Conceptual Design of Laser Fusion Reactor KOYO-F Based on Fast Ignition Scheme

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Abstract. Recent progress on fast ignition (FI) enables 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. In this design activity, we newly evaluated the gain curve for FI basing on latest simulation code. 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. New reactor scheme for a liquid wall reactor that has no stagnation point of ablated gas and a rotary shutter system to protect the final optics are 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 basing 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 allayed SiC composite pipes whose surfaces were covered by a liquid LiPb film penetrating through the pipe wall. In this design work, cooled Yb-YAG ceramic lasers were newly used for compression and heating lasers. Cascade-type, liquid- wall chambers are employed as the modular reactors. Outline of the gain estimation, the laser system and the chamber are reported.

2. Gain Estimation

The gain performance for fast ignition targets was evaluated by parametric numerical study using 2-D burn simulation code FIBMET[4]. FIBMET is based on 1-fluid 2-temperature Eulerian hydrodynamic code written in 2-D cylindrical coordinates (r-z). The electron thermal conduction (Spitzer-Harm's model), 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. With regard to the external fast heating, uniform heating rates ware assumed for the bulk electron in the cylindrical region (30 μm spot diameter, 1.0 g/cm^2 optical depth) at the core edge for 10 ps. 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. 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. In **FIG.1**, we plotted the gain curve obtained using the simulation results for 6 different-sized targets.

When the total laser energy E_{Ltot} is less than 40 kJ, the burning process can be called “Driven-ignition” region where external heating is the major process. The size of the compressed core is comparable to that of heating region assumed here. During the heating pulse injection, the temperature of bulk ion rises continuously up to about 10keV. After finishing the external heating, however, the core density and the temperature are rapidly decreased due to 3D expansion since the surrounding cold region confining the heated region does not exist. Then, the fusion output power begins to decrease and the obtained gain is smaller than 1.

The region 40<E_{Ltot}<300 kJ can be called “self-ignition” region where heating of α particles works well. The imploded core size is larger than the external heating region so that a certain amount of cold fuel surrounds the heating region. Under this situation, if the heating energy is sufficiently large, the core temperature continues to increase due to alpha-particle self-heating after the external heating. The burn wave then propagates into the cold region, which sustains an increase in fusion output power. The core size is, however, not sufficient to achieve the explosive fusion burning such as a detonation wave. In the self-ignition region, the gain becomes larger than 1 but is not sufficient for a reactor.

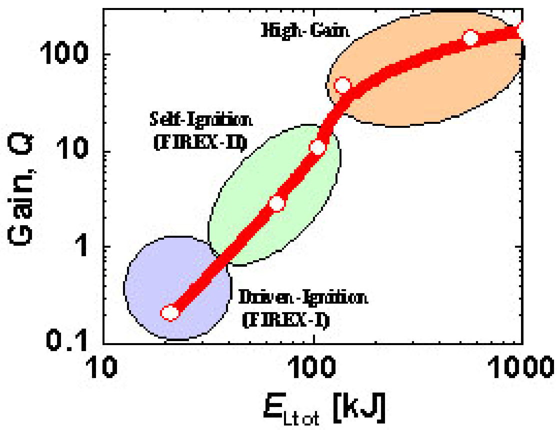


FIG.1 Gain curve for fast ignition core (ρ=300g/cm^3, α=2). The open circles stand for each core (ρR = 0.7 ~ 3.3g/cm^2) and the red curve presents the envelope for the gain obtained in each core.

To achieve the explosive burning and then the high gain (>100), the required compressed core ρR is larger than 1.6 g/cm^2, and total driver is higher than 300 kJ. In FIG. 2, the time evolution of burning process of a high-gain fast ignition target (ρR = 2.67g/cm^2 with 18.4kJ heating; the corresponding values of laser energy are 500kJ for implosion and 61kJ for heating.). Due to the 10ps external heating, the ion temperature at the core edge becomes higher than 10keV. In this heated region, the temperature and then the fusion power continuously increase due to the alpha-particle self-heating after the external heating. The surrounding region is heated by the energy transport from the heated region due to the electron thermal conduction and alpha-particles, and then the burning area gradually spreads out. The ion temperature at the heated region reaches 30keV at 40ps (30ps after the external heating). Through this transition period (~30ps) after the external heating, the burning wave becomes a detonation wave and the explosive burning is achieved. As the results, a high burn-up rate (26.5%) and a high gain (Q=142) are obtained.

