US/Japan Workshop on Power Plant Studies
April 6-7, 2002, San Diego

Design Windows and Roadmaps for Laser Fusion Reactors

Yasuji Kozaki

Institute of Laser Engineering, Osaka University

Outline

1. Design windows for attractive laser fusion reactor
2. Critical issues
3. Roadmaps

INTRODUCTION

- Based on the recent progress of implosion physics and diode pumped solid-state laser, KOYO design study has been carried out as a joint project of universities, industries, and international collaborations.

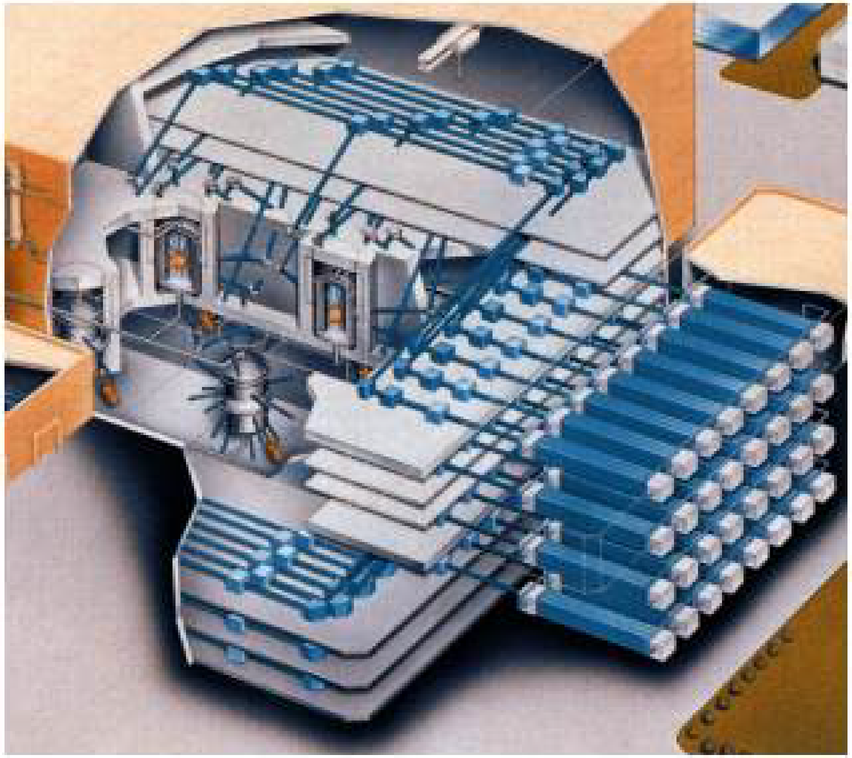
- Following the KOYO design study Systems Analysis of laser fusion program has been conducted by the Committee on Laser Fusion Research Strategy (chair Y.Kozaki) organized in the ICF Forum.
- A network analysis technique PERT and GERT (Graphical Evaluation and Review Technique) , which was applied for TOKAMAK program by Sekiguchi committee organized by Institute for Future Technology in 1983 has been applied for evaluating the IFE research program in a similar way.

- We are now investigating the roadmaps of a laser fusion research program and new reactor concepts with considering the recent progress of the fast ignition physics, under the Committee on Laser Fusion Roadmap (chair K.Tomabechi, vicechair Y.Kozaki) organized in the IFE Forum.

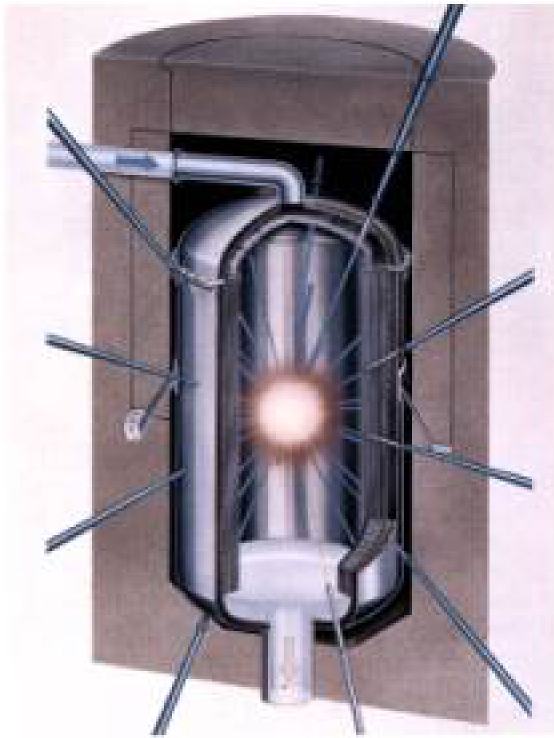
Characteristics of laser fusion power plnts

ILE OSAKA

1． Separabillity of major system and high potential for modular plants
2． Pulse power and pulse repetition plants
3． Potential for small size plants, simple reactors



Laser fusion power plant KOYO
4 reactor modules (700 MWe x 4)



Liquid wall reactor modules

Conditions of economically attractive fusion plants

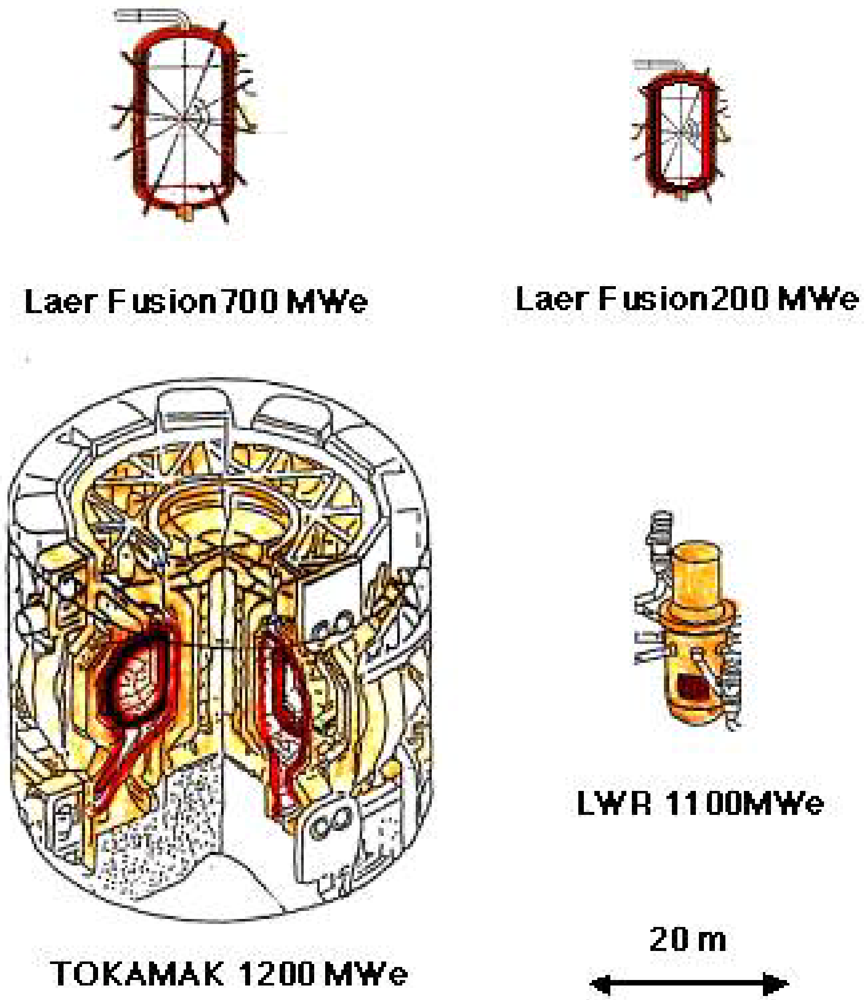
ILE OSAKA

IFE (Laser)

Fusion gain G ⇨ laser energy
power balance $\eta G \geqq 10$
⇨ laser cost
pulsed operation ⇨ pulse rep-rate
geometry ⇨ separability
⇨ final optics

