The ARIES-IFE study aims at identifying design windows, trade-offs, and key physics and technology uncertainties for various IFE chamber concepts. Three main classes of chambers are under study: solid walls, solid structures with protective zones (e.g., wetted walls), and thick liquid concepts. Both direct and indirect targets are considered. Study was started in June 2000 and will be completed by Dec. 2002. This paper summarizes our research on solid-wall concepts. We have produced accurate target output spectra. Analyses indicate that accurate spectra as well as the time of flight of ions have significant impact on the thermal response of the wall. We propose the use of an armor to separate energy/particle accommodation function from structural and efficient heat removal function: Armor is optimized to handle particle and heat flux and First wall is optimized for efficient heat removal. Design windows for dry-wall chambers have been developed.

1. Introduction

The ARIES-IFE study, a national US effort involving universities, national laboratories and industry is an integrated study of IFE chambers and chamber interfaces with the driver and target systems. Rather than focusing 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. An essential of element of such a study is the detailed characterization of the target yield and spectrum. We have selected heavy-ion indirect target designs of LLNL/LBL and direct-drive target designs of NRL as our reference targets. Detailed spectra from these two targets have been calculated -- their photon and ions/debris spectra are vastly different. Three main classes of chamber concepts are analyzed including dry walls, solid structures with protective zones (e.g., wetted walls), and thick liquid concepts. The design window for each of these six combinations of target and chamber is being explored. The ARIES-IFE study was initiated in June 2000 and is to be completed by December 2002. This paper is a brief summary of our result for dry wall chamber concepts. We will present design windows for several systems such as target injection and tracking, thermal response of the first wall, and laser or heavy-ion propagation and focusing. Detailed and up-to-date information can be found on the ARIES Web site and bibliography of ARIES-IFE research [1].
2. Target Design, Injection, and Tracking

Six classes of target designs were considered and two of them were chosen as reference targets for the ARIES-IFE study. They are NRL advanced direct-drive targets [2] and LLNL/LLBL heavy-ion indirect-drive targets [3]. Detailed spectra of target emissions at 100 ns past target ignition were calculated [4]. The energy partitioning between different channels is summarized in Table I. Photons (X-ray) and ions/debris spectra of these targets are vastly different. The direct-drive target has a relatively lower yield and very little energy in the X-ray channel compared to the indirect-drive target. As such, these two targets probably bracket the possible IFE target outputs and spectra.

During injection in the chamber, the cryogenic IFE targets are heated by friction with the chamber gas and thermal radiation from the chamber walls. Recent studies indicated that only target temperature increases of ~1 K could be tolerated during injection to maintain the required target uniformity for a symmetrical burn. Major concerns are melting of the ice layer as well as thermal stresses induced in the DT ice. Our analysis of target heating during injection in the chamber indicated that indirect drive targets are well protected by the hohlraum and no major constraints were found. On the other hand, survival of direct-drive targets during injection imposes severe constraints on the chamber environment. We have found that the NRL direct-drive target injected in a typical IFE chamber (~6 m major radius filled with Xe) at 200-400 m/s can survive only if the gas pressure is < 50 mTorr and wall temperature is < 700ºC [5]. This is a severe requirement, as past studies, such as SOMBRERO [6], indicated the need for a protective Xe gas at a significant pressure (0.5 Torr) to prevent unacceptable wall erosion.

The target injection system should place the target in the chamber with a high-precision placement (± 5 mm). Indirect and direct-drive targets require tracking and beam steering to ±200 and 20 µm accuracy, respectively. For ex-chamber tracking, the chamber gas results in a large deflection of the target (~20 cm for 0.5 Torr of Xe) that should be accounted for in the injection system. In addition, even 1% density variation in chamber gas causes a change in predicted position of 1 cm (at 0.5 Torr). Target tracking and beam steering are less difficult at low gas pressure (for manageable effect at 50 mTorr, density variability must be <0.01%). It appears that both low gas pressure and in-chamber tracking are required for successful target racking and beam steering [5].

