Preprint
UCRL-JC-144831

Inertial Fusion and High-Energy-Density Science in the United States

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This article was submitted to
Second International Conference on Inertial Confinement Fusion Science and Applications
Kyoto, Japan
September 9-14, 2001

September 6, 2001

U.S. Department of Energy

Lawrence Livermore National Laboratory

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Inertial fusion and high-energy density science worldwide is poised to take a great leap forward. In the United States, programs at the University of Rochester, Sandia National Laboratories, Los Alamos National Laboratory, Lawrence Livermore National Laboratory (LLNL), the Naval Research Laboratory, and many smaller laboratories have laid the groundwork for building a facility in which fusion ignition can be studied in the laboratory for the first time. The National Ignition Facility (NIF) is being built by the Department of Energy's National Nuclear Security Agency to provide an experimental test bed for the U.S. Stockpile Stewardship Program (SSP) to ensure the dependability of the country's nuclear deterrent without underground nuclear testing. NIF and other large laser systems being planned such as the Laser MegaJoule (LMJ) in France will also make important contributions to basic science, the development of inertial fusion energy, and other scientific and technological endeavors. NIF will be able to produce extreme temperatures and pressures in matter. This will allow simulating astrophysical phenomena (on a tiny scale) and measuring the equation of state of material under conditions that exist in planetary cores.

1. Introduction

The development of experimental facilities for studying inertial fusion and high-energy-density physics has spanned many decades since the advent of particle accelerators and lasers. Soon after the invention of the laser in the early 1960's it was postulated that energetic laser beams might be used to compress and heat a capsule containing deuterium and tritium to the point where fusion ignition and burn could occur. Energetic laser and ion beam pulses were also found to provide a means for inducing extreme temperatures, pressures, and shock environments in materials and for producing a variety of plasma conditions for scientific study. In inertial confinement fusion (ICF), ignition occurs when energy production and alpha particle deposition from the central hot spot are sufficient to initiate a self-sustaining burn wave that propagates into the surrounding main fuel. Target gain is defined as the ratio of thermonuclear energy produced to driver energy on target. A generally accepted level of energy production in ICF requires target gains high enough that the product of gain times driver efficiency is ~10. This implies target gains of 30-100 depending on driver efficiency. NIF's point ICF target design provides a target gain of 20 for 1.8 Megajoules of laser energy into the hohlraum.[1]

By 1990 the amount of progress made in understanding how to generate inertially confined fusion and high energy densities in materials was sufficiently advanced to allow serious review of laboratory microfusion concepts for the U.S. Inertial Fusion Energy Program. In the executive summary of the Laboratory Microfusion Capability Phase II Study, it is stated that the objective of the Inertial Confinement Fusion (ICF) program since its inception in the early 1970's has been to obtain a high yield (up to 1000 Megajoules or nearly a quarter-ton of TNT equivalent) microfusion capability in the laboratory.[2] This objective is clearly still valid today

