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Review of Japanese fusion program and role of inertial fusion

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Abstract. The high compression of 600 times liquid density and the recent fast heating of a compressed core to 1-keV temperature have provided proof-of-principle of the fast ignition concept, and these results have significantly contributed to approve first phase of the Fast Ignition Realization EXperiment (FIREX) project. The goal of FIREX-I is to demonstrate fast heating of a fusion fuel up to the ignition temperature of 5–10 keV. Although the fuel size of FIREX-I is too small to ignite, sufficient heating will provide the scientific viability of ignition-and-burn by increasing the laser energy thereby the fuel size. Based on the result of FIREX-I, the decision of the start of FIREX-II to achieve ignition-and-burn can be made. The FIREX program is under the collaboration of the Institute of Laser Engineering and the National Institute for Fusion Science.

PACS. 52.50.Qt Plasma heating by radio-frequency fields; ICR, ICP, helicons – 52.55.Hc Stellarators, torsatrons, heliacs, bumpy tori, and other toroidal confinement devices – 52.57.-z Laser inertial confinement – 52.57.Kk Fast ignition of compressed fusion fuels

1 Introduction

The objectives of the fusion program in Japan are clearly highlighted by the following four points. The first point is that it an energy development program. The second point is that there is a strong interest to produce a large scientific output. The third is that a strong interest exists in plasma physics, High energy density, nonlinear phenomena, space and astrophysics, etc. The fourth is the contribution to the technology area.

On January 8th 2003, the Ministry of Education, Culture, Sports, Science and Technology (MEXT) issued an important report on the fusion entitled "Future Direction of National Fusion Research". This report proposes a newly defined grand design of Japanese fusion research, which encourages a paradigm shift of fusion research from the multilateral approaches to the concentrated ones with enhanced mutual collaboration. This was a necessary process to prepare for hosting ITER in Japan. It is said that LHD (helical) and FIREX (laser) should be nominated to the major science programs, and that JT-60 (tokomak) and IFMIF (fusion material development) to the major development programs. The latter two programs directly support the ITER program, whereas the former two programs aim at advanced concepts of fusion reactor. The role of research in universities is recognized again to be very important to provide the research basis of plasma physics, fusion science, and reactor engineering. Since the National Institute of Fusion Science (NIFS) is a part of the Inter-University Research Institute Corporation, it has an increasing responsibility to fulfill the collaboration among universities.

It is a key for fusion research to understand the phenomenon of high energy density and temperature plasmas. Fusion research has been always providing the new database necessary for us to advance to the next step. "High Energy Density and Temperature Plasmas" reveals the domination of equilibrium, stability, and transport processes.

In Japan, laser fusion has been recognized as a proof-of-principle level experiment, which is to be carried out by the Institute of Laser Engineering (ILE), Osaka University. Now, ILE is conducting the first phase of the FIREX (Fast Ignition Realization EXperiment) project. The previous high compression of 600 times liquid density and the recent fast heating of a compressed core to 1 keV in temperature have provided proof-of-principle of the fast ignition (FI) concept, and these results significantly contributed to the promotion of FIREX-I program. The goal of FIREX-I is to demonstrate the fast heating of a fusion fuel up to the ignition temperature of 5–10 keV. Although the fuel of FIREX-I will not ignite due to the small fuel size, sufficient heating will provide the scientific viability to achieve the ignition-and-burn in FIREX-II phase, the decision of which will be made based on the result of FIREX-I. The FIREX program is being carried out under the collaboration of ILE and NIFS, including development of cryogenic targets, holistic simulation systems, and diagnostic equipments.

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2 Efforts to establish a new direction of national fusion research in Japan

A Working Group on fusion research has been organized by the Special Committee on Basic Issues, Subdivision on Science Council for Science and Technology, Ministry of Education and Science (MEXT) in September 2001, which played an important role to establish the new direction of fusion research in Japan preparing for the start up of the construction of the ITER project. Especially, the WG examined ways to establish centralization and efficient implementation among representative researchers in this field. The final report was submitted to the Government on January 8th in 2003.

The key points of assessment by the peer review are that the fusion community should

(1) have a clearer contribution to ITER and stronger international competitiveness;
(2) enrich research programs leading to the wider possibilities of fusion reactors;
(3) enrich research programs leading to universal scientific understanding;
(4) enrich training programs (education of students training of young researchers).

