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AUTHOR(S): Stephen M. Younger

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Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

SUMMARY OF PROGRESS IN INERTIAL CONFINEMENT FUSION

Stephen M. Younger
Los Alamos National Laboratory
USA

1. INTRODUCTION

Progress in inertial confinement fusion (ICF) has been very rapid over the past two years. Significant advances have been made in the production of smooth laser beams, the focusing of light ions beams, and the development of heavy ion accelerators. The availability of advanced target diagnostics on several major drivers has resulted in an extensive database of target performance over a wide range of conditions. Theoretical models of ICF targets are approaching the predictive level with two and even three dimensional calculations becoming routine. Within the next several years information should be available to allow confident extrapolation to ignition on the next generation driver.

2. DRIVER TECHNOLOGIES

2.1 Glass lasers

The advanced state of glass laser technology is demonstrated by the available of research scale facilities in many countries and major facilities for target shooting in Japan, France, and the United States. The Nova laser at the Lawrence Livermore National Laboratory (LLNL) in the USA is the largest laser in the world and routinely provides up to 40 kJ of 351 nm light in a total of ten beams for target experiments. Because its beams are arranged in two opposite cones, Nova is best suited for the indirect drive approach. The Phebus laser at Limeil, France is very similar to two opposing beams of the Nova laser and is also used for indirect drive experiments. The Gekko XII laser at Osaka University, Japan, is a twelve beam laser that can provide 10 kJ of frequency tripled (351 nm) light for both direct drive and indirect drive target experiments. The Omega laser at the University of Rochester, USA is currently being upgraded to 30 kJ in 60 beams for direct drive target experiments.

In addition to the major target shooting facilities, there are a number of smaller glass lasers in the few hundred joule to kilojoule class. While not able to perform some classes of implosion experiments because of limited energy (for the case of indirect drive targets) or irradiation uniformity (for the case of direct drive targets) these facilities have proven valuable in studying many individual processes important for ICF including laser plasma instabilities, ablation, x-ray conversion, and hydrodynamic instabilities. The availability of such facilities has enabled more institutions to become involved in ICF with the benefit of many new creative ideas entering the field.

Research on glass lasers has concentrated on the improvement of beam quality. While uniform irradiation is absolutely essential to the direct drive approach, recent studies have demonstrated that it is also important for indirect drive owing to the sensitivity of laser plasma instabilities to hotspots in the drive beams. Illumination uniformity depends on the distribution of the laser intensity across a single beam diameter, the precision with which the beam is placed on the target, and the relative balance of the many beams involved in an experiment. Concerted efforts have reduced beam balance uncertainties to less than 10% and allow routine beam placement to within tens of microns.

Beam smoothing on glass lasers has been accomplished by several techniques. Random phase plates can be inserted after the final amplifier to break the original drive beam into many beamlets with slightly differing phases, resulting in a scrambled pattern on the target. The fixed pattern on the phase plate means that the intensity distribution is not strictly random, but a significant improvement over unsmoothed beams is achieved. The use a broadband pulse reduces the coherence time of the individual beamlets and improves the randomness of the illumination pattern. This technique, known as smoothing by spectral dispersion (SSD), is expected to produce beams with uniformity in the few percent range. Finally, in the induced spatial incoherence scheme an incoherent beam is propagated through the amplifier chain to produce a smooth intensity distribution on the target.

There are three major glass lasers under development at present. Osaka University, Japan, has proposed a 100 kJ upgrade of the Gekko XII laser to approach or possibly reach ignition. This facility has been described as using conventional amplifier design and could employ advanced beam smoothing techniques.

Already under construction at the University of Rochester is the Omega Upgrade laser intended to explore the pre-ignition regime using direct drive. Omega Upgrade will produce 30 kJ in a 40 TW shaped pulse at 351 nm. With sixty beams, illumination uniformity of 1-2% is expected using SSD. Prototype tests for the two final disk amplifier stages have been completed successfully and completion of the facility is expected in the mid-90's.

