

# Probing the quantum vacuum with ultra intense laser pulses

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**Abstract.** This article presents 1) The theoretical background of strong field physics along with vacuum structure and stability; 2) The instrumental developments in the area of pulsed lasers and considers the physics case for the construction of ultra-intense laser facilities; and 3) The applied and fundamental uses of ultra-intense lasers.

## 1 Introduction

We survey the use of high intensity lasers in the exploration of the fundamental properties of the vacuum and particle acceleration. The rapid technological advance in laser pulse technologies creates hope that in the foreseeable future it will be possible to reach laser intensities allowing exploration of empty space, the vacuum, under the influence of laser pulse strong fields. In the next generation of high intense laser facilities, the peak power will approach the exawatt regime. That is 100 000 times the world grid power, albeit compressed into a brief instant. This will help produce high energy radiation and particle beams with an extremely short time structure, thus offering a new paradigm for the exploration of the structure of vacuum. It will also help respond to some of the most fundamental questions: how can light propagate in vacuum, how can vacuum define the speed of light and how can it define the mass of all elementary particles. We also present an extended discussion of the current status of high intensity laser pulse production. Particle production in “empty” space is the historical path which guides our interest and continues to motivate our study of the “nothing”, the vacuum.

### 1.1 Vacuum and the aether

The word “vacuum” derives from the ancient Greek “distance, interval” and more specifically, the question if the Earth and the Moon are separated by a void, i.e. empty space which we now call “vacuum.” It is the word “chaos” which was the prequel for this emptiness. The word chaos, due to its association with creation myths, mutated to mean the disorder filling the empty space. The word “aether” is the pure air breathed by Gods in the Greek mythology, the 5th element (quintessence) of Plato

and Aristotle. This “aether” is today “dark energy”: we believe that the Universe is pushed apart by the dark energy which accounts for 70% of all present day energy content in the Universe. This dark energy is not divisible and thus not ponderable, yet its presence is very tangible.

The present day context was anticipated by Albert Einstein, who in his renown Lorentz Lecture of 1920 [1] stepped back from his early criticism of the aether, and wrote in conclusion: *Recapitulating, we may say that according to the general theory of relativity space is endowed with physical qualities; in this sense, therefore, there exists an aether. According to the general theory of relativity space without aether is unthinkable; for in such space there not only would be no propagation of light, but also no possibility of existence for standards of space and time (measuring-rods and clocks), nor therefore any space-time intervals in the physical sense. But this aether may not be thought of as endowed with the quality characteristic of ponderable media, as consisting of parts which may be tracked through time. The idea of motion may not be applied to it.*

Only the original conveys the exact meaning intended by the author. Thus we reproduce this pivotal paragraph in the original German: *Zusammenfassend können wir sagen: Nach der allgemeinen Relativitätstheorie ist der Raum mit physikalischen Qualitäten ausgestattet; es existiert also in diesem Sinne ein Äther. Gemäß der allgemeinen Relativitätstheorie ist ein Raum ohne Äther undenkbar; denn in einem solchen gäbe es nicht nur keine Lichtfortpflanzung, sondern auch keine Existenzmöglichkeit von Maßstäben und Uhren, also auch keine räumlich-zeitlichen Entfernungen im Sinne der Physik. Dieser Äther darf aber nicht mit der für ponderable Medien charakteristischen Eigenschaft ausgestattet gedacht werden, aus durch die Zeit verfolgbaren Teilen zu bestehen; der Bewegungsbegriff darf auf ihn nicht angewendet werden.*

## 1.2 Light propagation in the vacuum

This was the year 1920; quantum physics was not yet discovered. Einstein could not yet know that the classical space, free of matter, is filled with quantum fluctuations. Einstein’s aether can have structure, being the ‘quantum vacuum, and this vacuum defines, for example, how light propagates, as noted first by Werner Heisenberg and his collaborators [2,3] and Victor Weisskopf [4]. The quantum fluctuations in the vacuum allow light-light scattering and the conversion of electromagnetic field energy into particle and antiparticle pairs.

In particular, a light quantum, a photon, traveling in the vacuum, can fluctuate into a particle–antiparticle pair. This pair is virtual, and since the energy of a single light photon is much smaller than that of a material particle pair, we say, the pair is “off-mass-shell”. This transmutation of a photon into a virtual pair and back, is called vacuum polarization since this process also alters the nature of the Coulomb law at short distances.

