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Titel:
Fast Track Approach towards Laser Fusion Energy in Japan

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Topics:

- General, including complete IFE concepts
- Drivers (including driver-specific technologies
- Reactor engineering and balance of plant

Executive Summary:

In order to realize high-gain fusion burning, a fast ignition scheme is being explored in Japan. In addition, the development of high-repetition and high-power lasers is being promoted with the goal of a laser fusion reactor that performs repetitive operation. As a fast track for the realization of laser fusion energy reactors, a new strategy of IFE in Japan is currently under consideration. The new approach is hydrogen production by fusion energy and its supply by 2050 as HYPERION project: Hydrogen-production Plant with Energy Reactor of Inertial-fusion. Towards the HYPERION project, a high repetition rate laser system of 10 kJ is under development for the purpose of not only accelerating the development of key technologies for the fusion reactor but also exploring a wide range of scientific fields such as high energy density science and fostering human resources.

Introduction:

The goal of laser fusion energy research is to provide energy to humanity, but there are several milestones for this goal. One of them is the ignition and burning of fusion fuel. In Japan as well, a number of achievements have been made with the purpose of achieving laser fusion power generation. A large laser based on a single shot has been developed, and research has been conducted to realize a fusion ignition plasma, which is a physical issue. By the early 1990s, a fusion ignition temperature of 10 keV [1] and a fuel compression density of 1000 times [2] were achieved separately. In the United States, the National Ignition Facility (NIF) consisting of the world's most powerful laser system started operation in 2009. In August 2021, the NIF demonstrated self-sustaining fusion burning, which is essential for extracting energy from nuclear fusion.

Under these situations, laser fusion is at the stage of promoting research and development as a potential new energy source. For this purpose, it is necessary to study the fusion plasma physics, which cause fusion burning with higher gain, as well as the engineering studies to cause repetitive fusion reactions.

In Japan, we started exploring a new ignition scheme, the fast ignition, in the late 1990s. This fast ignition scheme has the advantage of being able to independently optimize fuel compression and fuel heating by using separate lasers to compress the fuel at high density and heat the compressed fuel. On the other hand, the realization of a large and repetitive high-power laser is essential for the engineering approach. To solve this challenge, we have been developing high-repetition high-power solid-state lasers 10 kJ/> 10 Hz/> 100 kW as J-EPoCH project: Japan Establishment for a Power-laser Community Harvest. Based on the above, we are proposing the HYPERION project, which targets the use of laser fusion energy for hydrogen production by 2050.

Laser Fusion Plasma Physics for the Fast Ignition

In the fast ignition (FI) scheme, an ultra-intense laser light generates high energy particles such as relativistic electron beam (REB) to heats a high density compressed fuel. The first demonstration of fast heating of laser compressed fuel has been made with a cone geometry for the efficient propagation of the heating laser pulse to generate the REB close to the high-density core plasmas [3,4].

Details of the heating mechanisms was investigated through experiments and simulations. Based on these understanding, We have succeeded in creating pressures of 2.2 Peta-Pa with a laser energy (implosion + heating lasers) of only 2.5 kJ [5] by fast heating of the imploded high-density plasma as in the fast ignition scheme. This result was achieved through the understanding of the fast heating physics in the imploded plasmas. As the experimental results show, it has been found that the high-density REB can heat up the core plasma with very high efficiency. However, the electron flow was quite high, and there might be a concern whether the stable energy transport for ignition could be realized. In the high densities of the core plasma, collisions processes are dominant and instability is suppressed. On the other hand, when the temperature is high, electrons diffuse non-locally and become stable. In other words, electron flow becomes unstable in the regions where the density is not so high and the temperature is below a certain level. Based on this classification of the transport of high-density REB, the REB could be stably transported to the core in the future ignition experiments as well as in current heating experiments.

Optimal fuel compression for the FI is critical to realize the efficient ignition of the laser fusion. The FI scheme can optimize separately the processes of the fuel compression and the heating of the compressed fuel. We find that a solid spherical fuel target will be more feasible, to stably obtain high-density fuel compression without a risk of the hydrodynamic instability. High density compression of the solid sphere attached a Au cone target, which could be hydro dynamically stable, had been experimentally demonstrated[8]. Based on 2D simulation results, about 130kJ would be required to obtained $\rho R_{\mathrm{max}} = 1.0\ \mathrm{g\ cm^{-2}}$ using a solid sphere and multi-step laser pulse [6]. More efficient coupling > 20% would be expected through the optimal heating processes to initiate ignition and burning of the compressed fuel with 50-100kJ heating laser energies [7].

High Repetition Laser System J-EPoCH for HED Science and LFE

We are developing a 100J/100Hz high power lasers with an active mirror amplification scheme using Yb:YAG ceramics pumped by laser diodes. Based on this system, we are now planning a new type of high-power laser system to explore a variety of new fields of sciences in the J-EPoCH project. This facility integrates all the state-of-arts high power laser technologies, based on the 160 beams of 100Hz /100J laser module, providing high repetition 10kJ long pulse lasers, 5-20PW short pulse lasers and different kinds of laser plasma accelerators, and laser-driven radiation sources such as x-rays and neutrons.

