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Laser-confined fusion

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An approach for producing a large quantity of neutrons is proposed. It involves compression of a fuel foil and confinement of the resulting plasma between two intense laser pulses. It is shown that two circularly polarized laser pulses of amplitude $a=7$ illuminating a deuterium-tritium foil of areal density 3.3×10^{18} cm^{-2} can produce about 4.2×10^{6} neutrons per joule of the input laser energy.

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In connection with the peaceful use of fusion energy, there has been much interest in inertially confined plasmas (ICPs) produced by lasers or particle beams (see, e.g., Refs. [1–6]). Although ICPs are in fact unconfined, it is expected that gainful self-sustained fusion reaction, or ignition, would occur before the plasma disintegrates. On the other hand, many other applications for the neutrons from the nuclear reactions in ICPs do not require ignition of a chain reaction. The recently available tabletop lasers with ultrashort pulse and ultrahigh intensity are particularly suitable for these applications [7–10].

Ditmire *et al.* [7] proposed a scheme of neutron production using modern tabletop lasers. There, a femtosecond (fs) laser pulse interacts with a deuterium cluster. The atoms are rapidly ionized by the intense light and the resulting electrons fly off, leaving the ions behind, and an intense space-charge field is created. The Coulomb explosion that follows causes the deuterium ions to gain high kinetic energies, and fusion reaction occurs when they collide. About 10^4 neutrons per shot, or 10^5 per joule of laser energy, were produced. On the other hand, Fritzler *et al.* [11] detected more than 1×10^6 neutrons from the direct interaction of a 62-J laser with an underdense deuterium plasma. The main weakness of these approaches is that the ion density is relatively low in clusters and underdense plasmas, and it rapidly becomes even lower during the interaction, while the fusion reaction rate is proportional to the square of the ion density.

In this paper we propose an alternative approach for producing neutrons: from a DT foil (plasma) confined by laser fields. In the present laser confined fusion (LCF) approach, neutrons are produced by the (fusion) reaction $\mathrm{D}+\mathrm{T}\rightarrow\mathrm{He}^4$ (3.5 MeV)$+n$ (14.1 MeV). Two circularly polarized laser pulses illuminate a frozen DT (others such as CD_2 can also be used) foil from both sides simultaneously. The atoms are ionized rapidly and the electrons are pushed inward by the light pressure. The ions are then pulled inward by the space-charge field, but at a much longer time scale. If the foil is sufficiently thick, the ions need some time to catch up with the electrons. The ion velocity will remain comparable to, but smaller than, the electron velocity. In the compressed quasistationary state, the ion density and temperature, which can be much larger than that of the electrons because of the large ion mass, can be sufficiently large for fusion reaction to occur. Clearly, a compact neutron source based on LCF can have many modern applications.

As a specific example, we consider a not-too-thin frozen DT foil (half deuterium and half tritium) of areal plasma density $N_s=3.3\times10^{18}/\mathrm{cm}^2$ confined by two identical circularly polarized laser pulses of wavelength 1 μm and amplitude $a(=eA/mc^2)=7$, where e and m are the electron charge and mass, and c is the vacuum light speed. For simplicity, we assume that the two laser pulses have the same phase, i.e., $\phi_{21}=\phi_2-\phi_1=0$. In general, this configuration leads to unstable interaction [12,13]. However, if the foil is not extremely thin, the interaction can continue for a sufficiently long time for effective neutron production. In fact, in the simulations we failed to find any observable change of the foil within the time of neutron production. That is, although the relative phase can be important for ultrathin foils, it is not crucial for the purpose here. By using a suitable pulse front, one can obtain a quasistationary state with the desired ion temperature.

