DESIGN WINDOWS OF LASER FUSION POWER PLANTS AND CONCEPUTUAL DESIGN OF LASER-DIODE PUMPED SLAB LASER

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Abstract

An analysis of the design space available to laser fusion power plants has been carried out, in terms of design key parameters such as target gain, laser energy and laser repetition rate, the number of fusion reaction chambers, and plant size. The design windows of economically attractive laser fusion plants is identified with the constraints of key design parameters and the cost conditions. Especially, for achieving high repetition rate lasers, we have proposed and designed a diode-pumped solid-state laser driver which consists of water-cooled zig-zag path slab amplifiers.

1. INTRODUCTION

A conceptual design and economic analysis of laser fusion power plants has been carried out in the KOYO design study [1]. Through this design study, we examined the key issues which may affect the technical and economical feasibility of laser fusion power plants.

Following the KOYO design study, we developed a system design and economic evaluation code of laser fusion power plants, which can be used for parametric study on key design parameters. Based on discussing the constraints of key design parameters such as reactor pulse repetition rate (rep-rate) and laser pulse rep-rate, the design windows of laser fusion power plants, which use laser diode pumped solid state lasers are analyzed, and the requirements of key technologies are identified.

To realize economically attractive laser fusion plants, it is necessary to develop the high rep-rate and low cost lasers. For achieving high laser rep-rate, removing the heat from the laser gain medium is essentially important. One of the effective approach is a zig-zag path slab, which can be cooled on both sides with flowing water. Then we are designing a laser-diode pumped slab laser, and studying the capability and constraints to achieve high repetition laser.

2. PRINCIPAL DESIGN PARAMETERS AND DESIGN CONSTRAINTS

2.1 Principal Design Parameters and Basic Relationships

System designs of laser fusion power plants are mainly depend on key design parameters related to power balance and pulse rep-rate. In the laser fusion modular power plants, reactor module (chamber) thermal power Pct and total plant thermal power Pt are, $Pct = r_C E_L GM$, $Pt = n Pct$.

Then the power balance of laser fusion power plants is expressed as follows,

$$Pn = {}^{-}{}_{T} Pt - P_L - Pa = n\, r_C\ {}^{-}{}_{T} Ef\ GM - Pa - r_L E_L / {}^{-}{}_{D} \qquad (r_L = n\, r_C)$$

where the notations of parameters are shown as follows; G: target gain, Pt: total plant thermal power, M: blancket power gain, Pe: gross electric power, r_C: reactor pulse rep-rate, Pn: net electric power, r_L: laser rep-rate, P_L: driver input power, ${}^{-}{}_{D}$: laser efficiency , Pa : other recircurating power, ${}^{-}{}_{T}$: thermal efficiency, Pct: reactor module thermal power, E_L: laser energy, n: reactor module number.

2.2 Target Gain Curves

The target gain G can be given by simple functions of E_L in high gain areas as first ordered approximation : $G = 100\ (E_L / E_0)^{1/3}$; $G = 100$ at $E_L = E_0$ MJ

This scaling rule depends on simple physics that maximum burning fusion power is proportional to radius of pellet, while fuel heating energy (E_L) is proportional to volume of pellet.

For the central spark concept we selected rather optimistic case, $G = 150\ (E_L/4)^{1/3}$, in KOYO design study. In this study we selected for more conservative case: $G = 100\ (E_L/4)^{1/3}$.

For the fast ignitor concept as an advanced heating concept, we considered two gain curves, the upper bound and the lower bound logically: $G = 300\ (E_L/0.5)^{1/3}$ and $G = 100\ (E_L/0.5)^{1/3}$.

2.3. Constraints of Key Design Parameters

The design space available to laser fusion power plants is obtained by the relationships and the constraints of the principal design parameters logically, although there are many uncertainties on the key physics and technologies. Table 1. shows the key design parameters and the constraints.

