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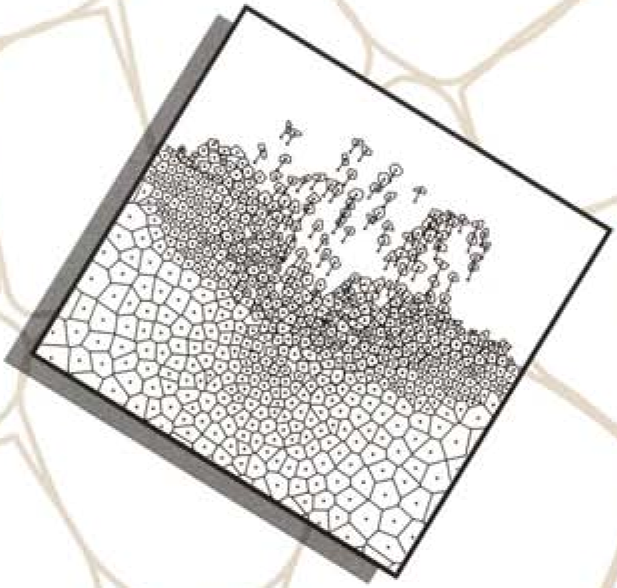

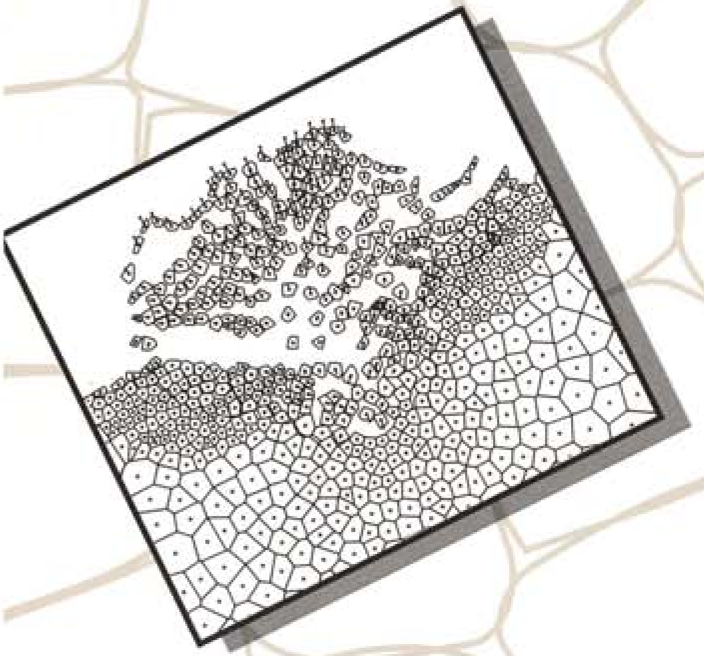

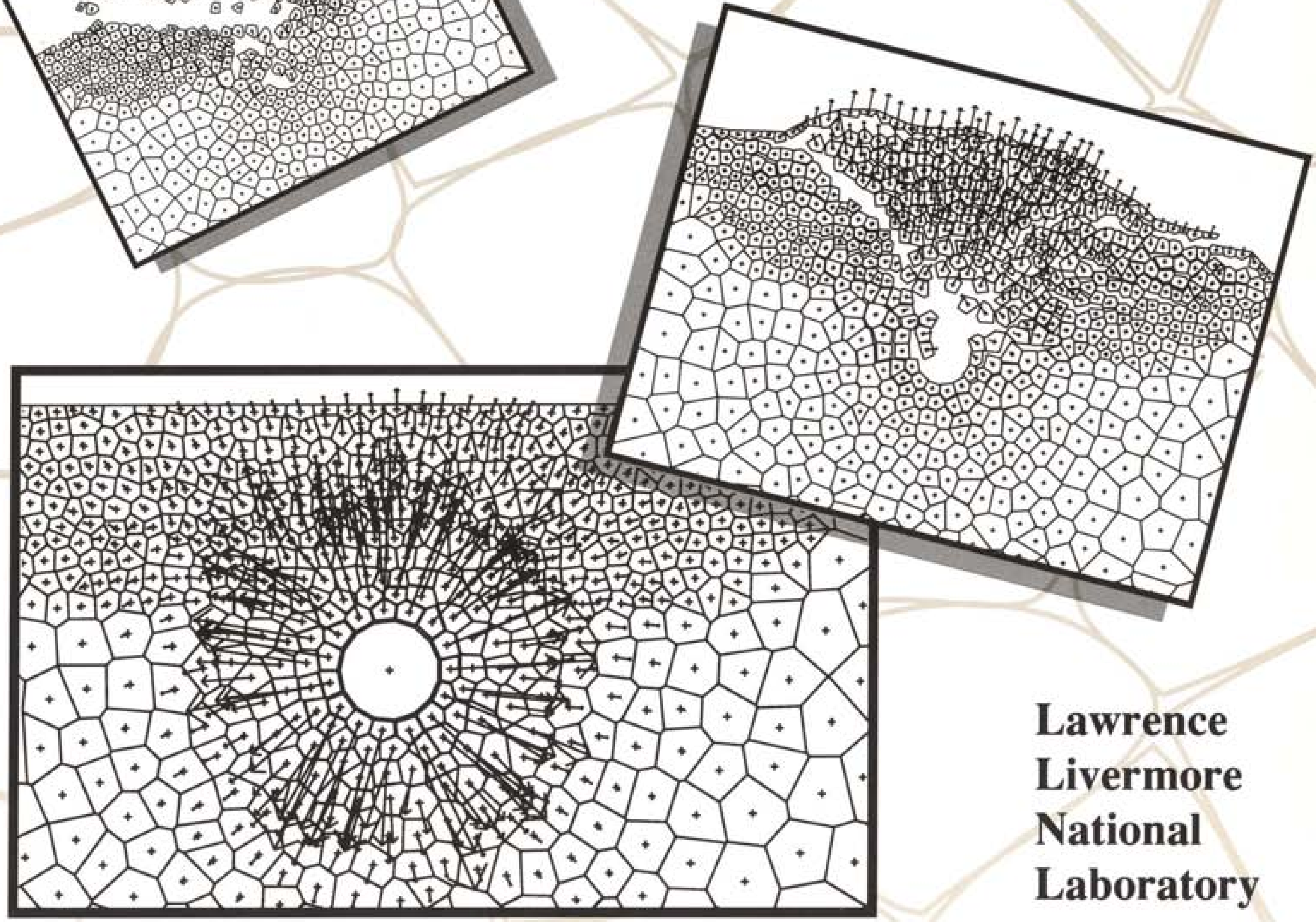

**Lawrence
Livermore
National
Laboratory**

High-Intensity Short-Pulse Lasers

We are developing short-pulse laser systems capable of producing extreme values of laser intensity and electric field strength. These sources will make possible research in an entirely new physical regime.

For further information contact Michael D. Perry (415) 423-4915.

For laser pulses of a given energy, the shorter the pulse the higher the peak power. A decade ago, 1 ns was considered a short pulse. Shortly after that, "ultrafast" dye lasers pushed the limit to a few picoseconds. Recent developments now enable us to work with pulses a thousand times shorter, as short as 6 fs.[1] By applying these techniques to glass laser systems, we can achieve, in principle, focused intensities approaching 10^{21} W/cm^2—more than a million times the intensity available from our Nova laser.

In this article we briefly survey the several areas of research that have needs for high-intensity, short-pulse lasers. We outline the possible approaches to these types of laser and describe our development of a table-top glass laser system capable of producing pulses with peak power in excess of 10 TW. This is the first step in our program to produce the first petawatt laser (10^{15} W), capable of achieving focused intensities of 10^{21} W/cm^2.

Potential Areas of Application

The availability of a 1000-TW laser system capable of producing focused intensities exceeding 10^{21} W/cm^2 will make possible the study of matter at field strengths that have until recently been thought unattainable in the laboratory, opening an entirely new physical regime to study. Such a laser has possible applications in many areas of research, including nuclear physics, plasma physics, laser-atom interactions, x-ray lasers, spectroscopy, and inertial confinement fusion.

