ULTRAHIGH-INTENSITY LASERS: PHYSICS OF THE EXTREME ON A TABLETOP

By stretching, amplifying and then compressing laser pulses, one can reach petawatt powers, gigagauss magnetic fields, terabar light pressures and 10^{22} m/s^2 electron accelerations.

Gérard A. Mourou, Christopher P. J. Barty and Michael D. Perry

Over the past ten years, laser intensities have increased by more than four orders of magnitude[1] to reach enormous intensities of 10^{20} W/cm^2. The field strength at these intensities is on the order of a teravolt per centimeter, or a hundred times the Coulombic field binding the ground state electron in the hydrogen atom. The electrons driven by such a field are relativistic, with an oscillatory energy of 10 MeV. At these intensities, the light pressure, $P = I/c$, is extreme, on the order of giga- to terabars. The laser interacting with matter—solid, gas, plasma—generates high-order harmonics of the incident beam up to the 3 nm wavelength range, energetic ions or electrons with mega-electron-volt energies (figure 1), gigagauss magnetic fields and violent accelerations of 10^{21} g (g is Earth's gravity). Finally, the interaction of an ultraintense beam with superrelativistic particles can produce fields approaching the critical field in which an electron gains in one Compton wavelength an energy equal to twice its rest mass. Under these conditions, one observes nonlinear quantum electrodynamical effects. In many ways, this physical environment of extreme electric fields, magnetic fields, pressure, temperature and acceleration can be found only in stellar interiors or close to the horizon of a black hole. It is fascinating to think that an astrophysical environment governed by hydrodynamics, radiation transport and gravitational interaction can be re-created in university laboratories for extremely short times, switching the role of the scientist from voyeur to actor.

What is spectacular is that the laser involved is extremely compact—it fits on a tabletop—and relatively inexpensive—costs run around \$500 000. It can deliver high average power and be built and operated by students. It can be installed near very large instruments such as synchrotrons: at the Advanced Light Source of Lawrence Berkeley National Laboratory or at the European Synchrotron Research Facility in Grenoble, France, to conduct time-resolved x-ray experiments in the femtosecond range, or at the Stanford Linear Accelerator Center (SLAC) to test nonlinear quantum electrodynamics by the interaction of the high-intensity pulses with super-relativistic electrons.

Some of the new tabletop-laser principles have been implemented on existing large laser systems built for laser fusion. Lawrence Livermore National Laboratory, Los Alamos National Laboratory, the Commissariat à l'Energie Atomique (CEA) in Paris, the Rutherford Appleton Laboratory in the UK and the Institute of Laser Engineering in Osaka, Japan, have all added subpicosecond pulse capabilities to their nanosecond lasers, pushing their peak power by three orders of magnitude from 1 terawatt to 100–1000 TW.

Figure 2 presents the focused intensity of lasers as a function of time. It shows a rapid increase in the early 1960s, followed by a long plateau at 10^{15} W/cm^2. It took about 20 years, until 1987, for laser power to increase again. Note also the similarity in slopes between the early 1960s and the past ten years, and remember that it was during that period of very rapid increase in intensities in the 1960s that most of the nonlinear optics phenomena were discovered. In a similar way, the spectacular increase in intensity of four to five orders of magnitude that have occurred in the past decade should lead to exceptional discoveries.

Finally, from an educational point of view, these compact lasers offer the advantage of bringing some of the research traditionally done on large instruments to human-size setups in university laboratories. Their small scale and large numbers should greatly foster multidisciplinary work and attract students to scientific disciplines.

Evolution of laser peak power

Since their inception in 1960, lasers have evolved in peak power by a succession of leaps, each three orders of magnitude. These advances were produced each time by decreasing the pulse duration accordingly. First the lasers were free running, with durations in the 10 μs range and peak powers in the kilowatt range. In 1962, modulation of the laser cavity quality factor enabled the same energy to be released on a nanosecond time scale, a thousand times shorter, to produce pulses in the megawatt range. In 1964, locking the longitudinal modes of the laser (mode locking) enabled the laser pulse duration to be reduced by another factor of a thousand, down to the picosecond level, pushing the peak power a thousand times higher,

GÉRARD MOUROU *is the A. D. Moore Distinguished University Professor of Electrical Engineering and Computer Science and director of the NSF Center for Ultrafast Optical Science at the University of Michigan in Ann Arbor.* CHRISTOPHER BARTY *is director of ultrafast science at the Institute for Nonlinear Science at the University of California, San Diego.* MICHAEL PERRY *is associate program leader of the laser science and technology group at Lawrence Livermore National Laboratory in Livermore, California.*

