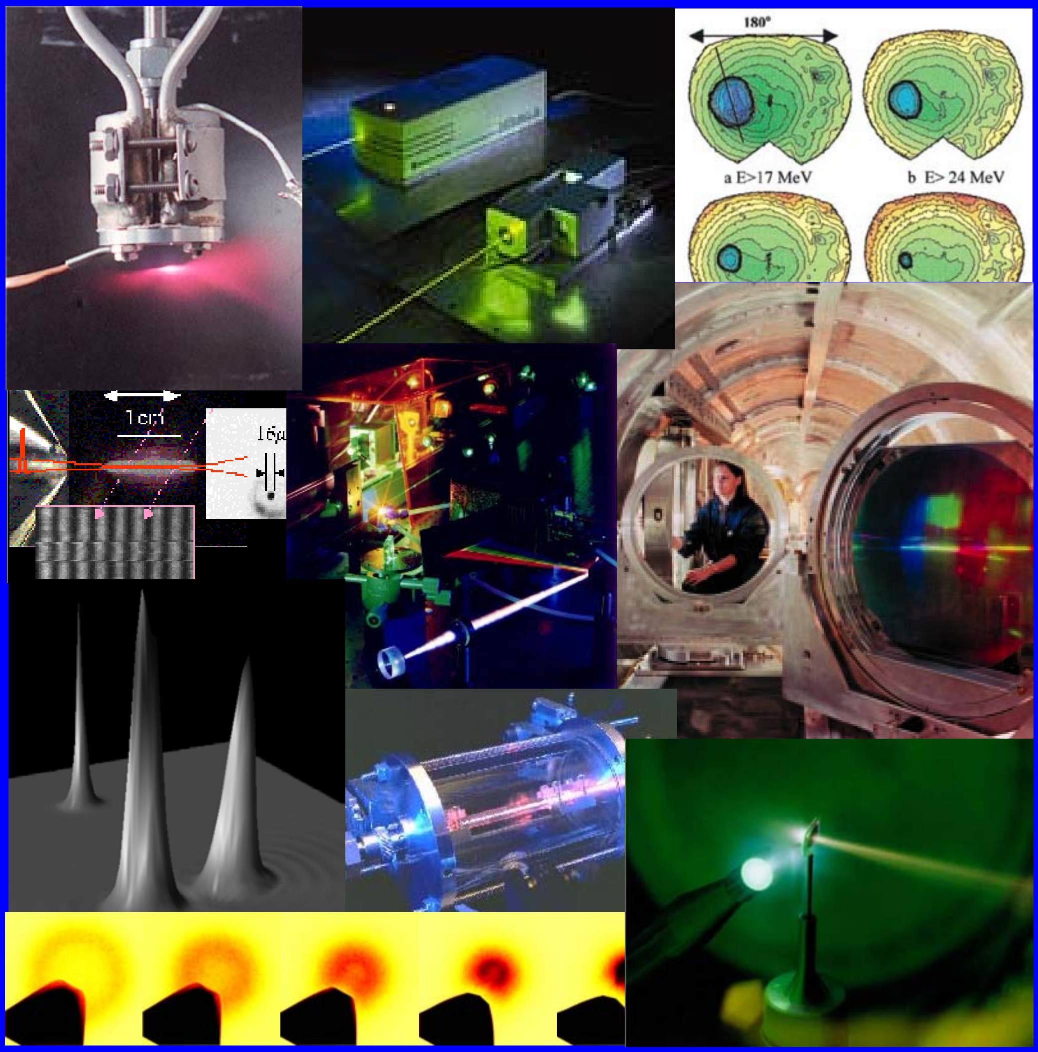
THE SCIENCE AND APPLICATIONS OF ULTRAFAST, ULTRAINTENSE LASERS:

Opportunities in science and technology using the brightest light known to man



A report on the SAUUL workshop held, June 17-19, 2002

THE SCIENCE AND APPLICATIONS OF ULTRAFAST, ULTRAINTENSE LASERS (SAUUL)

A report on the SAUUL workshop, held in Washington DC,
June 17-19, 2002

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Executive Summary

This report is the result of a workshop held during June 17-19, 2002 in Washington, DC where many of the leaders in the field met to assess the scientific opportunities presented by research with ultrafast pulse, ultrahigh intensity lasers. This workshop and report were supported by the Department of Energy Office of Basic Energy Science (BES), the Office of Fusion Energy Science (OFES), the National Nuclear Security Agency Office of Defense Programs (NNSA DP) and the National Science Foundation Division of Physics (NSF).

The workshop highlighted many exciting research areas using ultrahigh intensity lasers, ranging from plasma physics and fusion energy to astrophysics to ultrafast chemistry to structural biology. Recent progress in high intensity laser technology has made possible applications with light pulses unthinkable only ten years ago. Spectacular advances are now possible with the newest generation of petawatt lasers (lasers with peak power of one quadrillion watts) and unprecedented temporal structure. The central finding of the workshop and this report is that ultra-high intensity laser research offers a wide range of exciting opportunities, and that the continued growth and current leadership of the USA in this field should be aggressively maintained.

This report isolates five areas where opportunities for major breakthroughs exist with ultrafast, ultraintense lasers (UUL):

- Fusion energy using UULs to ignite an inertial fusion capsule.
- Compact, high gradient particle accelerators.
- Ultrafast x-ray generation and time resolved structural studies of solids and molecules.
- The creation of extreme states of matter and their application to puzzles in astrophysics.
- The generation of attosecond bursts of radiation and the study of electron dynamics.

After assessing the state of these areas, this report has come to four central conclusions:

1. Science studied with UULs is presently one of the fastest growing subfields of basic and applied research in the United States, Europe and Japan.
2. Applications of UULs are much broader and are now more interdisciplinary than at the birth of this field in the early 1980s. Consequently, opportunities for UULs in many fields of science have blossomed in recent years.
3. The state-of-the-art lasers that make possible these applications are now much more complex and more expensive than in past years.
4. It is imperative that a new mode of organization be developed in this research field to maintain its vitality in the USA and to make available the facilities and infrastructure needed to exploit current opportunities.

This report proposes that a network of institutions devoted to research in UUL science be organized, funded by both the DOE and the NSF. Such a network would enable the cross disciplinary interaction among subfields that is becoming a major part of high intensity laser research. A national network would also coordinate activities at next generation of petawatt peak power and kilowatt average power lasers that are now needed to work at the frontier of high intensity research.

1 Introduction

1.1 Overview

Science and technology have been the engines of progress in all areas of American life, including medicine, energy, defense, national security, and the economy as a whole. Applications and spin offs associated with lasers have been particularly numerous, and many of them are known to almost everyone, ranging from CD players to smart bombs to out-patient vision correction.

Laser development continues at a rapid pace world wide with major US leadership in the frontier of many exciting fields. One important frontier in which the US has been a traditional leader is in research on super-intense, ultrashort pulse lasers, where recent advances are projected to have a major impact on diverse and inter-related technologies, some with direct relevance to many areas of national need including homeland security, renewable energy, and advanced medical analysis. These areas lie near the core of our national strength and economic well-being. Progress continues in this field at a rapid pace, and the United States is in the forefront of this research; however, the pace of growth is creating an urgent need for a new class of facilities with infrastructure unlike that currently available within the US.

Existing ultrafast, ultraintense lasers cover quite dramatic extremes, for example, providing exceedingly delicate control of microprocesses of nature as well as enabling powerful material compression to intra-stellar densities. Super-intense laser beams uniquely carry light waves with electric strength greater than the force that binds atoms. There is no other implement known to science which can exert a *controllable* force this strong on macroscopic matter. The development of this tool over the past two decades has been punctuated by a series of scientific breakthroughs.

The time duration of pulses from these lasers can be extremely short. State-of-the-art ultrashort lasers produce pulses which are faster than the time scale over which atoms move in vibrating molecules or rearrange during chemical reactions. Consequently, they allow a new kind of probing and control of the fastest atomic and molecular processes of nature. *Control on such fast time scales is technologically unattainable in other ways*, and applications are being pursued in an array of studies ranging from advanced material properties to the chemical structure of biomedical building blocks.

The ability to reach such extreme conditions has led to research with very concrete, practical consequences. A number of important scientific and technological opportunities could be impacted by research with high intensity lasers. These include:

- Direct observation of the ultrafast motions of the electrons controlling the molecules of life, the dynamics of proteins or the motion of atoms in semiconductors.
- Near-term demonstration of advanced methods of electric power generation.
- Compact sources of intense particle beams for physics research and medical applications.
- Creating conditions in a laboratory that mimic those found in some of the farthest reaches of the cosmos.
- Low cost production of medically important short-lived radio-isotopes.

The scientific advances from higher and higher intensity light beams, have occurred because of rapid advances in laser technology over the last two decades. American scientists have played a leading role in building this laser technology and identifying the new avenues of science that it enables. As these advances have been applied to problems of deeper significance and greater difficulty, the lasers have grown increasingly complex. Until now, single academic and industrial research laboratories could maintain the science facilities needed for broad creative research in this area. In addition, a few US government laboratories have built larger, specialized facilities to reach tightly focused and very long range national goals using lasers. A surprisingly productive symbiosis between these very different laser research and development activities has been maintained.

Because of the generational evolution of this research, a detailed reassessment of the high intensity laser research field is imperative. We now require a new generation of more complex laser facilities to capitalize on this potential; hence a reevaluation of the manner in which this kind of research is pursued in this country is required. In this report we describe the science opportunities that now present themselves in this field and propose a plan for organizing the community that will enable the United States to capitalize on these opportunities.

1.2 Summary

To exploit fully the opportunities made possible by new laser technologies, the leaders from the communities of ultra-short science and ultra-high field science came together to isolate the most significant new directions and to formulate a pathway through which the US can maintain its leadership.

This report is the result of a workshop held during June 17-19, 2002 in Washington, DC (the Workshop on the Science and Applications of Ultrafast, Ultraintense lasers – the SAUUL Workshop) where many of the leaders in the field met to assess these scientific opportunities. This workshop and report were supported by the Department of Energy Office of Basic Energy Science (BES), the Office of Fusion Energy Science (OFES), the National Nuclear Security Agency Office of Defense Programs (NNSA DP) and the National Science Foundation Division of Physics (NSF). The Agenda and participants of the workshop can be found in the appendices of this document. Participation included scientists from universities, national laboratories and industry, including researchers from many sub-disciplines, all with extensive experience in the science and application of high intensity lasers.

The community represented at this meeting identified a number of scientific opportunities in high intensity laser science. It also assessed the need for new classes of lasers and technology to exploit these opportunities. This calls for a program, with coordination and focused centers of intellectual activity and supporting facilities that spearhead initiatives in specific directions, networking the combined strengths of our national laboratories and our universities. This will be a new mode of operation for this community, with much greater coordination and an increased reliance on a small number of larger scale laser facilities. Because of the cross disciplinary nature of applications of high intensity lasers, and the fact that the lasers required to stay at the forefront of the field are more complex and more expensive than in years past, more formal coordination is necessary. Such coordination will allow, within the budget constraints of modern science funding in the United States, the development of national laser centers that will serve the needs of many researchers while maintaining the creative edge of American science: the individual investigator. The science opportunities in this field make developing a new strategy imperative.

This strategy will provide immense benefit to many segments of our economic and scientific well-being, from ensuring leadership in advanced energy generation, to understanding the intricate structures of the molecules of life, to increasing the likelihood of future Nobel prizes in fundamental sciences. As has been demonstrated many times before, modest, targeted investments in cutting-edge sciences and technologies at the right time can have orders-of-magnitude payoffs to our economic well being and our national strength in advanced technology and knowledge. This report identifies such a need. Not only will we maintain dominance in the high intensity laser applications identified below, but we will impact the growth of many industries such as optics, laser technology, materials development, advanced medical diagnostics and many others.[1] This program will increase the output of American scientists and technologists from our institutions of higher learning, reducing our reliance on the importation of foreign technical and scientific workers.

This workshop and its report were motivated by potential national impact of ultra-fast, ultra-high intensity lasers. In a recent report[1] of the National Research Council, high intensity laser science was cited in three of the four grand challenges for physics in the 21st century. The relevant grand challenges cited are in the areas of Quantum Manipulation, Complexity and the Structure & Evolution of the Universe. Also cited is the impact of high intensity laser science on national energy production and defense. It is a rare trait that a scientific discipline has such far reaching impact from the most fundamental question of nature to the well-being of American daily life. With the excitement surrounding the opportunities, it is clearly important for the US to maintain unquestionable leadership in this area into the 21st century.

1.3 Scientific impact areas

Presently, scientific opportunities using ultrafast, ultraintense lasers ("UULs") exist in a wide range of areas. These applications span a number of "traditional" scientific disciplines, such as

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[1] *Physics in a New Era: An Overview,* National Academy Press, Washington, DC, (2001).

plasma physics and fusion research, atomic molecular & optical (AMO) physics, femtosecond chemistry, astrophysics, high energy physics, materials science, biology and medicine. Areas where a strong impact is possible include:

1) NOVEL INTERACTIONS WITH ATOMS, MOLECULES AND ELECTRONS

The interaction of intense, ultra fast laser pulses with atoms and molecules is the most mature field of study in this research area. However, the study of the most fundamental interaction has and will continue to provide the future building blocks. For example, the development of lasers with focused intensity in the ultra-relativistic regime ($>10^{19}$ W/cm^2) presents a new range of unexplored basic phenomena. These include relativistic effects in photoionization, collective excitation and free electron nonlinear optics arising from relativistic motion of electrons in an ultrahigh intense laser field. Furthermore, our recently developed ability to sculpt the laser-matter interaction at the quantum level offers new avenues of exploration and application. Control at the quantum level offers the possibility of producing new states of matter and new materials. Interactions with accelerated electrons make possible studies of the nonlinear aspects of Quantum Electrodynamics (QED), perhaps the most tested physical theory, in new regimes of parameter space.

2) ADVANCED ULTRA FAST X-RAY SCIENCE

UULs can produce very bright bursts of x-rays through the production of very short lived, high temperature laser plasma. Such x-ray bursts are being used to study ultrafast structural dynamics in solids and molecules. Soon dynamic studies in complex biological molecules like proteins will be possible. Extending beyond these exciting applications is recent work on

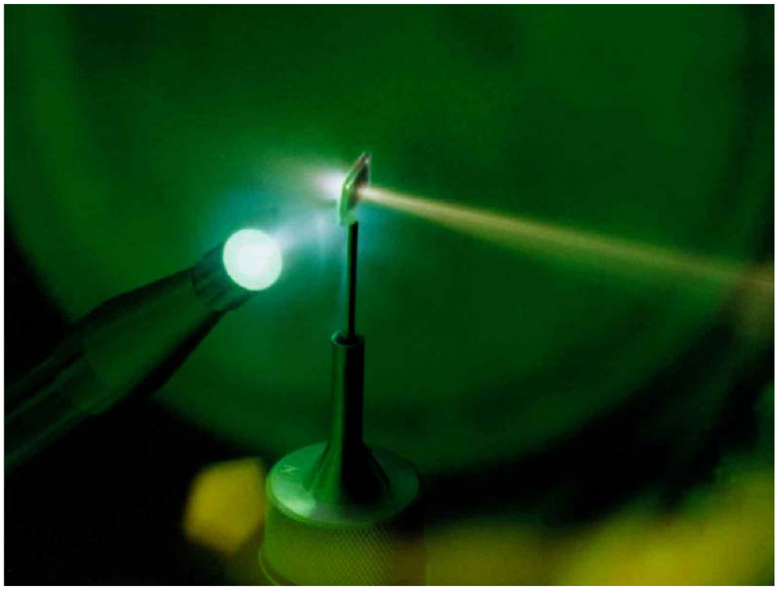

***Figure 1.3.1**: Photograph of the LLNL Petawatt laser striking a solid target and producing a cone of accelerated electrons and protons with energy up to 100 MeV. The laser enters from the left.*

producing “hyperfast” extreme ultraviolet (XUV) and x-ray sources, with pulse durations (attosecond) never produced or measured previously by humankind. Made possible by high peak power UULs, these hyper-fast XUV pulses and their application are at the present frontier of ultrafast research. In fact, attosecond (10^{-18} s) x-ray pulses may enable study, for the first time, of the movement of electrons in an atom or molecule as it undergoes a quantum or chemical transition.

3) HIGH ENERGY DENSITY SCIENCE

A high-energy ultrafast laser can heat solid density material on a time scale much faster than the material expands. This heating at high density produces very exotic states of matter, in some cases with pressure well above ten billion atmospheres (10 Gbar). This approach enables novel equation-of-state measurements and atomic physics studies in this extreme matter. Matter in these states is normally found only in the interiors of planets, dense stars and nuclear detonations. So laboratory experiments which impact the study of stellar interiors or defense issues are now possible.

4) LABORATORY ASTROPHYSICS

The extremes in temperature possible with UULs now make possible laboratory experiments that will aid in understanding exotic astrophysical events. These experiments include hydrodynamic studies of shocks generated by the short laser pulse, studies relevant to the study of supernovae dynamics and the structure of the interstellar medium. Even more exotic astrophysical applications include the production of relativistic, matter-anti-matter (electron-positron) plasmas with an ultrahigh intense focus. Such pair plasmas are believed to play a role in enigmatic gamma ray bursts.

5) FUSION ENERGY RESEARCH

At the ultrahigh intensities now achievable with UULs the enormous electric fields can accelerate electrons to very high energy (many millions of electron volts). Ultrafast, ultrahigh intensity laser production of fast electrons is currently a promising candidate to aid in the ignition of an imploded inertial confinement fusion (ICF) pellet by externally heating the fusion fuel. Initial results from Japan and elsewhere are promising. While the prospect of achieving fusion gain high enough for viable energy production is with conventional ICF, fast ignition with UULs holds the promise to achieve the necessary high gain with the generation of ICF facilities currently under construction.

6) ADVANCED ELECTRON AND PROTON ACCELERATORS

Current UULs can accelerate particles to relativistic velocities. They can do this directly with the strong fields associated with high focused intensity, or through the creation of fields in plasmas (Figure 1.3.1). Great promise now exists of the acceleration of particles by lasers in both cases. Wakefield accelerators have demonstrated electron beams from gaseous targets with energies in excess of a 100 MeV, and similar energies have been observed in the acceleration of protons from thin solid targets irradiated at relativistic intensity. This acceleration, while modest by the standards of modern accelerators, is remarkable for the fact that it is achieved over an incredibly small length on the order of 1 mm. This raises the possibility of a future class of compact, high-energy accelerators or even scaling such laser based accelerators to ultrahigh particle energy (>1 TeV).