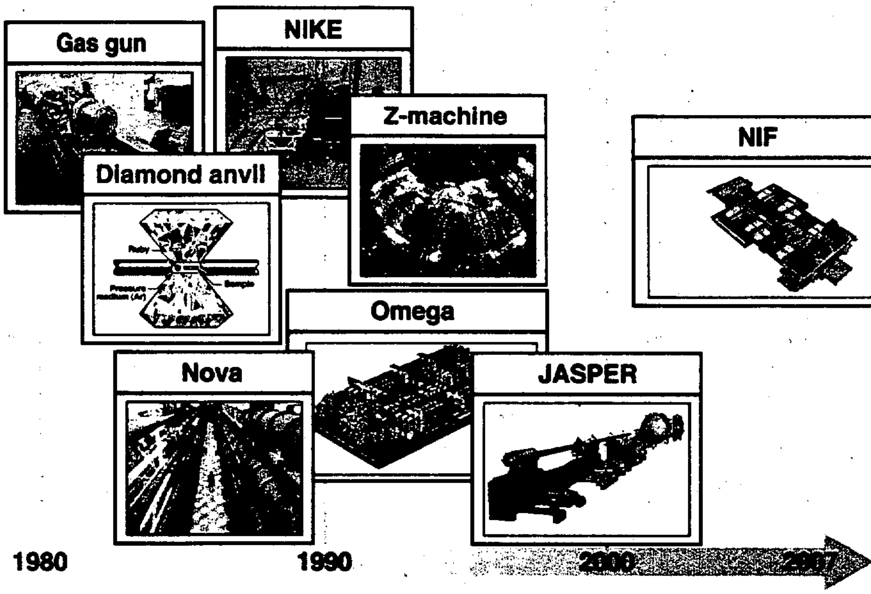


Figure 1. Major U.S. inertial fusion facilities and other facilities/capabilities for achieving a range of material energy densities.

and we are now well on our way towards reaching this goal with the completion of NIF in the next few years.

In addition to NIF many other facilities have been utilized in the U.S. for the study of inertial fusion and the physics of matter over a range of energy densities and temperatures. Figure 1 shows some of these facilities and the approximate time they were first available for scientific research.

Recently the NNSA issued a comprehensive study of the role of high-energy-density physics in the U.S. Stockpile Stewardship Program.[3] This "High-Energy-Density Physics Study Report" was notable for the thorough examination of the current and future directions that the U.S. might take. Among the key findings and recommendations of this Study were that a vital HEDP Program is an essential component of the SSP. The baseline HEDP Program, including completion of the 192-beam NIF, on the approved baseline, meets the SSP requirements and is the appropriate path forward. Also the Study recommended that the NNSA continue with the baseline HEDP Program, including the Omega Laser at the University of Rochester, Laboratory for Laser Energetics (LLE); the Z machine at Sandia National Laboratories, Albuquerque; and the 192-beam NIF at LLNL, including the goal of ignition.

2. The National Ignition Facility

The National Ignition Facility currently under construction at LLNL will be a U.S. Department of Energy/National Nuclear Security Administration (NNSA) national center to study inertial confinement fusion and the physics of extreme energy densities and pressures.[4] It will be a vital element of the NNSA Stockpile Stewardship Program, which ensures the reliability and safety of U.S. nuclear weapons without full scale underground nuclear testing. The SSP will achieve this through a combination of above ground test facilities and powerful computer simulations using the NNSA's Accelerated Strategic Computing Initiative (ASCI). In NIF up to 192 extremely powerful laser beams will compress small fusion targets to conditions where they will ignite and burn, liberating more energy than is required to initiate the fusion reactions. NIF experiments will allow the study of physical processes at temperatures