In our one-dimensional particle-in-cell (PIC) simulation based on the LPIC++ code [14], the ion mass is taken to be 2.5 times the proton mass, or $m_i/m_e=4590$, which is the average mass of deuterium and tritium ions. The pulse length is 400 laser periods. At the end of the compression, the ion temperature T_i is about 20 KeV, and the electron temperature is much smaller than the ion temperature. The areal thermal energy of the hot plasma is $\frac{3}{2}N_sT_i=1.6\times10^4$ J/cm^2, with the electron thermal energy neglected. If the area of the hot plasma is 10×10 μm^2, the thermal energy is 0.016 J. This much energy is emitted in only 0.12 fs by the laser pulse of amplitude $a=7$. In fact, only a small fraction of the laser energy has been used to heat the DT foil. The compressed-state plasma density and laser field are shown in Fig. 1. The foil thickness is compressed to $\Delta=0.013$ μm, and the ion density is about $2400n_c$ (corresponding to 10 g/cm^3). The ion mass density is still much smaller than that (200 g/cm^3) for inertial confinement fusion (ICF). Nevertheless, it is much larger than that obtained from clusters or underdense plasmas [7,11]. The neutron production rate is $P_{\mathrm{neutron}}=n_Dn_T(\overline{\sigma v})_{DT}\Delta=1\times10^{25}/\mathrm{cm}^2$ s, where the reaction rate $(\overline{\sigma v})_{DT}=4.2\times10^{16}$ cm^3 s^{-1} for $T_i=20$ keV is used. The deuterium (n_D) and tritium (n_T) densities are both $1200n_c$. Thus, $\sim4.2\times10^6$ neutrons can be produced per joule of pumping laser energy.

The results for a thicker DT foil of areal density $8.8\times10^{18}/\mathrm{cm}^2$ are shown in Fig. 2. In order to maintain the

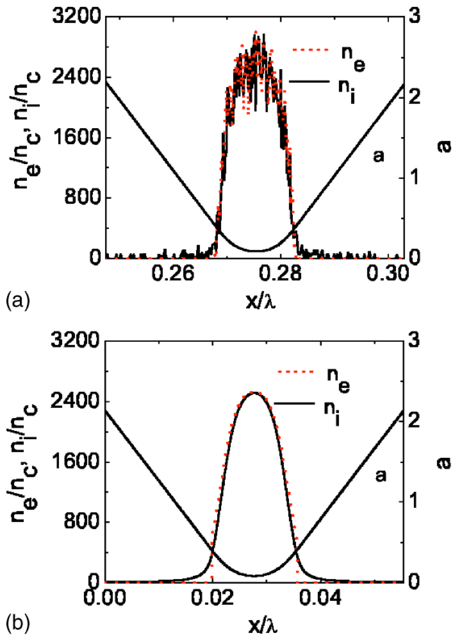

FIG. 1. (Color online) Electron and ion density profiles and laser field a as a function of the foil depth x/λ. Two circularly polarized laser pulses of amplitude $a=7$ and phase $\phi=0$ illuminate the foil from opposite sides. The laser-pulse length is 400 wave periods and the areal plasma density of the foil is 3.3×10^{18} cm^{-2}. (a) The result of the simulation after a stationary state is reached. (b) The corresponding analytical result.

same peak amplitude as in the thin foil case, a longer ($\sim$500 instead of $\sim$400 laser periods) pulse is needed to compress the plasma to the same plasma density and temperature. We see that after compression the plasma density is similar to that of the preceding case. However, since the total number

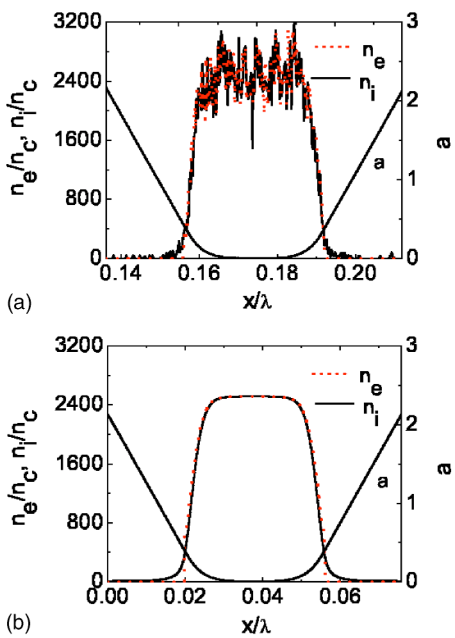

FIG. 2. (Color online) Same as in Fig. 1, but the laser-pulse length is 500 wave periods and the areal plasma density is 8.8 $\times10^{18}$ cm^{-2}.

of ions has increased, more neutrons are produced. On the other hand, more laser energy (longer pulse) is needed to compress the thicker DT foil. In general, given the laser parameters, one can easily find the optimum foil thickness.

