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Overview of the Los Alamos National Laboratory Inertial Confinement Fusion Program

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Abstract

The Los Alamos Inertial Confinement Fusion (ICF) Program is focused on preparing for a National Ignition Facility. Target physics research is addressing specific issues identified for the Ignition Facility target, and materials experts are developing target fabrication techniques necessary for the advanced targets. We are also working with Lawrence Livermore National Laboratory on the design of the National Ignition Facility target chamber. Los Alamos is also continuing to develop the KrF laser-fusion driver for ICF. We are modifying the Aurora laser to higher intensity and shorter pulses and are working with the Naval Research Laboratory on the development of the Nike KrF laser.

I. Introduction

The Los Alamos National Laboratory Inertial Confinement Fusion (ICF) Program is developing ICF for both defense and civilian applications. Potential civilian applications of ICF include electricity, process heat, and basic physics. Defense applications include the study of high-energy-density physics relevant to nuclear weapons and the use of the output of high-gain targets for weapons effects tests.

Los Alamos is advancing the state-of-the-art in target physics, driver development, and target fabrication for ICF. Based on the recommendations of the National Academy of Sciences review of the ICF Program [1] and the Fusion Policy Advisory Committee Review that included ICF energy applications [2], the U.S. ICF Program has decided that the next major step in the U.S. ICF Program will be a National ICF facility capable of demonstrating ignition of ICF targets.

A technical contract specifying the milestones necessary to better understand target physics for the National Ignition Facility has been defined. As described in Reference 1, there are two categories of experiments: (1) hohlraum/plasma physics, which includes driver-plasma coupling, generation and transport of x-rays, and the development of energy efficient hohlraums, and (2) hydrodynamically equivalent capsule physics, which includes hydrodynamic stability and the effects of nonuniform drive on the capsule performance. As described in Section II, Los Alamos is strongly involved in calculations and experiments related to both of these categories.

Target fabrication work is being performed in three areas. First, considerable effort is going into fabricating targets for Los Alamos experiments being performed on Nova. These experiments are mainly directed at understanding ignition target physics. The second area of target fabrication work is developing new materials and techniques for future Nova experiments. The third area of target fabrication work is developing techniques for the National Ignition Facility. Central to this effort is developing the techniques for producing a uniform cryogenic D-T layer inside a capsule and for diagnosing the frozen fuel inside the capsule. This will be described in more detail in Section III.

Los Alamos is also developing the KrF laser as a driver for ICF. As described in Section IV, the Aurora KrF laser at Los Alamos is being reconfigured to a higher-intensity KrF laser called Mercury. The main purpose of this second-generation laser is to demonstrate laser physics and laser design concepts, but it will also be used to develop experimental methods which can be applied to Nova. The final report of National Academy of Sciences ICF Program Review states that "A KrF laser driver is a prime backup should the glass laser program falter." As described in Section IV, the KrF laser has several target coupling advantages over the glass laser, including a shorter wavelength (leading to higher absorption and x-ray conversion efficiency), broader bandwidth (higher threshold for laser-plasma instabilities), smoother beams (higher x-ray conversion efficiency and more uniform energy deposition profiles for direct drive), and more accurate and high-dynamic-range pulse shaping (resulting in implosions on a lower adiabat which leads to higher target gain). In addition, projections indicate that KrF lasers can meet the efficiency and repetition-rate requirements for energy applications, whereas the Fusion Policy Advisory Committee states "Unless 'breakthroughs' in solid-state pumping or advanced target designs prove to be feasible, the inefficiency, expense, and necessary cooling associated with glass lasers eliminate this driver technology from further consideration for energy applications."

Los Alamos is also working with the Naval Research Laboratory (NRL) on the development of the Nike KrF laser. This will allow Nike, being constructed at NRL, to progress on an accelerated schedule. Cooperation between Los Alamos and NRL on this project is beneficial to the development of KrF lasers for fusion.

II. Target Physics

Los Alamos is participating in a concerted national effort to resolve the most important remaining uncertainties about laboratory ignition. A technical contract has been defined that describes the experiments and theoretical research that should be performed to resolve these issues. As described in Reference 1, the contract has two principal elements: (1) hohlraum/plasma physics, and (2) hydrodynamically equivalent capsule physics. Table I shows a breakdown of the hohlraum/plasma physics (HLP) element into seven separate categories and the hydrodynamically equivalent capsule physics (HEP) into five separate categories: it lists the Los Alamos activities in each of these areas.