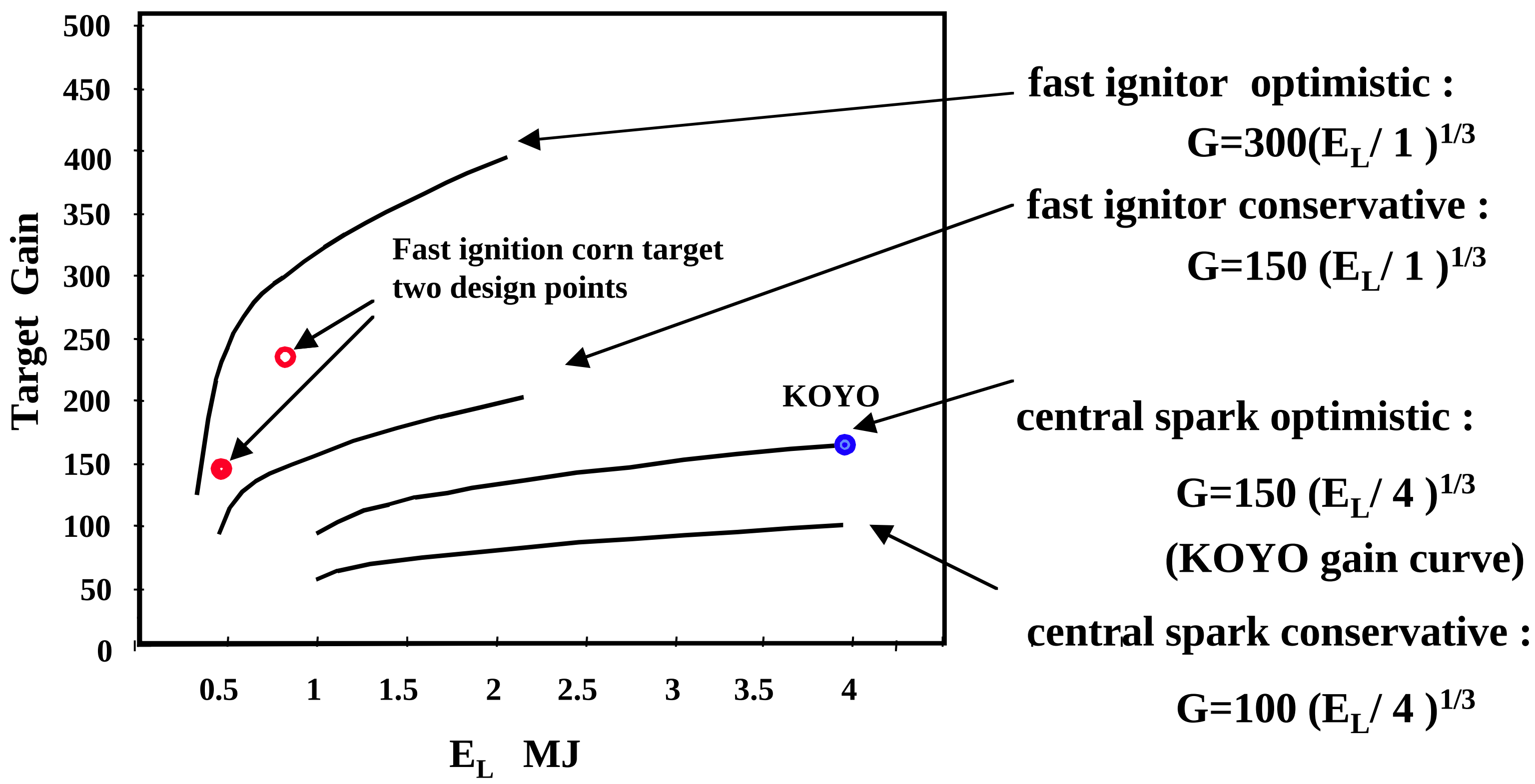
MFE (DT)

plasma β ⇨ magnet cost
neutron wall loading
⇨ reactor size
geometry ⇨ complex
⇨ maintainability



[Comparison of reactor size]

Gain curves for central spark and fast ignition



- Target gain G can be given by simple functions of $E_L^{1/3}$ in high gain region.

-Because maximum burning fusion power is proportional to radius of pellet, while fuel heating energy E_L is proportional to volume of pellet.

COE of single and multi module plants with r_c constraints

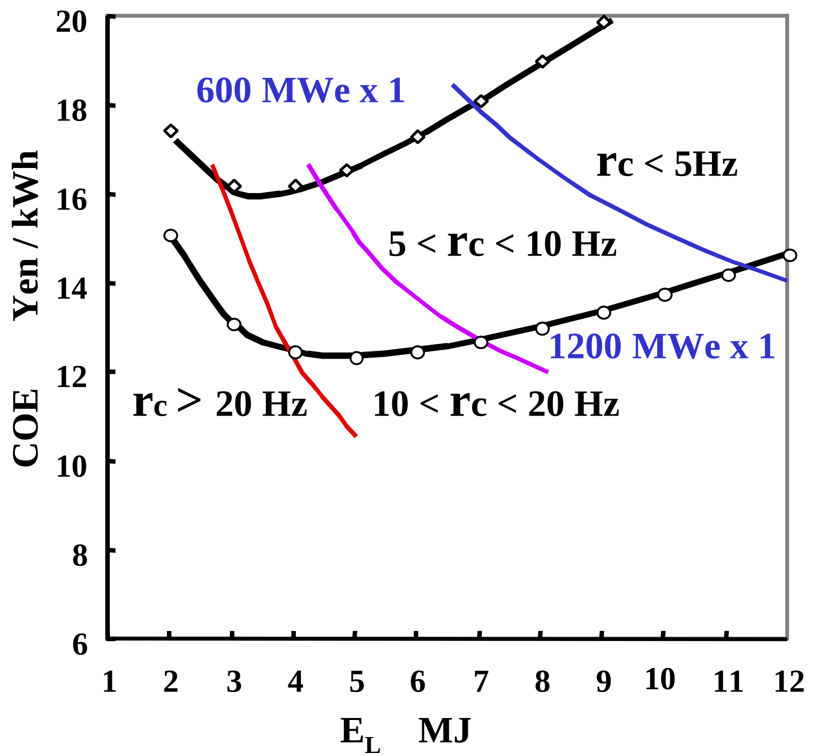


Fig. (1) COE of single reactor plants

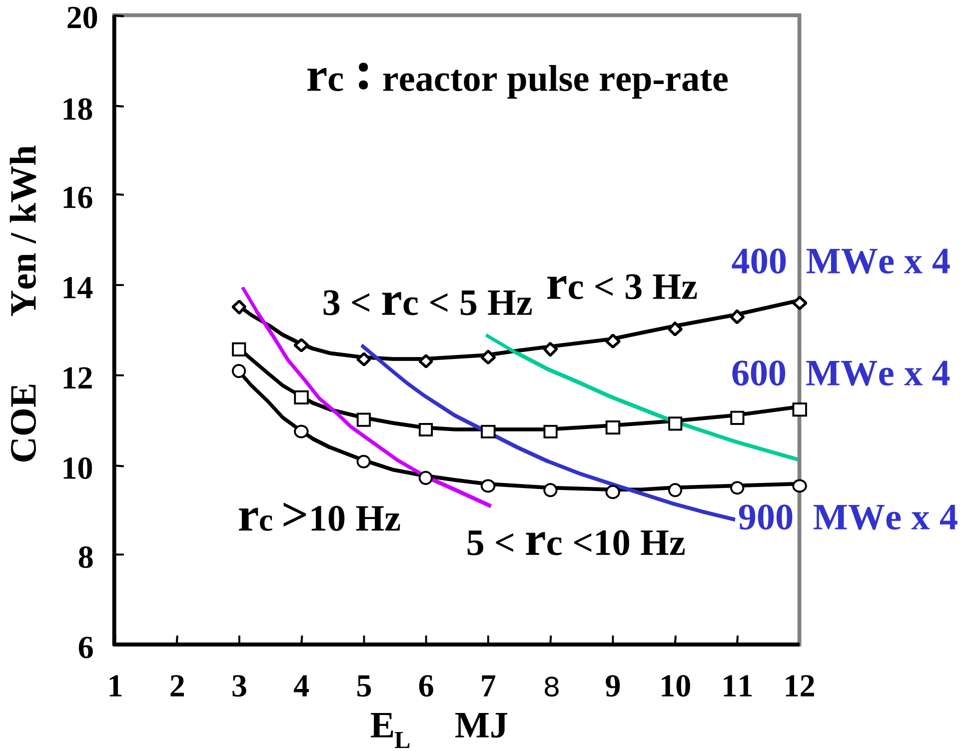
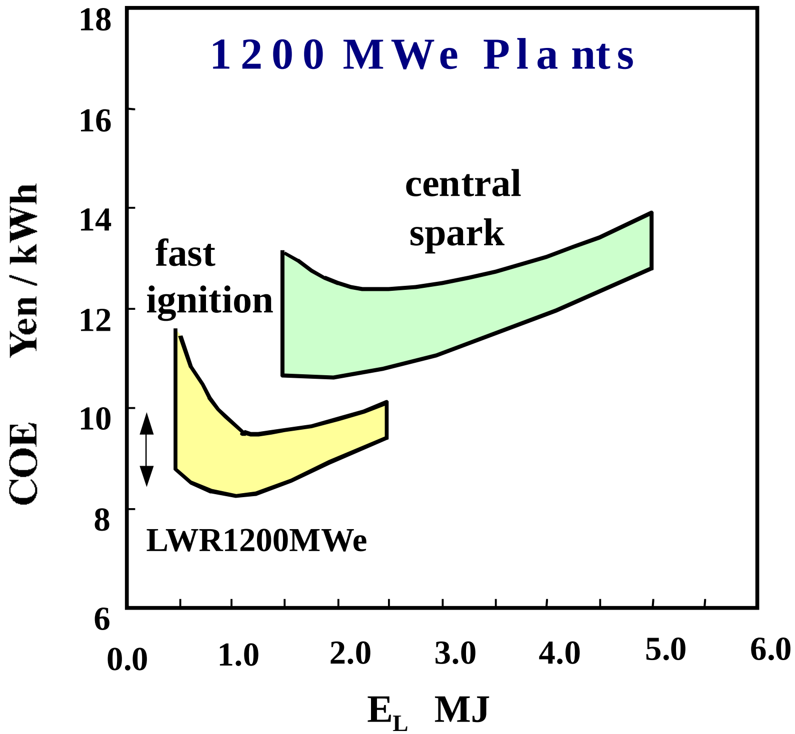


