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Extreme Light Fields and Their Fundamental Applications

*Paper by RAS Foreign Member G. A. Mourou,
Corresponding Member RAS A. M. Sergeev, Cand. Sci. (Phys.–Math.) A. V. Korzhimanov,
A. A. Gonoskov, and Corresponding Member RAS E. A. Khazanov*

Since the invention of lasers in 1960, one of the main directions in their development has been increasing their peak output power. For this purpose, works on increasing the laser pulse energy and decreasing the pulse duration have been undertaken. The important milestones in this direction became the inventions of methods of Q-switching and mode locking in lasers, which provided the generation of picosecond pulses with 10 MW peak powers achieved by the late 1960s. Further increase in the laser pulse energy was complicated by the breakdown of optical amplifying elements, while a decrease in the pulse duration was restricted to the amplification band width of optical materials available at that time.

The main breakthrough in the development of super-high-power lasers occurred in 1985 after the invention of the method for amplification of so-called chirped optical pulses [1]. The method is based on increasing the laser pulse duration by means of linear frequency modulation in a dispersion system (stretcher), which can consist of a pair of prisms or diffraction gratings arranged in a certain way. In this case, the group elements of the pulse with different frequencies are spatially separated and the pulse intensity decreases by a few orders of magnitude, which allows its safe amplification without the breakdown of optical elements. After amplification, the pulse can be compressed with the help of a dispersion system (optical compressor), which acts oppositely to the stretcher and also consists of one or two diffraction gratings (Fig. 1). In this case, the amplified laser radiation interacts with matter during compression only on the surface of gratings where the optical breakdown threshold is considerably greater than that for radiation propagating inside an optical material.

In 1986, Ti:sapphire crystals were discovered with a record broad amplification band in the spectral range from 650 to 1100 nm, which can be used in principle to amplify laser pulses with a duration of down to 1–2 optical field cycles.

These discoveries caused the rapid development of super-high-power laser systems (Fig. 2). In 1996, output radiation power exceeding 1 PW was achieved in the Nova facility in the United States [2]. Laser radiation was amplified in neodymium glass, another popular material having a considerably narrower amplification band than that in Ti:sapphire crystals, but allowing the manufacturing of large-aperture elements for operation with optical beams several tens of centimeters in transverse size. The facility emits ~1-kJ subpicosecond pulses. Today, several petawatt neodymium-glass and Ti:sapphire systems exist in the world [3].

It was shown in 1986 that super-high-power radiation can be produced by using *optical parametric amplification* [4]. However, this method was experimentally realized only in the mid-2000s ([5], p. 3655; [6], p. 421). At present, petawatt laser systems based on parametric amplification in DKDP (*deuterated potassium dihydrogen phosphate*) crystals are built at the Institute of Applied Physics, RAS, and the Russian Federal Center in Sarov [7].

Several projects for the development of multiterawatt systems exist in the world, in particular, at the Institute of Applied Physics in Russia [3]. The focusing of such high-power radiation can produce a radiation power density exceeding 10^{22} W/cm². Already at radiation intensities on the order of 10^{16} W/cm², the electric field of the wave is comparable with the intra-atomic field, while at the intensity of 10^{18} W/cm², which is called *the relativistic intensity*, the oscillation energy of an electron in the wave field is comparable with its rest energy; i.e., the electron motion becomes relativistic.

Super-high-power lasers find wide practical applications, being comparatively compact sources of extreme light fields, beams of charged particles (electrons, protons, and light ions), and X-rays, including attosecond pulsed X-rays.

