

Fusion Energy with Lasers, Direct Drive Targets, and Dry Wall Chambers

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ABSTRACT. We are carrying out a coordinated, focused effort to develop Laser Inertial Fusion Energy. The key components are developed in concert with one another and the science and engineering issues are addressed concurrently. Significant progress has been made in this program: We have generated target designs that show it could be possible to achieve the high gains (>100) needed for a practical fusion system. These designs feature a low density CH foam that is wicked with solid DT, and over coated with a thin high-Z layer. These results have been verified with three independent 1-D codes. We are now evaluating these designs with 2D and 3D codes. Significant advances have been made with the two types of lasers are being developed: Krypton Fluoride (KrF) gas lasers and Diode Pumped Solid State Lasers (DPSSL). Both have recently achieved "first light", and both have the potential to meet the fusion energy requirements for rep-rate, efficiency, durability and cost. This paper also presents the advances in development of chamber operating windows (target survival plus no wall erosion), final optics (aluminum at grazing incidence has high reflectivity and exceeds required laser damage threshold), target fabrication (advanced foams and high Z overcoats), and target injection (new facility for target injection and tracking studies).

1. Introduction

We are carrying out a coordinated, focused effort to develop Laser Inertial Fusion Energy (Laser IFE). The approach is based on lasers, direct drive targets, and dry wall chambers. We are developing the key components for this concept in concert with one another and are addressing the science and technology at the same time. This integrated approach ensures Laser Fusion Energy will be developed as a coherent system.

The attractiveness of this approach lies in its inherent simplicity, its separable architecture, and the modular nature of the laser driver. The targets are spherical shells, which can be fabricated in

droplet generators, and thus naturally lend themselves to mass production. None of the target components need to be recycled. The first wall is a passive structure that does not have to hold vacuum. This allows the wall to be made in individual sectors that can be replaced during the plant lifetime. It also allows more choices for the first wall material, such as advanced composites that may have radiological advantages. The separable nature of the power plant allows the principal components to be developed separately before being integrated into the system. Just as importantly, it allows economical upgrades as new technologies are developed. The laser is modular, and would consist of a number (about 60) of identical beam lines. Hence it is only necessary to develop one of these lines to develop the entire system. All of these factors significantly reduce the development costs for this approach.

2. Progress

Significant progress has been made in this program. We have developed target designs, based on codes that are being benchmarked with experiments, which show gains of 120-180. Gains > 100 are considered sufficient for a fusion power plant. These are 1-D calculations [1]. Integrated 2-D designs are under development and look promising. Two types of lasers are being developed: Krypton Fluoride (KrF) gas lasers, and Diode Pumped Solid State Lasers (DPPSL). Both have the potential to meet the fusion energy requirements for rep-rate, efficiency, durability and cost. In chamber designs, we have established an operating window for target yield, chamber radius, and chamber gas pressure that will avoid first wall vaporization, allow target injection without compromising the frozen DT fuel, and operate at reasonable efficiency. However, long term material behavior is an open issue. Thus we have started an effort to address this, including exposing candidate first wall materials to ions and x-rays at fusion relevant parameters. Results have been compared with codes. We are also developing models for how the chamber conditions evolve between shots. In final optics, we have established that a grazing incidence aluminum mirror is both highly reflective ($>98\%$) and exceeds the required laser damage threshold by a large margin ($> 40 \text{ J/cm}^2$ vs. the required $5\text{-}8 \text{ J/cm}^2$). In target fabrication, we have found that an Au-Pd alloy coating outside the target will meet the requirements for the target physics, DT permeation times, and the high IR reflectivity needed to help the target survive as it traverses the hot chamber. We have produced divinyl benzene foam shells on a batch basis that can meet the requirements for low oxygen content and straightforward overcoating. We have started construction of an injector to study target injection and tracking.

2.1 Target Physics

A typical high gain target direct drive design is shown in Figure 1.

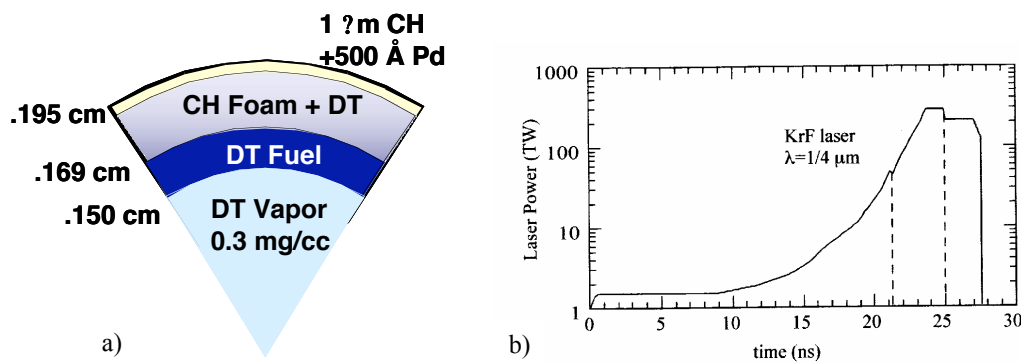


FIG.1. a) Typical NRL high gain target design. b) Laser pulse shape. Dashed lines are zoom points.

The current designs share several common features:

1. The laser pulse has a low intensity “foot” followed by a rise to maximum intensity.
2. The ablator is composed of a low density foam with DT wicked into it. The foam can significantly increase the laser absorption.
3. The design preheats the ablator by some means (shock, x-rays, or a combination). This raises the isentrope of the ablator, and hence lowers the growth rate of the Rayleigh Taylor instability. In some designs the ablator is preferentially heated, while the fuel remains on a lower isentrope. This increases the stability, without materially reducing gain.
4. The laser is “zoomed:” the spot size is decreased in radius to match the compressing target. (This reduces the amount of light lost to refraction and/or absorbed far away from the ablation surface, and thus increases the absorption and coupling efficiency of the design.)
5. The designs include a thin high Z layer (such as Pd) outside the target. This has been shown experimentally to significantly reduce the imprint of laser non-uniformities, and hence mitigates the seeding of hydrodynamic instabilities [2]. This is shown in Figure 2.

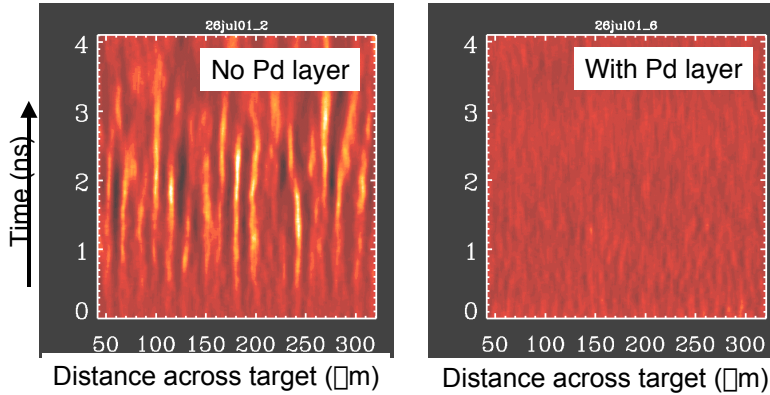


FIG.2. X-ray streak radiographs of ablatively accelerated planar targets show no measurable instability growth with 1200 Å Pd layer on target front surface

Our first high gain targets [1] used radiation preheating, an incident laser energy of 1.3 MJ, and had energy gains well above 100. These targets had an average isentrope within the fuel region, γ nearly equal to one. (γ is the ratio of the total DT pressure to the Fermi-degenerate pressure). A one-dimensional analysis showed the Rayleigh-Taylor instability induced less than 6 e-folds of net growth when averaged over the initial surface roughness spectrum. This corresponds to less than 400 times the initial perturbation amplitude. The high-Z coating was previously kept on the outside of the ablator to ensure that it would be blown off before the laser pulse reached high intensities. This design choice relies on shocks, rather than x-rays to establish the higher isentrope of the ablator because the x-rays do not penetrate far enough into the ablator. The high-Z material was originally chosen to be gold, but was later changed to palladium because the latter's permeability to hydrogen (DT) is important for target fabrication. Based on a number of calculations, any mixture of Au and Pd would present similar target performance; the only difference being the required thickness of the coating. The predicted 1-D gain of these targets, as a function of the Pd layer thickness, is shown in Figure 3. The figure also shows results from a second-generation, higher yield (400 MJ) target design.

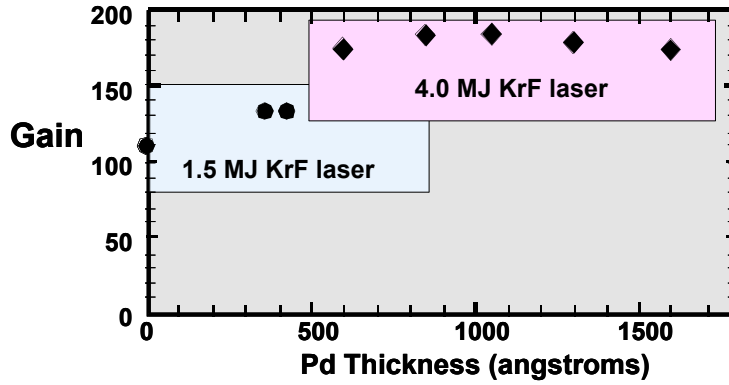


FIG. 3. Target gain as a function of Pd thickness

In another design, the high-Z material is uniformly mixed with the ablator. The intensity of the foot pulse is the same as required for an $\Gamma=1$ design. The high-Z material (Au in the present case but again, it could be other materials) can increase the isentrope of both the ablator and the fuel. Thus to minimize the fuel preheating only small amounts of high-Z material have been added. With an incident energy of 2.5 MJ (KrF light) and zooming, the gain of the target was predicted to be 163. One-dimensional dispersion relations for this target predict that the single fastest growing mode (near $L = 100$) grew 6.8 e-folds. (We picked the $L = 100$ as this spectrum distribution is not well-known, it this is the fastest growing mode.)

We are now using the NRL FAST series of codes to evaluate these targets with high-resolution 2D fully integrated simulations. These resolve all the wavelengths relevant to the hydrodynamic instability. We account for all known sources of non-uniformity: inner and outer surface roughness (based on NIF pellet specifications), laser imprint from optical smoothing (based on ISI and SSD modeling) and low-mode laser pointing and power imbalances (based on modeling from the NIF laser system). Simulations are ongoing for the NIF base-line pellet design, and are beginning for the NRL-designed high-gain KrF-driven pellets. An example calculation is shown in Figure 4.

