Conceptual Design of a Fast-Ignition Laser Fusion Reactor Based on a Dry Wall Chamber

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Abstract. The fast ignition is quite attractive for a compact laser fusion reactor, because a sufficiently high pellet gain is available with a small input energy. We designed an inertial fusion reactor based on Fast-ignition Advanced Laser fusion reactor CONcept, called FALCON-D, where a dry wall is employed for a chamber wall. A simple point model shows that the pellet gain \(G \sim 100\) is available with laser energies of 350kJ for implosion, 50kJ for heating. This results in the fusion yield of 40 MJ in one shot. By increasing the repetition rate up to 30 Hz, the fusion power of 1.2 GWth becomes available. Plant system analysis shows the net electric power to be about 0.4 GWe. In the fast ignition it is available to employ a low aspect ratio pellet, which is favorable for the stability during the implosion phase. Here the pellet aspect ratio is reduced to be 2 ~ 4, and the optimization of the pulse shape for the implosion laser are carried out by using the 1-D hydrodynamic simulation code ILESTA-1D. A ferritic steel with a tungsten armour is employed for the chamber wall. The feasibility of this dry wall concept is studied from various engineering aspects such as surface melting, physical and chemical sputtering, blistering and exfoliation by helium retention, and thermo-mechanical fatigue, and it is found that blistering and exfoliation due to the helium retention and fatigue failure due to cyclic thermal load are major concerns. The cost analysis shows that the construction cost is moderate but the cost of electricity is slightly expensive.

1. Introduction

Reactor designs based on the central ignition concept have been carried out in many groups. ARIES group in US has studied the feasibility for dry- and wetted-wall concepts[1]. Now HAPL project is exploring an inertial fusion reactor with a dry wall[2]. Osaka University in Japan has designed a central ignition reactor KOYO[3], where a liquid wall of LiPb is employed. Recently, to explore the feasibility of the fast ignition for the inertial fusion reactor, Osaka University has carried out a KOYO-fast reactor design[4], by taking recent knowledge on fast ignition physics and progress on laser
technology into account. In addition, HiPER project in Europe[5] is promoting the fast ignition concept, as well.

In a fast ignition reactor a fusion yield in one shot can be remarkably reduced (typically 1/10 of that in the central ignition). This could mitigate the design of the first wall of the reactor chamber, and might make it possible to introduce the dry wall concept instead of the liquid wall[6]. Here we have paid much attention to the advantages of the fast ignition in comparison with the central ignition, and designed an inertial fusion reactor called FALCON-D (abbrev. Fast-ignition Advanced Laser fusion reactor CONcept - Dry wall version). In FALCON-D a dry wall is employed for the chamber wall, and the repetition of the pulse is increased up to 30 Hz. This results in the fusion power of 1.2 GWth, and the electric power is evaluated to be 0.4 GW. Attractive features of the fast ignition might open a new strategy for the inertial fusion reactor development.

2. Design of FALCON-D reactor

2.1 Pellet gain and core pellet design

In evaluating the pellet gain, an isentrope factor $\alpha$ and an coupling efficiency $\eta_i$ of the implosion laser play important roles. Since the isentrope factor of $2 \sim 3$ is realized in present experiments, we assumed to be $\alpha = 2.0$ and 2.5. For the coupling efficiency of the implosion laser we assumed two cases of $\eta_i = 5\%$ and 7\%. In the fast ignition case the coupling efficiency $\eta_h$ of the heating laser becomes important. Here we assumed the coupling efficiency of the heating laser to be $\eta_h = 20\%$.

Figure 1 shows the fusion gain as a function of the laser energy for the central- and fast-ignition cases. In the case of the central ignition the laser energy of a few MJ should be injected so as to achieve a pellet gain larger than 100, resulting in the fusion yield of a few hundreds MJ. While, in the fast ignition case the pellet gain of $G \geq 100$ is achievable with the input laser energy of $E_{in}=400kJ$ (350kJ for implosion laser, 50kJ for heating laser) under the condition of isentrope $\alpha=2$ and implosion laser coupling efficiency $\eta_i = 0.05$, where high density compression (300g/cm$^3$) is assumed. If $\eta_i =0.07$ is available, $G = 135$ is achievable with $E_{in}=300kJ$. Then the fusion pulse is estimated to be 40MJ in FALCON-D reactor.