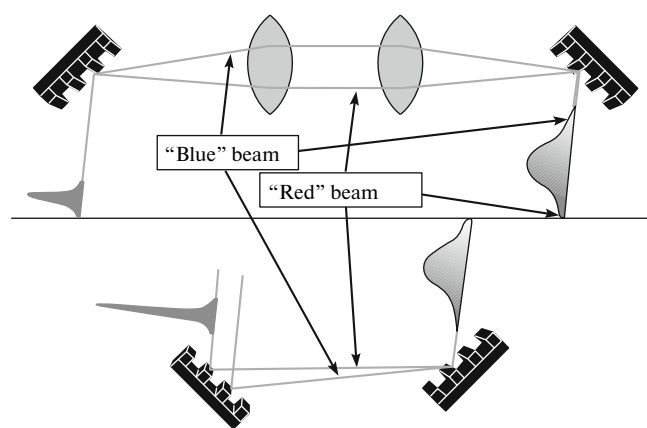


Fig. 1. Schematic view of the method for amplifying chirped pulses. (Top) The operation principle of a stretcher: a short pulse is transmitted through a dispersion system in which optical paths at different wavelengths are different. As a result, the output pulse of the stretcher becomes spatially stretched and chirped. (Bottom) The operation principle of a compressor representing a dispersion system reversed to the stretcher. The output pulse of the compressor again has a short duration.

DEVELOPMENTS OF SUPERHIGH-POWER FEMTOSECOND LASERS IN RUSSIA

Dye and excimer lasers. To generate super-high-power laser radiation, an active medium with a broad emission band that can generate ultrashort pulses is required. Such media were used for the first time in dye and excimer lasers. Dye lasers use solutions of some organic molecules. Polyatomic organic molecules having many electronic energy levels exhibiting relatively broad ($\sim 10\%$) amplification bands. Active media in excimer lasers usually consist of a mixture of two gases, inert and halogen (for example, xenon and chlorine or krypton and fluorine). During a discharge in gas, excimers, i.e., excited diatomic molecules consisting of inert and halogen gas atoms, are produced. An excimer molecule is unstable and decomposes by emitting a photon. The first high-power femtosecond laser setup built in Russia in 1986 under the supervision of S.A. Akhmanov and V.M. Gordienko at Moscow State University was based on the combined use of dye lasers and excimer amplifiers [8]. The setup emitted 6-GW, 350-fs pulses at a wavelength of 308 nm. By 1993, 0.1 TW of output power was achieved on this setup for the same pulse duration.

A disadvantage of dye and excimer lasers is their large dimensions and complicated maintenance, and for this reason they were gradually replaced in femtosecond optics by solid-state lasers. However, currently some renaissance is observed in the development of super-high-power excimer lasers, and a joint project is being developed at the Lebedev Physics Institute, RAS, and the High-Current Electronics Institute, Siberian Branch, RAS, for building the THL-100 laser

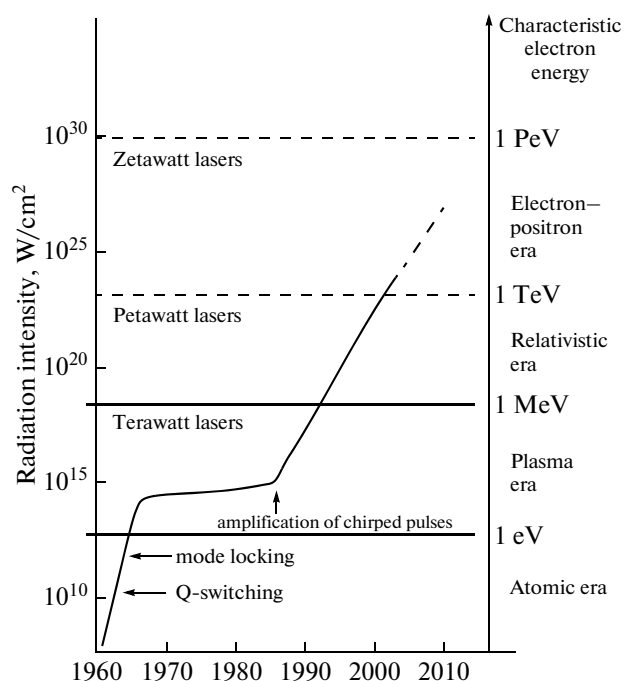


Fig. 2. Diagram of the increase in the radiation intensity of lasers. On the right are presented characteristic electron energies in the radiation field.

facility emitting 100-TW, 50-fs pulses. The start complex will be based on a Ti:sapphire system, and the final amplification will be performed in a XeF(C-A) photochemical amplifier pumped from six sides by vacuum UV radiation from an electron-beam converter.