The important outputs are the following,

(1) WG recommends the rearrangement and integration of existing facilities, and designates "Centralized Joint Research Devices (LHD, JT-60U, FIREX-I, IFMIF)" to enable new research opportunities for the fusion research community;
(2) recognizes the importance of the promotion of the inter-university and inter-institution cooperative researches;
(3) the necessity to create new and advanced research programs with challenging targets.

The WG showed the grand design of Japanese fusion research from now, which is shown in Figure 1.

This is a stratified strategy, which means that to advance fusion research, the integration of science and technology is strongly required.

Then the role of NIFS is clearly suggested by the WG Report. The first point is the necessity to keep close relations with universities as an Inter University Institute. The second point is that NIFS has an increased responsibility as a center of excellence of fusion research. And the third point is the important educational function in cooperation with the Graduate University for Advanced Studies (SOKENDAI). Since these were originally defined as the objectives of NIFS founded in 1989 as Inter-University Institution. Thus the WG confirmed again the framework to develop fusion science research in Japan.

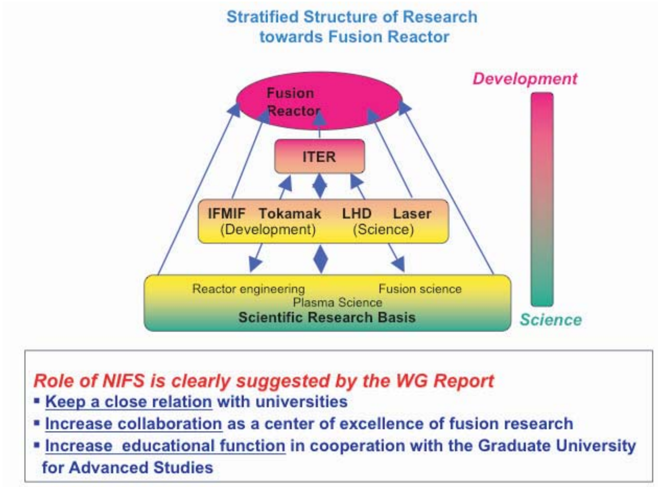

Fig. 1. (Color online) Grand design of Japanese fusion research.

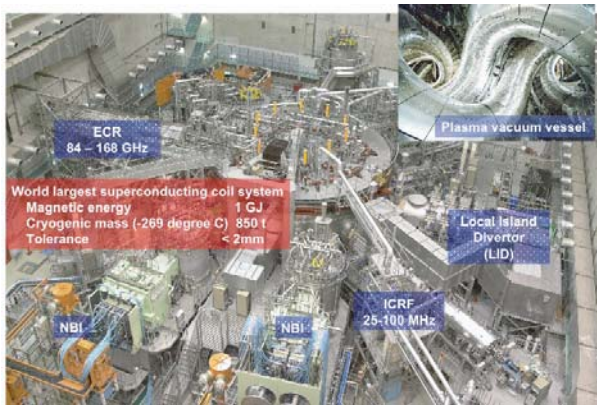

Fig. 2. (Color online) Present view of Large Herical Device (LHD).

3 Progress of the LHD project

The Large Helical Device (LHD) is the largest heliotron device with superconducting coils in the world. Since experiments started in 1998, the development of engineering technologies such as heating devices, diagnostics and plasma control systems, and the demonstration of large-super-conducting-machine operations have contributed to an understanding of physics in current-less plasmas and verification of the capability of full steady-state operations. View of LHD machine is shown in Figure 2.

Objectives of LHD are well summarized in Table 1 and the major specifications of the LHD are shown in Table 2. Achieved electron and ion temperatures have gone up every experimental campaign and approached 10 keV and 13.5 keV, respectively [1]. The pulse length of a discharge has approached 3900 s in the 8th campaign as shown in Figure 3. Especially, steady state and high-beta experiments, which are the most important subjects for the realization of attractive fusion reactors, have progressed remarkably and produced two world-record parameters, i.e. highest average beta of 4.4% in helical devices [2] and highest total input energy of 1.3 GJ in all magnetic confinement devices [3]. High beta plasma production has successfully advanced year by year by an increment of heating power as shown in Figure 4. The highest beta value was obtained in FY2005 experiments, and the plasma was produced and maintained by two neutral beam

Table 1. Role of Large Herical Device (LHD) project (construction started in 1989).

