by tightly focusing the laser pulse ($d_f \simeq 1.2$ μm, where d_f is the diameter of the focal spot), the HERCULES laser demonstrated a peak intensity of 2×10^{22} W cm^{-2} [8]. Furthermore, the possibility of mastering multipetawatt-level laser powers is currently being discussed, and construction of such lasers is being carried out [9–12], which will make it possible to achieve even higher intensities.

In connection with the search for the most promising targets, ultrathin (nanometre/submicron) foils have attracted a lot of attention in recent years [7, 13]. Their active introduction in the experiments on the interaction of high-power laser radiation with matter is possible due to the achievement of a high level of intensity contrast ratio of ultrashort laser pulses (10^{10}–10^{11}) [14], which suppresses the parasitic effect of the target destruction before the arrival of the main pulse. Under conditions when the foil thickness is comparable to the relativistic depth of the skin layer, effective interaction of radiation with the plasma formed in the entire volume is possible. In this case, the first step in the study of the interaction of intense laser pulses with ultrathin targets is, of course, to investigate the direct acceleration of electrons initially at rest by neglecting plasma effects, which corresponds to the approximation of probe particles. This approach was used in [15] and generalised to the case of a plasma field of thin plasma foil [16].

The above examples are related to the acceleration of electrons in the interaction of laser pulses with plasmas of different targets. Another acceleration mechanism, so-called vacuum acceleration, is based on acceleration of the electrons directly by a laser pulse, i.e., direct laser acceleration. Mechanisms of direct laser acceleration of electrons (vacuum acceleration) have been studied theoretically in a number of papers, for example [15, 17–25]. In particular, to describe direct acceleration of electrons by linearly polarised pulses under tight focusing conditions the authors of [15, 18] used an approach, free from restrictions on the relationship between the focal spot size and the wavelength, which is based on the use of exact diffraction Stratton–Chu integrals [26, 27] or the method of spectral representation of fields satisfying Maxwell's equations.

I.V. Glazyrin, A.V. Karpeev, O.G. Kotova, K.S. Nazarov Russian Federal Nuclear Center – E.I. Zababakhin All-Russian Scientific Research Institute of Technical Physics, ul. Vasil'eva 13, 456770 Snezhinsk, Chelyabinsk region, Russia;
V.Yu. Bychenkov P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; Center for Fundamental and Applied Research, All-Russian Research Institute of Automatics (VNIIA), ROSATOM State Atomic Energy Corporation, Sushchevskaya ul. 22, 127055 Moscow, Russia;
e-mail: bychenk@lebedev.ru

Received 19 December 2014; revision received 5 February 2015
Kvantovaya Elektronika **45** (6) 551–555 (2015)
Translated by I.A. Ulitkin

In this paper, we use a scheme of direct laser acceleration of electrons, where the particles are not initially at rest, as in the majority of the above mentioned papers, but pre-accelerated to relativistic energies, i.e., an electron bunch, for example, from a conventional accelerator. In this case, the focusing of laser radiation is assumed quite smooth, similar to that used for wakefield acceleration, and does not require involvement of the complex structure of the electromagnetic fields in the focal region into consideration.

2. Scheme of the acceleration

The idea of the proposed scheme of electron acceleration goes back to paper [28]. It consisted in the fact that in front of the surface of a thin metal target (foil) there is rarefied plasma (gas ionised by a pre-pulse), through which a laser pulse passes, trapping electrons and accelerating them in the direction of its propagation to the foil. The energy of the electrons within the pulse increases in proportion to its local intensity, and at the time of reaching a maximum intensity the pulse is reflected from the target, allowing the electrons to move forward inertially with the energy accumulated during the pulse action. The possibility of such acceleration is associated with a sharp violation of adiabatic acceleration of particles upon reflection of the pulse from the target. If the target were absent, the electrons would accelerate in the region of intensity growth of the laser pulse, and then would decelerate at its decline as it propagates. For a plane wave the total effect of acceleration would be zero [29, 30]. Violation of the adiabatic process, for example because of the small size of the focal spot [31], very short pulse duration [32] or the injection of electrons in the pulse during the tunnelling ionisation of atoms [33], leads to the residual energy of the electrons, but it is usually small. In the previously proposed scheme [28], electrons were at rest, and for a relativistically intense linearly polarised laser pulse ($a_0^2 \gg 1$) their energy reached a maximum, corresponding to $\gamma = a_0^2$. Here γ is the standard relativistic factor of the particle; $a_0 = 0.85 \times 10^{-9}\lambda\sqrt{I}$ is the maximum amplitude of the laser pulse; λ is the laser wavelength in μm; and I is the intensity of the laser pulse at the maximum in W cm^{-2}.

