Progress of Laser Fusion in the last 40 years and Expected Prosperous Applications

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Abstract. Inertial confinement fusion has remarkably developed in the last 40 years. In the 21st century, we can expect fusion energy for civilian use. We had performed two types of fusion experiments: High Temperature Demonstration and High Density Demonstration. The former experiment attained a neutron yield $10^{13}$ using the LHART target driven by the GEKKO XII laser. The latter achieved the 1000 times normal density using the random phased laser beams which realized the Edward Teller proposal of IQEC 1972. Now, the FIREX project to explore fast ignition is going on. The heating process of energetic electrons as well as ions is a key issue of the fast ignition. Investigation on the extreme condition of plasma in high density and high temperature which are introduced by the PW laser give us a new field of nuclear science. On the way to the final fusion goal, we can expect various fruits in the field of high power laser applications, such as laser-induced nuclear reaction, EUV light source for lithography, nuclear transmutation, laser astrophysics, medical application of particle beam and so on.

1. Introduction

The recent worldwide goal has been to attain the breakeven of energy balance by implosion fusion. Our exciting results are a neutron yield of $10^{13}$ per laser shot by subjecting a novel, large high aspect ratio target (LHART) to 10kJ laser radiation from the GEKKO XII glass laser, and also the imploded fuel density of 1000g/cm$^3$ by a deuterated plastic shell target with the random phased laser beams. In USA and France, the mega joule laser systems are under construction expecting the spark ignition by the indirect drive. As an alternative way, the FIREX project of the fast ignition has started at ILE. We use 10 petta watt short-pulse laser LFEX-I to ignite the precompressed fuel which is uniformly imploded by the GEKKO XII 10 kJ laser.

The present key issues of IFE research are the development of high power driver systems including laser-materials, components and new technologies of irradiation, as well as the processing of advanced full pellets and the fuel supply systems which enable the ignition to achieve an optimal IFE pellet gain greater than 100. Last but not least is the feasible design of the IFE reactor for the commercial use.

Applications of the inertial confinement fusion efforts are not only energy production but also various new fields, x-ray lasers, nuclear processing, cosmology, particle acceleration, EUV light source, neutron source and medical application.
2. Progress of Laser Fusion Research

In 1969, we started the laser plasma experiment at the Institute of Plasma Physics, Nagoya University. The GEKKO I glass laser (10J, 1.06mm, 1ns) was used for the irradiation experiment of He cooled deuterium targets. This was the first trial of laser induced fusion to get the neutron yield $10^4$ in Japan. The experimental result seemed to be exciting but actually the real scientific outcome was to discover the anomalous absorption of laser in dense plasma [1]. This was the most powerful campaign for laser fusion. This year the 1st International Workshop on Laser Interaction and Related Plasma Phenomena was initiated by H. Schwarz and H. Hora which was the precursor of the IFSA.

In 1972, Edward Teller gave a famous lecture “Modern Internal Combustion Energies” at the 8th International Quantum Electronics Conference (IQEC) in Montreal. The theme was the implosion of fusion fuel up to 1000 times of the normal density. In the early 70s, we started to build the GEKKO IV phosphate glass four beam laser (2kJ, 1ns, 2TW) competing with the Angus laser of the LLNL. We had also engaged in the CO2 laser, LEKKO series. These were a counter part of the LANL program and the relativistic electron beam REIDEN raced against the Sandia group.

As for a fusion fuel target design, “Cannon Ball” target was devised which was an indirect irradiated scheme composed of double shells [2]. At the LLNL, the same idea named “Hohraum Target” was studied under the classification, which was to be disclosed after 20 years.

In 1985, the High Temperature Demonstration Experiment was performed to yield $10^{13}$ neutrons by using the LHART (Large High Aspect Ratio Target) [3]. One of the most important techniques for the uniform irradiation was to prepare the random phased laser beam [4]. We could suppress the interference of laser beams preventing the speckle patterns to attain the irradiation uniformity better than 99%. These days every laboratory follows this technology of beam smoothing.

In 1989, we set in the High Density Demonstration Experiment that was proposed by Edward Teller 17 years ago. The necessary conditions for this objective were to attain the uniform irradiation and also to provide extremely spherical fuel targets. The random phase plate was a very pertinent tool. The diagnostics to measure the high pR value ($\rho$ is the fuel density and R is the radius of the fuel) were developed by using an activation method of Si by neutrons [5]. The experimental results showed the compressed density up to 1000g/cm$^3$, which was four times of the solar density. This was a super shot of the GEKKO XII green laser.

