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IFE Chamber Physics Research Needs:
A White Paper

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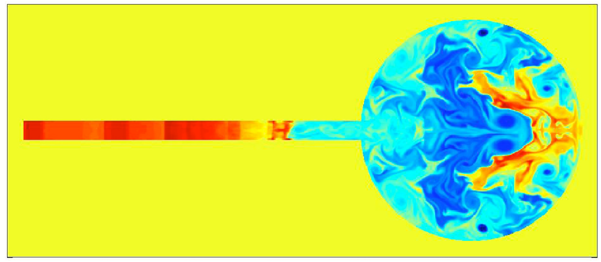

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Abstract

Chamber physics research explores the interactions of ignited IFE target emissions with surrounding materials, and attempts to solve key questions related to chamber operability and survival. The scope of chamber physics includes prompt transport and deposition of particles and energy immediately following target ignition, materials interactions and responses, and chamber dynamics and recovery. In the context of a fusion energy system, IFE chamber physics is analogous to the boundary plasma physics and plasma-material interactions research performed within magnetic fusion energy programs. Understanding and quantifying IFE chamber phenomena requires basic research involving a variety of physical science disciplines, including radiation transport, gasdynamics, shock physics, phase change physics, atomic physics, plasma physics, and solid state materials science. The current status and future research needs for chamber physics is summarized in this document.

1. Introduction

Inertial fusion targets emit neutrons, ions, x-rays and gamma rays during a very short period of time – of the order of nanoseconds. Following each target explosion, particles and radiation propagate into the surrounding medium, interact with materials in various states of matter, and finally are converted into heat and, in the case of breeding blankets, fuel to supply further fusion reactions. Depending on the chamber design, the target emissions may interact with solids, liquids, gases and/or plasmas. The ensuing materials responses are intense, in some cases passing into the regime defined as "high energy density" by the NRC Committee on High Energy Density Physics [1].

Chamber physics research explores these basic interactions and responses, and attempts to solve key questions related to chamber operability and survival. Understanding and quantifying these phenomena requires research involving a variety of disciplines, including radiation transport, gasdynamics, shock physics, phase change physics, atomic physics, plasma physics, and solid state materials science.

Extensive research has been and continues to be carried out on *target physics* through NNSA-funded activities. The primary emphasis of the NNSA work is driver-target interactions and the compression and ignition of capsules. The resulting interactions of target emissions with surrounding materials enjoy far less attention. Post-burn physics is generally considered outside the scope of the NNSA mission, except to the extent it impacts the operation of facilities such as NIF.

Chamber physics begins where target physics leaves off – with the intense burst of particles and energy emanating from the ignited target. The purview of chamber physics includes the interface between the "core" burning plasma in the target and the surrounding structures which contain the IFE events. In this respect, chamber physics is analogous to boundary plasma physics and plasma-material interactions research performed within DOE-funded magnetic fusion energy programs.

The chamber environment evolves through many orders of magnitude in temperature and density as the extreme conditions immediately following target ignition evolve toward the semi-quiescent conditions preceding the next target insertion. Three categories of science issues are considered here, roughly corresponding to the three primary time scales of the evolution of the chamber environment:

1. Prompt transport and deposition of particles and energy immediately following target ignition
2. Materials interactions and responses
3. Chamber dynamics and recovery

The current status and future research needs for each of these generic chamber science issues are briefly summarized below.

2. Transport and deposition of particles and energy

Energy transport phenomena determine the temporal and spatial profiles of the energy deposition, as well as the energy spectrum in various elements of the chamber. This, in turn, determines the initial conditions and severity of the materials responses.

Several modeling tools exist for simulating the radiation hydrodynamics of an IFE fireball expanding into a low-pressure gas/plasma background. These models require validation, primarily as a result of uncertainties in equation-of-state and atomic physics data. In addition, most readily-available models are limited to one spatial dimension. This regime of chamber physics shares much in common with astrophysical phenomena (such as supernova remnants [2]), laser-plasma and other high energy density physics research. Indeed, the challenge to develop and validate multi-dimensional radiation hydrodynamics and atomic physics tools is shared by all of these fields.

Multi-dimensional simulation of post-ignition chamber phenomena is computationally very challenging. Since many of the NNSA-developed codes are not widely available to university researchers, theoretical collaboration with the broad IFE community is limited. The IFE program would benefit from developing an open source simulation capability in the area of chamber physics, perhaps in coordination with a similar activity in target physics (which was recommended by the 2003-04 FESAC IFE Panel [3]).

Relevant exeriments can be carried out in facilities which provide short-pulse (nanosecond) sources of energy, such as lasers [4] and Z-pinches [5]. Energies of the order of 50 J allow access to relevant parameter regimes [6]. Higher yield experiments on facilities such as Omega and NIF clearly would be valuable; however, a program of exploratory research on smaller facilities would provide a very cost effective means to develop the underlying science and experimental techniques in order to maximize the utilization of larger national facilities.