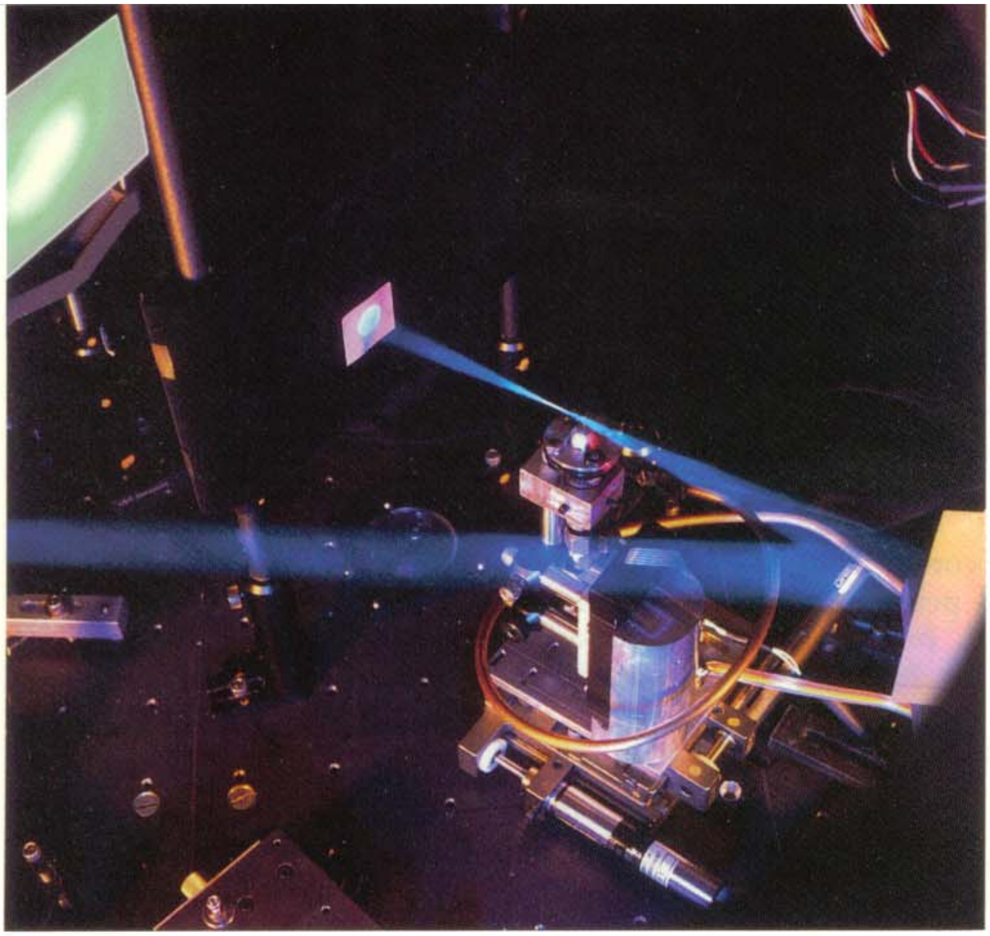


FIGURE 1. ULTRAINTENSE PULSE of laser light comes to a focus, where it interacts with a 1 mm wide jet of helium gas propagating upward, producing a high-energy, collimated beam of electrons with energies up to 50 MeV. The electrons light up the phosphor screen at the upper left. Aluminum foil, which appears pink in this photo, blocks the laser light.

to the gigawatt level.

At that point, the intensities associated with the ultrashort pulses were becoming prohibitively high. At intensities of gigawatts per square centimeter, the material index of refraction becomes linearly dependent on the intensity, varying like $n = n_0 + n_2 I$, where n is the index of refraction, n_0 the index of refraction at low intensity, n_2 the nonlinear index of refraction and I the intensity. The result is that, for a beam with a Gaussian radial intensity distribution, the center of the beam sees a larger index of refraction than its sides. The optical elements inside the cavity thus become positive lenses that unacceptably deform the beam's wavefront quality. Consequently, the only way to increase the peak power was to increase the diameter of the beam at the expense of instrument size, repetition rate and cost.

Although the pulse duration kept decreasing steadily, the intensity-dependent nonlinear effects kept the peak power about constant at the gigawatt level for a square-centimeter beam until 1985–87, when the technique of chirped pulse amplification was demonstrated (figure 2).[2] In CPA, the ultrashort pulse is not amplified directly, but is first stretched and then amplified, before finally being recompressed. CPA reconciles two apparently conflicting needs: to have the highest fluence for efficient energy extraction, and to have minimum intensity to avoid the undesired nonlinear effects.

CPA had a dramatic impact in short-pulse amplification. First, one could for the first time use superior (by a factor of 1000) energy storage media such as neodymium:glass, alexandrite, titanium:sapphire and chromium:$LiSrAlF_6$ instead of dye and excimer. So a CPA laser system, using these good energy storage media, could produce peak power 10^3–10^4 times higher than could dye or excimer systems of equivalent size. Second, CPA could be easily adapted for use with very large scale, expensive lasers already built for laser fusion. By simple beam manipulations, a stretching at the beginning and a compression at the end of the amplifying chain, laser fusion systems built to amplify nanosecond pulses to the terawatt level could be converted to amplify subpicosecond pulses to produce petawatt pulses.

This dramatic reduction in size, by three-to-four orders of magnitude for the same peak power, is similar to the one that occurred in electronics in 1960, when circuits went from discrete (millimeter) to integrated (micrometer). And it is similar to the size reduction brought about by the advent of laser diodes, whereby meter-sized lasers became miniaturized to millimeter-sized lasers. As in electronics, this reduction also led to advances in speed, efficiency, reliability and cost.

Chirped pulse amplification

CPA (figure 3a) involves impressive manipulations:

Metric prefixes

milli	10^{-3}	kilo	10^{3}
micro	10^{-6}	mega	10^{6}
nano	10^{-9}	giga	10^{9}
pico	10^{-12}	tera	10^{12}
femto	10^{-15}	peta	10^{15}
atto	10^{-18}	exa	10^{18}
zepto	10^{-21}	zetta	10^{21}
yocto	10^{-24}	yotta	10^{24}