If a second photon arrives just when the first photon exists in its electron–positron pair state, it can scatter from this virtual charged particle pair. In this way, light scatters light. In a direct extension of this argument, a strong electromagnetic field applied in the vacuum can deflect the virtual electrons and positrons. Therefore, there is an index of refraction of empty space filled with fields. In principle, light can be bent by applied electro-magnetic fields just as it can be by gravity; the deformation of space-time geometry bends light.

In this sense empty space has a structure. Because the Compton wavelength of an electron,  $\hbar/mc = 386$  fm (fermi=femto meter=one in  $10^{15}$  part of a meter, the radius of a proton) is 3 million times shorter than a typical optical wavelength, vacuum structure does not massively obstruct the propagation of light. However, light

propagating in the Universe over cosmological distances experiences nonlinear vacuum effects, such as photon splitting, in the presence of external magnetic fields. For our considerations, it is important to recall that mid-last century Julian Schwinger showed explicitly that a coherent ideal “plane light wave” cannot scatter from itself, or be influenced by itself, no matter the field intensity [5]. This is the only form of light known to which the vacuum is exactly transparent.

### 1.3 Elementary particle mass

By a natural extension of the argument presented by Einstein, the vacuum not only defines the velocity of light and how light propagates, but it defines the masses of all elementary particles. There are two ‘standard’ particle model mechanisms of mass generation:

1. Fermi’s weak interactions have been unified with electromagnetic interactions – the mechanism of this unification includes the recently experimentally-confirmed Higgs particle. This particle of mass  $M_H = 125$  GeV comes along with a large vacuum energy scale  $\langle h \rangle v = 246 \simeq 2M_H$  GeV. All elementary particles are thought to derive their mass as a specific fraction of  $\langle h \rangle$ . Thus a change in vacuum expectation value  $\langle h \rangle$  of the Higgs field would naturally alter inertial mass of all particles.
2. The strong interactions provide the actual mechanism explaining the inertial mass of visible matter. The mechanism which confines quarks into a small space domain, and thus assures “color confinement, generates via the quantum zero-energy the dominant part of the mass of all matter in our Universe”.

In both cases, the physical properties of the aether encode the information which is needed to define the particle mass, indeed the mass and thus, via the equivalence principle, the gravity of visible matter. The vacuum is the carrier of the elementary mass-energy scales. In that sense, aether exists and is in fact the frontier of experimental and theoretical research today.

### 1.4 A short history of the Universe

The quantum vacuum structure we address is present all over the Universe. Let us look back to the time about 1/100 000 of a second after the Big Bang, when the temperature was higher than about  $kT > kT_{cr} = 0.15$  GeV. We find quarks which can move freely in the “deconfined” Universe in which nucleons are dissolved and their constituents, quarks, roam freely. At that early time the Universe was nearly symmetric with respect to quarks and anti-quarks, up to the tiny nano-scale matter asymmetry. The residual matter surrounding us is this asymmetry, a remnant from this epoch, after most matter and antimatter annihilated.

The partners of quarks are the very light electrons which at that stage of the early Universe already possessed the properties that we know today. Contrary to intuition, the heavy particles, protons and neutrons, turned out to be more fragile: they entirely dissolve in the quark-gluon phase. The drastic change of one property of the vacuum, the melting of confinement, does not imply that all or any other properties are impacted, much the same as it is with material systems.

Well beyond the conditions in which the strong interaction vacuum melts, at 1000 times higher temperature the electro-weak vacuum will melt and we expect that all visible particles we know of lose their mass. It is believed that at that early . . . time – on the scale of a nanosecond or shortly before – physical processes were active

which led to the formation of the matter-antimatter asymmetry that sustains our existence.

Research into the origin of matter in the Universe relies on ideas that the form of matter present is dependent on ambient conditions and specifically the temperature, and that the matter-antimatter asymmetry was created in a different “molten” vacuum state, present in the early Universe following the big-bang. It is commonly believed that even at this matter-generating high temperature that dark matter plays mostly a spectator role, considering its weak coupling with visible matter. When exactly dark matter decoupled from visible matter is subject to an intense debate at present.

### 1.5 Recreating the early Universe in the laboratory: Heating the vacuum

If we are ever to understand the mechanisms of matter creation and matter stability we need to find a way to study the vacuum experimentally. The study of vacuum structure is, by necessity, focused on experiments involving a small domain of space-time. This follows considering the Stephan-Boltzmann law which allows us to evaluate how much energy is needed to heat a given empty volume to a prescribed temperature.

