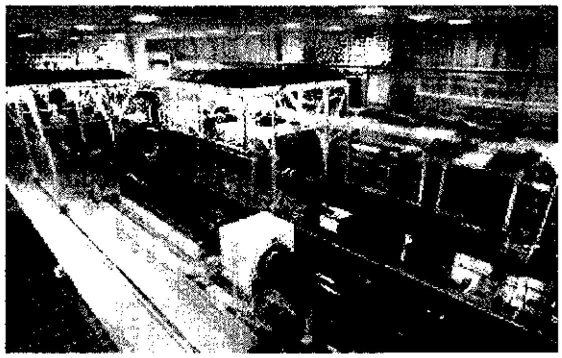
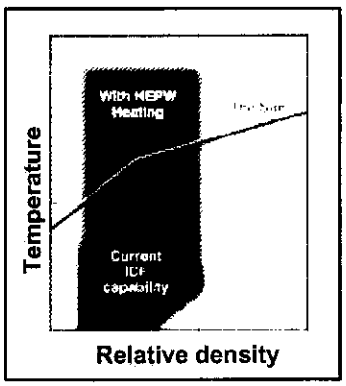
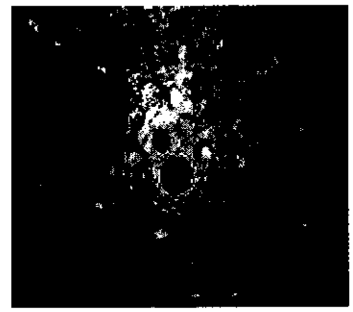


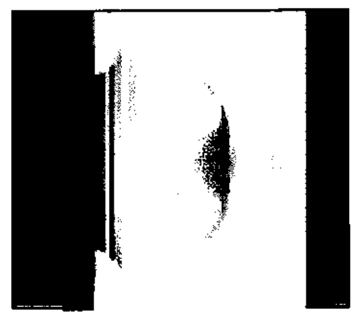


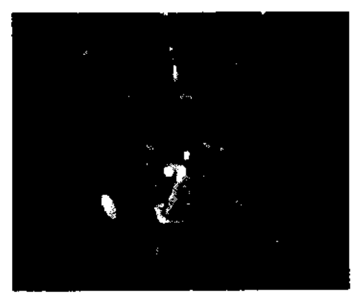


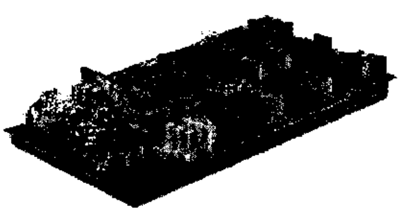
# High Energy Petawatt Lasers and the Stockpile Stewardship Program

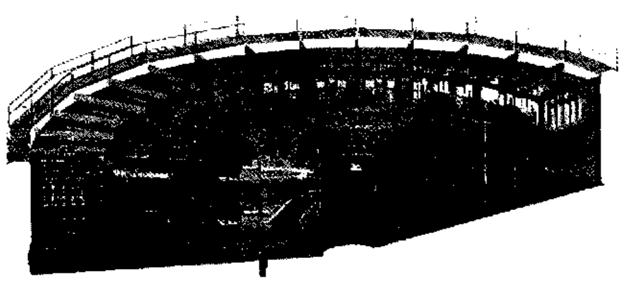
July 1, 2003

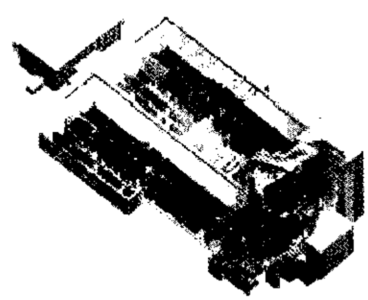












National Nuclear Security Administration

# High Energy Petawatt Lasers

# and

# the Stockpile Stewardship Program

July 1, 2003

National Nuclear Security Administration
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

First Printing, June 9, 2003

NNSA National Nuclear Security Administration

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National Nuclear Security Administration

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# Preface



High-energy petawatt lasers are an important new capability for the Stockpile Stewardship Program and the nation. This report describes the value of this capability and Defense Programs plans for implementing it within the SSP. I would like to thank both the laboratory and Headquarters' staff who contributed to the report, including David Meyerhofer of the Laboratory for Laser Energetics, University of Rochester, Mike Key, John Caird, and Chris Barty of Lawrence Livermore National Laboratory, John Porter of Sandia National Laboratories, Juan Fernandez of Los Alamos National Laboratory, and Christopher Keane, Richard Thorpe, Ralph Schneider, Mary Ann Sweeney, Terri Batuyong, and Tom Finn at Headquarters.

Thank you for a job well done.

Dr. Everet Beckner
Deputy Administrator for Defense Programs
National Nuclear Security Administration

# 1. Introduction

In the mid 1990s, the United States was the pioneer in petawatt laser physics. Today, U.S. leadership in the field has eroded, with Japan and Europe taking the lead in the deployment of high-energy petawatt (HEPW) lasers. Recognizing the positive impact HEPW lasers could have on the Stockpile Stewardship Program (SSP), the National Nuclear Security Administration (NNSA) intends to revitalize U.S. involvement in this field. This report outlines the integrated goals, objectives, and implementation strategy for HEPW laser technology development and construction at NNSA's major inertial confinement fusion (ICF) facilities.

## 1.1 Stockpile stewardship and the High-Energy-Density Physics Program

The mission of the SSP is to maintain a safe, secure, and reliable nuclear weapons stockpile. To support this mission, leading edge technologies and science must be pursued in a number of areas. As shown in Figure 1, these areas form the five pillars upon which the stewardship program is constructed.

