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Fast-ignition Laser Reactor Design With a Dry Wall and a High Repetition Laser

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Fast Track in Laser Fusion Development

Design Concept is based on
@ Fast ignition
@ Dry wall
@ High repetition laser

↓

@ Low laser energy : P_laser = 0.3~0.4MJ
with a pellet gain G = 100~150

@ Low wall loading : P_wall = 2~3 J/cm2/shot
with R = 5 ~ 6 m chamber

@ High repetition laser : frequency = 20 ~ 40 Hz

Fast Ignition vs Central Ignition

Central ignition	Fast ignition
Isobaric	isochoric

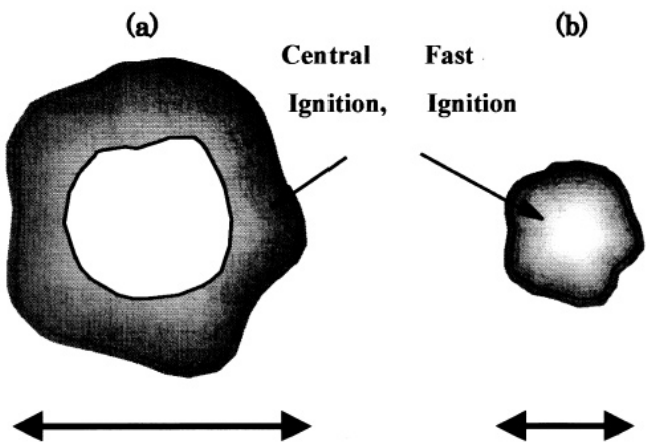


Fig. 2 Comparison of the central ignition isobaric core plasma structure (a) and the fast ignition isochoric core plasma structure (b).

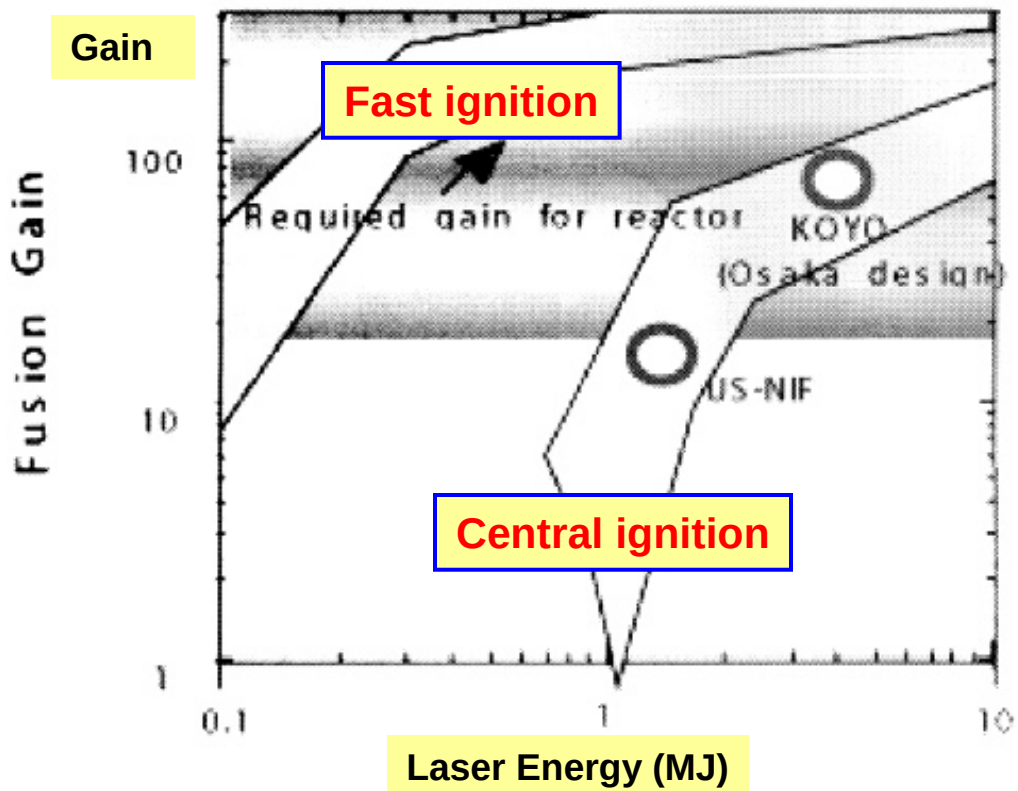


Fig. 3 Laser energy dependents of fusion gains for fast ignition and central ignition.