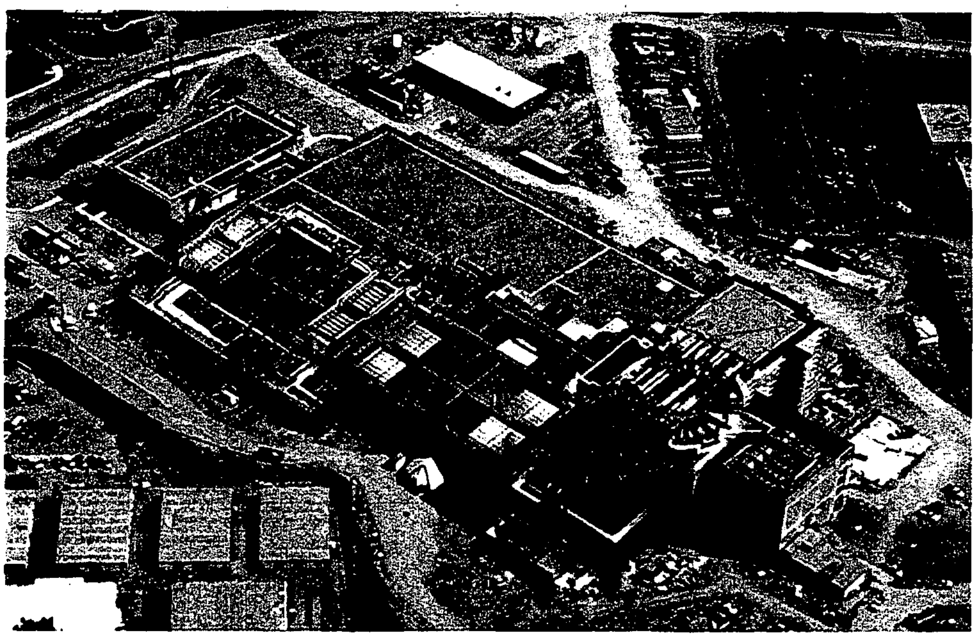


Figure 2. Aerial view of the National Ignition Facility taken in April 2001, with a CAD rendering of one of the laser bays and the target bay superimposed. NIF's conventional facilities are scheduled to be complete in September 2001.

approaching 10 keV (radiation temperatures approaching 300 eV) and 10^7 GPa. These conditions exist naturally only in the interior of stars and in nuclear weapons explosions. Figure 2 shows a recent aerial photograph of the NIF site superimposed with a computer-generated rendering of one of NIF's laser bays, switchyard and target bay. NIF's laser system and optical components are housed in an environmentally controlled building. Other facilities include a large cleanroom for assembly and refurbishment of NIF laser components (in the upper left corner of Fig. 2), and the target diagnostics building located near the NIF target bay (in the lower right corner of Fig. 2).

NIF's laser system, the heart of the facility, features 192 high-power laser beams. Together, the laser beams will produce 1.8 million joules (approximately 500 trillion watts of power for 3 nanoseconds) of laser energy in the near-ultraviolet (351 nanometer wavelength). This can be compared with the energy that was available in the Nova laser, which was operated at LLNL between 1983 and 1999. Nova was configured with 10 laser beams, each of which produced approximately 4.5 kilojoules of energy. Currently the largest operating laser is the Omega Laser at LLE. Omega consists of 60 laser beams delivering a total of 40 kilojoules of energy.

Progress on the construction of NIF is substantial. NIF's conventional facilities are nearly 100% completed and our industrial contractor has already installed over 1500 tons of laser hardware in the facility. All of NIF's facilities have begun operating under the required cleanliness protocols. Today NIF has over 75% of the special glass slabs needed for its laser amplifiers, and over 50% of the large crystals required for optical switches and frequency conversion systems. Major production contracts have been awarded to provide the high quality optics for NIF's 192 laser beams. NIF is scheduled to deliver its first four laser beams to the center of its 10-meter diameter target chamber in June 2004 and completion of its full complement of 192 laser beams is planned for September 2008.

NIF's 10-meter diameter high-vacuum target chamber contains a large number of laser entry ports as well as over 100 ports for diagnostic instrumentation and target insertion. Each