7) PULSED ION AND NEUTRON SOURCES

Intense laser interactions with solid and gas targets can drive acceleration of heavy ions to high energy. Certain UUL interactions can also lead to the production of a burst of neutrons (Figure 1.3.2). These sources may have application in studies of radiation damage of materials. The bursts of ions or neutrons are unique and present the possibility of using them as a impulsive excitation in impulsive pump-probe experiments that look at how these particles interact with other matter. This is relevant in understanding the radiation-induced damage of materials, an unsolved problem impacting future fusion reactors among other areas.

8) BIOLOGY AND MEDICAL APPLICATIONS

The application of UULs in biology and medicine is now becoming viable. Laser generated x-ray sources have been used in proof-of-principle biological imaging including ballistic imaging that uses the pulsed nature of the source. UUL based x-ray sources may yield unprecedented spatial resolution in biological studies. Ultrafast x-rays may enable dynamics studies of biological molecules (like protein folding). More speculative, but of great potential importance, is the possibility of using UUL accelerated protons or heavier ions in hadron cancer therapy. In addition, the production of short-lived isotopes with accelerated particles produced by compact UULs may enable novel medical diagnostics health facilities.

More explicit discussion of these application areas as well as technical bottlenecks is described in Section 2, Scientific Opportunities.

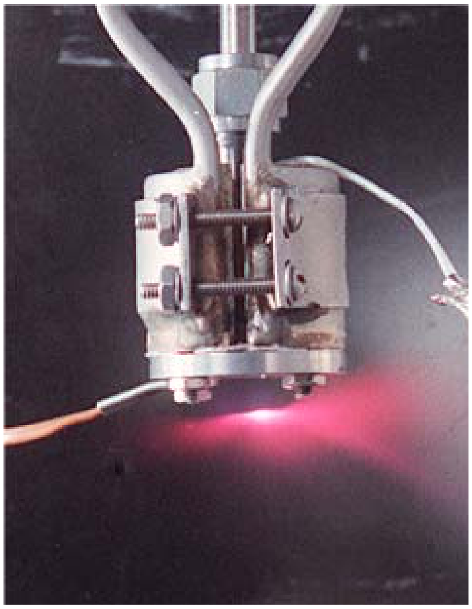

Figure 1.3.2*: A plasma produced by the irradiation of a gas jet of deuterium clusters by an intense femtosecond laser. This hot plasma produces a burst of neutrons from the fusion reactions driven by the hot deuterium ions created when the clusters explode.*

1.4 The Technology of UULs and its Impact

Advanced laser technology drives the science thrusts described above. Advances in peak power to a petawatt (10^{15} W) and beyond over the last fifteen years have been at the core of the scientific and technological innovations enabled by intense pulses of light (Figure 1.4.1). In fact, recent technical developments make pulse peak powers one thousand times beyond the existing record (1 exawatt) plausible.

The United States has been the undisputed leader in the technology of UULs. Most significant advances and milestones in this technology have come from the US and the US is well positioned to maintain this leadership. The revolutionary development of chirped pulse amplification (CPA) at the University of Rochester in 1985 spawned this entire field. CPA enabled the *efficient* amplification of ultrafast pulses to high energy with compact laser systems. CPA lasers are now widespread throughout the world, with for example, virtually every ultrafast chemistry laboratory using at least one such system. The extremely high peak powers and focused laser intensities achievable with modern lasers has its origin rooted in the development of CPA.

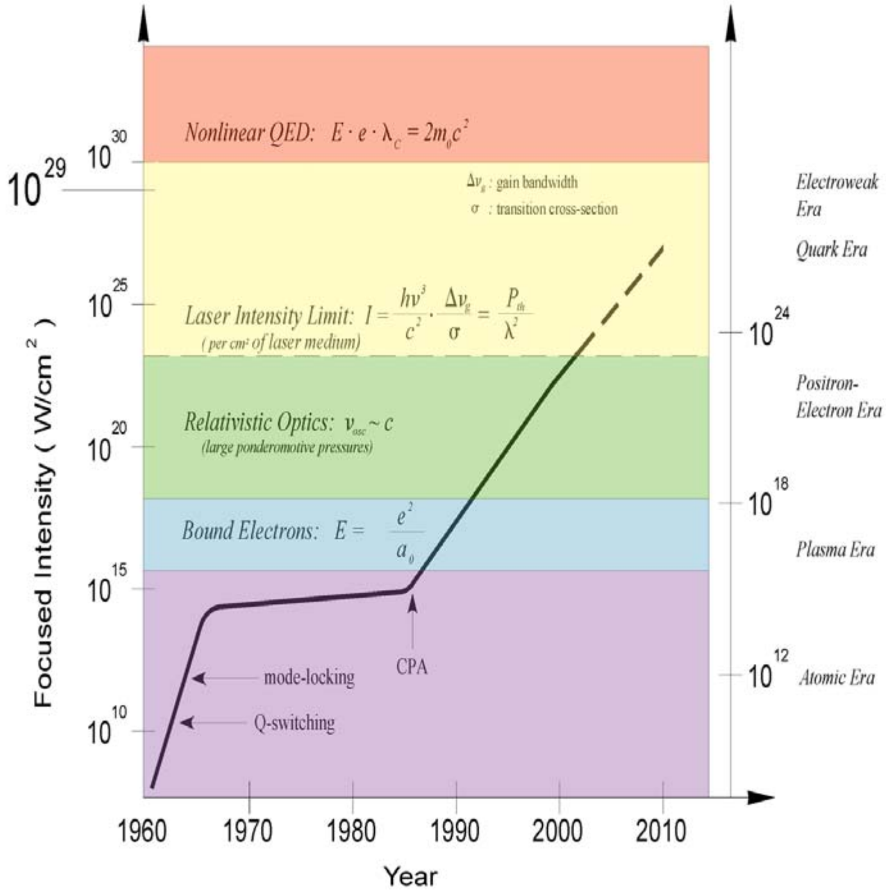

Figure 1.4.1: *Illustration of increase in accessible peak intensity with year. Increase beyond intensity of 10^{23} W/cm^2 in the coming decade is speculative and will require major breakthroughs in laser technology.*

CPA technology has been successfully applied at many different scales. UULs range from the compact, few square ft, millijoule class lasers that are the workhorse of femtochemistry to very large scale, ultrahigh power lasers. The UUL technology considered in this report spans science and application using lasers which typically deliver laser pulses with duration of between 20 fs and 1 ps and pulse peak power greater than a few trillion watts (terawatts), instantaneous powers that exceed the combined power output of all power plants in the United States. Scaling of CPA technology culminated in 1996 with the activation of a petawatt power laser (1000 terawatts or 10^{15} W) at the Lawrence Livermore National Laboratory (figure 1.4.2). This world record setting high intensity laser is now being emulated at a number of laboratories worldwide.

***Figure 1.4.2**: The LLNL NOVA Petawatt (10^{15} W/cm^2) laser large compression gratings. The now decommissioned NOVA laser was the first PW-class laser. No PW-class lasers are in operation in the US, although they do (or will soon) exist at a number of labs in Europe and Japan.*

Chirped pulse amplification involves a series of optical manipulations that enable amplification of short laser pulses. A laser operating in a special “phase-locked mode” produces a low power pulse of ultrafast light. Nature dictates that this short pulse in time must have a broad spectrum of component frequencies. The CPA approach firsts stretches the pulse in time by a factor of around ten thousand from its original duration by spreading the component frequencies in time using 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. 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 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.

Without question, CPA has had a profound scientific impact. CPA has enabled tabletop scale multi-TW lasers in many guises and represents a gain of over a thousand in compactness over previous, similar peak power lasers, such as the NOVA laser at LLNL. Furthermore, the adaptability of CPA architecture has permitted a boost of nearly three orders of magnitude in power attainable by existing large scale lasers around the world, including the Vulcan laser in the UK, P102 in France, the GEKKO laser in Japan, in addition to the decommissioned petawatt on the NOVA laser in the US. A benefit derived form the technology has been the fostering of a symbiotic relationship between the government laboratories and university researchers. The intellectual demarcation that once existed between large-scale facilities and university laboratories was reduced by the ability of both to address similar/complementary problems. Consequently, the technology brought back to university laboratories experiments that could, previously, only be conducted on large facilities.

CPA has made an immense contribution to education, which facilitates economic development. As the impact of optics in society grows, the importance of exposing the brightest students in physics, chemistry and engineering to laser technology and its applications made possible by tabletop CPA lasers cannot be overestimated. The economic and societal potential for this technology is significant. More than 1000 CPA lasers have been sold, representing over $200M in business worldwide. Spin offs of this technology in unexpected areas continue to grow. For example, the study of damage threshold in CPA systems has led to the development of micromachining and femtosecond eye surgery (cornea transplant, glaucoma, refractive correction). In the first six-month after its introduction ten thousand patients have now received this procedure.

1.5 Grand Challenges

With these many, varied science impact areas in mind, a number of grand challenges exist in the field of ultrafast, ultraintense laser science. We believe that these challenges include:

1. *Can we probe and control dynamics on a sub-femtosecond (attosecond) time scale?*
2. *Is it possible to make controlled nuclear fusion useful and efficient by heating plasmas with an intense, short pulse laser?*
3. *Can we create and study matter at extremes in pressure (over a billion atmospheres) and temperature (over ten million ºC) to aid national security or give us greater insights into the workings of stars and planets?*
4. *Can we learn about exotic astrophysical phenomena, such as supernovae or gamma ray bursts, in a laboratory experiment?*
5. *Can the structure and dynamics of complex molecules (like proteins or other large macromolecules) be probed, as the atomic constituents move with bright pulses of femtosecond x-rays?*
6. *Are new classes of compact particle accelerators possible and could these be scaled to build a future TeV collider?*
7. *Is it possible to construct a laser with a peak power of over 1 exawatt (1 quintillion watts or 10^{18} W) that would allow us to study matter subject to unprecedented forces?*

The possibilities residing in these grand challenges will be discussed in the sections that follow.

2 Scientific Opportunities Presented by Research with Ultrafast, Ultraintense Lasers

This section discusses the scientific opportunities and applications enabled by Ultrafast, Ultraintense Lasers (UUL). These opportunities represent the input of ideas from many US researchers in UUL science present at the SAUUL workshop. This chapter covers a broad spectrum of scientific areas, from the most fundamental questions in physics to everyday devices that could impact upon the economics, health and security of American life. Many of these scientific issues can be addressed within the next decade with proper organization and investment of the US scientific community.

The wide scope of science opportunities discussed in this section is indicative of the interdisciplinary nature of UUL science. Much of these scientific opportunities will be most effectively opened if a new paradigm for organizing the UUL community in the US is pursued. The UUL community now needs larger scale, more complex short pulse lasers to work at the state of the art in the areas discussed below. In addition, may of the science areas discussed in this section would clearly benefit from the development of research centers of gravity that would provide an intellectual synergism and would leverage the resources of all the national science agencies for maximum impact (a structure developed in more detail in Appendix A). The current model for investing in redundant, highly specialized infrastructure and expertise would be minimized resulting in effective investment and scientific impact. Such Center and facility needs are discussed at the end of each science sub-section (in sub sections entitled “What is needed”). These Center and laser needs could advance the mission of different agencies, causing an effective synergy of agency resources in a joint investment strategy. The synergy can be envisioned in a number of configurations:

First, although each section is organized to identify Centers for individual scientific needs, it is conceivable that a single Center could have a dual mission. For instance, a Center based on high-average power infrastructure can explore both basic atomic and molecular science as well as x-ray source science. Second, Centers can enhance the scope of science performed at facilities already existing or planned within an agency’s portfolio. The *“What is needed”* sections identifies a number of these opportunities at accelerator-based and ICF facilities.

2.1 Basic High-Field Science

2.1.1 Introduction

The fundamental science of high intensity interaction with atoms and molecules is a large and rich area of research. The foundations laid by fundamental discoveries have enabled many of the high intensity applications and provides a roadmap towards the future. There are three important directions in this field that the next generation of ultrafast, ultraintense lasers (UUL) sources can impact.

1. Control of strong-field dynamics on the attosecond time-scale.
2. Study of light-matter interaction with fields at relativistic energies.
3. Short wavelength nonlinear optics.

Attophysics: Ultraviolet optical pulses less than one femtosecond long have now been produced, opening the field of attosecond science and technology (1 attosecond $\equiv 10^{-18}$ s). Realization of attosecond pulses would provide the shortest electromagnetic pulses known to man. Such sources constitute the first direct probe acting on time scales characteristic of the evolution of electronic wave functions in atoms and molecules, essential freezing all motion. The development of this capability will have tremendous fundamental and practical consequences in atomic physics, chemistry and material science. Such pulses could address important questions about the stabilization of atoms and ions against laser ionization, the evolution of complex wave packet states, electron transfer in the condensed phase, and fast electronic processes in solids. The ability to control electronic motion, which is the basic component in the structure of any material, allows the possibility of producing new states of matter and new materials.

Attosecond science is enabled by technological advances in the ability to sculpt precisely the electromagnetic field. Control of the intensity (number of photons), phase and wavelength open many new, challenging areas for study. Ultra-high power pulses can be used to generate intense, ultra-short pulses with wavelengths from the visible to x-rays through a variety of processes such as harmonic generation, x-ray lasers and other non-linear processes. These pulses can be used to drive coherent quantum processes in regimes where the underlying dynamics can be directly followed.

Relativistic intensity. High power focused laser pulses can accelerate electrons to relativistic energies in less than one optical cycle. This is a novel probe of fundamental atomic and plasma dynamics in the relativistic regime. Fundamental interactions such as photoionization must be modified as relativity becomes dominant. Relativistic quantum electrodynamics in laser driven plasmas can be studied in detail. Using precisely characterized, high-power pulses, investigations of quantum dynamics within a regime that is both extremely important and generally very difficult to explore become achievable.

Short wavelength nonlinear optics. A third revolution in our approach to study and control matter will be enabled by nonlinear optics in the short wavelength regime, e.g. x-rays. Nonlinear optics has had a tremendous impact in all fields of science and technology, and was recognized with the 1981 Nobel Prize in physics awarded to two of its pioneers, N. Bloembergen and A.L. Schawlow. Just as the first high-powered visible lasers opened this new area of science, so the new class of high intensity, short wavelength sources usher in a new domain of nonlinear phenomena. The high frequency output of these novel sources is capable of exciting nonlinear processes for inner shell and tightly bound systems. Modern single-photon x-rays techniques can be extended into the multiphoton regime providing powerful and unique probes of matter.

2.1.2 Scientific Frontiers

Attosecond probing of the quantum dynamics of atoms, molecules and condensed materials can be accomplished using pulses generated by the interaction of short, high-energy laser pulses with a non-linear medium (see Figure 2.1.1). In essence by making photons from photons, specific pulse lengths and wavelengths, both substantially shorter than those of the incident laser pulse, can be produced. Although these processes tend to be inefficient, the understanding of laser-atom interaction dynamics achieved over the past decade has led to orders-of-magnitude improvements in conversion efficiencies and pulse duration. Computer control of pulse generation can achieve optimization through feedback loops in the production of a desired product state. These studies have led to many advances in nonlinear optics and in the ability to guide electron-photon and electron-electron interaction dynamics.

Studies of complexity in simple quantum systems is an enormously important research area as the understanding acquired can be extrapolated to even more complicated dynamical processes. The flexibility of the coherent pulses created using high-energy sources offers the capability to completely represent the dynamics of the processes of interest. The freedom available in selecting the wavelength, pulse shape and energy and the high repetition rates and large bandwidths will allow the continuous examination of any quantum dynamical process.

Attosecond pulses can be used to freeze and probe evolving electronic charge distributions, providing a series of snapshots of the state changes as they progress. This provides a completely new window on the interaction dynamics of electrons that in turn drive the changes in structure in multi-atom systems. A simple example would be internal conversion within a molecule leading to a new electronic configuration and structure of the system. A direct probe of the localized crossing of molecular potential energy surfaces can be achieved during the transformation of the states.

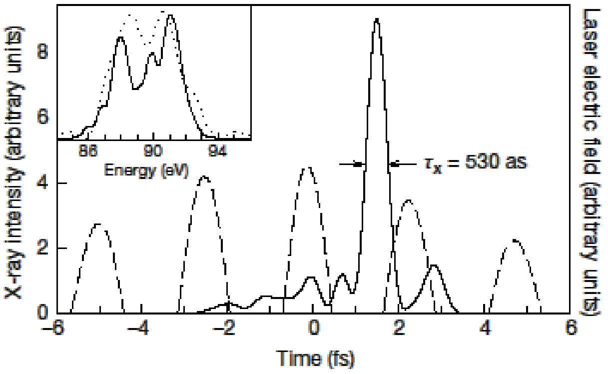

***Figure 2.1.1**: Reconstruction of a sub-femtosecond extreme ultraviolet (90 eV photon energy) laser pulse (the solid line) produced by extreme nonlinear high harmonic generation in an atomic gas excited by an ultrafast (few femtosecond) laser pulses. This experiment heralds in the field of attophysics which can revolutionize the study of the electronic motion in matter. [M. Hentschel, et al., Nature 414, 509 (2001)]*

Attosecond pulse research includes pump-probe studies of excitation and subsequent evolution of quantum-dynamical processes; quantum control of state populations and therefore structural evolution; and direct probing of electron correlation. These pulses allow wavelength studies of few-photon multiple ionization that can be completely characterized using high repetition-rate coincidence techniques. Investigations of multiphoton core-hole (hollow atom) production can provide simple, yet detailed pictures of the correlated electron responses by following the subsequent relaxation dynamics.

High power, short wavelength sources may provide few-photon imaging capabilities, and an avenue to short wavelength precision spectroscopy using time-dependent pulses.

Super intense laser-matter interaction physics. The regime of super-intense laser science is achieved when the native electrostatic interactions in the matter become secondary to the laser field. Here relativistic effects become increasingly important, eventually dominant factors in the system response. With optical and near infrared lasers, at intensities between 10^{16} and 10^{20} W/cm^2 relativistic effects alter the photon-electron, electron-electron and electron-nuclear interactions. For example, multiple ionization dynamics, and laser-induced photon (harmonic) emission are affected. At extreme intensities, above 10^{23} W/cm^2, tests of quantum electrodynamics become possible. Processes such as light scattering from light and particle creation can be studied.

