Nucl. Fusion **50** (2010) 014006 (6pp) doi:10.1088/0029-5515/50/1/014006

Inertial fusion power development: the path to global warming suppression

Kunioki Mima

Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka Suita, Osaka 565-0871, Japan
The Graduate School for the Creation of New Photonics Industries, 1955-1, Kurematsu, Nishiku, Hamamatsu, Sizuoka 431-1202, Japan
and
Institute of Nuclear Fusion, University Politecnic de Madrid, J.Abascal, 2, 28006 Madrid, Spain

E-mail: mima@ile.osaka-u.ac.jp and k.mima@gpi.ac.jp

Received 22 July 2009, accepted for publication 26 November 2006
Published 30 December 2009
Online at stacks.iop.org/NF/50/014006

Shortly after the demonstration of the first lasers, it was proposed that nuclear fusion induced by laser energized implosion could be utilized for energy generation. Today, there are many facilities worldwide undertaking IFE research, and after decades of experiments, theoretical developments and simulations, it is expected that the laser fusion ignition will be demonstrated in the next few years. If this does indeed happen, we will see a new era toward the realization of a fusion power plant.

PACS numbers: 28.52.Av, 52.57.−z, 89.30.Ji

1. Laser and laser fusion from past and present to future

In 1917, Albert Einstein suggested the theory of stimulated emission of light that led to the development of the laser. The first laser based on Einstein's theory was demonstrated by T.H. Maiman's experiment in 1960. In 1964, Nicolai Basov, A. Prokhorov and C.H. Townes received the Nobel prize in physics. Right after the oscillation experiment of laser, it was suggested by J. Nuckolls, Professors Edward Teller and Stirling Colgate in the USA and Andrei Sakharov in the USSR to use nuclear fusion induced by laser energized implosion to solve the energy problem. The laser implosion for the fusion ignition and burn was opened up to the public somewhat later by the work of Nuckolls *et al* in *Nature* (1972) [1], in which spherically imploding shock waves discovered by Guderley [2] were extended to laser fusion. The pioneering works for heating plasmas to the thermonuclear temperature with laser have also been published by Basov and Krokhin [3], Dawson [4] and Hora [5]. Since then laser fusion research has been conducted all over the world. Since then, many IFE facilities, for example GEKKO I, GEKKO II, GEKKO IV, GEKKO MII, GEKKO XII at the Osaka University, JANUS, CYCLOPS, ARUGUS, SHIVA, NOVA at LLNL, OMEGA at the University of Rochester, PHEBUS at Limeil, CEA, ASTERIX Iodine laser at MPQ, Garching, GRECO at LULI, Ecole Polytechnique, AngaraV at Kruchatov, HELIOS at LANL, Shengan II at the Shanghai Institute of Optics and Fine Mechanics, PBFA/Z-Machine at SNL, VULCAN at Rutherford, PHAROS and NIKE at NRL, and so on have been constructed for investigating implosion physics. Many difficult issues such as anomalous absorption and related preheating problems, irradiation uniformity, hydrodynamic instabilities and high quality pellet fabrication have been addressed by those facilities for more than 30 years, After 30 years of research by experiments, theory and simulations, it is now expected that laser fusion ignition will be demonstrated by the NIF (National Ignition Facility) at LLNL, USA, before the end of 2011 and by LMJ at CESTA/CEA, France. If the NIF and/or LMJ ignition campaigns are successful, then fusion research will enter into a new era towards the realization of a fusion power plant. It will be a fast track to supplying fusion energy to the electric power grid. It will contribute to global warming suppression. Towards the future development of inertial fusion energy (IFE), three research networks in North America, EU and East Asia have been organized and it is necessary that they are closely interconnected through international conferences such as the IAEA FEC, the IFSA Conference (Inertial Fusion Science and Applications), which is the successor of the LIRPP (the International conference on Laser Interactions and Related Plasma Phenomena initiated by H. Hora and H. Shwarz, in 1969), and so on.

