Efficient Fusion Neutron Generation Using a 10-TW High-Repetition Rate Diode-Pumped Laser

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The first use of a high-repetition-rate laser-diode (LD)-pumped laser in a fusion target experiment is demonstrated. An LD-pumped Nd-solid state laser's output is coupled to a Ti:sapphire laser, enabling the resulting HAMA laser to generate 2-J, 815-nm-wavelength output with a pulse width of 150 fs and a repetition rate of 10 Hz. A photon-to-photon efficiency of 1.25% (electric-to-photonic 0.7%) is achieved, which is an order of magnitude higher than that of current flash-lamp lasers. Irradiation of a 500-μm-thick deuterated polystyrene film by a 0.6 -J pulse yielded 10^5 DD fusion neutrons. The efficiency from the electric input to the neutron yield is 10 times higher than the flash-lamp-pumped table-top lasers.

Keywords: laser-diode(LD)- pumped laser, ICF roadmap, DD fusion neutron, neutron source

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The National Ignition Facility (NIF) [1] is expected to begin fuel burning soon. However, the flash-lamp-pumped lasers typically used are unsuitable for power plants, because the electric-to-photonic conversion efficiency of the flash lamp is less than 0.5%. A power plant requires a laser with an efficiency of more than 10%. The solution is the use of high-repetition-rate laser-diode (LD)-pumped lasers [2–6]. Here we demonstrate the first use of an LD-pumped laser, HAMA, in fusion target experiments. HAMA generated 2 J with a pulse width of 150 fs at 10 Hz and its efficiency was 1.25%. Irradiation of a 500-μm-thick deuterated polystyrene film by a 0.6-J HAMA pulse yielded 10^5 DD fusion neutrons [7]. The efficiency from the electric input to the yield is $8{\times}10^5$ neutrons/kW, 10 times higher than those using flash-lamp-pumped table-top lasers [8–10]. The results will also assist in developing industrial and commercial neutron sources. The present result is still far from a true working accelerator sources (a neutron generator). Typically a deuteron beam of 1 mA generates 10^9 n/s, whereas, our results show 10^5 n/s from 15 nC, corresponding to 7×10^9 n/mA. However, since current neutron sources using accelerators are too big to meet industrial demands, a compact neutron source using a laser must have an advantage over the rf sources.

Figure 1 shows the key issues together with the roadmap for achieving an inertial confinement fusion (ICF) power plant [11]. Soon the National Ignition Facility (NIF)

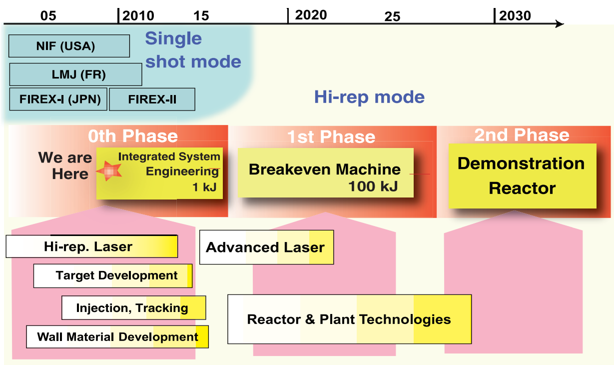

Fig. 1 Key issues and paths to an ICF power plant. Upper left region represents current experiments in single-shot mode. Other regions indicate the main path using repetitive-shot mode toward a fusion power plant. This main path is divided into three phases: engineering test and neutron production(zeroth or pre-phase), break-even machine (first phase), and demonstration (second phase). Yellow boxes indicate problems that need to be resolved. We focuse here on the first step toward achieving the main path, by a star.

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is expected to achieve ignition and burning of fuel. This will demonstrate that energy can be generated from nuclear fusion. Although this represents an important milestone toward developing an fusion power plant, the main stage for achieving inertial fusion energy does not use single-shot mode, but rather it uses repetitive-shot mode. The main path to the fusion energy is shown on the central row. A lot of works are necessary to realize a power plant [12]. One key issue is the development of a high-repetition-rate, high-efficiency laser with output energies of the order of kilojoules or greater. Another is fuel fabrication and high-repetition fuel injection. In addition, power plant technology, such as an innovative wall materials, will need to be developed.