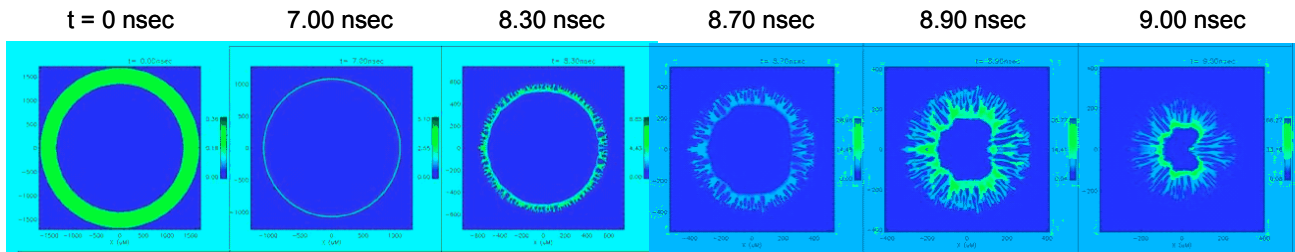


FIG. 4. 2-D simulations of a NIF pellet implosion

We have also carried out 2-D single mode calculations for a 400 MJ target design with LASNEX. This target is slightly larger than that shown in Figure 1, and has a 6 μm thick pure CH outer layer. The calculations show that the stability is enhanced by adding a single high intensity spike early in the foot of the laser pulse. This prepulse shock heats the ablator to a higher isentrope (with a concurrent reduction in Rayleigh Taylor growth) but decays before reaching the fuel.

In these calculations particular attention has been paid to reduce the numerical noise inherent in laser energy deposition when modeling 2-D growth rates. We are now able to demonstrate full, time-dependent implosions to ignition with 2-D laser ray-trace in operation from time zero. Numerical noise growth amplitudes at the fuel/ablator interface at ignition have been reduced to $\sim 10^{-11}$ - 10^{-10} cm. This is comparable to that observed with indirect-drive targets driven by a uniform temperature x-ray source.

In Figure 5 we plot the single mode growth factors (e-folds) versus spherical mode number, $l = \sqrt{r(t)/\lambda(t)}$, for the three pulse shapes shown. Pulse shape A is the “conventional” foot plus main drive, whereas B and C include the aforementioned prepulse. At spherical mode numbers around $l \sim 75$ -100, growth factors have been reduced from ~ 10.5 (standard pulse shape) to ~ 6.5 e-folds (tailored pulse shape with prepulse). These are comparable to growth factors seen for indirect drive heavy-ion targets. As shown in Fig 5, the 2-D growth factors are in good agreement with the semi-analytic Betti-Goncharov 1-D model [3] plus Bell-Plesset convergence.

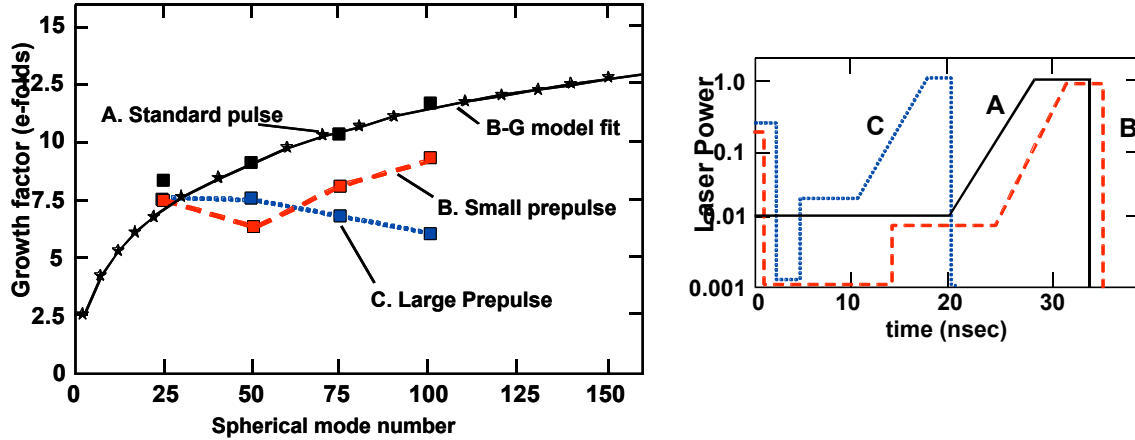


FIG 5: Single mode e-folds versus spherical mode number for the pulse shapes shown at right

We have assessed the impact of these growth factors on late time shell breakup by application of the non-linear, multimode saturation model of Haan [4] employing an initial roughness spectrum based on NIF specifications. The results are summarized in Table I. Note that late-time shell breakup (defined as the bubble amplitude divided by the shell thickness) has been reduced from $\sim 80\%$ for the standard pulse shape to a negligible 2% for the tailored pulse shape.

TABLE I: EFFECTS OF SHAPED PULSE ON TARGET PERFORMANCE

Pulse Shape (see Figure 5)	Laser (MJ)	Yield (MJ)	Gain	Maximum Shell Breakup Fraction (%)
A (standard)	2.4	430	180	83
B (Small prepulse spike)	2.5	420	170	21
C (large prepulse spike)	3.1	360	110	2

2.2. KrF Laser

KrF laser development is being carried out with the Electra Program at NRL. The key components are: an efficient and durable pulsed power system, a durable electron beam emitter (cathode), a long life, high transmission foil support structure (hibachi), a recirculator to cool and quiet the laser gas, and long life optical windows [5]. Electra should produce 400-700 J in 100 nsec. The technologies will be directly scalable to a fusion power plant sized laser beam line.

The Electra laser facility is shown in Figure 6. We have built a first generation pulsed power system to develop the laser components. The system produces two 500 keV, 100 kA, 100 nsec electron beams, each 30 cm high by 100 cm wide. The pulsed power system can run at 5 Hz for 5 hours (100,000 shots) and e-beam runs of several thousand shots are commonplace. The system has run as a laser oscillator in burst mode, and in early tests has produced 190 J of laser light per pulse. Although considerable progress has been made in all areas, we have made three significant advances in the pulsed power, hibachi, and KrF physics modeling.



FIG. 6. The Electra Laser Facility. Electra has produced 190 J per pulse of laser light

2.2.1. Advanced Pulsed Power

We have developed an all-new solid state, laser-triggered switch that will become the basis for a pulsed power system that can meet the IFE requirements for rep-rate, durability, and cost. The switch uses a four-junction silicon device that is optically triggered by two diode lasers. The lasers flood the entire switch volume with photons, whose energy is just above the band edge of the silicon. This gives ultra fast switching times (compared to other solid state switches), on the order of 100 nsec. The lasers are kept on during the entire electrical pulse, which results in high efficiency. Using a four-junction device enables operation at voltages of 20 kV. We call this device a *Laser Gated and Pumped Thyristor*. For the first tests, we modified an off-the-shelf Thyristor to accommodate a single diode laser and the necessary optical coupling. The switch operated at 3.2 kV for 10^5 shots at 5 Hz. The current density was 2.7 kA/cm^2 (121% of the IFE requirement) and rate of rise of was $1.4 \times 10^{10} \text{ A/sec/cm}^2$ (154% of the IFE requirement). We then built a second generation switch using advanced, purpose-built construction techniques, with two-sided pumping. This switch has operated at 15.2 kV and held 24 kV in a pulse charge. This revolutionary pulsed power switch has a wide range of other pulsed power applications.

2.2.2. Hibachi (foil support structure)

We have developed a hibachi concept that demonstrates energy deposition transmission efficiency of up to 75% on Electra (500 keV), with the potential to go to greater than 80% at full system operating voltages (750 keV). The energy deposition efficiency is defined as the ratio of the energy deposited in the laser gas divided by the energy in the diode. The high transmission efficiency was achieved with two innovations: 1) Eliminating the anode foil on the diode side of the hibachi structure, and 2) Patterning the electron emitter into strips so the beam “misses” the hibachi ribs. While these are conceptually simple, they are difficult in practice: The beam strips spread due to the highly non-uniform electric fields caused by eliminating the anode, and the beam rotates and shears due to the applied magnetic field. We compensate for these by narrowing the emitter and “counter-rotating” the emitters so the beam “strips” are propagating parallel to the ribs when they get to the hibachi. This concept is shown in Figure 7. As a side note, patterning the beam into strips also delays and reduces the “transit time” instability that is characteristic of large area electron beams [6].

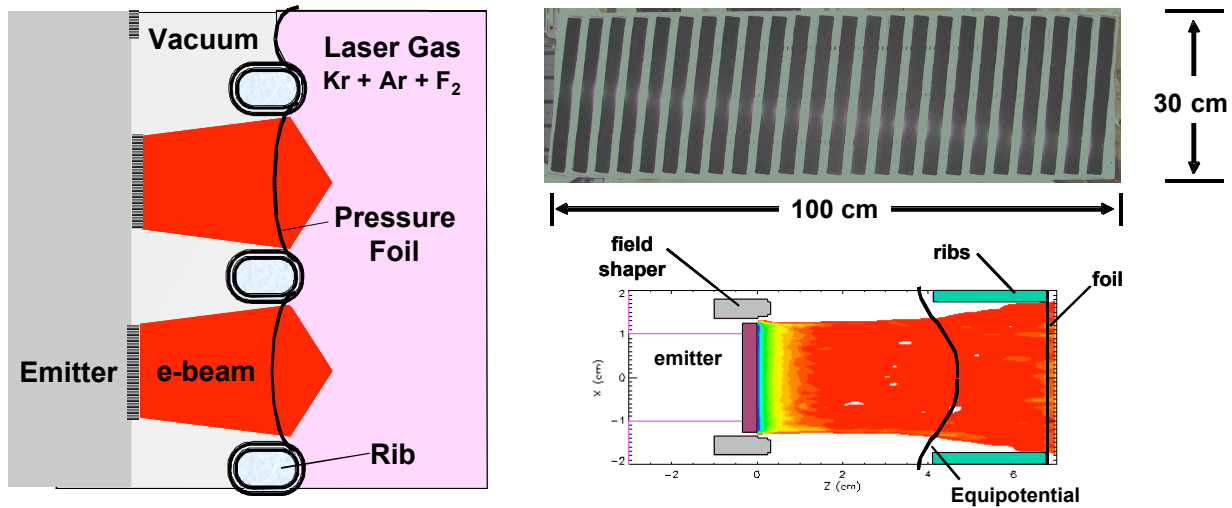


FIG. 7. Drawing of hibachi concept (left,) photo of cathode showing the counter-rotated emitter strips (upper right), and LSP modeling of beam propagation past ribs (lower right)

While the topology of the cathode strips can be determined empirically, this does not give us the predictive capability needed to design larger systems. This is a rather complex phenomenon to model and requires a full 3-D PIC simulation of the exact experimental geometry, including the rib structure, laser gas, and magnetic field. We achieved this by running the Large Scale Plasma (LSP) code developed by MRC, Albuquerque on our own massively parallel homegrown processors. The simulations accurately predict both the cathode counter rotation angle and the energy deposition efficiency. A simulation of a beam “strip” is also shown in Figure 7.

