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A New Concept of Laser Fusion Experimental Reactor with Fast Ignition Target

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Abstract. We have analyzed the design windows for laser fusion power plants based on fast ignition concepts, and examined the feasibility of a small-sized laser fusion experimental reactor suitable for developing their power plants. Target gain curves are assessed for power plants, having 90~200 MJ fusion yields with 600 kJ~1MJ lasers, and for an experimental reactor (LFER), having a 10 MJ fusion yield with a 200 kJ laser, i.e., 100 kJ for implosion and 100 kJ for heating. The pulse heat loads on the chamber wall of LFER are estimated as 2.5 J/cm^2 for a 2.5-m-radius solid wall chamber, and 16 J/cm^2 for a 1-m-radius liquid wall chamber. The fast ignition LFER can produce its fusion output approximately one order of magnitude smaller than that of the central ignition, so that we can use a rather small solid wall chamber for the first stage of the LFER operation. We can also expect to decrease laser cost drastically, although for the heating laser we must develop a long life final optics system. With the fast ignition LFER, we showed a possibility to demonstrate net electric generation in a reasonably short time.

1. Introduction

The fast ignition concept is attractive because a high gain can be achieved with small laser energy. Fast ignition experiments using a PW laser at Osaka University demonstrated a heating efficiency of 20 % at the ignition-equivalent laser intensity in 2002 [1]. We have analyzed the design windows for laser fusion power plants based on the fast ignition concept, and studied potentialities of a small-sized laser fusion experimental reactor suitable for developing their practical power plants.

Laser fusion power plants have three key subsystems, i.e., targets, lasers and reactor chambers, which are geometrically separable and can be designed with high flexibility and least mutual interactions. Focusing on the characteristics, laser fusion modular power plants, having multiple reactor chambers to be driven by one laser system, were proposed [2]. The design window analyses have been carried out, and we showed that laser fusion modular plants have high potential to become economically attractive power plants. We can use lasers efficiently in modular plants, under optimum conditions of chamber pulse repetition rates and reactor output powers, as we can choose pulse rep-rates of a laser and chambers independently [3]. This is very important for the smaller fusion pulse energy and the more compact fusion reactors such as fast ignition concepts. For the smaller fusion pulse energy it is important to achieve the higher pulse rep-rate chambers as well as the higher rep-rates lasers, and the optimum combinations of modular plants.

Based on the physics of fast ignition and the progress of relevant key technologies to laser fusion, such as DPSSL (Diode Pumped Solid-State Laser), the reactor design studies and road map analyses are under way, by the Committee on Road Map and Reactor Design for Laser Fusion Energy (chair K. Tomabechi, co-chair Y. Kozaki), organized by IFE Forum with participants from universities, national laboratories and industries in Japan. We have proposed an IFE road map, involving a compact fusion experimental reactor and flexible programs to develop the relevant key technologies. In this paper we discuss the design windows for laser fusion power plants and an experimental reactor based on fast ignition concept, and propose a new concept of small sized fusion experimental reactors.

2. Design Windows for Fast Ignition Laser Fusion Power Plants

2.1. Fast Ignition Cone Targets and Gain Curves

The fast ignition process consists of two steps, i.e., compression of fuel up to 1000 times solid density by implosion laser beams and ignition by a pico second heating laser. We have estimated the total laser energy necessary for the targets of power plants and an experimental reactor by using a relativistic Fokker-Planck (RFP) transport code for fast electrons coupled with 2D burn simulation code [4]. The target gain curves obtained are shown in Fig.1, illustrating points for the targets of an ignition experiment (FIREX-II), an experimental reactor (LFER), and power plants. Figure 2 shows cone targets, to be irradiated by the heating laser through the cone, for a PW laser experiment and a reactor of 90 MJ fusion yield. For power plants we considered the two typical cases, i.e., for 90 MJ fusion output with 600 kJ laser energy (target gain 150) and 200 MJ fusion output with 1 MJ laser energy (target gain 200).

