Summary of IFE Activities at LLNL

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1.0 Introduction

Lawrence Livermore National Laboratory (LLNL) is engaged in a broad range of activities that support the development of Inertial Fusion Energy (IFE). These include 1) the construction of the National Ignition Facility (NIF); 2) target design for both laser and heavy ion drivers, including work on fast ignition; 3) heavy ion driver development; 4) diode pumped solid state laser (DPSSL) development; and 5) chamber and power plant design and assessment activities. These efforts are summarized in this report.

2.0 National Ignition Facility

The NIF is being constructed at LLNL. The powerful neodymium-doped glass laser will be the world's largest, and its experiments will access high-energy-density and fusion regimes with direct applications to stockpile stewardship, energy research, science, and astrophysics. Enabling NIF Project technologies come from the Laser Science and Technology Program, which develops advanced solid-state laser and optics technologies, and the Inertial Confinement Fusion Program, which advances research and technology development in areas such as fusion target theory, design, fabrication, and testing. The project is a national collaboration between government, industry, and academia, including Sandia National Laboratories, Los Alamos National Laboratory, the University of Rochester Laboratory for Laser Energetics, General Atomics, the Naval Research Laboratory, and a multitude of industrial partners throughout the nation. When fully completed, NIF will use 192 beamlines grouped in 24 bundles to deliver about 1.8 MJ of 1/3 μm laser light to the target. First light is now anticipated in 2003, and the full 192 beams in 2008. Key to IFE will be the demonstration of ignition of a DT fuel capsule and target gain on the order of 20 or more.

3.0 IFE Target Design Program

The national Inertial Confinement Fusion (ICF) Program, supported by Defense Programs in the Department of Energy, has made significant progress in understanding the physics of inertial fusion. In particular, the indirect drive approach is sufficiently well understood to justify the construction of the NIF. However, significant additional work must be performed to move from this capability to the requirements of affordable energy from fusion. These improvements range from target gain increases, to consistency of the target design with various driver capabilities, to consistency of the target design with the illumination requirements of various chamber concepts and to consistency with target fabrication capabilities. The IFE target design program at LLNL includes work on heavy-ion targets, laser targets, advanced target concepts such as fast ignition and advanced fuels.

3.1 Heavy Ion Targets

For heavy ion fusion, the baseline approach is an indirect drive target with "distributed radiators" [1,2,3]. Because heavy ion accelerators are efficient, relatively low gains (~ 40) give an adequate driver efficiency times gain (ηG). By using indirect drive, we take advantage of the synergy with the ICF program. In addition, indirect drive targets generally allow the beams to enter the target from a small number of directions and are most compatible with thick liquid wall chambers like HYLIFE-II [4].

Recent work on the distributed radiator targets has been focused on a close-coupled design where a given capsule is imploded in a smaller hohlraum and roughly halves the ion beam energy required to obtain a given yield [5,6]. Gains of 130 at 3.3 MJ and 90 at 1.75 MJ ion beam energy have been obtained. Further reduction in required input energy is likely for this sort of design, limited mainly by achievable ion beam focusing.

The first calculations of a new target design, which allows a much larger ion beam focal spot, have been recently completed. The target is predicted to get a gain of 58 from 6.7 MJ of ion beam energy. The beam spot area increased by a factor of 2.7 over the "full-size" distributed radiator target (spot radius of 4.5 mm compared to 2.7 mm) with only a 15% energy penalty. This new target does introduce some new target physics issues including the use of a radiation shim to control early time asymmetries on the capsule.

In addition to hohlraum design, we have begun work on optimizing the high yield fuel capsule for indirect drive, IFE targets. To study the robustness of these high yield capsules to surface perturbations, two dimensional single mode and multi-mode simulations of capsules absorbing ~ 1 MJ were performed [7]. For the same surface roughness spectrum and amplitude, these capsules are much more robust than ignition scale capsules. In fact, the baseline HIF Be capsule appears to be able to withstand surface roughnesses (both ablator and ice) several times rougher than ignition scale capsules. Single mode growth factor calculations of perturbations seeded on the inner ice surface suggest that, in contrast to ignition scale capsules, the thicker high yield capsules are much less susceptible to feed out of perturbations from the ice surface. We took advantage of this improved stability at the larger scale by replacing the beryllium ablator with a plastic (CH) ablator in a new design. This has several notable advantages from the fusion energy perspective: it is thought that it might be easier to mass produce with high quality surface finish, it is possible to inspect and if necessary smooth the DT ice layer, diffusion DT filling is rapid, implying many fewer targets needed in the queue and a much smaller tritium inventory is necessary. The cost of these advantages is that the plastic must be driven at a higher drive temperature (265 eV rather than 250 eV) to make up for its poorer performance as an ablator. We are currently studying the trade off between surface finish requirements and drive temperature.