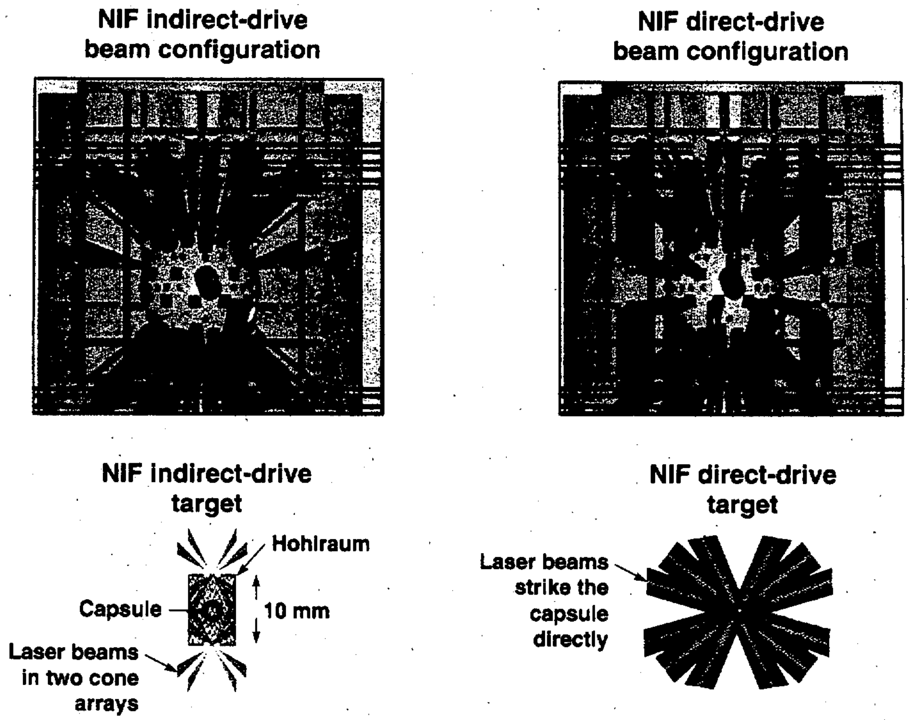


Figure 3. (a) Indirect drive and (b) direct drive configurations for NIF.

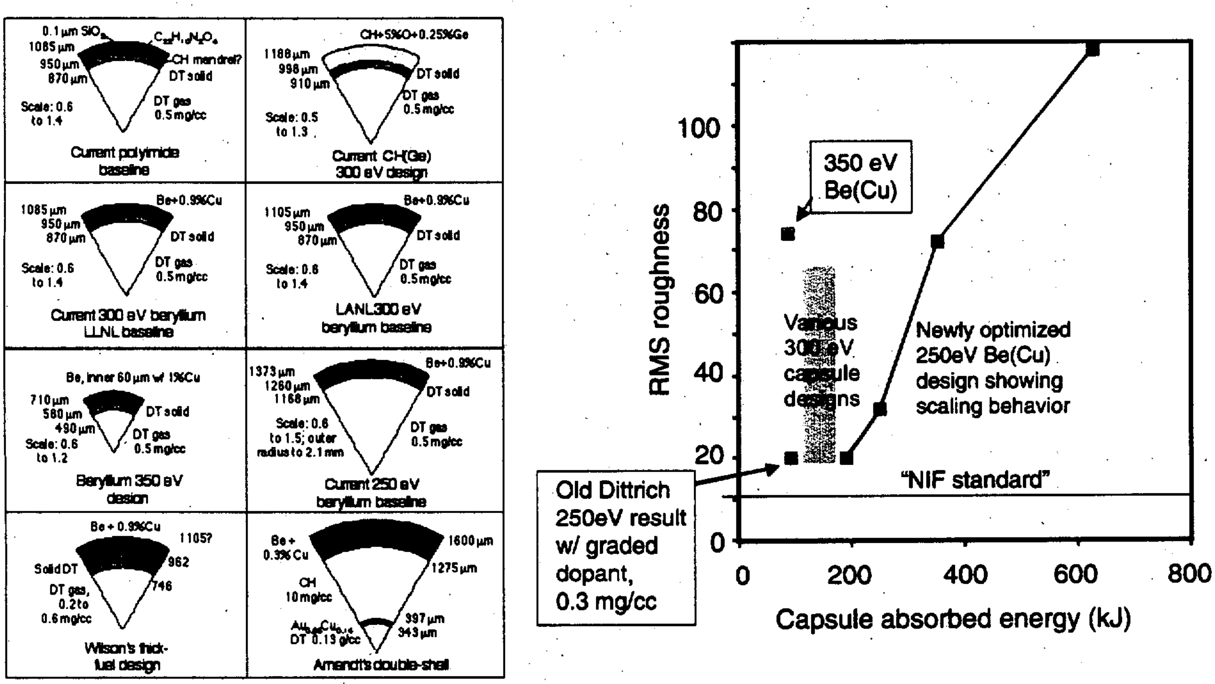
port allows a quad of 4 laser beams to be focused to the center of the target chamber through a final optics assembly. The NIF target chamber and final focusing system has been designed with maximum flexibility for experimental users. During initial operation, NIF is configured to operate in the "indirect drive" configuration, which directs half the laser beams into two cones in the upper and lower hemispheres of the target chamber (shown in Figure 3a). This configuration is optimized for illuminating fusion capsule mounted inside cylindrical hohlraums using x-rays generated from the hot walls of the hohlraum to indirectly implode the capsule. NIF can also be configured in a "direct drive" arrangement of beams, by moving some quads of beams from the upper and lower hemispheres into a more symmetric arrangement of beams (see Figure 3b). Direct drive ignition requires better energy and power balance between laser beams and better beam smoothing and focusing but the simpler geometry makes direct drive inertial confinement fusion more attractive for ultimately producing a viable power production plant.

