Overview of future directions in high energy-density and high-field science using ultra-intense lasers


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Abstract

The increasing proliferation of 100 TW class ultrashort pulse lasers and the near completion of a number of petawatt class lasers worldwide is opening many frontiers in laser science. Some of the most exciting frontiers rest in high energy-density science and high field physics. A multi-TW laser can create heated matter with pressure in excess of a Gbar and can create electric fields of ten to one hundred atomic units. In this paper some of the recent advances in high energy density science and high field physics made using high intensity short pulse lasers will be reviewed with illustrative examples from work performed at the University of Texas and Lawrence Livermore National Laboratory.

1. Introduction

The increase in light intensity available in the laboratory over the previous 20 years has been astounding. Laser peak power has climbed from gigawatts to petawatts in this time span, and accessible focused intensity has increased by at least seven orders of magnitude. Such a dramatic increase in light brightness has accessed an entirely new set of phenomena. High repetition rate table top lasers can routinely produce intensity in excess of $10^{19}$ W/cm$^2$, and intensities of up to $10^{20}$ W/cm$^2$ are possible with the latest petawatt class systems (Mourou et al., 1998; Mourou and Umstadter, 2002; Perry and Mourou, 1994). Light-matter interactions with single atoms are strongly non-perturbative and electron energies are relativistic. The intrinsic energy density of these focused pulses is very high, exceeding a gigajoule per cm$^3$. The interactions of such intense light with matter lead to dramatic effects, such as high temperature plasma creation, bright X-ray pulse generation, fusion plasma production, relativistic particle acceleration, and highly charged ion production (Mourou and Umstadter, 2002).

Such exotic laser–matter interactions have led to an interesting set of applications in high field science, and high energy density physics (HED physics). These applications span basic science and extend into unexpected new areas such as fusion energy development and astrophysics. In this paper some of these new applications will be reviewed. The topics covered here do not represent a comprehensive list of applications made possible with high intensity short pulse lasers, but they do give a flavor of the diverse areas affected by the latest laser technology. Most of the applications discussed here are based on recent experiments using lasers with peak power of 5–100 TW. How these experiments could be extended with a petawatt class laser will also be discussed.
1.1. State of the art in high intensity short pulse lasers

Many important leaps in laser technology have driven the rapid advances in HED and high field science over the last 15 years. The enabling advancement for this technological progress was the invention of chirped pulse amplification (CPA) lasers (Strickland and Mourou, 1985). This technique, first demonstrated by Strickland and Mourou in 1985 is illustrated in Fig. 1. A broad bandwidth, mode-locked laser produces a low power, ultrafast pulse of light, usually with duration of 20–500 fs. This short pulse is first stretched in time by a factor of around ten thousand from its original duration using diffraction gratings. This allows the pulses, now of much lower peak power, to be safely amplified in the laser, avoiding the deleterious nonlinear effects which would occur if the pulses had higher peak power (Koechner, 1996). These amplified pulses are, finally, recompressed in time (again using gratings), in a manner that preserves the phase relationship between the component frequencies in the pulse. The CPA output has a duration near that of the original pulse but with an energy greater by the amplification factor. In high-energy CPA systems, severe nonlinearities occurring when the pulse propagates in air can be a major problem, so the pulse must be recompressed in an evacuated chamber.

The first generation of CPA lasers were based mainly on flashlamp pumped Nd:glass amplifiers (Danson et al., 1998; Kitagawa et al., 2002; Patterson and Perry, 1991; Strickland and Mourou, 1985). These glass based lasers are usually limited to pulse duration of greater than about 300 fs because of gain narrowing in the amplifiers (Blanchot et al., 1995). The most significant scaling of this approach to CPA was demonstrated by the Petawatt laser at Lawrence Livermore National Laboratory in the late 1990s (Perry et al., 1999). This laser demonstrated the production of 500 J per pulse energy with duration of under 500 fs yielding over $10^{15}$ W of peak power. Since this demonstration, a number of petawatt laser projects have been undertaken around the world (Service, 2003).

The second common approach to CPA uses Ti:sapphire as the amplifier material. This material permits amplification of much shorter pulse durations often down to 30 fs. However, the short excited state lifetime of Ti:sapphire (~3 μs) requires that the material be pumped by a second laser (usually a frequency doubled Nd:YAG or Nd:glass laser). The inherent inefficiencies of this two step pumping usually limit the output energy of such a laser to under a few joules of energy per pulse. A number of multi-terawatt lasers based on Ti:sapphire now operate in many high intensity laser labs world wide (Yamakawa et al., 1999; Walker et al., 1999; Patterson et al., 1999). An example of a typical table top scale multi-terawatt system is the laser we have constructed at the University of Texas. This optical schematic of this system, which delivers 0.75 J in 35 fs pulses at a 10 Hz repetition rate, is illustrated in Fig. 2. To date, the largest scaling of Ti:sapphire technology has been to the 100 TW power level (Yamakawa and Barty, 2000; Patterson et al., 1999) with energy of up to 10 J per pulse. Scaling of Ti:sapphire to the petawatt power level is being pursued in Japan and will likely be achieved within a year or so (Service, 2003).