Solid-state lasers. The first *multiterawatt laser* was made in Russia in 1997. The Progress-P laser system based on amplification in neodymium glass was built at the Research Institute of Complex Tests of Optoelectronic Devices under the direction of A.V. Churukheva. This laser emitted ~ 1.5 -ps, 40-J pulses, providing ~ 30 TW of output power. Later, similar 10-TW systems were built at the Central Research Institute of Machine Building and at the All-Russia Research Institute of Technical Physics.

The first *terawatt Ti:sapphire laser* in Russia was built at the Institute of Applied Physics, RAS, also in 1997. This work was directed by I.A. Babin and A.N. Stepanov and was supported by the Russian Academy of Sciences. The laser emitted 70-fs, 70-mJ pulses. Today similar systems operate at a number of institutes. Among them, the unique system based on Cr:forsterite active crystals should be distinguished, which was built under the direction of A.B. Agrant at the Joint Institute of High Temperatures, RAS, in 2003. This laser emits 80-fs, 2-TW, 1240-nm pulses at a pulse repetition rate of 10 Hz. The laser system built at the Institute of Laser Physics, Siberian Branch, RAS, at 2005 has the same pulse repetition rate. This

Ti:sapphire system developed under the direction of Academician S.N. Bagaev, E.V. Pestryakov, and V.I. Trunov emits 45-fs, 3-TW pulses.

PEARL and PEARL-10 facilities. In 2006, a sub-petawatt laser system was built at the Institute of Applied Physics, RAS, under the direction of RAS Corresponding Member E.A. Khanin in collaboration with the Russian Federal Center, All-Russia Research Institute of Experimental Physics. This work was supported by Rosatom [6]. The operation of this system, called PEARL (PEtawatt pARametric Laser), is based on the optical parametric amplification of chirped pulses.

Optical parametric amplification is a three-wave nonlinear process in which a pump photon decays into a signal-wave photon and an idler-wave photon with the signal-wave amplification. The main advantages of this method are the high gain (up to 10^4) per transit through a nonlinear crystal and the absence of thermal losses. One of the disadvantages of the method is its high sensitivity to the pump quality and the accuracy of synchronization of pump and signal pulses. In addition, a crystal is required in which superbroadband phase-matching conditions would be fulfilled. Superbroadband parametric amplification is performed in BBO (beta barium borate), LBO (lithium triborate), KDP (potassium dihydrogen phosphate), and DKDP crystals. The latter can be grown with a rather large aperture (up to $40 \times 40 \text{ cm}^2$) and are the most promising media for pulse energy amplification up to several kilojoules.

The PEARL system, using a DKDP crystal with an aperture of $10 \times 10 \text{ cm}^2$ in the final cascade, can generate 25-J, 45-fs pulses with a maximum power of $\sim 560 \text{ TW}$ at a pulse repetition rate of one pulse per 20 min. This is the world's first subpetawatt facility based on optical parametric amplification. In 2008, a similar petawatt laser system was built in Sarov on the basis of the Luch laser facility. This system has an additional amplifier cascade for increasing the pulse power up to 1 PW (70-J, 70-fs pulses) [7].

Presently, several projects of multipetawatt laser systems are being developed in the world [3]: ILE-Apollon in France, VULCAN-10PW in Great Britain, and the ELI Pan-European project aimed, in particular, to achieve 200 PW of output power. The laser facility at the Institute of Applied Physics, RAS, is being modified to achieve the multiterawatt level. Researchers plan to shorten the laser pulse duration in the new PEARL-10 facility by half compared to the preceding PEARL system (from 43 to 20 fs) by using a new master oscillator, to double the pulse energy by increasing the pump energy from 180 to 270 J, to increase the output laser energy by a factor of 1.5 using a larger-aperture DKDP crystal ($12.5 \times 12.5 \text{ cm}^2$ instead of $10 \times 10 \text{ cm}^2$), and to reduce pulse compression losses

from 85 to 75%. This modernization should increase the output power of the facility from 0.56 to 5 PW.