TABLE1. PRINCIPAL DESIGN PARAMETERS AND CONSTRAINTS

Key design parameters	Design space	Design constraints
Target gain @	central spark concept	-beam number ~100
G	100~150 at 1~6 MJ	-irradiation nonuniformity ~ 0.5%
	fast ignitor concept	-physics uncertainties
	100~500 at 0.5~2 MJ	-short pulse laser energy
Reactor fusion pulse energy	central spark concept	-first wall ablation and evacuation time
$Ef = G\ E_L$	100~1000 MJ	
	fast ignitor concept	
	50~1000 MJ	
reactor pulse rep-rate	liquid wall concept	-evacuation condition(laser beam propagation and pellet injection)
r_C	1~10 Hz	
	dry wall concept	-chamber radius R=5~10
	5~30 Hz	-beam propagation in high Z gass
reactor chamber thermal power		-adequate reactor power size
$Pct = r_C\ Ef\ M$	500~5000 Mwth	-neutron wall loading, chamber radius
		-final optics damage and maintenance
Laser energy E_L	1~6 MJ	-laser cost (LD cost and laser diode pumping power)
laser efficiency $^{-}{}_{D}$	8~12 % (DPSSL)	-product of efficiency of many components
laser pulse rep-rate r_L	3~30 Hz	-cooling medium and compensation of thermal effect
		-life time of key laser components
Reactor module number n	1~10	-beam switching
		-layout of laser beam and final optics

3. COST ESTIMATION AND DESIGN WINDOW ANALYSIS

The economic modeling for laser fusion power plants has been developed in KOYO design study, which is aimed to compare the economic characteristic of various type of power plants with the common calculation methodology and cost data base. In this model the cost of equipments are estimated by calculating the mass of components and unit costs, and using cost scaling relationships. which are based on the COST MODEL developed by the IFTEC and SEA, for SPWR(modular type PWR, 1988) and for TOKAMAK reactor(1991).[1]

The cost scaling relationships on major facilities are described by using principal design parameters such as in TABLE1.

Fig. 1 shows the total direct capital cost and the laser cost versus laser energy for n numbers 750MWe module plants. The laser cost contribution to total plant cost can be highly reduced in modular power plants, becouse of using a laser as common facility for multi reactors. Fig. 2 shows the cost of electricity (COE) versus laser energy for one reactor module plants and 4 reactor module plants with the constraints of reactor pulse rep-rate r_C.

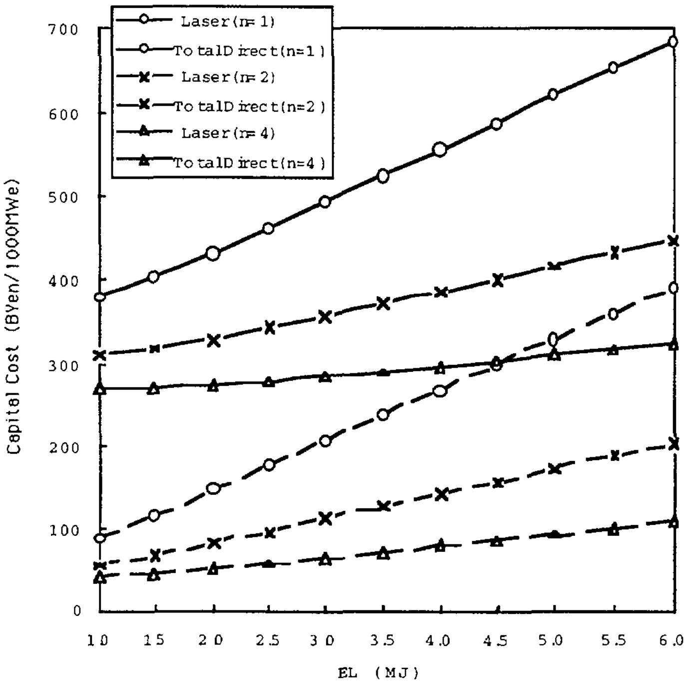

Fig. 1 Total direct capital cost and laser cost versus laser energy for 750MWe -n Mwe modular power plants (reactor module number n=1, 2, 4)

