New Laser Fusion without Implosion

K. Imasaki* and D. Li
Institute for Laser Technology, 2-6 Yamada-oka, Suita, Osaka, Japan

Abstract: Feasibility of new approach of laser fusion has been proposed and is discussed by an intense laser without implosion in plasma. The cross section of nuclear reaction is increased by the enhanced penetrability of nuclei through natural Coulomb barrier. In this approach, intense laser field more than 100 PW was required to distort the Coulomb barrier to obtain enough penetrability. Energy gain even with Deuterium-Deuterium reaction can be obtained using this scheme in Deuterium plasma. Reactor with neutron and direct conversion of charged particle beam individually is proposed. Charged particles from d-d reaction are guided at the end of reactor and directly converted by a MHD scheme into electric energy. The energy recover rate is so high and required smaller laser energy, which may make this energy cost cheaper than that of a fission reactor.

Key words: Laser fusion, nuclear reaction, nucleon, nuclear potential.

1. Introduction

Goal of fusion research is to get the clean and the sustainable energy besides an economical energy. When we compare with fission, we require with these items. Today, laser fusion has been developed precisely, and ignition of burning of D-T fuel may be expected in near future. But there are many issues for commercial reactors in ICF as the cost of complicated and precise pellet targets, irradiation uniformly, required high repetition rate of such large laser and so on. So it is hard to satisfy the economical condition even though we can achieve the ignition.

But from these points of view, a new laser fusion has been proposed. We have investigated a feasibility of the approach of laser driven nuclear reaction by intense laser field along this concept at laser peak [1]. We added and summarized an additional penetration around the laser peak and focusing point here. The intense laser field distorts the coulomb barrier, which enhances the tunneling. This forms the cloud by the tunneled nucleon and they react when they meet each other. This is a non-Gammon nuclear reaction. A more than 100 PW laser is required to distort the coulomb barrier to obtain enough penetrability for tunneling, however, the total energy of the laser and the cost of the energy by this way are significantly reduced. In this article, the model and gain for D-D reaction by this way are discussed.

A concept for thermonuclear fusion was firstly presented by Gamov and Teller [2]. After this research, investigations of thermonuclear fusion have been studied for a long time. A well-known reaction cross-section was obtained from LANL experiments and reaction rate was obtained from this as Maxwell distribution. Concerning the laser fusion, Nuckolls and Livermore scientists proposed an attractive way of compression by the implosion and since then the high performance lasers have been developed [3]. But an ignition is required in this case. We need the symmetry and the uniformity with high accuracy for irradiation besides a high power to ignite, these lead to an indirect target of which implosion efficiency is not good. So we need an enormous laser to ignite.

But for this purpose, intense laser technology is rapidly growing. Using such lasers we have proposed a feasibility of new approach of laser induced nuclear reaction using intense laser field. Such intense laser field distorts the coulomb barrier, which enhances the tunneling. This forms the cloud by the tunneled...
nucleon and they react when they meet each other. This is a non-Gamov nuclear and cross section is rather large, although more than 100PW laser was required to distort the coulomb barrier to obtain enough penetrability for tunneling [3].

In this way, ignition is not an essential point in usual ICF as a first point. So we may be free from several serious issues as symmetry and uniformity of lasers, though it is necessary to propagate in the uniform plasma for the intense laser below the critical density. A low price gas target and smaller energy laser is used, these lead to energy cost much lower than that of usual ICF. The high repetition of smaller laser is easier to get. This fact drastically reduces the laser energy cost to get an actual gain and shows an important characteristic of this way. The energy cost may be cheaper than that of the fission reactor in the real and future cases. Another point of this is the increment of fusion reaction rate due to the tunneling and cloud formation. The detail is discussed in section 5. We can expect a reactor using deuterium plasma.

In this article, modeling and assumptions for this scheme are discussed in section 2 and potentials of nucleus with laser field are estimated in section 3. Penetrability of nucleon through coulomb barrier and formation factor of nuclei with tunneled nucleon as a cloud are discussed in section 4. Energy gain by Deuterium-Deuterium reaction in plasma in this scheme is discussed in section 5 and section 6 is a brief note for this reactor in this way and summary and conclusion of the article are written in section 7.

