DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, 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 any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

UCRL-98669
PREPRINT

Received
JAN 30 1989

PROGRESS ON ACHIEVING THE ICF CONDITIONS NEEDED FOR HIGH GAIN

John D. Lindl

This paper was prepared for submittal to
the Eighth Topical Meeting on
the Technology of Fusion Energy
October 9-13, 1988
Salt Lake City, Utah

December 23, 1988

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

Lawrence
Livermore
National
Laboratory

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

John D. Lind?
Lawrence Livermore National Laboratory
P. O. Box 5508, L-477
Livermore, California 94550
(415) 422-5430

ABSTRACT

Progress during the past two years has moved us much closer to demonstrating the scientific and technological requirements for high gain ICF in the laboratory. This progress has been made possible by operating at the third harmonic of 1 μ m light which dramatically reduces concern about hot electrons and by advances in diagnostics such as 100 ps x-ray framing cameras which greatly increase the data available from each experiment. Making use of many of these new capabilities, major improvements in confinement conditions have been achieved for ICF implosions. In particular, in an optimized hohlraum on Nova, radiation driven implosions with convergence ratio in excess of 30 (volume compression $\sim 3 \times 10^4$) have performed essentially as predicted by spherical implosion calculations. This paper presents these results as well as examples of advances in several other areas and discusses the implications for the future of ICF with lasers and heavy ion beam drivers.

The objective of the ICF Program, since its inception in the early 1970's, has been to attain a high yield (100-1000 MJ) microfusion capability in the laboratory for defense and civilian applications. This will require achieving high gain (the ratio of fusion energy output to driver energy input) from an inertial fusion target driven by an approximately 10 MJ driver. In 1986, a National Academy of Sciences (NAS) committee completed a year long review of the ICF Program. The NAS review concluded that about five years would be required to obtain the data base needed for a decision about the future direction of the ICF program. However, in the intervening period, results from the Nova laser at the Lawrence Livermore National Laboratory (LLNL) and the Joint Livermore/Los Alamos classified Hailite/Centurion program have been obtained more quickly than anticipated.² Using appropriately scaled

targets, we have demonstrated most of the conditions needed to achieve high gain in the laboratory.

This progress has generated renewed enthusiasm within the Department of Energy (DOE) and the national ICF community for an aggressive approach toward developing the technology and cost base for a laboratory Microfusion Facility (LMF) and demonstrating high gain in the laboratory.

The various approaches to imploding capsules are often divided into indirect drive and direct drive targets. In indirect drive targets, the driver beams are aimed at a material near the capsule to generate x-rays which are then absorbed in the fusion capsule ablator to produce the implosion. The capsules and capsule issues for this approach are essentially independent of the driver if the driver can produce the required flux, spectrum, and temporal profile of x-rays. In direct drive targets, the driver beams are aimed at the surface of the capsule. With this approach, the capsules and physics issues, such as symmetry and hydrodynamic instability, are specific to each driver.

The Omega laser at the University of Rochester and the GEKKO XII laser at Osaka, Japan are the principal facilities worldwide devoted to the implosion of laser driven direct drive capsules. Significant progress has been made on this approach in the past several years. For example, the University of Rochester, using targets having initially solid density DT cryogenic fuel layers, has achieved compressed DT fuel densities of about 20 g/cc. However, laser intensity variations with these current lasers is an order of magnitude or more greater than is tolerable for the high convergence capsules required for high gain. For example, the yield from the Rochester high density implosions was only 10⁻⁴ to 10⁻² times those expected for a spherical implosion. Before the critical issue of the effects of hydrodynamic instabilities on these capsules can be investigated, significantly improved irradiation uniformity will be required.

Because radiation driven targets are largely independent of the source of x-rays, we have been able to take advantage of the copious quantities of x-rays produced by a nuclear explosion to investigate the properties of efficient high gain ICF capsules. This joint effort between Livermore and Los Alamos is called the Halite/Centurion Program and provides ICF radiation driven capsules with a unique advantage. Although laboratory drivers are currently too small to reach the conditions required for ignition and high gain, we can use the nuclear driven experiments to develop criteria that such a driver must satisfy for successful implosions.

The Nova laser is the primary U.S. laboratory facility devoted to the study of the indirect drive approach to inertial fusion. Nova's principal objective is to demonstrate that laser-driven hohlraums meet the conditions of beam/target coupling efficiency, beam irradiation symmetry, beam pulse shaping, target preheat, and hydrodynamic stability required for high gain. In the past two years, rapid progress has been made toward all these objectives. Various Nova experiments with about 20 kJ of 0.35 μm light have achieved major advances in the imploded fuel conditions for laser driven ICF. The remainder of this paper is primarily devoted to a comparison of theory and experiments done on the Nova facility.

