Status and Future Prospects of Laser Fusion and High Power Laser Applications

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Abstract. In Asia, there are many institutes for the R&D of high power laser science and applications. They are 5 major institutes in Japan, 4 major institutes in China, 2 institutes in Korea, and 3 institutes in India. The recent achievements and future prospects of those institutes will be over viewed.

In the laser fusion research, the FIREX-I project in Japan has been progressing. The 10kJ short pulse LFEX laser has completed and started the experiments with a single beam. About 1kJ pulse energy will be injected into a cone target. The experimental results of the FIREX experiments will be presented. As the target design for the experiments, a new target, namely, a double cone target was proposed, in which the high energy electrons are well confined and the heating efficiency is significantly improved. Together with the fusion experiments, Osaka University has carried out laboratory astrophysics experiments on photo ionizing plasmas to observe a unique X-ray spectrum from non-LTE plasmas. In 2008, Osaka university has started a new Photon research center in relation with the new program: Consortium for Photon Science and Technology: C-PhoST, in which ultra intense laser plasmas research and related education will be carried out for 10 years.

At APRI, JAEA, the fundamental science on the relativistic laser plasmas and the applications of laser particle acceleration has been developed. The application of laser ion acceleration has been investigated on the beam cancer therapy since 2007.

In China, The high power glass laser: Shengan-II and a peta watt beam have been operated to work on radiation hydro dynamics at SIOFM Shanghai. The laser material and optics are developed at SIOFM and LFRC. The IAPCM and the IOP continued the studies on radiation hydrodynamics and on relativistic laser plasmas interactions. At LFRC in China, the construction of Shengan III glass laser of 200kJ in blue has progressed and will be completed in 2012.

Together with the Korean program, I will overview the above Asian programs.

1. Introduction and Asian research networks
Laser fusion and high energy density science (HEDS) together with high power laser technology are developing in the world as well as in Asia. In this lecture, the status of the Asian community of this filed, and Asian history of the research are overviewed. Namely, the status and future prospects of
projects in China, Korea, India and Japan are described. In particular, for fast ignition research, the present and future of FIREX project at Osaka are discussed.

The major institutes and universities in the researches on high power laser, laser plasmas, high energy density science and laser fusion in Asia are the followings. In Japan, they are the Institute of laser Engineering and the Faculty of Engineering of Osaka University, the Kansai Photon Research Institute of JAEA, The Graduate School for the Creation of New Photonics Industries at Hamamatsu, and Institute of Chemical Research of Kyoto University, and so on. In China, there are the Shanghai Institute of Optics and Fine Mechanics, Laser Fusion Research Center at Mianyang, Institute of Physics, Institute of Applied Physics and Computational Mathematics at Beijing, and Shanghai Jiao Tong University, and so on. In Korea, Korean Atomic Energy Research Institute, Korean Advanced Institute of Science and Technology, and APRI of K-JIST. In India, they are Tata Institute of Fundamental Research Mumbai, and Bhabha Atomic Research Center at Mumbai, and Institute of Plasma Research at Ahmedabad. Those institutes are connected by some research networks for laser fusion, HEDS, and High Filed Science researches which are 1) AILN (Asian Intense Laser Network) including 20 institutes and universities are included, 2) APFA (Asian Plasma and Fusion Association), 3) Asian CORE program on “Development of next generation ultra-short pulse lasers for high field science” and so on. Those net works are going to be connected to the world wide net works like EU research group under the European Physical Society (EPS) and America research group under the American Physical Society (APS). (See Fig.1)

As for the laser fusion research, Japan and China are the leading countries. In Japan, the FIREX project has started since 2002 and the main facility, LFEX laser started the operation since 2009 March. On the other hand, the multi kJ lasers called SG laser have been developed and the 200kJ laser will be completed in 2012 at Mianyang, China. The both “SG project” and FIREX project are aiming at demonstration of ignition. The Japanese project is concentrated on the direct driven implosion and fast ignition. On the other hand, the SG project is for the indirect implosion and fast ignition. (See Fig.1)

The high field science has been widely developing in many countries. Namely, petwatt level lasers are operated at ILE and KPRI of JAEA in Japan, KPRI in Korea, and SIOFM in China. Further more, many projects related to ultra intense short pulse lasers are going on all over the Asian.
2. China and Korea Activities

2.1 China Program

Multi kJ level pulse laser facilities have been developed for the laser fusion and HEDS in SIOFM and Laser Fusion Research Centre (LFRC) at Mianyang. At SIOFM, the Shengan II laser (SG-II) are operated for laser plasma and fusion experiments. SG-II is 8 beam glass laser with 8kJ in 3ns, which is combined with the petawatt laser of 1kJ.1ps. Based upon the development of SG-II, the construction of SG-III has started and will be in operation in 2012. The SG-III is 48 beam system and will deliver 200kJ in 3ns at 0.351 μm wavelength. In China, ultra intense short pulse Ti-Saphire lasers are also operated. They are Xtreme Light III (XL-III) laser system (720 TW/ 30fs) at the Institute of Physics at Beijing and SILEX laser at LFRC (300TW). They are open for the international research community.