2. Modeling

Thermonuclear fusion is induced but it is necessary to get a high temperature and large volume due to the very small cross-section of thermonuclear fusion as shown in Fig. 1. So the well-known reaction rate obtained with Maxwell distribution is small. This leads a fusion machine very large. In high energy region more than 1 MeV, cross section is almost the same as a geometric size of a core of nuclei and extension of cross section to lower energy region eventually small showed although penetrability of nuclei by the tunneling.

Low temperature plasma with a density slightly lower than the solid laser cut off is considered in this model. Around the center of nuclei, there is a well of nuclear potential with radius of 5 fm, which is shown in region a by a gray line in Fig. 2. But in actual case, there are mesons for nucleon, which are working as an attractive force. Due to mesons, the nuclear potential can be shifted as a black solid line in Fig. 2. This effect is included here in the simple calculation of penetrability.

![Fig. 1 A cross section of fusion for typical nuclei.](image1)

![Fig. 2 Typical potential of nucleus with intense laser.](image2)
Coulomb barrier is dominant in outer region and this is schematically shown as a region b in Fig. 2. In normal case without intense laser, the field is decayed away with \( D^2 \). Here, D is a distance from nuclear core center.

At the foot of Coulomb barrier with intense laser, laser field becomes dominant. This is shown as a region c. This shows a picture at peak laser field. In the laser-dominated region, field is oscillated with the laser field. The distribution of nucleon is along the Fermi-Dirac model shown in Fig. 2. Intense laser is focused and is injected into the plasma as a Gaussian beam. Then, this laser can propagate through the plasma. During this, intense field by the laser is applied along the center of laser path. This field distorts the Coulomb barrier in each peak of each laser cycle, which promotes the tunneling. The tunneled nucleon forms a cloud of probability of de Broglie wave of nucleon. The cloud expands with group velocity \( v_g \) of tunneled nucleon. This expansion is kept in oscillating laser field with the energy of Heisenberg uncertainty. Tunneled nucleons form cloud around nuclei. When the cloud of tunneled nuclei meets each other, they immediately make a compound nucleus and react as a usual nuclear reaction. This is taken place during the laser pulse.

After the laser pulse, the nuclei with the cloud are diffused away so the probability to meet each other becomes rapidly decreased and reactions are eventually reduced. Nucleon at high level potential can be survive in the Coulomb potential barrier and can penetrate through. Nucleon at low level potential decays away and is stopped to return back a core center. This process is repeated many times in laser power peak, most of the nuclei are tunneled through the procedure.

Basic assumptions in this model are noted as follows [4]:

1. Plasma is formed with density up to \( 10^{21}/\text{cm}^3 \), which is below the cut off density of 1 micron meter wavelength of solid state laser. For simplicity, we assumed plasma density uniform and charge neutral and non-linear interaction was not induced. There are several ways to make plasmas with sufficient relative velocity. For an example, after the injection of jet of fuel from opposite sides in the reactor center, it is irradiated by an appropriate laser pulse from each end before the main pulse. The plasma with a sufficient relative velocity is produced. The plasma shape may be several tens cm in length with several cm in radius. Such plasma is formed and accelerated by lasers or ion beams on actual application [5]. Laser irradiation makes a mm radius active area as shown in Fig. 3. Wavelength of the laser is 1.06 \( \mu \text{m} \). Laser technology today for solid-state wavelength is well developed for laser fusion. So the solid-state laser is the first candidate for this intense laser to EW output. Their efficiency and repetition rate are improved as a laser fusion driver gradually. An optimal wavelength for this scheme may be shorter wave as 2 or 3 omega and is discussed elsewhere.