3. Thermal Response of Chamber Wall

3.1 Direct-drive targets

Because of the severe target injection constraint on the chamber gas pressure, the response of a chamber with no buffer gas was analyzed first. Starting from the detailed spectra of our reference targets, a 1-D slab geometry was used to compute energy deposition by photons and ions in the chamber wall (W and C). This time-dependent energy deposition in the wall was used

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Table I: Energy Partitioning for reference ARIES-IFE targets

<table>
<thead>
<tr>
<th></th>
<th>NRL Direct-drive (MJ)</th>
<th>Heavy-ion Indirect-drive (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver energy</td>
<td>1.3</td>
<td>3.3</td>
</tr>
<tr>
<td>X-rays</td>
<td>2.14 (1%)</td>
<td>115 (25%)</td>
</tr>
<tr>
<td>Neutrons</td>
<td>109 (71%)</td>
<td>316 (69%)</td>
</tr>
<tr>
<td>Burn product fast ions</td>
<td>18.1 (12%)</td>
<td>8.43 (2%)</td>
</tr>
<tr>
<td>Debris ions</td>
<td>24.9 (16%)</td>
<td>18.1 (4%)</td>
</tr>
<tr>
<td>Total</td>
<td>154</td>
<td>458</td>
</tr>
</tbody>
</table>

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as input to ANSYS to analyze the thermal response of the wall. Figure 1 shows an example temporal distribution of temperature at various spatial locations in a 3-mm W first wall. Back of the wall is cooled with a coolant at 500°C. The maximum temperature of the first wall is ~1,438°C, considerably lower than the W melting point at 3,410°C.

Similar analysis were performed for C wall and showed that C sublimation is negligibly small. These analyses indicate that no buffer gas is necessary for wall protection against NRL direct-drive targets. This is due to: 1) there is little energy in X-ray channel (which appears on the wall in ns time-scale) and 2) time-of-flight effect spreads the ion energy incident over the first wall over 1-3 µs, reducing the heat flux significantly. This can be seen in Fig.1. The temperature history of wall surface (the top curve) peaks very rapidly due to X-rays. Smaller peaks at 1 and 2 µs are due to fast and slow ions. Reference [7] provides a detailed description of chamber wall analysis.

These analyses indicate that most of the action occurs within 0.1-0.2 mm of the wall surface. Photon and ion energy deposition fall by 1-2 orders of magnitude within this region. Beyond this region, the first wall experiences a much more uniform heat flux with heat fluxes begin similar to those in MFE devices. As such, it is prudent to use a thin armor instead of a monolithic first wall. Armor can then be optimized to handle rapid particle and heat flux while the first wall is optimized for structural function and efficient heat removal at quasi-steady-state. Furthermore, as most of the neutrons are deposited in the back where blanket and coolant temperature will be at quasi steady state due to thermal capacity effect, most first-wall and blanket concepts developed for MFE will be directly applicable to IFE applications.

There are several possibilities for armor material: 1) W and refractories, 2) Carbon (and CFC composites), and 3) more exotic engineered material [7]. Each has its own set of potential advantages and critical issues that should be addressed with rigorous R&D. In particular, means for in-situ repair of the armor should receive special attention.

While the above analysis indicates that no buffer gas is necessary, chamber pumping requirements are much more reasonable at higher base pressures. Thus, it appears that a chamber with equilibrium wall temperature of 500-700°C filled with 10-50 mTorr of Xe satisfies requirements for all systems. A remaining concern is the impact of target-released ions (specially α particles) on the wall/armor life-time.

3.2 Indirect drive targets

The spectrum produced by indirect drive targets differs significantly from that of direct drive targets. The hohlraum converts capsule ion and x-ray debris into relatively soft X-rays leading to a large energy content in the X-ray channel. Our analysis indicated that without any buffer gas, the wall would not survive (substantial evaporation of both W and C walls). A series of BUCKY [8] simulations were performed in order to determine the minimum amount of Xe buffer gas. We
found that for a 6.5-m radius chamber, Xe pressure of > 200 mTorr is necessary. Presence of the gas does not affect target injection and tracking. In addition, higher gas pressures may be more suitable depending on heavy-ion driver beam transport mechanism (See Sec. 4). Similar to direct-drive chambers, use of an armor greatly improve the attractiveness of dry wall chamber concepts.

4. Beam Propagation and Final Optics

4.1 Lasers

The high intensity of the laser near the target can cause breakdown of the chamber gas. Data available in the literature are mainly for high gas pressures (> 10s Torr). In addition, it is possible that beam smoothness and wavefront errors lead to a lower threshold than an actual breakdown. Recent results from Nike indicate that Xe gas pressure should be kept below 100 mTorr. A detailed study of laser breakdown is planned at UCSD in the coming year.