2. The concept of laser fusion and its unique feature

Laser fusion is a unique scheme in comparison with the other fusion schemes such as tokamak and helical devices. In laser

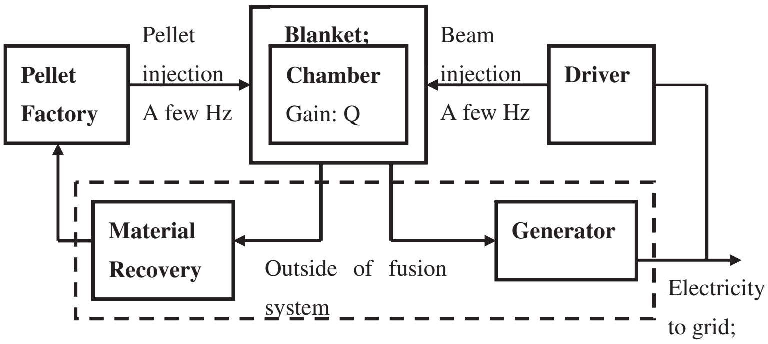


Figure 1. Energy and material flow diagram in laser fusion power reactor.

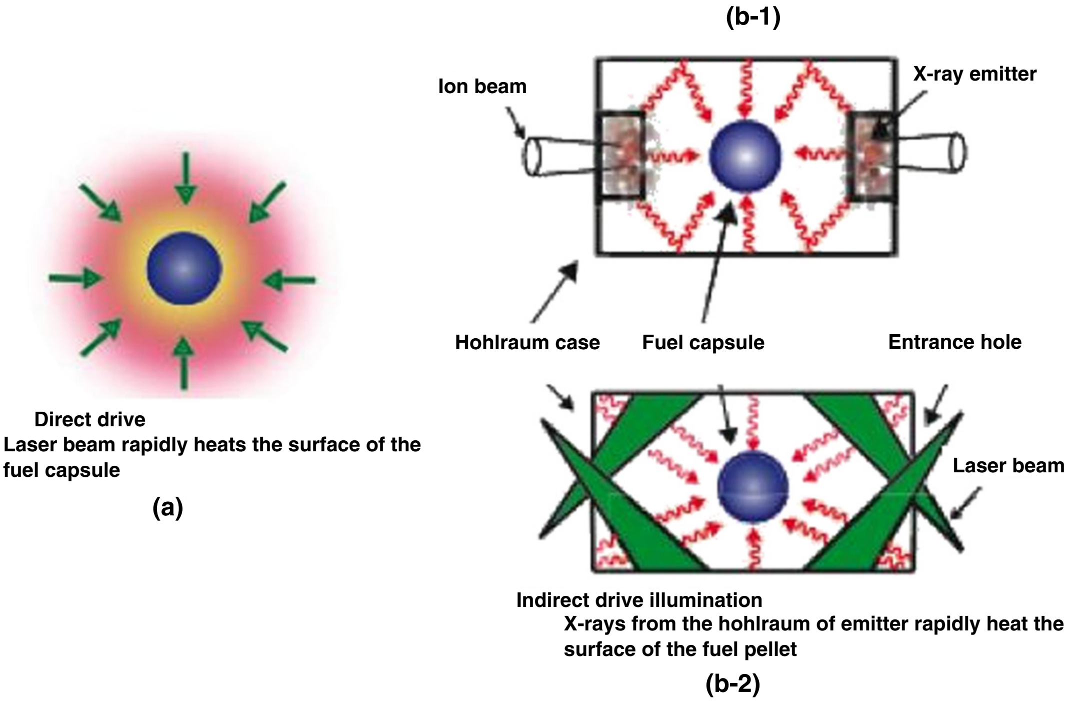


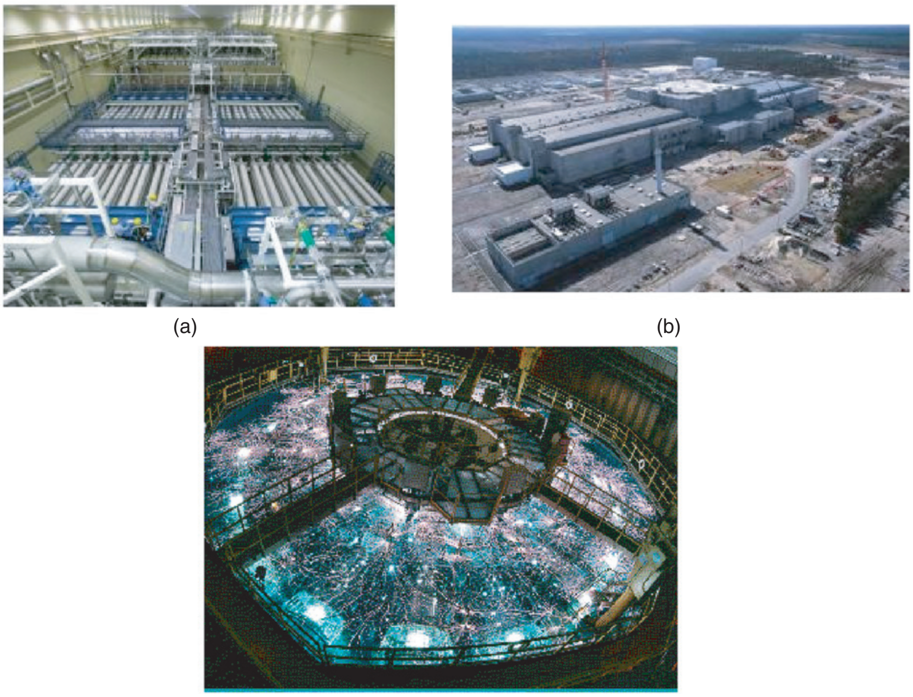
Figure 2. Inertial fusion schemes.

fusion, a tiny pellet is irradiated with many high power laser beams to compress the fusion fuel to 1000 times solid density which is higher than the plasma density at the centre of the sun and a part of the compressed fuel is heated up to 10 keV to be ignited. As shown in figure 1, several times every one second, a fusion fuel pellet is injected into the reactor chamber to generate fusion energy of a few gigawatts and about 1 GW electric power will be sent out to the grid. The key issues which should be investigated are the ignition and burning of the compressed fuel at present, and the high average power high efficiency laser technology, high repetition rate reaction chamber design and continuous pellet injection in the future.

