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Invited paper

The ultrahigh-peak-power laser: present and future

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Abstract. The technique of chirped pulse amplification has revolutionized our ability to produce high-peak-power pulses. It is possible to produce with tabletop systems pulses in the 10-TW range and peak intensities in the 10^{19} to 10^{20}-W/cm^2 range. With some refinements and with superior energy storage materials, even higher peak power in the petawatt range should be possible from tabletop systems. In this paper we show the ultimate achievable power and intensity, as well as their applications in science and technology. Their applications cover a wide variety of fields, such as precision surgery, micromachining, coherent and incoherent X-ray generation, thermonuclear ignition, particle acceleration, and nonlinear quantum electrodynamics.

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Until 1985, the amplification of ultrashort pulses was restricted to dye and excimer amplifying media, due to their ultrawide gain bandwidth and low saturation fluence. In 1985, this state of affairs was drastically changed by the technique of chirped pulse amplification (CPA) [1], which made possible the amplification of ultrashort pulses to unprecedented power levels by using solid-state amplifying media with vastly superior energy storage capability. The very large difference in storage capacity between amplifying media can be appreciated if we look at Fig. 1, comparing, for the same amount of stored energy, the size of different amplifying systems, such as dye, excimer, Ti:sapphire, Cr:LiSAF, Nd:glass, and Yb:glass. Optical nonlinearities, notably small-scale self-focusing, prevented efficient energy extraction. They were avoided, with the technique of CPA, by stretching the pulse in time prior to the amplification and then compressing it, as shown in Fig. 2. This technique, in parallel with the recent progress in ultrashort pulse generation [2], led to an explosion in laser peak power (see Fig. 3) by a factor of 10^3 to 10^4 and, as in the 1960s, has dramatically extended the range of the optical field to new scientific and technological territories. When these ultraintense pulses are focused over a spot size limited by the diffraction, ultrahigh intensities can be produced, characterized by large ponderomotive forces in the gigabar range and by the generation of nonlinearities due to the relativistic character of the electron motion.

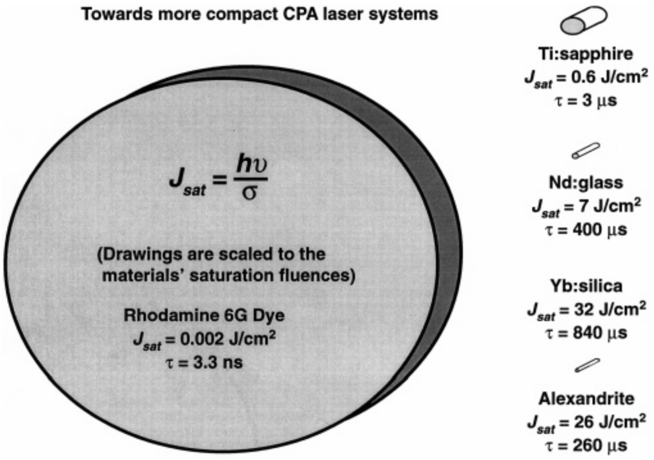

Fig. 1. Representation to scale of different amplifying media, for a given stored energy. Besides the vast differences in size, note the large differences in storage time τ. For instance, the large τ of Yb:silica makes it pumpable by inexpensive, free-running laser diodes

With some refinements in the stretching and compression scheme, we will soon be capable of amplifying these short pulses up to their theoretical peak power limit [3]. For superior energy-storage media, such as Yb:glass or alexandrite, this limit, as indicated in Fig. 3, is at the petawatt level for a beam cross section of 1 cm^2 (tabletop). The diffraction-limited, focused intensity corresponding to this limit is of the order of 10^{23} W/cm^2.

