

Industrial Applications of Laser Neutron Source

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Abstract. The industrial applications of the intense neutron source have been widely explored because of the unique features of the neutron-matter interaction. Usually, intense neutron sources are assembled with fission reactors or high energy ion accelerators. The big size and high cost of these systems are the bottle neck to promote the industrial applications of intense neutrons. In this paper, we propose the compact laser driven neutron source for the industrial application. As the first step of our project for the versatile applications of laser driven neutron source, Li-neutron and/or Li-proton interactions have been investigated for the application to the development of Li battery.

1. Introduction

The high density and intensity laser-matter interaction physics have been well investigated being directly related to the laser fusion research. Various physical processes have been clarified to generate neutrons, high energy electrons and ions, and intense x-ray and γ -ray by using relatively small laser energy with high intensity short pulses.

The high power pulse lasers with high efficiency and rep-rate operation are progressing rapidly aiming to develop the laser driver for the fusion power plant. The technology of the system consists of wide range of innovative engineering fields such as high power laser diode for pumping, new laser host materials of glass, ceramic, and/or crystal, precise pulse shaping and compression, frequency conversion, phase control and beam pointing. The developments of fusion driver are leading the front edge of industrial laser technologies. To promote the industrial application of the laser fusion technology, especially laser produced neutrons and protons, a specified committee: "Committee of Industrial Application of Laser Neutron Source" has started with the support of IFE forum getting the collaborations of academia, and related industries through out Japan. The collaborative research with Universidad Politecnica de Madrid has also started. This work is being performed partly under the IAEA program "Coordinated Research Project on Pathway to Energy from Inertial Fusion – an Integrated Approach".

2. Generation of Neutrons, Particle Beams by High Power Laser

Neutron generation by short pulse laser of order of ns to fs have been well investigated for many years. The physical model of typical examples is shown in Fig. 1. They are ①gas cluster target, ②thin film target, ③spherical pellet target for implosion. There are many optimized structures of each target such as density control, composite material and Z number optimization, layered structure etc. The pulse width and shape are also optimized according to the type of the targets and structures, of which features are also shown in Fig. 1.

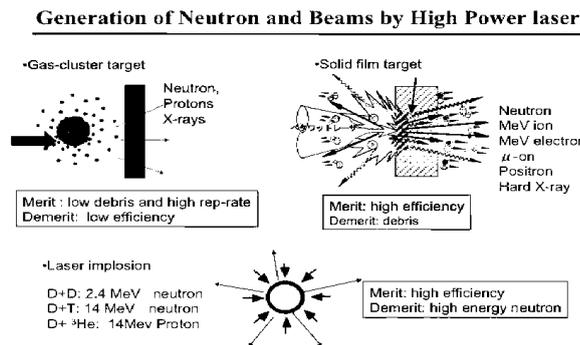


Fig. 1

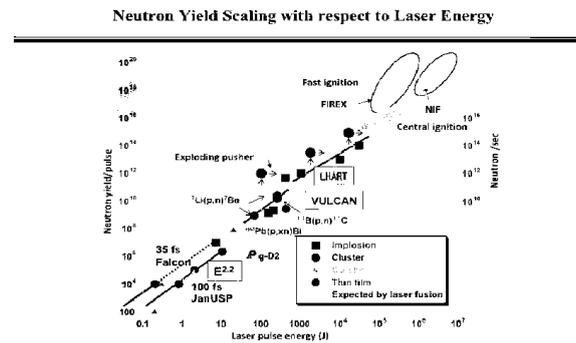


Fig. 2

Fig. 2 shows the compiled data of neutron generation as a function of injected laser energy with different pulse width depending on the related physical processes. The data points are basically single shot results. The rep-rate operation is needed for the industrial application as a neutron source. For this purpose, repeatable target feeding and high average power pulse laser must be developed. The right vertical axis shows the neutron fluence per second when the neutron production shots are repeated at 10 Hz to 1 kHz. It should be noted that fusion ignition can enhance the neutron production beyond the line $Q=1$ where the fusion energy is equal to the incident laser energy, and also it is expected to be demonstrated in near future of 2010~2015.

3. Industrial Applications of Laser Neutron Source

The applications of neutron sources in science and industry are discussed in the previous report in IFSA2007⁹⁾. It spans over wide fields of material science and technology, nuclear energetics, medical, and new methodology in diagnostics, especially in measurements of light elements such as Hydrogen and Li.

The required source neutron flux 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 of neutrons.

