Chamber Dynamic Response, Laser Driver-Chamber Interface and System Integration for Inertial Fusion Energy

M. S. TILLACK, F. NAJMABADI and A. R. RAFFRAY
University of California, San Diego, La Jolla, CA 92093-0417

Introduction

Enabling technologies for inertial fusion energy are beginning to receive the same level of scrutiny within the United States as magnetic fusion energy technologies have enjoyed for the past two decades. New, coordinated activities have been started within the framework of both the DOE Office of Fusion Energy Sciences and the DOE High Average Power Laser Program. The University of California at San Diego contributes to these activities in several key areas including chamber physics, driver-chamber interface and system integration.

The ARIES Team, which historically has focused its efforts on developing integrated power plant visions for magnetic fusion concepts, has begun a broad assessment of IFE chamber technologies including dry walls, walls protected with sacrificial layers and thick liquid schemes. The motivation for this work is to understand trade-offs and to identify design windows for promising concepts. This work is **not** aimed at developing a point design.

Up to now, most research on IFE chambers has focused on addressing whether or not the chamber wall survives the target explosion. However, another key uncertainty is whether or not the chamber environment will return to a sufficiently quiescent and clean low-pressure state following a target explosion to allow a second shot to be initiated within 100–200 ms. The chamber condition following a target explosion in a realistic chamber geometry is not well understood. A predictive capability in this area requires a combination of computer simulation of increasing sophistication together with simulation experiments to ensure that all relevant phenomena are taken into account, as well as to benchmark the calculations. Initial steps have been taken toward developing such a predictive capability.

The interface between a laser driver and the chamber environment poses particularly challenging problems. Large final optical elements can be both expensive and delicate, but must last of the order of 10^8 shots. In addition, the requirements on beam uniformity and wavefront control necessary in order to assure that targets will implode properly are difficult to meet, even in the absence of the many damage threats that exist in an IFE chamber. Three types of studies are underway at UC San Diego in order to address this problem:

1. Experimental studies of laser-induced damage to grazing-incidence metal mirrors,
2 Modeling and measurements of the wavefront distortion from imperfect surfaces to establish requirements which guarantee adequate beam characteristics on target, and
3. Studies of laser beam propagation in simulated chamber media, including determination of breakdown threshold of low-pressure impure gases and the wavefront distortions which occur near or beyond breakdown.

Assessment of Chamber Concepts for Inertial Fusion Power Plants

The ARIES-IFE study is a national US effort involving universities, national laboratories and industry performing integrated analyses of IFE chambers and chamber interfaces with the driver and target systems. Rather than focus on a single design point, the study aims at identifying design windows, trade-offs, and key physics and technology uncertainties for various IFE chamber concepts (see Fig. 1). An essential element of this study is the detailed characterization of the target yield and spectrum. We have selected heavy-ion indirect target designs of LLNL/LBL [1] and a direct-drive target design of NRL [2] as our reference targets. Detailed spectra from these two targets have been calculated – their photon and ions/debris spectrum are vastly different.

