A Target Fabrication and Injection Facility for Laser-IFE

M. S. Tillack, D. T. Goodin[a], N. B. Alexander[a], R. W. Petzoldt[a],
A. R. Raffray, D. Schroen[b], J. D. Sethian[c], and J. E. Streit[b]

UC San Diego, 9500 Gilman Dr., La Jolla, CA 92093-0417
[a]General Atomics, PO Box 85608, San Diego, CA 92186-5608
[b]Schafer Corporation, 303 Lindbergh Ave, Livermore CA 94550
[c]Naval Research Laboratory, 4555 Overlook Ave. S.W., Washington, DC 20375

***Abstract*. We have defined the characteristics of a target injection and tracking facility to validate the science and technology of full-scale components for a laser inertial fusion energy (IFE) power plant. This facility will be a key element of the plan to develop laser IFE with direct drive targets and solid wall chambers. It is the final step before construction of an engineering test facility. Elements of the facility include mass production (in batch mode) of cryogenic targets that meet the specifications of high gain, target injection into the chamber and target tracking in the chamber. The chamber will simulate the environment (background gas, wall temperature, *etc.*) envisioned for a laser IFE power plant, and the facility will include steering of a low-energy pulsed laser onto the target in flight.**

In this paper we describe the program goals and key science and technology issues which will be addressed in the facility, quantitative requirements for successful target injection, major characteristics of the various subsystems, and R&D which will be needed in order to prepare for its construction and operation.

I. Overview

The objective of the High Average Power Laser (HAPL) program is to develop fusion energy with laser drivers and direct drive targets. The program is being carried out with the participation and input of many institutions [1]. This integrated research program is based on a structured approach with defined metrics that must be satisfied to "qualify" the program for proceeding to the next phase.

Phase I (current work) is focused on establishing the basic science and feasibility of a rep-rated (5-10 Hz) laser IFE power plant. Phase I includes development of the key science and technologies, measurement of fundamental materials property data, and "proof of principle" experiments and engineering studies.

Phase II will bring together selected components to demonstrate their integration and operation for IFE. A major element of Phase II is the Target Fabrication and Injection Facility (TFIF), which will demonstrate the fundamental processes required for fueling a laser IFE power plant. Fig. 1 depicts the key elements of the TFIF, including fabrication and characterization stations, cryogenic transfer and handling equipment, injector, tracking systems, a simulated chamber environment, and illumination by a pulsed laser beam. In this paper we review the various subsystems present in the TFIF and describe how they are integrated together to provide a comprehensive demonstration of laser IFE power plant fuelling.

An IFE power plant operating at 5 Hz requires about 500,000 precision cryogenic targets per day. Providing this number of targets at a cost that is a reasonable fraction of the value of the power generated (about one tenth of the electricity value has been suggested) is a significant feasibility issue for inertial fusion. While the TFIF is not intended to produce 500,000 targets per day in Phase II of the program, each step of the fabrication and injection processes will be operated – at significant rates – with methodologies that are applicable to mass production and scaleup to 500,000 per day at low cost.

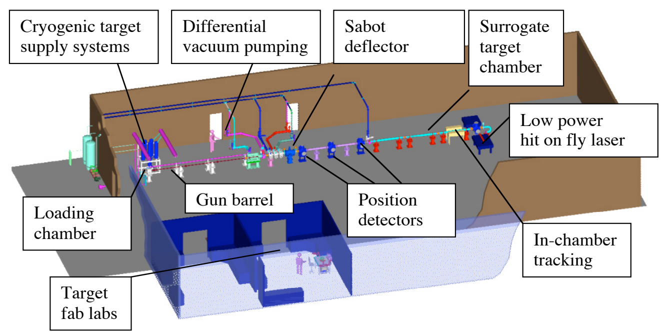

Fig. 1. Key elements of the Target Fabrication and Injection Facility

The TFIF will produce targets that meet the requirements of laser IFE. Cryogenic targets filled with a thin layer of DT fusion fuel must be supplied at a rate of 5-10 Hz for a 1000 MW(e) power plant. The target physical requirements and geometric precision are relatively stringent, as summarized briefly in Table I. Key parameters associated with the target injection process are listed in Table II.