The SG-III laboratory has three area: laser system, target chamber, laser component cleaning and assembling area. For fast ignition experiment, ultra intense short pulse laser will be also added in future. The plasma experiments with XL-III have been very successful to contribute to the relativistic laser plasma research.

Laser plasma physics and laser fusion researches have also been progressing in China. For an example, the Rayleigh-Taylor instability (RTI) of a directly driven plastic foil is measured by 13.9 nm EUV laser of a Nickel-like ion plasmas in SG-II experiments. A CH foil thickness with 50 μm wave length corrugation was irradiated with laser beams of 1-2kJ/0.53μm/2ns pulse width. As shown in the Figure 2, the bubble and spike structure as the nonlinear stage of the RTI mode was precisely measured. The experimental results have been compared with the 2-D simulation to validate the simulation code. Till the highly nonlinear stage, the experiments and simulation results agree well up to bubble and spike amplitude of 50 μm.

The ultra intense laser plasma interactions have also been investigated at IOP, Beijing and the SJTU by theory and simulation. For an example, on the high energy electron transport, the Kα X-ray images were taken for the pre-formed plasmas interacting with an obliquely injected 10TW laser pulse. The image is asymmetric for large incident angle (70°) and symmetric for 45° incident. The non-symmetrical distributions were probably induced by the electrons that escape into the vacuum and drawn back into the target again by the electrostatic fields. For more detail, see the proceeding by Y. T. Li [1]

The laser technology R&D in China has been progressing at the SIOFM and their collaboration institutes and universities. Nonlinear crystals, laser glass, large aperture deformable mirror, and so on has been developed. The deformable mirror fabricated at the Institute of Optics and Electronics, Chengdu CAS.

2.2 Korean program

At KAERI, GVI laser at Osaka was transferred and renewed as KLF (KAERI Laser Facility). It started the operation recently to do fast ignition experiments. A 100 TW OPCPA short pulse laser will be added in future. At KPRI, GIST, the 100TW Ti:Sapphire laser is operated at APRI. This Ti:Sapphire laser will be up graded to a half PW and start operation for users in 2010. The pulse energy and duration of the system are 20J and 40fs.

3. Japanese program

In 2008, the Photon Frontier Network (PFN) was
organized to explore frontier of photon S&T, to foster young researchers, and to promote collaborations among institutes, universities, and industries. Under the PFN, two centers are established as it was presented by Y.Kato in the plenary of this IFSA. One of them is the “Consortium for Photon Science and Technology” (C-PhoST) lead by R.Kodama. In the C-PhoST, plasma photonics, laser acceleration, high energy density science, laser fusion, laser plasma Thz radiation and so on are carried out together with the young scientists fostering. The more detail on the net work was presented by Y.Kato [2]. At the Advanced Photon Research Center (APRC), JAEA, fundamental physics, laser ion beam cancer therapy, and laser acceleration with super powerful lasers are studied. The main facility of the institute is the J- Karen laser which can deliver a laser pulse with a few J/30fs and very high contrast ratio of $10^{-10}$ [3]. The project on the laser produced proton therapy started 3 years ago. The project includes the development of ultra intense short pulse laser operated with 1 kHz, the proton acceleration physics and target design, proton beam irradiation system, medical research on the proton irradiation effects and so on. Recently, the cancer cells are irradiated with a laser produced proton beam to detect the effects of the irradiation. In this experiments, proton fluence on the sample was 20 Gy with 200 laser shots. It is shown that DNA double stranded breaks in the region irradiated by a laser- driven proton beam [4].

Laser acceleration experiments also advanced at APRC. The JLITE-X Ti-Sapphire laser of $0.16 \text{ J/} 40\text{fs}$ irradiated the gas jet target of Argon and Helium. The monochromatic electron beams are generated. The central energy of the e-beams is 24.8 MeV for Helium and 8.5 MeV for Ar. In particular, the probability of generation of mono energy beam is very high (88.4%) for the case of Argon gas target. Moreover, the angular collimation of the electron beam is very high for Argon gas. The divergence angle was 10 mrad for Argon and 31 mrad for Helium. as shown in the beam angular collimation (after K.Kondo Presented in ICUIL international conference) This difference of the beam divergence is interpreted by the laser beam channeling in the Argon gas target. Namely the clusters are formed in the Argon gas jet but not in the Helium gas jet. The laser beam is expected to be well guided in the cluster plasma in comparison with the usual gas plasma since the cluster plasma will have very strong positive susceptibility [5].