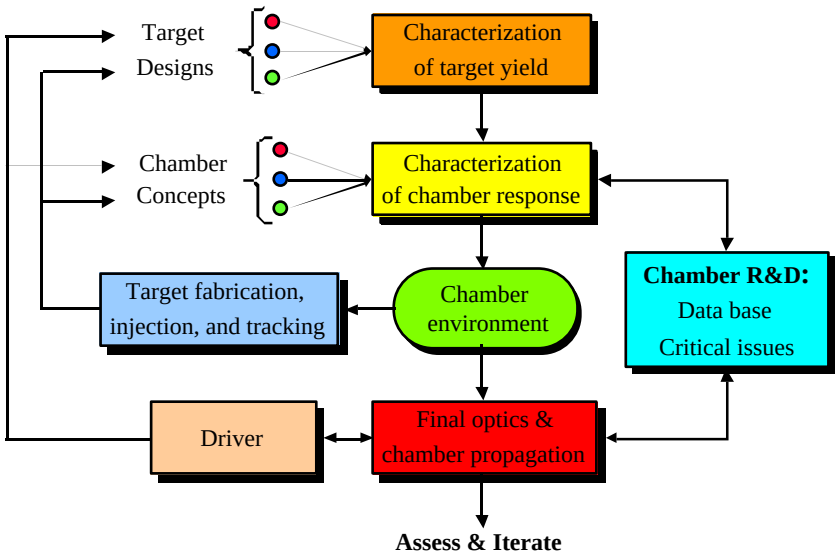

FIG. 1. ARIES Assessment Methodology

Three main classes of chamber concepts will be analyzed including dry walls, solid structures with protective zones (*e.g.*, wetted walls), and thick liquid concepts. The design window for each combination of target and chamber will be explored. For example, for dry wall chambers with direct-drive targets, analysis of target heating during injection in the chamber leads to upper limits on chamber gas and chamber wall temperature. Incident energy and particle fluxes on the wall of the chamber have been calculated and thermal response of the wall analyzed. Survival of the wall requires that the gas pressure in the chamber exceed a certain level in order to lengthen the energy pulse arriving at the wall. It appeared previously that no design solution was possible given these two constraints. Detailed analysis showed, however, that a design window for dry-wall chambers exists in which the gas pressure is low enough to allow for successful injection while ensuring wall survival. Similar analysis has been performed for an indirect drive target.

Driver/chamber interface issues also are under investigation in the ARIES-IFE program. These include analysis of: laser propagation in gas-filled chamber, grazing incident metal mirrors (GIMM) as final optics, propagation and focusing of heavy-ion beams in relatively high-pressure chambers and design and optimization of final focus magnets. Parametric systems analysis as well safety analysis is performed to identify relative advantages of each concept.

Chamber Dynamic Response

The long-term objective of chamber dynamic modeling is to create a fully integrated computer code to simulate and study chamber dynamic behavior, including hydrodynamics, particle and radiation transport, thermal behavior, chamber wall response and lifetime, and cavity clearing. Complex geometrical effects on gas-dynamics and heat transfer must be taken into account. Our modeling focuses on the relatively long-time phenomena starting from the target blast and proceeding through chamber clearing in preparation for the next target injection.

Initial studies are intended to lay the groundwork for continuing development by building the infrastructure of the code and several modules defining the physics of the various key phenomena (see Fig. 2). The code is being written in a modular fashion to allow straight-forward inclusion of new physics models. These modules include hydrodynamics (transient compressible Navier Stokes), radiation and energy deposition, and chamber wall interaction modules which will include the physics of melting; evaporation and sublimation, sputtering, macroscopic erosion, and condensation and redeposition.

