From Fast Ignition Realization Experiments (FIREX) to Electric Power Generation (LIFT)

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Abstract. One of the four beams of the short pulse laser (LFEX) for the fast ignition realization experiment (FIREX) project was successfully installed and the first integrated implosion experiment with the LFEX laser was performed from July 2009 to October 2009. Initial experimental results including implosion of the shell target by Gekko-XII, heating of the imploded fuel core by LFEX laser injection, and enhancement of the neutron generation due to fast heating have been achieved. Results indicate that 5-keV heating can be expected at full output of LFEX laser with improved heating efficiency. Beyond the achievement of central hotspot ignition on NIF and realization of the fast ignition concept at FIREX project, the research focus would then move to the demonstration of the delivery of the enabling IFE technology. An international fusion demonstrator named LIFT: Laboratory International Fusion Test facility is proposed. LIFT would have a design goal of high average power IFE production, with net delivery of electricity and optimization of the fusion technology required for subsequent exploitation. Success of the high power short pulse laser system LFEX not only drives the first phase of the FIREX project but also envisages the future ultrahigh intensity laser facility with the N-OPA technique. We initiated a new research project to construct extremely high intensity laser (GEKKO-EXA) which provides more than 0.1 EW power. Higher intensity than 10^{25} W/cm^2 is expected to open up a new field of high intensity laser physics and high energy physics.

1. Introduction

After 50 years journey from the innovation of lasers, one will soon achieve controlled thermonuclear ignition: By ignition, fusion energy will exceeds ten times the incident laser energy. Simply repeating the ignition-and-burn, however, requires sizable research and development. Fast Ignition can ignite with only about one tenth of laser energy that is necessary for conventional central ignition [1]. This compactness may largely accelerate Inertial Fusion Energy development. One of the most advanced fast-ignition programs is the Fast Ignition Realization Experiment (FIREX) program [2]. The goal of the first phase 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, the research focus would then move to the demonstrations of high gain and of the inertial fusion energy technology. These programs would converge onto an electric power generation at the proposed Laboratory Inertial Fusion Test (LIFT). Here presented are the recent progress of the FIREX program at ILE, Osaka University and some technical development toward the LIFT.

High power laser technology developed for the laser fusion could be utilized in various fields of science. Especially, ultrahigh intensity laser opens up a frontier of high field physics. Base on the recent development of broadband amplification technique, a single shot sub-exa watt system “GEKKO-EXA” is proposed, which is expected to deliver the intensity more than 10^{25} W/cm^2. Under such high intensity, quivering motion of the ions, not only electrons, is relativistic and interactions are nonlinear. Even the vacuum presents its nonlinear behaviour. As the high power laser system to activate the non-collinear optical parametric amplification (N-OPA), the design of the multi-pass amplification beam line for LFEX will be adopted.

2. Fast Ignition Realization Experiment (FIREX) program

The world largest short pulse laser LFEX, as a heating laser for fast ignition, was dedicated on March 2009. This laser utilizes Chirped Pulse Amplification (CPA) technique, which manipulates broad Fourier spectra of a short pulse laser so that the laser pulse is stretched, amplified and finally compressed. The most critical component of the CPA is obviously large format gratings that extend the accuracy of the state-of-art nano-technology to meter size (FIG. 1). These gratings have been developed in cooperation among Japanese and American optics industries organized by ILE, Osaka University. The LFEX laser consists of four beams. Each of the beams can provide 3 kJ in the long pulse of 3 ns, which is compressed and focused on to a single spot. In the last year, one beam was equipped with a pair of tiled gratings and successfully compressed form 2.2 ns to 1.2 ps with the energy of 1 kJ, which provided the power of about 1 PW. The rest three beams will be activated in 2010 and 2011 time frame and a short pulse laser with the highest power in the world will be available.

