Efficient Energy Conversion of the 14MeV Neutrons in DT Inertial Confinement Fusion

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Abstract

In DT fusion 80% of the energy released goes into 14MeV neutrons, and only the remaining 20% into charged particles. Unlike the charged particles, the uncharged neutrons cannot be confined by a magnetic field, and for this reason cannot be used for a direct conversion into electric energy. Instead, the neutrons have to be slowed down in some medium, heating this medium to a temperature of less than 10^3K, with the heat removed fom this medium to drive a turbo-generator. This conversion of nuclear into electric energy has a Carnot efficiency of about 30%. For the 80% of the energy released into neutrons, the efficiency is therefore no more than 24%. While this low conversion efficiency cannot be overcome in magnetic confinement concepts, it can be overcome in inertial confinement concepts, by surrounding the inertial confinement fusion target with a sufficiently thick layer of liquid hydrogen and a thin outer layer of boron, to create a hot plasma fire ball. The hydrogen layer must be chosen just thick and dense enough to be heated by the neutrons to 100,000K. The thusly generated, fully ionized, and rapidly expanding fire ball can drive a pulsed magnetohydrodynamic generator at an almost 100% Carnot efficiency, or possibly be used to generate hydrocarbons.

1. Introduction

In the LIFE [1] laser fusion concept of the Lawrence Livermore National Laboratory, the gain of the deuterium-tritium (DT) target must be kept low to protect the laser from being "toasted" by the photon flash of the DT micro-explosion. To make up for the low gain, it is there proposed to use the neutrons of the DT fusion reaction to make fission reactions in a blanket of burnt up fuel elements from nuclear fission reactors. This concept substantially increases the total gain, but it suffers from the same meltdown problem of conventional fission reactors.

The idea to use the 80% of the neutron energy released in the DT fusion reaction for nuclear micro-bomb rocket propulsion, by surrounding the micro-explosion with a thick layer of liquid hydrogen heated up to 10^5 K thereby becoming part of the exhaust, was first proposed by the author in 1971 [2]. Unlike the Orion pusher plate concept, the fire ball of the fully ionized hydrogen plasma would there be reflected by a magnetic mirror.

A later detailed study made by Logan in 1993 [3], also suggested to use the heat generated by the absorption of the 14 MeV neutrons in a blanket, but for a temperature 10 times less, or about 10,000 K. The much lower temperature results there from the addition of high Z-materials to the blanket, but also from the geometry. At a temperature of 10^5 K the blackbody radiation losses would become exorbitant. But even at a temperature of 10^4 K, the blackbody radiation losses are quite large. This is the kind of energy which cannot be magnetohydrodynamically converted with high efficiency into electric power. By comparison, the hydrogen at a temperature of 10^5 K is fully ionized and optically transparent, and therefore does not lose much energy by radiation, promising a conversion efficiency close to 100%.

The stopping length of the neutrons is determined by the material and the density of this material, but the mass of the material stopping the neutrons is determined by its geometric arrangement. With the thermonuclear energy released by the almost point-like source of a thermonuclear micro-explosion, the smallest mass is realized only if the micro-explosion occurs in the center of a neutron-stopping sphere, and to reach the highest possible temperature a sphere must be of liquid hydrogen, or even better pre-compressed liquid hydrogen. Pre-compression can be achieved by surrounding the liquid hydrogen sphere with a layer of high explosive, simultaneously ignited on its outer surface. Under a ten-fold compression, the radius of the hydrogen sphere would be reduced by the factor $10^{1/3}$ ~2.15, with the amount of hydrogen reduced ten-fold.

Along the line of this older idea, it is here proposed (see Fig. 1) to surround an inertial confinement fusion target with a thick spherical blanket of liquid hydrogen, transformed by the absorption of the 14MeV neutrons into a fully ionized plasma at a temperature of 10^5 K. This arrangement permits large gains of the DT micro-explosion, not possible in the LIFE concept, because the hydrogen blanket protects the laser from being "toasted." Following the ignition and burn of the DT target, this blanket is, by the neutrons absorbed in it, converted into an expanding hot plasma fire ball, which can drive a MHD Faraday generator or possibly be used to produce hydrocarbons.

For this concept to work, the blanket must be thick enough to slow down and stop the neutrons, but it should not be larger than is required to keep its temperature at about 10^5 K.