The final optical elements are exposed to a variety of damage threats, including neutrons and gamma rays, x-rays and ions from the target explosion, contamination by condensable gases and particulates, and the laser itself. Within this environment, the final optic must meet its design requirements on beam smoothness, absorptivity, wavefront error and lifetime (see Table II). Beam steering can be accomplished with refractive, diffractive or reflective optics.

For transmissive optics, radiation-induced darkening is a particularly serious concern. Absorption sites ("color centers") arise due to defects generated in the bulk material. For SiO₂, these color centers are close enough to the laser wavelength to cause substantial darkening. Recent studies suggest that defects may be annealed by heating [9]. For reflective optics, the primary option is grazing-incidence metal mirrors (GIMM's). Multi-layer dielectric mirrors are unlikely to survive neutron damage; in addition to the color center problem, small changes in geometry or mixing at layer interfaces would render the mirrors inoperable. For GIMM's, neutron damage is a far less serious concern; the most serious issue is reduction in laser damage threshold due to long-term exposure and contamination. Damage experiments and modeling are currently underway [9].

4.2 Heavy-ions

Because of relatively high buffer-gas pressure, ballistic transport cannot be utilized for dry-wall chambers. Pinch transport uses a final focusing lens to focus each beam to a small radius at the entrance to the chamber. The beam then propagates in the chamber at small radius to the target. All pinch modes depend on an azimuthal magnetic field (B₀) to contain the beams. Channel transport uses a preformed channel created in a gas (1-10 Torr) by a laser and a z-discharge electrical circuit to create a frozen magnetic field before the HIF beam is injected. Self-pinched transport uses the ion beam to break down a low-pressure gas (1-100 mTorr), and the beam's net self-magnetic field creates the confining magnetic field.

Channel transport has already been demonstrated with high-current light ion beams and 100's of kA of MeV protons have been efficiently transported over distances of up to 5 m. Channel experiments at LBNL have demonstrated stable channels with currents of 55 kA and a 4 mm radius. The present HIF channel transport scenario uses two clusters of beams. For each cluster, several beams are combined in an adiabatic lens (a tapered z-discharge) and then injected into a single main z-discharge channel. The main potential issues are the insulator at the chamber entrance and beam/channel stability. Recent ARIES studies of both of these issues have shown favorable results. Self-pinched transport has been demonstrated extensively in IPROP and LSP simulations for HIF parameters. Experiments on the GAMBLE II accelerator
have shown the onset of self-pinching for 100kA, 1 MeV proton beams, in agreement with
IPROP simulations. Several self-pinched transport scenarios are possible, ranging from using
two clusters of beams combined into two high-current self-pinched beams, to using a large
number (up to ~200) of individual beams. The main potential issues are beam front erosion,
aiming/tracking, multiple beam effects, and beam/plasma stability. ARIES studies of these areas
are continuing.

5. Summary and Conclusions
This paper summarizes ARIES-IFE research on dry-wall concepts. We have produced
accurate spectra of target emission for both direct-drive and in-direct drive targets. We have
found that details of target emission spectra have a significant impact on the thermal response of
the wall. In particular, time of flight of ions reduces heat flux on the wall significantly. For
direct-drive targets, the design window for successful target injection in a gas-filled chamber
(e.g., Xe) is quite small (gas pressure < ~50 mTorr, wall temperature < ~700°C). Contrary to past
studies, detailed thermal analysis indicates that no buffer gas is necessary to protect the wall.
This is due to the lower energy in the X-ray channel and accounting of ion time of flight. We
find that it is prudent to use a thin armor instead of a monolithic first wall. Armor can then be
optimized to handle rapid particle and heat flux while the first wall is optimized for structural
function and efficient heat removal at quasi-steady-state. In fact, by using an armor, most of
first-wall and blanket concepts developed for MFE will be directly applicable to IFE
applications. It appears that a chamber with equilibrium wall temperature of 500-700°C filled
with 10-50 mTorr of Xe satisfies requirements for all systems. For indirect-drive targets, we have
found no major constraints for successful injection of indirect drive targets in a gas-filled chamber
(e.g., Xe) because indirect-drive targets are well insulated by hohlraum materials.
Because of large energy in the X-ray channel, thermal analysis indicates that buffer gas (> 200
mTorr Xe) is necessary for the protection of the first wall/armor. The amount of the gas in the
chamber depends on details of beam transport schemes. These issues are currently under
investigation. Similar to direct-drive chambers, use of an armor greatly improves the
attractiveness of indirect-drive, dry wall chamber concepts.

References
[4] Target spectra for reference targets can be found at (courtesy of J. Perkins, LLNL).
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