A vital High-Energy-Density Physics (HEDP) Program is an essential component of the SSP. This was the conclusion of a NNSA study[1] mandated by Congress in the FY 2001 Energy and Water Development

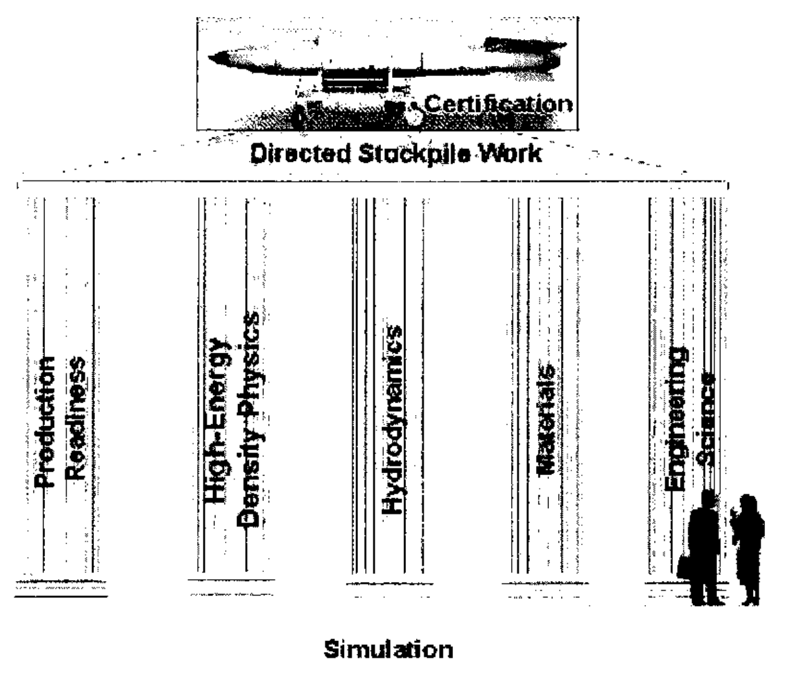


*Figure 1. The five pillars of stockpile stewardship: production readiness, high-energy-density physics, hydrodynamics, materials, and engineering science.*

Appropriation. The existing OMEGA laser facility at the University of Rochester's Laboratory for Laser Energetics (LLE) and the Z pulsed power facility at Sandia National Laboratories (SNL) provide the present HEDP capability to meet the needs of the SSP. The National Ignition Facility (NIF), now under construction and beginning initial experiments at Lawrence Livermore National Laboratory (LLNL), will become the flagship facility for HEDP studies.

Within the NNSA, the bulk of the HEDP Program is contained within the Inertial Confinement Fusion Ignition and High Yield Campaign (the ICF Campaign, or Campaign 10). Other HEDP Program activities are supported by the Science Campaigns (Primary Certification, Dynamic Materials Properties, Advanced Radiography, and Secondary Certification) and the Readiness in Technical Base and Facilities Program.

The goal of the ICF Campaign is to develop and use HEDP experimental capabilities, including fusion ignition, to provide data to support SSP requirements for modeling the performance and effects of nuclear weapons. The Campaign's strategic objectives are:

- Execute HEDP experiments required to support the stockpile as defined by the quantitative analysis of margins and uncertainties.
- Demonstrate ignition in the laboratory using the National Ignition Facility.
- Develop and demonstrate advanced concepts that support long-term requirements of the SSP, including ignition concepts that scale to high yield.
- Maintain a robust national HEDP Program infrastructure and contribute to broader national scientific goals.

## 1.2 High-energy petawatt (HEPW) lasers

ICF facilities operate in the multi-kilojoule to megajoule (one thousand to one million joules) energy range, with experiments typically several billionths of a second in duration. HEPW lasers are characterized by lasers with pulse durations a thousand times shorter but energies of one to several kilojoules. Powers are in the petawatt (quadrillion watt) range. The ability of HEPW lasers to deposit large amounts of energy on a time scale that is short compared to the duration of an ICF experiment will provide a major technical advance for the HEDP Program. HEPW lasers have three major applications:

- Advanced radiographic diagnostics,
- The ability to create unique states of matter, and
- Exploration of advanced ignition concepts.

## 1.3 HEPW laser technology and worldwide progress

The chirped pulse amplification technique, pioneered at the University of Rochester in the mid 1980s,[2] was the fundamental breakthrough that allowed short-pulse, ultra-intense lasers to be constructed. Using this innovation, table-top terawatt lasers with pulse durations and energies of about one picosecond (a trillionth of a second) and one joule, respectively, were constructed at a number of laboratories and universities worldwide. The next major step in short-pulse, high-power laser development was the 1996 demonstration of a petawatt (PW) laser using one beam of the Nova facility at LLNL.[3]

The United States was the world pioneer in PW laser physics, developing nearly all of the critical methods and technologies that enabled petawatt lasers. However, with the decommissioning of the Nova PW laser system in 1999,[4] Japan and Europe took the lead with the construction of a number of Nova-scale PW-class lasers. Table 1 summarizes existing PW capabilities worldwide.

The nuclear weapons programs in the UK and France, in particular, have recognized the importance of HEPW laser systems. The UK is implementing a plan to upgrade the Helen laser at the Atomic Weapons Establishment. The upgrade will include two HEPW beams, along with additional long-pulse, high-energy laser beams for compressing matter. France is constructing the Laser MegaJoule (LMJ), which is somewhat larger than the NIF (240 beams instead of 192 beams). An eight-beam prototype of LMJ, known as LIL, has been constructed at the Centre d'Etudes Scientifique et Technique d'Aquitaine near Bordeaux. The Commissariat à l'Énergie Atomique is evaluating the possibility of adding HEPW capabilities to the LIL facility. In addition, the Institute for Laser Engineering (Osaka, Japan) is embarking on an ambitious program to install both HEPW and ICF compression capabilities to study fast ignition (described in Section 2).