There are two main schemes for pellet implosion, i.e. direct and indirect drives. Those concepts are schematically shown in figure 2. In the direct-drive implosion, the surface of a fuel pellet is irradiated directly by laser beams (figure 2(*a*)). In contrast, in 'indirect-drive implosion', the driver energy is converted into soft x-rays, which fill a cavity (see figure 2(*b*)). The soft x-rays are then absorbed on the surface of the pellet to generate ablation pressure to drive the implosion. As the indirect fusion driver, laser beams (figure 2(*b*-2)) or heavy ion beams (figure 2(*b*-1)) have been widely investigated. In the case of heavy ion beams, they deposit the energy in radiation-emitter foils placed at the symmetry positions inside the beam entrance holes of a hohlraum. Then the emitted radiations are confined to the hohlraum and implode a fuel capsule.

The direct implosion (figure 2(*a*)) and the indirect implosion (figures 2(*b*-1) and (*b*-2)) have merits and demerits. The merit of direct implosion is high coupling efficiency from the input laser energy to the imploded core plasma energy. The demerit is the implosion hydrodynamic instability and spherical uniformity. Hence, much higher laser irradiation uniformity is required for the direct drive. On the other hand, the merit of the indirect drive is the high implosion uniformity and the stability because of the x-ray drive. However, the demerit is the low implosion efficiency. Hence, larger laser energy is necessary for ignition and high gain.

