



## Special Review

Review

# Backgrounds and Research Activities on Nuclear Fusion in Toyota Central R&D Labs., Inc. including Recent Collaborative R&D Project on High-repetition (> 1 Hz) Laser-implosion by Counter-illumination

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**■ABSTRACT■** Backgrounds and research activities on nuclear fusion in Toyota Central R&D Labs., Inc. including steady step progress in recent collaborative R&D project on high-repetition (> 1 Hz) laser-implosion by counter-illumination centering on the Graduate School for the Creation of New Photonics Industries in Hamamatsu from 2008 were reviewed tracking back to 1988. These activities have been started based on a concern how we get automobile fuel and energy for automobile production beyond the next four decades. The review involves development of X-ray lasers and laser plasma X-ray sources for analysis of nanometer sized materials in collaboration with Institute of Laser Engineering, Osaka University which was actually a springboard to enter the laser fusion project mentioned above, and researches on condensed matter nuclear phenomena in collaboration with former Laboratory for Nuclear Science in Tohoku University including transmutations and excess heat generation related to what is called as “cold fusion” as well as the laser fusion research.

**■KEYWORDS■** Laser Fusion, Implosion, Fast Ignition, Deuterium, Neutron, Electricity Generation, Transmutation, Excess Heat, Laser Plasma, Soft X-ray

## 1. Introduction

Putting aside the detailed practical strategies to get automotive fuel and energy for automobile production in the next four decades, we are in the grips of a concern how we get them beyond the next four decades. International Thermonuclear Experimental Reactor (ITER) project targeting nuclear fusion power generation is one of the approaches to get rid of this concern. This project is so gigantic that international collaborations and cooperation are indispensable. Nuclear fusion power generation is a too long term target for private companies to address. However, spirits of founders of active private companies in several prefectures in central Japan sometimes do not sit on their bottoms to wait for realization of a big target but try to realize it by themselves in a faster way, in a different approach, and in a compact style. The laser fusion project in the Graduate School for the Creation of New Photonics Industries (GPI) in collaboration with Hamamatsu Photonics, K. K., Toyota Motor Corporation (abbreviated hereafter as TOYOTA) and others is a typical example of this, in which

Toyota Central R&D Labs., Inc. (TCRDL) has been also involved since 2008. Hereafter, let me express this project as “CANDY” in abbreviation. The origin of this naming will be explained later.

## 2. Origins of R&D Related to Nuclear Fusion in TCRDL

### 2.1 R&D on X-ray Laser and Laser Plasma Soft X-ray Sources

The first chance in which the R&D activity in TCRDL came across the nuclear fusion research dates back to 1988 insofar as the author can tell. In these ages, expectations for novel functions of structured materials in nanometer size (nanophase materials, nanomaterials) such as nylon-cray hybrids (NCH)<sup>(1)</sup> and folded-sheet mesoporous materials (FSM)<sup>(2)</sup> were expanding. For the detailed analyses of nanoscale structures, a coherent soft X-ray source, what is called as an X-ray laser, was anticipated. After one year exploration on the state of X-ray laser sources at the time and ways to construct them by

an in-house project team, the first consultation with Prof. Y. Kato of Institute of Laser Engineering (ILE), Osaka University was made in September 1988 and a collaboration was started immediately in October 1988 sending forth a researcher (Dr. H. Azuma, abbreviated as HA, hereafter) to ILE. During his stay in ILE from October 1988 to March 1991, he engaged in recombination type X-ray laser generation experiment using high power laser Gekko XII and Gekko MII which were mainly used for laser fusion research. In addition to operation and maintenance of GXII and MII in place of Peter R. Herman who got back to Toronto University, Canada in September 1988, HA acquired proficiency in fundamental high power laser technologies such as (1) 100 picoseconds pulsed laser formation from nanoseconds pulsed 1.06  $\mu\text{m}$  YAG laser by mode-locking using an avalanche diode, (2) its chirping through an 1 m long optical fiber with a core diameter of 9  $\mu\text{m}$ , (3) compression of the laser pulse width to 28 picoseconds using a pair of diffraction gratings, and (4) 0.53  $\mu\text{m}$  second harmonic generation using a KDP crystal under the guidance of Chris Bertie of Stanford University (National Ignition Facility: NIF at present). He also fabricated a target made of NaF coated parylene ( $\text{C}_8\text{H}_8$ ) film on a stainless steel plate with a slit aperture for high power laser irradiation, and realized laser beam concentration into 4.5 mm  $\times$  0.03 mm on the target using combinations of a cylindrical lens and a convex lens. Putting a streak camera combined with a spectrometer on the extended line of the longitudinal direction of the long and thin irradiation area on the target, time dependent spectroscopy of X-ray laser was performed. He also developed the spectrometer for this experiment using a toroidal mirror specially designed by Prof. Kato as well as gratings because the conventional spectrometer employing a cylindrical light collecting mirror was not applicable to recombination type X-ray laser of weak intensity. The time dependent spectrometry was also performed putting the streak camera combined with the spectrometer on the direction at an angle of  $30^\circ$  from the above-mentioned extended line of the long and thin irradiated area on the target in order to make comparison with the spectrum measured on the direction along the longitudinal direction of the irradiation area. This comparison revealed amplification of light of 5.419 nm in wavelength corresponding to 3d-2p transition along the longitudinal direction of the irradiated area with a gain per unit length of the irradiated area of

$4 \pm 1/\text{cm}$ . In parallel with the experiment, computer simulation of plasma generation by high power density laser irradiation was performed under the guidance of S. J. Rose of Rutherford Appleton Laboratory, UK. Taking ten energy levels of a helium like ion and a hydrogen like ion which can be described only by main quantum number into consideration, a set of rate equations involving all the possible terms were calculated using von-Neumann-Richtmeyer Lagrangian algorithm based on one-dimensional one-fluid, two temperatures model and average ion model concerning to ions of other types.<sup>(3)</sup> The simulated results told the maximum gain of 12/cm was to be attained at 15-20  $\mu\text{m}$  above the initial target surface after 90 picoseconds of laser irradiation. Temporal integration of this time dependent gain gave 5/cm, which agreed with the experimentally obtained value of  $4 \pm 1/\text{cm}$ .<sup>(4)</sup> In 1990, gain-narrowing of the spectral width of recombination type X-ray laser was observed using a high resolution spectrometer: HIREFS reflection-grating monochrometer (HIREFS: high-resolution erect-field spectrometer). In 15 months until March, 1991, the following five experiments (1)-(5) related to X-ray laser were conducted using GXII. (1) Two targets of different length were irradiated by a laser at different timings to realize a system of a combination of X-ray laser source and an amplifier. (2) X-ray laser generation from a curved target taking the refraction of X-ray in a high density plasma. (3) Simultaneous observation of Balmer  $\alpha$  lines of Na and of F. (4) Electron impact excitation type X-ray laser generation using a Ge target. (5) X-ray holography experiment to evaluate the coherent length of X-ray laser.<sup>(5)</sup> Through these years in ILE where active researches on laser fusion was conducted, HA gained fundamental knowledges and experimental skills on high power laser experiments including laser fusion and X-ray laser as well as his doctorate.

After the two and half years' stay in ILE, HA was involved in a project to realize a compact X-ray laser source sponsored by Science and Technology Agency (at that time, STA) as a concept engineer. This project had been arranged under the initiative of Toyota Technological Institute (TTI) to make a proof of concept of X-ray laser proposed by Prof. T. Hara (TTI)<sup>(6)</sup> by amplification of emission lines of 8.884 nm, 10.23 nm, 13.00 nm, 14.76 nm from Li-like, or Be-like Al just after excitation by a high power laser, and the project was conducted under an implicit agreement of future commercialization of

products by small-and-medium-sized enterprise. For the assistance to the concept engineer: HA, a recruit from TOYOTA MACS Inc. joined this X-ray laser project in TTI.

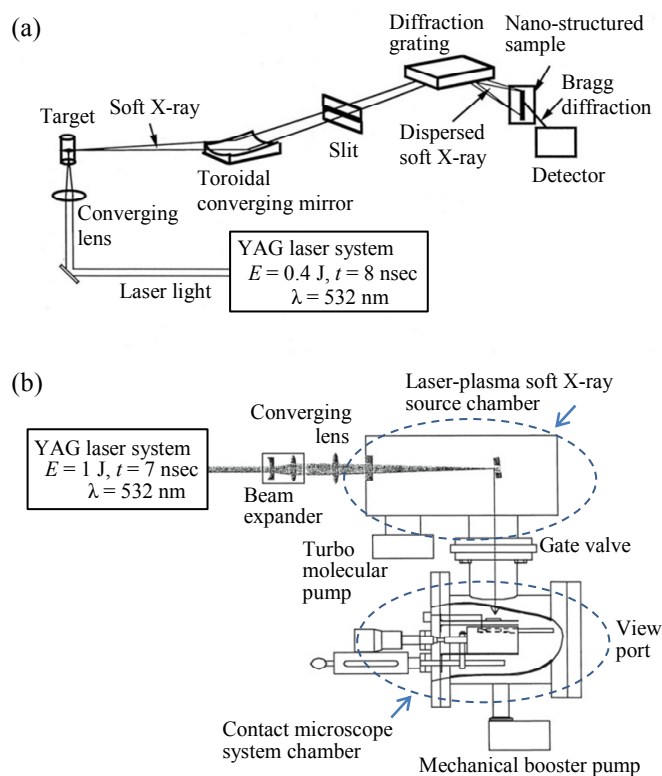
For the first step, a design of an apparatus was performed in which a target is irradiated by a train of laser pulses in a width of 100 picoseconds reformed from YAG laser together with a design of a measurement apparatus to observe corresponding X-ray emissions simultaneously. To make the system as compact as possible, the laser pulse train was divided into two optical paths, and after amplifications on each paths, the two amplified pulse trains were joined together again just before the target. As for observation of the X-ray emission, a streak camera was fully utilized which has become a key monitoring tool later in CANDY project. For this streak camera measurement, HA came across a young engineer Mr. Y. Nishimura (abbreviated as YN, hereafter) who was successively sent to TTI laboratory from TOYOTA MACS Inc., and HA transferred his technical know-hows and experiences having gained during his stay in ILE to YN. To give an appropriate delay of the start of the operation of the streak camera after the laser pulse irradiation on the target, the optical path for the delay was taken from end to end in the limited space of the laboratory in TTI. Finally, a lasing of X-ray laser was observed with its gain between 0.5 and 2.0, giving a success of the STA project. After the end of the project, TOYOTA MACS Inc. tried to find a way to commercialize the X-ray laser. However, the killer application of X-ray laser had not been clear at that time in contrast to the present status in which utilization of coherent X-ray source is beginning to prevail after the construction of SACLA. Therefore, the R&D target was changed from X-ray laser to incoherent laser plasma X-ray source and the R&D was conducted by HA and YN. **Figures 1(a)** and **(b)** show two configurations of apparatuses fabricated for typical trial applications of laser plasma soft X-ray source. Finally, it was commercialized as a laser plasma soft X-ray source for EUV lithography and sold to a Japanese stepper manufacturer as a testing light source to evaluate optics of EUV lithography. After this, YN was temporary transferred to TCRDL and related research was continued with HA. In this research, target application was a light source for EUV lithographic exposure of resist in collaboration with Litho Tech Japan Corp. who was developing apparatus for evaluation of resist for EUV lithography. Later we proposed TOYOTA to have YN

be involved in CANDY project. More recently, Toyota Technical Development Corporation (TTDC, the name changed from TOYOTA MACS Inc.) has sent YN to GPI as a doctorate student and he got his doctorate in 2016 related to the R&D in CANDY project. This was the second doctorate from TOYOTA group companies in CANDY project, where the first one is Dr. O. Komeda (abbreviated as OK) of TOYOTA. Now both OK and YN have become two of the main researchers in CANDY project.