2.2.3 KrF Physics Code development

We have developed the “Orestes” KrF Physics code to both predict the behavior of Electra and as a tool to design full scale (30-100 kJ) systems. Orestes has been benchmarked against a wide range of KrF experiments under different conditions. Using experimentally determined energy depositions, Orestes predicts the output for Electra to be between 550 J and 850 J, depending on the experimental conditions. See Figure 8.

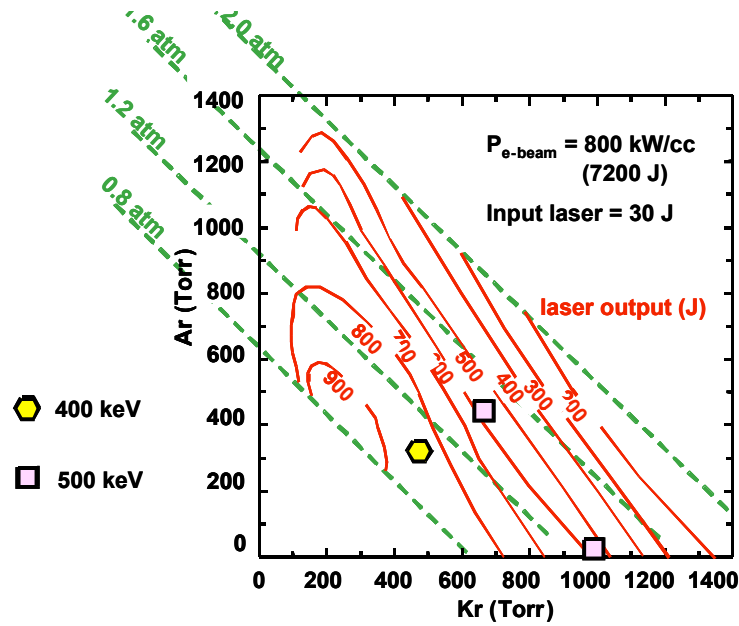


FIG. 8. Orestes Code predictions for Electra main amplifier for two different e-beam energies

2.3 Diode Pumped Solid State Laser

Diode Pumped Solid State Laser development is being carried out with the Mercury Program at LLNL. The ultimate goal is to produce a 100 J, 10 nsec, 10 Hz, 10% efficient laser. Like the Electra KrF laser, the technologies developed on Mercury are scalable to a full size power plant laser [7]. To achieve the goals of Mercury, three key technologies have been developed: high peak-power diode arrays [8], $\text{Yb}^{3+}:\text{Sr}_5(\text{PO}_4)_3\text{F}$ (Yb:S-FAP) crystalline gain slabs [9], and helium gas cooling of the gain media [10]. A picture of the facility is shown in Figure 9.

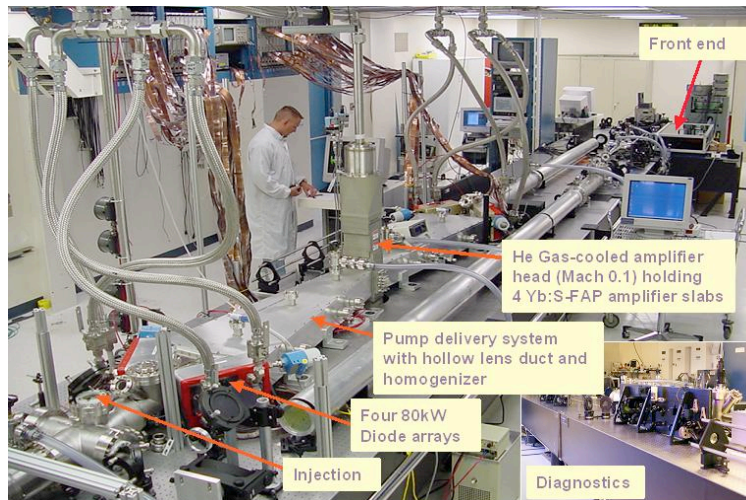


FIG. 9. The Mercury Laser with a single amplifier head (partially fitted with Yb:S-FAP slabs), producing 20 J of energy per pulse.

The system is schematically illustrated in Figure 10. The diode array light is guided to the amplifier through multiple reflections within a hollow lens duct and homogenizer. The diode pump light is delivered to the Yb:S-FAP amplifier slabs potted into aerodynamic vanes, which are cooled by helium gas flowing at Mach 0.1. By means of angular multiplexing, the beam is injected into the main cavity and relay-imaged two times through the amplifier head. The beam is then re-injected via a U-turn loop (called a “reverser”), which contains a birefringence-compensated Pockels cell [11] (used for ghost and parasitic beam suppression). This allows the beam to pass through the amplifier two more times. In collaboration with the University of Rochester, we have developed a device for “spectral-sculpting” the input beam, so as to maximize the output bandwidth for beam smoothing [12]. We have developed a dark field diagnostic, which operates at 10 Hz to monitor the system for the onset of damage. To date, we have activated one of two amplifier heads and generated 20 J in a 20 nsec pulse.

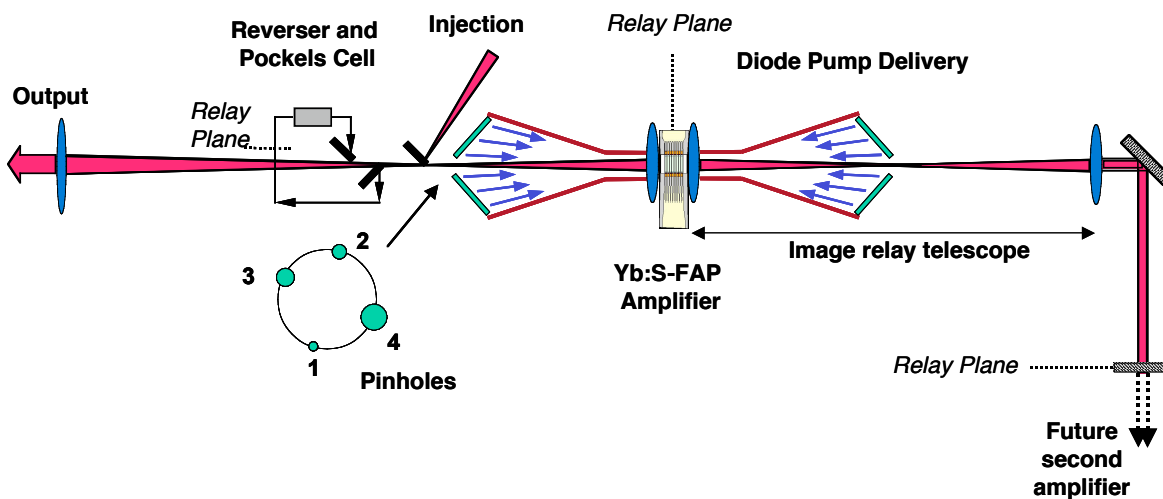


FIG. 10. Schematic of the Mercury Laser.

Significant improvements have been made in the growth of the ytterbium-doped strontium fluorapatite (Yb:S-FAP) crystals. While these Czochralski-grown crystals were initially plagued by a number of growth-related defects [13], they have been brought under control with newly developed procedures for the fabrication of the S-FAP crystal slabs, including water cutting, acidic-polishing and diffusion-bonding.

Significant advances have been made with the Mercury Laser system. Four diode arrays have been activated with each delivering 80 kW of peak power in a 750 μ s pulse. The first set of diode arrays and pump delivery optics have been completed, tested, and found to meet or exceed all specifications. An overall transfer efficiency of 83% through the pump delivery system was achieved, and the pump homogeneity matches our ray-trace models. A birefringence-compensated average power KD*P Pockels cell was fabricated and meets the 200:1 extinction requirement at 100 W average power. Four of the seven 4x6 cm Yb:S-FAP slabs are currently installed in the amplifier. An example of performance results for one amplifier head appears in Figure 11. Full power operation of this amplifier head is anticipated by early 2003, and is anticipated to produce 30 J at 10 Hz. To achieve this goal, wave front correction plates will be installed to remove the amplifier distortions; initial demonstrations of static wave front correct have been quite encouraging. The second amplifier head is expected to be activated in 2003.

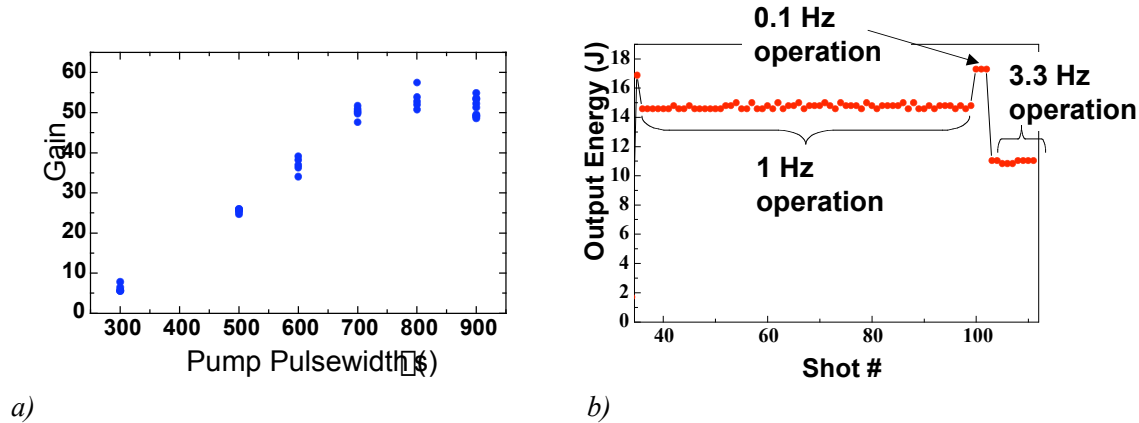


FIG.11. a) Small signal gain through the system. b) Operations plot showing output energy and stability for various repetition rates (right).

The Mercury Laser crew gratefully acknowledges the support of Coherent Inc. for laser diode bars, PolyScientific Northrop-Grumman for crystal growth, Onyx Corp. for diffusion-bonding the crystals, and Directed Energy Inc. for the diode pulsers.

2.4. Chamber Development

The explosion of the target in bursts of neutrons, gammas, x-rays and charged particles is the central event in Inertial Fusion. Everything that happens before (laser operation, focusing optics, target fabrication and injection, laser-plasma interactions, and implosion) has the goal of causing this event to occur. Everything that happens afterward (chamber protection, energy recovery, activation, and balance of plant) is influenced by the details of the target explosion.

The development of a successful chamber boils down to two key issues:

1. Can we identify an operating window, i.e. a set of chamber parameters (radius, materials, wall temperature, and environment) that simultaneously allows successful injection of the target, distortion free propagation of the laser beams, survival of the first wall, and high thermal efficiency.
2. Can the chamber “clear itself” to allow successful target injection and laser beam propagation for the next shot.

