Conceptual design and issue analysis of Laser Fusion Experiment Reactor (LIFT), - Target and Chambers -

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Abstract. We present a conceptual design of a laser fusion experimental reactor (LIFT) and analyze the issues related to the fueling and chamber systems. The LIFT is designed on a scheme of three phases where each phase has specific goals and dedicated chambers driven by the same laser. Based on our understanding, the critical issues include the control of fuel loading in the fueling system and the stability of injected target in the chamber system.

1. Introduction

Ignition and burn based on fast ignition will be successfully demonstrated in a single-shot experiment in the FIREX-II project of ILE Osaka Univ.. A laser inertial fusion test plant (LIFT) will then be constructed after this demonstration. To efficiently obtain technical designs for LIFT, requirements on how to position the target from the laser beams must be clarified through additional single-shot experiments. Moreover, repeated-target injection and synchronized laser irradiation with a beam steering system must be achieved to determine the specifications for injection with accurate laser irradiation. A modular laser system based on diode-pumped, tilled Yb:YAG ceramic must be also developed to allow 4-Hz operation with 10 % electricity-to-laser efficiency. The LIFT includes a full-scale laser system with a 500-kJ compression laser and a 150-kJ ignition laser. Appropriate target chambers are also assembled successively around this laser system without cooling the activated chambers. LIFT construction therefore consists of three phases with specific goals and dedicated chambers.

Phase I aims to demonstrate repeated fusion burns (40 MJ expected) at 1 Hz and to understand the physics of plasma and radiations at the wall by the 40-MJ fusion burn. The chamber has no blanket and cooling system. One batch of the fuel loading process has 100 targets, and the average temperature increase of the chamber is estimated to be 300 ^{o}C. On the other hand, Phase II is focused on demonstrating electric power generation. The chamber will have a water-cooled solid blanket, which is extensively developed for magnetic confinement fusion. Because of the limited operation time, blistering of the first wall is negligible. Lastly, Phase III is intended to demonstrate long time operation and to carry out material testing in order to obtain basic data for economic feasibility investigations. The chamber has a liquid LiPb wall and self-cooled liquid blankets. This phase currently has a half-year operation time based on the lifetime of the final multi-coated mirror. Since the final mirror is replaced every campaign, demonstration of remote replacement technique is also carried out for a commercial laser fusion plant, KOYO-F [1]. The fueling and chamber systems of each phase are discussed in the following sections.

2. Target and fueling system

Figure 1 shows the model targets for the three phases of LIFT. The fuel capsule is made with a low density (10 - 40 mg cm^{-3}) foam layer surrounded by another medium density (250 mg cm^{-3}) foam layer with closed cells. "Closed" refers to no liquid DT penetration during the fueling process. This foam layer is a structured wall which also serves as a thermal insulator. Insulation is necessary due to the large thermal load coming from the condensation of metal vapor in the chamber. The outer surface is then coated with a 0.1-μm thick nickel-layer as a shield from the thermal radiation from the chamber wall. Assembling a guide cone and a capsule using an industrial robot has already been demonstrated by General Atomics (USA). We make a narrow gap between the cone and the capsule so that liquid DT saturates at the low density foam layer through the gap.

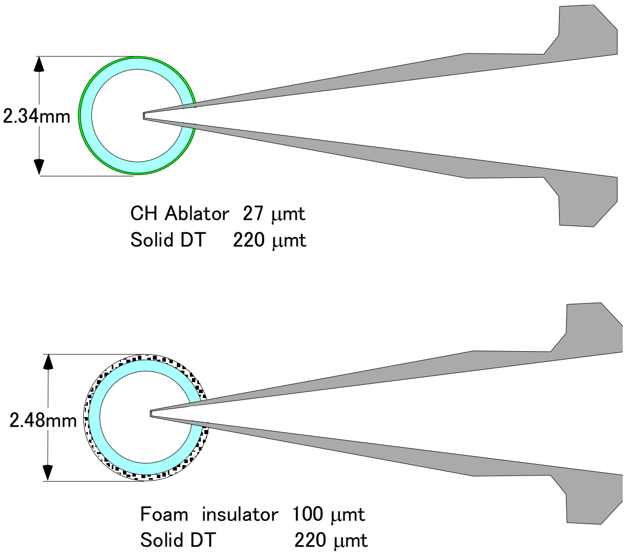

FIG. 1 Model targets for LIFT Phases I and II (up) and III (Down)