Spherical cryogenic targets will be fabricated, filled, layered, and characterized (with processes that are scalable). These targets will then be transferred to the injector using reliable handling equipment and procedures. Injection equipment and a high temperature test chamber will be built to demonstrate that the relatively fragile cryogenic targets can survive the entire injection process (including transport through a chamber operating under IFE conditions of wall and gas temperature, gas density, and gas density variations) and reach the target chamber center in a condition suitable for high gain. Target flight tracking information will be provided to optics and beam steering equipment that are scaleable to those to be deployed with power plant driver beams. The target will be "painted" with a low energy pulsed laser beam in flight at the simulated target chamber center to demonstrate the integrated capability of target injection, tracking, position prediction, and final beam steering. A suite of in-flight and ex-situ diagnostics will be used to verify the achievement of all aspects of target injection and survival. Development and verification of procedures and equipment for these intricate fueling steps will be a major step forward in demonstrating the feasibility of energy from inertial fusion.

*This work is sponsored by the US Department of Energy, NNSA/DP

TABLE I
SELECTED LASER IFE TARGET REQUIREMENTS AND NOMINAL PARAMETERS

Parameter	Value	Units
Foam capsule outer diameter	~4	mm
Foam shell density	100	mg/cc
Out of round	<1	% of radius
Non-centricity	<1	% of wall thickness
Capsule surface finish	~20	nm RMS
Inner DT ice surface finish	<1	μm RMS
Target production rate	500,000	per day
*Maximum target outer surface temperature**	19	K

*The target can be injected at temperatures well below this value (Sec. VI)

TABLE II
TARGET INJECTION REQUIREMENTS AND NOMINAL PARAMETERS

Parameter	Value	Units
Target placement accuracy	±20	mm
Target/laser alignment accuracy	±20	μm
Target tracking accuracy	±14	μm
Target injection velocity	~400	m/s
Target fuelling rate	5-10	Hz
*Target chamber wall temperature**	1150	˚K
*Target chamber residual gas pressure**	~50	mTorr
*Target chamber residual gas temp.**	6000	K

*Estimate of potential value – plant parameters are still being defined

II. CRYOGENIC TARGET FABRICATION

The direct drive baseline target design is a 4-mm diameter foam capsule with a 0.3-mm wall, a 1 to 5 micron full density polymer overcoat, and finished with a 300 to 1000 Å metal coat (see Fig. 2). This metal coat is designed to reflect thermal radiation, which is a prime consideration for target survivability during injection. The foam was specified to be elementally composed of only carbon and hydrogen and have approximately 1 micron cell size, with the ability to be fabricated at a density of 50 to100 mg/cm^3. This density range was chosen for strength during the diffusion filling process. To meet this foam specification we formulated a new foam system, divinylbenzene ($C_{10}H_{10}$). This foam is polymerized throughout a volume of solvent, a process well suited to microencapsulation and analogous to the acrylate systems [2]. Using a prepolymerization step, capsules can be made at the requested density using a triple orifice droplet generator [3]. We have also placed an overcoat over the foam capsules, using a technique pioneered by ILE [2] and demonstrated the gas barrier properties of this overcoat.

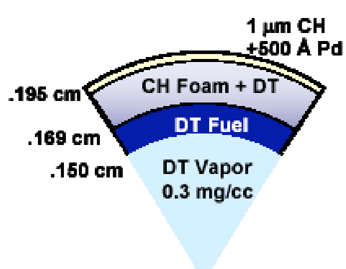

Fig. 2. Reference target geometry

Development work to date has been at the laboratory scale. While processes were chosen for scale up, there are several innovations we foresee in a true production facility. To maintain cleanliness and eliminate handling damage, we envision flow-though systems for capsule characterization (with an individual pass/fail criteria), overcoating, and solvent exchanges. An analysis of the processes using standard manufacturing techniques in an nth of a kind facility yielded an estimated cost per target of 17¢ [4].

Targets will be filled and layered in batch processes. The capsules would be diffusion filled with DT at near room temperature, cooled down to condensation (~20 K), and then circulated in a fluidized bed to provide a highly isothermal environment. The spherical foam shell is overfilled with DT fusion fuel to provide a smooth inner layer of solid DT. This allows the fuel in the capsule to preferentially sublimate at the thicker areas thus self-adjusting to provide a uniform DT "ice" layer.

III. TARGET HANDLING AND TRANSFER

Target handling in present-day cryogenic experiments is extraordinarily challenging, even for single targets [5]. Although all of the fundamental processes for target fabrication have been demonstrated in current-day systems (permeation filling, cooling without damage, cryogenic transfer, layering of the DT, characterization of the DT "ice"), these have generally been done with individual (single) targets. An important part of the operation of the TFIF will be the development and demonstration of reliable high-throughput transfer and handling systems and procedures for cryogenic targets.

