More Intense, Shorter Pulses

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ing filament. Another is to determine how bundles of cross-linked filaments elongate from formin attached to cellular structures. Formins have well-established distinct roles in fungi (*3*), but cell biologists must sort out the overlapping functions of more than a dozen formins in human cells.

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PHYSICS

More Intense, Shorter Pulses

Large-scale laser facilities may also provide the ultimate source of ultrashort laser pulses.

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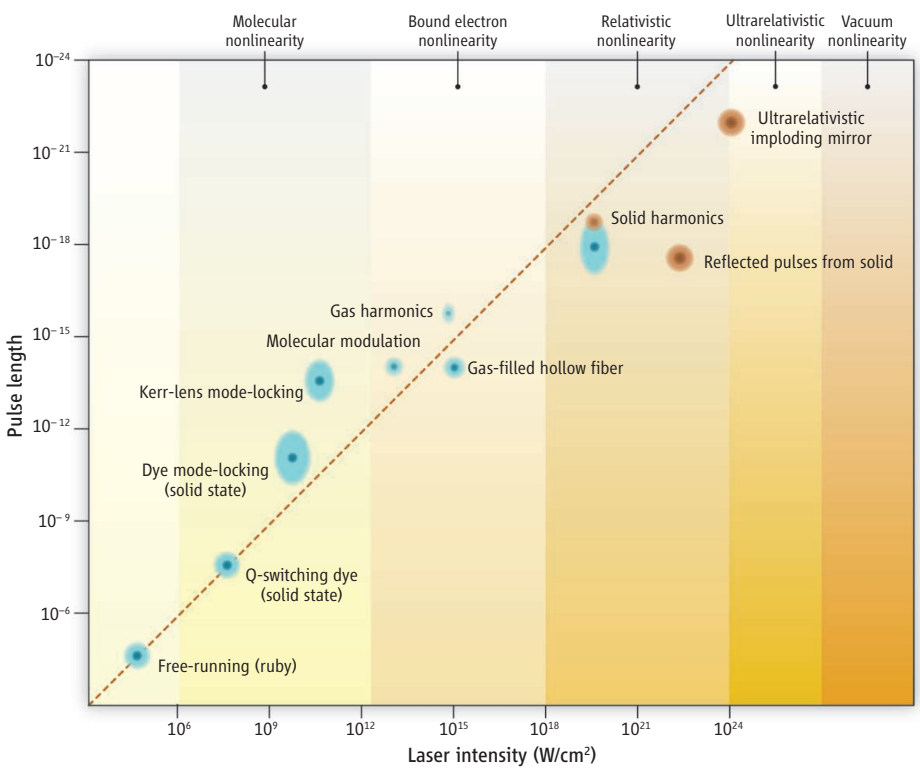
A few years ago, a new type of large-scale laser infrastructure specifically conceived to produce the highest peak power and focused intensity was announced: the Extreme Light Infrastructure, ELI (*1*), designed to be the first exawatt-class (10^{18} W) laser. This gargantuan power will be obtained by cramming a kilojoule of energy into a pulse only 10 fs in duration. Analysis of the history of laser development reveals that the pulse duration and intensity of lasers (or derived coherent radiation bursts) are linearly related over more than 18 orders of magnitude (see the figure). This observation leads us to the conclusion that the shortest coherent pulse should come from such a large-sized laser. If zeptosecond and perhaps yoctosecond pulses can be produced using kilojoule-megajoule systems, it would open a route to time-resolved nuclear physics exploration and the possibility of peeking into the nucleus interior in the same way that chemical reactions or atoms can be probed today.

The motivation underpinning the push toward such extreme power (*2*) is not only ultrahigh laser intensity and the associated field that could be attained, but also the prospect of producing exceedingly short bursts of energetic radiation and particles. Since the first laser demonstrated by Maiman in 1960 (*3*) that operated with kilowatt-scale peak powers and internal intensity in the kW cm^{-2} range with an overall pulse duration in the microsecond regime, the continual developments in laser design have produced peak intensities exceeding 1 TW cm^{-2} with pulses 10 fs or shorter (*4*–*6*). At this point, the pulse bandwidth for the broadest bandwidth amplifying material, Ti:sapphire.

Shorter pulses need to acquire a broader spectrum before they can be recompressed. This is accomplished in a gas-filled hollow fiber (*7*) that can achieve the single-wavelength limit of 2.6 fs for 800 nm. To go to even shorter than one light period, higher frequencies must be generated. This is done by high harmonic generation (*8*) in a gas jet. The laser intensity is increased by focusing the compressed pulse beam after the fiber and the compressor. A fraction of the harmonic spectrum is selected to produce pulses down to 0.08 fs (*9*).