The third major technology upon which a new generation of high peak power CPA lasers is being based is optical parametric chirped pulse amplification (OPCPA) (Ross et al., 1997). In this approach, amplification of the stretched pulses occurs not with an energy storage medium like Nd:glass or Ti:sapphire but via parametric interactions in a nonlinear crystal. This approach is quite attractive because of the very
high gain per stage possible (often in excess of $10^4$ per pass) and the very broad gain bandwidth possible in principal. To date, a number of CPA demonstrations with OPCPA have been published (Ross et al., 2000; Jovanovic et al., 2002; Leng et al., 2003). Though there are still significant technological issues to be resolved with OPCPA, this technique promises to lead to a new generation of high peak power, femtosecond lasers.

1.2. Overview of high energy density and high field physics with high intensity short pulse lasers

The physics accessible with this class of lasers is quite extreme. The science applications made possible with these extremes can be simply classified into two categories. First, by temporally compressing the pulses and focusing to spots of a few wavelengths in diameter, these lasers concentrate energy in a very small volume. A multi-TW laser focused to a few microns has an intrinsic energy density of over $10^9$ J/cm$^3$. This corresponds to about 10 keV of energy per atom in a material at solid density. As a result, quite high temperatures can be obtained. Such energy density corresponds to pressure in excess of 10 Gbar. Many applications of ultraintense lasers stem from the ability to concentrate energy to high energy-density which can lead to quite extreme states of matter.

The second class of applications arises from the high field strengths associated with a very intense laser pulse. At an intensity of over $10^{18}$ W/cm$^2$, an intensity quite easily achievable with modern table top terawatt lasers, the electric field of the laser exceeds ten atomic units, over $10^{10}$ V/cm. Consequently, the strong field rapidly ionizes the atoms and molecules during a few laser cycles. At intensity approaching $10^{21}$ W/cm$^2$, the current state of the art with petawatt class lasers, the electric field is comparable to the field felt by a K-shell electron in mid Z elements such as argon. The magnetic field is nearly 1000 T. An electron quivering in such a strong electric field will be accelerated to many MeV of energy in a single optical cycle. Such charged particles will experience a very strong forward directed force resulting from the Lorentz force.

The increase in laser intensity over the past twenty years accesses new regimes in both high field and high energy density physics. This is illustrated in Fig. 3, where new thresholds in intensity and the applications they enable are shown. In the following sections, we consider various basic and applied science applications of such intense laser pulses. Examples of physics at high energy density will be considered first, and then a couple of examples of the strong field of such intense pulses will be discussed.

2. High energy density science with ultraintense ultrafast lasers

2.1. Isochoric heating and probing of off-Hugoniot equations of state

High peak power femtosecond lasers are unique in their ability to concentrate energy in a small volume. A dramatic consequence of this concentration of energy is the ability to create matter at high temperature and pressure. Matter with temperature and density near the
center of dense stars can be created in the laboratory with the latest high intensity lasers. For example, solid density matter can be heated to temperature of over 10,000,000°C (>1 keV). Under these conditions, the particle pressure inside the sample is over 1 billion atmospheres, far higher than any other pressure found naturally on or in the earth and approaches pressures created in nuclear weapons and inertial confinement fusion implosions.

Study of the properties of matter at these extreme conditions, namely solid density (i.e. \(10^{22} \text{cm}^{-3}\)) or higher in the temperature range of 1–1000 eV, is crucial to understanding many diverse phenomenon, such as the structure of planetary and stellar interiors or how controlled nuclear fusion implosions (inertial confinement fusion or ICF) evolve. Yet, despite the wide technological and astrophysical applications, a true, complete understanding of matter in this regime is not in hand. A large obstacle is posed by the fact that theoretical models of this kind of matter are difficult to formulate. While the atoms in these warm and hot dense plasmas are strongly ionized, the very strong coupling of the plasma, and continuum lowering in the plasma dramatically complicates traditional plasma models which depend on two body collision kinetics (Spitzer, 1967). Even the question of whether electrons in this state are free or bound is not as clear cut as it is in a diffuse plasma.

Over the last 15 years, since the development of high energy short pulse lasers, there have been a number of experimental studies aimed at isochoically heating solid density targets with a femtosecond laser pulse (Audebert et al., 2002; Widmann et al., 2001). This class of experiments uses a femtosecond pulse to heat, at solid density, an inertially confined target on a time scale much faster than the hot material can expand by hydrodynamic pressure. This approach can be very powerful. Not only can spectroscopic diagnostics be implemented to derive information on the heated material (such as ionization state) (Nantel et al., 1998) but isochoric heating experiments can also enable laser heated pump–probe experiments. Pump–probe experiments can use an optical, or laser-generated X-ray pulse to probe the material on a time scale before it can expand. This yields, for example, conductivity information through reflectivity and transmission probing (Widmann et al., 2001), as well as XUV and X-ray opacity if a short wavelength probe is employed (Workman et al., 1997). The general experimental technique used in these experiments is illustrated in Fig. 4. The laser heats a thin slab of material, with thickness usually comparable to or less than an optical skin depth. Fig. 5 illustrates the parameter regime accessible with short pulse laser heating. Here, the phase space of aluminum is illustrated. When the material is heated from its initially cold, solid state, the plasma will be in the “strongly coupled” regime, denoted by the state in which \(G > 1\); even at temperature approaching 1 keV. Here \(G\) is the ratio of particle potential energy to its kinetic energy.