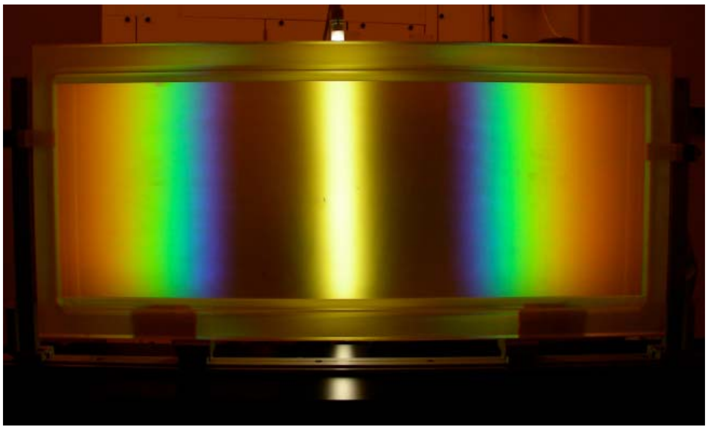

FIG. 1. The world largest and highest precision grating for pulse compression. Each grating has a size of 91-cm long and 42-cm hight with the grating of 1740 grooves/mm.

In the present fast ignition experiment, deuterated polystyrene shell targets are utilized as a fuel surrogate. It is also an important issue to develop solid deuterium targets. A new cryogenic technique is under development for fueling into the polystyrene capsule with a conical light guide. Controlling the temperature of the cone by laser heating, we have demonstrated an uniform deuterium solid layer without peculiar deformation. Another important progress is the development of a double cone targret [2], which increases the coupling efficiency from the fast electrons to the compressed core plasma by a factor of two. The double cone target has been first manufactured and successfully provided for the preliminary experiment (FIG.2). In order to enhance the core heating efficiency, further modification shown in FIG. 3 is proposed. In this new design, a tip which is made of low Z material extended closer to the centre of the shell to guide fast electrons effectively to the compressed core.

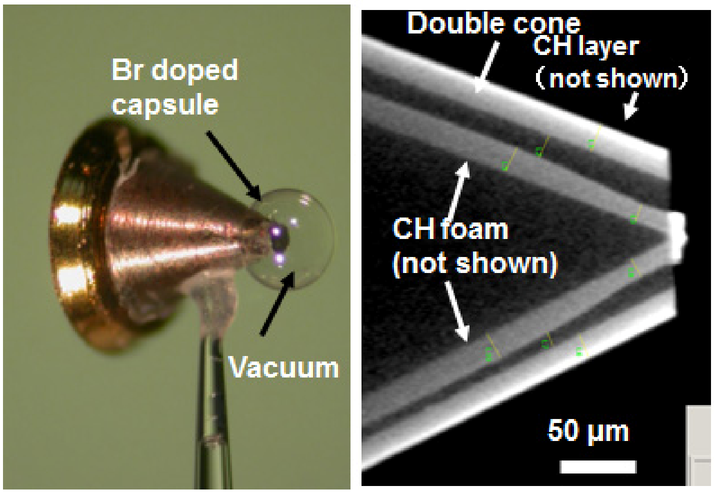

FIG. 2. A Double cone target and x-ray radiograph of its cone-tip part.

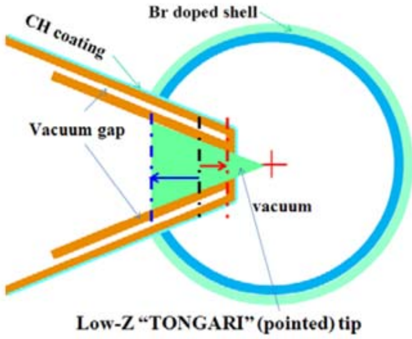

FIG. 3. Schematic view of new design of the double cone target. The low-z tip of the cone is extended to guide fast electrons close to the core and its bottom is enlarged to decrease the illumination intensity.

The first integrated experiment with the LFEX laser was performed form July 2009 to October 2009, using deuterated polystyrene shells with a gold conical light guide same as the previous experiments [3]. The diameter and the shell thickness of the shells were about 500 μm and 7 μm, respectively. Special care was taken for some plasma diagnostic instruments under the harsh environment of hard x rays generated by energetic electrons. The heating laser was injected through the cone. Neutron yield was increased up to 30 times that without heating. Figure 4 shows ion temperatures deduced from the neutron yield, fuel density and the fuel mass together with the scaling curves for the heating efficiency of 3, 5, 15 and 30%. Red dots indicate data points from the previous experiment [3] with the pulse width of 0.6 ps. Orange and green dots are the present results with 1.2-ps and 5-ps pulse width, respectively. It seems that there is strong pulse width dependence of heating temperature. The shorter the