The remainder of this document describes the potential benefits of HEPW lasers to NNSA (Section 2), the proposed configuration of HEPW laser systems for the Z accelerator, OMEGA, and the NIF, including the associated technology development (Section 3), the impact on broad national scientific goals (Section 4),

*Table 1: Existing worldwide PW laser capabilities. Pulse width is in picoseconds ($10^{-12}$ second) and energy is in joules (1 watt x 1 second).*

| Country | Laser | Pulse width (ps) | Energy (J) | Date complete |
|---|---|---|---|---|
| U.S. | Nova | 0.5 | 600 | May 1996; decommissioned 1999 |
| Japan | Gekko XII | 0.5 | 500 | 2001 |
| UK | VULCAN | 0.5 | 500 | Sept. 2002 |
| Germany | GSI | 0.5 | 500 | 2005 |
| France | LULI | 0.5 | 500 | 2005 |

and the potential role of universities (Section 5). NNSA's conclusions and actions for implementing HEPW lasers on the major ICF facilities are discussed in Section 6.

# 2. Impact of HEPW lasers on the Stockpile Stewardship Program



This section discusses the impact of HEPW laser systems on the HEDP Program and the SSP. It is organized according to the three principal applications of HEPW lasers.

## 2.1 Advanced radiography

The SSP mission requires the experimental diagnosis of objects of increased density and temperature in order to examine physical conditions close to those produced by nuclear weapons detonations and to improve weapons design codes. The most effective technique for diagnosing these objects is x-ray radiography.

X-ray radiography is an experimental technique in which an external source of x-rays is used to penetrate and determine the evolution of a complex object. It is a critical diagnostic tool on NNSA's ICF facilities for recording two-dimensional images of materials at extreme pressures. By pulsing the x-ray source on and off very quickly, an image can be obtained at an instant in time with minimal motional blurring, thus yielding a high spatial resolution image. By pulsing the source on and off *several times* during the few billionths of a second of a typical HEDP experiment, a movie can be made that reveals the motion of complex two-dimensional features.

HEPW lasers should produce brighter and more penetrating x-rays than is possible with the conventional radiographic techniques available today. These lasers will enable scientists to study thicker and denser objects at higher temperatures (that is, closer to the conditions in actual weapons) and with higher resolution.

The measurements that x-ray radiography make possible are critical for validating complex radiation-hydrodynamics computer models used in weapons system assessments. With HEPW laser systems, imaging at picosecond temporal resolution becomes possible. The current state of the art (longer-pulse lasers coupled with gated detectors) is in excess of 30 picoseconds.

Today, long-pulse, kilojoule-class lasers produce x-rays that are limited to energies of $\leq$10 kiloelectronvolt (keV) for radiography measurements with high spatial resolution.[5] For reference, a 6-keV x-ray can penetrate a 35-micron-thick sample of solid aluminum or a 1-micron-thick sample of solid gold. (A micron is one millionth of a meter, and a typical human hair is about 100 microns thick.) An HEPW laser will be capable of producing an x-ray probe with an energy of 10 to 100 keV. A 60-keV x-ray can penetrate a sample of solid aluminum that is 15,000 microns (1.5 cm = 0.6 inches) thick or a sample of solid gold that is 135 microns thick. Hence, with HEPW lasers, scientists will be able to study objects that are hundreds of times thicker and/or denser than is presently possible.

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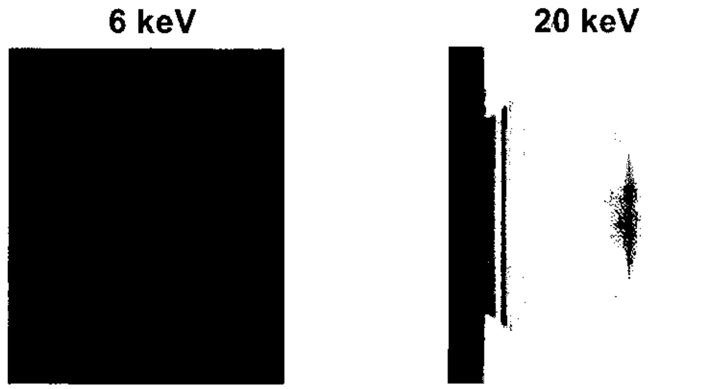


*Figure 2. Computer-generated simulation of x-ray radiograph for complex hydrodynamics experiments planned on the Z accelerator. 6-keV x-rays cannot penetrate the sample so the left image appears nearly black and unexposed. Important features become visible using the higher x-ray probe energies of a HEPW laser system.*

An example of the advantage of the higher probe energies with HEPW lasers is illustrated by the computer simulation in Figure 2 of the evolution of a high-temperature, high-density plasma. For comparison, the simulation has been performed using both the highest energy x-ray radiography source that is routinely available today (6 keV) and an x-ray source that should be produced with a HEPW laser system (20 keV). The higher probe energy is crucial to validating advanced simulation codes.

High-brightness backlighting is also important when the object being backlit is at a high temperature. In this case, the x-ray emission from the object can overwhelm the signal from currently available backlighters. Such a backlighter could be used as a tool, with an advanced simulation code, to determine how to adjust the target geometry, x-ray pulse shape, or other conditions in order to produce more symmetric compression of the fuel inside a fusion capsule.

HEPW lasers could also provide a more efficient radiographic capability. For many experiments envisioned at the NIF, as much as a quarter to one-half of the beams on the facility would be needed for conventional radiography. In contrast, a single HEPW laser could provide the necessary radiographic capability. Adding a HEPW capability to the Z-Beamlet laser would also greatly extend the radiographic possibilities for experiments on Z.

Although HEPW-generated x-ray radiography systems are quite promising, a large amount of developmental work (for both the x-ray source and the diagnostics) remains before the full potential of the new capability can be realized. These radiographic techniques are the subject of current research and can be developed initially on OMEGA, Z, and smaller facilities in preparation for implementation on the NIF.