The scheme depicted in Fig. 4 is that in which a laser directly heats a sample, and the energy deposits within an optical skin depth. Direct laser heating has drawbacks. Because of the small depth of such a skin depth, the expansion time of the sample is often only 100 or 200 fs. The few hundred fs release time of the heated material is comparable to the electron–ion equilibration time (Spitzer, 1967) and hampers interpretation of this kind of experiment. Microscopically rough surface finish of the very thin target often leads to a large uncertainty in the initial density, complicating analysis of the data. Consequently, it is desirable to explore mechanisms of
heating larger volumes (i.e. thicker layers) of material. One promising approach is to use fast bursts of penetrating radiation, such as protons or X-rays, to heat thicker layers of material than are possible with direct optical heating. Use of X-rays to perform isochoric heating was first proposed by Lee et al. in the context of X-ray free electron lasers sources (Lee et al., 2002, 2003). A multi keV X-ray pulse can, for example, penetrate many microns of material (depending on the wavelength and target Z). To explore the advantages which may arise from X-ray heating we have begun exploration of X-ray heating using high intensity laser based sources.

One way to produce an intense, ultrafast burst of hard X-rays for such an X-ray heating experiment is to use a high peak power short pulse laser to produce Kα radiation on a solid target, an idea shown in Fig. 6. Such X-ray radiation is produced during the illumination of a solid target by intense pulse because fast electrons are produced in the interactions. These electrons travel into the cold target and create inner shell excitations in the targets atoms. These X-rays have been shown to exhibit pulse duration under 1 ps if ultrafast laser illumination is employed. An experiment based on the concept is illustrated in Fig. 6. In our experiment we have chosen to study the heating of solid Al. To maximize the X-ray heating for a given X-ray fluence, it is desirable to choose a Kα source with photon energy just above the K-absorption edge of the Al. This choice of Kα X-rays maximizes absorption. Si Kα, with a photon energy of 1.74 keV, is optimum for X-ray heating of Al. If the Si X-ray yield is known, we can use the known photo ionization cross sections to determine explicitly the deposited energy density in the Al layer. In our experiment, X-rays were generated in the Si layer by irradiating it with an 800 nm laser pulse from a Ti:sapphire laser. Shots were performed on the JanUSP laser facility at Lawrence Livermore National Laboratory which delivers 100 fs pulses with energy up to 10 J (Patterson et al., 1999).

To derive information on the heated Al layer, we optically probe the target with a second 100 fs, 800 nm
pulse. This allows us to measure reflectivity of the material after heating as well as the expansion of the material along its release isentrope. Fig. 7 shows the various diagnostics fielded in the first set of experiments. Expansion of the heated aluminum layer is measured with an interferometer. The same probe pulse can give information about the heated target’s reflectivity. The other diagnostics measure radiation emitted by the target. An X-ray pinhole camera yielded an absolute measure of X-ray energy radiated at photon energies above \( B_{1 \text{ keV}} \), as well as an approximate source size. An X-ray CCD camera, positioned far from the target was used in photon-counting mode to give an absolute spectrum of X-rays passing through the aluminum layer. A knife-edge close to the target was used to measure the source size of X-ray radiation.

Interferometer data are presented in Fig. 8a. Expansion of the heated aluminum was inferred from interferometer fringe shifts and is plotted here as a function of time. The material appears to expand initially with a velocity of about \( 5 \times 10^4 \text{ m/s} \) over a time of \( \sim 5 \text{ ps} \). For comparison, the expected expansion velocity of a 5 and a 100 eV Al ideal gas are plotted in Fig. 8a. The material expansion then seems to accelerate 5 ps after the initial expansion. This apparent increase in temperature at later times may be attributed to fast protons emitted from the back surface of the Si target. We also measure the material reflectivity as a function of time. These data are shown in Fig. 8b. We derived reflectivity changes from the that of cold Al by examining the spatially imaged optical probe on the surface and comparing average pixel value in the center of the heated region to that in a region just outside in a region of cold Al. A transient increase in reflectance is seen a few picoseconds after main pulse arrival. The reflectivity of the heated aluminum raises by 70% over the cold Al within 5 ps after heating. We can attribute this to an increased free electron density caused by a cascade of Auger processes following the initial photo-ionization of Al K-shells by the X-rays.

A quantitative result from this approach will require improvement of the technique. In particular, it will be desirable to increase the X-ray yield, increasing the attainable temperature and the spatial scale of the heated target. Such X-ray flux increase should be possible with the use of a petawatt class laser to produce the X-rays. Assuming a \( 10^{-4} \text{ X-ray conversion efficiency, X-ray fluxes of } > 100 \text{ mJ/cm}^2 \text{ should be possible with a few hundred J, frequency doubled petawatt laser. Such intensity is one to two orders of magnitude higher than that demonstrated in our first experiments and would likely heat a target to nearly 100 eV.}

2.2. Ultrafast dynamics in shocked materials

Another class of high energy density experiments using high intensity short pulse lasers involves the study
of materials under shock compression. Equilibrium studies of shock compressed materials are often conducted with gas guns or explosives. However, the development of high power pulsed lasers opened the potential to study shock compression at much higher pressure and higher strain rate (Moshe et al., 2000). The laser pulse ablates the surface of a target and the material blow-off acts as a rocket engine which drives a shock into the underlying cold material. Because of the fast rise of such a laser shock drive, quite high strain rates, \( > 10^7 \text{s}^{-1} \) can be driven in a material. Furthermore, using ultrafast, high energy lasers as shock drivers permits time resolved pump–probe style experiments. This has the advantage of allowing study of shock dynamics on the microscopic scale. Such experiments require sufficient energy to drive a shock over an area large enough for effective probing. Multi-joule short pulse lasers can provide such a shock drive.

