A pathway to laser fusion energy in Japan

Hiroshi AZECHI
Institute of Laser Engineering, Osaka University, Osaka Japan.
Email: azechi@ile.osaka-u.ac.jp

Abstract. High-density compression of DT to one thousand times its liquid density is the critical path of inertial fusion and was demonstrated in Japan and US in late 1980's. The Osaka group has achieved high-density compression that meets one of the critical requirements for thermonuclear ignition and burn. Although the compression densities were well reproduced by computer simulations, the neutron yields were much lower than the simulation predictions by three orders of magnitudes, suggesting catastrophic collapse of a hot spark, from which thermonuclear reactions are triggered. In order to overcome this difficulty the international ICF community has adopted two approaches: one is to generate a larger hot spark than the mixed layer with MJ-Class lasers, such as NIF and LMJ. The other approach is to externally heat the compressed fuel. The second approach is the fast ignition. After the proof-of-concept experiment in 2002, we started the Fast Ignition Realization Experiment (FIREX) project to complete the world most powerful high-energy peta-watt laser “LFEX” as a heating laser.

1. Introduction
In the past half-century, being stimulated by the laser fusion concept by J. Nuckolls [1], various large-scale programs took off throughout the world aiming at ultimate goal of thermonuclear ignition. Namely, OMEGA (original) [2], GEKKO-XII [3], and NOVA [4] in 1980’s, followed by OMEGA (upgrade) [5], National Ignition Facility (NIF) [6], Laser Mega Joule (LMJ) [7], and more recently high energy peta-watt lasers, EP [8], LFEX [9], ARC [10] and PETAL [11]. Chinese Shenguang series [12] have also joined in and contributed to the world community. It appears, however, that start of any next laser fusion program depends on the success of ignition at NIF. In this article, in order to make good use of the next generation programs, I would like to review the key elements of successes and failures in the past and present programs along the laser fusion history in Japan.

2. High-density Compression
In early 1970’s, J. Nuckolls released a concept of inertial fusion [1], indicating that scientific breakeven could be achieved with only a kJ of laser energy if the fusion fuel is compressed to ten thousand times liquid density. Meanwhile, pessimists suspected such a rosy view in the earliest times saying that at high laser intensity necessary for fusion, plasma becomes collision-less, resulting in low laser absorption. This pessimism was dispelled by anomalous absorption found by C. Yamanaka [13], K. Nishikawa [14] and many other activities, starting full-scale investigation in the world. (The late study clarified anomalous absorption as to be eliminated, but its importance is taken over by “anomalous absorption conference”, one of the most importance conferences.)

From the early to mid 1980’s, new laser fusion facilities were built one after another, such as OMEGA at the University of Rochester [2], GEKKO-XII at Osaka University [3], and NOVA at Lawrence Livermore National Laboratory [4]. Development of the GEKKO laser facilities is schematically illustrated in Figure 1. The main target in early experiments was the realization of high...
temperature required for nuclear fusion, and the resultant high neutron yield attracted public attention as a symbol of nuclear fusion. The University of Rochester set the world record of neutron yield to reach $1 \times 10^{10}$. After that, Osaka University increased the yield to over $1 \times 10^{12}$ by the implosion mode called stagnation free [15]. The result appeared as a cover story of Nature. Furthermore, the University successfully achieved $1 \times 10^{13}$ neutrons with a fuel temperature of 100 million degrees required for nuclear fusion through optimization of the implosion mode [16]. The Lawrence Livermore National Laboratory recorded twice the number of neutrons with the same scheme but larger laser energy. (The record was broken ten years later when OMEGA (upgrade) achieved $1 \times 10^{14}$ neutron yield.)

In the late 1980’s, the research focus shifted from high temperature to high-density compression. C. Yamanaka formed three research teams with the same goal but different approach, stimulating intensive race and peer-review research. Among them, three key technologies were developed: uniform CD (deuterated polystyrene) shells made with density-matched emulsion technique developed by M. Takagi [17], random phase plates for uniform laser irradiation by Y. Kato [18], and a wealth of nuclear diagnostics, including secondary fusion reactions [19] for fuel $\rho R$ and mix measurements and scintillation streak camera [20] for burn time and duration measurements. Achievements of 100-200 times liquid density (XLD) by R. McCrory [21] and 600 XLD by H. Azechi and N. Miyanaga [22] became epoch-making experiments which verified the formation of a main fuel—one of two requirements of laser fusion. (The record was broken at OMEGA and NIF in 2010’s [23, 24].)