Most glass laser facilities are based on a single pass design whereby a series of amplifiers are used to amplify a small pulse from the front end. For a megajoule class facility the number of disk amplifiers required in a single pass configuration would dominate the cost of the facility, and research is ongoing to develop multi-pass amplifier designs that are more efficient both in terms of space and the amount of expensive laser glass involved. The University of Rochester and Livermore have demonstrated multi-pass amplifier designs and Livermore is now constructing a large scale proof-of-principle test of a multi-pass design called the Beamlet. The Beamlet will employ a large aperture pockels cell for beam switching out of the main amplifier cavity. Efficiency will be enhanced by the clustering of beamlines within a single large flashlamp cavity and precision control of pulseshaping and beam uniformity are provided for in the design. The Beamlet is intended to demonstrate, at full scale, the technology required to construct a megajoule class ignition laser at affordable cost, and is the prime candidate for the National Ignition Facility under consideration by the United States.

2.2 KrF Lasers

Krypton fluoride lasers are attractive candidates for ICF owing to their intrinsic short wavelength (0.25 μ), broad bandwidth, pulse shaping capability, high efficiency, and their ability to be repetitively pulsed. (The last feature is important for energy applications.) The Ashura laser at the Electrotechnical Laboratory in Japan is currently the largest KrF laser operating routinely and produces 660 J in six angularly multiplexed beams. The "Super Ashura" program is currently in progress with the design goal of 10 kJ in twelve beams.

Two KrF lasers are under construction in the United States. The Mercury laser at Los Alamos, planned for operation in 1993, is intended for basic KrF technology development and will consist of two main amplifiers delivering 150 J in a 200 ps - 5 ns pulse. A third amplifier planned for future expansion will allow an upgrade to 800 J.

The Nike laser at the Naval Research Laboratory is designed to produce 3 kJ in 44 angularly multiplexed beams (with an additional 12 beams available for target backlighting) in a 4 ns shaped pulse. Nike uses the ISI technique to achieve exceptionally smooth beams. The primary purpose of Nike will be to demonstrate the uniform acceleration of planar targets using a laser pulse close to the one required for direct drive ignition. Nike is expected to be completed in 1994.

2.3 Light Ion Accelerators

Light ion accelerators offer advantages for inertial fusion owing to their high efficiency, low cost compared to lasers, and simple beam-target coupling. Light ion accelerator technology achieved a significant breakthrough in 1992 with the focusing of lithium beams to high intensity. The Particle Beam Fusion Accelerator II (PBFA II) at Sandia National Laboratories (USA) has successfully generated nearly pure lithium beams with a divergence less than 20 milliradians. Beam intensities greater than 1 TW/cm^2 have been measured and are in excellent agreement with computer simulations. Several methods are under development to reduce beam divergence still further.

Osaka University has developed a multi-gap accelerator design with beam bunching, allowing the acceleration of carbon ions to 100's of MeV for a lower current driver design. A multiply ionized beam has be produced from a carbon source producing 400 A/cm^2.

2.4. Heavy Ion Drivers

Heavy ions are considered a leading candidate for energy applications of ICF because of their high efficiency, reliability, and ability to be repetitively pulsed. Technology development in Europe is concentrated on the RF linac approach; in the United States the induction linac approach is under development. The Induction Linac Scaling Experiment (ILSE) at the Lawrence Berkeley Laboratory (USA) is designed to test beam physics at the same beam diameter required for a reactor driver. The major considerations associated with heavy ion accelerators are the achievement of high beam quality and the high cost of an accelerator that would permit significant target physics experiments.

