High Power Lasers

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In Summer 2002, JASON undertook a study for the National Nuclear Security Administration (NNSA) of the prospective scientific value of high energy petawatt (HEPW) lasers to the NNSA's Stockpile Stewardship Program (SSP). Our charge was principally to look at the potential value of such lasers to achieving an increased understanding of nuclear weapons physics, but with attention paid to the impact of HEPW lasers on unclassified new science, including inertial-confinement fusion (ICF), astrophysics, and high-field physics. We were also asked to assess the plan for petawatt laser facility development and research activities that is being developed by NNSA's major laboratories, including the technical and programmatic risks associated with it. The main report presents our detailed response to the study charge; this first chapter summarizes our findings,

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Contents

1 EXECUTIVE SUMMARY

1.1 Introduction

In Summer 2002, JASON undertook a study for the National Nuclear Security Administration (NNSA) of the prospective scientific value of high energy petawatt (HEPW) lasers to the NNSA's Stockpile Stewardship Program (SSP). Our charge was principally to look at the potential value of such lasers to achieving an increased understanding of nuclear weapons physics, but with attention paid to the impact of HEPW lasers on unclassified new science, including inertial-confinement fusion (ICF), astrophysics, and high-field physics. We were also asked to assess the plan for petawatt laser facility development and research activities that is being developed by NNSA's major laboratories, including the technical and programmatic risks associated with it. The main report presents our detailed response to the study charge; this first chapter summarizes our findings, conclusions and recommendations.

For purposes of this report an HEPW laser generates 0.1–1 kJ or more of 1 μm wavelength light in a $\sim$1 ps pulse, thereby having a power of $\sim 10^{15}$ W. Focussing such a high power laser to $> 10^{17}$ W/cm^2 on different configurations of solid targets has been demonstrated to generate short X-ray pulses as well as intense electron and proton beams with energies as high as tens of MeV. For NNSA missions, the $\sim$ 1ps X-ray pulses are ideal for stop-motion X-ray radiography of fast-moving targets, such as imploding fusion fuel capsules in the inertial confinement fusion (ICF) program. The intense charged particle beams can potentially be used to heat 0.1 mm-scale solid-density targets to temperatures as high as 1 keV for materials science experiments. Also, because HEPW lasers can generate $>$ 10 keV X-rays much more efficiently than ns time-scale laser backlighters, HEPW laser backlighters will enable the study of thicker and/or higher Z targets than can now be investigated, including in laboratory experiments to evaluate age-related changes in materials in nuclear weapons. HEPW lasers may also enable achievement of fast-ignition in the ICF program.

Our study focussed on the value of these actual and potential capabilities of HEPW lasers to the NNSA's missions, on the state-of-the-art of PW laser technology, on the value to the NNSA of having a vigorous university program involving PW lasers, and on the importance of having an integrated, prioritized national HEPW laser research and facility development program plan.

1.2 Findings and Conclusions

1. The value of HEPW lasers to the SSP. HEPW lasers are of interest to several fields of science that are important to NNSA, particularly in materials science, equations-of-state, opacities, simulation of age-related effects on nuclear weapons materials, and the properties of dense plasmas with temperatures ranging from $\sim$ 1 eV to $\sim$ 1 keV. The most immediate and low-risk application of HEPW lasers will be for advanced X-ray radiography in weapon physics and materials science experiments, and in the ICF program. The resulting data will contribute to understanding the physics of nuclear weapons, and to validating the physical models in the computer codes being developed as part of NNSA's Advanced Strategic Computing Initiative (ASCI).

2. HEPW laser technology. The technology proof-of-principle was provided by the now-dismantled laser that operated at Lawrence Livermore National Laboratory (LLNL) from 1996 to 1999 and achieved 600 J in 0.5 ps. Facilities at the $\sim$500 J level are now operating or being constructed in Japan, France, the U.K., and Germany. There remain some technological challenges to achieving the highest energy (1–5 kJ) and power level HEPW laser pulses, but we expect these technologies to be in hand within the next few years.

3. HEPW targets and diagnostics. The technological challenges may be more severe here than for the HEPW lasers themselves. For example, the stated requirements for HEPW X-ray backlighter may be difficult to achieve in some materials science experiments in which spatial accuracy requires both several tens of keV X-ray photon energies and high intensity from a source that is $\sim 10\mu$m in diameter.

4. X-ray backlighting. "Advanced" X-ray backlighting capability, i.e., $>$ 10 keV X-ray energies and $\sim$ 1 ps pulse duration, has already been demonstrated. The Z facility at Sandia National Laboratories, Albuquerque (SNLA), and the OMEGA facility at the University of Rochester Laboratory of Laser Energetics (LLE) could use this backlighting capability today, if they had it, in conjunction with their implosion facilities. The National Ignition Facility (NIF) could carry out materials science and opacity research even before the full NIF implosion capability is a on-line; such experiments could benefit from HEPW laser X-ray backlighter, assuming that capability is judged to be a sufficiently high priority use of NNSA's HEPW program resources. However, we do not believe that the importance of these experiments at the NIF relative to other SSP programmatic needs is adequately established at this time.

5. Materials science. The pressures encountered in nuclear weapon explosions reach the tens of Mbar to many Gbar range, virtually all of which is as yet unexplored in the laboratory. HEPW lasers, operated in conjunction with implosion facilities, will allow the exploration of a substantial portion of the relevant pressure and temperature ranges, over part of which theory and modeling results may differ by tens of percent. Therefore, any good measurements would be valuable. A major open question is how much of that potentially accessible parameter space do we really need to investigate for each material to understand nuclear weapon operation? Another is how accurately must material properties be measured to be adequate for weapon certification?

6. Fast-ignition. In ICF, fast-ignition using HEPW lasers calls for generating a small spot on a compressed deuterium-tritium fusion fuel target of such high temperature as to initiate a propagating front of thermonuclear burn throughout the much larger target. With fast-ignition, it is possible that symmetry, total energy and shock-timing requirements placed on the fuel-implosion driver (laser, Z-pinch, or ion-beam) may be relaxed relative to the baseline ICF approach (initiation of fusion reactions in a central hot spot). Fusion yields achievable at the NIF, the refurbished Z, and OMEGA facilities using fast-ignition may be considerably higher than for the baseline approach for a given total laser energy. Computer simulations and initial experiments have been encouraging.

7. Frontier Science with ultra-high power lasers at Universities. Petawatt lasers would be highly desirable for certain non-NNSA science. Examples are physics at very high electric fields and various schemes for advanced particle accelerators. However, such forefront academic high energy density science with lasers does not necessarily require *high energy* PW lasers, even for science of concern to NNSA. Laboratory astrophysics experiments on Rayleigh-Taylor instabilities may benefit from HEPW lasers for diagnostic purposes, but in general, terawatt-class lasers will do the job. University-based research with TW-PW lasers will serve as an attraction for high-quality undergraduates and MS/Ph.D. students to areas of science and technology of interest to NNSA.

8. The HEPW laser plan so far. The components of the Draft HEPW Laser National Plan presented to us this summer constitute more a set of laboratory wish lists than a cohesive NNSA weapon laboratory/ICF research community plan. The time is ripe for intensive and detailed community effort to establish the mission need for proposed research activities, to set research and facility development priorities, and to construct prioritized research plans for different budget levels.

9. Framework for setting priorities. We are concerned that inadequate attention has been paid to the relative importance of the proposed HEPW laser research activities in the overall SSP program. The Quantification of Margins and Uncertainties (QMU) method can be applied to such activities as X-ray backlighting for weapon physics experiments and materials science experiments with special nuclear materials. The importance of research activities that do not fit into the QMU process can be viewed in the spirit of the QMU, i.e., are they valuable to NNSA's overall long-term goals, including achieving ignition at the NIF?

1.3 Recommendations

1. The HEPW Laser National Plan. We recommend that the NNSA laboratory community move quickly to develop a plan that represents a true integration of the capabilities and potential contributions of all the NNSA-funded weapon physics and ICF laboratories (LLNL, LANL, SNLA, LLE and GA). Prioritized research and facility development plans (both objectives and schedules) should be laid out for different budget levels. A step-by-step flexible approach that takes into account the technological risks of various proposed applications and the research needed to mitigate the risks should be adopted. Proposed activites should not impact the baseline NIF cost and schedule, nor unduly disrupt other major baseline program activities such as the OMEGA direct-drive ICF research campaign. The Plan should use a systematic approach to quantifying the connection between the proposed research activities and stockpile stewardship goals in the spirit of the QMU philosophy.

1a. Review Board for the HEPW Laser National Plan. We further recommend that a Review Board be established, consisting of knowledgeable scientists and engineers both from within and from outside NNSA programs, to oversee the development of the HEPW Laser National Plan. This Board should insure that the Plan pays due regard to prioritization, collaboration, and integration of research activities and facility development.

1b. Initiate Activities Expeditiously. However, we also recommend that the NNSA begin initial HEPW laser activities without delay, perhaps even prior to establishment of the Review Board. These should include preparing facility designs in support of developing the National Plan, low-risk, relatively low-cost activities such as developing a few-hundred-Joule, ~ 1 ps X-ray backlighter for the Z facility, and carrying out risk-reducing science experiments related to SSP applications on existing ≥ 0.1 PW lasers in the U.S. and abroad.

2. Technological Development. We recommend that any significant technology development for HEPW lasers in the National Plan, such as high-damage-threshhold gratings, should be a community effort that is compatible with application at the NIF if and when appropriate.

3. X-ray backlighting. We recommend that HEPW laser X-ray backlighter capability be developed and implemented at NNSA implosion facilities on schedules and with priorities compatible with each facility's operational status, and in a way that does not disrupt or delay its primary goals. We believe it is important that the NIF's baseline program cost and schedule are not affected by premature HEPW laser research and development activities.

4. Materials science. We recommend that a systematic documentation be carried out to determine the weapon materials science data that are really required for understanding nuclear weapons, for stockpile stewardship, and ultimately for weapons certification. In some cases, the experimental accuracy requirements may drive the need for higher energy petawatt laser facilities than would be required otherwise; we recommend that the importance of such accurate data be carefully assessed. The required accuracy of measurements may be determined through sensitivity studies using computer simulations followed by application of the QMU process.

5. Fast-ignition. We recommend continued fast-ignition research, including small-scale experiments at international locations and at U.S. facilities when these are capable of the appropriate experiments, as well as code development for fast-ignition studies. If the small-scale experiments continue to look promising, we recommend that the NNSA proceed with the development of larger-scale fast-ignition capability in conjunction with implosion facilities. We further recommend that the necessary "floor space" at the NIF be reserved for HEPW laser beam implementation for fast-ignition, but that fast-ignition research should not impact NIF's baseline cost and schedule.

6. University programs. We recommend that the NNSA support a vigorous program in ultra-high power laser research at universities using short-pulse lasers in the TW to PW regime, but not necessarily *high energy* petawatt lasers. Instead we recommend that an academic user program on HEPW lasers at NNSA laboratories, such as that at the OMEGA laser facility at LLE, be established as it will benefit the SSP in the long run.

2 INTRODUCTION

2.1 Introductory Remarks

This report presents the results of the 2002 JASON Summer Study on potential applications of high-energy, short-pulse lasers to understanding the physics of nuclear weapons. This study, the Charter for which is given in detail in Section 2.4, was requested by Dr. Christopher Keane of the National Nuclear Security Administration (NNSA). In essence, we were asked to examine the national plan that is now being developed to exploit recently-developed High Energy Petawatt (HEPW) laser technology for the benefit of stockpile stewardship.

For purposes of this report, the lasers of interest deliver peak powers of > 0.1 petawatt (1 petawatt $\equiv$ 1 PW $\equiv 10^{15}$ W) of 1 μm wavelength light for times ranging from perhaps 0.5 to 5 ps. Energies delivered to a target (typically a 0.01–1 mm diameter spot on the target for the applications of interest) range from 50 J to 5000 J. Shorter pulse, lower-energy PW lasers have many possible applications in general science (to be discussed in Section 3.3). However, for the reasons to be described in Section 2.3, applications related to understanding nuclear weapons explosions require of the order of 100 J or more.

The ability to generate HEPW laser beams at nearly 1 kJ and 1.5 PW has already been established by the successful conversion of an arm of the NOVA laser at Lawrence Livermore National Laboratory (LLNL) from a nanosecond beam to a picosecond beam in the mid-1990's.[1, 2] Unfortunately, that laser no longer exists. Moreover, the ability to do a broad range of exciting science with PW lasers is certainly not in question, as evidenced by a string of Physical Review Letters articles and many full-length journal articles in the last few years (see references in Section 3). The main questions we address in this report, at the request of Dr. Keane, are how valuable this technology might be to the NNSA stockpile stewardship mission, what are the risks associated with its proposed applications, and is the scope and phasing of the HEPW laser National Plan reasonable. Ancillary questions concerned the value of HEPW lasers to the DoD and to U.S. science in general.

In this context, it is important to point out that high energy density physics (HEDP) studies, within which HEPW laser research activities would fit, contribute to stockpile stewardship through helping the NNSA's scientists and engineers improve their understanding of the physics and technology that underlines the well-established effectiveness of our nuclear weapons. Generally speaking, high energy density implies energy densities considerably higher than solid material at room temperature, i.e., > 1000 J/cm^3. The research that falls within the HEDP program includes several forefront areas of science and technology, such as inertial confinement fusion (ICF) and studies of materials properties under extreme density, temperature and pressure conditions. Maintaining, indeed enhancing, experimental, theoretical and computational capability and expertise in applicable areas of HEDP is a major component in our ability to certify the stockpile as safe and reliable for the indefinite future.

In support of this study, we heard many briefings by scientists from the four NNSA laboratories that carry out most of NNSA's weapon-related high energy density research: LLNL, Los Alamos National Laboratory (LANL), the Laboratory of Laser Energetics (LLE) of the University of Rochester, and Sandia National Laboratories, Albuquerque (SNLA). We also heard from a representative of the Atomic Weapons Establishment (AWE) in the United Kingdom, from one of the original developers of HEPW laser technology [1] (who is now at General Atomics (GA)) and from several university scientists who are interested in the basic science applications of HEPW lasers. We greatly appreciate the efforts of Dr. David Meyerhofer of the LLE, who helped organize the briefings and also provided us many relevant references and other written material. We also wish to acknowledge many useful discussions on this subject with Dr. Claire Max of JASON who, because of her employment by LLNL, has recused herself from participating in the final preparation of this report.