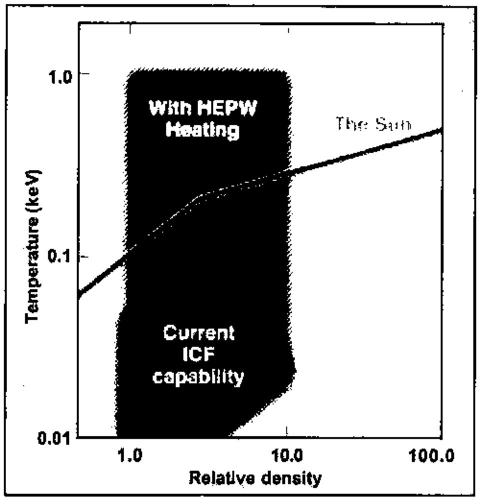


*Figure 3. Schematic showing high-energy-density states of matter accessible with addition of HEPW lasers. Density values are normalized to the uncompressed (normal) density of matter.*

## 2.2 Creating unique states of matter

A key objective of the HEDP Program is to examine a variety of physical phenomena associated with unique states of matter present in nuclear explosions. This examination is essential to the development of advanced capabilities for weapons assessment and, ultimately, for warhead certification. As shown in Figure 3, NNSA's ICF facilities will provide an important range of extreme temperatures and pressures necessary for accessing these conditions in the laboratory. Coupling HEPW lasers with these facilities would significantly broaden the available range.

The short duration of HEPW pulses means these lasers can heat materials to high temperatures before they can appreciably expand. Integrating short-pulse HEPW lasers with the major long-pulse ICF facilities would greatly expand the range of plasma conditions available. To study the properties of matter at high energy density, long-pulse ICF facilities compress relatively large volumes of material to densities that are a few times the uncompressed density, while keeping the corresponding temperature increases close to the theoretical minimum. The compressed plasmas can be subsequently heated or probed by one or more HEPW lasers. The advent of a laboratory capability to probe these extreme conditions would also play a major role in advancing the nation's broad scientific goals.

## 2.3 Fast ignition

Fast ignition[6] offers a potential alternative approach to achieving ignition and higher fusion gain from ICF targets. It falls within the *advanced concept* goal of the ICF Campaign.

The primary ignition concept being pursued at NNSA facilities and that is planned for demonstration on the NIF is known as *hot spot ignition.*[7] In this concept, a high-power laser or pulsed power device is used *both* to compress a mass of deuterium-tritium fuel and to heat the central portion of the fuel to thermonuclear fusion conditions. Most hot spot ignition targets consist of a deuterium-tritum gas surrounded by a solid shell of deuterium-tritium fuel (a cryogenic target). Successful production and testing of cryogenic targets is a critical component of the ignition program.

In fast ignition,[6] the fuel core would be compressed in a conventional ICF

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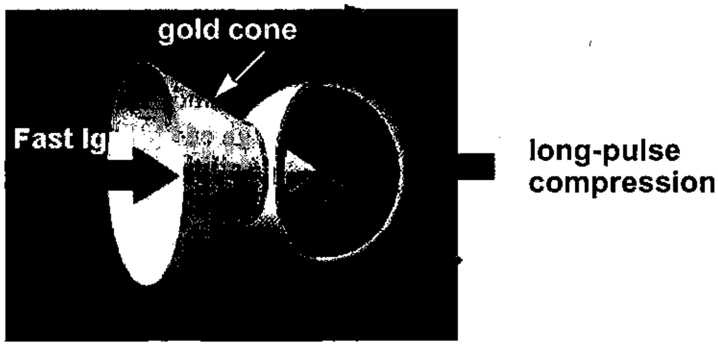
*Figure 4. Schematic of the fast ignitor target concept. The gold cone allows the fast ignitor HEPW laser beam to focus directly onto the already compressed fuel without passing through the ablated mass of the capsule outer surface.*




facility such as NIF, OMEGA, or Z. The core would then be heated by firing a HEPW laser at just the right moment so that the energy from the short-pulse laser is efficiently coupled to the core, either by fast electrons or protons. Figure 4 shows a representation of a conical target of the type that was used in Japan to obtain efficient short-pulse laser heating of a compressed core.[8]

Considerable work remains before fast ignition could be demonstrated. A coordinated research effort, well balanced among experiment, theory, and modeling, would be needed to advance the concept from the present stage of significant promise with significant uncertainties to the point at which a full-scale effort to demonstrate fast ignition would be justified.

# 3. HEPW laser configurations proposed by SNL, LLE, and LLNL and the required technology development



This section describes concepts proposed by SNL, LLE, and LLNL to add HEPW laser capabilities to Z, OMEGA, and the NIF in a phased approach, together with the laser technology development that would be needed. In the initial phases, these proposals range from relatively minor modifications of existing lasers to the construction of additional beams. The scale of the final HEPW laser capabilities that would be needed at each facility depends primarily on the compression energy delivered to a target. As explained in Section 6 (pages 19-21), the priorities of the Future Years Nuclear Security Plan (FYNSP) will limit the extent to which these proposed concepts could be adopted.

## 3.1 HEPW laser at Sandia National Laboratories

SNL has proposed a phased approach to add a PW capability to the existing Z-Beamlet laser. Z-Beamlet is the former Beamlet laser at LLNL that was activated at SNL on Z experiments in 2001. Its original mission, while at LLNL, was as a research laser to develop, test, and refine technology options for the NIF. Z-Beamlet is now a multi-kilojoule, nanosecond (billionth of a second) radiographic diagnostic laser and is well suited for modification to an HEPW system.

Figure 5 shows a schematic of the proposed Z-Beamlet petawatt laser with the refurbished Z. The refurbished

