developing a femtosecond multijoule laser setup (like ICAN) with a kilohertz pulse repetition rate and a high pulse contrast on the picosecond scale. The obtained proton energy scaling $\varepsilon_{\max} \propto E_{\mathrm{L}}^{0.7}$ proves the possibility of using thin solid foils irradiated by such a laser for nuclear applications. At the same time, preliminary calculations show that it is necessary to initiate detailed studies of the ion parameters that can be achieved by using laser mechanisms of particle acceleration from low-density targets. Even if these parameters are only slightly improved, low-density targets may be advantageous because of their lower sensitivity to the laser pulse contrast. Here, the main practical goal is the development of nanoporous targets having a good homogeneity and a density comparable to the critical one.

Acknowledgments
Most of the studies considered in this paper were supported by the Russian Foundation for Basic Research (grants 12-02-00231, 13-02-00426, 14-02-31407-mol_a, 14-01-00828, and 14-29-09244-ofi_m) and grants from the President of the Russian Federation for the Support of Leading Scientific Schools (NSh-1424.2014.2, NSh-3003.2014.2) and part of the studies related to low-density targets is supported by the RSF grant No. 14-12-00194.

References

1. Gaillard S A et. al. *Phys. Plasmas* **18** 056710 (2011)
2. Snavely R A et al. *Phys. Rev. Lett.* **85** 2945 (2000)
3. Mackinnon A J et al. *Phys. Rev. Lett.* **88** 215006 (2002)
4. Fuchs J et al. *Nature Phys.* **2** 48 (2006)
5. Henig A et al. *Phys. Rev. Lett.* **103** 245003 (2009)
6. Lévy A et al. *Eur. Phys. J. Special Topics* **175** 111 (2009)
7. Dollar F et al. *Phys. Rev. Lett.* **108** 175005 (2012)
8. Vshivkov V A et al. *Phys. Plasmas* **5** 2727 (1998)
9. Esirkepov T, Yamagiwa M, Tajima T *Phys. Rev. Lett.* **96** 105001 (2006)
10. Brantov A V et al. *Phys. Rev. ST Accel. Beams* **18** 021301 (2015); arxiv:1409.3356
11. Bulanov S S et al. *Phys. Rev. E* **78** 026412 (2008)
12. Bychenkov V Yu et al. *Plasma Phys. Rep.* **27** 1017 (2001); *Fiz. Plazmy* **27** 1076 (2001)
13. Roth M et al. *Phys. Rev. Lett.* **86** 436 (2001)
14. Bychenkov V Yu, Tikhonchuk V T, Tolokonnikov S V *JETP* **88** 1137 (1999); *Zh. Eksp. Teor. Fiz.* **115** 2080 (1999)
15. Borghesi M et al. *Plasma Phys. Control. Fusion* **43** A267 (2001)
16. Mackinnon A J et al. *Rev. Sci. Instrum.* **75** 3531 (2004)
17. Nemoto K et al. *Appl. Phys. Lett.* **78** 595 (2001)
18. Bychenkov V Yu, Brantov A V, Mourou G *Laser Part. Beams* **32** 605 (2014)
19. Bulanov S V, Khoroshkov V S *Plasma Phys. Rep.* **28** 453 (2002); *Fiz. Plazmy* **28** 493 (2002)
20. Bychenkov V Yu, Brantov A V *Eur. Phys. J. Special Topics* **224** (2015), to appear
21. Mourou G et al. *Nature Photon.* **7** 258 (2013)
22. Korzhimanov A V et al. *Phys. Usp.* **54** 9 (2011); *Usp Fiz. Nauk* **181** 9 (2011)
23. Romanov D V et al. *Phys. Rev. Lett.* **93** 215004 (2004)
24. Brantov A, Bychenkov V Yu *Contrib. Plasma Phys.* **53** 731 (2013)
25. Govras E A, Bychenkov V Yu *JETP Lett.* **98** 70 (2013); *Pis'ma Zh. Eksp. Teor. Fiz.* **98** 78 (2013)
26. Mora P *Phys. Rev. Lett.* **90** 185002 (2003)
27. Bychenkov V Yu, Kovalev V F *Quantum Electron.* **35** 1143 (2005); *Kvantovaya Elektron.* **35** 1143 (2005)
28. Wilks S C et al. *Phys. Plasmas* **8** 542 (2001)
29. Kovalev V F, Bychenkov V Yu, Tikhonchuk V T *JETP* **95** 226 (2002); *Zh. Eksp. Teor. Fiz.* **122** 264 (2002)
30. Brantov A et al. *Contrib. Plasma Phys.* **53** 161 (2013)
31. Passoni M et al. *Plasma Phys. Control. Fusion* **56** 045001 (2014)
32. Korzhimanov A V et al. *JETP Lett.* **86** 577 (2007); *Pis'ma Zh. Eksp. Teor. Fiz.* **86** 662 (2007)
33. Bulanov S S et al. *Phys. Plasmas* **17** 043105 (2010)
34. Brantov A V, Bychenkov V Yu *Plasma Phys. Rep.* **40** 505 (2014); *Fiz. Plazmy* **40** 591 (2014)
35. Roth M et al. *Phys. Rev. Lett.* **110** 044802 (2013)
36. Van Noorden R *Nature* **504** 202 (2013)
37. Benard F et al. *J. Nucl. Med.* **55** 1017 (2014)
38. Bulanov S V et al. *Phys. Usp.* **57** 1149 (2014); *Usp. Fiz. Nauk* **184** 1265 (2014)
39. Krasnov N N *Int. J. Appl. Radiat. Isotop.* **25** 223 (1974)
40. Ziegler J F "Particle Interactions with Matter" (2010), http://www.srim.org/
41. Qaim S M et al. *Appl. Radiat. Isotop.* **85** 101 (2014)
42. Lefebvre E et al. *J. App. Phys.* **100** 113308 (2006)
43. Davis J et al. *Plasma Phys. Control. Fusion* **52** 045015 (2010)
44. Bychenkov V Yu, Kovalev V F *JETP Lett.* **94** 97 (2011); *Pis'ma Zh. Eksp. Teor. Fiz.* **94** 101 (2011)
45. Kaplan A E, Dubetsky B Y, Shkolnikov P L *Phys. Rev. Lett.* **91** 143401 (2003)
46. Bychenkov V Yu, Kovalev V F *Plasma Phys. Rep.* **31** 178 (2005); *Fiz. Plasmy* **31** 203 (2005)
47. Andriyash I A, Bychenkov V Yu, Kovalev V F *JETP Lett.* **87** 623 (2008); *Pis'ma Zh. Eksp. Teor. Fiz.* **87** 720 (2008)
48. Kovalev V F, Bychenkov V Yu, Mima K *Phys. Plasmas* **14** 103110 (2007)
49. Sarkisov S G et al. *Phys. Rev. E* **59** 7042 (1999)
50. Macchi A et al. *Plasma Phys. Control. Fusion* **51** 024005 (2009)
51. Kovalev V F, Shirkov D V *Phys. Usp.* **51** 815 (2008); *Usp. Fiz. Nauk* **178** 849 (2008)
52. Kovalev V F, Bychenkov V Yu *Phys. Rev. Lett.* **90** 185004 (2003)
53. Miller M A *Izv. Vyssh. Uchebn. Zaved. Radiofiz.* **1** 110 (1958)