For the diagnostics of Li-ion battery and fuel cell, thermal neutron flux of $10^{11} \sim 10^{12}$ /sec is required. For the medical applications like BNCT, the flux is $10^{12} \sim 10^{13}$ /sec. For semiconductor doping (NTD), the flux is $10^{13} \sim 10^{14}$ /sec. For material processing like annihilation of radio-activity in which long life radio-active elements in a used nuclear fuel are transmuted by fusion neutron, fusion material test, and fusion-fission hybrid in which a under critical fission reactor is driven by fusion neutron irradiation, the flux higher than 10^{15} /sec is required.

In the following section, the laser driven nuclear processes are discussed for the applications to the new diagnostics which are necessary for the developments of Li ion battery and Hydrogen fuel system.

4. Application of Laser Produced Neutron and Ion to Li-ion Battery Diagnostics

4.1 Diagnostics

In the R&D of the lithium ion battery, it is necessary to diagnose the damage of electrode and the dynamics of lithium and negative ions in the electrodes and electrolyte. Neutrons and ions are appropriate and unique tools for the Li-ion battery diagnostics. However, because the conventional

irradiation facilities are huge and nowadays only specialized nuclear research site can be used, the speed of material developments for the advanced battery is limited. Neutron and ion sources driven by lasers could provide a compact combined system for this purpose. The applications of laser driven neutron and ion for observing electrodes, lithium, negative ions are discussed here. The images of diagnostic systems are the facility at University of Texas in the reference ²⁾ for neutron diagnostics and the Fig. 3 for proton diagnostics. Here, an intense short pulse laser irradiates a solid target or cluster to generate mono-energy protons. Laser produced MeV protons are guided and directly injected onto the Li-ion battery to probe Li-ion depth profile, negative ion depth profile and so on. Otherwise, the protons are injected into liquid Li metal target to generate low energy neutrons. The neutrons are decelerated to thermal neutrons that are used for the Li battery diagnostics as discussed in the reference [4] or in some other new methods.

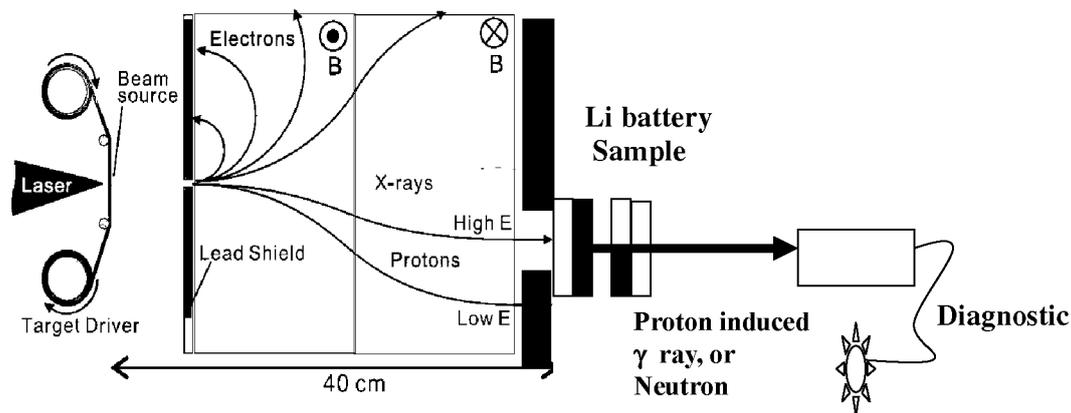


Figure 3 A schematic diagram of application of laser produced proton beam to

4.2 Laser neutron diagnostics

On the other hand, neutrons generated by ultra intense short pulse laser can be also applied for the Li battery diagnostics. The thermal neutron scattering, excitation, and reactions of light elements are used for the diagnostics. As an interesting example, we describe the application of neutron absorption reaction. The reaction: ${}^6\text{Li} + n \rightarrow t(2.7\text{MeV}) + \alpha(2.1\text{MeV})$ could be used for measuring Li depth profile by observing the emitted t and/or α energy spectrum. Namely, the t and α energy spectra correspond to the Li number density. The lowering of energy of t or α corresponds to depth of the place where the reaction takes place. In this way, the Li depth profile can be measured³⁾. Multi-MeV protons generated by laser are used for generating sub-MeV neutrons through p-Li reactions.