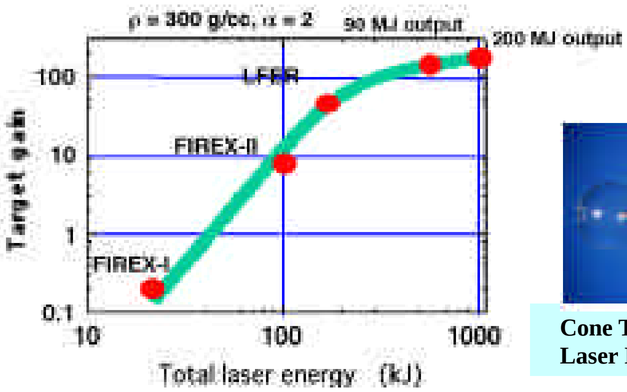

Fig.1 Target gain curve of fast ignition

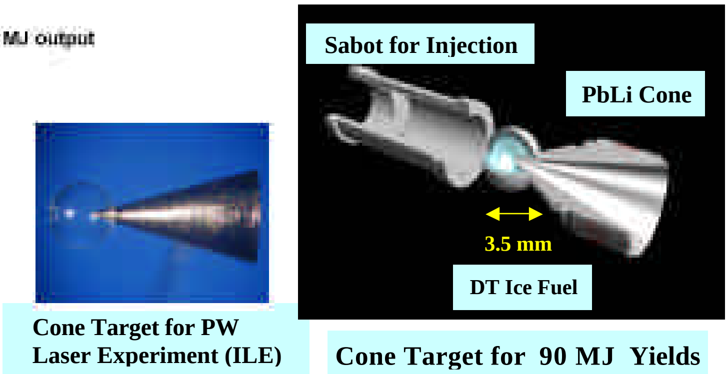

Fig.2 Cone targets for PW laser experiment and a reactor of 90 MJ fusion pulse

There are still some uncertainties on fast ignition physics, especially in heating efficiency with igniting laser and in compressing cone targets to high density. Also, it is very important to mitigate the requirements on the pulse width and beam focusing of the heating laser. Cone targets may allow efficient heating not only by eliminating the affection of ablated plasma, but also by focusing the laser beam, and keeping the accuracy of target injection, so as to help to achieve ~4 Hz pulse repetition rates reasonably easily than without cone, as will be discussed later.

2.2. High Repetition Rate Laser Drivers

We consider that for laser fusion power plants, it is necessary to develop an approximately 1 MJ laser system with more than 10 Hz repetition rate. For the high rep-rates lasers, we have developed so far a diode-pumped, zig-zag slab, Nd:silica-phosphate glass laser amplifier HALNA 10 (10 J, 10 Hz). We have a confidence that the next step100 J, 10 Hz DPSSL module (HALNA 100) can be developed [5]. We are making effort for developing higher rep-rates ~20 Hz, and long life lasers, using new laser materials such as Nd:YAG ceramic, Yb:YAG ceramic, and new mixed materials. For fast ignition reactors we should also consider several 10 psec short pulse lasers. We are now searching for a suitable DPSSL concept using Yb:YAG ceramic, both for implosion lasers and heating lasers considering their inherent good characteristics.

2.3. Reactor Chamber Conditions due to Fusion Pulse Loads and Pulse Repetition Rate

As burning of inertial fusion occurs in very short time, i.e., in less than 0.1 nsec, chamber walls are exposed to high peak power of X-rays, ions, and neutrons. For protecting the first wall from these pulse loads, various chamber concepts using liquid wall or solid wall have been proposed.
We consider liquid wall chambers, covered with thin liquid layers on solid walls (wetted wall concepts) or with thick liquid layers. On the liquid surface the pulse loads of X-rays, high energy alpha particles and low energy ions from fusion burning are absorbed in a thin surface layer and cause ablation of the surface layers up to several μm in depth. The ablated metal vapor should be condensed quickly before the next shot. In order to keep the first wall materials within an allowable damage level, we must design solid wall chambers with a larger chamber radius or using chamber buffer gas, but at the same time avoiding the adverse impacts on target injection and laser beam propagation.
Energies and spectra of X-rays, charged particles, and neutrons from burning target have been calculated by using ILESTA-1D, and MEDUSA-Q for KOYO targets [6], and we are now assessing the cases of fast ignition cone targets. The energy percentages and average energies of X-rays, alpha particles, and ions from a typical 400 MJ central spark target are, 35 keV, 1.0% (X-rays), 3.5 MeV, 2.5% (alpha particles), 0.1~1MeV, 14.5% (ions), respectively.
Although we are still assessing the fast ignition case, we think that primarily the energies and spectra of X-rays, alpha particles, and ions may different from those of the central spark cases in terms of the energy rate of alpha particles. The directly lost alpha particles of the cone targets may become 2~3 times larger than those of the central spark targets. Because the burning of the fast ignition targets propagates from one side to around.
Those differences of fusion pulse energies and spectra between fast ignition and central spark ignition should be examined carefully, as the heat deposit on and response of the surface are very sensitive to alpha particle energies. Figure 3, 4 show the energy deposition and ablation depth for a 200 MJ central spark target, which may give a prospect for the fast ignition case.