PACS numbers: 41.75.Jv, **52.35.–g**, 52.38.Kd
DOI: 10.3367/UFNe.0185.201501g.0089

Plasma-based methods for electron acceleration: current status and prospects

I Yu Kostyukov, A M Pukhov

Abstract. We present a short review of the current status of plasma-based methods for electron acceleration. Plasma acceleration mechanisms are described, with an emphasis on the most important experimental results and theoretical models. Some new areas of research in plasma-based methods are discussed. We also analyze future prospects for plasma accelerators and their usage in electromagnetic radiation sources of high-intensity.

Keywords: laser-plasma acceleration methods, laser pulse, electron beam, self-injection.

1. Introduction

Charged particle accelerators are one of the most important inventions of the 20th century. At the present time, accelerators are extremely important tools in the field of high-

I Y Kostyukov Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russian Federation;
Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, Russian Federation
E-mail: kost@appl.sci-nnov.ru
A M Pukhov Heinrich-Heine Universität Düsseldorf, Düsseldorf, Deutschland; Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, Russian Federation

Uspekhi Fizicheskikh Nauk **185** (1) 89–96 (2015)
DOI: 10.3367/UFNr.0185.201501g.0089
Translated by A L Chekhov; edited by A Radzig

energy physics, expanding our knowledge about Nature and, particularly, about the structure of matter. The most recent impressive discovery, made with the accelerator, is the direct experimental observation of the Higgs boson. This discovery was a result of the collective work of many scientists at the world's largest accelerator complex at the European Organization for Nuclear Research (CERN) [1]. This complex is a gigantic structure built around a circular accelerator with a circumference of about 27 km. It should be noted that, during the construction and operation of such a unique installation, many scientific and engineering problems have been solved. These problems were related to various aspects, such as processing of the huge amounts of data, maintaining the required vacuum in the accelerator, and constructing particle detectors, etc. Possibly, the global hypertext project, known now as the World Wide Web (WWW), started in 1989 as a result of CERN's intranet development [2]. Thus, the advanced accelerator complexes are making a significant contribution not only to fundamental physics, but also to applied science, industry, information technology, etc.

Although the highest energy of accelerated electrons (≈ 105 GeV) was reached at the circular accelerator LEP (Large Electron–Positron Collider) at CERN [3], the most promising accelerators are the linear ones. This is due to the fact that radiative losses in a ring accelerator are much higher than in a linear one. Since the electron rest mass is described by the relation $mc^2 \approx 0.5$ MeV, where m is the electron rest mass, and c the speed of light, the relativistic gamma-factor for accelerated electrons in LEP would be $\gamma \approx 2 \times 10^5$. The energy of accelerated electrons at the Stanford Linear Accelerator Center (SLAC) reaches nearly 50 GeV, and the length of the accelerator is approximately 3.2 km [4].

Electron accelerators are one of the most important parts not only in lepton colliders, whereby high-energy physics is studied, but also in sources of hard electromagnetic radiation with high intensity: synchrotrons and free electron lasers (FELs) in optical and X-ray ranges, as well as sources of gamma-quants which are emitted from the electron beam as a result of the Compton backscattering from the laser beam. For example, part of SLAC is utilized in an X-ray free electron laser (Linac Coherent Light Source, LCLS) [5]. There are approximately 26,000 different accelerators in the world. Most of them are used in medical and scientific applications, as well as in various industry domains — from materials processing and the action upon biological objects to performing diagnostics and structure analysis.

The so-called Livingston plot [6, 7] illustrates the fast development of accelerators. Up to recent times, the electron energy in accelerators had been exponentially increasing with time. However, it is obvious now that the accelerator energy growth rate is significantly decreasing. In order to reach a higher particle energy, larger accelerator complexes need to be built. For example, the International Linear Collider (ILC) project assumes that for a lepton energy of 500 GeV a 40-km long accelerator would be needed [8]. For petaelectron-volt energy levels (1 PeV $= 10^{15}$ eV), the accelerator dimensions would be comparable to the size of the Earth — that is, would have an astrophysical scale. An obvious way to decrease the size (and possibly the cost) of accelerators, without changing the resulting energy of the accelerated particles is to employ higher accelerating gradients or stronger accelerating electromagnetic fields. The accelerating field strength in modern accelerators is close to the technological limit, due to the possible development of a multipactor discharge and accelerating gap breakdown. However, various research is being carried out in order to develop new accelerating structures and new materials that would prevent breakdown in strong field regimes [9]. But it seems likely that standard accelerating methods are not able to increase the acceleration gradient by several orders of magnitude.

Recently, alternative methods for charged particle acceleration have become of great interest. These methods are based on acceleration in plasma and laser fields and eliminate the problem of the breakdown in accelerating structures. Plasma-driven accelerating structures allow using electromagnetic fields with a strength that is several orders of magnitude higher than in standard metal or dielectric accelerating structures. The idea of applying plasma fields for charged particle acceleration was proposed for the first time in the USSR by Ya B Fainberg in 1956 [10]. Longitudinal electric fields that can accelerate electrons are generated in a plasma wave, which is excited behind the electron bunch moving in plasma. The next important step in the development of plasma acceleration methods was the work by T Tajima and J M Dawson [11], where it was proposed to use a laser pulse for plasma wave excitation.

Acceleration directly in laser fields is also of great interest, particularly because of the fast development of laser technologies. At present, the intensity of a focused laser beam already exceeds 10^{22} W cm^{-2}. The electric field strength at such intensities amounts to ~ 0.3 PV m^{-1}. This means that the charged particle can be accelerated in such a field, reaching the energy of 1 PeV after passing only 3 m. However, the electric field in an electromagnetic wave is normal to the propagation direction and its strength and direction change periodically in spacetime, which makes it impossible to perform sequential acceleration in such a simple system. Various laser pulse configurations and initial electron distributions have already been studied for a long time in order to effectively accelerate electrons in a vacuum without exploiting solid-state structures which can be damaged by strong electromagnetic fields [12]. Another method consists in using plasma which allows converting transversal laser fields to accelerating longitudinal plasma fields. The acceleration scheme proposed by Tajima and Dawson [11] is related to this technique.