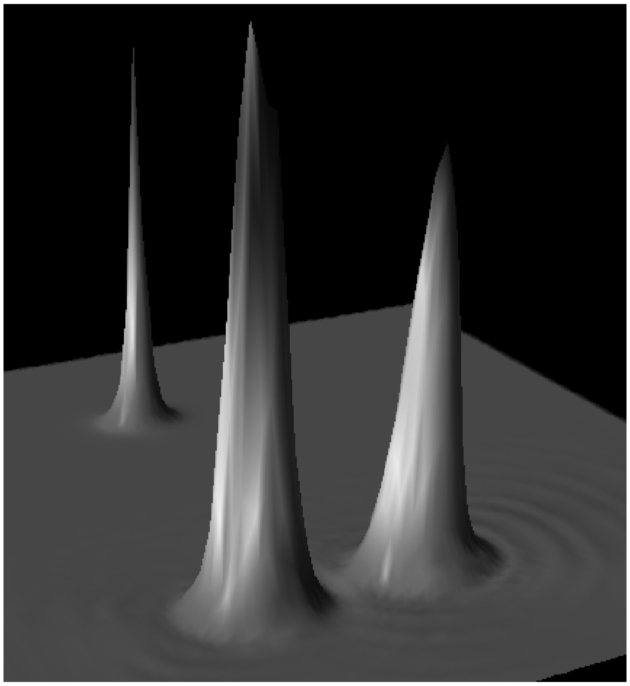

***Figure 2.1.2**: Normal hydrogen ground state electron density distribution (background) and the strikingly distorted, bi-local distribution (foreground) for the new ground state created in a short, super-intense, high-frequency laser pulse. In this state an atom becomes more difficult rather than easier to ionize as the intensity of the laser pulse is increased. Understanding these new states are of great fundamental importance and are enabled by UULs. [Figure courtesy of K. C. Kulander (LLNL).]*

One very interesting regime which can be explored by pulses produced by high-energy sources will be that where the intensity is very high and the wavelength is short enough (frequency high enough) that the electron can no longer follow the oscillating field. An interesting and surprising prediction has been made that at high-intensity and high-frequency the ground state of atoms will become greatly distorted, responding essentially to the cycle-averaged potential field. These new exotic structures have been studied extensively theoretically (see Fig. 2.1.2) and are predicted to become more immune to ionization as the intensity increases. Experimental verification of this atomic stabilization effect is awaiting the creation of sufficiently intense, coherent short wavelength sources. The exotic structures are predicted to occur in multi-electron, and multi-atom systems. Their electron- and photoemission properties will differ very dramatically from those being studied presently with longer wavelength lasers.

Nonlinear optics at wavelengths below 100 nm is currently nonexistent because of the absence of light sources with adequate peak power. The international community is discussing potential fourth generation light sources capable of generating high intensity XUV/x-ray radiation. The options include single-pass free electron lasers, high-harmonic generation, x-ray lasers and plasma-driven x-ray sources. All these sources except the FEL approach are enabled by UULs. Furthermore these UUL driven sources are essentially laboratory scale systems. Figure 2.1.3 shows a high harmonic source based on a small-scale (< 25 cm length) hollow core fiber. This source is capable of generating efficient coherent (Figure 2.1.4) XUV radiation using quasi-phase matching and with high average power (kilohertz repetition rate). Researchers are actively pursuing the scaling of this source, among others, into the Gigawatt (10^9 W) peak power regime.

The emergence of these sources will open a new realm of nonlinear optics applied into the short wavelength regime. The fundamental and important difference will be to exploit the nonlinear response of inner-shell electrons on reduced length scales. Unlike conventional nonlinear optics, the valence electrons of matter will be transparent. The impact that modern synchrotron sources have had in providing unique and powerful probes of matter will be

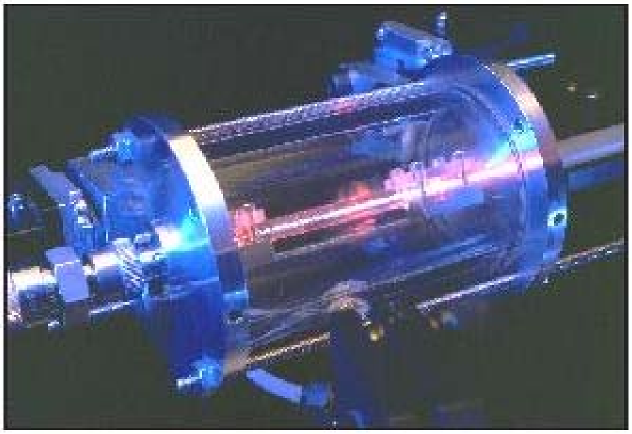

Figure 2.1.3: *The picture shows a compact (less than 25 cm in length) hollow core fiber source for producing coherent XUV pulses of light. Intense pulses from a UUL are focused in the fiber and the XUV light is generated over the length of the fiber (white illuminated region in the center of the picture). This scheme makes use of the properties of the target inert gas and fiber to achieve high conversion efficiency into the XUV. This scheme, among others, has the potential of providing gigawatt XUV/x-ray radiation in the near future for use in nonlinear optics. [Courtesy of M. Murnane and H. Kapteyn (JILA/Colorado).]*

revolutionized by future fourth generation sources. The techniques of x-ray absorption spectroscopy, e.g. EXAFS, XANES, and imaging can access new atomic states and provide unprecedented dynamical and structural probes for material and the biological sciences. Furthermore, short wavelength nonlinear optics could be exploited for producing more exotic forms of light, e.g. sculpted x-ray pulses, and even shorter wavelengths.

In conclusion, very exciting areas of research of both fundamental and practical significance will become possible with the availability of high-energy, coherent light sources. Fields of research that are now unattainable due to the lack of short wavelength, high bandwidth intense pulses will become accessible. This will rapidly become a major scientific frontier.

2.1.3 What is needed

CENTER CONCEPTS:

1. Centers are required for exploring the scientific forefronts of the fundamental physics of the laser-atom interaction. The specialized facilities required would be 10-100 TW laser systems for studying relativistic dynamics and high repetition rate, high average power TW-class lasers for hyperfast (attosecond) pulse generation. These Centers would benefit from a broad intellectual pool of scientists and engineers, both in experiment and theory, sharing a common goal of addressing the complex integration of advanced concepts. Such Centers would benefit not only from local expertise but a network of external users.
2. Centers investigating the fundamental physics at extreme interaction energies or exotic matter are also needed. A unique Center concept would be to collocate a ≥100 TW-class laser at a relativistic particle source (RHIC, SLAC). This would allow access to deeply bound ions (highly stripped) and the relativistic energies would provide a Lorentz boost in intensity and time dilation in the particles frame.

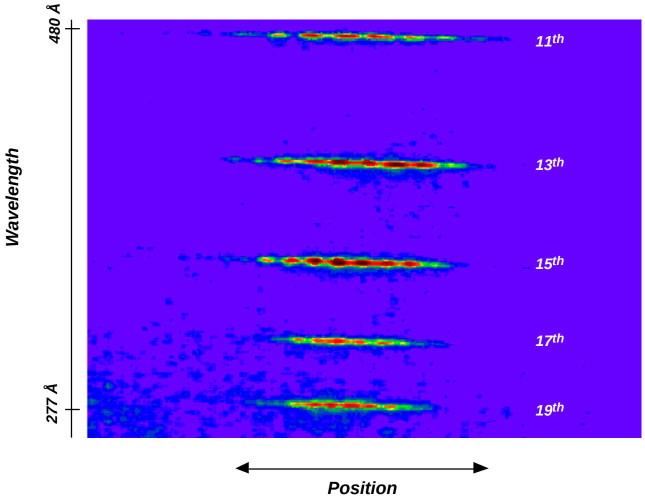

Figure 2.1.4: *Picture of patterns produced by interference between two slits illuminated by femtosecond soft x-ray pulses resulting from high harmonic conversion of an intense 527 nm laser in a Argon gas jet. Such studies have demonstrated that soft x-rays driven by UULs have both spatial and temporal coherence. These high coherent properties of the light are absent in synchrotron light sources and enable novel experimental studies of matter in the x-ray regime, e.g. nonlinear optics, interferometry. [Courtesy of Imperial College Laser Consortium).]*

2.2 Ultrafast X-ray Generation and Applications

2.2.1 Introduction

X-ray applications of ultrafast, ultraintense lasers (UUL) are diverse and rich. There are several distinct communities that will benefit from the UUL centers. For some of these applications, the laser produces x-rays with special properties (e.g. sub-picosecond duration) that are used to probe materials. Other applications use lasers to excite systems, which are then probed by x-rays from synchronized electron synchrotron light sources or XFEL's. A third class of activities need the laser for both the high-energy pump and the x-ray probe. Both high-energy lasers and high peak power lasers will be useful. In addition, high repetition rate and high average power can be particularly important. We subdivide this section into several distinct themes:

1. X-ray probe of dynamics of photo-excited materials: The science case.
2. Laser-pumped x-ray lasers: opportunities for advancement, and applications.
3. Tabletop incoherent x-ray sources: extending their capabilities.
4. X-ray science at 3rd and 4th generation electron synchrotron facilities.

2.2.2. The Structure and Dynamics of Photo excited Materials

Ultrafast, ultraintense lasers will revolutionize our understanding of photo-excited materials, both at moderate and high levels of excitation. At the higher levels of excitation, lasers will be used to create extreme material states, corresponding to solid densities at a few electron volt energy and pressures of 10-100 Gbars. Creation of materials in this "warm dense matter" (WDM) regime is of fundamental interest since materials in this regime falls in between "standard" condensed matter and "plasma" descriptions of matter. The formation of WDM, together with the use of ultrafast x-rays to probe their initial properties, will provide important experimental data for developing an "equation-of-state" description of highly excited materials. Equally important, the subsequent evolution of WDM material will provide an important opportunity for studying phase transition kinetics. WDM states typically correspond to materials driven to the "supercritical fluid" regime of a phase diagram. The relaxation upon expansion promises an important opportunity to study materials in the vicinity of liquid-gas (L-G) critical points. Here a material can be driven to the spinoidal region of the L-G phase space where a homogeneous material phase is unstable and phase transition kinetics are not well understood. Further metal-insulator transitions can be expected to occur upon expansion of a supercritical fluid. Time resolved x-ray spectroscopy offers a novel technique to study the relative rates of spatial (Wilson-Bloch Mechanism) separation and electron correlation (Mott-Hubbard Mechanism) effects in metal-insulator transitions.

Ultrafast pulses of 10 keV or greater x-ray photons with high power fluxes are essential for the imaging of high energy density plasmas. These plasmas range from those that will be produced on the National Ignition Facility (NIF), to those of the x-ray source itself. Since these plasmas evolve on fast timescales ~100 fsec and achieve densities many times that of solid materials, both coherent and incoherent x-rays will be needed: Incoherent x-rays will make possible <100fs time-resolved backlighting measurements (radiography) and coherent x-rays will

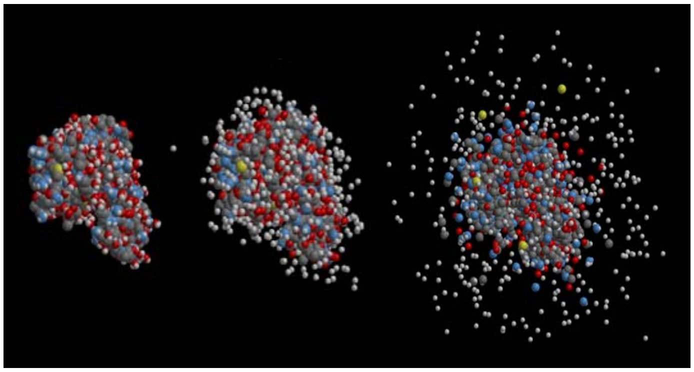

***Figure 2.2.1**: Protein exposed to 50 femtosecond x-ray pulse, and disintegration with time. The images show the structure at the beginning, middle and end of the x-ray pulse. The development of intense x-ray sources discussed in this section can offer a new approach for structural determination of macromolecules. The specific calculation shows the radiation-damage-induced explosion of T4 lysozyme (white: hydrogen, gray: carbon, blue: nitrogen, red: oxygen, yellow: sulfur). Integrated x-ray intensity was 3×10^{12} photons/100 nm diameter spot (3.8×10^{6} photons/A^{2}). [Figure from Neutze et al, Nature **406**, 752 (2000).]*

permit interferometry, yielding plasma structural information on unprecedented time and space scales.

Although there are efforts using UULs to provide short pulse x-rays for materials studies, virtually no progress has been reported on understanding the x-ray pulse structure. Since this pulse structure is determined by the laser-driven plasma dynamics itself, it is important to measure and understand the plasmas that are creating the x-rays. A thorough understanding of the roles of absorption and laser acceleration (wakes versus direct ponderomotive acceleration) in generating the hot electrons for target impact will be aided by imaging of the plasma density structure through backlighting with auxiliary short pulse x-rays.

In lower excitation states, ultrafast x-rays can play a unique role in probing transient structural dynamics in systems of chemical and biochemical importance (figure 2.2.1). Transition state chemistry (understanding intermediate chemical structures) is an important scientific frontier as evidenced by the 1999 Nobel Prize in chemistry, awarded for the use of visible ultrafast light to probe the transition state. Visible light, however, provides only indirect information about the structure. Obtaining direct structural information via x-ray diffraction and absorption represents an important scientific frontier in the study of chemical and biochemical reactions.

2.2.3 Novel Ultrafast X-ray Sources (X-ray technology)

SOFT X-RAY LASERS FOR EUV LITHOGRAPHY

Extreme ultraviolet lithography (EUV) is the leading candidate for printing the next generation of integrated circuits starting in 2007. Its implementation combines high average power incoherent radiation for printing and requires compact sources of 13.5 nm coherent radiation for *in-situ* metrology of EUV optics on masks at the factory. Approaches to realizing compact 13.5 nm sources include electron collision excitation; multiply charged ions; and recombination schemes based on population inversions in *3-2* and *2-1* transitions in H-like ions.

In order to have compact 13.5 nm laser, it is important to develop UUL (~100 fsec, <1 TW) at relatively high repetition rate. Alternatively, ultrafast pulse lasers using energy of the order of 1 J can produce saturated pulses of radiation at discrete wavelengths between 13.5 and 14 nm by producing transient inversions in nickel-like ions, much as the *4d-4p* line of nickel like cadmium at 13.2 nm.

XUV/X-RAY COHERENT SOURCES

A UUL interacting with a gaseous atomic target produces bright, coherent XUV/x-ray radiation via high harmonic generation. These are compact sources with the potential for producing unprecedented pulse durations on the atomic time-scale (attosecond) and intensities necessary for opening the field of short-wavelength nonlinear optics. Recent demonstrations of microjoule output in the XUV range have been reported. The energy and wavelength scaling of these sources is actively being pursued, as well as novel target configurations using atomic state preparation or micro-engineered structures. These sources could be pumped by high repetition rate UULs producing average power outputs in the XUV approaching 3rd generation synchrotrons.

X-RAY LASER IN THE "WATER WINDOW" (4.3-2.4 NM)

Lasing can be generated on the *2-1* transitions of H-like C-VI ions at 3.4 nm using optical field ionization. However it would require ultra short pumping laser beams on the order of 5x 10^{18} W/cm^2. The result would be a laser at 3.4 nm with good coherence, making possible holographic high resolution imaging of biological cells in their natural environment.

X-RAY LASERS TO SEED X-RAY FREE ELECTRON LASERS (XFEL)

Work on development of XFEL is progressing around the world. One of the major cost and technical difficulties associated with development of the XFEL is related to the central component of the XFEL, e.g. the 100 m (and more) long undulator. However if appropriate x-ray "seed pulse" could be developed and injected into an XFEL, the length of undulator could be dramatically reduced (down to less than 20 m). The principles of direct or indirect laser (high-gain harmonic-generation) seeding of FELs have been demonstrated at long wavelength (> 200 nm) in a number of electron facilities. In each case, the reduction in gain length, e.g. undulator length, were significant in comparison to self amplified spontaneous emission (SASE) schemes.

Using ultrahigh intensity and ultrafast pulse lasers for developing 3.4 nm laser in *2-1* transition in C-VI would provide such a seed pulse for XFEL. Although the wavelength of a "seeded" XFEL would be longer than a free running one (3.4 nm rather than 0.15nm), it would be easier and less expensive to demonstrate the feasibility of an XFEL at an already very short wavelength (and useful) in the water window. Using high-gain high-harmonic generation within the XFEL, with 3.4 nm radiation as the fundamental, it would make it possible to reach 0.3 nm (11th harmonic) and even down to 0.14 nm (23d harmonic.) with high output intensity (100kW).

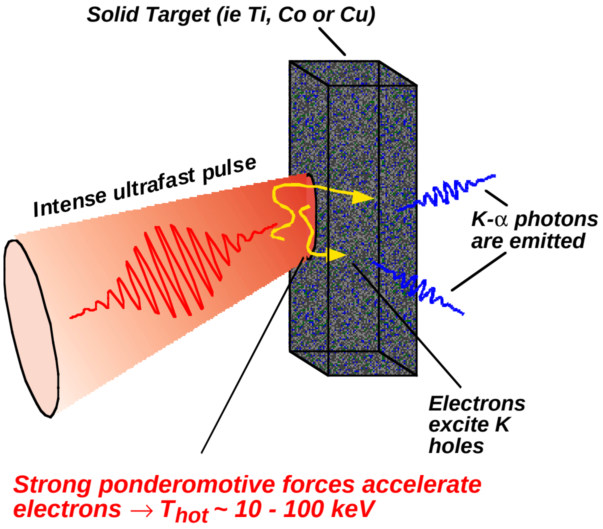

Figure 2.2.2*: Schematic of K-alpha x-ray production by an ultrafast laser pulse on a solid target. The electric field of the intense laser accelerates electrons into the solid target material. These electrons excite inner shell electrons in the atoms of the cold material. When these inner shell excitations decay, x-rays can be emitted, often with pulse duration of well under a picosecond.*

2.2.4 Laser-produced x-ray sources and applications

There are two generic “novel” categories of multi-KV experiments that exist for higher, short pulse (< picosecond) x-ray flux:

1. Diffraction
2. Absorption or extended x-ray absorption fine structure spectroscopy (EXAFS)

Optimization of these x-ray sources driven by UULs will be critical in enabling new classes of experiments. Successful time-resolved diffraction experiments have been conducted using K-alpha sources based on 1-watt lasers (Figure 2.2.2). These experiments investigated dynamics in structures with a high degree of order and large scattering cross sections, i.e. ideal diffractors (Figure 2.2.3). Next generation experiments will involve broader categories of materials and structures with either less order and/or lower scattering cross sections. Dynamics of thin metals (low order, good cross sections) will require one to two orders of magnitude higher x-ray flux than is presently available. Furthermore, powder pattern dynamics of organics (direct observation of photo-induced chemistry) will require an additional 1 to 2 orders. Scaling of existing techniques at constant intensity on target will thus require 3 to 4 orders of magnitude increase in laser average power. Development of short pulse lasers beyond 10W remains a technical challenge. Scaling to 1-10KW average power will require pulsed pump sources of order 2-20 KW. Safety, cost, maintenance and technical issues related to such lasers are beyond individual PI’s and are well suited to large-scale Centers. Similar arguments can be made with respect to scaling of Thompson scatter sources for time resolved absorption spectroscopy and EXAFS. Present Thomson sources also operate with nominal 10 W average power laser sources.