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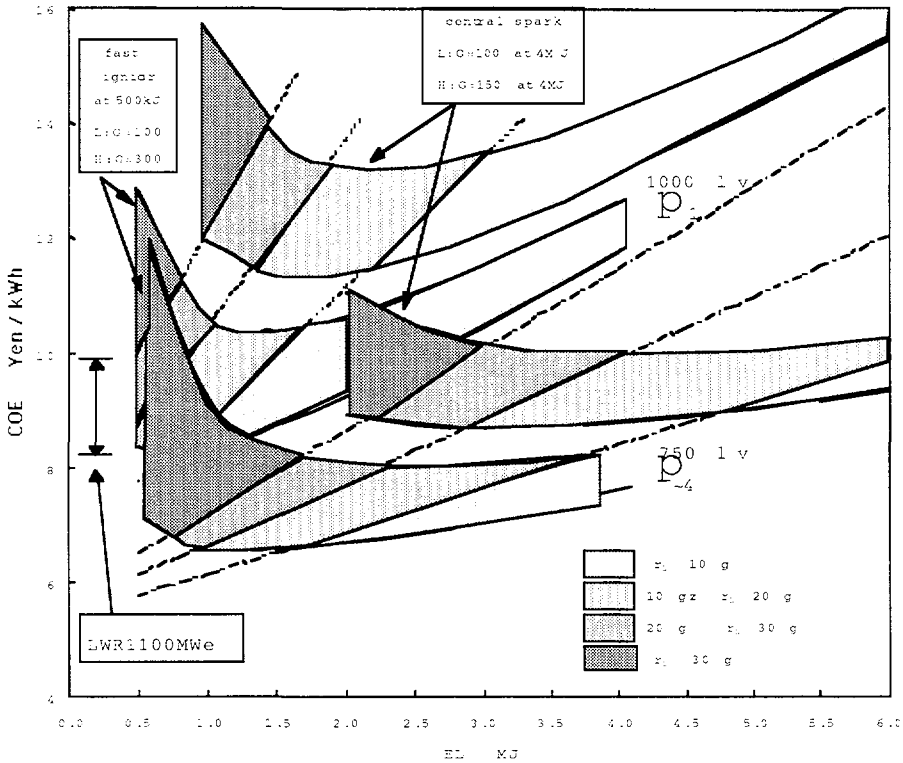

Fig. 3 Design windows with the constraints of laser pulse rep-rate r_L ,for 4 target gain curves (COE versus laser energy for 1000MWe -1 and 750MWe -4 MWe modular power plants)

The design windows are shown for the four cases of pellet gain curve, and the two cases of the combination of net electric power and reactor module number in FIG.3. COE is shown as a function of E_L with the limitting condition of r_C and r_L . The gain curves for the conventional central spark model and the fast ignitor model are given as a function of E_L.

The major limitting factor of design windows is r_C in the case of n=1, and r_L in the case of n=4. It is noticed that in the case of small laser energy and small fusion pulse output, the design windows are strongly restricted by laser pulse rep-rate or reactor pulse rep-rate. For the small fusion pulse output and high reactor rep-rate, dry wall concept is suggested as a powerful candidate .

4. CONCEPUTUAL DESIGN OF LASER-DIODE PUMPED SLAB LASER

For the high laser rep-rate, a crucial point is to remove the heat in the laser gain medium. Zig-zag path slab has an advantage that the laser beam does not pass through the cooling medium as it propagates by means of total internal reflections. Using this advantage, the slab is cooled on both sides with flowing water having high cooling capability.

Fig. 4 shows the schematic design of a driver module for power plants. This module consists of 15 beamlets and each beamlet has a double 4-pass system as it plays the role of both pre-amplifier (4-pass system) and main amplifier (4-pass system), which results in a compact system.

Each beamlet is amplified from 10 μ J input energy to 700 J of blue output energy. The module has, therefore, 10 kJ total blue output energy, and operates at 12 Hz with 10.4 % overall efficiency. Thermal effects such as focusing and birefringence are compensated by using a SBS (Stimulated Brillouin Scattering) phase conjugation mirror and a 45 degree Faraday rotator, respectively. It is favorable that there is no large scale Pockels cell in the module.