2. Plasma acceleration principles

Let us now briefly discuss the main principles underlying the plasma acceleration. Plasma oscillations comprise electron oscillations in plasma, which are excited behind a driver that moves with a speed close to the speed of light in plasma. The driver can be either a relativistic bunch of charged particles or a laser pulse [13, 14]. In the first case, plasma electrons are disturbed from an equilibrium condition by the electromagnetic field of the bunch, and in the second case by the ponderomotive force from a laser pulse. The ponderomotive force, or the Miller force [15], pushes the charged particles away from the region with a highly intense laser field. Ions, due to their large mass (in comparison with the electron), can usually be assumed to be at rest during either time intervals on the order of a pulse length or l_b/c, where l_b is the length of the charged particle bunch. As a result of quasineutrality violation, the regions with a strong longitudinal electric field emerge in a plasma wave, and the plasma oscillation phase, as well as the regions themselves, moves with the speed of the driver. If we put a relativistic charged particle, which moves in

the same direction as the driver does, in the accelerating field region, it would propagate together with the wave for a long time and would accelerate to high energies.

As an example, let us consider plasma wave excitation with a short laser pulse. We will assume that the laser pulse propagates along the x-axis with the speed v_d and has a Gaussian envelope. In this case, the normalized vector potential of the laser field is expressed as

$$a(\xi) = a_0 \exp\left(-\frac{r^2}{r_l^2} - \frac{\xi^2}{l_l^2}\right) \cos\left(\omega_l t - \frac{\omega_l x}{v_{ph}}\right),$$

where $a_0 = eA_0/(mc^2)$ is the normalized amplitude of the laser pulse vector potential, l_l is the laser pulse length, r_l is the laser pulse radius, ω_l is the laser frequency, and v_{ph} is the laser-wave phase velocity in plasma. In the linear regime ($a_0 \ll 1$), the dependences of the electron concentration perturbation and the longitudinal-field strength on the traveling coordinate $\xi = x - v_d t$ have simple forms

$$\delta b_e = -n_0 f \exp\left(-\frac{2r^2}{r_l^2}\right) \sin\left(\frac{\omega_p \xi}{c}\right),$$

$$E_x = -E_0 f \exp\left(-\frac{2r^2}{r_l^2}\right) \cos\left(\frac{\omega_p \xi}{c}\right),$$

where n_0 is the unperturbed plasma density, $E_0 = mc\omega_p/e$ is the characteristic electric field strength in the plasma wave, $\omega_p = (4\pi e^2 n_0/m)^{1/2}$ is the electron plasma frequency, and f is a coefficient which depends on the driver and plasma parameters:

$$f = \left(\frac{\sqrt{\pi} a_0^2}{2}\right) \frac{\omega_p l_l}{c} \exp\left(-\frac{\omega_p^2 l_l^2}{4c^2}\right).$$

Thus, during half of the plasma wave period $T_p = 2\pi c/\omega_p$, the longitudinal force accelerates the electron, and during the other half it slows it down. It follows from the expressions obtained that the pulse length which is optimal for plasma wave excitation has to be close to the plasma wave period. The maximal accelerating field strength would be E_0 [GV m^{-1}] $\approx \sqrt{n\,[10^{14}\ \text{cm}^{-3}]}$. For a plasma density of $n_0 = 10^{19}$ cm^{-3}, the electric field strength in the plasma wave can exceed $E_0 = 300$ GV m^{-1}, which is several orders of magnitude higher than the electric field strength in modern accelerators (~ 0.01 GV m^{-1}).

The plasma wave is constituted not only by a longitudinal electric field but also by transverse electric and magnetic fields, and the electron is subjected to transverse forces as well. In the linear approximation, the transverse force depends on ξ as the sine, and on radius r linearly in the vicinity of x-axis. During one half of the plasma wave period, the transverse force is focusing for the electron, while during the other one it is defocusing. However, the phase of the transverse force is shifted with respect to the longitudinal force phase by $\pi/4$. Therefore, only a quarter of the plasma wave period is suitable for stable acceleration. During this time interval, the longitudinal force will accelerate the charged particles, and the transverse force will focus them (Fig. 1).

If an electron initially finds itself in the accelerating phase, then its energy would increase. In this case, the electron speed can exceed the driver speed and, accordingly, the phase velocity of the plasma wave. As a result, the electron can

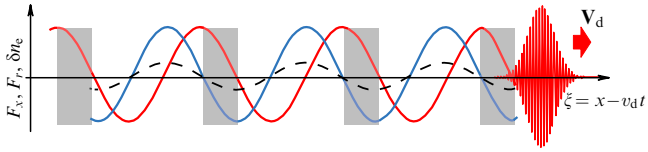

Figure 1. (Color online.) Distributions of the longitudinal force acting on the electron (red line), the radial force (blue line), and the electron concentration perturbation (black dashed line). The position of the laser pulse is marked by the red line. The regions which are applicable for electron acceleration ($F_x > 0$, $F_r < 0$) are indicated by grey color.

'overtake the wave' and leave the accelerating phase. This means that the acceleration is limited by dephasing [13, 14]. Let us assume that $\gamma \gg \gamma_d$, where $\gamma = (1 - v^2/c^2)^{-1/2}$ is the gamma factor of the electron after being accelerated, and $\gamma_d = (1 - v_d^2/c^2)^{-1/2} \gg 1$ is the driver gamma factor. In an ultrarelativistic approximation, we can write down the relations: $v \approx c(1 - 1/2\gamma^2)$, and $v_d \approx c(1 - 1/2\gamma_d^2)$. In the linear regime one has $\gamma_d \approx \omega_l/\omega_p$, because the group velocity of the laser pulse propagation in plasma is determined by $v_d \approx c(1 - \omega_p^2/2\omega_l^2)$ with the assumption that the plasma density is much less than the critical density: $\omega_p^2 \ll \omega_l^2$. Hence, the dephasing length — the distance which an electron passes while crossing the accelerating and focusing region — can be estimated in the following way:

$$l_{deph} \approx \frac{(\pi c/2\omega_p)\, c}{v - v_d} \approx \frac{\pi c}{\omega_p} \gamma_d^2 \approx \frac{\pi c}{\omega_p} \frac{\omega_l^2}{\omega_p^2}.$$

The energy increment that the electron will gain in this case has the form

$$\Delta W \approx eE_x l_{deph} = mc^2 \pi f \gamma_d^2 = mc^2 \pi f \left(\frac{\omega_l^2}{\omega_p^2}\right).$$

The smaller the plasma density, the higher the driver speed, the dephasing length, and the energy that the electron acquires during its acceleration.

While traveling in plasma, the driver spends its energy on plasma wave excitation. Therefore, the electron acceleration is also limited by the driver energy depletion. If the driver is a short laser pulse ($l_l < 2\pi c/\omega_p$), the length that characterizes the pulse energy depletion can be estimated as follows: $l_{pd} \approx (2\pi c/\omega_p)(\omega^2/\omega_p^2)\, a_0^{-2}$ [13, 14]. Let us note that the driver propagation in plasma can also be accompanied by other nonlinear effects (for example, the diffraction and self-focusing of the laser pulse or Coulomb expansion of the charged particle bunch). The influence of nonlinear effects leads to a change in the driver parameters, which can limit the particle acceleration, too.