Three aspects of the pulse at the laser focus present opportunities for experiments in a wide range of physics. The first involves the extraordinary electric field, which at an intensity of 10^{21} W/cm^2 is nearly 100 TV/m. This is about 200 times stronger than the field binding electrons to atomic nuclei. No atom can survive it unscathed. As the intensity rises throughout the laser pulse, any species present at the focus will undergo multiphoton ionization.

The second is the high energy density, which at an intensity of 10^{21} W/cm^2 is more than 30 GJ/cm^3. This energy density is equivalent to that of a 10-keV blackbody and is more than a hundred times that produced in current laser fusion plasmas.

The third is the quiver energy of a charged particle, the energy it acquires by oscillating in response to an applied electromagnetic field. This "pondermotive" potential is usually neglected in laser-atom interactions because it is seldom more than a few millielectron volts. At the intensities that would be available with the proposed laser, the quiver energy of a free electron would be more than 20 MeV, and the motion would be extremely relativistic.

Recombination X-Ray Lasers

Since we first demonstrated stimulated amplification in the soft x-ray region at 20 nm, much of the effort in the field has been directed toward pushing the operating wavelength below the carbon *K*-absorption edge at 4.376 nm. To do this, however, we would need at least a hundred times as much pump laser intensity; reaching the saturation fluence with such an x-ray laser would take even more pump power. Achieving this by increasing the beam energy in present systems is currently unreasonable; our Nova laser is already at the practical upper limit. The other approach is to increase the peak power by reducing the pulse width.