In the central ignition case the aspect ratio of the pellet would be 5 ~ 10 so as to produce a hot spark at the central region. However, this brings about the increase of the in-flight aspect ratio up to 100 or more, which is unfavourable for the Rayleigh-Taylor (R-T) instability. While, in the fast ignition case the pellet with the low aspect ratio could be applicable, because it is not necessary to produce the hot spot by the implosion laser. We adopted the pellet with the aspect ratio of 2 $\sim$ 4 in FALCO-D design. The optimization of the pulse shape for the implosion laser are carried out by using the 1-D hydrodynamic simulation code ILESTA-1D[7]. It is also found that the burning condition strongly depends on the injection timing of the heating laser. The pellet gain larger than 100 is achievable, if the heating laser is injected between the time interval of less than 100 pico seconds just around the maximum implosion phase.

Since the instantaneous production of the hot spark is required during the implosion phase in the central ignition, the uniform implosion should be strongly imposed. This results in an introduction of a huge number of laser beams; e.g., 192 beams are employed in National Ignition Facility. Since the condition of the uniform implosion is remarkably mitigated in the case of the fast ignition, we adopted 32 laser beams system, where one of these beam lines is utilized for the heating laser, and another one is sacrificed for the access port of the maintenance. In addition, the mitigation for the high uniformity of the pellet is a great advantage from the viewpoint of the pellet fabrication technology.

2.2 Dry wall design
A small fusion power in one shot is quite preferable for the first wall of the chamber. Especially if the heat load to the first wall could be reduced to the level of 2–3 J/cm² in one shot, the utilization of solid materials would become available, because the surface temperature would be suppressed below the melting temperature. Since the fusion power in one shot is designed to be 40 MJ with a chamber radius of 5.6 m in FALCON-D reactor, the averaged heat load on the first wall is estimated to be 2 J/cm². We therefore adopted a dry wall concept, and selected a tungsten armour bonded on a ferritic steel, where the thicknesses of the ferritic steel and tungsten are 3mm and 1mm, respectively, and the ferritic steel is cooled with the supercritical water.

The simulation results of the 1-D ILESTA code was incorporated as the heat load to the tungsten armour. The temperature increase due to the X-ray is quite small, and the maximum temperature at the wall surface reaches around 1400 K due to the heating of carbon debris. Since the melting and recrystalization temperatures of tungsten are 3680 K and ~2400 K, respectively, we can expect that the tungsten armour could hold against the heat pulse. The thermal stress would bring about the plastic strain for the tungsten, and the fatigue due to the cyclic stress would become important[8], and careful attention should be paid to the bonding between the tungsten and the ferritic steel[9].

Sputtering, blistering and exfoliation due to charged particles, especially alpha particles, are considered. Since the loss thickness due to physical sputtering is estimated to be 0.08 mm per year at maximum, physical sputtering would be not so significant. HALP group is intensively studying the effect of blistering/exfoliation due to helium, and reported that blistering and exfoliation of tungsten take place at the helium fluences of around 10^{21}/m² and 10^{22}/m², respectively[10]. Since alpha particles are deposited at the depth of ~2μm, this thickness of tungsten would be lost when exfoliation occurs. In FALCON-D design helium fluence per one shot is 2.4×10^{16}/m². Taking the repetition rate of 30 Hz and an availability of 75%, the exfoliation due to helium leads the loss of tungsten wall with several millimetres per year.

The thermomechanical analysis with a commercial FEM code ANSYS shows that the surface region undergoes large plastic deformation, although the immediate failure does not take place in one shot. However, the fatigue failure is a strong concern for this plastic deformation. Therefore, the helium retention and fatigue failure might be main concerns for this dry wall concept.