In addition to traditional "rad-hydro" and atomic physics simulations, the possibility of collective effects in the post-ignition chamber environment adds another dimension to this subject. For example, beam-plasma instabilities may lead to strong damping of ions emanating from IFE targets. Magnetic field effects on plasma expansion has been studied for many years, both as a purely scientific subject as well as a potential means to extract energy or divert target emissions for IFE [7,8].

3. Materials interactions and responses

Surrounding and intercepting the energy from an exploding IFE target are the condensed phase structures which may be in a liquid or solid state. Materials responses in the various elements of the chamber include hydrodynamic flows, shock waves, phase change, solid state molecular dynamics and micromechanical behavior of solids. Materials responses determine the lifetime and reliability of chambers, and also serve as boundary conditions on the chamber dynamics and recovery.

Initial studies have been performed in many of the relevant subdisciplines, but these studies have only scratched the surface in an attempt to quantify the severity of the issues for fusion. Much more work is needed in order to establish the feasibility and characteristics of IFE chambers.

The issues are considerably different for solid-wall as compared with liquid-wall chambers. For solid-wall chambers, the primary concern is damage accumulation by thermomechanical or energetic particle-induced microstructural changes. For example, experiments have been initiated recently within the High Average Power Laser (HAPL) program to quantify ablation and fatigue behavior of wall materials subjected to x-rays, ions, and thermal loads from laser and pulsed IR heating sources.

Liquid protected chambers reduce or eliminate these concerns over solid structure thermo-mechanics, but raise entirely new concerns over the hydrodynamic and phase change behavior of liquids. In some cases, such as the thick liquid heavy ion chamber of the HI VNL [9] or Z-IFE [10] the combination of high yield from x-rays (with nanosecond temporal pulse width), short absorption depth and small stand-off to the first surface can convert the near-surface region to a dense plasma resulting from absorbed energy density in excess of 10^{11} J/m^3, which extends into the regime defined as "high energy density" by the NRC Committee on High Energy Density Physics [1].

The response of liquids to sudden energy deposition includes both pressure-driven and thermally-driven phenomena. For example, isochoric heating by neutrons has been studied in order to characterize the resulting fracture of thick liquid jets [11]. Studies of the shock propagation through the gas phase, including the interface with single and multiple jets, also has been explored under the auspices of the OFES IFE Technology program [12,13]. Further studies are needed in order to support the evolution of design concepts, especially in the relatively new area of Z-IFE chamber shock mitigation.

The creation of aerosol is another fundamental issue with liquid-protected chambers. Residual aerosol in the chamber will interfere with successful propagation of targets and drivers in succeeding shots. In addition, the physics of phase change also plays an important role in determining the impulsive loading of liquid surfaces. Initial studies have been performed on homogeneous nucleation and heterogeneous growth of clusters in partially ionized ablation plumes [14]. Phase change also can occur at the liquid surface (through evaporation) or within the volume of the liquid, through an explosive phase change process called "spinodal decomposition" [15]. Modeling of spinodal decomposition is particularly challenging, due to the strong non-linearity of the material response near the spinodal line.

4. Chamber dynamics and recovery

The chamber medium following a target explosion is a high-temperature ionized gas in disequilibrium, with strong spatial gradients throughout the chamber. In order to operate IFE devices in a repetitive mode, a moderately low-temperature, quiescent condition must be established in the chamber prior to the injection of cryogenic targets and driver beams. The challenge is significantly different depending on the target and driver designs. For solid wall chambers, mass loss is minimized such that the key issues relate to the thermal and fluid-dynamic evolution of the chamber gas/plasma mixture. For liquid wall chambers, additional issues include phase change, aerosol transport and shock mitigation.

Numerical modeling has been performed on both liquid and gas-protected IFE chambers. Model development usually begins with a fluid-dynamic solver at the heart of the simulation, upon which addition physics is added, as needed, to adapt to IFE-specific phenomena. For example the Spartan code was developed over the past 2 years to solve the 2-D transient compressible Navier-Stokes equations with a second order Godunov method for capturing strong shocks, full accounting of dissipative terms, adaptive mesh refinement for uniform accuracy throughout the fluid domain and arbitrary boundaries resolved with an embedded boundary method [16]. This simulation tool is currently under development to add capabilities such as radiation transport and atomic physics in order to support the HAPL program. Similar computational development activities are needed for liquid chamber concepts, with a special emphasis on phase change and aerosol transport modeling [17].

Although experiments have been performed to help validate individual aspects of chamber recovery modeling, few (if any) integrated experiments have been performed. One of the most significant limitations is the nature of the energy source used to initiate the event. Recent small-scale experiments have used lasers, electrothermal discharges, and even shotgun blasts. The availability of facilities such as Electra [18] and Mercury [19], which provide clean sources of short-pulse energy with 100-1000 J, will enable a variety of useful integrated tests to be performed.

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