Issue and Design Windows of Laser Fusion Reactor Chambers

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Abstract. Based on recent progress of fast ignition physics, we examined the design windows and the issues for the laser fusion modular plants, which have several compact reactor modules (100~240 MWe), driven with a rather high rep-rates laser (15~20 Hz). As fast ignition targets may give us the fusion pulse energies, 20~200 MJ with 200 kJ~1MJ laser, we can design a small power size 240 MWe reactor, with 200 MJ fusion pulse energy and 3 Hz rep-rates. The smaller pulse energies mitigate pulse loads on the chamber walls and the final optics, then we can flexibly design large size 1200 MWe modular plants by using 5~10 small size reactor modules. For 200 MJ fusion pulse energy, we propose a 3m radius liquid wall chamber, considering the threshold of alpha particles intensity without making ablation. For the smaller fusion pulse energies, less than 100MJ, the solid wall chambers with the armors of W coating SiC could be candidates, in the cases of larger chamber radius ~8m or with using buffer gas. We identified the issues of liquid wall and solid wall, for the KOYO-Fast design, using the fast ignition cone targets.

1. Introduction

In laser fusion power plants key subsystems, which are targets (fusion plasma), lasers and reactor chambers, are geometrically separable and can be designed with high flexibility in mutual interactions. Focusing on this characteristics, a laser fusion modular power plant "KOYO" design, which has four reactor chambers driven by one laser system, was proposed [1]. Based on KOYO design studies, design window analyses have been carried out, and we showed that laser fusion modular plants have high potential for economically attractive power plants. We can use lasers efficiently in modular plants, under limiting conditions of chamber pulse repetition rates and reactor output powers, as we can choose pulse rep-rates of a laser and chambers separately [2]. This is very important for smaller fusion pulse energy and more compact fusion reactors such as fast ignition concepts. Recent experimental and theoretical progress of fast ignition concepts gives us the some confidence for the assumptions of design windows on fast ignition target physics for getting higher fusion gain with smaller laser energy. For smaller fusion pulse energy it is much more important to achieve higher pulse rep-rates chambers as well as higher rep-rates lasers, and optimum combinations of modular plants.

As fusion burning of inertial fusion occurs in very short time, less than 0.1 nsec, chamber walls are exposed by high peak power X-rays, ions, and neutrons. For protecting the first wall from these pulse loads, various chamber concepts using liquid wall or solid wall have been proposed. These chamber concepts depend on target designs, both in fusion yields and compatibility to chamber environment. Furthermore the chamber design windows depend on the configuration of modular plants, which can be optimized through comprehensive plant design for various sizes of reactors and power plants. We should consider optimum plant configuration, not only from the optimization of chamber design, but also from the optimization of laser rep-rates and lifetimes.

Fast ignition concepts may give strong impact on the design windows and issues of laser fusion chambers. In this paper we give a brief summary of tasks for chamber design and analysis, identify key chamber issues, and propose the design windows for fast ignition laser fusion plants.

2. Tasks of Analysis and Issues for Laser Fusion Chamber

In liquid wall chambers, which are covered with thin liquid layers on solid walls (wetted wall concepts) or with thick liquid layers, pulse energies of X-rays and ions from fusion burning are absorbed in thin surface area and make ablation of several µm layers. Ablated metal vapor should be condensed quickly for next shot. For solid wall concepts we must keep the first wall materials in allowable damage level by decreasing pulse heat load with larger chamber radius or using chamber buffer gas, at the same time avoid adverse impacts on target injection and laser beam propagation. Figure 1 shows the major tasks of analysis for liquid wall and solid wall chambers.