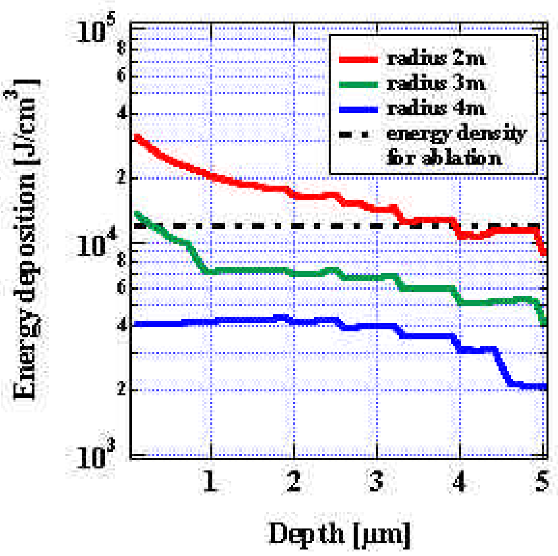

Fig.3 Energy deposition by X-rays and alpha particles from a 200 MJ central spark target.

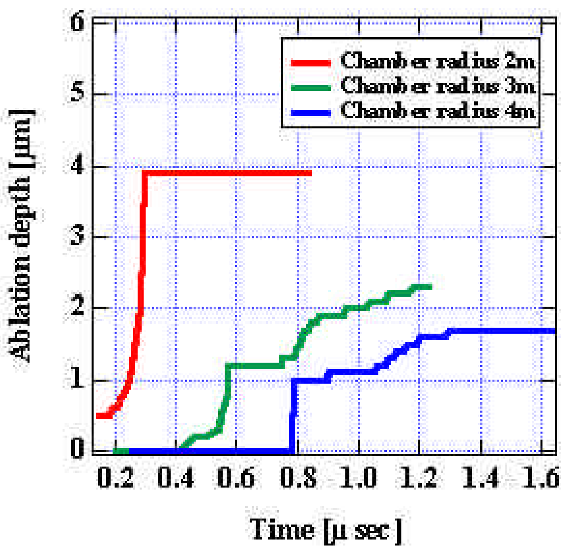

Fig. 4 Ablation depths of liquid surface in the case of a 200 MJ central spark target.

Figure 3 shows that the energy depositions by alpha particles are rather deep due to their long ranges (about 14 μm), so that the total ablation depths have a certain threshold, such as 4μm for r=2m, and about 2μm for r=3m and 4m, as shown in Fig. 4. Those results show clearly that the ablation depths depend on the alpha particles when beyond a certain intensity (for less than 2~3m radius chamber), but not so in the larger radius cases.

The chamber pulse rep-rates are restricted by the speed of exhausting the ablated metal vapor, and also by the vacuum conditions necessary to target injection and laser beam propagation. For the fast ignition cone targets the chamber gas pressure requirement may be mitigated to ~0.05 Torr, as the heavy cone materials can guard DT cryo-target and afford precise trajectory [7]. For the propagation of the heating laser beam (~30 psec pulse width), the vacuum conditions of roughly ~0.01 Torr are required for the beam focusing.
The condensation speeds to achieve less than 0.01 Torr have been estimated by developing the DSMC (direct simulation of Monte Calro method) code, and the results indicate that the evacuation speeds are sufficiently fast, ~100 msec, when the liquid free surface are well cooled or fresh [8]. Designs for a stable and quickly renewal liquid surface are important, and further studies are necessary on the critical issues, which may prevent restoring chamber conditions for the next shot, such as forming clusters or droplets, and splashing from the liquid layers.