3. TARGET PHYSICS

3.1 Laser Plasma Interactions

Extensive studies of stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) have been undertaken over the past several years. These instabilities are of concern since they scatter laser light into unwanted directions and can produce high velocity electrons that can result in fuel preheat and hence a less effective implosion. Beam smoothing has been demonstrated to reduce laser plasma instabilities by a factor of 100 or more, although Livermore has reported a complex time history to the scattered light that needs to be addressed further. Filamentation has also been shown to be suppressed by beam smoothing. Unsmoothed beams can produce long lasting channels in the plasma.

Most laser plasma instability experiments have used laser-exploded foils as plasma sources with separate probe beams for interaction studies. Typical parameters are plasma lengths of 300-1000 microns and temperatures of 300-1000 eV. Experiments to study laser plasma instabilities in hohlraums are in progress.

3.2 Hohlraum Physics

Temperatures higher than 200 eV have been reported for laser driven hohlraums. The results of implosion experiments that are sensitive to the x-ray irradiation symmetry have been presented and indicate that control over implosion dynamics can be achieved at least at the level compatible with current drivers. Osaka University has studied drive symmetry in hohlraums using implosions with convergence ratios up to 20:1 and high resolution x-ray imaging. Both the Osaka and the Livermore groups report that flux uniformity of the order of 1% is possible.

There have been extensive experiments to study x-ray conversion efficiencies of various high-Z materials and to study ablation of low-Z ablator materials including beryllium and plastic. Many of these experiments were performed on smaller drivers.

The transport of x-rays in cylindrical geometry has been studied in cylindrical geometry by the Garching group, including the effect of plasma blow-in and stagnation within the cylinder. This stagnation has been shown to produce x-rays late in time compared to the original drive pulse.

3.3 Implosion Instability and Mix

The success of inertial fusion rests on the ability to symmetrical compress a target to high convergence without the introduction of excessive wall material into the fuel that could inhibit ignition and burn. Major progress in the understanding of hydrodynamic instabilities has been reported over the past few years.

Theoretical models of linear Rayleigh-Taylor instability growth have been confirmed by planar experiments at several laboratories. Single mode grown and two mode coupling have been examined using both direct and indirect drive and are in good agreement with the Takabe formula. Growth factors of 60-70% of classical have been demonstrated and several stabilization mechanisms are under investigation. Cylindrical and spherical implosion studies are in progress to test the effect of convergence on instability growth, the former by axial imaging and the later by spectroscopic and other diagnostics. (The use of an argon loaded fuel and a chlorine loaded pusher allows spatial discrimination of material.) The results of indirectly driven implosion symmetry studies were reported by American, French, and Japanese groups.

Ablation physics has been studied by many laboratories. The Bombay group reported experimental studies of high-Z loaded ablators that indicate that relatively low levels of x-ray generation can suppress some forms of instability growth.

Three dimensional calculations of instability grown are now possible on the largest supercomputers. While not all of the relevant physics can be included at the same level of detail as in current two dimensional calculations, 3D results are beginning to provide important information on instability growth and mix. Preliminary 3D studies of mix in during the later phase of the implosion, performed by the Rutherford-Appleton Laboratory, suggest departures from two dimensional behavior.

The "start up" problem remains a significant issue for direct drive implosions. During the early part of the laser pulse, before the formation of a plasma corona, initial laser beam non uniformity can be imprinted onto the pusher, effectively creating seeds for hydrodynamic instability growth. Hybrid designs that employ x-ray pre-illumination of the target have been proposed to create a plasma corona prior to the arrival of the main direct drive laser pulse.

3.4 Ion Target Interactions

The PBFA II accelerator at Sandia has been used for an initial series of target physics experiments. Direct drive exploding pusher capsules have been driven by proton beams to a compression of 5:1. Protons have also been used to study ion beam driven hohlraums. Hydrocarbon foams mounted in gold cylinders have been heated with 30-50 kJ of beam energy. It was shown that the foam both enhanced the radiation and tamped the motion of the Au case. Lithium experiments are in progress on PBFA II with the promise of driving hohlraum targets at greater than 1000 TW/gm.