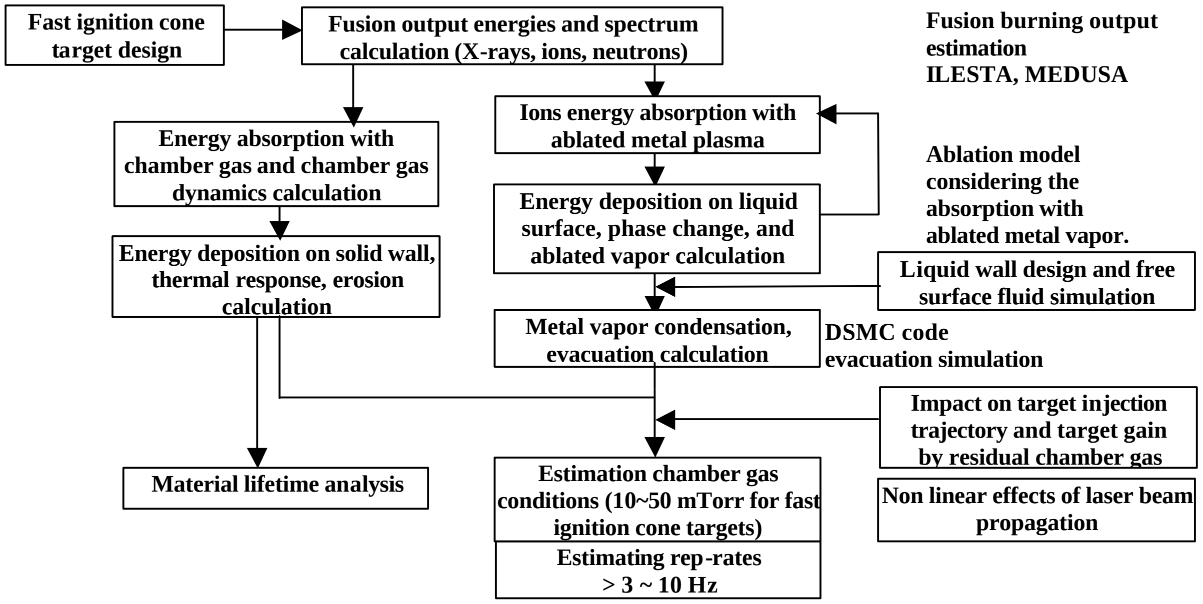

Fig. 1 The major tasks of analysis for liquid wall chambers and solid wall chambers.

Energies and spectra of X-rays, charged particles, and neutrons from burning target are calculated by using ILESTA-1D, and MEDUSA-Q for KOYO targets [3], and we are now estimating for fast ignition cone targets. Figure 2 and TABLE 1 show the energies and spectra of X-rays, alpha particles, ions, and neutrons from a typical central spark KOYO target.

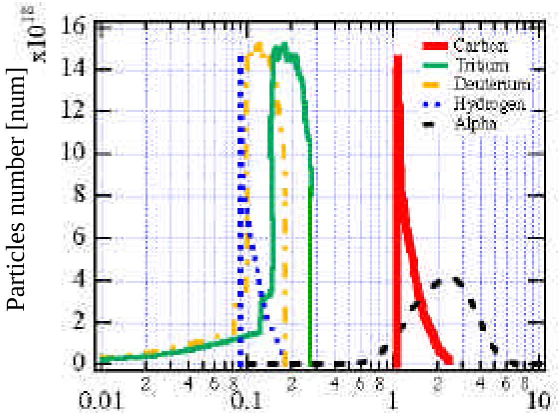

Fig. 2 Energies and spectra of ions from burning

TABLE 1 ENERGIES AND SPECTRA
(A central spark target in KOYO design)

	Average Energy	Range µm	Energy MJ (%)
X-rays	35 keV		4 (1.0%)
α particles	3.5MeV	14	10 (2.5)
Ions	C 1MeV	0.5	58 (14.5)
	H,D,T: 0.1~0.2MeV	20	
Neutrons			328 (80)
Total			400 MJ

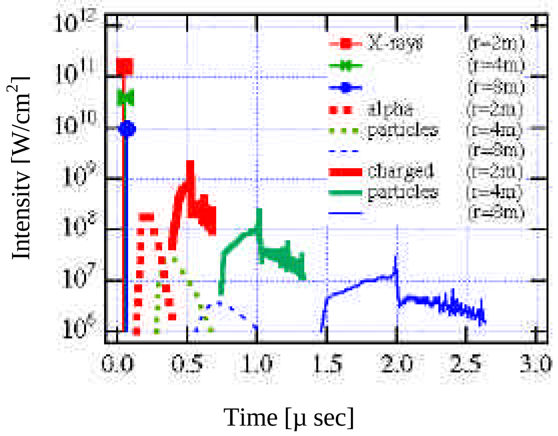

Fig. 3 Pulse loads of X-rays and ions on chamber wall (400 MJ KOYO target, radius r=2,4,8m)

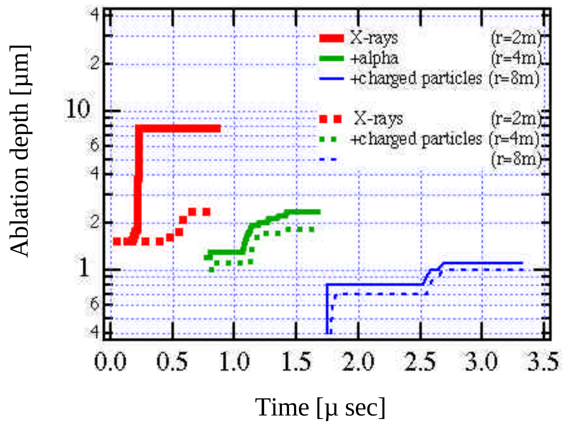

Fig. 4 Ablation depths of liquid surface (with and without considering alpha particles load)