As the laser field amplitude or the bunch charge increases, the excited plasma wave becomes nonlinear [16]. In this case, the dependence of E_x on ξ turns close to saw-like instead of sine, and the electron concentration dependence on ξ puts itself close to a periodic sequence of delta functions. The plasma wave period increases under these conditions. Finally, as the laser field amplitude exceeds some threshold, the plasma wave breaks and the strongly nonlinear regime becomes possible (bubble regime for laser–plasma interaction [17], and blowout regime for plasma–beam interaction [18]). In this case, a spherical-like plasma cavity — bubble is formed instead of a periodical plasma structure behind the

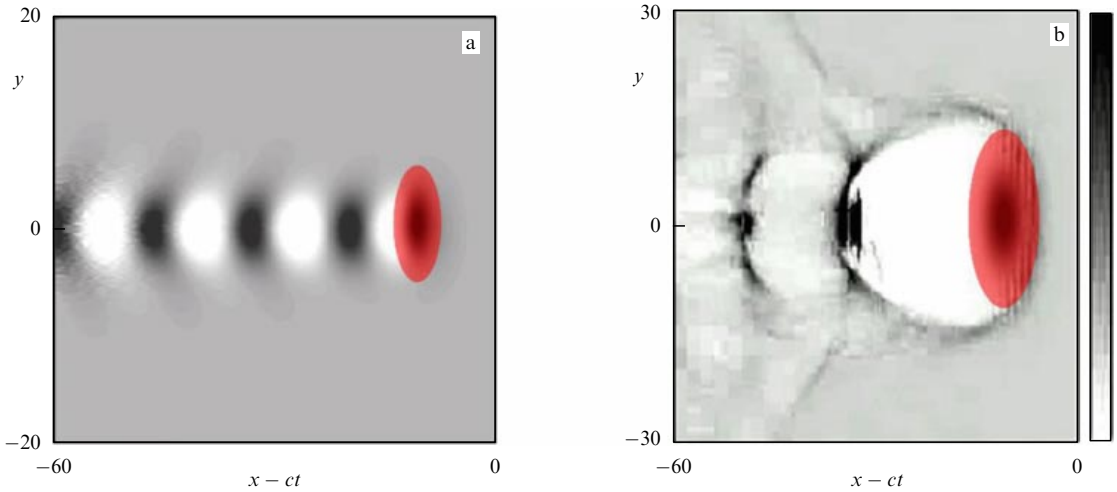

Figure 2. (Color online.) Typical electron concentration distribution obtained by numerical modeling for (a) linear and (b) strongly nonlinear regimes of interaction between the laser pulse and plasma. Darker grey color corresponds to higher electron concentration. Red color indicates the position of the laser pulse.

laser pulse, and this cavity is almost free of plasma electrons (Fig. 2). An important feature of this regime is self-injection — the process of trapping plasma electrons by the plasma cavity and accelerating them to high energies. As the results of the numerical modeling show, the energy spectrum of the accelerated electrons can be close to quasimonoenergetic [17], which is very important for various applications. The self-injection of plasma electrons into an accelerating plasma structure is an important and useful phenomenon which allows not using external injectors in plasma accelerators.

3. Experiments on the plasma acceleration of electrons

The main experiments on laser-driven plasma acceleration began in the middle of the 1990s. The typical scheme of such experiments is quite simple. A strong laser pulse in a vacuum hits the gas jet formed by a supersonic nozzle. The leading edge of the pulse ionizes the gas, and the main part of the pulse thus propagates in plasma. A bubble is formed behind the pulse. It traps plasma electrons and accelerates them to high energies. After leaving the jet, the electrons are deflected by the magnet. The degree of deflection allows reconstruction of the electron energy spectrum to be made.

The first experiments immediately evidenced the possibility of plasma acceleration. However, until 2004 the measured spectra of accelerated electrons were close to thermal ones, and for the most part the energy of the electrons did not exceed several dozen MeV. Article [17] predicted the possibility of achieving a strongly nonlinear regime with a quasimonoenergetic spectrum of accelerated electrons. After this article was published in 2002, many laboratories started to work on experimental validation of this regime. In 2004, three laboratories announced the observation of quasimonoenergetic electron bunch generation as a result of interaction between strong laser pulses and gas jets [19–21]. Particularly, in experiments performed at the Laboratoire d'Optiquée Appliquée (LOA, France), the energy of the accelerated electrons reached 170 MeV with a spread in energy near 20% [21].

The next important step was to exceed the energy level of 1 GeV for the accelerated electrons [22]. Experiments using the laser setup at Lawrence Berkley National Laboratory (LNBL) in the USA resulted in accelerated electron bunches with an energy near 1 GeV, a 30-pC charge, and a spread in energy of about 2.5%. In order to obtain a long dephasing length and high energy of accelerated electrons, a laser pulse with a power of 40 TW propagated along the plasma channel of 3.3 cm in length and a relatively small density of $\sim 4 \times 10^{18}$ cm^{-3} of the surrounding plasma. The presence of the channel ruled out laser pulse diffraction and, apparently, increased the acceleration length to a value close to the dephasing length.

At approximately the same time, LOA succeeded in demonstrating a controlled injection of electrons into the accelerating plasma structure by exploiting counterpropagating laser pulses [23]. The experimental setup was the following. The main laser pulse propagated in a gas jet with an amplitude of the laser field slightly lower than the self-injection threshold, so the plasma electrons were not trapped by the bubble. Another weaker pulse propagated towards the main one. In the pulse intersection region, plasma electrons were trapped into the cavity generated by the main pulse, and were then accelerated in it. Since the acceleration length was approximately equal to the distance between the pulse intersection point and the end of the jet, the acceleration length and the energy of the accelerated electrons could be controlled by choosing the intersection point. Experiments exhibited the possibility of generating electron bunches with the energy tunable in the range from 50 MeV to 200 MeV. Also, the control over self-injection was demonstrated by choosing the plasma density profile along the propagation direction of the laser pulse [24] and by introducing special gas additives, which caused the emergence of free electrons as a result of the ionization of inner shells of the additive atoms directly inside the accelerating plasma structures [25–27].