A volume in Fast ignition is 1/5~1/10 times as small as that in Central ignition.

Dry Wall vs. Wetted Wall

One of critical issues in reactor design for ICF plants is a high heat load pulse on the first wall.

Dilemma with liquid metal wall

Using a liquid metal wall design will allow a higher heat load pulse than that in a dry wall design.

However, the evaporation of liquid metal on the wall deteriorates a vacuum condition in the chamber, and the repetition rate of laser pulse is restricted (< a few Hz).

A lower fusion power in a shot with a lower repetition rate will results in a lower fusion output and a higher cost of electricity.

A noble solution to remove this restriction is to place multiple chambers in a plant.

➔ **Koyo-Fast reactor design at OSAKA University**

But such multi-chamber concept might require complicated laser transmission lines. This fact should increase the construction cost.

Dilemma with dry wall

To choose a solid wall will remove the difficulty in the repetition rate, but a heat load capacity of the solid wall is much less than that of the liquid metal wall, and the chamber size and the cost will also increase.

Such dilemma is an essential difficulty in the design of fast ignition ICF reactors.

In our present study, we have considered to make the most merit of the fast ignition by

minimizing the single fusion pulse E_f

and the size of solid wall chamber R

and

maximizing the laser repetition rate f_L

This is a new challenging path against the above dilemma.

System Code Development

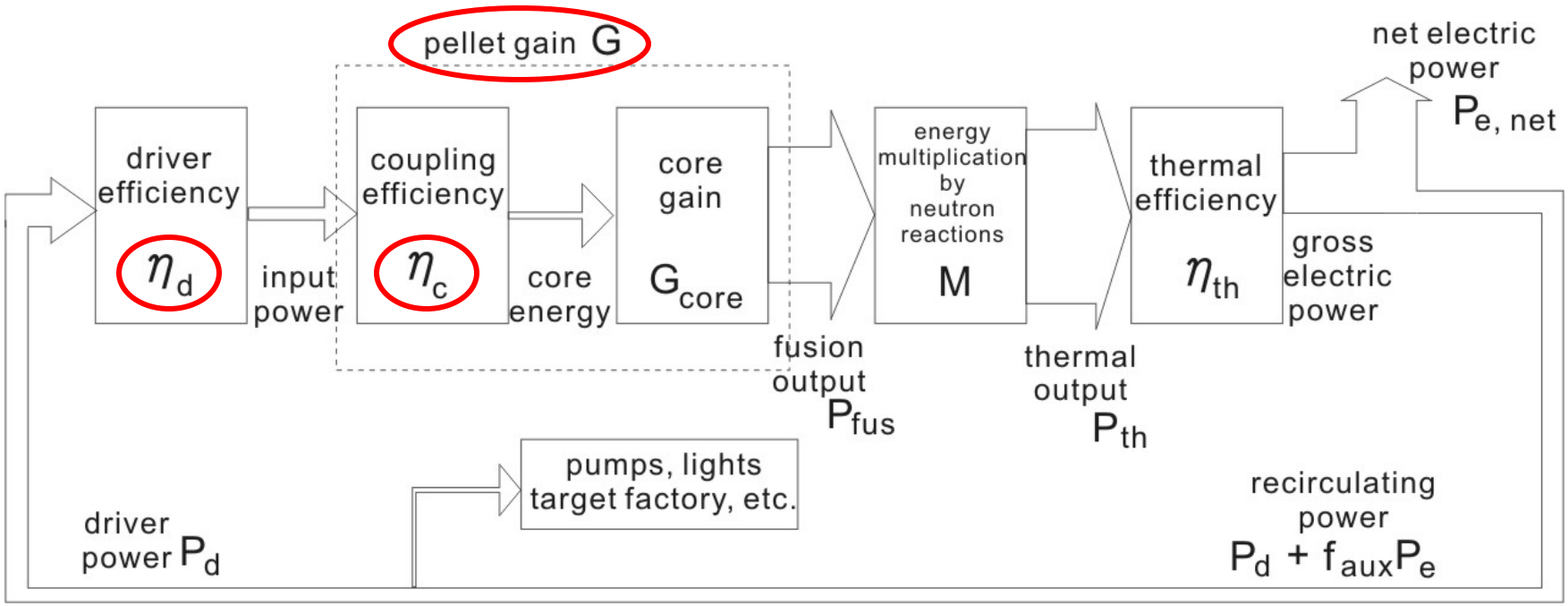
- We have developed a simple system code which can evaluate the reactor performance including the cost estimation.
- The most critical point of a laser fusion reactor design is the estimation of target gain.
- Considering that the code is applied to a sensitivity analysis, we have adopted a simple local energy balance equation including the effect of the range of fusion-born fast ions in the fuel*1