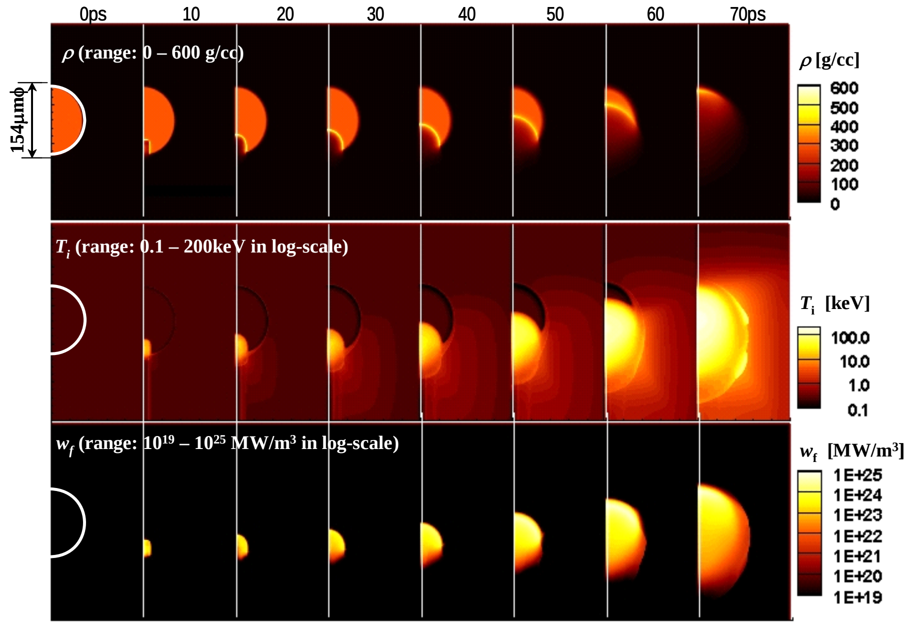


FIG. 2 Time evolution of burning process of a fast ignition target (ρR = 2.67g/cm^2 with 18.4kJ heating; the corresponding values of laser energy are 500kJ for implosion and 61kJ for heating.). Special distributions of the density of plasma (up), the temperature (middle) and the fusion yield (low) are shown every 10 ps.

In the larger core case (ρR = 3.3g/cm^2, 1MJ implosion laser energy), the confinement time becomes longer, so that the burn-up rate increases. The heating laser required for ignition does not change. Thus, the higher gain (Q = 170) is obtained.

2. 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. A Nd:glass has been used as a 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 too low to extract the storage energy efficiently with commercial optics. Tuning the cross section by controlling the ceramics temperature has been proposed. The preferred temperature is between 150 K and 270 K shown in FIG. 3(a). [5] Also, thermal conductivity, thermo optic coefficient (dn/dT) and coefficients of thermal expansion are improved at low temperature,[6,7] resulting in less thermal effects of thermal lensing 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. 3(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.