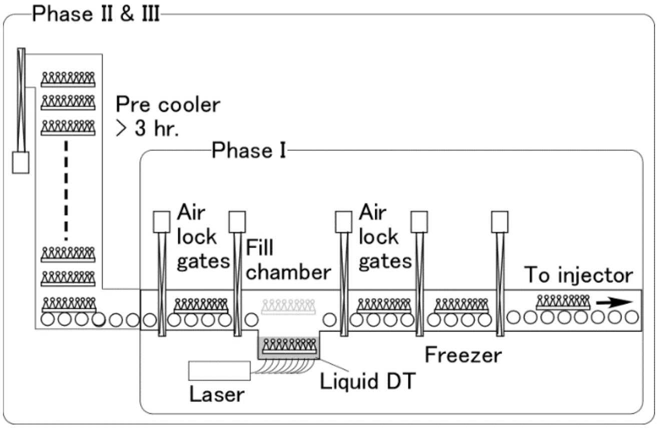

FIG. 2 Conceptual design of a batch process fuelling system based on thermal cavitation technique.

Figure 2 illustrates a conceptual batch process fueling system based on thermal cavitation technique. Conventional diffusion need over one day to fill the cavity with the required fuel mass. 100 targets are placed on an egg plate and are sent to a fill room through gate valves. After immersing the targets in liquid DT, weak laser beams from optical fibers heat the targets to evacuate liquid DT from the central void. Only the low density foam layer will be saturated with liquid DT [2]. After freezing the liquid DT in the foam, the targets are sent to the injection system. Only one egg tray will be tested in Phase I, while continuous operation is necessary for Phases II and III.

With regards the system illustrated in FIG. 2, two critical issues arise from the batch fueling process. One is the accuracy of fuel mass in the foam layer, and the other is the influence of the saturated vapor in the void to the stability of target at the center of the chamber. In our previous experiment, the accuracy of fuel mass in a 500-μm diameter foam shell is ± 5 %. This mainly comes from unstable breakage of the meniscus between the shell and the liquid hydrogen surface [3]. We expect better accuracy for larger shells because the gravitational force exceeds the surface tension in a larger shell case and because the uncertainty for the mass in the meniscus becomes smaller. Our final goal is to attain ± 1 % fuel mass accuracy to synchronize timing of the peak of compressed fuel density and the ignition laser. Since the gap is always open, solid DT in the target is thermally unstable. Too much thermal load on solid DT would also disturb the configuration of the target when it is injected into the chamber.

After fuel loading, the target is set in a sabot and is subsequently inserted into a revolver. Our target injector consists of a gas gun for main acceleration to 95 m s^{-1}, a coil gun for fine adjustment to 100 ± 1 m s^{-1}, a sabot releaser, some orbit detectors, and a rotating neutron shutter. This target injection system has two critical issues. First, the yaw (or pitch) angle of the target from the center of the chamber must be less than ± 2 % to prevent the conflict of the heating laser with the guide cone. Our preliminary experiments of a real size target injection (gas gun + sabot releaser, single shot at room temperature) showed 88 ± 3 m s^{-1} velocity and ± 0.6 ° angle. We found, however, the yaw angle at the chamber's center is one order larger than our goal. Second, the evacuation of the residual injection gas in the barrel should be considered. The influence of the residual gas on the cryogenic layer must be studied. If it is unacceptable for a 4-Hz operation, the use of sequential multi-injectors should be an option.