Theoretical studies of light and heavy ion fusion targets have been reported by groups in Italy and Japan and suggest that two beams may not be sufficient to achieve the required capsule illumination uniformity. While not an issue for light ion fusion, this requirement could complicate heavy ion fusion designs.

3.5 Computer Codes and Computations

Two and, to a lesser precision, three dimensional calculations of ICF targets are now routine in many laboratories. Because of the difficulty of treating even hydrodynamics in three dimensions approximations are necessary including in the equation of state, the models for thermal conduction, opacities, and more. Hence 3D calculations at present are more of an exploratory than a predictive nature.

Very large scale two dimensional calculations have been performed by Los Alamos with the aim of providing a self-consistent description of indirect drive targets. Agreement with experimental data is reported to be good, an encouraging sign for the extrapolation to ignition target designs.

Although most ICF hydrodynamics codes are Lagrangian, Eulerian calculations are becoming increasingly important for the study of instability growth and the transition from the non-linear to the turbulent stages. The Osaka group reported impressive Eulerian calculations of the later stages of instability and mix.

Although numerical calculations will undoubtedly continue to be the mainstay of ICF target theory and design, recent analytic solutions to 2D and 3D hydrodynamics problems developed at Los Alamos provide benchmarks for code comparison, especially for the difficult numerical problem of high convergence implosions.

3.6 Target Diagnostics

Improvements in target diagnostics have led to both a wider variety of data and improved precision in experimental measurements. Optical measurements of laser plasma instabilities are improving and promise to provide quantitative estimates of scattered and absorbed light in realistic target configurations.

X-ray imaging continues as a standard implosion diagnostics. Gated x-ray imagers now provide spatial resolution of 5 μ and temporal resolution of 80 ps. Using strip lines, many sequential frames of the implosion can be recorded. (Since the diagnostic records capsule self-emission in the keV range, only the part of the implosion near stagnation is usually seen.) Fast (20 ps) high energy (5-7 keV) backlighting techniques are being developed to provide an additional imaging capability that is not dependent on capsule self emission. Although conceptually straightforward, the interpretation of any imaging method for ICF implosions is complicated by the complex density and temperature gradients in the capsule.

Neutron diagnostics will become more important as experiments shift attention to higher convergence implosions which are opaque to x-rays. In addition to radiochemical activation, large area single hit detectors have been developed for ion temperature measurements and neutron imaging has been applied to some experiments.

The next generations of diagnostics will increasingly rely on electronic recording rather than film due to the higher radiation levels associated with ignition level experiments. Increased emphasis will also be placed on the integration of various diagnostic methods to achieve a total picture of capsule performance.

3.7 Target Fabrication

High precision fabrication of complex direct and indirect drive targets has become routine. Complex metallic and organic layers can be provided for diagnostic or hydrodynamic functions and foams with cell sizes much smaller than 1 μ can be produced with high uniformity and density control. The routine nature of target fabrication is a significant achievement when one considers the much greater complexity and precision required of modern target experiments.

Almost all proposals for ignition targets involve cryogenics. The Osaka group has demonstrated an impressive technology for cryogenic implosions on the Gekko XII laser. Los Alamos reported the successful formation of solid DT layers with uniform surface and thickness characteristics.

4. PULSED POWER APPROACHES TO ICF

Several Russian groups have reported work on the application of high energy pulsed power generators to inertial fusion. The Angara V accelerator at the Kurchatov Institute at Troisk has been used to generate radiation temperatures in excess of 130 eV. This method employs a cylindrical implosion of xenon gas onto a coaxial molybdenum loaded carbon foam. Upon impact, the kinetic energy of the xenon is thermalized and radiation is produced. The molybdenum in the central foam region traps the radiation, allowing the radiation temperature to increase to its maximum value. Simple analytic scaling laws predict that more energetic facilities might reach substantially higher temperatures, making this technique attractive for ICF applications. Issues related to instability growth during the implosion and the spectral content of the radiation need to be addressed.