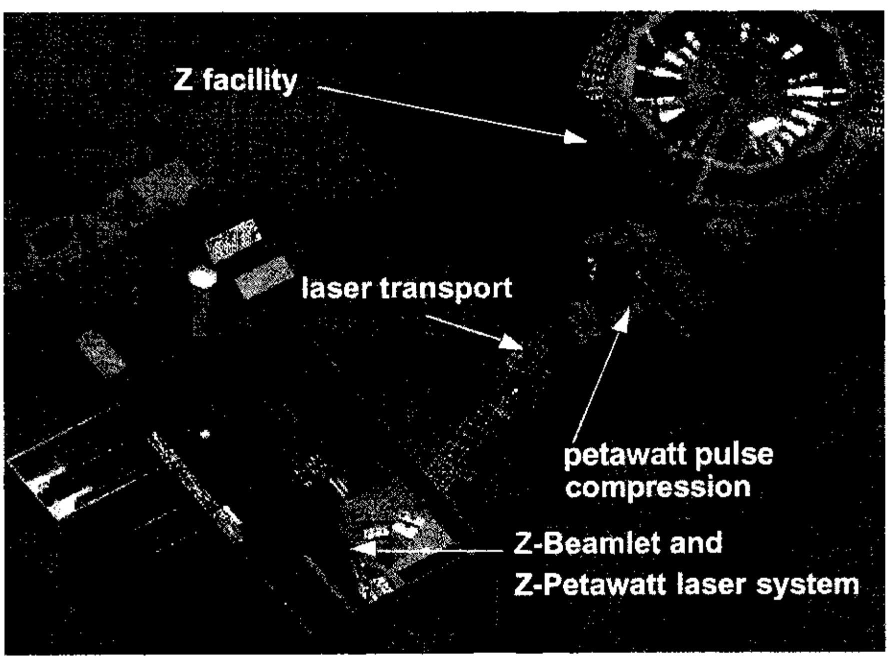



*Figure 5. Layout of Z-Beamlet and the proposed Z-Petawatt laser system coupled to the refurbished version of Z.*

Z will become available in 2007 with the replacement of aging parts, improved reliability, flexibility, and accuracy, and higher energy.

The first phase of SNL's HEPW laser development plan would be to construct a half-aperture prototype using Z-Beamlet. This prototype beamline would produce a several-hundred joule, 0.5-petawatt output beam comparable in performance to the European and Japanese systems that are operating or being constructed. The performance and reliability of the short-pulse laser technology, deployed in a NIF-style multiple-pass laser architecture, would be evaluated and refined before incorporating the new technology into the full-aperture Z-Beamlet system. Techniques to radiograph samples at higher energies and with more penetrating x-rays would be developed during this time. Laser-target interaction experiments would be carried out as well. This first phase is expected to be completed early in FY 2004.

The second phase would transport, focus, and synchronize the half-aperture prototype laser system with Z. The third phase would provide a stand-alone, multi-kilojoule, multi-petawatt laser capability for the full-aperture Z-Beamlet. The final phase would implement the full multi-kilojoule HEPW laser capability for high-energy radiography and fast ignition experiments on the refurbished Z.

## 3.2 HEPW laser at Laboratory for Laser Energetics

The initial goal of the proposed OMEGA EP (extended performance) project is to add a HEPW capability adjacent to OMEGA, as shown in Figure 6. The full OMEGA EP project would consist of four NIF-like beams, but with technology improvements that could allow a higher shot rate. The first two beams would have a HEPW laser capability (~3 kilojoules, 1 petawatt). These beams would pass through a beam switchyard and be directed to either a new PW-laser target chamber or to the 60-beam OMEGA target chamber. The new OMEGA EP laser bay would be provided by the University of Rochester.

The two HEPW lasers would be used for radiography and fast ignition studies. For radiography in ICF implosion experiments, the two beams would allow images to be taken at different times, x-ray energies, or orientations. The addition of a separate HEPW target chamber (as shown in Figure 6) would allow parallel 60-beam implosion experiments to be conducted on OMEGA.

In addition to providing advanced backlighting capabilities, the two HEPW beams would allow the investigation of a fast ignition concept. For fast ignition experiments, one of the two HEPW beams would create a channel through which the other short-pulse beam would pass into and heat the compressed core of an ICF target. This concept would be compared experimentally to the cone-target configuration that is shown in Figure 4 in Section 2. A cryogenic target

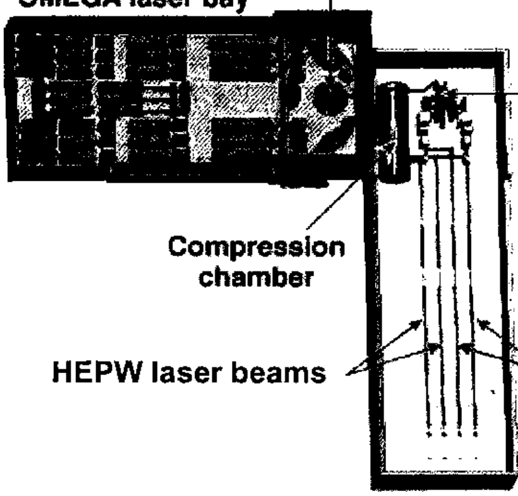



*Figure 6. Schematic of proposed OMEGA EP project. The initial phase of the project would involve adding two short-pulse lasers that can also be operated in a long-pulse mode. Two additional long-pulse laser beams may be considered in the future.*

handling system is operational at OMEGA and would allow tailoring of the compressed core of the target for fast ignition research.

## 3.3 HEPW laser at Lawrence Livermore National Laboratory

The proposed HEPW laser plan for the NIF is a phased approach for adapting several NIF beamlines. These NIF beamlines could alternate between a *normal* long-pulse operational mode and a short-pulse HEPW mode, with a change-over period between these modes that is estimated to be consistent with the NIF shot cycle. Relatively minor modifications would be made to the selected beamlines to produce up to five kilojoules per beamline at pulse durations of about five picoseconds. A schematic for the proposed implementation of these HEPW lasers is shown in Figure 7.

The first step in the NIF plan would involve the conversion of a single beamline to HEPW laser operation to provide a backlighting capability to enhance SSP experiments that are expected to take place on the partially completed NIF and subsequently benefit the full NIF. The deployment plan would call for an initial HEPW laser capability of two kilojoules in ten picoseconds. A short-pulse oscillator system would be located in the existing NIF Master Oscillator Room, and a new diffraction grating pulse compression chamber would be constructed. The HEPW beam would be redirected as shown in Figure 7, and a modified final optics assembly incorporating a parabolic mirror would focus the HEPW beam onto a target.

This first step would not involve any modifications to the main laser components in operation at the NIF.

The second step would involve phased upgrades to boost the HEPW laser capability to five kilojoules and convert up to four beams in a NIF quad to HEPW operation, using the above approach.