THEORY AND EXPERIMENTS

In contrast to magnetic fusion, confinement during thermonuclear burn is not an issue for ICF. For ICF, the fundamental issue is producing the proper imploded configuration of the fuel. If the proper configuration is achieved, there is universal agreement that the fuel will produce the amount of energy predicted by both computer simulations and analytic models.

In order to achieve the proper configuration, all of the plasma, atomic, transport, and hydrodynamic processes associated with beam-target interaction and implosion must behave properly, and the illumination must be controlled to high precision to achieve the desired spherical symmetry. To achieve the required symmetry and to achieve adequate control over hydrodynamic instabilities during implosion, we have adopted indirectly driven (or hohlraum) targets as the main approach at Livermore. In our Nova experiments, we now measure and accurately model hohlraum temperature, hohlraum temperature gradients, capsule temperature, capsule symmetry, neutron production time, burn width, the fuel density-radius product (ρr), and the size of the burn region. Hot electron preheat, a dominant concern for 1 μm and longer wavelengths, is not important for 0.35 μm lasers such as Nova as shown in Fig. 1. Plotted

Fig. 1. Because of collisional stabilization, hot electron production with 0.35- μm light on gold is small at all plasma densities and scale sizes for most conditions of interest to radiation drive.

In Fig. 1 is the fraction of the incident laser light scattered by the Raman parametric instability versus the ratio of the electron collision frequency to the Raman growth rate. This instability has been the dominant source of high energy electrons in multikilojoule experiments. These high energy electrons cause target preheat which limits compression. Since the ratio of the electron collision frequency to the Raman growth rate scales approximately as λ^{-4} (where λ is laser wavelength) at fixed intensity, the plasma collisionality increases very rapidly as the laser wavelength decreases. For $\lambda = 0.35 \mu\text{m}$ and intensities of $10^{14} - 10^{15} \text{ W/cm}^2$, typical of most ICF targets, the level of hot electrons is well below the maximum tolerable levels.

Details of hohlraums will not be discussed in this paper. Instead, recent experiments to diagnose the imploded core of the target will be described. If the imploded core has the proper configuration (and therefore the proper yield), it indicates that all of the other processes have been adequately understood and controlled and that good symmetry has been achieved.

In most high-gain target designs, the appropriate fuel configuration consists of a central "hot spot" of fuel surrounded by a spherical shell of colder, high density fuel. The deuterium-tritium fuel in the hot spot must have a ρr product greater than about 0.3 g/cm^2 to capture the alpha particle energy. The temperature of the hot spot must be greater than 4 or 5 keV to achieve ignition. For efficient fuel burn, the colder fuel must have a ρr product of a few g/cm^2 usually at a density of a few hundred g/cm^3 (~1000 times solid density). For high-gain designs, the radius of the hot spot is typically about 1/40 of the initial capsule radius. We refer to the ratio of initial capsule radius to the radius of the hot spot as the convergence ratio; thus typical target designs have a convergence ratio of about 40. Simple models indicate that the capsule drive must be symmetric to an accuracy of the order of the reciprocal of the convergence ratio. For example, a convergence ratio of 40 requires illumination uniformity accurate to roughly 2.5%.

The energy available from Nova (currently about 20 kJ for routine experiments) is not large enough to achieve $\rho r = 0.3 \text{ g/cm}^2$ in the hot spot or $\rho r = \text{a few g/cm}^2$ in the cold fuel. We can however do hohlraum target experiments with drive pressures and geometries that scale to adequate ρr and high gain with a 5-10 MJ driver.

Many diagnostics are used to measure the features of the imploded core.³ These include nuclear activation techniques and scintillator detectors to measure neutron yield, photoconductive detectors to measure neutron emission time, time-of-flight measurements of primary and secondary neutrons to determine ion temperature and fuel areal density (ρr), an

x-ray pinhole framing camera and a neutron camera.⁴⁻⁶ The latter two diagnostics are used to image the burning fuel core.

A schematic diagram of the x-ray framing camera is shown in Fig. 2. The time resolution is about 150 ps. Figure 3 shows two pictures taken with this camera. One shows a symmetric implosion within the resolution of the experiment and one shows an implosion purposely designed to produce an asymmetric implosion. For comparison, the corresponding numerical calculation from LASNEX is also shown.