$$Q_{\mathrm{fus}} - Q_{\mathrm{rad}} - Q_{\mathrm{cond}} - Q_{\mathrm{mech}} > 0$$

for determining self-ignition condition.

*1 S.Atzeni, Jpn. J. Appl. Phys. **34** (1995) 1980.

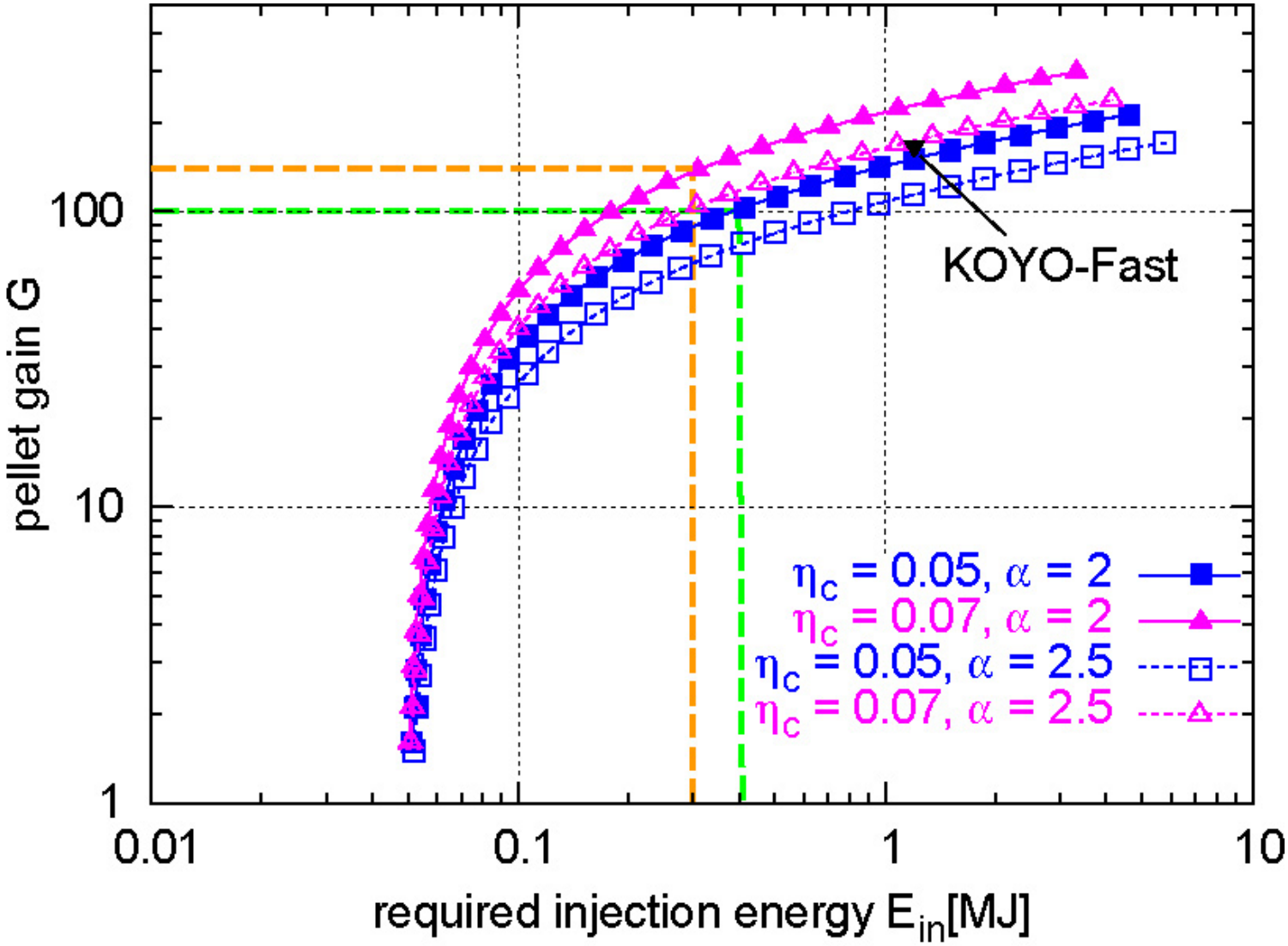
IFE Power Flow



$$G_{core} = \frac{E_{fus}}{E_{in}} = \frac{\frac{n_{fuel}}{2} Q_{DT} V_{fuel} f_b}{\underbrace{\frac{3}{5}\alpha\varepsilon_F n_{fuel} V_{fuel}}_{\text{implosion}} + \underbrace{n_s k_B T_s V_s}_{\text{heating}}}$$

α : isentrope, ε_F : Fermi Energy $\left(= \frac{\hbar}{2m_e}\left(3\pi^2 n_e\right)^{\frac{3}{2}}\right)$, f_b : burn fraction $\left(= \frac{\rho_{fuel} r_{fuel}}{\rho_{fuel} r_{fuel} + \beta(T)}\right)$, $\beta(T) = \frac{8 m_i c_s}{<\sigma v>}$

Gain curve for various implosion parameters



- We can find that the design point of the target gain $G \geq 100$ with the injection energy of 400kJ under a relatively conservative condition of $\alpha = 2, \eta_c = 5\%,$ $\eta_h = 20\%$.

- If $\eta_c = 7\%$ is allowed, G =135 can be achieved with the injection energy of 300kJ (implosion 250kJ, heating 50kJ).

- The minimum fusion pulse energy with acceptable target gain is 40MJ.
- In this case, we can design the solid wall chamber with R =5.6 m if pulse heat load limit of 2J/cm^2 is allowed.

Cost Estimation