The All Russian Institute of Experimental Physics is pursuing several interesting approaches to fusion. High explosive driven magnetic flux compression generators have been demonstrated at the 200 MJ level with operation times in the range 2-10 μs. Cylindrical implosions with megajoule kinetic energies have been achieved and some quasi-spherical implosion work has also been reported. The general approach followed in this work is to preheat and premagnetize a plasma in preparation for implosion. The preheat means that convergence ratios required for ignition are much more relaxed than for traditional ICF designs. The magnetization of the plasma means that a slower implosion velocity can be tolerated due to suppressed thermal losses. Both of these features are compatible with the very high energy electrical generators already perfected by the Russian groups.

5. FUTURE PLANS

Encouraging for progress in inertial fusion is the involvement of a number of smaller groups using modest laser or pulsed power facilities. Detailed studies of specific processes on such machines provide valuable support and new ideas for later application on major national drivers. The availability of high speed, large memory computer technology provides a similar advantage for theorists.

The next major step in the international ICF program will be the demonstration of ignition and burn in the laboratory. Significant progress has been achieved in many aspects of target physics, and within a few years one might expect a thoroughly benchmarked predictive theoretical capability to be demonstrated that allows a confident extrapolation to ignition requirements. At the same time, advances in laser and ion beam technologies have improved the quality and reduced the cost of advanced drivers to the point where an ignition facility of acceptable cost can be designed.

Under the auspices of the US Department of Energy the Lawrence Livermore National Laboratory is leading an ambitious American effort to construct an ignition class glass laser called the National Ignition Facility. Government approval to begin a design study for this facility has been obtained and major progress has been made on the demonstration of multi-pass amplifier technology that is expected to significantly reduce the cost of this 1-2 MJ glass laser over that associated with a single pass amplifier configuration. Current plans call for a major decision to proceed in 1995 and facility completion by 2002. Following machine characterization and initial target physics studies, ignition could be achieve in 2005.

The Institute for Laser Engineering at Osaka University has proposed a 100 kJ upgrade of the Gekko XII laser that is expected to approach or possibly even reach ignition. Although not fully funded at the time of this writing, much of the technology required for this upgrade has already been demonstrated.

The Omega laser at the University of Rochester is now being upgraded to 30 kJ which will allow the important pre-ignition regime to be explored in detail using direct drive. The results of these experiments will be used to evaluate an direct drive option for the US National Ignition Facility.

KrF laser technology is expected to make major advances within the next two years with the continued operation of the Ashura laser in Japan and the completion of two new facilities in the United States. In particular, the Nike laser is anticipated to produce the very smooth beams required to test smooth (although planar) target acceleration analogous to that which is required in an ignition target.

Major developments in light ion accelerators have led to renewed interest in this driver for fusion applications. Over the next several years one may expect extensive target physics studies to be performed on light ion machines, as well as a reduction in the already impressive beam divergence. While ion beam fusion lags substantially behind laser fusion in the amount of target physics information available, the relatively low cost of such machines and the expected simple beam-target coupling continue to make them attractive candidates.

For longer term applications, heavy ion accelerators are being developed to test beam control at diameters equal to that required for reactor applications.

Finally, the lessening of international tensions has led to the reporting of very impressive work using pulsed power by Russian scientists.

7. SUMMARY

Based on recent progress in laboratories around the world, it is not unreasonable to expect that ignition and burn will be achieved on the next major ICF facility, a capability that could be available early in the next decade. Within the next few years the exercise of existing experimental and theoretical capabilities is expected to resolve most of the remaining critical issues associated with inertial fusion, including the achievement of very smooth target illumination, control of laser-plasma instabilities, demonstration of efficient ion-target coupling, characterization of hohlraum physics, and demonstration of control of hydrodynamic instabilities that affect high convergence implosions.