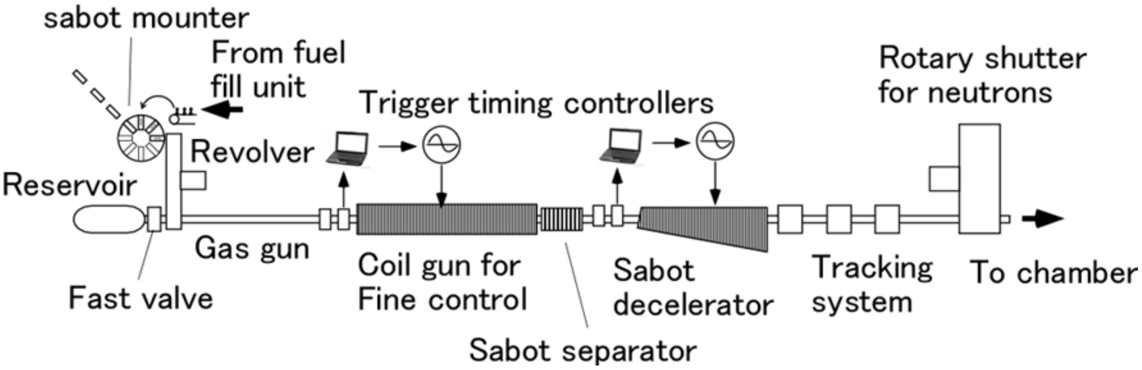

FIG. 3. Conceptual design of a target injection system

3. Chamber system and radiation safety

All LIFT phases have cylindrical symmetry and a beam layout to allow chamber access from the top. Twenty-eight compression beams are located at the latitudes of ± 18.876 ° and ± 53.444 ° to achieve the heating uniformity of 99 %. The intensity ratio of beams in the higher latitudes to those in the lower latitudes is 0.533 [4]. The ignition beam and the target injector are located in line with the equator plane. The chamber of Phase I is made up with SUS 316 stainless steel vessel whose inner radius is 3.5 m and has no blanket and cooling system. The peak temperature and the average temperature of the inner surface after 40 MJ × 100 shots is estimated to be 1400 °C and 300 °C, respectively. Since the total neutron fluency is low, conventional transmitting optics can be used for the final optics. For Phase I, 36 campaigns are planned in three years. The intensity of γ-rays on the chamber surface at the end of Phase I after one-month cooling is estimated to be 1.6×10^{11} MeV s^{-1} m^{-2}. More details of Phase I are reported elsewhere [5].

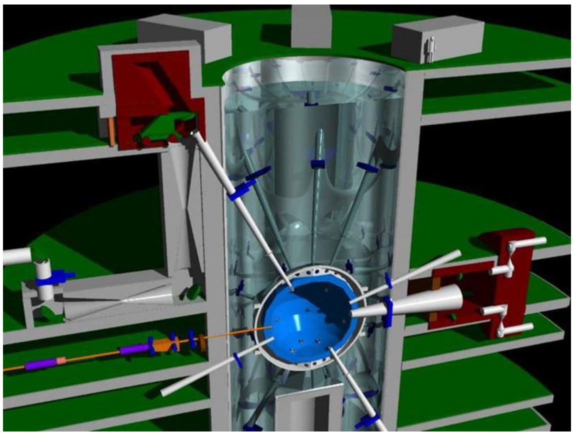

FIG. 4. Phase II chamber system

Phase II aims to demonstrate generation of electric power. The operation time of one campaign is assumed to be two weeks. A cross-sectional image of the chamber system for Phase II is shown in FIG. 4. Phase II will have a dry wall chamber with a water-cooled solid blanket that has been developed for magnetic fusion. The chamber is immersed in water to simplify neutron shielding around the beam ducts. Although our final goal is a liquid-walled chamber with a self-cooled liquid LiPb blanket, a solid blanket with Li_2TiO_3 pebbles is chosen to reduce the time for development. Natural Li without isotope enrichment is also used. A model of the Phase II blanket shown in FIG. 5 is used to estimate the neutron spectra and the tritium breeding ratio (TBR) on the chamber wall using PHITS ver. 2.71 [6]. The structural material is F82H, and the 1-cm thickness of the first wall includes reinforcement structures in the blanket. There is a 50-cm wide gap between the blanket and the chamber wall as a pipe space. For the calculations, isotopes nucleated from daughter isotopes are not considered.

The neutron spectra before and after the blanket are shown in FIG. 6. The peak intensity of 14-MeV neutrons is reduced by 1/15 and 1/100 after passing through the blanket and reaching the chamber surface, respectively. The γ-ray power generated in the chamber after one campaign of Phase II is shown in FIG. 7. Monitoring systems such as those for the chamber wall temperature must survive this sever condition. The dose rates after one campaign in Phase I and II are summarized in Table I. Although the total number of neutrons nucleated in the Phase II campaign is 6000 times more than those in Phase I, the dose rate at the surface of the chamber immediately after the end of a Phase II campaign was less than those of Phase I. This can be explained by the decay time of the isotopes. Generally, decay times of activated isotopes with neutrons are shorter than 2 weeks. A number of isotopes saturates after 4 times the decay time. Isotopes with longer decay time increases proportionally with the number