This multi-purpose high-repetition laser system will also open a new frontier of laser fusion energy development. The high repetition system will realize data-driven analysis of fusion plasma for the optimal target design as well as testbed of laser fusion reactor engineering with a fusion subcritical reactor [8]. The reactor consists of a dedicated target chamber, a target delivery system, a hollow sphere core and a vacuum system with tritium recovery, except for the laser system. We apply the past-well-known experiments at GEKKO-XII laser facility with a Large High Aspect Ratio Target (LHART) [9, 10]. Based on this result, the fusion reaction in the J-EPoCH facility would have the potential to be a point fusion neutron source with a yield of 10^{13} n/shot. The subcritical reactor is a simple system configuration and can operate in relatively lower vacuum condition compared to the magnetic fusion reactors. This is one of the advantages of the laser fusion research and it make engineering research with interchangeable cores available. A variety of fusion engineering experiments would be conducted by preparing cores dedicated for research purposes. The system applies neutrons that come from subcritical fusion reactions. The subcritical research reactors with interchangeable cores can be used not only for inertial confinement fusion experiments but also for various purposes such as magnetic confinement fusion engineering. The core consists of an inner shield, a neutron multiplier, materials for the neutron–thermal (n-t) energy conversion or tritium breeding and a neutron reflector. The core size is not modified for each purpose. Based on the neutron yield of 10^{13} n/shot of the LHART experiments, $\sim 10^{14}$ n/m^2 s fusion neutron flux by 1 Hz operation of the J-EPoCH is applicable for material tests. Furthermore, the reactor with the B4C and the LiPb cores will realize the first fusion thermal power generation of 14 W and the tritium yield of 9.1×10^{11} /shot, respectively. The laser fusion subcritical research reactor has the potential to conduct fusion engineering experiments such as neutron irradiation effect, fusion power demonstration, n-t conversion and tritium breeding.

HYPERION as Fast Track towards Laser Fusion Energy

It is said that the commercial use of fusion power generation will be after 2050. In comparison, we have recently proposed a new strategy based on clean hydrogen production by laser fusion thermal energy: the HYPERION Project (Hydrogen-production Plant and Energy Reactor of Inertial-fusion). This is a Fast Track strategy to realize commercial use of laser fusion energy without connection to the commercial power grid by 2050, instead of the conventional strategy of direct grid connection of fusion power. This will not only shorten the development period of the fusion reactor, but also shorten the development steps, leading to a reduction in development costs.

In the HYPERION project, a small fusion test reactor with a hydrogen production system (hydrogen production target: >1.7t/h) will be realized around 2040 using a medium gain laser fusion target with a laser system (0.5MJ/2Hz/1MW/electric efficiency: 20%). In addition, by 2050, we hope to achieve a commercial reactor for hydrogen production that drives four fusion reactors (4Hz/ reactor) with an advanced laser system (0.5MJ/16Hz/8MW). This will result in a clean hydrogen production rate of >27 t/h or 130,000 t/y per plant (55% availability) and hydrogen production cost <2.3$/kg (current green hydrogen production cost: 3-8$/kg).

In order to realize this goal, it is necessary to accelerate the development of key advanced technologies as well as human resource development within 10 years. We can construct a subcritical fusion reactor with a multipurpose large repetition rate laser device (10 kJ/10-100 Hz/0.1-1 MW) such as the J-EPoCH described above, and demonstrate the principle of hydrogen production and power generation by fusion energy. This will be the start of the development of almost all the elemental technologies for laser fusion reactors. The hydrogen power generation system will be developed separately by other hydrogen utilization technology development projects, and here we can focus on the development of technology directly connected to fusion energy. In addition, a large repetitive laser device such as J-EPoCH, which enables a variety of applications, is expected to dramatically increase opportunities for human resource development.

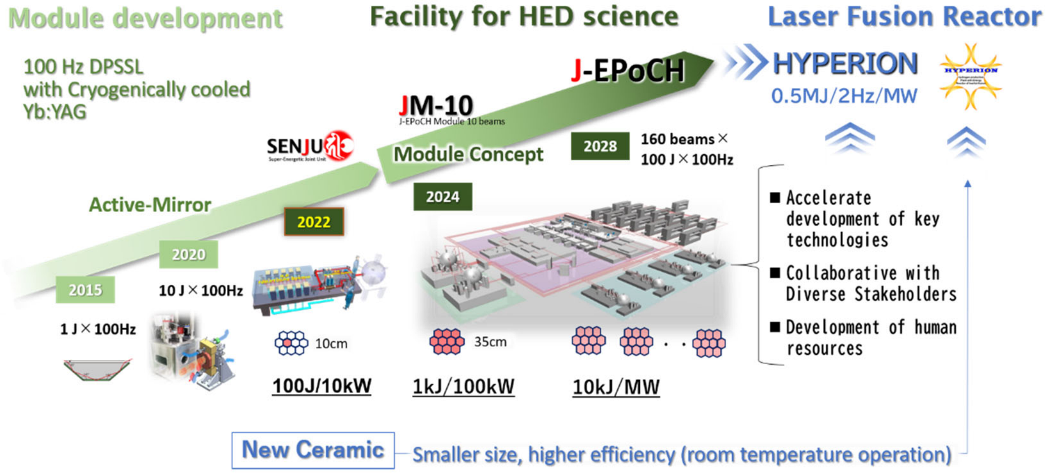

Figure 1 Progress and Prospect of Development of the Large-Scale High-repetition Laser Systems

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