High power lasers can access much higher shock pressures, up to 1 to 10 Mbar, than are obtainable with gas guns or easily derived with small to mid-scale explosive experiments (Trainor et al., 1979). More important, however, is the fact that an intense laser can produce a probing pulse, synchronized to the shock driving pulse, to examine the dynamics of the material. This probe can be optical, and can probe the surface properties (like conductivity through reflectivity) with high time resolution. In addition, an intense laser can produce a bright burst of X-rays (via mechanisms discussed in the last section) that can probe the dynamics of the materials on the lattice level. This approach can, in principle, begin to examine atomic motion behind the shock (and around defects) (Wark et al., 1989), a possibility which could yield unprecedented information on deformation mechanisms and defect generation.

Despite the vast number of previous shock compression studies, a detailed understanding on a lattice level of shocks is still lacking. This is particularly true at very high strain rates \( (> 10^8 \text{s}^{-1}) \) since conventional deformation mechanisms are not valid and limited data exist. It is known, for example, that currently accepted constitutive models are quite speculative in this strain rate regime. The issues surrounding high strain rate shock dynamics are illustrated in Fig. 9.

Fundamental to shock propagation in a crystal is the formation, and propagation, of defects and dislocations (Asay and Shahinpoor, 1993). For example, when a crystal is shocked beyond its elastic limit, it is well known that plastic flow takes place. In the extreme limit of a strong shock the material behaves hydrostatically; the material strength is negligible, and the crystal lattice is compressed equally in all three directions. This plastic flow normally occurs at shock pressure above the Hugoniot Elastic Limit (HEL) which rests at pressure of a few tens of kbar for most materials. For the plastic flow to occur, dislocations must be present at the interface between the compressed and uncompressed lattice. This can be seen in the illustration of Fig. 9, where the dislocations shown schematically at the shock front allow the unit cells to be compressed equally in all directions. Only recently have these dynamics, such as density and type of dislocation production, come under study, mainly using molecular dynamics simulations (Holian and Lomdahl, 1998), and there are only limited experimental studies to corroborate these calculations.

Another important phenomenon with complications at the lattice scale occurs when the material is shocked to high enough pressure that it melts. The transition from crystalline solid to amorphous melting on the ultrafast time scale is also not well studied.

Ultrafast optical probes can shed light on these dynamics. The principle behind these experiments is illustrated in Fig. 10. It is possible to use the fact that the linear and nonlinear optical properties of a material differ when the solid becomes a liquid. This means that the material reflectivity will change as it undergoes a phase transition to a liquid and its nonlinear optical properties can change. The later fact can be exploited if second or third harmonic is generated off the back of a target that is shocked and the harmonic intensity is monitored via pump–probe techniques. This approach has been used in the study of femtosecond laser induced melting in semiconductors such as silicon (Shank et al., 1983).

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Fig. 9. Illustration of the manner in which microscopic defects get generated in a plastic shock deformation.

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To illustrate the possibilities in optical time resolved probing of laser produced shocks, we have performed the experiment illustrated in Fig. 11. We use the University of Texas THOR Ti:sapphire laser illustrated in Fig. 2. The uncompressed, 600 ps pulse from THOR drives a shock in a thin sample, which is a slab of tin 4 μm thick in our initial proof of principle experiments (chosen to match the shock transit time driven by our 600 ps pulse). This shock is driven by about 1 J of light focused to a 0.4 mm spot. This slab is probed on the back side with part of the laser that has been split from the shock driver laser and compressed to 40 fs time duration. In this way, the ultrafast probe pulse is well synchronized to the shock driver. A CCD camera images the reflection off the back surface of the tin slab. The probe pulse is itself split and sent through an interferometer to derive simultaneous information on the amount of shock driven expansion on every shot. Typical data are shown in Fig. 12 where the reflectivity of the slab 2 ns after the drive pulse begins irradiating the surface is shown. As can be seen, a well defined region of the tin, where the shock has broken out on the back side, has dropped in the reflectivity.

A measurement of the reflectivity in the center of the shocked region as a function of time is plotted in Fig. 13.
We observe a quick (<200 ps) drop of the reflectivity to 90% once the shock breaks out from the target surface. A slower, further fall of the reflectivity follows this rapid drop. The dynamics leading to this behavior are still not understood but the early time drop may result from shock melting while the later reflectivity fall may derive from some microscopic break-up of the surface. The implementation of nonlinear optical probing in the future will help to remove this ambiguity. Future work will benefit from shocking at higher pressure over thicker target slabs using higher energy laser pulses.