## 2.2 Study on Condensed Matter Nuclear Phenomena and Cold Fusion

Although the report of M. Fleischmann and S. Pons<sup>(7)</sup> (MF and SP) accompanied by S. E. Jones<sup>(8)</sup> in 1989 stirred up the laboratory members of TCRDL and some experiments to reproduce the MF and SP experiment were conducted by some members including scientists of ion beam technology and electrochemistry in TCRDL, I remember those members turned out to be skeptical about MF and SP.

In late December, 2002, it was announced by



**Fig. 1** Applications of laser plasma soft X-ray sources: (a) structural analysis of nano-structured materials, (b) contact microscopy.

Emeritus Prof. K. Kohra of the University of Tokyo that a special symposium was to be held on January 31st, 2003 in Tokyo under the auspices of No. 145 committee on crystal processing and evaluation technologies and No. 141 committee on micro beam analyses in Japan Society for the Promotion of Science (JSPS). The aim of the symposium was to evaluate the exotic experiment conducted by Emeritus Prof. K. Ikegami of Osaka University who was continuing his research in Uppsala University, Sweden. His experiment was on enhanced Li-D nuclear fusion in molten Li under the irradiation of low energy ( $< 30$  keV) deuterium ion beam. He detected unidentified radiation of the energy which cannot be explained by conventional D-D fusion or Li-D fusion radiation spectra. In this symposium, a skeptical comment was made by Emeritus Prof. M. Kawai of Kyusyu University based on the common sense of conventional physics of nuclear fusion while supporting comments were made by Prof. A. Takahashi of Osaka University, Prof. N. Kitamura of Kobe Nautical College, and Prof. J. Kasagi of former Laboratory for Nuclear Science in Tohoku University. Prof. Takahashi explained his theoretical work on possibility of low energy nuclear fusion in a condensed matter by shielding effect of electrons and cooperative motions of absorbed deuterons.<sup>(9,10)</sup> Prof. A. Kitamura reported his experimental work on 800 times enhancement of D-D nuclear fusion probability during 20 keV  $D^+$  or  $D_2^+$  ions irradiation to Ti or Pd. Prof. Kasagi reported his experimental work on 50 times enhancement of D-D nuclear fusion probability during 10 keV  $D^+$  ions irradiation to Fe, Pd, and PdO. Prof. Kasagi also found that the enhancement rate of D-D nuclear fusion increased with decrease in the acceleration voltage indicating low energy fusion.<sup>(11)</sup> On February 5th, 2003, Emeritus Prof. K. Ikegami was invited to TCRDL to deliver a lecture on the same topic as that in the special symposium of JSPS to introduce his research to TOYOTA group companies and several institutes of Nagoya area including Prof. K. Ueda of TTI and Prof. F. Okuyama of Nagoya Institute of Technology who had suggested anomalous heat generation during deuterium ion irradiation to Palladium metal.<sup>(12,13)</sup> Through the discussions with the attendees, we came to know the fact that researchers of plural different sections of TOYOTA group companies including TOYOTA had been surveying or even supporting some cold fusion researches including the work of Y. Iwamura et al. on the Sr-to-Mo and Cs-to-Pr transmutation during  $D_2$

gas permeation through a Pd foil with its surface coated with Pd (40 nm)/CaO (2 nm)/(Pd (18 nm)/CaO (2 nm))<sub>4</sub> multilayers,<sup>(14)</sup> the work of Y. Arata et al. on excess heat generation during deuterium absorption by Pd metal<sup>(15)</sup> and the work of J. Kasagi et al. mentioned above.<sup>(11)</sup>

Echoing these activities in TOYOTA group, an in-house half year project including T. Hioki (abbreviated as TH, hereafter), HA and T. Motohiro (abbreviated as TM), on current situation and possibility survey on condensed matter nuclear fusion were started in April in 2003. In this project, TH and TM attended the 10th Int'l. Conf. on Cold Fusion (ICCF10), August 24th-29th, 2003, Boston, Massachusetts, USA and came to know that active discussions had been made under the names of Japanese, such as, "Arata Effect", "Iwamura Effect" and "Kasagi Effect", internationally. In parallel with the current situation survey, TH performed low energy deuterium ( $< 100$  keV) ion irradiation to molten Li and found radiation of charged particles at the energy similar to that observed by Prof. Ikegami. In one of the repeated experiments, neutron generation was observed during the day time continuously until the compressed deuterium gas cylinder got empty. However, after replacing the empty cylinder with a new one in the evening, the neutron generation was not observed any more that day. Prof. J. Kasagi also performed a similar experiment and observed similar radiation of charged particles. According to these results, Prof. Kohra organized informal meetings on these experimental reproductions three times during 2003-2004 at University of Tokyo and Tohoku University. In these meetings, TCRDL had constructed intimate intercommunication with Prof. Kasagi.

From the fiscal year of 2007, an advanced research center (ARC) was established in TCRDL and a program on nuclear phenomena in condensed matter was started under the program manager TH as one of two starter programs of ARC. In this program, objective experimental reproduction of Iwamura Effect was targeted. As for Sr-to-Mo transmutation, we could not distinguish transmutation products of Mo as Y. Iwamura because of interference of S signal on a XPS spectrum. The S on the surface was that diffused out from inside of the Pd foil and segregated on the surface during  $D_2$  permeation process. After developing the method to eliminate the most of the segregated S on the sample surface, we applied TOF-SIMS analyses to detect the possible transmutation products of Mo which was to give peak

at  $m/e$  ratio of 96, and we did detect the peak at  $m/e = 96$ . However, isotope abundance ratio did not fit that of Sr which had been key evidence of transmutation in Iwamura's work. The further inspection revealed the peak of  $\text{Ca}_2\text{O}$  also appeared at  $m/e = 96$ , and we judged that the existence of Mo could not be proved again. However, we could reproduce Cs-to-Pr transmutation beyond doubt.<sup>(16)</sup> Although the amount of Pr detected was far less than that in Iwamura's experiment possibly due to lower permeation rate of  $\text{D}_2$  in comparison with that of Iwamura's experiment, it was surely detected under the help of the state of the arts analyses in ICP beyond the usual detection limit by N. Takahashi and S. Kosaka in the analytical section of TCRDL. Prior to this, Technova group including Prof. A. Takahashi and Prof. N. Kitamura had succeeded to reproduce Arata Effect.<sup>(17)</sup> TH also conducted excess heat experiment using Pd nanoparticles impregnated in mesoporous silica: FSM<sup>(2)</sup> to reduce aggregation of Pd nanoparticles by heat of chemical reduction of oxide on the Pd nanoparticles by  $\text{D}_2$  and by heat of absorption in the successive absorption of  $\text{D}_2$  into Pd.<sup>(18)</sup> After this first heat generation mainly caused by chemical reactions went away, we examined heat generations by  $\text{H}_2$  absorption and  $\text{D}_2$  absorption, alternatively and repeatedly. In every repeated cycle, we found the temperature rises at  $\text{D}_2$  absorption were always larger than those at  $\text{H}_2$  absorption. It seems that exchange of absorbed  $\text{H}_2$  for  $\text{D}_2$  or vice versa, nor the differences of vibrational properties such as specific heat or heat conductivity between hydrides and deuterides might not explain this isotope effect, that is, the difference of temperature rises between  $\text{H}_2$  absorptions and  $\text{D}_2$  absorptions.<sup>(19)</sup> Figure 2(a) shows an apparatus used for the reproduction of Cs-to-Pr transmutation and Fig. 2(b) shows an apparatus used to find the difference of temperature rises between in  $\text{H}_2$  absorption and in  $\text{D}_2$  absorption by Pd nanoparticles in TCRDL. These successive reports on reproductions of Iwamura Effect and Arata Effect fostered momentum of research on condensed matter nuclear phenomena. In December 8th-9th, 2012, TH hosted 13th meeting of Japan CF research society in Nagoya and in October 2nd-7th, 2016, 20th Int'l. Conf. of Condensed Matter Nuclear Science (ICCF20) was successfully held in Sendai, Japan in which TH and TM were involved in the committee members. These activities also made backgrounds for adoptions in some national projects including ImPACT<sup>(20)</sup> (nuclear transmutation) and other on-going project on excess heat generation in one of

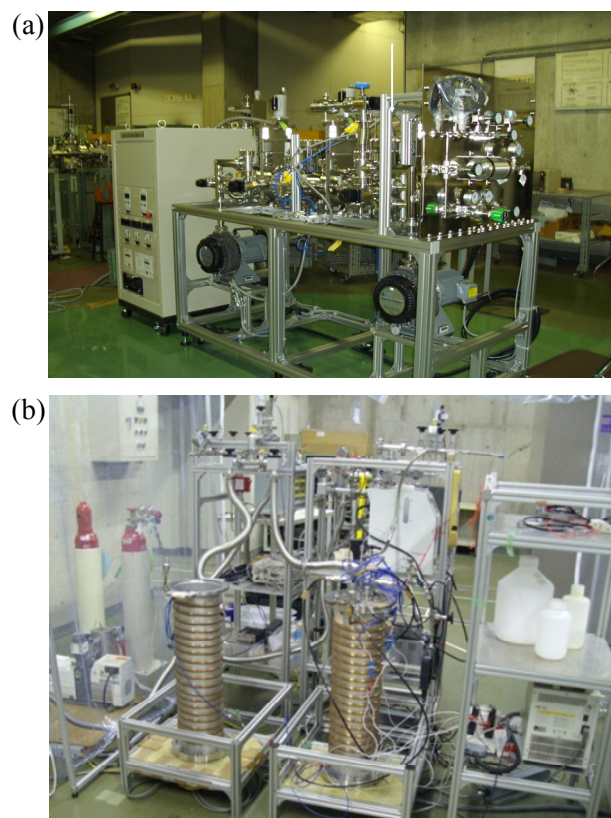
which NISSAN MOTOR CORPORATION is working as one of the key players.

### 3. Collaborative R&D Project on Laser Fusion in Hamamatsu

During R&Ds related to nuclear fusion as mentioned above, TCRDL was also asked to make a technical contribution to the CANDY project in 2008, and members of TCRDL including Dr. T. Kajino, Mr. M. Kakeno, Mr. S. Ohshima, and Mr. T. Nishi (by rotation) in addition to HA, TH and TM have been involved in the project. The contribution of TCRDL to this project has been continued until 2016. In this section, R&D in CANDY project mainly from 2008 to 2016 is reviewed.