3.2 Laser Targets

For laser drivers, the baseline approach is direct drive targets such as the ones designed by the Naval Research Laboratory [8]. We have employed LASNEX [9], our 2-D radiation-hydro-burn target design code, to look at the fusion performance and 2-D stability of laser driven, direct-drive IFE targets. We have paid particular attention to reducing the numerical noise inherent in the 2-D modeling of such target with concurrent laser energy deposition. For the first time, we are able to demonstrate a full, time-dependent implosion to ignition with 2-D laser ray-trace in operation from time zero. In collaboration with the Naval Research Laboratory, we are now assessing the stability of their current laser direct-drive target designs.

3.3 Output Calculations

In order to design a reactor chamber, we need to know what form the energy produced by the targets will have (neutrons, x-rays, charged particles). We have employed LASNEX to obtain the energy and particle output spectra from both laser direct-drive targets and heavy ion direct and indirect-drive targets. By adding extra thickness to the hohlraum wall for indirect drive targets, calculations predict that we have some control over the amount of energy that ends up in x-rays versus charged particles. We have disseminated this information to the ARIES reactor design team in a collaborative effort to characterize the impact on IFE reactor chamber design and protection. Relative to the indirect-drive targets, we observe that the laser direct-drive targets exhibit much lower x-ray outputs, but the majority of their non-neutron yield is directed into D and T ions from the unburned fuel in the range 10's-100's keV. Such energetic ions will determine the pressure of the chamber buffer gas necessary to protect the solid first walls.

3.4 Advanced Target Concepts

We are exploring the prospects for inertial confinement fusion targets based on the advanced fuels (D-D and D-^{3}He). One big advantage of such fuels is that, with appropriate design, the majority of the fusion energy escapes the target as energetic charged particles and not as fast neutrons. This suggests the potential of employing advanced, non-thermal energy conversion systems and the application to directed thrust for advanced space propulsion. Of course the reactivities of such advanced fusion fuels only become comparable to that of D-T at significantly higher fuels temperatures. Thus such advanced fuel targets will require typical areal densities of ~10 g/cm^2 for adequate fuel burn-up and gain. Accordingly, fast ignition techniques are required to make these concepts viable at (compression) driver energies in the ≤10 MJ range. Adequate performance may be achievable by depositing the fast ignition energy in a small, pre-compressed ignitor region of D-T fuel that acts as a sparkplug for the main D-D or D-^{3}He fuel. The overall tritium inventory in the capsule can be less than 1%, and with appropriate design, these targets can be self-sustaining in tritium through the D(d,p)T branch of the D-D reaction, thus obviating the need for tritium breeding in the external plant.

4.0 Heavy Ion Drivers

Heavy Ion Fusion (HIF) driver research in the U.S. is coordinated by the HIF Virtual National Laboratory (VNL), which includes, Lawrence Berkeley National Laboratory (LBNL), Princeton Plasma Physics Lab, and LLNL. The HIF Program's long-range goal is to develop the scientific basis for IFE driven by high-brightness heavy ion beams. The research is divided into four broad areas: 1) The High Current Experiment (HCX); 2) studies of drift compression, beam focusing and propagation in fusion chambers; 3) ion beam simulations and theory; and 4) ion sources and injectors.

4.1 The High Current Experiment (HCX)

The single-beam HCX [10], currently being built, will be the first heavy-ion electric and magnetic quadrupole transport experiment with line charge density and pulse duration comparable to those expected for a driver. The expected advances in the understanding of the physics of intense ion beam transport and acceleration will enable the determination of the optimal beam size and pulse duration.

The HCX is being assembled in at least two phases: HCX Phase 1 will be a relatively short precursor (~1 year), configured primarily as an electrostatic transport experiment. The goal is to quantify the emittance growth of a single driver scale beam (~700 mA and 5-7 μs pulse length) through a combination of 40 electrostatic (6 plasma periods) and a small number of pulsed magnetic quadrupoles with various fill factors, quadrupole offsets, and beam centroid steering corrections. Ten quadrupoles are planned to be in operation by October 2001. The second phase of the HCX will better quantify intense beam transport characteristics in magnetic quadrupoles that are needed for a driver design. A first superconducting prototype quadrupole for HCX has been successfully tested in a separate experiment at LBNL.

4.2 Drift Compression, Beam Focusing, and Propagation

This area covers the region from the exit of the accelerator to the target. In terms of spatial configuration, it includes three major sections: 1) the pulse compression region that consists primarily of a long drift region in which a beam with a head-to-tail velocity tilt is compressed from ~100 ns at accelerator exit to ≤ ~10 ns near the target chamber; 2) The final focus magnet section, consisting of a number of discrete, high field magnets, the primary function of which are to prepare the beam with the right entrance condition for final transport into the chamber, and 3) the ballistic neutralized drift region that extends from the last magnet to the target through a Flibe-filled chamber.

