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An approach of laser induced nuclear fusion

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Abstract

An approach to an alternative laser fusion in a magnetic field with an intense laser of exa watt level will be discussed. Such a strong field in an exa watt laser will induce enhanced nuclear tunneling through the propagation in plasma. This causes an enhanced nuclear reaction for fusion. We discuss the possibilities to apply this to nuclear fusion energy and to obtain break even in a 100 kJ laser.

Keywords: Coulomb barrier; Laser fusion; Nuclear reaction

1. INTRODUCTION

Significant progress has been made to develop intense lasers for various applications (Borghesi *et al.*, 2007; Bourdier *et al.*, 2007; Kumar *et al.*, 2006; Patin *et al.*, 2006; Sakai *et al.*, 2006; Sherlock *et al.*, 2006). One outstanding example is inertial fusion energy by lasers. Today, peta watt (PW) lasers are already in operation (Danson *et al.*, 2005), and installing exa watt (EW) lasers are under consideration in Europe. When lasers with a total power of more than 10 EW are developed, a power density of up to 10^{28} W/cm^2 will be available. Such strong fields associated with such power density will accelerate ions and electrons. High-energy particles accelerated in intense laser fields have been demonstrated with present-day laser technology and there are schemes under discussion to improve the affect even further (Ledingham *et al.*, 2003; Lifshitz *et al.*, 2006; Flippo *et al.*, 2007; Winterberg, 2006). Moreover, the possibility to generate a very intense laser field will facilitate unique new applications (Li & Imaskai, 2005; Chyla, 2006).

In this paper, we discuss the effect of 10 EW laser beam focused onto a 10^{-7} cm^2 area, which is close to the diffraction limit. The electric field in this case is E_L (V/m) = 2.7×10^{16}, which is strong enough to distort the coulomb barrier of nuclei around 100 to 1000 fm from the nucleus core center. This distorted field promotes a tunneling effect, which enhances fusion reaction rates even in low temperature plasma.

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2. BASIC CONCEPT

At first, an intense laser with high dense target plasma is used. We can produce cluster channels with an injection. After this, we irradiate them with an appropriate first laser pulse before the main pulse, and produce plasma. The shape of the preformed plasma is more than a few tens of centimeters in length with millimeters in radius. For the fusion energy conversion, and to keep plasma confinement in a short duration between two laser pulses, mirror magnetic field may be applied to this plasma.

EW laser, main pulse, is focused, and is injected into the plasma as a Gaussian beam. EW laser propagates through it. During this, intense field of 10 EW laser is applied along the center of laser path. This field distorts the coulomb barrier in each cycle of laser peak, which promotes the tunneling. The tunneled nuclei form a cloud of probability de Broglie wave of nucleon during effective period of a laser.

The cloud expands with the group velocity, v_g, of tunneled nucleon. This expands during the laser pulse in an oscillating field. When the cloud of tunneled nuclei meets each other, they immediately make a compound nucleus, and make fusion reaction. This is induced during the laser pulse.

Electric field with laser and without laser in nuclei for a simple case is roughly indicated in Figure 1. At the center of nuclei, the nucleons are trapped in nuclear potential with de Broglie wave motion. This radius is about 5 fm and the nucleon hits the inner wall. In normal cases, penetrability has very small possibility, but EW laser makes it enlarger. In this case, the nucleon wave with exponential decay penetrates Coulomb barrier, and thereafter make

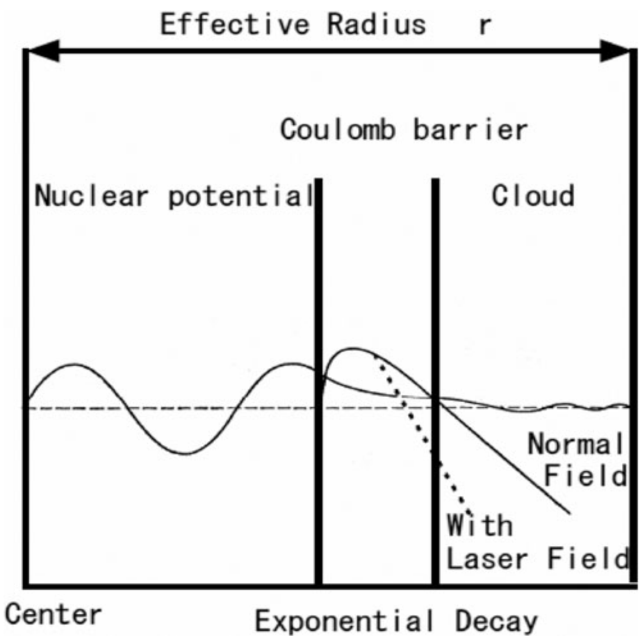

Fig. 1. Normal Coulomb barrier and laser effect around nuclear core.

a cloud of possibility outside the Coulomb barrier as shown in Figure 1.