The CPA technique has been demonstrated with a variety of systems, from the small-size, doped-fiber amplifier system delivering microjoules [4] to building-size systems such as the ones existing at Limeil, France [5], at the Rutherford-Appleton Laboratory [6], or at the Fusion Facility at Osaka [7], delivering pulses with energy of 100 to 1000 J. It is at Lawrence Livermore National Laboratory (LLNL) that the record power, exceeding a petawatt, was demonstrated [8]. The technique has been demonstrated with a variety of materials – first with Nd:glass [1, 2] then alexandrite [9],

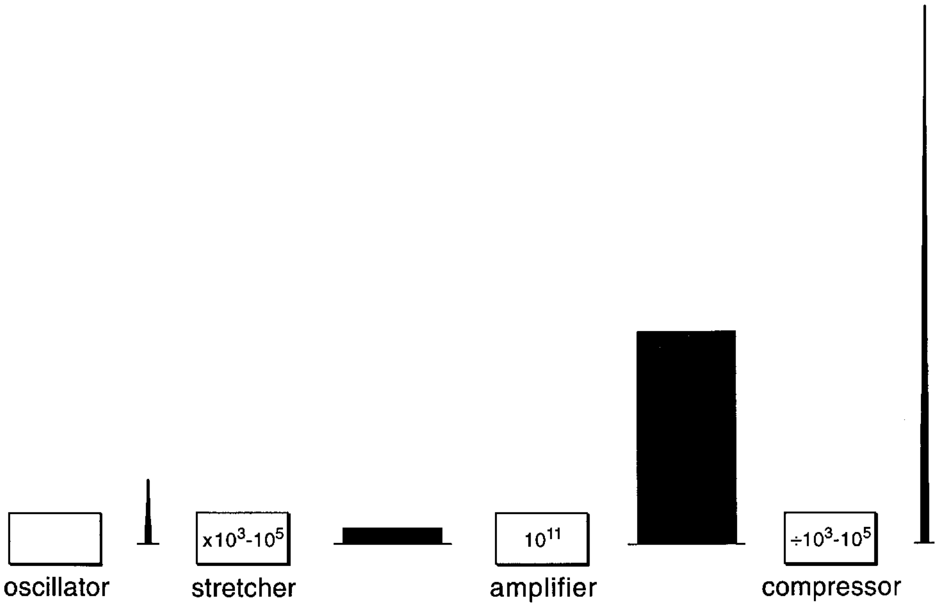

Fig. 2. Chirped-pulse amplification concept, showing the extensive pulse manipulation – stretching 10^4 times, amplification 10^{11}, and recompression by 10^4

Ti:sapphire [10, 12] Cr:LiSAF [13], or a combination [14]. Because of their small size, CPA terawatt systems have an average power and repetition rate 10 to 100 times greater than dye or excimer femtosecond systems and their energies can be concentrated over a diffraction-limited spot. This is not generally the case for large-scale lasers with a spot size several times the diffraction limit. Figure 4 illustrates the evolution of the peak intensity (W/cm^2) as a function of years, along with the different laser techniques.

CPA-type lasers have begun to have a profound impact in laser–matter interaction. This has dramatically extended the field of optical science. But perhaps its most important virtue has been to bring back to universities a science that had only been possible in large facilities.

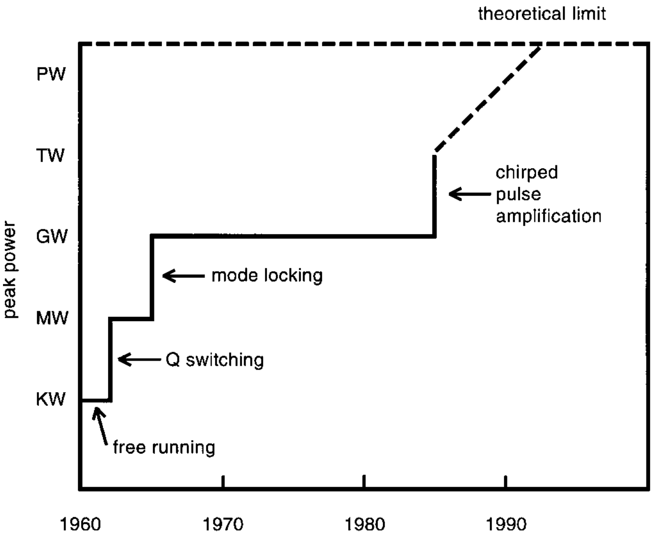

Fig. 3. Peak power versus years, showing the different laser techniques that led to increased power