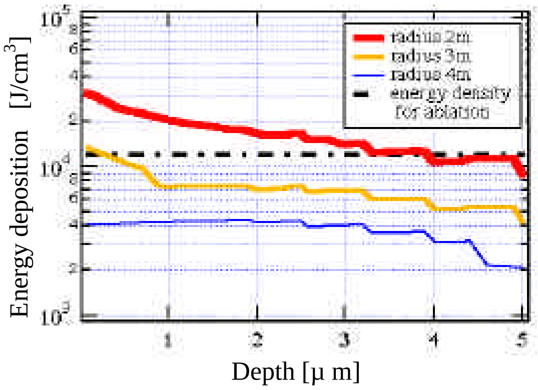

Fig. 5 Energy deposition by alpha particles from 200 MJ target

We should notice that the high energy alpha particles (about 15% of total ions energies), which yield in burning final phase and directly loss, should be estimated in a right way. Pulse load on chamber walls are calculated by the energies and spectra of X-rays and ions, and time of flight, as shown in figure 3, when the chamber gas is rarefied (<10 mTorr). Energy depositions on chamber walls are calculated by cross sections of photon interactions, and stopping power for fast ions (mainly alpha particles) and debris ions (charged particles shown in Fig. 3). For estimating surface ablation depth we have developed a simulation code involving energy deposition, heat conduction, phase change, moving boundary, and energy absorption by ablated plasma [3~5]. Figure 4 shows the ablation depth of liquid surface for the KOYO target and various chamber radiuses, with, and without considering the alpha particles load. Figure 4 show clearly that the ablation depths depend on the alpha particles beyond a certain intensity (2~3m chamber radius), but in larger radius only depend on debris ions, because alpha particles deposit their energies in long range, ~10 μm, while debris ions (C and low energy H, D, T) deposit in short range, 0.5~2 μm. Figure 5 shows the energy deposition by alpha particles in 200 MJ target case, in which the total ablation depths are 4μm for r=2m, and about 2μm for r=3m, and 4m, like Fig. 4. For precise estimation of the ablation depth, it is necessary to get exact experimental data of ion-material interactions.

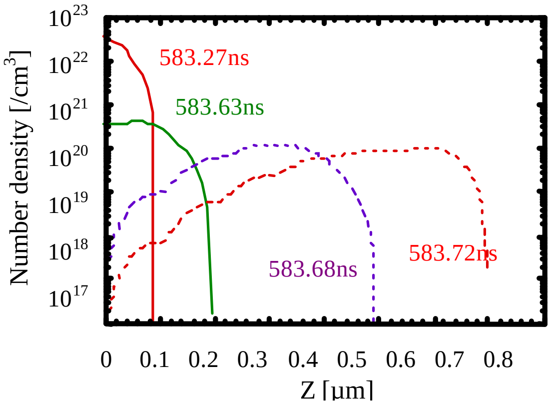

Fig.6 Density profiles of ablated plasmas

The momentum and temperature of the ablated plasmas are also important to give initial conditions of chamber evacuation. Figure 6 shows a preliminary estimation of the density profiles of ablated plasmas with the time evolution from the ablation starting time (0.583µsec in Fig.3,), using stopping power obtained by dielectric functions of plasmas and Bethe formulas [5]. The ablated plasmas blow off instantaneously with the large velocity of over sound velocity caused by their large pressure gradient, as forming clumps, which may make clusters and aerosols.

For evaluating the feasible chamber pulse rep-rates, we should estimate the condensation speeds, which depend on chamber vapor pressures and liquid surface conditions. For higher vapor pressures (>0.1Torr), condensation characteristic times are rather short, ~40 msec. For lower vapor pressures, near to saturation vapor pressures, condensation slows down. We have estimated condensation speeds under 0.01 Torr by developing the DSMC (direct simulation of Monte Calro method) code, and shown that the evacuation speeds are sufficiently fast, ~100 msec, when the liquid free surface are well cooled or fresh [6]. Designs for the stable and quickly renewal liquid surface are important, and studies on the critical factors, which may prevent evacuation, such as forming droplets, boiling explosion, and splashing of the liquid layer, are necessary. For the fast ignition cone targets, required chamber gas pressure may be mitigated to ~50mTorr, as the heavy cone materials can guard DT cryo-target and afford precise trajectory [7].

[Key Issues for Liquid Wall Chambers]

Major key issues for establishing liquid wall concepts are summarized as follows.

1) To make stable free liquid surface which can be renewal quickly for fast vapor condensation.
2) To estimate the behavior of ablated plasmas and their condensation speed on to liquid wall.
3) Experiment on ablation or splashing of liquid surface by using pulse ion beams for examine the dependence on pulse intensity, and conditions of liquid surface.