2.4. Design Windows for Fast Ignition Laser Fusion Power Plants

We have analyzed the design windows for power plants based on the fast ignition gain curve and the conditions of their key technologies. Table l. shows the typical parameters of the fast ignition power plants, comparing with the central spark cases. For the requirements of 1200 MWe plants we can use several reactor modules in modular plants concept, or we have to achieve larger rep-rates and/or larger pulse energies.

Table 1. THE KEY DESIGN PARAMETERS FOR LASER FUSION POWER PLANTS

	Laser energy MJ	Target gain	Fusion pulse energy MJ	Pulse rep-rates Reactor (Laser)	Net output power MWe	
					1 reactor	Modular plant
Fast ignition	0.2 (ignitor 0.1)	~50	10	1~3	1~3	for experimental reactor
	0.6 (ignitor 0.1)	150	90	4.5(18)	150	150×4 600 MWe
	1.0 (ignitor 0.1)	200	200 KOYO-Fast	4 (16)	300	300×4 1200 MWe
Central spark	2	100	200	4 (16)	300	300×4 1200 MWe
	4	100 ~ 150	400 ~ 600 (KOYO)	~ 3 (6)	~ 600	600×2 1200 MWe

We selected those key parameters, by considering mainly the upper bounds and the lower bounds of the fusion pulse energies, laser energies, and the pulse repetition rates of chambers and lasers, and the reactor module numbers for the required plant output. The minimum fusion pulse energies and laser energies must be sufficient to achieve high gain conditions. We have estimated that the minimum laser energies required are 600 kJ for 90 MJ fusion pulse and 1 MJ for 200 MJ fusion pulse, with the conditions of laser efficiency of 6~10%.

The upper boundary of chamber pulse rep-rates are restricted by the chamber restoring time and the intervals of target injection, which are estimated as about 3~5 Hz in liquid wall chambers.

Because the cone targets seem so effective to reduce the requirements for laser beam focusing and to keep the target injection accuracy, we could expect more than 4Hz pulse repetition rates reasonably easily than the cases without cone for target.

For the solid wall chambers, the upper limit of fusion pulse energies may be given by the restriction of pulse heat loads to the bare solid wall. We consider the solid wall chamber design windows, where the wall material should be kept under the allowable temperature without adverse thermo-mechanical response and erosion, but they are very narrow as a results of the trade-off between large chamber radius and filling gas pressure. We have estimated a necessary chamber radius beyond 8 m for 100 MJ fusion pulses, and 4 m for 20 MJ pulses without buffer gas, for central spark targets [6]. For fast ignition targets, we should further examine the effects of the large amount of alpha particles (approximately over 30% of total ions energies), which pass through chamber gas and metal vapor from cone materials without stopping, and also the effects of soft X-rays emitted from the high Z plasma of cone materials absorbing ions energies.

We should also assess the upper limit of the fusion pulse energies and average power in terms of the neutron load on the chamber wall materials and the final optics. For avoiding the impact on final optics by the neutral particles and ions from the ablated wall materials and the cone targets, we should pay particular attention to a protection schema of final optics. We consider rotary shutters, which make the beam port open only for a few ms in every shot cycle for stopping neutral vapor particles [5].
We should also consider the combinations of magnets for removing alpha particles and other charged particles, and the buffer gas in the laser beam lines for X-rays. But for the neutron damage on the final optics, we must consider not only developing long lifetime optical materials, but also setting final optics at a reasonable distance, i.e., at 30~50 m from the chamber center, especially for the heating laser. After all, we may have to consider the optimum reactor module power in the trade-off between the larger reactor output power and the larger building with the longer final optics distance, or the shorter replace intervals of the final optics.

