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Fusion technologies for Laser Inertial Fusion Energy (LIFE)*

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Abstract. The Laser Inertial Fusion-based Energy (LIFE) engine design builds upon on going progress at the National Ignition Facility (NIF) and offers a near-term pathway to commercial fusion. Fusion technologies that are critical to success are reflected in the design of the first wall, blanket and tritium separation subsystems. The present work describes the LIFE engine-related components and technologies. LIFE utilizes a thermally robust indirect-drive target and a chamber fill gas. Coolant selection and a large chamber solid-angle coverage provide ample tritium breeding margin and high blanket gain. Target material selection eliminates the need for aggressive chamber clearing, while enabling recycling. Demonstrated tritium separation and storage technologies limit the site tritium inventory to attractive levels. These key technologies, along with the maintenance and advanced materials qualification program have been integrated into the LIFE delivery plan. This describes the development of components and subsystems, through prototyping and integration into a First Of A Kind power plant.

1. INTRODUCTION

Delivery of fusion power soon enough to make a difference to current energy policy requires an attractive option for baseload electricity production from about 2030 onwards. To do so requires a demonstration plant in the 2020's and thus a paradigm shift from incremental construction of fusion research facilities. An approach that could meet this requirement is known as Laser Inertial Fusion Energy (LIFE) [1, 2]. During pilot plant operations, LIFE is being designed to have a fusion power of up to 1000 MW, a power that enables full demonstration of system integration and provides a relevant platform upon which to conduct accelerated materials testing to extend the performance envelope of plant operations. The fusion engine subsystem is key in rapidly demonstrating these technologies necessary for power plant electricity generation. Figure 1 shows the fully assembled fusion engine subsystem inside the fusion operations building with an inset showing the fusion chamber inside the vacuum vessel. The fusion chamber subsystem is designed to be periodically replaced to facilitate on going operations.

The fusion chamber is an important subsystem of the engine that must satisfy a number of interrelated requirements including:

- Fabricate from commercially available materials;
- Transmit thermal power to the balance of plant ($0.5\,\mathrm{MW/m^2}$ thermal load initially);
- Operate at high temperature for good thermal efficiency ($T \geq 500\,^\circ$C for ηth $\geq$40%);
- Remove residual target debris from previous fusion shots (material recovery $\geq$99%);
- Maintain high system availability for consistency with overall plant availability of $\geq$92%;
- Produce tritium to replace that burned in previous targets (tritium breeding ratio $\geq$1.02);

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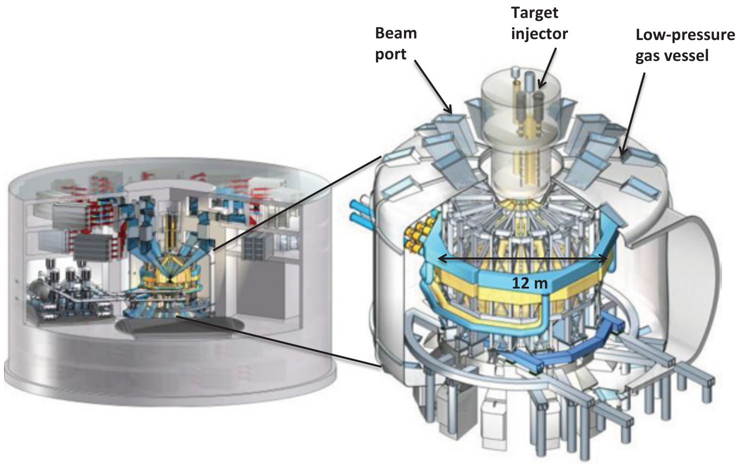

Figure 1. LIFE fusion chamber inside vacuum vessel and plant.

- Enable target and laser beam propagation to chamber center (propagation ≥95%);
- Support 10–20 Hz operation;
- Tolerate irradiation at appropriate levels (10 displacements per atom initially);
- Allow periodic replacement of the First Wall and Blanket assembly.