All target handling equipment following the filling step must be kept at a relatively fixed temperature in order to avoid damage to the targets. All target handling after removal from the precise, isothermal temperature environment of the layering system must take place just prior to injection. If the temperature of the layered target decreases by more than a few degrees, then internal stresses may cause damage due to cracking or debonding at interfaces. If the temperature increases by more than a few degrees, then weakening of the DT ice may cause unacceptable deformations. If nonuniform temperatures are allowed on the targets during handling, then the symmetry of the DT layer will soon be destroyed.

Expected issues to be addressed for mass-production include static "cling" of targets, damage to target surfaces during handling, uniformity of the temperature environment, and wear and precision of fast-moving equipment in the vacuum/cryogenic environment. Developing and demonstrating the methodologies and equipment for transfers and handling of targets at 5-10 Hz under these conditions is a vital and key feature of the TFIF workscope.

IV. TARGET INJECTION

The injection system must take the cryogenic layered targets, protect them from thermal or mechanical damage and accurately position them (±20 mm) at speeds up to 400 m/s into a hot chamber at a rate of 5-10 Hz. Two methods of injection are being investigated at this time: a gas gun and electromagnetic acceleration (a backup method). Detailed trade studies for power plant applicability will be performed, based on results from TFIF data, to determine the acceleration method for the ETF.

The gas gun is a relatively simple and well-developed projectile acceleration technology, but has warm gas that must be kept isolated from the targets and the fusion chamber. This complicates the thermal protection of the cryogenic targets and requires large differential gas pumping systems. The gas gun injector layout is shown in Fig. 1. With an EM device, the sabots could be open in front and could be decelerated and returned to the target loading system for re-use. An EM accelerator would also eliminate the large differential vacuum pumping system and simplify the job of keeping the targets cryogenic.

In the TFIF, cryogenic targets will be loaded into sabots, accelerated to typical injection velocities, and tracked as they enter a high-temperature test chamber. This test chamber will be operated to simulate the thermal environment of a power plant as seen by the target during injection. The surrogate target chamber will have high temperature walls (up to 1150 K) and we will evaluate methods to produce or simulate the high temperature chamber gas (up to 6000 K). Diagnostics at the position corresponding to the target chamber center will determine the condition of the target on-the-fly via rapid shadowgraphy and optical analyses with ultra-short high-intensity light sources.

V. Target Tracking

The target tracking system, as configured in the current experimental setup (Fig. 3) measures the initial trajectory and velocity of the target and predicts, on the fly, the exact position of the target (near chamber center) that the target will be when it initiates a trigger pulse. The trigger pulse triggers verification detectors (DCC) at chamber center and the beam-steered laser. The predicted coordinates are provided to the beam-steering controllers during the flight of the target from detector D2 to DCC.

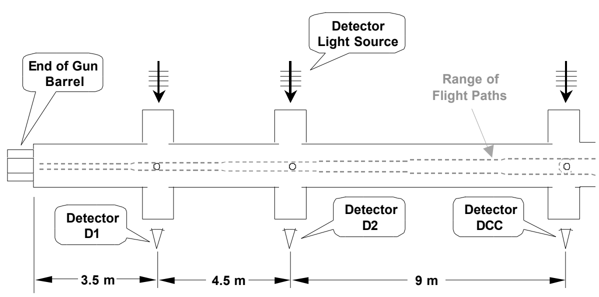

Fig. 3. Layout of the tracking system

It is anticipated that in order to meet the aiming requirements, the target will need to be tracked to close to chamber center. One way to do this is to predict the target's final position at chamber center from its measured velocity and position as it leaves the injector. The laser steering mirrors are then moved to focus the laser onto the predicted target position. At some distance into the chamber the target velocity and position are recorded again, and the mirrors adjusted to focus on the new predicted position. This method can be repeated several more times as the target traverses the chamber.

The tracking system will be developed on the TFIF. To be representative of an IFE reactor, the prediction detectors, D1 and D2, are located at least 9 m from chamber center detectors, DCC. This is the predicted position of the first tracking station. This accounts for the IFE chamber and neutron shielding. Additionally, components of D1 and D2 are positioned at least 0.5 m from the target flight path. In a reactor this would allow the components to be well shadowed by the neutron shielding. The tracking system aims to predict the target position to within ±14 µm. This is half (quadrature) of the ±20 micron error budget required for a zoomed-illumination target [6]. The other half is allocated to the pointing of the laser beams.