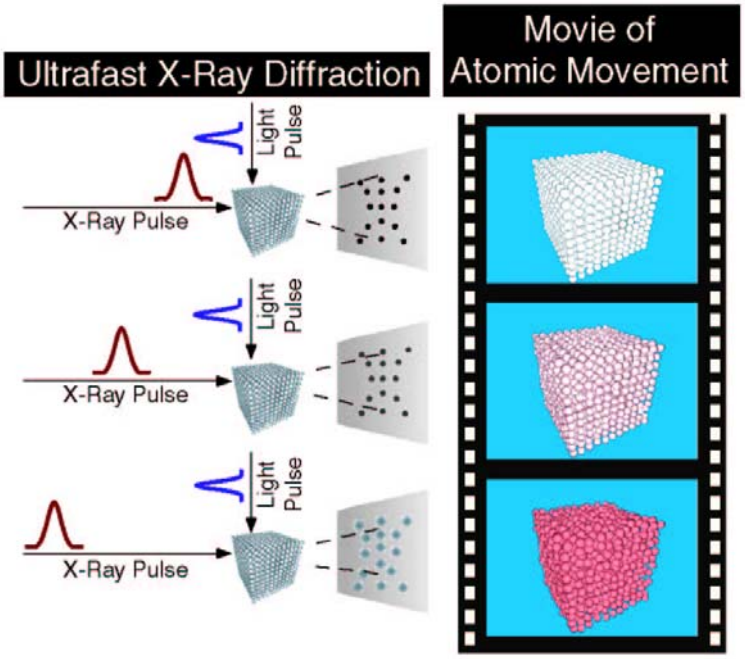

Figure 2.2.3*: Movie of x-ray diffraction pump-probe experiment. A pump pulse from a UUL laser initiates an ultrafast event in the solid, e.g. rapid heating. The ultrafast x-ray pulse (probe) interrogates the diffraction pattern of the solid as a function of delay after the pump pulse. A series of snap shots reveals the change in the solid's structure. Experiment similar to the one illustrated has the potential of becoming a routine technique for studying the dynamics of matter. [Courtesy of C. Siders, CREOL].*

In addition to increasing laser average power, the average flux at laser operated x-rays can be significantly improved by better utilization of solid angle collection efficiency and by optimization of laser to x-ray coupling efficiency. Initial numerical models of "nano-engineered" targets suggest a 1-2 order of magnitude improvement over current configurations. Taken together, improvements in average power at up to 10^7 can be expected.

2.2.5 Activities at large-scale electron-based light sources

Sub-picosecond x-ray sources at 3rd generation synchrotrons and XFELs will gain much of their utility from pump-probe experiments with high-powered lasers. One of the important impediments to progress in fields that use this technique is the absence of UUL sources at major electron-based light source facilities. In fact, although all major electron machines use lasers to drive the photo-cathode front ends of the accelerator, high-energy ultra fast laser sources are still generally absent on the experimental floor. Notable exceptions are the high energy density ultra-fast laser that was built by the Melissinos and Meyerhofer group at SLAC in the 1990's for studies in high energy physics; and milli-joule-class kHz CPA lasers installed on a few beam lines at ESRF, ALS, and APS synchrotrons. The barrier towards increased utilization has been a cultural difference between the electron- and optical-based communities. Establishment of autonomous laser Center(s) collocated with electron-based facilities could significantly enhance the scientific agenda of these facilities, as well as independent scientific contributions. Some of these are outlined in the BESAC document "LCLS: The First Experiments". The areas discussed below can be separated broadly into warm dense matter research, laser probing of near solid density plasmas, and laser-plasma spectroscopy of ions in plasmas.

LASER-BASED PLASMA PRODUCTION FOR ELECTRON-BASED LIGHT SOURCES.

Performing plasma-based studies at synchrotrons or XFELs requires a method of generating the plasmas to be studied. The accelerator-based light source can function as a probe of a plasma that must be produced by some other mechanism. The simplest way to generate diverse plasmas is to employ at least two laser systems. The first would be a high-energy laser that can produce high-energy-density, i.e. hot dense plasmas; the second would be a short-pulse laser that produces fast electron/fast ion-heated plasmas.

Specifications of the high-energy laser system. To explore the high-energy-density regime, one needs a high-energy and high-intensity laser system consisting of two beams of > 100 Joules in 1 ns with a wavelength of ~500 nm and ~250 nm. Further, there is the need for an additional beam for lower density probing, e.g. a 250 nm probe beam with picosecond capability. Synchronization of this larger laser system with the accelerator light source is critical.

Specification of the short-pulse laser system. There is a need for an additional short-pulse capability in the range of a few tens of femtosecond to generate short, bright bursts of x-rays or electrons for additional absorption or scattering experiments. This ability would provide higher resolution temporal studies than currently available from accelerator-based light sources and provide an important complementary probe.

2.2.6 What is needed?

CENTER CONCEPTS:

1. Center with flexible laser-plasma x-ray sources driven by sub-50-fsec 10-100 W average power systems with output lasers at kHz, 10Hz, and sub-Hz operation. At least one such system should be co-located with a high energy, Petawatt-class laser driver. This petawatt laser may be developed in support of high energy density and fusion research described in later sections. This would represent a coordinated use of facilities with large capital investment.
2. Center or research with high repetition rate, high average power short pulse system collocated with electron-beam machines (LINAC and synchrotron) to produce extreme states of matter. Such a center would have significant overlaps with the fundamental interaction center discussed in section 2.1.
3. Center for the exploration of fundamental concepts for novel short-wavelength and hyperfast x-rays sources. Specialized facilities would require high repetition rate, TW-class laser systems for high average power x-ray production.
4. Multiple single-PI-maintained Watt average power systems for inter-and multidisciplinary applications.

2.3 High Energy Density Science and Lab Astrophysics

2.3.1 Hot dense matter

UULs 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 under truly staggering conditions. It appears that matter with temperature and density near the center of dense stars can be created in the laboratory with the latest high intensity lasers. Solid density matter can be heated to temperature of over 10,000,000 °C (>1 keV) (Figure 2.3.1). Under these conditions, the pressure inside the matter 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. That such extreme conditions can be reached in the laboratory opens a virtually new field of study.

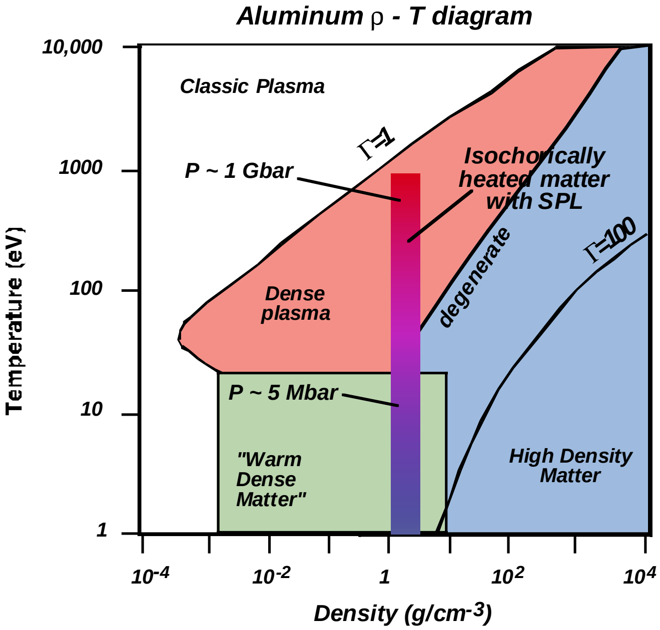

***Figure 2.3.1**: Diagram illustrating different physical regimes in temperature and density of hot aluminum. The states accessed by isochoric heating with a UUL is also illustrated.*

Understanding the physics of matter at these extreme conditions, namely densities of solid or higher in the temperature range of 1 eV to 1000 eV, is crucial to understanding many diverse phenomenon, such as the structure of planetary and stellar interiors, how controlled nuclear fusion implosions (inertial confinement fusion or ICF) evolves or how matter is compressed in nuclear weapons detonations. Yet, despite the wide technological and astrophysical applications, a true, complete understanding of matter in this regime is not in hand.

Of the extreme states of matter that are encountered in the applications described, understanding in the warm-dense matter (WDM) regime is particularly vexing. This regime is characterized by conditions in which the ion-ion potential energy is comparable to the thermal energy (i.e. the “strongly coupled plasma” regime). This regime truly represents a region intermediate to solid-state physics and plasma physics. We really do not understand this regime with the same detail that we understand solids or low-density plasmas.

In plasmas typical of most astrophysical, space, and industrial settings the particle number densities are typically very tenuous, often below 10^{15} cm^{-3} with temperatures near one million degrees Kelvin. Theoretical descriptions of such plasmas are greatly simplified since electrons and ions are weakly coupled to each other. Thermodynamic properties can be easily expressed in terms of ideal gas properties that neglect interparticle correlations and collisions can be treated perturbatively. This widely used formalism for understanding plasmas does not work in the hot dense regime. Experiments coupled with more sophisticated theories and simulations are the only way to understand this very complex, extreme state of matter.

Experimental access to this regime is difficult. The most common, and most successful approach has been to examine shocks created by gas guns or long pulse lasers. The importance of these studies cannot be overstated. They have provided unique data, which have affected our view of the structure of the interior of Jupiter and the implosion dynamics of ICF capsules. But the temperatures accessible with these more traditional experiments are limited. With UULs however, higher temperatures may be generated.

The duration of the UUL pulses are much shorter than the time scale over which a heated sample will expand. So the laser can heat a target, initially at solid density up to a temperature of 10 million degrees in less than 100 fs. The properties of the short lived, high temperature, solid density sample can then be studied.

Many experiments have been performed using short pulse lasers to isochorically heat solids over small volumes. The utility of these kinds of experiments is only now being realized, however, to date, it has been limited because the available lasers had limited energy/peak power. This limits the amount of material that can be heated, so that density and temperature gradients are large, and well-controlled studies are very difficult. However, the next generation of petawatt class lasers will eliminate many of these problems. Short pulse lasers with energy of 100 to 1000 J will enable a new class of isochoric heating experiments. Petawatts with 100 fs or short pulses will be able to heat optically large areas (> $1mm^2$) and thicker slabs (many μm) to temperature greater than 1 keV.

Larger scale systems, such as ~ 1ps, kJ class petawatts might be exploited to heat samples in more unique ways. For example, there has been very good progress recently on the acceleration of high brightness beams of multi-MeV protons during the interaction of a UUL with thin solid targets. These protons could themselves be used to heat a second target. Since protons can penetrate many microns in a target, and are generated with good efficiency, thicker targets, many microns into the target could be heated. This will lead to longer disassembly times and fewer gradients. Heating with x-rays is also promising as a way to heat targets, though larger lasers are required because the conversion efficiency from laser energy to x-ray energy is low (<0.1% in many cases).

2.3.2 Astrophysics

1) SUPERNOVAE PHYSICS AND UUL DRIVEN RADIATIVE SHOCK WAVES

Astrophysical shock wavess play an important role in the evolution of the inter-stellar medium (ISM) providing an energy source, and triggering a variety of phenomena including star formation. On galactic time-scales, supernovae are a frequent source of such shock waves, which expand into the surrounding ISM 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. It is believed that these phenomena lead to the spectacular gaseous structure observed around the remnants of old supernovae.

Understanding of these astrophysical phenomena has progressed rapidly in last decade. For example, theoretical simulations indicate that strong radiation transport leads to a number of consequences on, for example, the stability of shock waves and mixing between different layers in supernovae. These effects are believed to have important consequences on the evolution of supernova remnants and the complex structure observed around many of them.

Because of the complicated dynamics associated with 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. UULs may be an ideal way to create idealized radiative shock waves in the laboratory. UULs can deposit large amounts of energy in small volumes over very short time. (See Figure 2.3.2 for an example.)

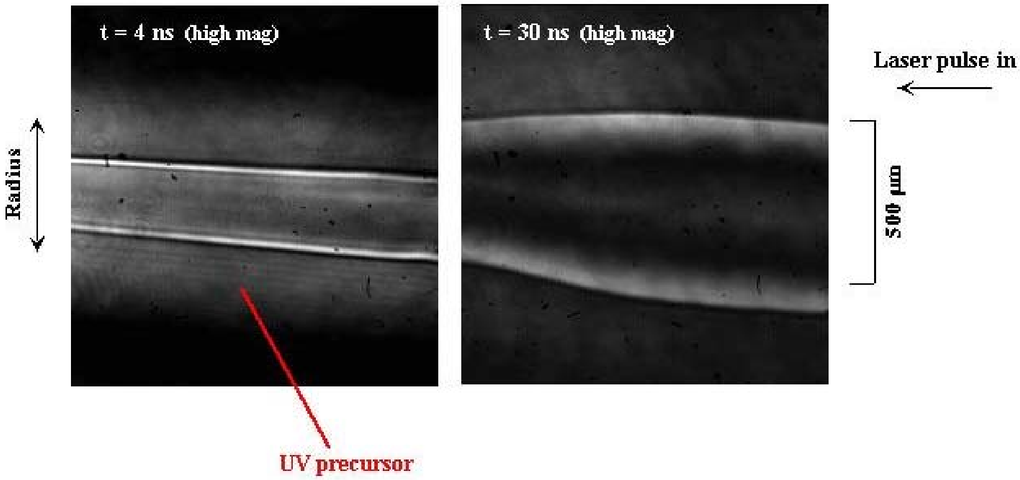

Figure 2.3.2*: Examples of data showing Schleiren images of a blast wave in xenon. That a radiative shock occurs in this experiment is shown by the presence of a UV precursor ahead of the shock front. A smooth shock front is observed in this case.* [1].

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[1] M. J. Edwards, et al., *Phys. Rev. Lett.* **87**, 085004 (2001).

While initial experiments (like those shown in Figure 2.3.2) were of small (mm) scale, the advent of Petawatt class lasers will enable similar kinds of experiments with much larger, centimeter scale blast wave. This next generation of lasers will allow studies of instability growth and will begin to shed light on the nature of instabilities in astrophysical shocks.

2) UUL PAIR PLASMA PRODUCTION AND UNDERSTANDING GAMMA RAY BURSTS

Gamma ray bursts are among the most enigmatic phenomena in the universe. A number of theories have been advanced to explain their very large energy release and their 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. The dynamics of these extremely exotic plasmas are not well understood and no terrestrial experiment has yet been able to access such extreme conditions.

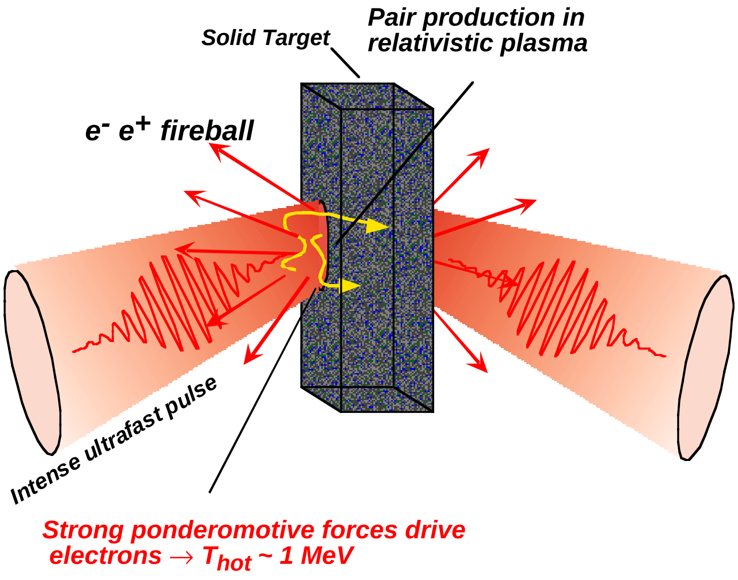

Figure 2.3.3: *Double illumination of a target with two petawatt laser beams could lead to the production of an electron-positron pair plasma.*

Such matter-antimatter plasmas, however, might now be created in a laboratory with a petawatt class laser (Figure 2.3.3). 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. Lasers with intensity exceeding ~ $2\text{x}10^{18}$ W.cm^{-2} couple most of their energy to superthermal electrons with temperature $kT > mc^2$ (where m is the electron rest mass and c is light speed). Positrons are created when the relativistic electrons interact with high-Z target ions. 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 (~ 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 ~10^{-3} of the background electron density, or approximately 10^{22} cm^{-3} for solid gold targets, far exceeding any other laboratory source of positrons.[2] Detailed numerical simulations by other groups (Nakashima and Takabe) confirm this prediction.

2.3.3 What is needed?

The use of UULs to access very extreme states of matter is one of their most exciting applications of these systems. To fully realize the promise of creating and studying such states, will require a new generation of lasers. Many of these experiments will need multi – terawatt lasers. Advances in laser technology, even at this level will be necessary for truly useful experiments. For example, isochoric heating experiments demand laser pulses, which are very “clean” on the rising edge of the pulse. Any low intensity light preceding the main pulse can heat the material a small amount, and drive some material expansion, which prevents true isochoric heating from solid and well-known density. Advances in prepulse suppression will be very important.

These high energy density applications are limited by the small pulse energy available in current UULs. The development of high contrast, petawatt lasers will be crucial to establishing the wider applicability of these techniques to astrophysics and materials science. Petawatt class UULs will be needed to heat large sample volumes, or for creating large numbers of MeV protons and x-rays for bulk heating.