Fig.2(2) COE of 4 module plants

- Multi reactor module plants can be optimized in rather low r_c (reactor pulse rep- rate), 3~5Hz.
- While single reactor module plants are optimized in higher rep-rate, 10~20Hz. (Gain curve: central spark conservative case, LD unit cost: 3.1Yen/W)

COE Sensitivity to Target Gain Curve



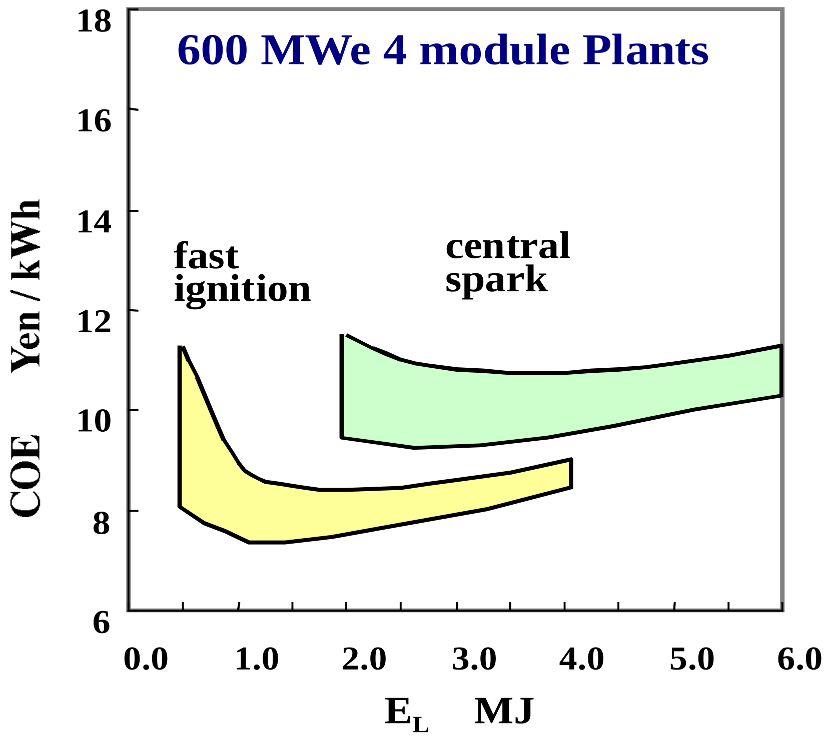


Fig.1(1) COE of 1200 MWe Plants

Fig.1(2) COE of 4 x 600 MWe Plants

Gain Curves	Central Spark	upper line	: $G = 100 (E_L MJ / 4)^{1/3}$
		lower line	: $G = 150 (E_L MJ / 4)^{1/3}$
	Fast Ignition	upper line	: $G = 150 (E_L MJ / 1)^{1/3}$
		lower line	: $G = 300 (E_L MJ / 1)^{1/3}$

LD Cost : 3.1 yens / W

COE Sensitivity to Laser Cost

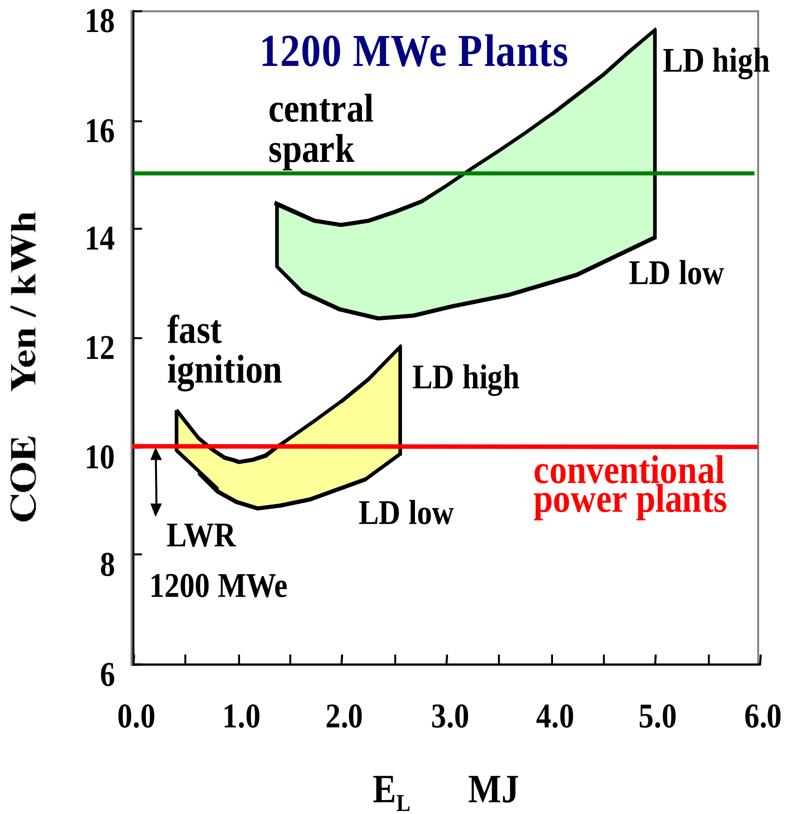


Fig.2(3) COE of 1200 MWe plants

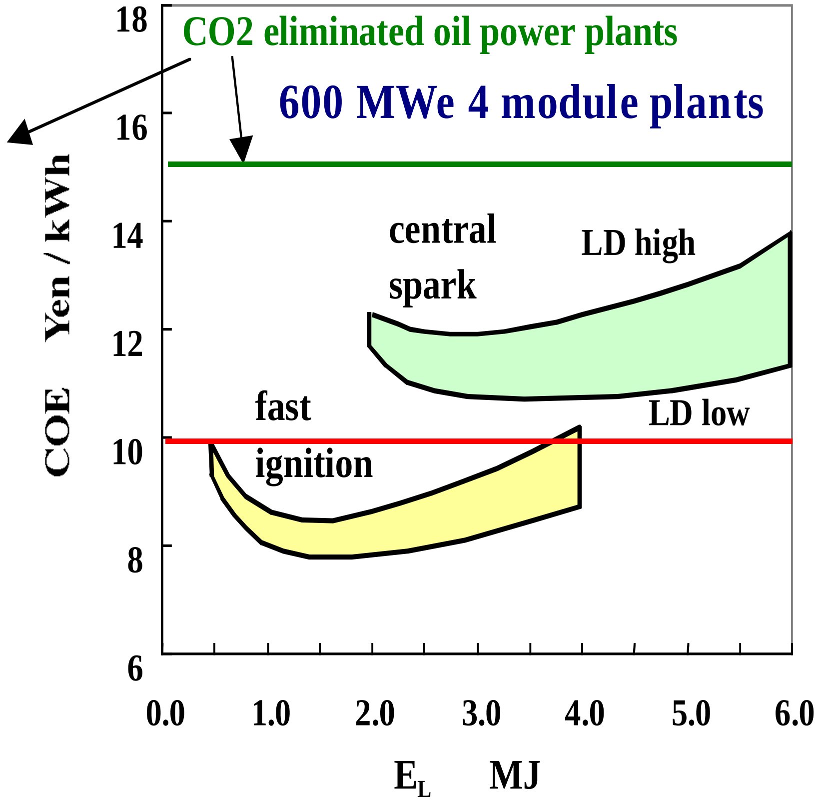


Fig.2(4) COE of 600 MWe x 4 plants

LD Cost : 3.1~6.2 yens / W , Gain curves are conservative cases :
Central Spark $G=100\ (E_L MJ/4)^{1/3}$; Fast Ignition $G=200\ (E_L MJ/1)^{1/3}$

- LD unit cost of 3 yens / W is required to compete with conventional power plants in central spark modular plants, and even if LD cost of more than 6 yens / W can compete with the fossil fuel power plants with CO2 eliminated .