2.4.1 Operating Windows

A major consideration in chamber design is the “threat spectrum”: i.e. the neutrons, gammas, x-rays and charged particles produced by the target that are absorbed by the first wall. We have calculated this energy partitioning using LASNEX [14] and the one dimensional Lagrangian radiative hydrodynamics code BUCKY [15]. The results from the two codes are quite similar. We have done this for both the 154 MJ and high yield targets. In both cases only 1-2% of the output is in the form of x-rays, and those x-rays are very energetic (half of the energy is emitted

in photons of above 30keV). Deeply penetrating charged particles (“burn ions”) comprise 13-14% of the target output, and “debris ions” comprise 15-16%. The latter are moving considerably slower, allowing time of flight spreading to greatly mitigate the total threat to the wall. The balance of the energy release is, of course, in neutrons.

The second major consideration in chamber design is material choices. The challenges facing IFE include most of those of magnetic fusion (MFE) systems with a few additional considerations. For both systems a driving concern is the environmental acceptability of the power plant, calling for extensive use of low-activation materials such as ferritic steels, carbon fiber or silicon carbide composites, and tungsten. For both systems thermodynamic efficiency is important, which tends to favor higher operating temperatures. In fact, the energy flux to the wall in an IFE chamber has many of the same characteristics (frequency, particle flux, affected area, base temperature) as an ITER Type 1 ELM mode [16]. The unique consideration for IFE is the fact that while the time-averaged heat flux and neutron dose rate is comparable to magnetic fusion power systems, the specific loading is substantially higher due to the pulsed nature of the system. Specifically, for a power system operating at several Hz, the neutrons, photons, fast ions, and debris ions arrive at the wall within 2.5 μ s. This yields an instantaneous heat loading of 10,000 MW/m² as compared to 10 for an MFE plant. Similarly, the instantaneous neutron displacement rate in IFE can be 10 displacements per atom per second compared to 10⁻⁶ for MFE. As a result of these considerations, the two current leading candidates for the chamber first wall material are carbon fiber composites (as in the SOMBRERO Study [17]) and tungsten. The selection is based on both high thermal conductivity and high sublimation (C) or melting temperatures (W).

Figure 12 gives an operating window for a 154 MJ target. The example is for a 3 mm thick Tungsten armor a chamber radius of 6.5 m and a coolant temperature of 500 °C. There is no gas in the chamber. Note the tungsten stays well below the melting temperature of 3410°C.

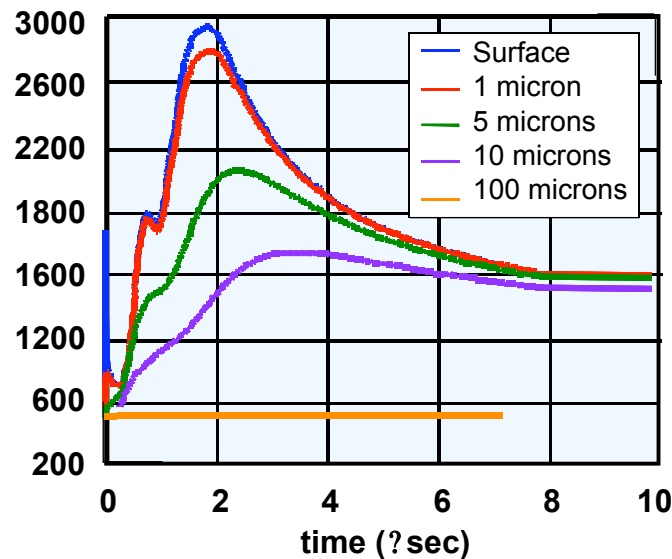


FIG. 12: Predicted temperature profiles of first wall in an IFE chamber

Similar results were obtained for a C armor except that the initial photon-induced peak is much smaller since the photon energy deposition goes deeper inside the C and the maximum temperature is $<2000^{\circ}\text{C}$ with an associated annual sublimation loss of less than $1\ \mu\text{m}$.

In these calculations the energy deposition in the W armor was first calculated for a 1-D slab geometry based on photon attenuation calculations (including photo-electric and Compton scattering effects [18]), and on ion energy deposition (including both electronic and nuclear stopping powers from SRIM [19]). The calculation procedure included the time of flight spreading of the photon and ion energy deposition [20]. The thermal analysis was then carried out using a 1-D model including melting and evaporation [20]. Temperature-dependent properties were utilized for both C and W. The methodology used to calculate target survival is discussed in Section 2.7.

We are also establishing a self consistent operating window for the higher yield ($\sim 400\ \text{MJ}$) target designs. This gives more flexibility in the power plant design. For example, a 1000MW power plant, using the efficiencies assumed in the SOMBRERO study [17], would require a 5 Hz repetition rate for a 400 MJ target, and a 15 Hz repetition rate for a 150MJ target. If the repetition rate is limited either by the time for chamber clearing (See Section 2.4.4) or laser considerations, the higher yield, lower repetition rate target may be more attractive. The BUCKY code [15] was used to explore the options for this case. Calculations of the x-ray and ion spectrum are shown in Figure 13.

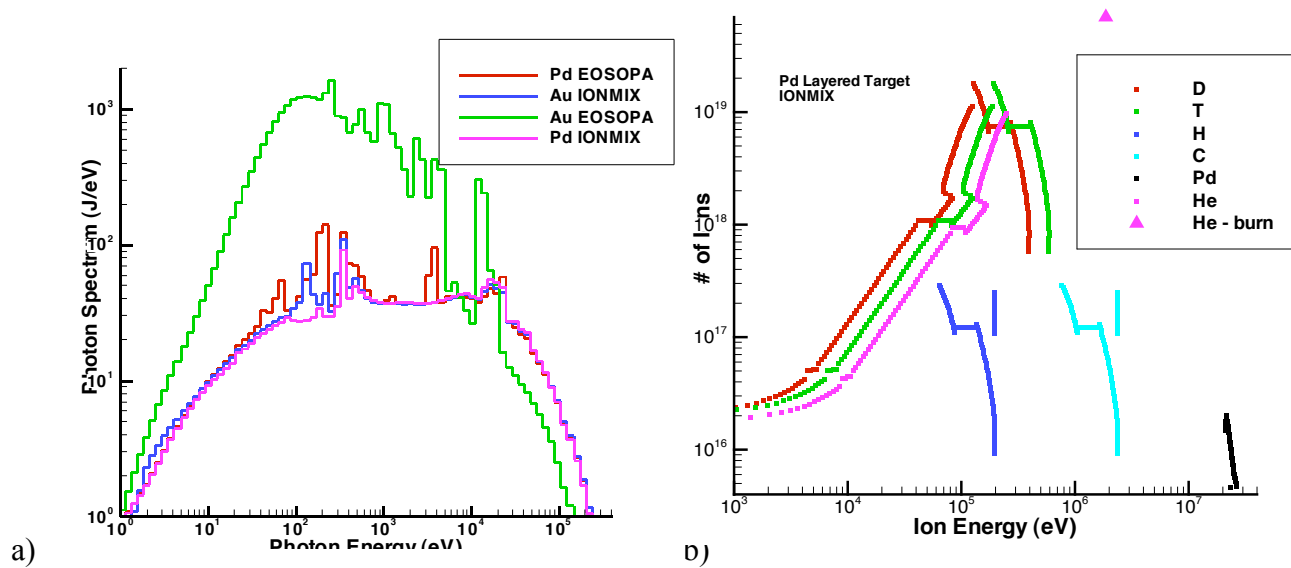


FIG. 13. a) Time-integrated x-ray spectra emitted by high-Z-coated laser direct-drive targets designed at NRL. The coating was either $300\ \text{\AA}$ Au or $1200\ \text{\AA}$ Pd. Either EOSOPA (LTE) or IONMIX (Non-LTE) opacities were used. Target yields were from 300 to 400 MJ. b) Time integrated ion spectrum from Pd-coated laser direct-drive target designed at NRL. IONMIX (non-LTE) opacities were used. Target yield was about 350 MJ. Codes are explained in Section 2.4.2.

For this target, the chamber must be filled with a Xe buffer gas. This slows the debris ions and slowly reradiates their energy at a rate determined by the emission opacity of the Xe. For the low density, high temperature conditions of the Xe at the time the ions transit the chamber, the opacity of the Xe is determined using IONMIX [21], a collisional radiative equilibrium screened hydrogenic model which interpolates between the low density, high temperature coronal equilibrium and the high density, low temperature Saha equilibrium. The constraints for these studies were chosen such that the Xe pressure be no higher than 25 mTorr, and that the first wall sublimation be less than one monolayer per shot. For a 6.5 m radius graphite chamber starting at 1000C, the minimum Xe density required to avoid wall ablation is 80 mTorr, a value incompatible with target survival during injection as it is currently understood (See Section 2.7). Increasing the chamber radius to 8.1m reduces the threat to the wall sufficiently such that sublimation is avoided using 25mTorr of Xe. Figure 14 displays the wall surface temperature evolution for an 8.25m radius graphite chamber under the influence of the target emissions above.

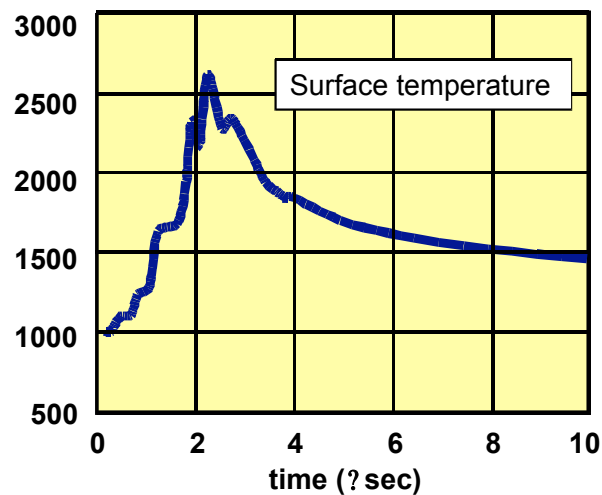


FIG. 14. Wall surface temperature for an 8.25m radius graphite chamber and the high yield DD target.

Both of these design window studies illuminate a few key points:

1. The photon energy deposition is very fast and creates an instantaneous temperature rise (for example, 1150°C in the case of the 154 MJ target with tungsten armor). The wall temperature peaks several microseconds later after the ions impact the wall.
2. With the 154 MJ, tungsten wall target, the temperature stays below 3000°C. It is not clear whether total melt avoidance would be required, as this would depend on the stability of the melt layer and on the material form and integrity following resolidification. However, even assuming a melting point limit (3410°C), the results indicate some margin for adjustment of target yield, chamber size, coolant temperature and protective gas pressure.
3. Similar arguments apply to the high yield target and graphite wall...the temperature peaks at 2700 °C, which is well below the temperature at which significant sublimation will occur.

4. In both cases the “action” takes place in a very thin region ($< 100 \text{ }\mu\text{m}$). This gives us the option to separate the functions of the first wall into two components: A thin armor, that is resistant to the target emissions, and an underlying substrate to providing the supporting structure and interface with the blanket. Note that the blanket sees effectively steady-state conditions.