The feasibility of direct-drive ignition was demonstrated by the high density compression experiments at the Institute of Laser Engineering (ILE), Osaka University [6], and the



(a) (b)

(c)

Figure 3. (*a*) The NIF main amplifier laser bay which was completed and achieved an output energy of 1 MJ. (*b*) The laser and target chamber buildings of LMJ at CESTA/CEA, Bordeaux, France, which will be completed in 2014. (*c*) The Z-Machine: a pulse power machine to produce a high power x-ray of megajoules.

Laboratory for Laser Energetics, University of Rochester [7]. In the ILE experiments, targets made of DTCH plastic were imploded with the GEKKO XII laser smoothed by a random phase plate (RPP) invented at ILE, Osaka [8], to compress the pellets to 600 g cm^{-3}. In the Rochester experiments, deuterium filled targets are imploded to 100 times solid density. Recently, the upgrade OMRGA experiments demonstrated 500 time compression of a D_2 cryogenic target.

On the other hand, the high density compression together with the high neutron yield was demonstrated by indirect-drive implosion at LLNL with the NOVA laser in the 1980s [9–11]. Based upon those results, the OMEGA laser was upgraded to higher than 30 kJ of 60 UV laser beams and the NIF construction at LLNL (figure 3(*a*)) was started in 29 May 1997 and completed in May 2009. It has already achieved an output laser energy of more than 1 MJ with 0.35 μm wavelength and a few nanoseconds pulse width. LMJ at CESTA, Bordeaux (figure 3(*b*)), and the Z-Machine at Sandia National Laboratory are also high energy indirect drive experimental facilities. The Z-Machine (figure 3(*c*)) is a pulse power machine that generates a 1.6 MJ x-ray pulse in 8 ns from a z-pinch to study indirect-drive implosions [12].

Figure 4 shows the present prediction of fusion gain and ignition for indirect drive and direct drive. The green hatched area between 0.5 and 10 MJ laser energy is the expected fusion gain for the direct and the indirect drive. The laser energy for the indirect-drive ignition is estimated to be about 1 MJ. It will be demonstrated in the NIF and LMJ (figure 4) ignition campaigns (in 2010–2015). After the ignition demonstration for the indirect drive, both facilities will be available and devoted to direct drive and fast ignition demonstration.

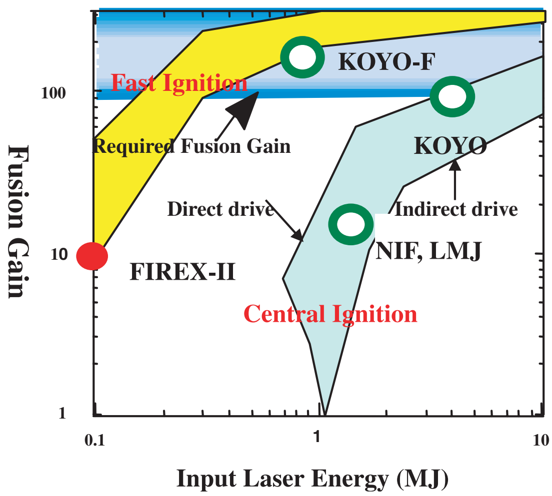


Figure 4. Predicted fusion gain for central ignition and fast ignition. NIF and LMJ are the ignition demonstration facilities for the central ignition. FIREX-II is the planned facility for the demonstration of fast ignition.

Since the invention of the new laser technology, so-called chirped pulse amplification (CPA), by Strickland and Mourou [13], ultra intense short pulse laser technology has advanced rapidly. Actually, the peak power of the short pulse laser has been increasing by a factor of 2 annually after it reached over 1 TW in 1990. The petawatt (10^{15} W) lasers were constructed in 1998 at LLNL and in 2001–2004 at ILE, Osaka University, and at the Rutherford Appleton Laboratory. The ultra-intense laser technology development introduced the new fusion concept, the so-called 'fast ignition'. It was proposed by