Table Design windows of laser fusion modular plants, pulse energies, pulse rep-rates, and output power

	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)	100	20	3	25	mini size
				10	80	small size plant
	0.4 (ignitor 0.1)	150	60	4 (24)	100	100 × 6 600 MWe
	0.8 (ignitor 0.1)	250 KOYO Fast	200	3 (15)	240	240 × 5 1200 MWe
Central spark	2	100	200	3 (15)	240	240 × 5 1200 MWe
	4	100 ~ 150 (KOYO)	400 ~ 600	~3 (6)	~ 600	600 × 2 1200 MWe

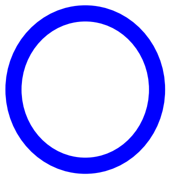
Table 2 Key design parameters, constraints, and critical issues

Key design parameters	Design windows	Design constraints and issues
Target gain G	central spark concepts 100~150 at 1~4 MJ fast ignition concepts 100~300 at 0.2~1 MJ	-beam number ~90 -irradiation nonuniformity ~0.3 % -required ignitor laser energy ~100 kJ -ignitor timing and focusing (~50 ps, ~50 μm)
Fusion pulse energy $Ef = G E_L$	central spark concepts 100~600 MJ fast ignition concepts 20~300 MJ	-first wall protection -for liquid wall: ablation and evacuation -for solid wall: charged particles intensities
Reactor pulse rep-rate r_C	liquid wall concepts 3~10 Hz dry wall concepts 3~20 Hz	-evacuation time <300 ms (conditions for laser beam propagation and pellet injection) -chamber radius R< 5~10m -beam propagation in high Z gas
Reactor thermal power $Pct = r_C\ Ef\ M$	100~4000 MWth	-adequate reactor power size -neutron wall loading, chamber radius -final optics damage and maintenance
Laser energy E_L laser efficiency η_D laser pulse rep-rate r_L	0.5~4 MJ 8~12 % (DPSSL) 3~30 Hz	-laser cost (especially laser diode cost) -product of efficiency of many components -cooling medium, thermal effect compensation -life time of key laser components
Reactor module number n	1~10	-beam switching -layout of laser beam and final optics

Corn target size and mass

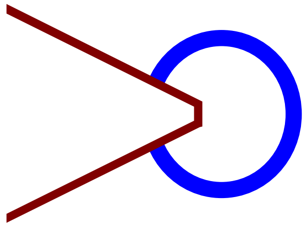
- considering protection of chamber wall and optics -

r = 2 mm
M(fuel) = 2 mg

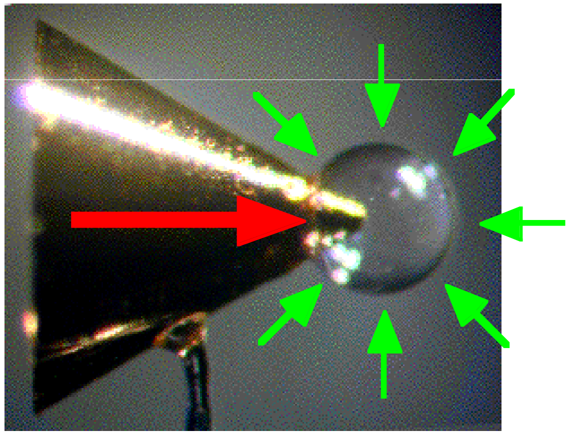


240 MJ DT target without corn

r (corn) = 6 mm
M(corn) = 40 mg Pb



240 MJ corn target



Corn Target Experiment

Requirements for IFE chambers (1)

ILEOSAKA

What factors give the economically attractive laser fusion power plants?

- **Target gain and laser energy (gain scaling) >> Fusion pulse energy**
  >> Laser energy (cost)
- **Pulse repetition rate >>Fusion output power**
- **Neutron loading on the first wall and the final optics**
  >> The size of chamber and reactor building (Lifetime of material)
- **Intensity of X-rays and charged particles on the first wall and the final optics (Limiting factors of reactor size and rep-rate, or not ?)**

Requirements for IFE chambers (2)

ILEOSAKA

Results of economic analysis on laser fusion plants

- **The sensitivity analysis on LD cost show that even if in the case of central spark concept (conservative target gain curve), the broad design windows of attractive power plants can be obtained in modular plants.**

- **When fast ignition can be achieved, the required laser energy is so small that very attractive fusion power plants can be achieved. But in the case of small laser energy and small fusion pulse energy, the design windows are strictly restricted by the rep-rates of laser pulse and/or reactor pulse.**

- **In modular power plants the requirement for reactor pulse rep-rates is mitigated, but laser rep-rate and beam sharing control may be critical issues for lower COE.**

Issues and major subjects on liquid wall chamber

ILE OSAKA

X-rays , charged particles Energies

↓

Energy absorption

↓

Liquid surface ablation

Fusion burning output estimation

ILESTA, MEDUS

X-rays ~ 30 keV

Charged particles 0.1keV ~ 1MeV

Ablation model with plasma absorption by abrated plasma

Free surface liquid flow cooling

Evacuation of metal vapor

DSMC code, Tsunami code

Nonlinear effect on laser beam

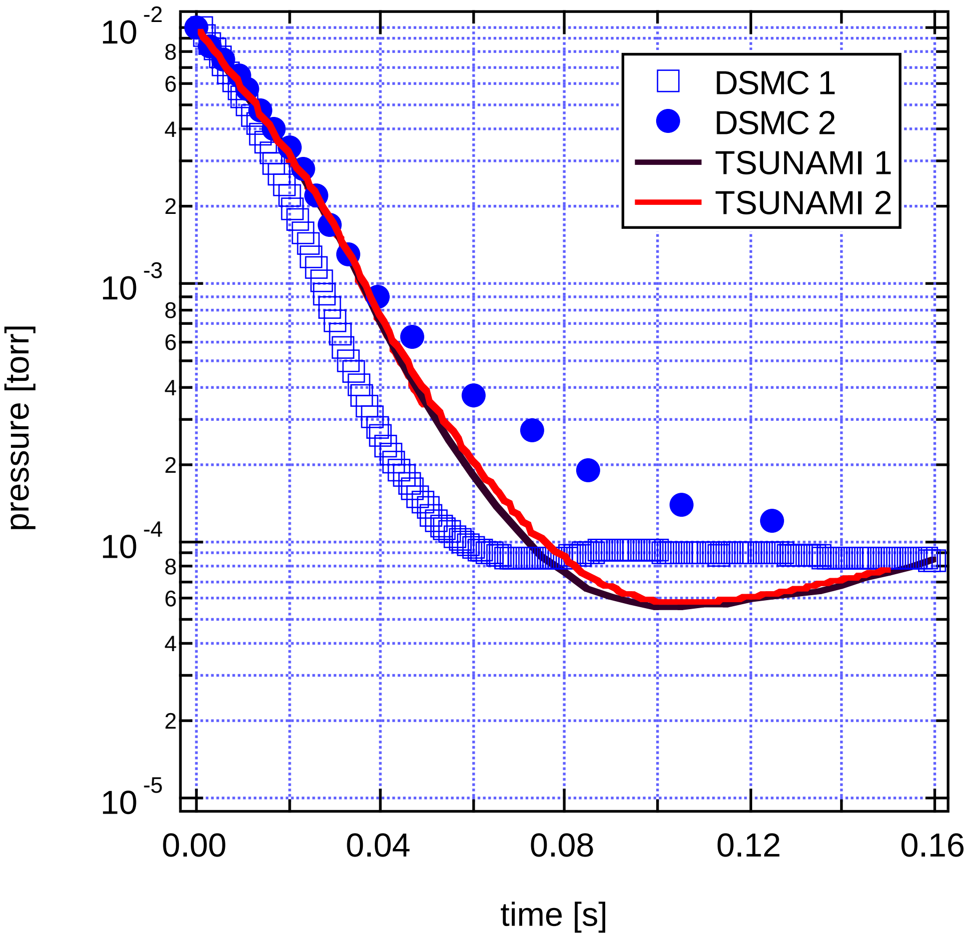
Impact on pellet injection

Required vacuum level

$<10^{-2} \sim 10^{-4}$ Torr

Estimating rep-rate >3 ~ 10 Hz

Results of evacuation simulation with DSMC code and TSUNAMI code in different boundary conditions



DSMC 1
DSMC code with condensation ratio is 0.98

DSMC 2
DSMC code with condensation ratio is 0.92

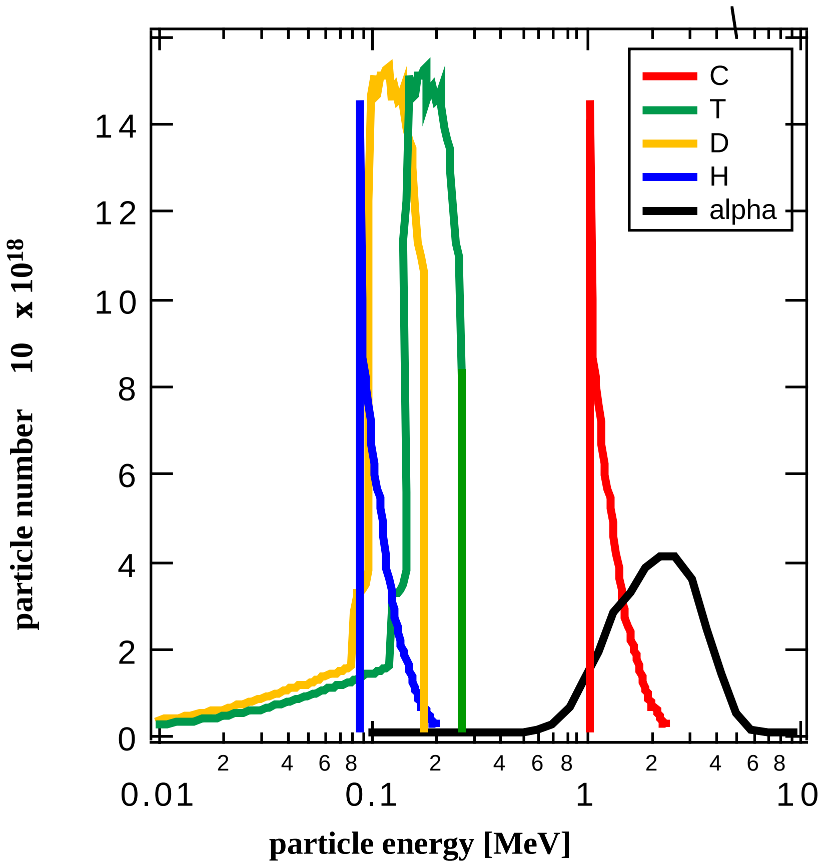
TSUNAMI 1
TSUNAMI code without viscosity

TSUNAMI 2
TSUNAMI code with viscosity (8.77 $\times 10^{-5}$ pa*s) using the value of Hg of 873 K and 1 atm

The results of DSMC code and TSUNAMI code with different conditions.
The differences of results with different condensation ratio and viscosity are not so large as those with surface temperature.