Each of these steps would provide new backlighting capabilities and unique access to matter at higher temperatures, as shown in Figure 3. These capabilities would maximize the value of early experiments on the NIF and, in some cases, might accelerate the schedule for providing data specific to stewardship by several years.

## 3.4 Technology development plan for major ICF facilities

High-energy, short-pulse laser systems are operational around the world; hence, there are no major obstacles to constructing these lasers at NNSA ICF facilities. However, the existing short-pulse systems presently cannot operate in the kilojoule and higher energy range required by NNSA. Therefore, NNSA is pursuing advanced technology development to enhance performance of these systems for use on its major ICF facilities. The most important task in this technology program is the development of advanced diffraction gratings, which compress (shorten) the laser pulse into the picosecond regime.

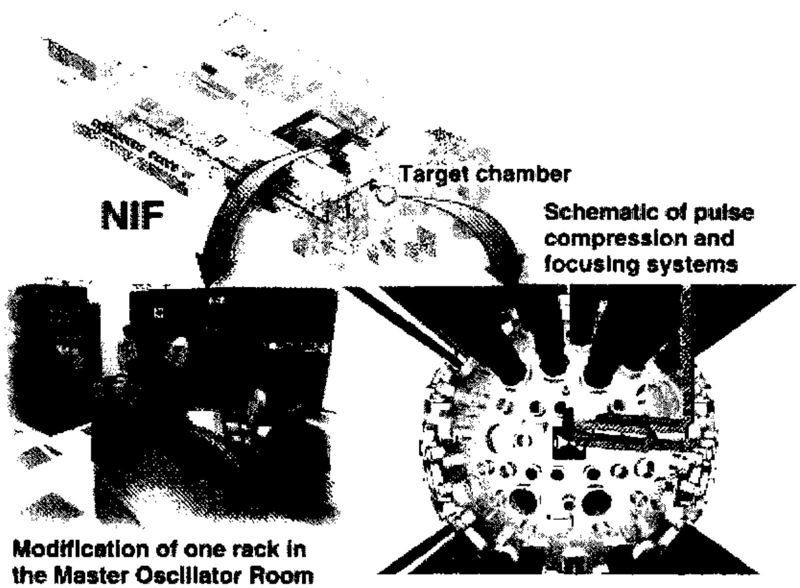



*Figure 7. Schematic of proposed HEPW laser adaptation of one NIF beamline. The NIF amplifier chain would require no changes. A new pulse generator, a grating compressor, and final optics assembly would be installed. In a phased program, up to four HEPW beams (a NIF quad) could be redirected to grating compressors and focused on target through the same equatorial port in the target chamber.*

The ability of diffraction gratings to withstand an intense amount of laser light without being damaged is a key factor in determining the level of HEPW laser energy that can be delivered to an object. Currently, most HEPW laser facilities worldwide use standard gold-coated gratings that can withstand fluences of approximately 0.2 joules per square centimeter. For NNSA's needs, gratings with damage thresholds up to ten times higher must be developed. Gratings composed of alternating layers of nonconducting material, called *multi-layer dielectric gratings*, may satisfy this requirement. A coordinated effort to develop these gratings is underway at LLE and LLNL in collaboration with various industrial partners. Small-scale multi-layer dielectric gratings have been fabricated with promising results. The gratings must meet size, damage threshold, and efficiency requirements. Gratings as large as one meter squared may eventually be required. NNSA is investigating technologies to produce dielectric gratings of this size directly. The possibility of building large gratings from a set of smaller gratings (known as *tiling*) is also being examined.

Collaborative work is ongoing in other technology development areas that will be needed to maximize HEPW laser performance. The *master oscillator*, where the laser pulses at the NIF, OMEGA, and Z-Beamlet originate, must be modified for HEPW laser operation. Damage-resistant reflective optics, as opposed to normal lenses, would also be needed to focus the HEPW laser energy onto targets. Advanced laser diagnostics must also be developed. While these basic HEPW laser technologies have been demonstrated, they would have to be adapted for implementation at each major NNSA ICF facility.

# 3

# 4. Impact of HEPW lasers on national scientific goals



Short-pulse high-intensity lasers, including HEPW lasers, provide new opportunities for understanding high-energy-density plasmas that have applications beyond NNSA's stockpile stewardship goals. Several national studies[9-11] have recognized the growing worldwide importance of this field and have recommended specific research activities and actions to realize the opportunities afforded by the OMEGA, Z, and NIF facilities. Highlights and key recommendations of these studies are summarized below.

- The National Research Council (NRC) report, *Frontiers in High Energy Density Physics*,[9] concludes that "research opportunities in this crosscutting area of physics are of the highest intellectual caliber and are fully deserving of the consideration of support by the leading funding agencies of the physical sciences." The report highlights the importance of studying matter under extreme conditions and recommends significant investments in advanced infrastructure, including upgrades, modifications, and additional diagnostics for existing ICF facilities.

- A second NRC report, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*,[10] identifies research in the study of matter under extreme conditions as an important scientific opportunity. It recommends that "unique laboratory facilities such as high-power lasers, high-energy accelerators, and plasma confinement devices . . . be used to explore physics in extreme environments as well as to simulate conditions needed to understand some of the most interesting objects in the universe including gamma-ray bursts." The report further recommends that "the agencies cooperate in bringing together the different scientific communities that can foster this rapidly developing field."

- A recent workshop, *Science and Applications of Ultrafast, Ultraintense Lasers*,[11] sponsored by DOE and the National Science Foundation (NSF), concludes that ultra-intense laser-matter interactions is an area of increasing scientific importance, not only in astrophysics but potentially in other disciplines, such as biology, medicine, and energy production. NSF and DOE's Office of Basic Energy Science and Office of Fusion Energy Science are supporting research in these areas.

The findings and recommendations of these reports are an important endorsement of the value of HEPW lasers to the strategic objectives of the HEDP Program. NNSA's plan for implementing HEPW capabilities at its major compression facilities is consistent with these recommendations, and the plan will help realize the broad scientific value of HEPW lasers for the nation.