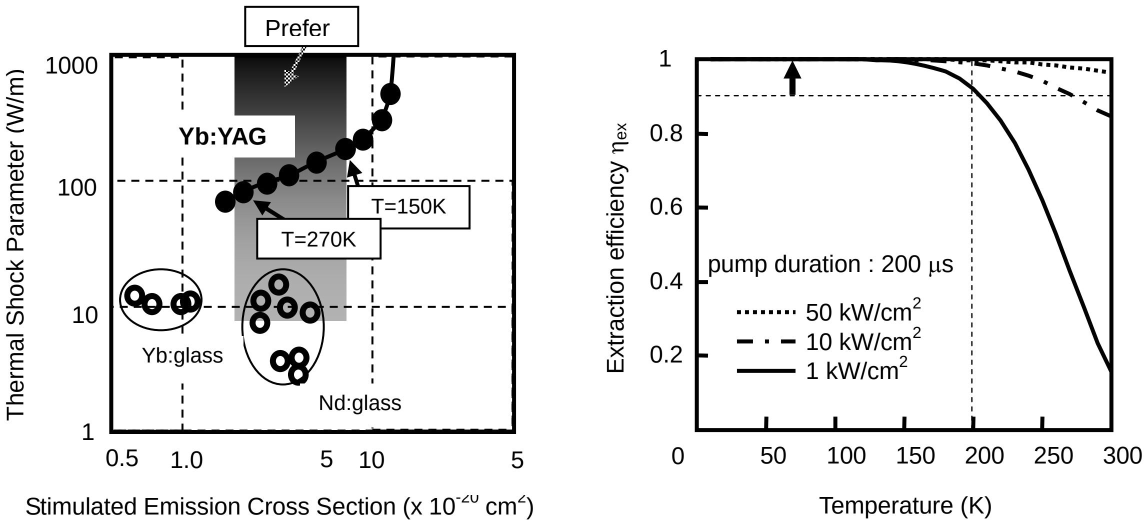


FIG. 3 Stimulated emission cross section of IFE laser materials (a) and theoretical extraction efficiency with Yb:YAG temperature (b).

A new laser driver has been conceptually designed using a cooled Yb:YAG ceramics. The rough construction diagram is shown in FIG. 4. A small-energy nano-second pulse is generated in NIR (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.

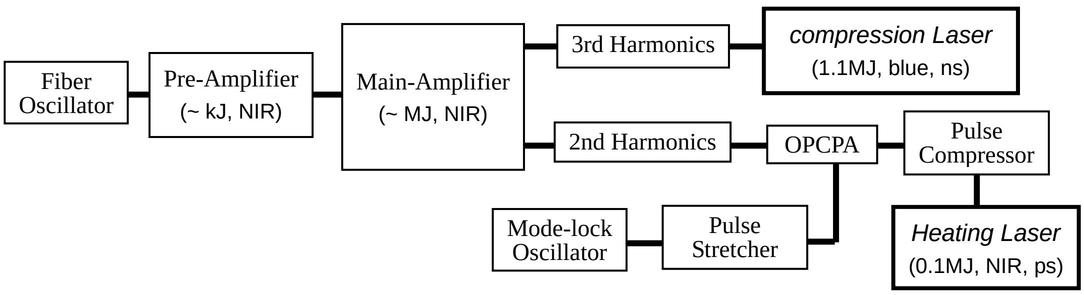


FIG. 4 Construction of the reactor laser system.

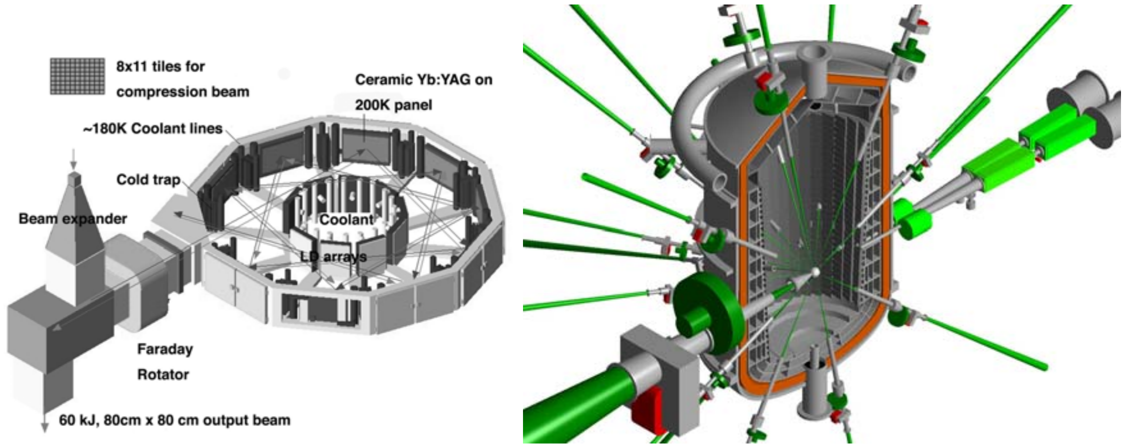
A main amplifier module is illustrated in FIG. 5(a) An active-mirror scheme, which has double functions of laser amplification and laser beam reflection, is adopted for the first time instead of the conventional disk scheme. The active mirror is an Yb:YAG ceramics disk with an anti-reflection (AR) and 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. The total electric input power for both of compression and heating lasers is roughly estimated at 156 MW including a cooler system in Table 1. The overall electrical-optical efficiency is as high as 12%. The net main amplifier volume is calculated to be about 3000 m^3, which is comparable to a reactor chamber, shown in FIG. 5(b).

