Assessment of Chamber Concepts for Inertial Fusion Energy Power Plants – The ARIES-IFE study*

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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 spectrum. 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 design of NRL as our reference targets. Detailed spectrums from these two targets have been calculated -- their photon and ions/debris spectrum 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].

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2. Target Design, Injection, and Tracking

Six classes of target designs were considered and two of them were chosen as reference targets for ARIES_IFE study. They are NRL advanced direct-drive targets [2] and LLNL/LLBL heavy-ion indirect-drive targets [4]. Detailed spectra of target emissions at 100 ns past target ignition are are calculated [4]. The energy partitioning between different channels are summarized in Table I. Photons (X-ray) and ions/debris spectrum 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.

Table I: Energy Partitioning for reference ARIES-IFE targets

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

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 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 target during injection imposes sever constraints on the chamber environment. We have found that NRL direct-drive target injected in a typical IFE chamber (~6 major radius filled with Xe) at 200-400 m/s can survive only if the gas pressure is < 50 mTorr and wall temperature is < 700^{o}C. This is a server 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 mm accuracy, respectively. For ex-chamber tracking, the chamber gas results in large deflection of 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 1000 mm (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 server 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 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 slab for a coolant temperature of 500°C. The maximum temperature of the first wall is ~1438°C, considerably lower than the W melting point at 3410°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.

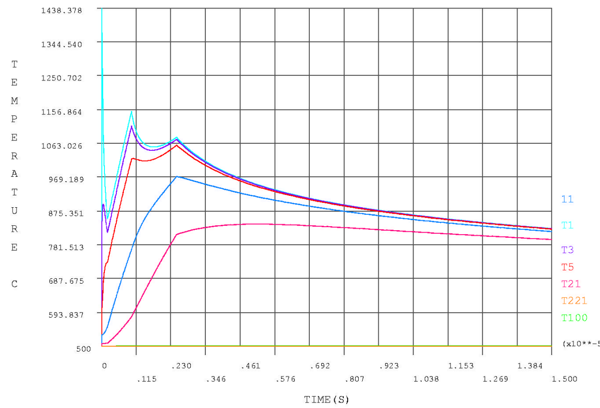

Fig. 1. Temperature history in a W wall at depths of 0, 1, 2, 5, 10, and 20 mm (respective curves from the top) for NRL direct-drive target in a chamber with no buffer gas.

These analysis indicate that most of the action occurs within 0.1-0.2 mm of the wall surface. Photon and ion energy deposition falls by 1-2 orders of magnitude within this region. Beyond this region, 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 neutrons deposited in the back where blanket and coolant temperature will be at quasi steady state due to thermal capacity effect, most of 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, there are benefits in having some gas. First, without any buffer gas, the target-released ions will be implanted in the armor, reducing its lifetime. Most of these ions will stop in 10-50 mTorr of Xe. Secondly, chamber pumping requirements are much more reasonable with a 10-50 mTorr base pressure in the chamber. 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.

3.2 Indirect drive targets

The spectrum produced by indirect drive target 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 the scheme for recycling hohlraum material and 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 leads to 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 particulate, 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 SiO_2, 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. Beam then propagates in the chamber at small radius to the target. All pinch modes depend on an azimuthal magnetic field (B_θ) 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 design window for successful target injection in a gas-filled chamber (*e.g.,* Xe) is quite (gas pressure < ~50 mTorr, wall temperature < ~700^{o}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 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^{o}C filled with 10-50 mTorr of Xe satisfies requirements for all systems. For indirect-drive targets, our analysis of design window for successful injection of indirect drive targets in a gas-filled chamber (*e.g.,* Xe) has found no major constraint 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 as well as the desire to stop and recycle the hohlraum material in the gas. These issues are currently under investigation. Similar to direct-drive chambers, use of an armor greatly improve the attractiveness of dry wall chamber concepts.

References

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