In 1991 I received the 1st Edward Teller Medal at the 10th International Workshop on Laser Interaction and Related Plasma Phenomena in Monterey. The accomplishment of the 1000 times compression of the normal density opened a door to the final stage of the laser fusion [6]. The Livermore began to construct the NIF (National Ignition Facility) aiming the fusion ignition by the indirect drive at 2010. The French group also started to build the LMJ laser for a similar scheme. In these situations, we have promoted the FIREX (Fast Ignition Realization Experiment) Program which is to ignite a compressed fuel by the additional laser heating. Recently the petta watt laser has been realized by using a new technology of chirped pulse amplification. This development has reminded us to use an old idea of additional heating which was proposed by T. Yamanaka in 1983 at ILE [7], but at that time no powerful PW laser was available.

Recently the fast ignition was reported by M. Tabak [8]. The new advancements of the fast ignition at ILE, Osaka University are very remarkable. The energy injection to a compressed fuel pellet through a cone by CPA PW laser (500J, 500fs) induced the additional heating which increased the neutron yield up to 1000 times of the case without heating [9].

In the cone target, an ultra-intense laser light $10^{19}$W/cm$^2$ is partially reflected in a cone and guided to the tip of a cone where relativistic electrons are generated. Since the electrons are accelerated to 100 MeV along the laser propagation direction, strong return current is driven on the side wall and relativistic electron flows are pinched by magnetic field of 10 MG at the top of the cone. Even then a nonlinear force drives ions axially to contribute the impact heating. Cone target ignition process is studied by using the Fast Ignition Integrated Interconnected code FI3 which connects a radiation hydro code (PINCO), a collective PIC code and a Fokker-Planck hydro code. The FI3 code has been applied to analyze the cone shell target experimental results. The heated cone plasma temperature reaches
about 1 keV by the simulation [10]. This is lower than the experiment data. The ion heating, magnetic field effects and 3D treatment seem to be important to investigate.

The FIREX program is to adopt the direct implosion for a pre-compression stage. The LFEX (Laser for Fast Ignition Experiment) is a four beam PW laser (10 kJ, 10 ps, 1.06 μm) to demonstrate the ignition temperature of 5–10 keV [11]. The second phase FIREX-II is to ignite and burn by a new system of 50 kJ igniter and 50 kJ compressor. The pellet gain will be about 10. The nuclear fusion ignition will be testified by the FIREX-II. Beyond the FIREX, we will proceed to the realization of the Laser Fusion Experimental Reactor. Reactor lasers are the most important technology for energy production. Recent study of diode pumped ceramic laser HALNA (DPSSL) shows a promising scope such as the high repetition operation 10 Hz, high efficiency 7% and high energy output 1 kJ in one unit [12]. Target and reactor technology is the third critical issue to the goal. The integrated inertial fusion energy reactor concepts are a target of systematic research and development.

3. Expected High Power Laser Applications

On the way to the final goal of laser fusion research, we can expect various prosperous fruits in the fields of high power laser applications. Recent advances of laser technology enable us to generate energetic particle and intense radiation in the relativistic regime. When the short pulse intense laser propagates in plasmas produced by optical field ionization, it excites the plasma wave due to the extraction of electrons by the ponderomotive force. The phase velocity of this wakefield is nearly equal to the speed of light behind the laser pulse. Electrons entering this wakefield can be accelerated to relativistic energy. In our experiment, using the cone-capillary plasma provided by laser intensity $2 \times 10^{15}$ W/cm$^2$, the wake field acceleration has reached 50 MeV. However the energy spectrum of electron has a wide spread [13].

As for the ion accelerations, the laser irradiation of $10^{18}$ W/cm$^2$ to a thin film target produces energetic electrons which penetrate the target to induce the charge separation between the back surface of the target and electrons. Then ions are drawn out and accelerated to the high energy.

Energetic protons and ions are likely to have many applications due to the compactness and flexibility of the laser particle source. The possibility of generating particles, such as electrons, protons, heavier ions and neutrons, as well as bremsstrahlung, just by changing the target provides a versatile and compact new accelerator [14]. Nuclear transmutation by Compton $\gamma$-ray is one of the most interesting applications [15]. The compton cross section is very small, on the order of an electron classical radius. Using a super cavity of high Q, it is possible to accumulate the laser power by conversional YAG lasers. As a preliminary experiment, the New Subaru electron storage ring whose energy 1 GeV, electron current 1 A average, 200 A peak and energy spread 0.1% is used for the electron beam source. The super cavity can store the power 10 MW whose cavity length is 10 m and reflectivity is 99.9% respectively. The generated $\gamma$-ray by compton scatter is energy 15 MeV, photon number $10^{15}$/sec. Nuclear transmutation from $^{129}$I to $^{129}$Xe is observed. A key point of the nuclear transmutation of long life fission products is to use ($\gamma$, n) process.