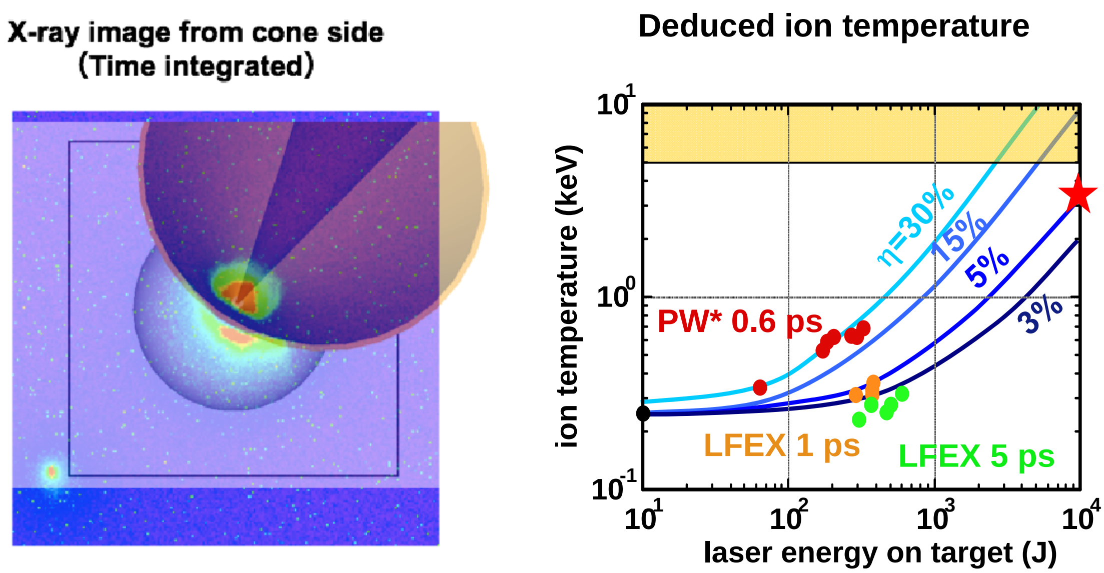

FIG. 4. FIREX-I integrated experiment. Left: Time-integrated x-ray image of the fast ignition target. Cartoon of the initial target is overlaid. Right: Ion temperature vs. heating laser energy. The parameter is the pulse width of the heating laser.

pulse width is, the higher the ion temperature favorably becomes. We presume that the rising part of the laser pulse preforms a plasma from which too high energy electrons are generated, resulting in decoupling between the hot electrons and the compressed core. Therefore the shorter rise time is preferable. On the contrary, the pulse width must be long (5-10 ps) to limit the maximum laser intensity below which the high coupling efficiency (20-30%) is maintained [3]. The lesson from this experiment is therefore that the suitable pulse shape is rectangular with about 1-ps rise time to eliminate a preformed plasma, whereas the laser intensity is kept relatively low. The star in FIG. 4 represents the expected temperature with the constant coupling efficiency, which is maintained up to 10 kJ heating laser energy for 10-ps pulse width. Figure 4 thus gives a confidence that ion temperature will increase up to the 5-keV level with such rectangular laser pulse.

Formation of a high density core is another important issue for efficient heating. Target performance of the FIREX-I project is analysed on the basis of the integrated simulation with 2-D PIC code, 2-D Fokker-Planck code and 2-D radiation-hydro code. The effect of Rayleigh-Taylor instability was investigated by using 2-D radiation hydrodynamic simulation code to optimize the target design for the project. It was shown that the averaged maximum core areal density with perturbation simulating the experimental condition for the target surface roughness and laser illumination non-uniformity is less than half of that for the clean case without perturbation even for the implosion of the cone-guided shell. One possible remedy proposed is slow implosion scheme [4]. In this scheme, implosion velocity is kept below 2×10^7 cm/s and in-flight shell thickness is thick enough to prevent the crucial shell breakup caused by the hydrodynamic instability. In our preliminary study using 1-D hydrodynamic code, an optimized target for the FIREX-I experimental condition, with the radius of 240 μm and the thickness of 15 μm, surveyed to show the increase of the compressed density by 10%.

3. Laboratory Inertial Fusion Test (LIFT)

Given the demonstration of the ignition temperature at FIREX-I and the ignition-and-burn at NIF, the inertial fusion research would then shift from the plasma physics era to electric power era. It would take 10 years for technology development and 10 more years for power generation test. The technology includes high rep-rate laser; target injection, tracking and beam staring; and fusion chamber and blanket. These technologies would converge into an integrated engineering test facility, the goal of which is to repeatedly generate a core plasma of FIREX-I level at a 1-Hz rate. The mission of FIREX-II would expand to cover this goal. Given the demonstration of repeated plasma production, the next research program for a laser fusion experimental reactor, depicted in FIG. 5, should be initiated with the goal of demonstration of power generation around 1030, which we name Laboratory Inertial Fusion Test (LIFT) [5].