FUNDAMENTAL PHYSICAL STUDIES USING MULTITERAWATT AND PETAWATT LASERS

Superhigh-power laser systems have numerous potential applications. The most promising are the laser-plasma acceleration of charged particles (electrons, protons, and light ions) up to a few gigaelectronvolts and the generation of highly bright attosecond pulses in the X-ray and gamma-ray spectral ranges. Note that laser technologies offer a number of advantages compared to alternative methods. One of them is a comparatively simple synchronization of super-high-power laser pulses and secondary particle and photon sources based on them, which allows one to perform unique experiments in the physics of extreme fields and high energies. In addition, laser systems are relatively compact, whereas linear particle accelerators of energies up to many gigaelectronvolts are several kilometers in size. A laser facility providing similar possibilities occupies an area of about 100 m^2 .

Laser-plasma acceleration of electrons. The acceleration of charged particles by high-power laser pulses interacting with a plasma is based on the excitation of the wake plasma wave by the pondermotive force of a laser pulse propagating in a transparent plasma. The excited wave has phases with a longitudinal electric field accelerating electrons along the laser pulse propagation direction. Because the accelerated zones move at a phase velocity equal to the group velocity of the laser pulse in the plasma and close to the speed of light, the electrons found in the acceleration phase and moving at the relativistic velocity can remain in the acceleration phase for a long time, acquiring a considerable energy. Such electrons are called *captured* electrons.

In the linear interaction regime, when the amplitude of the excited wave is small, the main problem is the capture of accelerated electrons, and, therefore, external injectors of different types are often used. By now $\sim 1\text{-GeV}$ electrons have been produced in the linear acceleration regime [9]. For this purpose, a path 3 cm in length was used which represented a specially prepared low-density plasma in a capillary discharge. The diffraction divergence of the laser beam was compensated by a waveguide structure in the capillary.

As the laser intensity is increased, the plasma wave becomes nonlinear and overturns at some amplitude. In this case, the so-called cavitation regime can appear (which is often called the bubble regime). In this regime, a cavitation region is formed behind the laser pulse, which looks like a small bubble completely devoid of electrons (Fig. 3). Quasi-monoenergetic electron beams were probably first obtained in this

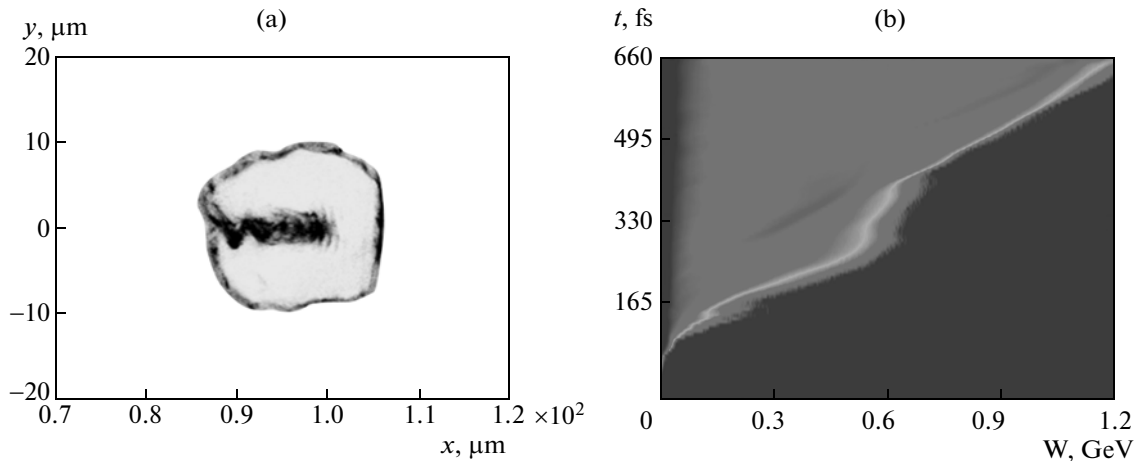


Fig. 3. Electron capture in the linear acceleration regime. (a) Structure of the cavitation region behind a high-intensity laser pulse propagating in a transparent plasma; the black and white gradient is the electron concentration; the “tongue” inside the cavitation region consists of captured electrons accelerated up to relativistic energies; (b) the time evolution of the electron energy distribution; a gradient demonstrates the amount of electrons per unit energy; the maximum electron energy increases continuously.

regime. Electrons are accelerated, as a rule, in a gas jet a few millimeters in thickness.