CENTER CONCEPTS:

1. Center devoted to high energy density plasma physics and light matter interaction. This center could be based around a mid-energy, high pulse contrast petawatt laser. Such a laser would have 20 – 200 J in a 20 –200 fs pulse. The laser resources and petawatt of this center would also be of use in studying the fundamental physics discussed in section 2.1. This center would also, likely utilize high energy petawatt laser drivers (>1 kJ) that are necessary for fusion fast ignition research (described in section 2.4). Finally, HED science conducted here would benefit substantially from the development of ultrafast x-ray sources in the centers discussed in section 2.2 as these x-ray sources can be used to probe tranient effects produced in petawatt laser plasmas.
2. Center focusing on laboratory plasma astrophysics. This center would also require the use of multi-terawatt to petawatt lasers and could leverage machines developed for high energy density physics, fusion physics or basic high field physics. This Center would require larger scale machines (up to many kJ) and would rely heavily not only on the facilities developed for the other fields described (basic science, x-ray development) but also could use the large scale multi-petawatt lasers that will need to be built for fast ignition research.

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[2] E. P. Liang et al. *Phys. Rev. Lett.* **81**, 4887 (1998).

2.4 Fusion Energy and Fast Ignition

2.4.1 Introduction to the fast ignition concept

Ignition with inertial confinement fusion (ICF) is central to defense interests and is the major goal of the multi-billion dollar laser, the National Ignition Facility (NIF) being constructed by NNSA at LLNL. Inertial Fusion Energy (IFE) is a potential long-term solution to providing a secure energy supply, free from global warming consequences. This is an important element of the National Fusion Energy program managed by the OFES branch of DOE. New opportunities arising from the development of ultra-intense lasers promise to provide both a lower energy threshold for ignition and a higher energy gain in the fusion burn. The fast ignition concept, in which fusion fuel (deuterium – tritium ice) is first compressed and then ignited by a high intensity laser pulse could realize these promises (Figure 2.4.1). The initial implosion could be carried out with several different high energy density drivers.

The requirements of the fuel compression phase are relaxed for fast ignition relative to conventional ICF because there is no requirement to produce a central hot spot. The symmetry of the drive, the drive pressure and the sphericity of the target can be relaxed. New aspects, such as the development of implosion around a cone to provide a path for the ignitor beam may facilitate this concept.

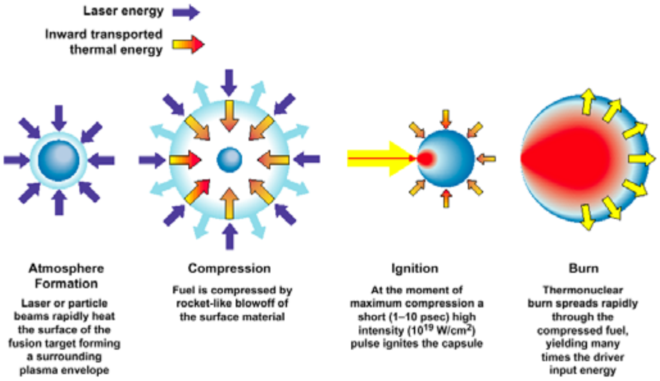

Figure 2.4.1*: Fast ignition concept for fusion energy research. A high-energy laser, such as the NIF laser, compresses the fuel by direct or indirect drive. The short Petawatt pulse heats the fuel at maximum compression for efficient thermonuclear burn. The success of this technique would make inertial confinement fusion less sensitive to the symmetry of an implosion and relaxes the requirements on the drive laser. Ultimately this make inertial fusion energy much more economically viable.*

2.4.2 Principal physics and engineering issues facing fast ignition

The coupling of ultra-short pulse lasers to the compressed core of an ICF implosion is the central issue in fast ignition(FI). UUL lasers couple to the external regions of a compressed target, near the critical surface (where the laser frequency is equal to the local plasma density). This can be 100’s of μm from the high-density region where ignition occurs. The UUL energy is converted to energetic electron or ion beams that penetrate to the high-density region. The physics is novel and has great intrinsic scientific interest. There are many unresolved questions about the coupling and it is not clear how much of the UUL energy can be coupled to the core. For example, understanding the divergence and energy deposition physics of an intense electron beam is essential to validating the FI concept. Recent experiments in Japan have given a strong impetus to fast ignition by showing that there can be a >20% efficient transfer of short pulse laser energy to the ignition hot spot. This is evidenced in 1000x enhanced thermo-nuclear burn in a laser driven implosion in which the compressed fuel was irradiated with a 300J, laser pulse.

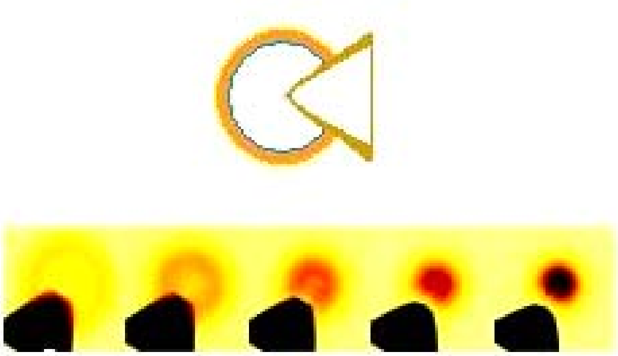

Figure 2.4.2: *Cone target hydro experiment at the Omega laser at LLE for delivering the igniter pulse on target. The cone funnels the Petawatt to the fuel core.*

Full-scale fast ignition with 300x-energy gain at 1MJ drive energy is estimated to require about 100kJ, in 20 ps in the ignitor laser and this could in principle be accomplished with relatively minor modifications to the NIF.

The feasibility of fast ignition and the possibility of designing the required driver and target are critically dependent on the development of an understanding and numerical modeling of the relevant complex physical processes. The problem challenges the current capabilities of the most powerful tera-flop computers. It requires the development of new kinds of numerical models, particularly hybrid particle in cell (PIC) codes. Crucial to progress are experiments designed to develop physical understanding and to benchmark numerical models.

The development of integrated fast ignition experiments, combining fuel compression and ignitor pulse heating, requires large-scale facilities. Presently the largest HEPW facilities are, or will shortly include, three in Europe and one Japan. These are 0.5 kJ, 1 PW lasers alongside long pulse laser compression or ion beam facilities. They are either in operation or will operate in the next two years. NNSA is currently carrying out technical R&D and developing designs and plans to adapt major driver facilities (the OMEGA laser at LLE, the NIF at LLNL and the Z/ Zbeamlet facility at SNL) for high-energy petawatt (HEPW) operation. The NNSA program would be a significant enchancement of current capabilities available overseas and it will most probably provide the flagship tests of fast ignition with ignitor pulse energies from 1 to 20 kJ from about 2006 onwards. Europe and Japan may also transition to this level of laser facility performance, with plans under consideration.

The physics basis of fast ignition is undergoing vigorous investigation worldwide (Figure 2.4.3). The most significant work is being carried out using laser facilities capable of a large number of shots at picosecond pulse energies in the range 10 – 100 J and powers up t o 100 TW. he essence of the research is to understand the key physical phenomena in fast ignition. It is convenient to describe these phenomena in the order of their occurrence as ignitor laser pulse approaches the fast ignition fuel.

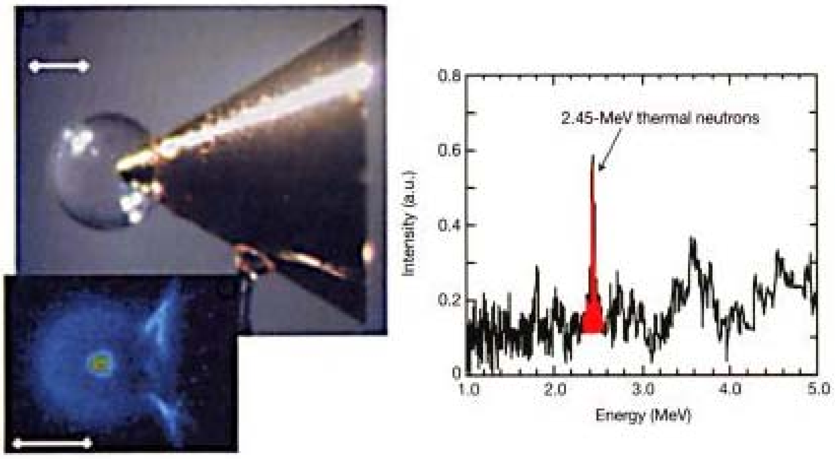

Figure 2.4.3: *Japanese, University of Osaka, results on fast ignition with a cone target. Shown are the target (top left), x-ray pinhole camera image of the implosion (bottom left) and the neutron spectrum resulting from the injection of the short pulse laser. An enhancement of fusion neutrons by a factor of 1000 was observed when a high intensity short pulse laser was shot down the copper cone (seen at left) at the time of peak compression of the spherical target.*

Interaction with sub-critical density plasma in the relevant relativistic intensity regime (up to 10^{20} Wcm^{-2} for fast ignition) is the initial process that occurs as the ignitor laser meets low density plasma either in a laser formed channel or in a cone inserted into the implosion to provide a path for the ignitor beam. Three-dimensional(3-D) particle in cell simulations give a numerical model of the relativistic self focussing, parametric coupling to plasma waves, and particle acceleration. Experimental diagnostics provide evidence to challenge the models. This FI phase has benefited from the most research but more work is required to fully understand it.

The laser is strongly absorbed at its critical density and the transfer of its energy to a beam of multi- MeV relativistic electrons must be understood. The transfer efficiency, the energy spectrum and directionality of the electron source can be modeled with 3-D PIC methods and measured experimentally. Results depend on laser pulse duration and intensity and the atomic composition of the plasma (D-T in a channel configuration or Au in the cone scheme). Here again more extensive studies are needed to give a firm basis for fast ignition target design.

The transport of relativistic electrons is probably the most challenging problem in fast ignition. In electron ignition the electrons directly create the ignition hot spot. In the newer proton ignition scheme, the electrons accelerate protons that provide the energy for ignition. In either case electron beam propagation is the central problem. The complexity is evidenced by the fact that the electron current is of the order of giga amps and exceeds the Alfven current limit by a factor of about 10^6. A cold electron return current must cancel the beam current and it induces a strong Ohmic electric field, which can limit the penetration of the beam. The Curl of the E field induces a growing azimuthal B field, up to a limit at which the net current is equal to the Alfven limit. The B field acts to guide or focus the electron beam. The opposed beam current and cold return current is subject to ‘ two stream’ instabilities, notably the Weibel like filamentation instability.

As the electron beam passes through material interfaces and boundaries the index of refraction changes lead to surface currents and additional B field sources.The plasma heats up and its conductivity changes. The self-consistent interplay of these phenomena is the essence of the electron transport problem.

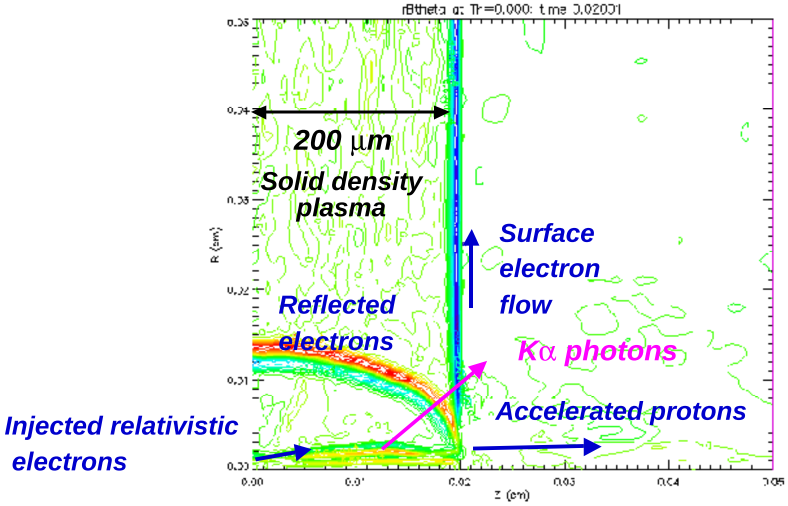

Figure 2.4.4*: Simulation showing interplay of physical processes during high intensity production of hot electrons on a solid target*

Experimental measurements are beginning to allow direct measurements of heating of solid matter by relativistic electrons and the electron beam distribution at the rear surface of a target is being measured. One interesting observation is that the characteristics of the emerging electron beam depends sensitively on the conductivity of the target and the number of material interfaces.

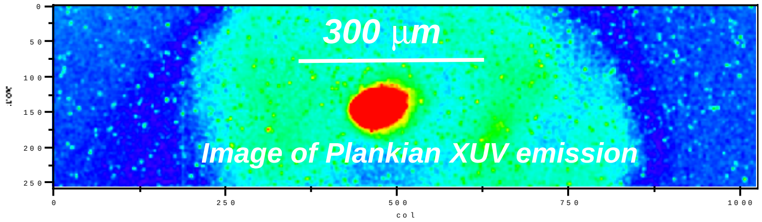

Figure 2.4.5: *X-ray image of electron heating in solid density Al*

More precise measurement will be made through diagnostic innovations. The necessary hybrid PIC codes capable of a complete numerical description of the interaction are also being developed but have not yet been significantly used. While direct coupling of a PW laser to the compressed core of an ICF implosion will mitigate interface effects, the use of a cone to guide the PW beam ensures that there will be at least one material interface present. The field is ripe for detailed physics investigations of the component processes such as transport effects at interfaces.

Proton generation and focusing is one of the newest physical phenomenon in this field and is of great interest. Protons are generated through the Debye sheath formed at the vacuum interface at the rear surface of a thin foil target. Relativistic electrons reflux in the foil and the charge density at the rear surface is determined by the transport characteristics. The electric field in the Debye sheath drives the proton acceleration. It field ionizes hydrogen-containing molecules providing a source of ultra-cold ions. Where the field is strongest the sheath moves off the surface most rapidly. It develops an non-planar shape imparting a transverse component to the proton acceleration. Electrons neutralize the proton beam. The beam flow is laminar and initially perpendicular to the surface but an off-axis angle develops with time, increasing from the center to the edge of the beam. The focal properties of beams from concave spherical surfaces required to focus the beams depend on the subtle connection between off axis angles and spatial distribution of electron charge density in the Debye sheath. For fast ignition the beam must focus to <50 µm spots over distances >500 µm. Both modeling and experiments are developmental and there is much scope for innovative research.

The deposition of energy by both electrons and protons in high density plasma, including strongly coupled and Fermi degenerate regimes has subtle features which must be understood for a full description of fast ignition

The above description highlights opportunities for individual researchers with access to moderate-sized high intensity lasers capable of large numbers of shots, to perform research into the basic phenomena of fast ignition and for related theory and modeling developments requiring access to super computers.

2.4.3 What is needed?

CENTER CONCEPTS:

1. Center devoted to the physics short pulse heating of compressed targets. Success in fast ignition research will require integrated experiments (and simulation) on a range of laser

facilities. The basic science for fast ignition will require mid to high energy petawatt class lasers, the class of laser needed for much of the HED science discussed in section 2.3.

2. At the core of fast ignition success will be experiments using multi-kJ picosecond petawatt lasers coupled to large implosion facilities. Because of the large scale of these kinds of systems, they will be constructed at large, programmatic machines like the Omega laser at the University of Rochester, the Z machine at Sandia National Laboratory and ultimately at the NIF laser at LLNL. Construction of these large, high energy petawatt lasers will, almost certainly, be a part of the existing large national inertial confinement fusion program. Nonetheless, these kinds of facilities will also have enormous use in the research described in the other sections, including HED science, lab astrophysics particle acceleration and high field science.

2.5 Advanced Particle Acceleration and Ultrafast Nuclear Science

2.5.1 Introduction

Historically, breakthroughs in particle accelerator technology have been the foundation for numerous innovations in science and technology. Medical x-ray machines, microwave ovens, televisions and air-traffic-control radar were all once unfamiliar terms describing uncommon technologies. Today's gigantic atom- and electron-smashing accelerators at SLAC, Fermilab, RHIC and CERN are perhaps the last of a generation of billion-dollar particle accelerators that are used to elucidate the inner working of the cosmos and the very building blocks of matter itself. These devices use conventional electric and magnetic field elements to accelerate the particles. Ultrafast, ultrahigh intense lasers (UUL), producing bursts of light only a few optical oscillations in duration and focusable to spot sizes of a few microns, allows the creation of sufficient electromagnetic waves for acceleration. The instantaneous oscillating electric fields associated with UULs are many orders of magnitude higher than achievable by any other means. These field strengths are sufficiently large to fully ionize single atoms up to charge states in excess of ~50 within a single optical cycle, and to accelerate electrons instantaneously to relativistic speeds. The highly transient current densities associated with this outflow of electrons creates azimuthal magnetic fields in the GigaGauss range, two orders of magnitude higher than through conventional methods and approaching those thought to exist on the surface of neutron stars and white dwarfs. This new genre of high field physics is already beginning to impact many areas of science. The capability to subject matter to such incredibly high energy densities, to such intense fields will lead to many new discoveries in atomic, nuclear and condensed matter science. This science has traditionally been an area of American leadership, richly rewarded with Nobel Prizes, and through the acknowledged trickle-down of knowledge and expertise, numerous other advantages to America's economic and intellectual well-being. American science has long claimed leadership in the fundamental understandings of matter in the cosmos, and ourselves in it, as a demonstrable benefit of our political and economic system. The technologies discussed here may well be central to the US maintaining this position.

Extremely high electric fields generated with UULs can accelerate charged particles to super-fast speeds. This will lead to a new generation of compact, ultra-high energy, short pulse and low emittance accelerators. Given the impact of previous accelerator technologies, this new form of particle accelerator could ultimately well have far-reaching consequences.

2.5.2 Relativistic electron acceleration

Laser-driven electron acceleration is advancing past the stage of initial discovery and demonstration to the stage of detailed scientific understanding, optimization, development and deployment. The current emphasis of experimental research is the production of high brightness (low emittance, high charge, ultra-short duration) electron beams using laser driven accelerators. To date, most experiments have operated in the so-called self-modulated laser wakefield regime where the laser pulse length is long compared to the plasma period. In these experiments, a high power laser pulse is focused into a neutral gas. The peak laser intensity typically is on the order of 10^{19} W/cm^2, exceeding the ionization threshold in gases such as hydrogen or helium by several orders of magnitude. When the laser pulse propagates through the ionized gas (plasma), it can become amplitude modulated and drives up large amplitude plasma density oscillations. These large amplitude plasma waves propagate with phase velocity close to the speed of light and can trap and accelerate electrons to multi-MeV energies in distances on the order of a millimeter. The electron beams emerging from these plasma-based accelerators typically contain multi-nanoCoulombs worth of charge (10 billion electrons per pulse) with femtosecond (10^{-15} s) duration, but unfortunately with 100 % energy spread.