Basic assumptions in this model are noted as follows: (1) Plasma is formed in a magnet field with density up to $10^{21}/\text{cm}^3$. Plasma density is uniform and charge is neutral. (2) Gaussian laser beam of 2 μm in diameter with annular shape for a long and tight focusing. (3) Nucleons are trapped in nuclear potential and hit the inner wall of coulomb burrier with nucleon kinetic energy of up to 100 eV. (4) After tunneling, nucleons diffuse away with de Broglie wave group velocity in the oscillating laser field. (5) After the laser pulse, reaction is stopped. This cloud may exist after the laser pulse, but such nuclei are diffused away so we limit the nuclear fusion reaction within laser pulse. (6) A compound nuclei is formed instantaneously when the cloud meets each other. (7) Wave length of Laser for this is 1.06 μm. Only the electric field is required. In this sense, the longer wave length is favorable, but the laser technology today for solid-state laser of 1 μm wavelength is well developed for laser fusion. So the solid-state laser is the first candidate for EW laser.

When intense laser of EW level is applied, the field of a dashed line is formed as shown in Figure 1. At the period of laser intensity peak, coulomb barrier is distorted. Such field can be calculated as follows. Here, A is the laser field of the applied laser, and can be written as,

$$A(V/m) = 2.7 \times 10^3 I^{1/2} (W/cm^2). \tag{1}$$

Here, I indicate the power density of the intense laser. With a simple model, the potential induced by the laser field can be written as $\varphi_L = -Er$, where the field can be simply given as $E = A\sin(\omega t)$. Then, we have the total laser potential as

$$\varphi_{total} = \frac{Z_1 e}{4\pi\varepsilon_0 r} + \varphi_L = \frac{Z_1 e}{4\pi\varepsilon_0 r} - A\sin(\omega t) r. \tag{2}$$

The first term is the coulomb field and the second term is the laser field. Let us consider two extreme cases for the Coulomb barrier. At the laser peak, we can derive the following two equations from Eq. (2). One is

$$U_1 = \left(\frac{Z_1 e}{4\pi\varepsilon_0 r} - Ar\right) Z_2 e. \tag{3}$$

And at the other is

$$U_2 = \left(\frac{Z_1 e}{4\pi\varepsilon_0 r} + Ar\right) Z_2 e. \tag{4}$$

In Eq. (3), one can decrease the barrier. Let us focus on U_1. Providing $Z_1 = Z_2 = 1$, we can calculate, and figure out U_1 in Figure 2.

We assume that the charge of nucleon is concentrated at the center to simplify the calculation, because the most important region for fusion reaction is the field between 100 fm to 1000 fm from the center. Under this assumption, Figure 2 indicates the calculated results of fields with and without laser. The field is distorted and makes effective tunneling and fusion reaction enhancement by the laser when laser intensity exceeds more than 10^{24} W/cm^2.

T, the penetrability, is calculated as follow assuming a simple uniform rectangular potential case (Balantekin & Takigawa, 1998). Then, the penetration rate for a simple

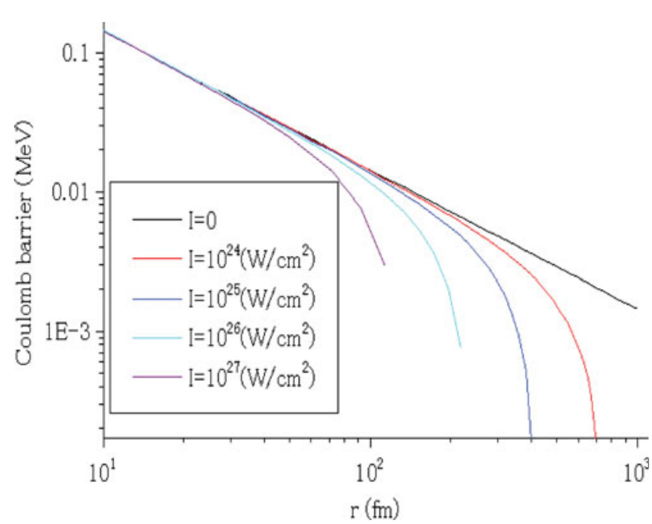

Fig. 2. (Color online) Calculated coulomb barrier with laser field of hydrogen nuclei.