In Russia, experiments on laser-driven plasma acceleration were performed at the Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS) in 2008–2010. The subpetawatt laser system PEARL (PEtawatt pARametric Laser) was commissioned at IAP RAS in 2006 [28]. In the peak mode, the laser pulse energy reached 25 J with a pulse

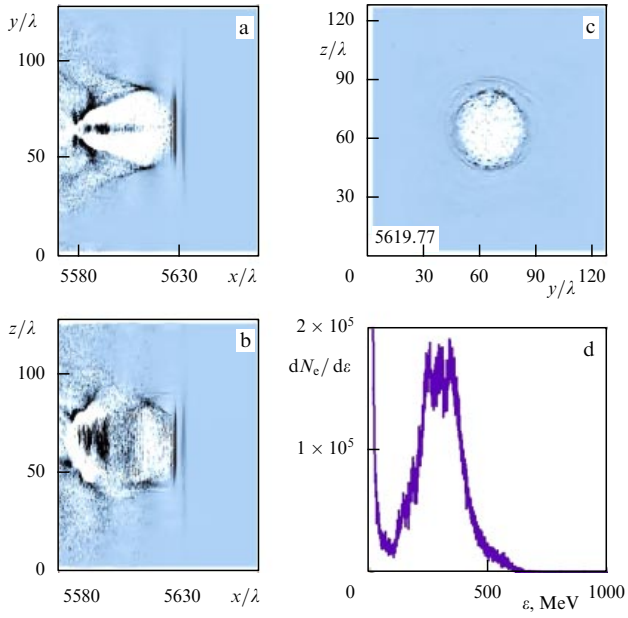

Figure 3. Electron concentration distributions (a)–(c) and accelerated electron spectrum (d) obtained by three-dimensional numerical modeling for the experimental parameters of the PEARL setup [29].

length of 46 fs, which corresponded to the power of 0.56 PW. In order to perform the experiments, the laser system was combined with a vacuum chamber completed with a focusing system, nozzle for the gas jet formation, and an equipment for laser radiation and electron beam diagnostics [29]. Electrons with an energy of several hundred MeV were registered in the experiments, and it was shown that there is a plasma density range where the acceleration is effective [30]. The obtained experimental data are in good agreement with the results of three-dimensional numerical modeling by the particle-in-cell method, using the QUILL code [31]. Figure 3 displays the results of numerical modeling: the final electron concentration distribution and accelerated electron spectrum for the PEARL experimental parameters.

The experimental findings on plasma acceleration at the SLAC accelerator were published in 2007. A bunch of relativistic electrons with an energy of 42 GeV was employed as a driver exciting a plasma wave with the accelerating field [32]. The bunch propagated in lithium vapor through a distance of 0.85 cm. The leading edge of the bunch ionized the gas and excited the plasma wave, wherein the electrons from the trailing edge of the bunch were accelerating. As the experiments have shown, some of the electrons from the rear edge of the bunch doubled their energy — its value increased to 85 GeV.

During the last several years, powerful new laser systems have been put into operation. These systems have allowed significantly increasing the energy of the accelerated electrons. In 2012, the University of Texas laser system (laser pulse energy $\leqslant 150$ J, and pulse length 150 fs) produced quasimonoenergetic electron bunches with the energy of about 2 GeV, ≈ 63 pC charge, and a spread in energy near 10% [33]. The accelerated electrons were generated in a gas cell which formed a plasma layer with a density of $\approx 5 \times 10^{17}$ cm^{-3} and thickness of 7 cm during the interaction with the pulse. Electron bunches with an energy on the order of 3 GeV, several pC charge, and a rather broad distribution were obtained at the APRI GIST [1] petawatt laser system in Korea (laser pulse energy 30 J, and pulse length 30 fs) [34]. Accelerating plasma structures were formed in two gas jets with diameters of 4 and 10 mm, respectively. The first jet generated relativistic electrons which were then additionally accelerated in the accelerating plasma structure formed by the laser pulse in the second jet. Finally, the BELLA (Berkley Lab Laser Accelerator) petawatt laser system at LBNL generated in 2014 a bunch of accelerated electrons with the energy of 4.2 GeV, 6 pC charge, and with a spread in energy of $\approx 6\%$ [35]. The laser pulse power amounted to 300 TW. The formation and acceleration of the electron bunch occurred in a plasma channel of 9 cm in length and plasma density of $\approx 7 \times 10^{17}$ cm^{-3}.

4. Theoretical models

The properties of plasma oscillations, including nonlinear ones (before breaking), were theoretically investigated in the pioneering work of A I Akhiezer and R V Polovin [16], where the electric field strength at the instant of wave breaking was calculated. The problem of exciting plasma oscillations by electron beams was studied by Ya B Fainberg [36] and J B Rosenzweig et al. [18]. The plasma oscillation amplitude was calculated as a function of plasma and beam parameters. One-dimensional analytical models describing the excitation of linear and nonlinear plasma oscillations by short laser pulses are presented in Refs [37–39]. These models were generalized for the case of exciting plasma oscillations in a plasma channel [40] and their excitation as a result of self-modulation of long laser pulses in homogeneous plasma [41].

With a powerful enough laser pulse, the interaction with plasma undergoes a strongly nonlinear regime: the plasma wave behind the pulse turns over and, instead of a periodical structure, a plasma cavity — bubble emerges with almost no electrons inside (Fig. 2b). A one-dimensional description is not applicable in this case, because the bubble is a three-dimensional structure. Moreover, due to the crossings of the electron trajectories, the hydrodynamic approximation does not hold true either, and a kinetic plasma description is needed. These circumstances, together with strongly nonlinear plasma dynamics, make the theoretical description of the strongly nonlinear regime a very complicated issue. Therefore, the first theoretical models for the description of this regime were based on a phenomenological approach [42], which, notably, allowed calculating the field distribution inside the bubble and analyzing the dynamics of the electrons accelerated in it.

It follows from the results of numerical modeling that the shape of the cavity evolves slowly, and it is close to spherical. Then, assuming that the cavity is a spherical electron 'hole' with motionless ions inside, which moves with the speed of light in plasma along x-axis, one can calculate the spacetime distribution of the electromagnetic fields inside the cavity:

$$E_x = \frac{m\omega_{\rm p}^2}{e}\,\frac{x-ct}{2}\,, \quad E_y = -B_z = \frac{m\omega_{\rm p}^2}{e}\,\frac{y}{4}\,,$$

$$E_z = B_y = \frac{m\omega_{\rm p}^2}{e}\,\frac{z}{4}\,.$$

[1] Advanced Photonics Research Institute (APRI), Gwangju Institute of Science and Technology (GIST).

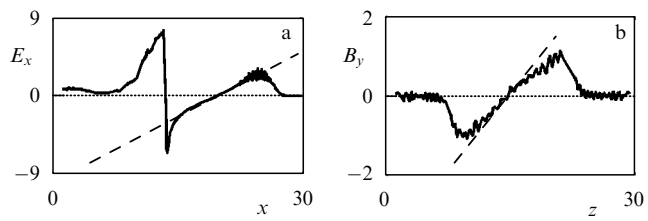

Figure 4. Spatial distribution of the electromagnetic field: (a) E_x and (b) B_y — inside the bubble at the time moment $l_{\text{int}} = 25c/\omega_{\text{p}}$. The numerical modeling results are shown with the solid line, and the analytical results with the dashed line. The strength of the fields is normalized to the quantity $mc\omega_{\text{p}}/|e|$. The coordinates x and z are presented in c/ω_{p} units.