In general, one of the HEP or HLP milestones may involve a series of many experiments. For example, in HLP-4 (symmetry control in hohlraums), plans are being prepared for at least five independent experiments. These experiments may extend over more than one year. Certain experiments may be better performed at different facilities. In some cases, whole new classes of diagnostics must be developed in order to achieve the required precision. Los Alamos has already installed a new optical scattering diagnostic on Nova and will soon provide an advanced neutron time-of-flight spectrometer to measure ion temperatures of high-convergence implosions

There is one additional target-physics activity that Los Alamos is strongly involved in that is not listed above: the design of the ignition target. It is important to determine, as well as possible, the target and driver parameters and sensitivities before the National Ignition Facility is constructed. For example, it is crucial to define the target performance sensitivity to laser pointing accuracy, pulse-shape accuracy, beam balance, etc., before final design of the laser system is complete. This high-priority work is proceeding.

III. Materials and Target Fabrication

The Los Alamos target fabrication program has recently made great progress, including the first experimental verification of beta heating (forming a symmetric D-T fuel layer through the use of the tritium decay beta, which heats concentrations of fuel and spreads them out). The target fabrication effort at Los Alamos can be divided into three elements: support for current experimental programs, development of target fabrication techniques to make the targets needed to complete the technical contract described in Reference 1, and development of target fabrication techniques necessary for making targets for the National Ignition Facility.

Development of new target fabrication techniques so that the target physics technical contract can be completed includes fabricating new hohlraum designs. We are also exploring the use of the scanning tunneling microscope for target fabrication. Additionally, we are developing new composition foams of both ultra-low and high densities for use in ICF targets.

For the National Ignition Facility, we are developing diagnostics for the thickness variations and smoothness of beta-layered targets. We are designing an experiment to use LANCE to measure the small-angle scattering of neutrons off of the frozen D-T surface to infer the surface roughness. We also plan to contribute to the design of the cryogenic target insertion and support mechanism. Additionally, we are developing doped plastics and foams for use in shell fabrication.

IV. KrF Laser Development

The KrF laser has several advantages over the more-developed glass laser for ICF.[3] These advantages arise from three fundamental characteristics of KrF lasers.

1. The KrF laser operates with a fundamental wavelength that is near ideal for ICF target coupling and with a bandwidth approaching 1% (400 cm^{-1}). Without the need for inefficient narrow-bandwidth frequency multiplication crystals, it can operate with the broad bandwidths necessary to reduce laser-plasma instabilities. Additionally, it operates without a nonlinear frequency conversion component, which simplifies the delivery to target of accurate, high-dynamic-range pulse shapes needed to optimally implode ICF targets.
2. The short energy storage (~7 ns) of the KrF laser, coupled with the long electron-beam-pump time (0.3-2 μs) needed for high efficiency, require the KrF laser to operate in a long-pulse mode and have the pulse shortened for target irradiation. Several pulse compression techniques have been demonstrated, but angular multiplexing appears particularly attractive because of its higher efficiency and linearity. Angular multiplexing involves the generation of a single pulse in the front end with the proper pulse shape: this pulse is then divided, sequentially delayed to form a train of pulses, and run through a chain of quasi-steady-state amplifiers with each pulse identified by its own propagation path. Removal of the time delay after amplification allows identical beams with high-dynamic-range pulse shapes to be simultaneously delivered to the target.
3. The gaseous lasing medium is pumped by relatively efficient electron beams and allows the laser beams to be more uniform (low B-integral effects). The laser medium is immune to damage. A

beam smoothing technique developed by NRL called induced spatial incoherence (ISI), which can significantly improve the beam smoothness, can be applied to a KrF laser. [4] Because of the inherently smooth beams, the KrF laser is attractive for both direct and indirect drive. The efficient gaseous laser medium can also be flowed through the laser cavity in a repetitive operation that meets the requirements for an electric power plant driver.[5]

The Los Alamos Aurora KrF laser has demonstrated many of the technologies required for KrF fusion lasers, including alignment-system techniques that allow simultaneous alignment of a large number of beams in a very short time. [6] Aurora has also demonstrated the concept of angular multiplexing for KrF fusion lasers [7] and the feasibility of large amplifier modules. [8] In addition, Aurora has demonstrated that the high-dynamic-range pulse shapes needed for high-gain targets can be propagated through the laser system without significant distortion.