The numerical simulation and experiments performed on the PEARL facility at the Institute of Applied Physics, RAS, show that an important problem for acceleration is that the self-capturing of electrons occurs much later after the formation of the accelerating structure. In addition, the cavitation structure experiences a complex evolution during acceleration, and therefore, special conditions should be produced to allow efficient electron capture [10].

The record electron energy 1.45 GeV was achieved at Lawrence Livermore National Laboratory in the United States by using 110-TW, 60-fs laser pulses. The laser beam width was 15 μm , which is close to optimal conditions for producing a cavitation bubble. The gas jet length was 1.3 cm, and the plasma concentration in it was $1.3 \times 10^{18} \text{ cm}^{-3}$ [11].

Laser-plasma acceleration of ions. One of the first experiments on the laser acceleration of protons was performed in the petawatt channel of the Nova facility [12]. A 0.5–5 ps, $3 \times 10^{20} \text{ W/cm}^2$ laser pulse irradiated a solid target to produce a 55-MeV proton beam leaving the target from its rear side. To explain this result, the mechanism of proton acceleration by the surface layer of heated electrons [Target Normal Sheath Acceleration (TNSA)] was proposed. According to this mechanism, electrons heated by laser radiation are ejected from the target and form a negatively charged layer producing an electric field capable of accelerating protons and other light ions from the target.

To generate a monoenergetic ion beam, foils of heavy metals with a thin coating on the rear side are used as targets. The coating contains only light ions:

protons and carbon ions. The light ions are accelerated first of all in the accelerating field. Because the initial conditions for all accelerated ions are almost identical, they have the same output energy. The energy scatter in experiments did not exceed 25%.

At high radiation intensities, more efficient is *the laser piston or light sail* scheme. In this scheme, a thin foil is accelerated by the light pressure as a whole, which requires a sufficiently high radiation intensity; however, the use of circular polarization alleviates this requirement. The advantages of this scheme are the high efficiency, the high density of the obtained ion bunches, the low divergence of the generated beam, and its short (femtosecond) duration.

Experiments on the acceleration of ions by light pressure are rare thus far. Researchers at the Max Born Institute (Germany) irradiated carbon films with a thickness from 2.9 to 40 nm by 1.2-J, 45-fs circularly polarized laser pulses [13]. The high pulse contrast ($10^{11}:1$ at a time period shorter than 10 ps) provided the nondestructive interaction of laser pulses with targets. The formation of a 30-MeV C^{6+} ion beam was observed in experiments.

A similar principle is used in the acceleration scheme where the accelerating field in a thin heavy metal layer is produced by *squeezing out electrons by pondermotive forces* [14]. It was shown the energy of accelerated ions increases with decreasing target density [15]. In this case, the lower boundary of the admissible plasma concentration is determined by the relativistic self-induced transparency threshold. Analytic calculations confirmed by direct numerical simulations (Fig. 4) showed that the irradiation of a 1- μm thick layer with the electron concentration of $1.5 \times 10^{22} \text{ cm}^{-3}$ by a 10^2 W/cm^2 pulse produces the electric

