FEMTOLASERS AND HIGH-INTENSITY LASER-MATTER INTERACTIONS

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Summary

Femtolasers arose owing to the mode-locking technique which allowed producing laser pulses of femtosecond duration. The invention of the chirped pulse amplification and the development of high-fluence laser gain media and large-aperture nonlinear crystals made it possible to amplify femtosecond laser pulses to unprecedented powers, in excess of petawatt. A tight focusing of these pulses can produce so high intensity that the electromagnetic radiation almost instantaneously ionizes matter placed in the focus creating relativistic plasmas, whose dynamics can be dominated by effects of quantum electrodynamics.

This extremely high intense light can break the vacuum, creating matter in a form of electron-positron pairs. Such immense light conditions which in nature can happen only at distant stars are now possible to realize artificially on Earth with present-day technology using femtosecond laser pulses compressed to the power of a zettawatt. In this way the advent of the relativistically strong lasers has opened up an entirely new field of optics, extending right up to the domains of nuclear physics and high-energy physics with possible implications for the study of the highest energies in astrophysics, such as ultrahigh-energy cosmic rays. Besides a great impact on many fields of science, the high-intense lasers can underlie important applications in branches of national economy such as electrical power industry, public health and nuclear waste disposal.

1. Introduction

Lasers are light sources with unique properties, capable to produce light pulses with extraordinary coherency and monochromaticity, as well as very short durations and extremely high powers and intensities. Since its invention in late 1950s, lasers were quickly found to be extremely useful in industry, medicine, consumer microelectronics, in the military, etc. Lasers become indispensable instruments of research in all fields of natural sciences. A utility of a laser, from the point of view of potential applications, is determined by its parameters, such as wavelength bandwidth, output power, pulse duration, focusability, repetition frequency, energy-conversion efficiency, stability, and last but not least – the cost.

Since construction of the first laser, researchers were eager to obtain the laser pulse duration as short as possible for two reasons:

1. Electromagnetic radiation with relatively small energy, compressed into a sufficiently short time interval, may produce great peak powers. Being focused downto a diffraction limit, it can reach huge intensities. Increasing pulse powers and intensities is very important for investigations of radiation-matter interaction.
2. Shortening of light pulses, which are utilized in fast phenomena studies, leads to proportional increase of the time resolution of experiments. Chemical reactions and complex processes in molecular biology have characteristic time-scales from picosecond (10^{-12} s) to femtosecond (10^{-15} s). A laser pulse with duration in this range can work as a stroboscope which makes a snapshot of the process in a two-step scheme, “excitation–probing”. An object such as molecule is excited by a short laser pulse and then, after a very short period, its changed state is probed by another short laser pulse. Utilizing shorter and shorter pulse durations, one can trace changes more and more precisely. At the end of the 1980s this technique gave birth to *femtochemistry*. In 1999, A. H. Zewail was awarded the Nobel Prize in Chemistry for his pioneering work in this field.

Over the past 4 decades laser pulse durations have continuously shortened from the microsecond (1 μs = 10^{-6} sec) range in the free running regime to the nanosecond range (1 ns = 10^{-9} sec) in the regime of so-called Q-switching, and finally to the picosecond (1 ps = 10^{-12} sec) and few-femtosecond (1 fs = 10^{-15} sec) range in the regime of mode locking. A laser can be referred as femtosecond laser if its pulse has duration from a few to hundred femtoseconds. Such pulses have a broadband optical spectrum, and are generated in the regime of mode locking. [For comparison: 200 femtoseconds – the fastest chemical reactions, such as the reaction of pigments in a human eye to light.] With the special technique of light amplification, called chirped pulse amplification (CPA), a femtosecond laser can generate pulses with power in the terawatt (1 TW = 10^{12} watt) and petawatt range (1 PW = 10^{15} watt). [For comparison: 1.7 terawatt – average electrical power consumption of the world in 2001.] A terawatt laser pulse focused to a 10 micron focal spot gives intensity 10^{18} W/cm^2, for which the corresponding magnitude of electromagnetic wave forming the pulse is well above the electric field binding the electron in the hydrogen atom. Motion of a single electron in an electromagnetic field of this strength is essentially relativistic, which means that the kinetic energy of electron becomes comparable or even higher than the electron rest energy equal to mass of the electron at rest multiplied by square of speed of light, $m_e c^2$.