- Cost estimation is carried out by the empirical scaling laws based on the result of magnetic confinement fusion reactor design study, except for laser system.

- The estimation of laser system cost is referred to that of KOYO reactor, designed by Institute of Laser Engineering, Osaka University.

	Design by UT/CRIEPI		Koyo-fast
Chamber	Dry Wall Single chamber	Liquid wall 4 chambers	Liquid wall 4 chambers
Breeder	Solid breeder	Liquid breeder	Liquid breeder
Electric Power	0.4 GWe	0.4 GWe	1.2 GWe
Laser repetition	30 Hz	16 Hz	16 Hz

Tab.1 main parameters of our reference design

	UT/CRIEPI design Dry wall/Solid Breeder (normal/advanced)	UT/CRIEPI design Liquid wall	KOYO-Fast
chamber radius[m]	5.75	1.8 (minimum)	*3.0 (minimum)*
implosion efficiency η_c	0.05 / **0.07**	0.05	*0.05*
heating efficiency η_h	0.2	0.2	*0.2*
input energy[MJ]	0.4 / **0.3**	0.6	*1.2*
target gain	102 / **135**	120	*167*
fusion pulse [MJ]	40	72.5	*200*
pulse heat load [J/cm^2]	2.0	36	*36*
repetition rate [Hz]	30	16	*16*
thermal output[MW]	1378	1345(336x4)	*3664(916x4)*
laser recirculating power [MW]	153 / **122**	118	*240*
electric output [MW]	367 / **400**	400	*1200*
plant construction cost [B\]	320 / **313**	295	*(523)*[*2]
COE [\/kWh]	24.3/ **21.8**	18.9	*(10.5)* [*2]

