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Study on Peripheral System and Issues for Heavy–Ion Inertial Fusion Reactor

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A heavy-ion inertial fusion (HIF) reactor design concept generally follows that of laser fusion reactors, sharing common reactor and peripheral systems. This is because HIF is configured by replacing the laser in laser fusion with high-current heavy-ion beams, and the same concepts are applicable in other components. The current status summary and key issues of HIF systems were studied in comparison to laser fusion, identifying both shared and unique features [1]. Specific challenges in HIF include beam transport within the reactor chamber, vacuum system design, beam port protection, and radioactivation of particle accelerators [1].

The required injection velocity for HIF fuel targets was assessed considering constraints such as solid fuel melting and heat conduction. Unlike laser fusion, HIF allows lower injection velocities, which simplifies power plant operation and target attitude control. Reduced gas pressure in HIF chambers also minimizes displacement of fuel pellets by residual gas. Estimations from previous studies suggest required injection velocities between 100–1000 m/s [1], depending on target design and thermal conditions. Numerical analysis indicated that radiation from the chamber wall significantly raises the target temperature, especially at higher wall temperatures [2]. For example, with a 900 K wall and 1500 K background gas, the DT fuel in a fuel pellet may exceed its melting point during a 0.1 s flight. Assuming a 5 m reactor radius, an injection velocity of 50 m/s is found to be reasonable.

The reactor radius was also examined from the perspective of vacuum system design. To ensure proper heavy-ion beam transport, gas pressure must remain below a threshold to avoid beam degradation through gas collisions [1]. Since fusion reactions and residual hydrogen isotopes increase chamber pressure, vacuum pumps with adequate capacity are required [1]. The HIF system demands a lower operational pressure than the laser fusion system, necessitating more advanced vacuum technology to maintain high-quality beam transport conditions [1].

The expansion dynamics of a direct-drive HIF fuel pellet after ignition were numerically investigated [1]. As the fuel expands, it transitions from a fluid regime to free-molecular flow. Kinetic energy distributions of the resulting ions were calculated, revealing species-dependent arrival times at the chamber wall. These results were compared to data from direct-drive laser fusion and indirect-driven HIF targets, underscoring the importance of species-specific energy analysis in the fuel pellet design. Although radiation transport was neglected, it was noted that X-ray emission accounts for 25% of the energy in indirect-driven targets, versus 1.4% in direct-drive targets, suggesting the necessity of including X-ray effects in HIF modeling.

In inertial confinement fusion reactors, a liquid wall is often proposed to absorb pulsed fusion output energy. As the liquid surface evaporates during each pulsed fusion output, a fresh flow of liquid metal continuously replenishes the chamber wall. However, the evaporated liquid metal contributes to residual gas, complicating vacuum recovery and hindering rapid, repeated operation. Additionally, because the liquid metal flow tends to separate along the chamber walls, complete coverage is difficult to maintain. This highlights the need to evaluate solid wall designs and assess material resilience under pulsed intense fusion loads.

Tungsten has emerged as a promising candidate for solid wall materials. Experimental studies simulated inertial fusion output by irradiating tungsten samples with pulsed lasers below the ablation threshold [3]. Despite relatively low energy fluence (1 J/cm²), the cracks were experimentally observed at depths of 0.4–2.9 μm from the sample surface. To investigate this, heat conduction simulations modeled the temperature distribution caused by a 17 ns laser pulse, and the calculation results indicated the peak temperature did not reach the boiling point. This suggests that cracking was not caused by porosity typical in laser welding, but rather by non-uniform thermal stress and localized variations in yield strength due to steep temperature gradients in the depth direction.

Additionally, damage to wall materials caused by high-energy alpha particles was investigated through experiments using a particle accelerator, and it was shown that the penetration depth of alpha particles into tungsten samples was deeper than conventional known [4]. We are also considering building a material testing system that applies an intense pulsed load to samples by irradiating with a high-intensity pulsed electron beam [5] using an intense pulsed power device.

References

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