If at the beginning of direct laser acceleration the electrons were not at rest and had relativistic energy ($\gamma_0 > 1$), then, as will be shown below, they could achieve a γ_0 times higher energy. Such a scheme can be implemented using an electron beam that is captured by a coaxially propagating relativistically intense laser pulse in the direction of a thin, light-reflecting target. This is illustrated by Fig. 1.

In the scheme in question an intense laser pulse catches up with the electron bunch, for example from an accelerator (Fig. 1a). Before it there is a foil. The laser pulse captures electrons that are accelerated, gaining pulse energy until they find themselves in the peak of the pulse intensity (Fig. 1b). In this case, part of the electrons is lost due to the finiteness of the transverse size of the laser pulse. If the pulse reaches the foil, when the electron bunch is at its centre, and is reflected from the foil, the electrons continue to move with the greatest possible energy (Fig. 1b). Obviously, the thickness of the target should be sufficient for the pulse not to pass through it and simultaneously not too large for the electrons not to lose a significant fraction of its energy. It follows that the target thickness should be chosen comparable, but slightly higher than the threshold value for the relativistic transparency [34] $\sim\lambda a_0 n_c/n_e$, where n_e is the electron density of the foil, and n_c is the critical density. The typical thickness of the target is from ten to several tens of nanometres.

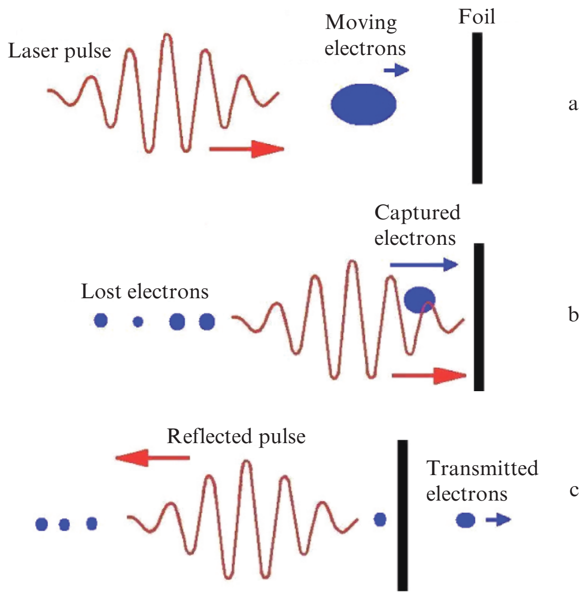

Figure 1. Scheme of direct laser acceleration of the electron bunch.

3. Vacuum electron beam acceleration

To qualitatively assess the effect of direct laser acceleration, we consider the motion of an electron in a plane electromagnetic wave described by the vector potential $\boldsymbol{A}$:

$$E = \frac{1}{c}\frac{\partial \boldsymbol{A}}{\partial t},$$

$$\boldsymbol{B} = \nabla \times \boldsymbol{A}, \qquad (1)$$

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = -e\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B}\right),$$

$$\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} = \boldsymbol{v},$$

where the vector potential for an elliptically polarised light wave propagating in the x direction has the form:

$$\boldsymbol{A} = A_0(0, \delta\sin\theta, \sqrt{1-\delta^2}\cos\theta).$$

Here $\theta = \omega t - kx$; $k = 2\pi/\lambda = \omega/c$; A_0 is the vector-potential amplitude; and δ is the polarisation parameter. In the case of linear polarisation $\delta = 0$, and when the polarisation is circular, $\delta = 1/\sqrt{2}$. Considering only one electron instead of a bunch, we do not lay claim to a rigorous description of the acceleration of the entire ensemble of the electrons, but only seek to qualitatively establish their ultimate energy. In essence, we do not take into account here that an electron bunch may have not only a significant size (compared with the pulse length), but also a significant Coulomb field, affecting the interaction of electrons with a laser pulse.