As the pulse width decreases and the peak power increases, different and increasingly efficient lasing schemes, such as those relying on inner-shell photo-ionization, become possible. In this approach, the high-intensity primary beam strikes an intermediate material to produce a very short, high-intensity burst of x rays that photo-ionize the lasing medium (usually a gas). Researchers at Stanford University recently achieved saturation in krypton at 90 nm on a table-top system using chirped-pulse amplification.[2]

X-ray laser schemes based on three-body recombination (Figure 1) are expected to benefit most from the development of high-intensity, short-pulse lasers. In these schemes, a dense plasma of fully stripped ions is allowed to cool adiabatically by expansion into a vacuum, populating the high-lying states of the hydrogen-like ions (nuclei holding one electron) by three-body recombination. This process, coupled with the fast radiative decay of the lower levels, leads to population inversions among levels with principal quantum numbers between 2 and 4.

High-intensity picosecond or subpicosecond pulses capable of producing highly charged ions by multiphoton ionization create a unique plasma ideally suited for recombination because the laser pulses are too short to heat the plasma significantly. Hence, a very dense, cold plasma is created far from thermal equilibrium, with ion states determined almost solely by the peak laser intensity rather than by the plasma conditions. Since the three-body recombination rate increases with plasma density and also increases rapidly with decreasing electron temperature, such a dense, cold plasma would be nearly ideal for a recombination laser scheme.

To demonstrate the potential of a high-intensity, short-pulse source such as our high-brightness laser (HBL) for recombination x-ray laser experiments, we have calculated the gain on the 3 → 2, 4 → 3, and 4 → 2 transitions in hydrogen-like carbon or aluminum following photo-ionization by a typical 1- to 2-ps pulse from the HBL. A 1.05-μm infrared laser light intensity of 10^{18} W/cm^2, well within the HBL's capabilities over lengths exceeding 1 cm, should be enough to produce fully stripped carbon or aluminium.

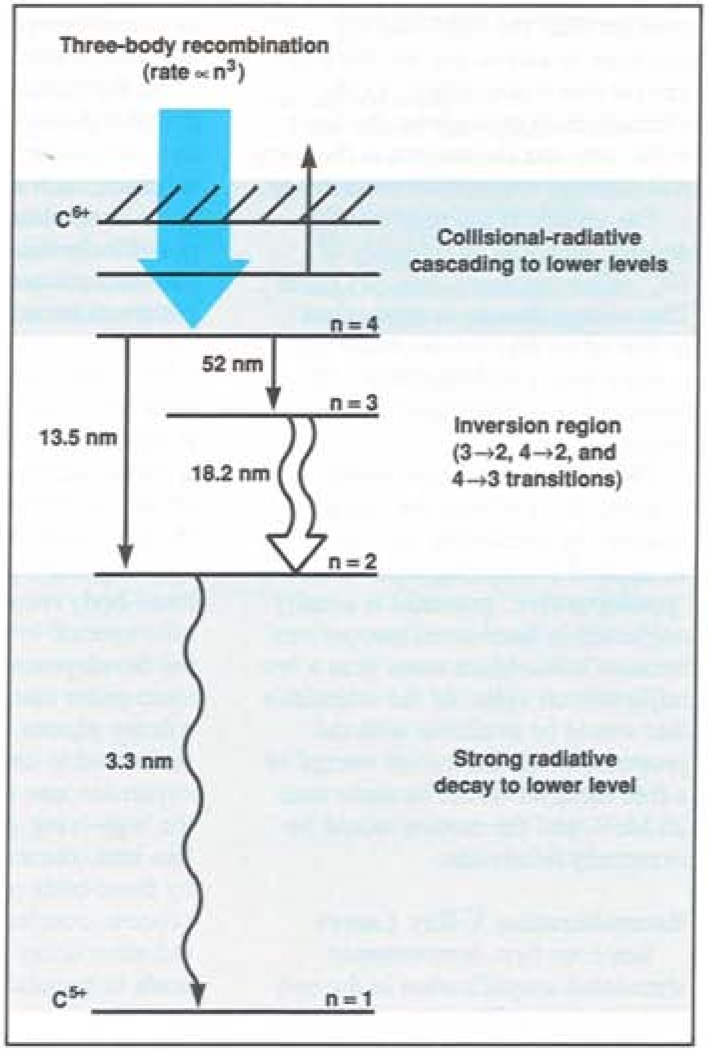

Figure 1. Scheme for producing an ultrashort-wavelength x-ray laser in a rapidly expanding carbon plasma by three-body recombination. Three-body recombination rapidly populates the n = 4 and n = 3 levels of the five-times ionized (hydrogen-like) carbon ions. Stimulated decay from the n = 3 to the n = 2 level produces 18.2-nm x rays.

Our simulation starts with a cylindrical plasma consisting of fully stripped carbon (or aluminum) ions and lets it expand freely into a vacuum. We assign the plasma an "effective" temperature equal to that required to produce fully stripped ions in ionization equilibrium, and set the ion temperature equal to the electron temperature at all times. (These temperature assumptions represent a worst-case limit, since the ions may actually be much cooler than the electrons if the laser pulse is too short to produce significant heating.)