Although the compression densities were well reproduced by computer simulations, the neutron yields were much lower than the simulation predictions by three orders of magnitudes, suggesting catastrophic collapse of a hot spark, from which thermonuclear reactions are triggered. This collapse occurred even though the Rayleigh-Taylor instability is significantly moderated by material ablation that removes the perturbation away from the unstable surface. The quantitative ablative stabilization was first experimentally verified [25].

So it requires extremely high spherical symmetry to form a hot spark at the centre of the fuel. The direct drive scheme in which a fuel target is directly irradiated by laser has difficulty in forming a hot spark because of the limitation of the number of beams and lack of irradiation uniformity. Stimulated by random phase plates, various technologies of beam smoothing were developed one after another, including the induced spatial incoherence (ISI) of Naval Research Laboratory [26], the smoothing by spectral dispersion (SSD) of University of Rochester [27], and the partially coherent light (PCL) technology of Osaka University [28], lowering residual non-uniformity to only 1% level or less.

On the other hand, the indirect-drive scheme in which laser beams are converted into X-rays driving a fuel capsule to implode is superior in irradiation smoothing over the direct-drive scheme, so the United States had focused its main effort on the indirect-drive scheme. In the early 1990’s, they
succeeded in hot spark formation, albeit at the expense of energy efficiency injected into a fuel target [29]. The National Academy of Science vigorously reviewed a sequence of results, and issued the famous Koonin Report [30] stating that 11 out of 12 assignments which are conditions for starting the ignition program have been achieved, and because the only failed condition of forming a hot spark under similar conditions to ignition is difficult to realize with the current experiment facility, this failure is not a valid excuse for delaying the program. In response to this, construction of NIF was started and commissioned. The similar LMJ project is in progress in France. Figure 2 illustrates that high temperature and high density demonstrations provided scientific bases of these ignition programs.

The times from the early to mid 1990’s when there were discussions on construction of NIF overlapped with the period when science and technology policy was seriously reviewed. The US quit underground testing after Cold War, and in its place, established the Science Based Stockpile Stewardship [31] in which nuclear forces are maintained and managed through virtual simulation experiments. The NIF is regarded as a multi-purpose research facility to promote nuclear fusion energy development and fundamental science, as well as a facility to clarify the equation of state and the opacity for X-rays of material under high-temperature and high-density conditions.

In passing, it was 1980, in the midst of Cold War, when the indirect-drive scheme was proved to be classified. The review itself of “Cannonball Target” proposed by H. Azechi independently from the indirect-drive scheme was refused by Physical Review Letters for security reasons [32]. Subsequently Max Planck Institute for Quantum Optics in Germany and Osaka University published their experimental results of indirect drive [33], making weaker the validity of them being classified, and in the end of 1993, reflecting the end of the Cold War, most of the research results were declassified on the grounds that there was no concern for nuclear proliferation.

3. Birth of the Concept of Fast Ignition
During this period, researchers also sought for a more advanced ignition scheme and proposed a new ignition idea in the early 1990’s that a fuel is imploded in high density beforehand, and another laser is injected to the implosion core to heat fuel before hydrodynamic disassembly [34]. This scheme is called “fast ignition”. Fuel plasma used for fast ignition has a solid structure, so the scheme can obtain a larger gain with lower laser energy as compared to the central ignition. Russian group also proposed similar idea [35].

Here, let me describe the story of the birth of fast ignition. A brainstorming meeting on a new laser fusion scheme was held in 1983 before operation of GEKKO-XII, and T. Yamanaka proposed a concept of “additional heating” using fast electrons generated by picosecond laser [36]. This proposal was almost the same as the current fast ignition, but the realization of the idea required “future”
invention of an ultrashort pulse laser technology. The proposal was not published but only printed as an internal document. At the end of 1980’s, concept of additional heating, high density fuel to be heated, and high energy short pulse laser were all in the Laboratory. However, it was an American researcher who combined them and proposed the idea of fast ignition for the first time. This incident caused Japanese researchers to seriously think about the ability to seek for a fundamental solution of a problem by calling upon a great amount of insight from different people.