Because of the redirection of the U.S. ICF Program towards demonstrating ignition and the choice of an upgrade of the Nova laser at LLNL as the lead candidate for the driver, it has been decided that we would reconfigure Aurora to operate with higher intensities and lower operating cost. To do this, we have elected to operate with fewer, smaller, amplifiers and to decrease the pulse duration to ~200 ps. Design verification tests of the energy extraction in this short-pulse mode have already been performed, and good agreement with theory has been achieved. These results are shown in Figure 1.

Our new KrF laser is called Mercury. Mercury will fill the dual roles of providing a conservatively designed KrF laser technology testbed and a facility useful for developing target experiment concepts which can then be applied on larger facilities. Aurora's centered optical system will be replaced with an all reflective system that demonstrates the technologies appropriate for future KrF laser-fusion systems. Interstage temporal encoding and separating the amplifiers by time-of-flight will dramatically reduce optical damage problems. Significant improvements in pulsed-power reliability have already been achieved. The operating cost of

Mercury will be significantly lower than that of Aurora. Mercury is currently in the design phase.

It is currently planned that Mercury will have two phases. The first phase will operate with 150 - 200 J of laser light focused to a 200-µm spot diameter. The point-design parameters for Phase I of the Mercury Project are listed in Table II. Phase I will use two e-beam-pumped amplifiers: the existing Small Amplifier Module (SAM) and a new amplifier configuration (mostly existing equipment) currently called the Final Amplifier (FA). Aurora equipment will be used as much as possible to reduce the initial cost and construction schedule. Phase II will upgrade Mercury by doubling the number of beams delivered to target to increase the energy to ~0.8 kJ.

V. Support of Nike and the Nova Upgrade

Los Alamos is working with NRL to accelerate the schedule of the Nike KrF laser. In particular, we are collaborating on

- design verification tests for beam propagation and Raman scattering,
- amplifier performance calculations,
- the optical design of the Nike system,
- optical diagnostics development,
- fabrication of some optics and mounts, and
- design and procurement of the target chamber.

The National Ignition Facility target chamber is being designed in a collaboration between Los Alamos and LLNL. Issues such as final optics protection, first wall protection, nucleonics, chamber design, stress and vibration analysis, EMI, ES&H, and quality assurance are being examined.

VI. Summary

The Los Alamos ICF Program has four major elements. The first, and by far the largest, is a theoretical and experimental effort to better understand target physics to enable an early commitment to a National

Ignition Facility. Second, target fabrication technologies necessary to support the existing and future target experiments planned on the Nova laser and to prepare for target experiments on the National Ignition Facility are being developed. Third, KrF laser development is being continued at Los Alamos. The Mercury laser will operate with significantly higher intensities. Finally, we are collaborating with the NRL on the development of the Nike KrF laser, and working with LLNL on the design of the National Ignition Facility target chamber.

VII. Acknowledgements

My appreciation also goes to Melissa Cray and Nelson Hoffman for information on target physics and to Larry Foremen for information about the target fabrication program at Los Alamos. Bob Donham provided useful information on the Mercury work and the Nike collaboration. As always, J. Al Sullivan, Ralph Berggren, and John McLeod provided useful comments on this manuscript.

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Table I
Los Alamos contributions to the target physics technical contract

Designation	Description	Los Alamos Effort
HLP-1	Pulse-shaped hohlraum behavior	Collaborating
HLP-2	High-temperature hohlraums	Collaborating
HLP-3	Hohlraum energetics	
	- Laser entrance hole	Leading
	- Wall ablation	Collaborating
	- Colliding plasmas	Leading
HLP-4	Symmetry control in hohlraums	
	- Time averaged	Collaborating
	- Time dependent	Leading
HLP-5	SRS and SBS in long scalelength plasmas	Collaborating
HLP-6	Filamentation	Collaborating
HLP-7	Conversion efficiency	Collaborating
HEP-1	Diagnosis of fuel densities from pulse-shaped implosions	Collaborating
HEP-2	Rayleigh-Taylor instabilities	
	- Planar	Collaborating
	- Cylinders	Leading
HEP-3	Multimode mix in spheres	Collaborating
HEP-4	Low-convergence-ratio implosions controlling instabilities	Collaborating
HEP-5	High-convergence-ratio implosions	Collaborating