Figure 2 shows two curves for the calculated 3 → 2 (18.2-nm) gain in carbon. The long, low pulse represents the result of irradiating a 5-μm-diam carbon fiber with a 100-ps pulse, giving an initial electron temperature of 90 eV, an electron density of 1.2 x 10^{20}/cm^3, and an initial plasma radius of 20 μm. The peak 3 →2 gain in this case is about 8 cm^{-1}, in close agreement with previous calculations.[3]

The high spike in Figure 2 represents the calculated 3 → 2 gain as a function of time following irradiation of a similar carbon fiber with a 1-ps pulse. The initial temperature in this case is the same (90 eV), but the density is much higher (10^{21}/cm^3) and the radius smaller (5 μm) because the plasma has had little time to expand during the laser pulse. The gain in this case is much higher (about 40 cm^{-1}), primarily because of the higher density at the end of the laser pulse.

The calculations, while still preliminary, illustrate the enormous potential of short-pulse, high-intensity lasers for producing short-wavelength (x-ray) lasers. As we learn more about x-ray lasers, it is apparent that we will be able to attain efficient, small-scale, x-ray lasers only by using intense, short-pulse, visible lasers as the pump source.

Electron-Positron Pair Production

A focused intensity of 10^{21} W/cm^2 should be more than enough to produce relativistic plasma waves that would efficiently accelerate electrons to perhaps 10 MeV.[4] Most of the energy of these electrons would be converted into energetic bremsstrahlung radiation, but about a millionth would appear in the form of electron-positron pairs. For an incident pulse energy of 1 kJ, this corresponds to more than 10^{10} pairs per pulse, a number that would be easily detectable with standard coincidence counting systems.[5]

The positrons produced would quickly combine with electrons outside the laser focus, forming positronium, which would decay over its characteristic lifetime of 125 ps. The resulting pulse of 511-keV x rays radiating from the vicinity of the laser focus would have a power of about 10 MW. Such a bright source of 511-keV radiation may have many applications in nuclear physics and solid-state studies.

Laser-Plasma Linear Accelerator

High-energy particle accelerators operating on conventional principles have become enormous and very expensive. A "beat-wave" accelerator excited with a short-pulse laser could theoretically achieve acceleration gradients of almost 30 GeV/m (about a thousandfold higher than in present linear accelerators).[6] Calculations indicate that our HBL would be able to power an acceleration stage 30 cm long, yielding 10-GeV electrons; a hundred such stages in series would yield 1-TeV electrons. Smaller-scale experiments with similar laser-plasma techniques are currently under way at several laboratories.

Laser Enhancement of Nuclear Beta Decay

Even at the enormous intensity of 10^{21} W/cm^2, the electric field of the laser is only about a millionth of the field strength within the nucleus. However, intense laser fields can influence nuclear phenomena indirectly. One such indirect mechanism involves polarizing the inner-shell electrons by the strong field; another involves modifying the final states of decay products, which would make observable changes in the decay rates. For example, it has been calculated that a laser intensity of 1.3×10^{18} W/cm^2 would increase the beta-decay rate of tritium by twenty thousandfold.[7]

Optically Induced Nuclear Fusion

When a laser pulse ejects electrons from the focus region, the intense electric field (and space charge) also strongly accelerate the ions left behind. At laser intensities exceeding 10^{19} W/cm^2, the pondermotive potential can maintain electrostatic potentials greater than 1 MeV. This electrostatic field can then accelerate ions to several tens of kilovolts before the laser field disappears.

As a specific example, a 10^{20}-W/cm^2 picosecond laser pulse focused into a deuterium-tritium gas mixture would accelerate deuterium ions to about 20 keV. On striking neutral tritium atoms outside the focus, these energetic deuterium ions would produce nearly 10^8 fusion reactions within 100 ps. This enormously bright source of 14.1-MeV neutrons would be valuable for calibrating neutron diagnostics for our laser program.

Short-Pulse Technology

The fundamental Fourier Transform relationship that exists between laser pulsewidth and bandwidth requires the lasing medium to have a broad bandwidth in order to produce a short pulse. For a Gaussian pulse, this relation is $\Delta v \Delta t > 0.441$, where Δv is the bandwidth and Δt is the laser pulsewidth. (For the shortest pulse on record, 6 fs at $\lambda = 550$ nm, the corresponding bandwidth is more than 70 nm, nearly one-third of the entire visible spectrum, resulting in a multicolored laser beam.) Until very recently, only organic dyes, rare-gas halide excimers, and special laser glasses had bandwidths of more than even a few nanometers.