Based on conclusion 4, we have started to investigate refractory armored composites (RAC). One option is to deposit a thin layer of tungsten on an SiC composite. We have successfully produced uniform, fully dense tungsten layers bonded with high strength to SiC. Future tests, including high-cycle fatigue and high-heat flux, are planned. A potentially more robust, refractory armored, reduced activation, steel system is also under development.

While the identification of chamber operating windows is a major step, there are still significant challenges to be met in establishing a viable chamber concept:

1. The results are highly dependent on simulations of complex physical processes which in turn are based on codes that have not been well benchmarked under relevant conditions.
2. Long term material behavior, is an issue, in particular tritium retention for carbon and helium retention for tungsten.

2.4.2 Code Validation

2.4.2.1 Threat Spectra at first wall.

The general partitioning of target output energy among neutrons, charged fusion products, debris ions and x-rays from directly-driven targets is readily understood from kinematic arguments. However, detailed simulation of the threat spectra that *actually hits the wall* is an extremely complicated physics problem, particularly in the presence of a background gas or plasma afterglow. Validation of these types of calculations will be done as target experiments proceed from driver-energy-dominated to nuclear-energy-dominated on NIF, Omega and Z. Near term improvements include adding an “average atom” non-LTE opacity capability to BUCKY. This helps to resolve uncertainties because the target plasma ionization is dominated by radiative processes, thus rendering the assumption of Local Thermodynamic Equilibrium (LTE) invalid for calculating opacity [22], [23]. Fusion product generation and transport are included in BUCKY simulations but the models need validation and updating. In fact, the target plasma can reach a condition where collisions can no longer prevent plasma inter-penetration. A Monte-Carlo fluid code is being investigated to study this issue [24]. Finally, it has recently been observed in Omega direct-drive experiments that the targets can charge up to the point that potential drops in excess of 1 MV are present [25]. This strongly affects the ion spectra emitted from the target, and BUCKY will need to include the required physics to model charge-up.

2.4.2.2 Materials Response

To benchmark our code predictions of material damage thresholds, we exposed candidate chamber first wall materials to ions and x-rays at fusion relevant fluences and spectra. Our

objective is to develop a predictive capability that will allow us to assess the suitability for a particular material. We performed exposures with the Z (single shot x-rays) and RHEPP (repetitively pulsed ions) facilities at Sandia. Table II compares the experimental results, theoretical predictions, and anticipated threat for the two high gain targets shown in Figure 3.

TABLE II: SUMMARY OF EXPOSURES OF CANDIDATE FIRST WALL MATERIALS

	Material	Predicted Ablation Threshold	Measured Ablation Threshold	Measured Roughening Threshold	Predicted Threat to wall	
					154 MJ target	400 MJ target
X-rays (10 nsec exposure)	Pyrolytic Graphite	4.0 J/cm ²	3.5 - 4 J/cm ²	2.5 J/cm ²	0.40 J/cm ²	1.20 J/cm ²
	Tungsten	not done yet	2 J/cm ²	1.3 J/cm ²		
IONS (□ 100 nsec exposure)	Pyrolytic Graphite	4.5 J/cm ²	3.5 - 4 J/cm ²	2.5 J/cm ²	8.5 J/cm ² (1.82 J/cm ²)	21.1 J/cm ² (4.54 J/cm ²)
	Tungsten (pure)	4.75 J/cm ²	5 J/cm ²	1.25 J/cm ²		
	Tungsten + 25% Re	Not yet modeled	5 J/cm ²	3.5 J/cm ²		

Note that the measured ablation thresholds are close to the code predictions. The predicted threat to the wall assumes a 6.5 m radius chamber. The number in parenthesis for the ion threat was obtained by applying a $t^{1/2}$ correction for the pulse width. The ions from RHEPP are produced in □100 nsec, whereas in an IFE chamber they are emitted in a double humped distribution over 2.1 sec. This scaling is only an approximation, as its validity depends on several factors (such as the ratio of the thermal diffusion length to the energy deposition length). The main reason for doing it here is to demonstrate that both Z and RHEPP are producing relevant threats. While W+Re has a comparatively high ion roughening threshold, the addition of Re brings up radiological issues. We caution that these results are obtained with room temperature samples, and the behavior at IFE relevant wall temperatures will be examined. (Recall that the wall is sequentially heated by x-rays, burn product ions, and then debris ions. See Figure 12.) In addition, the long-term effects of roughening will be investigated. We have also performed exposures with engineered materials. There is some evidence that a carbon fiber matrix has higher damage thresholds.

We are also concerned about the so-called sub-threshold x-ray damage that only becomes relevant after many cycles. This will be studied with the new repetitive x-ray source XAPPER, which is being installed at LLNL. The source, produced by PLEX LLC, uses a radiofrequency-initiated Z-pinch [26], along with a grazing incidence ellipsoidal optic to deliver high fluences of low-energy (100-500 eV) x-rays to a sample. XAPPER will be used to access the very high cycles (up to 10^6 pulses at 10 Hz) of x-rays to study surface effects for optics and wall materials for energy deposition levels lower than apparent threshold levels based upon low-cycle tests and single-shot calculations.

We have also set up a small laser test facility at UCSD to investigate long term material behavior. Our analysis indicates that most of phenomena leading to mass loss from the wall

depend primarily on the evolution of the wall temperature (temporal and spatial) and the chamber environment. Only sputtering and radiation (ion & neutron) damage effects depend on “how” the energy is delivered. The lowest cost repetitively pulsed option to provide the temperature evolution is with lasers. Moreover, lasers provide a “clean” source of energy for wall simulation experiments. Our modeling has shown a 10-ns laser pulse can simulate temperature evolution in the wall sample that is prototypical of laser IFE chambers [27]. Peak wall temperature and temperature gradients in the wall can be easily adjusted by controlling the laser energy and/or modification of laser pulse shape.

2.4.3 Long Term Material Behavior

The long-term effect of the fast ions with the chamber wall is of particular concern for dry-walled IFE systems. It is anticipated that 0.1 to 2 MeV He, D², T³ and H will penetrate several microns into the chamber wall. With carbon, the main concern is the build up in tritium inventory due to co-deposition in colder regions. Additional concerns are dimensional stability, and thermal conductivity following neutron irradiation as well as physical and chemical sputtering. Good dimensional stability and thermal conductivity have recently been demonstrated for a high quality 3-D composite irradiated at 800°C. Studies to higher, IFE relevant, temperatures (including tritium retention) are planned.

The main issue with tungsten is helium retention: The 3.45 MeV alpha particles embed themselves in the tungsten and, because of the extremely low mobility of helium, coalesce into bubbles which eventually cause the material to fracture. For example, for the anticipated fluence of 2×10^{18} He/m²-s, it is estimated that this process will remove about 2 cm/yr from the wall. This is unacceptable, as the initial tungsten armor would be less than a few mm thick. We are addressing this issue with a multi-prong approach:

1. The unacceptable removal rate is based on assumption of limited helium mobility in tungsten. While this is documented at temperatures below 800 °C [28], the behavior at the elevated temperature of an IFE wall is unknown (note from Figure 12 the wall gets to almost 3000 °C). Accordingly we are determining the diffusion of helium in pure tungsten and the effect of the pulsed heating on the helium distribution. In our experiments, tungsten is being irradiated at ~ 600°C and cyclically heated to > 1500°C while using nuclear reaction analysis to determine fate of the implanted helium.
2. We are exploring the use of engineered materials such as tungsten fibers, or nano-deposited tungsten. The idea is to provide a very short migration path for the helium to be transported back to the chamber. This can be accomplished either by having the structure smaller than the helium mean free path (estimated to be on the order of a few tenths of microns) or by having very small scale porous structures.
3. We are investigating the virtues of allowing the outermost surface of the wall to melt for a few microseconds (i.e. at the peak of the ion bombardment). This may allow the material to self anneal on each shot.

2.4.4 Magnetic Deflection

An option for the protection of the chamber wall and/or final optics that is being explored is the use of magnetic fields. For moderate (~ 1 T) uniform magnetic fields, one can limit the 1-D plasma expansion to ~ 4 m, greatly reducing the ion fluxes on the wall. 3-D effects and production of neutrals, however, are expected to reduce the effectiveness of the approach. Protection of the final optics may be accomplished with a two-prong approach: gas puffs on the order of several Torr-m are sufficient to stop the heavier, charged particles, while small magnets with fields of < 0.5 T are capable of deflecting the lighter particles, such as the He ions. The bulk chamber protection, as well as that of the final optics, is being analyzed using a particle-in-cell code, LSP, from Mission Research Corporation.

2.4.5 Chamber Dynamics

In a rep-rated laser-fusion facility, the pulse repetition rate is limited by the time it takes for chamber environment to return to a sufficiently quiescent and clean low-pressure state following a target explosion to allow a second shot to be initiated. Laser propagation and beam quality on the target as well target injection and tracking are impacted by the number density, temperature, mix of chamber constituents, and turbulence in the chamber.

The physical phenomena occur on different time scales. In the first few microseconds, the x-ray burst and ions from the fireball traverse the chamber, deposit their energy in the chamber constituents and finally on the chamber wall. After this phase, the chamber environment evolves mainly in the hydrodynamics time scale and a new equilibrium condition is achieved after certain time interval (typically 100-200 ms). The aim of chamber dynamics and simulations research is to understand the chamber evolution and dynamic over this “longer” time scale and understand the constraints imposed by the chamber dynamics. We have developed a simulation code for this purpose.

The code solves the 2-D transient compressible Navier Stokes equations. The code uses split Godunov integrator in the CGF from [28, 29] that is second-order accurate in regions of smooth flow capturing shocks with a minimum of numerical dissipation and overshoot. Several improvements have been made to make the code suitable for IFE applications:

1. In order to preserve the second-order accuracy of numerical algorithm, calculations are performed on a rectangular logical mesh. Arbitrary chamber geometry (e.g., inclusion laser beam ports) is handled by using an embedded boundary algorithm [30] that is also second-order accurate.
2. Viscous terms are added to the split Godunov integrator as viscosity plays an important role in evolution of IFE chambers in long time scale. The viscous interaction between the fluid and the embedded boundary was tested on the models of channel flow and lid driven flow in a square cavity. The channel direction was oriented at an arbitrary angle with respect to the mesh.

3. During the time-scale of interest (100-200 ms or longer), the shock wave from the blast traverse the chamber many times. It became clear that a single homogeneous grid cannot be used for modeling large pressure disturbances due to its large density and requirement of excessive computational time. As a result, we have implemented an Adaptive Mesh Refinement Algorithm, AMR [31]. The integration of this algorithm into the code was done in collaboration with scientists at Lawrence Berkley National Laboratory [32]. At present, our code can handle the strong shock waves in a computationally efficient manner, with fine grid surrounding the shock and coarse grid placed where the gradients of dependent variables are low.