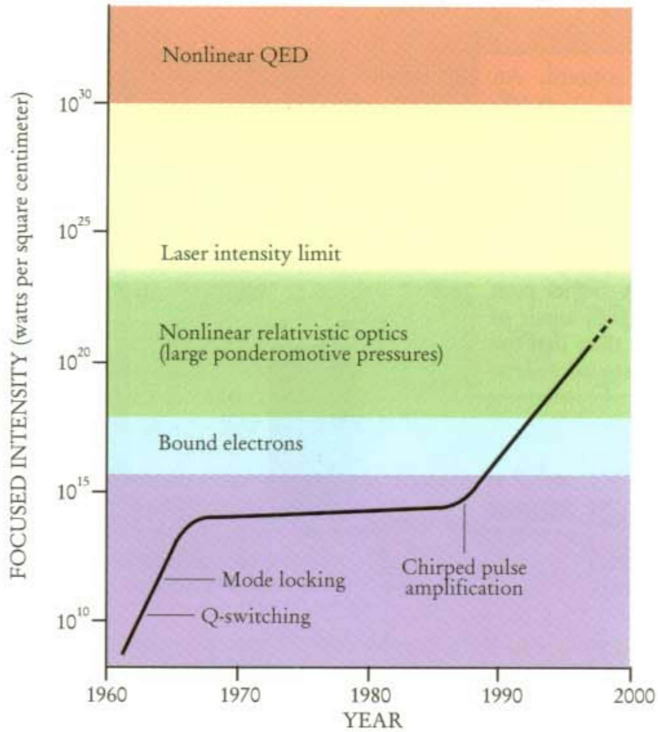


FIGURE 2. LASER INTENSITY versus year for tabletop systems, showing various physical thresholds. After an initial increase in the 1960s, the intensity plateaued for about 20 years, due to limitations caused by nonlinear effects. Over the past decade the intensity has been increasing with a slope similar to that of the 1960s, crossing into fundamentally new physical regimes. The laser intensity limit is the maximum possible stored energy (that of a complete population inversion) divided by the minimum possible pulse duration (the reciprocal of the gain bandwidth), for a beam of 1 cm^2 cross section. Note that lasers cannot reach the regime of nonlinear quantum electrodynamics.

stretching by 10^3–10^5, amplification by 10^{11} (from nanojoules to tens of joules) and recompression by 10^3–10^5. Because we want the highest intensities on target, it is important that these manipulations be performed with the highest degree of fidelity, so that the pulse possesses the highest temporal contrast and the beam is diffraction limited. To reach this goal, two main hurdles had to be overcome: the accommodation of the large stretching/compression ratio, and the amplification of large pulse spectra.

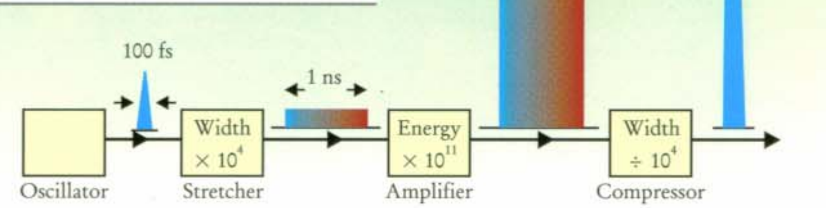
How can one stretch and compress a short pulse over so many orders of magnitude with impunity and fidelity? The ability to do so came with the discovery of the matched stretcher and compressor. The first CPA system used the positive group velocity dispersion (in which the red wavelength goes faster than the blue) of a single-mode fiber to temporally spread the frequency components of the ultrashort pulses.[2] After passing through the fiber, the pulse is stretched with the red component first, followed by the blue. It is then amplified to the desired level and recompressed by a pair of parallel diffraction gratings. As demonstrated by Brian Treacy of United Aircraft Research Laboratories, a grating pair exhibits a negative group velocity dispersion (blue goes faster than red). (See the bottom part of figure 3b.) However, the fiber stretcher and diffraction grating compressor did not have their dispersive characteristics exactly matched, so the recompression was not perfect, leading to temporal wings in the pulse, and hence limiting the stretching/compression ratio to about 100.

In 1987, we became aware of a "compressor" designed by Oscar Martinez at the University of Buenos Aires for optical communication, to compress pulses at a 1500 nm wavelength.[3] (See the top part of figure 3b.) In this spectral domain, light in optical fibers experiences a negative group velocity dispersion. The proposed dispersive system was a telescope of magnification 1 placed between two antiparallel gratings. A close look at this device convinced us that it had the exact same dispersive function as the Treacy compressor, but with the opposite sign. In other words, it was the Treacy compressor's perfect conjugate—with the important consequence that any arbitrary short pulse in theory could be stretched to any pulse duration and then recompressed to its original shape. We immediately demonstrated a stretching factor of 10^3–10^4 with a Nd:glass system, to produce the first tabletop terawatt laser system.[2] With the discovery of the matched stretcher–compressor, a very high hurdle was cleared. The amplification of pulses at the 10 fs level can require stretching up to 10^5. In this case, as shown by Christopher Barty, it is necessary to design the expander to match the compressor and all the dispersive elements in the laser—the gain medium, mirrors and other optical elements.[4] The other alternative, used by Henry Kapteyn and his coworkers at Washington State University, is to use very short length amplifying media to minimize the stretching/compression ratio.[4] After compression, it is imperative that the pulse at the several-terawatt level propagate in a vacuum to avoid wavefront distortion and filamentation due to air's nonlinear index of refraction.