2.3 Cost evaluation

In addition to the cost of electricity (COE), the capital cost of the plant might be important issues, if we consider the early introduction of the fusion power into the energy market. In magnetic fusion reactor such as tokamak, it is not so easy to design a low power fusion power plant, because some critical volume would be indispensable to achieve an ignition condition. In addition, the modulation of the fusion power is quite difficult, because many issues such as confinement characteristics, beta limit, operation density, current drive and so on are complicately linked. Therefore, tokamak fusion reactors have been designed with an electric power of 1 GWe or more. These power plants might be applicable for the base load of the huge electric network system.

While in the laser fusion reactor the control of the fusion power could be available by adjusting a repetition rate of the pellet. Especially it would be feasible for designing a fusion power plant with a small electric power (e.g., a few hundreds MW) with a moderate capital cost. This would make it possible to introduce a laser fusion reactor into a small size network system, and to utilize as a load-following power plant, although the COE might be slightly expensive.

The direct construction costs of plant systems were estimated by using the system code employed in the MCF reactors, except for the system related with laser components. We evaluated the laser system cost, referring that of KOYO and KOYO-fast reactor. In addition we employed the fueling cost model of KOYO reactor design for the evaluation of the construction cost of pellet factory. In calculating annual fueling cost, only costs of deuterium and initial loaded tritium are considered.

The cost estimation results are shown in Table 1. Here it is expected that the cost of the laser diode system would be reduced by a factor of a few hundreds in the future. The contribution from the laser system to the total cost is not so large (i.e., ~10 % in total capital cost), because the total laser energy
is kept at 400 kJ. This implies that the COE and the capital cost would not be so sensitive to the expectation on the cost reduction of the laser system. Although the cost of electricity (COE) of FALCON-D reactor is relatively high as a commercial plant, the plant has the moderate construction cost with a dry wall chamber, which can be constructed without much engineering difficulty. Then this design would be in flexible use in the electric grid system.

Table 1. Cost evaluation of the FALCON-D reactor

| Component                     | Cost (BYen) | COE (Yen/kWh)   |
|-------------------------------|-------------|-----------------|
| Buildings and facilities      | 55.4        | 18.24           |
| Chamber and blanket           | 60.1        | 10.90           |
| Turbine & electric equipment  | 62.7        | 0.19            |
| Heat transport system         | 26.8        | 29.34           |
| Pellet factory, and injector* | 55.0        | *2 FCR is assumed to be 10.97%. |
| Other plant equipment         | 36.4        | *3 Not including pellet manufacturing cost |
| Laser system                  | 33.5        |                 |
| Indirect cost and interest    | 74.4        |                 |
| Total plant capital cost      | 403.2       |                 |

*1 The cost of pellet factory is assumed to be 40 BYen.

3. Design of FALCON-D reactor

We have designed a fast-ignition laser fusion reactor with a dry wall, called FALCON-D. The pellet gain $G \approx 100$ is available with laser energies of 350kJ for implosion, 50kJ for heating, resulting in the fusion yield of 40 MJ in one shot. By increasing the repetition rate to be 30 Hz, the fusion power of 1.2 GWth is available, and the net electric power of about 0.4 GWe is achievable. The pellet with the low aspect ratio of 2–4 can be introduced and the pulse shape of the implosion laser is optimized by using the 1-D hydrodynamic simulation code ILESTA-1D. A dry wall of a ferritic steel with a tungsten armour is employed, and the feasibility of this dry wall concept is studied from various engineering aspects such as surface melting, physical and chemical sputtering, blistering and exfoliation by helium retention, and thermo-mechanical fatigue. It is found that blistering and exfoliation due to the helium retention and fatigue failure due to cyclic thermal load are major concerns. As for the maintenance scheme the first wall and blanket system is divided into 20 sectors and a large maintenance port is introduced for replacing the blanket sector. The result of the cost analysis shows that the contribution from the laser system to the total cost is not so large, and the construction cost is moderate.

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