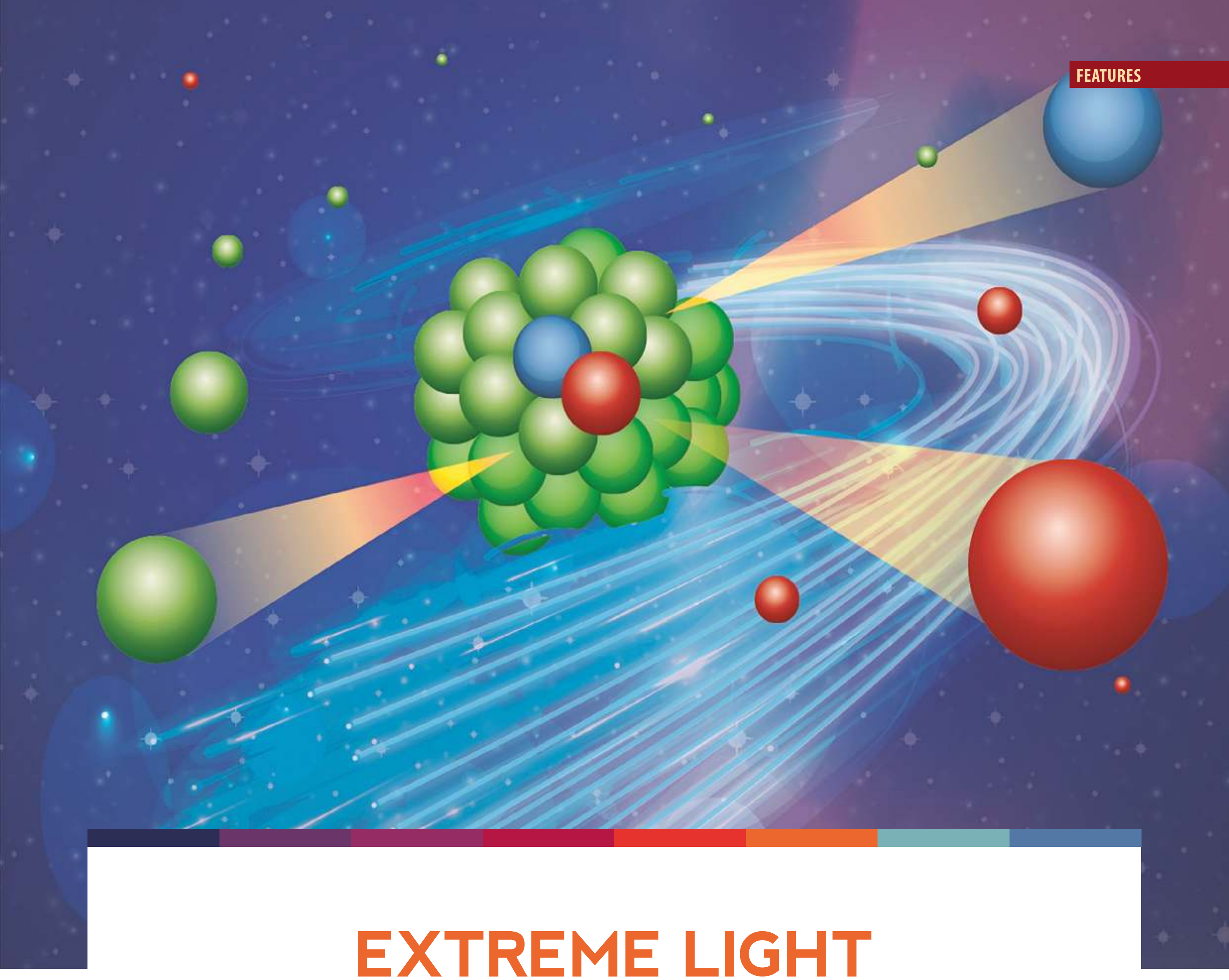

EXTREME LIGHT

AN INTENSE PURSUIT OF FUNDAMENTAL HIGH ENERGY PHYSICS

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By the compression of petawatt pulses to multi-exawatt, a new route for the generation of Schwinger intensities capable of producing high-energy radiation and particle beams with extremely short time structure down to the attosecond-zeptosecond regime is being presented. Far from the traditional laser investigation in the eV regime, this laser-based approach offers a new paradigm to investigate the structure of vacuum and applications to subatomic physics.