2.2 High Energy Petawatt Lasers

2.2.1 HEPW laser technology status.

An HEPW laser has a pulse lasting from a fraction of a ps to a few ps, as well as high energy ($\sim$ 1 kJ). It is impossible (at least at present) to generate directly such short laser pulses at high energy, because lasing materials and optical elements that can produce and withstand the tremendous power do not exist. If direct amplification of an ideal laser beam were possible, non-linear effects from the high intensity in the lasing medium would cause self-focusing of the laser beam, rendering it unusable because of beam distortion and concentrated regions of damage to the medium and to optics. In consequence, an HEPW laser works by amplifying a much longer pulse, in the ns regime, and then compressing this pulse in time by an ingenious combination of diffraction gratings [3]. There are two sets of problems. One set arises from the large bandwidth of the compressed pulse, which must be preserved during amplification of the stretched pulse, and from unwanted parts of the stretched pulse which end up being amplified. The other set comes from the high power and fluence on the final pulse compressor gratings and on the final optics.

The first chirped-pulse amplifier (CPA) technology demonstrated by Strickland and Mourau [3] used a Nd:glass laser system. However, the first true HEPW laser, the NOVA PW, used a Ti:sapphire laser as a regenerative amplifier for the first stages of amplification [1, 2]. After multiple amplifying passes through the lasing medium (necessary because the Ti:sapphire laser, although capable of broad-band gain, had little gain per pass) the beam was optically switched out for further amplification (often in a Nd:glass laser). However, during the regenerative amplification a string of so-called pre-pulses leaked out of the optical switch before they were fully amplified. The result was that a single high-energy short pulse was accompanied by a long-lasting precursor of lesser-energy pulses that require multiple Pockels cells to eliminate. Another contributor to a distorted pulse was amplified self-emission (ASE). Both of these unwanted additions to the main pulse can cause unacceptable damage to optics and/or targets when the PW regime is reached.

A way of avoiding these complications is the Optical Parametric Chirp Pulse Amplifier (OPCPA) that was developed in the UK [4]. In OPCPA, the small-signal stretched pulse ($\sim$1 ns), with the desired bandwith, is mixed with a strong pump laser beam in a non-linear medium such as β-barium borate (BBO) crystals. There is one pass or at most a very few passes through the gain medium, greatly ameliorating the pre-pulse problem, and ASE is reduced by an order of magnitude or more. The gain of the medium is high, so the gain region is physically shorter and there is a smaller self-focusing effect. In order to have faithful reproduction, including bandwidth, of the signal pulse, the pump pulse must be smooth in space and constant in time over the time of non-linear mixing. This system replaces the Ti:sapphire regenerative amplifier, although a Ti:sapphire laser may be used to provide the pump laser beam.

OPCPA technology has been used in a number of places, including at LLE, in Japan and Britain, and at LLNL [5]. The LLNL researchers claim that the wavelength and pulse energy demonstrated in their OPCPA system are suitable for a kJ-class HEPW laser at the National Ignition Facility (NIF). Prepulses were reduced to a level 10^{-7} below the main pulse, nearly good enough for HEPW laser use.

Technological risks for further development of OPCPA seem to be moderate, since they mostly involve incremental improvements. These include: further reduction of pre-pulse levels; improving timing synchronization and jitter in mixing the power and signal beams; and controlling pulse-shape distortion due to dispersion in the lasing medium.

2.2.2 High-damage threshold grating and other technology challenges

There are certainly technology challenges for gratings used in compressors. For a kJ-class HEPW laser, these gratings might have to be quite large physically, in the range of 0.5-1 m across. Gold-coated glass gratings, such as those used in the LLNL Petawatt Laser built from NOVA equipment, have a damage-fluence threshhold of about 0.4 J/cm^2 for a wide range of pulse durations, from fs to about 100 ps (and an increasingly-higher threshhold for longer pulses). Damage to these gold gratings is largely by Ohmic heating from the intense fields of the impinging laser pulse, and a HEPW laser would require 2500 cm^2 of gratings per kJ of laser energy. The grating is oriented at an angle to the laser beam in actual use. Therefore a HEPW laser of 5 kJ would require gold gratings almost 2 m in length, a considerable technological challenge.

Now under development at General Atomics, LLE, and LLNL are multilayer stacked-dielectric gratings based on fused silica. These gratings have damage fluence threshholds dependent on pulse duration, but for pulses of a few ps the experimentally determined threshhold [6] is up to an order of magnitude higher than that for Au (2-4 J/cm^2, increasing with pulse duration from 0.5 to 10 ps). Some of the technology issues for these newer gratings include: actually achieving the highest claimed damage threshholds on large area grating; minimizing the size of the overall compression facility; techniques for building large gratings and/or fitting together smaller gratings at the required tolerances for optical coherence across the entire grating array; finding the best technique for fabricating the dielectric stack (*e. g.*, ion-beam sputter coating); and designing stacks with reduced intrusion of laser electric fields.

In addition, there are significant technology issues associated with damage to the final optical elements that are exposed to the compressed HEPW laser beam. It does not appear to us that any of the technology questions involved with gratings and final optics carry undue risk, although certainly considerable effort still remains.

There are several other technical risk areas at high energies, including control of gain saturation in the main amplifiers; synchronization of the HEPW laser with other lasers; adaptive-optics beam control; minimizing the effect of debris shields at the target; and protecting the amplifier from back-reflection of a high-power laser beam. The risks in these technology areas again appear to be moderate because they are based on incremental improvements, not on fundamentally-new techniques.

Our judgment of technical risk is based on HEPW lasers whose pulses are not much shorter than 1 ps, and energies not much higher than 5 kJ per beam. Outside this regime, the technology challenges appear to increase rapidly.

2.3 Why Are We Potentially Interested in High Energy PW Lasers for NNSA Missions?

High-energy petawatt lasers could be an important tool for HEDP studies and for adding to our understanding of nuclear weapon operation in four direct ways. First, HEPW lasers focussed to $> 10^{17}$ W/cm^2 can efficiently produce X-rays with photon energies greater than 10 keV for X-ray backlighting of thicker objects, and with less motion-blur, than can be done at present. This capability would enable high quality radiographs to be produced in some important weapon-relevant physics and materials science experiments that could not presently be fully diagnosed. Second, HEPW lasers would extend the range of densities and temperatures that will be accessible for high energy density material properties experiments. Third, it is possible that HEPW lasers could enable ignition and high gain inertial confinement fusion (ICF) to be achieved with substantially reduced total laser, z-pinch or ion beam energy through the concept known as fast–ignition. Finally, all such NNSA–relevant HEPW laser experiments, as well as other high-energy density experiments that might be done with ultrahigh power lasers (for example for laboratory astrophysics), would provide a database that can contribute to the validation of the physics models included in the large-scale computer codes used to predict nuclear weapon performance. Some of the science opportunities that would be opened up by PW lasers are discussed in Section 3, including both NNSA-relevant science and general science possibilities. Some of the more important NNSA-relevant potential applications of HEPW lasers are discussed in detail in Section 4. It is also of importance to NNSA that the excitement of research with state-of-the-art laser systems will attract promising young scientists to HEDP research, and will challenge the community already at the NNSA laboratories with important and exciting new frontier science, as discussed in Section 5.

The need for several tens of joules to several kilojoules to accomplish NNSA-relevant applications follows from the nature of each application. For X-ray backlighting, it is necessary to generate enough photons of the required energy to obtain a high-quality radiograph of the experimental object of interest, even if that object is a strong radiator itself. For heating solid-density matter to high temperature and pressure, uniform irradiation of sufficiently large test samples to obtain, after analysis, adequately accurate materials properties, leads to the need for PW beams with ~ 1 kJ energy. For achievement of fast–ignition, a few tens of kilojoules or more are expected to be needed in PW beams to ignite thermonuclear reactions in deuterium-tritium fusion fuel that is already compressed to ~ 100 gm/cm^3 by a separate driver (laser, z-pinch or ion beam). In all three cases, the fact that the object being radiographed, heated, shocked or ignited does not move much in 1 ps is important, a feature that would be even more true with a still shorter pulse. However, delivering the required energy in, for example, a 50 fs pulse is not yet possible, may never be, and is not expected to be needed for NNSA's applications in any case.

2.4 The Study Charter

The Charter for this study is as follows [7]:

- Programmatic benefit: To what degree does the proposed program of work benefit stockpile stewardship? This should include (but not limited to) an assessment of the value of PW lasers to inertial fusion, weapons physics, radiography, materials properties studies, and basic science.
- Technical risk: Is the proposed technology development plan sound? Is the overall level of technical risk for the program acceptable?
- Scope and phasing of activities: Significant PW upgrades are proposed for a number of facilities within the HEDP Campaigns. Comment on the value added of PW capabilities for each of these facilities. What is the appropriate integrated schedule for installation of PW capabilities at these facilities?
- DoD applications: Comment on the value of PW lasers and PW laser technology development activities to DoD.
- University role: Comment on the value of university PW facilities to the PW program and stockpile stewardship. Include in your assess-

ment university PW facilities and programs not tied to major HEDP Campaign implosion facilities.

- New scientific frontiers: Comment on the value of the PW program to the overall vitality of science in the U.S.

The (Draft) Petawatt National Plan [8] as it now stands (the "proposed program of work" in the first bullet above) is really a compilation of activities proposed by each of the four NNSA laboratories for development of individual petawatt laser programs. Therefore, it is not clear what the final plan will look like after it is converted into an NNSA "Petawatt National Plan." We believe strongly that there should be such a plan and we have carried out our study with the idea that our findings and recommendations may help NNSA formulate it. These are detailed in Section 6 and were briefly summarized in Chapter 1, the Executive Summary.

In the introductory and summary material in this Chapter, and in more detailed discussion in Chapters 3–6, the programmatic benefits, the technical risk, and the scope and phasing of various aspects of a Petawatt National Plan are addressed. Regarding Department of Defense (DoD) applications, such as to missile defense, we have had only limited exposure to them. We expect, based upon similar situations in the past, that DoD organizations will be satisfied to monitor NNSA-sponsored PW technology development, becoming willing users if and when the technology is developed. By contrast, we expect that making the technology available even at modest level to university research groups will be valuable to the NNSA. We can anticipate the development of innovative ideas, and we can be sure of an increase in young researchers (graduate students and post doctoral fellows) as well as new faculty who will be trained in high energy density (HED) science. In addition, some of the undergraduates who will be introduced to HED science through student research projects will stay in the field as graduate students. The excitement of working with even 10J, 10–100 TW lasers will attract many students of the sort NNSA will need for the success of its mission to assure the safety and reliability of our nuclear weapons for decades to come.

3 WHAT CAN A PETAWATT LASER DO?

3.1 Broad Categories

3.1.1 Conversion of PW radiation into energetic particles

Much of the scientific excitement aroused by PW lasers is due to their ability to generate highly relativistic electrons, as well as protons with energies of 10s and even 100s of MeV. This capability arises because, for a 1 μm wavelength laser with power exceeding 3×10^{18} W/cm^2, electrons are accelerated by the transverse oscillating electric field of the laser to relativistic "quiver velocities" eE/mω (where e and m are the electron charge and mass, respectively, E is the electric field amplitude, and the laser angular frequency is ω). The ponderomotive force on the electrons then produces a "DC" longitudinal acceleration with concomitant currents and charges. The laser energy tends to be absorbed or backscattered at densities such that the plasma frequency (suitably modified for compression and relativistic effects) exceeds the laser frequency. For 1 μm light this implies a "critical" plasma density of 10^{21}/cm^3, scaling as frequency squared. For some applications, such as wake field accelerators, the plasma density is subcritical. However, for a laser impinging on ordinary solid density matter, or especially for compressed ICF targets, the plasma instantaneously produced will be supercritical. In the subcritical case simulations indicate a fairly simple steady state pattern is set up which may be suitable for wake field acceleration.

Particularly in the overdense case, collective interactions are very important. The current and charge separation induced by the accelerated electrons must be compensated by cold electrons or, on a longer time scale, by ions. Theory indicates the electron current tends to filament, the so-called Weibel instability, with concomitant growth of transverse energy, i.e., defocusing. Simulations in 3 D, which as yet are restricted to time and space scales shorter than those of interest, indicate that these filaments eventually merge into one or a few beams, each carrying about one net Alfven current. These simulations are still controversial and the scaling of defocusing and possible energy loss in the process is quite unclear. [9]

Preliminary flat target experiments, at much below laser energies of interest, show a good conversion (50%) of laser energy into fast (few MeV) electrons which propagate through the target with modest energy loss and are concentrated in a 20–40 degree cone. Clearly it is a very complex situation and many more experiments are needed. These are currently proceeding abroad at LULI in France, Vulcan in the U.K., and Gekko in Japan.

Also of interest are experiments in the U.S. [10] and elsewhere [11] showing conversion of electron energy to ions. Surprisingly the ions appear to be very well collimated and hence suitable for diagnostic application at least for nearby objects. [10] Several mechanisms have been proposed for the ion beam production. However it now appears that at least the well collimated ions are formed when a target foil for the electrons is in vacuum and the fast electrons emerge from the rear surface of the foil. Lack of charge neutrality will then set up an electric field at the surface which accelerates ions. These emerge normal to the rear surface and some focusing has even been obtained by curving the surface. Energies around 10 MeV and 5% conversion of laser energy into collimated ions [12] have been obtained with low energy (few J) PW lasers, in agreement with simulations. The beam quality was sufficiently good in those experiments that radiographic images were made with them. [11] For higher energy lasers and hence higher ion currents there remains a question whether collective effects will allow such favorable results. There is also interest in producing higher Z ions by this approach, and ion beam experiments at high energy facilities abroad are underway [13].

3.1.2 Generation of X-rays with energies > 10 keV

The efficiency of generating X-rays with high energy ns laser beams suffers substantially if the lower cutoff energy of interest is > 10 keV. That is because the mechanisms by which the X-rays are generated by a ns beam are line radiation and bremsstrahlung from a thermal plasma, and plasma electron temperature scales very slowly (as the 2/7 power) with the laser power [12]. This scaling is a result of increasingly rapid cooling of plasma due to radiation and thermal conduction as the laser power density increases and drives the temperature up.

The PW laser has two major advantages over a ns laser for generating higher energy X-rays and generating them more efficiently when it is focussed onto a solid surface. First, in ~ 1 ps, thermal conduction is negligible even with focal spots as small as 10 μm. Second, the power density in the focal spot is sufficiently high that some of the electrons in the plasma become very energetic, even relativistic, between collisions, and do not thermalize before inducing line emission in the target material. If the electrons are sufficiently energetic to exceed the K-shell electron excitation energy in the target material, K-shell emission is possible. According to Kilkenny [12], the optimum electron energy for K-shell emission from a given atom is about 6 times the ionization energy.

The effective temperature of the high energy electrons in a resonant acceleration model scales as $7(I\lambda^2/\ 10^{15})^{0.33}$ keV up to about 30 keV, where I is in W/cm^2 and λ is μm. At this energy, the mechanism for generating the high energy electrons supposedly switches to ponderomotive acceleration and the scaling should become $0.5 \times [(1+(I\lambda^2)/2.8\times 10^{18})^{1/2} - 1]$ MeV [12]. Experiments, however, appear to verify the resonant acceleration scaling up to the few hundred keV level, but in the form 100 (I $\lambda^2/10^{17})^{0.33} keV$ [14]. Thus, by varying the focussed PW laser, assuming 1 μm light, in the range 10^{17}–10^{18} W/cm^2, it is possible to efficiently produce K-shell radiation from near 10 keV, using a Zn target, to near 50 keV using a Gd target. The conversion efficiency of PW laser energy into relativistic electrons is 10s of percent, and the conversion of electron energy into K-shell X-rays is $\sim 1\%$ of that. Therefore, the net conversion efficiency from PW laser energy into K-shell photons is in the 0.1–1 % range.