4. Progress of Fast Ignition Study
In the mid 1990’s, with the completion of OMEGA (upgrade) and approval of construction of NIF, the US inertial fusion community shifted from competition to a new era of unification. In light of this situation, K. Mima of Osaka University immediately upon the appointment as a director decided to focus the laboratory on fast ignition and constructed GEKKO-PW peta-watt laser. European research institutes also started basic research of fast ignition. The US, to the contrary, shut down NOVA-PW laser [37] that could provide peta-watt outputs and concentrated on NIF.

The first task of the fast ignition study was to make a laser reach the high density fuel neighborhood. Hole boring that creates a laser propagation path by removing corona plasma using light pressure, or relativistic anomalous penetration, were experimentally verified one by one [38]. It was learned that laser propagation in plasma accompanies energy dispersion, and to avoid it, R. Kodama and K. Mima of Osaka University set a perspicacious little hook. They attached a hollow cone to the fuel ball to inject heating laser from the inside of the cone. The fuel temperature reached about 1 keV in an experiment conducted in 2002, resulting in the neutron-yield increased by three orders of magnitude as compared to a case without heating [39].

5. Fast Ignition Realization Experiment Program (FIREX)
Since high-density compression as high as 600 times liquid density and heating to 1 keV temperature have been achieved, the next milestone for the research became realization of fusion ignition and burn. This program is called Fast Ignition Realization Experiment (FIREX).

The FIREX program is separated into two stages: in the first stage, a compressed fuel will be heated with a heating laser (10 kJ/10 ps) to the ignition temperature of about 5 keV. At this stage, alpha particles escape from the fuel without significant heating, causing no ignition. In the subsequent second stage, lasers for compression and heating are both upgraded to 50-100 kJ level and thereby fuel plasma larger than the range of an alpha particle can be generated and fusion ignition and burn is expected. Because inertial confinement time becomes longer according to increase in laser power and fuel size, high fusion gain required for a commercial reactor can be obtained. It is expected that there will be no serious problems in a step from ignition and burn to high fusion gain, so the research on core plasma physics is thought to be completed at the FIREX stage.

At this time, there was a strong need to reorganize fusion activities to invite ITER program into Japan. A fusion working group was established in the Council for Science and Technology with T. Yamanaka, H. Azechi, and K. Mima as members. After two years serious discussion, the Council submitted a report titled “Future Direction of National Fusion Research” saying that FIREX will expand the possibility of realization of fusion energy through a scheme qualitatively different from the magnetic fusion scheme by applying the latest laser technology and science in an extreme state, and the first stage of FIREX will be one of major projects to be prioritized by the nation [40]. The increase of heating laser energy in the past quarter century is illustrated in Figure 3.

Our recent studies identify three scientific challenges to achieve high heating efficiency in the fast ignition scheme with the current GEKKO and LFEX laser systems: (i) control of relativistic electron beam (REB) energy distribution, (ii) guiding and focusing of REB to a fuel core, and (iii) formation of a high areal-density core [41]. The control of the electron energy distribution has been experimentally confirmed by improving the intensity contrast of the LFEX laser up to >10^8 and an ultra-high contrast of 10^{11} with plasma mirrors. After the contrast improvement, 50% of the total REB energy is carried by a low energy component of the REB, whose slope temperature is close to the ponderomotive scaling.
value (~1 MeV). To guide the electron beam, we apply strong external magnetic field to the REB transport region [42-44]. Guiding of the REB by 0.6 kT field in a planar geometry has already been demonstrated at LULI 2000 laser facility, in a collaborative experiment lead by CELIA-Univ. Bordeaux [45]. Considering more realistic fast ignition scenario, we have performed a similar experiment using the kilo-Joule LFEX laser to study the effect of guiding and magnetic mirror on the electron beam. A high density core of a laser-imploded 200 µm-diameter solid CD ball was radiographed with picosecond LFEX-produced K-alpha backlighter. Comparisons of the experimental results and integrated simulations using hydrodynamic and electron transport codes suggest that 10% of the efficiency can be achievable with the current GEKKO and LFEX laser system [46].

6. Lessons Learnt from the Previous Programs

To summarize the lessons from the previous programs, we follow three critical elements for success proposed by Mencius, ancient Chinese philosopher, that is, 1) Heavenly Timing, 2) Geographical Advantage, and 3) Harmony among People. The lessons we could learn from GEKKO-XII are 1) Heavenly Timing: Oil crisis in 1973 and 1979 urged political and financial support; 2) Geographical Advantage: good distance from the policy-making capital; and 3) Harmony among People: there was a director’s strong leadership. Contrary, at the time of the high neutron yield and high-density compression, the fusion committee in Japan had already selected a large magnetic fusion machine, Large Helical Device (LHD), as the next fusion facility, and as a result, our proposal of the ignition project, KONGOH, finally failed to take off.