Tab. 2 cost comparison between our design and liquid wall reactor (Unit: B\)

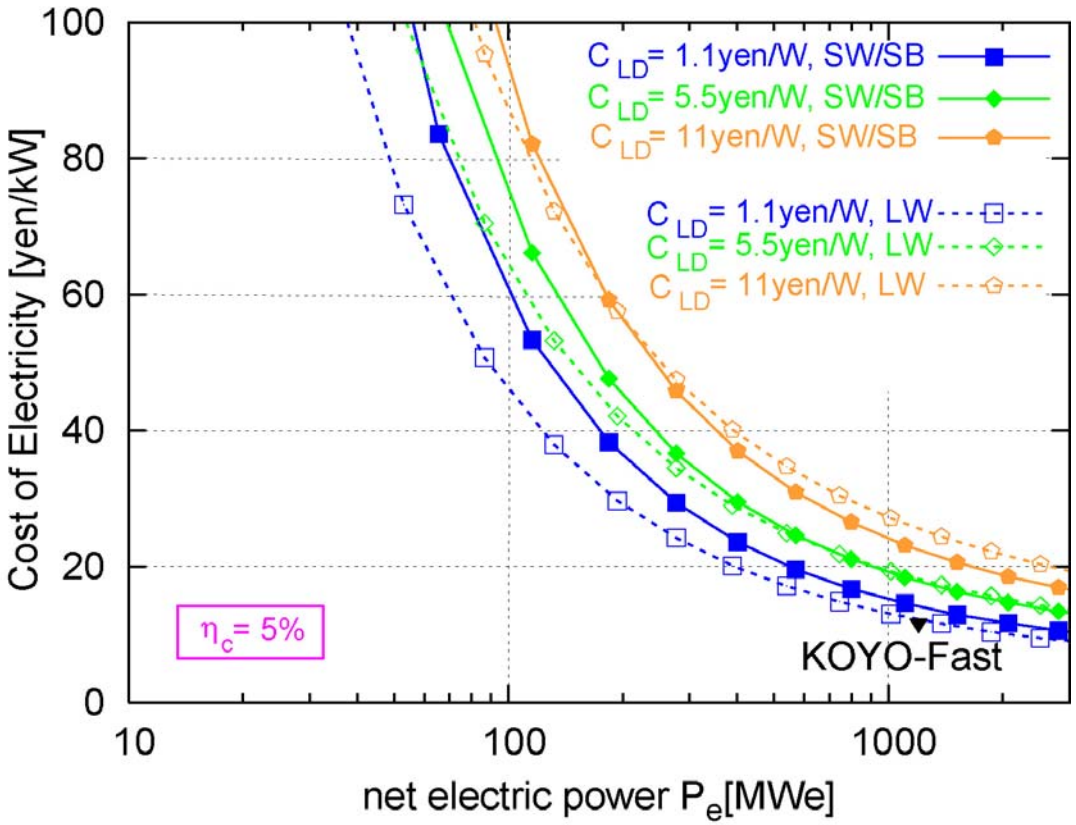
	Dry Wall Solid Breeder		Wetted Wall
chamber radius [m]	5.6		1.8
thermal power [MWth]	1379		1345 (336×4)
laser energy [MJ]	5.1		7.4
buildings and facilities	37.8		34.2
first wall, blanket and vessel	60.0		17.8
turbine and electric plant equip.	70.1		79.7
other plant equipments (heat transport, tritium recovery, target injection, etc.)	68.7		74.5
laser system (LD components)	24.0 (19.0)		34.8 (27.7)
total direct engineering cost	260.6		241.0
owner's cost	26.0		24.1
interest during construction	32.8		30.4
total plant capital cost	319.5		295.5

Tab. 3 comparison of cost of electricity (Unit: \/kWh)