# 5. University activities in high energy petawatt lasers



Strong university programs and facilities are essential to foster the field of high-energy-density physics. NNSA, the DOE Office of Science, and the National Science Foundation are funding university research using petawatt lasers. NNSA, in particular, has sponsored university research involving short-pulse, ultra-intense lasers since FY 1998 through the Stewardship Science Academic Alliances and other programs. Table 2 lists the universities receiving funds from NNSA in this research area.

The two NRC reports cite the key role universities play in maintaining and advancing the nation's excellence in science and technology by developing and testing new ideas as well as training the next generation of scientists. Many young scientists, both in the U.S. and overseas, are already attracted to the challenging new science of high-energy laser-matter interactions. One of the HEDP Program strategies is to enhance the education, recruiting, and retention of scientists within the mission areas of NNSA. Activities in the rapidly evolving HEPW laser field will naturally attract university researchers and graduate students.

Most university-scale short-pulse lasers have powers of one tenth of a petawatt or less. However, valuable ultra-intense experiments can be carried out on these relatively modest laser systems. It would be beneficial to have a limited number of university-based petawatt lasers available with an energy about one-tenth that of the proposed NNSA HEPW lasers.

The NNSA has a long-standing program, the National Laser User Facility, that provides access to OMEGA for researchers at other institutions. Experimental time on NNSA HEPW lasers would be made available to university researchers under this program or a similar program at LLNL, LLE, and SNL.

*Table 2. NNSA-sponsored university research involving short-pulse lasers.*

| Institution | Research area |
|---|---|
| Colorado State | Study of dense plasmas with ultra-bright soft x-ray laser diagnostics |
| Princeton | Plasma effects during fast ignition in ICF |
| UC Berkeley | Advanced x-ray diagnostics to study materials at high energy density |
| Univ. Colorado | Imaging of laser plasma interactions with XUV radiation |
| Univ. Nevada | Terawatt facility at University of Nevada Reno |
| Univ. Rochester | High-energy laser-plasma interactions relevant to fast ignition |
| U. Texas | High-intensity laser science |

# 6. NNSA implementation strategy for HEPW lasers

## 6.1 JASON recommendations

NNSA tasked the JASON group to examine the applications of HEPW lasers to stockpile stewardship. In its April 2003 report,[12] the group noted that substantial gains in weapon-related science would be enabled by the use of HEPW lasers for x-ray backlighting, materials science, and advanced ignition concepts, especially in conjunction with OMEGA, Z, and eventually the NIF.

The key JASON recommendations are:

- An implementation plan should be developed that utilizes the capabilities of all NNSA sites in an integrated manner.
- Initial HEPW laser activities should begin without delay, including facility designs, low-cost construction, and small-scale experiments at existing U.S. and foreign facilities.
- HEPW laser capabilities should ultimately be installed at each major compression facility (NIF, OMEGA, Z); however, such activities at NIF should not be allowed to interfere with the NIF construction project.
- HEPW laser technologies should be developed as a "community effort" compatible with their eventual application at the NIF.
- A vigorous program in ultra-intense laser research should be supported at universities, and academic user programs should be established to use the HEPW lasers at NNSA laboratories.

## 6.2 NNSA conclusions

NNSA has incorporated the recommendations from the NRC and JASON studies into three conclusions for implementing HEPW laser activities within the HEDP Program.

*Conclusion 1: NNSA expects that HEPW lasers will be needed for the SSP mission and should ultimately be installed at all major ICF compression facilities (NIF, OMEGA, Z).* The use of HEPW lasers for backlighting dense targets is an advance of major importance that alone justifies HEPW laser capabilities at these facilities. Access to conditions of extreme temperature and density allowed by HEPW lasers would provide a new capability that significantly increases our ability to probe key issues in regimes of importance to nuclear weapons. HEPW lasers also open the possibility of new paths to ignition in the laboratory.

*Conclusion 2: NNSA will adopt a phased approach in developing HEPW laser capabilities consistent with the FYNSP budget.* The immediate implementation of a full HEPW capability at NIF, OMEGA, and Z on an achievable schedule would cost about $15-30 million per year. This is not supportable within the current NNSA FYNSP priorities. NNSA accepts that HEPW lasers are an important advance that will bring new capabilities to the HEDP Program.

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However, the intent is to proceed with an integrated and phased national plan to develop and apply this capability in a way that minimizes technical risk. This implementation will respect commitments and be carefully balanced against other program priorities. Final decisions on HEPW funding will be made as part of the FY 2005 budget formulation process and the final FY 2004 appropriations.

*Conclusion 3: NNSA's support of HEPW lasers will contribute to broad national goals in HEDP science, as outlined in the recent NRC reports.* NNSA will work with the DOE Office of Science and other agencies to assure that its implementation of HEPW lasers supports the national scientific interest. NNSA will also encourage continued collaboration on HEPW laser technology under its existing international agreements.

## 6.3 NNSA actions

Specific NNSA actions for implementing these three conclusions are as follows.

*Action 1: Develop HEPW grating technology.* The major remaining HEPW laser technology issue is the development of large-aperture, high-damage-threshold gratings. Congressional funding above the FYNSP was applied to this area in FY 2002 and FY 2003. NNSA's FY 2004 budget request includes $2 million at LLNL and $2 million at LLE to develop multi-layer dielectric gratings and investigate the concept of tiling. NNSA will involve the broader laser technology community in the development of gratings to ensure that the appropriate production capabilities will be available when needed.

*Action 2: Implement HEPW* laser *capabilities at the OMEGA facility.* In FY 2002 and FY 2003 Congress provided $2 million and $13 million, respectively, to fund construction of a short-pulse HEPW laser system at LLE. NNSA has completed a mission need study for OMEGA EP and validated the need for two HEPW beams. No funds are available in the current ICF Campaign FYNSP for HEPW laser construction. However, as part of the FY 2005 budget formulation process, NNSA is considering a modest funding increase to the ICF Campaign for an HEPW laser capability on OMEGA at the Laboratory for Laser Energetics. The objective is to have a single HEPW laser beam at LLE by the end of FY 2006 and a second beam by the end of FY 2009. Construction of these two short-pulse beams would be as outlined in the plans for the OMEGA EP Project. NNSA has no plans to support the long-pulse beams and the auxiliary target chamber proposed as part of the OMEGA EP project.