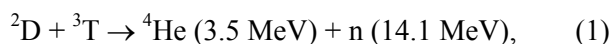
#### 3.1 History of Laser Fusion

After the conceptual representation of "laser implosion" in 1972, constructions of high power



**Fig. 2** Apparatuses (a) used for the nuclear transmutation experiment and (b) used to find the difference of temperature rises between in  $\text{H}_2$  absorption and in  $\text{D}_2$  absorption by Pd nanoparticles.

glass lasers were continued in step-by-step manner such as Gekko II (1973), Gekko IV (1977), Gekko MII of two beams of 340 J (1979) in ILE, leading to 30 kJ glass laser Gekko XII (1983) of 12 beams of 2 kJ (total 24 kJ). When these high power lasers hit a small target pellet containing deuterium-tritium (D-T) fusion fuel (This is called as “direct drive” approach.), materials of the pellet surface are emitted outward by ablation and remaining pellet materials are pushed inward because of counteraction, that is, “implosion”. This implosion may cause a shock wave to travel through the pellet into the middle. Although the laser energy may not be able to go deep into the pellet because of shielding of laser plasma on the pellet, heat may be also transported inward through electronic heat conduction, heat radiation and fast electrons. If the shock wave and all these energy transport could converge from 12 directions and meet in the middle, the density and temperature may briefly reach the Lawson criterion and start and sustain fusion reactions:



where  ${}^2\text{D}$  and  ${}^3\text{T}$  stand for deuterium atom and tritium atom, respectively. The superscripts in  ${}^2\text{D}$  and  ${}^3\text{T}$  indicate atomic mass. Here, 3.5 MeV and 14.1 MeV are kinetic energies of  ${}^4\text{He}$  ( $\alpha$  particle) and n (neutron), respectively. Neutrons emitted in all directions with kinetic energy as high as 14.1 MeV can be absorbed in so-called a blanket surrounding the reaction center made of for example Pb-Li layer and deposit the heat which makes the Pb-Li into a molten metal to work as a heat carrier to transfer the heat to a heat exchanger. At the heat exchanger, water vapor is produced to rotate a steam turbine of dynamo-electric generator. Therefore, the kinetic energy of neutron: 14.1 MeV is converted into electricity. On the other hand, the kinetic energy of  $\alpha$  particle can be deposited in the surrounding DT fuel because  $\alpha$  particle is large enough to be stopped by the surrounding D and T. Then ideally, the above fusion reaction processes are accelerated producing more  $\alpha$  particle to cause further fusion reactions ( $\alpha$  burning). This  $\alpha$  burning ideally continues until the fuel in the pellet is consumed. This feedback process:  $\alpha$  burning is the mechanism that leads to one of the final goals of laser fusion called as “ignition”. The process described above is called “central ignition” scheme.

In 1986, number of neutrons emitted attained  $1 \times 10^{12}$ , which was a world record at that time.<sup>(21)</sup> In 1991, extra-high density 600 times as large as

usual solid density was attained by laser implosion in ILE.<sup>(22)</sup> These were imperative milestones towards the ignition. In U. S., after construction of 100 kJ lasers “NOVA” completed in 1986, the further development for MJ laser was accelerated based on the attainments in ILE, Japan. In 2009, construction of National Ignition Facility (NIF) comprised of 192 laser beam lines of total output power of 1.8 MJ was completed. In France, “Laser Mégajoule” (LMJ) comprised of 176 laser beam lines of total output power of 1.8 MJ was also commissioned near Bordeaux in 2014 under the French Alternative Energies and Atomic Energy Commission (CEA). The primary tasks are conjectured to be refinement of fusion simulation for nuclear weapons both in NIF and LMJ. In contrast to ILE, 192 or 176 laser beams do not hit the target pellet surface directly but hit the inner surface of a cylinder called as “hohlraum” covered with heavy metal such as gold, and then X-rays are given off from this inner wall and hit the target pellet (indirect drive approach). The X-rays having shorter wavelength than the plasma wavelength are not shielded by the laser plasma and heat the surface of the pellet more efficiently than in the case of direct drive approach. The materials of the heated surface are emitted outward and remaining pellet materials are pushed inward because of counteraction, that is, implosion leading to fusion reactions as in the case of direct drive approach. For another important milestone along the path to ignition, we should attain the stage in which released fusion energy becomes equal to or greater than the amount of energy used to confine the fuel by laser beams: “fuel energy”, that is, the fuel gain  $\geq 1$ . In NIF in 2014, the milestone of achieving fuel gains greater than 1 has been reached for the first time in the world.<sup>(23)</sup> For example, the fusion energy of 26 kJ was released at the fuel energy of 10 kJ attained by the input laser of 1.8 MJ. Further increase in fuel gain is being attempted now. One of large challenges is instability of the interface between the confined high density core and surrounding plasma (Rayleigh-Taylor instability).

Meanwhile, a quite different approach has also emerged triggered by development of ultra high intensity peta watt (PW) lasers with chirped pulse amplification (CPA) technology.<sup>(24)</sup> In this new approach, after a D-T capsule is imploded to an isochoric condition,<sup>(25)</sup> the imploded core at its maximum compression is irradiated with a laser pulse in a few tens of a picosecond. The duration of this irradiation is much shorter than the

hydrodynamic disassembly time of the irradiated spot, and generated hot electrons at the cut off region penetrate into the core and form a hot spot, from which  $\alpha$  burning spreads over the core. This approach is called as “fast ignition scheme” in contrast to the “central ignition scheme” mentioned former. By the fast ignition scheme, the adverse influence of the Rayleigh-Taylor instability of the imploded core is mitigated and requested laser energy to attain ratio of fusion burning can be reduced to about the eighth part of that in the central ignition scheme. In ILE, it was demonstrated that the imploded plasma was efficiently heated up to about 1 keV accompanied by several orders of magnitude of increase in the neutron yield by injecting a PW laser into an imploded plasma.<sup>(26,27)</sup> Based on these result, construction of a 10 kJ/1-10 ps laser for first ignition: LFEX (Laser for Fast Ignition Experiment) was started and completed in 2009 in ILE.

### 3.2 Onset of CANDY Project

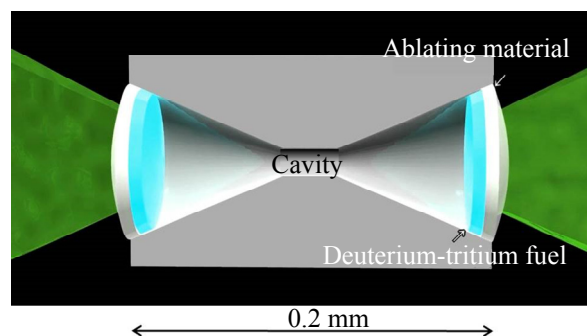
Although the NIF and ILE together with other institutes have shown a steady state progress in laser fusion technologies as described above, the lasers used in these studies can yield one laser pulse per several hours because of necessity of taking time to cool down their gigantic laser medium. However, the blanket must be frequently heated by neutron absorption to transfer energy out of the reactor to heat exchanger keeping its molten state. Therefore, a high repetition laser to yield neutrons by frequent nuclear fusions is indispensable. To meet this request, a plan for a compact and high repetition laser fusion project was mapped out by Prof. Y. Kitagawa and related members in GPI on July 20th in 2006. Along this plan, the CANDY project was put on the move from the fiscal year of 2008.

The fundamental consent of this CANDY project is to drive R&D to realize a working nuclear fusion reactor for electrical power generation at the electricity price under ¥ 4/kWh or thermal hydrogen production in the competitive lower cost. To realize this, much compact low cost laser system was also necessary in contrast to the big facility as in ILE with 12 laser beam lines and NIF with 192 laser beam lines. The idea of Prof. Kitagawa was counter-illumination of specially designed target as shown in Fig. 3 using only two laser beams for implosion and additional delayed two laser beams for first ignition. The specially designed target has

a cylindrical outer shape and has funnel shaped inner holes from the both ends of the cylinder. The two funnel shaped holes are connected with each other at the center of the cylinder. The holes at the both ends of the cylinder are leathered with sheets of ablator. To both the inner sides of the ablator sheets, sheets including D-T fuel are applied. When the ablator sheets are counter-illuminated, ablation takes place and deuterium and tritium fuel is pushed forward toward the center of the cylinder based on the principle of action and reaction. As the fuel proceeds towards the center, the space of the holes decreases compressing the fuel three-dimensionally. Therefore, Prof. Kitagawa envisaged that laser imploded core can be formed by only two laser beams. Since the shape of this target resembles that of Japanese hand drum, the target shown in Fig. 3 is called as drum-shaped target.

### 3.3 High Repetition Laser System for Counter-illumination

The laser system having been used from the beginning of CANDY project is a laser-diode-pumped high-repetition-rate “HAMA” laser which gives an imploding laser beam of amplified optical parametric chirped pulse of 3.6 J and 800 nm in the 0.4 ns pulse. As schematically shown in Fig. 4, the details of the HAMA laser system are as follows:<sup>(28)</sup> A seed beam of 1 J and 815 nm in wavelength is supplied at 10 Hz by a laser named as BEAT, and amplified via Ti: sapphire crystal of 50 mm in diameter and 20 mm in length named as HAMA amplifier. The HAMA amplifier is pumped by a high power laser of 10-12 J and 527 nm in wavelength converted from a laser of a wavelength of 1053 nm



**Fig. 3** Specially designed target for only two beams for implosion called (Japanese hand) drum-shaped target.

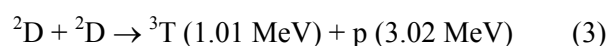
from a laser-diode-pumped Nd: glass laser system (diode pumped solid state laser: DPSSL) named as KURE-I (Hamamatsu Photonics K.K.) by using a frequency doubler based on the optical nonlinearity of a CsLiB<sub>6</sub>O<sub>10</sub> crystal. The KURE-I gives a laser of pulse energy of 21.3 J, a pulse width of 8.9 ns at 10 Hz. The total system is called as HAMA laser system, which gives an output laser of 3.6 J and 800 nm in the 0.4 ns pulse at 1.25 Hz. The output of HAMA laser system is divided into two beams, one for imploding and another for heating the imploded core. The imploding beam is divided into two beams (long beam 1 and 2), which are transported using different paths to the target chamber. The pulse width, energy and intensity of both beams are almost the same around 0.4 ns, 0.55 J,  $5.7 \times 10^{13}$  W/cm<sup>2</sup>. The other beam for heating is time delayed and pulse compressed to a 110-fs Gaussian beam by two pairs of gold-coated plane gratings (1740 grooves/mm). This beam is then divided again into two heating beams (short beam 1 and 2). Short beam 1 is co-aligned to long beam 1 and short beam 2 to long beam 2, respectively. A cross-beam divider stage enables us to co-align the four beams to counter-illuminate both sides of a target. The beam diameter is 60 mm.

A pair of 7.6-cm-diameter off-axial paraboloidal dielectric-coated mirrors (OAP) counter-focused the beams, such that long beam 1 and short beam 1 are focused from the right-hand direction of the target and long beam 2 and short beam 2 approach from the left-hand side as shown in Fig. 4. The focal length is

165 mm. All the beams are p-polarized on the target. The focal spot size is 32  $\mu$ m (the energy concentration in the spot is 17%) and the pointing accuracy on the target is within  $\pm 50$   $\mu$ m, or  $\pm 0.3$  mrad.