One of the technical problems for IFE is heat loading of the first wall of the fusion vessel. In the laser fusion power plant utilizing a liquid wall of LiPb, such as “KOYO-F” [6], clearance of the ablated LiPb is of great importance. If ablated LiPb stagnates at the center and lots of clusters are formed, high repetition operation would be difficult. To cope with this problem, an integrated ablation simulation code has been developed taking the condensation process into account by Luk’yanchuk model [7]. It is shown that an inner wall surface with saw teeth structure like the “KOYO-F” is expected to reduce the amount of residual clusters below the allowable level.

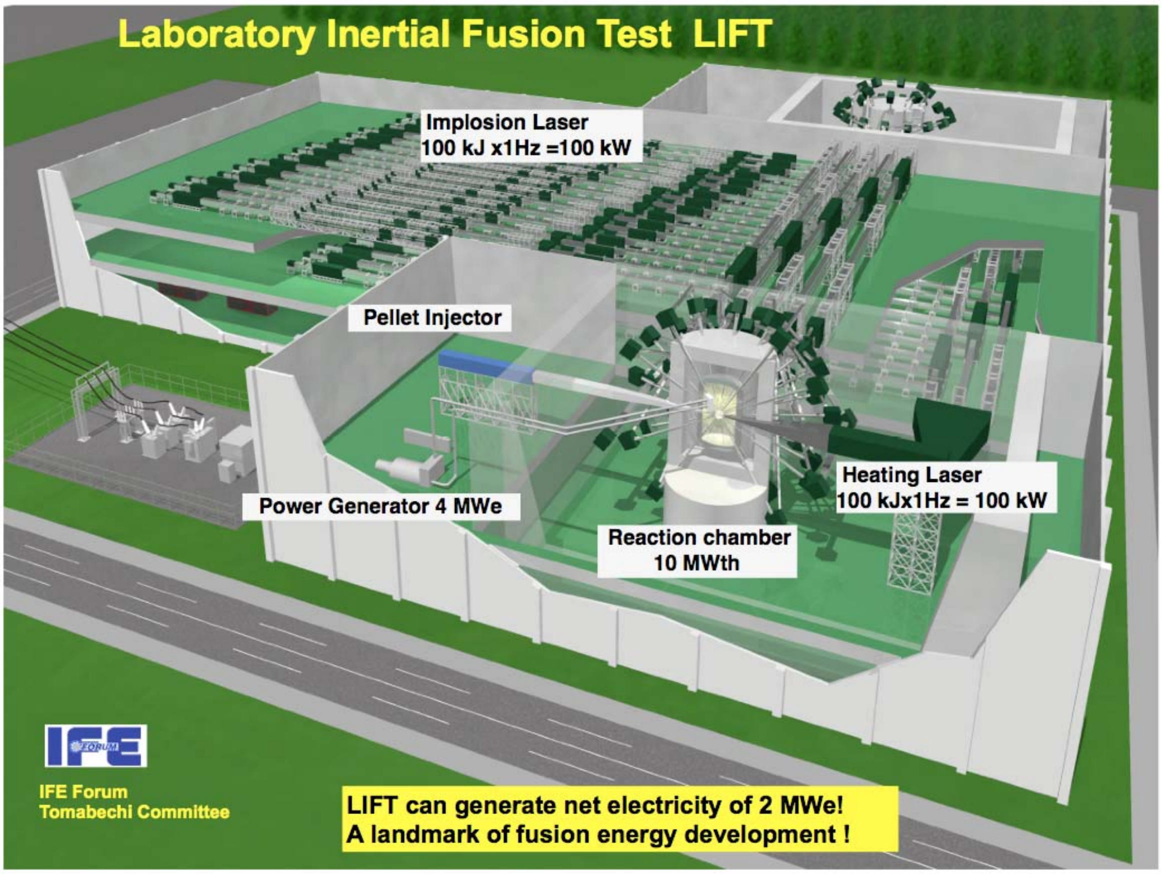

FIG. 5. Proposed test reactor LIFT that will net electricity by 2030.