As temperature rises, we first excite electron and positron pairs, then heavier particles, and at unexpectedly low temperature, with  $kT$  being 6 times lower than the energy-mass equivalent of the proton, we melt the vacuum structure and free quarks replace protons. One must, however, remember that this “low” temperature we talk about is far above that possible even in the center of heavy stars and neutron stars. The lifespan of the hot vacuum in the laboratory is limited by speed of radiative cooling and heat flow dynamics and it is generally accepted that it cannot be longer than the light needs to cross the diameter of this domain.

Particle accelerators offer access to this quark-gluon plasma (QGP). In collisions of heavy ions at RHIC-BNL, (NY, Long Island) and at CERN (Geneva, Switzerland), the heated strongly interacting matter reaches temperatures which “melt” the confining vacuum structure. This is done by accelerating the heaviest atomic nuclei to the highest energies possible. In most head-on collisions the two clouds of 500 quarks which make up a heavy atomic nucleus collide, and experiments show that the energy available in the collision is thermalized. That means that instead of a few high energy particles we observe many thousands of newly produced particles which share in the total energy available.

The QGP domain is of the size of an atomic nucleus, large on the scale of the proton size, but extremely small compared to our dimensions. For this reason the energy needed to form the QGP is below 10 erg (6.24 TeV). The thermal energy content scales with the fourth power of the temperature, and the third power of the radial size. In order to reach the 1000-times higher electro-weak transition temperature in a volume with 10-times smaller radius, an energy content which is a billion times higher, that is at the level of a few kJ will be required.

No particle accelerator we can imagine could possibly deliver the required energy to such a small volume. Even if we were to build a solar system accelerator, fundamental properties of strong interactions which are increasingly weakening at high energies (“asymptotic freedom”) limit the amount of usable thermal energy available. However, kJ is well within the energy content available in ultra high intensity pulsed lasers. The technological challenge here is to find a way to focus a good fraction of the pulse energy into an elementary particle volume. In this way we could reach the energy concentration required for the study of early Universe physics beyond quark-gluon plasma, that is the electro-weak vacuum structure, baryon stability, and even quintessence, the aether.

On the way to this very extreme concentration of energy a field mired in physical and technological problems challenges us. The focus of 1 kJ of energy into a 10,000 bigger radius  $0.1 \text{ \AA}$  will allow the formation of a near atomic size deconfined quark-gluon plasma phase which has a longer lifespan, allowing the equilibration of electromagnetically interacting particles with the quarks. Absence of matter brought in by e.g. colliding nuclei results in a more symmetric matter – antimatter condition akin to that of the early Universe.

However, while the target radius is 10,000 times larger than in typical accelerator experiments, it is also 10,000 times smaller than typical focal radii achieved by ultra-high intensity lasers today. The achievable focal radius of a laser is, for a single beam limited by its wavelength, which currently is in the optical/near-IR regime,  $\simeq 1 \mu\text{m}$ . However, in collisions of many phase-synchronized laser beams it is possible to reduce the size of the focal volume well below the diffraction limit. We cannot discuss here in any detail the design of such a futuristic system. However, it will resemble NIF or MegaJoule in that it will involve 100's of concentric beams which will need to be phase locked, a technological challenge that is already addressed today in the context of the ICAN project.

If such a system can be realized, a plethora of physics becomes available for experimental exploration, and, of course, we can still carry out a most interesting experimental research program as the energy density in the focal area increases and the size of the focal area shrinks. As an example, even for the rather “large” nano-size focal domain, we still reach temperatures 100s time greater than that in the center of the Sun. Here we will be able to form in the vacuum a hot electron-positron-photon plasma. This should allow exploration of a domain of plasma physics otherwise beyond our reach. Moreover, such a time-pulsed state is an intense source of heavier particles, muons and pions.

## 1.6 Vacuum stability and pair production

The gap between the valence and conduction band of the best insulator, the vacuum, is twice the energy equivalent of the electron mass,  $V_0 = 2mc^2/e = \text{one million Volts}$ . Such high potential differences are commonly achieved in specialized nuclear accelerators (Tandems, van der Grafs), although over a rather large distance. The vacuum does not begin to spark since the electron-positron pair must materialize on two ends of the potential well and this is a macroscopic distance apart for laboratory devices. The electric field strength controls the speed of the vacuum sparking.