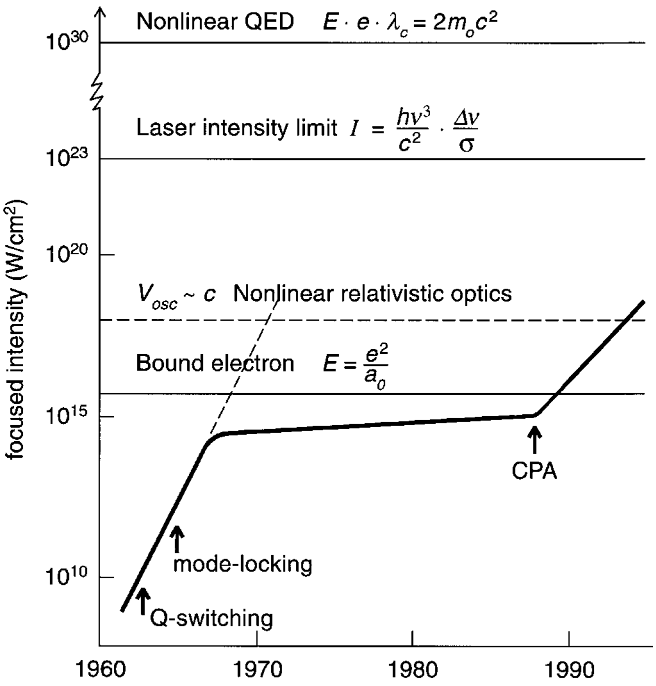

Fig. 4. Laser-focused intensity versus years

1 The chirped pulse amplification technique: cheating mother nature by 10^4 times

Within the five years that followed the inception of lasers in 1960, laser peak power increased rapidly from the kilowatt to the gigawatt by steps of three orders of magnitude (Fig. 3). These steps resulted because the stored energy in the amplifying medium could be released in a shorter and shorter pulse duration: microseconds for the free-running [15], nanoseconds for the Q-switched (QS) [16], and picoseconds for the mode-locked (ML) laser [17]. Once the intensities reached gigawatt power per cm^2 of beam, they could not be increased further because of nonlinear effects, such as an intensity-dependent index of refraction, $n = n_0 + n_2 I$ (n_0 is the index of refraction, n_2 is the nonlinear index of refraction, and I is the intensity), in laser components such as Pockels cells and amplifiers, windows, etc. This nonlinear effect leads mainly to wave-front deterioration [18] and small-scale self-focusing [19] leading to beam filamentation and irreversible damage. It impels the laser amplifier to be run at intensities less than a $\mathrm{GW/cm^2}$. Conflicting with this condition is the requirement that for efficient energy extraction, the input pulse energy per unit area (fluence), F_{in} ($\mathrm{J/cm^2}$) has to be as high as possible and of the order of the saturation fluence. This condition leads to an input intensity condition of the order of $F_{\mathrm{s}}/T_{\mathrm{p}}$, where T_{p} is the pulse duration and F_{s} the saturation fluence. $F_{\mathrm{s}} = h\nu/\sigma$, where h is the Planck constant, ν the transition frequency, and σ the emission cross section. The last condition says that for short T_{p} in the picosecond–femtosecond range, only inferior (small F_{s}, i.e., $\mathrm{mJ/cm^2}$) energy-storage materials, such as dyes and excimers, are acceptable. It excludes excellent energy storage media with large F_{s} in the $\mathrm{J/cm^2}$ range, which would require totally unacceptable input intensities in the $10\text{-}\mathrm{TW/cm^2}$ range for picosecond pulses, i.e., 10^3 to 10^4 times larger than the onset of nonlinear effects.