2. In the first stage without the intense laser, nucleons are trapped in nuclear potential and hit the inner wall of Coulomb barrier in many times of laser

---

**Fig. 3** Model for nuclear reaction with a cloud around nuclear core.
power peak with nucleon kinetic energy up to a few kilo eV. The typical round time from the motion is estimated to be $10^{-20}$ to $10^{-21}$ sec so this is much shorter than the laser peak period. This is shown in Fig. 4 for normal nuclei. The usual thermonuclear fusion reaction is induced by nuclei with high velocity to run up the Coulomb potential barrier and meet the tunneling nucleon (dashed line) in the Coulomb potential barrier.

(3) One of main issues for penetrability is nucleon energy level. Nucleon distribution in the core is determined by the Fermi-Dirac model as shown in Fig. 1. The nucleon in Coulomb barrier is free from the nuclear potential so the energy level of nucleon can not be determined around the foot of barrier simply. In this article, energy level $E$ is assumed for typical level and is varied from +5 to 1 keV. We will discuss it in later section.

(4) A typical relation of laser waveform and its defined field peak are shown in Fig. 5. Around the laser peak per cycle, laser field distorts the nuclear Coulomb barrier to promote tunneling. So the summarization for tunneling is calculated including the laser field. Then such tunnelled nucleon forms a cloud around nuclei. So the cycle number corresponds with the formation factor of cloud. This is repeated every cycle in a laser pulse of more than a hundred fs.

(5) Gaussian laser beam of 2 m in diameter with annular shape for a long and tight focusing is applied. First sixth of laser pulse is rise time. Power crest is 2 thirds of laser pulse and it is an effective period of laser tunneling. After this, the laser pulse is decayed away with one sixths of the pulse. It is an enough time to tunnel out of the region $b$ of Fig. 2.

(6) Clouded nuclei are piled up through the laser pulse. Cloud life may be limited by a pion life span of 10 ns in free space, but it is also limited by the effective laser pulse due to the diffusion in the focusing area for the nuclear reactions. Then the nuclear reaction is decreased rapidly after the laser pulse, which may be shorter than the pion life span. So we set effective reaction duration laser pulse 8.

(7) In Fermi and Dirac model, temperature is high enough not to prohibit the reactions between nuclei. The distribution is shown in Fig. 6 in usual one.
New Laser Fusion without Implosion

3. Nuclei in Laser Field

3.1 Coulomb Barrier and Nuclear Potential

At the center of nuclei, there are mesons to combine nucleons as is well known. They reduce the Coulomb potential and make attractive force to the nucleons around the center. This force is estimated by nuclear potential as shown in Figs. 2 and 4. A simple Coulomb potential is shown as a dashed line that we used in a model in Fig. 4. Precise total nuclear potential is estimated by Yukawa model with appropriate mesons. The difference was recognized around the center at 5 to 10 fm when the model was set and a solid line shown in Fig. 4 was obtained. The initial value of barrier around the core is reduced significantly, which is effective for tunneling and this makes penetrability be enhanced.

3.2 Coulomb Barrier with Laser Field

The nucleon wave traveling through Coulomb barrier realizes an exponential decay, and finally it is reflected in most of cases. When intense laser is applied, the field in the foot of Coulomb barrier is distorted at the laser intensity peak. Then the possibility to penetrate the barrier gets increased.

A is field of applied laser and can be written as,

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

where $I$ indicates the power density of the laser. With a simple model, the potential induced by the laser field can be written as $\phi_L = -Er$, where the field can be given as $E = A \sin(\omega x)$. Then, we have the total nuclear potential with mesons, Coulomb barrier and laser as

$$\phi_{\text{total}} = Z_1 e \frac{1}{4\pi\epsilon_0 r} + \phi_L - V_0 e \frac{r}{r_0}$$

$$= Z_1 e \frac{1}{4\pi\epsilon_0 r} - A \sin(\omega x) r - V_0 e \frac{r}{r_0} \quad (2)$$

The first term is Coulomb field, the second term is laser field and the third term is nuclear potential with paions. Here we use Yukawa potential from paion and can be written using $V_0 = 109$ MeV, $r$ a distance in fm and $r_0 = 1.13$ fm in usual case.