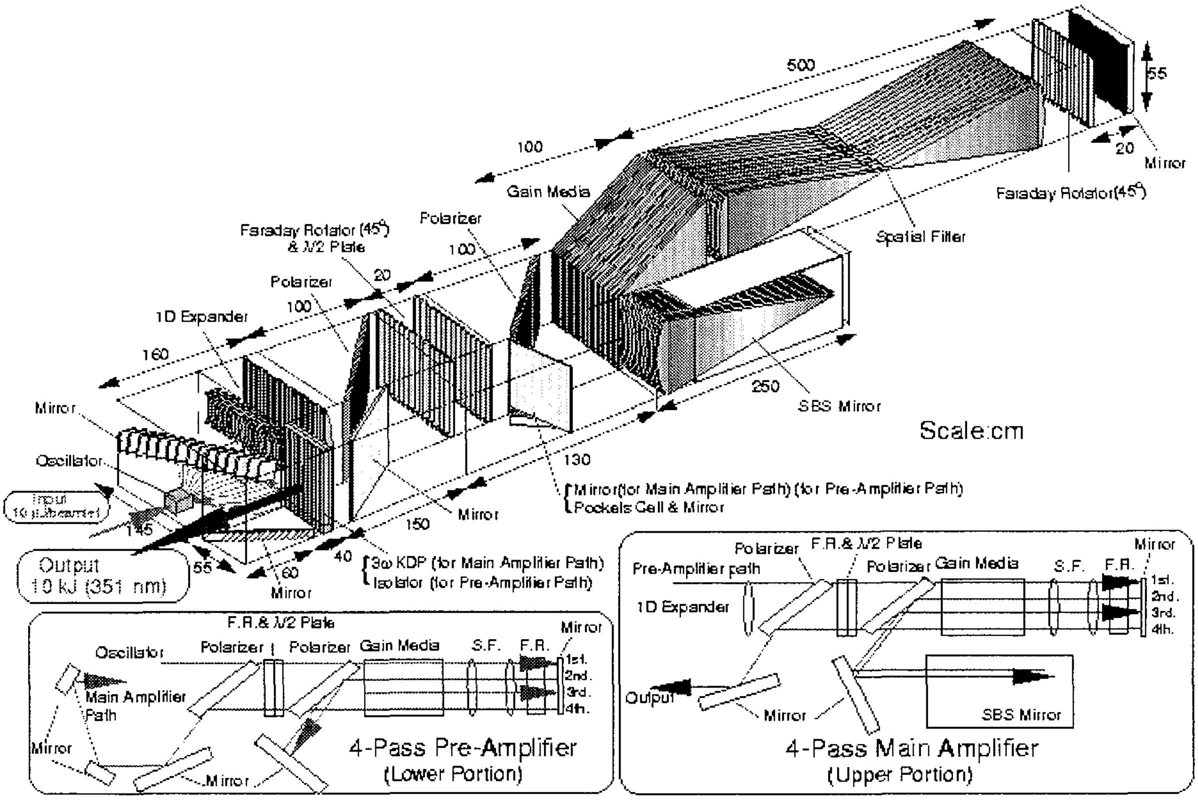

FIG. 4 Schematic design of the module of laser-diode pumped zig-zag slab laser, which has 10kJ total blue laser output at 12Hz rep-rate.

5. CONCLUSION

We can design attractive laser fusion power plants, through the flexibility of key design parameters, especially in modular power plants. The design windows are strongly restricted by the reactor pulse rep-rate in single reactor module plants, and by the laser rep-rate in modular plants. Then the key technolpgies related to high rep-rate lasers, and high rep-rate chamber concepts should be developed.

REFERENCES

[1] Y.Kozaki et al., Proc.Seventh Int.Conf.on Emerging Nuclear Energy Systems, Makuhari, (1993)
[2] K. Naito, M. Yamanaka, M. Nakatsuka, T. Kanabe, K. Mima, C. Yamanaka, and S.Nakai: Jpn.J.Appl.Phys. 31, (1992) 259.

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