In the pulse compression area, preliminary studies of the envelope and dispersion were carried out, and sensitivity to compression ratio for the Integrated Research Experiment (IRE) was studied with a beam fluid code HERMES. Third order aberration in final focus was studied with WARP 3D and the quadrupole lattice was optimized to minimize aberration effects. Since the physics of chamber transport is quite complex, the primary method of attack is with fully electromagnetic particle-in-cell simulations [11,12]. The physics of neutralization is also studied in scaled experiments. An experiment at LBNL using HCX and/or a lower energy beam at MBE-4 to study magnetic focusing and neutralization at higher perveance is being planned, and engineering design has begun. A plasma source and associated diagnostics are being developed at PPPL. The plan is to have the hardware brought to LBNL for the final beam experiment after testing and checkout at PPPL.

4.3 Ion Beam Simulations and Theory

We are working to apply and improve computational and theoretical tools so as to provide comprehensive simulation and modeling of ion beams, from the source to the target. The simulation and theory work guides our research and supports the other three research areas. Here we present a brief overview of the full spectrum of this work [13].

The HIF program has developed the fundamental understanding of ion beams with orders of magnitude more charge than in traditional accelerators, but important issues remain. The primary tasks include:
- Development of the necessary beam physics knowledge base.
- Development of the scientific basis for future fusion accelerators, including an IRE and a full-scale driver.

- Analytical and numerical studies contributing to the design and interpretation of experiments including the HCX, injector, planned focusing experiments and scaled experiments nearing completion.
- Development of the computational tools.

4.4 Ion Sources and Injectors

Heavy Ion-Driven Inertial Fusion requires beams of high brightness in order to achieve high power density at the target for high target gain. Thus the main goal of a HIF driver is to start with bright beams at the ion sources and minimize the beam loss and emittance growth during beam acceleration and transport. The performance and limitations of ion sources have significant impact on the entire driver system. The best ion source concept is the one that can simultaneously achieve high current, high current density and low ion temperature.

We are presently investigating two alternative approaches to produce 1.0 A level heavy ion beams for driver-scaled experiments such as the HCX [14]. The traditional way is to use a large diameter (> 10 cm) surface ionization source. A preliminary design based on this concept showed a very large structure with high storage energy.

The second and more recent approach is to extract multiple beamlets (of a few mA each) at very high current density near 100 mA/cm^2, and then merge the beamlets after they are individually accelerated to more than 1 MeV. The goal here is to achieve brightness by obtaining high average current density (including the grid transparency factor) in order to compensate for the high ion temperature and emittance growth from the merging process. Our leading source technology for this option is the plasma ion sources that have the advantage of being able to produce a variety of noble gas ions in comparison to the alkali metal ions from the surface sources.

5.0 Diode Pumped Solid Sate Lasers

We have begun building the “Mercury” laser system as the first in a series of next generation diode-pumped solid-state lasers for inertial fusion research [15]. Mercury will integrate three key technologies: diodes, crystals, and gas cooling, within a unique laser architecture that is scalable to kilojoule and megajoule energy levels for fusion energy applications. The primary near-term performance goals include 10% electrical efficiencies at 10 Hz and 100 J with a 2-10 ns pulse length at 1.047 μm wavelength.

The Mercury laser amplifier head and gas cooled architecture has been designed in a modular and scalable fashion, with the laser slabs mounted in aerodynamic vane elements. Gas flows over the faces of the laser slabs in the cooling channel to remove the waste heat generated during the lasing process. The assembled slab and vane cassette are then inserted into the amplifier head. The first laser head assembly was fabricated and installed in the Mercury laboratory. In order to fully test the amplifier head and pump delivery system this year, surrogate gain media (Nd:glass) were placed in the vane elements within the amplifier head. This allows us to test the pump delivery efficiency, pump light uniformity within the laser slabs, gas flow dynamics, and thermal deposition profiles. Once the Yb:S-FAP crystals are ready, we can easily switch the surrogate slabs with the crystals. We have assembled one out of four pump delivery arms.

A critical technology for realizing inertial fusion energy is in the cost and efficiency of laser diode arrays. Existing diode technical performance specifications do not currently meet the demanding requirements of IFE. In addition, the manufacturing costs will have to be reduced by approximately two orders of magnitude to make IFE economically viable. Together with an industrial partner, Coherent-Tutcore, we made significant progress on the development of aluminum-free 900 nm laser diode bars. We packaged, characterized and life-tested arrays of 900 nm laser bars using this diode material. About 25% of the diode tiles have been completed thus far.