	Dry wall Solid breeder		Wetted wall Liquid breeder
capital*1	14.53		12.34
operation & maintenance*2	5.16		4.28
fueling*3	4.71		2.30
COE	24.40		18.92

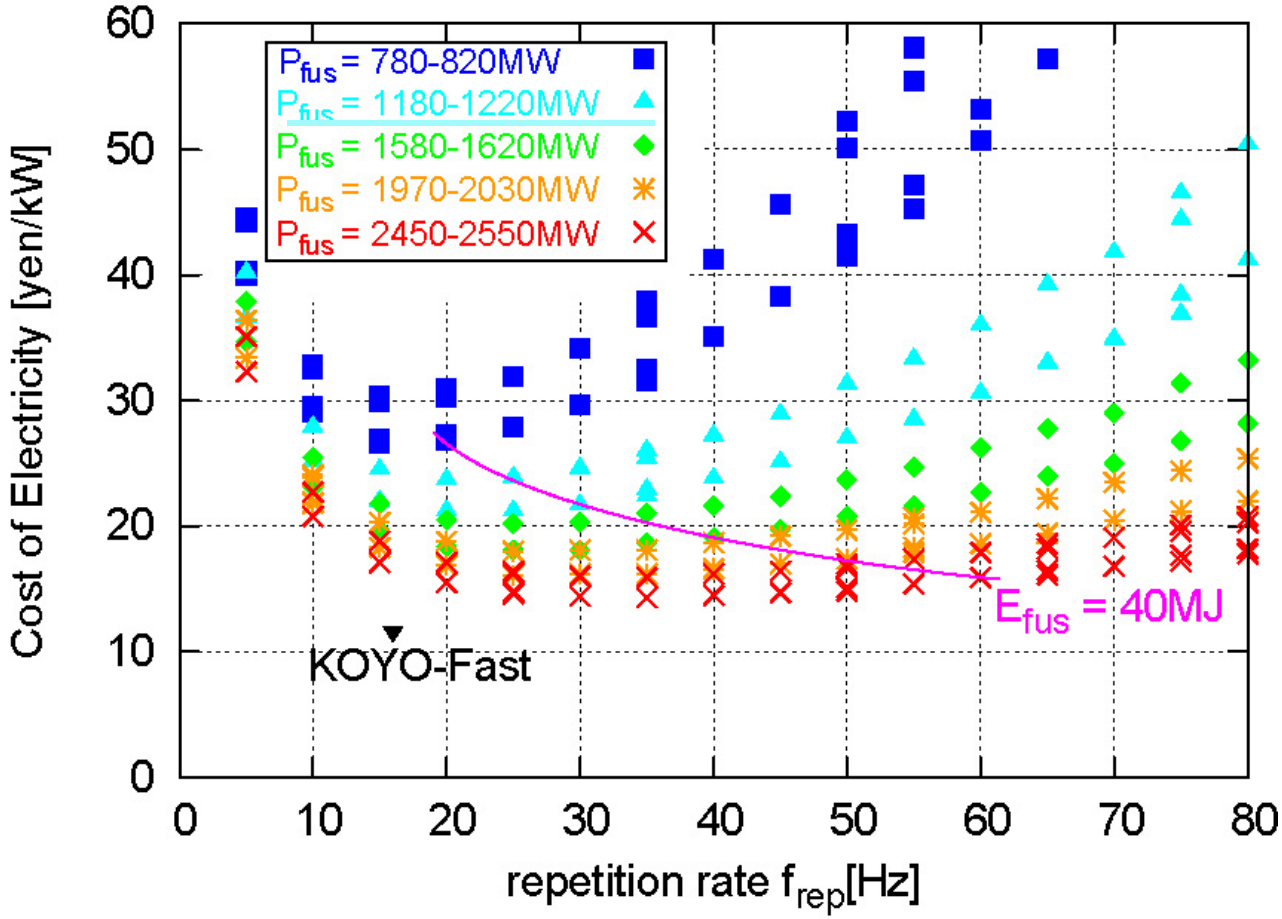
*1 FCR (Fixed Charge Rate) is 10.97%
*2 including periodical replacement cost of blanket and laser final optics
*3 assuming that the target fabrication cost is \16 in spite of the target size

COE vs. Net Electric Power
(Solid Wall/Solid Breeder and Liquid wall cases)



Three cases for the cost of LD laser (1.1 Yen/W, 5.5 Yen/W and 11 Yen/W) are assumed.