Some examples of the computational capabilities of our chamber dynamics and clearing code are shown below. We consider a cylindrical IFE chamber with a diameter of 6.5 m filled with Xe. One laser beam channel is included. The initial conditions for density, pressure, velocity, and energy of Xe gas are taken from the BUCKY [15] code after the temperature of the gas has fallen below 1 eV and radiation has become negligible. Figure 15 shows the pressure and velocity distribution in the model IFE chamber 1.6 ms after the blast. By this time the blast wave has bounced from the chamber wall and is converging back toward the chamber center. A pressure wave is traveling in the beam port towards final optics. Figure 16 shows the density distribution around the entrance of the laser beam channel at this time. The multi-dimensional nature of phenomena is clearly shown in these figures.

The code is currently investigating chamber conditions (pressure, velocity, density variations) 100-200 ms following the target blast. These non-uniformities have strong impact on target injection in the chamber and laser propagation. We are studying the convection in the chamber, both due to off-center target blasts and gravity, and are modeling the impact of pressure waves on the final optics. We are also in the process of upgrading the code to handle multi-species transport in the chamber. Of particular interest is the transport of dust in the laser beam channels.

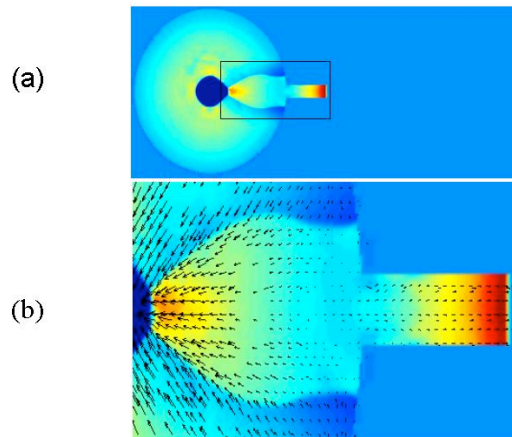


FIG. 15. Conditions in the IFE chamber 1.6 ms after the target blast, a) pressure and b) velocity distribution. The blast has been reflected (once) from the chamber wall. A pressure wave is traveling in the laser beam channel toward the final optics.

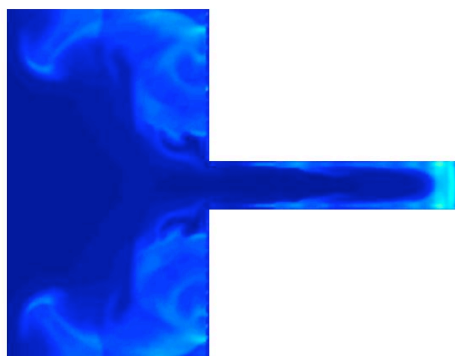


FIG 16. Density distribution around the entrance of the laser beam channel 1.6 ms after the target blast.

2.5. Final Optics

The final optics steer the laser beams to target center. It is the only optical component that lies in direct line-of-sight of the target emissions.

2.5.1 Grazing Incidence Metal Mirror

Our front-runner final optic concept is a grazing incidence metal mirror (GIMM): Pure aluminum surface bonded to a cooled, neutron transparent substrate [34]. The mirror may have an environmental over coat [35]. Operation at a shallow angle ($\sim 85^\circ$) gives the dual advantage of reduced absorption for s-polarized light and lower average fluence on the surface due to the large footprint of the beam. Experiments have established that, at least in small laser spot sizes, the aluminum mirror is both highly reflective ($>98\%$) and can significantly exceed the required laser damage threshold ($> 50 \text{ J/cm}^2$ vs. the required $5\text{-}8 \text{ J/cm}^2$).

Laser damage is one of the most serious concerns for grazing-incidence mirrors. If the mirror operates at fluences beyond the normal incidence damage threshold, then minor defects may result in localized heating which causes further damage. The presence of contaminants, which could propagate from the chamber up the beamlines, might exacerbate this further by creating a source term for localized defects. Therefore, initial testing has been focused on the basic stability of metal surfaces during long-term exposure. Aluminum is currently the preferred material due to its high reflectivity for UV wavelengths and the relatively large industrial database. Specifications for the damage threshold of commercially available Al-coated mirrors typically call for 20 mJ/cm^2 of absorbed energy. With the reduced absorption and increased footprint of a grazing-incidence mirror, this should translate into a damage threshold of roughly 20 J/cm^2 measured across the incident beam. We have set the goal laser fluence for the GIMM at 5 J/cm^2 normal to the beam. This implies $\sim 400 \text{ m}^2$ of total mirror surface area for a 2 MJ laser.

The data was acquired using pure diamond-turned Al and a 2-J 10-ns frequency-doubled Nd:YAG laser ($\lambda = 532 \text{ nm}$). For these specimens, a natural density, 20-30 μm thick oxide coating is present. The results are shown in Figure 17. The results confirm survival up to 10^4

shots for fluences above 20 J/cm^2 [36]. Exposures at fusion-relevant UV wavelengths, as well as with larger areas are underway.

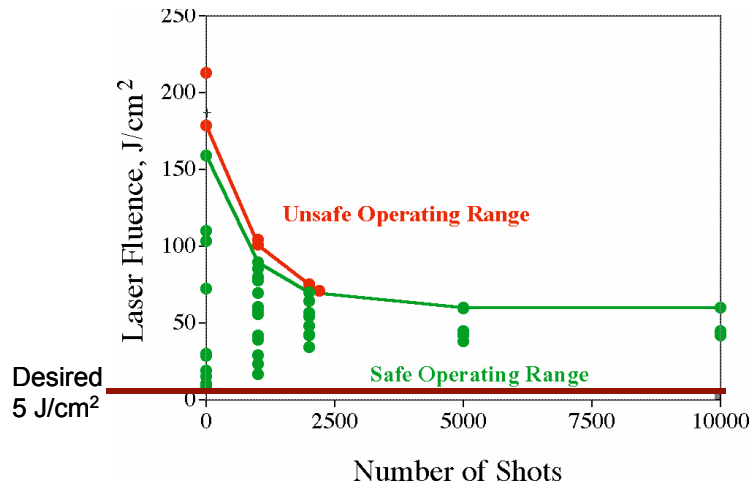


FIG. 17. Laser-induced damage threshold (fluence is measured normal to the beam).

The morphology of damage in pure Al appears to be primarily thermo mechanical in nature. Figure 18 shows a micrograph of the surface near a catastrophic damage site following 10^4 shots. Several types of roughness are evident. Large channels, thought to be the result of internal slip bands that propagate to the surface, appear in somewhat random fashion. Smaller elongated “notches” appear in an orientation that corresponds with the direction of light propagation. These notches represent a rippling of the surface in a direction that does not affect the angle of incidence. Apparently, ripples aligned so as to produce a more normal angle of incidence to the beam are less likely to persist. The fine lines oriented at $\sim 45^\circ$ are machining grooves resulting from diamond turning.

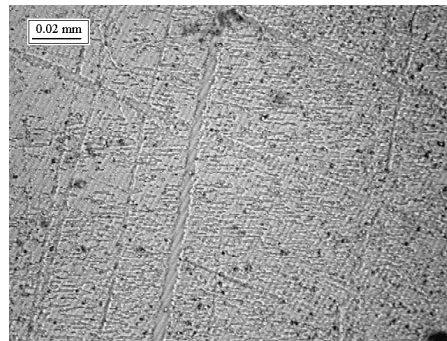


FIG. 18. Morphology of thermo mechanical damage to the surface

Since power plant optics are expected to be fabricated using thin coatings on a low-activation substrate, data on solid Al surfaces provide only a baseline for future testing of coated mirrors. Industrial collaborators recently have begun to fabricate coated optics in order to demonstrate acceptable adhesion and damage threshold (MER Corp.) and to demonstrate the feasibility and optical characteristics of environmental protective surface coatings (PVD Products, Inc.).

Multi-layer Fresnel, Kirchhoff scattering and ray-tracing analyses have been performed in order to better understand the optical characteristics of ideal and defected mirrors [37]. For example, a thin carbon coating on an oxidized Al mirror is harmful compared to a less absorptive water contaminant. Further studies are needed to fully characterize the effect of contaminants and their maximum allowable size and density, to demonstrate acceptable performance of prototypic coated substrates, to explore the effect of target emissions and to scale up and integrate the final optic into integrated research facilities.

In addition to laser damage, the final optic is subjected to neutrons, x-rays, gamma rays and charged particles. Table III summarizes these threats at that the final optic location, which is 20-30 m from the target chamber center. The threats assume no fill gas in the chamber. While the threats on the optic are significantly reduced compared to that on the chamber walls at 6.5 m, these must still be addressed in view of the stringent beam quality requirements for target implosion. Our plan is to assess the effects of these threats on the optic. If they are found to be serious, we will then pursue mitigation techniques such as fast shutters, magnetic deflection, etc.

TABLE III: FINAL OPTIC THREATS

Threat	Target Emission	Final Optic
X-rays	5.6 MJ/shot	0.11 J/cm ²
Neutrons	280 MJ/shot	19.6 krad/s; 0.36 MW/m ² ; 9.7 $\times 10^{12}$ n ^o /cm ² -s (14 MeV)
γ -rays	<< 1 MJ/shot	3.2 krad/s
Ionic debris	110 MJ/shot	2.2 J/cm ² per shot; 0.15 MW/m ²

2.5.2 Transmissive optics

In transmissive optics, the key issue is color center production by either neutrons or gammas, which lead to optical absorption at the laser wavelength. Our work has concentrated on SiO₂. We found that heating an SiO₂ optic allows the defect concentration to saturate at acceptable levels, at least at the DPSSL wavelength of 351 nm. For example, a 0.5-mm-thick Fresnel lens operated at a temperature of 300°C, is expected to have a laser absorption of <5% [38]. While a SiO₂ optic at a stand-off distance of 20 m would reach an equilibrium temperature of ~300°C, the defect population may be reduced further by deliberately operating the optic at a higher temperature and taking advantage of thermal annealing. A decrease in the defect population leads to a corresponding reduction in the optical absorption. Figure 19 shows the laser absorption as a function of operating temperature of the final optic. For operation at 500°C, for example, the optical absorption falls to ~0.6%. The power required to heat the optics to 500°C is on the order of 5 MW, which is more than compensated by the savings in required input power to the lasers.

The absorption is still too high at the KrF wavelength of 248 nm. This fact, plus the issues in fielding a thin, large area optic, have led us to give more attention to the GIMMs.