Ion spectra of fusion output (400 MJ target)

ILE OSAKA



spectrum of fusion ions

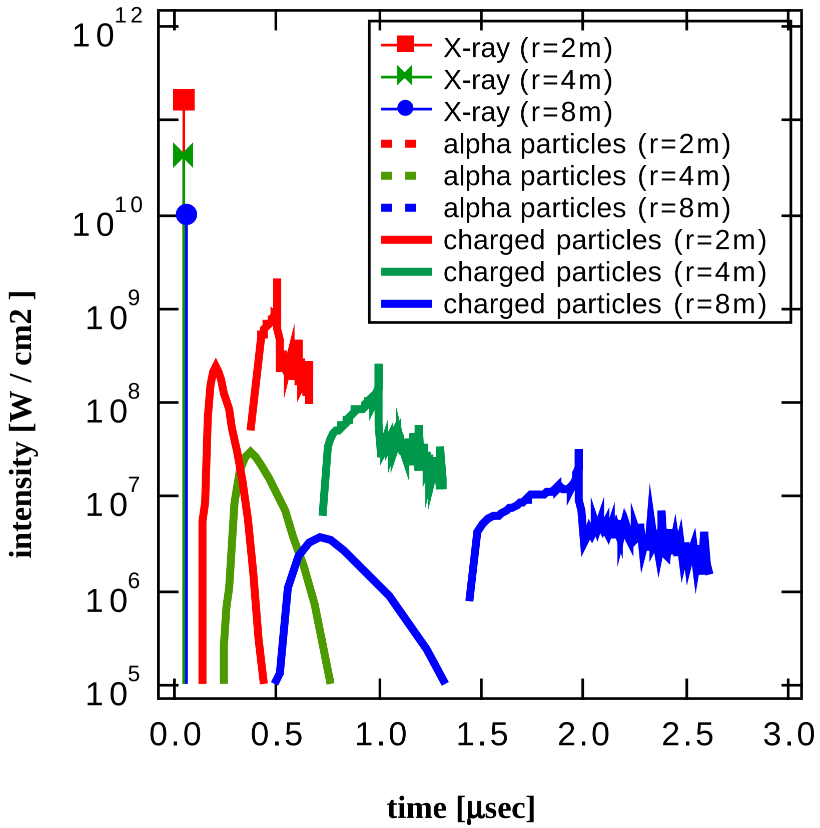
(400 MJ direct irradiation targets)

	energy MJ	average energies	%
X-rays	4	30 keV	1.0
alpha particles	10	3.5 MeV	2.5
charged particles	58	C: 1 MeV H,D,T: 200 keV	14.5
neutrons	328 MJ	14.7 MeV	82.0
fusion output	400 MJ	-	100

- X ray spectrum is much harder than indirect target
- particles and fast ions energy are 1-4 MeV

Pulse heat loads on chamber walls (400 MJ target case)

ILE OSAKA



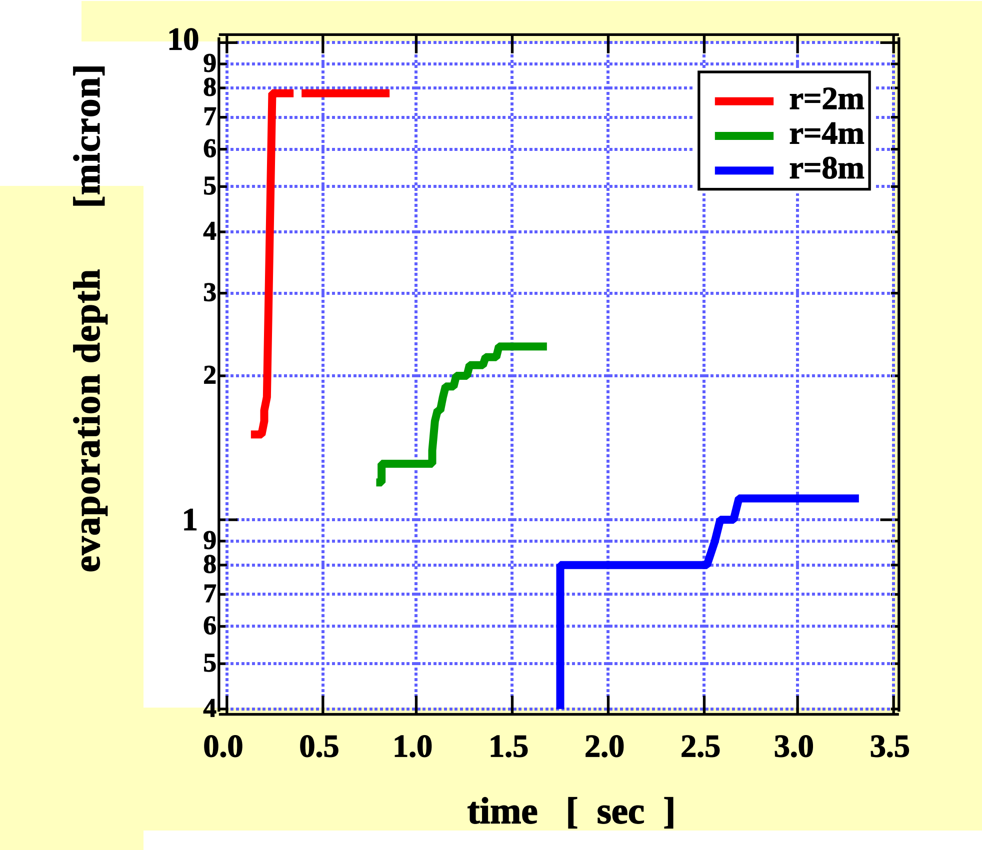
Thermal pulse power on first wall

(400MJ targets) radius 2m, 4m, 8m

	r=2m	r=4m	r=8m
X-ray peak 10^{10} W/cm^2	16	4.0	1.0
alpha peak 10^{8} W/cm^2	2.4	0.3	0.037
Ions peake 10^{8} W/cm^2	19	2.4	0.3
alpha pulse width μsec	0.3	0.6	1.2
Ions pulse width μsec	0.4	0.8	1.6
Total pulse load J / cm^2	144	36	9
Average power 3Hz,W/cm^2	432	108	27
Neutron load 3Hz, MW/m^2	20	4.9	1.2

Ablated depth and mass of liquid wall (400 MJ case)

ILE OSAKA



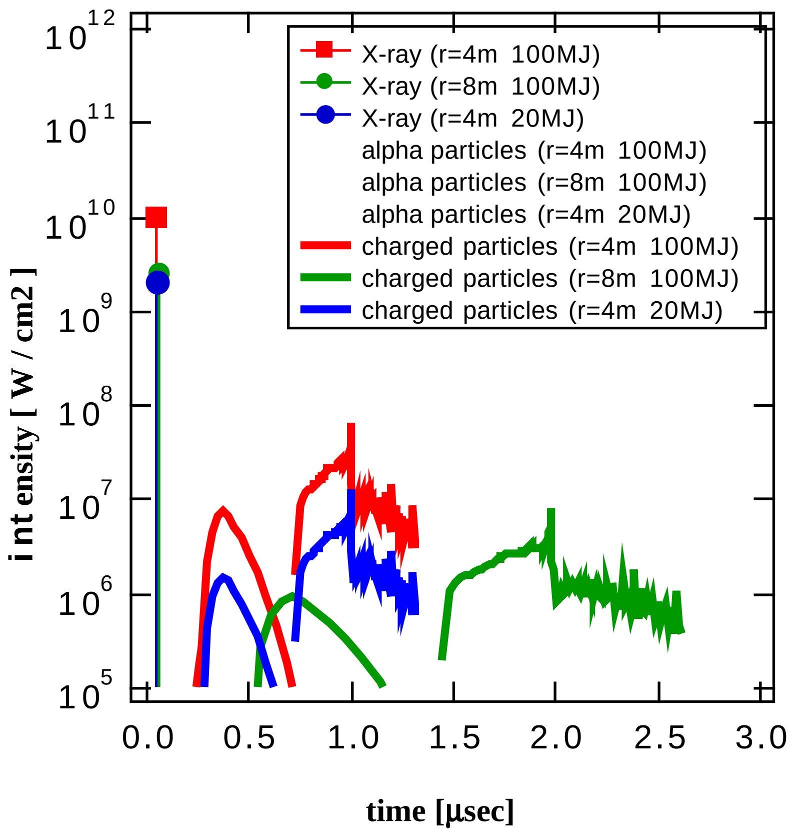
CHAMBER RADIUS	FLUENCE	ABLATION DEPTH	ABLATION MASS
2m	144 J/cm^2	7.8 micron	4.4 kg
4m	36 J/cm^2	2.3 micron	5.2 kg
8m	9 J/cm^2	1.1 micron	10.0 kg

In the case of 2m chamber radius, the ablation depth is almost equal to the renge of alpha particles, as the energy deposit with alpha particles is enough to ablate the mass of this depth.