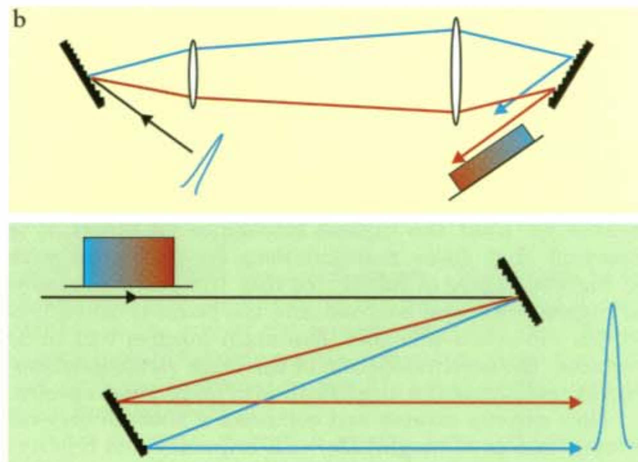
Ultrashort pulses have enormous spectra. From the uncertainty principle, a pulse with a Gaussian envelope will have a minimum-duration-bandwidth product $\Delta\nu{\cdot}\tau$ of 0.4, where $\Delta\nu$ is the pulse bandwidth and τ is the pulse duration (full width at half maximum). A 10 fs pulse will have a bandwidth of 80 nm. All the spectral components must be amplified equally over many orders of magnitude at the risk of narrowing the pulse's bandwidth and lengthening its duration after compression. For ultrashort pulses, this limitation was removed with the invention by Peter F. Moulton at Lincoln Laboratory of ultrabroadband amplification media such as Ti:sapphire.[1] Ti:sapphire has a gain bandwidth that can theoretically support the amplification of pulses of less than 5 fs in duration. It was first used in high-peak-power systems by Jeffrey Kmetec, John J. Macklin and James F. Young at Stanford and by Roger Falcone's group at Berkeley.[1] It has excellent thermal properties, making amplification at a high repetition rate, 10–1000 Hz, possible—an improvement of two-to-three orders of magnitude over systems based on dye or excimer. A higher repetition rate at constant peak power leads directly to higher experimental utility. With 10–1000 Hz Ti:sapphire CPA systems, it is possible to apply signal-averaging techniques to investigations of interactions between high-field lasers and matter. This capability is used fully in experiments involving low signal-to-noise ratios, where signal averaging is necessary.

a

FIGURE 3. CHIRPED PULSE AMPLIFICATION. **a:** The CPA concept. An oscillator produces a short pulse, which is then stretched by a factor of 10^3 to 10^5, from the femtosecond to the nanosecond regime, reducing its intensity accordingly. The intensity is now low enough that the pulse can be amplified and the stored energy can be safely extracted from the amplifier without fear of beam distortions and damage. After extraction, the pulse is recompressed, ideally to its initial width. **b:** The matched stretcher and compressor. The stretcher (top) is composed of a telescope of magnification 1 between two antiparallel diffraction gratings. Note that in this configuration the red wavelengths have a shorter path than the blue ones. Conversely, the compressor (bottom) is composed of a pair of parallel gratings in which the optical length for the blue is shorter than that for the red. The gratings are matched over all orders.



b



At the University of California, San Diego, a 50 TW, 20 fs Ti:sapphire amplification chain has been constructed (figure 4). Systems with similar characteristics have been built at the Ecole Nationale des Techniques Avancées in Palaiseau, France, the University of Tokyo and the Japan Atomic Energy Research Institute in Kansai. Extension of these concepts to higher peak power and higher repetition rate is straightforward and currently under development. In Japan, the Kansai group is designing and testing components for a petawatt (20 J, 20 fs) 1 Hz laser, which is scheduled for construction in 1999. At the University of Bordeaux and at the National Science Foundation's Center for Ultrafast Optical Science at the University of Michigan, funds have been allocated and designs completed for the construction of high-repetition-rate 1 kHz, 1 TW laser facilities.

Pulse generation and characterization

Ultrashort pulses as short as a few optical cycles have been available for ten years. However, what has made it possible to routinely generate pulses shorter than 10 fs was the outstanding discovery in 1991 by Wilson Sibbett of the University of St. Andrews, in Scotland, of Kerr lens mode locking,[5] together with the successive refinements made by Kapteyn's group at the University of Washington, Ferenc Krausz and his coworkers at the Vienna Technical University in Austria and Ursula Keller and her coworkers at the Technical University of Zürich.[6] Such systems will provide a robust source of short seed pulses at the nanojoule level for CPA systems.

The concept of generating ultrashort pulses by Kerr lens mode locking is simple and uses simultaneously Ti:sapphire's very large bandwidth and intensity-dependent index of refraction (described above). Figure 5a shows a simplified diagram of a laser cavity. The pulse is measured by doing an interferometric, second-order autocorrelation in a frequency-doubling crystal (figure 5b).

The Petawatt Project, intended to explore the feasibility of fast ignition for inertial confinement fusion, was carried out by Michael Perry's group at Lawrence Livermore.[7] It illustrates beautifully the adaptability of CPA. The researchers use a beam of the large NOVA system, a Nd:glass laser chain built to amplify nanosecond pulses to the kilojoule range. Although conceptually simple, the adaptation of CPA on this laser chain required the development of sophisticated new technology—in particular, very large diffraction gratings with a diameter of 75 cm, an efficiency greater than 90%, a flatness better than $\lambda/10$ and a good damage threshold. Thus, 1.3 kJ before compression could be extracted in 800 ps and compressed to a 430 fs pulse, producing 1.3 PW with an irradiance approaching 10^{21} W/cm^2—the highest peak power and irradiance ever produced.[7] The petawatt system has been operating with a 46 cm diameter beam and 75 cm grating. The large gratings forming the compressor were mounted in a vacuum chamber to avoid self-focusing in air. These gratings were increased to the full 94 cm size in October 1997, thereby allowing operation of the petawatt at 1 kJ after the compressor with a 58 cm diameter beam.