We divide the roadmap for achieving a fusion plant into three phases. The zeroth phase involves developing 1-kJ drivers by performing engineering tests and producing neutrons. The first phase is to develop a breakeven machine that uses a 100-kJ driver. The second phase is to demonstrate a commercial reactor. We have developed an LD-pumped laser system with a repetition rate of 10 Hz. This repetition rate is high enough for this stage. We are currently in the zeroth phase, as indicated by the star in Fig. 1. Next steps, such as LIFE in US and HiPER in Europe, are also proposed [13].

We are the first to apply the high-repetition-rate ultrahigh-intensity HAMA laser in nuclear fusion experiments. HAMA consists of a pump laser (KURE-I) and a seed beam supplier laser (BEAT). KURE-I is an LD-pumped Nd:glass laser system (Hamamatsu Photonics) [5], which pumps the seed beam from the BEAT laser, Ti:sapphire optical parametric chirped-pulse amplification system (OPCPA) at 1.25 Hz [14, 15], where a second harmonic YAG laser parametrically amplifies frequency chirped seed pulses in a β-$B_aB_2O_4$ (BBO) crystal.

In a vacuum chamber, two pairs of gold-coated plane gratings (1740 grooves/mm, Jobin Yvon/Horiba) compress the amplified seed to a 150-fs Gaussian beam. The shot-to-shot fluctuation of the pulse energy is currently 20%. The total efficiency from the electric input to the photonic power was 0.7%. Flash-lamp-pumped lasers are unsuitable for power plants since the electric-to-photonic conversion efficiency of flash lamps is less than 0.5%, almost all of the energy is expended as heat, which produces adverse effects in the laser medium. A commercial power plant requires a laser having an efficiency of more than 10%. Since HAMA is an LD-flash-lamp hybrid system, where a flash-lamp-pumped seed is amplified by an LD-pumped laser, its final efficiency is not on the order of 10%. At the same time, the gold coating on the compression grating reduces the transport efficiency. We are designing a full LD-pumped system, which will realize 10% efficiency in the near future.

Using an off-axial 5-cm-diameter gold-coated mirror (OAP) of F/2.2, we focused a p-polarized beam obliquely onto the target plane at an angle of 30°. The focal spot size was 15 µm ($1/e^2$) and its intensity was 2.2×10^{18} W/cm^2. The target is a deuterated polystyrene $(C_8D_8)_n$ square plate, which is typically 500 µm thick, 20 mm wide and 16 mm high. One target plate accommodates 100 continuous 100 shots. To ensure that each pulse irradiates a fresh area on the surface every 1.25 Hz, we translated the target surface at a speed of 1 mm/s. The spatial fluctuation of the illumination is lower than 100 µm, which is less than the Rayleigh length of 250 µm.

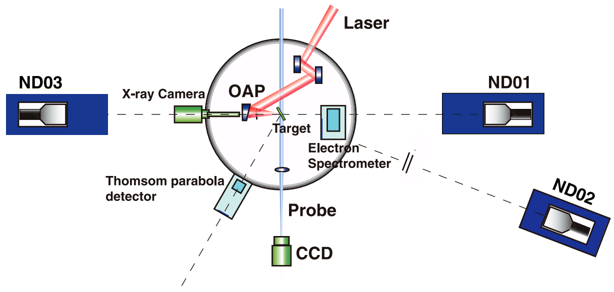

Fig. 2 Experimental setup for production and detection of DD fusion neutrons. Sizes and positions of neutron detectors as well as their shielding walls are scaled to the chamber size, which has an inner diameter of 70 cm. OAP is abbreviation of an off-axial parabola mirror.

