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Concept of Laser Fusion Power Plant Based on Fast Ignition

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Recent progress on fast ignition (FI) and cooled Yb:YAG ceramic laser enable us to design an IFE power plant with a 1MJ-class, compact laser whose output energy is 1/4 of previous central ignition scheme. Basing on the FI scheme, we conceptually designed a laser fusion power plant driven with cooled-Yb:YAG, ceramic lasers. The cooled Yb-YAG ceramic was newly chosen as the laser material. We found that the heating laser for ignition could be constructed with the cooled Yb:YAG ceramics as well as the compression laser with acceptable electricity-laser conversion efficiencies including the electric power for the cooling system. A new reactor scheme for a liquid wall reactor that has no stagnation point of ablated gas was proposed.

1. Introduction

The fast ignition scheme is very attractive because a high gain can be achieved with smaller lasers that were considered to share major part of the construction cost of a laser fusion power plant. In 2002, our fast ignition experiments with a petawatt (PW) laser in Osaka University demonstrated a heating efficiency of 20 - 30 % at ignition-equivalent laser intensity.[1] This promising result promoted design activity to figure out the final goal for the power plant. After a report of the Roadmap Committee of IFE Forum[2], we organized a Design Committee of Laser Fusion Power Plant 1) to make a reliable scenario for the fast ignition power plant based on the latest knowledge of elemental technologies, 2) to identify the research goal of the elements and 3) to make the critical path clear.

In our previous KOYO design based on central ignition scheme, 4 modular chambers were driven by turns with 4MJ/pulse, 10 Hz lasers to yield 4000-6000MWth fusion energy and 2400MW electric power[3]. The laser was a glass laser (HAP4) driven by diodes. The first wall of the chamber was protected with arrayed SiC composite panels whose surfaces were covered by liquid LiPb films penetrating through the pipe walls. The critical point of this design was poor ability of vacuum pumping by cryogenic effect. When the flows on the SiC pipes were simple laminar flows, the surface temperature near the bottom of the reactor become too high to evacuate ablated metal vapor in the designated time.

In this design work, 1) cooled Yb-YAG ceramic lasers were newly used for compression and heating lasers. 2) The target gain was evaluated using latest simulation codes. 3) Cascade-type, liquid- wall chambers are employed as the modular reactors. 4) The ablation of the first liquid wall and the chamber clearance were discussed basing on new idea of stagnation-free chamber geometry. 5) Scenario for fuel loading in batch process was proposed. In this paper, laser system and chamber issue are discussed focusing on behavior of ablated first wall material.

2. Gain Estimation

The gain performance for fast ignition targets was evaluated by parametric numerical study using 2-D burn simulation code based on 1-fluid 2-temperature Eulerian hydrodynamic code written in 2-D cylindrical coordinates (r-z). The electron thermal conduction, radiation effect, α-particle heating and external fast heating are taken into account. The radiation and the α-particle transports are treated by multi-group flux-limited diffusion model. As the initial core profile, we assumed uniformly-compressed DT spherical plasmas (ρ = 300 g/cc, T = 0.2 keV, α = 2) at the center of the simulation box. With regard to the external fast heating, uniform heating rate was assumed in the cylindrical region (30 μm spot diameter, 1.0 g/cm^2 optical depth) at the core edge for 10 ps. For gain estimation, the coupling efficiencies from the laser to the core plasma were assumed as 5% for implosion and 30% for the core heating. The obtained gain curve is plotted in Fig.1. To achieve the explosive burning and then the high gain (>100), the required compressed core ρR must be larger than 1.6 g/cm^2, and total driver must be higher than 300 kJ.