The main challenges that are pursued today are controlled trapping and acceleration of the electrons to minimize the electron energy spread, laser guiding and plasma channels to extend the acceleration distance for the development of a 1 GeV module. To control the energy spread, optical injection techniques have been proposed and are being tested experimentally, in which background electrons are injected in a modest amplitude wave, by the use of one or more laser pulses. These laser pulses can boost the momentum or modify the phase of the electron orbits such that they can catch the plasma wave and be accelerated by it. To increase the mean energy of the electron beam, experiments are underway to guide high intensity laser pulses over extended distances. Electron energies up to 200 MeV have been reported in the self-modulated regime, but a combination of acceleration distance, pump depletion and dephasing of the electron with respect to the plasma wave typically limit the maximum energy achieved. To increase the acceleration distance requires laser guiding in a plasma channel (Figure 2.5.1) like those first developed at the University of Maryland[3]. Development of such methods is expected to result in the development of a GeV electron acceleration module.

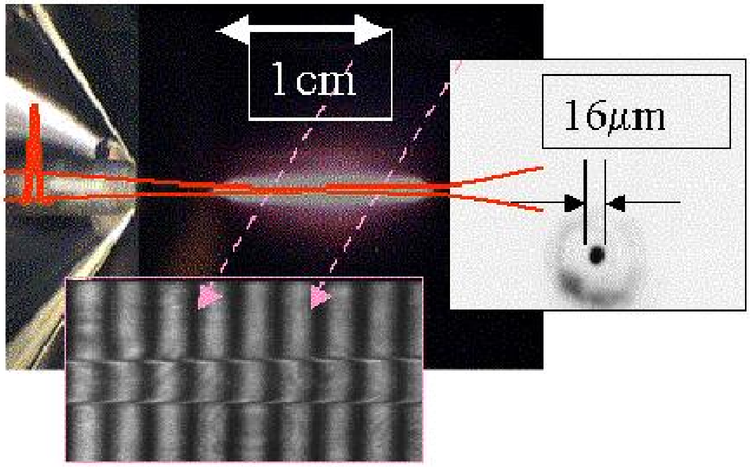

***Figure 2.5.1**: Luminescence from a fully ionized helium channel formed when a Nd:YAG laser pulse is focused by a conical axicon lens to a 1.5 cm line (left top). This channel is similar to that first demonstrated at the U. of Maryland[3]. Bottom image is a transverse interferogram of the channel and the image to the right is the mode profile. [Courtesy of the University of Texas].*

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[3] C. G. Durfee and H. M Milchberg, *Phys. Rev. Lett.* **71**, 2409 (1993).

To carry out these experiments, several temporally synchronized laser pulses are needed. Simulations indicate that the main laser pulse should have peak power on the order of 100 TW for acceleration of 10^9 – 10^{10} electrons to 1 GeV energy. High repetition rate systems (> 10 Hz) are required to allow rapid exploration of parameter regime. This implies average laser power on the order of 100 W or more. For such systems, laser diode pumped amplifiers need to be developed and is actively being pursued by several groups in the US, Europe and Japan. Several approaches are being followed.

Already the principal advantages of laser–driven electron acceleration over conventional techniques can be clearly identified. These are:

Extremely compact source. Laser-driven acceleration can accelerate electrons up to 100-1000 GV/m versus 10-100 MV/m by conventional methods.

Ultra-short, intense bursts of particles. Currently pulses in the femtosecond range have been generated, but the future portends sub-femtosecond bursts with as many as 10 billion electrons.

Highly energetic electrons. The acceleration of electrons to the GeV level may be possible within dimensions of ~ 1 cm. Higher energies will require the use of multi-staging and other advance concepts.

Extremely low emittance. Electron emittance < 1 π mm-mrad are expected, considerably superior to conventional state-of-art RF technology. The consequences of this for multi-staging and the interaction of the electrons with targets are considerable.

The grand challenge of accelerator technologists and the theorists who motivate them has long been the development of the multi-TeV Electron-Positron Collider. The unique properties of laser-driven accelerators provide a potential pathway to making this a reality. Such an achievement will open the way to exploring the Higgs sector, Unruh and Hawkin radiation and many other fundamental features of our universe. UUL technology may also open the possibility of developing a “gamma-gamma” collider that would further elucidate the underlying particle physics.

2.5.3 Pulsed high-energy protons and heavy ions

Recent experiments with ultra-high intensity laser pulses interacting with thin film targets have shown that a beam of high-energy, (MeV), collimated protons can be produced. In the simple configuration of these experiments these protons, originating from hydrogenous material on the front and rear sides of the target, are accelerated by Coulomb attraction to the relativistic electrons generated in the primary laser plasma interaction (Fig. 2.5.2). The forward-going ultra-short burst of collimated protons produced has an energy that increases with laser intensity, so far reaching energies of ~ 50 MeV (Figure 2.5.2), and the conversion efficiency to protons increases also with laser intensity (so far reaching ~10%). Moreover the proton emittance can be less than 0.006π mm-mrad, a100-fold improvement over conventional technology. This unique source of protons already complements conventional accelerator-based proton sources. These have higher energy, approaching GeV’s, but the duration of the laser generated particles is much shorter, and their fluence orders of magnitude higher. These sources we can see many near- and intermediate-term improvements, which will likely lead to practical applications. These include:

- *Proton cancer therapy* is being developed because it spares healthy tissue and allows much higher doses than conventional medical radiography. Over 30,000 patients have been treated for various forms of cancer (uveal melanomas, meningiomas, acoustic neuromas and many other hard-to-reach cancers of the spine, brain and torso) in the last 10 years by using high energy (< 120 MeV) proton beams derived from major accelerator facilities (a few at present in North America). Studies indicate a future need for some ~100 centers nationally. Laser-driven proton accelerators could be the enabling technology that would allow these facilities to be compact enough, and low enough in cost, to be based in major hospitals.
- *Medical proton tomography.* Proton tomagraphy is an advanced form of medical imaging that is superior to conventional x-ray imaging in that it possesses higher resolution and is less invasive to body tissue. It's development runs parallel to proton therapy, and is also currently limited by the size and complexity of the proton source. It requires protons energies of ~ 100 MeV. Laser-based sources will release this restriction and allow future development of this advanced form of medical imaging mature to practical systems.
- *Picosecond high resolution dense-matter imaging*. Active consideration is currently being given to using this unique ultra-short laser-driven proton source for high-resolution projection imaging of compressed matter targets. One of the central requirements of the DoE Inertial Confinement Fusion program is the requirement to visualize with picosecond and micron time and space resolution the tomography of super-dense compressed capsules of fusionable matter. Although this application is unlikely to

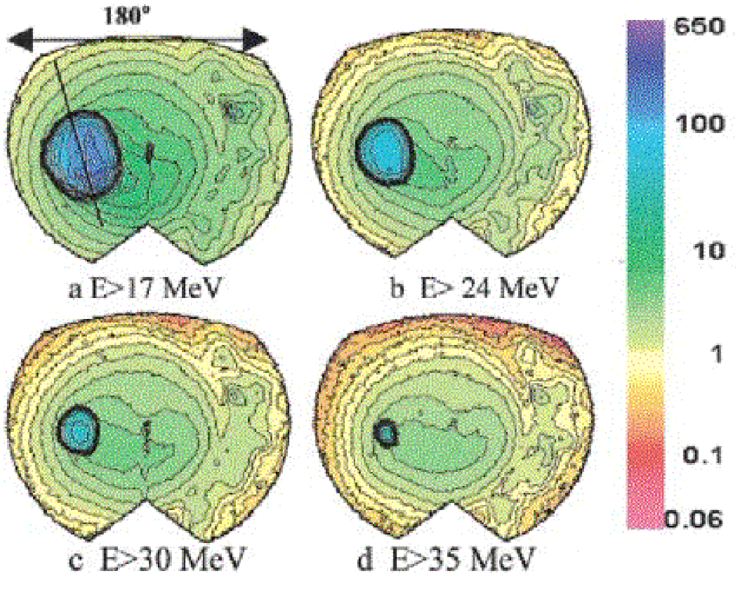

Figure 2.5.**2: Data from the LLNL Petawatt laser showing well collimated, multi-MeV proton beams accelerated at the back surface of a target. The high-energy proton beam is uniform and with low emittance. These sources show promise in many applications from medical ion beam cancer therapy to the production of short-lived radionuclides. [Figure from Snavely et al. Phys. Rev. Lett.* ***85*, 2945 (2000).]*

become a growth industry, its benefits to national defense will be considerable.

In addition to acceleration of protons, the same technique can be used to accelerate heavy ions. This has very recently been demonstrated, and we can expect to see much further progress in the future.

Thus, in just brief time since the discovery of this source of protons, some fairly concrete possible practical applications are on the horizon, assuming that research in this area is intensified. It must be noted that since the demise of the LLNL PetaWatt laser, the baton in this field has now passed to the British and the Japanese, both of whom are commissioning their own Petawatt lasers this year. American researchers in this field, particularly those in our universities having increasing difficulty in contributing to this field, let alone keeping a leadership position, primarily because high intensity laser facilities are not available.

2.5.4 Ultra-fast, low energy nuclear science and materials studies

The availability of intense collimated bursts of relativistic electrons also provides, through the bombardment of a solid materials, an intense source of γ-rays, adding to the suite of intense, ultra-short bursts of nuclear radiation that can be generated with high intensity lasers.

Bright emission of radiation and particles from a point source has many applications in high energy density science. In addition they can be used for imaging studies of transient phenomena in warm and cold condensed-matter. Proton imaging is being considered, for example, as a viable diagnostic of inertially confined fusion capsules.

These new capabilities open up many new possibilities for scientific studies and possible practical applications in nuclear and materials science. These new sources are inherently synchronized to ultra-short optical beams, and through conversions to bright K_α x-ray sources. They, therefore, provide a rich array of synchronized probe and diagnostic capabilities. Elegant ultra-short x-ray diffraction studies can now provide time-resolved structural analysis of materials subjected to intense radiation bombardment.

An ultra-short burst of γ-rays, together with the high energy protons, can be used, through either $[\gamma,n]$ and $[p,n]$ reactions, to create short-lived radio-isotopes. A number of exciting demonstrations have already been made. This offers an alternative approach to conventional accelerator technologies for short-lived isotope production for clinical medical and materials applications. The British are already pursuing this field with a view to establishing localized centers of isotope production, perhaps affiliated with major hospitals.

With the strong connection of UUL science to many areas of biology, medicine, physics, astronomy, materials science, chemistry and engineering, this field is poised for quick exploitation. US universities are strong in all these areas. Their access to open laser-based particle and radiation facilities would allow rapid investigation of many different ideas and opportunities. It is from these investigations that new sciences, new technologies, and ultimately new practical benefits to society would be born.

2.5.5 Radio Isotope Production

When Louis Alvarez conceived the idea of photonuclear production of positron-emitting nuclides at LBNL about twenty years ago, there were no readily available, intense sources of high-energy photons that could allow photonuclear-produced radioisotopes to be competitive with cyclotron-based sources. However, in recent years the demand for positron emitting isotopes and the improvements in accelerator technologies have led to a reinvestigation of the photonuclear (γ, n) reaction as a method for production of ^{11}C, ^{13}N, ^{15}O, and ^{18}F. Electron accelerators, now being used for radiotherapy, are potential sources for generating radioisotopes if the beam intensity were increased and appropriate targets developed. A dual use machine --- radiotherapy as well as isotope generation --- is an attractive alternative to produce biomedical radioisotopes in sufficient amounts for diagnostic imaging versus maintaining a separate accelerator facility.

Laser driven accelerators are radically different from conventional accelerators as they rely on advanced high power laser technology and plasmas. These accelerators have the unique feature of being able to accelerate electrons as well as protons and heavy ions. Photo-nuclear (γ,n) as well as proton induced activation then becomes possible with the same machine. Another major advantage of the laser driven accelerators are their compactness, which allows for production of radioisotopes in close proximity to the medical imaging systems, permitting use of novel short-lived isotopes.

2.5.6 What is needed?

To drive this advanced acceleration research a small number of geographically-distributed research Centers based on high intensity laser facilities and open to research across the broad fields outlined above, would allow American science to take the lead along so many of these paths. Much of the work in this field overlaps to some extent with the x-ray source development described in section 2.2. It also would have an impact on HED research as proton sources could be used to probe the HED or fast ignition plasmas discussed in sections 2.3 and 2.4.

CENTER CONCEPTS:

1. Center devoted to the physics of wakefield generation and plasma acceleration of electrons. Much of this work can be conducted with table-top multi-terawatt lasers, though large scale, 1D wakefield experiments would benefit from the petawatt class lasers that will be needed for science discusses above (sections 2.1 - 2.4).
2. Center working on the acceleration of protons and heavy ions. Such work would be coupled to the accelerator community and, possibly, the medical community. 100 TW to 1 PW size lasers will be needed, but, once again, such systems are similar to those proposed in the previous sections, so work in the field could, likewise, benefit from the development of a coordinated set of high intensity laser facilities around the US.

3 Advanced UUL Technology

3.1 Overview

Technological innovation has driven discovery in the high field optical sciences since the development of chirped pulse amplification (CPA) by Mourou and Strickland in 1985. It has had a broad scientific impact that quickly expanded the boundaries of high field physics. With the development of kilohertz repetition rate femtosecond CPA lasers the technology was immediately adopted by the chemistry community for use in studying chemical dynamics. Today, this technology has made it as far as the local opthalmologist – the latest in LASIK eye surgery techniques incorporate CPA lasers.

Based on this recent history, we can expect four things from the future support of advanced short pulse laser development. First, the technology will continue to create opportunities in high-field science. Second, advanced lasers will open new area's of high-field science that have not yet been identified. Third, there will be a broad scientific impact of these technologies – they will be incorporated in the fields of chemistry and biology for instance. Fourth, new commercial applications and industries will be created.

The development of advanced short pulse lasers goes beyond technologies that result in increased intensity. Other figures of merit for these lasers include, pulse contrast, wavelength, bandwidth, spatial and spectral phase. Different applications may also place a high value on other parameters such as average power, pulse repetition rate, and pulse-to-pulse stability. Research that results in a significant enhancement of the aforementioned figures of merit will impact the science that is performed with these lasers. Consequently, research funding for improving these performance characteristics should be encouraged.

Research in advanced short pulse laser development has other benefits as well. For instance, it is a proven mechanism that enables programs run by single principal investigators (PI) to actively participate and make significant contributions to large, national facility high-intensity science programs. Chirped pulse amplification is the prime example. It will be incorporated in all large national laser facilities, but its original inception is based in a single PI, University laboratory.

It is extremely important to note that many optical advances resulted from programs such as the National Ignition Facility at Lawrence Livermore. With the completion of NIF there will be no clear national funding initiative to further develop high power lasers and optics. Thus, it is imperative that the high-field optical science community considers where the funding for this type of work (advanced laser development) will come from in the future.

3.2 Important Research Areas in UUL Development

The application of high intensity lasers has broadened dramatically over the past fifteen years as evidenced by the many fields of investigation covered in this report. Clearly, no single laser is optimal for all these applications – the laser must be optimized for the application. We can however, group the basic laser schemes into three classes as shown in the table below of this section: high energy, short pulse, and high average power.

High energy is distinguished by a pulse energy of few joules or greater (after compression). In general this class of laser requires greater infrastructure to support its operation. Short pulse lasers are characterized by a compressed pulse width of 100 fs or less. This class of laser is found in many single PI laboratories with pulse energies up to several hundered millijoules. High average power lasers are those CPA systems capable of 10 W or higher average powers. These sources are found in both national labs and single PI environment.

Classification using this scheme makes it possible to examine how improvements to the aforementioned figures of merit translate into performance for that class of laser. Further, it illustrates that there are real technological differences between the laser classes for the same figure of merit. For instance, while all classes of laser would benefit from improved grating design, the performance characteristics of the grating for each class is quite different. For high energy lasers, larger gratings with higher damage threshold are needed. For short pulse systems gratings with high diffraction efficiency over a broad wavelength range are desirable, and finally, for high average power systems gratings with improved thermal characteristics are necessary.

From this chart we see that research in advanced laser development should be encouraged along lines that would improve one or more of these figures of merit, even if the impact is within a single laser class. The research should not represent a frivolous improvement in performance, in general we are speaking of order of magnitude performance enhancement.

Below, we present a more detailed overview of proposed research venues.

Gratings

Gratings with very high efficiency 98% have been demonstrated at a laser wavelength of 1.06µm. The same gratings have damage threshold > 1J/cm^2 which is higher than existing gratings. For shorter pulse systems (20-40 fs) dielectric gratings with high diffraction efficiencies over a bandwidth range of 80-100 nm are needed. The average power damage

Laser parameter ***Laser Class***

	High Energy	***Short pulse***	***High Average power***
Gratings	Increase size, bandwidth, and damage threshold	Increased Bandwidth	Increased power handling capability, damage threshold and bandwidth
Contrast (pulse cleaning)	Improve beyond 10^7	Improve beyond 10^7	---
Focusability (spatial phase control)	Optimal focusing	Optimal focusing	Optimal focusing, Specialized spatial beam patterns
Spectral phase control	Miminize pulse duration ; pulse shape control	Miminize pulse duration ; pulse shape control	Minimize pulse duration; pulse shape control
Secondary compression	Increased intensity by decreased pulse duration	Increased intensity by decreased pulse duration	Increased intensity by decreased pulse duration
Amplifier design	Reduce effects of parasitics	New architectures for simplifying system.	Improve thermal handling capability
Materials	--	Directly diode-pumped materials for reducing system complexity	Increase scalability;

Table 3.1*: Three General classes of high field lasers and figures of merit in their further development.*

threshold needs to be improved for high power CPA systems. All these improvements will require basic R&D on grating designs and damage mechanisms.

Phase-locked gratings.