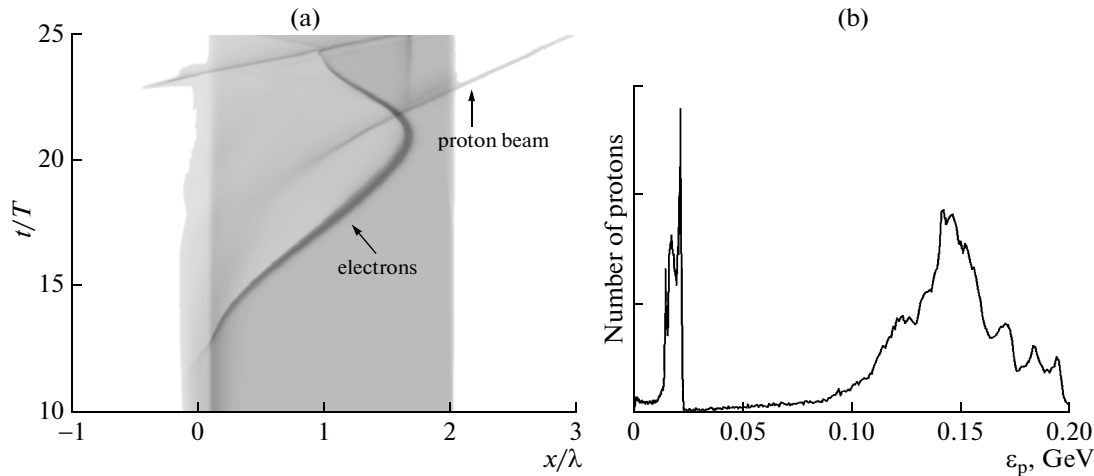


Fig. 4. Numerical simulation of proton acceleration by electrons squeezed by pondermotive forces. (a) Spatiotemporal dynamics of electrons and protons; the electron layer squeezed in a plasma and a proton beam leaving the layer are shown; (b) the energy distribution of protons. Calculation parameters: a 10^{22} W/cm ^{2} , 20-fs laser pulse with the Gaussian envelope; the concentration of unperturbed electrons is 10^{22} cm $^{-3}$; plasma ions Au $_{197}^{6+}$. Protons are initially distributed in a thin 100-nm thick layer on the irradiated side of the plasma layer.

potential difference amounting to a few hundred megavolts.

The development of this scheme is the concept of cascade amplification based on the *relativistic-induced layer transparency* [16]. This effect is observed in sufficiently thin plasma layers irradiated by circularly polarized light. If the incident field intensity is high enough, all electrons are squeezed out into a thin layer with a thickness smaller than that of the skin layer, resulting in the almost free propagation of laser radiation. The propagated laser pulse can be used to produce the electric potential difference in the next layer. The one-dimensional numerical calculation showed that after the propagation of the incident 30-fs, 10^{22} W/cm ^{2} pulse through four foils, a 200-MeV proton beam is formed.

Sources of attosecond record high-intensity radiation. The generation of high harmonics on the surface of a solid target was first observed in the early 1980s. Upon irradiation of solid targets by 10^{14} – 10^{16} W/cm ^{2} radiation from a CO $_2$ laser, the laser radiation harmonics up to the 29th harmonic were detected in the reflected signal. This result was explained by the resonance absorption of laser energy and excitation of plasma oscillations at multiple frequencies. In this case, the natural limit of the number of generated harmonics was the plasma frequency.

In the mid-1990s, the Doppler mechanism of harmonic generation was proposed which predicted the generation of harmonics with a frequency proportional to the square of the relativistic electron factor and was not limited by the plasma density.

This assumption was confirmed numerically and experimentally.

Moreover, it was shown [17] that the emission of electrons in the ultrarelativistic limit has a synchronous nature, and therefore, the cut-off frequency is proportional to the cube of the relativistic electron factor rather than to its square. This result was confirmed experimentally on the VULCAN facility ([18], p. 456), where the generation of X-rays with energies up to 3.5 keV was observed upon irradiation of a solid target by a 2.5×10^{20} W/cm ^{2} laser pulse. In this case, the radiation sources had an extremely high brightness (more than 10^{22} photons per second per 1 mm ^{2} within 1 mrad ^{2} per 0.1% of the spectrum at wavelengths smaller than 4 nm).

Of special interest is the possibility to generate attosecond pulses. Several schemes were proposed, among them the selective filtration of radiation and the use of ultrashort tightly focused pulses and variable-polarization pulses.

One of the most intriguing aims of converting optical radiation to attosecond pulses is the achievement of superhigh radiation intensities for observation of vacuum nonlinearity effects. Estimates show that at radiation intensities on the order of 10^{26} W/cm ^{2} , the creation of electron–positron avalanches should be observed in a vacuum. Such intensities can be achieved generating high-power attosecond pulses with amplitudes exceeding that of the incident radiation.