The laser pulse, whose intensity is so high that it causes relativistic dynamics of plasmas, is said to be relativistically strong. At these conditions, any material is converted to plasma, resulting in generation of strong collective fields, which leads to a change of radiation frequency, transformation of the laser pulse energy into the energy of plasma waves, acceleration of charged particles (electrons and ions), etc. The investigation of these phenomena, on the one hand, has been called forth by increasing power of laser pulses; on the other hand, it has become necessary due to numerous promising applications such as charged particle acceleration, (inertial) thermonuclear fusion, hadron therapy in oncology, generation of X-ray and terahertz radiation, etc.

For laser intensities above 10^{18} W/cm^2, the interaction of the laser pulse with matter is rich in strongly nonlinear processes in which the relativistic effects play the key role. A complexity of investigation of these processes is determined by the dominance of nonlinear and kinetic effects in the plasma dynamics and is usually aggravated by the lack of symmetry entailing an irreducibly high dimensionality of the problem. In this situation, along with the analytical methods, the numerical simulations of laser-plasma interactions become an irreplaceable powerful tool of investigation. Multi-dimensional simulations of full-scale interaction have become available through the rapid progress of massively parallel and vector supercomputers and development of computer science. In the case of femtosecond relativistically strong laser pulses, three-dimensional (3D) particle-in-cell (PIC) codes up to now provide an unrivalled opportunity for adequately describing a vast variety of aspects of nonlinear dynamics of laser plasmas, including the generation of coherent nonlinear structures such as plasma wakefield, relativistic solitons and vortices, the regime of nonlinear wave breaking, the acceleration of charged particles to high energies, the emission of high-intense electromagnetic radiation with frequency in a wide range from terahertz to X-ray.

2. Race for Laser Intensity

In the evolution of laser technology, we observe that, along with shortening of laser pulse durations, the achievable intensity of focused laser pulse is rapidly increasing, as sketched in Figure 1 [Here the term “intensity” is equivalent to the term “irradiance”, power of electromagnetic radiation incident at a surface, per unit area. As is the convention in many publications, we express the laser pulse intensity in watts per square centimeter, W/cm^2]. This rapid progress was stimulated by the introduction of four important techniques – Q-switching (R. W. Hellwarth, 1961), mode locking (H. W. Mocker and R. J. Collins, 1965), chirped pulse amplification (D. Strickland and G. Mourou, 1985), and optical parametric chirped pulse amplification (A. Dubietis et al., 1992). The increase in laser intensities predetermined the discovery of the major effects in nonlinear optics, which led to an explosive expansion of the field of applications and justified the race for higher laser intensities. The availability of terawatt and petawatt lasers has extended the horizon of laser physics from atomic and condensed-matter studies to plasma, nuclear, and high-energy physics.

One of the simplest methods for obtaining a short pulse is to cut out the pulse from a continuous radiation by a light shutter. In this case the duration of the pulse is about the time period when the shutter is open and the time-scale of leading and trailing edges of the pulse is determined by the characteristic time of the shutter opening and closing.

Mechanical shutters are used in photography, providing durations as short as hundred microsecond. Rotating mirrors or prisms were used as shutters at the dawn of laser technology. Much shorter durations, of the order of nanosecond (10^{-9} s), can be accessed with so-called Kerr cells and Pockels cells which are now widely used. Both are based on electro-optic effect of inducing birefringence of a material in response to a strong electric field, which can be applied to the material using an external electric circuit. The induced refractive index change is proportional to the field magnitude in the Pockels effect and to the square of the field in the Kerr effect. The shortest duration secured by shutters of this type is determined by the electric circuit which controls the cell. Since shutters cut out the pulse from a longer beam, the pulse peak power is not greater than the power of the beam.

The power of the pulse can be greatly increased if the shutter is placed inside the *laser cavity*, so as it can modulate the cavity Q-factor. When the shutter is closed, it causes large cavity losses (so the Q-factor of the cavity is low) thus preventing the *lasing* (generation of laser light, when *stimulated emission* is dominated rather than *spontaneous emission*). At this time the *gain medium* accumulates the energy, so the number of excited ions or atoms increases. The stored energy can be much greater than the saturation energy. When the shutter opens, cavity losses are quickly reduced; light can now make many roundtrips in the cavity and its power quickly grows. The peak power is reached when the gain is balanced with cavity losses, which are now low (so the Q-factor of the cavity is high).

All accumulated energy or its large part is emitted in a form of a short pulse, known as a “giant pulse”. The output peak power of the pulse can be orders of magnitude higher than the power accessible with the same gain medium in continuous wave operation. A technique which uses this principle is called Q-switching. The output pulse duration is about the characteristic time of the shutter opening, or, if the shutter is sufficiently quick, it is determined by the laser cavity size. Duration of pulses from Q-switched lasers is always well above the time needed for light to make a roundtrip in the cavity. It varies from nanosecond in the case of meter-size cavities to tens of picoseconds for microchip lasers.