The cost of grating grows exponentially with their size. Large aperture gratings also have an enormous weight and make large scale laser systems unwieldy. In a manner similar to that used in astronomical instruments, phase locked gratings composed of many small, relatively inexpensive light weight optics would be preferable. Phase locked gratings could be used for very high stretching-compression ratio CPA systems.

Pulse Contrast

Pulse contrast is the ratio of the peak laser intensity to the intensity in the laser prepulse defined at a a suitably chosen cut-off point. Contrast is an important consideration in high intensity lasers as the prepulse intensity can alter the interaction of interest. Typical contrast ratios for current CPA systems is on the order of 10^7. For solid target interactions at 10^{13}W/cm^2 one needs contrast ratio > 10^{10} to prevent a plasma from being formed before the main intense pulse arrives. One possibility is the use of double-CPA where the laser pulse will be amplify to the mJ level in a first CPA. It can be cleaned temporally and spatially at that level by using, for instance, hollow core fiber before it is injected into a second CPA to the multi-joule level. Further research is necessary to increase contrast ratio in the next generation of petawatt class lasers. In addition, new devices are needed to help routinely characterize the laser contrast for typical day-to-day operation.

Post pulse compression

Research into new postpulse compression techniques is necessary to overcome the issue posed by limited bandwidth gain amplifier materials. High intensity systems are presently limited to about 20 fs pulse duration by gain narrowing and gain saturation effects. Many applications would benefit from a shorter pulse width (10 fs) to achieve higher intensities at energy levels from the millijoule to the joule range. The post compression could be done by using system in free propagation mode using nonlinear effects, or plasma compression. There is a great scope for new technology in this area.

Spectral shaping: phase and amplitude control

Research is necessary to further develop and enable arbitrary waveform control. With the increased bandwidths that are now available through different frequency conversion schemes it is desirable to have pulse shapers that can accommodate this bandwidth and provide increased spectral resolution for enhanced pulse shape control. As the laser fields approach the single cycle regime, the initial conditions become extremely important. One of the great challenges of this research is to produce phase controlled pulses over the entire laser chain. The interaction of several pulses with absolute phase control would open fundamentally new possibilities. Work concentrating on high intensity pulses with controlled absolute phase is, therefore, very desirable.

Spatial phase control/focusability

One of the least expensive ways to improve the laser intensity is through the development of technology that improves the focus of the amplified CPA laser. Adaptive optics have been used to produce perfectly diffraction limited spot. Adaptive optics can help to provide an ideal but also well known intensity distribution on target that facilitates the comparison between simulation and experiment. Adaptive optics also make possible to use uncorrected inexpensive low f/# optics ~1. Adaptive optics in conjunction with low f# optics will make it possible to reach the highest possible intensity on target. To illustrate this point relativistic intensities have been produced by focusing few optical cycle pulse 10fs over one wavelength with only 1mJ.

Wavelength

In many high-field interactions, pump-probe type geometries are necessary. The difficulty is to create a broad range of wavelengths that must be created synchronously. For instance, ultrafast x-ray absorption experiments may require broad band 5 keV radiation as a probe, with an intense pump in the visible. More fundamental atomic physics interactions will require even broader wavelength accessibility. Research that develops new methods for producing stable, synchronized multi-wavelength sources will have a broad impact on the science that can be performed with these systems at the single PI level.

New materials.

Engineering of new materials that exhibit high saturation fluence (high storage energy) and high damage threshold, good thermal conductivity, diode pumpable for efficiency that lead to a reduction in the size and complexity of present sources is very desirable. This would include new laser materials and new nonlinear materials for frequency conversion. New materials should be scalable in aperture. The scalablity could be acheived using material matrices enabling the construction of high energy sources.

Pump lasers

Pump lasers for the oscillators and the amplifiers for short pulse systems remain very costly and limit the scalability of these systems. Research into new pump systems would encourage methods for overcoming these limitations. For example, frequency-doubled, high-power fiber lasers could increase the average power of Ti:sapphire lasers. In optical parametric chirped pulse amplification the complexity of the laser has been shifted to the pump laser and these type of lasers would clearly benefit from further development of the pump laser.

3.3 New architectures for short pulse laser amplification

In laser architecture, very little has changed from the original chirped pulse amplification design of Mourou and Strickland in 1985 and P. Maine et al 1987. It would be very desirable to have exploratory research/engineering programs that examine new methods for producing energetic ultrashort pulses for high intensity applications. Potential areas of advance in this arena include:

Large aperture Pockels cells

Regenerative amplifiers when used properly produce high quality (spatial and temporal) pulses. They can have a very high gain systems. The stretched pulse can be amplified from the nJ to the 100mJ level, i.e. a gain of 10^8 in one step, while preserving the pulse bandwidth and beam quality. It would be, in principle, possible to go much higher in energy by using larger regenerative amplifiers. The has been prevented in the past by the lack of large diameter Pockels cells that are required for the pulse injection and extraction. With current technology, a large diameter Pockels cell needs to use a long crystal which is incompatible with the integrity of the ultrashort pulse. A technology developed at LLNL, based on transparent plasma electrodes makes possible the construction of large diameter, thin Pockels cell. This kind of technology could make PW lasers much simpler. The entire system that would be otherwise composed of a multitude of amplification stages would be replaced by a single regenerative amplifier.

High focused intensity laser development (10^{24}-10^{25}W/cm^2)

Since the invention of the laser, high focused intensity has been a collective figure of merit that has encouraged the central application of new discoveries. As each of the particular figures of merit discussed in the previous sections is improved, the application of the new technology or science into a system aimed at improving the generation of extreme intensities can continue to provide a common framework for application and improvement of these parameters. A program aimed specifically at the generation of extreme focused intensity would provide the high field community with a center of attention and training for those entering the field and would result in the discovery and development new high field capability. Without such a central goal and funded program in high field laser development, the effort to develop the individual laser research areas would lack a common voice. Such a program might build on present high energy capability on present high power (Petawatt) programs or as a consortium among high energy and high power labs and various individual PIs. The goal of extending focused intensity to 10^{24}-10^{25} W/cm^2 would incorporate all of the stated research areas and would provide access to unprecedented pressures, temperatures and accelerating gradients.

4 Present State of UUL Research Worldwide

Research in high intensity lasers and laser-matter interactions is extremely vibrant all over the world. There is substantial interest in this field not only in the United States but in Japan and Europe as well.

UUL research has been traditionally led by the United States. Chirped pulse amplification was invented in the US in 1985 and many of the pioneering experiments on high field interactions, both with quantum systems (atoms and molecules) and plasmas have taken place in the US. Important breakthroughs in this field in the US have included:

- the invention of CPA at the University of Rochester
- the first observation of high order harmonic generation at the U. of Illinois at Chicago
- the first demonstration of a Petawatt laser and its use in experiments at ultrarelativistic intensity at LLNL
- the first observation of strong field double ionization at LLNL
- the first demonstration of multi-photon Compton scattering at SLAC
- the first anti-matter (positron) production with a laser at SLAC
- the first demonstration of femtosecond x-ray generation through inverse Compton scatter at LBNL
- the first application of UULs to precision laser eye surgery at the U. of Michigan.

These firsts have been accompanied by a vast range of pioneering research campaigns including field leading studies in non perturbative above threshold ionization and harmonic generation at Bell Labs, Michigan, LLNL, Colorado and many other places; in non-sequential strong field ionization at LLNL, Brookhaven and elsewhere; in the applications of femtosecond x-ray pulses at UC San Diego, LBNL and U. of Michigan; in the acceleration of electrons by laser generated wakefields in plasmas at UCLA, U. Michigan, U. of Texas and LBNL; and in laser –solid density plasma interactions at a large host of places including LLNL, U. Michigan, and General Atomics.

Leading laboratories in this field in the US over the past ten years include Lawrence Livermore National Laboratory (which demonstrated the first Petawatt laser in 1996), the Laboratory for Laser Energetics in Rochester (where CPA was first demonstrated), the University of Michigan Center for Ultrafast Optical Science, Brookhaven, and ATT Bell Labs. Major university efforts in high intensity science include U. of Maryland, UCLA, UC Berkeley, U. of Texas, U. of Central Florida, Princeton, U. of Delaware, U. of Colorado and UC Davis. The United States has led the field in a number of areas, including laser driven wakefield generation, laser driven proton acceleration and the development and application of ultrafast x-ray sources.

Although the US has been the traditional leader in this field, the effort in UUL science has exploded dramatically around the world in recent years, with much of the activity occurring in Japan (Figure 4.1), the UK, France and Germany. Serious research efforts in high intensity lasers are also growing in Sweden, Canada, Italy, the Czech Republic, Israel, Korea and China. In fact, the extensive global effort in this field world wide was highlighted by a recent workshop sponsored by the Global Science Forum of the Organization for Economic Cooperation and Development. This workshop was held in Japan during may of 2001, and had 56 participants from 14 countries. It assessed the state of the field world wide and examined ways in which the international community might cooperate to advance science in this area. (The report generated by this workshop can be accessed at: *http://www.oecd.org/sti/gsf*)

The growth in UUL science during the last few years outside the US has been stunning. The table and map below shows the widespread proliferation of high intensity laser systems around the world. As shown in the table below and the map of figure 4.2, nearly 20 lasers with peak power of 10 TW or more are operational around the world. These lasers generally fall into two categories, large scale Nd:glass systems with pulse duration of a few hundred femtoseconds and low repetition rate (~1 shot/10-30 minutes), and more compact, femtosecond lasers based usually on Ti:sapphire, which exhibit pulses with <100 fs duration and repetition rate of up to 10 Hz. As can be seen in the map of figure 4.2, activity outside the U.S. is concentrated in Europe and

***Figure 4.1**: The Gekko XII laser in Osaka, Japan, on which a Petawatt laser is near completion.*

Japan. Furthermore, since the initial successes of the LLNL Petawatt, petawatt laser construction projects have been initiated in Japan, the UK, France and Germany. In fact, at least six petawatt lasers are under construction world wide and two petawatts are already complete and beginning scientific studies in Japan and the U.K. These petawatt systems are summarized in table 4.2 and illustrated on the map in figure 4.4. Other nations like Canada and Sweden are likely to begin petawatt laser projects in the near future.

Representative list of short pulse laser facilities above 10 TW currently operating world wide

Facility	***Peak Power***	***Type***	***Pulse duration***	***Pulse Energy***
RAL, UK	1 PW	Nd:glass/OPCPA	600 fs	600 J
ILE, Japan	700 TW	Nd:glass/OPCPA	700 fs	350 J
JAERI, Japan	100 TW	Ti:sapphire	20 fs	2 J
MBI, Germany	100 TW	Ti:sapphire	50 fs	5 J
LLNL, USA	100 TW	Ti:sapphire	100 fs	10 J
LULI, France	100 TW	Nd:glass	300 fs	30 J
LOA, France	100 TW	Ti:sapphire	25 fs	2.5 J
ILE, Japan	60 TW	Nd:glass	500 fs	30 J
LLE, Rochester	30 TW	Nd:glass	1 ns	30 kJ
Lund, Sweden	25 TW	Ti:sapphire	35 fs	1.2 J
CUOS, USA	25 TW	Ti:sapphire	30 fs	1 J
Texas, USA	18 TW	Ti:sapphire	40 fs	0.7 J
Jena, Germany	17 TW	Ti:sapphire	60 fs	1 J
Ibaraki, Japan	13 TW	Ti:sapphire	50 fs	0.6 J
CREOL, USA	13 TW	Cr:LiSAF	75 fs	1 J
CUOS, USA	10 TW	Nd:glass	400 fs	4 J
NRL, USA	10 TW	Nd:glass	500 fs	5 J
ILE, Japan	10 TW	Ti:sapphire	100 fs	1 J
LBNL, USA	10 TW	Ti:sapphire	45 fs	0.5 J
RAL, UK	10 TW	Ti:sapphire	50 fs	0.5 J
Soreq, Israel	10 TW	Ti:sapphire	45 fs	0.45 J
Garching, Germany	10 TW	Ti:sapphire	100 fs	1 J

Table 4.1

Map of short pulse laser facilities above 10 TW world wide

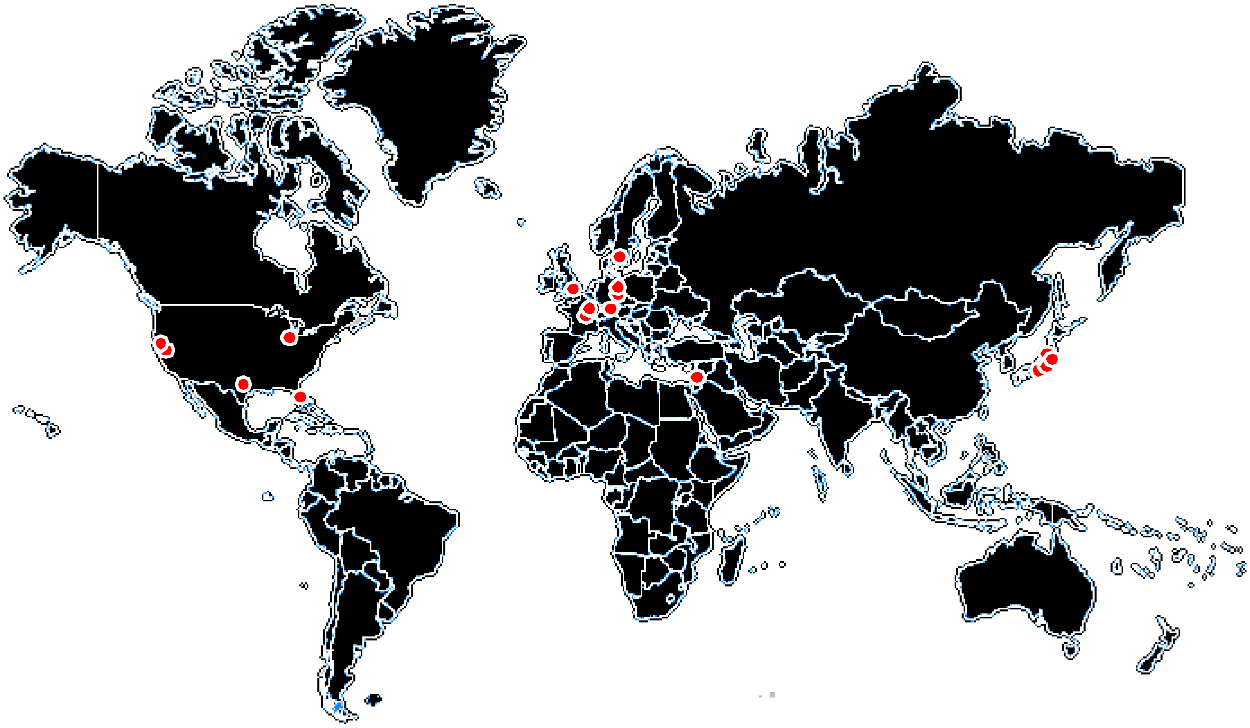

Figure 4.2

***Figure 4.3**: Radiation shielding being installed on the target chamber of the RAL Petawatt laser in the United Kingdom.*

Petawatt laser facilities completed or currently under construction

Facility	***Design Peak Power***	***Type***	***Pulse duration***	***Pulse Energy***	***Status***
LLNL, USA	1.25 PW	Nd:glass	400 fs	500 J	Decommissioned
RAL, UK	1 PW	Nd:glass/OPCPA	600 fs	600 J	Operating
ILE, Japan	1 PW	Nd:glass/OPCPA	700 fs	700 J	Operating @ 700 TW
JAERI, Japan	1 PW	Ti:sapphire	20 fs	20 J	Under construction
LULI, France	1 PW	Nd:glass	300 fs	300 J	Under construction
Sandia, USA	1 PW	Nd:glass	500 fs	500 J	Under construction
CELIA+CESTA, France	2 PW	Nd:glass	500 fs	1000 J	Under construction
Jena, Germany	1 PW	Yb:glass	150 fs	150 J	Under construction
GSI, Germany	1 PW	Nd:glass	400 fs	400 J	Under construction
FOCUS Center, USA	1 PW	Ti:sapphire	25 fs	25 J	Under construction

Map of Petawatt laser facilities operating or currently under construction world wide

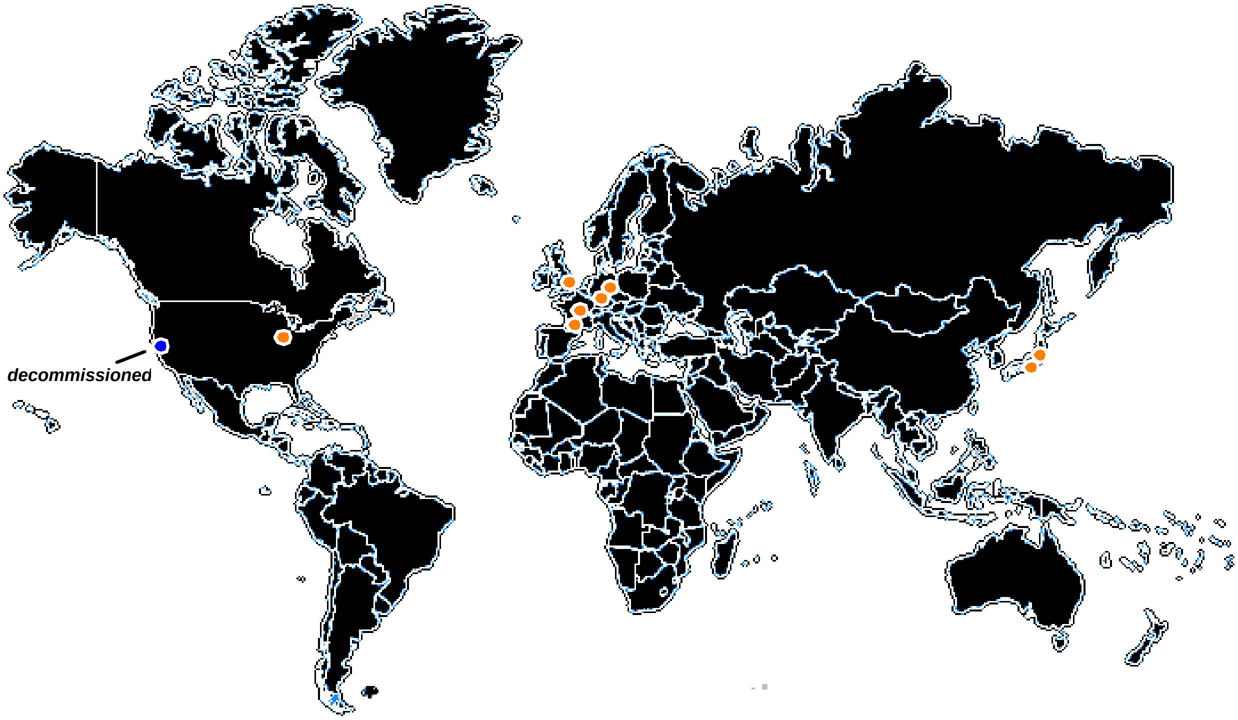

Figure 4.4

5 Conclusions and Findings

This report concludes with the principal findings of the steering committee. The main conclusions can be summarized in four points:

1) **The ultrafast, ultraintense laser (UUL) research community is growing rapidly, and research in this area is among the fastest growing research fields in the world.** The proliferation of high intensity chirped pulse amplification lasers around the world is remarkable. The development of the table – top scale versions of these lasers has brought the science of high intensity laser-matter interactions to universities and has made possible participation of laboratories even in developing countries. While only a handful of terawatt class lasers existed only ten years ago, there are now quite literally over a hundred such lasers throughout the world. Conversely, the development of chirped pulse amplification has made possible unprecedented peak laser powers using large aperture lasers. With the demonstration of a petawatt of power on the LLNL Nova laser six years ago, numerous labs around the world have undertaken petawatt development projects and many are nearing completion. With this proliferation of these high intensity lasers both at the table-top and at the petawatt scale has come vastly broader participation in the science of high intensity light matter interactions and the applications these interactions enable.