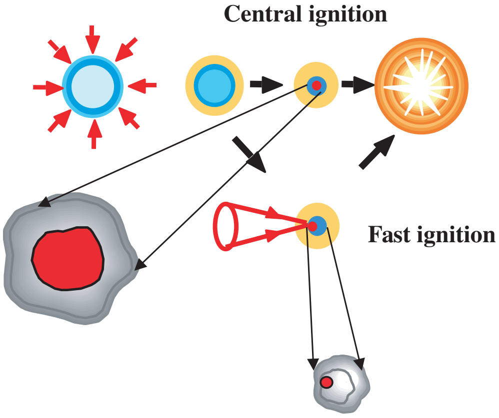


Figure 5. Central ignition and fast ignition. The plasma density of the hot spark in fast ignition is expected to be 3–5 times higher than that for central ignition. Therefore, the hot spark size indicated by the red area is much smaller in fast ignition. Thus, the required laser energy for ignition and high gain will be smaller by one order of magnitude.

Yamanaka [14], Basov *et al* [15] and Tabak *et al* [16, 17]. As shown in figure 5, the radius of the hot spark where the ignition starts is much smaller than that of the central ignition hot spark, since the density and pressure of fast ignition hot spark are much higher. Because of this, the laser energy required for the fast ignition could be smaller than that for the central ignition by one order of magnitude as shown in the fast ignition gain curve of figure 4. Furthermore, in the isobaric implosion core for high gain, the hot spark radius is about half of the total radius. Therefore the plasma ρR for fast ignition could be two times larger than that for the central ignition when the implosion laser energy is the same. This is the reason why the fusion gain is higher for fast ignition as shown in figure 4. This is the most important merit of fast ignition. The demerit of fast ignition is that a novel laser technology is required and that the heating physics has not matured. However, many research programmes are progressing or planned to solve these problems. The FIREX-I project at ILE, Osaka University, and the OMEGA-EP project at LLE, University of Rochester, are two such examples. They are important projects for demonstrating the efficient heating of imploded plasmas to produce ignition equivalent density and temperature plasmas. The LFEX laser for FIREX-I and the OMEGA-EP laser which started operation recently, are shown in figures 6(*a*) and (*b*). Many more projects have been started or planned, which are FIREX-II at ILE, Osaka, HiPER together with the forerunner, PETAL (see http://www.hiper-laser.org/) proposed by the EU, and Shengan-II Petawatt at SIOFM, Shanghai, China, NIF-ARC at LLNL, USA, and so on. So, the feasibility of fast ignition will be clarified in a few years. The NIF-ARC, FIREX-II and HiPER are the ignition facilities for fast ignition. So, fast ignition demonstration experiments are expected by these facilities when the present on-going experiments provide promising results.

3. Fusion reactor technology

An IFE power plant consists of four major, separate but interconnected sub-systems (elements of a power plant) as shown in figure 1, the functions of which are as follows. (a) The driver, usually either a laser (figure 7(*a*)) or a particle accelerator (figure 7(*b*)), converts electrical power into short pulses of light or particles and delivers them to the fuel pellet in the proper spatial and temporal form to cause implosion, ignition and thermonuclear burn. (b) In the pellet factory, fuel pellets are manufactured, filled with DT fuel and sent to the reactor and then injected into the reaction chamber. (c) In the reaction chamber, the injected fuel pellet (target) is tracked, i.e. its position, flight direction and velocity are measured precisely. Driver beams are directed to the target to implode it and to produce thermonuclear energy with a repetition rate of a few times a second. The thermonuclear emissions are captured in a surrounding structure called a blanket, and their energy is converted into thermal energy (heat). Tritium is also produced in the blanket. (d) In the rest of the plant, two major processes for material and energy are performed. Tritium and some other target materials are extracted from the re-circulating blanket fluid material and from the reaction chamber exhaust gases. Then these extracted materials are recycled to the target factory. The thermal energy in the blanket fluid is converted into electricity, a portion of which is conditioned and re-circulated to power the driver.

