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Power photonics for Green Earth –strategic approach to the better life–

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Abstract. We have investigated the pathway to realize Laser Inertial Fusion Energy (LIFE) as the primary energy for society, which is vital for the Green Earth (environmentally sustainable economic growth and prosperity for all mankind). The next step toward the fusion power plant is the engineering development of the elements and the integrated system of the LIFE. An integrated system development will open new applications to sciences and industries in many fields such as high energy density physics, advanced manufacturing, nuclear material processing, space, and medical engineerings, with the deployment of high rep-rate, high-average and peak power lasers.

1. INTRODUCTION

Laser fusion research started soon after the invention of laser. The purpose was clearly fixed on the development of new energy sources, which are clean, safe and abundant, in order to provide the primary energy for the future. The physics of laser-driven implosion and compression have been thoroughly investigated within an active collaborative and interactive international research community. We achieved temperatures of 10^8 K which is necessary for abundant fusion reactions to occur and densities of 10^3 times compression over the initial pellet density required for energy gain in separate experiments at ILE, Osaka University. We are now at the new phase where the fusion ignition, burn and energy gain are expected to be achieved with the Mega-Joule lasers such as NIF of the U.S. and LMJ of France in the time frame of 2011∼2015.

Along with the research activities of world-leading laboratories into the physics of the implosion, the International Atomic Energy Agency (IAEA) has been promoting international collaborative projects for the development of Inertial Fusion Energy. The first systematic project was performed taking the collaboration of more than 80 experts of the world. The result was published as a comprehensive book of 450 pages titled as "Energy from Inertial Fusion" in 1995. Since then, two successive Coordinative Research Projects (CRP) have been undertaken, the first entitled "CRP on the Elements of Power Plant Design" from 2000 to 2004 and the second entitled "CRP on the Integrated Approach to Inertial Fusion Power Plants" from 2006 to 2010.

The progresses of high energy density physics being stimulated by IFE research and the high average power laser engineering of short pulse for IFE driver, are opening and creating new science opportunities and industries in material processing, radiation sources, charged particles and neutron sources, new material creation, and medical applications. These will provide important new technologies for the green earth and sustainable growth for the 21st Century. It appears that we are entering the new Era of Photonics.

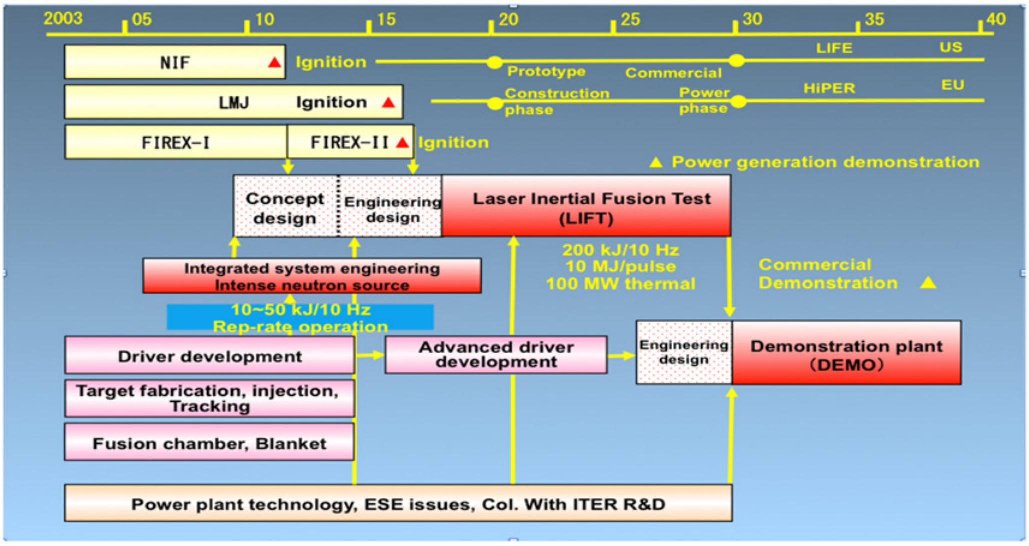

Figure 1. Roadmap to IFE power plant.

2. PATHWAY TO IFE - PHYSICS AND ENGINEERING DEVELOPMENTS

The roadmap to IFE power plant is shown in Figure 1. The NIF at LLNL is expected to demonstrate laser fusion Ignition, Burn and Energy Gain (IBG) at around 2011-2012. The LMJ in France is under construction with the scheduled completion of the system to be 2016. FIREX-I (fast ignition realization experiments) has been completed and the initial experiments on the PW, kJ igniter beam coupling with compressed fuel by GEKKO XII were successfully performed in 2011 at ILE, Osaka.