Let us consider two extreme cases for this potential at the laser peak. We can derive following equations from Eq. (2).

One is

$$U_1 = \left( Z_1 e \frac{1}{4\pi\epsilon_0 r} - Ar \right) Z_2 e \left( r - V_0 \frac{r}{r_0} \right) \quad (3)$$

And the other is

$$U_2 = \left( Z_1 e \frac{1}{4\pi\epsilon_0 r} + Ar \right) Z_2 e \left( r - V_0 \frac{r}{r_0} \right) \quad (4)$$

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

Under this assumption, each line in Fig. 7 indicates
the calculated results of fields with various laser intensity peak on Eq. (3).

Fig. 7 indicates the detail of the barrier potential around grand level with various lasers. In actual case, tunneled nucleons are traveling through the barrier and come out to the free space, which make a cloud.

3.3 Penetrability and Formation Factor

The transmission rate $T$ is calculated as follows using a potential of nuclei discussed in Section 3.2. Then transmission rate of the nucleon passing through the barrier is expressed as

$$T = \exp(-\int_{x_1}^{x_2} \beta(x) \, dx)$$

where

$$\beta(x) = \left(\frac{2m}{\hbar^2}\right)^{\frac{1}{2}} \left[U(x) - E\right]^{\frac{1}{2}}$$

Here $m = 938.28$ MeV/$c^2$ is for proton, and $\hbar = 6.58217 \times 10^{-6}$ MeV·S. A simple transmission rate $T$ is modified and penetrability, $P$ is defined as

$$P = \frac{fT}{\int f \, dx}$$

where $f$ is a collision time of the nucleon with inner wall produced by nuclear potential and Coulomb barrier. Setting nuclear potential radius 5 fm in usual case, one can estimate $f$ to be more than 10,000 through nucleon kinetic energy corresponding to 1 MeV during the laser peak. In actual case, $E$ in Eq. (6) corresponds to this relation of energy level of the nucleon. It should be determined by experiments, but for this simple calculation in this paper, we use parameters 0 eV to 10 keV. Then, the penetrability is calculated as shown in Fig. 8 from the Eqs. (5)-(7) with various parameters.

Comparing with quantum well model, significant enhancement was observed in the region of laser power.

![Fig. 7](image1.png)  
**Fig. 7** Nuclear potential and Coulomb barrier with various intensity of laser powers are varied from $10^{28}$ w/cm$^2$ to $10^{24}$ w/cm$^2$.

![Fig. 8](image2.png)  
**Fig. 8** Penetrability with Laser peak power.
around $10^{24}$ to $10^{26}$ W/cm$^2$. This is due to nuclear potential effect around the center. A typical estimated to be 0.01 to 0.1 fs. So penetrability obtained in Eq. (5) is valid in our case during the laser peak.

Here we define $F$ as a formation factor of cloud of tunneled nucleon after penetration. Probability of the formation of cloud can be written as

$$F = P \cdot N_c$$

Here $N_c$ is a cycle number of laser pulse crest, which can be taken as 200 to 2,000 in this case. When $F$ is approaching to one, the saturation with depletion of nuclei and so on will be taken place. On the calculation result of Fig. 9, this effect is included. In this region, the $F_s$ for saturation level can be roughly written using $F$ as,

$$F_s = \frac{F}{F + 1}$$  \hspace{1cm} (8)

Typical results of Eq. 8 are shown in Fig. 9. Here, two cases of cycle number for 200 in 900 fs pulse length and 20,000 in 10ps of pulse length as a various pulse cases are shown.

4. Nuclear Reaction Rate

When clouds meet each other, nuclear reactions are taken place. From this model reaction rate is estimated and is shown in Fig. 10. A radius of cloud is calculated as

$$r = V_\xi <t>$$  \hspace{1cm} (9)

where $V_\xi$ is the group velocity of de Broglie wave of nucleon and $<t>$ is a average time of cloud holding in the reacting area. In the unit period of $t$, each nucleus has a relative velocity of $V_r$ with cloud density of $n_c$. We introduce $r$, a radius of the cloud diffusion area of tunneled nucleon wave during the laser pulse of 1 ps to 100 ps. Thereafter, the reaction rate is written as:

$$R_r = F_1 F_2 \pi r^2 V_r$$  \hspace{1cm} (10)

In this equation, $F_1$ and $F_2$ are formation factors of laser tunneling nuclei for $n_1$ and $n_2$ of two species. $n_1$ and $n_2$ are number density of reacting plasma.