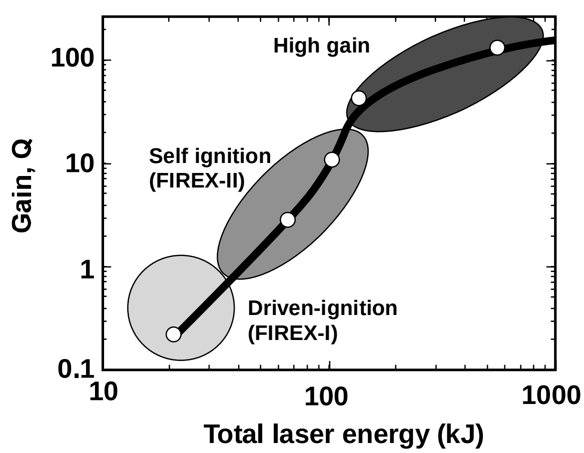
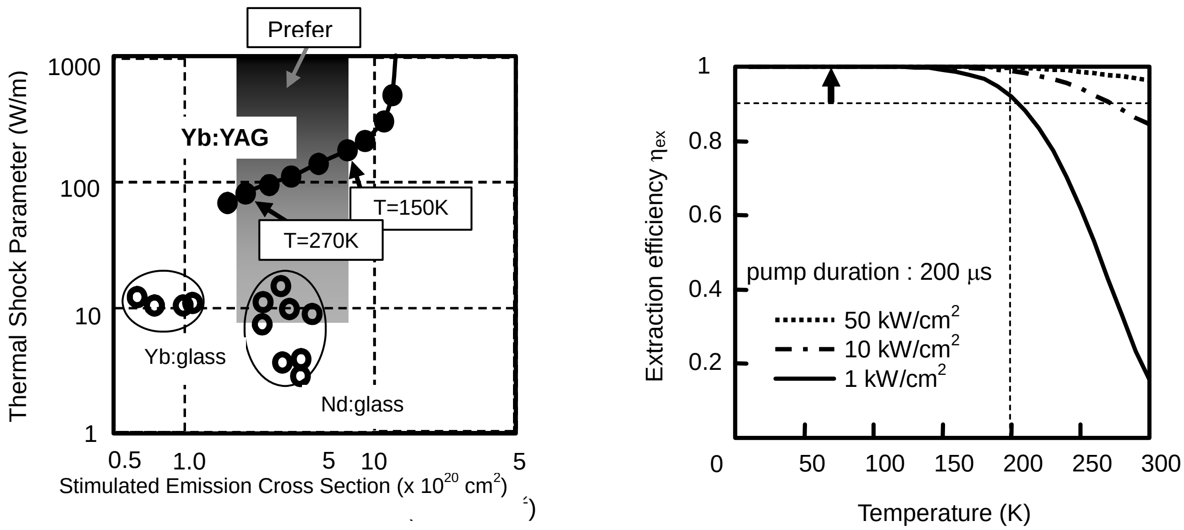


Fig. 1 Estimated gain of fast ignition targets

3. Laser System

Current computer simulation indicates thermonuclear gain of 170 will be achieved with 1.1 MJ / 10 ns compression laser and a 100 kJ / 10 ps heating laser. In addition, the overall efficiency more than 10% and the repetition rate of 16 Hz should be required in a commercial reactor. A diode-pumped solid-state laser is a prior candidate for such reactor lasers. In previous designs, Nd:glass has been used as high-pulse-energy laser material for IFE researches. The poor thermal strength is, however, undesired for the repeatable reactor laser. Three important factors are required for the reactor laser material, production capability of large-aperture materials, high thermal strength and proper stimulated emission cross section. An Yb:YAG ceramics[4] is focused on due to its size-scalability and great thermal strength. The stimulated emission cross section is, however, too low to extract the storage energy efficiently with commercial optics. Tuning the cross section by controlling the ceramics temperature has been proposed.



(a) (b)

Fig. 2 Cross section for stimulated emission of IFE laser materials (a) and theoretical extraction efficiency with Yb:YAG temperature)b)

The preferred temperature is between 150 K and 270 K as shown in Fig. 2(a) (See ref. 5). Also, the thermal conductivity, the thermo optic coefficient (d*n*/d*T*) and the coefficients of thermal expansion are improved at low temperature[6,7] resulting in less thermal lensing effects and thermal birefringence.

The theoretical extraction efficiency from the diode-pumped Yb:YAG ceramics is calculated as a function of temperature for various pump intensities, shown in Fig. 2(b). Intense pump is necessary to obtain a high efficiency at room temperature because of quasi-three-level system in Yb:YAG. It is hard to produce such intense pump by using stacked laser diodes with low brightness of at most 3~4 kW/cm^2 and poor spatial beam profile. If the Yb:YAG ceramics is cooled below 200K, more than 90% efficiency would be obtained even in diode pump. Considering the efficiency of the cooling system, the ceramics temperature is decided at 200 K.