The OPCPA preamplifier suppress the pre-pulse perfectly, but the amplified spontaneous emission (ASE) remains. Since the energy is only at the joule level or lower on the target, second-harmonic interferometry has observed no apparent preplasmas.

Although the prepulse may be charged with hot electron generation, it will not be charged with neutron generation, since neutrons are generated inside the CD solid. The laser around the front surface generates high-energy deuteron beams, which impact the solid CD and collide with the static deuterons, generating DD fusion neutrons.

Three neutron detectors ND01, ND02 and ND03 are distributed around the chamber, as shown in Fig. 2. The detectors' sizes and positions as well as the shieldings are scaled to the chamber, which has an inner diameter of 70 cm.

ND01, consisting of a 100-mm-diameter plastic scintillator (BC408) coupled to a 1-inch-diameter photomultiplier (H10425), is placed 1 m from the target along the laser beam axis. The front side is shielded by a 20-cm-thick lead plate, and the other sides are shielded by 5-cm-thick lead plates. A 20-cm-thick lead plate reduces the 2.45-MeV neutron leakage to 0.16. A similar detector (ND02) is positioned 3.3 m from the target at an angle of 52° to the target normal (or 22° to the laser axis). The front lead plate is 10 cm thick, which reduces the neutron leakage to 0.4. ND03 is a 6-inch plastic scintillator (NE102) coupled to a 2-inch photomultiplier (H7195) located 1.09 m from the target (180° counter to the axis). The front lead plate is 20 cm thick. The output is connected to

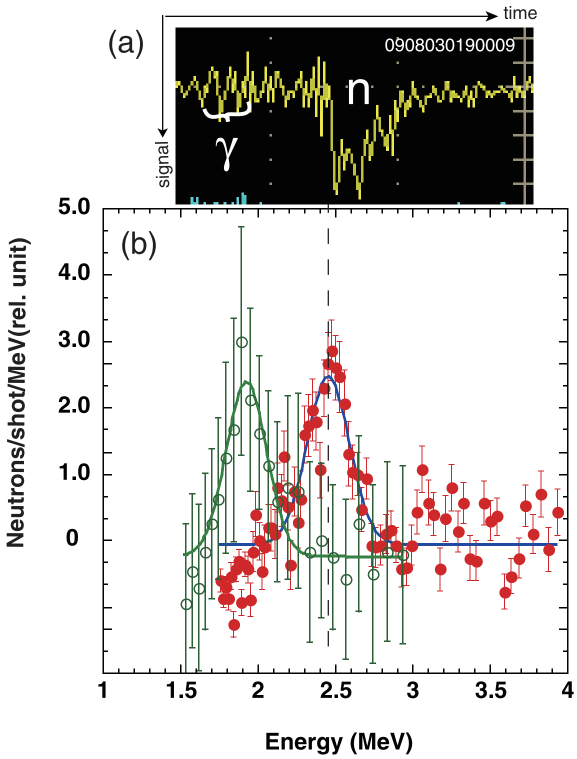

Fig. 3 (a) Single shot neutron time-of-flight signal of ND01 from the CD plane: 100 mV/div, 40 ns /div. Initial 40-ns noises are caused by γ rays. (b) Comparison of forward and backward neutron spectra. Forward ND02 signal (solid circles) is averaged over 27 shots at 3.3 m and 0°. Backward ND03 signal (open circles) is averaged over 32 shots at 1.09 m and 180°. These data are fit by Gaussian functions centered at 2.46±0.012 MeV with a width of 0.193 MeV and centered at 1.93±0.014 MeV with a width of 0.184 MeV, respectively. Error bars represent the standard errors. Vertical dashed line indicates the 2.45-MeV point.

a 1-GHz digital oscilloscope (Tektronix TDS5104B). The total temporal resolution is 4 ns. Each detector was calibrated by the use of a ^{252}Cf source (Eckert & Ziegler, A3036-2). One neutron to ND01 corresponds to a signal of (30 ± 15) mV×4 ns on the oscilloscope, for example.