### 3.4 Target Fabrication: Contribution of TCRDL to CANDY Project

As the practical step by step approach, it was envisaged to realize high repetition implosions of the drum-shaped targets by a revolver type target holder as shown in Fig. 5 in the first stage. In addition to this, DT-fusion scheme as expressed in the reaction formula (1) was replaced by D-D fusion scheme as expressed in the nuclear reaction formulae (2) and (3) in the initial stage of the project.



The nuclear reactions (2) and (3) take place at the same probability of 50%. Since the kinetic energy of neutron 2.44 MeV is much less than 14.1 MeV, the nuclear reaction (1) which is also called as hot fusion must be employed in practical fusion reactors in the future.

In addition to this, the two-storied ablator/fuel layer placed as the “drumskins” on the both sides of drum-shaped target shown in Fig. 3 was substituted by three types of single layer target made of

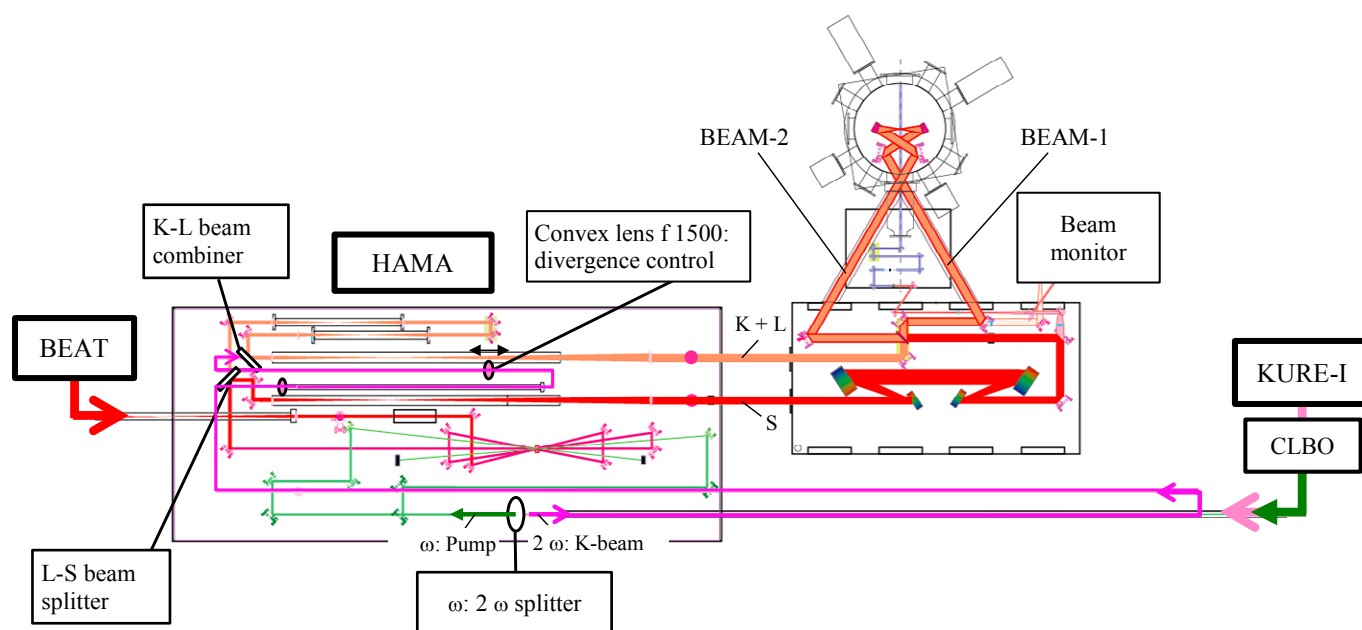


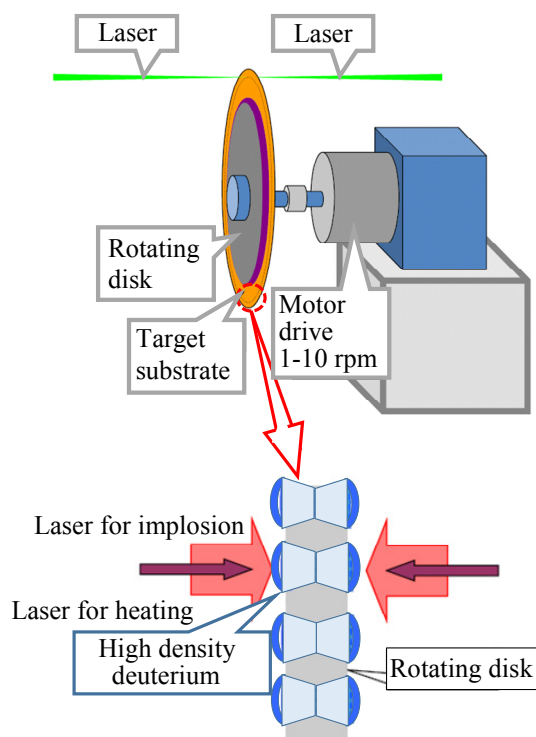
Fig. 4 Schematical representation of the HAMA laser system.



(a) deuterated polymers, (b) foamed polymer such as polyethylene with its holes filled with heavy water  $D_2O$  ice, and (c) solid metal deuterides having been developed for fuel cell vehicles in the automobile industry. The single layer target of (c) can realize the highest volume density of deuterium but has lowest weight density among the three. Moreover, (c) needs a substrate to deposit hydrogen absorbing alloys. Although the foamed polymer (b) sponge  $D_2O$  easily, it must be frozen to ice before laser illumination. Although deuteration is possible for limited numbers of polymers such as polyethylene, polypropylene, polystyrene, polybutylene, deuterated polymers can be easily shaped into films, solid spheres and hollow spheres. Thus all three have drawback and advantage.

### 3. 4. 1 Fabrication of Deuterated Polystyrene Films for the Target

Commercially available deuterated styrene monomer with its deuterium content of 8.98% in butylated hydroxytoluene supplied by Cambridge Isotope Laboratories, Inc. was used for polymerization.

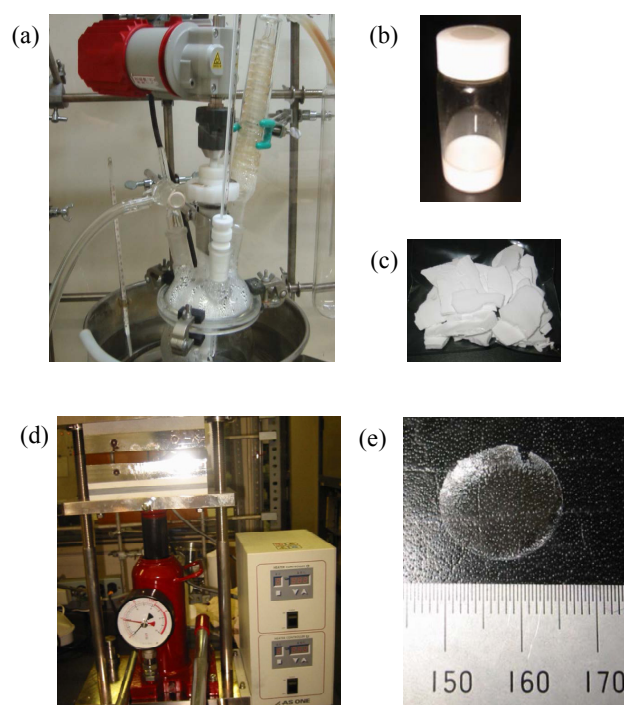


**Fig. 5** Revolver type target holder to realize high repetition implosions of the drum-shaped targets.

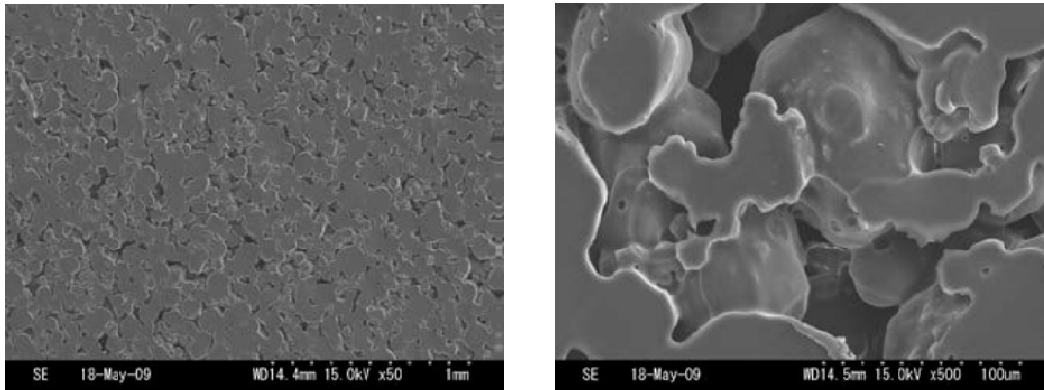
After interblending deuterated styrene monomer, heavy water and pH adjuster for five hours as shown in **Fig. 6(a)**, 2,2'- azobisisobutyronitrile was added to initiate polymerization. After one more hour interblending, white solution as shown in **Fig. 6(b)** was obtained. This solution was frozen in liquid nitrogen and dried in a vacuum drying oven. **Fig. 6(c)** shows the obtained purified deuterated polystyrene with its average molecular weight of 115 k and its distribution of 3.15. Using a pressing machine as shown in **Fig. 6(d)**, 3.7 mg deuterated polystyrene was made into a sheet on a slide glass at 170 degree of centigrade and 20 MPa. The resultant deuterated polystyrene was peeled off from the slide glass by rapid cooling with liquid nitrogen. **Figure 6(e)** shows the resultant circular sheet of 15 mm in diameter and 15  $\mu m$  in thickness. The density of the film was 1.05  $g/cm^2$  and the number density of deuterium atoms was  $4.5 \times 10^{22}$  per cubic centimeter.

### 3. 4. 2 Fabrication of Deuterated Polyethylene Foam Impregnated with Heavy Water

**Figure 7** shows SEM images of commercially available polyethylene foam of 0.1 mm in thickness.



**Fig. 6** Fabrication procedures of deuterated polystyrene films for the target.



**Fig. 7** SEM images of commercially available polyethylene foam of 0.1 mm in thickness to be used for impregnation of heavy water for the target.

The foam was once soaked into heavy water and then evacuated in a vacuum chamber using an oil-sealed rotary pump. At the vacuum chamber pressure of 133 hPa, bubbles came out of the sample. Further, the sample was sustained at 133 Pa for one hour. Resultant polyethylene foam was confirmed to involve heavy water by the wavelength of the peak of molecular vibration in optical absorption spectra. The foam gains weight at about 9% indicating ratio of involved deuterium by weight to be 1.8%, or the number density of deuterium atoms to be  $4.2 \times 10^{21}$  per cubic centimeter.