A new laser driver has been conceptually designed using a cooled Yb:YAG ceramics. The rough construction diagram is shown in Fig. 3. A small-energy nano-second pulse is generated in near infrared (λ~1030 nm) at the fiber-based oscillator. The pulse is amplified to ~kJ energy with pre-amplifiers. The pulse is divided into 40 beams spatially and each pulse is finally amplified to 55 kJ at a main amplifier module. The net pulse energy is up to 2.2 MJ with 40 beams. Then, 32 and 8 laser beams are frequency-converted in blue (λ ~343 nm) and green (λ ~515 nm), respectively, by using nonlinear crystals. The blue output energy of 1.1 MJ is for the compression laser. The green of 0.35 MJ is used as a pump source of the following optical parametric chirped-pulse amplification (OPCPA). A pico-second laser pulse from another mode-lock oscillator is temporally stretched to amplify its pulse energy by using 3-stage OPCPAs. The amplified pulse is compressed again in pico-seconds with 0.1 MJ pulse energy for the heating laser.

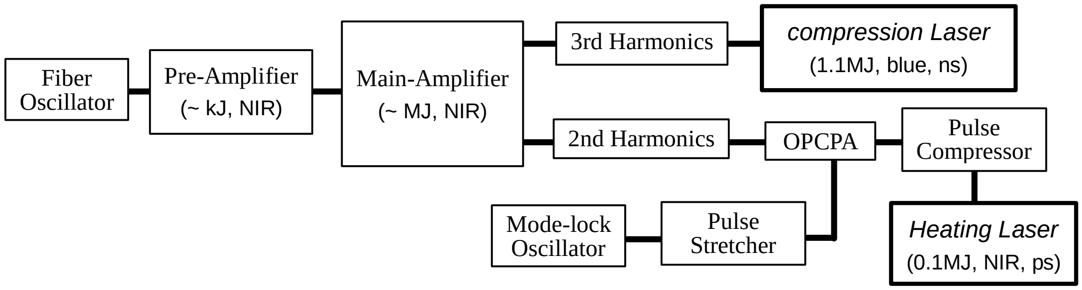
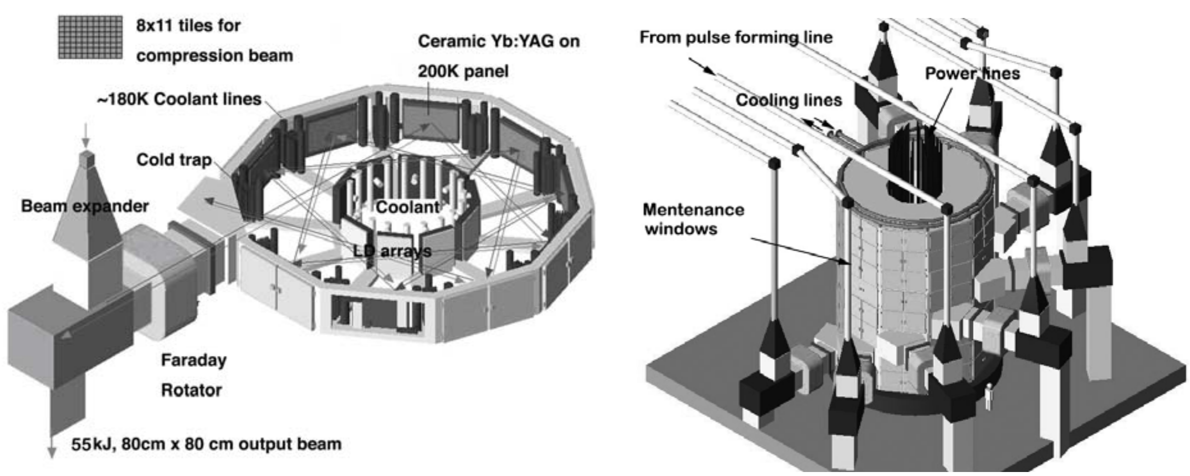