2.3. Astrophysics and radiative hydrodynamics

Another area of shock physics which can be studied with high intensity lasers is that of strong shocks in gases. Such shock studies have some relevance to astrophysical phenomena. Astrophysical shocks play an important role in the evolution of the interstellar medium providing an energy source, and triggering a variety of phenomena including star formation (McKee and Draine, 1991). On galactic time-scales, supernovae are a frequent source of such shock waves, which expand into the surrounding medium sweeping up material into a thin, dense shell. If the circumstellar medium is sufficiently dense, radiation can play an important role in the energy transport dynamics of the supernova remnant blast wave (Bartel et al., 2000). It is also believed that various shock instabilities associated with these radiative shocks, including the well known Vishniac overstability, have an important effect on the structure of interstellar matter (Vishniac, 1983). Because of the complicated dynamics associated with these astrophysical phenomena, there is a strong motivation to produce radiative blast waves in the laboratory. A radiative blast wave can occur over a wide range of temperatures and densities in astrophysical shocks, but is more difficult to achieve in the laboratory. Nonetheless, high Mach number, laser driven blast waves in certain dense gases can reach the high temperatures needed to enter the radiative regime (Grun et al., 1991).

To create a laser driven radiative blast wave, it is necessary to produce a localized, high temperature plasma in a modest density gas without perturbing the surrounding medium with the incoming laser. One way to do this is to utilize the now well characterized high absorption efficiency of high intensity femtosecond lasers in gases containing large clusters (Ditmire et al., 2000; Shigemori et al., 2000). An intense laser focused into a strongly absorbing cluster gas will produce a hot, elongated filament which will subsequently develop into a cylindrical shock (Ditmire et al., 1997a).

How this is done with a short pulse laser and how these blast waves can be probed is demonstrated in Fig. 14. This figure illustrates a specific experiment on blast waves conducted at LLNL using the 35 fs Falcon Ti:sapphire laser (Edwards et al., 2001). The blast waves were produced by focusing 0.1 J, 35 fs laser pulses with an f/15 lens into a gas jet expelling a plume of neon, argon or xenon gas. A cylindrical plasma filament ∼50 µm in diameter stretching across the 4 mm width of the gas jet resulted from the irradiation. The evolution of the blast wave in the gas was probed by splitting a small portion of the laser energy and passing it perpendicular across the plasma filament. Two probing techniques examined the blast wave: interferometry, which yielded information about the electron density profile, and dark field imaging, which gave images sensitive to gradients in the electron density. The time history of a shock was found by varying the temporal delay of the probe pulse with respect to the driving pulse.

From the interferograms, we observed the clear formation of a blast wave produced by the explosion of the heated cluster plasma. Characteristic interferograms and deconvolved electron density profiles of blast waves produced in argon and xenon are illustrated in Fig. 15a. In the case of argon, a weak shock is formed in the weakly absorbing gas and a clean shock front is observed. The xenon profile also exhibits a well formed, sharp shock front, however, we also observed significant ionization of gas ahead of the shock front. This indicates an ionization precursor formed by radiation emitted from the hot plasma and deposited in the otherwise undisturbed ambient gas. Such a radiative precursor is one of the classic signs that an exploding plasma is driving a radiative shock wave. Interestingly, we also observed an increasing rate of deceleration of the Xe shock which suggested that radiative energy loss played a significant role in the evolution of the blast wave (Edwards et al., 2001).

These experiments also examined how this radiative flow dynamic affected the blast wave stability. The presence of instability growth was sought experimentally by examining “dark field” imaging. We examined all gases in our experiments (Ne, Ar and Xe), though we expected potential instability growth only in the case of the strongly radiating Xe. Dark field images of a Xe blast wave at times 4, 30 and 110 ns are shown in Fig. 15b. The shock front is located at the thin bright region which appears extremely smooth down to the scale of the instrument resolution. ∼10 µm, even at the latest time. These data suggest that no radiative instabilities were present in these experiments, or at least were not growing fast enough to be significant on the time scale of this experiment.

Further studies on these short pulse laser produced radiative shock systems will benefit immensely if shocks can be created which persist for longer and retain a high mach number to greater radius than in this initial experiment. Once again, the use of a petawatt class laser will make such larger scale experiments possible. For the
Fig. 14. Schematic of the radiative blast wave experiment illustrating how the blast wave is created by irradiation of a cluster jet with a femtosecond pulse and then is diagnosed by a delayed optical probe pulse.

Fig. 15. Data showing the formation of a blast wave in the gas jet. (a) Deconvolved electron density profiles of shocks in argon and xenon gas 6 ns after irradiation. A UV radiative ionization precursor is clearly seen in the xenon shock data. (b) Dark field images of the shock evolving in xenon showing the evolution of a smooth shock front out to 110 ns.
self similar blast waves studied here, the shock velocity (the parameter most important to determining if the shock is radiative) scales with the initial deposited laser energy, $E$, as $E^{1/2}$ for a constant radius. So an increase of laser energy from the 0.1 J used in our experiment on Falcon to a 100–1 kJ short pulse laser will enable high Mach number experiments to be conducted in a clustering gas with radii extending out to over 1 cm, an improvement of two orders of magnitude in size. With this test bed, it should be possible to study many of the details of radiative shock propagation in the lab.

### 2.4. Neutron generation and time resolved radiation damage dynamics

The use of high intensity short pulse lasers to produce short bursts of X-rays is a well known application of these lasers (Wharton et al., 2001; Gauthier, 1994). The high temperature plasmas created by a focused ultrafast pulse can emit a pulse of X-rays in the 1 keV to 1 MeV range, depending up on the laser intensity and focal conditions. Such X-ray production has been utilized by a number of groups in ultrafast X-ray probing experiments (Siders et al., 1999; Von der Linde et al., 2001). With the increase in the laser energy and peak power available, the generation of other sources of radiation is now being investigated.