Efficient conversion of the electron energy into K-shell photons as just discussed requires that the target material be a substantial fraction of an electron range thick. As a result, the electrons scatter and spread out relative to the original laser focal spot as they slow down in the target, emitting the desired photons along the way. Therefore, the X-ray source spot is not as small as the laser focal spot, and the more energetic the electrons (requiring a thicker target to stop them), the more the electrons will spread. As such, a pinhole is necessary to limit the source size in a radiography application if fine spatial resolution is needed. Because a pinhole cuts down on the photons available for radiography and because it is difficult to make and align a $\sim$ 10 μm diameter pinhole in a material that is thick enough to work at > 100 keV (for bremsstrahlung radiation), high resolution imaging may be limited to below 100 keV (K-shell X-rays). However, this would not be a limitation to using > 100 keV X-rays from a PW laser for isochoric heating of mm-cm scale objects to $\sim$ 1 eV.

3.1.3 Increase the accessible range of high-energy-density states of matter

With conventional techniques such as anvils and gas guns, materials properties have been studied to pressures of perhaps 5 Mbar. In a typical experiment a material sample is shocked and its pressure, density, and energy density are inferred from velocity measurements and the Rankine-Hugoniot relations. Temperature is often not measured directly. Because of the way the experiments are done, materials parameters are studied only on the Hugoniot.

HEPW lasers, operating alone or in conjunction with other lasers for compression, can potentially extend the range of experimentally-accessible pressures to those of interest for nuclear weapons physics, for the cores of the giant planets, and very near the surface of neutron stars, i.e., to some tens of Mbar to many Gbar. Such conditions are achieved by isochoric (constant-density) heating of matter, possibly pre-compressed by ns-class lasers, by HEPW laser-generated charged particles. The sample has no time to expand and change density during the ps time-scale heating phase. The equation-of-state (EOS) data inferred from an isochoric experiment are obtained far from the Hugoniot, and will allow adding to the materials data base in regions which are now completely unexplored, thereby providing severe constraints on theory and modeling.

As we have already discussed, HEPW lasers are expected to be able to provide X-ray backlighters at X-ray energies considerably higher than available in ns-scale laser backlighters, up to the K edges of high-Z materials, such as U at 94–98 keV. These X-rays can penetrate relatively large targets, which may be needed in some of the high pressure materials science measurements. HEPW lasers can also generate energetic (up to tens of MeV) protons as we have also already discussed. These may also have uses in target diagnostics [12].

It is claimed that HEPW lasers can be used in X-ray absorption fine structure (EXAFS) experiments at high pressure, which can, in principle, yield data on the mean spacing of atoms in a shocked sample. The important first step is, of course, a bright source of X-rays in the right energy range produced as discussed in Section 3.1.2; one then studies the scattered photon characteristics to determine the lattice spacing (see Section 4.3.2). However, measurements on a sample shocked to a pressure large enough to compromise the lattice structure are not easy to interpret with the EXAFS technique. It is also claimed that HEPW lasers will allow for determination of high-pressure materials strength parameters through studies of Rayleigh-Taylor growth patterns (the growth rate depends on these strength parameters), but the required accuracy will be difficult to achieve, and such experiments would need independent confirmation by other techniques.

3.1.4 Fast Ignition

Conventional ICF targets rely on a hot spot ignition scheme in which a nanosecond laser implodes a thin shell of solid fuel surrounding a dilute gas [15]. At the end of the implosion, the shell is supposed to be compressed to a high density, requiring a low adiabat. The central gaseous fuel is heated by the final convergence to a temperature of about 10 keV, at which it can start a fusion burn that propagates outward through the dense compressed fuel. The requirements for such a two-fuel-region implosion are very demanding on laser pulse shape and symmetry, although modelling indicates that a margin exists for successful ignition on NIF.

It was proposed by Tabak et al., in 1994 [16] that an alternative might be to separate the 2 functions, i.e. first compress a thin shell target surrounding a vacuum to a very high density on a low adiabat, and then use a ~ 1 ps multi kJ laser pulse to deliver enough energy via accelerated electrons or ions to reach 10 keV in a hot spot on the surface of the compressed fuel. Fusion reactions in the hot spot can then ignite the rest of the fuel. The advantages are that a high compression without a high central temperature is easier to obtain, i.e., is less demanding on the symmetry, energy and pulse shape (shock timing) for the main laser, and it may even allow green light to be used instead of ultraviolet light.

Modelling shows that such a surface hot spot can indeed lead to ignition of the compressed fuel if some 10s of kJ are deposited by particle beams produced by a HEPW laser. The exact requirement is still highly uncertain so that it is by no means clear the scheme works or offers a significant improvement (with reasonable Petawatt laser facility investment) over conventional (central hot spot ignition) targets. However, the potential for more thermonuclear yield for a given laser energy has excited a great deal of interest in the world ICF community.

The largest uncertainty concerns the ability of the PW laser to penetrate the corona of plasma blow-off around the compressed target and deliver its energy to a small area near the compressed fuel. The PW laser energy must then be converted to energetic electrons or protons as discussed in Section 3.1.1. These particle beams are subject to complex collective modes making them difficult to focus. Intensive modelling and many experiments are underway with hopeful preliminary results. Two schemes that have been proposed as penetration aids for the laser energy are illustrated in Figure 1. One involves a ~ 100 ps channel-boring laser, and the other utilizes a metal cone that penetrates the target and keeps the blow-off plasma out of a conical region through which the PW laser shines.

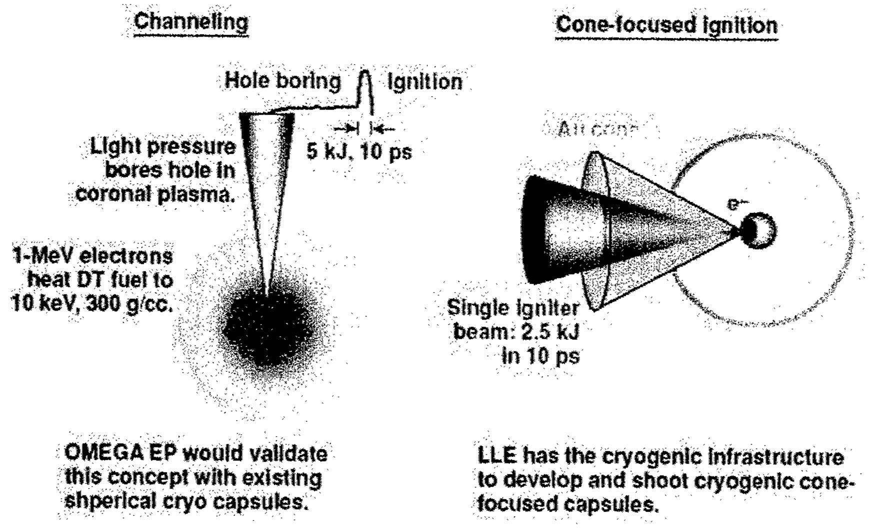

Figure 1: The two viable fast-ignition concepts share fundamental issues: hot-electron production and transport to the core. (Modified from a figure provided by T. Craig Sangster of LLE [17].)

The most impressive experimental success to date has been achieved with a gold cone at the Gekko laser in Osaka as shown in Figure 2. In this experiment a 500 J PW laser was focussed on pre-compressed fuel at 100 gm/cm^3. An increase of a factor of 10^3 in neutron yield was observed at the highest laser power tested. While the absolute 10^7 yield is unimpressive, the results agree with simulations of what is to be expected in this underpowered case if 30% of the PW laser energy is deposited, presumably as electrons, in a small hot spot. The diagnostics were fairly convincing, including dependence on PW laser power and timing, as well as neutron spectra indicating a true thermonuclear yield. Of course the issue remains quite open whether such efficient focussed deposition can be attained with a more energetic (5 kJ) HEPW laser and with better compressed and diagnosed targets such as those available on OMEGA.

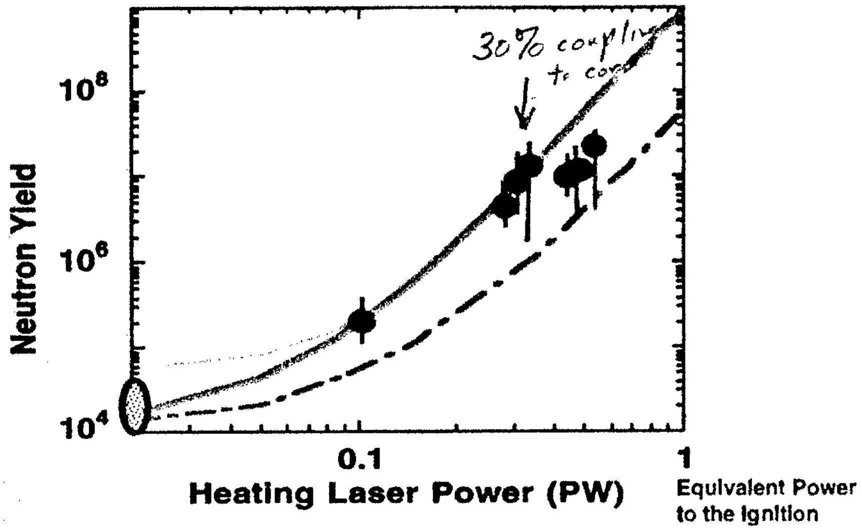

Figure 2: Neutron yield is enhanced as the HEPW laser power is increased. The increased yield is consistent with about 30% of the laser energy being coupled into the dense fuel [18].

3.2 Science issues of potential importance to the NNSA

3.2.1 Isochoric heating

Isochoric heating is a particularly important application of a HEPW laser in EOS and material strength studies because, as introduced in Section 3.1.3, it allows studies of regions of phase space which are off the Hugoniot and which are very poorly characterized either experimentally or in models. Isochoric heating must be sufficiently fast that the sample material does not expand (stays at constant density) during the heating. Therefore, HEPW lasers with their time scales of ~1 ps are essential. In materials science experiments (e.g., EOS determination) relevant to the NNSA, the heating must occur over a sufficiently large spot to achieve the desired accuracy in spatial measurements; spot sizes up to 1 mm can be required. The reason for large size in bulk-strength-of-materials measurements is that targets with only a few crystal grains can give results which are misleading if extrapolated to bulk matter.

A 1 kJ ~ 1 ps (10^{15} W) HEPW laser with a wavelength λ of 1 μm illuminating a 1 mm spot will produce both thermal electrons and supra-thermal [19] electrons, the initial temperature of which will be tens of keV, corresponding to deposition ranges (in intermediate- and high-Z matter) of a few tens of μm. These supra-thermal electrons will quickly thermalize to temperatures in the range of 100 eV. Both kinds of electrons lead to similar pressures. A heavy-metal sample $0.1 \times 0.1 \times 3 \times 10^{-3}$ cm^3 will be heated to a temperature and density corresponding to a pressure in the range of 40 Mbar or so. A sample 100 μm on a side will yield pressures in the Gbar range, but it may be that the accuracy of certain measurements will be inadequate with this size of target (see Section 4.3).

Targets can be heated isochorically with protons produced in a thin foil target between the laser and the sample. These protons, as described in Section 3.1.1, have energies upwards of 1 MeV and may deposit only a fraction of their energy in thin samples of interest. This must be accounted for in determining attainable temperatures and pressures. On the other hand, MeV protons are a good way of heating a sample quite uniformly in depth.

The density of the sample can be tuned by pre-compression with the main beams of the ns time scale laser or Z-pinch facility at which the HEPW laser is located. Temperatures are presumably most simply measured by looking at the self-emission of the sample in a number of wavelengths.

3.2.2 EOS experiments that use HEPW laser backlighters

As an example of an important property of a relevant material that can be determined, consider so-called equation-of-state measurements. There are a variety of shock experiments which follow the same principles of experiments at lower pressures using, for example, gas guns. They measure the velocities of a propagating shock and the material velocity behind the shock in order to deduce the density, pressure, and internal energy according to the Rankine-Hugoniot relations. A typical laser-based experiment uses ablation pressure from the ns beams to drive a flyer plate into a target. According to Lindl [15], the ablation pressure scales as

$$P[\mathrm{Mbar}] = 40\{\frac{I[10^{15}W/\mathrm{cm}^2]}{\lambda[\mu m]}\}^{2/3} \tag{3-1}$$

so that the NIF lasers should be able to produce 10s of Mbar to Gbar pressures on a 1 mm × 1 mm flyer plate. The HEPW laser enters as an important diagnostic facility, able to produce X-rays on a backlighter of sufficient energy and intensity to penetrate the 1 mm target as discussed in Section 3.1.2.

Isentropic compression experiments can also be carried out using z-pinch and lasers drivers [20, 21]. As in the shock-based experiments, the target size necessary to achieve adequate measurement accuracy to obtain material properties with the prescribed accuracy can require the advanced radiography capability of HEPW laser X-ray backlighters.

3.3 Basic Science Possibilities with PW Lasers

Focused petawatt laser beams can a) create unique physical conditions in matter or in vacuum that enable exploring specific science questions and testing theoretical models, and b) create new "tools" (e.g., the short-pulse X-ray backlighters or intense particle beams that we have already discussed) for experimental physics. Although some of the basic science applications are very similar to those motivated by NNSA mission needs and HEDP program goals, others are not. The basic science applications may be grouped into four broad categories:

1) Direct observations of important states of matter not otherwise achievable in laboratory experiments;

2) Laboratory experiments, the parameters of which may be "scaleable" to regimes important in astrophysics;

3) Development of "tools" which may, ultimately, be used in explorations of new physical regimes and phenomena; and

4) Possible new physics in superstrong electric and magnetic fields.

We present below some suggestions of what may be accomplished by high and medium energy petawatt laser-based experiments in these four groups (including some suggested applications which do not seem very promising). For the most part, these applications involve physical states and phenomena that are already roughly understood. However, although what would be measurable could, in principle, someday be calculated with confidence from known basic physics, existing computational strengths are far from adequate to obtain quantitative results. Many of the results could be relevant to nuclear weapon science, but our point here is to see if the major facilities that may be needed by NNSA will also interest academic scientists and graduate students. If so, a pipeline of new recruits for the NNSA laboratories may be created.