3. Experimental Programs on NIF

The NIF Project is now entering the installation and commissioning phase over the next few years. In the time between first light in 2004 and project completion in 2008, approximately 1500 experiments in support of the SSP, inertial confinement fusion, high-energy-density physics, weapons effects, inertial fusion energy, and basic science will have been performed.

Fusion ignition and burn on NIF remains the ultimate goal of U.S. Inertial Fusion Program. To achieve this goal experiments and modeling in support of inertial fusion are being carried out at a number of institutions. At LLNL the indirect drive ignition program is focused on preparing for ignition experiments on NIF. The target design program is directed toward more accurately predicting target performance of the present suite of NIF designs and developing new, more robust design concepts. During the past year, three-dimensional modeling and optimization of ICF capsules continued to be performed using a code developed jointly with the NNSA ASCI initiative. The first ever 3D simulations of a full octant of an ignition capsule were successfully carried out, modeling the effects of typical hohlraum asymmetry. Detailed 2D simulations of ignition designs, away from the "point" design, were also carried out to determine surface roughness requirements. There is now a significantly, improved calculational understanding of the target designs for all three primary ablator options for NIF (beryllium, polyimide, and polystyrene). High-convergence (20x), high-growth-factor implosions experiments using the Omega Laser have been performed that demonstrated close agreement with 1D and 2D integrated hydrodynamics simulation. These experiments used the highly symmetric NIF-like hohlraum illumination geometry on Omega. Symmetry diagnostic techniques for NIF performed as expected on Omega, indicating flux asymmetry can be measured to the required accuracy.

Additionally, a number of ignition capsule and hohlraum designs are being studied at LLNL and other laboratories. Figure 4a shows examples of recent capsule designs being considered for ignition targets, the details of which are given in S. Haan et al., presented at this Conference.[5] A number of issues have been studied for these designs including surface roughness, asymmetry, effects of defects, contaminants and fill holes. Conclusions indicate that beryllium and polyimide capsule designs, while challenging from a fabrication standpoint appear feasible for ignition on NIF. A key result of these calculations is that higher drive capsule absorbed energy significantly loosens the requirements for capsule surface roughness as shown in Figure 4b.



(a) (b)

Figure 4. The figure on the left shows examples of recent capsule configurations that have been studied for ignition on NIF. Calculations of some of these configurations are shown on the right showing the relationship between surface roughness versus capsule absorbed energy for ignition.