One interesting radiation source is laser produced fusion neutrons. The production of a high flux burst of fusion neutrons could be of considerable importance to the study of radiation induced damage in materials (Averback and Rubia, 1998). The manner in which neutrons damage materials is an area of active study, particularly in the context of developing future fusion reactor wall materials (Perkins et al., 2000). However, high flux sources of clean fusion neutrons are not widely available. A laser produced source could enable such damage studies. In addition, the short duration inherent in laser driven radiation sources could allow time resolved studies of neutron damage. A laser driven source of neutrons might also serve as a source for fast neutron radiography where the small source size could lead to high spatial resolution.

Using intense femtosecond lasers to produce high fluxes of fusion neutrons may now be possible by exploiting interactions of intense lasers with atomic clusters. There have been a wide variety of experiments in recent years which have shown that when an intense laser interacts with a cluster of atoms or molecules of a few hundred to a few thousand atoms, the cluster explodes quite violently, ejecting ions of high kinetic energy (Perkins et al., 2000; Ditmire et al., 1997b; Lezius et al., 1998). How this happens is illustrated in Fig. 16, which shows the results of a particle dynamics simulation of a small (55 atom) Ar cluster irradiated by a 50 fs laser pulse at modest intensity ($10^{16}$ W/cm$^2$) (Ditmire, 1998). Because of the rapid rise time of the pulse, tunnel ionized electrons from the Ar atoms in the cluster are heated and ejected by the laser field on a time scale faster than the argon ions can move. The space charge forces created by this ejection of electrons leads to a radial explosion of the cluster. The laser cluster interactions are quite efficient at converting laser energy to ion energy.

These exploding clusters can drive nuclear fusion under the right conditions (Balcou et al., 2001; Ditmire et al., 1999; Zweiback et al., 2000). Here, ions released from energetic explosions of deuterium clusters irradiated with femtosecond laser pulses drive DD fusion. Neutrons are released in the DD fusion by the well known reaction $D + D \rightarrow He^3 + n (+3.3$ MeV of excess energy). In this experiment, a high intensity, focused ultrafast laser pulse traverses a gas of deuterium clusters and rapidly heats them. These clusters subsequently explode, ejection deuterium ions with energies of many MeV. This process creates a plasma filament with a diameter roughly that of the laser focus and a length comparable to the extent of the gas jet plume ($\sim 2$ mm). The fast deuterium ions ejected from the exploding clusters can then collide with ions ejected from other clusters in the plasma.

Initial experiments on this system indicated that fusion yields of up to $10^4$ neutrons/shot were possible using 100 mJ, 35 fs laser pulses (Zweiback et al., 2002). Estimates for the needed neutron flux to induce sufficient damage to be observable by optical or X-ray pump probe techniques indicate that at least $10^9$ n/shot will be necessary, so a large scaling in yield is still necessary before a usable laser based source can be realized. To examine the feasibility of a laser based fusion neutron source using exploding clusters, we have studied the neutron yield scaling quite carefully. The yield will be dependent on a number of parameters, the ion energy from the exploding clusters (since the fusion cross section is strongly dependent on ion energy), the deuteron density, and the heated plasma volume. If more energetic cluster explosions can be generated at higher average gas density, it seems likely that sufficient neutron flux can be obtained for some applications.

The results of recent experiments studying the fusion yield scaling of a femtosecond laser irradiated deuterium gas jet are shown in Fig. 17. The gas plume was irradiated by a single pulse of 800 nm light from the Lawrence Livermore National Laboratory JanUSP laser. The laser energy was varied to a maximum pulse energy of 10 J and we varied the duration of the compressed pulse from 100 fs to 1 ps by varying the grating spacing in the pulse compressor. After recompression this pulse was focused into the gas plume by a 300 mm focal length off-axis parabolic mirror producing a vacuum focal spot diameter of $\sim 10\mu m$ yielding a peak intensity of $2 \times 10^{19}$ W/cm$^2$ in vacuum, an intensity sufficient to fully strip the 5–10 nm D$_2$ clusters in our jet.
target. The neutrons were detected with scintillating plastic detectors coupled to photomultiplier tubes. We find that the fusion yield scales nearly as the square of the laser energy, a finding which holds true both for 100 fs and 1 ps laser pulses. This yield scaling is also consistent with earlier data taken with a lower energy, 35 fs Ti:sapphire laser (also shown in Fig. 17). At laser energy over 5 J, roughly $10^6$ neutrons per shot were observed. This scaling can be simply explained by the volume increase of the plasma at higher laser energy.

These data indicate that fusion yield increases strongly with laser energy. With a petawatt class laser delivering $>100$ J, we might expect that, if this yield scaling is maintained, nearly $10^9$ n/shot might be possible. This would result in a fluence near the target of nearly $10^{11}$ n/cm² per shot. Such high fluxes will significantly damage a material and would lend themselves to time resolved neutron damage studies. Presently, the ion energies achievable in the cluster explosion tend to be limited by the size of the clusters. As a result, higher intensity pulses do not lead to any significant increase in ion energy (Madison et al., 2003). However, further improvements in the target jet could lead to larger cluster production in deuterium and even higher fusion efficiency.

3. High field physics with ultraintense ultrafast lasers

Each of the applications in the previous section relied on the high energy density concentration possible with an intense short pulse laser. Of course, at the high intensity reachable, the field strength of these laser systems is quite large (over 10 atomic units). This has lead to a number of unique possibilities in high field research.