Organic dye lasers have inherently large bandwidths because of the very large number of vibrational and rotational modes associated with each electronic level in the dye molecules; commercial lasers capable of producing subpicosecond pulses of a few kilowatts are available. However, when such pulses are amplified for applications requiring much higher power, the short storage time of the high-gain dye amplifiers

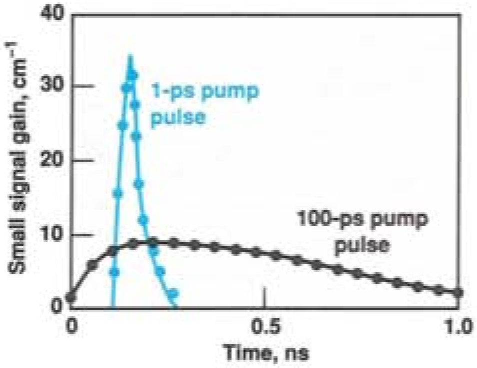

Figure 2. Calculated gain ($3 \rightarrow 2$ transition) for a laser formed by three-body recombination upon irradiating a 7-μm carbon fiber with the beam from our high-brightness laser. With a 100-ps pulse, the initial conditions are a plasma temperature of 90 eV, a plasma radius of 20 μm, and an electron density of 10^{20}/cm^3. The calculated gain is low and spread over a relatively long interval (black curve). With a 1-ps pulse, the plasma temperature is still 90 eV, but the plasma radius is only 5 μm and the electron density is 10^{21}/cm^3. The result is a much higher gain and shorter pulse (blue curve).

results in amplified spontaneous emission (ASE), which robs the amplifiers of energy and introduces a low-level background pulse lasting several thousand times longer than the subpicosecond pulse. Even with elaborate techniques for isolating the amplifier stages from one another, this ASE can amount to a few percent of the total pulse energy, enough to interfere with many high-intensity experiments.

We have developed a dye laser system that avoids ASE by pumping the amplifiers with a laser pulse shorter than the storage time of the dye (Figure 3). This 80-ps pump pulse permits the short "seed" pulse from the laser oscillator to extract nearly all the stored energy in the amplifier before ASE can develop. The result is a 1-ps pulse with a maximum energy of 5 mJ (or a 350-fs, 2.8-mJ pulse) with less than 0.01% of ASE background, obtained without any elaborate isolation between amplifier stages.

However, this performance is close to the limit that can be obtained from dye laser systems because of the very small saturation fluence (about 1 mJ/cm^2) common to all organic dyes. This means that even dye amplifiers several centimeters in diameter can produce pulse energies of only a few millijoules while maintaining a short pulse.

Excimer lasers are also limited by low saturation fluences and short storage times. Although a few large-diameter excimer systems have recently been developed that amplify subpicosecond pulses up to an energy of nearly 300 mJ, the cost and complexity of the elaborate measures required to combat ASE have seriously limited their usefulness.

Solid-State Lasers and Chirped-Pulse Amplification

Solid-state amplifier materials such as neodymium glass, alexandrite, and titanium-doped sapphire all have high saturation fluences, making it possible to extract several joules of energy from modest-scale laser systems. They also have the large-gain bandwidths needed to amplify subpicosecond pulses. Their limitation comes from the tendency of bright beams to self-focus destructively (a result