In Fig. 3 (a), 0.6-J laser irradiation of the target yields an ND01 signal of 1280 mV·ns, or 10±5 neutrons to the detector through the 20-cm-thick lead shield. Assuming the same emissions in all directions, the total yield becomes $(1.3 \pm 0.4) \times 10^5$ neutrons/shot for 4π str (that is all over the entire solid angle). The initial 40-ns-preceding noises are caused by γ rays. An electron spectrometer and Thomson parabola detect MeV electron and ion leakage from the target, respectively.

Figure 3 (b) compares the neutron time of flight spectra from ND02 (solid circles) and ND03 (open circles). The ND02 signal is averaged over 27 shots and the ND03 signal is averaged over 32 shots. Each vertical intensity is normalized by the other on the graph. The error bars indicate the shot-to-shot standard error. Fitting a Gaussian function to the data of the ND02 data reveals that the peak is centered at 2.46±0.012 MeV. The peak shift from 2.45 MeV is 0.02 MeV or less. The spectral broadening ΔE_n is 0.19 MeV near the peak, suggesting a deuteron temperature T_i of 5.5 keV according to the thermal plasma model $\Delta E_n = 82.5\sqrt{T_i}$ keV [16]. Whereas, our beam fusion model gives $\Delta E_n = 35\sqrt{T_i}$ keV. Then a ΔE_n of 0.19 MeV yields a T_i of 30 keV. On the laser axis (not shown in the figure) ND01 measured a peak at 2.45±0.058 MeV. On the other hand, fitting a Gaussian function to the ND03 data reveals that the peak shift is −0.54±0.014 MeV relative to 2.45 MeV. ΔE_n is 0.18 MeV, which is similar to those measured by ND01 and ND02. Similar peak shift differences between the forward and backward directions were reported in previous works as for the oblique and p-polarized incidences [10, 17]. The angular dependence of the ion temperature derived from ΔE_n and the neutron Doppler shift due to ion drift are not yet clear.

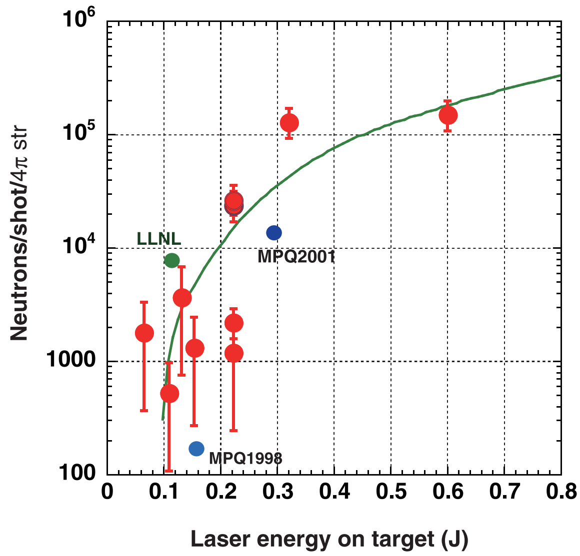

Fig. 4 Neutron yield versus laser energy. Yield is normalized to 4π solid angle. Error bar shows 80 to 30% shot to shot error. LLNL (cluster) is from [8], MP1998 (CD plane) is from [9] and MP2001 (CD plane) is from [10]. The curve is calculated by a thermal-beam fusion model. Laser absorption is 20%.

Figure 4 shows that the yield increases with increasing the laser pulse energy. For pulse energies lower than 300 mJ, the yield fluctuates by as much as one neutron every few shots, whereas for pulse energies higher than 400 mJ, it increases to almost one or more neutrons per shot. This is due to the laser power fluctuation of 20%, which, as the calculation below shows, produces a yield fluctuation of 80% at low energies but 30% at high energies. Consequently, in the former case, the number of neutrons that enter the photomultiplier eventually decreases to zero. The horizontal axis is the pulse energy on target and the vertical axis is the yield per 4π angle.

