The FIREX Program on the Way to Inertial Fusion Energy

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Abstract. Thermonuclear ignition and subsequent burn are key physics for achieving laser fusion. Laboratory ignition with very large laser systems is now anticipated with the National Ignition Facility (NIF) in the US and Laser Mega Joule (LMJ) in France. Fast ignition has a potential to achieve ignition and burn with about one tenth of laser energy required for these programs. With the fast ignition, the fuel compression and heating are separated, with ignition initiated by a short very high power laser pulse incident on the already compressed fuel. The fast heating of a compressed core, together with high-density compression, has provided the scientific basis for the start of the Fast Ignition Realization EXperiment (FIREX) project. The goal of the first phase (FIREX-I) is to demonstrate ignition temperature of 5-10 keV, followed by the second phase to demonstrate ignition and burn. Coupled with the achievement of central ignition on NIF and LMJ, the research focus would then move to the demonstrations of high gain and of the inertial fusion energy technology. These programs would converge onto a laser fusion test reactor that can deliver net electric power by 2030. We would expect the test reactor program as a truly international activity.

1. INTRODUCTION

By the time of thermonuclear ignition by lasers, it will have passed more than 20 years since the end of the Cold War. Global warming is instead becoming the central issue that humankind has to solve. Fission energy is obviously one of the primary solutions for this. The magnetic fusion community has started the ITER program to participate in solving the global crisis. What about inertial fusion?

Although the National Ignition Facility (NIF) in the US and Laser Mega Joule in France are anticipated to demonstrate first ignition and burn in a controlled way, there still exists a quite large distance towards realization of fusion energy, that needs operation of gigantic lasers in high repetition. This large distance is the primary reason why inertial fusion is NOT viewed by many people as an energy program. Compact ignition schemes are therefore critically important for energy development. One promising approach is the fast ignition (FI) [1-3] illustrated in Fig. 1. The fusion fuel is first imploded by irradiating laser light just like the standard fashion except for the insertion of a cone in some cases. At the

Fig. 1. Concept of fast ignition. A hot-spark is created much faster than disassembly of the compressed core.
maximum compression timing, a high-intensity short-pulse laser is injected through the cone. Since the heating laser pulse is much shorter than the hydrodynamic time scale, a high-density hot-spark can be created before significant hydrodynamic disassembly. The most distinct advantage of FI is that it can ignite at a laser energy of only about 1/10 of that required for the central ignition. The compactness of FI will open a new electric market, such as peak electric demand.

2. PROOF-OF-PRINCIPLE EXPERIMENT

In order to achieve FI with reasonably small-size lasers with several tens to a hundred kJ, one need 1) high density compression of thousand times liquid density and 2) good coupling from laser to thermal energy of the fuel with an efficiency of 20-30%. The first issue to be addressed was whether one can achieve high-density compression with cone targets. Contrary to the intuition, the shell material concentrates at the close proximity to the cone tip [4] as shown in Fig. 2. The compressed density, deduced from x-ray radiography, did not very differ from the density data of no-cone implosion that scales as high as 600 times liquid density [5]. This is because the implosion velocity is much higher than the rarefaction wave that destroys the integrity of the shell. Accordingly the shell implodes almost ballistically without any significant influence from the cone. Subsequent studies of the cone implosion are reviewed in Ref. [6]

As for the cone heating, it is expected that the laser light is concentrated into the tip of the cone by laser interference. Relativistic electrons are then generated by intense laser fields and guided into the top of the cone [7]. In the experiment shown in Fig. 3, the fast heating of the compressed core raised the temperature from 0.4 keV without heating to 0.8–1 keV at about 0.5 PW heating. As a result, the fusion neutron yield increased by three orders of magnitude. More importantly, the neutron yield data indicate that a sizable fraction of 20-30% of the laser energy is converted to the thermal energy of the core.

3. FIREX PROJECT

The consequent milestone is obviously to demonstrate ignition and burn. The program to achieve this milestone is named as Fast Ignition Realization EXperiment (FIREX). In order for the program to be flexible, it 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 (10kJ/10ps) laser [8]. This is followed by the second phase to demonstrate ignition and burn.