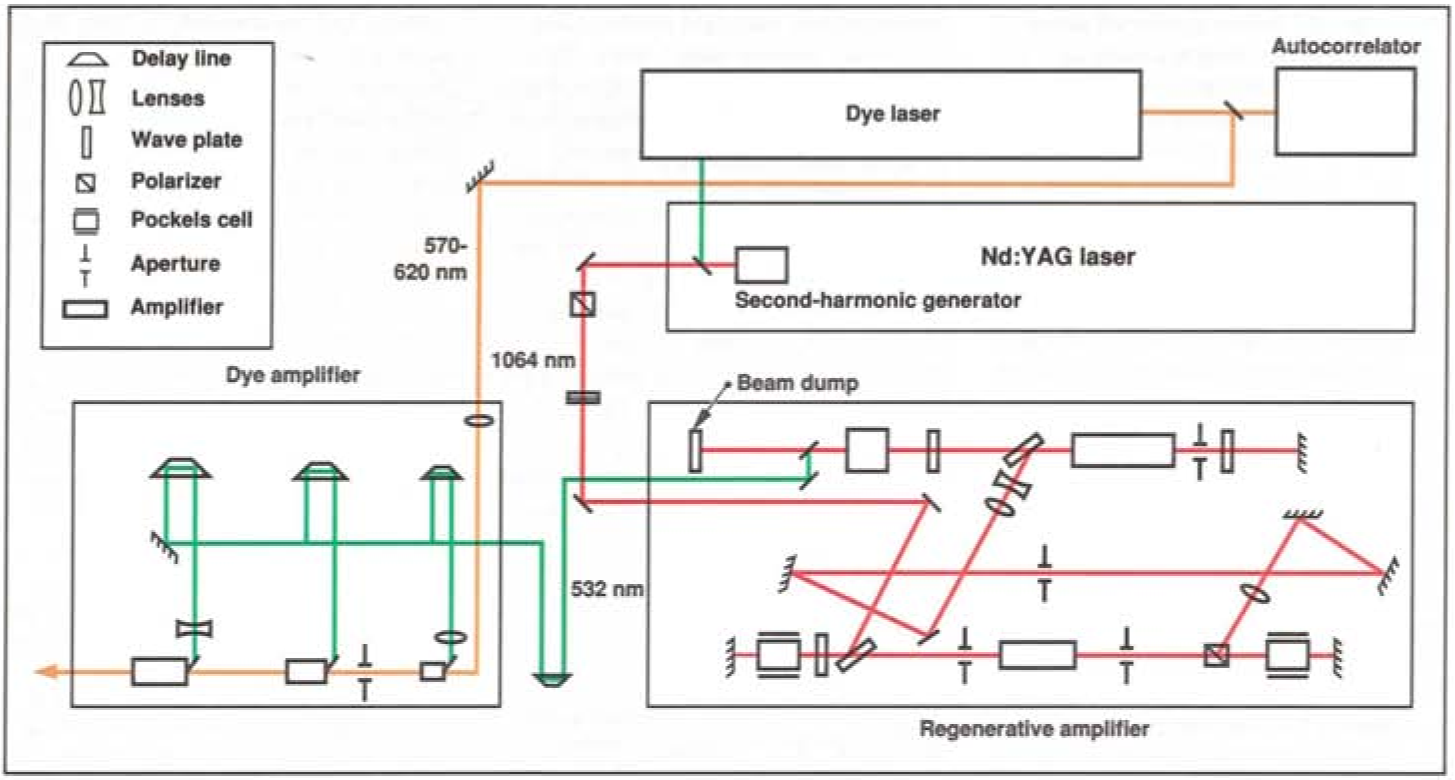

Figure 3. Schematic arrangement of our short-pulse dye laser designed to avoid amplified spontaneous emission (ASE). The mode-locked Nd:YAG laser pumps the dye amplifiers with a 70-ps pulse, shorter than the dye's storage time. Hence the subpicosecond pulse can extract nearly all the amplifier's stored energy before ASE has time to occur. Delay lines are adjusted to maintain precise synchronization between the 70-ps pump pulse and the subpicosecond dye pulse as it passes through the various stages of amplification.

of nonlinearity in the index of refraction), which makes it necessary to limit the intensity present in amplifiers of reasonable length to less than 10 GW/cm^2.

We are working on a technique known as chirped-pulse amplification (CPA) that holds the promise of removing this obstacle. Briefly, the idea is to use nonlinear refraction to generate a broad-bandwidth pulse that can be stretched out in time so that it can be amplified without harming the amplifier, and then compress it back into a short pulse of extremely high power.

The first step is to produce the short pulse. In an ideal material with a perfectly linear refractive index (constant regardless of light intensity), even a very powerful laser pulse would pass through unchanged. In real materials the frequency spectrum of the pulse is broadened by an amount that depends on the incident intensity, which (with a powerful enough pulse) can result in a controllable frequency sweep or "chirp." This produces a pulse that is moderately short (~50 ps) but broad in bandwidth. By controlling the chirp, this pulse can be compressed to a subpicosecond pulse.

In a chirped pulse, the different frequencies occur at different times. A device that delays certain frequencies relative to others can, in principle, stretch a short pulse over a longer time or, alternatively, compress a long pulse into a short one.

A diffraction grating, which sends light rays of different frequencies in different directions, can serve as the basis for such a device (Figure 4). A pair of gratings can be arranged in such a way as to send the higher-frequency (bluer) light over a longer path than the lower-frequency (redder) light, stretching out the pulse. Conversely, delaying the redder light more than the bluer compresses the pulse.