In the unit period of $t$, each nucleus has a relative velocity of $V_r$ with cloud density of $n_c$. This is given by the group velocity of tunneled nucleon wave and is estimated to be $10^6$ cm/s. So $r$ is $10^{-6}$ cm in our case, $\nu$ is a relative velocity of nuclei each other by the thermal motion or differential accelerated particle velocity by laser. We use a typical velocity of $2 \times 10^6$ cm/s.

Then reaction rate can be calculated for a density of plasma using parameters of relative velocity as shown in Fig. 10. Here, we can use a usual reaction model between the molecules shown in Fig. 11. $R_{eff}$ is effective radiuses. Gaussian intense laser with tightly focusing is injected into such plasma. Fig. 12 shows a contour of laser intensity in such plasma.

![Fig. 9](image-url)  \hspace{1cm} Formation factors of cloud for long pulse cases.
5. Energy Gain by the Reactions

This model is applied for D-D plasma. The energy from nuclear reaction is produced as $E_f$ from this simple model and can be written as

$$E_f = BQ R r n_1 n_2 Vol t_L$$  \hspace{1cm} (11)

where $Q$ is energy from one event of nuclear reaction, $n_1$ and $n_2$ are number density as noted. $Vol$ is a volume of region in length $l$ with radius $r_L$ of laser focusing area, and $t_L$ is a duration of laser pulse.

This is a kind of inertial confinement fusion. $B$ is a burning rate of the fuel. During the active reaction time, the density of fuel is varied as $dn/dt = R n_0^2$, and this can be written as $1/n - 1/n_0 = R t_0$. Here $t_0$ is a characteristic time and is written as $t_0 = r_L/v_{pe}$. $v_{pe}$ is a perpendicular component of plasma particles velocity in a focused area. In this case, burning rate $B$ is determined as $B = (n_0 - n)/n_0$. Then, $B$ is rewritten as $B = R t_0 / (R t_0 + 1)$, where $t_0$ is a confinement time of particles with cloud in plasma. This equation indicates the burning rate and come to almost 1 by a simple estimation because reaction rate is very large and thermal velocity is very small. Then, a gain of the energy $G$ from the reactions is determined by

$$G = E_f / E_L$$ \hspace{1cm} (12)

where $E_L$ is the laser energy in $t_L$ of one pulse and can be written as $E_L = \pi r_L^2 I t_L$. When $G$ is equal to 1.0, it is called break-even. In optimistic case, we can expect break-even around 100 kJ laser and can obtain gain 10 around several 100 kJ although very high laser intensity with 10 ps pulse is required. When we use deuterium-deuterium reaction as a gain medium, hydrogen production by high temperature is possible in the reactor by this scheme [6].

6. Conceptual Reactor

6.1 Conceptual Reactor Configuration

The essential point of this article is to get efficient...
New Laser Fusion without Implosion

and economical energy with D-D reaction. For this purpose, we need an efficient reactor. Here we introduce a reactor to recover charged particles and neutrons produced by D-D reaction. Especially charged particle energy recovery is important for D-D reaction. So from the point of this view, the reactor for new laser fusion has a magnetic field to separate neutron and charged particles to have a high efficiency. In this reactor, we use a direct energy conversion of charged particles. High conversion efficiency with efficient laser makes engineering breakeven with low gain in the range of 10.

Here, we can assume the same burning rate of D-D fusion as

\[ \text{D-D} \rightarrow n + ^3\text{He} \text{ and } P + T \]

Then, (3/8) of total energy becomes from neutron and (5/8) of total energy becomes from charged particle. We therefore divide the energy into two classifications. One is neutron and other is charged particle beam. So, the gain of each is given as follows.