One can predict the ultimate peak power per square centimeter of beam that can be obtained for a given amplifying medium by using the following simple argument. The maximum energy that can be extracted from an amplifier is on the order of the saturation fluence, $F_s = h\nu/\sigma$, where σ is the transition cross section, h is the Planck constant and ν is the laser frequency. With the shortest pulse duration $\tau = 1/\Delta\nu$, where $\Delta\nu$ is the gain bandwidth, the maximum theoretical peak power per square centimeter of beam is therefore given simply by $P_{\rm th} = h\nu\Delta\nu/\sigma$. The maximum focusable intensity will then be equal to this power over a spot area, λ^2, limited by diffraction: $I_{\rm th} = h\nu^3\Delta\nu/(c^2\sigma)$. The highest intensity will

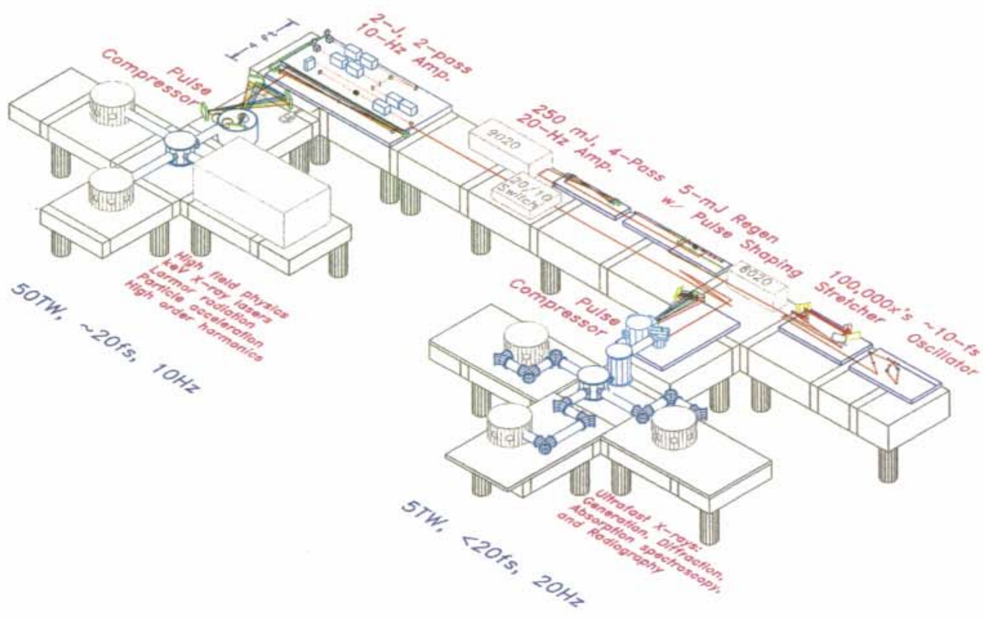


FIGURE 4. AMPLIFICATION CHAIN. The schematic represents a tabletop titanium:sapphire chirped pulse amplification system at the University of California, San Diego, that can produce 5 TW and 50 TW laser pulses.

therefore be produced by the amplifier with the smallest transition cross section and the largest bandwidth.

Here are some examples. P_{th} varies from 200 TW for Ti:sapphire to 3000 TW for ytterbium:glass. 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 0.3 exawatts. This power, focused over a diffraction-limited spot size of a few square micrometers, could produce on-target intensities in the 10^{24} W/cm^2 range!

Ultrahigh-intensity applications

Figure 2 shows laser intensities and the physical regimes that are becoming accessible. Given the large amount of activity in this field, here we only highlight the applications, focusing on intensities greater than 10^{18} W/cm^2, where phenomena are dominated by relativistic effects. Review articles by Chandrashekhar Joshi and Paul Corkum (PHYSICS TODAY, January 1995, page 36) and by Perry and Gérard Mourou[1] cover applications in the intensity range 10^{14}–10^{18} W/cm^2.

At intensities greater than 10^{18} W/cm^2, the field of the laser is much larger than the Coulomb field binding the ground state electron in the hydrogen atom, $E_{at} = 5 \times 10^9$ V/cm. At 10^{19} W/cm^2, the laser electric field is close to 10^{11} V/cm, 20 times E_{at}. At these intensities, the electrons have a relativistic character. They acquire a cycle-average oscillatory energy ("quiver energy") $E_{osc} = m_0c^2(\sqrt{1 + 2U_p/m_0c^2} - 1)$ greater than the electron rest energy, where m_0 is the electron rest mass. For example, at 10^{19} W/cm^2, for $\lambda = 1$ μm, this quiver energy is on the order of 1 MeV, or twice the electron rest energy $m_0c^2 =$ 0.5 MeV. The relativistic nature of the electron motion requires the use of the full Lorentz force, $\mathbf{F} = q(\mathbf{E} + \mathbf{v}/c \times \mathbf{B})$, where q is the charge of the electron; $\mathbf{E}$ and $\mathbf{B}$ are the vector electric and magnetic fields of the laser respectively; $\mathbf{v}$ is the quiver velocity; and c is the speed of light. Note that in linear and nonlinear optics (of the bound electron), the force due to the magnetic field is always neglected, because the quiver velocity of the electron is small compared to c. Above 10^{18} W/cm^2, the magnetic and electric force applied to the electron become equal and responsible for extremely large light pressure, $P = I/c$. At 10^{19} W/cm^2, the light pressure reaches the respectable value of 0.3 Gbar. It will have some profound implications in most of the applications described below.