Significant progress has been made in understanding the growth characteristics and defect chemistry of Yb:S-FAP [Yb^{3+}:$Sr_5(PO_4)_3F$] crystals. The growth of full size crystals has been a challenge due to a number of defects, including: cloudiness in as-grown boules, bubble core defects, grain boundaries, and cracking in larger diameter boules > 4.0 cm. We have recently produced boules that meet the Mercury specifications and which have been fabricated into one laser slab at this point.

A simple scaling of beam smoothing has been established which is helpful in the analysis of prospective IFE laser drivers. By applying spectral shaping to the amplifier input and broadband frequency conversion with dual triplers, the gain narrowed bandwidth can be increased to ~1 THz for DPSSLs. Such a laser amplifier (e.g., Mercury and its successors) is therefore promising for use as a driver in an IFE power plant.

The reliability, availability and maintainability of the laser components should be deemed to be acceptable for a future Integrated Research Experiment (kJ-class laser coupled with average-power target chamber), and have a plausible means of attaining the driver requirements of IFE.

6.0 Chambers and Power Plants

In the U.S., IFE chamber and target technology work is funded by the Department of Energy's Office of Fusion Energy Sciences (OFES) and High Average Power Laser (HAPL) Program. These are separate, but closely coordinated efforts. The focus of the OFES work is primarily on systems for heavy ion drivers while the HAPL work focuses on laser drivers. The scope of the work includes the following:

- R&D planning – collaborating with driver designers and target physics colleagues to define development path to IFE power
- Chamber design – focusing on requirements for high rep-rate operation and protection of chamber structures
- Driver/chamber interface – developing approaches for protection of final focus magnets and laser optics
- Safety and environmental (S&E) – conducting assessments and making design improvements to create attractive power plants
- Target fabrication and injection – developing accurate, low-cost, high-pulse-rate systems for ion and laser drivers
- System integration – fitting all the pieces together, assuring that chamber and target technologies are compatible with target designs and drivers and making sure that the final power plant is attractive.

LLNL assists DOE in coordinating the OFES funded work and also conducts technical tasks in all of the above areas except target fabrication and injection.

6.1 Chamber Design and Chamber Driver Interface

Previous IFE power plant conceptual design studies identified many different driver/chamber/target options and the critical technical issues associated with them. At this time, R&D in the U.S. is primarily focused on two promising options. One is the renewable thick-liquid-wall chamber (e.g., HYLIFE-II [4]) with indirect-drive targets and a heavy ion driver, and the other is the gas-protected, dry-wall chamber (e.g., Sombrero [16]) with direct-drive targets and a laser driver.

In recent years, LLNL has focused on the HYLIFE-II design. Key issues for thick-liquid wall chambers include 1) establishing the protective liquid pocket and beam port protection jets after disruption by each pulse, and 2) condensing vaporized liquid and clearing drops to allow target injection and beam propagation for the next pulse. Several university experiments (at Georgia Institute of Technology, the University of California, Berkeley, and the University of California, Los Angeles (UCLA)) are addressing the issues of producing the type of jets needed, condensation, and flow recovery. LLNL has focused on the design integration with particular attention to the interface with the heavy ion driver, which may have 100 beams or more.

The key issue for the driver chamber interface for heavy ion drivers is the design of superconducting final focusing magnet array consistent with chamber and target solid angle limit for the required number of beams, standoff distance to the target, magnet dimension and neutron shielding thickness. Work over the past year has shown that the magnets can be adequately protected from radiation damage to the point that they are expected to survive for the 30-year life of the power plant [17].

LLNL is also working on final optics design, protection, and radiation damage studies for laser final optics. This work is in early stages and is funded by the HAPL Program and coordinated with the University of California, San Diego and the University of California, Los Angeles. It includes radiation exposure of candidate optics material, high temperature annealing, and neutron damage modeling.

6.2 Environmental, Safety and Economic Assessments.

LLNL has been active in improving S&E assessment tools for IFE and applying these tools to the analyses of the SOMBRERO and HYLIFE-II power plants. Working closely with the Idaho National Engineering and Environmental Lab (INEEL), we have modified the MELCOR and CHEMCON codes, which are the standard codes used by Magnetic Fusion Energy Program. Analyses of worst-case accident scenarios for SOMBRERO and HYLIFE-II have shown relatively favorable results assuming average weather conditions, but additional work is needed for the conservative weather case [18, 19].

7.0 Conclusion

LLNL has a significant effort devoted to the development of IFE. In additional to building the NIF, which will demonstrate a key milestone for the feasibility of IFE, LLNL is designing targets for both laser and heavy ion drivers (including fast ignition), developing heavy ion drivers as a major part of the HIF Virtual National Laboratory, developing DPSSL technology, and playing key roles in chamber and power plant design and assessment work.

In all these areas, key physics, engineering and integration issues have been identified, and the R&D programs are focused on resolving them in a self-consistent manner.

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