Since the burning wave travels through the entire fuel at a velocity much faster than any other hydrodynamic velocity, the burning proceeds no matter what the fuel size is. The energy gain increases simply with increasing the size of the compressed core. Indeed, our two-dimensional hydro-code simulation predicts that energy gain increases monotonically from 5-10 at FIREX to more than
100 at reactors. 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 50kJ/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 be relatively small to barely fit to the existing GEKKO building. Figure 4 shows the timetable of the whole FIREX project. The first experiment will start in FY2008, followed by the integrated experiment until the end of FY2010. The start of the FIREX-II project can be judged according to the success of the FIREX-I project. If the subsequent FIREX-II project will start as proposed, the ignition and burn will be demonstrated in parallel to National Ignition Facility and Laser Mega Joule so that both central and fast ignition schemes can be compared.

The Council for Science and Technology under the Ministry of Education, Culture and Sports, Science and Technology (MEXT) has positively evaluated the proposal of FIREX and made a recommendation to start FIREX-I in the report entitled “Future Direction of National Fusion Research”[9]. Subsequently, Atomic Energy Commission of Japan, Advisory Committee on Nuclear Fusion, has reported that “Based on its (FIREX-I) achievement, decide whether it should be advanced to the second-phase program aiming at the realization of ignition and burning” in the report entitled “National Policy of Future Nuclear Fusion Research and Development” [10].

Figure 5 shows a recent picture of the heating laser, that has a 4-beam and 4-pass regeneration amplifier system. For short pulse operation, broad band laser light has to be amplified. A high energy of 3 kJ/1beam has been demonstrated at the broad band operation. The full beam equivalent of 12 kJ is above the design value.

4. BEYOND FIREX

The field of Inertial Fusion Energy (IFE) from the FIREX Project is on the verge of a transformational event with the expected achievement of central ignition within the next few years. It is imperative that the IFE community prepares for this event by agreeing on a credible plan for its development from scientific demonstration to commercial energy production.

At present, there are significant research programmes in the USA, Europe and Asia with plans for intermediate scale facilities for advanced ignition research such as FIREX-II, HiPER and various options within the USA including Advanced Radiographic Capability on NIF. These regional programmes need to be aligned into a single international strategic plan with coordination of the research at an international level. Coordination would accelerate the research and help to produce a program whose scale would be able to meet the critical need for clean energy production in a reasonable timescale. We envisage the coordination of our near term research in the period 2009-2012 to achieve a demonstration of energy gain of $Q \approx 0.1$ via advanced ignition schemes on FIREX-I and
OMEGA-EP. Coupled with the achievement of central hot-spark ignition on NIF in the same period, the research focus would then move to the demonstration of high gain and the delivery of the enabling IFE technology. These programs would converge onto a truly international fusion demonstrator, which we have named International Laboratory Inertial Fusion Test facility (i-LIFT) illustrated in Fig. 6. A 100-kJ, 1-Hz implosion laser and another 100-kJ, 1-Hz heating laser will generate a 10-MW thermal power at the energy gain of 50. Among the thermal output, 40% of the energy is converted to electricity by a power generator. A half of the electricity, 2 MW, will be used to drive the laser with 10% efficiency, whereas another half will be transferred to the Grid. The power and stability of the experimental reactor are merely comparable to those of a typical wind power machine. But the net electrical power production will be a landmark of fusion energy development. The concept has been developed from an earlier study in Japan [11]. Figure 7 shows the logical load-map for the Inertial Fusion Energy development. If enough funding is given, power generation can be expected by 2030.

5. SUMMARY AND CONCLUSIONS
In summary, the proof-of-principle experiment has demonstrated efficient heating up to 0.8–1 keV temperature. Based on this achievement and previously achieved high-density compression, FIREX-I has started to demonstrate ignition temperature. Once the ignition temperature is achieved, FIREX-II should be started to demonstrate ignition and burn in parallel to NIF/LMJ ignition. Coupled with the achievement of central hot-spark ignition on NIF in the same period, the research focus would then move to the demonstration of high gain and the delivery of the enabling IFE technology. These programs would converge onto a truly international fusion demonstrator by 2030.

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