Electron acceleration. In subcritical gases, the pressure produced by a focused pulse can displace the electrons as it propagates. The electrons are pulled back by the ions once the pulse goes by, producing a large plasma wave oscillating at the electron plasma frequency $\omega_p = (4\pi n_0e^2/\gamma m_0)^{1/2}$, where n_0 is the plasma density and γ is the relativistic factor. The plasma wave trailing the laser pulse forms a train of accelerating buckets, each with a duration equal to the plasma period. The accelerating gradient resulting from the charge displacement is given by $E_0 = mc(\omega_p/e)$, or $E_0 = n_0^{1/2}$ when E_0 is in units of V/cm and n_0 is in units of cm^{-3}. For example, a plasma with a density $n_0 = 10^{18}$/cm^3 is capable of supporting a field $E_0 = 100$ GV/m, which is approximately three orders of magnitude larger than that in a conventional linac. This concept, proposed by Toshiki Tajima and John Dawson at UCLA in 1979, is known as laser wakefield acceleration and was reintroduced independently by L. Gorbunov and V. Kirsanov of the P. N. Lebedev Physics Institute and by Phillip Sprangle and his coworkers at the Naval Research Laboratory in the late 1980s.[8] It has been demonstrated over the past few years by a number of groups in the US, UK, Japan and France.[9] In figure 1, which illustrates this simple concept, we can see on a phosphor screen a collimated beam of a few nanocoulombs of electrons with mega-electron-volt energy. These electrons were produced by a laser pulse of intensity exceeding 10^{18} W/cm^2 interacting with a helium gas jet 1 mm thick. In this experiment, there is no external injection involved; the electrons are self-trapped. Although the quick acceleration to relativistic energy, over only 0.1 mm, confers to the beam a remarkably low geometrical emittance (product of the beam size and its divergence) almost as good as the laser, this self-injection technique results unfortunately in a broad energy spread, making the approach unattractive for some applications.

To produce better beam monochromaticity, controlled injection is necessary. The very large field gradient is obtained at the expense of very short acceleration buckets, on the order of 50 fs. Monoenergetic injection into one of these extremely narrow buckets becomes an impossible challenge, given that the shortest injection pulses are on the order of a picosecond. Injecting with a picosecond electron pulse will uniformly seed a number of buckets, producing a wide energy spread. An elegant solution to this seemingly hopeless situation has been devised by Donald Umstadter of the University of Michigan[10] and is now being tested by a number of laboratories in the US, France and Japan. In this scheme, an ultrashort laser pulse of 20 fs duration is sent orthogonally to the plasma wave. The resulting ponderomotive force from the large transverse intensity gradient dephases some of the electrons and pushes them into a selected part of the bucket. According to particle-in-cell simulations, with today's lasers this simple, inexpensive, tabletop, all-optical technique has the potential to produce subfemtosecond pulses of electrons with 100 MeV energy and an energy spread on the order of a few percent. A variation of this optical injection technique has been proposed by Eric Esarey at the Naval Research Laboratory[11] and has the potential to produce an energy spread of less than 1%. It is important to recall that relativistic particles are less affected by space charge, which scales like $1/\gamma^2$. This violent acceleration to the relativistic regime over 100 μm, instead of meters, is certainly the key to the generation of ultrashort electron pulses with copious electric charge in the femtosecond and subfemtosecond regime.

Self-focusing, harmonic generation. The plasma frequency becomes intensity dependent due to the relativistic mass change and produces a change of the index of refraction across the beam, $n = (1 - \omega_p^2/\omega^2)^{1/2}$, with a maximum on axis. This causes the beam to self-focus, as predicted by Claire Max and coworkers at LLNL, to a micrometer-sized filament and to guide the laser, as observed by the groups of Charles Rhodes at the University of Illinois at Chicago and of Gerard Mainfray at CEA in France.[8] When self-guiding of a laser pulse in such a filament occurs simultaneously with wakefield acceleration of electrons, the divergence of the accelerated electron beam is observed to decrease dramatically due to the increase in $p_\parallel/p_\perp$, reaching in fact the space-charge limit ($p_\parallel$ and $p_\perp$ are the parallel and perpendicular electron momenta).[12] Eventually, the very large radial intensity gradient should expel the electrons and ions from the filament, as predicted theoretically by Patrick Mora of the Ecole Polytechnique in Palaiseau, France, and recently observed experimentally by Umstadter and his group at Michigan.[13] The large beam current density of 10^{12} A/cm^2 in the filament (nanocoulombs in 100 fs), will produce magnetic fields of gigagauss strength.

In solids, the very large pressure is also responsible for the generation of harmonics.[14] Pushing on the steep vacuum–solid interface at the laser frequency effectively phase modulates the reflected beam at the same frequency. This oscillating mirror gives rise to a series of sidebands on the reflected spectrum, separated by ω or 2ω. Up to the 70th harmonic has been observed at Rutherford Appleton Laboratory,[15] reminiscent of the first relativistic harmonic generation produced at Los Alamos National Laboratory with a carbon dioxide laser at 10.6 μm. (See PHYSICS TODAY, January 1995, page 36.)

ICF Fast Ignitor. In overdense plasma, because of the very large radiation pressure—far exceeding the thermal pressure—combined with the large lateral ponderomotive force due to the pulse's transverse gradient, and a reduction of the plasma frequency by γ, an incident pulse will penetrate over several wavelengths. This effect, referred to as "hole boring," is achieved with relatively long (100 ps) pulses and plays an important role in the Fast Ignitor concept of inertial confinement fusion.[16] The essential idea, as illustrated in figure 6, is to preimplode a deuterium–tritium capsule to an isochoric (uniform density) condition. At the point of maximum compression, a side of the imploded core is irradiated with a laser pulse much shorter than the 10 ps hydrodynamic disassembly time of the irradiated spot.

Hot electrons (200 keV < E < 1 MeV) generated by the interaction of the intense (10^{19}–10^{21} W/cm^2) light with plasma rapidly equilibrate in the dense fuel. The energy equilibration of the electrons raises the overall ion temperature to 5–20 keV, initiating fusion burn. High laser pulse energy is required to produce enough hot electrons to heat a sufficient number of ions to initiate fusion burn. Nearly perfect beam quality is required in the laser to achieve a small spark region. The Fast Ignitor concept offers the possibility of high target gain at reduced total drive energy, compared with conventional inertial confinement fusion.