(1)	Realization of a high fusion triple product (density × ion temperature × energy confinement time). → Extensive confinement study is requisite for a fusion reactor. → Confinement improvement leads to a compact reactor.
(2)	Demonstration of a stable long-pulse discharge.
(3)	Clarification of the role of radial electric field in plasmas with high ion temperature.
(4)	Realization of beta as high as 5% and exploration of related physics.
(5)	Control of edge plasmas by divertor for simultaneous achievement of confinement improvement and a stable long pulse discharge.
(6)	Investigation of high energy particles in helical fields. → Experiment is necessary to simulate physical properties of alpha particles of fusion plasma.
(7)	Implementation of deuterium discharges and study of isotope effects.

Table 2. Specifications of LHD.

External diameter	13.5 m
Plasma major radius	3.9 m
Plasma minor radius	0.6 m
Plasma volume	30 m^3
Magnetic field	3 T
Total weight	1.500 t

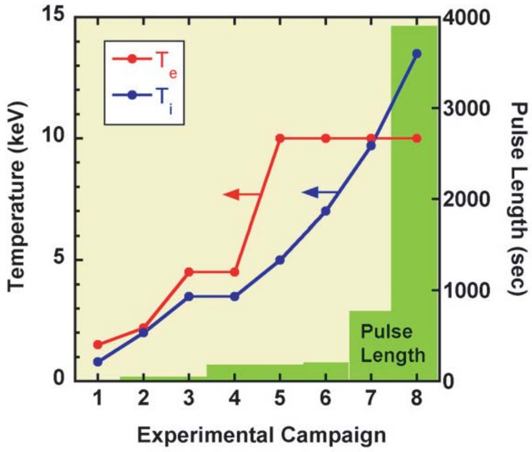

Fig. 3. (Color online) Progress of achieved electron, ion temperatures, and pulse length of discharge.

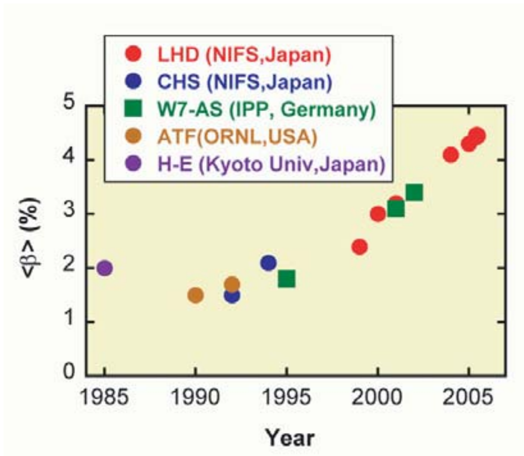

Fig. 4. (Color online) Development of beta value achieved in various helical devices vs. year.

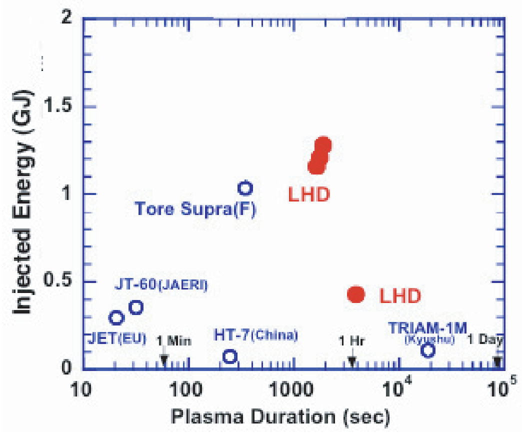

Fig. 5. (Color online) Maximum injected energies of major steady-state.

injection (NBI) systems with a total power of 11.9 MW. Serious magneto-hydrodynamic instabilities which lead to a degradation of plasma confinement have not been observed, which means that the helical device has a high capability for high beta plasma production. Long pulse operation has been prolonged beyond 1 h. The relationship between maximum injected energy and plasma duration is shown in Figure 5. The plasma was heated and sustained by Ion Cyclotron Resonant Frequency (ICRF) heating an additional Electron Cyclotron Heating (ECH) and NBI heating. The central ion temperature was around 2 keV. The average input power was 680 kW and the plasma duration was 31 min 45 s. As a result, the total input energy to the plasma reached 1.3 GJ, which is the largest energy injected to high temperature plasmas at the keV level among all magnetic confinement devices, including tokamaks and helical devices. These results can be attributed to the physical realization of a highly improved magnetic configuration for neoclassical as well as anomalous transport in conjunction with the advantages of a superconducting device. The target and achieved plasma parameters are listed in Table 3.