We propose a standard 1200 MWe modular power plant of which 4 reactors are driven by a 1 MJ laser system, i.e., 900 kJ, 1 nsec pulse laser for implosion and 100 kJ, ~30 psec laser for heating. Each reactor module generates 200 MJ fusion pulses in 4 Hz, i.e., 800 MW fusion power, and 300 MWe net electric power.

3. A Small Laser Fusion Experimental Reactor based on Fast Ignition

3.1. Road Maps for IFE and Missions of Fusion Experimental Reactor

We have discussed road maps for laser fusion energy development, and identified issues to be solved and elements of program necessary to be carried out in a coordinate manner. Then we have considered the major experiment facilities specified from their given missions. Table 2 shows major fusion experiment facilities and power plants, with their missions and key parameters.
FIREX is aimed at establishing fast ignition physics and demonstrating ignition. The missions of LFER are integration of technologies necessary for power plants in a small scale and short operation time, but scalable to a DEMO plant which should demonstrate practical power generation. Figure 5 shows the relationships of these facilities and the R&D program of

necessary technologies as a road map for IFE. LFER is planned for three phases. In the phase-I high gain targets and integrated high rep-rate technologies are tested. In the phase-II using solid wall chamber, reactor technologies are tested comprehensively, such as testing blanket modules for tritium breading and power generation.

Table 2. MAJOR FUSION FACILITIES AND THEIR MISSIONS AND SPECIFICATIONS

Facility	**FIREX**	**LFER**	**DEMO**	**Commercial plants**
Milestones	Fast ignition physics establishment and ignition demonstration	Demonstration of integrated reactor technologies and net electric power	Demonstration of practical power generation	-
Objectives	**PhaseI (FIREX-I)** : Heating to ignition temperature (~10 keV) **PhaseII (FIREX-II)** : Ignition and burning	**Phase I :** high rep-rate burning **Phase II:** Solid wall with test blanket, and liquid wall chamber test **Phase III:** Net power generation, long time operation	- Demonstration of a reactor module for practical power plants - Credibility and economical potential demonstration	- Economically, environmentally attractive plants (Competitive COE) - Modular plants for scale up, flexible construction
Laser	~100 kJ implosion 50 + heating 50	200 kJ (~ 1 Hz)	0.6~1 MJ (~ 4 Hz)	0.6~1.2 MJ (10~ 30 Hz)
Fusion pulse energy, power output	~1 MJ (1 shot / hour)	10 MJ 10 MWth/ 4 MWe Net output 2MWe	100 ~200 MJ 330 ~ 660 MWth 100 ~ 300 MWe	100 ~200 MJ 4 Hz× (4~8) reactors 600 ~ 1200 MWe