*Action 3: Implement HEPW laser capabilities at Z.* In FY 2002 and FY 2003 Congress provided $3 million and $5 million, respectively, to fund construction of a short-pulse HEPW laser capability at SNL. Consistent with JASON recommendations, modification of the existing Z-Beamlet laser at SNL would be the quickest path for providing an HEPW laser capability and is therefore desirable. However, no additional funds are available in the current ICF Campaign FYNSP for this activity. As part of the

FY 2005 budget formulation process, NNSA will work with SNL to determine the pace and timing appropriate for implementing a HEPW laser at Z.

*Action 4: Implement HEPW laser capabilities for the NIF.* As the flagship facility for the HEDP Program, HEPW lasers should be installed at the NIF to exploit its full scientific capabilities for stockpile stewardship experiments. As discussed in Section 3.3, relatively minor system changes would be necessary to convert a NIF beamline for initial HEPW beam implementation, and this initial HEPW laser capability could have beneficial impacts on early SSP deliverables. However, funding for this activity has not been made available within the current FYNSP budget.

Regardless of funding or feasibility, it is important that LLNL develops and deploys HEPW beam modifications without impacting the cost or schedule for the NIF Project and other HEDP Program commitments. NNSA will continue to work with LLNL to determine an implementation plan for HEPW lasers at the NIF that is consistent with the FYNSP budget and the requirements of the NIF Project.

*Action 5: Support university involvement and adopt a user-facility approach within the national HEPW plan.* Additional university research in areas relevant to HEPW lasers will be considered within the mix of research supported by the Stewardship Science Academic Alliances Program. As recommended in the JASON report,[12] HEPW lasers at major ICF implosion facilities will be operated as user facilities to provide appropriate access to the academic research community.

National Nuclear Security Administration

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# Appendix A – Glossary and Acronyms

| | |
|---|---|
| backlighter | strong radiation source used during experiments to image target or material |
| Campaigns | technically challenging, multi-year, multi-functional efforts conducted across the NNSA national laboratories, production plants, and the Nevada Test Site |
| cm | centimeter |
| cryogenic | low temperature; fusion fuel in liquid or solid state |
| dielectric | nonconducting material |
| diffraction grating | optical component for splitting a beam spatially into separate parts based on the frequency of these separate parts |
| DOE | Department of Energy |
| eV | electron volt = energy acquired by an electron falling through a potential difference of 1 volt, approximately $1.602 \times 10^{-19}$ joules |
| fast ignition | ICF ignition concept based on cold compression of fusion fuel, followed by rapid heating of the fuel core using an intense, ultrashort-pulse HEPW laser |
| FY | fiscal year |
| FYNSP | Future Years Nuclear Security Plan |
| Gekko XII | 500-joule, 0.5-picosecond petawatt laser in Japan |
| HEDP | high-energy-density physics |
| Helen | 0.9-kilojoule, 1-terawatt laser at the UK Atomic Weapons Establishment for which plans exist to upgrade to petawatt level |
| HEPW | high-energy petawatt |
| hot spot ignition | concept whereby a laser or pulsed power device both compresses fusion fuel and heats the central portion to thermonuclear fusion conditions |
| hydrodynamics | motion of fluids |
| ICF | inertial confinement fusion |
| ICF Campaign | Inertial Confinement Fusion Ignition and High Yield Campaign, sometimes referred to as Campaign 10; bulk of HEDP Program is within this campaign |
| ignition | point at which a small addition of energy causes a significant increase in the rate of thermonuclear fusion |

| | |
|---|---|
| J | joule = unit of energy equal to work done when a force of one Newton acts through a distance of one meter |
| K | Kelvin = unit of temperature equal to 1/273.16 of the thermodynamic temperature of the triple point of water |
| keV | 1,000 eV |
| kJ | kilojoule = 1,000 joules |
| LANL | Los Alamos National Laboratory |
| LIL | Laser Integration Line, an 8-beam laser facility at Commissariat à l'Énergie Atomique |
| LLE | Laboratory for Laser Energetics |
| LLNL | Lawrence Livermore National Laboratory |
| LMJ | Laser MegaJoule, a 240-beam, 1.8-megajoule ICF facility being developed in France |
| LULI | French facility where an HEPW laser system is being constructed |
| micron | millionth of a meter |
| MJ | megajoule = million ($10^6$) joules |
| nanosecond | one billionth ($10^{-9}$) of a second |
| NIF | National Ignition Facility, 192-beam ICF laser facility being constructed at LLNL |
| NNSA | National Nuclear Security Administration |
| Nova | 10-beam laser facility at LLNL that was decommissioned in 1999 |
| NRC | National Research Council |
| NSF | National Science Foundation |
| OMEGA | 60-beam laser facility at University of Rochester's Laboratory for Laser Energetics |
| OMEGA EP | OMEGA extended performance: proposed project at LLE that would add an HEPW capability to the 60-beam OMEGA laser |
| petawatt | quadrillion ($10^{15}$) watts |
| ps | picosecond = one trillionth ($10^{-12}$) of a second |
| SNL | Sandia National Laboratories |
| SSP | Stockpile Stewardship Program |

| | |
|---|---|
| TW | terawatt = trillion ($10^{12}$) watts |
| UK | United Kingdom |
| VULCAN | HEPW laser system in the UK |
| W | watt, a unit of power equal to one joule per second |
| x-ray | high-energy light that, because of its penetrating power, is used in radiology and radiography |
| x-ray radiography | process of obtaining an image of an object by passing x-rays through it |
| Z accelerator | a pulsed-power facility at SNL, often referred to as Z |
| Z-Beamlet | x-ray backlighting diagnostic to image targets and z-pinch plasmas in Z experiments |
| ZR | refurbished version of Z |