As noted above, it is anticipated that in-chamber tracking will be required. (However, models show that this may not be needed if the chamber gas has pressure less than 0.1 mTorr and relatively little motion.) One concept for this in-chamber tracking, to be developed in Phase-II, is to use additional detection stations, similar to D1 and D2 with the detector and light sources located on opposite sides of the chamber. Additional chamber environmental controls will allow development and testing of the capability for target tracking under extremely challenging chamber gas conditions. An alternative method for in-chamber tracking is also being evaluated and developed by Physical Optics Corp. under a DOE grant In this alternate system, interference patterns are set up in the target's path within the chamber. Variations in reflected light intensity from the target are used to calculate target position relative to the known position where the target enters the interference fringes. This system will supplement the ex-chamber tracking functions of the current experimental setup to provide a comprehensive determination of target position in the injection demonstration system.

VI. Target Survival

Following injection in the chamber, the target is exposed to heating from energy-exchange with the chamber fill gas and from chamber wall radiation. The target must accommodate the resulting heat fluxes and maintain a high degree of spherical symmetry and surface smoothness to satisfy the fusion micro-explosion physics requirements.

The maximum heat flux that can be accommodated by the target (assuming it starts at ~18 K and the outside DT surface temperature cannot exceed the triple point) is about 0.6-0.7 W/cm^2 for a typical flight time of ~15 ms. Based on wall radiation only, this can be met if the outside of the target is highly reflecting (emissivity <0.05) and the chamber wall is less than 1000 ˚C. Based on chamber gas energy exchange only and for an assumed condensation coefficient of unity, this can be met if the density of a ~4000 K Xe gas in the chamber is less than ~3 mTorr (Xe at standard temperature). The latter may be too low for protecting the first wall from ions [7,8] created by the more energetic targets under consideration.

The allowable heat flux can be increased by one of several methods. One is to inject the target at a lower temperature. Preliminary target design studies suggest that the target can be 12 K or less (*i.e.,* no gas inside the DT shell) and still yield high gain. With the target velocity above, for every degree K that the target is cooled below the triple point temperature, an additional ~0.34 Wcm^2 can be absorbed on average. Another approach with higher leverage is to coat the outside of the target with a thermally insulating foam. Studies show the allowable heat flux can be increased by 20x or more with this approach. The third approach is to evaluate the effect of allowing the outside of the target to go above the triple point [9]. All of these are under study.

Recent results for example show that if a vapor region does exist at the interface between the target outer coat and DT region, as illustrated in Fig. 4, it might self-heal due to density changes as DT solid turns to liquid provided the heat flux is above a critical value and the vapor region size below a critical value.

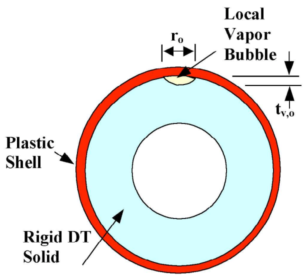

Fig. 4. Schematic of direct-drive target showing a vapor region at the DT/plastic outer coat interface

An R&D plan is proposed to help better understand the target thermomechanical and phase change behavior as it is injected, and to lead to a demonstration of target survival under the expected range of prototypical conditions. The plan starts with property measurements of DT and foam, particularly thermomechanical properties, at cryogenic temperatures. Increasingly integrated experiments follow. Examples of such experiments include better characterization of the energy exchange from the gas to the cryogenic target as a function of the target surface conditions, assessing the solid phase change behavior behind an insulating foam layer in a simple geometry using solid DT or a possible simulant, and performing the same assessment in a stationary target geometry over which gases at various temperature and density are injected to simulate the energy exchange and target response during injection. Important measurements include temperature history and vapor region (bubble) volume change.

These experiments would lead (some could also be done in parallel) to fully integrated experiments in the target injection facility where cryogenic target survival would be demonstrated over prototypical velocities and chamber conditions. Key issues for that facility include diagnostics and interface of the target injection with chamber conditions covering prototypical range of gas density (corresponding up to ~50-100 mTorr of Xe at standard temperature) and temperature (up to 4000-6000 K if possible) and of wall temperature (~1000-1200 K). Controlling this interface would require a system such as a shutter to insulate the "cool" target injection component from the "hot chamber".