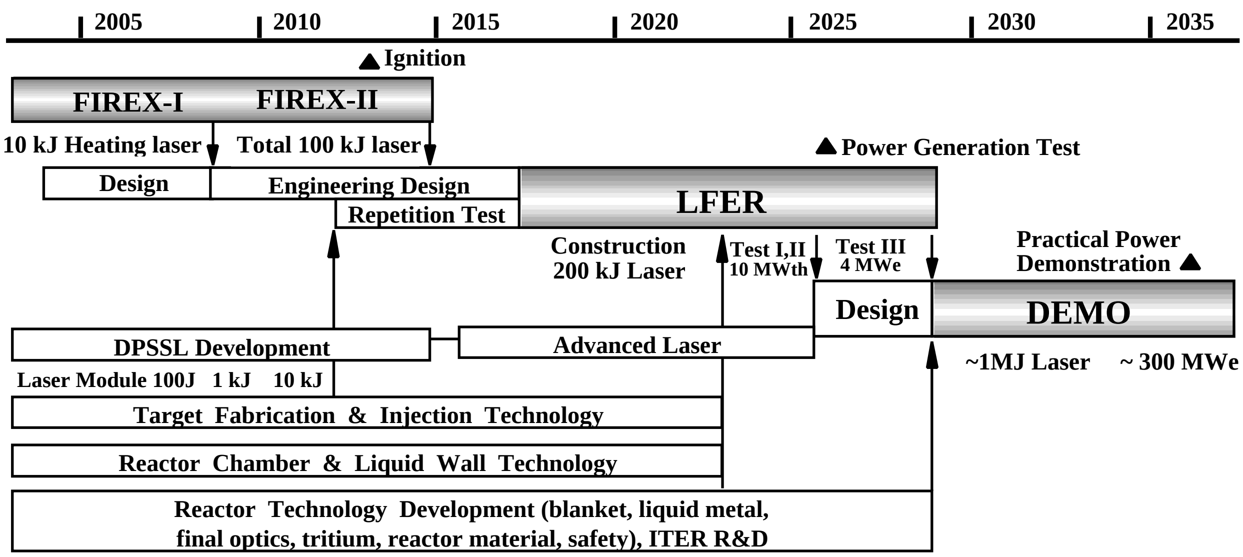

Fig. 5 A road map for IFE based on fast ignition

In the phase-III, the chamber may be changed to a liquid chamber with full blanket and, tested for net power generation. After achieving these missions, LFER may be used as a material test reactor by long hour operation as a self-sustaining reactor.

3. 2. Basic Concept of a Small Fusion Experimental Reactor

We have considered a small fusion experimental reactor using fast ignition cone targets and DPSSL laser systems. Reactor chamber sizes are determined primarily by pulse heat load on the first wall. We consider LFER chambers, having a radius and pulse thermal load of 2.5 m and 2.5 J/cm^2 for solid wall, and 1 m and 16 J/cm^2 for liquid wall, respectively (Fig. 6). The liquid wall chamber in phase-III of LFER should be tested for the DEMO reactor chamber, of which radius, pulse thermal load, and average heat load are considered as 3 m, 35 J/cm^2, and about 100 W/cm^2, respectively. Figure 7 shows an overall layout and the key systems of LFER.