We showed that we could circumvent these seemingly unreconcilable conditions – the simultaneous need for high input energy and low input intensity – by, prior to amplification, stretching the short pulse. In doing that, we could lower the intensity by a factor equal to the inverse of the stretching ratio, without changing the input fluence necessary to efficient energy extraction. After being stretched, the pulse can be amplified safely in a high-energy-storage amplifying medium. Once the amplifier energy is efficiently extracted, the stretched pulse is recompressed, ideally close to its initial value.

We realized after the fact that this CPA technique, like most of the laser techniques – Q-switching, mode-locking, and the laser itself – was a transposition in the optical domain of the technique of chirped radar in the microwave regime. Researchers in radar also faced the same dilemma of reconciling the need for large pulse energy for long distance ranging with the short pulses required for ranging accuracy. The main difference is that they do not recompress the chirped pulse after amplification but recompress the echo, instead, avoiding the nonlinear propagation effect in the atmosphere. Chirped radar uses an impressive stretching/compression ratio of 200 000. The complete analog of chirped radar in optics was demonstrated by A. Braun et al. [20], when they showed that via the recompression of the echo, optical ranging could be increased a thousand times with submillimeter accuracy retained.

Today the optical manipulations involved in CPA are almost as spectacular as the one in radar and show how robust and general is this concept. Maybe the most sophisticated one has been demonstrated by Barty et al. [21] and Chambaret et al. [22] The initial pulse is as short as 10 fs with subnanojoule energy. It is stretched almost 10^5 times and amplified by a factor up to 10^{11} to the joule level, then recompressed by 10^3 to 10^5 close to the initial pulse duration. The main difference with chirped radar, chiefly concerned with energy and pulse duration, is that laser–matter interaction at ultrahigh intensity demands that the pulse be of extraordinary quality in both the spatial and the temporal domains – that is, clean over 8 to 10 orders of magnitude and with a wave front better than $\lambda/10$. Any prepulses will create a preformed plasma, so the laser will interact with the target in an unknown state. The generation of this "perfect" pulse could only be accomplished with the invention of the conjugated stretcher-compressor-amplifier system [23].

2 Conjugate stretching compression: the key to efficient and perfect CPA systems

It is essential in CPA to use a large stretching-to-compression ratio for efficient extraction. The larger the ratio, the better the energy storage materials we can use, leading to more compact systems for the same peak power. To reach this goal, we must fulfill the condition that the sum of the phase functions of the stretcher, amplifier, and compressor be equal to zero over the entire frequency range of the amplified pulse. The first CPA system used fiber for stretching – using the positive group velocity dispersion of the fiber at 1.06 mm – and gratings for compression, as demonstrated by B. Treacy [24]. In this embodiment, the stretcher and compressor were matched over a very limited spectral range (10 Å) leading to a stretching-to-compression ratio of only 100. The real breakthrough was the discovery of the matched stretcher-compressor demonstrated in 1987 [23]. In this configuration the stretcher, originally proposed for optical communications by O. Martinez [25] as a compressor for pulses with a negative chirp, is composed of a telescope with a magnification of 1 between a pair of antiparallel gratings. Pessot et al. [23] showed that this "compressor", used as a stretcher, not only exhibited positive group velocity dispersion but also was matched over all orders with the standard Treacy compressor made of two parallel gratings, and consequently it could be used to amplify femtosecond pulses. This grating-based stretcher-compressor today constitutes the basic architecture of all high-peak-power laser systems.

For ultrashort pulses, the phase conjugation among stretcher, amplifier, and compressor has to be accomplished exactly. The simplest approach, taken by Kapteyn et al., minimizes the stretching ratio by keeping the amount of material in the amplifier to a minimum. They succeeded in amplifying 30 fs to the multiterawatt level [26]. A different system, championed by Barty et al. [27], involves low grooves-per-mm gratings, a cylindrical mirror, etc., and a careful positioning of all the components. This system has produced sub-20-fs, 50-TW pulses. Finally, Chambaret et al. [22], first, and S. Watanabe [28] demonstrated an aberration-free stretcher of Offner type and have clearly shown [22] the importance of the surface quality of optics in the generation of high-quality pulses. They produced pulses at the 30-TW level with 30-fs duration.