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potential barrier is expressed as

$$T = \exp\left(-2\int_{R}^{R_1} \beta(x)dx\right), \quad (5)$$

where

$$\beta(x) = \left(\frac{2m}{\hbar^2}\right)^{1/2}[U_1(r) - E]. \quad (6)$$

Here $m = 938.28$ MeV/c^2 is for proton, and $\hbar = 6.58217 \times 10^{-16} \times 10^{-6}$ MeV $\times$ s. Finally, probability of the formation of cloud by tunneling can be written as $F = \Phi T$. Here Φ is a collision time of nucleon to inner wall of nuclear potential. Setting nuclear potential radius at 5 fm in the usual case, one can estimate Φ to be 100 to 1000 with nucleon velocity corresponding to 10 eV to 200 eV (Fig. 3). In an actual case, E in Eq. (6) corresponds to this relation of energy level and kinetic energy of nuclei, and should be determined by experiments. But for this simple calculation, we used parameters to evaluate as shown in Figure 3.

The region of F is much smaller than one, this is valid. But when F is approaching to one, saturation with depletion of nuclei and so on will be provoked. In this region, the penetrability Fs can be roughly written as

$$Fs = F/(F + 1).$$

For the calculation as shown in Figure 3, this effect is included.

For laser irradiation, nucleon energy cannot be fixed. This may be changed by the main pulse and pre-pulse of laser, so we give typical cases as shown in Figure 3.

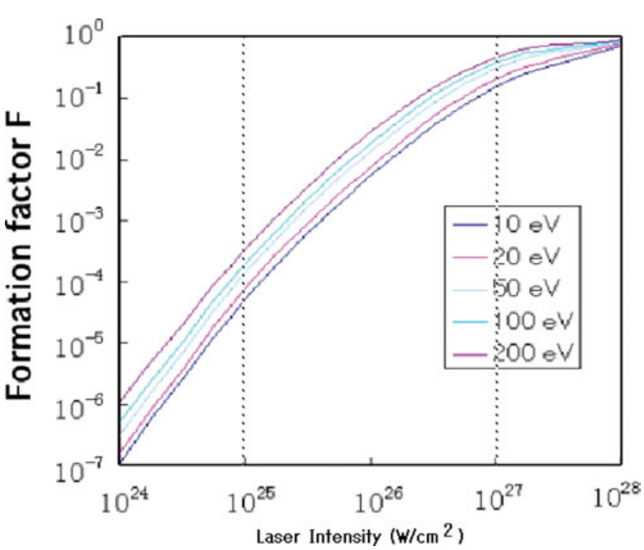

Fig. 3. (Color online) Laser intensity and calculated penetration rate T for F.

In a normal case without laser, this reaction rate in cm^3/s is as small as 10^{-20} for the Gamov peak of low temperature (Ichimaru, 1993).

There are clouds around the nuclei and they meet each other in some probability. Thereafter, they make compound nuclei immediately and fusion reaction is induced. The reaction rate R in this scheme is written as

$$R = F_1 F_2 \pi r^2 v.$$

In this relation, F_1 and F_2 are probabilities of laser tunneling nuclei for n_1 and $n_2 \cdot n_1$ and n_2 are number density of reacting plasma of two species like deuterium and tritium, respectively. Here, we introduce r, the radius of the cloud diffusion area of tunneled nucleon wave, estimated from effective period of laser pulse of 10 fs. This is given by the group velocity of tunneled nucleon wave and is estimated to be 10^7 cm/s. So r is 10^{-7} cm in our case. v is a relative velocity of nuclei each other by the thermal motion or differential accelerated particle velocity by laser. Here we use a typical velocity of 2×10^8 cm/s. In an actual case, we can control the particle relative velocity much higher than usual thermal velocity when we use a pre-pulse or double pulse of laser.

Then, fusion energy ε_f from this simple model is written

$$\boldsymbol{\varepsilon}_f = \varphi Q R n_1 n_2 V_0 \boldsymbol{\tau}_L.$$

Here, Q is the energy from one event of nuclear reaction, n_1 and n_2 are number density as is noted. V_0 is a volume of region in length l with radius rL of laser focusing area, and $\boldsymbol{\tau}_L$ is a time duration of laser pulse as 10 fm. φ is a burning rate of the fuel and can be written as $\varphi = 1/(1 + R\tau_L n)$ when $R\boldsymbol{\tau}_L n$ is much smaller than 1. Here, we take n lower than cut-off density to propagate the laser beam for several tens cm of focused region. So the density of plasma we choose is slightly lower than cut-off density, as shown in Table 1.

Then, a net gain of the energy G from fusion reaction for commercial reactor is

$$G = \eta_L \eta_c \boldsymbol{\varepsilon}_f / \boldsymbol{\varepsilon}_L.$$

$\boldsymbol{\varepsilon}_L$ is the laser energy in τ_L and can be written as $\boldsymbol{\varepsilon}_L = \pi \mathbf{r}_L^2 I$ $\tau_L \cdot \eta_c$ is efficiency of conversion from fusion energy to electric energy: η_L is efficiency of laser total system.