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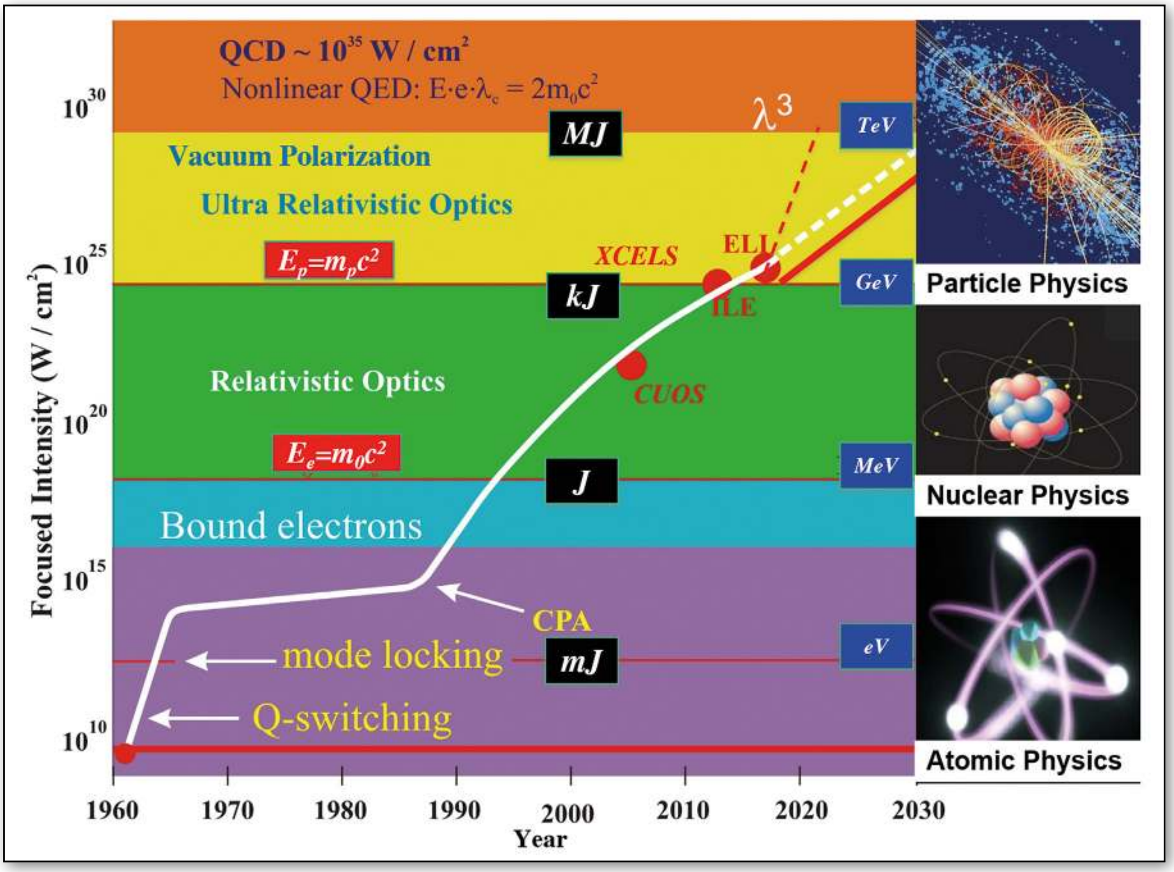
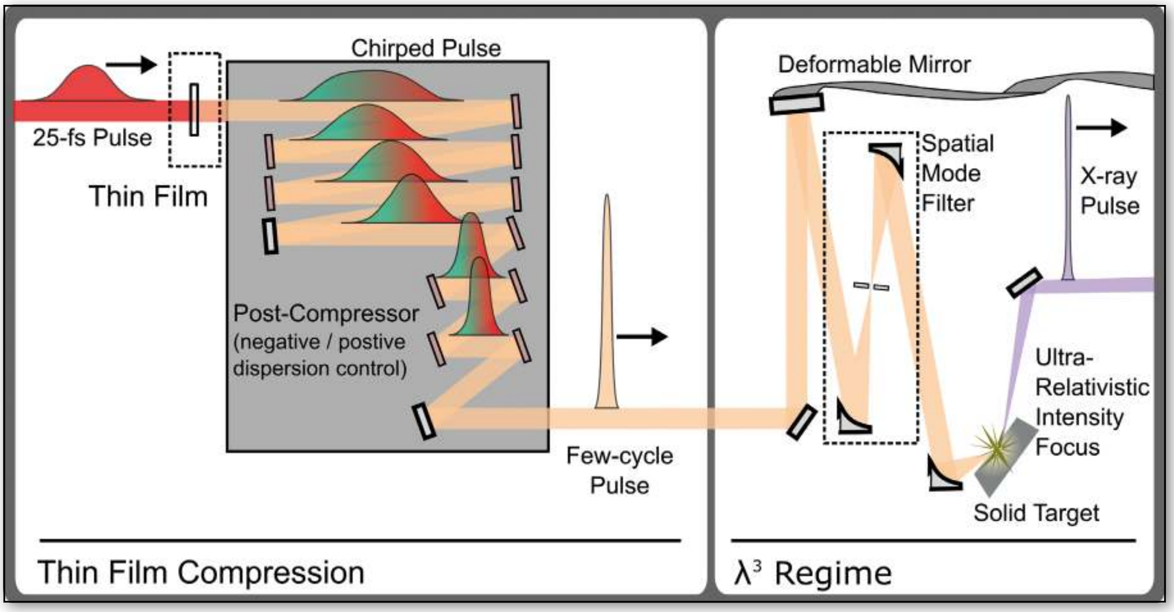
Over the past 30 years peak laser power has progressed to the petawatt (10^{15} W) and is expected soon to reach 10 PW. A level considered as the limit not only in power but also in size and cost. Recently, it was realized that the peak power could not be increased only by increasing the energy but by dramatically decreasing the pulse duration to the subattosecond time scale while maintaining the energy at the 10-1000 J level, corresponding to peak power improvement of several thousand times. The extraordinary large peak power will provide accelerating gradient 6 orders of magnitude higher than can be accomplished with RF based accelerators. Fundamental subatomic physics and applications have been hitherto, mainly driven by high energy fermionic beams and it is heady to think that a 10 km TeV accelerator could fit on the top of one finger. This is a feat likened to electronics where over the same period of time (1950-today) centimeter sized vacuum tubes have been replaced by the nanometer-scale transistor. This opportunity will radically transform the laser field hitherto centered mostly in atomic physics or eV physics. A revolution to the field will make accessible new regimes of physics dealing with the physics of TeV energies and beyond, cosmos acceleration, vacuum nonlinearities, light-mass weak coupling fields such as, dark matter and dark energy, nonlinear QED and QCD fields, radiation physics in the vicinity of the Schwinger field, zeptosecond dynamical spectroscopy of vacuum, as well as affordable proton sources for proton therapy . For scientists the applications will be innumerable, based in particular on laser wakefield acceleration (LWFA) providing abundant sources of protons, neutrons, neutrinos, muons, and gamma-rays [2].