2. THE USE OF INDIRECT DRIVE TARGETS

A critical component of the LIFE chamber design is the selection of indirect-drive targets. Not only will these targets be able to be tested on the National Ignition Facility (NIF), but they enable self-consistent protection of the cryogenic fuel and survival of the chamber wall. The approach takes advantage of the fact that indirect-drive targets are thermally robust and can accommodate relatively high gas pressures within the chamber, allowing for a xenon gas density of 6 μg/cc [3].

The xenon within the chamber completely ranges-out the ion debris (~10% of target output) within decimetres radius, thus protecting the chamber wall from the otherwise debilitating ions. An additional 12% of the target output is emitted as x-rays with a spectrum that is very effectively attenuated in the xenon, with the prompt x-ray heating of the wall being correspondingly reduced. For 130 MJ fusion yield, this prompt x-ray peak is 35 °C (above an ambient 500 °C). Over a timescale of approximately 100 μs, the gas re-emits soft x-rays and a Marshak wave arrives at the chamber wall. This heating increases the wall surface temperature to 570 °C. These low-temperature pulses allow a bare metal to be used as the first wall, negating the need for refractory armour.

The xenon gas is initially heated to several eV, but it rapidly cools via radiation to a temperature of ~0.5 eV. At that time, the charge state of Xe is very close to zero as it “stalls” from a radiative cooling perspective. Unless convection or radiative cooling from residual target debris provides significant additional cooling, the gas temperature at the time of the next shot (~60 ms later) will be ~6000 K. As shown in Figure 2, only 1–2% of the incoming, 3ω laser is lost to inverse Bremsstrahlung near the target as the laser reaches peak intensity.

The xenon fill gas permits the use of near-term materials while being compact. During the initial phase of operation, the replaceable LIFE chamber would be constructed from a reduced activation ferritic-martensitic steel and would be subject to a damage rate of 10 displacements per atom per full-power-year of operation (10 dpa/fpy). In-situ materials testing will allow the performance limits of these steels to be evaluated using a fully representative fusion environment, and will also allow testing of emergent materials if required, such as oxide-dispersion strengthened ferritic steel.

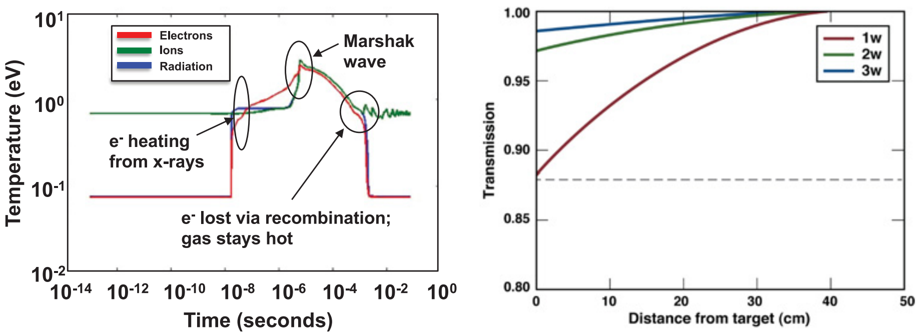

Figure 2. Laser beam propagation through 6 μg/cc xenon results in minimal losses.

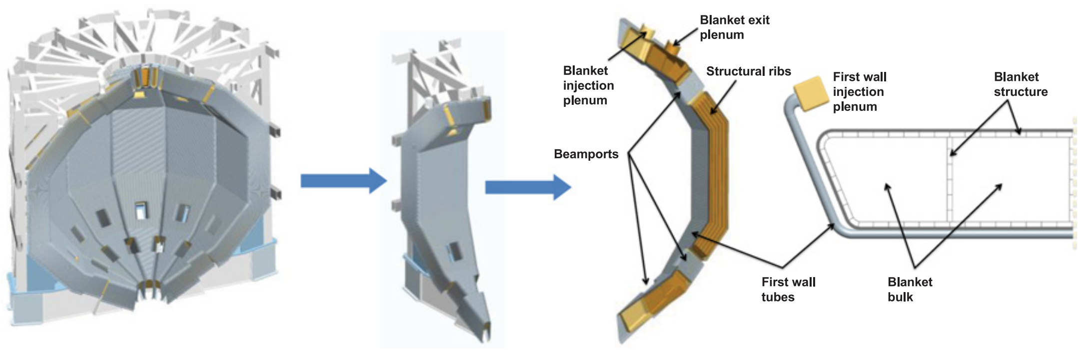

Figure 3. LIFE chamber design is modular, replaceable and fabricated from existing materials.