There have been many advances in understanding over the past five decades resulting from intensive studies at many laboratories throughout the world relating to the basic processes such as laser-matter interaction, energy transport by radiation, thermal and non-thermal particle generation, ablation and hydrodynamics, and hydrodynamic stability related to the implosion process. The experimental results of pellet implosion and fusion reaction have been compared with the numerical simulation results, which were reinforced by the individual verification for each elementary process. The demonstration of IBG by NIF is the culmination of this international research effort into the physics research on inertial fusion.

In the new era after the demonstration of IBG, the main tasks for IFE development should be on the engineering issues related to high rep-rate integrated systems. The key elements are Ⓐ driver, Ⓑ target, and Ⓒ fusion chamber and blanket, all with the rep-rate operations for the consideration of the power plant. The separability of the driver, target, and chamber technologies enable independent development, while maintaining the close connection and collaborations of independent groups of the world.

Based on the speed of development of fusion technologies, the engineering for the integrated system must be developed which include the interface issues between the driver, target and chamber technologies. This integrated system which is shown at the middle in Figure 1 could be also the intense neutron source for the fusion material test and also for the industrial application.

Beyond this integrated systems and engineering phase, the power generation demonstration systems are proposed such as LIFE (Laser Inertial Fusion Engine) in the US, HiPER in EU which are marked on the future line of the NIF and LMJ in Figure 1, and LIFT (Laser Inertial Fusion Test facility) in Japan.

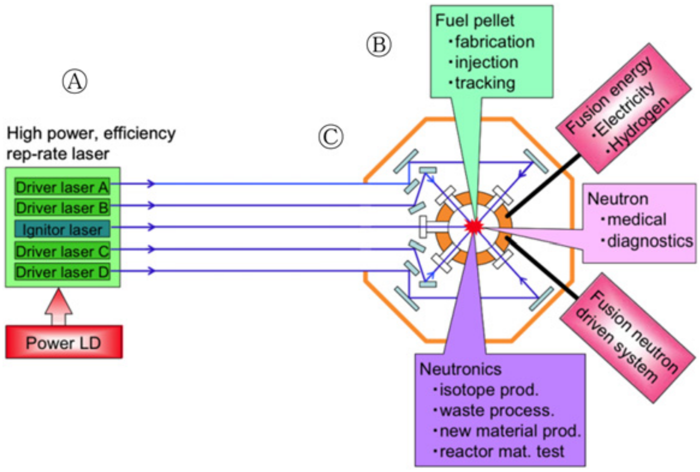

Figure 2. Integrated IFE system and its application to industries.

3. INTEGRATED IFE SYSTEM AND REP-RATE DRIVER [1]

3.1 Integrated IFE system

The concept of an integrated IFE system is shown in Figure 2. It consists of Ⓐ: driver system, Ⓑ: fuel target system, and Ⓒ: reaction chamber system. Surrounding the reaction chamber, neutron diagnostics and application instruments are installed depending on the research program.

For an integrated system with rep-rate operation, the required specification for the key elements of driver, target, and chamber are different from those of a research facility with single shot operation. Specifically the interface issues between the key elements must be considered and investigated. They are: target tracking and shooting by laser beams; the influence of chamber environment on target injection and laser beam propagation; final optics on the beam port etc. Within these key technical issues, the most critical issue is the driver development for which innovative technologies are extremely important.

3.2 Driver development

For any IFE power plant, a high efficiency, ~10 Hz rep-rate operation, long life, and low cost driver has to be developed. We can see remarkable progresses in high power laser technologies which can improve the design and performance of the power plant driver.

(1) The high power Laser Diode (LD) with high conversion efficiency of 73% at CW operation has been achieved, and further improvement can be expected. For the cost reduction of high power LD stuck, VCSEL (Vertical-Cavity Surface-Emitting Laser) is preferable where the monolithic process on wafer base could make the high power emitter array. It has been reported that the enough high output power density of 3.7 kW/cm^2 at 100 μs and 0.3% duty cycle for the laser pumping has been achieved with VCSEL [2].

(2) New laser materials are under development including crystal, glass, and ceramic materials. The Yb ceramic YAG demonstrated very high potentiality for IFE driver with temperature control for optimizing the emission cross section and thermal shock parameter. New laser material based on silica glass has been developed which shows high peak power operation [3].