The Ultra-Intensity Pursuit

Since its invention the laser has been ideally suited to focus on atomic physics, or eV physics of electronic interactions. With the advent of Chirped Pulsed Amplification (CPA) [3] and later Optical Parametric CPA (OPCPA) there has been a considerable leap in peak power and intensity of 6 to 8 orders of magnitude, peaking from 10^{15} W/cm^2 to 10^{22} W/cm^2 or 4 orders of magnitude above the level where the electron quiver energy equals the rest mass energy of the electron, associated with pulse intensities of 10^{18} W/cm^2. Above this limit is the relativistic regime of the electron and the threshold for subatomic

▼ FIG. 1: Laser Intensity through the years. Note the steep slope in intensities that occurred during the 1960s. This period corresponded to the discovery of most nonlinear optical effects due to the bound electron. We are today experiencing a similar rapid increase in intensity opening up a new regime in optics dominated by the relativistic character of the electron freed through photoionization. A few years ago we called it high intensity when the electron in a quiver energy was around 1 eV. Today high intensity corresponds to electron quiver energies of the order of mc^2 ~0.5 MeV. The dashed line corresponds to what could be obtained with significant increases in beam size or by increasing the number of beams. The red-dashed line corresponds to the "short cut" obtained using the double-compression technique.





▲ **FIG. 2:** Two Stages of Compression. The Thin Film Compression stage relies on the interplay between the spectral broadening produced by self-phase-modulation and the group velocity dispersion necessary to stretch the pulse in a sub-millimeter, large aperture material. The combination of both effects contributes to create a linearly frequency-chirped pulse with increased spectral content compared to the initial pulse that can be compressed using dispersive elements such as chirped mirrors. The second stage of compression requires delivery of the single-cycle pulse with appropriate tight focusing quality to produce and apply a compressed pulse with an ultra-relativistic intensity to a solid target plasma emitting X-rays by up-conversion.

physics including nuclear and particle physics. The next intensity level leads to a quiver energy equal to the proton rest mass, or 10^{25} W/cm^2. It is these enormous intensities that are attempted to be delivered by the various large-scale European laser infrastructures such as those being built at ELI, LMJ and Apollon, as well as others in Russia, China and Korea. These facilities rely on CPA/OPCPA technology housed in 100 m size buildings and have reached the affordable limits to modern techniques in terms of size and cost. To explore the regime up to the Schwinger intensity (10^{29} W/cm^2) —defined as the intensity threshold for vacuum electron-positron pair production—requires an additional 3-4 orders of magnitude increase in pulse energy and is well beyond what is currently affordable. A radical change in technology is required to truly make this dramatic leap.

The method proposed is to efficiently compress pulses with tens of joules to sub-attosecond (10^{-18} s) durations and tightly focus over a spot size such that the peak intensity will be in the Schwinger range of 10^{29} W/cm^2. Note that by using a Fourier-Heisenberg argument, the subattosecond pulses are composed of a spectral range containing keV energy X-ray photons. The strategy that we have adopted for the efficient production of high energy subattosecond pulses is done in two steps depicted in Figure 2. The compression technique will first shorten a typical 20 fs, 20 J near-infrared (NIR) pulse into a single-cycle while maintaining upwards of 15 J of energy. The second step utilizes a relativistic plasma mirror to drastically compress the pulse from 2.5 fs to the attosecond and even the zeptosecond (10^{-21} s) regimes.

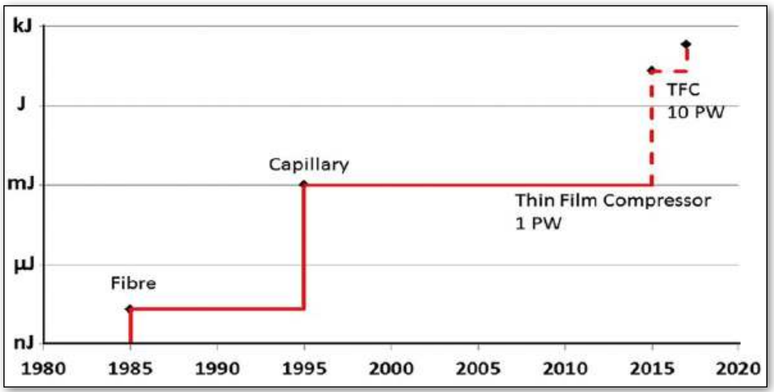
Current compression techniques rely on a fused silica hollow-core capillary, filled with noble gases for the spectral broadening required but the resulting pulse energies from these schemes are typically limited to the sub-mJ level. To go higher in energy, bulk compression was attempted by Corkum and Rolland [4] with the pulse free-propagating rather than guided. The pulse was relatively long around 90 fs with an input energy of 500 μJ leading to an output pulse of 100 μJ in 20 fs. As the material nonlinearity is strongly influenced by changes in the beam intensity, this scheme is impaired by the Gaussian intensity profile of the beam. A non-uniform broadening develops compounds with small-scale intensity features. These make the pulse impossible to compress uniformly except in the peak region of the beam that can be considered as constant. This crucial limitation to the efficiency frustrated the initial attractiveness of this arrangement.

To solve the uniformity problem we have recently proposed a new scheme for compression to the single cycle regime suited for high energy pulses in the tens of Joules level. This Thin Film/Plate Compressor [5] relies on the fact that current high energy and short pulsed lasers are designed to produce top hat pulses in amplitude and phase for efficient energy extraction. Using thin and inexpensive sheets of plastic, or alternatively thin, sub-millimeter glass plates, it has been shown through numerical simulations that we can produce identical self-phase-modulation across the beam that would lead to a uniform pulse compression. Plastic is the ideal candidate as it is much cheaper to fabricate than quartz and glass at the required thicknesses of a fraction of a millimeter but modern glass making may allow for appropriate candidate substrates as well. The large aperture (~0.5 m) material must be capable of withstanding high intensity laser shots without breaking while being easily replaceable as it degrades with use. Note that the thickness needs to be uniform but not necessarily flat to be effective as the nonlinear material. Numerical simulations were carried out assuming a plastic film interacting with a laser similar to that recently commissioned at the CETAL PW laser facility based at the Institut National de Laser, Plasma et Radiophysique (INFLPR) in Magurele, Romania [5, 6] and experimental plans are underway to test the conclusions of these simulations. This CPA laser system is designed to deliver 27 J of energy within 27 fs yielding a 1 PW laser pulse at a wavelength of 800 nm. Once focused to a diffraction limited size this single cycle pulse should belong the so called Relativistic λ^3 regime [7].

