Addressing Key Science and Technology Issues for IFE Chambers, Target Fabrication and Target Injection

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Abstract. Significant progress has been made in the development of high repetition rate chambers, target fabrication and injection for inertial fusion energy (IFE) for both heavy ion and laser drivers. Research is being conducted in a coordinated manner by national laboratories, universities and industry. This paper provides an overview of U.S. research activities and discusses how interface considerations (such as beam propagation and target survival during injection) impact design choices.

1. Introduction

The U.S. has a significant R&D effort to develop the science and technology needed for inertial fusion energy (IFE). Here we focus on work that addresses the issues related to the fusion chamber, the interface between the chamber and the driver, target fabrication, and target injection.

2. Fusion Chambers

Chamber research for heavy-ion-driven IFE currently focuses on a thick-liquid-wall chamber concept, HYLIFE-II [1]. This chamber uses jets of flibe (F, Li, Be molten salt) or flinabe (F, Li, Na, Be molten salt) to protect structures from target emissions including high-energy neutrons. The key issues under study are the formation of the liquid jets that make up the protective blanket and re-establishing the protective configuration between pulses (including clearing drops that could interfere with beam propagation or target injection). Several university-scale experiments are addressing these issues. At UCB, experiments with water jets have demonstrated 1) the ability to produce very high quality (low surface ripple) cylindrical jets that are needed for the beam port region, 2) repetitive disruption (by chemical detonation) of an array of 96 jets [2], and 3) formation of vortex flow that can be used to protect the inner surface of beam pipes in the region of the final focus magnets.

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Experiments at GT are characterizing surface ripple for various nozzle designs and flow conditions in the turbulent liquid sheets proposed for the protective blanket (see Fig. 1) [3]. GT is also conducting experiments and modeling on wetted-wall chambers that use a thin film of liquid to absorb short ranged target emissions [4,5]. UCLA recently activated a plasma-gun-based facility to study vaporization and condensation of flibe, including flowing liquid to enhance condensation [6]. LLNL is responsible for systems integration and modeling of the driver/chamber interface including radiation protection for the final focus magnets [7]. LLNL also conducts safety and environmental assessments including effects of target materials that enter the flibe. The ARIES team recently carried out an evaluation of the thick-liquid-wall chamber as part of their work on IFE.

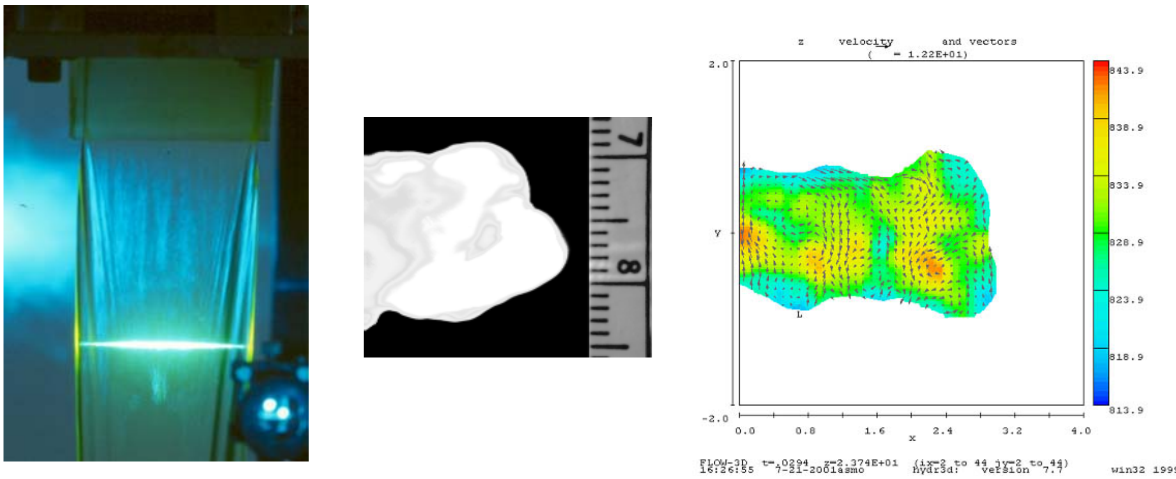


Fig. 1. Characterization of surface quality of turbulent 10 cm × 1 cm water jet: Laser induced fluorescence diagnostic at GT (left), resulting image of edge region (center), 3D simulation carried out by UCLA (right).