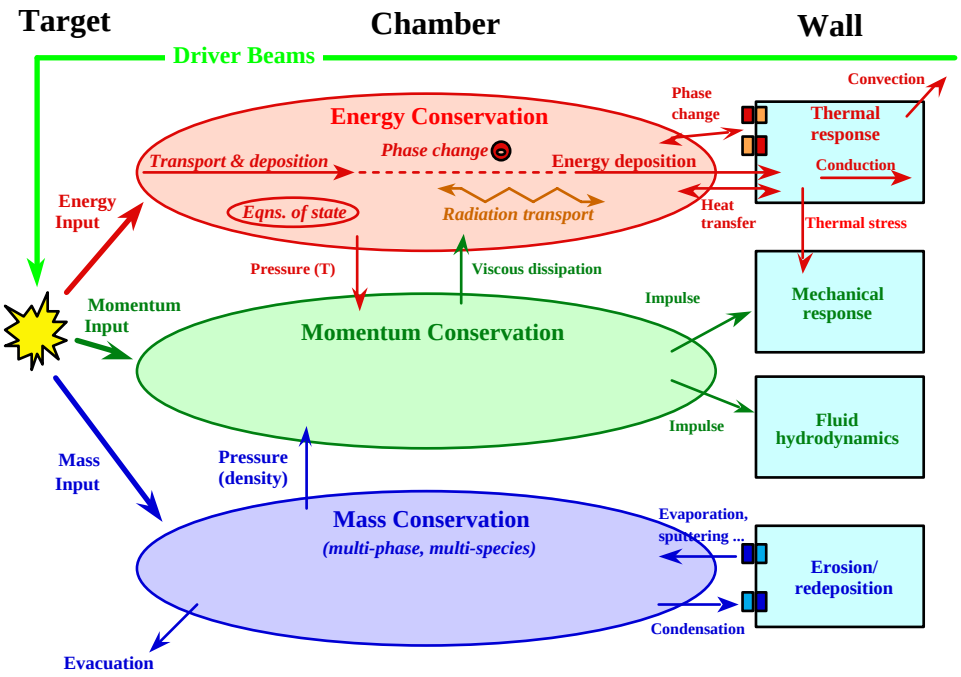

FIG. 2. Multi-physics model of chamber response

Simulation experiments will be needed to ensure that all relevant phenomena are taken into account and to benchmark the calculations. While a test facility with fully prototypical conditions (including neutrons, x-rays, and debris) requires an ignited target within a factor of 10 yield as compared with a power plant chamber and similar repetition rate, simulation experiments of most relevant phenomena can be performed with an x-ray burst of sufficient energy to produce prototypical energy density in the chamber gas and on the surrounding walls. Our work is focused on relevant experiments that can be carried out in a facility producing 100-1000 J of x-ray energy.

Laser Driver-Chamber Interface Studies

The final optic of a laser-driven IFE reactor is exposed to direct line-of-sight threats from the target explosions: neutrons and gamma rays, x-rays and high-energy ions, and contamination. One of the top candidates for a robust optic that can withstand this environment is a grazing-incidence metal mirror [3]. As seen in Fig. 3, aluminum is the top candidate due to its superior reflectivity deep into the UV spectrum where most IFE target designs operate (1/3 or 1/4 μm).

In order to compensate for their relatively poor reflectivity and low damage threshold at normal incidence, metal mirrors are used at a shallow angle of incidence. The ability of such a final optic to survive long-term exposure (~10^8 shots) at laser fluences well beyond the normal-incidence damage threshold is still in question, particularly in the presence of damage threats which may create defects and/or contamination on the mirror surface. Both modeling and experimental verification of laser-induced damage to grazing-incidence metal mirrors are being performed. In addition to the studies of surface damage, modeling and measurements of the wavefront distortion to defected surfaces are underway to determine the ability to maintain adequate beam characteristics on target.

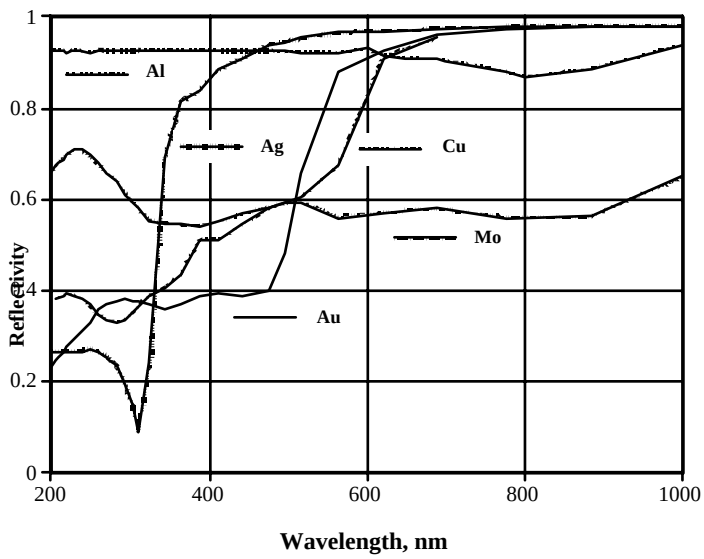

FIG. 3. Normal incidence reflectivity of several metals

As the laser beams converge onto the target at the center of the chamber, they approach or exceed the laser breakdown threshold. Laser breakdown is not well studied in the low gas pressure regime expected in a gas-protected dry-wall IFE chamber. Data are scarce below ~10 Torr (see Fig. 4). The effect of impurities, including aerosol and particulate debris, further complicates the behavior. A particular concern for IFE is the possible distortions to the beam which may occur near or beyond breakdown; the requirements on beam symmetry and smoothness place severe constraints on propagation through chamber media.