The future development of high average power driver with high efficiency, and low cost for the IFE power plant will open new industrial applications such as intense neutron source and particle accelerator

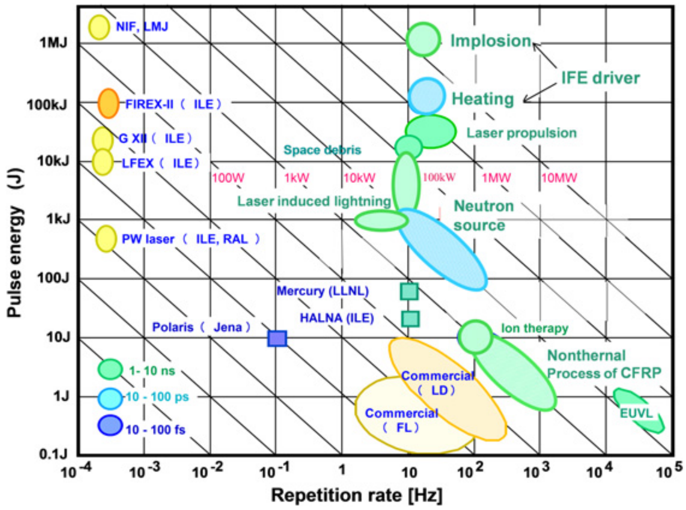

Figure 3. Setting progress of short pulse, high average power laser and new applications.

by a high peak intensity laser, and non-thermal material processing and EUV light source with a short pulse high rep-rate laser.

The recent progress of short pulse, high average power laser and it applications are summarized in Figure 3. Lasers of 1 kW high average power with rep-rate operation are under development or construction for industrial applications such as material processing. The next plans are designed to reach 10 $\sim$ 100 kW level for the brand new applications such as neutron source, laser induced lightning, and clearing of space debris. The 100 kW average power laser (10 kJ $\times$ 10 Hz) is just one module with reasonable size, which consist the IFE driver of MJ and MW level. Therefore the development of 10 kJ module is the final target of the IFE driver development.

4. DEVELOPMENT OF LASER NEUTRON SOURCE AND ITS APPLICATIONS [4,5]

4.1 Generation of neutrons by high power laser

Neutron generation by short pulse laser of order of ns to fs has been extensively investigated for many years. The typical targets for specified physical models are ① gas cluster target, ② thin film target, ③ spherical pellet target for the implosion.

Figure 4 shows the compiled data of neutron generation as a function of injected laser energy with different pulse widths, depending on the related physical processes. The data points are basically single shot results. The rep-rate operation is needed for industrial application as a neutron source. It should be noted that fusion ignition can enhance neutron production beyond the line Q = 1 where the fusion energy is equal to the incident laser energy.

4.2 Industrial applications of laser neutron source

The applications of neutron sources span over wide fields of material science and technology, nuclear energetic, medical, and new methodology in diagnostics, especially in measurements of light elements such as Hydrogen and Li.

The required neutron source intensity is evaluated from the necessary neutron energy and flux density at the sample of the specific application, and the design of energy moderation and guiding

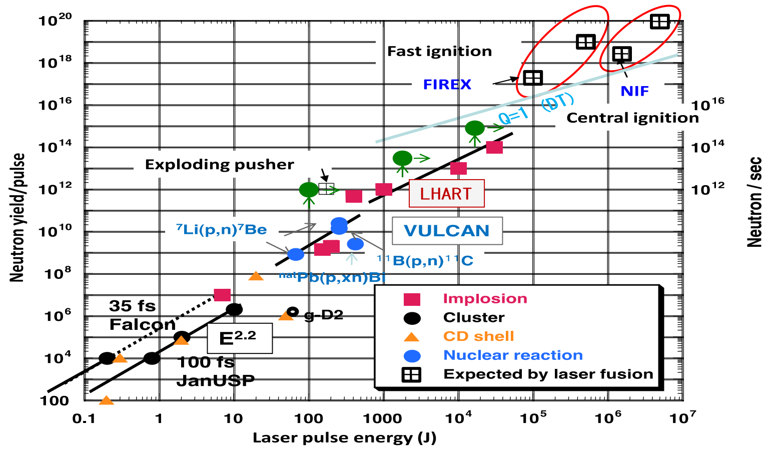

Figure 4. Neutron yield scaling with respect to laser energy.