### 3. 4. 3 Fabrication of Deuterated Pd/Ti Thin Films on Polyethylene Film

As the model sample of hydrogen absorbing metal, pulsed laser depositions of Ti thin film of 56 nm in thickness succeeded by Pd thin film of 9 nm in thickness were performed on a polypropylene film substrate. The resultant film sample was suspended with copper wire in a stainless tube and  $D_2$  gas was filled in it at 10 atm. **Figure 8** shows this film after  $D_2$  gas soaking. The color of the film changed a little bit reddish. From the weight gain, the number density of deuterium atoms was obtained to be  $7.8 \times 10^{22}$  per cubic centimeter.

### 3. 5 Experimental Set up for Pulsed Laser Illumination

**Figure 9** shows the geometry of the laser illumination. In this case, illumination was performed only from one side of the sample using only one-half



**Fig. 8** Deuterated Pd/Ti thin films on polyethylene film.

of the optical system for the counter-illumination shown in Fig. 4. Three scintillation counters 1-3 for neutron detection were located out of the reactor vacuum chamber at the different distances from the focal point of OAP on the sample. Here, protons emitted by the nuclear reaction formula (3) cannot penetrate the reactor vacuum chamber wall because of its positive charge although it has larger kinetic energy than the neutron emitted under the nuclear reaction (2). Since the velocity of neutrons emitted under the nuclear reaction (2) is fixed, the neutron of the D-D fusion origin is to be identified by detection at the fixed time delay from the laser pulse illumination depending on the distance between the scintillation counters and the focal point of OAP on

the sample. A Thomson parabola time-of-flight ion spectrometer (Thomson parabola) is also connected to the reactor vacuum chamber. To eliminate the effect of cosmic radiation, the scintillation counters are covered by accumulated lead bricks except for the direction of the reactor center.

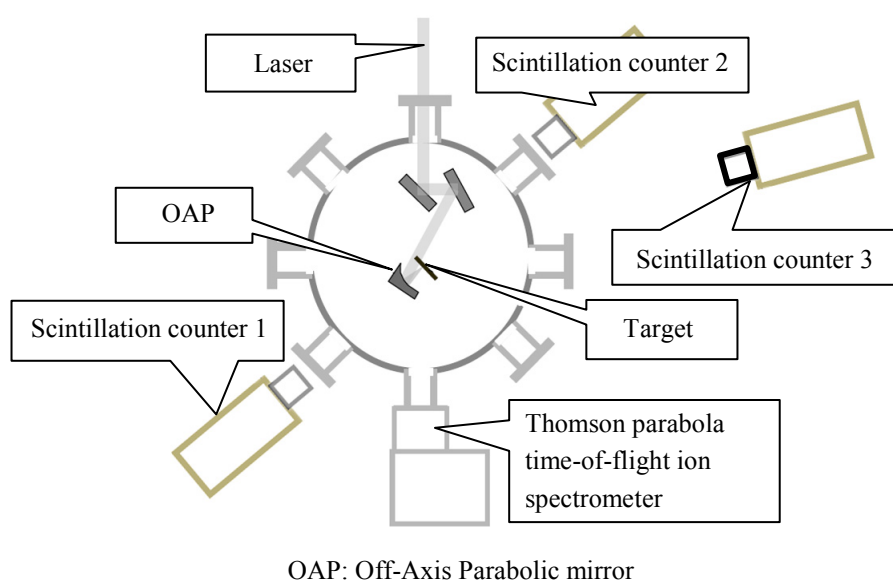
### 3. 6 Results of the Pulsed Laser Illumination

**Figure 10** shows external appearance of the three types of the targets after pulsed laser illuminations at 587 mJ/141 fs. Since the samples are continuously shifted in the plane of the sample surface during the pulsed laser illuminations at every one second, the equally-spaced through-holes aligned in line could be observed. From all the three types of the targets,  $D^+$  ions were detected by Thomson parabola as shown in Fig. 10.  $H^+$  ions were observed in the cases of (a) deuterized polystyrene (CD) film target and (c) metal deuteride thin film target. Especially from the Pd/Ti metal deuteride thin film as target,  $D^+$  and  $H^+$  ions of the kinetic energy over 800 keV were observed. Multiply-charged titanium ions such as  $Ti^{3+}$ ,  $Ti^{4+}$  and  $Ti^{9+}$  were also observed. According to the digital oscilloscope signal on outputs of scintillation counters, it was estimated that 4000 neutrons per pulse of 2.44 MeV were emitted towards all the solid angle in the case of polyethylene foam filled with heavy water, and 3000 neutrons per pulse in the case of CD, but not in the case of metal deuterides. **Figure 11** shows the

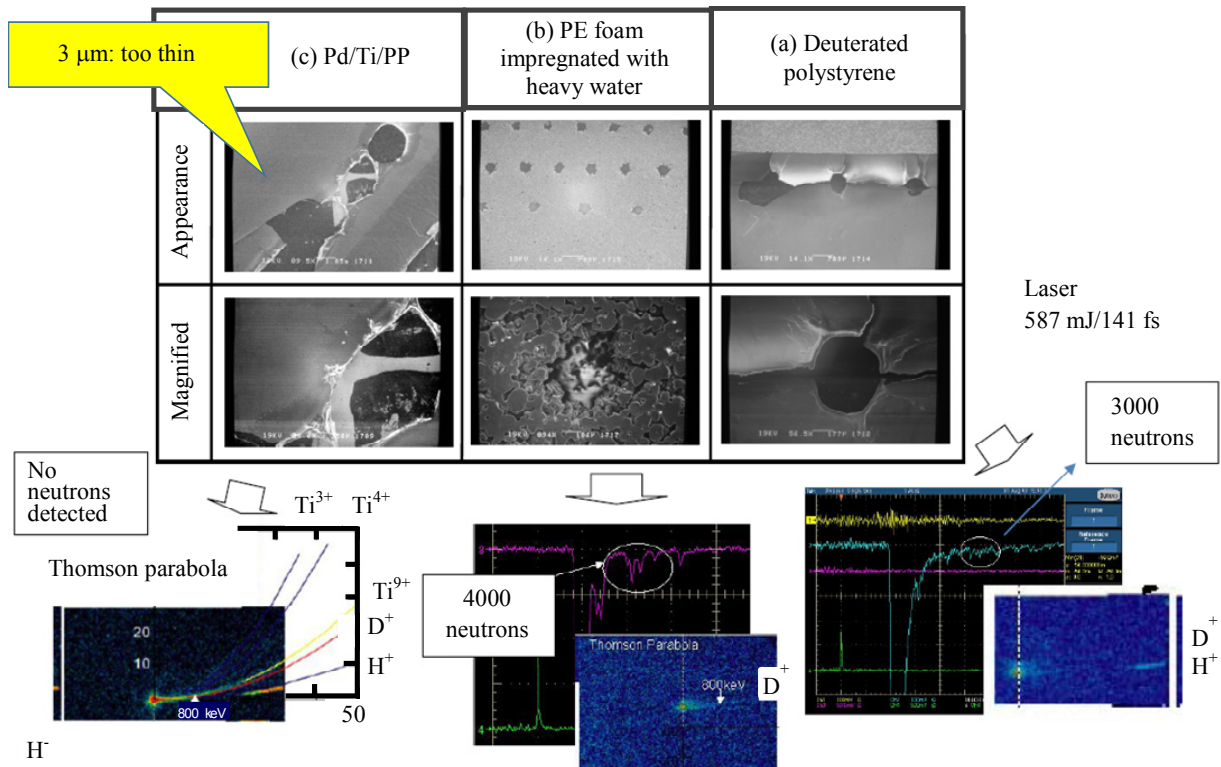
results of pulsed laser illuminations at 543 mJ/165 fs on deuterated Pd thin film (20 nm)/deuterated Ti thin film (80 nm) on CD substrate (500  $\mu m$ ). It was estimated that 5000 neutrons per pulse were emitted. However, it was estimated that 18000 neutrons per pulse were emitted in the case of a CD without Pd/Ti thin films. This shows that existence of metal deuterides is not favorable for neutron emission. The external appearance showed that pulsed laser illumination could not make through-holes indicating that 500  $\mu m$  is too thick for the target of CD film.

### 3. 7 Repetitive Counter-illumination of Double CD Films

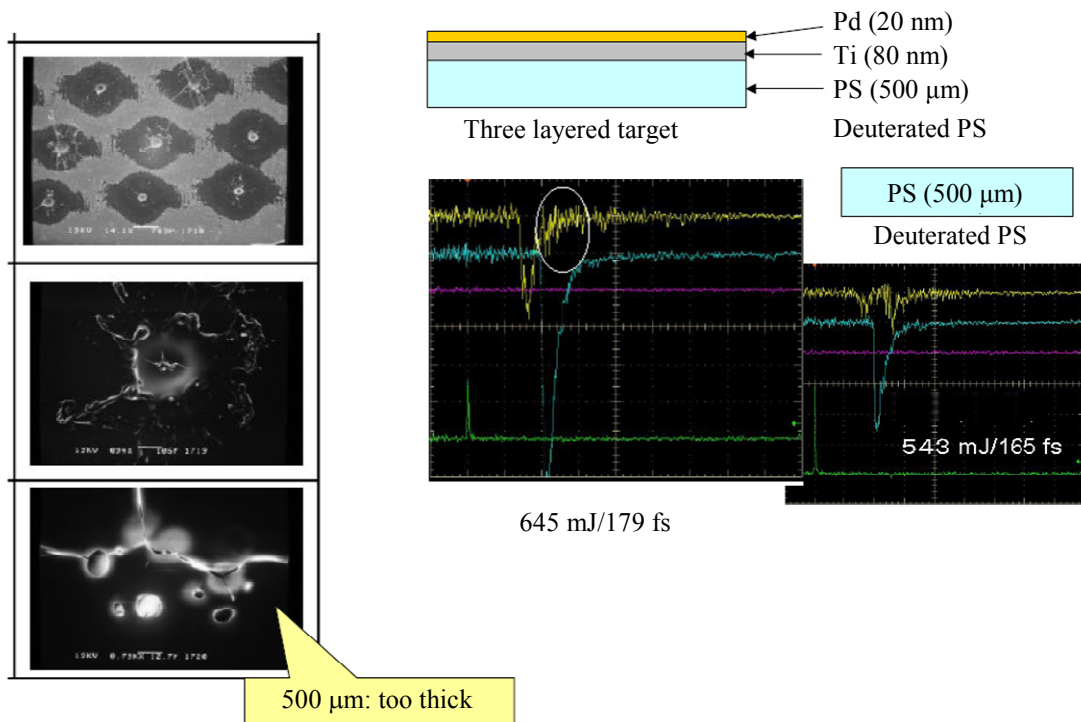
A schematic illustration of the initial design of a motor drive revolver type disk shaped target of 200 mm in diameter and of 50-200  $\mu m$  in thickness for repetitive counter-illumination is already indicated in the upper part of Fig. 5. The rotation speed was 1-10 rpm. As shown in **Fig. 12(a)**, through-holes of 0.05-0.1 mm in diameter were located equidistantly at about 1-2 mm on the outer periphery, which enabled continuous repetitive pulsed laser illuminations at 1 Hz for 10 minutes. The CD film targets were attached on both sides of the revolver type target. The through-holes can be fabricated by drilling or excimer laser beam machining to be straight or drum-shaped as shown in Fig. 12(b).