In [19], the process of laser energy conversion to an attosecond pulse was exactly analyzed and a simple analytic model was constructed which takes into account the possibility of energy storage in a plasma.

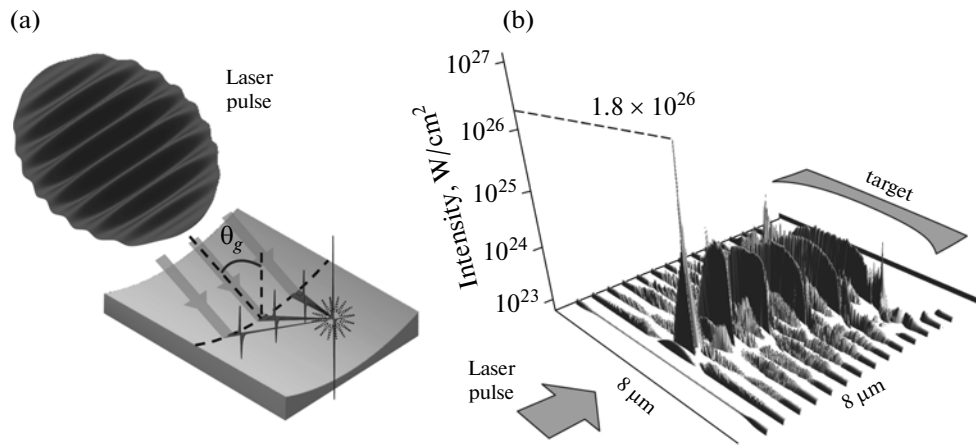


Fig. 5. Simulation of inclined irradiation by a linearly polarized laser pulse. (a) Schematic view of a target in the form of a groove for obtaining the radiation intensity required for observation of vacuum nonlinearity effects; (b) the intensity distribution at the moment of focusing giant attosecond pulses generated on the target surface, obtained by numerical simulation in the reference system moving along the groove directrix. Simulation parameters: the laser radiation intensity is $10^{23}\ \text{W}/\text{cm}^2$; the electron concentration in a target is $10^{23}\ \text{cm}^{-3}$ under optimal conditions. Simulations were performed using the ELMIS parallel code [20].

To observe vacuum nonlinearity effects, the authors of [19] proposed the concept of a target with the surface in the form of a weakly curved groove irradiated at optimal parameters so that the groove directrix is located in the radiation incidence plane (Fig. 5a). As the numerical simulation by the particle-in-cell method shows, a 10-PW laser pulse producing the intensity of $10^{23}\ \text{W}/\text{cm}^2$ in focus can provide an intensity of $1.8 \times 10^{26}\ \text{W}/\text{cm}^2$ in a region a few nanometers in size (Fig. 5b).

OUTLOOK FOR THE FULL-SCALE PARTICIPATION OF RUSSIA IN THE ELI PROJECT

To further develop super-high-power laser systems in Russia, it is very important for our scientists to take part in big European projects such as HiPER and ELI. The Pan-European ELI project is aimed at the development of the whole infrastructure of high-power lasers systems for investigation in a variety of directions. The project assumes the building of four facilities in different countries. At present three locations have been chosen for this purpose in Hungary, the Czech Republic, and Romania, the construction cost of each of the facilities being about 280 million euros. In Hungary, the generation of attosecond pulses will be studied; in the Czech Republic, laser-plasma accelerators and new X-ray and gamma-ray sources will be developed. In Romania, a facility for investigations in the field of photonuclear physics will be constructed. The construction of an exawatt laser system is planned in the future for fundamental studies of vacuum and matter with record radiation intensities. The dislocation of this system is not determined thus far, and there are strong grounds to believe that such a system can be

constructed in Russia. The experience in the construction of super-high-power lasers, the results of experimental and theoretical investigations of the interaction of extreme light fields with matter, and, finally, the building of the multiterawatt PEARL-10 system are strong arguments in favor of the participation of Russia in this unique international megaproject.

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