The field strength for which this vacuum decay occurs at the zepto-second scale (light travels a distance of the Compton wavelength  $10^{-12} \text{ m}$  in 10 zeptoseconds) is the so called “Schwinger” critical strength,  $E_s = 1.3 \times 10^{18} \text{ V/m}$ , for which the potential step  $V_0$  arises over the electron's Compton wavelength. The critical field is named after Schwinger, though Heisenberg-Euler first gave the result. However, Schwinger did discuss the vacuum decay rate in greater depth, providing the full interpretation of the result and derived the more general formula applicable to the case when both electric and magnetic fields do not vanish.

Achieving this Schwinger field strength,  $E_s$ , is a clearly defined objective of all high intensity laser facilities. This corresponds to an intensity  $I_0 = 4.65 \times 10^{29} \text{ W/cm}^2$ . The corresponding laser power when this intensity is considered within the typical focal domain of  $\mu\text{m}^2$ , this value is  $P_0 \simeq 4.65 \times 10^{21} \text{ W}$ , that is 4 650 EW ( $E = \text{exa} = 10^{18}$ ). An approach to reach this regime is described below. EW-class laser systems are reaching the experimental design stage. For comparison, today one can buy an off-the-shelf PW-class ( $P = \text{peta} = 10^{15}$ ) laser system.

Following the work of Heisenberg and Schwinger of 60–70 years ago we know (but often ignore) that any macroscopic electric field is in a metastable state, a state is capable to rapidly decay into particle pairs just as a radioactive isotope decays. Akin to the radioactive decay, the process of field conversion to pairs involves tunneling, and thus, as the macroscopic field decreases, the lifespan increases rather rapidly. For a field of strength  $E_s/30 = 5 \cdot 10^{16}$  V/m the lifespan is at the level of the lifespan of the Universe  $\simeq 10^{21}$  s, which means that for all practical purposes such laboratory field configurations are stable.

For fields closer to the Schwinger value  $E_s$  we can observe massive materialization of pairs for fields existent at time scale of fs to as ( $10^{-15}$ – $10^{-18}$  s). The materialization of electrical fields into electron-positron pairs is a diagnostic tool allowing us to reach an understanding how well we achieve the best laser energy focus. The abundant formation of electron-positron pairs is the first of many vacuum effects we will be looking for as we strive to focus the laser energy into smaller and smaller volumes.

## 2 Pulsed lasers

### 2.1 The making of the ultra high intensity lasers: CPA

All ultrahigh intensity lasers systems are pulsed lasers. Instead of emitting a continuous wave (cw) of light as, for example, a presentation laser pointer, they emit pulses of light of short duration. There are three principle parameters to consider when discussing ultra-intense lasers: the total pulse energy  $E_{\text{pulse}}$ , the pulse duration  $t_{\text{pulse}}$  and the achievable focal size  $F = \pi R_{\text{focus}}^2$ , where the light wavelength limits the focal radius  $R_{\text{focus}}$ . From these three parameters then follows the achieved intensity:  $I = E_{\text{pulse}} / (t_{\text{pulse}} \cdot F)$ . According to Maxwell equations, the laser intensity is proportional to the square of the field strength present in the pulse.

This field strength in the pulse is responsible for vacuum instability and thus we are interested in increasing  $I$ . This can be achieved either by increasing the pulse energy, or decreasing the pulse duration and decreasing the size of the focal spot. The spot size for one or a few pulses is irreducibly limited by the laser wavelength. The laser energy and not the power determines the laser size and cost, which prompts one to work with the lowest pulse energy possible. Therefore, the most economical and effective way to reach high peak power pulses would be to amplify the shortest possible pulse. However, this is not possible because as the pulse gets amplified, nonlinear effects due to the large intensity set in. Notably, the index of refraction  $n$  becomes a linear function of  $I$ . This effect will: 1) alter the laser beam quality, making it impossible to focus the beam to a diffraction limited spot size; 2) cause the beam to self-focus into small filaments whose large intensity may irreversibly damage the materials of the component being traversed. So, since the mid-sixties, efficient, ultrashort pulse amplification that would preserve the beam quality, seemed unattainable. However the solution was offered in 1985 with the invention and demonstration of the concept of Chirped Pulse Amplification (CPA) [6].