The superconducting magnet system consists of a pair of continuous helical coils and three pairs of poloidal coils, and their magnetic stored energy is about 1 GJ. The numbers of cool-down and excitation cycles have reached 8 and exceeded 800, respectively, in seven years of operation. No

Table 3. Plasma parameters achieved at LHD.

	Target (∼2003)	Achievements
Fusion triple produc	2.0×10^{19} keVm^{-3} s	2.3×10^{19} keVm−3 s
Ion temperature	1.1 keV:$T_i(0)$	0.8 keV:$T_i(0)$
density	4.8×10^{19} m^{-3}	8×10^{19} m^{-3}
confinement times	0.36 s	0.37 s
Electron temperature		
central ele. temperature	10 keV	10 keV
at density	5×10^{18} m^{-3}	5×10^{18} m^{-3}
Ion temperature		
central ion temperature	10 keV	10 keV
at density	3.5×10^{19} m^{-3}	3×10^{18} m^{-3}
Beta	$\beta = 4.4\%$ at $B = 0.45$ T	$\beta = 4.4\%$ at $B = 0.45$ T
Pulse length	756 s	1 h 5 min 110 kW
(steady-state operation)		31 min 45 s 680 kW

degradation has been observed in the coil performance, and stable cryogenic operational schemes at 4.4 K have been established [4]. The operation with a toroidal magnetic field of up to 2.9 T at $R = 3.6$ m has been applied to plasma experiments. An upgrade of the cooling capability by employing 3.0 K sub-cooled helium is planned. The sub-cooling R&D experiment has successfully demonstrated the actual applicability to LHD [5]. This suggests that the operation with a toroidal magnetic field of more than 3 T is available, and application to LHD is planned in the nearest future.

Three NBI systems are based on negative ion sources with the accelerating voltage of 180 keV and their total power is 14 MW. In addition, the perpendicular NBI system with positive ion sources at 40 keV is newly available in the FY2005 experiment. The ECH systems with 2.3 MW, and ICRF heating systems with 2 MW have also been prepared and have realized long pulse discharges of 65 min with 110 kW and 30 min with 520 kW, respectively. Innovative fueling and pumping systems have been utilized in the experiment. In particular, the Local Island Divertor has demonstrated its high capability of particle control. The physics and engineering results from the LHD experiment directly contribute to the design study for a D-T fusion demo reactor FFHR with an LHD-type heliotron configuration [6].

The role and position of LHD become very clear if we refer the report on the ITER broader approach. The group of experts identified three main classes of activities/functions within a broader approach, as follows:

(1) primarily ITER oriented: joint implementation of ITER (including a possible remote data centre);
(2) ITER/DEMO oriented: satellite tokamak function — ITER/DEMO Physics support function;
(3) primarily DEMO oriented: DEMO Concept Definition, Design and Co-ordination of R&D Activities in Physics and Technology IFMIF.

Here, the overall assumption is that strong domestic programs will continue, which support and complement the above activities and functions. And, the main functions in support of DEMO will be to explore operational regimes and issues complementary to those being addressed in ITER. In particular these will include (1) steady state operation; (2) advanced plasma regimes higher normalized plasma pressure; and (3) control of power fluxes to walls. The important point is that these were included in the objectives of the LHD project more than 15 years ago. LHD will contribute ITER project.

4 Fast ignition study

It is a very good opportunity to express the high potential of Japanese IF research. The concept of fast ignition is that a fuel is first employed by uniformly irradiating laser light, followed by fast injection of a second high-intense laser pulse at the exact timing of the maximum compression. Subsequent heating of the fuel triggers thermonuclear ignition, thereby driving a burn wave propagating through the entire region of the core. The most significant advantage of the fast ignition is that it can ignite at the laser energy of only about one tenth of that required for the conventional central ignition. The reason of the low energy requirement is that the fuel volume for fast ignition is much smaller than that for the central ignition. The concept of the fast heating is first proposed by Yamanaka in 1983 [8] and independently by Basov in 1992 [9], and the final concept based on peta-watt laser was come out by Tabak in 1994 [10].