3 How high can we go? Toward the theoretical peak-power and intensity limits

After the dramatic increase obtained recently in peak power, the logical question that we need to answer is how high can we go? This question can be answered quite simply by saying that the maximum energy that can be extracted from an

Table 1. Theoretical peak power per cm^2 of Beam (in the amplifying medium)

Laser type	Cross section $/1 \times 10^{-20}$ cm^2	$\Delta\nu$ /nm	T_p /fs	P_{th} /TWcm^{-2}	Storage Time: τ /µs
Nd:glass phosphate	4	22	80	60	300
Nd:glass silicate	2.3	28	60	100	300
Ti:sapphire	30	120	~ 8	120	3
Alexandrite	1	100	10	2000	200
Cr:LiSAF	3	50	15	300	70
Yb:silica	0.5	200	8	3000	800

amplifier, is of the order of the saturation fluence, $F_s = h\nu/\sigma$, and the shortest pulse duration T_p, is limited by the gain bandwidth of the amplifying medium, $\Delta\nu$. The theoretical peak power per cm2 of beam is therefore given simply by $P_{th} = h\nu\,\Delta\nu/\sigma$. It is worth noting that this intensity corresponds to the Rabi intensity of a p pulse, necessary to flip the population of the excited state during the dephasing time of the material. The maximum focusable intensity will then be $I_{th} = h\nu^3\Delta\nu/c^2\sigma$. The highest peak power will therefore be obtained with the smallest transition cross section and the largest bandwidth amplifying materials (see Table 1). P_{th} varies from 60 TW for Ti:sapphire to 3000 TW for Yb:glass. By using Yb:glass, a material that can be obtained in large dimensions, a system with a beam size of 10 cm by 10 cm could produce peak power of 0.5 EW (an exawatt is 10^{18} W). This power, focused over a diffraction-limited spot size of 1 mm^2, could produce on-target intensities in the 10^{25} /cm^2 range. From Table 1 we can see that the storage time (fluorescent lifetime) varies over many orders of magnitude. Because of their very large storage time, Nd:glass and Yb:glass are good candidates for diode pumping.

4 Average power and pulse shaping of the CPA systems

The largest average power is necessary for most applications in order to increase the signal-to-noise ratio. CPA systems have not only increased the peak power of lasers by three to four orders of magnitude, but have also contributed to improving the average power of femtosecond systems by at least two orders of magnitude. This is largely due to the small dimensions of the laser amplifier and, in the case of Ti:sapphire, to the excellent heat conduction. With previous femtosecond systems, based on dyes or excimers, the average power was typically around 10 mW. With CPA Ti:sapphire systems, the average power was raised to 1 W [10]. This power has since been increased to the 5-W level [29] by cooling the Ti:sapphire material to liquid-nitrogen temperature. At this temperature the heat conduction becomes exceptionally high and equivalent to that of copper [30]. In the future, with the use of materials with small quantum defects between the absorption and the emission wavelengths, such as Yb:glass, pumped by laser diodes, and with rotation of the laser medium [31], the average powers of petawatt systems could reach the kilowatt level.

Finally, one of the interesting features of CPA is the possibility of performing pulse shaping. In the pulse stretcher, all of the frequency components are spatially spread so it is easy, by using a simple phase and/or amplitude mask in the Fourier plane, to spatially filter some frequency components [32, 33] and to obtain, after pulse compression, a pulse with a prescribed shape. Pulse shaping is important in the area of coherent control and, as we will show later, to drive a wake field efficiently.

5 Laser-matter interaction at ultrahigh intensities

Figure 4 shows the achievable focused intensities over the years and the rapid progress that we have had and are experiencing at this moment, due to the combination of ultrashort pulse generation and our ability to amplify pulses using chirped pulse amplification. Very much as with nonlinear optics in the early 1960s, new scientific thresholds are being crossed. At intensities greater than 10^{15} W/cm^2, we leave the regime of nonlinear optics of the bound electrons to penetrate into new physical territories characterized by electric fields much larger than the coulombic field. Under these conditions, the electron quiver velocity is close to the speed of light, producing large light pressures and, due to the short duration, no hydrodynamic motion. These fundamentally new features open up a new regime in laser–matter interaction. We will review them by giving some examples of the new physics and applications that become accessible: high harmonic generation, ultra-accurate micromachining and surgery, nonlinear relativistic effects, laser acceleration, thermonuclear ignition, and nonlinear QED.