Fig. 3 Construction of the reactor laser system

A main amplifier module is illustrated in Fig. 4(a). An active-mirror scheme, which has double functions of laser amplification and laser beam reflection, is adopted for the first time instead of the conventional disk scheme. The active mirror is an Yb:YAG ceramics disk with an anti-reflection (AR) and a high-reflection (HR) coating on its optical surfaces.[8] The active-mirror scheme makes energy extraction easy because a laser pulse experiences two-pass amplification at one reflection. That results in less pass number in amplification, leading to relax restriction in designing. The disk temperature is conductively cooled at 200 K through the HR-surface. The temperature rise is about 30 K at 16 Hz operation, which is not significant in beam distortion. Nine active-mirrors are set at the vertices of the polygon of the module. The 1.7 MW laser diode stacks (λ=940 nm) is concentrated at the center of the polygon. A ~10J seed pulse travels via nine active-mirrors and turned back on the same trace by using a high reflector end. The 55 kJ amplified pulse is extracted by using an optical isolator with a Faraday rotator and a polarizer pair. The beam size is 80 cm x 80 cm. The amplifier module size is 8 m in diameter and 1.5 m in height. The blue 2.2 MJ is produced with 40 modules at 16 Hz. About 500 millions diode stacks are needed. These amplifier units are stacked as shown in Fig. 4(b) to make a compact driver system. The laser material can be replaced easily through the outside maintenance windows. Laser diodes can be accessed using the central pipe shaft. The net main amplifier volume is calculated to be about 3000 m^3, which is comparable to a reactor chamber.



(a) (b)

Fig. 4 Active mirror amplifiers for one beam(a). Laser beam form a pulse forming line is expanded to 80cm x 80 cm in the cross sectional size. A phase conjugation mirror will be used to return the laser beam. Stacked amplifier tower for 8 beams (b). Power plant KOYO-F needs 4 towers for the compression laser and one tower for the heating laser.

TABLE I: SPECIFICATION FOR LASER SYSTEM

	Implosion Laser	Heating Laser
Laser Power	16 MW (1.1MJ, 16Hz)	1.6 MW (0.1MJ, 16Hz)
LD Electrical - LD Optical	60%	
LD Optical - 1ω	42%	
LD Electrical - 1ω	26%	
1ω - 3ω	70%	-
1ω - 2ω	-	80%
OPCPA Efficiency		40%
Pulse Compression Efficiency		80%
Transportation Efficiency	90%	90%
Harmonic Generation and Transportation	63%	23%
Electric Input Power	110MW	28MW
Crystal Heating Power	6.6MW	!.7MW
Cooler Electric Power	22MW	.7MW
Electric Power Demands	132MW	24MW
Total Electric Power	166MW	
Over All Efficiency	12%	

The total electric input power for both of compression and heating lasers is roughly estimated at 156 MW including a cooler system in TABLE I. The performance of the cooling system for whole laser system must be 2 MW at 200K. Such big cooling system can be constructed with existing technology (a 600kW cooling system at 200K is commercially available with construction cost of several million dollars). The cooling efficiency (cooling power at 200K / input electric power) of 30-40% can be expected. The overall electrical-optical efficiency is as high as 12%.

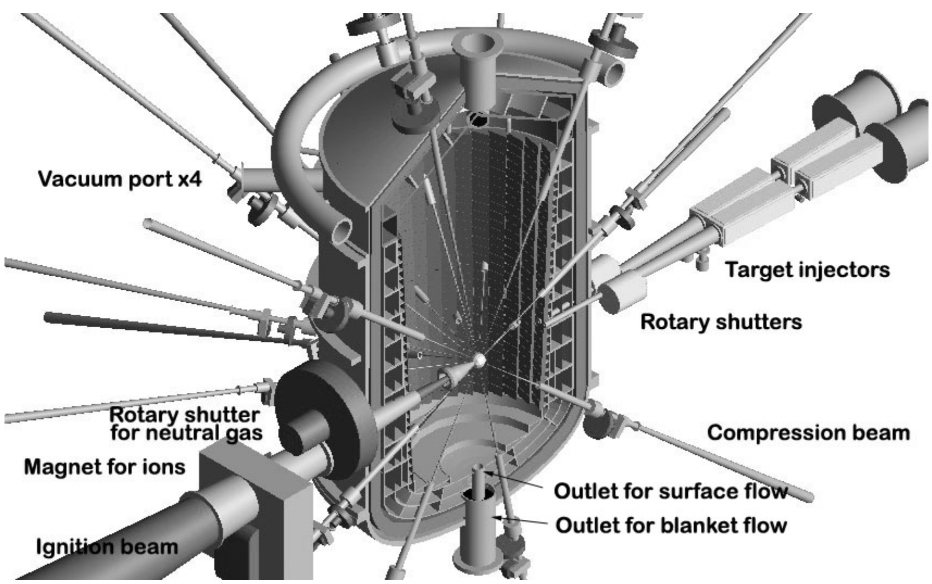


Fig. 5 Cross section of a modular reactor of KOYO-F. The target is emphasized by 150 times for visibility.

