Role of the NIF in the Development of ICF Applications

W. J. Hogan

This paper was prepared for and presented at the 9th International Conference on Emerging Nuclear Energy Systems Tel-Aviv, Israel June 28-July 2, 1998

April 23, 1998
DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.
ROLE OF THE NIF IN THE DEVELOPMENT OF ICF APPLICATIONS

William J. Hogan

Lawrence Livermore National Laboratory
PO BOX 808, LIVERMORE, CA 94550

The National Ignition Facility (NIF) is a 1.8 MJ (at 351 nm), 192 beam laser facility being built at the Lawrence Livermore National Laboratory (LLNL) to achieve inertial fusion ignition in the laboratory. The NIF Project is being designed and built by a team from LLNL, Los Alamos National Laboratory, Sandia National Laboratory, and the University of Rochester. When completed in 2003, it will be a multipurpose facility that will be used for many applications in national security, energy, and the basic sciences. In addition to the National Security Mission, these applications include, for example, electric power generation, space propulsion, and study of basic astrophysical phenomena in the laboratory. Such applications receive benefit both through the state-of-the-art technology developments necessary to build NIF and through specific experiments that will be performed on NIF.

Laser Technology Developments:

One of the candidate drivers for Inertial Fusion Energy (IFE) power plants is the diode pumped solid state laser (DPSSL). Many technology developments for NIF are highly useful for a DPSSL-based IFE system even though NIF is predominantly flashlamp pumped. Improvement of optical damage thresholds, development of the 40 cm aperture plasma electrode pockels cell (PEPC) switch, stable diode-pumped optical pulse generation system with temporal, spatial, and coherence control, fast growth of potassium dihydrogen phosphate (KDP) crystals, and faster, lower-cost

manufacturing of large aperture precision optics will have a marked positive impact on
the prospects for this driver.

NIF will include more than 7500 large aperture (>0.3 m diameter) optical
components that will have a total precision optical surface area greater that 3000 m².
That is 40 times the area of the precision optics in the Keck telescope. Research at
LLNL has resulted in a factor of three increase in the damage threshold of large optics
compared to Nova (up to 45 J/cm² at 1054 nm, depending on the location). LLNL
research with optics vendors has produced new mass production techniques that will
lower the cost of each large optic by about a factor of three. The development of the
large aperture PEPC switch (see Figure 1) allows the laser beams to traverse the main
amplifiers four times to more efficiently extract the energy stored there. The PEPC
switch and frequency conversion of the 1054 nm light into 351 nm light require very
large (about 250 kg) KDP and deuterated KDP crystal boules. For Nova, growth of each
crystal boule required approximately 2.5 years. A new, fast growth technique has grown
the necessary full scale boule in less than 8 weeks. This fast growth allows iterative
decision making to optimize production yield of these crystals. Table 1 summarizes the
advances in optical component production methods that have been developed for NIF.
Figure 1. The Plasma Electrode Pockels Cell switch allows four passes in the main amplifier, increasing energy extraction efficiency. Here a stack of four PEPC switches are assembled together in a Line Replaceable Unit (LRU) for easy assembly and maintenance.

Table 1. Advances in all areas of optics manufacturing are necessary to meet the NIF requirements at reasonable cost.