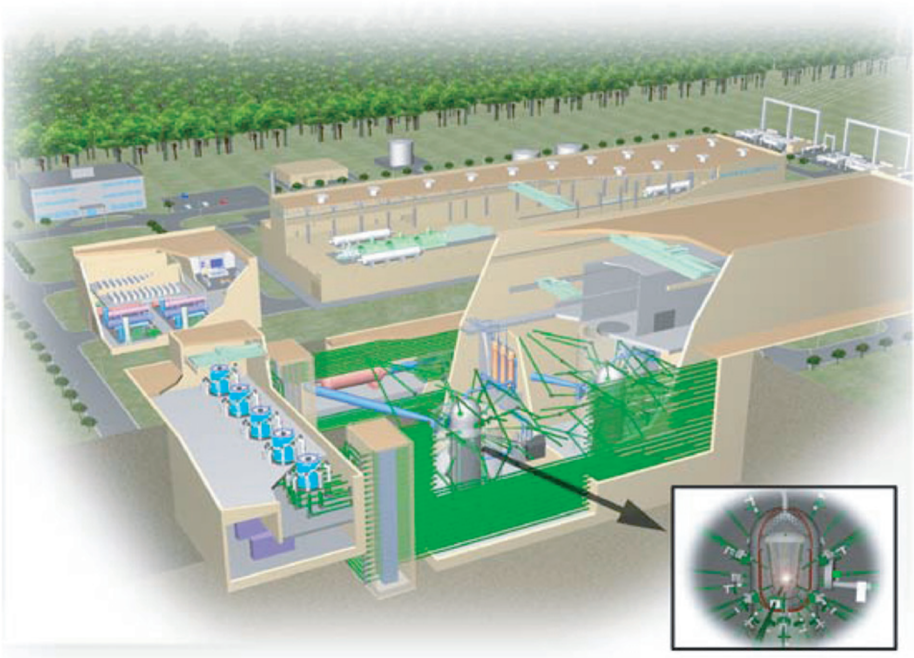
After the demonstration of the ignition by NIF/LMJ, the high gain target design will be very reliable since the simulation codes for the target design will be validated with a small extension of the scale. Therefore, it is very likely that repetitive ignition experiments will start with a high energy and high average power driver. A few reactor concepts such as KOYO (1994), KOYO-F (figure 7(*a*)) [18] and HYLIFE [19] have been proposed. The typical characteristics of the fusion reactor of fast ignition are shown in table 1. Here, the circulation electric power is required to be less than 20%. Then the required fusion gain will be higher than 150 for laser (driver) efficiency of 8%. If the driver efficiency is higher than 10%, the required gain could be lower than 100. This requirement determines the required laser pulse energy. In the case of central ignition, the implosion pulse energy will be more than 2 MJ for a gain of 100 and that for the fast ignition will be about 1 MJ.

The repetition rate of each chamber is limited by the recovery of the chamber environment before the next shot. The time interval between two shots depends upon the chamber wall material, chamber size, laser propagation stability, residual gas effects on injected pellet trajectory and so on. In KOYO-F, the laser repetition rate is 16 Hz and the chamber recovery time is 250 ms. Hence, the four chambers with 4 Hz operation can be driven. The related science and technology for the laser fusion reactor are under investigation, in particular on the critical issues which are shown as follows.

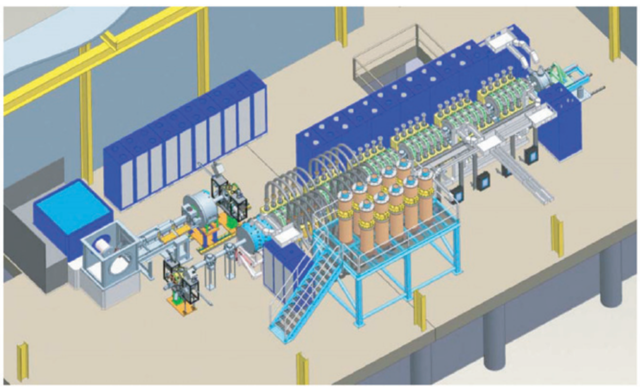
(1) Chamber wall design: heat pulse loading and quick recovery of the chamber condition after the shot.
(2) Pellet injection: pointing accuracy, injection timing and protecting cryogenic fuel pellets from damage by remnant gas and heat.
(3) High quality pellet mass production.
(4) High efficient, long life, stable laser development.
(5) Laser injection: beam steering and timing and laser window protection.