The pulse duration can be shortened further if a shutter placed into the cavity works periodically with the period equal to the cavity roundtrip time. In this case the shutter does not block the light completely, when it is closed, but slightly modulates its amplitude. This modulation, synchronous with the light roundtrip in the cavity, causes establishing a constant phase relationship between modes of the laser cavity, which enables interference between modes to produce a train of short pulses, separated by the cavity roundtrip time.

The laser is then said to be *phase-locked* or *mode-locked* and the corresponding technique is called mode-locking. Instead of externally controlled shutter a *saturable absorber* (an optical element in which the absorption of light decreases with increasing light intensity) can be used. The actual strength of the modulation does not have to be large, since the same light is modulated at every roundtrip. The pulse duration is proportional to the cavity roundtrip time and inversely proportional to the number of modes N. Gain media with large bandwidth allow obtaining pulse durations below 6 fs, as was demonstrated by L. Gallmann et al. (1999).

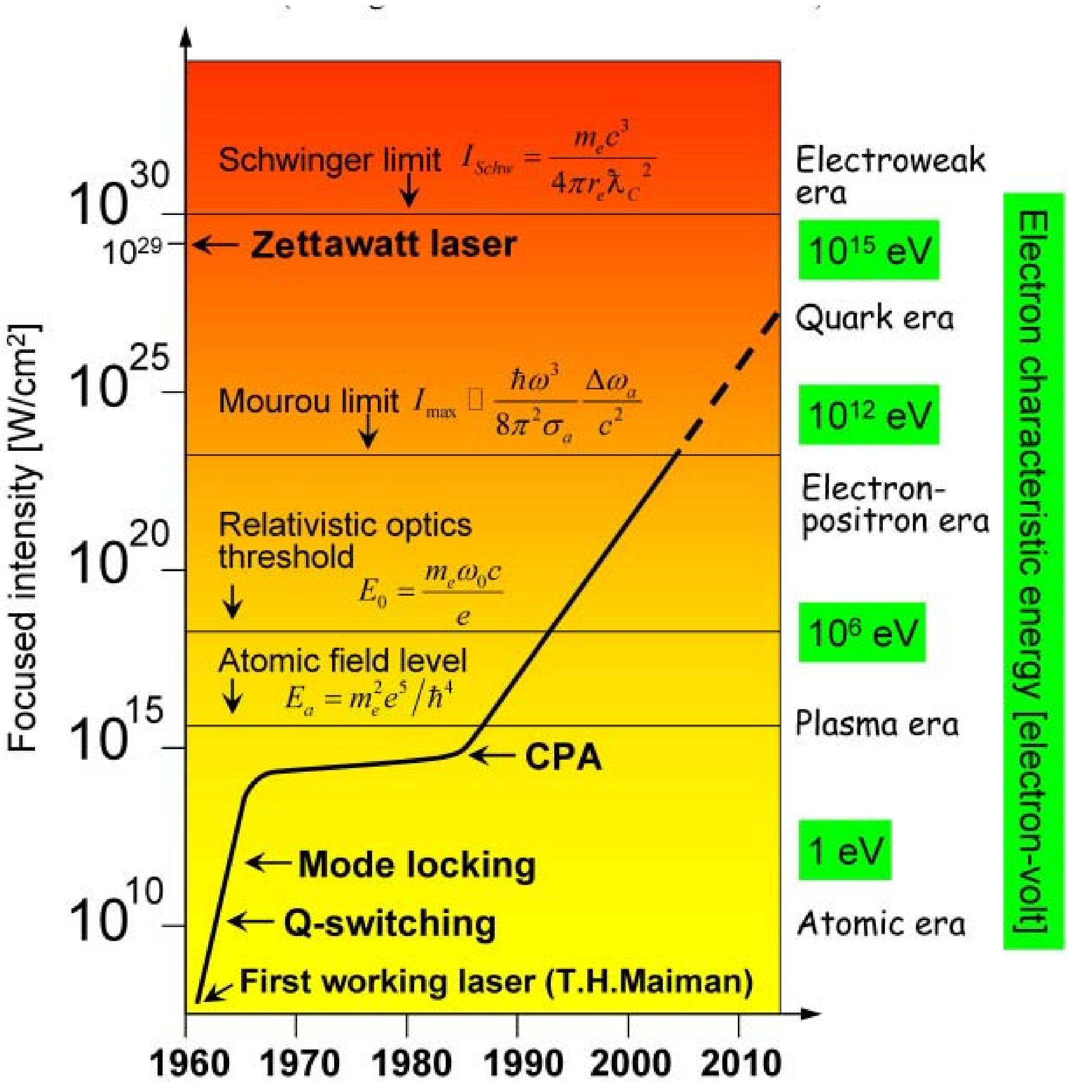

Figure1: Focused laser pulse intensity vs years.