<table>
<thead>
<tr>
<th>Discipline</th>
<th>NOVA Technology</th>
<th>Key technology advancement for NIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser glass blanks</td>
<td>Batch melting and forming, post-processing</td>
<td>Continuous melting and forming</td>
</tr>
<tr>
<td>Crystals</td>
<td>&quot;Low&quot; growth rate, ~1 mm/day</td>
<td>Rapid growth; ~10 mm/day</td>
</tr>
<tr>
<td>Fused silica substrates</td>
<td>Round boules, standard size</td>
<td>Optimized boule geometry with higher product yield</td>
</tr>
<tr>
<td>Lens/plano optics fabrication</td>
<td>Loose abrasive grinding Planetary polishing</td>
<td>Improved grinding High-speed polishing Deterministic figuring (square optics)</td>
</tr>
<tr>
<td>Optical coatings</td>
<td>Large chambers, electron-beam evaporation</td>
<td>Improved process design and control Reduce defects/improve damage</td>
</tr>
<tr>
<td>Gratings/phase plates</td>
<td>SiO₂ electron-beam deposited Reactive ion etch (small aperture)</td>
<td>Meniscus coating of photoresist Holographic exposure, wet or reactive ion etch</td>
</tr>
</tbody>
</table>
For a power plant, the higher the driver efficiency in converting electricity to beam energy on target, the lower the target gain that is required for an economical plant. If target gains of 100 are achieved, the driver must be about 10% efficient. It has long been thought by many that solid state lasers were too inefficient to be a good power plant driver. The efficiency of Nova is about 0.1%. However, the new NIF multipass architecture, combined with the closely compacted square beams will result in about 1% efficiency for NIF, an improvement of a factor of ten. By tuning the narrow band pump frequency of an efficient diode laser array to the absorption band, DPSSL’s promise to improve NIF’s efficiency to 10-15%, and to improve the pulse repetition frequency to the 5-10 pulses per second required of a power plant driver, but this has yet to be demonstrated. In a development in parallel with construction of NIF, LLNL is constructing a 100 J integrated demonstration of many of the features of a DPSSL driver for IFE. The Mercury laser should be ready for testing in 2000. These NIF and DPSSL improvements dramatically lower the cost per Joule of putting laser light onto a target and show that the DPSSL is a serious and attractive IFE power plant driver candidate.

NIF Experiments: Inertial Fusion Energy

The NIF experimental campaign necessary to achieve ignition has been considered in detail. NIF target experiments that establish the feasibility of producing more thermonuclear energy than is deposited in the target by the lasers will establish the fundamental scientific feasibility of IFE. It is well established that to be economically practical, the product of the driver efficiency and target gain in an IFE power plant must be greater than about ten. It is postulated that a DPSSL driver could have a wall plug efficiency of 10-15%. A heavy ion driver might have an efficiency of 25-35%. Thus a target gain of 30 to 100 is needed. While the anticipated target gain on NIF is only about ten, the underlying principles of target ignition and propagation on
thermonuclear burn will be established and all that would be necessary to obtain the required gain is to compress a larger quantity of cold fuel. This would require a somewhat larger driver. Alternatively, the fast ignitor concept may prove feasible and, added to the NIF, the targets might then produce the required gain with no increase in driver size. The NIF will be capable of studying ignition on both indirect drive and on direct drive targets (see Figure 2).

![Figure 2. The NIF baseline target configuration is indirect drive (Fig. 2a). If 24 of the 48 four beam clusters are moved to positions around the equator and additional beam smoothing is added in the preamplifier, direct drive experiments can also be fielded (Fig. 2b).](image)

NIF experiments will also investigate the physics of target types driven by other drivers. For example, some experiments will specifically model the physical conditions inside a heavy or light ion target. In heavy ion targets, the ion energy is deposited in small radiators near the ends of a hohlraum. The radiators generate X rays and the propagation of those X rays to the fusion capsule can be studied in NIF by designing a similar energy transport geometry (Figure 3). Similarly, X ray transport in a light ion target can be simulated in a NIF target.
Non-ignition NIF experiments, using laser energy deposited in an empty hohlraum, in gas bags or on metal targets can produce very large bursts of X rays to study first wall effects in IFE reaction chambers of various designs. In particular, absorbing the laser energy in combinations of materials with overlapping K edges can produce a flux of X rays with a variety of desired spectra. These X rays can then be used to study the effect of an IFE target on the first wall materials of a power reactor. If we use an array of X-ray sources, the first wall experiment can be made to simulate a much larger source. Such tests can explore the response of first wall designs and help in the design of an Engineering Test Facility/Demonstration Power Plant.

NIF ignition experiments can also study isochoric heating by neutrons in liquid curtains typical of many IFE power plant designs. Neutrons from IFE targets will deposit energy throughout any thick liquid wall and instantaneously raise its temperature and pressure. How such liquids "explode" and what the droplet size...
distribution is will determine how effectively a reaction chamber can recondense the vaporized material and return to the initial conditions for the next pulse. NIF experiments will be the first opportunity to study this phenomenon in detail.