Table 1 Rough estimation of powers and efficiencies for lasers.

	Implosion Laser	**Heating Laser**
Laser Power	18 MW (1.1MJ, 16 Hz)	1.6 MW (0.1MJ, 16Hz)
LD Electrical – LD Optical	60%	
LD Optical – 1ω	42%	
LD Electrical – 1ω	**25%**	
1ω – 3ω	70%	-
1ω – 2ω	-	80%
OPCPA Eff.	-	40%
Pulse Compression Efficiency	-	80%
Transportation Efficiency	90%	90%
Harmonic Generation and Transportation	**63%**	**23%**
Electric Input Power	110 MW	28 MW
Crystal Heating Power	6.6 MW	1.7MW
Cooler Electric Power	22 MW	5.7 MW
Electric Power Demands	132 MW	24 MW
Total Electric Power	166 MW	
Overall Efficiency	**12%**	

3. Reactor and system

The power plant consists of 4 module reactors powered by one laser system. One module reactor has 32 compression beams, one heating laser, and two target injectors as shown in FIG. 5(b). Important features of this chamber are 1) the focus position is vertically off set to simplify the protection mechanism of the ceiling, 2) the first wall of the reactor is a cascade flow of liquid LiPb 3). The panels of the first wall are tilted by 30 degree to avoid stagnation of evaporated vapor at the chamber center.



(a) (b)

FIG. 5 Main amplifier module for one beam out of 32 beams (a) and cross sectional view of a modular reactor. The target is emphasized by 150 for visibility.

Each beam port has a rotary shutter and an electro magnet to prevent the final optics from neutral vapor and ions, respectively. The rotary shutter consists of three disks synchronously rotating at 32 Hz, 16 Hz and 4 Hz respectively. This shutter system can be installed in not only compression beams (10 - 15 cm in the diameter) but also the heating beam (60 cm in the diameter) without conflicting neighboring beams as shown in FIG. 5(b). These shutters synchronize with the fire rate of the module reactor and opens only 4ms during one period of repetition. Beam ducts are filled with 0.1 Torr hydrogen gas to dump the neutral gas coming into the beam duct during the shutter opening. The amount of LiPb vapor coming into the beam duct was calculated to be 20 mg/sec that deposits on the inner surface of the beam duct. This deposition is not so serious because it can be easily removed by heating the beam duct to 250 C^{o} every week without disturbing system operations.