3.3.1 Direct Observation of Important States of Matter Not Otherwise Achievable in the Laboratory

The first class of experiment is close to that discussed in Section 3.2. High power lasers in the ns range can effectively compress matter through ablation pressure and/or by generating shock waves. Carrying out such experiments in planar geometry enables measurements of material properties, such as the equation-of-state, through its compressibility and other observables, studies of hydrodynamic stability properties, radiative hydrodynamics, etc. Again as in the case of research relevant to NNSA, in these experiments adequately accurate measurements may require X-ray radiography through gm/cm^2 thicknesses of material, thereby requiring bright sources of the higher energy photons that can be generated using HEPW lasers. Thus, the HEPW laser enables the observation in this case.[1] In other experiments, an HEPW laser can also generate charged particle beams to heat solid density or even pre-compressed matter, in which case the HEPW lasers can contribute doubly by helping to generate the experimental conditions and by enabling the necessary measurements.

Data from such experiments can lead to quantitative descriptions of:

- the equation-of-state of hydrogen relevant to the interiors of Jupiter, Saturn, Uranus and Neptune;

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[1] Note that both the short pulse of the PW laser and the penetrating power of the X-rays it produces are required to make adequately accurate measurements in many experiments.

- opacities of stellar matter at kT ~ 10–100 eV;
- the transitions to turbulence in hot plasma flows and jets;
- the physics of very dense, relatively cold (strongly coupled) plasmas (i.e., Coulomb energies of the particles > thermal energy);
- Rayleigh-Taylor and other hydrodynamic instabilities;
- radiative shocks.

Another suggested HEPW laser application to new states of matter is the creation of a relativistically hot electron-positron (pair) plasma. Detecting the pair plasma and studying its properties would be a significant achievement, and there may even be applications of such plasmas if they can be made "routinely." However, such an experiment is not likely to provide a new contribution to basic science, since it is extremely doubtful that data from possible measurements will reveal any discrepancy from calculations based on already extremely well tested Quantum Electrodynamics (QED). The suggestion that measurements of a laboratory pair plasma's properties might have an impact on astrophysical Gamma-ray Burst model calculations based upon assumed extreme relativistic pair flows would be difficult to defend.

"Cluster explosions," sudden laser-driven expulsions of electrons in a cluster of $10^2 - 10^6$ atoms, followed by the Coulomb field-driven explosive reaction of the remaining cluster of charged nuclei, should be achievable with only modest energy petawatt lasers. While such an experiment would be an achievement to diagnose, it is unlikely that something fundamentally new and important would be learned from it. However, once again there may be interesting applied physics reasons for doing the experiment, such as developing a pulsed neutron source by exploding a deuterium cluster close to a deuterium or tritium "target."

3.3.2 Laboratory experiments can be designed for which measurements may be scaleable to important astrophysical regimes.

Astrophysically interesting regimes cannot be approached in the laboratory but experiments can be designed so that important dimensionless parameters are similar. Examples include:

- laboratory observations of Rayleigh-Taylor instabilities which may be scaleable to supernova explosions and their interaction with the ambient interstellar medium; instabilities in that interaction are a commonly assumed source of most cosmic rays;
- radiative hydrodynamics; radiative collapse of jets; radiative shocks;
- tests of radiative transport codes; line transport in velocity gradients; photoionized plasmas;
- relativistically hot plasmas.

A promising existing example of the applicability of X-ray backlighting of systems with astrophysically important instabilities is illustrated in Figures 3 and 4. The experiments in this figure showed that two-dimensional single-mode perturbations did not become turbulent. However, images from experiments with three dimensional perturbations were consistent with turbulence onset. An ultimate goal is understanding whether hot dense plasmas undergo a transition to turbulence at high Reynolds numbers in the same way as ordinary fluids do. Understanding this quantitatively could have application to both supernovae and stockpile stewardship. [Note: At the present time, the numerical viscosity inherent in computer simulation codes with their finite spatial and time resolution is, typically, too high to support this application to very high Reynolds number flows.]

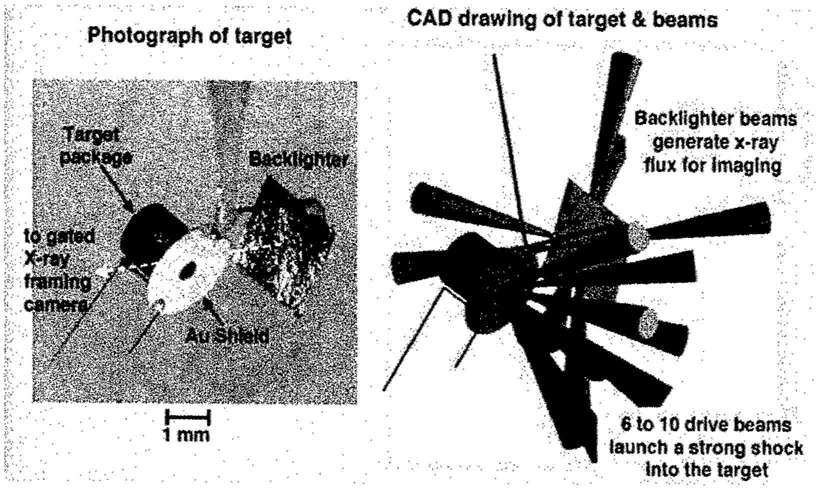

Figure 3: Experiments with the OMEGA laser to probe regimes of hydrodynamic instability in supernova remnants. (Figure provided by P. Drake [22].)

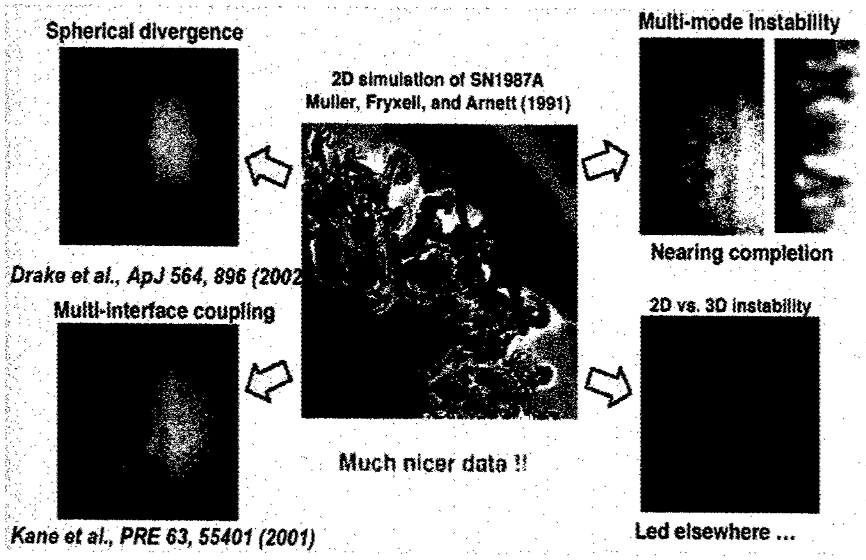

Figure 4: Experimental X-ray backlighter illumination of four different Rayleigh-Taylor instability regimes that may be relevant to supernovae. Also shown is a computer simulation that does not particularly resemble any of the experimental images. (The experiments were carried out at the OMEGA facility at LLE.) (Figure from P. Drake, [22].)

3.3.3 Development of tools which may have uses for the exploration of new regimes and phenomena.

This includes using petawatt lasers to create

- high intensity short-pulse bursts of 10s – 100s of keV, or even, MeV X-rays. We have already discussed the value of X-ray backlighting as a diagnostic both for NNSA and in astrophysical applications (Figure 4). MeV X-ray bursts may also be useful for nuclear physics;
- high energy (MeV-GeV) ion pulses. This application of the short duration super-strong electric field (TeV/cm) which the PW laser delivers when focussed to $\sim 10\mu$m could be the basis for a new kind of particle beam accelerator, or a new kind of injector into a conventional accelerator.

3.3.4 New Fundamental Physics in Superstrong Electric and Magnetic fields

As noted above, a focused 10^{22} W/cm^2 HEPW beam can give superstrong electric fields ($E > 10^{11} V/\text{cm}$) and magnetic fields (B $\sim 10^9$ G). Is it worthwhile to try to make measurements of electron (or nucleon) properties and dynamics in such fields? This is a regime in which conventional QED makes accurately calculable predictions. Aside from the great difficulties in measuring departures from these predictions in the super-strong E or B of a PW laser, is there room for surprises? It is hard to argue for a significant possibility that there might be because QED predictions have already been so accurately confirmed in the laboratory in the super-strong fields inside atoms. These can also greatly exceed those which could be achieved from a HEPW laser.

a) The average electric field over the orbit of an electron in a hydrogen-like atom with nuclear charge Z is

$$E \sim 10^9 Z^3 \text{ V/cm}.$$

The electron Lamb shift, an extremely accurate QED test, has been confirmed to extraordinary accuracy in low Z ions (and the H-atom).

b) Excellent confirmation also exists in μ mesonic atoms where

$$E \sim 10^{14} Z^3 \text{ V/cm}.$$

c) Some electrons in atoms move in super-strong magnetic fields from other electrons or from nuclear magnetic moments. In a He atom the average magnetic field on one of the electrons from the magnetic moment of its partner is about 10^6 G. A typical magnetic moment of an atomic nucleus is about 10^{-23} G-cm^3, corresponding to a surface field at a nucleus exceeding 10^{15} G. In the case of a μ-meson in the K-shell of a Z > 30 μ-mesonic atom, that kind of magnetic field exists over most of the meson wave function.

QED predictions have not only been well tested in fields up to and much greater than those potentially available from HEPW lasers, they have been confirmed to such extraordinary accuracy that, realistically, confirming QED again at petawatt laser field strengths would be interpreted as a test of the experiment rather than of QED.

The same criticism is appropriate for a suggested confirmation of "Unruh radiation," which describes a way in which QED predictions for a uniformly accelerated electron differ from its predictions for an unaccelerated one. It would be a very difficult experiment and would have to be done extraordinarily accurately. Again, the experimental results would almost certainly be considered a test of the experiment rather than of the QED predictions.

Figures 5 and 6 (provided to us by Todd Ditmire) illustrate and list many of the possible science applications that can be, in principle, addressed with < 500 J (mid-scale) and > 500 J (large-scale) HEPW lasers. Table 1 is more specific about the laser requirements.

3.4 Facility requirement for basic science

Among the wide variety of possible applications of PW lasers to non-NNSS science experiments, some may require laser pulse energies > 100 J, e.g., for X-ray backlighting of thick objects or for isochoric heating of a solid density target. Some may even need high energy ns-time-scale compression facilities. In our view, there is no need to have large-scale HEPW facilities at universities other than perhaps a single national user facility such as the arrangement now in place for ns laser experiments at LLE. It would be a major burden for the university program responsible for the facility (witness the LLE program size to effectively run the OMEGA facility for NNSA). Because of the added capability and range of experiments possible when implosion and HEPW capability are co-located, LLE would seem to be the most cost effective university for NNSA to place a HEPW laser national user facility for university users. Security issues at the weapons laboratories can be expected to be more of a problem than at LLE. University users who wish to do HEPW laser-based experiments at the highest energy levels at Z/ZR and eventually NIF should be encouraged to apply for time in collaboration with lab scientists, or if security arrangements permit, on an outside user basis.

Lower energy PW facilities are another matter. Petawatt or near-PW facilities with shorter pulses and energy < 50 J per pulse already exist or are being installed at the University of Michigan, the University of Texas and the University of Nevada, Reno. While major installations, these facilities should be manageable for university groups, especially in research center arrange-

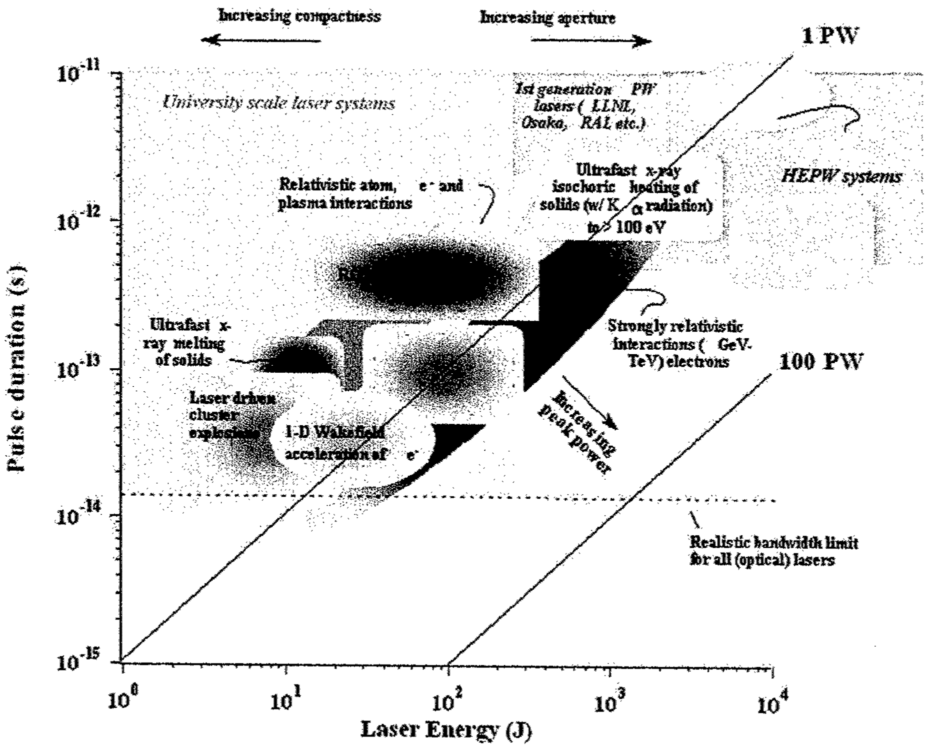

Figure 5: Laser parameter ranges required for various applications of Petawatt lasers. (Figure provided by T. Ditmire [23].)

Mid-scale Petawatt lasers **(i.e. University and Center based facilities** **Energy <∼ 500 J** **Pulse duration 20-500 fs**	**Large-Scale Petawatt lasers** **(i.e. HEPW lasers at implosion facilities)** **Energy > 1 kJ** **Pulse duration 500 fs - 1 ps**
• Relativistic interactions	• Ultra relativistic (∼ TeV) interactions
• Ultra relativistic (∼ TeV) interactions	• X-ray isochoric heating
• Direct optical isochoric heating	• Multi-MeV – GeV proton acceleration
• Wakefield acceleration	•Isochoric heating of shock compressed matter
• Cluster Explosions	• Radiative blast waves
• Neutron source/materials damage	• Pair plasma production
• Radiative blast waves	• Fast ignitor
• Time resolved x-ray absorption spectroscopy	• Time resolved x-ray absorption spectroscopy
• Ultra high B-field production	• Ultra high B-field production
• High energy, femtosecond coherent XUV prod.	
• Strong field coherent control - recollision physics	
• Fs x-ray production via inverse Compton scatt	

Figure 6: Laser energies required for various basic science applications of HEPW lasers. (From T. Ditmire [23].)