[Key Issues for Solid Wall Chambers]

1) To search the design widows where the wall material can be keep under the allowable temperature without adverse thermo-mechanical response, and erosion (Fig. 3,4 show the small pulse and large chamber radius cases, 20 MJ 4m, and 100MJ 8m, with no buffer gas).
2) To estimate the optimum gas pressure for material protection and from target injection.

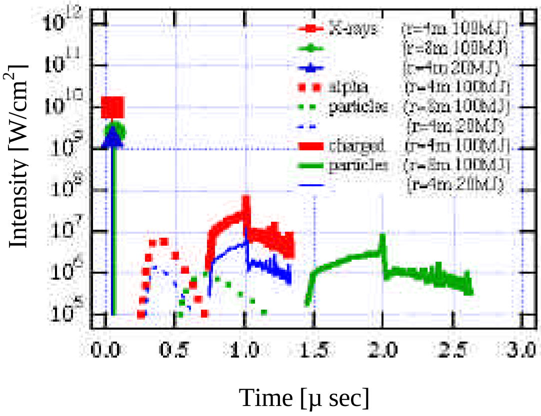

Fig.7 The Pulse loads of X-rays and ions on the solid wall from 20 MJ, and 100 MJ targets

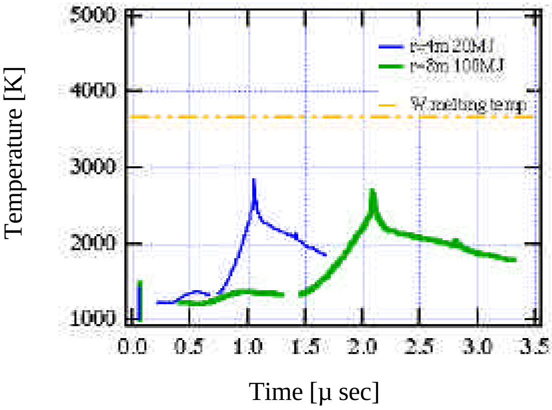

Fig.8 Surface temperature transition (20 MJ, r=4 m, 100 MJ, r=8 m)

3. Design Windows of Laser Fusion Chambers

The design windows of laser fusion power plants are mainly given by the fusion pulse energies, the pulse heat loads, and neutron loads on the chamber wall and final optics, the pulse rep-rates of reactors and lasers. Recent progress of fast ignition physics shows the high potential for very compact fusion reactors, 20~200MJ fusion pulse energies. In modular plants we can select the smaller reactor powers with the lower reactor pulse rep-rates, where the total plant power can be adjusted for required output by using multi reactor modules and rather high rep-rates lasers. In the smaller fusion pulse cases, higher laser rep-rates are very important for economical power plants. For the high rep-rates lasers, we have developed a diode-pumped, zig-zag slab, Nd:silica-phosphate glass laser amplifire HALNA 10 (10 J, 10 Hz), and successfully tested [8]. We have a confidence that a next 100 J, 10 Hz DPSSL module (HALNA 100) can be developed, and we will be making effort for achieving further higher rep-rates 20~30 Hz lasers, using new laser materials, such as Nd:YAG ceramic and new mixed material. Table l. shows the typical parameters, using central spark targets and fast ignition targets. For the requirements of 1200 MWe plants we can use several reactor modules in modular plants, or we have to achieve larger rep-rates and/or larger pulse energies. Based on these estimation we have started the KOYO-Fast design study with fast ignition cone targets, 200 MJ fusion pulse energies, 3 Hz reactor rep-rates, 3m radius liquid wall chamber with considering alpha particles intensity, and 15 Hz laser rep-rates for driving 5 reactor modules.

Table 2. THE KEY DESIGN PARAMETERS FOR LASER FUSION POWER PLANTS

	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	24	mini size plant
				10	80	small size plant
	0.6 (ignitor 0.1)	150	90	3.3 (20)	100	100×6 600 MWe
	1.0 (ignitor 0.1)	200	200 KOYO-Fast	3 (15)	240	240×5 1200 MWe
Central spark	2	100	200	3 (15)	240	240×5 1200 MWe
	4	100 ~ 150	400 ~ 600 (KOYO)	~ 3 (6)	~ 600	600×2 1200 MWe

4. Conclusions

We examine the design windows and the issues for the laser fusion chambers and power plants. As fast ignition targets may give us the fusion pulse energies, 20~200 MJ with 200 kJ~1MJ laser, we can design a small size ~240 MWe fusion reactor, with ~200 MJ fusion pulse energy and 3 Hz rep-rates. The small pulse energies mitigate the chamber technical constraints, and we can flexibly design large size ~1200 MWe modular plants. For rather large fusion pulse energy, ~200 MJ, we propose a 3 m radius liquid wall chamber, considering the threshold of alpha particles intensity without making ablation. For the smaller fusion pulse energies, the solid wall chambers could be candidates, in cases of larger chamber radius ~8m or with using buffer gas.

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