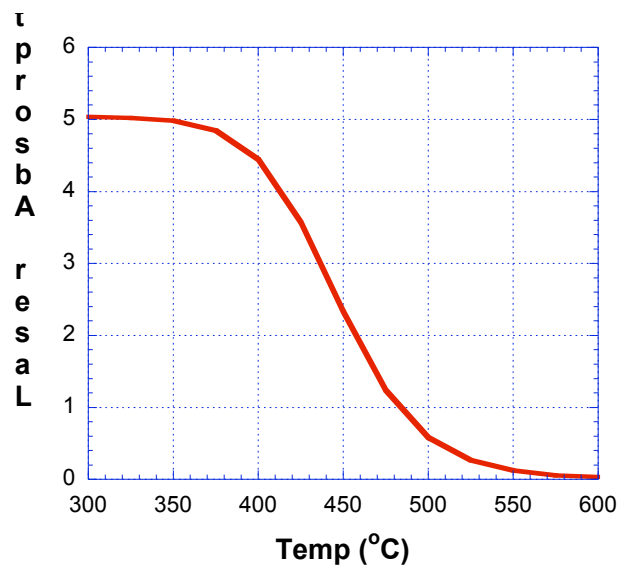


FIG. 19. Heating the SiO_2 final optic to 500°C would reduce optical absorption (at 351 nm) to $\sim 0.6\%$.

2.6. Target Fabrication

We have concentrated on developing target fabrication techniques that can eventually scale to mass production at low cost. For example, we are developing advanced divinyl benzene foam shells using microencapsulation, a process well suited to mass production. The material was chosen because it meets the requirements for low oxygen content and straightforward overcoating. Up to 300 shells, with the proper diameter, densities, and wall thickness, have been produced in a single batch. See Figure 20. In the coming year we will work on concentricity, reproducibility, and overcoating. Measurements show an Au-Pd alloy meets the requirements for DT permeation times (almost as good as pure Pd), and has high IR reflectivity (almost as good as pure gold) to help the target survive as it traverses the hot chamber. A high gain target will require a smooth surface (less than 1 μm RMS) on the inner surface of the DT ice layer. We are developing a batch process based on a fluidized bed technology. Experiments with a room temperature surrogate (oxalic acid) and an external infrared heat source (to mimic the natural heat from the tritium decay) have demonstrated the feasibility of this approach. We have developed models of material responses during the permeation filling step, as well as the tritium inventory in the target facility. These models project the total tritium inventory in a laser fusion power plant could be under 300 g. [39], which is below the normally acceptable value of 1 kg.

We have performed a cost analysis for fabricating the direct drive targets discussed in Section 2.1. This analysis was based on a chemical engineering analysis of all the process steps and assuming a commercial process plant environment. See Figure 21. The analysis includes process flows, mass-energy balances, plant utilities, raw materials, quality control, waste handling and recycle, capital equipment cost amortization, and staffing requirements. The results give an estimated cost of producing a direct drive target of about 16.6 cents each. This is well under the 25 cents each called for by power plant studies [17], and is a significant breakthrough in addressing a major technical feasibility issue of IFE

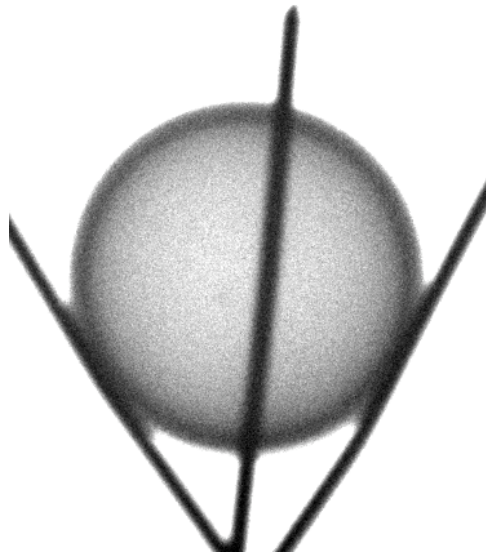


FIG. 20. X-ray radiograph of a polymerized divinyl benzene foam shell. Shell is 4 mm diameter, has a wall 300 μ m thick, and a density of 100 mg/cc.

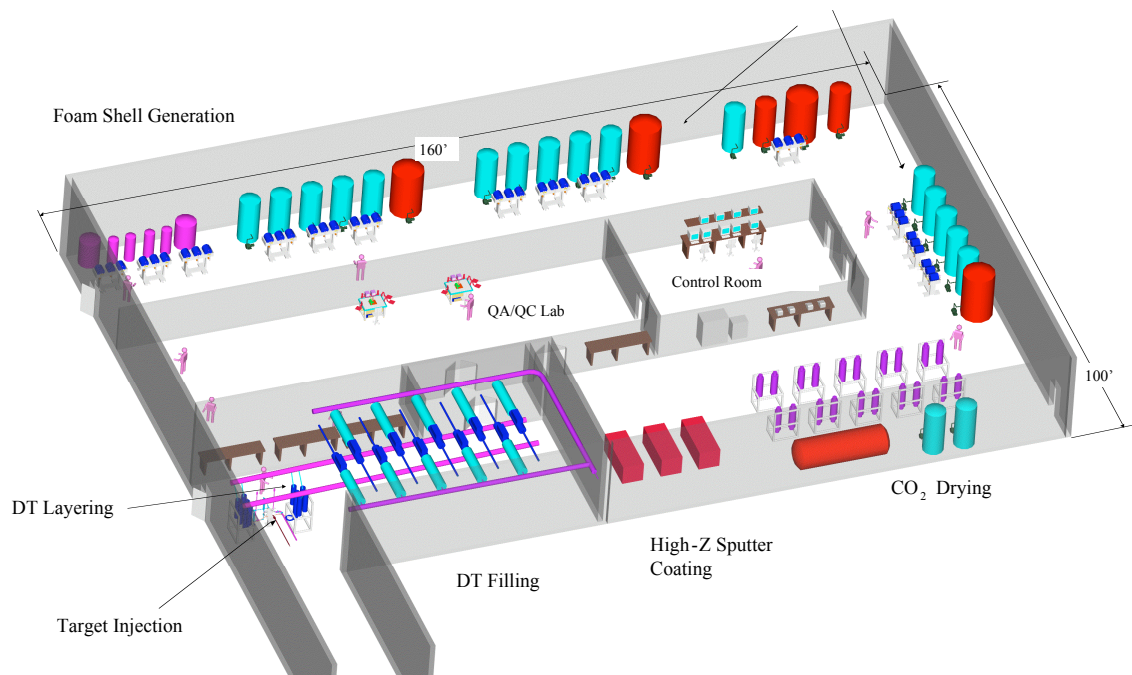


FIG. 21. Preliminary plant layout for fabrication of high gain, direct drive targets. Plant parameters are (a) 500,000 targets per day, (b) targets spend 2-3 weeks on the assembly line, (c) installed capital cost: \$97M, (d) annual operating cost: \$19M, and (e) estimated cost per target: 16.6 cents.

2.7 Target Injection

The two key issues with target injection are accuracy and target survival. In a power plant the target must be delivered to the chamber center at a rate of 5-10 Hz, with a precisely predicted target location. Target placement must be within ± 5 mm of a specified point at the target chamber center. Target tracking must be accurate enough to enable precise alignment of the driver beams with the actual target position. Direct drive targets will require alignment of the centerline of the driver beams with the centerline of the target to less than about ± 0.02 mm. Target position prediction must be accomplished early enough to allow time for beam steering.

We have started construction of a system to study injection and tracking. See Figure 22. This injector is designed to accelerate any IFE target (both indirect and direct drive) and thus is important for any repetitively pulsed IFE/ICF concepts. For the direct drive targets, we have demonstrated the concept of a separable sabot to protect the target during acceleration. We are also performing experiments to measure the DT mechanical properties (for prediction of target survival during the high g-loading of injection). Equipment is being constructed to develop and demonstrate accurate placement and precise tracking of targets during the injection [40].

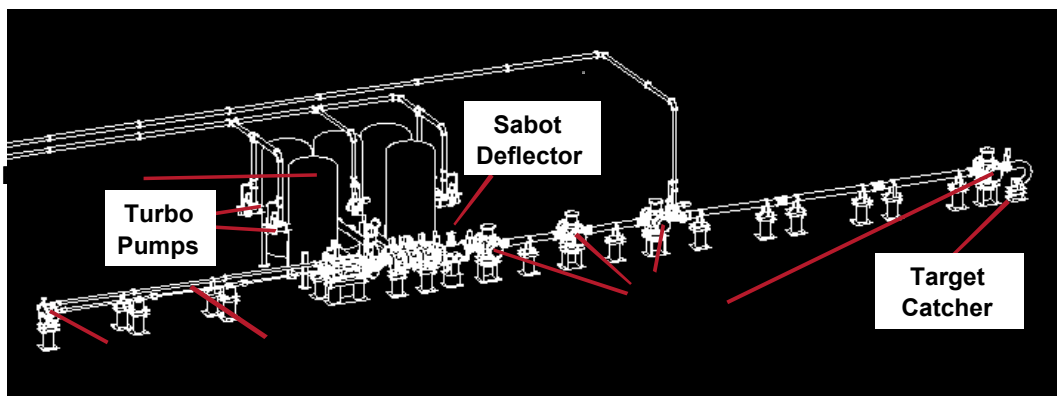


FIG.22 .Drawing of target injection and tracking system (under construction).

Target survival, or how fast the target warms up on its way to the chamber center, is one of the key factors that determine the chamber operating window described in Section 2.4 (Figure 12). The target warm-up in the chamber is calculated by determining the heat load on the target due to both radiation from the wall and convection from the gas. One possible "limit" for target survival is when the internal stresses due to thermal expansion (non-uniform heating of the DT ice from the outside) are greater than the yield stress, degrading the inner ice surface smoothness by deformation. A more likely limit for target survival is when the outside layer of DT exceeds the triple point, 19.79 K, at which point the smooth outer surface of the solid cryogenic ice layer may be compromised (i.e., transition to liquid or even a gas phase). All the calculations are based on the best available data on DT and plastic cryogenic properties, and are carried out over the target time of flight. The time of exposure is very short, as the flight time in the chamber is

only 10's of milliseconds (e.g., 16 ms at 400 m/s for a chamber radius of 6.5 m). Target survival is determined by how fast the DT can respond to the external heat load, how fast the heat is transported from the surrounding hydrocarbon layer to the outer surface of the DT, and how fast the heat can be transported away from the DT surface. If the outer surface of the DT undergoes a phase change to liquid (i.e., exceeding the triple point) and circumferential movement of the liquid does not affect the areal mass distribution, the effect on the target implosion will be minimal. However, if the DT phase change is to the gas state, bubbles may form (at the boundary of the hydrocarbon layer with the ice) which could adversely impact the target stability. Whether the phase change is to liquid or to gas is governed by the local pressure at the interface of the outer DT surface and the hydrocarbon layer just above it. Thus, target survival is determined by the cryogenic material properties under these rapidly changing conditions. Accurate and representative material property data are required for modeling. Materials property measurements, modeling of these effects, and integrated experiments (i.e., DT and DT + foam thermal exposure experiments) are underway to provide a thorough understanding and prediction of target thermal performance during injection.