The lessons we have learned from FIREX-I are 1) Heavenly Timing: very narrow window opened between LHD completion and ITER cite decision; 2) Geographical Advantage: technical data of fast ignition were just in time for the Committee discussion; and 3) Harmony among People: Data, committee discussion, and new proposal were coherently made, even without charismatic leadership.

7. Next Program

The current situation is characterized as disappearance of Cold War and Oil Crisis that had strongly driven large-scale science. In light of this situation, we have reviewed our next generation program of FIREX-II to be conducted as an international one. In parallel to the ignition program, we set another program using a repetitive multi kJ laser. This program would result in considerably good understanding of fusion science, as well as basic high energy-density science and industrial applications.
References

[1] J. Nuckolls et al., Nature 239, 139 (1972).
[2] J. Bunkenberg et al., IEEE J. Quantum Electron. QE-17, 1620 (1981).
[3] C. Yamanaka et al., Phys. Rev. A 6, 2335 (1972).
[4] J.T. Hunt and D.R. Speck: Optical Engineering 28, 461 (1989).
[5] T. R. Boehly et al., Opt. Commun. 133, 495 (1997).
[6] G. H. Miller, E. I. Moses, and C. R. Wuest, Nucl. Fusion 44, 228 (2004).
[7] M.L. Andre, Fusion Engineering and Design 44, 43 (1999).
[8] J.H. Kelly et al., Journal de Physique IV 133, 75 (2006).
[9] N. Miyanaga et al., Journal De Physique IV 133, 81 (2006).
[10] Tomás Díaz, Science and Technology Review 12, 12 (2011).
[11] A. Casner et al., High Energy Density Physics 17, 2 (2015).
[12] H. Zhang et al., Phys. Plasmas 21, 093401 (2014).
[13] C. Yamanaka et al., Phys. Rev. A 6, 2335 (1972).
[14] K. Nishikawa: J. Phys. Soc. Jpn. 24, 916 (1967), ibid 1152 (1967).
[15] H. Takabe et al., Phys. Fluids 31, 2884 (1988).
[16] M. Takagi et al., J. Vac. Sci. Technol. A9, 2145 (1991).
[17] Y. Kato et al., Phys. Rev. Lett. 53, 1057 (1984).
[18] H. Azechi et al., Appl. Phys. Lett. 49, 555 (1986); H. Azechi et al., Phys. Rev. Lett. 23, 2635 (1987).
[19] H. Azechi et al., Appl. Phys. Lett. 55, 945 (1989).
[20] R. McCrory et al., Nature 335, 225 (1988).
[21] H. Azechi et al., Laser and Part. Beams 9, 193 (1991).
[22] V. Goncharov et al., Phys. Rev. Lett. 104, 165001 (2010).
[23] A. J. Mackinnon et al., Phys. Rev. Lett. 108, 215005 (2012).
[24] H. Azechi et al., Phys. Rev. Lett. 98, 045002 (2007).
[25] R. H. Lehmberg and J. Goldhar, Fusion Tech. 11, 532 (1987).
[26] S. Skupsky et al., J. Appl. Phys. 66, 3456 (1989).
[27] H. Nakano et al., J. Appl. Phys. 73, 2122 (1993).
[28] M.D. Cable et al., Phys. Rev. Lett. 73 2316 (1994).
[29] http://www.nap.edu/catalog/5730.html
[30] R. Jeanloz, Physics Today 53, 44 (2000).
[31] This was finally published in H. Azechi et al., Jpn. J. Appl. Phys. 20, L477 (1981).
[32] R. Sigel et al., Phys. Rev. A 38, 5779 (1988); H. Nishimura et al.: Phys. Rev. A 43, 8323 (1991).
[33] M. Tabak et al., Phys. Plasmas 1, 1626 (1994).
[34] N. Basov, J. Sov. Laser Res. 13, 396 (1992).
[35] T. Yamanaka, Enhanced heating by psec laser pulse, Experimental Proposals for Kongoh Project Phase I, Institute of Laser Engineering Internal Report, Osaka University, 5-6 (1983).
[36] http://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu4/toushin/1213875.htm
[37] S. Fujioka et al., Phys. Plasmas 23, 056308 (2016).