(a) (b)

Figure 6. Two integrated fast ignition experimental machines. (*a*) The LFEX laser (10 kJ/a few picoseconds heating laser) together with the GXII laser. (*b*) The OMEGA-EP laser (two beam system, 5 kJ/a few picoseconds).



(a)



(b)

Figure 7. (*a*) Design of the fast ignition power plant. It is driven by a diode-pumped solid-state laser operated with 16 Hz/1.1 MJ. The system consists of four reactor chambers. Each chamber is operated with 3 Hz. The total output electric power is about 1200 MW (Norimatsu T. *et al* 2007). (*b*) A heavy ion beam driver is developed at LBNL as the HIBF virtual laboratory of USA. This will be the test bed of the high power heavy ion beam accelerator.

Table 1. Basic specification of KOYO-F.

Net output	1200 MWe (300 MWe × 4)
Laser energy	1.1 MJ
Target gain	165
Fusion output per pulse	200 MJ
Pulse rep. rate in reactor	4 Hz
Blanket energy multiplication	1.2
Thermal output per reactor	916 MWth
Total output at plant	3664 MWth (916 MWth × 4)
Thermal to electricity efficiency	41.5% (LiPb temperature 500°C)
Total electric output of plant	1519 MWe
Laser efficiency	11.4% (compression), 4.2% (heating), total 8% (including cooling power)
Rep. rate of laser	16 Hz
Recirculating power for laser	240 MWe (1.2 MJ × 16 Hz/0.08) (Yb-YAG laser operating at 150–220 K)
Total plant efficiency	1200 MWe (1519 MWe–240 MWe –79 MWe aux.)

Chamber design. As for the chamber wall, a liquid wall, a wetted wall and a dry wall have been proposed and investigated. In the dry wall case, the pulse heat load is limited by the ablation of the inner surface. Hence, the chamber size for a given fusion energy is larger than those for the wetted wall and the chamber recovery time will be longer. On the other hand, the liquid wall chamber could be small since the surface ablation by the fusion explosion is not a problem in this case because the ablated material will be reabsorbed on the liquid wall. Therefore, the chamber size could be small and it could be operated with high repetition rates. However, the target debris removal from the liquid and heat removal and tritium confinement and separation in the heat and material cycle will be the main problems. The wetted wall concept like KOYO-F may solve the above problems by introducing the dry wall protected by the liquid layer.

Laser driver R&D. A diode-pumped solid-state laser is a prior candidate for the laser fusion reactor driver. A Nd : glass has been used as a high-pulse-energy laser material for IFE research. The poor thermal strength is, however, undesirable for the repeatable reactor laser. Three important factors are required for the reactor laser material, production capability of large-aperture materials, high thermal strength and proper stimulated emission cross section. An Yb : YAG ceramics developed by Kawanaka *et al* [20] is focused on due to its size scalability and significant thermal strength. The stimulated emission cross section is too low to extract the storage energy efficiently with commercial optics. Tuning the cross section by controlling the ceramics temperature has been proposed. The preferred temperature is between 150 and 270 K [21]. Also, thermal conductivity, thermo-optic coefficient (dn/dT) and coefficients of thermal expansion are improved at low temperatures [22], resulting in less thermal effects of thermal lensing and thermal birefringence. Lasers other than Yb : YAG ceramics are also explored in the US, EU and so on.