4.3 Laser produced proton diagnostics and mono energy proton generation

[Proton diagnostics]

When MeV protons are injected into Li- battery, protons react with light nuclei like Li, F, and so on to produce γ rays and/or neutrons. Since these nuclear processes are threshold reaction, we can deduct ion density depth profile from the proton beam energy dependence of γ ray yield and/or neutron spectrum. The proton induced γ -ray diagnostics has been known as the PIGE (Proton Induced Gamma Emission) ⁴⁾. Energy spectrum of neutrons induced by the reaction ${}^7\text{Li} (p, n) {}^7\text{Be}$ can be used for diagnostics of Li depth profile, since neutron energy depends on proton energy. Although the energy spread is the critical issue, the laser produced protons are unique as a probe beam because of very low transverse emittance and short pulse. The energy spread could be overcome by introducing energy selector as shown in Figure 3. Let's take a quasi mono-energy proton beam with $(\Delta E / E)_{\text{FWHM}} \sim 0.1$ ⁵⁾. For obtaining a beam of 1% energy spread, 10% of the total flux can be used. In the case of Li ion battery, the width of a typical sample is 200 μm . Therefore, the spatial resolution obtained by this proton beam diagnostics like PIGE could be a few μm . This resolution is not very good, but interested in the field of Li ion battery community.

[Mono energy proton generation by structured clusters]

Mono-energy protons can be generated by irradiating an ultra intense short pulse laser on clusters of hydrogen-high Z atom mixture. When the fraction of proton charge is much smaller than the total cluster charge and the Z/M of the high Z ion is small enough compared with that of proton, then we can assume that protons are accelerated in a Coulomb field of the charged high Z sphere. Namely, the final velocity of proton (the proton velocity at $r = \infty$) is given by

$$E = Mv_f^2/2 = Zn_0 e^2 (3R^2 - r_0^2) / (6\epsilon_0),$$

where R is the initial size of the cluster and r_0 is the initial radial position of the proton layer. So, the energy difference between protons at r_0 and $r_0 + dr_0$ is given by $dE = -Zn_0 e^2 r_0 / (3\epsilon_0) dr_0$. The proton number in a spherical shell of inner radius r_0 and outer radius $r_0 + dr_0$ is

$$n_p 4\pi r_0^2 dr_0 = -4\pi r_0^2 n_p (dr_0/dE) dE, \text{ where } r_0 = (3R^2 - 6E\epsilon_0/Zn_0 e^2)^{1/2}.$$

When $N(E) dE$ is number of proton in the energy range of $(E, E+dE)$, then, $N(E)$ is given by

$$N(E) = 2\pi n_p (6\epsilon_0/Zn_0 e^2)^{3/2} (R^2 Zn_0 e^2 / 2\epsilon_0 - E)^{1/2},$$

where $R^2 Zn_0 e^2 / 3\epsilon_0 = E_{min} < E < E_{max} = R^2 Zn_0 e^2 / 2\epsilon_0$, otherwise $N(E) = 0$.

In this case, the FWHM of the proton energy spectrum is 30%.

For the nuclear reaction diagnostics by proton, this proton energy spectrum is too broad and energy selection is required. However, the proton beam brightness for the probing is 3 times higher than conventional laser produced proton beam. On the other hand, this proton can be used for producing low energy neutrons. In the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction, the maximum neutron energy is 1MeV when maximum and minimum proton energy are 3MeV and 2MeV. Proton energy spectrum from a high Z cluster in which hydrogen is weakly doped. When the total charge of cluster is 1.25×10^{-10} C, then, $E_{max} = R^2 Zn_0 e^2 / 2\epsilon_0 = 2.75$ MeV and $E_{min} = 1.83$ MeV. The cluster radius R is 0.1 μm . This neutron source could be useful for a compact thermal neutron diagnostic system because sub-MeV neutrons have large scattering.

The application of intense neutron source is becoming increasingly important in developing new methodology in research and engineering. The laser driven neutron and ion beam sources will provide a compact and versatile facility for the industrial applications.

5 Summary

We are now getting into the new phase of development in the Laser Inertial Fusion Energy (LIFE) with the accumulated results of scientific and engineering researches and developments through out the world for many years. The most challenging and significant issue toward LIFE is the high power laser development of rep-rate operation with high efficiency, compact, and low cost for construction and maintenance. The progress of laser technology is opening wider fields of industrial applications in manufacturing, medical, biological and energy engineering.

The application of intense neutron source is becoming increasingly important in developing new methodology in science and engineering. The laser driven neutron and ion beam sources provide the compact and versatile facility for the industrial application. The feasibility has been examined theoretically and a new project for the industrial application has been proposed.

References:

- [1] S. Nakai et al IFSA2007 Proceeding Journal of Physics:Conference Series 112(2008)042070
- [2] K. Unlu, B.W. Wehring, J. Radioanalytical and Nucl. Chem. 217(1997)273
- [3] S.M. Whitney, et al. J. Radioanalytical Nucl. Chem. 282(2009)173
- [4] R. Mateus, A. P. Jesus, B. Braizinh, J. Cruz, J.V. Pinto, J.P. Ribeiro, Nuclear instruments and methods B 190(2002)117-121
- [5] For an example, B.M. Hegelich, *Nature* **439**, (2006) 441-444