Since then, a lot of work has been devoted to understand elementary processes of fast ignition. But there has been few integrated experiment that demonstrates the concept of fast ignition. The ILE has a unique capability to conduct such experiments. GEKKO XII is a 12 beam green laser with uniform irradiation system suitable for high-density compression, whereas Peta-Watt is a 1-beam red laser delivering 1-kJ energy in 1 ps, The timing of these two lasers are completely synchronized.

Figure 6a illustrates the target configuration of the integrated experiment [11], where we have inserted a gold cone into a spherical shell to provide an entry path for the heating laser into the vicinity of the compressed core. Even with the non-uniformity introduced by the cone, the target density was well within the experimental scaling of the uniformly irradiated targets [12]. This is because

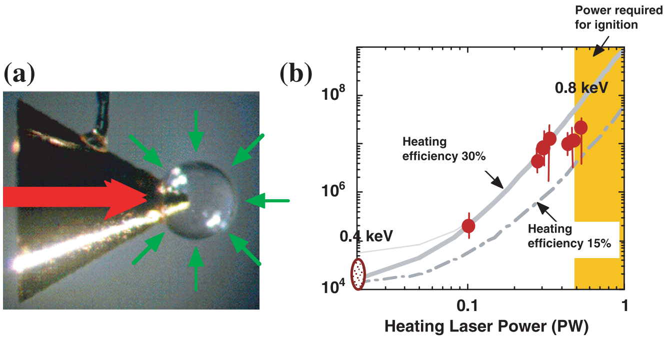

Fig. 6. (Color online) (a) A fuel shell attached with a gold cone for laser entry; (b) DD neutron yield as a function of the heating laser power [11].

the implosion process is highly supersonic, whereas the influence of the cone propagates along the shell only with the sound velocity. It follows, therefore the implosion ends before the most part of the shell suffers the influence of the cone.

The heating of the compressed core has resulted in the temperature increase from 0.4 keV (without heating) to 0.8 keV (at about 1-PW heating). This temperature was measured from Doppler broadening of the neutron time-of-flight spectra and from the bremsstrahlung emission spectra. Consequently, the neutron yield was increased by three orders of magnitude, as shown in Figure 6b. The neutron yield is also calculated for various heating efficiencies (increment of thermal energy in the core/laser energy). It appears that the observed neutron yield is well bounded by two predictions with heating efficiency of 15% and 30%. This efficiency is high enough to ignite a core with only several tens of kJ.

There are two physics bases to be studied for better understanding of fast ignition. As for the fast heating, we have clarified the heating mechanism by using planar targets with and without a cone [13]. It is expected from the PIC simulation that both the laser light and the hot electrons generated on the inner surface of the cone are favorably concentrated into the tip of the cone. In the experiment with a cone, the angular distribution of the electron emission was narrowed by a factor of two. Consequently, the temperature of the plane target was increased by a factor of 2–3. These results are quantitatively in agreement with the prediction.

The second physics basis is the Rayleigh-Taylor (RT) instability as the primary obstacle against to high-density compression. We have found a new mitigation scheme of the RT instability on the bases of good understanding of the instability. When targets are doped with proper high-Z material with proper amount, the X-rays from the high-Z atoms generate a new ablation structure in front of that driven by electron thermal conduction. The X-ray driven ablation is much more stable than the generic electron ablation because of the high ablation velocity and the long density scale-length, whereas electron ablation is almost completely stabilized by extremely high ablation velocity there. Figure 7 compares the RT growth in