“This laser-based approach offers a new paradigm to investigate the structure of vacuum and applications to subatomic physics using ultrashort, coherent keV x-ray.”

The application of such a relativistic intensity field to a solid target plasma is what gives rise to the dramatic compression and photon up-conversion of the ultrashort NIR pulse to an even shorter X-ray pulse. A laser-driven reflective surface within the plasma that moves in and out under the influence of the incident pulse acts as a so-called relativistic mirror. In this relativistic regime Naumova *et al.* [7] predicts a reflected pulse duration T—compressed by the relativistic motion of the mirror toward the pulse—scaling as $T = 600$ (*attosecond*)/a_0. Here a_0 is the normalized vector potential of the laser pulse, which is unity at 10^{18} W/cm^2 and scales as the square root of the intensity. Considering the scaling for an incident intensity of the order of 10^{22} W/cm^2 the pulse reflected from this high efficiency relativistic mirror is predicted to be compressed and necessarily up-converted in photon energies to achieve coherent keV X-ray pulses at the exawatt (10^{18} W) level power. A modest 1 J of reflected energy contained within an attosecond pulse duration is sufficient to produce an exawatt pulse. Any compression achieved below this timescale relaxes the energy requirements to produce similar powerful pulses.

▾ **FIG. 3:** Evolution of Pulse Compression in the single cycle regime. Early work by Grischkowsky *et al.* [9] compression technique which relies upon the nonlinear response of a material to a high intensity pulse within a single mode fiber. In their experiment a picosecond pulse with nJ energy was further compressed to a duration of tens of femtoseconds. This work triggered an enormous interest that culminated with the introduction by O. Svelto, F. Krausz et al [10] of a fused silica hollow-core capillary, filled with noble gases and demonstrated that a 20 fs pulse can be further compressed to 5 fs, or 2 cycles of light, at 800 nm. Due to the energy losses associated with coupling the laser pulse spatial mode into a single-mode fiber or hollow-core capillary the resulting pulse energies from these schemes are typically limited to the sub mJ level.



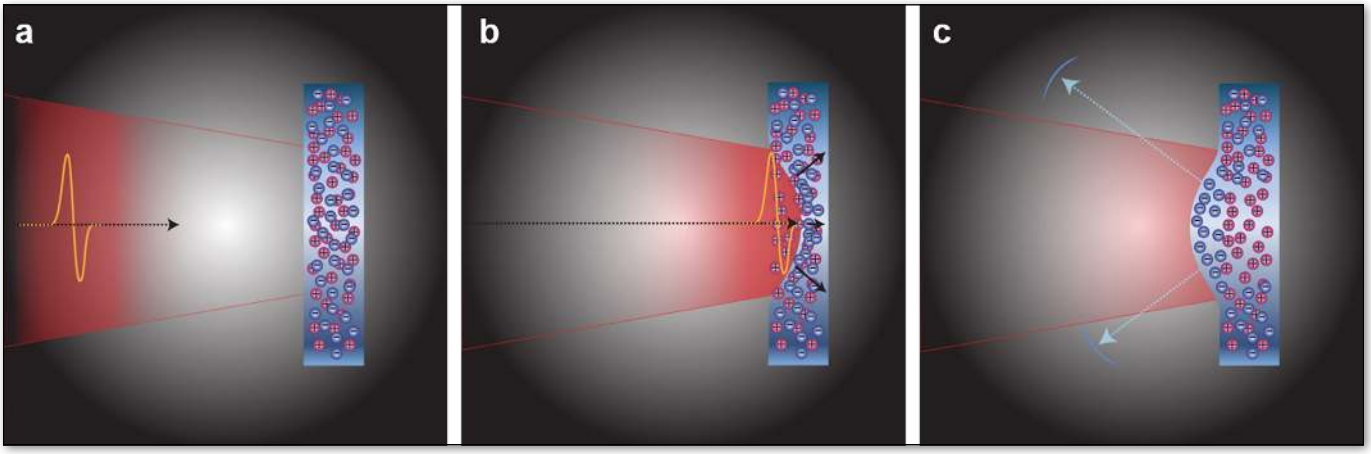
Applications of High Energy, Short Pulses