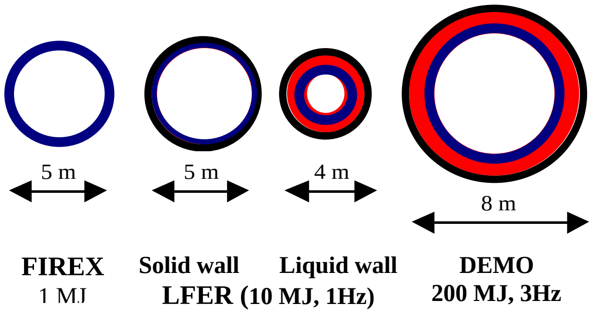

Fig.6 Chamber sizes of major fusion facilities

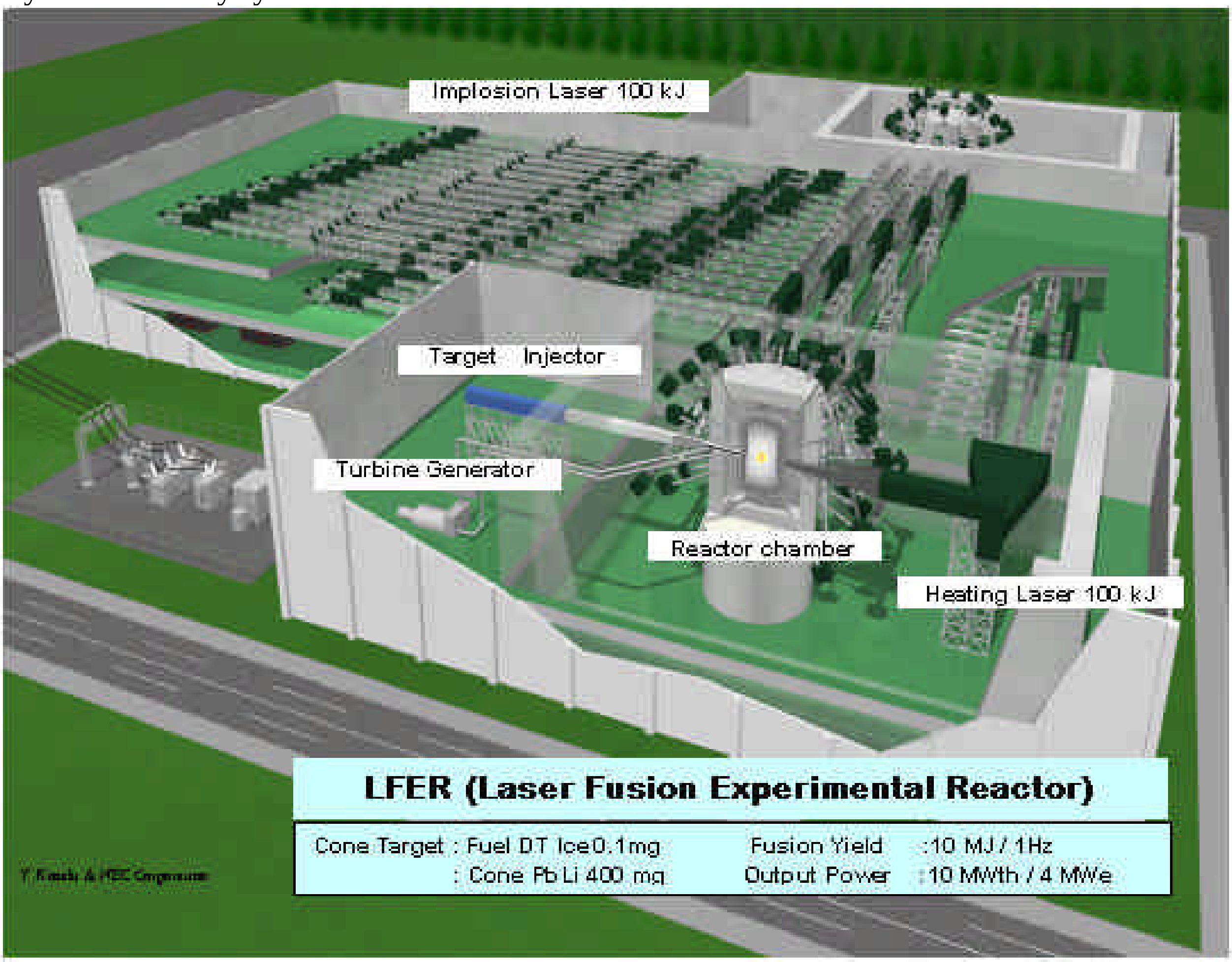

Fig. 7 Laser fusion experimental reactor using fast ignition targets and DPSSL lasers

There are two 100 kJ laser systems, i.e., for implosion and heating, placed separately on the two floors in a laser building. For a heating laser, large final optics and a long beam line are placed oppositely to a target injector. We consider two chambers, i.e., a solid wall chamber for Phase-I and II experiment, and a liquid wall chamber for net electric power demonstration. Around the chambers, there are about 60 final optics and beam lines of implosion lasers in spherically symmetric layouts. In regard to the final optics of the heating laser and the shielding of laser beam-lines, there are still many remaining problems to be examined in detail. Although in a small scale, we could foresee the basic configurations, layouts, and sizes of the fast ignition laser fusion plants.

4. Conclusions

We have examined the design windows and the issues of the fast ignition laser fusion power plants, and shown the possibility of small size, ~300 MWe fusion reactors, with ~200 MJ fusion pulse energy, ~4Hz rep-rates. Using these reactor modules we can flexibly design large scale, ~1200 MWe modular plants driven by a ~16 Hz high rep-rate laser system. The small pulse energies mitigate technical constraints of the chamber as well as the final optics issues. We have also shown the possibility of a very small fusion experimental reactor with fast ignition concept.
We propose a small laser fusion experimental reactor (LFER), having fusion pulse energies of 10 MJ with 200 kJ laser, i.e., 100 kJ for implosion and 100 kJ for heating. LFER is aimed at integrating the technologies necessary to power plants and demonstrating net electric power generation in a small scale and short operation time, but scalable to a DEMO plant.
With LFER, we could consider a possibility to demonstrate electricity generation in a reasonably short time. It may be achieved by coordinated development efforts on relevant individual fusion technologies. It is important to advance both fast ignition physics research and reactor technology development in a coordinated manner.

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