Chamber research for laser-driven IFE has been focused on dry-wall designs that employ either advanced materials, a chamber fill gas, or both to alleviate the threat from short-ranged target emissions (x-rays, ions and debris) [8,9]. Survival of the first wall (from pulsed heating and radiation damage effects) for an acceptable time (in terms of the plant lifetime) is a key issue for dry-wall chambers. An important consideration for the gas-protected concept is the effect of the gas on the cryogenic target during injection. Analysis indicates that there is a design window of target yield, chamber radius and gas pressure that will avoid first wall vaporization and permit target injection without damage to the fuel. An unresolved issue with this configuration is the long-term damage to the chamber wall from x-rays and ions (particularly the alpha particles). All of these are being investigated further, including the behavior of the wall material at IFE relevant temperatures, more detailed calculations of the ion and x-ray flux hitting the wall, and the possibility of using magnetic fields to divert the ions. Effort is being devoted to improving chamber dynamics models that predict the time evolution of post-shot chamber conditions (vaporization, condensation, aerosol formation) and to benchmarking these models with experiments. Experiments and modeling of first wall response to pulsed x-ray and debris heating have been carried out and more are planned.

3. Driver / Chamber Interface

The final focus magnets for heavy ion (HI) drivers are located as close to the chamber center as possible in order to achieve small beam spot sizes on the fusion target, which is necessary to achieve implosion symmetry and high target gain. The most recent HI driver design has

120 beams, with 60 coming from each side of the indirect-drive target. The inner edge of the final focus magnet for each beam line is only 6 m from chamber center. The array of magnets must be closely packed in order to meet the geometric requirements of the target, which places constraints on the amount of neutron shielding that can be incorporated into the design. Work has been carried out to determine the shielding requirements for these magnets, and results of these detailed 3D neutronics calculations indicate that it is possible to provide enough shielding that the magnets will survive for the assumed 30 year life of the fusion power plant [7].

For laser driven IFE, the final optics can be located farther from chamber center (>20m), but they are in the direct line of sight of the target emissions. Experiments and analyses on radiation damage induced degradation of optical properties have been ongoing. Results to date indicate that a thin (1mm) transmissive grating made of fused silica will be acceptable for Diode Pumped Solid-State Lasers (DPSSL) [10]. The color center growth saturates at an acceptable level. Most of the recent work on reflective optics (for use with both DPSSL and krypton fluoride lasers) has been with highly polished, grazing incidence aluminum mirrors [11]. Figure 2 shows the allowable laser fluence as a function of cumulative pulses and indicates a baseline level that is well above the 5-10 J/cm^2 needed for IFE designs. It is likely that these will be implemented with a thin Al layer on a neutron damage resistant substrate. For either reflective or transmissive final optics, damage from debris and x-rays may have to be mitigated and several techniques to minimize these threats have been proposed (e.g., gas puffs and magnetic deflection).

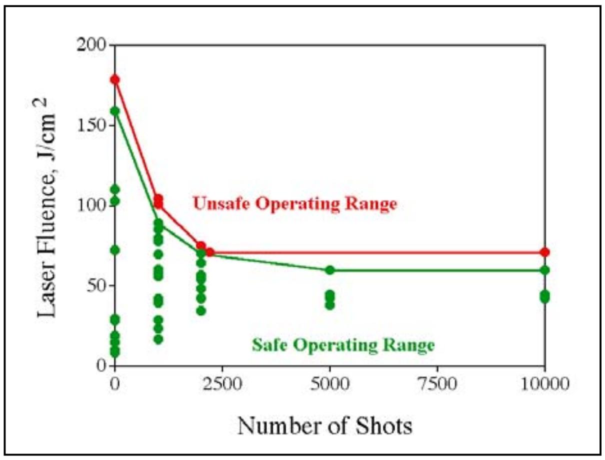
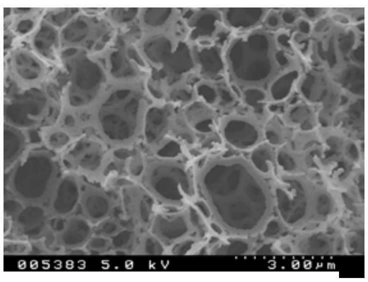


Fig. 2. Allowable laser fluence vs. number of pulses for pure Al mirror.