Table 1: Pulse width, energy and power requirements for basic science applications of Petawatt-class-lasers. (After T. Ditmire [23].)

Application	Laser Requirements
Relativistic interactions (ionization etc.)	High E-field (duration/energy not important) - $>$ TW
Ultra relativistic ($\sim$ TeV interactions)	High E-field (laser power only weakly important) - ≥ 1 PW
Direct optical isochoric heating	Very short pulse (≤ 100 fs to beat expansion)/high contrast
X-ray isochoric heating	High energy (due to low x-ray conversion)/ 1 ps pulse
Isochoric heating of shock compressed matter	Short pulse (≤ 1 ps)/high energy (≥ 1 kJ)
Wakefield acceleration	Short pulse (≤ 100 fs) to drive at reasonance/high power for 1D focusing
Cluster Explosion	Short pulse (≤ 100 fs) to beat cluster expansion
Neutron source/materials damage	Short pulse(≤ 100 fs) to drive D_2 clusters/high energy (≥ 100 J) to achieve adequate n yield
Multi-MeV - GeV proton accleration	< 1 ps pulse. > 100 TW to produce hot enough electrons to acc. p^+'s
Radiative blast waves	Medium to high energy (>10 J) to drive large diameter waves
Pair plasma production	High energy (> 1 kJ)/long pulse (> 1 ps)
Fast Ignition	Very high energy ($>>1$ kJ)/long pulse (≥ 10 ps)
Time resolved x-ray absorption spec.	High energy (> 100 J)/short pulse ($<$ 1ps, depending upon time scale of dynamics)
Ultra high B-field production (multi megagauss)	High peak power (> 100 TW) to drive hot electrons
High energy, femtosecond coherent XUV prod.	Short pulse (≤ 1 ps)/More energy yields more XUV photons (low conversion eff.)
Strong field coherent control - recollision physics	High E-field (laser power only weakly important) - ≥ 1 PW
Fs x-ray production via inverse Compton scatt.	> 100 TW/laser co-located with 10-100 MeV e^- linac

ments such as the NSF Center at the University of Michigan. Such facilities will serve as effective training grounds for graduate students, undergraduates and post doctoral staff in high energy density science skills and high power laser skills that will make them attractive as potential future staff scientists for the NNSA laboratories. New young university faculty will also be introduced to the NNSA program goals by being directly involved with such facilities. Figure 5 in particular shows that several interesting classes of experiments can be carried out with sub-picosecond PW pulses (with energies below 100 J). If NNSA supports such facilities at universities, it is certainly possible that those facilities will be able to attract additional funds for specific basic and applied science projects from other agencies, such as NSF and the Department of Energy's Office of Energy Sciences, further increasing the level of HEDP research in the U.S.

3.5 Department of Defense applications

We had limited exposure to potential Department of Defense (DoD) applications, largely because we do not expect the DoD to contribute financially to the U.S. HEPW laser research and development activities. We did learn about a possible application to ballistic missile defense (for decoy discrimination) that could benefit from HEPW development, and we understand that there may be other applications. Historically, however, in research and development situations such as this one, the DoD has been satisfied to monitor Department of Energy/Defense Programs – sponsored Technology development.

4 THE IMPORTANCE OF PW LASERS FOR NNSA MISSIONS

4.1 High Power Lasers and Stockpile Stewardship

NIF as originally designed, upon achieving ignition, was intended to create in the laboratory conditions of extremely high energy density that come closer to those occurring in an exploding nuclear weapon than can be achieved by any other means. This is illustrated in Figure 7. As we discussed in the report from which Figure 7 was drawn [25], as well as in earlier sections here, data from a thorough diagnosis of material properties and behavior under such conditions will contribute importantly to NNSA's

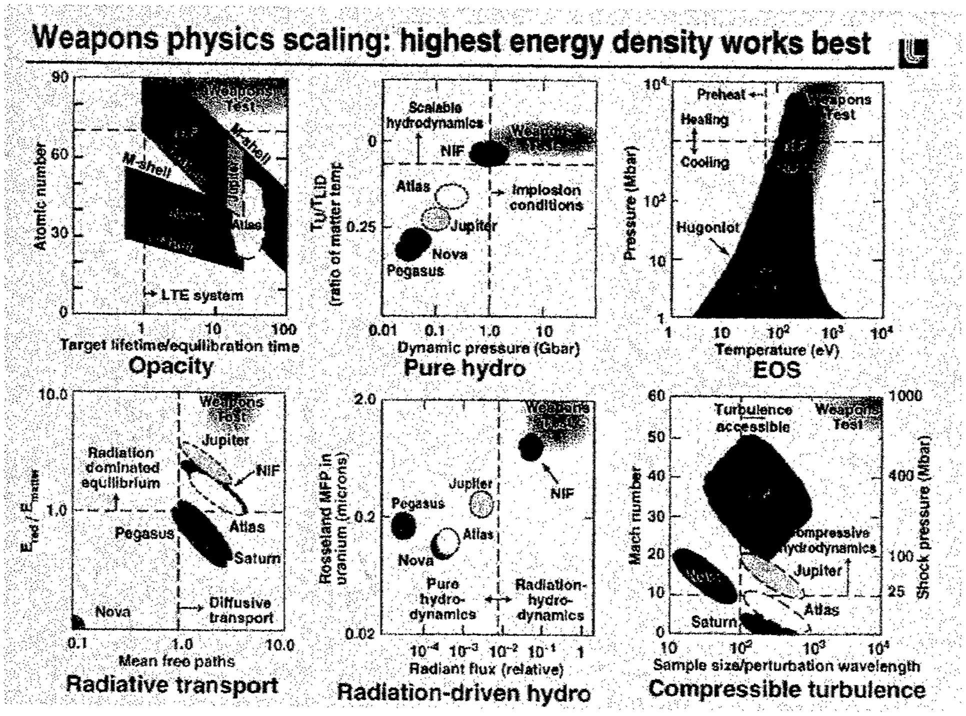

Figure 7: Comparison of parameter-space coverage by various facillities.

Stockpile Stewardship Program (SSP) by enabling weapons scientists to:

1. Validate newly developed, high-fidelity 3-D codes against experimental observations under conditions closely related to those of secondaries and radiation channels;
2. Improve our understanding of boost mixing, of the effect of mix at various interfaces on booster burn, and on the resulting yields and performance margins of primaries, as well as of the fundamental physics of hot, dense plasmas containing both hydrogen and a high-Z component;
3. Determine the equations-of-state (EOS) and opacities of nuclear weapon materials under conditions of interest.

These capabilities are important – particularly as the U.S. seeks to maintain the reliability and safety of our nuclear deterrent under the restraints of the existing moratorium on nuclear-yield-producing tests. Our confidence in the deterrent relies increasingly on diagnostic information concerning the behavior of aging weapons, on components remanufactured or refurbished by modern industrial practices, and on numerical simulations utilizing codes that have been validated against observations of materials under conditions experienced during an actual explosion.

The recent advances in petawatt laser technologies have opened significant, and potentially very important, new opportunities for enhancing our understanding of nuclear weapons by extending the capabilities at the NNSA implosion facilities. First of all, they could enable laboratory determination of the physical properties of the materials that constitute modern thermonuclear weapons over the full range of the phase space for pressure, temperature and density created during the operations of primaries and secondaries to final full yield operation. (See classified appendix [24]). This includes the intriguing possibility of in-depth heating of the highest Z materials, such as U and Pu, with penetrating protons. In addition, and of greatest value initially, is the potential for X-ray backlighting, including both short (< 1 ps) and relatively long (1-10ps) pulses. These backlighting beams could provide detailed diagnosis of states of matter and of variations in physical properties, such as densities of mixes of several constituents, under the extreme conditions achieved during explosions in weapon-relevant materials. Achieving such bright X-rays sources with energies up to the characteristic K-shell radiation from heavy metals (e.g., 94–98 keV for U) will be invaluable for radiographic imaging purposes in weapon physics experiments.

In spite of our enthusiasm for the potential capabilities of HEPW lasers, we cannot fully assess the critical need for all possible material science data over the full range of density, temperature and pressure phase space beyond the extensive reach already anticipated at NIF [see Figure 7]. Nor can we assert with confidence that the desired diagnostic capabilities will be achieved over the full range of energies envisioned for the X-ray backlighting beams. Nevertheless, the potential contributions of HEPW lasers to stockpile stewardship are so significant that the effort to develop these beams should be pursued in a program that is supported strongly. However, the program should be executed adaptively, flexibly, and with strong "red" team peer review so that facility construction does not proceed before the science base that justifies it is in hand.

We see no serious difficulties in building effective backlighting beams up to at least a few 10's of keV, or in carrying out materials science experiments that are important to the SSP. Regarding fast–ignition, the most recent neutron amplification results in experiments (see Figure 2) reported from Osaka, Japan [18] are impressive and encouraging, but there is still a long, high–risk research and development path ahead of achieving fast–ignition of ICF capsules. Work towards this goal can and should be pursued on existing ultra-high power lasers in the U.S. and abroad, as well as at the NIF, if and when appropriate, where it could have a major impact on the SSP. Assuming fast-ignition science points toward the value of experiments at the NIF, presumably after test-bed experiements at ZR and OMEGA, we believe that such work at the NIF should proceed only if and when it can be done without causing any delay in the NIF's achieving its present program goals.

It will be of particular importance to clarify what is both technically possible and important to accomplish with HEPW lasers added to compression facilities. Such clarification will require careful consideration, including costs and benefits, of other technical means of enhancing confidence in stockpile performance through increasing performance margins [26], and ensuring change discipline during weapons refurbishment and the replacement of limited lifetime components.

We will now consider in detail a possible reasonable approach for building up HEPW laser capability and research activities.

4.2 Phasing in HEPW Laser Capability

The NNSA weapon laboratories, LLNL, LANL and SNLA, are charged with assuring that the nuclear weapons in the stockpile will continue to be safe and reliable for the indefinite future in an era of no nuclear-weapon-testing. As a result, stockpile stewardship was enhanced by establishing a multifaceted science-based stockpile stewardship program, including the HEDP research program, into which HEPW laser research activities must fit. The goals of the HEDP program are [7]:

1. To execute HEDP experiments required to support the SSP;
2. To demonstrate ICF ignition on the National Ignition Facility;
3. To develop advanced concepts/alternate paths to high yield ICF;
4. To develop required advanced laser and pulsed power technologies;
5. To develop advanced sources for weapons effects testing; and

6. To attract, train and retain top-quality talent to the SSP.

Implicit in goals 1–3 is the validation of physics models included in many nuclear-weapon-related computer codes. Proposed HEPW laser research activities must be evaluated and prioritized with these goals in mind.

How valuable are these opportunities offered by HEPW lasers to NNSA missions and how high a priority should they have within the NNSA's high energy density physics program? We believe that important and unique research capability will be enabled by HEPW lasers, especially in conjunction with the laser and z-pinch implosion facilities at the LLE, at SNLA and, in a few years, at the NIF. However, we are not in position to determine the priority that these research opportunities should have among themselves or within the HEDP program. (We have been told that the budget for HEPW laser research and facility construction will have to come from the overall HEDP program budget.) At the time of our Summer Study, the NNSA-supported laboratories interested in extending their HEDP research capability by adding HEPW laser facilities had produced a "draft" high power laser national plan.[8] This draft plan was essentially a compilation of individual proposals rather than an integrated plan that listed the possible HEPW laser research activities in order of importance to NNSA's mission needs. There was no indication at all of the relative importance of any of the research activities by any of the participants (LLE, SNLA, LLNL and LANL) even within their individual research plans. Facility development was proposed in each plan without regard to facilities that might be built elsewhere and used collaboratively.

Thus, the first thing that should be done by the NNSA HEDP community is to develop an integrated HEPW Laser National Plan with prioritized facility development and prioritized research schedules laid out for different budget levels. The plan should document the connections between the proposed research and achieving an improved understanding of nuclear weapon physics. It should be based on proposals from all of the laboratories and should have well-founded costs and schedules for each proposed facility and research activity.

Some HEPW laser applications are relatively low cost and possible to implement in the near term with low risk, while others require substantial research and development to reduce risk before their substantial cost can be justified. Results from early research should determine later steps, including the rate of growth of the total activity. For example, there might be three steps in the growth of the program, starting with applications to X-ray backlighting.

4.2.1 X-ray backlighting

The improved backlighting capability offered by PW lasers at the > 40 J level (> 0.1 PW) is going to be implemented by SNLA on the Z/Beamlet facility within about a year [27]. This diagnostic capability, as modest as the laser energy may be in the present context, will be extremely valuable as a testbed for the development of practical K-shell backlighters with photon energies ≥ 10 keV for all of the laboratories. However, there will be an immediate value to the SSP of this advanced radiography capability. We can expect that weapon-physics experiments being carried out on Z using the Z/Beamlet laser X-ray backlighter by LANL scientists will be extended to configurations, sizes and materials that are more relevant to nuclear weapons than those that can be done now, particularly if the laser energy is pushed towards 1 kJ over the next 2–3 years by the use of larger gratings in the pulse compression step. The minimum laser energy necessary for good measurements in a variety of different experiments will be known within a year or two after the start of experiments. These results, together with other data that might be gathered on the sub-PW systems in the U.S. (JanUSP and Trident) and the PW systems elsewhere, such as at the facilities in the U.K. [11] and

Japan [28], can be used to guide the development of PW backlighter systems for the NIF without affecting that facility's ability to meet its baseline schedule. Improved X-ray backlighting capability is expected to have great value as a diagnostic for ICF implosions as well as for the weapons physics experiments mentioned above. Therefore we think that the LLE should look for a cost-effective option that would bring a PW X-ray backlighter diagnostic capability to the OMEGA chamber as soon as possible, whether or not the full major upgrade proposed [29] for the OMEGA Laser facility (2 HEPW lasers and 2 high energy beam nsec beams) is undertaken as part of the NNSA HEPW program.

HEPW laser-based X-ray backlighter diagnostic systems are too expensive to think of in the same way as X-ray streak cameras. In addition, their capabilities are still to be determined in practice. However, much like a streak camera, HEPW laser backlighting is likely to become a workhorse diagnostic tool for optimizing progress in the ICF program, for understanding special weapon physics experimental configurations, and for diagnosing materials science experiments, as targets in all of these important areas of research become thicker (more gm/cm^2 and/or higher Z).

4.2.2 Intermediate level experiments (and fast-ignition science)

With gold gratings already capable of enabling few-hundred joule PW lasers, and more capable multilayer dielectric gratings not far behind, $\leq$1 kJ PW lasers could be producing relatively large-area materials data at nuclear-weapon-relevant pressures and densities within perhaps as few as 3 years at SNLA. HEPW lasers at this energy may also enable X-ray backlighting with K-shell radiation in the many tens of keV energy range, permitting even thicker, higher Z targets to be used in experiments. This level of HEPW laser backlighting capability should be experimentally tested expeditiously, as it will determine the backlighter design scaling needed for the NIF. It is also necessary to determine experimentally if large area, uniform proton beams can be produced for isochoric heating to high temperature.