Considering that before the arrival of the pulse, the electron moving in the x direction had a kinetic energy $mc^2(\gamma_0 - 1)$, from (1) we obtain for linearly polarised light

$$\gamma_1 = \gamma_0 + \frac{a_0^2}{2}\frac{1}{\gamma_0 - \sqrt{\gamma_0^2 - 1}}, \quad (2)$$

and similarly for the circular polarisation

$$\gamma_2 = \gamma_0 + \frac{a_0^2}{4}\frac{1}{\gamma_0 - \sqrt{\gamma_0^2 - 1}}. \quad (3)$$

Expressions (2) and (3) determine the maximum possible energy of the electrons after reflection of a linearly or circularly polarised laser pulse from the foil. For ultra-relativistic electrons ($\gamma_0 \gg 1$) the ultimate particle energy for linearly and circularly polarised laser pulses are as follows:

$$\gamma_1 = \gamma_0(1 + a_0^2), \quad \gamma_2 = \gamma_0(1 + a_0^2/2). \quad (4)$$

According to (4) for an ultra-relativistically intense laser pulse ($a_0^2 \gg 1$) the final electron energy $\gamma_1 \simeq \gamma_0 a_0^2$ is twice the corresponding value γ_2.

Estimates for vacuum electron acceleration are approximate, because they are obtained for a plane laser wave. In a real situation it is necessary to consider the three-dimensional acceleration of the electron bunch under conditions of a limited cross section of the laser beam and a finite-space charge of the electron cluster. In this geometry the electrons are naturally lost due to their exit (scattering) from the region of the strong field; this fact should be taken into account. In this regard, in order to provide a quantitative interpretation of the acceleration process of the electron bunch, we have performed a three-dimensional numerical simulation by the particle-in-cell (PIC) method, the results of which are presented below.

4. Numerical simulation of vacuum acceleration of the electron bunch

The interaction of the electron bunch in vacuum with its coaxially overtaking laser pulse for different values of a_0 and γ_0 was numerically simulated using a PICNIC three-dimensional electromagnetics code. The initial size of the electron bunch (for definiteness it is a uniformly charged ball of diameter $d_b = 0.5$ μm) was chosen much smaller than the transverse size of the cylindrical laser beam d_f = 30 μm. The FWHM duration of the laser pulse was τ = 30 fs; its spatial shape was chosen Gaussian in the propagation direction and in the transverse direction. The model used corresponded to the light pulse with a wavelength λ = 1 μm, propagating within the Rayleigh length $\pi d_f^2/\lambda \approx 3$ mm. The charge of the electron bunch varied from 10 pC to 1 nC, and the electron density of a thin plasma foil with a thickness of 100 nm was about 10^{23} cm^{-3}. The calculations were performed for both the linear and circularly polarised laser pulses. The acceleration provided in Section 2 is, in general, well reproduced, which is shown in Fig. 2, illustrating the laser–bunch–foil interaction for three consecutive time instants (cf. Fig. 1).

In contrast to the simple analytical model presented in Section 3, the ponderomotive scattering of the electron bunch and its ultimate Coulomb energy result in the (observed in the numerical experiment) significant spreading of the electron (Fig. 2c) and the formation of a wide energy spectrum (Fig. 3). Despite this, the behaviour of the maximum energy of the accelerated particles is well described by formulas (2)–(4);

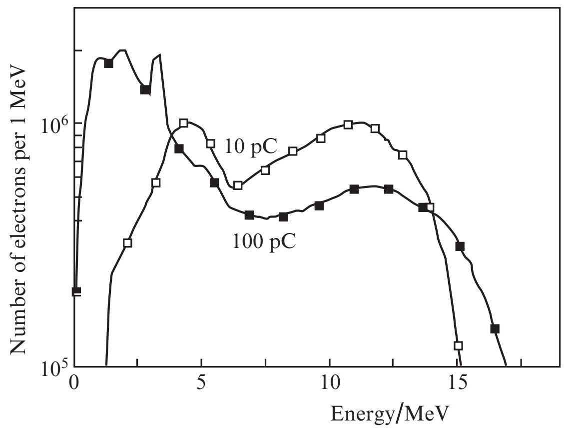

Figure 3. Spectra of the electrons for different initial bunch charges formed in the case of electron acceleration by a circularly polarised laser pulse at $\gamma_0 = 2$ and $a_0 = 5$.