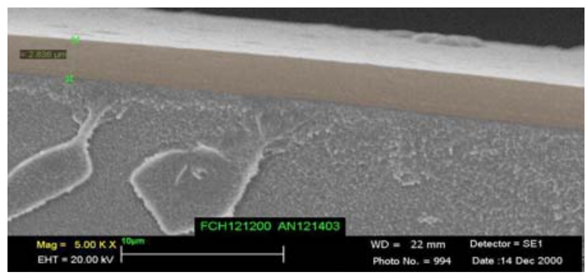
4. Target Fabrication and Injection

The target fabrication facility of an IFE power plant must supply about 500,000 targets per day, including manufacturing the spherical fuel capsule and other materials, filling the capsules with the DT fusion fuel, redistributing the frozen DT uniformly around the inside of the capsule (layering), and assembling the hohlraum (for indirect drive). Target fabrication work has concentrated on investigating and developing the various materials needed by the target designs and on fabrication techniques that could eventually scale to low cost and high production rate. For indirect drive targets, very low density foams doped with high-z materials, which make up the energy deposition material hohlraum, have been developed (see Fig. 3). Development of additional foam fabrication methods is underway, including laser-assisted chemical vapor deposition (LCVD), which may allow growth of micron-scale controlled structures for *in-situ* fabrication of the hohlraum foam components [12]. For both indirect and direct drive targets, a small-scale fluidized bed that is capable of coating mandrels with relevant ablator materials has also been built (Fig. 3). For direct-drive targets, alloys of high-z capsule coatings are being optimized to give the desired properties of high reflectivity (for survival of the direct-drive cryogenic target in the high temperature chamber) and high permeation (for permeation filling with hydrogen isotopes). Models of material responses during the permeation filling step, and models for tritium inventory in the target facility have been developed and used to project acceptable quantities of tritium for plant operation for direct drive targets [13].

The target is injected into the target chamber at a rate of 5–10 Hz. The DT layer must survive acceleration in the injector as well as exposure to the extremely rapid heat flux from the chamber walls. The target must remain highly symmetric and have a smooth inner ice surface finish when reach the chamber center. Current cryogenic target research constrains the target temperature to be constant within 0.5 K. Current target designs call for the target temperature (in order to get the optimum DT gas density inside the target) to be about 18.5 K. Models of the thermo-mechanical effects on the advanced materials during injection have been developed. Fundamental measurements of the properties and response of DT under these unique conditions are being carried out. The target must be positioned at the center of the chamber with a placement accuracy of ±5 mm and an alignment of the beams and the target of ±20 μm or ±200 μm for direct drive and indirect drive, respectively [14]. An experimental injection and tracking system is being constructed to develop technologies and to demonstrate meeting these challenging requirements.



2% Au doped foam,
30 mg/cm^3



~3 μm thick polymer coating deposited on a mandrel using fluidized bed technology

Fig. 3. Example of metal-doped foam for heavy ion target (left) and a spherical capsule with a polymer coating produced in a fluidized bed (right).

Progress has been made on modeling the cost of target production. Assuming target costs can contribute ~10% to the cost of electricity (a reasonable goal), we can afford about $0.25 each for 400 MJ targets. We have performed a cost analysis of manufacturing the direct drive target in a commercial process plant environment. This modeling includes process flows, mass-energy balances, plant utilities, raw materials, quality control, waste handling and recycling, capital equipment cost amortization, and staffing requirements. Preliminary inputs to the model indicate that the total cost of the direct drive target, including insertion into the injector, is $0.16, significantly less than the goal. For indirect drive, more detailed hohlraum requirements, cheaper materials and easier fabrication processes are still being evaluated, but the cost for manufacturing the shell, then filling and layering is about $0.11 each [15]. This is very encouraging because it leaves significant margin for the manufacture of the unique hohlraum components and assembly of the hohlraum with the shells. Evaluation of the cost of manufacturing the hohlraum itself, as well as assembly, is underway.

Conclusion

A research program to develop the science and technology of high pulse repetition rate chambers, target fabrication and target injection systems is in place and has made significant progress in recent years. Success in these areas, coupled with the continued development of efficient, high rep-rate drivers (lasers, heavy-ion accelerators and z-pinches) and the future demonstration of ignition on the National Ignition Facility (NIF) are critical to the development of IFE.

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