The strengths of the electric and magnetic fields inside the bubble are linear functions of coordinates and time, the same as in the case of, for example, field strengths inside a charged ion ball moving with the speed close to the speed of light. However, the strength of the longitudinal electric field is negligible in the case of an ion ball. This difference is connected with the fact that ions inside the bubble are motionless, i.e., the current, caused by the particle motion, is absent. The predictions of this simple phenomenological model are in a good agreement with the results of three-dimensional numerical modeling by the particle-in-cell method, using the VLPL (Virtual Laser Plasma Lab) code [43] (Fig. 4). It is worth noting that the particle-in-cell (PIC) method allows modeling the laser–plasma interaction virtually *ab initio*, by solving relativistic equations of motion for several hundred million quasiparticles, modeling real plasma particles, and solving Maxwell equations for electromagnetic fields [43].

If we know the bubble field distribution, the dynamics of a relativistic electron trapped by the bubble can be analyzed. The electric field in the rear part of the cavity accelerates electrons, and slows them down in the front part. The energy that an electron acquires after crossing the rear part of the cavity is expressed as

$$\Delta W = mc^2 \, \frac{(\gamma_{\text{d}} \omega_{\text{p}} r_{\text{p}}/c)^2}{2} \, ,$$

where γ_{d} is the gamma factor of the bubble, which coincides with that for the laser pulse, and r_{p} is the bubble radius. If the electron is not located exactly on the x-axis ($y = z = 0$), transverse focusing forces act on it and their amplitude increases together with the distance from the axis. As a result of the influence of these forces, the electron, while accelerating, undergoes transverse betatron oscillations around the x-axis. The betatron oscillation frequency takes the form $\omega_{\text{b}} = \omega_{\text{p}}(2\gamma)^{-1/2}$, where γ is the electron gamma factor. Because the frequency decreases, as the electron energy increases during acceleration in the bubble, the betatron oscillation amplitude decreases as well [42].

A simple phenomenological model also allows estimating the plasma bubble parameters, for which the plasma electron self-injection into the cavity takes place [44, 45]. The predictions of the model discussed are in qualitative agreement with the predictions of other models investigating the influence of plasma parameters on self-injection: (1) plasma density jumps along the cavity propagation direction [46, 47], (2) cavity shape evolution [48, 31], and (3) ionization of atoms of a special gas additive inside the bubble under the action of the laser field [27]. However, it should be noted that the phenomenological self-injection model is relatively hard to use for the direct analysis of experiments and results on numerical modeling in a broad parameter range. The problem is that there is no simple analytical model yet that connects the plasma cavity parameters with the laser pulse parameters. Moreover, the laser pulse evolution itself in plasma in a strongly nonlinear regime is a complicated and insufficiently studied phenomenon.

The next important step that helped to overcome the self-inconsistency of the phenomenological model was made in Ref. [49], where the dynamics of the plasma electrons moving in the electron layer around the bubble were added to the model. This electron layer screens the bubble field in plasma outside the bubble. With the assumption that the electron number density in the layer is constant in the transverse direction, the equation which describes the bubble shape was derived. The generalized model also allowed taking into account the influence of the electron bunch, trapped by the bubble, on the shape of the bubble itself.

An alternative approach to describing the strongly nonlinear regime was proposed in Ref. [50], where it was suggested to take advantage of the similarity and dimensional methods and not to analyze the details of the inner processes that are responsible for the laser pulse and bubble dynamics. This approach in the limit of $a \gg 1$ showed that the interaction is governed by the parameters $S = n_0/(an_{\text{cr}})$ and $\Pi = l_{\text{l}}/r_{\text{r}}$. In this case, by applying numerical modeling for various laser–plasma parameters, one can obtain, for example, an estimate for the characteristic energy of accelerated electrons: $W \approx 0.65mc^2(P_{\text{l}}/P_{\text{rel}})^{1/2} l_{\text{l}}/\lambda_{\text{l}}$, where P_{l} is the laser pulse power, λ_{l} is the laser radiation wavelength, and $P_{\text{rel}} = m^2c^5/e^2 \approx 8.5$ GW is the relativistic self-focusing power. The model based on the similarity method allowed connecting through simple relations the parameters of the accelerated electrons with the initial laser–plasma parameters. Predictions made in the framework of this model turned out to be in good agreement with the results of 3D PIC numerical simulations. One should note that the models resting on the similarity methods, and the phenomenological model were generalized for the case where the laser pulse propagates not in homogeneous plasma, but in a deep plasma channel (the plasma density in the central part of the channel is close to zero) [51].

5. Alternative laser and plasma acceleration schemes

Recently, various schemes of lepton colliders based on plasma-driven accelerators have been discussed [52, 53]. The main disadvantages of laser–plasma accelerators, which limit their applicability in lepton colliders, are low energy conversion efficiency and low repetition rate in modern powerful laser systems. As a result, the overall energy conversion efficiency and repetition rate of laser–plasma accelerators turn out to be several orders of magnitude lower than those for conventional accelerators. Therefore, great attention is paid to the search for new laser schemes where these disadvantages could be overcome. One such scheme, which has been actively investigated lately, particularly in the framework of the ICAN project [54], is based on the synchronized operation of a large number of fiber lasers, which can operate with a high average power. Modern technology development allows performing the coherent

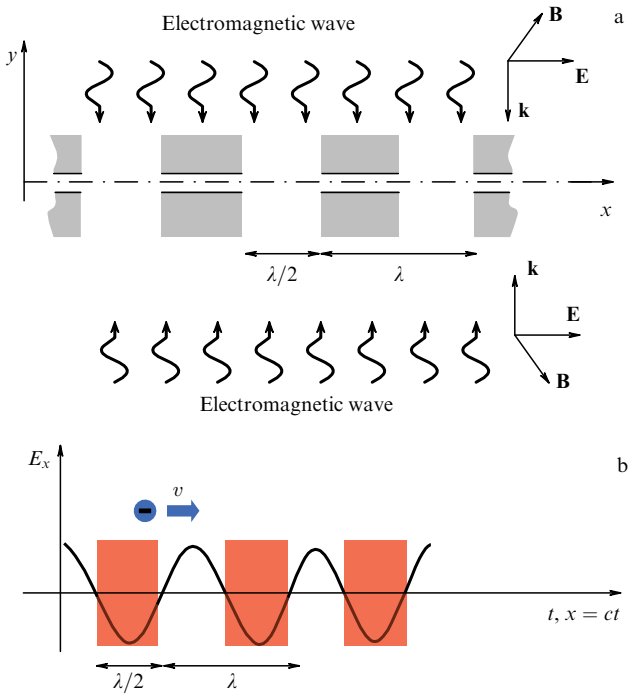

Figure 5. (Color online.) (a) Electron acceleration schematics in a standing electromagnetic wave with plasma elements. Structures with over-critical plasma are indicated by grey color. (b) Regions with accelerating electric field (indicated by red color).

combination of pulses from a large number of lasers through fast feedback. The principles of coherent pulse combination were demonstrated by the example of 64 fiber lasers [55]. It is important to note that the combination process can be controlled. This makes it possible to obtain complicated laser field distributions which can be used in charged particle acceleration.

