Impact of Fast Ignition on Laser Fusion Energy Development

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Abstract. Reviewed are the early history of Japanese laser fusion research and the recent achievement of fast ignition research at Institute of Laser Engineering (ILE), Osaka University. After the achievement of high density compression at Osaka University, LLE of University Rochester, and LLNL, the critical issue of Inertial Fusion Energy (IFE) research became the formation of hot spark in a compressed plasma. In this lecture, the history of the fast ignition research will be reviewed and future prospects are presented.

1. History of laser fusion research in Japan
In late 1960’s, the nuclear fusion driven by high power laser was proposed and the neutron generation in laser plasmas was demonstrated by the experiments. However, it was realized that when laser intensity was getting higher, the nonlinear laser plasma interactions like the parametric instabilities, for examples, electromagnetic decay into an electron plasma wave and an ion acoustic wave, oscillating two stream instability, two plasmon decay instability, and so on are important. Those instabilities and related nonlinear plasma wave phenomena have been explored for producing hot dense laser plasmas by laser. The nonlinear wave phenomena in laser plasmas are called anomalous absorption of intense laser. The international conferences (for example, Anomalous Absorption Conference), workshops (US-Japan Seminar on Laser Plasma Interactions) and international schools (Laser Plasma Summer School at the (International Center for Theoretical Physics (ICTP) Trieste, Italy) were held. In the 1970’s, the key concept of the laser fusion, namely the implosion was proposed by J. Nuckolls [1] and technology R&D of multi beam high power laser and large scale laser construction have stared. The turning point of the laser fusion research in Japan was the Fuji seminar which was held in November, 1974. It is the important event for Japan laser fusion community because the Fuji seminar initiated the laser fusion research in Japan. As shown in the Fig. 1, most of the world class leading scientists in laser fusion research participated the seminar. After the seminar, R&D and construction of GEKKO lasers have started at the Institute of Plasma Physics of Nagoya University and at the Institute of Laser Engineering of Osaka University. As a goal of the GEKKKO laser development, GEKKO XII glass laser was constructed. In the following, the research progresses of laser implosion in Japan are briefly reviewed.
2. Review on Laser Implosion and Ignition Research in Japan

In the late 1980’s, high density compression with laser implosion was achieved in Japan [2] and USA [3][4]. In the GEKKO XII laser experiments, high density compression up to 600 g/cc was realized [2]. However, the implosion symmetry was not enough to form a tiny hot spark. The neutron yield was degraded by a few orders of magnitude in comparison with 1-D simulation. This is because of the implosion non-uniformity caused by the target and irradiation non-uniformities and the hydrodynamic instabilities. Namely, a hot spark was not formed at the center of an imploded pellet because of the turbulent mixing with surrounding low temperature plasmas. In order to overcome the difficulty, the laser fusion community have been concentrating the efforts on two schemes: 1) improvement of uniformity and construction of giant laser to produce larger hot spark and 2) exploring a new scheme (fast ignition) to produce the hot spark by external fast heating.

As known well, the first approach will be demonstrated by the NIF and LMJ projects. The second approach is the “fast ignition”. As the projects related to this scheme, FIREX at ILE, Osaka, OMEGA PW at Rochester, and so on have started recently. Although the fast ignition is very attractive, some critical issues should be overcome. They are high energy peta watt laser technology, physics on the coupling of peta watt laser energy to thermal energy of core plasmas. Those two major critical issues will be over come in the fast ignition projects in Japan, US, EU, and China. This lecture focuses the discussions on the plasma physics related to fast ignition.

The FIREX-I project is for the proof of principle of fast ignition with 10 kJ short pulse laser named LFEX (Laser for Fast Ignition Experiments). And then the FIREX-II project will follow, in which the ignition will be demonstrated with 50 kJ peta watt laser heating.

There are two ways of heating dense plasmas in consideration, which are relativistic electron heating [5] and high energy ion heating generated by ultra-intense lasers. In the Japan-UK collaboration research since 2000 [6], we invented a cone guide target to guide a laser and electron beam to very close to dense core plasma with a relatively small spot size. After the first step toward POP experiment in 2002 [7], the full scale heating experiments will be performed in the FIREX-I [8] and OMEGA PW projects till 2010. Prediction of implosion and heating characteristics of cryogenic
foam shell cone target with experiments, Hydro, Fokker Planck, and PIC simulation became accurate in a past few years. The present understanding of Osaka group on the implosion and heating physics will be discussed in this lecture.

The fast ignition is attractive because required laser energy is 10 times smaller than that for the central hot spark ignition. However, the success of the fast ignition scheme depends upon the engineering of large-scale short pulse laser and the physics of large scale relativistic laser plasma interaction. They are the real frontier of the high power laser science. We could say that the fast ignition is still “high risk and high return scheme”.