When the radius is larger than 3m, the ablation depth increases softly with increasing fluence of charged particles, as the over 90 % of charged particles energy is absorbed with ablated liquid metal plasma.

Pulse heat loads on chamber walls (20 MJ, 100 MJ case)

ILE OSAKA

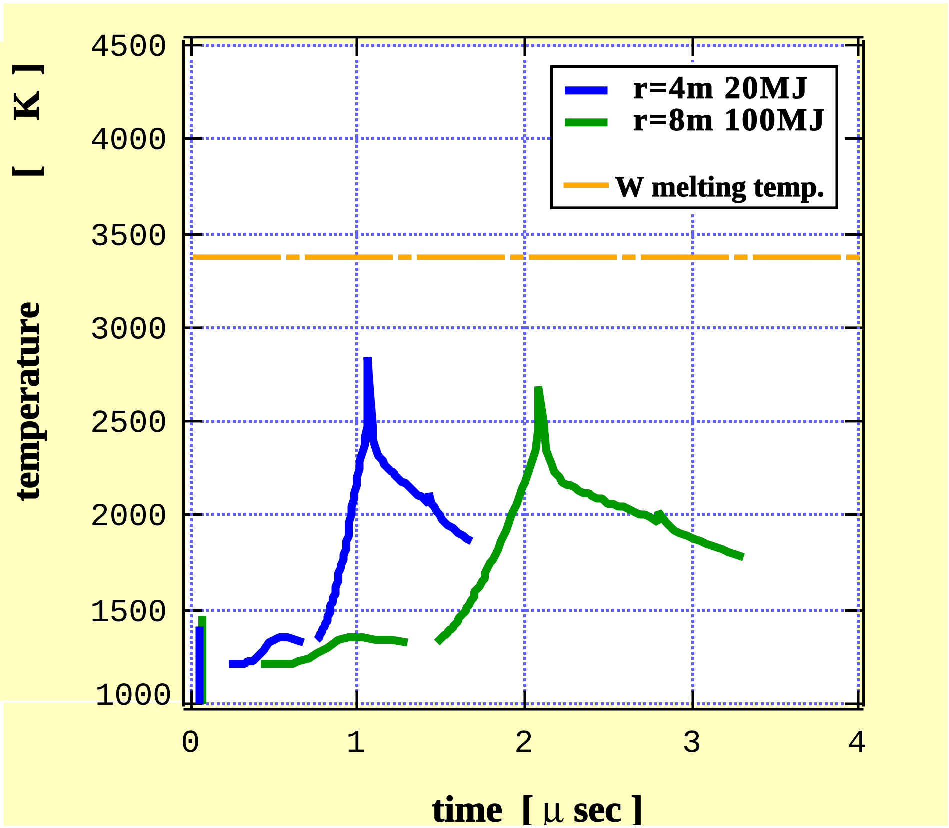


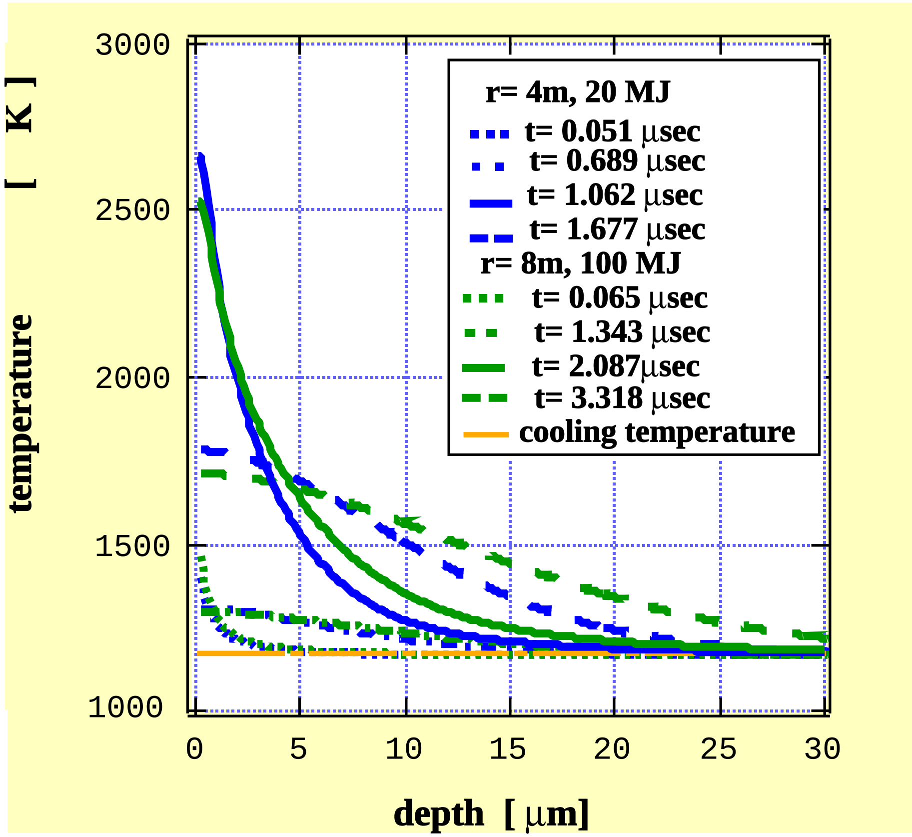
Thermal pulse power on first wall
(20 MJ targets) radius 2m, 4m, 8m

	20 MJ r=4m	100 MJ r=4m	100 MJ r=8m
Laser energy kJ	200	500	500
Gain	100	200	200
X-ray peak 10^{10} W/cm^2	0.2	1.0	0.25
α peak 10^8 W/cm^2	0.015	0.075	0.009
Ions peak 10^8 W/cm^2	0.16	0.8	0.08
Total load J / cm^2	1.6	9.0	2.25
Average power 10Hz,W/cm^2	16	90	23
Neutron load 10Hz, MW/m^2	0.7	4.1	1.0

Energy density and temperature profile of dry wall

ILE OSAKA



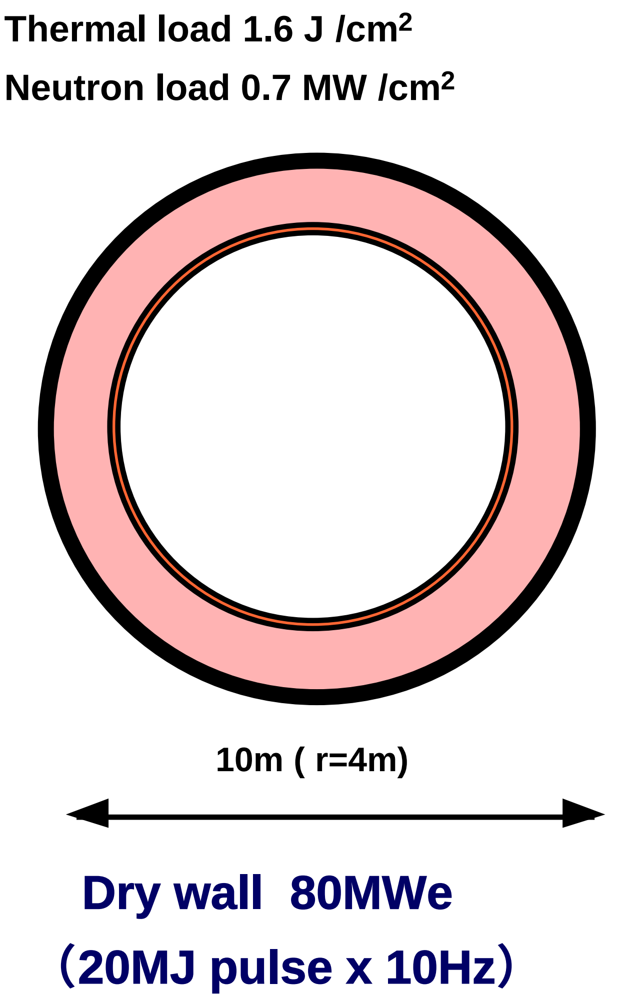


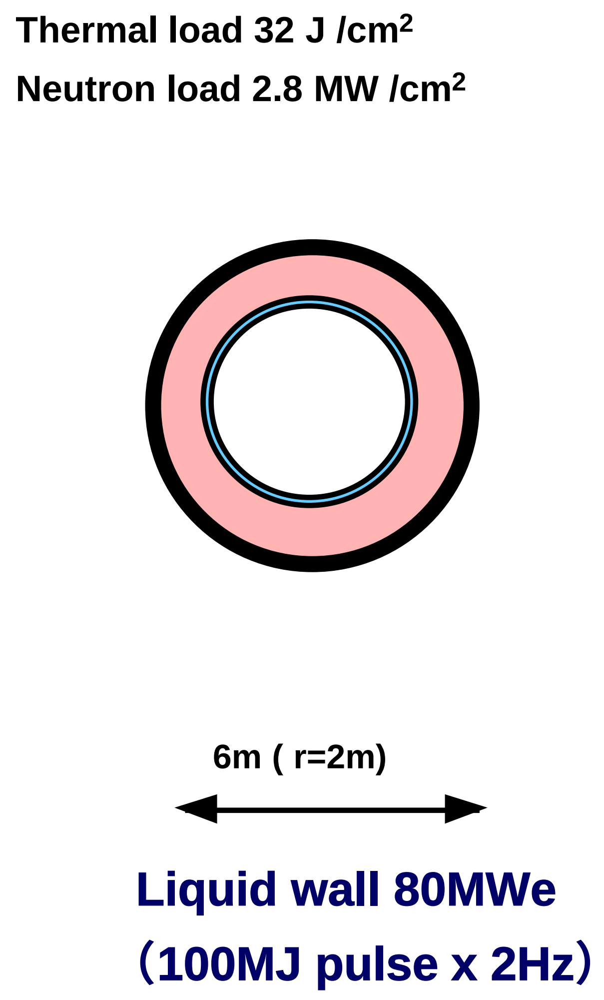
The peak surface temperature are about 2700K (r=4m, 20MJ case, at t=1.062µsec), and 2500K (r=8m, 100MJ case, at t=2.087µsec).