In normal reactor case, neutron conversion efficiency is around 30% and charged particle conversion efficiency is 80%. The total efficiency to the electricity in this case is as high as 50%. Direct conversion make efficiency high such level. Schematic energy flow of this reactor with typical parameters is listed in Table 1. Blanket gain is an option in actual case. The fuel in the case is deuteron so charged particle plays an important role. When a larger blanket gain can be expected more than 2, blanket material and gain is important [8].

This reactor configuration has similarities of mirror machine for magnetic confinement. Charged particles generated in the target as plasma are trapped in the magnetic field. They come out gradually through the end loss. A characteristic time is to be few tens microsecond although the burning time of high dense laser fusion target is much less than nano-second. A Lamoure radius of energetic ions in magnetic field is set less than one tenth of radius of the mirror machine devises of this reactor, where the plasma is confined.

Instabilities in this system should be considerable but the efficiency for final conversion is not affected so strongly. Very low dense plasma is confined easily in micro-second period because the density of the plasma is less than \(10^{10} \text{/cm}^3\) when the target plasma is expanded and comes to be uniform in this mirror magnetic field [4].

In this reactor, the charged particles are trapped by the magnetic field and are guided their direction along the field. This causes the reduction of stress in the wall and blanket but the magnet coil obtains this. But direct stress is reduced in strength and time significantly.

A new laser is started to develop. This shows a high laser gain, feasibility of large size scalability and high thermal conductivity. Still the laser experiments are just started, however this material shows several favorable features [6]. Fig. 14 shows a schematic picture of this conceptual reactor. Energies from neutron and charged particles are mainly produced at the center of this reactor by a D-D reaction and following burning processes in the reactor. Most of the charged particle energy and few of the neutron energy are deposited in the plasma during inertial time. Neutron and charged particle are separated by the magnetic field and deposit their energy in a blanket or direct converter, respectively. Several ways of direct conversion were investigated. [5] An efficiency of direct conversion has been 70% to 90%.

Recent laser technology allows us to take a total efficiency of laser system from 30% to 40% including electric power source. Such efficient laser and direct conversion induce a engineering break-even with low gain of target of 20 to 30 in this case.

A large part of the charged particles generated by the fusion reaction collide in the center plasma and deposits their energy. This makes plasma and plasma expands to the volume of the confinement region of 10 m³, although the target volume is 1mm³. In this case, the expansion is occurred to be \(10^{10}\) times, besides the time expansion of sub-ns burning time expands to
Table 1  Parameters for gain in Deuteron reactor.

<table>
<thead>
<tr>
<th>Parameters for gain in Deuteron reactor.</th>
<th>Issues</th>
</tr>
</thead>
</table>
| Fuel for reaction D - D \[
\frac{n + 3\text{He}}{P + T} = 1/1
\] | Two plasma groups with Laser accelerated or plasma jet etc. |
| Relative velocity of plasma particles \(10^7\) to \(10^9\) m/sec | Slightly lower than the cut off density of the laser |
| Density \(10^{21}/\text{cm}^3\) | de Broglie wave group velocity |
| \(V_g\) \(10^{17}\) to \(10^{20}\) cm/sec | \(F = 0.3\) |
| Laser intensity \(10^{24.5}\) W/cm² | - |
| \(<\tau> = \) laser pulse length or averaging duration of clouded | to 100 ps |
| Nucleon Energy level around barrier foot \(+ 1\) keV to \(- 5\) keV | Diffraction Limit |

**Fig. 13**  Schematic energy flow of the reactor with typical parameters.

**Fig. 14**  Illustration of the reactor with mirror magnetic field and graphite solid blanket.

Microsecond confinement time with the end loss. So the particle in the end loss can be separated as a charged particle easily and converted into electric power directly.