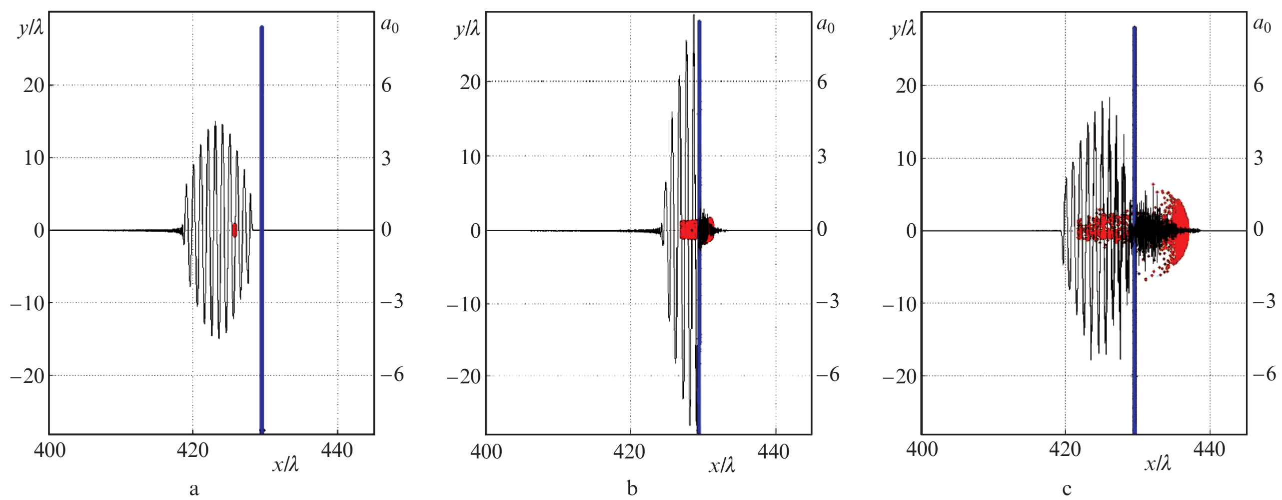

Figure 2. (Colour online) Typical picture of PIC-simulation of direct acceleration of an electron bunch by a linearly polarised laser pulse (from left to right). Along with the distribution of the electrons shown is the distribution of the electric field of the laser pulse.

this fact is illustrated by the numerical results presented in Fig. 4. As expected, under conditions of a relativistically strong electron beam and laser intensity the maximum energy of the accelerated particles for a linearly polarised pulse is two times higher than for a circularly polarised pulse. For a small space charge of the bunch (less than 10 pC) the spectrum of the accelerated electrons represents a single-peak with an appropriate relativistic factor γ_1 (2) or γ_2 (3). Along with a significant scattering of the accelerated electrons, a small number of particles, due to the Coulomb explosion, gain power, even slightly exceeding the maximum energy which meets the theoretical estimates (2) or (3). For the spectrum shown in Fig. 3 ($\gamma_0 = 2$, $a_0 = 5$) in the case of an initial charge of 10 pC, part of the electron energy reaches an energy of 15 MeV, whereas the theoretical maximum energy is about 13 MeV. The electrons with a charge of about 0.5 pC reside in the energy range of 10–15 MeV. At an initial charge of 100 pC, the corresponding parameters are 17 MeV and 0.2 pC. The spectrum was calculated for the electrons flown about 200 μm behind the foil: here was the boundary of the computational domain.

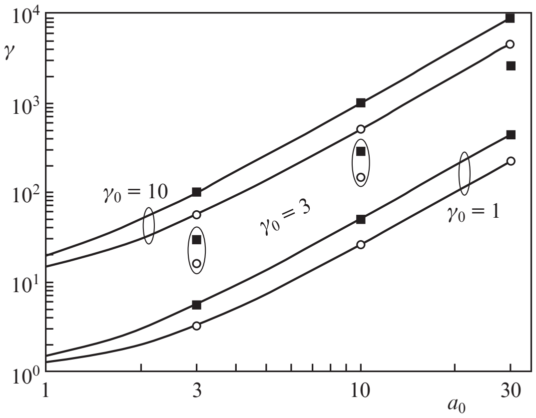

Figure 4. Maximum energy of the electrons in vacuum acceleration by (■) linearly and (○) circularly polarised laser pulse as a function of the laser field amplitude a_0 and the initial beam energy γ_0.