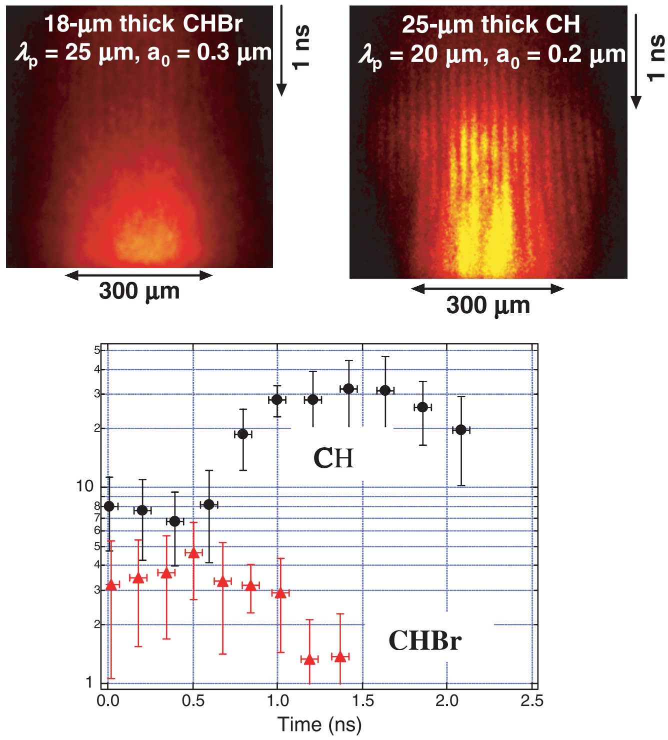

Fig. 7. (Color online) Rayleigh-Taylor growth in CH and CHBr.

a generic plastic (CH) target with that in a plastic target doped with Br by 3 atomic%. Two pictures show the X-ray backlighting images. Like Röntgen picture, the perturbation is recorded as an X-ray intensity distribution. The temporal change of the distribution was recorded with an X-ray streak camera. It is clearly seen in the right figure that the RT in Br doped target is well stabilized.

4.1 FIREX project

To date, two major milestones towards fast ignition have been achieved: the high density compression up to 600 times liquid density [12] by the GEKKO XII laser, and the fast heating of the compressed core up to 1-keV temperature [11] by the Peta Watt (1 kJ/1 ps) laser. The consequent step is to start the FIREX project. In order for the program to be flexible, the project is divided into two phases. The goal of the first phase is to demonstrate the ignition temperature of 5–10 keV by a high-energy peta-watt (10 kJ/10 ps) laser [15] that is currently under construction. The goal of the planned second phase is to demonstrate ignition and burn. Figure 8 shows a recent picture of the 10 kJ peta-watt laser, which is built beside the existing GEKKO XII. The laser is a 4-beam and 4-pass regeneration amplifier system. The first high-energy shot of more than 1 kJ/beam was demonstrated on March 2005. The pulse compressor system will be installed soon.

If sufficient heating will be demonstrated, the start of the FIREX-II project will be seriously considered.

Fig. 8. (Color online) Recent development of FIREX-I.

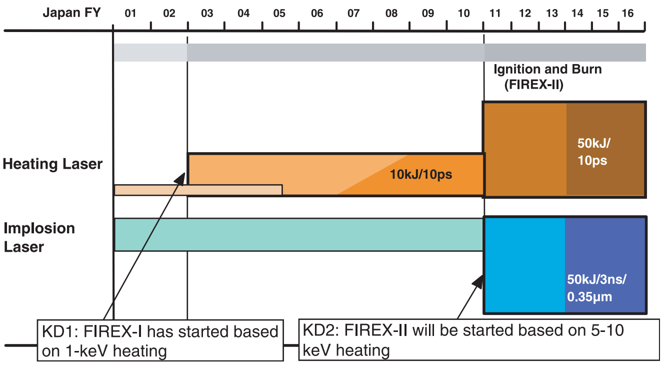

Fig. 9. (Color online) Timetable of FIREX project.

Although the expected energy gain (fusion energy/laser energy) in the FIREX-II project is only 10 at maximum, it can be increased simply by increasing the size of the compressed core, that is, by increasing the confinement time. Our two-dimensional hydro-code simulation predicts that energy gain increases monotonically from the FIREX to the reactor and it saturates at high gain region due to the depletion of the fuel. There is no essential difference between the FIREX-II plasma and the reactor plasma except for the size. This is why ignition and burn in FIREX is so important. In the FIREX-II project, the implosion laser is planned to be a 92 beam, 50 kJ/3 ns blue laser, whereas the heating laser to be a 50 kJ/10 ps red laser. The physical size of the whole laser system will fit to the existing GEKKO building.