The chirped pulse amplification technique offered very high amplification, relatively low cost and reduced size of the laser system, so that the CPA lasers could be easily combined with large particle accelerators, which gave rise to an immediately flourished new field of research in experimental high-energy physics.

In 1996, researchers at Stanford Linear Accelerator Center (SLAC, Stanford University, USA) observed quantum electrodynamics (QED) processes — nonlinear Compton scattering and electron-positron pair production — in collisions of 46.6 GeV and 49.1 GeV electrons of the Final Focus Test Beam with terawatt laser pulses of 1053 nm and 527 nm wavelengths from a Nd:glass laser with peak intensity of the order of 0.5×10^{18} W/cm^2 (C. Bula, et al., 1996). In their experiments the electric field of the laser pulse in the reference frame of electrons was close to the QED critical field (so-called Schwinger field). At the moment all the colliders are considering the incorporation of

CPA technology to produce γ-rays for photon-photon collisions, i.e., to create a γ–γ collider as suggested by V. I. Telnov (1990).

A number of technological problems arise on a path to high powers. First, sufficiently powerful pump sources are necessary. Then, efficient removal of heat is required, because a part of the pump power is inevitably converted into heat. The resulting temperature gradients and subsequent mechanical stress cause lensing and depolarization loss, which lead to distortion of the laser pulse beam, a decrease of gain efficiency (the gain per unit pump power), and sometimes to destruction of the gain medium.

The laser pulse is amplified in a *gain medium* through the effect of *stimulated emission*. The gain in laser pulse energy becomes smaller if the laser pulse (output) energy overcomes some threshold, the *saturation energy*. This is because the amount of extractable energy stored in the *gain medium* via pumping is limited by the number of excited ions or atoms in the *gain medium*.

The *saturation energy* per unit area is called the *saturation fluence*. To maximize the output energy of the laser pulse, the laser must operate in the regime when the fluence of the laser pulse (energy per unit area) is of the order of the *saturation fluence*, because in this case most of the energy stored in the *gain medium* is extracted. The *saturation fluence* is inversely proportional to the *emission cross section* of the gain medium (also called the *laser cross section*) which quantifies the probability of the *stimulated emission* of excited ion or atom.

Therefore for higher energy extraction, the media having low *emission cross section* is preferable. In the case of femtosecond laser pulses, the medium must exhibit a significant gain for radiation frequencies in a sufficiently broad range (so called *gain bandwidth*), to embrace the laser pulse spectrum as much as possible.

An amplification of a femtosecond laser pulses to terawatt powers is severely complicated by a necessity to keep the laser pulse fluence and intensity below the thresholds, beyond which the gain medium and optical components undergo unacceptable (e. g., permanent) damage or exhibit nonlinear effects impairing the laser pulse quality. This is the reason for the power and intensity plateau seen in Figure 1.

For example, an amplification of 100 fs laser pulse to power 10 TW (so, the output energy is 1 J) requires that the intensity determined by the laser fluence delivered over pulse duration must be below the limit of the order of GW/cm^2 imposed by the need to prevent nonlinear effects and optical damage in the gain media and optical components.

Thus the laser beam sectional area must be of the order of 10^4 cm^2 and corresponding saturation fluence must be about 10^{-4} J/cm^2, which leads to unattractively large and expensive laser systems based on gain media with a very large *emission cross section* (dyes and excimers).

Before invention of the CPA technique, amplification of femtosecond laser pulses to terawatt range was limited to a few large-scale high-priced multi-beam facilities in several national laboratories.

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Biographical Sketch

Timur Zhenisovich Esirkepov graduated from Moscow Institute of Physics and Technology (MIPT) in 1993. He has a degree of Candidate of physico-mathematical sciences (equivalent to Ph. D.) awarded by the same institute in 1996. From 1993 until now he has been worked at MIPT, where at present time he is holding a position of senior staff scientist. From 2002 he is working as a visiting researcher at Kansai Photon Science Institute, a branch of Japan Atomic Energy Agency, Japan. His scientific interests include relativistically strong laser-matter interactions, methods of laser-driven charged particle acceleration, strongly nonlinear coherent structures in plasmas and fluids, and computational physics. T.Zh.E. has published in co-authorship more than 100 papers in scientific journals.