3. CHAMBER DESIGN

There are several key features to the LIFE chamber design. These include its modularity, the lack of beam tube connections to the chamber, the fact that the chamber is not a vacuum barrier, and the selection of liquid lithium as the primary coolant for both the first wall and blanket. Figure 3 shows a ½ section of the LIFE chamber with the first wall, blanket and support structure. The chamber consists of twelve identical factory-built sections, which would be shipped to the power plant site. These modules are mounted to the support frame with groups of three modules being connected to four cooling manifolds in the maintenance bay. The full chamber is then transported to the engine bay for final installation requiring only connection of two cooling pipes per manifold to main coolant feed pipes (eight total) that penetrate the vacuum vessel and shield wall.

The first wall is composed of a series of few-cm-diameter pipes plumbed in parallel and attached to injection and extraction plena mounted to the sides of the blanket. Coolant entering the blanket at 515 °C flows down through the blanket cooling channels, turns around at the bottom of the chamber, and flows up to ultimately exit at 575 °C.

3.1 Liquid lithium coolant

Liquid lithium is the primary coolant for both the first wall and blanket. Advantages of liquid Li include its low density and resulting low hydrostatic pressures, good heat transfer properties (Pr ~0.05) and excellent corrosion properties as long as the coolant is maintained in a relatively pure state (e.g., $<$100 wppm nitrogen). It is a low activation coolant requiring a low pumping power due to its low viscosity, density and high specific heat. Its superior tritium breeding is sufficient to allow multiple blanket modules during the commissioning phase to be dedicated to materials testing alone.

Lithium's key challenge is its high chemical reactivity. This can be mitigated through well-understood engineered prevention, detection and response features. Some of these features include the use of steel liners on potentially exposed concrete surfaces and an inert cover gas to prevent Li-air reactions in the event of a leak.

Lithium's affinity for hydrogen isotopes results in high solubility, and thus permeation rates much lower than for molten salts and other coolants. This is a major benefit with regard to routine emissions. The high affinity also means that very localized tritium recovery systems can be utilized to maintain the site-wide tritium inventories to levels that are attractive from a safety perspective. An appropriate tritium recovery process was developed and demonstrated in the mid-1970s by Maroni and his group at Argonne National Laboratory [4]. This "Maroni process" intimately contacts the liquid lithium with a molten lithium salt such as LiCl-KCl. The lithium and salt are subsequently centrifugally separated, and the tritium is removed as a gas following electrolysis of the salt [4]. All parts of the Maroni process were demonstrated, however, they were not integrated into a complete system. For LIFE, processing of the lithium can limit the tritium content to only 100 weight parts per billion (wppb) requiring approximately eighty units such as those built and demonstrated by Maroni (45 cm in height and 25 cm in diameter). An integrated system would occupy approximately 30 m^3, including piping and redundancy, consuming only $\sim$ 1 MWe to maintain the total tritium inventory within the lithium loops at ~50 g.

3.2 Tritium breeding and blanket gain

The LIFE chamber design can close the tritium fuel cycle without the use of beryllium or lithium isotopic enrichment. The current design has a tritium breeding ratio (TBR) of up to 1.58 and a chamber energy gain of 1.11. Excess TBR can be traded for additional energy gain and on going work has achieved a chamber energy gain, including penetrations for beamports, target injection and pumping, as high as 1.26 while reducing the TBR to 1.05.

4. CONCLUSIONS

A LIFE engine concept has been developed to meet plant primary criteria and formulated with a detailed delivery plan to impact near term energy policy. The plant and fusion engine are designed to demonstrate full integration of the LIFE systems, demonstrate a closed tritium fuel cycle and act as a materials testing platform for future upgrades. The LIFE target performance can be demonstrated on the NIF, resulting in high confidence of engine performance prior to construction of a pilot plant. These key features enable a near-term delivery of LIFE consistent with the needs of the energy market.

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