Notably, the laser field strength can be several orders of magnitude higher than that of the plasma fields excited by the laser radiation. Therefore, charged particle acceleration by the laser fields themselves has been of great interest to scientists for a long time. As was mentioned in Section 1, it is hard to directly use the laser-wave transverse electric field, which periodically changes its direction, for acceleration. However, it was shown in Ref. [56] that by invoking ICAN technologies and dense plasma structures the charged particles can sequentially be accelerated with a laser field at long distances to high energies.

Let us assume that a periodical dense-plasma structure is placed in the field of a standing electromagnetic wave formed by two counterpropagating plane waves (Fig. 5a). The vectors of the wave are parallel to the y-axis, and the electric field is parallel to the x-axis. The periodical structure along the x-axis consists of vacuum gaps and layers of dense plasma, which is opaque to the electromagnetic wave. The thickness of the gaps and layers is the same and equals half of the laser wavelength λ. An aperture is made inside the dense plasma layers, so the accelerated charged particle can move freely through the layer. Such dense plasma layers can be formed for a short time by fast ionization of solid-state layers in a superstrong field of an electromagnetic wave.

Let the relativistic charged particle move along the x-axis. Since the speed of the particle is close to the speed of light, at one half of the laser wavelength the particle finds itself in the accelerating field, while at the other half it is in the decelerating field (Fig. 5b). If the decelerating part of the particle trajectory would coincides with the dense plasma layer, where the field is absent, the particle will only be influenced by the accelerating electric field. In order to increase the acceleration efficiency, the standing electromagnetic wave can be generated locally in the region where the accelerated particle resides, by coherent combination of pulses from an ICAN laser. As the results of numerical modeling show [56], the electron can be accelerated in this configuration to energies of 200 GeV at distances of about 10 cm, which is much higher than the acceleration gradient of even high-gradient plasma accelerators.

Another plasma acceleration scheme has been actively discussed lately in the framework of the AWAKE (Advanced Wakefield Experiment) project, coordinated by CERN. In this scheme, a bunch of relativistic protons, generated in, for example, the Large Hadron Collider (LHC) at CERN, is planned to be used as a driver exciting a plasma wave [57]. One of the advantages of the proton driver is its ability to travel long distances (several kilometers) without significant variation. In this case, by using rarefied plasma, a long dephasing length can be provided. As estimates show [58], the accelerated electron energy can reach several TeV. This setup also inherits the LHC advantages: a high repetition rate of accelerated particle bunches and high efficiency (in comparison with that of laser–plasma accelerators). Among the problems of such a setup is the electron injection into the plasma wave and the absence of short proton bunches needed for effective plasma wave generation. In order to solve the latter problem, the plasma wave is planned to be excited by a long proton bunch in the self-modulation regime, when the bunch, as a result of developing modulation instability, separates into a periodical sequence of short bunches [59].

6. Conclusions

During recent years, plasma acceleration methods have demonstrated impressive progress. The accelerated electron energy in experiments with laser pulse drivers has reached 4.2 GeV, and in experiments with an electron beam driver it has more than doubled, reaching 85 GeV.

At the present time, other promising plasma acceleration schemes are also being discussed, in which the role of the driver would be played by the proton bunch or the laser field of the ICAN laser.

It should be noted that relativistic electrons produced as a result of laser–plasma interaction can effectively generate electromagnetic radiation. For example, electrons due to betatron oscillations, which they experience while being accelerated in a plasma cavity, emit broadband electromagnetic radiation in the X-ray range [60–62].

As experiments have shown [63–65], an X-ray radiation source based on the betatron mechanism can provide a brightness which is comparable to that of third-generation synchrotrons. The high efficiency of the electromagnetic radiation generation by electrons in the plasma cavity is caused by the large value of the transverse forces bending the trajectory of the accelerating electron. The strength of these forces is several orders of magnitude higher than the strength of the corresponding forces in conventional radiation sources, which emerge during the particle motion in the magnetic fields of the ondulators. Laser–plasma X-ray sources, which have advantages over synchrotrons, such as

small dimensions and ultrashort pulse durations, can be utilized in medical researches, as well as in investigations associated with nanotechnologies and materials science.

The effective generation of electromagnetic radiation is a positive factor for radiation sources, but it leads to large radiation losses during particle's acceleration. These losses become especially significant for high electron energies. The electron dynamics in plasma accelerators with the radiation reaction force taken into account were studied in papers [66–69]. Particularly, paper [69] reports that in the limit of high electron energy the unlimited increase in the radiation reaction force stops due to a decrease in the beam radius as a result of nonlinear electron dynamics under acceleration in the presence of the radiation reaction force.

Despite the success achieved in plasma methods of electron acceleration, a series of unsolved problems limits the broad application of plasma accelerators. Among the disadvantages of these accelerators, one can distinguish the low energy conversion efficiency discussed above, the low repetition rate of modern powerful laser systems, and an insufficiently low spread in energy of accelerated electrons. The last fact prohibits using plasma accelerators in X-ray free electron lasers (XFELs). It is believed that the employment of laser–plasma accelerators can sufficiently decrease the dimensions and the cost of modern powerful sources of coherent X-ray radiation and gamma-ray radiation. Also, there is still no sufficiently full self-consistent theory for laser–plasma interaction, which would take into account various nonlinear and kinetic effects, such as electron self-injection into accelerating plasma structures.

Acknowledgments

This study was supported by a Russian Federation Government grant (14.B25.31.0008), RFBR grant (13-02-00886-a), and the project of the 7th Framework Program of the European Union, FP7EUCARD2.