In CPA, a short pulse is first produced by an oscillator. Its energy is at the nJ level. It is stretched in time by a very large factor up to  $10^6$  by dispersive elements, such as a pair of diffraction gratings. This is possible because of the large amount of Fourier frequencies forming the ultrashort pulse. Each frequency takes a different route, and will take a different time to traverse the dispersive element. Once the frequency components have been dispersed the pulse has been stretched, with the red part of the spectrum ahead followed by the blue part. Note that this operation has not significantly changed the pulse energy content. Consequently, the pulse intensity has dropped in the same ratio, e.g.  $10^6$ , implying that it could be amplified to an energy level

$10^6$  times higher and still remain compatible with the available optical conditions. Because of the low intensity level, the beam quality and the laser component integrity will be preserved. Once the pulse is amplified, it is re-compressed to its initial time structure using a compressor that will exactly undo what had been done by the stretcher. The compressor will reroute the frequencies in such a way that they will all travel an identical optical length throughout the entire system. We can marvel at how well this concept works, if we consider that in modern CPA, the pulse is stretched and compressed by a factor  $10^6$  while in-between it is amplified by a very large factor.

With CPA, the intense and ultra intense lasers performed a quantum leap in achieving shorter pulse durations and therefore higher power and higher intensities. At the moment there are two types of amplifying media:

1. Nd:Glass as laser medium, with pulse durations of ps and pulse energies in the 100 to 1000J range and a shot rate of about one pulse an hour. The first PW system, the now decommissioned Nova PW at LLNL belongs to this class, as does the Vulcan PW (RAL, UK), Gekko PW (ILE, Japan), Trident (LANL, USA), Titan (LLNL, USA), the Texas PW (UTA, USA) and Omega EP (LLE, USA).
2. Ti:Sapphire as laser medium. These systems amplify shorter pulses on the order of tens of fs and correspondingly smaller pulse energies of few Joules, with a shot rate of 10 Hz. 10–100 TW systems of these types are widespread and already commercially available today. Examples of those systems approaching the PW level are the just commissioned Gemini laser (RAL, UK) and the PW system at the Shanghai Institute of Optics and Fine Mechanics (SIOM, China) a PW system at the University of Nebraska, Lincoln (USA) and the PW LUIRE at the ILE (France). All these systems reach intensities on target of  $I = 10^{19}$ – $10^{21}$  W/cm<sup>2</sup>, with the highest published intensity being claimed by the Hercules laser at the University of Ann Arbor (USA), with  $10^{22}$  W/cm<sup>2</sup> which involves a pulse of 10 J, lasting 30 fs.

## 2.2 OPCPA – Optical parametric chirped pulse amplifier

A few years after the advent of CPA an elegant embodiment was demonstrated in which the conventional laser amplifier was replaced by an optical parametric amplifier (OPA). The OPA is an amplification mechanism that relies on nonlinear processes, where pump photons are broken into signal and idler photons. Among the advantages we note, the very high gain per pass, the very large bandwidth and the fact that thermal effects are absent in the amplifying crystal.

But, there are not only pros; among the cons we note: 1) OPCPA needs an excellent pump beam; 2) OPCPA does not store energy, and so requires a precise temporal overlap of the pump and signal pulses and so the pump needs to be in the single nanosecond range, which is quite short; 3) the efficiency is about half that of Ti:sapphire CPA; 4) as a corollary of 2) and 3), the repetition rate will be inherently lower than for a straight CPA. These considerations become dominant for a large scale laser system, where the cost of the system scales almost linearly with the laser energy.

The concept of OPCPA (Optical Parametric Chirped Pulse Amplification) was proposed and demonstrated by Piskarskas et al. [7]. On large systems it was pioneered at RAL. Taking the OPCPA approach to its next level in pulse energy, the Institute for Applied Physics in Nizhny-Novgorod, Russia demonstrated a 0.6 PW, 30 J, 40 fs system. One of the highest power systems operating today, the Texas PW laser uses a hybrid of these technologies. It uses OPCPA technology to achieve most of its gain at high bandwidth, up to a pulse energy level of  $\simeq 1$  J, which then gets

further amplified in a set of mixed Silicate/Phosphate glass amplifiers up to its final energy level of about 160 J. At a pulse duration of less than 150 fs, that equates to slightly more than 1 PW. Currently, the laser can be focused to intensities of  $\simeq 10^{21}$  W/cm<sup>2</sup>. Upgrades currently underway will add large aperture adaptive mirrors, short focal length focusing mirrors and a prepulse reduction system which will enable high contrast laser target interactions at  $\simeq 5 \times 10^{22}$  W/cm<sup>2</sup> over a duration of 50 optical cycles enabling the highest integrated intensity interactions on any current system and for the next few years.

Larger systems however are on the drawing board and are currently being designed.