3.0 Development of Laser Fusion Energy

The work discussed here is the first of a three-phase program to develop laser fusion energy: Phase I is basic science and technology development. Phase II is full-scale technology development and partial integration. Phase III is a fully integrated engineering test facility (ETF). Specific goals and milestones must be met before advancing from one phase to the next. Each phase represents increasing confidence, decreasing technical risk, and increasing cost. In all phases the various components will be developed in concert with one another to ensure we are developing laser fusion energy as an integrated system. The last phase (ETF) would demonstrate that the concept can generate repetitive fusion power and is expected to start within the next 10-15 years.

4.0 Acknowledgements

Many other people from numerous institutions have made contributions to this program. A complete list of participating institutions is as follows:

Government Labs: Naval Research Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratory, Princeton Plasma Physics Laboratory.

Industry: General Atomics, Titan-Pulse Sciences Division, Schafer Corp, Science Applications International Corp, Northrop-Grumman Corp, Coherent, Inc, Commonwealth Technology, Inc.

Universities: University of California, San Diego; University of Wisconsin; University of California, Los Angeles; and University of Rochester Laboratory for Laser Energetics; Georgia Institute of Technology.

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5.0 References

- [1] S.E. Bodner, D. G. Colombant, A.J. Schmitt, and M. Klapisch, "High Gain Direct Drive Target Design for Laser Fusion" *Phys of Plasmas* **7**, (2000) 2298.
- [2] S.P. Obenschain, D. Colombant, M. Karasik, C. J. Pawley, V. Serlin, A. J. Schmitt, J. Weaver, J. H. Gardner, L. Phillips, Y. Aglitskiy and Y. Chan, J. P. Dahlburg, M. Klapisch, "Effects of Thin High-Z Layers on The Hydrodynamics of Laser-Accelerated Plastic Targets" accepted for publication in *Physics of Plasmas*.
- [3] R. Betti et al., "Growth Rates of the Ablative Rayleigh-Taylor Instability in Inertial Confinement Fusion", *Phys. Plasmas*, **5** (1998) 1446.
- [4] S.W. Haan, "Onset of Nonlinear Saturation for Rayleigh-Taylor Growth in the Presence of a Full Spectrum of Modes", *Phys Rev A*, **39** (1989) 5812.
- [5] J.D. Sethian, M. Friedman, J. Giuliani, R. Lehmborg, M. Myers, S. Obenschain, F. Hegeler, S. Swanekamp, "Electra: A Krypton Fluoride Laser For Fusion Energy", *Inertial Fusion Sciences and Applications*, edited by K.A. Tanaka, D.D. Meyerhoffer and J. Meyer-ter-Vehn, Elsevier (2002) 495.
- [6] M. Friedman, M. Myers, S. B. Swanekamp, Y. Chan, J. D. Sethian, and S. Obenschain "Suppressing the transit-time instability in large-area electron-beam diodes," Accepted for publication in *Applied Physics Letters*, August 26, 2002
- [7] C. D. Orth, S. A. Payne, and W. F. Krupke, "A diode pumped solid state laser driver for inertial fusion energy," *Nuc. Fus.* **36** (1996) 75.
- [8] J.A. Skidmore, B.L. Freitas, J. Crawford, J. Satariano, E Utterback, L. DiMercurio, K. Cutter, and S. Sutton, "Silicon monolithic microchannel-cooled laser diode array," *Appl. Phys. Lett.*, **77** (2000) 10.
- [9] C. D. Marshall, S. A. Payne, L. K. Smith, H. T. Powell, W. F. Krupke, and B. H. T. Chai, "1.0047 μ m Yb:Sr₅(PO₄)₃F energy storage optical amplifier," *Selected Topics in Quantum Electronics* **1** (1995) 67.
- [10] S. B. Sutton and G. F. Albrecht, "Applied Optics **29**, 1183 (1991); A.J. Bayramian, C. Bibeau, K.I. Schaffers, J.K. Lawson, C.D. Marshall, and S.A. Payne, "Development of ytterbium doped Sr₅(PO₄)₃F for the Mercury Laser Project," in *OSA Trends in Optics and Photonics Series*, M.M. Fejer, H. Injeyan, U. Keller, ed(s)., Vol. **26** of OSA Proceedings Series, Optical Society of America, Washington, D.C. (1999), 635-641.
- [11] C.A. Ebbers, K. Kanz, and H. Nakano, "A thermally compensated, deuterated KDP Q-switch for high average power lasers," Conference for Lasers and Electro Optics, Baltimore Maryland, 2002.
- [12] I. J. Waxer, J. H. Kelly, J. Rothenberg, A Babushkin, C. Bibeau, A. Bayramian, and S. Payne, "Precision spectral sculpting for narrow-band amplification of broadband frequency-modulated pulses," *Optics Letters* **27** (2002) 1427.
- [13] K. I. Schaffers, J. B. Tassano, A. B. Bayramian, and R. C. Morris, "Review of the Growth of Yb:S-FAP Crystals for the Mercury Laser," submitted to the *Journal of Crystal Growth*.
- [14] Available at <http://aries.ucsd.edu/ARIES/WDOCS/ /ARIES-IFE/SPECTRA/>
- [15] R. R. Peterson, J. J. MacFarlane, and G. A. Moses, "BUCKY-1 - a 1-D Radiation Hydrodynamics Code For Simulating Inertial Confinement Fusion High Energy Density Plasmas" *Fusion Tech.* **30**, (1996) 783.
- [16] R. Raffray, G. Federici, A. Hassanein and D. Haynes "Dynamic Chamber Armor Behavior in IFE and MFE,". Presented at the 6th International Symposium on Fusion Nuclear

- Technology, 7-12 April 2002, San Diego, California, USA. Submitted for publication in Fusion Engineering and Design
- [17] W.R. Meier, "Osiris and Sombrero Inertial Fusion Power Plant Designs — Summary, Conclusions and Recommendations," *Fusion Engr. and Design* **25** (1994) 145. See also I. N. Sviatoslavsky, *et al.*, *Fusion Technology*, **21** (1992) 1470.
 - [18] Available at <http://aries.ucsd.edu/LIB/PROPS/PHOTON/>
 - [19] Available at <http://www.srim.org/>
 - [20] A. R. Raffray, D. Haynes and F. Najmabadi, "IFE Chamber Walls: Requirements, Design Options, and Synergy with MFE Plasma Facing Components," invited presentation at the 15th International Conference on Plasma Surface Interactions in Controlled Fusion Devices (15th PSI), Gifu, Japan, May 2002, *Journal of Nuclear Materials*, in press.
 - [21] J.J. MacFarlane *Comp. Phys. Commun.* **56**, (1989) 259.
 - [22] J.P. Apruzese, et al., "The Physics of Radiation Transport in Dense Plasmas," *Phys. Plasmas*, **9** (2002) 2411.
 - [23] Hans R. Griem, *Plasma Spectroscopy* McGraw-Hill, New York (1964).
 - [24] T. Bartel, S. Plimpton, and M. Gallis, "Icarus: a 2-D Direct Simulation Monte Carlo (DSMC) Code for Multi-Processor Computers," Sandia National Laboratories Report SAND2001-2901 (October, 2001).
 - [25] C. K. Li, F. H. Séguin, J. A. Frenje, S. Kurebayashi, R. D. Petrasso, D. D. Meyerhofer, J. M. Soures, J. A. Delettrez, V. Yu. Glebov, P. B. Radha, S. P. Regan, S. Roberts, T. C. Sangster, and C. Stoeckl "Effects of Fuel-Shell Mix upon Direct-Drive, Spherical Implosions on OMEGA," *Phys. Rev. Let.* **89** (2002) 165002.
 - [26] M.W. McGeoch "Radio-Frequency-Preionized Xenon Z-pinch Source for Extreme Ultraviolet Lithography" *Applied Optics*, **37** (1998) 1651.
 - [27] F. Najmabadi, "Chamber Simulation Experiments", presented at the third workshop on High Average Power Laser Development, Pleasanton, CA, November, 2001. See <http://aries.ucsd.edu/HAPL/MEETINGS/0111-HAPL/najmabadi.pdf>
 - [28] W. Wang, J. Roth, S. Lindig, C.H. Wu, "Blister Formation of Tungsten Due to Ion Bombardment", *Journal of Nuclear Materials*, **299** (1999) 124.
 - [29] P. Colella, H. M. Glaz, R. E. Ferguson, "Multifluid Algorithms for Eulerian Finite Difference Methods", CGF 1/31/1997.
 - [30] P. Colella, H. M. Glaz, "Efficient Solution Algorithms for the Riemann Problem for Real Gases", *Journal of Computational Physics*, **59** (1985).264.
 - [31] D. Modiano, P. Colella, "A Higher Order Embedded Boundary Method for Time Dependent Simulation of Hyperbolic Conservation Laws", Proceedings of the ASME 2000 Fluids Engineering Division Summer Meeting, Boston, MA, June 2000.
 - [32] A. S. Almgren, J. B. Bell, P. Colella, L. H. Howell, Michael L. Welcome, "An Adaptive Projection Method for the Variable Density Incompressible Navier-Stokes Equations", *Journal of Computational Physics*, **142** (1998) 1.
 - [33] M. Day, Lawrence Berkeley National Laboratory, private communications, 2002.
 - [34] R. L. Bieri and M. W. Guinan, "Grazing Incidence Metal Mirrors as the Final Elements in a Laser Driver for Inertial Confinement Fusion," *Fusion Technology* **19** (1991) 673.
 - [35] N. M. Ghoniem and A. El-Azab, "Thermomechanical Design of the Grazing Incidence Metal Mirror of the Prometheus-L IFE Reactor," *Fusion Engineering and Design* **29** (1995) 89.

- [36] M. R. Zaghloul, M. S. Tillack, and T. K. Mau: "Laser-Induced Damage of Metal Mirrors Under Long-Term Exposure at Shallow Angle of Incidence," 19th IEEE/NPSS SOFE, Atlantic City NJ, Jan. 21-25, 2002.
- [37] T. K. Mau, M. S. Tillack, and M. R. Zaghloul, "Modeling of Mirror Surface Damage Effects on Beam Propagation in a Laser-Driven IFE Power Plant," 19th IEEE/NPSS SOFE, Atlantic City NJ, Jan. 21-25, 2002
- [38] J. F. Latkowski, A. Kubota, M. J. Caturla, S. N. Dixit, J. A. Speth, and S. A. Payne, "Fused Silica Final Optics for Inertial Fusion Energy: Radiation Studies and System-Level Analysis," Accepted for publication by *Fusion Science and Technology*.
- [39] M. Schwendt, A. Nobile, P.L. Gobby, W.P. Steckle, D.G. Colombant, J.D. Sethian, D.T. Goodin and G.E. Besenbruch, "Tritium inventory of inertial fusion energy target fabrication facilities: effect of foam density and consideration of target yield of direct drive targets", accepted for publication in *Fusion Science and Technology*
- [40] D.T. Goodin, N.B. Alexander, C.R. Gibson, A. Nobile, R.W. Petzoldt, N.P. Siegel, L. Thompson, "Developing Target Injection and Tracking for Inertial Fusion Energy Power Plants", *Nuclear Fusion*, **41** (2002) 527.