Astrophysics. It has been suggested by Tajima from the University of Texas at Austin, Hideaki Takabe from Osaka University, Setsuo Ichimaru from the University of Tokyo and Bruce Remington from Lawrence Livermore National Laboratory that astrophysical conditions such as opacity, density and temperature could be reproduced and tested at intensities of 10^{20} W/cm^2, corresponding to gi-

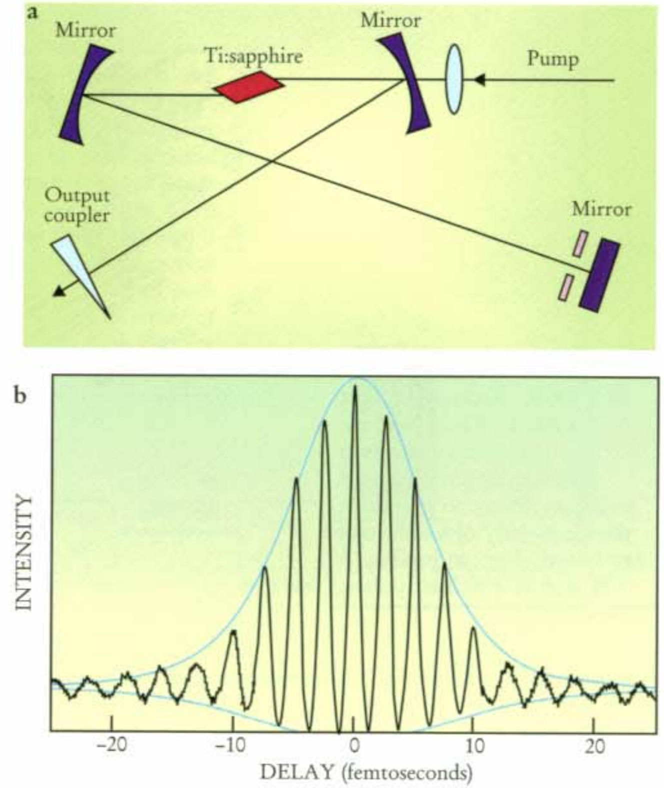


FIGURE 5. PULSE CAVITY AND OUTPUT TRACE. **a:** Schematic of an ultrashort-pulse cavity composed of broadband mirrors and a titanium:sapphire amplifying medium. The amplifying medium is optically pumped, usually with a continuous wave argon laser. Besides its role as an amplifier, the Ti:sapphire acts as a lens with an intensity-dependent focal length due to its intensity-dependent index of refraction. The cavity is calculated to be stable for the highest intensity or the shortest pulse duration. To get the shortest pulse duration, the dispersion of the pulse in the crystal is compensated by frequency-chirped mirrors as shown here, or by a sequence of prisms. The output coupler must be wedged to avoid Fabry–Perot effects. **b:** The interferometric autocorrelation trace of the output pulse produced by mixing the signal with itself in a second harmonic crystal. The pulse is 7.5 fs long, full width at half maximum. (Schematic courtesy of Ferenc Krausz.)

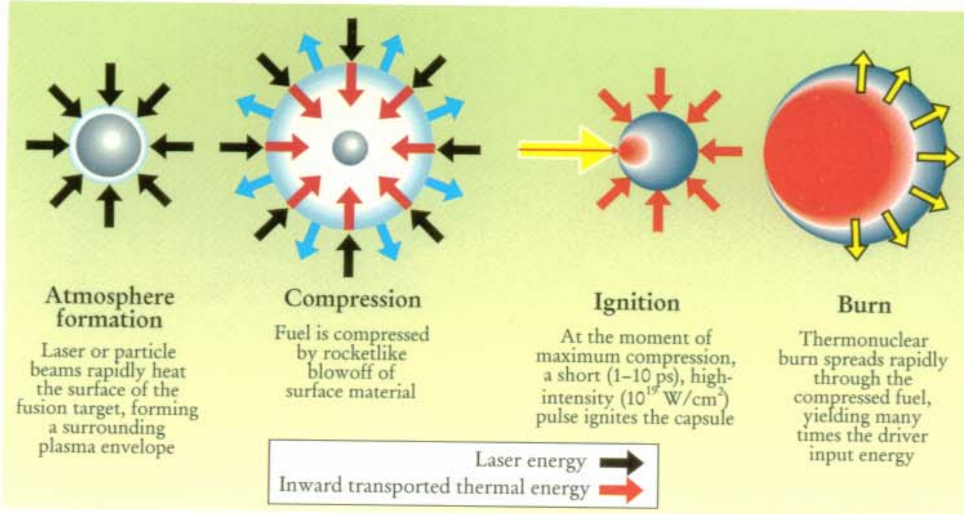


FIGURE 6. FAST IGNITION in inertial confinement fusion. The diagram shows the four main steps. A high-intensity laser pulse ignites the fuel at the moment of maximum compression.

gabar pressures. One proposal is to look at the rates of nuclear fusion—such as thermonuclear and pycnonuclear (pressure-induced nuclear)—that are greatly modified by the state of dense matter. Ultrahigh-pressure metal physics with ultrahigh-intensity lasers could be applied to understand the phase transformation, metallization and crystallization of hydrogen in stellar interiors and to help investigate the physical mechanisms governing supernovae, stars and nebulae.

In ponderomotive acceleration, electrons are accelerated from a cold start to c in a fraction of a picosecond, corresponding to $10^{21}\,g$. Recently, Roland Saubrey at the University of Jena in Germany reported a measured plasma acceleration of $10^{17}\,g$ with an intensity, modest by today's standards, of 10^{18} W/cm^2. This violent acceleration is the same as that found near the horizon of a black hole. Accelerations up to $10^{25}\,g$ could be obtained at 10^{23} W/cm^2 and produce detectable Unruh (vacuum fluctuation) radiation, according to Pisin Chen of SLAC and Tajima. These few examples illustrate the exciting possibility of using ultrahigh-intensity lasers in a laboratory setting to test general relativity and the structure of the vacuum.