Cost of electricity on laser repetition rate



- According to the result of parameter survey, the optimum laser repetition rate is around 30Hz with a fixed fusion output from the viewpoint of the plant cost.
- We select the design point of Pfus ~ 1.2 GW (40MJ×30Hz) for our reference design.

- Owing to the small output power, the cost of electricity (COE) of the reference design is much higher than that of current commercial plants.

- However, it is remarkable that the plant construction cost of the reference design is lower than the value assumed in the design of a typical fusion commercial plant.

⇨ This design point can be located as a first-step reactor of the laser fusion development, and it provides the design possibility of a small power commercial fusion plant, which have been considered to be difficult in the past.

- Compared with a liquid wall reactor with the same output power, both the plant construction cost and the COE of the reference design is about 20% higher.

- The difference in cost arises from high mass unit cost of the solid breeder material and high fueling cost due to the high repetition rate of the pellet.

- The cost increase due to the chamber size increase with the adoption of a solid wall is canceled out by the cost reduction of the laser system with the decrease of the laser power.

Design Possibility of a 1GWe-class Dry Wall Plant

- We also examined the design possibility of a large power, i.e., a 1GW-class commercial plant with a solid wall chamber.

- Typical parameters are as follows;

  R = 8.6 m,

  P_laser = 730 kJ (680 kJ for implosion and 50 kJ for heating)

  P_fusion = 94 MJ/shot (3270 MWth)

  COE = 12 ~ 14 Yen/kWh

  (ref. Wetted wall design Koyo-Fast is estimated to be ~ 10.5 Yen/kWh in our system code.)

- The COE of a solid wall/solid breeder reactor is not so much higher than that of a liquid wall/liquid breeder reactor.

Conclusion

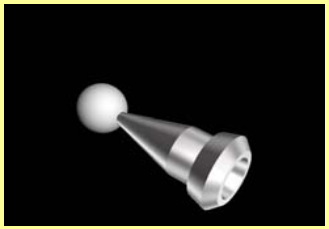
- We have developed a system code for designing a laser fusion reactor and examined the design possibility of the reactor with solid wall chamber.

- A medium size plant (the chamber radius R = 5.6 m and electric output Pe = 400 MWe) can be designed with a solid wall chamber and a laser of which repetition rate is 30Hz. This design point can be located as the first-step reactor in the laser fusion development, and it has the possibility of realizing low power commercial fusion plant.

- The cost difference in the solid wall reactor and liquid wall one arises from not only the difference in chamber size but also the difference in the cost of breeder material and pellet manufacturing.

- A solid wall reactor would be economically competitive with a liquid wall reactor with the same output power. In the case a solid wall reactor give a significant impact on the laser fusion development by its easiness in the construction and the operation.

Critical issues



1) Dry wall design will not allow us to use the so-called 'Cone target' with metal cone for ignition laser. The fast ignition with no cone may impose a critical difficulty.

2) Feasibility of 30 Hz power laser, as well as 30 Hz injection of targets.

3) Even with 2 J/cm^2, the pulse load on the first wall is still very severe for the first wall material.
Some new materials, like tungsten carpet(1) or tungsten form(2) , will be required.

4) Cost of Electricity of such moderate output (~400 MWe) reactor.

(1)A. R. Raffray, L. A. El-Guebaly, G. Federici, D. Haynes, F. Najmabadi, D. Petti, and the ARIES-IFE Team, Fusion Science & Technology 46 417-437, (2004).
(2)M Andersen, S. Sharafat and N. Ghoniem, 'Thermo-Mechanical Analysis of a Micro-Engineered Tungsten-Foam Armored IFE FW', in 7th Int. Symp. Fus. Nucl. Technol. (ISFNT-7) S2-05-O-02, Tokyo (2006)