4. Chamber

Figure 5 shows a cross section of the modular reactor of KOYO-F. The power plant KOYO-F has 4 modular reactors. Each reactor is operated at 4 Hz by turn. Main features of this design are as follows. 1) the fire position is vertically off-set to simplify the protection scheme of the ceiling. 2) There is no horizontal area on the ceiling to avoid formation of droplets.[9] 3) The first wall is liquid LiPb with cascade flows to obtain fast pumping of evaporated vapor by cryogenic effect. If the surface flow is a simple laminar flow, the surface temperature becomes too high to obtain cryogenic pump effect when it reaches near the bottom of the chamber. 4) The first panels are tilted by 30 degree to avoid stagnation of evaporated vapor. In the case of KOYO-F, 10kg of LiPb evaporates after a laser shot. If the evaporated vapor collides at the center and loses its momentum, it becomes difficult to obtain high repetition rate. 5) The final optics are protected by compact rotary shutters and buffer gas in the beam duct. 6) Each modular reactor has two injectors that are alternatively operated at 2 Hz. This slow injection rate comes from evacuation of residual gas in the barrel of the gas gun.

The thermal load on the ceiling is close to that of dry wall design. To avoid blistering of the first wall, temperature of the ceiling is kept slightly lower than the other area to form a thin, protective liquid-LiPb membrane. The material of the ceiling must be wetable with LiPb to make continuous membrane. The lifetime of such material due to erosion is a future issue.

Ablation of the liquid Pb was calculated using DECORE (DEsign COde for reactor) that included atomic model, equation of state, phase change, radiation heat transfer and hydrodynamic equations. Influence of Li was ignored for simplification.

Figure 6 shows ablation of the 550C^o Pb surface including oblique incidence effect of α particles. The fusion yield was 200MJ. The radiations from the burning plasma used in this simulation were mentioned elsewhere.[10]

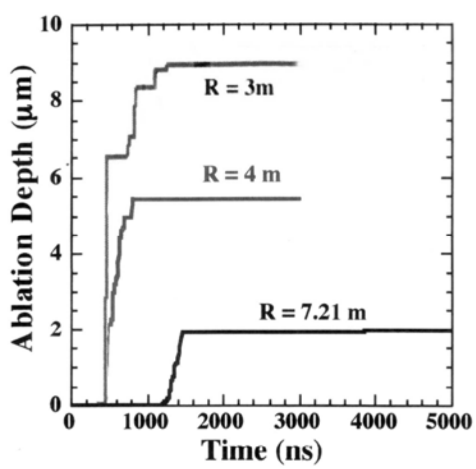
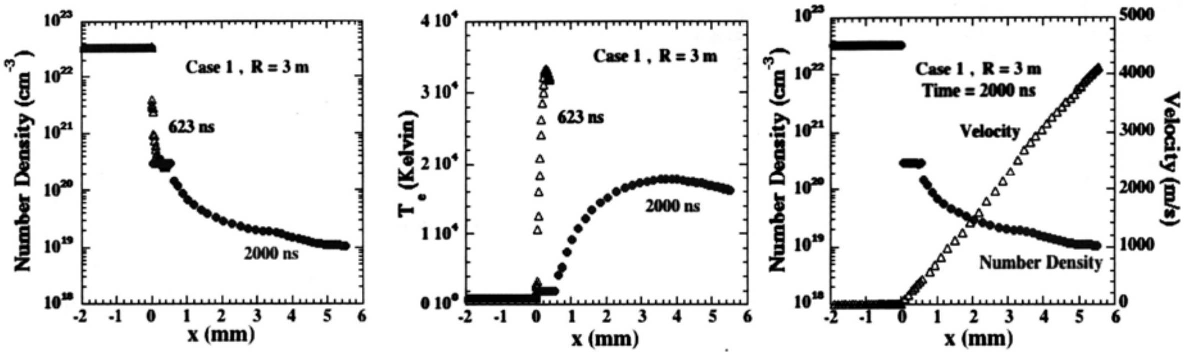


Fig. 6 Ablation depths of liquid Pb at the side and bottom (R=3m), 40 degree above horizontal plane (R=4m), and the ceiling (R=7.21m) of KOYO-F, respectively.