Nonlinearity of Vacuum. A coherent, exawatt x-ray pulse that can be focused tighter than current NIR laser systems is capable of reaching the Schwinger intensity and produce sizable nonlinearities in vacuum due to the expected pair production. This is even though the nonlinear index of refraction of vacuum is 18 orders of magnitude smaller than that of a typical optically transparent medium such as glass. In treating the pair production process as a nonlinear index it is fascinating to imagine the physics of vacuum nonlinearity to pulse compression, self-focusing and the generation of filaments in vacuum analogous to those produced in air by NIR pulses [8]. The properties would be limited by "vacuum breakdown" or pair creation as the intensity approaches 10^{29} W/cm^2.

Giant Laser Wakefield Acceleration in Solid: CERN on a chip! The high frequency photons offer the advantage of driving wakefields in high density matter. The critical density of a plasma, n_c, is defined by a given laser frequency and increases with increasing photon frequency or energy. For 1eV optical photons, n_c is about 10^{21} /cc, while for X-ray photons of 10 keV n_c is about 10^{29} /cc and is well above solid densities. In LWFA, the energy gain is limited by the critical density of the plasma with the high intensity LWFA energy gain given by

$$\varepsilon_e = a_0^2\, mc^2 (n_c/n_e),$$

where n_e is the electron density. Therefore going to a higher photon energy allows for a greater achievable energy gain. An important benefit of a higher density plasma is that it supports a larger acceleration gradient. Shifting to extreme X-ray driven wakefield acceleration dramatically allows the acceleration to larger energies to be achieved over shorter distances suggesting TeV energies over centimeter distances. The accelerating lengths of the order of TeV/cm are 10^3 times larger than previous results achieved for optical lasers in gases and 10^6 times that of current radiofrequency technology. They suggest acceleration performances to levels achieved only at CERN,



▲FIG. 4: Reflection from a Relativistic Mirror. (a) A high intensity single-cycle pulse encounters a solid target plasma and (b) pushes the plasma electron critical density surface further into the plasma until the laser field reaches equilibrium with the electrostatic potential that has developed between the displaced electrons and stationary ions to pull the critical surface back so that (c) a portion of the incoming pulse is compressed as it is swept up by its encounter with this relativistically moving reflective surface. Deformations in the target surface due to the shape of the focus help to spatially isolate portions of the reflected beam.

in Geneva not over kilometers, but over a few centimeter focus and supported by a laser facility such as the PW level facilities currently being built.

Conclusion

Modern high peak power laser producing PW and 10PW pulses with top hat distribution, combined with Thin Film/Plate Compressor could have the capability to produce 100 PW pulses with single cycle or 2.5 fs. Focused on a spot size limited by the laser wavelength, their interaction with solids is expected to generate attosecond or even zeptosecond multi-exawatt pulses in the X-ray regime with the acumen to drive giant acceleration in crystal in the TeV/cm regime. This would form the basis of an all-optical high energy physics field providing the means to investigate vacuum structure, dark matter, dark fields and the like. In addition the technology could underpin new compact sources of protons, neutrons and muons with applications in fundamental physics and societal applications like proton therapy or nuclear waste transmutation. ■

About the authors

Gérard Mourou is a Professor Haut College at the École Polytechnique and Director of the International center for Zetta-Exawatt Science and Technology (IZEST). He is also an Emeritus Professor of the University of Michigan. He is the recipient of numerous awards including the 2009 Charles H. Townes Award from The Optical Society.
Toshiki Tajima is the Norman Rostoker Professor at University of California at Irvine and is well known as the inventor of laser electron acceleration in 1979. He is Deputy Director of IZEST, Chairman of International Committee for Ultrahigh Intensity Lasers (ICUIL), and spokesman of the Collaboration THEXAC (Transformative High Energy X-ray Acceleration in Crystal). He has received many awards, including most-recently the 2015 Enrico Fermi Prize.

Jonathan A. Wheeler is currently a researcher with IZEST based at École Polytechnique who has studied ultrafast attosecond physics during his post-doctoral work at CEA-Saclay, Laboratoire d'Optique Appliquée. He got his Ph.D. at the Ohio State University.

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