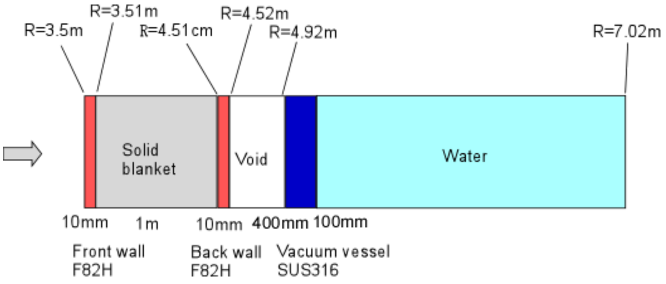

FIG. 5. Model of Phase II blanket used to estimate the γ-ray radiation (neutron spectra) and TBR

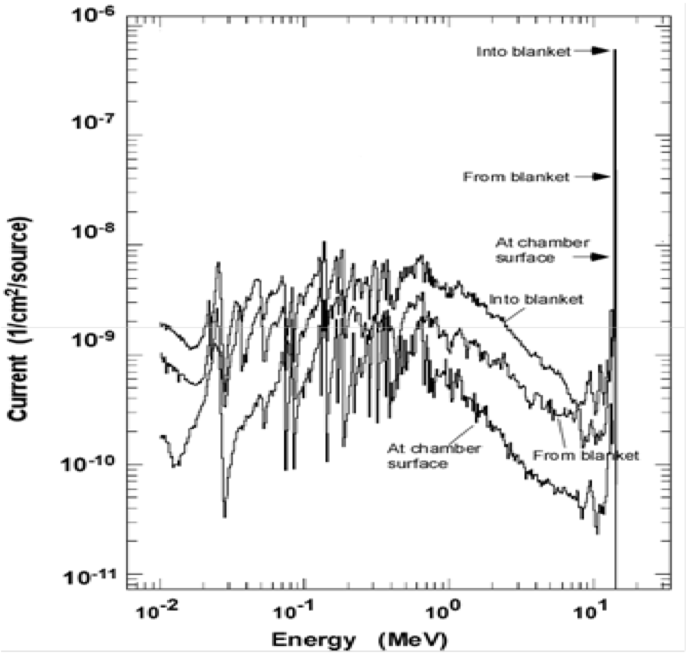

FIG. 6. Spectrum of neutrons at blanket and vacuum chamber

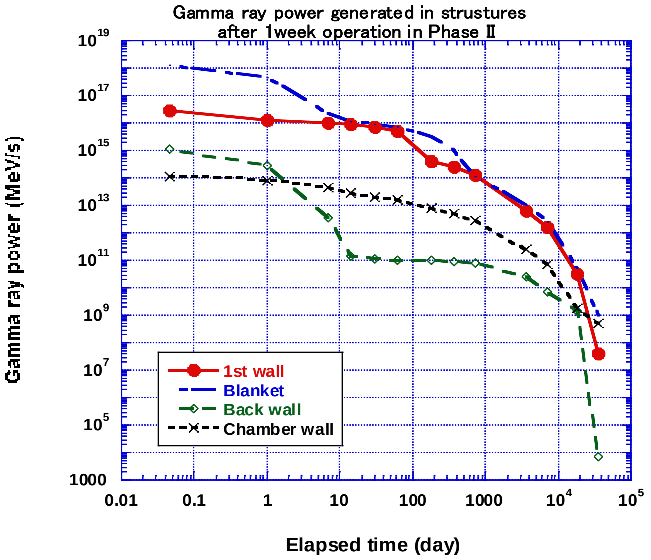

FIG.7 γ-ray power from the chamber of Phase II after one-week operation.

of neutrons. As a result, the dose rate of Phase II becomes more than that of Phase I after one week of cooling.

Table I Radiation field on the chamber after 1 campaign

	1hour	1day	1week	1year
PhaseI	11	0.041	0.004	7.20E-04
PhaseII	0.73	0.28	0.04	5.54.E-03
			unit	Sv/h

Moreover, the TBR of this system is 1.07 which includes loss of neutrons through beam ports and vacuum pumping ports. In this calculation, tritium dissolved in the structural materials is ignored.

Phase III aims to demonstrate long time operation and to carry out material testing to investigate economic feasibility. The current operation time is aimed to be half-year based on the final optics that are directly irradiated by neutrons. A cross-sectional image of the chamber system for Phase III that has a liquid LiPb wall is shown in FIG. 8. The chamber has an inner radius of 1.5 m to obtain the same α-particle load on the surface of the commercial plant KOYO-F. The surface flow forms a cascade with a step-height of about 30 cm. The flow on each front panel is provided from the back open flow (FIG 9) so that the surface is refreshed every shot to obtain cryogenic pumping effect [7].

