A new approach of laser induced nuclear fusion in plasma by intense laser propagation

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Abstract. New approach of laser fusion in magnetic field with an intense laser of Exa watt level is discussed. Such strong field of EW laser will induce enhanced nuclear tunnelling through the propagation in plasma. This causes an enhanced nuclear reaction. We discuss the possibility to apply this to nuclear fusion energy and to obtain break even in 100kJ EW laser.

1. Introduction

Significant progress has been made to develop intense lasers for various applications. One outstanding example is inertial fusion energy by lasers. Today, Peta watt (PW) lasers are already in operation and Exa watt (EW) lasers are under consideration to install in Europe. When lasers with a total power of more than 10EW will be installed, a power density up to $10^{28}$ W/cm$^2$ will be available in future. Such strong field associated with such power density accelerates ions and electrons.

High-energy particles accelerated in the intense laser fields have been demonstrated with present day laser technology already and there are schemes under discussion to improve the effect even further [1]. Moreover, the possibility to generate a very intense laser field will facilitate unique new applications [2].

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

2. Basic concept

At first, intense laser with high dense target plasma is used. We can produce such plasma by Z pinch or the channel of injected clusters. In the latter case, we irradiate them by an appropriate first laser pulse before the main pulse and produce plasma. The shape of the preformed plasma is several tens cm in length with mm 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 10EW 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. This forms a cloud of probability de Broglie wave of nucleus during effective period of a laser.

The cloud expands with group velocity, $v_g$, of tunneled nucleon. This expands during the laser pulse in 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 Fig.1. At the centre of nuclei, the nucleons are trapped in nuclear potential with de Broglie wave motion. This radius is about 5fm and the nucleon hits the inner wall. In normal case, 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 a cloud of possibility outside the Coulomb barrier as shown in Fig.1. Basic assumptions in this model are noted as follows.

1. Plasma is formed in a magnet field with density up to $10^{21}$/cm$^3$. Plasma density is uniform and charge is neutral.
2. Gaussian laser beam of 1m 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 barrier with nucleon kinetic energy up to 100eV.
4. After tunnelling, 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. Wavelength of Laser for this is 1.06 $\mu$m. Only the electric field is required. In this sense the longer wavelength is favorable but the laser technology today for solid-state laser of 1 $\mu$m wavelength is well developed for laser fusion. So the solid-state laser is the first candidate for EW laser.

**3. Penetrability through Coulomb barrier**

When intense laser of EW level of a few cycles is applied, the field of a dashed line is formed as shown in Fig.1. At the period of laser intensity peak, coulomb barrier is distorted. In this case, field can be calculated as shown in Fig.2.

We assume the charge of nucleon is concentrated at the centre to simplify the calculation, because the most important region for fusion reaction is the field between 100fm to 1000fm from the centre. Under this assumption, figure 2 indicates the calculated results of field in various laser intensity. The field is distorted and makes effective tunnelling 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. Then, the penetration rate for a simple potential barrier is expressed as...
Fig.4 Reaction of clouds for compound nuclei
Vo is a volume of region in length l with radius r of laser focusing area, and \( \tau_L \) is a time duration of laser pulse as 10fm. \( \varphi \) is a burning rate of the fuel and can be written as \( \varphi = 1/(1 + R \tau_L n) \), when \( R \tau_L n \) is much smaller than unity. Here, we take \( n = n_1 + n_2 \) 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 Tab.2.

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

\[
G = \eta_L \eta_e \frac{\epsilon_f}{\epsilon_L}
\]

\( \epsilon_L \) is the laser energy in \( \tau_L \) and can be written as \( \epsilon_L = \pi \tau_L \omega_L^2 I \tau_L \). \( \eta_e \) is efficiency of conversion from fusion energy to electric energy. \( \eta_L \) is efficiency of laser total system. \( \eta_e \) is an efficiency of energy recover system of reactor. We take a product of \( \eta_L \eta_e \) 0.5.

Laser is one beam with annular shape of Gaussian mode to obtain a tight focusing. Outer radius of this beam is about 1m. The energy from laser fusion is covered by graphite blanket and MHD -cone for energy recover.

The final output by fusion reactions are summarized in Tab.1. We can expect break-even in 100kJ level of 10EW one beam laser and gain of 5 in 300kJ one beam laser.

| µm wavelength solid state laser | Laser Peak Power | Laser Pulse | Laser Total Energy \( \epsilon_L \) | Fuel | Output Energy \( \epsilon_f \) | G |
|-------------------------------|-----------------|-------------|-------------------------------|-----|--------------------------|---|
| Break-even system             | 10EW            | 10fs        | 100kJ                         | D-T | 112kJ                   | 0.6 |
| Gain system                   | 20EW            | 15fs        | 300kJ                         | D-T | 2870kJ                  | 5  |

5. Laser Damping

There is another effect of deceleration of accelerated nuclei by intense laser. Such rapid deceleration of nuclei provokes an enhancement of penetration in a lower power laser than EW. Our simple estimation shows an increment of penetrability around \( 10^{23} \text{Wcm}^{-2} \).

When we use Li or B for nuclear fusion reaction, these nuclei are excited by laser damping and are induced to enhance penetration for fusion gain.

6. Conclusion

In this article, a feasibility of new approach of laser fusion of break-even and gain systems is discussed. D-T reaction is assumed to use but Li or B related reactions are expected in a same way 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 Brillou 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.

Heaver nuclei fusion reactions such as p+Li or p+B fusion reaction is applicable. These items are under investigation.

Reference

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