The unique features of the IFE reactor are (1) pulse operation, (2) variable output power, (3) small and high energy density burning plasma, (4) compact reactor, (5) large recirculation energy. These points are the merits and demerits of IFE power plants in comparison with the MFE power plants. The final comment on the IFE fusion reactor is the following. Since the inertial confinement plasma is small and of very high density, say the burning plasma radius is less than 100 μm, inertial fusion provides a localized strong neutron source. Therefore the inertial fusion neutron could be useful for driving the fusion–fission hybrid as proposed by Moses *et al* of LLNL [23] at the last IAEA Fusion Energy conference, 2008.

4. Concluding remarks

The ignition in laser fusion plasmas will be demonstrated by the NIF experiment in the near future. When the ignition is achieved, we may know how the ignition and burning occur and how to achieve ignition with a smaller laser. Based upon the progress in understanding ignition plasma physics, we could proceed to start the repetitive fusion test reactor design and construction. Then, IFE will be another route towards the realization of fusion power plants. I believe that IFE power plants will be unique and will contribute to the suppression of global warming.

References

[1] Nuckolls J., Wood L., Thiessen A. and Zimmerman G. 1972 Laser compression of matter to super-high densities: thermonuclear applications *Nature* **239** 139
[2] Guderley G. 1942 *Luftfahrtforschung* **19** 302
[3] Basov N.G. and Krohin O.N. 1963 *Proc. 3rd IQEC (Paris, France)* vol II, P.1373
[4] Dawson J.M. 1964 *Phys. Fluids* **7** 981
[5] Hora H. 1969 *Proc. Laser Interaction and Related Plasma Phenomena (9–13 June)* (New York: Plenum) p 365
[6] Azechi H. *et al* 1991 *Laser Part. Beams* **9** 193
[7] McCrory R.L. *et al* 1988 *Plasma Phys. Control. Nucl. Fusion Res.* **3** 17
[8] Kato Y. *et al* 1984 *Phys. Rev. Lett.* **53** 1057
[9] Campbell E.M. *et al* 1980 *Appl. Phys. Lett.* **30** 12
[10] Kaufmann R.L., Turner R.E. *et al* 1986/87 *Laser Program Annual Report: Laser driven Hohlraums*, LLNL, CA, UCRL-50055-86/87, pp 4-2
[11] Kaufmann R.L., Turner R.E. *et al* 1986/87 *Results from the Symmetry-I experimental Series on Nova*, LLNL, CA, UCRL-50055-86/87, pp 4-25
[12] Stygar W.A. *et al*. 2004 *Phys. Rev.* E **69** 046403
[13] Strickland D. and Mourou G. 1985 *Opt. Commun.* **56** 219
[14] Yamanaka T. 1986 *Internal Report of ILE* Osaka University
[15] Basov N.G., Gus'kov S.Yu. and Feokistov L.P. 1992 Thermonuclear gain of ICF targets with direct heating of ignitor *J. Sov. Laser Res.* **13** 396
[16] Tabak M., Hammer J., Glinsky M.E., Kruer W.L., Wilks S.C., Woodworth J., Campbell E.M., Perry M.D. and Mason R.J. 1994 Ignition and high gain with ultrapowerful lasers *Phys. Plasmas* **1** 1626
[17] Tabak M. *et al* 1991 *LLNL Internal Report*
[18] Norimatsu T. *et al* 2007 *Fusion Sci. Eng.* **52** 372
[19] Moir R.W. *et al* 1994 HYLIFE-II—a molten-salt inertial fusion energy power plant design—final report *Fusion Technol.* **24** 5
[20] Kawanaka J., Tokita S., Nishioka H., Fujita M., Yamakawa K., Ueda K. and Izawa Y. 2005 *Laser Phys.* **15** 1306
[21] Lu J., Takaichi K., Uematsu T., Shirakawa A., Musha M., Bisson J. F., Ueda K., Yagi H., Yanagitani T. and Kaminskii A.A. 2003 *Laser Phys.* **13** 940
[22] Slack G. A. and Oliver D. W. 1971 *Phys. Rev.* B **4** 592
[23] Moses E. *et al* 2009 *Nucl. Fusion* **49** 104022