(a) (b) (c)

Fig. 7 Density profile near the surface of liquid lead when the temperature takes its maximum value (623 ns) and end of debris heating (2000ns)(a) , temperature profile at the same timing (b), velocity distribution of ablated lead vapor(c).

Figures 7(a) - (c) show the density, temperature, and velocity distributions of Pb at the bottom and side surface at t=623 ns and t=2000 ns (end of debris heating). The time origin was the start of the heating laser and α particles began to heat the surface at t=200ns and the intensity exponentially decreased to 1/10 by t=350 ns. The initial liquid surface was at x=0. In these calculations, Ziegler's work[11] was used for the stopping power of α particles in liquid Pb.

These results indicate that there are two components in the ablated vapor. One is low density, hot, and fast (500-4000 m/s) component from the surface and the other is middle density, low temperature, and slow (<500 m/s) component from the area within the range of α particles. Due to the Bragg peak in the stopping power of α particles, the temperature distribution reached its maximum at slightly inside the surface. We can find that the surface is ablated as if a 10-μm-thick membrane is peeled off from the surface. Due to the heating effect of debris from the plasma, the temperature of the expanding front is higher than that of inside even after expansion. At t=2000ns, about 60% of ablated vapor exists in the slow component and the rest does in the fast component.

Calculations in the former paragraph were carried out only for t<2000 ns. It takes about 1 ms for the fast component reaches the other side wall of the chamber. During the flight, major vapor in the slow component would become aerosols. According to Luk'yanchuk, Zeldovich-Raizer Model,[12] 10-20 % of metal atoms in a spherically, freely expanding plume condense as the aerosols whose diameters range in 100-200 nm. In KOYO-F case, the expansion is 2D and the motion is blocked by high temperature, leading vapor. Formation of aerosols would much severe in the slow component.

Figure 8 shows number ratio of condensed Pb atoms to in-coming Pb atoms on liquid Pb surface. This result was obtained using Eisenstadt's model[13] assuming that reflecting atoms whose kinetic energy is larger than latent heat of condensation return to gaseous phase and reflecting atoms whose kinetic energy is less than latent heat of condensation are trapped on the surface. IF the temperature of in-coming atoms is 10000K, 65s% of the atoms condense on the surface. Almost 100% atoms in the slow component will condense on the surface in the first bounce.

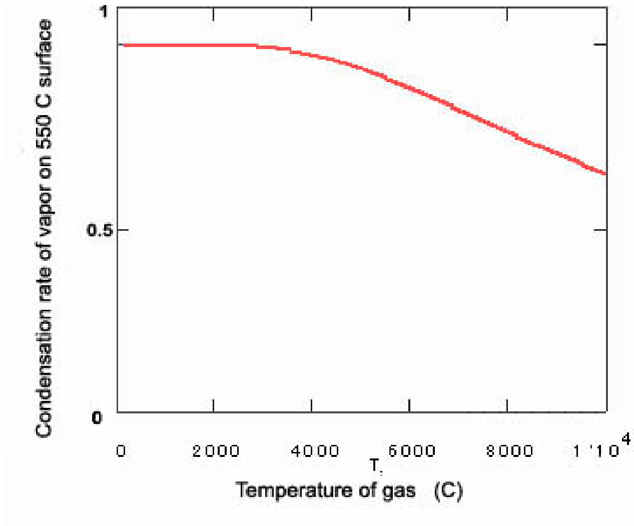


Fig. 8 Condensation ratio of Pb molecules to bombing on 550 C liquid Pb

More detailed analysis is necessary to determine the total condensation rate at the first bounce because the temperature of the gas depends on the expansion rate and the radiation heat transfer during the flight.