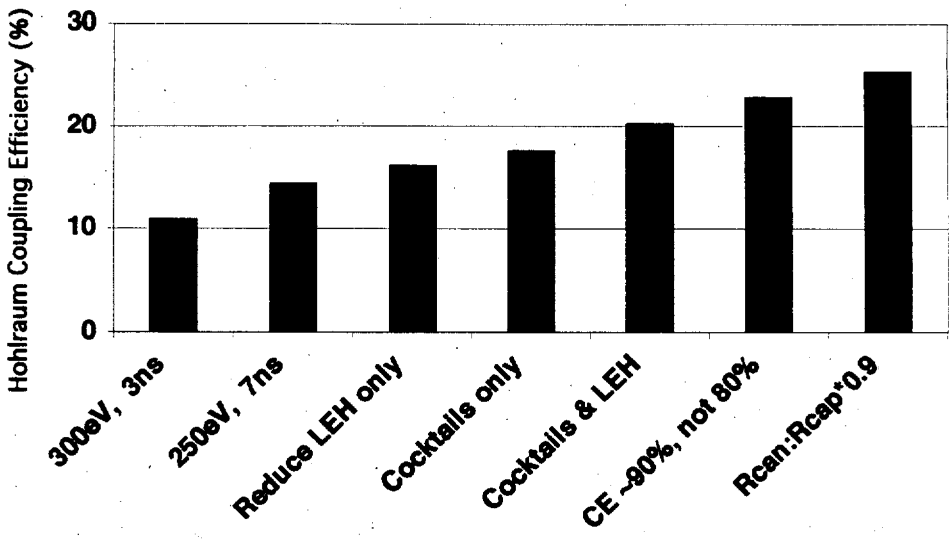


Figure 5. Hohlraum coupling efficiency increases by a factor of two or more based on optimization of design parameters shown in the chart.

Research is now focused on developing ways to increase hohlraum coupling efficiency through a variety of design enhancements, including optimizing the hohlraum geometry and laser entrance hole diameter, and treating the inner walls of the hohlraum with mixtures of elements to enhance x-ray conversion efficiency. Figure 5 shows the results from calculations by L. Suter of LLNL that suggest factors of 2 increases in coupling efficiency are possible, which could relax surface roughness requirements by a factor of 4 or more.[6]

Researchers from LLNL have received approximately 300 shots on this year's Omega schedule for high-energy-density physics, ignition physics, high-efficiency x-ray source development, and diagnostic development. Many of these shots involve collaborative work between LLNL, LANL, LLE and other institutions. Currently, the emphasis of the experimental work is on high-energy-density physics, utilizing roughly 200 of the 300 shots. Most of the remaining shots are dedicated to ignition-related experiments.

Examples of recent work include the development of a radiative shock test bed for Richtmyer-Meshkov and Rayleigh-Taylor experiments simulating astrophysical phenomena similar to that occurring remnant shock now being observed in the region near supernova 1987A. Radiative precursors have now been spectrally resolved in shocked silica foams and this data is being used to help develop sophisticated modeling capabilities. Figure 6 shows schematically the experiment fielded on Omega in April 2001 and an example of the data showing the precursor shock.[7]

Another area of active research utilizes energetic lasers to drive materials to hundreds of GPa pressures. New techniques have been developed to study pre-compressed materials using diamond anvil cells targets and double shocks to measure the equation of state and transport properties of planetary fluids on the Hugoniot and of planetary isentropes. Fluids such as water and mixtures with helium and hydrogen that are relevant to Neptune and Jupiter are being studied using these methods.[8] Additional research has studied recovered shocked samples from Omega that allows a quantitative understanding of lattice response to shock compression at ultra-high strain rates. Sample recovery allows detailed pre- and post-shock analysis with optical and electron microscopy. Dynamic multi-plane x-ray diffraction