Figures 4 and 5 show a schematic of the neutron imaging method and an unfolded neutron intensity plot as a function of position. This device currently has a resolution of about $35 \mu\text{m}$ but $10 \mu\text{m}$ resolution may be attainable. Figures 2 through 5 are illustrative of new diagnostics now being used on Nova; however, simple measurements of thermonuclear yield remain an important tool. Figure 6 gives the ratio of experimental yield to calculated yield for a variety of hohlraum targets fired on the Nova laser. This ratio is plotted as a function of convergence ratio. It is important to emphasize that calculated yield in this figure refers to the yield calculated using a one-dimensional model which assumes that the targets are perfectly spherical. Because of imperfect fabrication, nonuniform illumination, and instabilities, we do not expect real targets to be perfectly spherical; therefore the

Fig. 2. Schematic diagram of the x-ray framing camera. This camera uses a gated microchannel plate to obtain four independently gated x-ray pinhole pictures. Each picture has a framing time of about 150 ps.

**Experiment with
symmetric drive**

**Experiment with
asymmetric drive**

**Experimental
and calculated
self-emission
contours for the
asymmetric case**

Fig. 3. The top figure shows the imploded core of a target designed to implode symmetrically. The picture was taken using the framing camera in Fig. 2. Within the resolution of the experiment, the core is symmetric. The middle figure shows the imploded core of a target that was driven asymmetrically. The bottom figure shows the contour of the asymmetric implosion at 25% of peak intensity. The contour calculated by our LASNEX simulation code is shown for comparison. The agreement is excellent.

theoretically expected yield is smaller than the one-dimensional yield. Uncertainties in drive lead to uncertainties in the one-dimensional calculations indicated by the shaded band. Calculations that include the effects of asymmetries and instabilities are in progress.

For convergence ratios as high as 30 the measured yield is within about a factor of 2 of the one-dimensional yield. A control experiment with a 15% asymmetry gave a yield more than an order of magnitude smaller than corresponding experiments with good symmetry.

We are attempting to extend these encouraging results to convergence ratios higher than 30, but we believe that we are beginning to encounter the present limits of the Nova laser. In order to achieve good performance at higher convergence ratio we may have to improve the energy balance, timing, and pointing of the laser beams. A program to improve the Nova laser is in progress. In addition to improving the beams, we expect to increase the total energy to about 60 kJ which will allow us to implode larger targets.

Fig. 4. Schematic diagram of the penumbral neutron imaging camera. The neutrons are detected by an array of 2-mm-square scintillation detectors. The neutron image is obtained by numerically unfolding the coded image.

Fig. 5. The unfolded neutron image of a target showing a burning core with a radius of about 100 μm .

Fig. 6. Fusion yield divided by 1-dimensional calculated yield as a function of convergence ratio for a variety of targets. The shaded area indicates the uncertainty in the calculations and the point with error bars indicates typical uncertainty in the measurements. Comparison of the Nova points with older points from the Shiva and Novette lasers shows how much the results have improved.

Overall we find our results encouraging. As a general rule, small targets are usually more sensitive to small imperfections than the larger targets appropriate for an ICF power plant.

One caveat is very important. Most of our experiments have been performed using simple pulse shapes. We have not yet done experiments with the long, highly shaped pulses required for high-gain targets. We plan to do experiments with more complicated pulse shapes in the coming 2-3 years; however, tests of the very long pulses (~ 50 ns) appropriate for power production can not be done on Nova.

For indirect drive to be efficient and lead to high gain targets, the conversion of driver energy to x-rays must be efficient. The conversion efficiency for lasers is wavelength, intensity, material, and pulse length dependent. Shown in Fig. 7a and 7b are x-ray conversion results from Nova and Omega obtained by irradiating gold targets with 0.35 μm light. As shown in Fig. 7a, conversion efficiencies of about 70% are obtained on Nova for 1-ns pulses at intensities of 10^{14} W/cm². Conversion efficiencies on Omega were 10-15% higher, probably because of the improved beam uniformity obtained by overlapping 24 beams on a sphere. Figure 7b shows that conversion efficiencies are also pulse length dependent, reaching a conversion efficiency on Nova in excess of 80% for 4-ns pulses at intensities of mid 10^{14} . Targets driven by a 10 MJ laser would require pulse lengths of about 10-ns. We do not have data for these long pulses, but the current data makes us optimistic that by paying attention to beam uniformity, we will achieve conversion efficiencies of 80% or more at the intensities required by these targets of a few times 10^{14} W/cm².