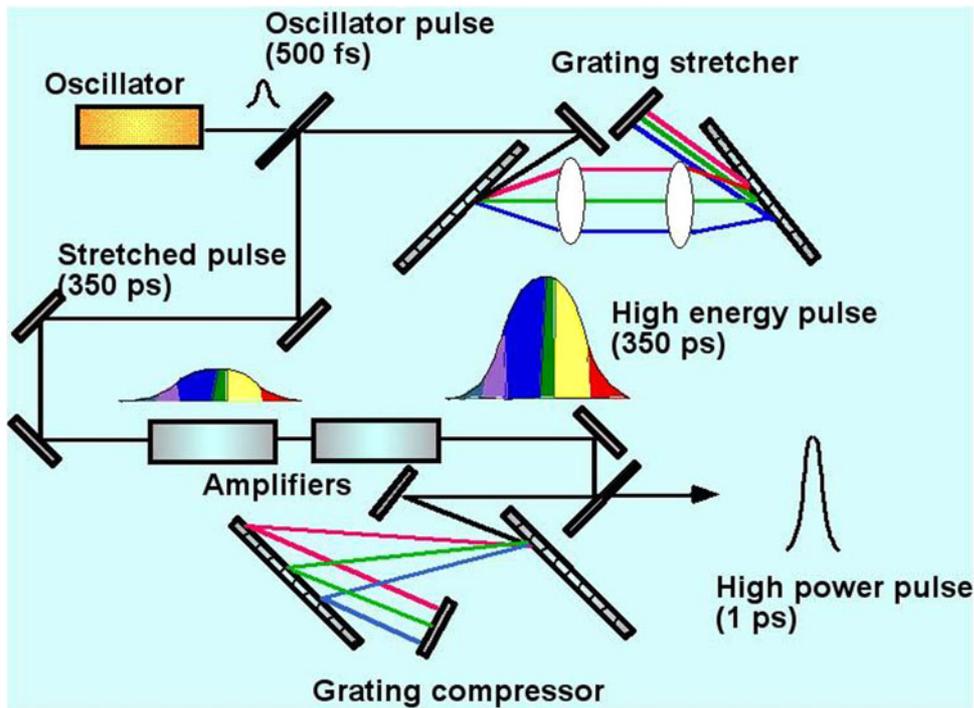
### 2.3 The highest intensity laser planned today will provide intensities $\simeq 10^{26}$ W/cm<sup>2</sup>

In order to reach the highest intensity while maintaining a good efficiency and a high repetition rate, the architecture of a laser today must be a hybrid-OPCPA-CPA system. It will utilize the OPCPA as the front end, where the efficiency is less of an issue, to preserve the pulse bandwidth to the highest energy level possible. However, because the system efficiency is dictated by the last amplifier, the latter will be Ti:sapphire CPA. This material possesses the largest known amplifying bandwidth. This architecture will ensure simultaneously the shortest pulses, i.e.  $\simeq 10$  fs, the highest energy per pulse (few kJ), the highest overall efficiency and the highest repetition rate. The final peak power should be in the range of 200 PW corresponding to an intensity, greater than  $10^{25}$  W/cm<sup>2</sup> for a diffraction limited spot size at 800 nm.

### 2.4 Bridging the gap; all the way to the Schwinger intensity regime

Note that this phenomenal intensity,  $10^{26}$  W/cm<sup>2</sup>, is still 3 orders of magnitude below the field instability limit. Simulations show that at this level few pairs will be created. There is need to boost the intensity all the way to the Schwinger limit. Therefore, we envision three ways of bridging the intensity gap:

1. Relativistic compression. Pulse compression, at the attosecond ( $10^{-18}$ ) or zeptosecond ( $10^{-21}$ ) level, could offer the possibility of also producing intensities in the Schwinger limit. Naumova et al. [23], described one embodiment resulting from the relativistic motion of the overdense plasma critical surface. Simulation shows that the critical surface moving at the speed of light could compress each cycle by a factor as large as several thousands with good efficiency. In addition, the extraordinarily large light pressure could bow the critical surface to make a spherical mirror that will focus by reflection the light on a tighter spot to reach the Schwinger intensity regime.
2. Lorentz-boosted field. It is possible to produce high energy electron beams with a very high Lorentz  $\gamma$  factor. For example consider a 50 GeV beam ( $\gamma = 10^5$ ) for a laser beam propagating against the electron beam, its field in the frame of reference of the electrons, will be enhanced by the  $\gamma = 10^5$ . This should bring the field acting in the rest frame of the electrons to a level much higher than the critical intensity.
3. Finally, we want to mention a path which is more hypothetical but that could be envisioned in the next 10–20 years. It is the direct generation of zettawatt ( $10^{21}$  W) pulses. This will require the production of a 10 fs duration pulse at the MJ level. It could be conceptually performed with “The Laser MegaJoule”, built in France or the NIF in the USA. The few MJ at  $2\omega$  available by these lasers could