Diagnostics at the position corresponding to the target chamber center will determine the condition of the target on-the-fly via rapid shadowography and optical analyses. Given target velocities of 200-400 m/sec, pictures must be taken in a few 10's of ns to retain micron resolution. This suggests exposure with a short-pulse laser; a relatively broad band diode laser should be used to avoid coherence speckle. The light-pulse has to be quite bright; to detect 100 1-eV photons per 2 micron pixel across a 2-mm shell requires 10 Joules of light (~10^{10} W/cm^2).

VII. Driver Interface

The final optical element that the laser driver encounters, prior to intercepting the targets, is necessarily open to the chamber and in the line-of-sight of the exploding targets. The design must be robust against damage threats, including 14-MeV neutrons. The reference concept under development at this time is a grazing-incidence metal mirror operating at an angle of ~85° from normal incidence. This mirror must maintain acceptable laser wavefront characteristics while it steers each beam onto the target at a distance of 20-30 m with a pointing accuracy of ~10 μm.

Phase-I research will demonstrate the ability to steer a beam onto individual plastic targets in flight with sufficient accuracy. This requires interfacing the target tracking system (described in Section IV) together with a mirror steering system. Diagnosing the aiming accuracy will be relatively straightforward, as the plastic capsules can be inspected after recovery to observe markings from laser ablation.

In the TFIF, we plan to field full-scale prototype mirrors with the relevant substrate size and construction, including actuators for adaptive wavefront control as well as internal cooling channels. The TFIF will demonstrate reliability and repeatability of the steering systems. The use of cryogenic ice targets adds another degree of complexity due to the difficulty in recovering targets for post-test analysis. The in-chamber imaging systems described in Section VI may be used for this purpose.

VIII. Summary

Fuelling a laser-IFE power plant involves achieving several challenging requirements. Substantial R&D is ongoing at present in order to establish the individual elements of the system. These include target fabrication processes, target handling and transfer, injection, tracking, chamber interfaces and driver interfaces. The Target Fabrication and Injection Facility is an essential element of the plan to develop inertial fusion based on lasers and direct drive targets. Its primary objective is to demonstrate the integrated operation of the fuelling system that will be required in order to move toward an Engineering Test Facility for laser IFE.

References

[1] J. D. Sethian, *et al.,* "Fusion Energy Research with Lasers, Direct Drive Targets and Dry Wall Chambers," *Nuclear Fusion*, **43** (2003) 117.

[2] M. Takagi, T. Norimatsu, Y. Izawa, and S. Nakai, "Development of Low Density, Low Atomic Number Foam Shell with Gas Barrier for Laser Fusion Target", Material Research Society Symposium Proceedings **372**, 199 (1995).

[3] J. Streit and D. Schroen, "Development of Divinyl Benzene Foam Shells For Use As Inertial Fusion Energy Reactor Targets", Fusion Science and Technology 43 (2003), May 2003.

[4] W.S. Richman and D.T. Goodin, "Cost Modeling for Fabrication of Direct Drive Inertial Fusion Energy Targets", Fusion Science and Technology **43**, (2003), May 2003.

[5] D. T. Goodin, et al., "Status of the Design and Testing of the OMEGA Cryogenic Target System (OCTS)," Presented at the 20th Symposium on Fusion Technology (SOFT), September 7-11, 1998, Marseille, France, and published in the Proceedings, Vol. 2, 949.

[6] S. E. Bodner, D. B. Colombant, A. J. Schmitt, and M. Klapisch, "High-Gain Direct-Drive Target Design for Laser Fusion," *Physics of Plasmas*, vol. 7 (6), pp. 2298-2301, June 2000.

[7] R. W. Petzoldt, D. T. Goodin, A. Nikroo, E. Stephens, N. Siegel, N. B. Alexander, A. R. Raffray, T. K. Mau, M. Tillack, F. Najmabadi, S. I. Krasheninnikov, and R. Gallix, "Direct Drive Target Survival During Injection in an Inertial Fusion Energy Power Plant," *Nuclear Fusion* **42** (2002) 1351-1356.

[8] A. R. Raffray, M. S. Tillack and J. Pulsifer, "Target Thermal Response and Gas Interactions," UCSD Technical Report, UCSD-ENG-092, June 2002 (http://aries.ucsd.edu/LIB/REPORT/ENG.shtml).

[9] A. A. R. Raffray, J. Pulsifer, M. S. Tillack and X. Wang, "Effect of Outer Insulating Porous Plastic Foam Layer on Target Thermal Response During Injection," UCSD Technical Report, UCSD-ENG-096, October 2002 (http://aries.ucsd.edu/LIB/REPORT/ENG.shtml).