Neutron is scattered in the blanket as a friction but this amount is 3/8 of total energy. Their most of the
energy is deposited in the blanket of coolant and graphite or carbon compound. Combination of mirror machine and graphite blanket is expected to withstand the temperature more than 800 K. Neutron to thermal energy conversion is the most important issue in this design. The detail simulation by neutron scattering is on the way. The rough estimation for a temperature of 800K is assumed to get an efficient production. The temperature of blanket sets production efficiency about 50% by a simple model of Carnot’s cycle.

Blanket gain is optional with a hybrid fission blanket. Here we consider this reactor with solid-state blanket of graphite for neutron energy capture. We can sustain the temperature high with enough safety. For graphite blanket, the temperature can be reached more than 1000 K or more.

The first wall may be stainless steel. It is easy to replace economically per several years. After the replace, it is kept away for a long time to repose geologically. The structure material is SiC and graphite. The low Z with a simple structure makes low activation and can be replaced at appropriate time under regular investigation as fission reactor [6]. We can use it for life span of the reactor. The advantage of graphite blanket is to exhibit low activation and, in the case of the accident, released radioactivity is greatly reduced. The graphite may moderate the neutrons below activation energy levels. Outer shell is concrete to withstand the high temperature and stress. This is covered and is supported by the reinforced concrete vessel. This also plays a role for neutron shielding.

6.2 Reactor Parameters

Reactor parameters are listed in Table 1. The inner radius, which is the same as first wall radius, the neutron density on the first wall should be chosen with 10 to 30 MW/m² for usual cases. But the neutron density exceeded in our case at the center part. We can replace the wall frequently here. The length is determined from mirror magnet field. The mirror ratio of 10 is taken for a confinement of plasma and to obtain a conversion to electricity for a breakeven. From conservative parameters, the length of 8 m is given. The blanket thickness for neutron energy deposition is calculated using Monte Carlo code of MCNP5.

Direct plasma energy converter is set both sides of the reactor as a MHD energy converter. There are several methods for this. Here, we use a very simple and primitive one. The escaped plasma from the mirror end goes into the transport section of the length of several meters, in which plasma is transported and is focused to the end. Their motion is guided and is along the magnetic field. Finally the charged particles convert their most of kinetic energy into a electric energy through this way.

A coolant candidate that we are expecting to use is SiC. It is injected at 500 K from the outer layer and is heated gradually during the passage of each layer. Finally the temperature is 1,000 K at the first layer just before the first wall. [6, 7] We add a simple mirror magnetic field to this reactor. This avoids a direct bombardment of charged particles on the first wall. As well known, mirror machine is a kind of amplifier that the possibility of amplification scheme in plasma is investigated. Here, we point out a possibility of amplification that a denser plasma with smaller mirror field. A Gain curve in the scheme is shown in Fig. 15. This may be balance the commercial reactor and the energy cost may be cheaper than that of the fission reactor in the real and future cases.

![Gain curve of the reactor](image)
7. Conclusions

In this article, a feasibility of new approach of laser fusion for break-even or above by Deuterium plasma is discussed. We find out that the nuclear potential including mesons at the nuclear center played an important role for tunneling of Coulomb potential of outer foot of Coulomb barrier, which has not been expected. The penetrability is significantly enhanced. We obtained a significant gain on this scheme and based on this we designed a primitive reactor.

This is a new concept so there are many issues to be solved as an optimal wave length, relation of Coulomb burrier and energy level of three dimensions, nucleon kinetic energy and so on. Adding these items, these are issues for:

1) Saturation region on formation factor F;
2) Cloud behavior and life span;
3) Group velocity of nucleon and relative velocity of nucleon after tunneling;
4) Self-consistent field of Coulomb barrier region during the tunneling;
5) First wall structure to replace per several months.

Comments and your suggestion are very welcome.

It is obvious that we needs $10^{24.5}$ w/cm$^2$ but we need 200 kJ without uniformity and precious target. We only focus the laser beam tightly. There is a great advantage that we do not ignite the fuel. This may be proven in near future experiments.

Acknowledgments

The authors sincerely thank Prof. C. Yamanaka for his helpful suggestion and comments on this model and reactor.

References