References

1. CERN, http://home.web.cern.ch/
2. WorldWideWeb: Proposal for a HyperText Project, http://www.w3.org/Proposal.html
3. ALEPH, DELPHI, L3, OPAL Collab., CERN-EP-2000-055; http://l3.web.cern.ch/l3/paper/paper209.ps
4. SLAC National Accelerator Laboratory, Stanford University, https://www6.slac.stanford.edu/
5. Linac Coherent Light Source, http://lcls.slac.stanford.edu/
6. Livingston M S *High-Energy Accelerators* (New York: Interscience Publ., 1954)
7. Nash J "Current and future developments in accelerator facilities", in *Joint Meeting of the High-Energy Particle Physics and Astro-Particle Physics Groups of the Institute of Physics, 29–31 March 2010, London, UK*; http://www.hep.ucl.ac.uk/iop2010/talks/14.pdf
8. International Linear Collider, https://www.linearcollider.org/ILC
9. Bermel P et al. *Nucl. Instrum. Meth. Phys. Res. A* **734** 51 (2014)
10. Fainberg Ya B, in *Proc. CERN Symp. on High-Energy Accelerator and Pion Physics, 11–23 June 1956, Geneva* Vol. 1 (Geneva: CERN, 1956) p. 84
11. Tajima T, Dawson J M *Phys. Rev. Lett.* **43** 267 (1979)
12. Esarey E, Schroeder C B, Leemans W P *Rev. Mod. Phys.* **81** 1229 (2009)
13. Esarey E et al. *IEEE Trans. Plasma Sci.* **24** 252 (1996)
14. Andreev N E, Gorbunov L M *Sov. Phys. Usp.* **42** 49 (1999); *Usp. Fiz. Nauk* **169** 53 (1999)
15. Gaponov A V, Miller M A *Sov. Phys. JETP* **7** 515 (1958); *Zh. Eksp. Teor. Fiz.* **34** 751 (1958)
16. Akhiezer A I, Polovin R V *Sov. Phys. JETP* **3** 696 (1956); *Zh. Eksp. Teor. Fiz.* **30** 915 (1956)
17. Pukhov A, Meyer-ter-Vehn J *Appl. Phys B* **74** 355 (2002)
18. Rosenzweig J B et al. *Phys. Rev. A* **44** R6189 (1991)
19. Mangles S P D et al. *Nature* **431** 535 (2004)
20. Geddes C G R et al. *Nature* **431** 538 (2004)
21. Faure J et al. *Nature* **431** 541 (2004)
22. Leemans W P et al. *Nature Phys.* **2** 696 (2006)
23. Faure J et al. *Nature* **444** 737 (2006)
24. Geddes C G R et al. *Phys. Rev. Lett.* **100** 215004 (2008)
25. Pak A et al. *Phys. Rev. Lett.* **104** 025003 (2010)
26. Clayton C E et al. *Phys. Rev. Lett.* **105** 105003 (2010)
27. McGuffey C et al. *Phys. Rev. Lett.* **104** 025004 (2010)
28. Lozhkarev V V et al. *Laser Phys. Lett.* **4** 421 (2007)
29. Soloviev A A et al. *Rev. Sci. Instrum.* **82** 043304 (2011)
30. Soloviev A A et al. *Nucl. Instrum. Meth. Phys. Res. A* **653** 35 (2011)
31. Nerush E N, Kostyukov I Yu *Phys. Rev. Lett.* **103** 035001 (2009)
32. Blumenfeld I et al. *Nature* **445** 741 (2007)
33. Wang X et al. *Nature Commun.* **4** 1988 (2013)
34. Kim H T et al. *Phys. Rev. Lett.* **111** 165002 (2013)
35. Leemans W P et al. *Phys. Rev. Lett.* **113** 245002 (2014)
36. Fainberg Ya B *Sov. Phys. Usp.* **10** 750 (1968); *Usp. Fiz. Nauk* **93** 617 (1967)
37. Gorbunov L M, Kirsanov V I *Sov. Phys. JETP* **66** 290 (1987); *Zh. Eksp. Teor. Fiz.* **93** 509 (1987)
38. Sprangle P et al. *Appl. Phys. Lett.* **53** 2146 (1988)
39. Bulanov S V, Kirsanov V I, Sakharov A S *JETP Lett.* **50** 198 (1989); *Pis'ma Zh. Eksp. Teor. Fiz.* **50** 176 (1989)
40. Andreev N E et al. *Phys. Plasmas* **4** 1145 (1997)
41. Andreev N E et al. *JETP Lett.* **55** 571 (1992); *Pis'ma Zh. Eksp. Teor. Fiz.* **55** 550 (1992)
42. Kostyukov I, Pukhov A, Kiselev S *Phys. Plasmas* **11** 5256 (2004)
43. Pukhov A *J. Plasma Phys.* **61** 425 (1999)
44. Kostyukov I et al. *Phys. Rev. Lett.* **103** 175003 (2009)
45. Kostyukov I et al. *New J. Phys.* **12** 045009 (2010)
46. Bulanov S et al. *Phys. Rev. E* **58** R5257 (1998)
47. Suk H et al. *Phys. Rev. Lett.* **86** 1011 (2001)
48. Kalmykov S et al. *Phys. Rev. Lett.* **103** 135004 (2009)
49. Lu W et al. *Phys. Rev. Lett.* **96** 165002 (2006)
50. Gordienko S, Pukhov A *Phys. Plasmas* **12** 043109 (2005)
51. Pukhov A et al. *Phys. Rev. Lett.* **113** 245003 (2014)
52. Schroeder C B et al. *Phys. Rev. ST Accel. Beams* **13** 101301 (2010)
53. Nakajima K et al. *Phys. Rev. ST Accel. Beams* **14** 091301 (2011)
54. Mourou G et al. *Nature Photon.* **7** 258 (2013)
55. Bellanger C et al. *Opt. Lett.* **35** 3931 (2010)
56. Pukhov A et al. *Eur. Phys. J. Special Topics* **223** 1197 (2014)
57. Caldwell A et al. *Nature Phys.* **5** 363 (2009)
58. Lotov K V *Phys. Rev. ST Accel. Beams* **13** 041301 (2010)
59. Pukhov A et al. *Phys. Rev. Lett.* **107** 145003 (2011)
60. Leemans W P et al. *Phys. Rev. Lett.* **89** 174802 (2002)
61. Kostyukov I, Kiselev S, Pukhov A *Phys. Plasmas* **10** 4818 (2003)
62. Kiselev S, Pukhov A, Kostyukov I *Phys. Rev. Lett.* **93** 135004 (2004)
63. Rousse A et al. *Phys. Rev. Lett.* **93** 135005 (2004)
64. Kneip S et al. *Nature Phys.* **6** 980 (2010)
65. Cipiccia S et al. *Nature Phys.* **7** 867 (2011)
66. Michel P et al. *Phys. Rev. E* **74** 026501 (2006)
67. Kostyukov I Yu, Nerush E N, Pukhov A M *JETP* **103** 800 (2006); *Zh. Eksp. Teor. Fiz.* **130** 922 (2006)
68. Nerush E, Kostyukov I *Phys. Rev. E* **75** 057401 (2007)
69. Kostyukov I Yu, Nerush E N, Litvak A G *Phys. Rev. ST Accel. Beams* **15** 111001 (2012)