6 10^{14} W/ cm^2 nonlinear optics of the bound electron – multiphoton effects and optical breakdown

In this regime of intensities we differentiate the collisionless regime occurring in gases and the highly collisional regime occurring in solids, in particular during the dielectric breakdown of material preceding laser damage. The collisionless regime has been extremely active over the past 15 years. The main physical effects are known as multiphoton absorption [34–36] above-threshold ionization [37–44], and high harmonic generation [45]. The latter has a real practical application with its possibility of providing the short, xuv, coherent pulses important for time-resolved spectroscopy in this spectral range. By shortening the pulse duration to minimize ionization and increase the intensity, very high harmonics have been produced [46–48] reaching the water window. The collisional regime, leading to optical breakdown [49], has been much less studied in the picosecond–femtosecond time scale, but it has important technological consequences. In transparent solids, at these intensities the material is first transformed into an absorbing plasma. The subsequent absorption by the plasma causes heating, leading to irreversible damage. The electron generation process in solids is very different from the one in gases. For long pulses, electron generation is strictly dominated by avalanche. The initial electrons seeding the avalanche come from metallic or thermal ionization of shallow energy impurities. Between collisions the seed electrons are accelerated enough for their kinetic energy to exceed the ionization potential of the bound electrons, resulting in two free electrons. The process is called impact ionization; it repeats itself, leading to an avalanche. Via this mechanism, a plasma with a density greater than $10^{18}\,\mathrm{cm}^{-3}$ will be produced. At this density the laser light will be significantly absorbed to produce melting, vaporization, and physical damage.

For ultrashort pulses, the bound electrons can be directly ionized through multiphoton absorption. Because it is an m-th-order process, its cross section is very small. Therefore, only for very short pulses will this process play a determinant role. For long pulses, for which the avalanche is seeded by the impurities, the damage threshold will depend strongly on the spatial distribution of the impurities and will be subject to statistical fluctuations. For short pulses, the avalanche is not seeded by free electrons from impurities but by multiphoton ionization, which is a deterministic process. This difference in the seeding mechanisms is one of the causes of the deterministic character of the damage threshold for short pulses as opposed to the statistical one for long pulses, the second cause being the saturation of the impact ionization coefficient as a function of the electric field [50]. Recently, the breakdown threshold as a function of the pulse duration has been investigated [50, 51] and has shown that the damage fluence deviates from the traditional square root of the pulse width. More importantly, the large statistical variation for long pulses is not present for short pulses. The deterministic character of the ultrashort pulses means that ablation with a feature size smaller than the wavelength [52] can be produced with a completely new set of applications for short pulses, in micromachining, high-density data storage [54], and eye surgery [55].

7 10^{18} W/ cm^2: the nonlinear relativistic regime

7.1 Interaction with solids

In this regime, light–matter interaction is dominated by the relativistic quiver motion of the electrons, which translates into large light pressure. In laser-matter interaction with long pulses, the plasma produced during the interaction has a thermal pressure that is always greater than the light pressure. This is no longer true for short pulses, where the light pressure associated with their intensity can easily be in the gigabar range, surpass the thermal pressure, and modify the critical surface. This effect was first observed by Liu and Umstadter [56]. These authors were able to time resolve the effect of the light pressure on the critical surface. This large light pressure was conveniently used by Kieffer et al. [57] to produce solid-density plasma of $4 \times 10^{23}\,\mathrm{cm}^{-3}$. The high temperature and high density allows an ultrashort X-ray source in the keV range to be produced in this way. The high densities were obtained when excellent contrast pulses were used to eliminate prepulses that can cause a plasma before the main pulse is turned on. A pulse duration of 300 fs has been demonstrated and used in a time-resolved EXAFS experiment [58]. Recently, experiments at higher intensities have revealed even higher densities.