A typical fusion device in this schema is shown in Figure 4 (Imasaki & Li, 2007). Laser is one beam with annular shape of Gaussian mode to obtain a tight focusing. Outer radius of this beam is about 1 m. The energy from laser fusion is covered by graphite blanket and MHD electrode set at both ends of linear magnetic confinement machine. This magnetic field makes plasma to hold in a short period and make charged particles escape away from loss-cone for energy recover.

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Table 1. *Typical characteristics and parameters for this scheme*

	Characteristics	Remarks	Parameters
Laser	Solid state laser with 1.06 μm wave length	Gauss Beam	10 exa watt at peak power
τ_L	Laser pulse length	3 cycles	10 fs
Φ	A round time of nucleon in center nuclear potential	$\Phi = (2r_c/v_n)\tau_L$, which is given by nucleon kinetic energy as v_n the velocity of nucleon in nuclear potential of radius r_c	30 to 1000 in 1/4cycle
F	Tx Φ *T: penetrability*	$F = F_1 = F_2$ for each nuclei of fuel Deuterium and Tritium.	Break even system 0.5 Gain system 0.6
v	Relative velocity for nucleus each other	This is determined by the particle energy and controlled by the double pulsed laser or pre-pulse	Break even system 2×10^6 m/s Gain system 3×10^6 m/s
l	Length of laser characteristic focused area path.	Gauss beam propagation length at center region of 10 exa watt for area of 10^{-7} cm^2	Break even system 0.4 m Gain system 0.6 m
v_g	Group velocity of de Broglie wave after tunneling	Acceleration was not included	Break even system 2×10^5 m/s Gain system 3×10^5 m/s
φ	Burning rate	$\varphi = \mathbf{1/(1 + Rn\tau_L)}$ *when* $Rn\tau_L << 1$	0.9
V_0	Volume of fusion region	S $\times$ l S:10^{-7} cm^2, cross section of laser focused area with radius near diffraction limit	Break even system 4×10^{-6} cm^3 Gain system 6×10^{-6} cm^3
n	$n_1 = n_2$, $n_1 + n_2$ Plasma Density in cm^3	Lower than the cut-off density of solid state laser with 1.06 μm wavelength.	(1/2)10^{21}

This schema is also applicable to use fuel as B or Li. These reactions are neutron free and they are applicable for commercial case for further future. The energy from the fusion reaction is recovered in direct electric converter. Parameters are summarized in Table 2.

3. CONCLUSION

In this article, a feasibility of new approach of laser fusion of break-even and gain systems is addressed. Deuterium and tritium reaction is assumed to used but Li or B related reactions are expected in a same way

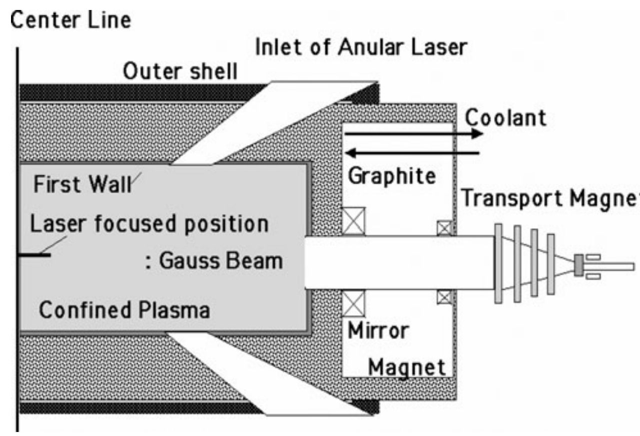

Fig. 4. Laser fusion devices with beam propagation in this schema.

Table 2. *Total system output for break-even and gain system*

	Laser peak power	Laser pulse duration	Laser total energy εL	Fuel	Output Energy εf
Break-even system	10 EW	10 fs	100 kJ	**D-T**	62 kJ
Gain system	20 EW	15 fs	300 kJ	**D-T**	670 kJ

for actual commercial reactor, however higher power is required. These reactions are neutron free and can be expected a very clean energy source. In addition, long sustainability for their rich abundance is expected. Stimulated Raman and Brillion scattering are not considered because the laser pulse is much shorter than the plasma wave frequency.

There are many issues to be solved as a relation of Coulomb burrier shape of three dimensions, saturation mechanisms, nucleon kinetic energy and so on. These are summarized as follows: (1) Saturation region on F; (2) Theory for heavy nuclei of α-decay with penetration is used for light nuclei tunneling; (3) Cloud behavior in a laser pulse and after; (4) Compound nucleus formation processes; (5) Laser efficiency and repetition; (6) Relative velocity of each particle. These items are under investigation.

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