5. Discussion of the results

Using the above numerical simulation we demonstrated that the simple idea of direct vacuum acceleration of a relativistic electron beam by an intense laser pulse to ultra-relativistic energies works in a real three-dimensional geometry. However, the practical realisation of the idealised theoretical scheme presents a number of challenges for the most interesting parameters of the laser and the electron bunch. This concerns both the achievement of GeV energies and the possibility of obtaining a sufficiently large number of particles with a maximum energy.

As predicted by theoretical estimates, the final energy of the electron beam is proportional to $I\gamma_0$. Accordingly, the higher the intensity of the laser or the initial energy of the electron, the greater the length L where the maximum energy is gained. However, in a focused laser beam the length of effective acceleration is limited by the Rayleigh length L_0, which requires fulfilment of the condition $L \lesssim L_0$. Thus, in the above-discussed acceleration scheme it must start at a distance L from the reflecting foil. Limiting the acceleration length by the Rayleigh length substantially reduces the energy the accelerated electron beam, which, in the formal use of estimates (4), can reach a very high level. For example, by injecting a bunch from a compact electron accelerator with an energy of about 20 MeV a modern laser [8] with an intensity of $\sim 10^{22}$ W cm^{-2}, according to (4), can increase the electron energy up to 1 GeV, i.e., by 50 times.

To understand the role of finite length of the caustic, we estimate the acceleration time of the electrons, T, as the time during which the electron moving with velocity v, drifting inside the pulse, will pass half its length $c\tau/2$ (τ is the duration of the laser pulse), i.e., $T \simeq c\tau/[2(c - v)]$. Then the acceleration length L will be cT, and in a strongly relativistic case

$$L \simeq c\tau\gamma_0^2 \frac{a_0^2}{2}. \tag{5}$$

Accordingly, for the relativistic values of the laser intensity and the energy of the electron bunch, the condition $L \lesssim L_0$ gives the following restriction on the region of their variation:

$$\gamma_0 a_0 \lesssim \sqrt{\frac{\pi d_f^2}{c\tau\lambda}}. \tag{6}$$

For a given initial beam energy $\gamma_0 > 1$, condition (6) limits the laser field amplitude, and this limitation is the lower, the greater the focal spot and shorter the laser pulse. According to (4) and (6) the maximum possible energy of the particles in vacuum acceleration of a relativistic electron beam is

$$\gamma_{\max} \approx \frac{\pi d_f^2}{c\tau\lambda\gamma_0}. \tag{7}$$

For example, in accelerating the electron bunch with the energy of 1 MeV by a laser pulse with $\lambda = 0.8$ μm (a Ti:sapphire laser), $d_f = 30$ μm and $\tau = 30$ fs, the energy of the particles at the optimum position of the reflecting foil can be more than an order of magnitude greater than the initial energy of the beam.

The acceleration length and hence the final energy of the electrons can be increased by using a rarefied plasma (gas or another low density target, which are naturally ionised at the leading edge of the laser pulse). In this case, due to the self-focusing the ultimate acceleration length will increase significantly and be much greater than the length of the caustic, which will fully make it possible to achieve energies determined by formulas (4).

One more obstacle to the effective vacuum acceleration is associated with a significant scattering of the accelerated beam of electrons. Numerical calculations show that for a Gaussian beam a greater number of electrons are scattered and only a smaller fraction reaches the foil with the energy predicted by the theory. Strong scattering in the Gaussian beam has more to do with the ponderomotive action of light on the electrons than with its own Coulomb field of the bunch. To reduce this effect, use can be made of wave beams with a minimum intensity on the axis and a maximum intensity outside it, which will allow better confinement of the electrons within the pulse. An example is a one-ring Laguerre–Gaussian beam and a first-order Bessel beam. Preliminary numerical calculations do show a better electron capture by such beams and a more accelerated charge. Thus, for the Laguerre–Gaussian laser beam with a three times lower intensity on the axis than at the periphery, for the parameters of Fig. 3 we managed to increase to 2 pC the charge of the accelerated electrons from the bunch with a charge of 100 pC at energies above 10 MeV, their maximum energy reaching 20 MeV.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant Nos. 14-29-09244-ofi-m, 15-02-03042-a) and the RF President Grants' Council (State Support to Leading Scientific Schools Programme, Grant No. NSh-1424.2014.2).