The ultrahigh light pressures that can be produced by these pulses are at the crux of the so-called fast ignition concept [59], which decouples compression from ignition of the D-T target. First the D-T fuel is assembled (by compression) by the long nanosecond pulse. At the point of maximum compression, the ultrashort pulse interacts with the target and an injected beam of high-energy electrons that deposit by collision their energy in the center of the target, igniting the thermonuclear reaction. A CPA laser delivering 1 kJ of energy in 1 ps (PW) has been built at LLNL to validate the fast ignitor concept.

7.2 Laser-matter interaction in gases

The focusing of pulses with an intensity of $10^{18}\,\mathrm{W/cm}^2$ and above in a subcritical-density plasma drives the free electrons relativistically. Their quiver velocity is expressed by $\gamma = (1 + a^2)^{1/2}$, where γ is the relativistic factor associated with the transverse motion of the electrons and $a = \gamma v_{\mathrm{osc}}/c$ is the normalized vector potential, equal also to $eE/m_0\omega c$. As a result of the beam spatial intensity distribution, the electrons will experience a mass change according to their radial position. The mass change will translate into a modification of the index of refraction, $n = [1 - (\omega_{\mathrm{p}}/w)^2]^{1/2}$, where $\omega_{\mathrm{p}} = (4\pi n_{\mathrm{e}} e^2/\gamma m_0)^{1/2}$ is the plasma frequency. We see that in the high-intensity part of the beam, the index of refraction will be higher, because of the higher electron mass, and the plasma frequency lower. This index change, in space and in time, will translate into a self-focusing [60] and self-phase-modulation [60] effect, analogous to the self-focusing, self-phase-modulation well known in “classical” nonlinear optics. This relativistic self-focusing is expected to occur at $P_{\mathrm{c}} = 17\left(\omega/\omega_{\mathrm{p}}\right)^2$ and has been observed by a number of groups [61], as have indications of relativistic self-phase-modulation [62]. The self-focusing will increase the energy in the channel to a new level of intensity, i.e., $10^{20}\,\mathrm{W/cm}^2$. It is expected that at this intensity level, the very large transverse intensity gradient will push the electrons outside the channel, to create an evacuated intensity channel in a process called cavitation [63].

The laser pressure, combined with ion inertia, can provide an electrostatic restoring force that can drive a high-amplitude electron plasma wave (EPA). By this process some of the laser energy is converted to a longitudinal electrostatic wake field traveling nearly at the speed of light, which can continuously accelerate the electrons [64–66] in the direction of the laser beam to GeV in a distance as short as a centimeter. That is 10^4 times larger than some of the highest field gradients produced by conventional means. Thus laser wake fields, combined with the significant reduction in the laser size obtained with CPA, could dramatically reduce the size of electron accelerators. It is worth noting that this potential reduction by a factor of 10^4 is the same as that obtained in lasers with CPA technology. Terawatt lasers used to be as large as a building; today they fit on a tabletop. To help appreciate this factor of 10^4, let us recall that it is the same factor as the one between a vacuum lamp and a CMOS in an integrated circuit.

The generation of a large electrostatic wave amplitude was inferred from the presence of high-order satellites in the Raman forward scattering and by accelerated electrons from the self-modulated wake field [67, 68]. The self-modulated

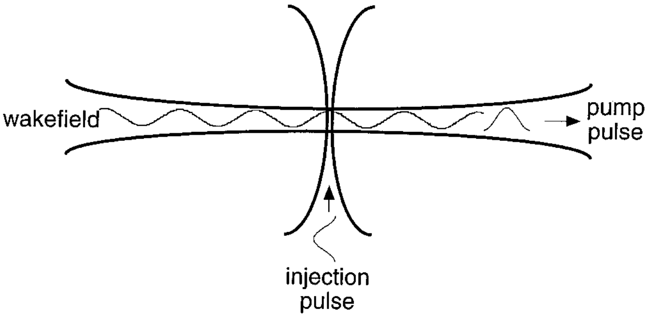

Fig. 5. The LILAC (laser injected laser accelerator) is an all-optical injection technique. First, a pump beam creates acceleration buckets traveling close to *c*. An auxiliary probe beam, by ponderomotive force, dephases some of the electrons that will be trapped in the accelerating bucket