We also expect ion beams to achieve high x-ray conversion efficiency at sufficiently high focused intensities as shown in Fig. 8. Ion beams and lasers have opposite intensity scalings as shown. Laser beams are absorbed at low density and produce a high temperature corona. Electron conduction must transport energy from this region to a region of optimal temperature and density for x-ray conversion. As intensity increases, the losses involved in this process increase and we obtain a lower conversion efficiency. Ion beams on the other hand, because of their long range, do not heat material to a sufficiently high temperature for efficient radiation unless the intensity exceeds a certain minimum which increases as the range of the ions increases. Achieving this required intensity is the major challenge for ion beam driver approaches to ICF.

All high gain ICF capsules require a layer of cryogenic fuel that can be as thick as several hundred microns. Laboratory implosion experiments to date, such as those recently done at the University of Rochester, or earlier experiments at KMS Fusion and Livermore employ techniques which are only useful for producing

Fig. 7a. X-ray conversion efficiency with $0.35 \mu\text{m}$ light exceeds 70% for nanosecond pulses with $I \sim 10^{14} \text{ W/cm}^2$.

Fig. 7b. X-ray conversion efficiency depends on the duration of the laser pulse.

Fig. 8. Calculation for ion beams predict high x-ray conversion efficiency above a threshold intensity which depends on the range.

layers which are a few microns thick. At Livermore, we have been developing targets which rely on low density, low-Z foams to produce layers of arbitrary thickness as shown schematically in Fig. 9. The foam, which wicks up DT by surface tension forces, provides a matrix to define the shell dimensions. The required precision on shell dimensions is obtained by machining or molding the foam. Figure 10 shows an example of a foam hemishell machined from 0.05 g/cc CH foam. Targets such as these are suitable for the inexpensive mass production techniques that would be required for an ICF Reactor.

CONCLUSIONS

Although much experimental work remains to be done, the results of the last two years give us increased confidence in the gain predictions we have previously published and in the ultimate success of ICF. In fact the experimental results have been sufficiently encouraging that we at Livermore have begun shifting resources from target physics to driver development.

The national ICF program is also giving increased emphasis to new drivers. At a recent congressional hearing, the Assistant Secretary for Defense Programs in the U.S. Department of Energy (DOE) testified⁸: "The consensus of the ICF community and DOE is that the program has progressed much more rapidly than the 1985-1986 [National Academy of Sciences ICF Review] Happer Committee or anyone else anticipated in 1985. In fact, several significant scientific firsts have been achieved in the last year. These results have presented the U.S. with the opportunity to embark on a new phase in the ICF program, the planning of a Laboratory Microfusion Facility." The present goal is to complete the LMF within a decade.⁸

ACKNOWLEDGMENT

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Fig. 9. Use of low density, low-Z foam to define and stabilize a cryogenic DT shell, allows an attractive single shell target design.

50 mg/cm³ CH foam

Machined to $\lesssim 1 \mu\text{m}$ surface finish

Wicks up liquid DT to provide a thick, freestanding fuel layer

Fig. 10. Plastic foams with a density as low as 0.03 g/cm³ and submicron cell sizes are now available.

REFERENCES

1. Review of the Department of Energy's Inertial Confinement Fusion Program, Commission on Physical Sciences, National Research Council, National Academy of Sciences, National Academy Press, March 1986.
2. A detailed review of the Livermore ICF program is given by E. Storm, J. Lindl, E. Campbell, T. Bernat, L. Coleman, J. Emmett, W. Hogan, J. Hunt, W. Krupke, W. Lowdermilk, Lawrence Livermore National Laboratory Report UCRL-99383 (1988).
3. The Laser Program Annual Reports from Lawrence Livermore National Laboratory are excellent sources of information on diagnostics. The 1986 Report was published as Lawrence Livermore National Laboratory Report, UCRL-50021-86. Earlier reports have the same number except the last two digits which indicate the year.
4. J. D. Kilkenny, P. Bell, R. Hanks, G. Power, R. E. Turner, and J. W. Wiedwald, Nuclear Instruments and Methods, Aug 1988 (to be published).
5. D. Ress, R. A. Lerche, R. J. Ellis, S. M. Lane, and K. A. Nugent, Science (to be published).
6. D. Ress, R. A. Lerche, R. J. Ellis, S. M. Lane, and K. A. Nugent, Nuclear Instruments and Methods, August 1988 (to be published).
7. Testimony provided by Mr. Troy Wade, Department of Energy Assistant Secretary for Defense Programs, to the Subcommittee on Procurement and Military Nuclear Systems of the U.S. House of Representatives Armed Services Committee. March 2, 1988.
8. Department of Energy Inertial Confinement Fusion Program Plan Summary for Fiscal Years 1988-1992. February 1988, and Laboratory Microfusion Capability, Phase I. Department of Energy Report, 1988, to be published.