Table II
Mercury point-design specifications for Phase I

Parameter	SAM	FA
Dimensions (cm)	11 x 11 x 100	35 x 40 x 200
Pressure (torr)	900	600
Gas mix (Kr/F_2)	0.1 / .003	0.1 / .003
g_o (cm^{-1})	.03 / .045*	.06
g_o/α	10.	10.
I_{sat} (MW/cm^2)	0.92	0.70
Input beam energy (mJ)	4.4	26 / 54*
Output beam energy (J)	.14 / .29*	10.3 / 11.7*
Stage Gain	33 / 67*	406 / 223*
Number of channels	12	24

Energy transmission: SAM→FA	0.36
Energy transmission: FA→Target	0.58**
Energy to target (J)	143 / 223*

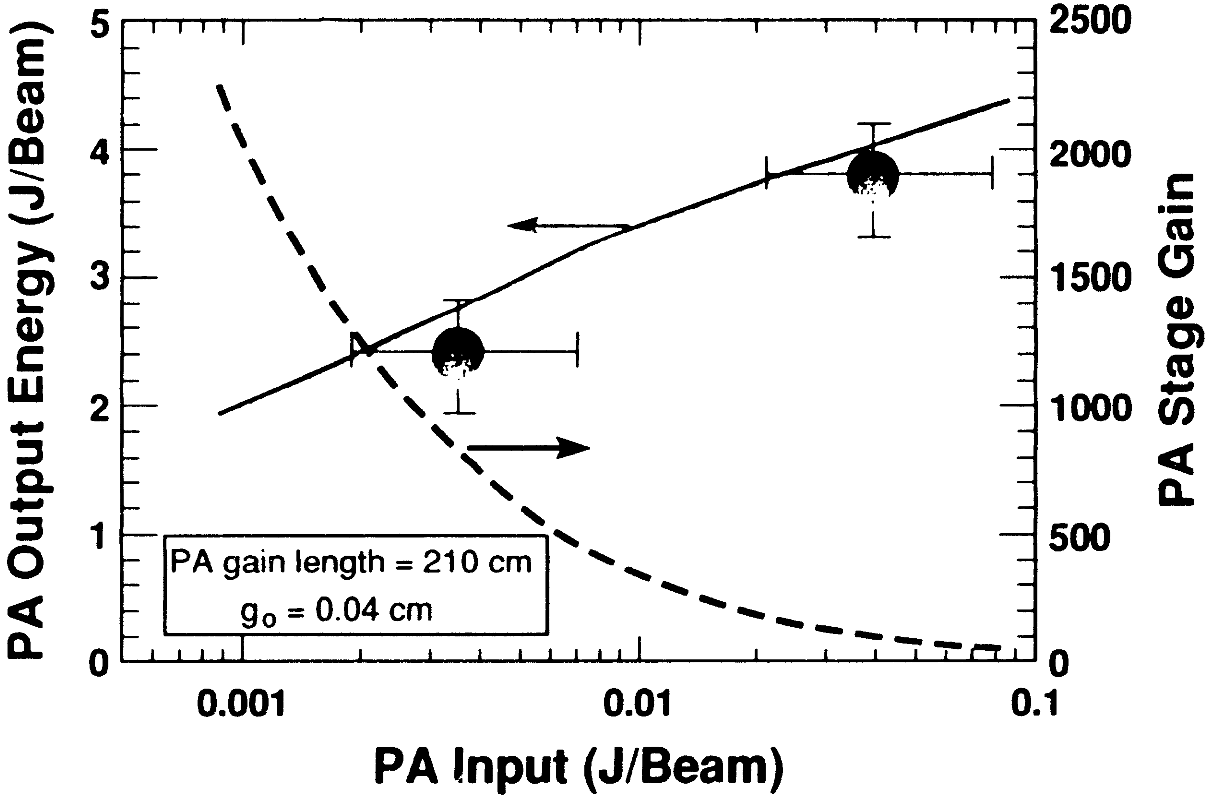
* Multiple values are for SAM / upgraded SAM options

** Includes fill factor losses

Figure Captions

1. Design verification tests of the short-pulse energy extraction for Mercury have show good agreement with theory. These results indicate that the high stage gains desired for Mercury are feasible. The two data points shown in the graph correspond to the solid line of output energy.

Figure I



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