At ending of charged particles pulse, the surface temperatures are about 1700K in both cases.

Chamber sizes of dry wall and liquid wall for same output

ILE OSAKA





Dry wall chamber : for smaller purse energy and higher rep-rates

Liquid wall chamber : for larger purse energy and smaller radius chamber

What factors give plant sizes?

- Fast ignition target design :Target gain 250 with laser energy 800 kJ

→ Fusion pulse energy 200 MJ

→ 60 MJ with laser energy 400 kJ

- Optimum plant output power

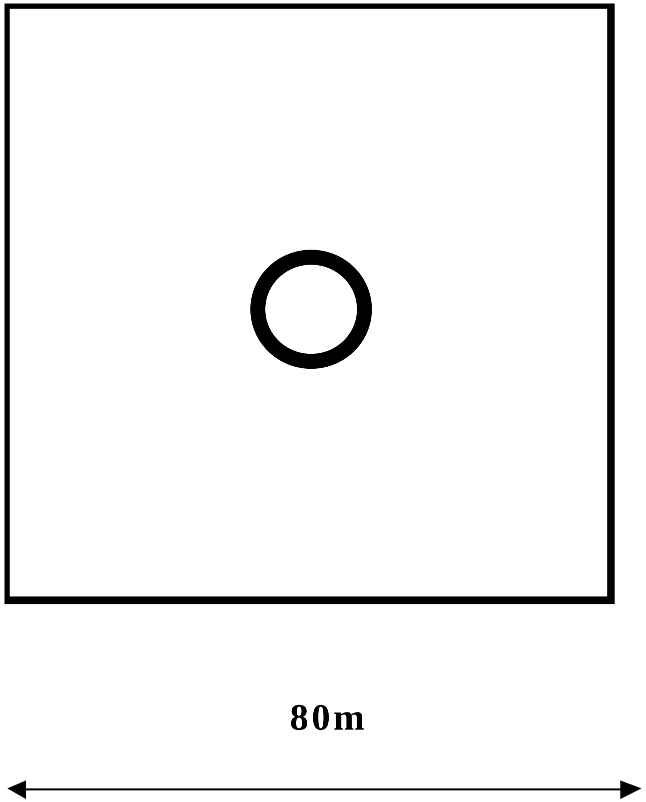
→ Scale merits : the 2/3 power law(such as fission plants)
1200 ~ 1500 MWe (~ 2400 MWe in modular plants)

→ Small size merits: flexibility of construction and fitting in demand
: assembling in factory and small indirect cost

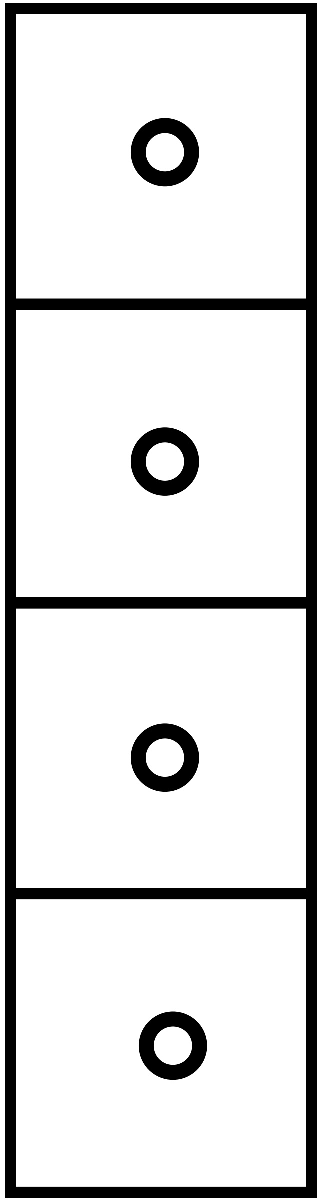
- Especially in laser fusion plants,

→ Decreasing neutron flux on final optics >> Small size of reactor buildings

→ Modular plants with multi small reactors and a high rep-rates laser can give the deign flexibility.



1200 MWe Reactor Plant and Building



300 MWe x 4 Reactors Plant and Buildings

(Beam layout is a critical issue)

Critical Issues and Major Tasks

Physics issues and major tasks (2002~2015)

- **Fast ignition physics establishment and demonstration of ignition and burning (PW project, and FIREX)**
- **Hydro dynamic equivalent experiment of high gain target (EPOC: high uniformity ~50kJ laser facility)**

Driver issues and major tasks (~2012)

- **High repetition high power laser (100J and 1kJ DPSSL module, and excimer laser module development)**
- **LD cost down technologies**
- **Long-lifetime-laser-material development**

Pellet technologies issues and major tasks (~2012)

- **Cryo-target fabrication and corn target technologies**
- **Pellet injection, tracking, and shooting technologies**

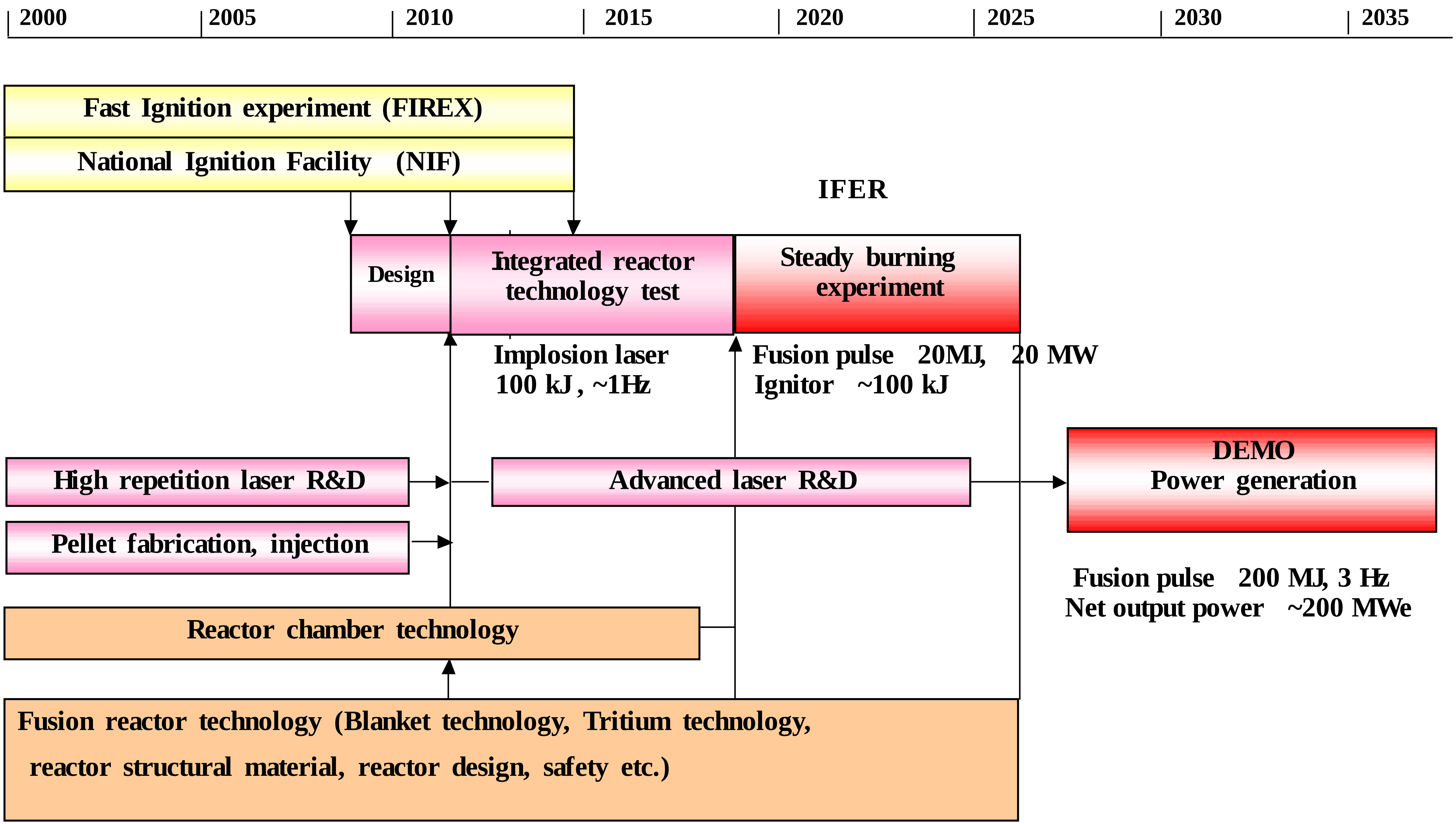
Reactor technologies issues and major tasks (~2012)