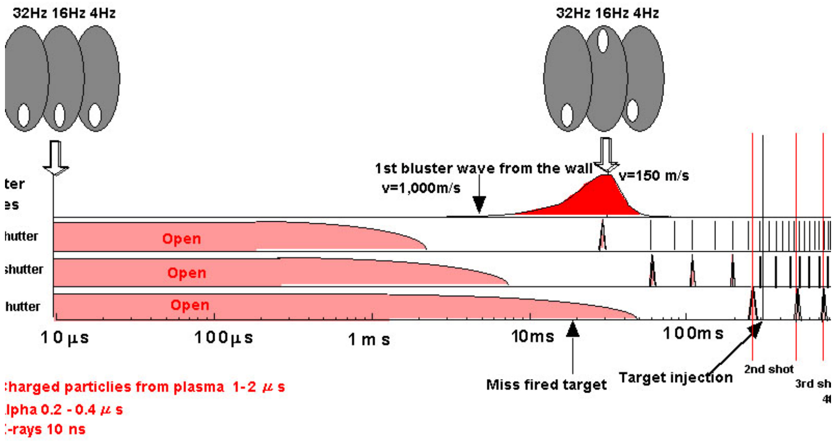
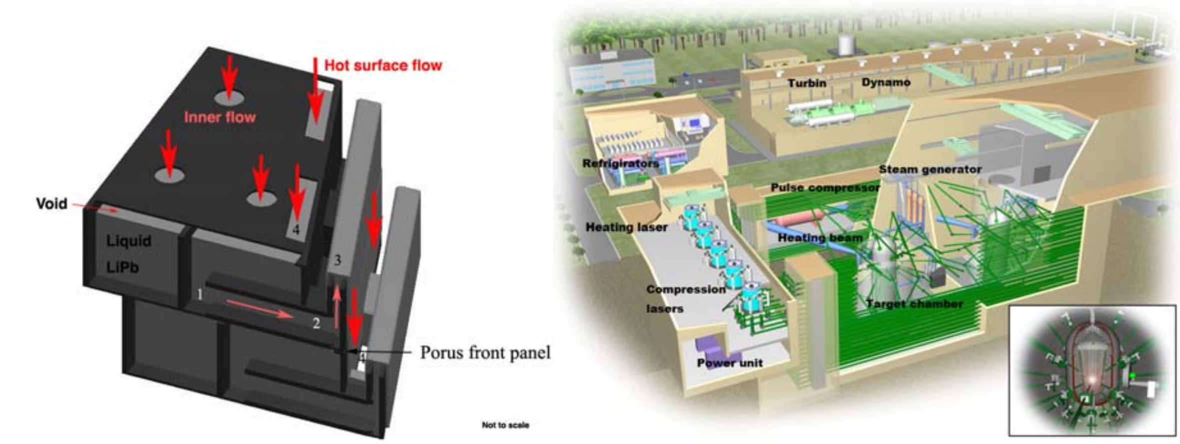


FIG.6 Timing chart of synchronized rotary shutters and neutral gas from the first wall.

The cooling system has two flows to save the electric power for recirculating pumps; one is an outer main loop with closed surface and the other is an inner flow with free surface. When the surface flow is a simple laminar flow, the surface temperature becomes too hot to evacuate the ablated vapor by cryogenic pump effect although the temperature increase per shot is only

2 degree. So, the surface flow must be a turbulent flow. We newly designed a cascade flow that mixes hot LiPb at the surface with inner cold LiPb every step by step. Figure 7(a) shows the unit cells for the surface flow in two steps. The inner cold LiPb is extracted at the point 1 and flows through a horizontal pipe to the gushy point 3. The gushed LiPb flows down along the front panel and goes into windows 4 to be mixed with inner cold LiPb. The front panel is porous metal saturated with liquid LiPb to continuously form a protective flow.

Beam ports sticking out of the liquid first wall are protected by sacrifice membranes that are formed by keeping the surface temperature lower than surrounding area. This temperature control enhances the condensation of LiPb vapor. When we assume a maintenance period of 2 years and 3mm-thick, allowable erosion, the provability for direct exposure of the front panel to plasma must be less than 10^5. This would be critical to this scheme and more detailed analysis is necessary to discuss the reliability of this reactor.



(a) (b)

FIG. 7 Cross sectional view of a cell for surface flow (a) and Birds view of the power plant KOYO-F. Size of laser system became much smaller than that for KOYO.

We have examined the design windows and the issues of the fast ignition laser fusion power plants shown in FIG. 7(b), and shown the possibility of middle sized, ~300 MWe fusion reactors, with ~200 MJ fusion pulse energy, ~4 Hz rep-rates. The specification for the power plant is summarized in Table 2

Table 2 Basic specification of KOYO-F

Net output	1200 Mwe (300MWe x 4)
Laser Energy	1.1 MJ
Target gain	165
Fusion output per pulse	200 MJ
Pulse rep-rate in reactor	4 Hz
Blanket energy multiplication	1.2
Thermal output per reactor	916 MWth
Total output at plant	3664 MWth (916 MWth x 4)
Thermal to electricity efficiency	41.5 % (LiPb temperature 500C)
Total electric output of plant	1519 MWe
Laser efficiency	11.4 % (Compression), 4.2%(heating), Total 8%(including cooling power)
Rep-rate of laser	16 Hz
Recicirculating power for laser	240 MWe (1.2 MJ x 16 Hz / 0.08) (Yb-YAG laser operating at 150 - 220K)
Total plant efficiency	1200 MWe (1519 MWe- 240 Mwe-79MWe Aux.)

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