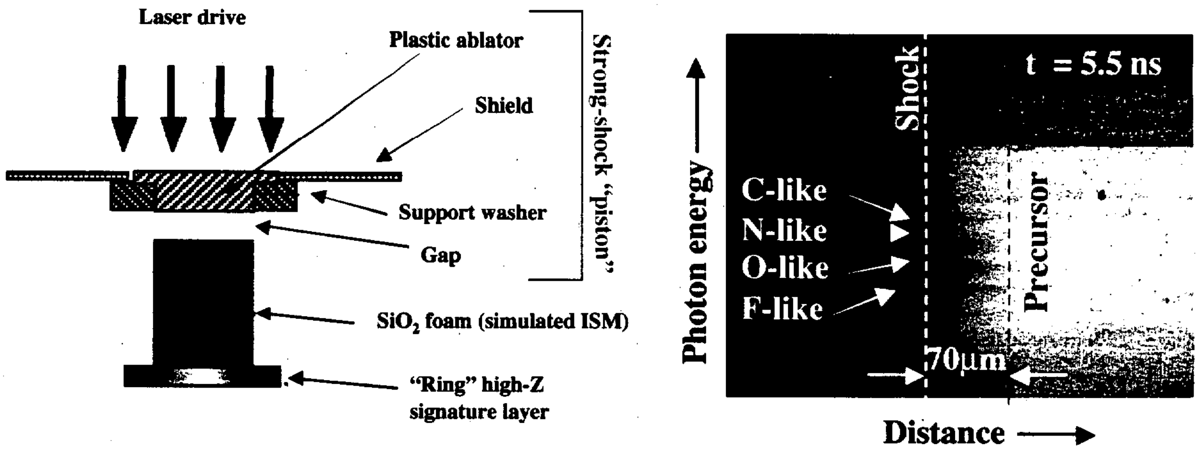


Figure 6. The schematic on the left shows a radiative shock experiment fielded on Omega. Spectrally resolved precursor shock data in silica foam is shown on the right.

experiments featuring simultaneous Bragg and Laue diffraction to measure the multi-phase material states in shocked materials are now being carried out on Omega.[9]

New diagnostics are also being developed that are allowing for the first time high resolution temporal and spectral analysis of cold, warm, and hot plasmas up to solid density. X-ray Thomson scattering as a high-density temperature and density diagnostic has recently been demonstrated for the first time on Omega. The scattered x-ray spectrum from solid density, ~ 10 eV Be plasma was measured and the Compton downshifted and Doppler broadened Thomson spectrum was observed as expected. The development of this diagnostic involved fielding a new gated highly oriented pyrolitic graphite (HOPG) spectrometer on Omega that can also be utilized on NIF when it becomes available.[10]

These are just a few of the experimental capabilities being developed that will be fielded on NIF. Many more experiments are envisioned and are actively being planned. The NIF Mission Support Group has been working with the experimental user communities to develop user shot requirements and shot plans for NIF. After project completion, NIF is expected to provide approximately 750 shots per year for experimental users. Recently NIF was designated as a National User Facility with the support of the National Nuclear Security Administration Office of Defense Programs. The first Director of NIF is Dr. George H. Miller, from LLNL, who also serves as the Associated Director for NIF Programs at LLNL. A National User Support Organization is now being put in place to provide the necessary interface between the user communities and the national NIF Program. Detailed information on how to propose and field experiments on NIF will be developed over the next year and placed on the NIF Programs web site, as it becomes available.[4]

In anticipation of the availability of NIF as a national user facility a number of preparatory activities have been taking place. These include establishing and fostering focused NIF user communities, developing NIF governance plans for experimental use of the facility, and, most importantly, continuing a diverse and vital high-energy-density and inertial fusion energy experimental program on a number of currently available facilities. At LLNL, LANL, and a number of other U.S. Laboratories and Institutions, the focus of experimental activities has been at the Omega Laser and at the Z machine. Many new experimental techniques and methods for diagnosing and characterizing NIF-scale physical phenomena are being developed and tested on these facilities prior to being fielded on NIF.

4. Conclusion

The National Ignition Facility is the culmination of over 30 years of research on lasers for high-energy-density and laser fusion experimental physics. The NIF Project has come a long way since the first DOE critical decision in January 1993 affirmed the need for NIF and authorized the conceptual design process. In that time NIF has met every scientific and technical challenge and is now in the final stages of design and construction prior to commencing installation of the 192 laser beams. By 2004 this unique facility will be providing the first glimpses of conditions heretofore only found in the most extreme environments imaginable under repeatable and well-characterized laboratory conditions for the benefit of national security and science.

Acknowledgements

The author would like to express his appreciation for the many people, institutions, and industrial partners that are diligently working to provide the National Ignition Facility for national and international users. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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