- **Chamber wall protection technologies (for FIREX , and the high rep-rate burning experiment)**
- **Liquid wall chamber feasibility studies, simulation on liquid wall ablation, evacuation, and free liquid surface control**
- **Reactor structural material and final optics (pulse irradiation with charged particles and neutrons)**
- **Consistent reactor design (developing new power plant concepts and establishing a experiment reactor design)**

Table Milestones and major facility specks on a laser fusion roadmap

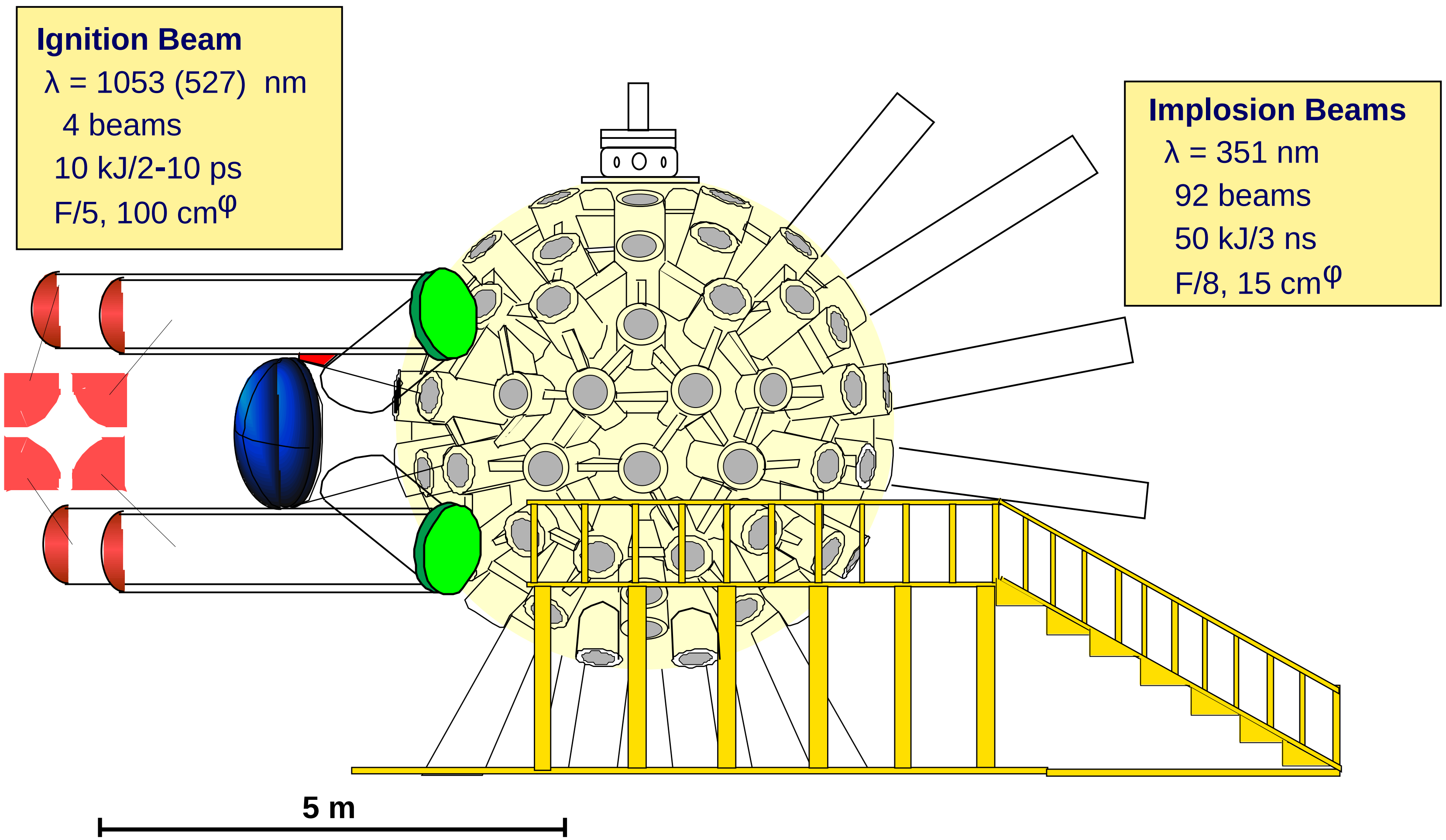
Milestones	Establishment of plasma physics	Steady burning experiment	Demonstration of power generation	Goal
Facility	FIREX	IFER	DEMO	Commercial plants
Purpose,	Demonstration of ignition and burning - 1st stage: Driven burning physics (Break even Q~1) Second stage: ignition and burning (α heating physics Q~10)	Integrated test of burning technologies - High gain, and high rep-rate fusion burning - High rep-rate laser - Reactor chamber test, tritium breeding blancket, material test, etc.	Integrated test of prototype power plant - Demonstrate of relliable power generation (facility performance, lifetime) - safety, and prospect for COE	Economically and environmentally attractive plants - COE (6~10 Yen/ kWh) - Modular plants for using the characteristics of laser fusion - Flexibility of construction and operation
Conditions for starting and selection	- High density implosion (already demonstrated) - Short pulse laser heating physics (scaling for keV level heating) - Ultra high intensity laser technologies (already developed)	- Steady fusion output with fast ignition (Although evaluating the results of central spark concepts with US NIF, EPOC.) - Selection of driver based on module development - Selecting the chamber concepts (liquid wall and/or solid wall)	- Selecting the optimum target irradiation methods, and drivers - Lliquid metal cooling and/or gas cooling (consi-dering multi chambers test) - Technologies scalable to commercial plants by multi module and scale up	
Laser energies	~ 80 kJ implosion 50+ heating ~30	200 kJ implosion 100+ heating 100	400 ~ 800 kJ	400 ~ 800 kJ
Target Gain	~ 10	100	150 ~ 250	150 ~ 250
Fusion pulse energies	~ 1 MJ	20 MJ	100 ~ 200 MJ	100 ~ 200 MJ
Pulse rep-rate	1 shot / hour	~ 1 Hz	~ 3 Hz	3 Hz × (5~10)
Fusion output power	-	20 MWth	120 ~ 240 MWe	1200 MWe
Laser efficiency	1 %	6 ~ 8 %	10 %	10 %
Construction cost	22 ~ 40 BYen	100 ~ 200 BYen	200 ~ 300 BYen	~ 360 BYen

Road maps for laser fusion reactors



FIREX II Target Chamber System

ILE Osaka



The basic design guidelines for KOYO - Fast

1) Target: Fast ignition target with corn
- laser energy 800 kJ, fusion gain 250, fusion pulse energy 200 MJ
- Reactor pulse rep-rate 3 Hz, 600 MWth
- Blanket energy multiplication 1.1, reactor thermal output 660 MWth
- Energy conversion efficiency 43%
- Reactor electric output 284 MWe, and auxiliary electric power 6%
- Laser recirculating power 24 MW (8.94%), laser efficiency 10% DPSSL case
- Net electric power of one reactor module 240 MWe, and 5 reactors modular plant 1200 MWe
2) Laser: DPSSL implosion 700kJ, ignitor 100 kJ (option excimer laser)
- efficiency 10%
- rep-rates 15 Hz
- laser gain medium HAP4, or Nd-YAG ceramics
3) Chamber: Liquid fast flow covering first wall with thin liquid layer
- Pb
- rep-rates ~3 Hz
4) Final optics: Fused silica optical wedge for implosion lasers (unsettled yet for ignitor)

[Options]
- Small DT fuel target (laser energy 400 kJ, fusion gain 150) for solid wall chambers
- Advanced-fuel-corn-target with magnetic wall protection and direct energy conversion

Summary

- Analysis of design windows shows that even with the conservative target gain scaling, the broad design spaces for attractive power plants can be obtained in modular plants, although costs and lifetimes of lasers are critical issues.
- Fast ignition offers opportunities for smaller size plants with smaller laser energy, then give high potential for competitive COE.
- We identified critical issues which should be achieved for fast ignition targets, high rep-rates lasers, pulse energy protection chambers, etc.
- Results of network analysis shows that laser fusion programs have much flexibility and could promote with small size facilities and a rather small cost. Especially in fast Ignition case, we could establish physics base of ignition and burning with small size facility, and achieve reactor technologies with a small size steady operation reactor.
- For achieving fusion energy goals we have various options which are based on common fusion reactor technologies. Laser fusion options offer some good candidates, which also could be achieved by strong supporting with fusion reactor technologies development.