At ILE Osaka University, laser fusion, laser astrophysics, laser driven EUV source, laser Astronomical physics, hot dense matter physics, and so on have been explored. Because of the limitation of high reflectivity optics, the 13.5nm EUV is the only one candidate for the next generation lithography. As the 13.5nm EUV radiation source, laser produced Sn plasmas have been investigated for many years under the MEXT project at Osaka University. In 2007-2008, we discovered that very high conversion efficiency from laser energy to 13.5nm EUV radiation can be achieved. The irradiation geometry is shown in the Fig.3 where a few tens of micrometer droplets are injected with a few kHz repetition rate and irradiated with Nd-YAG pre-pulse of the intensity $10^{11} \text{W/cm}^2$ and after 1 μm sec, a CO$_2$ laser main pulse is irradiated. In the experiment, the conversion efficiency increased up to 3.5% to 2% band width around 13.5nm. This result is very promising for using Sn laser plasmas as the lithography radiation source.

In the laser plasma astrophysics, a recent topic is the physics of photo ionizing plasmas. X-ray spectroscopy of non-thermal equilibrium plasmas photo-ionized by intense radiation is a key to understanding compact objects, such as black holes, based on astronomical observations[6].
The experiments carried out by the international collaboration among China Korea and Japan studied photo-ionizing plasmas in laboratory under well-defined and astrophysical relevant conditions. Photo-ionized plasma is here generated using a 0.5-keV Planckian x-ray source created by means of a laser-driven implosion.

The measured x-ray spectrum from the photo-ionized silicon plasma resembles those observed from the binary stars Cygnus X-3 6, 7 and Vela X-1 8–10 with the Chandra x-ray satellite. This experiment demonstrates that an extreme radiation field was produced in the laboratory, however, the theoretical interpretation of the laboratory spectrum significantly contradicts the generally accepted explanations in x-ray astronomy. This model experiment offers a novel test bed for validation and verification of computational codes used in x-ray astronomy. The geometry of the experiment is shown in Fig.4.

As for the HEDS, the properties of hydrogen at high pressure and high density are of great scientific interest. The equation of state (EOS) of hydrogen at these conditions is essential for modeling of the interior structure of gas giant planets. The large diversity in the estimation of Jupiter’s core mass is resulted from the uncertainty in the EOS data especially in the region around the insulator-to-metal transition. The EOS of hydrogen isotopes has important practical applications for inertial confinement fusion, and metallic hydrogen is suggested as a prospective candidate of high-temperature superconductor [7].

4. FIREX projects

As for the fast ignition research at ILE, Osaka University, the LFEX laser for the FIREX-I project has completed and the integrated experiment on imploded plasma heating has started. The preliminary experiments indicate neutron enhancement although the input laser intensity was not high enough to realize high coupling efficiency. As shown in fig.5, when the peta watt laser shot coincides with the maximum compression timing, the neutron yield was enhanced.

For improving the coupling efficiency, a new target, so called double cone target has been proposed. Particle-in-cell simulations aimed at improving the coupling efficiency of input laser energy deposited to the compressed core by using a double cone are carried out. It is found that high energy electrons are effectively blocked by the vacuum gap inside the wing of the double cone. (see Fig. 6)

Two main mechanisms to confine high energy electrons are found, which are the sheath electric field at the rear of the inner cone wing and the quasi-static magnetic field inside the vacuum gap. However, the electrostatic retention of the high energy electrons terminates within a few hundreds of femto seconds as the vacuum gap fills with plasma. In comparison, the quasi-static magnetic fields, though arises up slowly in comparison with the electrostatic fields but continue to grow to the order of...
The generation mechanism of the quasi-static magnetic fields is discussed in detail, and it is concluded that the quasi-static magnetic fields continue to confine the high energy electrons for longer than a few picoseconds. The double cones result in the confinement and focusing of 22.3% of the input energy for deposition in the compressed core [8].

Figure 5 In this shot (shot number 3272) the shot timing is checked by the X-ray streak camera, LFEX X-ray signal and X-ray from the imploded core. The neutron yield is enhanced in this shot.

Fig.6 (Color). The electron energy density for single cone (a) and double cone (b) at time=1500fs. Here the electron energy density is normalized by $mn_e c^2$.

The multi beam LFEX laser will be completed by the April 2010 and the full beam LFEX experiment will start from Middle of 2010. The imploded high density plasma is expected to be heated up to the ignition temperature in 2011.

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