3. Fast ignition project and target design for proof of principle

In 2003, the 10 kJ short pulse laser construction started as the phase one of Fast Ignition Realization Experiment: FIREX-I. The goal of the FIREX-I is producing a hot dense plasma of ion temperature higher than 5 keV by using a cryogenic cone shell target [8]. The specifications of the 10 kJ laser short pulse laser: Laser for Fast Ignition Experiment (LFEX) are as follows. It is 4 beam system, where each beam is 40 cm square, the out put pulse energy is 3 kJ /beam with 3ns chirped pulse, after the compression, the one beam pulse energy is 2.5 kJ with 1ps pulse width, and 4 beams are coherently combined after the compression to be focused to 30 mm diameter spot. The amplifier has been tested to demonstrate 3.6 kJ with 3 nm wavelength band width. The one beam compression and focusing experiment will be carried out before the end of February, 2008. The full beam experiments will start in the end of 2008.

Cone shell target design for obtaining higher rr and better heating efficiency is under investigation. For designing target, an integrated simulation code has been developed [9]. It consists of hydro code (PINOCO) [10], collective PIC code (relativistic solid target-laser interaction simulation) [11], and charged particle transport code (Fokker Planck simulation) [12] as shown in Fig. 2. This integrated simulation code is called “Fast Ignition Integrated Interconnecting Code: FI3 code” [9]. The implosion hydrodynamics of a cone target is simulated by PINOCO and the density profile at the peta
watt irradiation is given to the PIC simulation. The relativistic electron phase space profile obtained by the PIC simulation is transferred to the transport code. Then the Fokker Planck simulation describes the heating processes. By using this integrated code, the target of FIREX-I is designed as shown in the following section.

As for the implosion hydro-dynamics, a critical issue is the interaction of imploding shell with the cone. In the 2-D hydro simulation, it was found that a tip surface of gold cone is ablated by X-ray emitted from the imploding plastic shell and the ablated gold plasma drugs the inward motion of the pellet shell to break up the plastic shell as shown in Fig. 3a. Because of the break up of the shell, the fusion fuel contained in the plastic shell spills out along the cone surface. It is found by two contact surfaces (two solid curves of Fig. 3a) which are the boundaries between gold plasma and deuterium plasma and between deuterium plasma and plastic plasma. Because the deuterium is lost, the implored deuterium plasma is lower (the peak value is 0.1 g/cm$^2$) as shown by a solid line in Fig. 3b.

In order to reduce the ablation of the gold cone surface by X-ray, we coated the outer surface with plastic. The effects of the ablated cone plasma on the implosion dynamics are significantly suppressed. As the result, the areal mass density reaches 0.2 g/cm$^2$ as shown by a broken line in Fig. 3b.

As for the heating by injecting a 10 kJ /10 ps laser through the cone, high energy electron generation and transport in the cone and the imploded plasmas have been investigated by the particle in cell code and the relativistic Fokker Planck code as shown in Fig. 2. When the cone inner surface is irradiated obliquely with relativistic laser intensity, electrons are accelerated along the laser propagation direction and a part of them are confined on the inner cone surface by self-generated magnetic fields and electrostatic fields as discussed in [3]. Since the high energy electrons are scattered and decelerated when they propagate in a high Z ion plasma on the inner surface, it is better to coat the inner surfaces with low Z material in order to reduce the scattering. The low Z coating is also effective for enhancing heating efficiency by making the electron spectrum soft [13].

The cone angle is also optimized for increasing the absorption efficiency of short pulse laser and controlling energy spectrum. When the cone angle is smaller, the absorption efficiency is higher as shown in Fig. 4. The absorption efficiency of Fig.4 is obtained from the 2-D PIC simulations which are described in the reference [3]. However, when the full cone angle is smaller than 30 degree, the electron spectrum is too hard to deposit the energy in the hot spark, namely the main part of electron
energy spectrum extends to higher than 10 MeV. The number of high energy electron generated in the range of 0.5 MeV~3 MeV is maximum for 30 degree cone.

Finally, the double wall structure of cone as shown in Fig. 5 is effective to enhance the fraction of electron energy concentrated to the tip of the cone. Therefore, an image of the optimized cone shell target for the FIREX-I will be like Fig. 5.

Figure 4 Cone angle dependence of absorption rate of peta watt laser

Figure 5. An advanced target design for FIREX-I

4. Prospects of FIREX project
The 10 kJ/ps laser will be completed in the end of FY2007 and the operation will start in FY 2008.
The fast step of the experiment will be performed with one beam out of 4 beams and the full beam experiment will start in the last quarter of FY2008. After plastic target experiments, DD cryogenic target experiments will follow in FY2009. The DT target experiments are expected to be after FY 2010, which is also important for studying tritium handling. If the experimental results are as our expectation, the ignition demonstration project: FIREX-II will start after the check and review of the Japan fusion community.

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