If we want to obtain even shorter pulses, we need to resort to even higher intensities, leave the nonlinear bound electron regime, and enter the high-energy relativistic regime, which is greater than 10^{18} W cm^{-2} for a wavelength of 1 μm. In this relativistic regime, the strength of the laser field propels the electrons to such high speeds that their "mass" changes as they oscillate. A laser pulse producing this intensity will make the target surface electrons oscillate in and out at relativistic velocity. As a consequence, any light hitting this oscillating mirror is modulated periodically, resulting in the generation of high harmonics (*10*, *11*). Relativistic high harmonic generation gives the prospect of a much broader



Shorter, more intense. An inverse linear dependence exists over 18 orders of magnitude between the pulse duration of coherent light emission and the laser intensity. These entries encompass different underlying physical regimes that exhibit molecular, bound atomic electron, relativistic plasma, ultrarelativistic, and vacuum nonlinearities. Blue patches represent experimental data; red patches denote simulation or theory.

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harmonic spectrum, and this has been experimentally verified (*12*) using the long pulse duration (300 fs) of the Vulcan laser at the 3200th harmonic order.

In a related scheme based on a pulse of a few cycles (*13*), the relativistic mirror ceases to be planar and deforms because of the indentation created by the focused laser beam. As it moves, simulation shows that it simultaneously compresses the pulses but also scatters them in specific directions. This technique may lead to an elegant method for both compressing and isolating individual attosecond pulses. For intensities on the order of 10^{22} W cm^{-2}, the compressed pulse could be on the order of only a few attoseconds. Such short, intense pulses could provide a way to produce beams of x-rays or even γ-rays by scattering the pulses off of bunches of free electrons. A similar concept called the "relativistic flying mirror" has been advocated and demonstrated (*14*), using a thin sheet of accelerated electrons. Reflection from this relativistic mirror leads to a high efficiency and pulse compression.

When one wishes to go to the γ-ray regime, the mirror that compresses the laser into γ rays must be of extremely high density (~10^{27} cm^{-3}) so that the laser may be coherently reflected into γ photons. One possibility is to use a combination of the relativistic flying mirror with the implosion of this flying mirror so that its density may be enhanced by a factor of 10 in each dimension (thus by a factor of 1000 in its density). This may be achieved by a large energy pulse (~1 MJ) at the ultrarelativistic intensity of 10^{24} W cm^{-2} on a partial shell of a concave spherical target. This imploding ultrarelativistic flying mirror (*15*) would be capable of coherently backscattering an injected 10-keV coherent x-ray pulse into a coherent γ-ray pulse with a duration of 100 ys (10^{-22} s).

We know that matter exhibits nonlinearities when irradiated with a strong enough laser; the manifested nonlinearities vary depending on the strength of the "bending" field (and thus the intensity). The stronger we bend the constituent matter, the more rigid the bending force we need to exert; the more rigid the force is, the higher the restoring frequency (or the shorter the time scale) is. The nonlinearities of matter may vary, but this response is universal, ranging over molecular, atomic, plasma electronic, ionic, and even vacuum nonlinearities.

The observed correlation between laser pulse intensity and duration over 18 orders of magnitude provides an invaluable guide for the development of future laser systems for ultra-intense and short-pulse experiments. Most notably, the correlation shows that the shortest coherent pulse in the zeptosecond-yoctosecond regime should be produced by the largest lasers such as ELI, the National Ignition Facility, and the Laser Mégajoule facility under construction in France, if they are reconfigured (*16*) as femtosecond pulse systems.

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CHEMISTRY

The Chlorine Dilemma

Chlorination of drinking water and municipal wastewater can create toxic chemical by-products, but alternatives pose their own set of hazards.

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Chlorine disinfection has been instrumental in the provision of safe drinking water, but the use of chlorine has a dark side: In addition to inactivating waterborne pathogens, chlorine reacts with natural organic matter to produce a variety of toxic disinfection by-products (DBPs). Regulatory guidelines were established in the United States for DBPs, such as chloroform, shortly after they were discovered in chlorinated drinking water in the mid-1970s, and the discovery of a potential link between DBPs and increased rates of miscarriages and bladder cancer led to more stringent regulations and substantial changes in the operation of water treatment systems during the past decade (*1*). These concerns and the risks associated with storing chlorine gas have recently led many drinking-water and wastewater treatment plants to discontinue the use of chlorine disinfection (see the figure). A series of recent studies suggest that some of these changes have had unintended consequences that pose risks to public health and the environment.

Chlorine DBPs can be controlled in drinking-water systems by more effective removal of natural organic matter—the main precursors of DBPs—through physical-chemical treatment processes such as enhanced coagulation and activated carbon filtration. Although these approaches are effective and pose no known health risks, they are generally the most expensive way of minimizing DBP formation. As a result, many utilities worldwide have opted for the less expensive approach of using chloramine. This less reactive form of chlorine is produced by adding excess ammonia to water before addition of chlorine.

One unexpected consequence of this substitution has been the production of a different set of toxic DBPs. Most notably, carcinogenic nitrosamines such as *N*-nitrosodimethylamine (NDMA) are produced when chloramines react with nitrogen-containing organic compounds (*2*). Formation of NDMA was first recognized at advanced water reclamation plants where chloramine was being used to disinfect sewage effluent before its passage through mem-

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