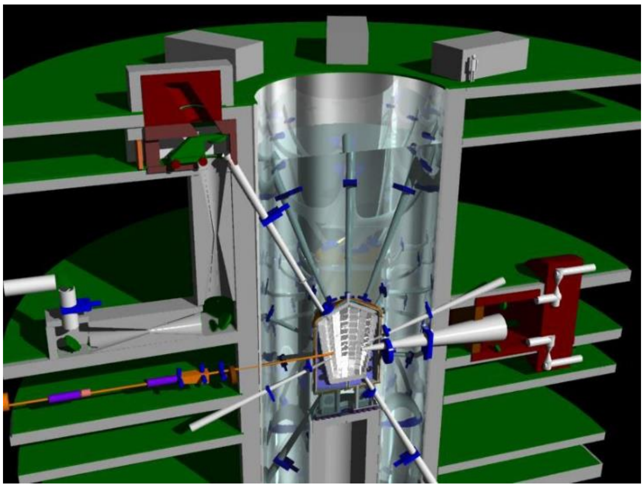

FIG. 8. Phase III chamber system

Issues related to the wet wall will be tested in this phase. These issues include evacuation of chamber to achieve 4-Hz operation, stability of the liquid first wall [8], contamination of the final optics, protection of beam ports [9], erosion of structure material with liquid LiPb, impurity control in LiPb, and tritium flow in the system [10,11].

TBR and heat decay in LiPb are also estimated using PHITS. Figure 9 shows a cross section of the self-cooled liquid LiPb blanket. Although the chamber of Phase III has cylindrical symmetry, a spherical symmetry model is used for a simplified calculation. The first wall is a 3-mm thick liquid LiPb flow on a front F82H panel. The middle zone is an open, 30-cm thick flow of LiPb being mixed with the first flow after two steps of cascade system to provide cool, fresh surface for vacuum pumping. The third flow is a 50-cm thick, closed LiPb flow to reduce the electric power for circulation. There is also a 50-cm thick space to support blanket modules. Five ppm Bi and 7.5 ppm Ti are added as LiPb impurities.

The obtained TBR is 1.7 including loss of neutrons through beam ports. The heat decay (β- and γ-rays) generated in LiPb immediately after a half-year operation is 2.2×10^8 W. The decay curve is also shown in FIG. 10. If we assume that the total mass of LiPb in the blanket, pipes, and heat exchanger is 980 tons, the temperature of LiPb without cooling increases at a rate of 1.1 K s^{-1}.

In some cases, all LiPb would be dumped into a tank below the chamber, and, the chamber loses all coolant (LOCA). The temperatures of the first panel and the vacuum vessel are shown in FIG. 11. For this calculation, the main process is radiation heat transfer, and the emissivity is assumed to be equal to 0.3. The maximum temperature is below the melting point of iron, but some deformation will still occur. The calculated surface temperature of the dump tank with a 380-m^2 surface area is 1100 K after 1 h under the same conditions. If the dump tank is constructed with three smaller tanks for a higher surface area, the maximum surface temperature becomes 850 K.