After repeating several bounce of the blast wave, residual vapor in the chamber becomes quasi- homogeneous where we can ignore hydrodynamic motion of residual gas. If we assume that fast component uniformly fill the chamber, the pressure in the chamber becomes order of 100 Pa. The heating effect of surface by the blast wave at the first bounce can be ignored in the view point of condensation coefficient because pulse width of blast wave is expanded to an order of 10 ms. So, residual gas in the chamber will be continuously evacuated to the designated pressure of 5-10 Pa before the next laser shot.[14]

When we look into a horizontal cross section of the chamber, ablated vapor from the bottom reaches on the ceiling with some interaction with vapors from the side wall. If we assume that ablated vapor from the bottom uniformly condenses on the ceiling, the thickness of condensed LiPb layer is 2.5 μm/shot that is larger than ablation rate. Of course this is too preliminary to discuss the formation of protection layer, we believe we can form the protection layer by enhancing condensation of residual vapor, especially lithium, in the chamber by keeping the surface temperature less than the other area in the chamber.

Another critical issue of this concept is protection of beam ports ejecting from the liquid surface. The top of the port is directly exposed to the radiation from the plasma. Our current solution is to use a porous plate through which liquid LiPb penetrate from inside. The temperature of the port is also kept colder than other area to enhance the condensation. If we assume the maintenance period of two years, the possibility for direct exposure must be less than $1/10^4$. More detailed research based on experiment is necessary to discuss the reliability of liquid wall scheme.

4. Summary

We have examined the design windows and the issues of the fast ignition laser fusion power plants. ~1200 MWe modular power plants driven at ~16 Hz The basic specification is summarized in TABLE II. For laser driver we have considered the DPSSL design using the Yb:YAG ceramic operating at low temperature (~200K). We have proposed the free fall cascade liquid chamber for cooling surface quickly enough to several Hz pulses operation by short flow path. The chamber ceiling and laser beam port are protected from the thermal load by keeping the surface colder to enhance condensation of LiPb vapor.

Acknowledgement

We authors thank steering board members and working members in Table III for useful discussions, calculations, analysis and writings. We also thank Mr. K. Masanori of Maekawa MFG. Co., LTD for providing information on a cooling plant.

TABLE II: BASIC DESIGN PARAMETERS FOR THE POWER PLANT KOYO-F

Net electric output	1283 MWe (320 MWe x 4)
Electric output from one module	320 MWe
Target gain	167
Fusion Yield	200 MJ
Laser energy / Beam number	1.2 MJ (Compression=1.1MJ/32beams, Heating=100kJ 1beam)
Laser material / Rep-rate	Cooled Yb:YAG ceramics at 150 - 220K /16 Hz
Chamber structure / Rep-rate at module	Cascade-type, free-fall liquid LiPb wall/4 Hz
Fusion power from a module	800 MWth
Blanket gain	1.2 (design goal)
Total thermal output from a module	916 MWth
Total thermal output from a plant	3664 MWth (916 MWth x 4)
Heat-electricity conversion efficiency	41.5% (LiPb Temperature 500 ^{o}C)
Gross electric output	1519 MWe
Laser efficiencies	13.1% (compression), 5.4% (heating), Total 11.8% (including cooling power)
Recirculating power for laser	164 MWe (1.2 MJ x 16 Hz / 0.118)
Net electric output/efficiency	1283 MWe (1519 MWe - 164 MWe - 72 MWe Aux.)/32.7%

TABLE III: MEMBERS OF REACTOR DESIGN COMMITTEE.

Steering board Y. Hirooka (NIFS.), F. Kan (Hamamatsu Photonics), M. Kikuchi (JAEA), T. Konishi (Kyoto Univ.), A. Koyama (Kyoto Univ.), K. Mori (Kawasaki Plant), T. Muroga (NIFS), M. Nishikawa(Kyushu Univ.), M. Nishikawa (Osaka Univ.), Y. Ogawa (Tokyo Univ.), K. Okano (CRIEPI.), M. Onozuka (Mitsubishi Heavy Ind.), Y. Owadano (AIST.), A. Sagara (NIFS.) Y. Suzuki (Laser Front Technol.), K. Tanaka (Nisshin Co.), N. Tanaka (Mitsubishi Heavy Ind.), K. Ueda (Univ. Electro-com.), Y. Ueda (Osaka Univ.), T. Yamanaka (Fukui Univ.), H. Azechi (ILE), N. Miyanaga (ILE), K. A. Tanaka (ILE)
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