Figure 9 shows the timetable of the whole FIREX project. The first experiment will start in FY2007, followed by the integrated experiment until the end of FY2010. If subsequent FIREX-II will start as proposed, the ignition and burn will be demonstrated in parallel to NIF and LMJ.

4.2 Reactor technology development

Reactor lasers are the second critical element for energy development. Recent study of diode-pumped solid-state laser (DPSSL) has demonstrated the high-rep rate (10 Hz) operation at reasonably high energy (10 J per pulse) at high efficiency (7%). One remaining issue of the reactor laser development is to find suitable laser materials. They must have a large thermal shock parameter and a suitable emission cross section. Our new material of ceramic crystal, Yb:YAG, has higher thermal shock parameter than any other previous materials by a factor of ten [16]. Although the emission cross section at room temperature is out of the required region, it can by tuned to be in the suitable region by cooling the crystal down to 150–270 K. Furthermore, the thermal shock parameter is increased by cooling because the reduced thermal motion of the atoms increases the thermal conductivity.

Target and reactor technology is the third critical element for energy development. We have established a mass-production technique of high performance plastic targets [17]. Targets with various sizes necessary for the current experiment to the future reactor use are already produced. The reactor concept based on fast ignition is under intensive consideration [18]. The reaction chamber will have vertically off-centered irradiation geometry to simplify the protection of the ceiling. The wall will be made of porous metal plates that are saturated with liquid LiPb. The final optics will be protected from debris by a differentially rotating shutter. The thermonuclear ignition by the FIREX project and reactor technology development will provide physics and technology basis to propose the first integrated machine towards energy source, that is, Laser Fusion Experimental Reactor (LFER). A 100 J $\times$ 1 Hz implosion laser and a 100 J $\times$ 1 Hz heating laser will generate 10 MWth at the energy gain of 50. About 40% of the output energy is converted to electricity by a power generator. A half of the electricity will be used to drive the laser with 10% efficiency, whereas another half will be transferred to the grid.

4.3 Summary of fast ignition study

In summary, the proof-of-principle experiment has demonstrated efficient heating up to 1 keV temperature. Based on this achievement and previously achieved high-density compression, FIREX-I has started to demonstrate ignition temperature. After the ignition temperature is achieved, FIREX-II will start to demonstrate ignition and burn in parallel to NIF/LMJ ignition. As for the key technologies for IFE reactors, diode-pumped solid state laser has demonstrated 10 Hz rep-rate and 7% efficiency required for IFE reactors. A cooled ceramic crystal of Yb:YAG has been innovated as a favorable laser material that has large size, high thermal conductivity and suitable emission cross section. The first wall and the final optics protection are under intensive investigation. Accordingly, we can conclude that the fast ignition has enlarged the possibility of IFE reactors.

We would also conclude that the roles and functions of fusion research in Japan are achieving long-term integration of physics and engineering necessary for energy development, promoting developmental research that follows the critical path, and insuring the development of the supporting technologies and basic sciences necessary for fusion research. Furthermore, they are also continually disseminating scientific results and leading the development of advanced science and technology in the field of nuclear fusion, and finally steadily training necessary human resources.

Finally, we would also like to mention that there are growing activities of high power laser science and laser fusion throughout East Asia. These are in China (Laser Fusion Research Center, Institute of Optics and Fine Mechanics, Institute of Appl. Phys. and Computational Mathematics, and Institute of Physics) and in Korea (Korea Atomic Energy Research Institute, and Korea Advanced Institute of Science and Technology).

5 Conclusion

In this paper roles and functions of fusion research in Japan are briefly reviewed. Japanese fusion research is achieving long-term integration of physics and engineering necessary for energy development. There are a lot of efforts to promote developmental research that follows the critical path. This means that required needs produced the system integration between science and technology. In Japan, the Working Group Report on fusion research issued in January, 2003 plays an important role. To put the fusion research forward, the development of the supporting technologies and basic sciences necessary for fusion research are both necessarily insured. As a result, this area is possible to disseminate scientific results and leading the development of advanced science and technology in the field of nuclear fusion. As a result, It is obviously necessary to train young human resources steadily.

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