3.1. Relativistic nonlinear optics

The most straightforward consequence of these strong optical fields is manifested in the interaction of the field with free electrons. At an intensity in which the normalized vector potential of the laser field,
$a_0 = eE/m_ec_0$, approaches 1, (where $E$ is the peak electric field of the light) the electron oscillation motion becomes relativistic during the course of a single laser oscillation. In a laser field with wavelength around 1 $\mu$m, this relativistic regime is reached at intensity around $1 \times 10^{18}$ W/cm$^2$. The relativistic quiver velocity of an electron at this intensity has two consequences. The electron mass in the lab frame increases and the electron motion becomes anharmonic. The $v \times B$ Lorentz force also becomes important. This leads to free electron trajectories in the laser field which deviate significantly from the simple, harmonic motion in non-relativistic fields. This is illustrated in Fig. 18 which shows the motion of a classical electron is a plane wave at an intensity of $3 \times 10^{19}$ W/cm$^2$ ($a_0 \approx 4$) after it has been tunnel ionized from an atom located at the origin. The motion of the electron is very anharmonic and the Lorentz force drives the electron in a trajectory that is directed to a large extent along the laser $k$ vector.

The relativistic motion of the electron has a number of consequences in the interactions of single electrons with intense laser fields. The anharmonic motion of the electron can lead to the re-emission of high order harmonics of the laser field (Lau et al., 2003; Banerjee et al., 2002). This could enable a very bright, femtosecond soft X-ray source. The mass shift of the electrons also affects the properties of a plasma. For example, the mass increase increases the effective plasma frequency of an irradiated plasma, so critical density plasma becomes effectively underdense (Vshivkov et al., 1998). This is known as relativistic transparency of a plasma (though this effect has not yet been observed experimentally). The relativistic shift of the plasma frequency has been observed in channeling of an intense laser beam in an underdense plasma. The increasing of the plasma frequency at higher intensity can create a focusing effect for a focused laser beam with an intensity profile peaked on axis. Such relativistic self focusing is now well established in experiments (Najmudin et al., 2000; Malka et al., 2000) and is well studied by simulations (Sentoku et al., 2000; Feit et al., 2001; Naumova et al., 2002).

3.2. Strong field ionization and ATI in super strong fields

Another consequence of the strong field Lorentz acceleration described above is the ionization of single atoms or ions at these very high intensities. When an intense laser field of sufficiently long wavelength illuminates an atom, the ionization can be described by tunnel ionization. This process is illustrated in Fig. 19a and occurs when the well known Keldysh parameter $\sqrt{I_p}/2U_p$ is less than one, (where $I_p$ is the ionization potential of the ion in question and $U_p$ is the ponderomotive or quiver energy of a free electron in the laser.) In the quasistatic regime (i.e. when the Keldysh parameter is $<1$), the ionization can be described by the distortion of the ion’s binding potential by the strong incident electric field (as pictured in Fig. 19a). The electron can then tunnel through the binding barrier. This tunnel ionization rate has a very strongly nonlinear increase with increasing laser intensity and therefore exhibits a threshold like behavior. The thresholds for various ions are shown in Fig. 19b. This figure illustrates that at the intensities likely achievable in the near future with petawatt class lasers, high Z ions can be fully stripped by this tunnel ionization.

Strong field tunnel ionization also has an interesting consequence in that it effectively ejects a free electron into the laser field at a well defined phase of the field, with ionization occurring predominantly at the peak of the field where the ionization rate is highest. The electron then acquires some drift energy from the field. This kinetic energy is often termed above threshold ionization energy (or the ATI energy) (Agostini et al., 1987).

In quasi-classical ATI at sub-relativistic intensities, the tunnel ionized electron picks up a drift velocity that is related to the phase in the laser oscillation at which it is ionized (Burnett and Corkum, 1989). In sub-relativistic (linearly polarized) fields, the electrons are ejected predominately in the plane of the laser polarization and the electrons drift is directed radially out of the laser focus. As the intensity is increased toward $10^{18}$ W/cm$^2$ (where the normalized vector potential of the laser field, $a_0$, approaches one), $v \times B$ forces start to affect the trajectories of the electrons and the electrons begin to be ejected in a direction forward of the polarization axis.

In a strongly relativistic field, these dynamics will be different. Ionization of a very highly charged ion effectively “injects” a free electron into the field at phase near the field peak. When the laser field $a_0 \gg 1$, the $v \times B$ force curves the trajectory of the electron along the laser propagation direction in a small fraction of the field cycle. The electron with $v_y \sim c$ can then “surf” along

![Fig. 18. Calculated trajectory of an electron liberated by ionization near the electric field peak in a plane laser field at intensity of $3 \times 10^{19}$ W/cm$^2$.](image)
with the field, acquiring energy from the electric field. In an infinite plane field, the electron has velocity slightly smaller than $c$; and will fall out of phase with the field. Consequently the electron will be decelerated in the following E-field half cycle. The finite extent of a focused laser beam, however, can allow some electrons to exit the region of high field before this phase reversal occurs, and the ejected electron will acquire quite substantial energy from the laser. This phenomenon was described in detail in Hu and Starace (2002). Hu and Starace found that electrons ionized from $V^{22+}$ by $8 \times 10^{21} \text{W/cm}^2$ pulses would be ejected with energy up to 2 GeV.