With ~ 1 kJ in a PW beam colocated with an implosion facility (OMEGA, Z/ZR and eventually the NIF), it is expected to be possible to carry out studies of the properties of materials used in nuclear weapons in regions of density, temperature and pressure space that cannot be accessed in any other way, including by the NIF alone, as we discussed in Section 3.2. However, just because a particular set of material conditions <u>can</u> be achieved with HEPW lasers, and some particular property <u>can</u> be measured, for example with a HEPW laser backlighter, does not mean that particular experiment is the best use of limited resources, including both manpower and budget authority. It will be especially important to prioritize these materials properties experiments, taking into account the value of specific data to understanding nuclear weapons, the equipment investment required for it, and the target fabrication and diagnostic difficulties (to be discussed in Section 4.3). Until specific experiments are effectively connected to specific important physics issues for understanding nuclear weapons, <u>and</u> priorities are established for such experiments both among themselves and within the overall HEDP program, we would not support major investment in HEPW facilities for these experiments.

With 2–5 kJ in each of two HEPW laser beams, it should be possible to learn a great deal about whether fast-ignition could ease the laser requirements for achieving ignition and gain at the NIF. Fast-ignition science experiments can be carried out in a direct-drive configuration at OMEGA and in indirect-drive configurations on the Z-machine, thereby helping to determine the requirements and optimal configurations for fast-ignition capability on the NIF. Many scientific choices can be evaluated, such as whether the energy can be delivered to the compressed fuel most effectively by electrons or protons (see Section 3.1.1), whether physical access to the compressed fuel (with conical structures) is better than hole-boring with a ~ 100 ps laser, etc. Such choices would be difficult, time-consuming and expensive to have to evaluate for the first time on the NIF. Also, we are concerned that such activities, if focussed at the NIF, would deflect the NIF from its primary initial mission of delivering 96 and then 192 beams to a hohlraum for indirect-drive ICF experiments on schedule and without further cost escalation.

4.2.3 Fast-ignition of compressed fusion fuel

If fast-ignition continues to be an attractive alternative path to hot-spot ignition for maximizing the fusion gain from DT fuel-capsule implosions after experiments at SNLA and/or LLE and/or international sites, the NNSA will surely want to have not only PW backlighters, but also PW fast-ignition beams in the long-range plans for the NIF. To retain this as an option, the NIF project team must make sure that the necessary space in the NIF beam-director and target-chamber rooms to implement fast-ignition remains available. However, until the testbed data is available to assist in developing design requirements and evaluating the possibility of achieving fast-ignition in detail, we believe that investment in PW hardware and human resources for fast-ignition experiments at the NIF is not warranted.

4.2.4 The connection to understanding nuclear weapons

We believe that the near and midterm opportunities for HEPW lasers discussed in Sections 4.2.1 and 4.2.2, have substantial potential value to the NNSA stockpile stewardship mission and we see them as relatively low-to-moderate risk. Over a 5–10 year time frame, some of these activities could contribute significantly to validation of the physical models of materials properties in integral ASCI codes that will be used in the weapon certification process. However, we also believe that the connection between the data from the many proposed experiments, and the accuracy with which parameters should be measured in some experiments, and achieving a better understanding of nuclear weapons needs to be evaluated more thoroughly. We consider some aspects of this issue for materials science studies in the next subsection.

4.3 The Uses of HEPW Lasers for Equation of State and Strength of Materials Studies

4.3.1 Initial remarks

Traditional methods for measuring a high-pressure EOS and constitutive material strength parameters, such as a compression modulus, include static devices such as diamond anvils, and shock devices such as explosively-driven flyer plates or gas guns. These are capable of pressures of a few Mbar at most (although the Russians claim a record of 25 Mbar in Ta for a spherically-imploded high-explosive shock [30]).

For stockpile stewardship purposes, the EOS and strength parameters of materials such as Pu are needed at pressures of 30 Mbar and above, with the lower pressures relevant to pre-boost primary performance and pressures in the multi-Gbar range needed to simulate explosion-time primary as well as secondary performance. It was argued by a number of our briefers that a HEPW laser adjunct for facilities such as OMEGA, Z/ZR, and the NIF will play an important role in yielding these EOS and strength parameters. A number of different techniques have been proposed, including classic shock techniques for determining the EOS on a Hugoniot, X-ray absorption fine structure (EXAFS) for determining density and compressibility, isochoric and isentropic (off-Hugoniot) experiments, and material-strength studies via Rayleigh-Taylor instabilities in solids.

The accuracy claimed to be required for some of these EOS/strength studies is quite high compared to the accuracy of existing studies, which at pressures greater than a few Mbar, is perhaps tens of percent.

4.3.2 Some general conclusions on EOS/strength studies

1. Except for isochoric heating of high density materials, HEPW lasers are not essential for producing the experimental conditions needed to study EOS and material strength for pressures less than 30 Mbar; these conditions can be produced by lasers now in existence or being built, such as OMEGA and the NIF, or by the Z/ZR pulsed power facility.

2. For isochoric heating of solid density or compressed matter to high temperature, short laser pulse duration (≤ 10 ps) is important to minimize hydrodynamic expansion during the experiment itself. Total energies of several hundred J or possibly several kJ are needed to heat samples (which may have to be fairly large) to the necessary temperatures. This implies that the highest energy individual PW lasers will be needed for isochoric heating experiments.

3. Stated accuracy requirements for EOS and strength are very demanding, and go well beyond the rather poor state of present-day knowledge of these matters at pressures greater than 10 Mbar. These requirements demand correspondingly great accuracy in fabrication of targets and experimental facilities. HEPW lasers will be helpful for diagnostic purposes because high accuracy demands rather large targets (to avoid curvature and other effects), and the high energy of X-rays generated by HEPW laser backlighters may be essential for penetration. It will still be difficult to achieve position or radiographic resolution better than perhaps 10 μm or so because high resolution will require use of a pinhole in front of the laser focal spot. The smaller this pinhole, the fewer X-rays will pass through, possibly requiring HEPW laser pulses

of more than a few kJ to achieve the required source brightness, an expensive proposition.

4. HEPW lasers are essential for using EXAFS on materials such as Pu, because only they can produce the pulses of K-shell X-rays needed for this method. But EXAFS may not be the method of choice. EXAFS yields the mean distance between neighboring atoms through oscillations in the X-ray cross-sections above K edges, but going from such data to densities is not trivial.
5. Bragg/Laue diffraction of X-rays can in principle yield interatomic distances and densities, but only if there is actually a lattice in the material under study. However, the lattice structure will be destroyed at pressures of many tens of Mbar, and so X-ray diffraction is not useful in the range of pressures so far unexplored by other experimental techniques.
6. One proposal for measuring high-pressure material strength is to follow the evolution of Rayleigh-Taylor unstable modes, for which the growth rate as a function of wavelength is affected by material strength. These experiments would demand extraordinary spatial accuracies that are beyond the current state of the art. Furthermore, in general, strength may well depend on strain and/or heating rates as well as the pressure.
7. While NIF will certainly be the premier facility for weapons physics experiments of all kinds when it is operating, there are good reasons to develop HEPW laser facilities at OMEGA and Z/ZR. OMEGA can certainly develop high pressures with the existing lasers there. The Z/ZR facility at Sandia can use larger targets than other facilities, and ZR will be capable of achieving pressures driven by magnetic fields of around 10 to a few 10's of Mbar.

As we are particularly concerned about the possibility of necessary experimental accuracy being overstated, we offer the following recommendations on this topic:

1. Designs and schedules for HEPW laser targets and backlighters should be prepared as part of the Petawatt National Plan for EOS/strength experiments at pressures of 30 Mbar and above, to evaluate at an early time the possibilities for reaching stated accuracy requirements.
2. If problems meeting the accuracy requirements arise, the weapons labs should revisit the basis for the accuracy requirements. Given the present state of knowledge of EOS and strength-of-materials at pressures greater than 10 Mbar, even relaxed accuracy requirements, if they can be met, will lead to a very substantial increase in our knowledge.

4.3.3 Further remarks on accuracy

A criterion of 1% for accuracy in EOS measurements at the NIF is given in Ref. [21]. This is quite demanding because of the correlation between the accuracy of an EOS determination and the accuracy of spatial positions of shock fronts, etc. The accuracy of measurements with HEPW laser backlighter X-rays is probably going to be in the range of 10 to 20 μm. Consider, for example, the problem of measuring a shock or material velocity of the order of 10^7 cm/s, relevant to the pressure range above tens of Mbar, with a goal of measuring this to 1% or 1 km/sec. If the accuracy of spatial measurements is 10 μm, then targets should be about 1 mm thick. For a target this size, the experiment lasts about 10^{-8} sec, and 1% of this, or 10^{-10} sec, is large compared to the time duration of the HEPW laser backlighter beams, which is about 1 ps. So there is no problem with getting the needed accuracy in time. However, 1% accuracy in space will require (comparatively) large targets and hence large HEPW laser energy and power.

The accuracy problem is not settled simply by doing accurate measurements of space and time in shock experiments. Shock experiments do not directly measure the temperature. Instead they measure (through velocity measurements) the pressure, density, and energy density of shocked samples. Generally it is difficult to make accurate comparisons of data at an unknown temperature with EOS models, since these often depend explicitly on temperature. And present-day models, when compared at a given pressure in the range of interest to us, often differ by tens of percent in their predictions of temperature and density [21].

4.4 Measurements with EXAFS

The fundamental equation of measurements using X-ray Absorption Fine Structure (EXAFS) [31] says that the scattering amplitude as a function of wavenumber k for X-rays in a range of energies near and above the K-edge of a material has a sinusoidal factor $\sin(2kr_i + \delta)$, where r_i is the distance between neighboring atoms. This factor comes from the interference of the wave function of an ejected photoelectron from one atom with the backscattered photoelectron wave function from a neighboring atom. This factor yields oscillations in the X-ray spectrum just above the K-edge. Naturally, the oscillations are cleanest when the X-rays do not have too broad a spread in energy (perhaps a few 10s of eV) and when the material is crystalline.

The need for a HEPW laser for measurements on materials such as Pu comes from the very high energy of the K-edge, about 100 keV. The HEPW laser can potentially produce a "point" source of such X-rays by focusing to a spot with $I\lambda^2$ exceeding 10^{18}W-μm^2/cm^2 to reach the necessary electron energies to effectively produce the necessary high energy photons. There is no question that a HEPW laser is needed to make the diagnostic X-rays for EXAFS, but the question is whether EXAFS can yield the accuracy said to be required for EOS/strength measurements. The problem is that at high pressures the sample will no longer be crystalline, and there will be a range of values of the nearest-neighbor distances r_i. In such circumstances, retrieving the density from the data is not trivial. It may be impossible to resolve the spread of distances in a meaningful way. Even when this resolution is possible, elaborate calculations are generally needed to extract meaningful physics from the data. A determination of temperature using EXAFS may be less challenging, however.

4.5 Establishing the Linkage Between HEPW-Laser Research and Stockpile Stewardship

On several occasions and in various forms in this report, we have called for explicit linkage between the proposed HEPW laser research and NNSA's stockpile stewardship missions needs. This linkage can potentially be made through the Quantitative Margins and Uncertainties (QMU) approach now being implemented for certification of weapons (and weapon components). For example, adequate performance margin for the primary driving the secondary stage of each nuclear weapon is recognized as one of the key criteria that must be monitored for systems with aging and/or refurbished components.

The ability to evaluate such performance margins depends on having a level of understanding that can be specified in terms of quantitative uncertainties within which specific material properties and processes must be known (see Classified Appendix [24]). The enhanced capabilities offered by HEPW lasers, both to achieve states of interest and to better diagnose material properties at weapon-relevant conditions, must then be quantitatively matched against the uncertainties mandated by QMU. To the degree that HEPW-assisted research can ensure measurements at states of interest and within the required uncertainties, the case is greatly strengthened for NNSA to vigorously pursue the deployment of the required capabilities (including lasers, associated instrumentation and computational modeling).

To be sure, there is much to be gained even with crude measurements

– i.e., with uncertainties larger than those derived from QMU – if those measurements are being made for the first time on important properties in a heretofore inaccessible but relevant regime. In this sense, we encourage a staged analysis, whereby the value of measurements having relatively low (but specified) resolution or reliability is evaluated at the same time as is the feasibility of (or required developments for) making measurements within the QMU-derived uncertainty limits.

5 VALUE OF PETAWATT LASER RESEARCH FOR RECRUITMENT AND RETENTION

5.1 University-Laboratory Connections in General

The recent blossoming of interest in using HEPW lasers for high energy density research is already a good example of the value of scientific interactions between the academic community and the U.S. National Laboratories. Not only are such interactions mutually beneficial, they are important in sustaining U.S. excellence in science and technology, which is the ultimate basis of U.S. economic well-being and security. The university community, the national laboratories, and industry are the three legs of a triumvirate that constitutes the U.S. science and technology enterprise. In the present research and development culture, no one of the three legs can thrive in isolation—all three are essential.

The primary rationale for a large investment in a national HEPW laser program is the predicted significant role for such lasers in HEDP research at the NNSA laboratories, as we have already discussed. In the near term this will be mainly a diagnostic role and for the heating of solid density matter to high temperature. In the long term there is also the potential use of HEPW lasers for fast ignition in ICF studies. The latter may facilitate ICF for future electric power generation. Although that is not in the NNSA's purview, it is the reason why many scientists originally joined the ICF program.

Applications of high power lasers to basic research in physics and astrophysics provide another rationale for a national HEPW laser program, but the connection has a different character than for the main rationale above. Direct involvement in the NNSA high energy density basic physics program by university faculty, postdoctoral fellows, and graduate students using PW lasers will primarily occur at lasers located in university facilities. Nevertheless, academic research will play a very important role in the future development and vitality of the HEPW laser program in its applications to stockpile stewardship.

Possible areas of academic HEDP research with TW-PW lasers range from those that are of interest to the NNSA, such as studies of strong shocks in solids, to such general science subjects as collective acceleration via laser plasma interaction, as was discussed in Chapter 3. Areas such as condensed matter physics, astrophysics, and ICF science and technology will clearly benefit directly from the data and knowledge gained in HEDP studies at universities. However, even more important to the NNSA is that HEDP research at universities is the main mechanism for ensuring a flow of new scientists and engineers who have the ability, training, and enthusiasm necessary for sustaining an effective science-based stockpile stewardship program. The same flow is necessary to ensure there are qualified scientists and engineers in industry for eventual commercial applications of HEDP knowledge and technology.

U.S. National Laboratories already have research activities in several fields with very successful associations with research programs at universities. However, the best known examples are not directly applicable to a national HEPW laser program. The three best known are the following.