Recalling that by the time of NIF ignition, it will have passed more than 20 years since the end of the Cold War. Global warming is, instead, becoming the serious problem. A flagship program is necessary to lift up inertial fusion community's spirits. We envisage the coordination of our near term research in the period 2010-2011 to achieve ignition temperature via advanced fast ignition schemes on FIREX-I and other facilities, such as, OMEGA-EP. Coupled with the achievement of central hotspot ignition on NIF in the same period, the research focus would then move to the demonstration of the delivery of the enabling IFE technology. We hope these programs would converge onto a truly international fusion demonstrator: Laboratory International Fusion Test facility (LIFT).

LIFT would have a design goal of high average power IFE production, with net delivery of electricity and optimization of the fusion technology required for subsequent exploitation. A key goal would be to secure the engagement of private industry and commercial investment for the ensuing deployment phase.

4. GEKKO-EXA laser system

The high power laser technology with efficient multi-pass amplification system developed for the LFEX laser could be adopted for an ultra-high intensity laser system. We propose a challenging "GEKKO-EXA" project which provides 200 PW with 2 kJ in four beams of 10-fs pulse width. Focusing the GEKKO-EXA beams in a micrometer spot, high intensity more than 10^{25} W/cm^2 can be achieved. That will be the highest pinnacle for the ultrahigh field science. Farther higher intensity could be pursued by using relativistic plasma engineering such as non-linear plasma mirror [8]. Even a fraction of the Schwinger field intensity could be in sight.

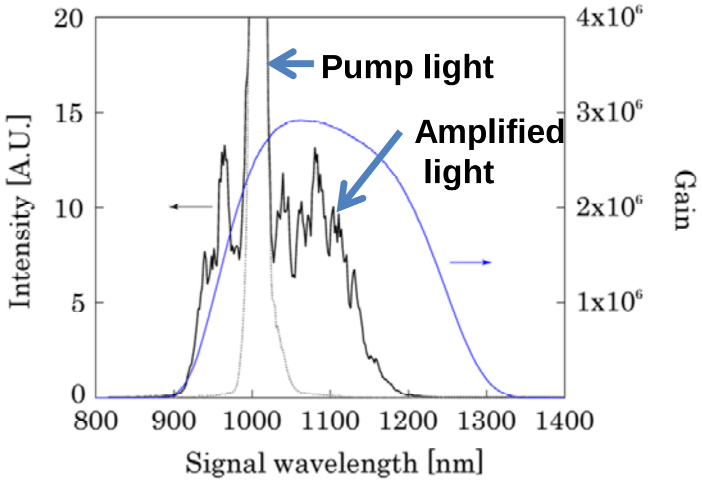

FIG. 6. Measured amplified spectrum (black solid line) and oscillator background (thin solid line). Calculated amplified spectrum (blue line) is also shown [9].

A few technical difficulties, such as the improvement of the damage threshold of the broadband optics, are to be overcome. The most important issue of broad band amplification was demonstrated by using optical parametric amplification with partially deuterated KDP [9]. Figure 6 shows the OPA gain of 2 x 10^4 was achieved with pump intensities of over 60 GW/cm^2 in a non-collinear geometry using 15-mm thick 13% deutrated KDP crystal. Although the amplified spectrum is suppressed in the longer wavelength region comparing with the calculated one (a blue line in FIG. 6) due to the strong absorption in DKDP, bandwidth amplification of 270 nm full-width at half maximum is successfully obtained.

5. Summary and future prospect

One beam line of LFEX laser was successfully installed to show the enhancement of the neutron yield by laser heating in the integrated experiment of the first phase of FIREX program (FIREX-I). Further construction of the LFEX is underway to finish the installation of all the compression gratings for four beam lines. 5-keV heating is expected with full output of the LFEX by tuning of the pulse shape and pre-pulse control.

Advanced target design of the double cone was proposed to enhance the heating efficiency. Slow implosion scheme was shown to be promising for the stable implosion in the present experimental condition of FIREX-I.

Realization of the central ignition on NIF and sufficient fast heating on FIREX will enable the international collaboration on IFE technology toward a laboratory inertial fusion test facility. We are expected to show the technical feasibility of IFE.

High energy laser technology developed for the LFEX laser was proposed to be extended for the ultra-intense laser system “GEKKO-EXA”. Higher intensity than 10^{25} W/cm^2 is expected to open a new frontier of high field science.

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