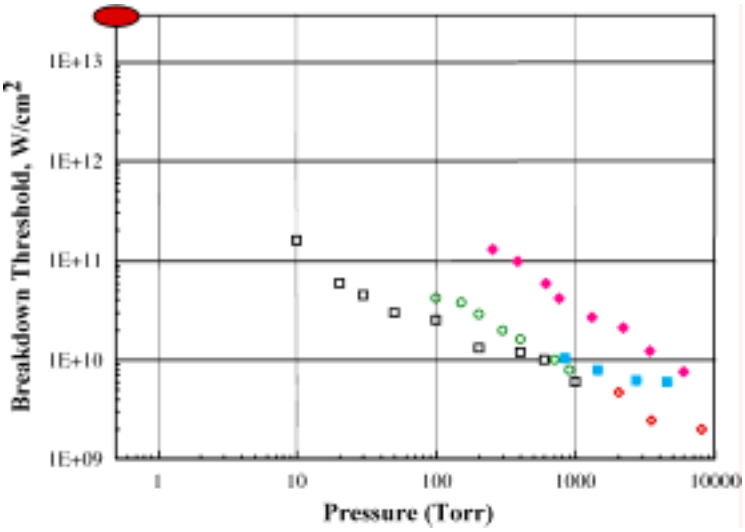

FIG. 4. Laser breakdown threshold in Xe [4-8]

Summary and Conclusions

Successful development of inertial fusion technology requires attention to a wide array of engineering phenomena. Many opportunities exist for collaborative research on small-scale simulation experiments as well as computational and theoretical modeling. Work carried out at the University of California San Diego includes three key elements:

1. Integrated system studies under the framework of the ARIES program,
2. Chamber dynamic modeling and simulation experiments, and
3. Laser driver-chamber interface studies.

References

1. D. A. Callahan-Miller and M. Tabak, “A Distributed Radiator, Heavy Ion Driven Target Driven by Gaussian Beams in a Multibeam Illumination Geometry,” Nuclear Fusion, **39**(7) July 1999.
2. S. E. Bodner, D. G. Colombant, A. J. Schmitt, and M. Klapisch, "High-Gain Direct-Drive Target Design for Laser Fusion," Physics of Plasmas **7**(6), June 2000, pp. 2298-2301.
3. R. L. Bieri and M. W. Guinan, "Grazing Incidence Metal Mirrors as the Final Elements in a Laser Driver for Inertial Confinement Fusion," Fusion Tech. **19** (May 1991) 673-678.
4. M. C. Gower, "KrF Laser-Induced breakdown of Gases," Optics Communications **36**(1), January 1981, p.43.
5. H. T. Buscher, R. G. Tomlinson and E. K. Damon, "Frequency Dependence of Optically Induced Gas Breakdown," Phys. Rev. Lett. **15**(22), November 1965, p. 847.
6. A. J. Alcock, K. Kato and M. C. Richardson, "New Features of Laser-Induced Gas Breakdown in the Ultraviolet," Optics Communications **6**(4), December 1972, p.342.
7. J. E. Murray, *et al*., "Spatial Filter Issues," Proceedings of Solid State Lasers for ICF, Paris (1996).
8. D. I. Rosen and G. Weyl, "Laser-Induced Breakdown in Nitrogen and the Rare Gases at 0.53 and 0.35 mm," Journal of Physics D, **20**(10) 14 Oct. 1987, p.1264-76.