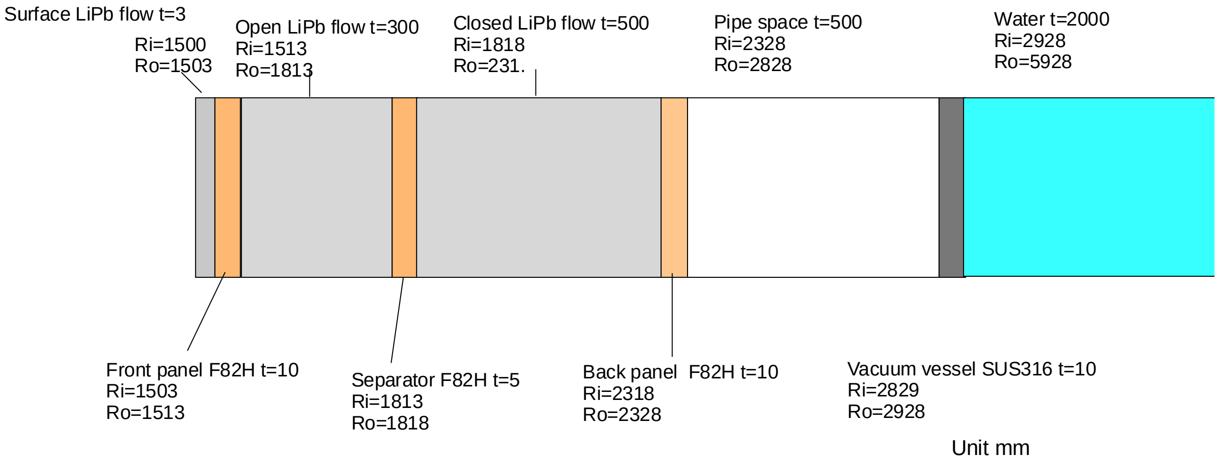

FIG. 9 Model of a Phase III LiPb blanket used to estimate TBR and heat decay after one campaign.

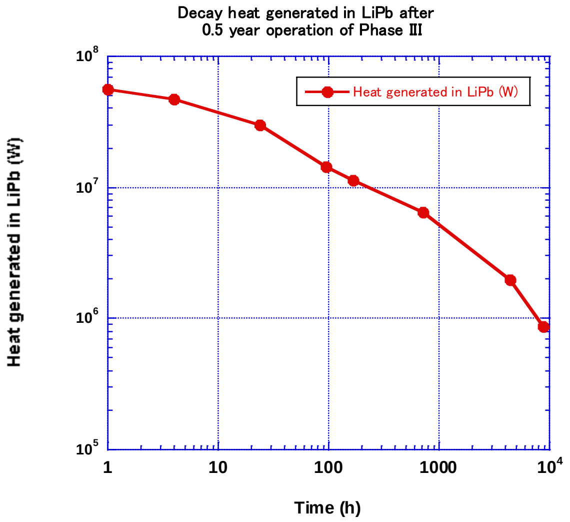

FIG. 10. Heat decay in a Phase III LiPb blanket after a half- year operation.

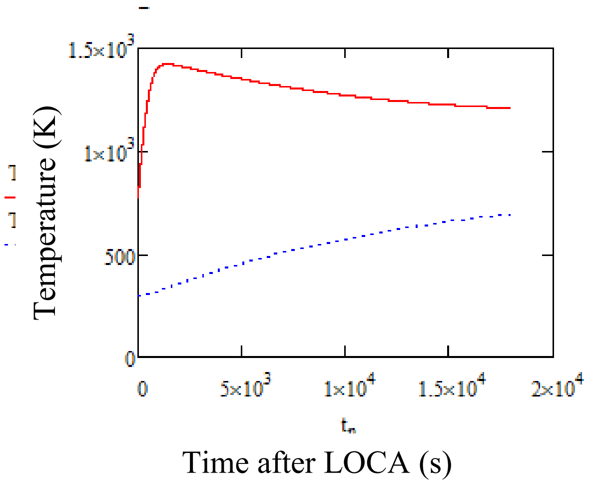

FIG 11 Temperature of front panel (solid line) and chamber (broken line).

4. Summary

We presented a conceptual design of a laser fusion experimental reactor (LIFT) based on fast ignition. To shorten the time for development, three chambers with different purposes are constructed successively around the same laser. With this endeavour, we found that the stability of the injected target and the control of fuel mass are the critical issues in the fuelling system. As of now, we have limited knowledge on the influence of accuracy of the gas gun barrel on the tumbling of the target. Since the fuel in the target is in an open system, the influence of thermal radiation from the chamber to the cryogenic layer is also critical.

Acknowledgement

We organized a conceptual design committee for the LIFT which includes staff from industry under support of IFE Forum. The committee consists of an advisory group and working groups

(WG) for core plasma, target, and chamber system. We are hereby grateful to the IFE Forum and the supporting companies. We likewise appreciate all the staff in the advisory group and WGs for their valuable comments and devoted contributions.

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Tsuji R.	Ibaraki Univ.	Tomabeche K.	Previous CRIEPI
Yoshida H.	Gifu Univ.	Ueda Y.	Osaka Univ.
CRIEPI	Central Res. Inst. Electric Power Industry		
GPI	Graduate school for creation of photonics industries		
ILT	Inst. Laser Technol.		
NIFS	Nat. Inst. for Fusion Science		
QST	Nat. Inst. Quantum and Radiological Systems Res.		

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