We assumed that thermal deuterons from the cut-off region collide with cold target plasmas to yield DD neutrons. The laser deposits its energy at the cut-off region, generating hot electrons [18]. The hot electrons raise and accelerate the deuterons to thermal beams, which penetrate the solid target, generating a nuclear reaction. The beam-fusion neutron yield is

$$Y_n = <\sigma v> n_{\mathrm{Dcut}} \cdot \tau_{\mathrm{pulse}} \cdot n_{\mathrm{Dsolid}} V_{\mathrm{solid}}, \quad (1)$$

where $<\sigma v>$ is the product of the reaction cross section and the deuteron beam velocity averaged over the one-dimensional Maxwellian distribution. Also, n_{Dcut} is the deuteron beam density at cut-off, and n_{Dsolid} is the cold deuteron density in the solid. V_{solid} is the reaction volume. We assume, for example, that 20% of a 0.6-J laser pulse is absorbed by the cut-off plasma in a 20-μm spot, generating hot electrons at a temperature of 50 keV, which will transfer energy to ions and generate a beam of the same longitudinal temperature. T_i is close to that estimated from $\Delta E_n = 35\sqrt{T_i}$. The beam current is estimated as 15 nC per shot. Beam fusion $<\sigma v>$ is 5×10^{-24} m^3/s. Thus, at a 0.6-J laser input, we have neutrons of 1.8×10^5 per 4π solid angle. The result is the curve shown in Fig. 4, which is close to the experimental points within the order of the yield. The curve is calculated by a thermal-beam fusion model. The laser absorption is 20%. The model seems to agree well with the experimental results.

We now estimate the neutron production rate per unit electric power. Current flash-lamp systems (10^4 neutrons for a 300-mJ illumination, for instance) require an electric power of 1 kW to produce 8×10^4 neutrons/kW [10], whereas HAMA system produces 8×10^5 neutrons/kW for the same 300-mJ illumination. This yield is 10 times higher than those of earlier table-top laser experiments [10].

We employed the high-repetition-rate LD-pumped laser HAMA for the first time in a fusion target experiment. HAMA generates 2-J, 815-nm output with a pulse width of 150 fs and a repetition rate of 10 Hz. Although the output energy is very low, we have achieved an efficiency of 1.25%, which is an order of magnitude higher than that of current flash-lamp lasers. An input of a 0.6 J from HAMA on a 500-μm-thick deuterated polystyrene target yielded 10^5 DD neutrons centered at 2.45 MeV at a rate of 1.25 Hz; these neutrons are generated by fast ignition [7]. The yield per shot is higher than the high-repetition-rate neutrons produced using commercial flash-lamp-pumped lasers [8, 9], as shown in Fig. 5.

The present LD-pumped laser yielded only fusion neutrons, but the laser development is anticipated to accelerate enabling implosion, fast ignition, and burning of fuel capsules. Several problems must be resolved to realize a power plant. These include target production, injection,

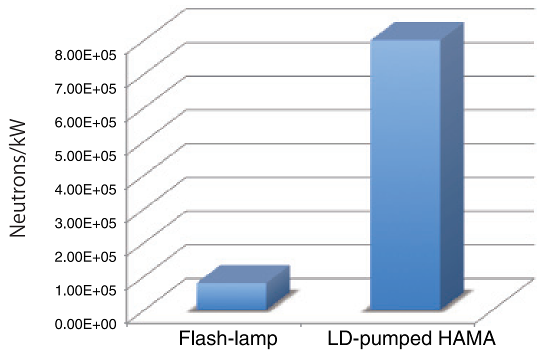

Fig. 5 Comparison of neutron yield per 1 kW input electric power between flash-lamp-pumped laser and LD-pumped HAMA laser. Flash-lamp data is from [10].

and tracking, as well as development of the final optics and first wall materials (see the yellow boxes in Fig. 1). The result presented in this letter is a first step toward achieving inertial fusion energy. The highly efficient neutron yield obtained suggests that it could also be used to produce cost-effective neutron sources.

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