**Fig. 9** The geometry of laser illumination performed only from one side of the sample using only one-half of the optical system for counter-illumination shown in Fig. 4.



**Fig. 10** External appearance of the three types of the targets after pulsed laser illuminations at 587 mJ/141 fs. Observation of high energy ion emission by Thomson parabola time-of-flight ion spectroscopy and detection of neutrons of DD-fusion origin by scintillation counters based on the time-of-flight method.

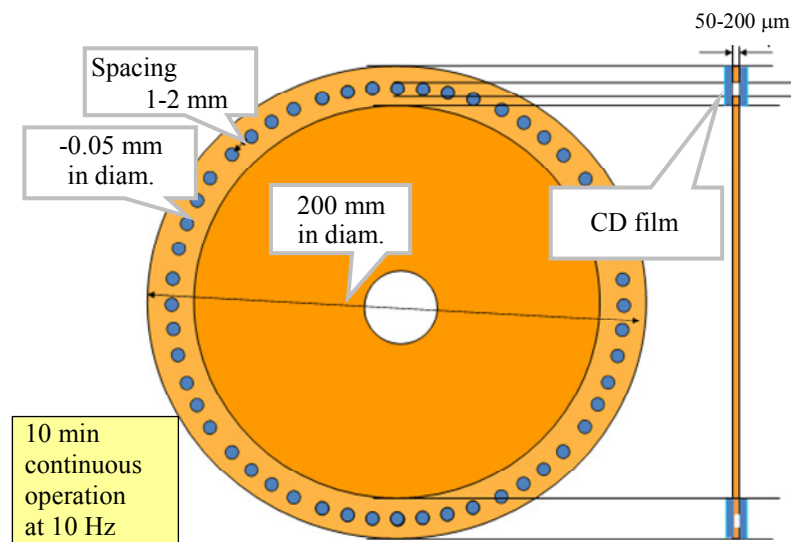


**Fig. 11** Neutron detection by pulsed laser illuminations at 543 mJ/165 fs on deuterated Pd thin film (20 nm)/deuterated Ti thin film (80 nm) on CD substrate (500 μm).

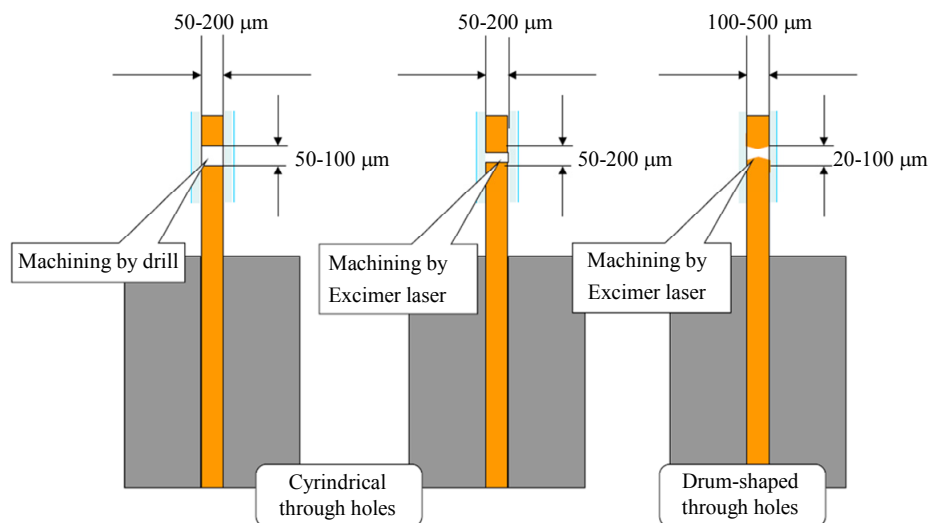
Further optimization of the design of the disk-shaped target was performed according to computer simulation of laser implosion by Dr. A. Sunahara of Institute for Laser Technology (ILT), the member of CANDY project. The optimum gap between the CD films was found to be 50  $\mu\text{m}$ . To realize this, the revolver disk was composed of three disks. The intermediate disk has a smaller diameter than 100 mm and thickness of 100  $\mu\text{m}$ . The CD films are attached on the inner walls of the outer disks as shown in **Fig. 13**. The distance between the CD films was 60-70  $\mu\text{m}$ , quite near to their theoretically obtained optimum value of 50  $\mu\text{m}$ . The gap space

between the two outer disk can be observed from the side in parallel with the disk. **Figure 14** shows light emission at the flash of counter-illumination of this revolver disk rotating every 0.1 sec synchronously with the laser pulse. Through this gap, time dependence of locations of X-ray emission could be observed with X-ray streak camera by YN who had got skills in operating X-ray streak camera since he co-worked with HA in the early 1990s as mentioned above. **Figure 15** shows the X-ray emission from CD films being imploded by the counter-illumination and heated observed by X-ray streak camera.

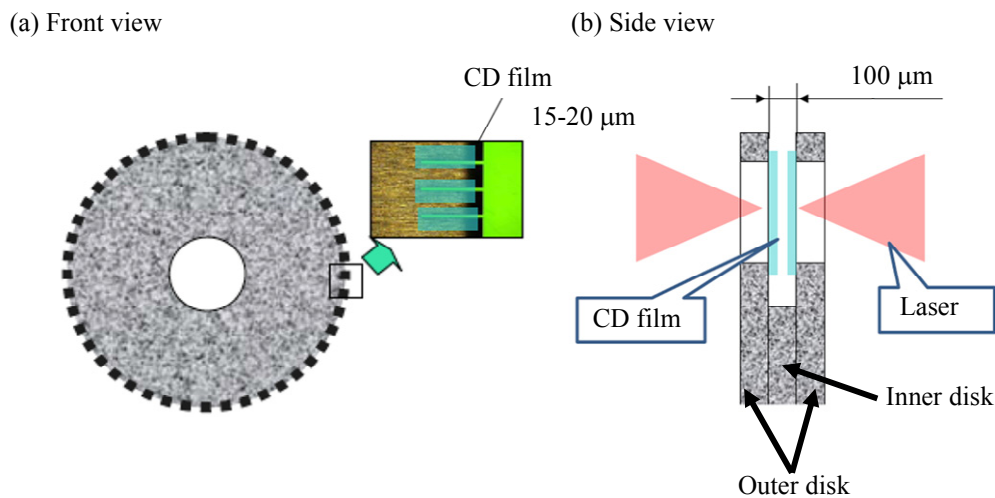
(a) Front view



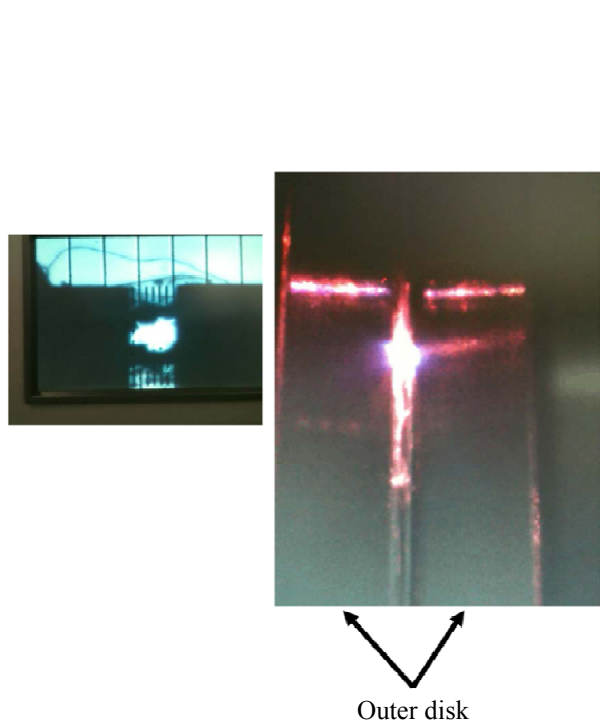
(b) Side views



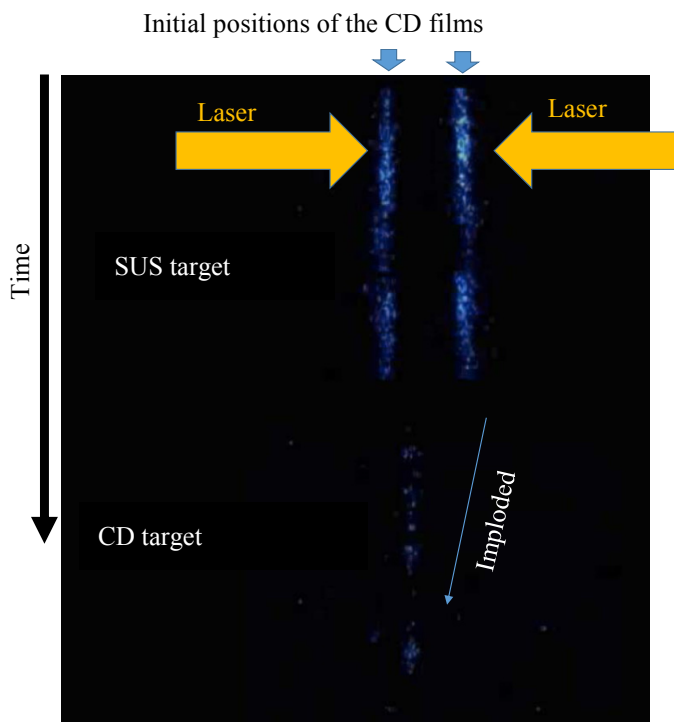
**Fig. 12** Schematic illustration of the initial design of a motor drive revolver type disk shaped target of 200 mm in diameter and of 50-200  $\mu\text{m}$  in thickness for repetitive counter-illumination.



**Fig. 13** Schematic illustration of the revised design of a motor drive revolver type disk shaped target of 100 mm in diameter for repetitive counter-illumination. The disk is composed of three thin disks. The CD films are attached on the inner walls of the outer disks.



**Fig. 14** Light emission at the flash of the counter-illumination of the revolver type disk rotating every 0.1 sec synchronously with the laser pulse.



**Fig. 15** X-ray emission from CD films being imploded by the counter-illumination and heated observed by X-ray streak camera.