References

1. Leemans W.P., Nagler B., el al. *Nat. Phys.*, **2**, 696 (2006).
2. Kneip S., Nagel S.R., Martins S.F., et al. *Phys. Rev. Lett.*, **103**, 035002 (2009).
3. Clayton C.E., Ralph J.E., Albert F., et al. *Phys. Rev. Lett.*, **105**, 105003 (2010).
4. Hyung Taek Kim, Ki Hong Pae, Hyuk Jin Chael, et al. *Phys. Rev. Lett.*, **111**, 165002 (2013).
5. Leemans W.P., Gonsalves A.J., Mao H.-S., et al. *Phys. Rev. Lett.*, **113**, 245002 (2014).
6. Mordovanakis A.G., Easter J., Naumova N., el al. *Phys. Rev. Lett.*, **103**, 235001 (2009).
7. Kiefer D., Henig A., Jung D., et al. *Eur. Phys. J. D*, **55**, 427 (2009).
8. Yanovsky V., Chuykov V., Kalinichenko G., et al. *Opt. Express*, **16**, 2109 (2009).
9. http://corels.ibs.re.kr/html/corels_en/research/research_0301.html.
10. http://www.hiper-laser.org.
11. http://www.eli-laser.eu/.
12. http://www.appl.sci-nnov.ru.
13. Henig A., Kiefer D., Markey K., et al. *Phys. Rev. Lett.*, **103**, 045002 (2009).
14. Dollar F., Matsuoka T., McGuffey C., et al. *AIP Conf. Proc.*, **1299**, 144 (2010).
15. Bochkarev S.G., Bychenkov V.Yu. *Kvantovaya Elektron.*, **37**, 273 (2007) [*Quantum Electron.*, **37**, 273 (2007)].
16. Popov K.I., Bychenkov V.Yu., Rozmus W., et al. *Phys. Plasmas*, **16**, 053106 (2009).
17. Galkin A.L., Kalashnikov M.P., Klinkov V.K., et al. *Phys. Plasmas*, **17**, 053105 (2010).
18. Popov K.I., Bychenkov V.Yu., Rozmus W. *Phys. Plasmas*, **15**, 013108 (2008).
19. Salamin Y.I. *Phys. Rev. A*, **73**, 043402 (2006).
20. Hartemann F.V., Fochs S.N., Le Sage G.P., Luhmann N.C. *Phys. Rev. E*, **51**, 4833 (1998).
21. Quesnel B., Mora M. *Phys. Rev. E*, **58**, 3719 (1998).
22. Galkin A.L., Korobkin V.V., Romanovskii M.Yu., Shiryaev O.B. *Kvantovaya Elektron.*, **37**, 903 (2007) [*Quantum Electron.*, **37**, 903 (2007)].
23. Fortin P.L., Piché M., Varin C.J. *Phys. B. At. Mol. Opt.*, **43**, 1 (2010).
24. Piazza A.Di., Hatsagortsyan K.Z., Keitel C.H. *Phys. Rev. Lett.*, **102**, 254802 (2009).
25. Maltsev A., Ditmire T. *Phys. Rev. Lett.*, **90**, 053002 (2003).
26. Stratton J.A., Chu L.J. *Phys. Rev.*, **56**, 99 (1939).
27. Varga P., Török P. *J. Opt. Soc. Am. A*, **17**, 11 (2000).
28. Wei Yu, Bychenkov V., et al. *Phys. Rev. Lett.*, **85**, 570 (2000).
29. Lawson J.D. *IEEE Trans. Nucl. Sci.*, **NS-26**, 4217 (1979).
30. Woodward P.M. *J. Inst. Electr. Eng.*, **93**, 1554 (1947).
31. Hartemann F.V., Fochs S.N., et al. *Phys. Rev. E*, **51**, 4833 (1995).
32. Yu M.Y., Yu W., Chen Z.Y. *Phys. Plasmas*, **10**, 2468 (2003).
33. Hu S.X., Starace A.F. *Phys. Rev. Lett.*, **88**, 245003 (2002).
34. Vshivkov V.A., Naumova N.M., Pegoraro F., Bulanov S.V. *Phys. Plasmas*, **5**, 2727 (1998).