We now give a simple one-dimensional analytical model of the compressed plasma. Models for laser confined plasmas involving immobile and cold ions have been considered earlier [12,13]. In the present problem, since the electron temperature is much smaller than the ion temperature, the electron plasma can be assumed to be cold. In the stationary state, the ponderomotive force of the intense laser pulse on the electrons is balanced by the electrostatic force arising from charge separation, or $\partial\gamma/\partial\xi=\partial\psi/\partial\xi$, where γ is the relativistic factor of electrons, $\psi=e\phi/mc^2$ is the normalized scalar potential, $\xi=\omega_L z/c$ is the normalized distance, and ω_L is the laser frequency. For the ions, the ponderomotive force can be neglected. So the space-charge electric force is balanced by the thermal pressure force, or $N_i(\partial\psi/\partial\xi)=-(T_i)(\partial N_i/\partial\xi)$, where N_i is the ion density normalized by the critical density n_c ($=1.1\times10^{21}$ cm^{-3} for a laser of wavelength 1 μm). The ion temperature T_i is normalized by mc^2. The ion density is then given by

$$N_i = N_0 \exp(-\gamma/T_i), \tag{1}$$

where N_0 is a constant determined by the areal density of the foil. Assuming that the laser field is given by $a=a_0(\xi)\exp(i\omega_L t+i\theta(\xi))$ with amplitude $a_0(\xi)$ and phase $\theta(\xi)$, from the Maxwell equations one obtains two constants of motion,

$$M = -\frac{\partial\theta}{\partial\xi}(\gamma^2-1), \tag{2}$$

$$W = \frac{\gamma}{2(\gamma^2-1)}\left(\frac{\partial\gamma}{\partial\xi}\right)^2 + \frac{M^2}{2(\gamma^2-1)} + \frac{\gamma^2}{2} + N_iT_i. \tag{3}$$

For $M=0$, valid for $\phi_{12}=0$ or large foil thickness, the electron density can be written as

$$N_e = \gamma(2W - 2\gamma^2 + 1 + \gamma N_i - 2N_iT_i). \tag{4}$$

Although because of thermal motion the ions can be everywhere, the cold electrons will have a sharp boundary. The laser light propagates as if in vacuum in the electron-free region, since the ions are too heavy to affect the short light pulse. The boundary conditions are thus the continuity of the transverse electric and magnetic fields on the surfaces of the electron plasma. The results are given in Figs. 1(b) and 2(b). In the stationary state the ion density is mainly determined by the ion temperature and laser intensity, and is almost independent of the areal density of the foil. The largest ion density (at the center) is

$$N_i^{\max} = \frac{2a^2}{T_i} \tag{5}$$

for a thick foil. For a laser pulse of $a=7$ and ion temperature $T_i=20$ keV (3.9×10^{-2}), we have $N_i^{\max}=2500n_c$, which is also in excellent agreement with the simulation result.

The analytical model assumes cold electrons. If electron thermalization and electron pressure effects have been included, the final ion temperature would have been less. It is thus of interest to estimate the electron thermalization time. For a DT plasma at density $2400n_c$ and temperature 20 keV the ion-electron collision rate is about $\nu = 3.2 \times 10^{-9} Z^2 \lambda n / \mu T^{3/2}$ $\mathrm{sec}^{-1} = 2 \times 10^{10}$ sec^{-1}. That is, about 50 ps are needed for the electrons and ions to reach the same temperature. This time is usually much longer than that for neutron production. Our simulations also do not show any observable change in the plasma density in the stage after the compression. Thus, the steady-state cold-electron model is suitable for estimating the behavior of laser confined plasmas.

In summary, we have proposed an approach for generating controllable quantities of neutrons from a DT-foil plasma produced and confined by two oppositely directed circularly polarized intense laser pulses. PIC simulations show that a quasistationary state can be reached, and a simple analytical model for the latter is given. From Eq. (5), one finds that ion temperature between 10 and 20 KeV is optimum for neutron production in the DT-foil plasma. Both the PIC simulations and the analytical model here are one dimensional, and are expected to be valid if the focusing area is sufficiently large.

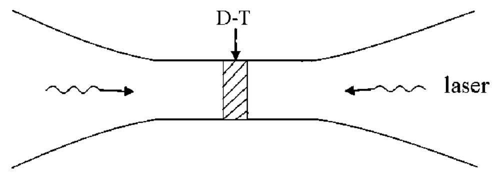

FIG. 3. Schematic drawing of a foil placed inside a preformed channel.

In practice, in order to have better confinement, the foil (fusion material) can be placed inside a preformed channel, as shown in Fig. 3. The channel can be a hollow fiber or created by a laser (see, for example, Refs. [15–20] and the references therein). The foil can also be pushed as a whole into the channel by appropriately controlled laser pulses [15,20]. Finally, the efficiency of neutron production can also be improved by carefully designing the laser pulse and target geometries.

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