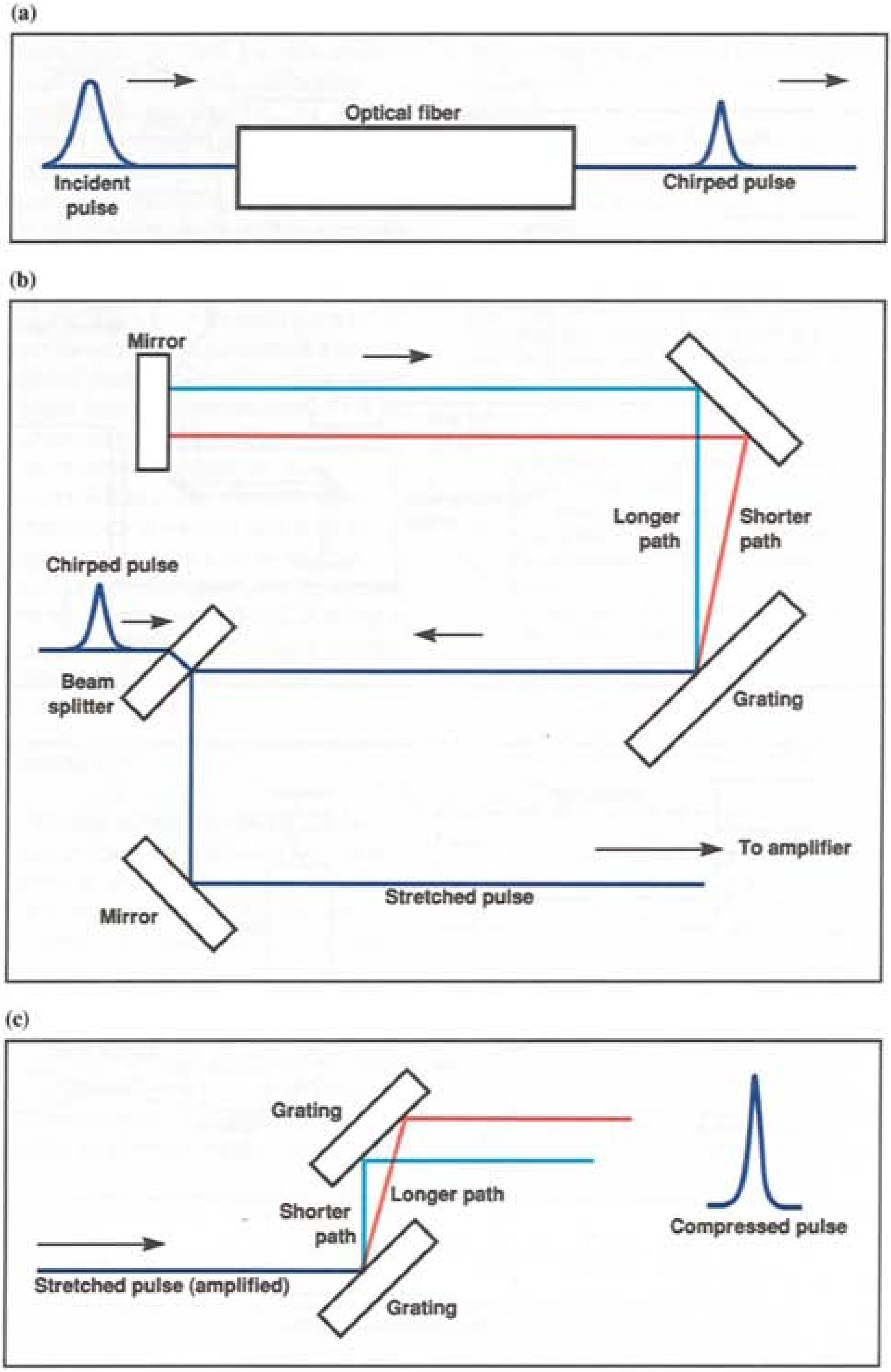

Figure 4. Optical components used in chirped-pulse amplification. (a) The optical fiber whose nonlinear index of refraction broadens the pulse both in time and in wavelength. The leading part of the pulse contains the longer wavelengths. (b) A pair of gratings arranged to send shorter wavelengths (blue) over a longer path, delaying them still further and stretching the chirped pulse. (c) A pair of gratings arranged to shorten the path of the short wavelengths, compressing the long, amplified pulse back into a short pulse.