**Fig. 1.** Ultra short pulses cannot be amplified directly. Even with a modest amount of energy, the intensity in the amplifier can reach phenomenal values that will produce undesirable nonlinear effects, namely, wave front distortions, component damages, etc. To decrease the intensity without changing the input pulse energy necessary for energy extraction- or the pulse bandwidth, we stretch the pulse with dispersive elements by factors of  $10^3$  to  $10^5$  thus decreasing the intensity by the same ratio. Once the pulse is stretched it can be amplified by a factor of  $10^6$  to  $10^{12}$  and then recompressed by a dispersive device (pair of gratings) to the pulse initial duration. Note that the sum of the phase functions of the stretcher, the compressor and the amplifier optical elements must be equal to zero over the full bandwidth. The amplifiers can be a conventional laser amplifier or an optical parametric amplifier (OPCPA) or both.

be used to pump a Ti:sapphire matrix of approximately 10 m diameter. We would use an OPCA front end to preserve the short pulse bandwidth. A 10 fs pulse with MJ energy, would lead to a zettawatt class pulse. It could be focused by a 10 m, segmented telescope mirror to a wavelength diameter spot size to produce a Schwinger-level intensity. A preliminary description of this ambitious system is given by Tajima and Mourou in this volume.

### 3 Use of ultra intense lasers

#### 3.1 Particle acceleration

The extraordinarily rapid advance in laser technology is driven by the promise of compact and cheap particle accelerators. As predicted in the seminal paper by Dawson and Tajima [8], in the relativistic laser pulse regime, electrons get accelerated to the speed of light within a fraction of the laser pulse, making the  $\mathbf{v} \times \mathbf{B}$  term

of the Lorentz force non-negligible and resulting in a net forward acceleration. Depending on the exact conditions of the target (e.g. plasma density, temperature, scale length, ionization degree) various schemes for electron acceleration, such as direct laser acceleration, wake-field acceleration, bubble acceleration, etc. can be exploited as discussed in other contributions to this volume and in Ref. [9].

This has led to the demonstration of GeV electron beams over acceleration distances of mere mm as compared to hundreds of meters in conventional accelerators. This opens the possibilities of utilizing such beams that heretofore were only accessible at large accelerator facilities and light sources at the table-top or laboratory scale and would therefore allow their application in Universities, hospitals or industry. Especially the possibility of a table-top x-ray free electron laser (XFEL) as a 5th generation light source for material science research, bio-molecular imaging and fundamental research as well as medical diagnostic purposes as a source for ultrahigh contrast, low dose medical imaging.

Also laser accelerated electrons can be used to act as a mediator to in turn accelerate heavier particles such as protons, carbon ions or other species. While electron acceleration schemes usually use low density gas targets to optimize the electron energy, in ion acceleration one needs to optimize the electron number at MeV energies. To this purpose, solid density targets, usually micron sized metal foils are employed. The laser, when interacting with those targets, accelerates electrons which penetrate the foil and setup a quasi static electric field at the rear side, forming a virtual cathode. This field, which is of the same order of magnitude as the laser field, i.e. many TV/m, ionizes and accelerates the ions of the rear surface. This process, known as Target Normal Sheath Acceleration (TNSA), has demonstrated MeV ion acceleration over micron distances, again outclassing conventional accelerators by many orders of magnitude in terms of shear acceleration gradient.

Recently a new ion acceleration mechanism, dubbed Break-Out Afterburner Acceleration (BOA) [10] has been observed in simulations [11–14], and in experiments [15–22], demonstrating ion energies of greater than 100 MeV/nucleon at intensities of  $10^{20}$ – $10^{21}$  W/cm<sup>2</sup>, specifically 160 MeV protons and 1 GeV carbon ions from a 130 TW laser were obtained. This portrays the potential of increasing the ion energies into the GeV region for currently achievable intensities of  $10^{21}$  W/cm<sup>2</sup> and well beyond that for higher intensities.