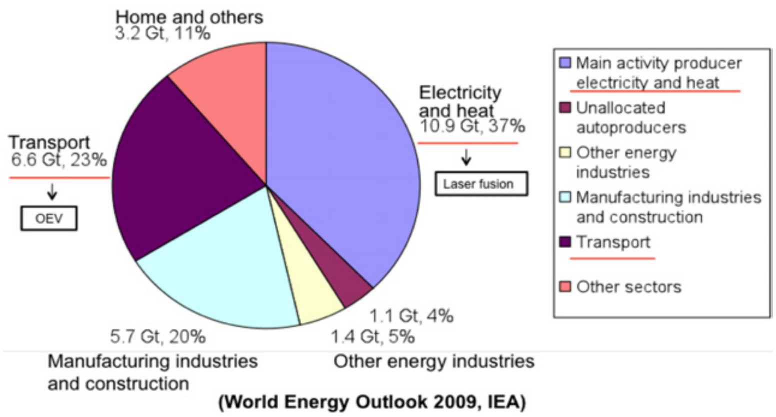

Figure 5. World CO_2 emission of different sectors.

of neutrons. For the diagnostics of Li-ion battery and fuel cell, the source neutron intensity of $10^{10} \sim 10^{12}$/sec is required. For the medical applications like BNCT, the intensity is $10^{12} \sim 10^{13}$/sec. For semiconductor doping (NTD), the intensity is $10^{14} \sim 10^{15}$/sec. For material processing, such as annihilation of radioactivity, fusion material tests and fusion-fission hybrid etc., intensity higher than 10^{15}/sec is required.

5. POWER PHOTONICS FOR GREEN EARTH

We are entering a new era, where steady economic growth must be achieved under sustainable conditions to maintain the environment for future generations. The world CO_2 emission of different sectors is shown in Figure 5.

Efficiency improvements and energy savings in the sectors of “Home and others” and “Manufacturing industries and construction” are progressing rapidly. In these sectors, the optics and photonic technologies are contributing greatly particularly solar batteries, LED lighting, laser processing, and precision optical monitoring for precise control of energy systems.

Table 1. Opto-Electric vehicle (OEV) development and its key issues.

Components	Issues to be developed	Photonics and Laser technologies
Solar generator	high efficiency, thin film	laser processing
Battery & capacitor	high energy density, light weight, Li Battery	neutron diagnostic
Motor & brake	direct couple to wheel, energy recovery, power control	NTD for Si
Frame & body	light weight, CFRP	laser processing
Power control	optical fiber harness	Fiber optics

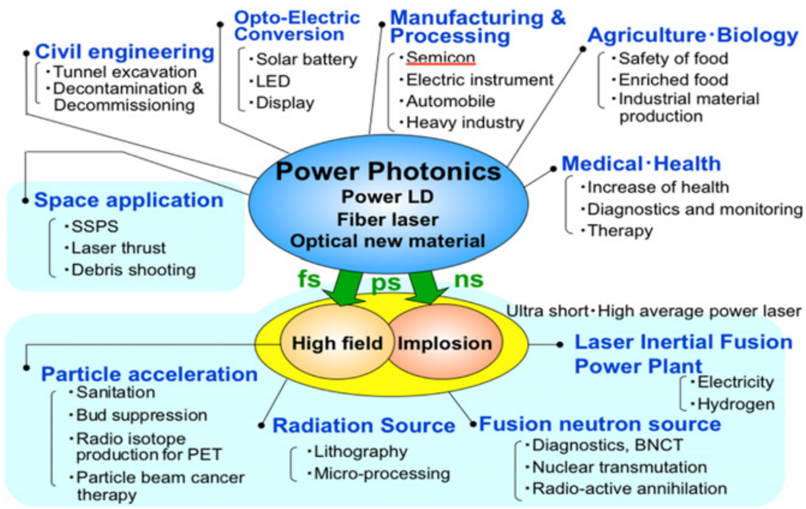

Figure 6. World new industries based on power laser technology.

The biggest source of CO_2 emission, energy sector, can be revolutionary changed and CO_2 emission can be reduced with the completion of the Laser Inertial Fusion Energy (LIFE).

The CO_2 emission of the second biggest source, Transport, can also be reduced with the application of photonic technology. The town car, which is used in daily living, could be designed to be gas-free Opto-Electric Vehicle (OEV). That is, electric vehicle with solar battery for energy production and Li battery for energy storage. The lightweight composite material CFRP is fully used for body and frame with the efficient recovery of the brake energy by precise power control. In the components of an OEV, the key issues and the possible contribution of laser technologies are summarized in Table 1. Optics and laser technologies play the essential role to realize the fossil fuel-free vehicle.

6. SUMMARY

We are entering the new era of Laser Inertial Fusion Energy (LIFE) development, where the dominant efforts will be focused on the engineering issues related to the LIFE power plant construction. This should provide the solution in the energy sector which is the biggest CO_2 emission source.

Along with the engineering development for the LIFE power plant, new industries will be created based on the power photonics, as shown in Figure 6.

It is widely said that the 21st century is the era of photonics. The LIFE development needs the most advanced and crucial technologies in the power photonics. It can also be the driving force for the Green Earth and Better Life of all humanity in the future.

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