Extreme ultraviolet (EUV) light source for lithography is one of the most interesting applications of high power laser. The EUV power 200 W at 13.5 nm of wavelength, 2% of bandwidth and 3% of conversion efficiency is attained. We have developed a high repetition (10 kHz) and high power (5 kW) Nd: YAG and CO$_2$ laser system to produce EUV plasma. We have constructed theoretical and experimental data base, such as atomic data, dependence of conversion efficiency on laser intensity, pulse duration and laser wavelength, energy spectra of fast ions for various lasers and target conditions [16].

The physics of laser fusion plasma has a same base as the core of astrophysics. The properties of a laser produced plasma, ionization state, high density and high temperature are very similar to the conditions of matter in stars. In the laboratory, various extreme plasma conditions are available in a laser produced plasma. Using this plasma as target and laser accelerated particles as projectiles, the dependence of nuclear reaction rates during nucleo-synthesis in stars may be investigated. The results
will improve the knowledge of the nuclear reaction rates used as inputs in the astrophysics codes that aim at reproducing the evolution of the stars [17].

Among the many applications currently is the laser production of ratio isotopes for medical purposes. Radio isotopes, $^{11}$C, $^{13}$N, $^{18}$F, $^{129}$I and $^{99}$Tc are used in medical imaging as PET-scintigraphy. Such short life isotopes are usually produced by cyclotrons or Van-de-Graaff accelerators. Now we may expect to use laser-driven nuclear activation on-site at a hospital [14].

The laser development and the proper preparation can be ensured for the near future, high intensity laser induced particle accelerator will have medical, technical and basic science applications.

4. Conclusion

The petta watt laser is now available due to the CPA technique. The combination of very high peak power and very short laser pulse has now opened a vast new field of unique and exciting applications.

The laser fusion research using the ultra high power lasers aiming the fast ignition gives a strong impact for the ICF. The laser matter interaction has produced the new fields. High energy electron and ion accelerated to the relativistic regime by lasers induce the nuclear reaction. Photo nuclear reaction and pair production are expected. Nuclear transmutation by ($\gamma$-n) reaction will resolve the waste issues of fission reactor. EUV light source for lithography is developed by the high power laser system. EUV light at 13.5 mm of wavelength, 200 W of output power and conversion efficiency of 3% will soon be available. Laboratory astrophysics can be extended on the same base of laser fusion physics.

We are expecting to open a new breakthrough in laser fusion research, such as fast ignition by ultra high power lasers and also extend the vast exciting applications of high power lasers in the 21st century.

References

[1] Yamanaka C, Yamanaka T, et al 1972 Phys. Rev. A 6 2335
[2] Yamanaka C and Nakai S, et al 1981 Jpn. J. Appl. Phys. 20 L477
[3] Yamanaka C and Nakai S 1986 Nature 319 757
[4] Kato Y, Mima K, Yamanaka C, et al 1984 Phys. Rev. Letters 53 1057
[5] Azachi H, Yamanaka C, et al 1991 Laser and Particle Beams 9 193
[6] Yamanaka C 1992 Laser Interaction and Related Plasma Phenomena ed. G H Miley and H Hora (Plenum Press) 5
[7] Yamanaka T May 1983 ILE Internal Report Osaka University 5
[8] Tabak M, Hammer J, Krueer W L, et al 1994 Phys. Plasma 1 1626
[9] Kodama R, et al 2001 Nature 412, 798, 2002 ibid 418 933
[10] Nagatomo H, Johzaki T, et al 2006 J. Phys. IV Frances, 133, 397
[11] Miyanaga N, Kanabe T, et al 2007 Annual Progress Report 2006 ILE Osaka University 13
[12] Kawasaki J, Izawa Y, et al 2007 ibid 171
[13] Mori Y, Sentoku Y, Kondo K, et al 2006 ibid 85
[14] Yamanaka C 2002 Rev. Laser Eng. 30, 185
[15] Imasaki K, Li D, Miyamoto S, et al 2006 Laser and Nuclei ed. H Schwaerer, J Magill, B Beleites (Springer) 147
[16] Izawa Y, Nishihara K, et al 2006 5th International EUVL Symposium (Barcelona)
[17] Takabe H 2001 Prog. Theo. Phys. Suppl. 143, 202