NIF experiments can also systematically examine how target performance deteriorates with relaxed target fabrication specifications, an issue that will strongly affect the design of a target factory. The cost of an IFE power plant target factory will depend strongly on how smooth the fusion capsule must be.

Finally, it is also possible that future modifications to NIF would allow experiments to demonstrate target injection, beam pointing and igniting a target “on the fly” as will be necessary in a power plant. Preliminary subscale versions of these experiments are also envisioned for the Mercury system.

**NIF Experiments: Inertial Fusion Space Propulsion**

Another paper at this conference discusses the possibility of using the inertial fusion process to propel spacecraft. NIF experiments could determine many issues related to the feasibility of the inertial fusion space propulsion (IFSP) concept. Figure 4 is a schematic showing how debris from a target expanding against the field of a superconducting magnet can be diverted to produce thrust in the VISTA concept\(^2\). For DT fusion, which was the focus of the VISTA study, there are several important feasibility issues. Only the expanding plasma from the target debris is effective in producing thrust, so the charged debris fraction is maximized. The target is designed to operate at as high a density-radius product (pr) as possible and is surrounded with a frozen layer of hydrogen to induce n-p knockon reactions. NIF experiments could certainly examine how large a fraction of target energy can be put into the expanding debris. The IFSP concept also is more attractive the higher the target gain. Therefore, NIF experiments to examine how high the gain can be through such advanced target designs as the fast ignitor are also relevant to IFSP. Finally, the coupling between the
expanding debris cloud and the magnetic field is strongly dependent on its conductivity vs time and this can be measured in NIF. Finally, it is even possible that a NIF experiment could be designed to introduce a magnetic field and measure the thrust created.

![Diagram of the VISTA concept for an ICF propulsion engine](image)

Figure 4. The VISTA concept for an ICF propulsion engine envisions a superconducting coil to produce thrust by diverting the expanding debris from a sequence of ICF target explosions.

**NIF Experiments: Astrophysics**

From the beginning it was recognized that the physical conditions (e.g. temperatures and pressures) created in ICF targets would have to be very similar to those at the center of the sun and other stars. This fact led us to consider whether specific phenomena relevant to astrophysical processes could be studied in ICF targets. The scaling factors are mind boggling. However, the first cursory comparison of hydrodynamic instabilities in ICF implosions and hydrodynamic instabilities in core
collapse supernovae revealed striking similarities (Figure 5). Furthermore, experiments were done on Nova to measure the opacity of iron at high temperatures and densities and these were used to help resolve discrepancies in astrophysical models of cepheid variable stars.

Figure 5. Striking similarities exist between hydrodynamic instabilities in ICF implosions and supernova explosions.

In 1996 and 1998 international conferences on “Laboratory Astrophysics with Intense Lasers” were held in Pleasanton, CA and Tucson, AZ respectively. At the last conference, there were 130 attendees from 13 countries. The 111 papers were organized into sessions on supernovae, relativistic plasmas, radiative shocks, and opacities and equations of state. The overall impression gained from these conferences is that high energy density laser-driven experiments can be very useful for verifying many aspects of computer codes used to model astrophysical phenomena. Experiments on Nova have
already been useful but the higher energy NIF experiments will be able to measure material properties at higher temperatures and pressures and follow instability growth and other physical processes longer and with fewer limiting boundary conditions. Ideas for specific laboratory experiments emerged in several new areas. The next international conference is planned for March 2000 at Rice University.

**Conclusions:**

This paper has explored a few of the ICF applications that will be explored on the NIF. Lack of space has prevented a comprehensive survey of all suggested applications. For example, the copious neutrons produced could be used to produce intense neutrino sources for scientific studies or to examine blanket designs for fissile fuel production or radioactive waste destruction.

For some applications, experiments on Nova have already demonstrated the ability to obtain useful data on relevant issues. For others, NIF itself will needed to produce the conditions necessary to prove feasibility. With so many possibilities it is likely that experiment time on NIF will be oversubscribed for some time.

**References:**