1) The major particle accelerators used for High Energy Physics research are located at national laboratories here and abroad. Although scientists employed at these national facilities are typically well represented among the accelerator users, the majority of users are associated with multi-university (and usually multi-national) groups consisting of university faculty members together with their postdoctoral research associates and graduate students. The number of faculty members from a given research university can vary from one to many. The user groups

are strongly represented on, and dominate the committees that decide on accelerator experiments and time allotments. This division of responsibility and activity between the inside and outside users works very effectively.

2) The situation in Nuclear and Intermediate Energy Physics in the U.S. (and abroad) is rapidly evolving into the high-energy-physics model of a small number of facilities at national laboratories and external, multi-university user groups that have strong influence over the experimental programs and future directions of the facilities.

3) The major synchrotron light sources today are also at national laboratory sites for the most part. Diverse outside user groups (each with a much smaller number of collaborators than in groups working on accelerator-based experiments) are mainly condensed matter groups at universities and from industry (e.g., Lucent and IBM). This outside user-community is the main reason for the construction of these sources and they are run in a manner designed to serve that community. As for the first two examples, national synchrotron facilities available for use by researchers based at universities (and industry) have been essential for keeping the U.S. at the forefront of science.

The above three successful examples are characterized by (1) a large, very strong community of faculty, students, and postdoctoral researchers in the field from many universities; (2) a unique facility at a national laboratory; (3) greater participation from the university users than from the in-house laboratory users.

None of the above three characteristics are present in the proposed national HEPW laser program. To a certain degree the existing OMEGA-laser-based National Laser Users Facility (NLUF) at the University of Rochester Laboratory for Laser Energetics operates in the mode of a national synchrotron light source, but the outside user community (see Table 2) is much smaller than the NNSA (inside) user community. HEPW lasers built at national laboratories are likely to be even less responsive to the wishes of outside users.

Table 2: University Users of the OMEGA Facility within the National Laser User Facility (NLUF) program, and former UR/LLE students and NLUF participants presently on NNSA laboratory staff. The NNSA-funded ICF research program at the Naval Research Laboratory (NRL) is also included.

NLUF Participation
20 U.S. Universities (22 recent Ph.D. student participants; ~ faculty
23 Universities total

Former LLE Graduate Students now in DOE/NNSA Laboratories
LLE 10
LLNL 2
LANL 3
NRL 3

NLUF Graduate and Post Graduate Students from Participating Universities now at DOE/NNSA laboratories
LANL 3
LLNL 6

The above differences give rise to the question of how best to maximize the number and quality of the young scientists who may wish to pursue a career in high energy density physics and/or HEPW laser science.

5.2 Recruitment and Retention for the HEDP Program

University graduate programs provide a venue for training new scientists and engineers in the specialized knowledge and skills required for state-of-the-art research in HEDP. The self-directed nature of university research allows for new ideas and surprises to be pursued without regard for the program relevance that is an important measure in the national laboratory community (or the immediate commercial applications that drive decisions in industry).

Thus, university programs can be cost-effective for both training the future personnel of the national laboratories and helping to develop the full potential of HEPW laser technology to HEDP research, both for the NNSA and for science in general.

Interactions between scientists at the national laboratories engaged in HEDP programs and similarly engaged university scientists provide students with the opportunity to became familiar with the culture of national laboratories and career opportunities at these laboratories. In spite of all the advances in communication, personal experience remains a dominant factor in human decisions. The same interactions are also important to scientists at the national laboratories because they allow the scientists to remain in contact with the larger scientific community, to receive recognition from their peers, and to remain up to date in areas not immediately related to their current activities. This is especially important as a retention issue for scientists whose everyday work takes place in classified areas that allow them little or no opportunity to publish in the open literature.

Most postdoctoral researchers choose to work in a subfield closely related to that of their thesis research. Very few of the graduates now going into HEDP-associated careers at the NNSA laboratories come from the relatively small group of students who do their graduate work at one of the universities with an on-campus HEDP facility or with faculty users of such a facility. A student will typically need to make the decision while still an undergraduate to join one of the small number of university HEDP programs in order to apply to one of them, and later go into the HEDP field as a graduate student. Transfer from a graduate program at one university to one in a different field at another university that has an HEDP facility is not simple or common – typically transfer will add a year or two to degree completion. At most universities and colleges, undergraduates (and their advisors) have little knowledge of the emerging field of HEDP studies, and even less of HEPW laser science.

The NNSA should recognize the constraints to the supply of graduate students as a problem with possibly attractive solutions. Summer undergraduate research programs at university-based PW laser facilities aimed at outside students who have completed their junior year in a technical discipline would contribute to expanding knowledge of the field of HEPW laser research among students interested in a research career just when they are thinking about graduate school choices. All of HEDP research centers funded out of NNSA's Stewardship Sciences Academic Alliances Program should be encouraged to have such summer undergraduate research programs. Those centers should also sponsor talks by staff members to undergraduate physics and engineering societies, print booklets for physics majors, etc., as a way to increase what might otherwise be too limited a flow of undergraduates into university graduate HEDP laser research programs.

Another mechanism for broadening faculty/student involvement in HEDP and HEPW laser based research would be through NNSA support for university faculty who want to spend a sabbatical leave at a HEPW laser facility. Accompanying graduate students should be welcomed and even courted. In some cases, individual graduate students could be accepted for interships at national laboratories, even if those students are not part of a user group from their home university. Co-dissertation advisors for PhD candidates within the same department or even different departments of the same university are common in the U.S. system. Perhaps co-dissertation advisors could be expanded to involve two universities if the NNSA would provide support for such arrangements.

5.3 Closing Comment

Petawatt laser development also contributes to supporting important decisions, reaching back to 1994–95, to include science as an integral part of the U.S. Science-Based Stockpile Stewardship Program, as it was called at that time. In the years since, subcritical experiments have improved equation-of-state models for nuclear materials greatly; the availability of new generations of supercomputers has allowed full three-dimensional simulations; codes have advanced to take advantage of the new computing power; and many above-ground experiments have provided valuable data for validating codes. Petawatt lasers were not part of the science based stockpile stewardship vision in 1994–95, but they came forth in the mid-to-late 90's from university research programs in basic science in the 80's and early 90's. Today they show great potential for advancing U.S. expertise in the science and technology of nuclear weapons. This is likely to be an on-going pattern.

6 FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

6.1 NNSA Science with Petawatt Lasers and the Petawatt Laser National Plan

Our principal finding is that there are likely to be substantial gains in nuclear-weapon-related science enabled by HEPW laser capabilities, especially in conjunction with OMEGA, Z/ZR and eventually the NIF. Weapon physics experiments will be possible in more realistic configurations and with weapon-relevant materials by taking advantage of the higher photon energy X-ray backlighting diagnostic capability of HEPW lasers. Materials science experiments will be possible over a wider range of density, temperature and pressure space by taking advantage of the isochoric heating capabilities of HEPW lasers over relatively large area targets. The higher energy and brightness X-ray backlighting diagnostic capability will also benefit those experiments, as well as ICF experiments that achieve higher densities and temperatures at implosion facilities (Z/ZR, OMEGA and the NIF) in the next few years. Finally, perhaps the application of HEPW lasers to the fast-ignition concept will prove viable and enable higher yield ICF to be obtained for a given (laser, z-pinch or ion beam) driver energy and symmetry.

While all of the above applications of HEPW lasers to HEDP research are potentially valuable to the NNSA, the mission need within the SSP, and the importance in the HEDP research program of most of these research activities is yet to be clearly established and documented. More specifically, the science case is yet to be made linking the wide range of proposed materials science measurements, and the accuracy said to be needed for those measurements, to SSP goals and needs.

Given the potential value of petawatt lasers to the SSP, and the fact that funding of HEPW lasers evidently must come from NNSA's existing HEDP program budget, it was certainly appropriate for the NNSA to ask its laboratories to develop a research and facility development program plan. However, the "first draft" Petawatt Laser National Plan provides little more than a compilation of wish lists of the four NNSA-supported major laboratories (LANL, LLE, LLNL and SNLA) interested in developing large-scale HEPW laser capability. It appears that there has been little collaboration in preparation of individual laboratory research and facility plans, no attempt to integrate capabilities and potential contributions of the various laboratories, and no attempt to lay out facility development steps and research activities for different budget levels. Finally, there has been little or no effort to prioritize proposed HEPW laser research activities and facility development steps among themselves or within the HEDP research program within which they fit.

The linkage between formally established SSP mission needs and the proposed HEPW laser research activities, and priority setting for those activities, might best be done making use of a method like the QMU approach now being implemented for weapon certification. The value to the SSP of some of the specific enhanced capabilities offered by HEPW lasers, such as to produce unique material conditions in the laboratory or to help diagnose a weapon physics experiment, can be determined by the impact each capability will have on evaluating, for example, the performance margin of the primary in a particular weapon. This process, or one like it, can be used to determine accuracy requirements for a specific set of EOS measurements, the importance of one set of material measurements versus another, the importance of a 5 kJ PW laser for backlighting weapon physics experiments at SNLA versus for material properties experiments at the NIF, the importance of diverting resources to HEPW laser facilities from some other activity within the HEDP program, etc., etc. The weapon laboratories should work together with NNSA to implement this process as part of formulating the Petawatt Laser National Plan.

We believe that unique research relevant to NNSA's missions will be made possible by HEPW laser facilities in conjunction with facilities capable of imploding/compressing materials to high density and heating them to high temperatures. We cannot assume that HEPW laser facilities in the rest of the world will enable us to collect that information, although Japanese and European PW facilities can materially help us determine how important HEPW laser capability might be to the NNSA. Therefore, we believe that it is important for the HEDP community to move forward expeditiously to determine the importance of HEPW laser capability to NNSA missions and how rapidly it should be developed subject to the budget constraints of the HEDP program.

6.1.1 Answers to some "Key Questions."

We now respond to the "key questions" posed to JASON in addition to the Charter by Dr. Christopher Keane in his July 3, 2002, briefing. Completion of the Petawatt Laser National Plan with the linkages of the science activities and facility development steps to the goals of stockpile stewardship is really required before some of these questions can be properly addressed. However, partial answers are given here for all of them.

1. Are HEPW capabilities required for the success of the high-energy-density physics program? We believe the answer is highly likely to be yes for some of the goals of the HEDP program. For example, carrying out more realistic weapon-physics experiments at implosion facilities than can be done now will require advanced HEPW laser-based X-ray backlighting, as will stop-motion X-ray backlighting in ICF implosions. Absent HEPW laser-based backlighting, some other equivalent diagnostic method will have to be invented and developed. HEPW lasers also open up unexplored territory in

EOS, material strength and ICF research that cannot be investigated in any simple way otherwise, but the priority of those experiments in the HEDP program is yet to be determined.

2. What are appropriate near- and long-term goals for a HEPW program? The immediate goal should be timely construction of an integrated, prioritized HEPW Laser National Plan that makes the scientific case for future short- and long-term goals. One possible long-term objective is to re-establish US leadership in HEPW laser technology and applicatons, with a primary goal of improving our knowledge of nuclear weapons physics and an important secondary goal of adding real value to the study of broader areas of high-energy-density physics.

3. Should it be a goal to maximize technical return per dollar and how is this to be done? Clearly, one wants to maximize the technical return per dollar, but this must be broadly defined to include, for example, training future HEDP and PW laser scientists and engineers. We believe that insistence on an integrated community HEPW laser research plan, rather than a set of competing proposals, will contribute to this goal while assuring program breadth, retaining complementary capabilities, and fostering some healthy scientific competition as well as collaborations between laboratories. Making use of at least the spirit of the QMU approach to determine HEPW laser research and facility development priorities will help assure that available funding maximally benefits the SSP.

4. Is construction of major new facilities called for, or will more modest near-term facilities serve? It is not yet quantitatively clear just how much energy per pulse is needed for HEPW lasers in support of particular NNSA missions. Facility size and cost increase rapidly with the required pulse energy (e.g., for energy storage and for larger gratings for pulse compression). We anticipate that HEPW lasers with pulse energy up to perhaps 1kJ per beam are likely to be considered high priority facilities in the Petawatt National Plan for a combination of reasons, and the budget may permit them to be considered modest facilities. The case must be carefully made for many HEPW lasers at one location, or even one such laser at, say, 5 kJ or more, since these are going to be sufficiently expensive to be considered major facilities.

5. Is a NNSA-funded major academic user facility advisable? We recommend such a facility. It could be based at any of the NNSA-supported laboratories with appropriate security procedures in place. However, it may be most appropriate for the NLUF at LLE to expand its user facility mandate if the Petawatt National Plan calls for HEPW laser capability there. Not only will this facility be critical in broad HEDP studies, as advocated above, but it will also furnish scientific connections that are likely to be invaluable to SSP scientists and technologists.

To proceed beyond these initial answers really requires the Petawatt National Plan and the linkages discussed above since the short- and long-term goals for the HEPW laser program must be a major result of the plan's preparation. The step-by-step, flexible approach we advocate (and formally recommend below) must be a part of that plan because the intermediate and long term applications tend to require more laser energy (i.e., are more costly) and/or are higher risk. As lessons are learned early in the program, cost-effective decisions can be made concerning the appropriate next steps. Thus, we believe that early HEPW laser program activities should include:

1. Numerical simulations and experiments that carefully address just how much beam energy is necessary to accomplish a given task (e.g., to measure an EOS to a satisfactory level of accuracy to achieve stockpile stewardship goals); and
2. Risk-reducing science experiments for specific applications before committing to high cost facilities, such as multiple fast-ignition beams for the NIF. Those HEPW laser activities identified as high priority in the

HEDP program and/or that are of importance to NNSA's stockpile stewardship mission through the QMU process can be addressed most cost-effectively in this way.

The question regarding the need for major facilities at the national laboratories also can be answered as part of the Petawatt Laser National Plan and the step-by-step procedure just discussed. For example, if it is determined that 2-4 kJ of PW laser energy is needed for a high priority set of EOS experiments, then it will be necessary to add that major capability to the appropriate facility. If fast-ignition direct-drive ICF science experiments are important in the HEDP program, then the necessary HEPW laser facilities should be built at the LLE. Any decision to go ahead with a major academic HEPW laser user facility will require the determination that it is important to the NNSA (and to U.S. science in general) for academic scientists to continue to have access to state-of-the-art HEDP facilities as they do now. We believe that HEPW laser facilities will be most useful in conjunction with facilities capable of implosion and/or matter compression using conventional ns-time-scale drivers. That is because of the wide range of potentially important experiments that can be done with the two drivers together in addition to experiments that can be done with the HEPW lasers alone. Therefore, we believe that a very strong case should have to be made to justify the cost of HEPW laser facilities other than at LLE, Z/ZR and the NIF. With that in mind, we would advocate that the best university location for a national user facility with >1 kJ HEPW laser capability is the LLE, and that some small fraction, perhaps 10%, of the highest energy HEPW laser pulses available at the Z/ZR facility and, eventually, at the NIF, be available to outside users. We do, however, advocate lower energy PW facilities at universities, as we discussed in Sections 3.3 and 5, and summarize next.