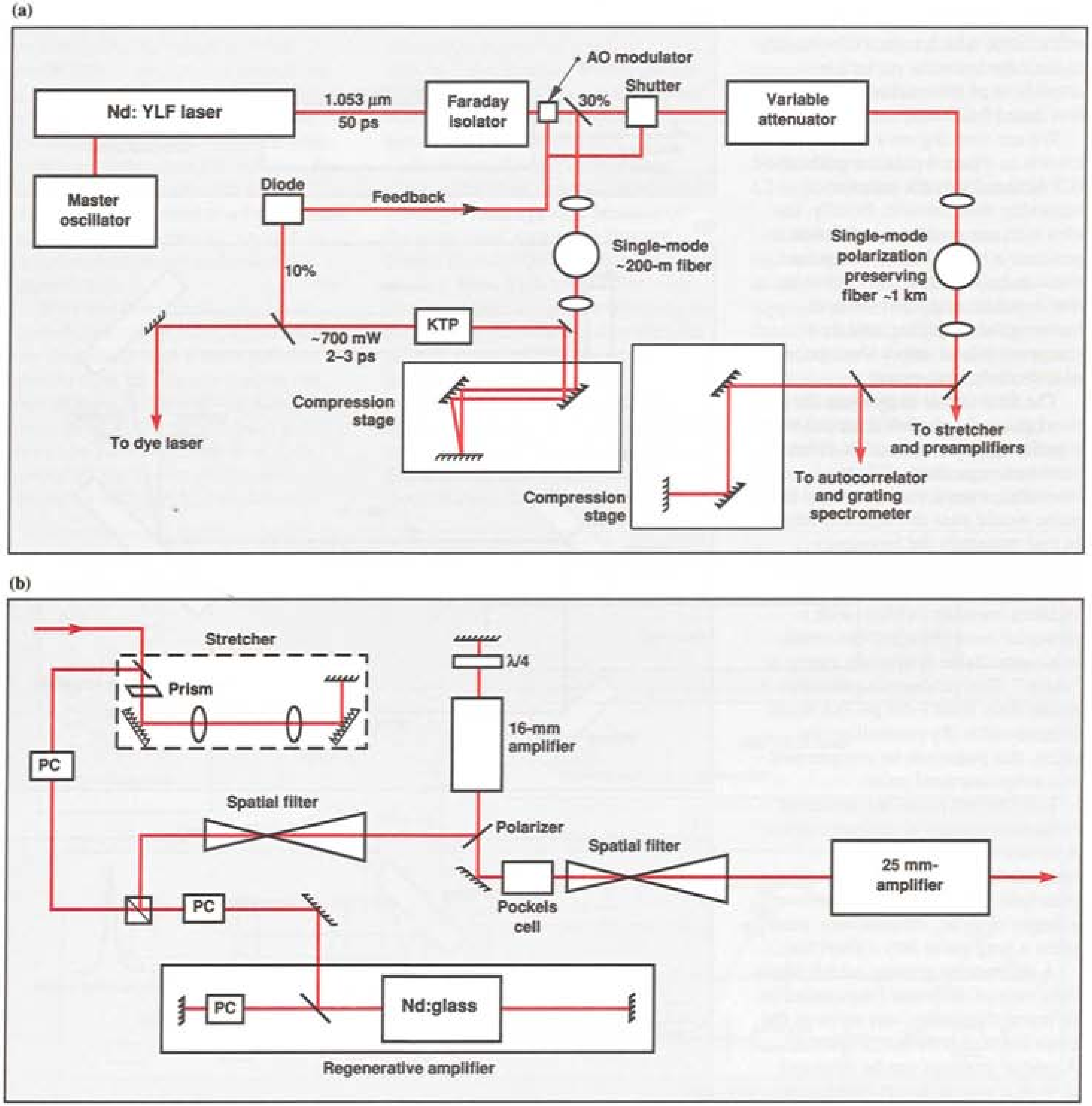

Figure 5. Schematic of our 3-TW picosecond laser system. (a) The oscillator section. The acoustic-optic (AO) modulator following the oscillator uses feedback from the final output to regulate the intensity of light incident on the chirp-producing optical fiber. (b) The amplifier section. The 1-ns pulse from the stretcher is spatially filtered before it enters the 16-mm amplifier. After two passes through this amplifier, it is spatially filtered again before going once through the 25-mm amplifier and thence to the pulse compressor, where it is compressed to less than 1 ps. The Pockels cells (PC) protect the amplifier rods from their self-destructive tendency to amplify back reflections.

We are developing a laser system employing this technique (Figure 5). The system starts with a cw mode-locked laser built around a rod of yttrium lithium fluoride glass doped with neodymium (abbreviated Nd:YLF) producing 3-kW, 50-ps pulses. We focus about 30% of the pulse into a long, single-mode, polarization-preserving, fused-silica optical fiber whose nonlinear refractive index imposes a frequency chirp about 5 nm wide onto the pulse, while group-velocity dispersion stretches the pulse from 50 to 150 ps. We then stretch the pulse to nearly 1 ns using a pair of antiparallel gratings, reducing its peak power by a factor of 20 before injection into the amplifier.

Next, using a regenerative amplifier, we amplify the stretched (and attenuated) pulse about a millionfold and then another factor of a thousand (to about 4 J) using a series of small neodymium-glass amplifiers similar to those used as preamplifiers in our Nova laser. Finally, we compress the pulse to about 1 ps with another pair of gratings. This design should produce nearly diffraction-limited pulse power in excess of 3 TW, which we should be able to focus to an intensity of more than 10^{18} W/cm^2. By adding a 5-cm amplifier before the final grating pair, we should be able to produce pulses nearly equal in power to those from Nova's most powerful beamline (>10 TW), but in a much smaller system. With additional component development, we should be able to obtain 1000-TW pulses capable of being focused to intensities exceeding 10^{21} W/cm^2.

Alexandrite and titanium:sapphire hold even greater promise for the amplification of ultrashort laser pulses. Their very broad spectral profiles and large saturation fluences should enable them to amplify 100-fs pulses. Already, our coworkers at the Laboratory for Laser Energetics, University of Rochester, have succeeded in using chirped-pulse amplification with an alexandrite regenerative amplifier to produce tunable 250-fs radiation with a pulse energy of more than 2 mJ. Adding a second alexandrite amplifier should boost the pulse energy to several hundred millijoules.

Summary

Recent advances in short-pulse laser technology should allow us to develop table-top laser systems that yield focus intensities exceeding those of our Nova laser system, the world's largest. Applying these techniques on large lasers using new solid-state materials should make it possible to produce pulses of more than 10^{15}-W peak power and focused intensities near 10^{21} W/cm^2. The ability to generate such a laser field opens up an entirely new physical regime for research and development. Fields of study expected to benefit include nuclear physics, plasma physics, laser-atom interactions, x-ray lasers, spectroscopy, and inertial confinement fusion.

Key Words: alexandrite; beta-decay enhancement; chirped-pulse amplification; electron-positron pair production; linear accelerator—laser plasma; laser—dye, high-intensity, Nova, recombination x-ray, short-pulse, solid-state; optically induced nuclear fusion.

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