2) **Applications of UULs are much broader and more interdisciplinary now than fifteen to twenty years ago.** With the proliferation of UULs around the world, the applications have, likewise expanded. While initial high intensity laser experiments in the early 1980s were aimed primarily at understanding intense light interactions with single atoms, studies with high intensity lasers now span many fields including plasma physics, astrophysics, materials science, chemistry and biology. For example, an ultrafast x-ray experiment may involve the

use of an intense laser making a plasma, producing x-rays which are used to study the dynamics of a molecule undergoing a chemical reaction. As a consequence of this kind of work, researchers from many, interdisciplinary fields have become involved in UUL research.

3) **The state of the art in high intensity laser technology is now much more complex and more expansive then in past years.** In the mid 1980s, the first table top terawatt laser was generated. Lasers like this were truly compact yet were at the frontier of power and intensity for some years. While the science and applications of these one terawatt class, single shot lasers is still extremely rich, particularly now that applications of the initial science breakthroughs made with these lasers are evolving, research at the frontier is moving toward more complex systems. The greater complexity has come about both from the increase peak power now possible as well as the high average power, ie repetition rate, now possible. State of the art high intensity laser facilities will soon make available peak powers well in excess of one petawatt and average powers in excess of one kilowatt. These systems require greater financial resources to build and operate than are typically associated with a small scale university laboratory. Consequently, research in this field will probably depend on a limited number of laser facilities distributed at national labs and at larger university based centers throughout the US.

4) **A new mode of organization is required in this research field to maintain its vitality in the USA and to make available the facilities and infrastructure needed to exploit current opportunities.** With these new trends in high intensity laser research, traditional single investigator efforts will no longer be adequate to exploit many opportunities. While single investigator research efforts will remain a core aspect of innovation in this field, the lasers needed to conduct research at the frontier are beginning to fall beyond the realm of feasibility of traditional single investigator efforts. Exploiting the new science opportunities will require a new mode of organization. This coordinated approach will be needed to determine just what facilities are needed and to make those that are constructed available to a wide research community.

With these conclusions as motivations, this report proposes that a network of institutions devoted to research in UUL science be organized, funded by both the DOE and the NSF. The organization of such a network is detailed in Appendix A. Such a network would enable the cross disciplinary interaction among subfields that is becoming a major part of high intensity laser research. Another significant benefit of such a network would be the establishment of a way to open access of all investigators to the next generation of high power lasers that will be built in this country. A network will also provide an efficient, coordinated assessment of the facility needs of the community. The proposed network would establish and coordinate research centers and single investigator research in this field and would foster the next generation of petawatt peak power and kilowatt average power lasers that are now needed to work at the frontier of high intensity research.

APPENDIX A *A plan for organizing the UUL community in the United States*

Motivation

The United States has been the traditional leader in the science and applications of high intensity lasers. With recent advances in the science and technology has come a new generation of opportunities. The highly interdisciplinary nature of these opportunities requires new forms of collaboration and cooperation within the national community. The required laser facilities that are more complex and expensive than in the past. A radically improved method of organizing the community is imperative.

The greatest obstacle to the successful realization of the opportunities presented in high intensity laser science is the availability of suitable laser facilities. The state of the art in high intensity lasers has reached the point that the required facilities are far larger than can be built and operated by single investigators. Presently, the necessary facilities do not exist in the United States.

Currently high-energy short pulse laser facilities are being proposed for construction at the DOE Defense Programs national labs and at LLE in Rochester. The proposed DOE facilities, alone, cannot fulfill the requirement because they will not be generally available and will only provide a small number of laser shots. There is a need for a collection of facilities, operating intensively and providing a large number of laser shots for a diverse range of scientific applications. These facilities must be open for proposed use from any member of the U.S. scientific community. The providers and capabilities of these facilities would be determined through peer-review to ensure adequate coverage of this field of research.

We envisage the establishment of a small number of centers, both at universities and at national laboratories. The centers will provide both a critical mass of expertise and the resources to maintain essential facilities for the community. The laser facilities that accompany some centers could be at Universities, or co-located at appropriate larger national user facilities (e.g., a kilowatt average power class short pulse laser synchronized to a synchrotron radiation source).

This coordinated network of centers would solve the problem posed in section 2, where a set of diverse applications all need similar technology and similar facilities. What’s more, there is clearly a synergy between fields. For example, research in x-ray source development of bright accelerated protons beams could aid in diagnosing HED or fast ignition plasmas. In turn HED research can lead to better x-ray or particle sources. Basic high field interaction research is important in many aspects of ultrafast x-ray source development, while, at the same time, ultrafast x-rays on the attosecond time scale can be used to probe fundamental aspects of electron dynamics in atoms and molecules. While distinct, each of the major science areas of UUL research have fundamental links and would all benefit from coordination and development of a core of new high power lasers around the US.

A plan to create a national network

To fulfill the promise of this field, we believe a coordinated national network devoted to the science and applications of high intensity lasers is required. This network would be similar in spirit to the "Lasernet" European network in this field, though a network in the US would have many significant differences. (Information on the European network can be found at http://www.lasernet-europe.de/.) The concept of such a network is illustrated in figure A.1. Currently, although an active community of high intensity laser scientists exist in the US, it is fragmented into single investigator groups at universities and research scientists at a few DOE national labs. The formation of a network would unify the community and greatly enhance its effectiveness.

High intensity laser science spans a large number of subfields. At present no single national funding agency has responsibility for this field as a whole. Instead, there are small, uncoordinated projects funded by different programs of the Office of Science at DOE, NNSA and the NSF. To maximize the effectiveness of investment in this field, and to minimize the number of large, expensive facilities, a coordinated, cross agency network is proposed. For example, a petawatt class laser facility has scientific applications in fusion energy (of interest to the DOE Office of Fusion Energy Science), high energy density matter (of interest to the NNSA's Stockpile Stewardship Program), to bright x-ray source development (of interest to the DOE's Office of Basic Energy Sciences), acceleration of electrons (of interest to the DOE's Office of High Energy Physics) and basic high field interactions with atoms (of interest to the NSF) and laboratory astrophysics (of potential interest to NASA). While it is unlikely that each of these agencies will be able to construct and maintain the appropriate facility for the science of interest, a coordinated effort to construct and maintain a small number of such Petawatt lasers widely available to all scientific users would be much more productive.

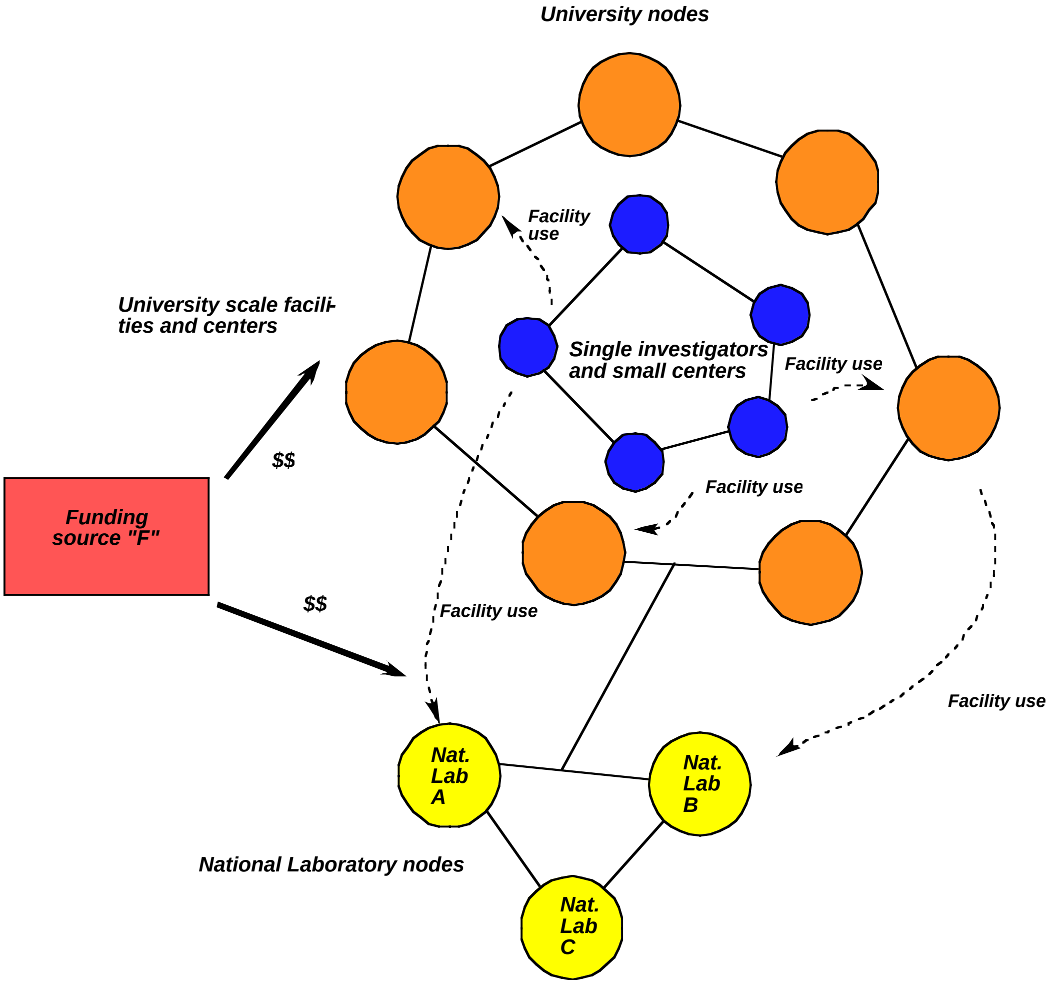

***Figure A.1**: Conceptual structure of a network in the US devoted to UUL science.*

Our plan suggests that the funding of individual nodes of the network be undertaken by the agency with the greatest interest in the science concentration of the node. However, it is essential that competition for nodes be assessed by the cross agency body (CAB) to ensure that effort is not duplicated and to permit the free access of the *entire* research community to facilities at particular nodes.

Action plan for establishment of a UUL network:

1) Formation of a funded cross agency body (CAB) that will solicit and evaluate proposals to form nodes of the network and construct or upgrade appropriate laser, computational or other facilities within the network.
2) The CAB would hold nation-wide competition for the formation of network nodes. The effective use of existing facilities and the provision of new facilities not available in the

US, would be the major consideration in the selection of nodes. Proposals that emphasize cross collaboration among facilities, nodes and disciplines would be given high priority.

3) The network is expected to include two kinds of nodes, with each node specializing in specific scientific themes. The first kind will include activities and facilities at National Labs and existing large scale laboratories (such as LLE). The second encompasses centers at Universities which are devoted to a sub field in high intensity laser science and which will construct and maintain mid sized laser facilities.
4) Single Investigators both in theory and experiment are a key component of the network. They will have access to the facilities at the network nodes, they will receive funding through peer-reviewed proposals to the CAB for use of the network, and through single agency peer-reviewed channels for support of their scientific programs.
5) The network will be a dynamic entity with a recurring competition, held by the CAB, to assess proposals to form new nodes or to ramp down and phase out nodes in areas where the science is no longer at the frontier.

The benefits of such a network are substantial. They include:

a) an efficient, coordinated assessment of the facility needs of the community;
b) broad access to state-of-the-art facilities for the entire community, including not only national laboratory researchers but investigators at Universities;
c) the creation of a mechanism that will enable funding of the best science and best proposals drawn from the entire national community, and that will eliminate the possible duplication of funding, or the missed opportunities for interdisciplinary scientific efforts.

Examples of possible node themes include:

1) Basic high field science
2) Computational high intensity physics
3) High energy density science.
4) Laboratory astrophysics
5) Fast Ignition
6) Hyperfast (attosecond) x-ray source development and applications
7) Structural dynamics
8) Advanced particle acceleration and ultrafast nuclear science
9) Ultrafast nuclear science

APPENDIX B

Agenda for the Workshop on the Science and Applications of Ultraintense, Ultrashort Lasers (SAUUL)

June 17-19, 2002

Hilton Hotel, Washington DC

Monday (6/17):

8:30 – 9:00	Introductory remarks *Rick Freeman (UC Davis)*
9:00 – 9:30	Overview of high intensity, short pulse laser technology developments *Mike Perry (General Atomics)*
9:30 – 10:00	Short pulse laser applications in ultrafast x-ray generation *Craig Siders (U. Central Florida)*
10:00 – 10:30	Coffee break
10:30 – 11:00	Laser-driven accelerators: current status and future prospects *Howard Milchberg (U. of Maryland)*
11:00 – 11:30	Ultraintese laser applications in astrophysics *Edison Liang (Rice University)*
11:30 – 12:00	A high energy PW national plan *David Meyerhofer (U. of Rochester)*
12:00 – 1:30	Lunch
1:30 – 1:45	Overview of working groups and goals *Lou DiMauro (BNL)* *Todd Ditmire (U. of Texas)*
1:45 – 3:00	Working groups
3:00 – 3:30	Coffee break

3:30 – 5:00	Working groups

Tuesday (6/18):

9:00 – 9:30	High intensity short pulse laser applications in basic high-field physics *Joe Eberly (U. of Rochester)*
9:30 – 10:00	High intensity short pulse laser applications in fusion and fast ignition *E. Michael Campbell (General Atomics)*
10:00 – 10:30	Coffee break
10:30 – 12:30	Working group interim presentations and general meeting discussion *Moderator: Martin Richardson (U. of Central Florida)*
10:30 – 10:50	Working group on Fusion Energy and Fast Ignition
10:50 – 11:10	Working group on Advance Particle Acceleration
11:10 – 11:30	Working group on Ultrafast X-ray Generation and Applications
11:30 – 11:50	Working group on HED and Lab Astrophysics
11:50 – 12:10	Working group on Basic High-Field Science
12:10 – 12:30	Working group on Advanced Laser Technology
12:30 – 1:30	Working Lunch (provided)
1:30 – 3:00	Working groups
3:00 – 3:30	Coffee break
3:30 – 5:00	Working groups

Wednesday (6/19):

9:00 – 12:00	Working group final presentations and general meeting discussion *Moderator: Wim Leemans (LBNL)*
9:00 – 9:30	Working group on Fusion Energy and Fast Ignition
9:30 – 10:00	Working group on Advance Particle Acceleration
10:00 – 10:30	Coffee break
10:00 – 10:30	Working group on Ultrafast X-ray Generation and Applications
10:30 – 11:00	Working group on HED and Lab Astrophysics
11:00 – 11:30	Working group on Basic High Field Science

11:30 – 12:00	Working group on Advanced Laser Technology
12:00 – 12:30	Final Discussion

Working groups and group leaders

Fusion Energy and Fast Ignition	*Mike Key (LLNL)*
Advanced Particle Acceleration	*Tom Cowan (General Atomics)*
Ultrafast X-ray Generation and Applications	*Phil Bucksbaum (U. of Michigan)*
HED and Lab Astrophysics	*Todd Ditmire (U. of Texas)*
Basic High Field Science	*Ken Kulander (LLNL/UC Davis)*
Advanced Laser Technology	*Jeff Squier (UCSD)*

APPENDIX C

List of workshop attendees

1)	Pierre Agostini	Saclay, France
2)	Chris Barty	LLNL
3)	Phil Bucksbaum	U. of Michigan
4)	Denise Caldwell	NSF
5)	E. Michael Campbell	General Atomic
6)	Tom Cowan	General Atomic
7)	Joe Dehmer	NSF
8)	Louis DiMauro	BNL
9)	Todd Ditmire	U. of Texas
10)	William Dove	DOE
11)	Mike Downer	U. of Texas
12)	Joe Eberly	U. of Rochester
13)	Eric Esarey	LBNL
14)	Roger Falcone	UC Berkeley
15)	Richard Fortner	LLNL
16)	Richard Freeman	UC Davis
17)	Thorton Glover	LBNL
18)	Wendell Hill	U. of Maryland
19)	Chan Joshi	UCLA
20)	Henry Kapteyn	U. of Colorado
21)	Michael Kreisler	DOE
22)	Mike Key	LLNL
23)	Ken Kulander	LLNL
24)	Allan Laufer	DOE
25)	Wim Leemans	LBNL
26)	Edison Liang	Rice
27)	Mary Martin	DOE

28)	David Meyerhofer	U. of Rochester
29)	Howard Milchberg	U. of Maryland
30)	John Miller	DOE
31)	Warren Mori	UCLA
32)	Gerard Mourou	U. of Michigan
33)	John Nees	U. of Michigan
34)	Michael Perry	General Atomics
35)	John Porter	Sandia
36)	Martin Richardson	U. of Central Florida
37)	Jorge Rocca	Colorado State
38)	Craig Siders	U. of Central Florida
39)	Ralph Schneider	DOE
40)	Jeff Squier	Colorado School of Mines
41)	Szymon Suckewer	Princeton
42)	Barry Walker	U. of Delaware
43)	Jonathan Wurtele	UC Berkeley
44)	Steve Zalesak	NRL