6.2 University Science Programs

The interaction of a petawatt laser with ordinary materials creates, for a fleeting moment, extremely high energy density regions of coupled electromagnetic radiation and highly ionized matter. Such conditions are normally not accessible in the laboratory but do occur in some astrophysical situations and in nuclear weapon explosions. The associated HEDP is important from a fundamental science perspective and has numerous potential applications, as we have discussed in Sections 3 and 5. The full potential of HEPW laser technology to contribute to HEDP basic science and applications is yet to be determined. Helping to "draw out" this full potential of HEPW lasers for the benefit of NNSA as well as for science in general is a major contribution that university programs and university laboratory connections can make. But there are others.

Involvement of university faculty and graduate students in forefront research involving ultra-high power lasers (whether TW or PW) will assure a continuing supply of talented young scientists from which the NNSA laboratories should be able to recruit future SSP staff. Collaborative research programs between the labs and universities will enhance the coupling of new ideas from universities to labs, bring university scientists directly into (unclassified) experiments of importance to NNSA, and improve the ability of the laboratories to recruit the best graduate students. Even if they are not involved in direct collaborations, the recognition by laboratory scientists that they are involved in forefront research that is exciting to scientists outside of their national laboratory community, and not only of interest to the nuclear weapons community, should encourage NNSA's best scientists to remain in the national laboratories.

It is important to reiterate that the highest energy petawatt lasers probably do not need to be spread around the country to have exciting university research programs. Many of the most interesting basic and applied science experiments that require PW lasers do not need the large facility investment, the large operating budgets and the large commitments of resources by a university that would go with $\sim$ 1 kJ facilities. Those academic experiments that really do require HEPW lasers can make use of facilities at the national laboratories in collaboration with laboratory scientists, or at the LLE, where an HEPW laser facility could be added to the already existing large-scale facilities available through the National Laser User Facility.

6.3 Summary of Findings and Conclusions

6.3.1 The value of HEPW lasers to SSP science

These lasers are very promising in several fields of science that are important to the NNSA, and are well worth developing in the United States at least to some extent. HEPW lasers can be used for advanced radiography, for studying strongly coupled plasmas, for generating intense short pulses of relativistic electrons and energetic ions, for generating high temperature, high density states of matter by isochoric heating (using the short electron or ion beam pulses) for materials science experiments involving states of matter that cannot be achieved any other way, possibly for fast-ignition of highly compressed fusion fuel, etc.

For the SSP, HEPW lasers can add much to our knowledge base of nuclear weapon science, particularly in the areas of materials science, equations-of-state, opacities, and simulation of age-related effects for nuclear weapons materials, little-studied in the United States outside the NNSA community. The HEDP experiments performed with HEPW lasers can play a major role in validating the physical models in the ASCI codes now under development for use in certifying nuclear weapons in the future.

In the long term, it is our expectation that the value of HEDP research, including HEPW lasers, to NNSA's missions will prove to be very large. As such, we believe that LLE and Sandia will continue to have important roles to play in HEDP research activities even after the NIF comes into full operation. One reason is that the three facilities will have different capabilities. Insufficient shot rate by any one facility, improved program flexibility, the need to study both direct-drive and indirect-drive ICF, the need to keep the low cost compression capability of pulsed power in the program, etc., all need to be taken into account when the long term Petawatt Laser National Plan is constructed.

6.3.2 HEPW laser technology

HEPW laser technology has already been developed to a large extent, including the now-dismantled HEPW laser based on the NOVA laser and operated at LLNL from 1996 to 1999. Facilities are operating or being constructed abroad in Japan, France, the U.K., and Germany. There remain some technological challenges to reaching the highest energy and power level HEPW lasers. These are in optical-parametric pre-amplification and the technology of gratings (used for compressing a chirped $\sim$ 1 ns pulse to ps time scales) that are of reasonable size and able to withstand the high power density and fluence of a HEPW laser. We fully expect the necessary capabilities to be developed during the next few years.

6.3.3 HEPW targets and diagnostics

The technological challenges may be more severe for target and diagnostic design than for the HEPW lasers themselves. For example, stated SSP-based requirements for HEPW backlighter accuracy and high X-ray energy are sufficiently stringent that detailed studies should be carried out of the necessary target and diagnostic designs to determine if they can actually be done. If the necessary HEPW X-ray backlighter capability is not achievable, understanding experimental results and tweaking target design to attain (and measure) specific desired experimental conditions will be very difficult.

6.3.4 X-ray backlighting

One of the predominant NNSA applications of HEPW lasers is X-ray backlighting at higher X-ray energies and much shorter time scales than can be achieved with the main implosion lasers at LLE, NIF, and by the present Z/Beamlet laser at SNLA. X-rays with energies measured in 10s to 100s of keV can be generated by HEPW lasers with ps pulse durations. With laser energies up to a few hundred joules, and x-ray photon energies up to a few tens of keV, this application is low risk and relatively low cost. The potential payoff of this diagnostic is substantial to the HEDP program. The Z-machine at SNLA and OMEGA at LLE could use this backlighting capability today, if they had it, to diagnose implosion experiments, as well as more realistic weapon physics experiments than can be done at present. The NIF could do significant materials science, EOS, opacity, etc., research even before the full NIF implosion capability is on-line; such experiments would benefit from HEPW laser-based X-ray backlighter capability constructed from a NIF quad, assuming that is determined to be high priority as part of the PW National Plan and if the budget permits. However, the full benefit to the HEDP program of HEPW lasers at the NIF will occur when that facility has substantial implosion capability. Early establishment of HEPW laser backlighters at such facilities as Z/ZR and LLE, valuable in their own regard, should also yield valuable experience and lessons learned that will benefit their use at the NIF.

6.3.5 Isochoric heating

Petawatt laser energy can be efficiently converted into energetic electron or proton beams, and possibly into other ion species beams as well, as discussed in Section 3. (However, the scaling of this capability to higher laser energy, especially for protons and other ion species, is still to be determined.) These particle beams can be used, in turn, to heat solid density, or even pre-compressed matter without a change in volume in a few ps to temperatures as high as ~ 1 keV (depending upon the laser energy and focal spot size of the particle beam on the sample). This capability would substantially increase the range of densities, temperatures and pressures that can be accessed for weapon-related materials science experiments, some of which could be important to understanding nuclear weapons.

6.3.6 Materials science

Pressures encountered in nuclear weapon explosions reach the many Gbar range, far above the few Mbar level achieved so far in the laboratory. Pressures of a few tens of Mbar to many Gbar can be achieved in the laboratory in the foreseeable future only with ultra-high intensity lasers. HEPW lasers will be useful, even essential, for diagnosing as well as for generating such pressures, and will lead to EOS, opacity and strength parameters for weapon-relevant materials in currently-unexplored regimes. But EOS and materials strength are areas where present accuracy requirements are quite stressing, as discussed in conclusion 6.3.3. HEPW lasers (operated in conjunction with other drivers) will allow the exploration of pressure and temperature ranges that are now virtually *terra incognita*, where theory and modeling results may differ by tens of percent, far worse than the accuracy requirements now called for in the laboratory research plans. Such discrepancies can be resolved by even modestly accurate data.

6.3.7 Fast-ignition

In ICF, fast-ignition calls for heating in just a few ps a small spot on a compressed deuterium-tritium fusion fuel target to such high temperature as to propagate a front of thermonuclear burn throughout the much larger target. With fast-ignition, it is possible that symmetry, total energy and shock-timing requirements placed on the fuel-implosion driver (laser, Z-pinch, or ion-beam) may be relaxed. Relatively inexpensive power and energy can be used for fuel compression, with only fuel ignition being the job of the HEPW laser beam. The thermonuclear yields achievable at NIF, ZR, and OMEGA may be considerably improved. Fast-ignition (or, for that matter, any other kind of ignition) has not yet been demonstrated, but there are already some encouraging initial experimental results on fast-ignition-enhanced neutron yields. HEPW lasers are essential for fast-ignition.

6.3.8 Frontier science with ultra-high power lasers at universities.

HEPW lasers will be highly desirable and even essential for certain non-NNSA science. An example is physics at very high electric fields, especially for the generation of highly relativistic electrons and various schemes for advanced particle accelerators. However, such forefront academic HEDP science with lasers does not necessarily require HEPW lasers, even for science of direct concern to NNSA. For example, laboratory astrophysics experiments on Rayleigh-Taylor instabilities may benefit from HEPW lasers for diagnostic purposes, but in general, terawatt-class lasers will do the job here. Creation of unique ultra-high-pressure states of matter is also of interest in basic science; the materials of interest are likely to be different from those of interest to the NNSA. The excitement of carrying out frontier research with ultra-high-power lasers will serve as an attraction for high-quality students to HEDP science and technology. Both Ph.D. students looking for dissertation topics and undergraduates looking for research projects, summer jobs and interesting graduate school opportunities will be attracted. Some of those students can later be recruited to NNSA laboratories.

6.3.9 The HEPW plan so far.

NNSA sorely needs an integrated HEPW laser national plan, with prioritized research plans (objectives as well as schedules) for different budget levels. The components of the plan presented to us this summer constitute more a set of laboratory wish lists than parts of a cohesive HEDP research community plan. In many instances, details of the science and technology (and their relevance to NNSA missions) remain to be given, and priorities remain to be set. This may simply reflect insufficient time having been available so far to develop the details; in any case, the time is ripe for intensive and detailed community effort.

6.3.10 Framework for setting priorities.

The NNSA needs a standardized method to determine the relative importance of the proposed HEPW laser research activities in the overall SSP program. The QMU method can be applied to such activities as X-ray backlighting for weapon physics experiments and materials science experiments with special nuclear materials. The importance of research activities that do not fit into the QMU process can be viewed in the spirit of the QMU, i.e., how valuable are they to NNSA's overall long-term goals, including achieving ignition at the NIF?

6.4 Recommendations

6.4.1 The HEPW laser national plan.

We recommend that the NNSA HEDP community move expeditiously to develop a Petawatt Laser National Plan that represents a true integration of the capabilities and potential contributions of all the NNSA-funded HEDP laboratories (LLNL, LANL, SNLA, LLE and GA). Facility development and prioritized research plans and schedules should be laid out for different budget levels, and a step-by-step flexible approach should be adopted.

The plan should quantify the connection between the proposed research activities and stockpile stewardship goals in the spirit of the QMU philosophy that is now being adopted for other SSP elements. The plan should take into account the technological risks of various proposed applications and the research needed to mitigate those risks before proceeding with each new step, especially if additional costly facilities are required. Proposals from each of the laboratories that are incorporated into the plan should include the science case, its relevance to SSP and HEDP goals (including NIF ignition, more realistic weapon physics experiments on Z/ZR, and the direct-drive ICF program at LLE), and well-founded costs and schedules for each proposed HEPW laser facility and research activity. Proposals from each laboratory should also indicate how implementation of various alternative paths would impact the baseline cost and schedule for that facility. We believe that proposed HEPW activities should not affect the baseline cost and schedule for the NIF under any implementation plan, nor should it unduly disrupt other major baseline program activities, such as the OMEGA direct-drive ICF research campaign.

The Petawatt National Plan should ensure that any significant technology development for HEPW lasers, such as high-damage-threshhold gratings, is a community effort that is compatible with application at the NIF if and when appropriate. The Plan should also include a vigorous research program at universities that have more modest facilities than those of LLE.

In summary, *the National Plan must be a prioritized, integrated, collaborative effort, with detailed documentation of the value added to the SSP of each significant research activity and facility development step.*

6.4.2 Petawatt National Plan Review Board in parallel with initial steps forward

We recommend that a Review Board be established, consisting of knowledgeable scientists and engineers both from within and from outside NNSA programs, to oversee the development of the HEPW Laser National Plan. This Board should insure that the Plan pays due regard to prioritization, collaboration, and integration. However, we also recommend that the NNSA begin initial HEPW laser activities without delay, perhaps even prior to establishment of the Review Board. These should include facility designs in support of developing the National Plan, low-risk, relatively low-cost activities such as a few-hundred-Joule, $\sim$ 1ps X-ray backlighter for Z/ZR, and risk-reducing science experiments for SSP applications using the $\sim$ 100 TW Trident and JanUSP lasers in the U.S., and $\sim$ 1 PW facilities abroad.

6.4.3 X-ray backlighting

We recommend that HEPW laser X-ray backlighter capability be developed and implemented at NNSA implosion facilities on schedules and with priorities compatible with each facility's operational status, and in a way that does not disrupt or delay its primary goals. The deployment of HEPW lasers for X-ray backlighting at NIF need not await the development there of symmetric implosion capability if such early deployment, for example for diagnosing materials science experiments, is sufficiently high priority in the Petawatt National Plan and the budget permits. Documentation of the HEPW laser backlighter hardware investment rationale for all facilities should address its value for specified SSP programs such as those involving mix, asymmetry, materials properties, and aging effects simulation. For ICF, the documentation should address issues of improving indirect-drive and direct-drive performance at the Z/ZR and OMEGA facilities, respectively, and the probability of ignition and high gain at the NIF. Any proposal of HEPW laser backlighters for laboratories not scheduled to have facilities for implosion and/or matter compression should need a very strong programmatic and scientific justification to warrant support by the HEDP program.

6.4.4 Materials science

We recommend that a systematic documentation be carried out of the relationship between weapons science materials data to be collected at proposed HEPW facilities and what data are really required for understanding nuclear weapons, for stockpile stewardship, and ultimately for weapons certification. Accuracy requirements of the SSP may make materials science targets and diagnostics the cost-determining or pace-setting program elements. Therefore, we recommend that design, cost, and schedule studies of materials science targets and diagnostics be carried out expeditiously to see if this is the case. In some cases, the experimental accuracy requirements may make the need for higher energy petawatt laser facilities than would be required otherwise. We note that validation of physical models in computer simulations will benefit greatly from even modestly-accurate initial materials science data in regions as yet unexplored experimentally.

6.4.5 Fast-ignition

We recommend continued fast-ignition research (which is presently supported by DOE's Office of Fusion Energy Sciences), including small-scale experiments at international locations and at U.S. facilities when these are capable of the appropriate experiments, as well as code development for fast-ignition studies. If the small-scale experiments continue to look promising, the US should proceed with larger-scale fast-ignition capability in conjunction with US implosion facilities. We recommend that the necessary space at NIF be reserved for HEPW laser beam implementation for fast-ignition. However, such activities should avoid impacting NIF's baseline cost and schedule.

6.4.6 University programs

We recommend that NNSA support a vigorous university research program in HEDP using short-pulse lasers in the TW to PW regime. The university program should include both support for TW-PW lasers at universities and a program for academic users who wish to do unclassified work involving the highest energy HEPW lasers at major NNSA facilities if national security permits.

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