### 3.8 Repetitive Counter-illumination of Shell Target

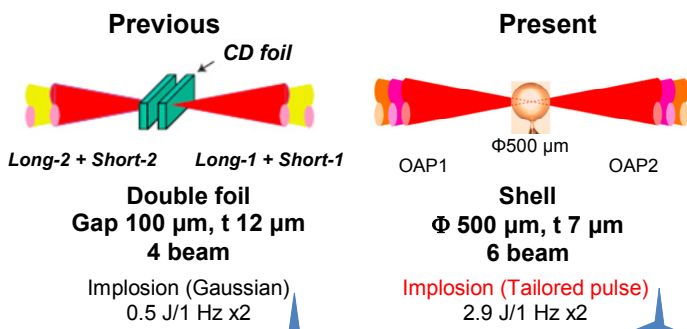
After the initial stage of study of 1 Hz repetitive counter illumination of double CD films, through the intermediary of researches on solid sphere bead target, spherical shell target of 500  $\mu\text{m}$  in diameter and 7  $\mu\text{m}$  in thickness was developed in Hamamatsu. **Figure 16** shows the comparison of these two targets by schematics at a glance. This spherical shell targets opened the door of infinitely continuous laser implosion supplying the shell targets. For the intermediary of researches for this goal, TOYOTA and TTDC developed motor drive free fall pellet (solid sphere bead of 1 mm in diameter made of CD)

loader as schematically shown in **Fig. 17(a)**.<sup>(29)</sup> By monitoring the timing of pass of the pellet using photodiode array, hit probability was drastically improved to over 90%. **Figure 17(b)** shows a shadowgraph of the pellet at the very instant of counter illumination of laser pulse using a probe laser beam that is emitted perpendicularly to the counter laser beam axis.<sup>(30)</sup>

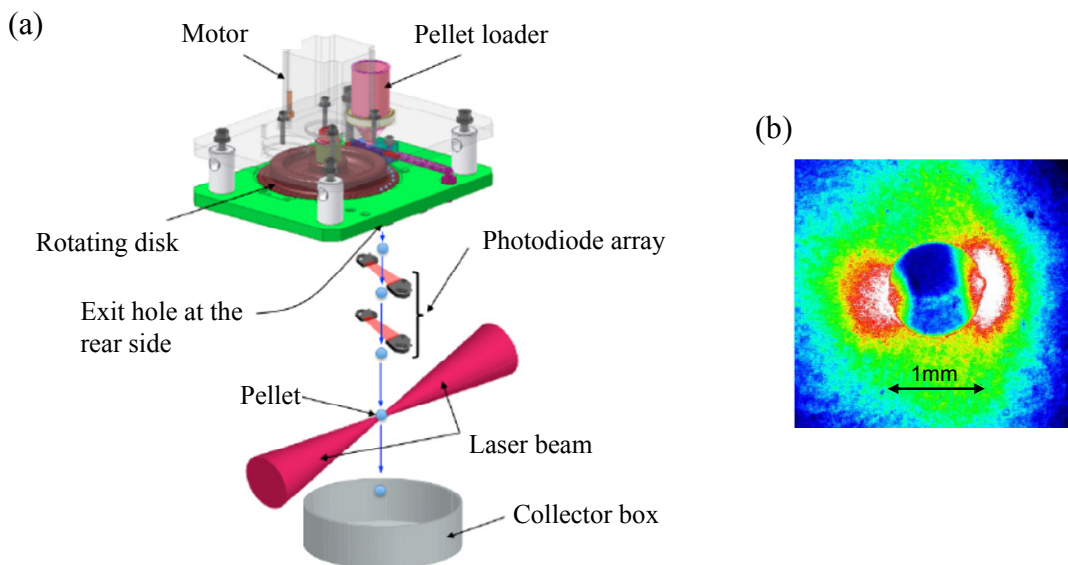
Recently, experiments of fast heating of imploded core have been successful in succession.<sup>(31-33)</sup> A tailored-pulse-imploded core with a diameter of 70  $\mu\text{m}$  has been flashed by counter-irradiating 110 fs, 7 TW laser pulses.

### 4. Conclusion

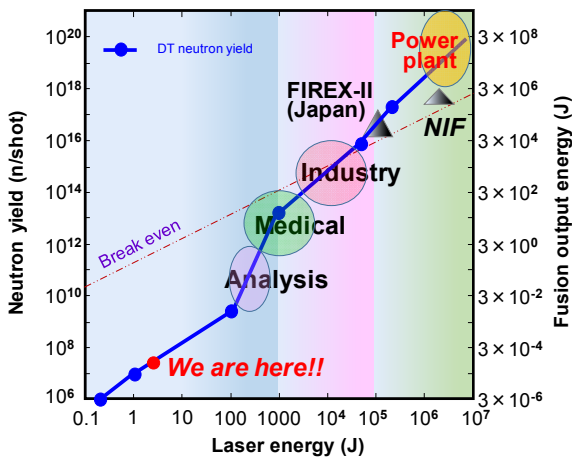
**Figure 18** shows the roadmap and milestones of the CANDY project.<sup>(34)</sup> The recent results show the progress of the project is quite on line in this figure. We have been working on 2 J laser until now. Very recently, 100 J class laser was successfully fabricated bringing the possibility of kJ laser in the near future. Realizing applications of a compact laser fusion as neutron sources in analysis, medical use, and industrial use such as doping in Si ingots, the project is to approach the final goal to get rid of concern about energy resources. **Figure 19** shows the concept model of a compact laser fusion power plant CANDY as the zeroth goal to construct a unified



**Fig. 16** Comparison of double foil target and spherical shell at a glance.



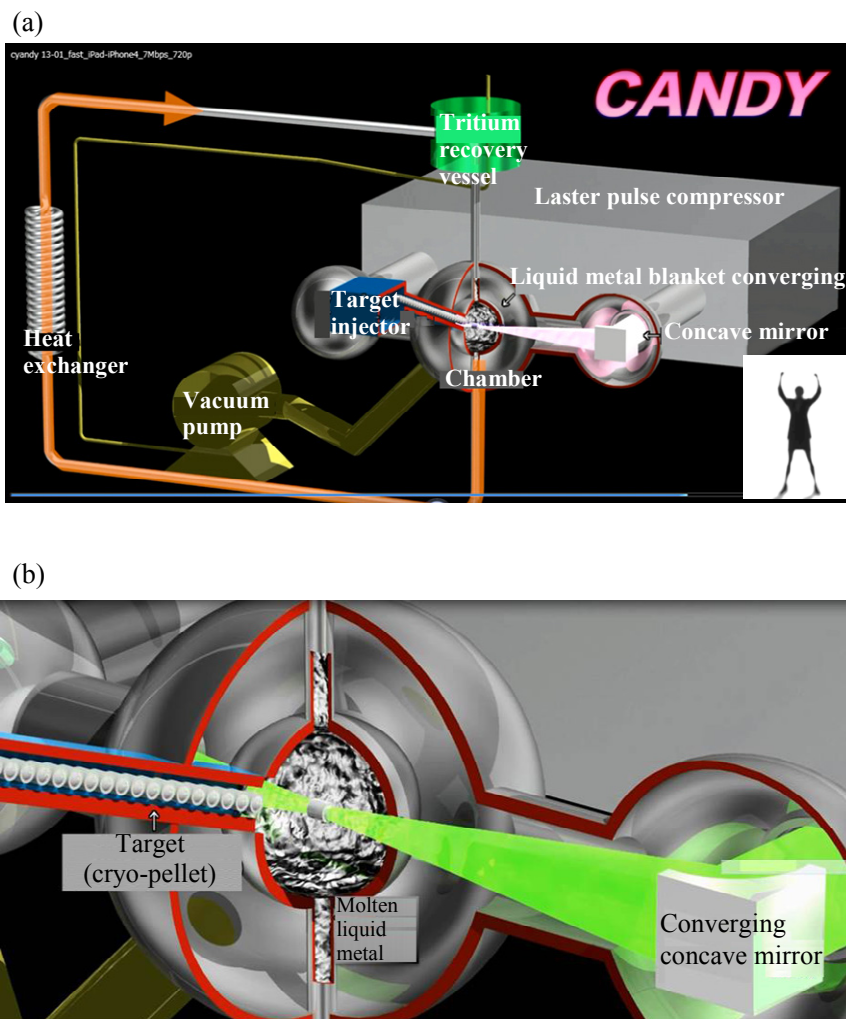
**Fig. 17** (a) Supply of solid sphere target pellets by free fall using motor drive pellet loader, and (b) a shadowgraph of the pellet at the very instant of counter illumination of laser pulse using probe laser beam, which is perpendicular to the counter laser beam axis.



**Fig. 18** Roadmap and milestones of laser fusion project “CANDY”.

experimental reactor<sup>(35)</sup> DT or DD cryogenic fuel pellet is injected at 10 Hz, to which the counter implosion beams are engaged followed by the fast heating beams. Neutron yield of  $5 \times 10^{12}$ /shot and energy gain around 0.7% are expected. A liquid Pb-Li blanket is to be installed to absorb neutrons and shield radiations. As is mentioned in the Sec. 3. 1, the absorbed neutrons deposit the heat which makes the Pb-Li into a molten metal to work as a heat carrier to transfer the heat to the heat exchanger shown in the left-hand side of Fig. 19(a).

CANDY was named after sweets wrapped by a sheet of wax paper and shielded by twisting the both sides of the wax paper because of the resemblance of the shape of the central reactor and two mirror chambers to focus lasers for counter illumination from the both sides of the reactor as shown in Fig. 19.



**Fig. 19** Concept model of a compact laser fusion power plant CANDY as the zeroth goal to construct an unified experimental reactor.