Quantum electrodynamics. As figure 2 indicates, electron–positron pair creation directly from lasers will require intensities on the order of 10^{30} W/cm^2. The required laser field E is the total rest energy over the Compton wavelength $\lambda_c = h/m_0c$; the field is therefore equal to $E = 2m_0c^2/e\lambda_c$ and corresponds to 10^{16} V/cm, which is about four to five orders of magnitude above the fields of today's lasers. Experimenters bridged this enormous gap by using the electric field enhancement produced in the frame of superrelativistic electrons.[17] Using the 50 GeV electron beam at SLAC, corresponding to a γ of 10^5, with a currently available high-power laser, the field is enhanced to about 10^{16} V/cm, approaching the critical field.

Multiphoton pair production, $\omega_\gamma + n\omega_0 \rightarrow e^+ + e^-$, has been observed, where ω_γ is the upconverted frequency from Compton scattering and ω_0 is the laser frequency. The same experimenters are studying nonlinear Compton scattering, $e + n\omega_0 \rightarrow e + \omega_\gamma$. Here the high-energy γ ray produced in the laser focus by an incident electron interacts before leaving the focal region. The process has been observed up to $n = 4$.

The developments that we have discussed in this article illustrate the synergy between science and technology. An advance in technology—CPA—has opened the door to scientific research in areas of physical extremes that until now were inaccessible in university laboratories.

References

1. M. D. Perry, G. Mourou, Science **264**, 917 (1994). This review article has other pertinent references.
2. D. Strickland, G. Mourou, Opt. Commun. **56**, 219 (1985). P. Maine, D. Strickland, P. Bado, M. Pessot, G. Mourou, IEEE J. Quantum Electron. **24**, 398 (1988).
3. O. E. Martinez, IEEE J. Quantum Electron. **23**, 1385 (1987).
4. B. E. Lemoff, C. P. J. Barty, Opt. Lett. **18**, 1651 (1993). J. Zhou, C. P. Huang, M. M. Murnane, H. C. Kapteyn, Opt. Lett. **20**, 64 (1995).
5. D. E. Spence, P. N. Kean, W. Sibbett, Opt. Lett. **16**, 42 (1991).
6. C. P. Huang, H. C. Kapteyn, J. W. McIntosh, M. M. Murnane, Opt. Lett. **17**, 139 (1992). F. Krausz, C. Spielmann, T. Brabec, E. Wintner, A. J. Schmidt, Opt. Lett. **17**, 204 (1992). C. P. Huang, M. T. Asaki, S. Backus, M. M. Murnane, H. C. Kapteyn, H. Nathel, Opt. Lett. **17**, 1289 (1992). B. Proctor, F. Wise, Opt. Lett. **17**, 1295 (1992). B. E. Lemoff, C. P. J. Barty, Opt. Lett. **17**, 1367 (1992). C. Spielmann, P. F. Curley, T. Brabec, F. Krausz, IEEE J. Quantum Electron. **30**, 1100 (1994). A. Stingl, C. Spielmann, F. Krausz, and R. Szipöcs, Opt. Lett. **19**, 204 (1994). I. D. Jung, F. X. Kärtner, N. Matuschek, D. H. Sutter, F. Morier-Genoud, G. Zhang, U. Keller, V. Scheuer, M. Tilsch, T. Tschudi, Opt. Lett. **22**, 1009 (1997).
7. M. D. Perry, B. C. Stuart, G. Tietbohl, J. Miller, J. A. Britten, R. Boyd, M. Everett, S. Herman, H. Nguyen, H. T. Powell, B. W. Shore, *CLEO '96*, 1996 Technical Digest Series, vol. 9, Opt. Soc. America, Washington, DC (1996), p. 307.
8. E. Esarey, P. Sprangle, J. Krall, A. Ting, IEEE Trans. Plasma Sci. **24**, 252 (1996).
9. A. Modena, Z. Najmudin, A. E. Dangor, C. E. Clayton, K. A. Marsh, C. Joshi, V. Malka, C. B. Darrow, C. Danson, D. Neely, F. N. Walsh, Nature **377**, 606 (1995). K. Nakajima *et al.*, Phys. Rev. Lett. **74**, 4428 (1995). D. Umstadter, S.-Y. Chen, A. Maksimchuk, G. Mourou, R. Wagner, Science **273**, 472 (1996). S. Le Blanc, M. Downer, R. Wagner, S.-Y. Chen, A. Maksimchuk, G. Mourou, D. Umstadter, Phys. Rev. Lett. **77**, 5381 (1996).
10. D. Umstadter, J. K. Kim, E. Dodd, Phys. Rev. Lett. **76**, 2073 (1996).
11. E. Esarey, R. F. Hubbard, W. P. Leemans, A. Ting, P. Sprangle, Phys. Rev. Lett. **79**, 2682 (1997).
12. R. Wagner, S.-Y. Chen, A. Maksimchuk, D. Umstadter, Phys. Rev. Lett. **78**, 3125 (1997).
13. S.-Y. Chen, R. Wagner, G. Sarkisov, A. Maksimchuk, D. Umstadter, Phys. Rev. Lett., to be published.
14. D. Von der Linde, K. Rzazewski, Appl. Phys. *B* **63**, 499 (1996).
15. P. A. Norreys *et al.*, Phys. Rev. Lett. **76**, 1832 (1996).
16. M. Tabak, J. Hammer, M. E. Glinsky, S. C. Wilks, J. Woodworth, E. M. Campbell, M. D. Perry, R. J. Mason, Phys. Plasmas **1**, 1626 (1994).
17. C. Bula *et al.*, Phys. Rev. Lett. **76**, 3116 (1996). ■