To examine these dynamics in more detail we have performed numerical simulations of ATI in a strongly focused, relativistic intensity femtosecond laser pulse (Maltsev and Ditmire, 2003). Our simulation solves the ionization rate equations for atoms at randomly selected points in the focus. We use ADK rates (Ammosov et al., 1986) for ionization, using Monte Carlo techniques to determine the ionization time of a given ionization state. Ionized electrons are born with zero energy and their trajectory is then calculated using the relativistic equations of motion. We use the full equations describing the electric field at a Gaussian focus, including the longitudinal components of the electric field. These longitudinal components actually play an important role in the relativistic electron dynamics (Quesnel and Mora, 1998).

We calculated ionization of $\text{Ar}^{17+}$ ions by an $800 \text{nm}$, 30 fs laser focused to a spot size radius of $5 \mu\text{m}$ and an intensity of $5 \times 10^{21} \text{W/cm}^2$. These results appear in Fig. 20. Here the ejected electron energies and the electrons' ejection angles with respect to the laser propagation direction are plotted for an array of test
electrons. These electrons emerge from the focus in a narrow cone along the laser propagation axis and exhibit energies up to 0.7 GeV. This is a dramatic departure from the usual, sub-relativistic ATI behavior which is well known from strong field ionization experiments. The longitudinal ponderomotive force is responsible for the forward directed electrons seen in this simulation. These kinds of strongly relativistic dynamics will be observable with the new generation of petawatt lasers.

3.3. Pair plasma production

Finally, we remark on one particularly speculative application of the strong fields and high oscillation energies associated with ultraintense lasers. When a plasma, such as that produced by irradiation of a solid target, is driven by a relativistic intensity, the oscillating electrons in the plasma have average energy exceeding twice the rest mass of the electron. This begins to mimic a “relativistic plasma”, i.e. a plasma in which the temperature is high enough that most of the electrons have relativistic energy. Such relativistic plasmas are believed to exist near black holes and probably play a major role in the production of gamma ray bursts (Crider and Liang, 2000).

Gamma ray bursts are among the most enigmatic phenomena in the universe. A number of theories have been advanced to explain the very large energy release and hard X-ray spectrum resulting from these gamma ray bursts. Most theories rest on the belief that plasmas near a black hole are so hot that matter and anti-matter (electrons and positrons) exist in equilibrium with each other (Crider and Liang, 2000). The dynamics of these extremely exotic plasmas are not well understood and no terrestrial experiment has yet been able to access such extreme conditions.

Such matter-antimatter plasmas, however, might now be created in a laboratory with a petawatt class laser. How this might occur is illustrated in Fig. 21. The development of petawatt-class lasers opens the door to the study of this new frontier in plasma physics and a new state of matter in the laboratory, high-density, relativistic $e^-e^+$ plasmas. A laser with intensity exceeding $\sim 2 \times 10^{18}$ W cm$^{-2}$ has a sufficiently strong electric field to couple most of the field energy to superthermal electrons with temperature $kT > m_e c^2$ (where $m_e$ is the electron rest mass and $c$ is light speed). Positrons are created when the relativistic electrons interact with high-Z target ions via the trident process and in a secondary manner by producing energetic photons which themselves produce a pair upon scattering from a nucleus. Gigagauss magnetic fields are also present, which help to confine the electrons. Using particle-in-cell (PIC) plasma simulations Liang et al. (1998) estimated the $e^+$ production rate for a thin ($\sim$ few μm) gold foil and found that petawatt-class lasers with sufficient pulse length can, in principle, achieve in-situ $e^+$ densities as high as $\sim 10^{22}$ cm$^{-3}$ of the background electron density, or approximately $10^{22}$ cm$^{-3}$ for solid gold targets, far exceeding any other laboratory source of positrons. Detailed numerical simulations by other groups (Nakashima and Takabe) confirm this prediction (Nakashima and Takabe, 2002). Such experiments will require the construction of the next generation of petawatt lasers but hold the promise to study some of the most exotic matter in the universe in the laboratory.

4. Conclusion

In this paper we have reviewed some of the recent and potential applications of high intensity short pulse lasers. Examples of many of these applications have been illustrated using results from our group. The kinds of experiments described here leverage the rapid advances in laser technology that now make possible table-top lasers with 10–100 TW and larger scale systems with power exceeding 1 PW.

The applications of these lasers tend to fall into two categories: those experiments relying on the ability of a high intensity short pulse laser to concentrate energy in a small volume, and those applications which use the very high electric and magnetic fields which are produced in a tightly focused high intensity laser. The former category leads to interesting high energy density experiments; experiments which probe the state of matter at pressures approaching 1 Gbar or which study the dynamics of strong shock wave propagating though matter. Many of these applications have relevance to astrophysics as they represent the only way known to access some of the exotic states of matter found in astrophysical objects in a terrestrial laboratory.

Fig. 21. Cartoon illustrating how an electron positron pair plasma could be created with a pair of petawatt laser beams.
The second category of experiments uses the large field strengths that accompany the high focused laser intensity. These high field experiments are presently centered on understanding the consequences of the relativistic motion of electrons in such a field. These relativistic effects lead to an entire range of nonlinear optical phenomena, harmonic generation, etc. and could lead to quite energetic electron production in strong field ionization. The next generation of petawatt lasers will certainly lead to an even greater, unexplored range of applications in both high energy density and high field physics.

References


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