regime [69] is the one where the plasma wavelength is shorter than the pulse duration, as opposed to the conventional wake field where the plasma period is longer than the pulse duration. Shortly after this, Umstadter et al. [70] demonstrated that the accelerated electrons were in fact coming out in a collimated beam with a transverse emittance and number of electrons ($> 0.5\,\text{nC}$) comparable with the best photoinjector.

They also showed that the accelerated electrons were exhibiting a very sharp threshold precisely at the critical power, P_c , for relativistic self-focusing. It might be surprising to see such a good emittance coming from such an unsophisticated system. This can be explained by the very large gradient, $> 100\,\text{GeV/m}$, experienced by the electrons. With this gradient, the electrons are quickly accelerated over a fraction of a millimeter to relativistic velocities before they have the time to be broadened by coulombic repulsion. Recall that the effect of Coulomb broadening in the relativistic regime follows $1/\gamma^2$. So the technique of laser wake-field acceleration has the additional advantage of producing electron pulses with a time structure in the femtosecond time scale. A refinement of this technique is currently being tested, in which the injection into the plasma wave, acting as an accelerating bucket, is achieved by an auxiliary pulse perpendicular to the main beam (see Fig. 5) [71]. This technique, called LILAC (laser-injected laser accelerator), has generated an enormous amount of interest in the scientific community because of its potential to revolutionize electron-beam technology.

8 Nonlinear Quantum Electronics

The possibility of creating electron–positron pairs from the laser field was proposed in the late 1960s [72]. As seen in Fig. 4, pair creation directly from the laser will require an intensity of the order of $10^{30}\,\text{W/cm}^2$. It is the energy required over the Compton wavelength, $\lambda_\text{c} = h/m_0c$, that it will take to create an electron–positron pair. The field is therefore equal to $E = 2m_0c^2/e\lambda_\text{c}$ and corresponds to $10^{16}\,\text{V/cm}$, which is about four to five orders of magnitude above the laser field of today´s laser. This enormous gap was bridged by using the electric field enhancement produced in the frame of superrelativistic electrons. With the 50-GeV electron beam at the Stanford linear accelerator, corresponding to a γ of 10^5, and a currently available high-power laser, the field is enhanced to $E \sim 10^{16}\,\text{V/cm}$, exceeding the critical field. The multiphoton pair production, $\omega_\gamma + n\omega_0 \rightarrow e^+ + e^-$, has been observed [73]. The same group is studying nonlinear Compton scattering, $e + n\omega_0 \rightarrow e' + \omega_\gamma$. In this case, the high-energy γ ray produced in the laser focus by an incident electron interacts before leaving the focal region. Processes up to $n = 4$ have been observed.

The linear Thomson scattering of optical light from an energetic electron beam will also upshift the frequency of the laser light by a factor of $2\gamma^2$. This has been used as an electron beam diagnostic for many years with long laser pulses, but in the current experiments by Kim et al. [74] and Leemans et al. [75], an ultrashort (200-fs) pulse is being scattered from a 50-MeV beam at the Lawrence Berkeley Laboratory, in which case an X-ray (0.4-Å) pulse of similar duration is produced.

9 Conclusion

Our ability to amplify pulses to extreme levels has opened the door to fundamentally new opportunities in science and technology. We are penetrating optics in the relativistic regime, with important applications in thermonuclear ignition or in the generation of high-energy photons (X-ray) or particles. In technology, unpredicted applications have arisen; in medicine, for instance, eye surgery without collateral damage is now possible. Amplificated pulses provide a new way to increase data storage and to perform micromachining. But maybe the most important attribute of the compact, ultrahigh-peak-power laser is that it brings some of the “big science” back to university laboratories.

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