## Acknowledgements

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## References

- (1) Usuki, A., Kojima, Y., Kawasumi, M., Okada, A., Kurauchi, T. and Kamigaito, O., "Characterization and Properties of Nylon-6-Clay Hybrid", *Abs. Paper Am. Chem. Soc.*, Vol. 200, 218-POLY, (1990), pp. 1155.
- (2) Inagaki, S., Fukushima, Y. and Kuroda, K., "Synthesis of Highly Ordered Mesoporous Materials from a Layered Polysilicate", *J. Chem. Soc., Chem. Commun.*, Vol. 8 (1993), pp. 680-682.
- (3) Annual Report of Rutherford Appleton Laboratory, RAL-90-26.
- (4) Azuma, H., Kato, Y., Yamakawa, K., Tachi, T., Nishio, M., Shiraga, H., Nakai, S., Ramsden, S. A., Pert, G. J. and Rose, S. J., "Short-pulse Pumping of a Recombination Balmer-alpha Laser of Hydrogenic Sodium", *Opt. Lett.*, Vol. 15, No. 18 (1990), pp. 1011-1013.
- (5) Kato, Y., Yamanaka, M., Daido, H., Shiraga, H., Azuma, H., Murai, K., Yuan, G., Miura, E., Kanabe, T. and Takagi, M., "Coherence and Double-pass Amplification in Ge Soft X-ray Laser", *Inst. Phys. Conf. Ser.*, No. 125, Sect. 1 (1992), pp. 9-16.
- (6) Hara, T., Hirose, H., Ando, K., Negishi, F. and Aoyagi, Y., "Compact Soft X-ray Laser Pumped by a Pulse-train Laser", *Inst. Phys. Conf. Ser.*, No. 125, Sect. 2 (1992), pp. 97-100.
- (7) Fleischmann, M. and Pons, S., "Electrochemically Induced Nuclear Fusion of Deuterium", *J. Electroanal. Chem.*, Vol. 261, No. 2A (1989), pp. 301-308.
- (8) Jones, S. E., Palmer, E. P., Czirr, J. B., Decker, D. L., Jensen, G. L., Thorne, J. M., Taylor, S. F. and Rafelski, J., "Observation of Cold Nuclear-fusion in Condensed Matter", *Nature*, Vol. 338, No. 6218 (1989), pp. 737-740.
- (9) Takahashi, A., Iida, T., Miyamaru, H. and Fukuhara, M., "Multibody Fusion Model to Explain Experimental Results", *Fusion Technology*, Vol. 27, No. 1 (1995), pp. 71-85.
- (10) Takahashi, A., Murata, K., Ochiai, K. and Miyamaru, H., "Anomalous Enhancement of Three-body Deuteron Fusion in Titanium-deuteride with Low Energy D<sup>+</sup> Beam Implantation", *Fusion Technology*, Vol. 34, No. 3 (1998), pp. 256-272.
- (11) Kasagi, J., Yuki, H., Baba, T., Noda, T., Ohtsuki, T. and Lipson, A. G., "Strongly Enhanced DD Fusion Reaction in Metals Observed for keV D<sup>+</sup> Bombardment", *J. Phys. Soc. Jpn.*, Vol. 71, No. 12 (2002), pp. 2881-2885.
- (12) Okuyama, F. and Takamori, H., "Evidence for Palladium Droplet Formation Due to Deuterium Ion Irradiation", *Nucl. Instrum. Methods Phys. Res. Sect. B*, Vol. 149 (1999), pp. 521-525.
- (13) Okuyama, F., "Growth of Palladium Nanocrystallites Induced by Hydrogen-ion Irradiation at Low Energies", *Appl. Surf. Sci.*, Vol. 182 (2001), pp. 280-285.
- (14) Iwamura, Y., Sakano, M. and Itoh, T., "Elemental Analysis of Pd Complexes: Effects of D<sub>2</sub> Gas Permeation", *Jpn. J. Appl. Phys.*, Vol. 41 (2002), pp. 4642-4650.
- (15) Arata, Y. and Zhang, Y., "The Establishment of Solid Nuclear Reactor", *J. High Temp. Soc.*, Vol. 34 (2008), pp. 85-93.
- (16) Hioki, T., Takahashi, N., Kosaka, S., Nishi, T., Azuma, H., Hibi, S., Higuchi, Y., Murase, A. and Motohiro, T., "Inductively Coupled Plasma Mass Spectrometry Study on the Increase in the Amount of Pr Atoms for Cs-ion-implanted Pd/CaO Multilayer Complex with Deuterium Permeation", *Jpn. J. Appl. Phys.*, Vol. 52 (2013), 107301.
- (17) Kitamura, N., Nohmi, T., Sasaki, Y., Taniike, A., Takahashi, A., Seto, R. and Fujita, Y., "Anomalous Effects in Charging of Pd Powders with High Density Hydrogen Isotopes", *Phys. Lett. A*, Vol. 373, No. 35 (2009), pp. 3109-3112.
- (18) Ichikawa, Y., Hioki, T., Sugimoto, N., Ichiki, A. and Motohiro, T., "Hydrogen Storage Capacity of Pd Particles Dispersed in Mesoporous Silicas", *J. Nanosci. Nanotechnol.*, Vol. 6 (2016), pp. 12947-12951.
- (19) Hioki, T., Azuma, H., Nishi, T., Itoh, A., Gao, J., Hibi, S., Motohiro, T. and Kasagi, J., "Absorption Capacity and Heat Evolution with Loading of Hydrogen Isotope Gases for Pd Nano Particles and Pd/ceramics Nano Composites", *239th ACS National Meeting*, San Francisco, USA, (2010), p.1155.
- (20) ImPACT, "Reduction and Resource Recycling of High-level Radioactive Wastes through Nuclear Transmutation", *Impulsing Paradigm Change through Disruptive Technologies Program ImPACT: R&D Programs*, <<http://www.jst.go.jp/impact/en/program/08.html>>, (accessed 2016-12-10).
- (21) Yamanaka, C. and Nakai, S., "Thermonuclear Neutron Yield of 10<sup>12</sup> Achieved with Gekko XII Green Laser", *Nature*, Vol. 319 (1986), pp. 757-759.
- (22) Azechi, H., Jitsuno, T., Kanabe, T., Katayama, M., Mima, K., Miyanaga, N., Nakai, M., Nakai, S., Nakaishi, H., Nakatsuka, M., Nishiguchi, A.,

- Norrays, P. A., Setsuhara, Y., Takagi, M., Yamanaka, M. and Yamanaka, C., "High-density Compression Experiments at ILE, Osaka", *Laser and Particle Beams*, Vol. 9, No. 2 (1991), pp. 193-197.
- (23) Hurricane, O. A., Callahan, D. A., Casey, D. T., Celliers, P. M., Cerjan, C., Dewald, E. L., Dittrich, T. R., Döppner, T., Hinkel, D. E., Berzak Hopkins, L. F., Kline, J. L., Le Pape, S., Ma, T., MacPhee, A. G., Milovich, J. L., Pak, A., Park, H.-S., Patel, P. K., Remington, B. A., Salmonson, J. D., Springer, P. T. and Tommasini, R., "Fuel Gain Exceeding Unity in an Inertially Confined Fusion Implosion", *Nature*, Vol. 506 (2014), pp. 343-348.
- (24) Strickland, D. and Mourou, G., "Compression of Amplified Chirped Optical Pulses" *Opt. Commun.*, Vol. 56 (1985), pp. 219-221.
- (25) 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., "Ignition and High-gain with Ultrapowerful Lasers", *Phys. Plasmas*, Vol. 1 (1994), pp. 1626-1634.
- (26) Kodama, R., Norreys, P. A., Mima, K., Dangor, A. E., Evans, R. G., Fujita, H., Kitagawa, Y., Krushelnick, K., Miyakoshi, T., Miyanaga, N., Norimatsu, T., Shozaki, T., Shigemori, K., Sunahara, A., Tampo, M., Tanaka, K. A., Toyama, Y., Yamanaka, Y. and Zepf, M., "Fast Heating of Ultrahigh-density Plasma as a Step towards Laser Fusion Ignition", *Nature*, Vol. 412 (2001), pp. 798-802.
- (27) Kodama, R., Shiraga, H., Shigemori, K., Toyama, Y., Fujioka, S., Azechi, H., Fujita, H., Habara, H., Hall, T., Izawa, Y., Jitsuno, T., Kitagawa, Y., Krushelnick, K. M., Lancaster, K. L., Mima, K., Nagai, K., Nakai, M., Nishimura, H., Norimatsu, T., Norrays, P. A., Sakabe, S., Tanaka, K. A., Toussef, A. and Zepf, M., *Nature*, Vol. 418 (2002), pp. 993-934.
- (28) Mori, Y., Sekine, T., Komeda, O., Nishimura, Y., Sunahara, A., Miura, E., Nakayama, S., Hanayama, R., Ishii, K., Sato, N., Kurita, T., Kawashima, T., Kan, H., Nakamura, N., Kondo, T., Fujine, M., Azuma, H., Hioki, T., Kakeno, M., Kajino, T., Motohiro, T., Sentoku, Y. and Kitagawa, Y., "Upgrade of Repetitive Fast-heating Fusion Driver HAMA to Implode a Shell Target by Using Diode Pumped Solid State Laser", *J. Phys. Conf. Ser.*, Vol. 688 (2016), 012070.
- (29) Komeda, O., Nishimura, Y., Mori, Y., Hanayama, R., Ishii, K., Nakayama, S., Kitagawa, Y., Sekine, T., Sato, N., Kurita, T., Kawashima, T., Kan, H., Nakamura, N., Kondo, T., Fujine, M., Azuma, H., Motohiro, T., Hioki, T., Kakeno, M., Sunahara, A., Sentoku, Y. and Miura, E., "First Demonstration of Laser Engagement of 1-Hz-injected Flying Pellets and Neutron Generation", *Sci. Rep.*, Vol. 3 (2013), Article No. 2561.
- (30) Hanayama, R., Komeda, O., Nishimura, Y., Mori, Y., Ishii, K., Nakayama, S., Okihara, S., Fujita, K., Sekine, T., Sato, N., Kurita, T., Kawashima, T., Kan, H., Nakamura, N., Kondo, T., Fujine, M., Azuma, H., Hioki, T., Kakeno, M., Motohiro, T., Sunahara, A., Sentoku, Y., Miura, E. and Kitagawa, Y., "Repetitive Solid Spherical Pellet Injection and Irradiation toward the Repetitive-mode Fast-ignition Fusion Mini-reactor CANDY", *J. Phys. Conf. Ser.*, Vol. 688 (2016), 012026.
- (31) Kitagawa, Y., Mori, Y., Komeda, O., Ishii, K., Hanayama, R., Fujita, K., Okihara, S., Sekine, T., Satoh, N., Kurita, T., Takagi, M., Kawashima, T., Kan, H., Nakamura, N., Kondo, T., Fujine, M., Azuma, H., Motohiro, T., Hioki, T., Nishimura, Y., Sunahara, A. and Sentoku, Y., "Fusion Using Fast Heating of a Compactly Imploded CD Core", *Phys. Rev. Lett.*, Vol. 108 (2012), 155001.
- (32) Kitagawa, Y., Mori, Y., Komeda, O., Ishii, K., Hanayama, R., Fujita, K., Okihara, S., Sekine, T., Satoh, N., Kurita, T., Takagi, M., Watari, T., Kawashima, T., Kan, H., Nishimura, Y., Sunahara, A., Sentoku, Y., Nakamura, N., Kondo, T., Fujine, M., Azuma, H., Motohiro, T., Hioki, T., Kakeno, M., Miura, E., Arikawa, Y., Nagai, T., Abe, Y., Ozaki, S. and Noda, A., "Direct Heating of a Laser-imploded Core by Ultraintense Laser-driven Ions", *Phys. Rev. Lett.*, Vol. 114 (2015), 195002.
- (33) Mori, Y., Nishimura, Y., Hanayama, R., Nakayama, S., Ishii, K., Kitagawa, Y., Sekine, T., Sato, N., Kurita, T., Kawashima, T., Kan, H., Komeda, O., Nishi, T., Azuma, H., Hioki, T., Motohiro, T. and Sunahara, A., "Fast Heating of Imploded Core with Counterbeam Configuration", *Phys. Rev. Lett.*, Vol. 117 (2016), 055001.
- (34) Motohiro, T., "Recent Research Activities for Future Challenges in Global Energy and Environment in Toyota Central R&D Labs., Inc. (TCRDL)", *Ceramics for Environmental and Energy Applications II, Ceramic Trans.*, Vol. 246 (2014), pp. 1-10.
- (35) Kitagawa, Y., Mori, Y., Komeda, O., Hanayama, R., Ishii, K., Okihara, S., Fujita, K., Nakayama, S., Sekine, T., Sato, N., Kurita, T., Kawashima, T., Watari, T., Kan, H., Nakamura, N., Kondo, T., Fujine, M., Azuma, H., Motohiro, T., Hioki, T., Kakeno, M., Nishimura, Y., Sunahara, A., Sentoku, Y., Miura, E., Arikawa, Y., Nagai, T., Abe, Y., Ozaki, S. and Noda, A., "Progress toward a Unified kJ-machine CANDY", *J. Phys. Conf. Ser.*, Vol. 688 (2016), 012049.

Figs. 4 and 16 (right)

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Fig. 16 (left)

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Fig. 17

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Fig. 18

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