The BOA mechanism works via a relativistic, kinetic plasma instability, and requires use of ultra thin, nanometer scale targets for current laser parameters. In order for the laser to interact with such an extraordinarily thin target, a fraction of its own wavelength in size, the contrast of the laser pulse, i.e. the ratio of the base of the pulse to its peak, has to be controlled within 12 orders of magnitude for today's ultrahigh intensity lasers. That corresponds to controlling the Earth-Moon distance to within a fraction of the thickness of a hair, which illustrates the technical challenge underlying the experiments.

Recent experiments at the Los Alamos Trident laser managed to achieve just that, accelerating Carbon ions to 0.5 GeV using a laser intensity of  $\simeq 10^{20}$  W/cm<sup>2</sup> and demonstrating BOA acceleration for the first time and reaching energies within an order of magnitude of those required for cancer therapy among other applications. If the technological issues of repetition rate, shot-to-shot fidelity, etc are solved by future improvements in laser technology, this will then enable a transfer of heavy ion therapy from a few large synchrotron facilities to a much smaller and cheaper laser system suitable for large hospitals. This promises to make a new therapy available to a wider public.

### 3.2 Brilliant X-ray sources

Recent numeric simulations show that even the thinnest possible target foils, only nanometers thick, are capable of absorbing laser pulse energy at the percentile level. If the laser energy conversion into kinetic energy of matter is the objective one can easily envisage a relatively good conversion efficiency: the laser amplification process is, by necessity, made efficient in order to allow high shot repetition rate, thus the overall efficiency to particle beam is expected to be in the 10% range.

Simulations also show that these nm targets required for BOA might be used as sources for ultra dense, mono-energetic electron bunches, which via Compton scattering could be used as the basis for an ultra compact, ultra brilliant coherent x-ray source, surpassing even other laser-driven schemes currently under consideration. However, these examples of applications are still far away from technical realization and require much more dedicated research. They do serve to amply illustrate the potential societal payoff from fundamental research into ultrahigh intensity lasers.

### 3.3 Strong fields

A side effect of particle acceleration directly relevant in the strong field context we discuss here is the separation of electrons from ions in laser-foil interactions. Experimental simulations of this situation have revealed that the electrical field strength which develops between electrons and the trailing ions is at the level of the fields present in the laser pulse. This is of importance since we are interested in studying the behavior of the vacuum in the presence of strong fields, and this mechanism is allowing to convert the transverse laser field into the field string.

Similarly, when we consider the interaction of a circularly polarized laser pulse with a foil, there is on the surface of the pulse a circular motion, a current induced in the foil which continues into the vacuum. This also generates a strong solenoidal magnetic field. The electrons which are in circular motion around the propagation emit intense synchrotron radiation which can be of considerable importance to many applications.

### 3.4 Heavy particle production

Finally, we must look at the electron-ion interaction in the foil. We can easily optimize these electron-nucleus interactions to yield hadrons such as pions or even antineutrons, or muons. Thus the laser-foil interaction region could serve in the EW domain as a source of secondary particles. Of course for this, one would need to master repetition rates at the scale of Hertz. However, a non-negligible advantage of this scheme is the pulsed nature of the source and its extraordinary intensity.

### 3.5 Aether and Quantum Vacuum

We move here back from the more applied interactions with matter to the laser-vacuum interaction. At issue is the question of what exactly are the holes we “burn” in the vacuum. Einstein viewed a local change of the aether to be in conflict with the philosophical considerations requiring the uniqueness of the laws of physics in the entire Universe. In his 1920 essay Albert Einstein did not allow “pieces” of the aether with a modified structure. He says: *The special theory of relativity forbids us to assume the aether consist of particles observable through time, but the hypothesis*

*of aether in itself is not in conflict with the special theory of relativity. Only we must be on our guard against ascribing a state of motion to the aether.* This text in original reads: *Das spezielle Relativitätsprinzip verbietet uns, den Äther als, aus zeitlich verfolgbaren Teilchen bestehend anzunehmen, aber die Ätherhypothese an sich widerstreitet der speziellen Relativitätstheorie nicht. Nur muß man sich davor hüten, dem Äther einen Bewegungszustand zuzusprechen.* Indeed, a vacuum which can be torn into pieces behaves just like ponderable matter, an excited hot vacuum domain hole at first sight seems to be just another particle. The present day study of domains of quantum vacuum with different local structure – the quark-gluon plasma – clearly departs from Einstein’s point of view. In departing from Einstein’s views we take the quantum vacuum as a wider concept, with its properties rooted in quantum physics, reaching beyond the aether.

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