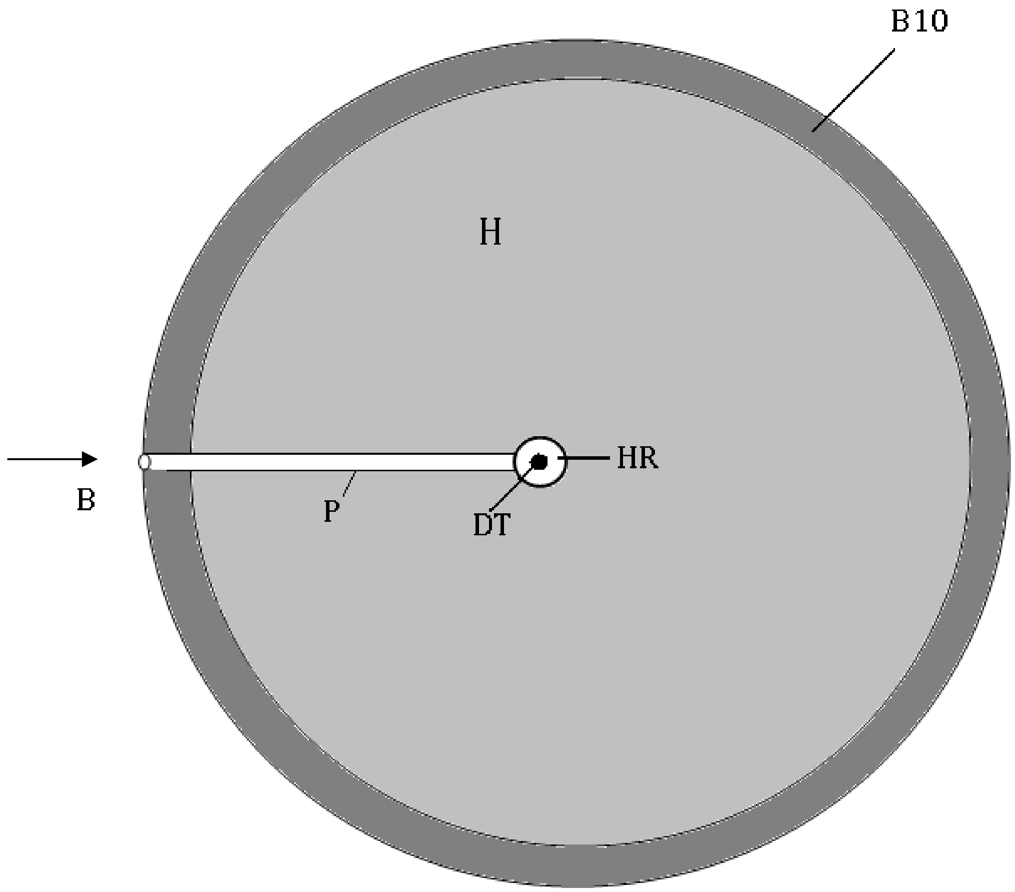

Figure 1

DT deuterium-tritium fusion target placed inside a hohlraum HR; B laser or particle beam to ignite DT target, with B projected through a thin pipe P. H liquid hydrogen, B10 solid boron shell of B10.

2. The Neutron Physics of the Proposed Scheme

As in fission reactors, the neutron physics is determined by the slowing down and diffusion of the neutrons in the blanket. Assuming that radius of the DT target is small compared to the outer radius of the neutron-absorbing blanket, one can approximate the neutron source of the burning DT target as a point source.

We use the Fermi age theory [4] for the slowing down of the neutrons from their initial energy E_o to their final energy E. The neutron-slowing down is determined by the Fermi age equation:

$$\frac{\partial q}{\partial \tau} = \nabla^2 q \tag{1}$$

where the "age" τ is given by:

$$\tau(E) = \int_E^{E_0} \frac{D}{\xi \Sigma_s E} dE \tag{2}$$

D is the neutron diffusion constant,

$$D = \frac{1}{3\Sigma_s (1-\mu_0)} \tag{3}$$

with Σ_s the macroscopic scattering cross section, $\Sigma_s = n\sigma_S$, where n is the particle number density in the blanket, and σ_s is the scattering cross section. Furthermore,

$$\mu_0 = \frac{2}{3A} \tag{4}$$

is a scattering coefficient for a substance of atomic weight A. For hydrogen, one has A = 1 and hence $\mu_o = 2/3$, making $D = 1/\Sigma_S$. The logarithmic energy decrement of the neutron deceleration is given by:

$$\xi = 1 + \frac{(A-1)^2}{2A} \ln \frac{A-1}{A+1} \tag{5}$$

For A = 1, one has $\xi = 1$.

Setting $E_0 = 14\text{MeV}$, $E = 10\text{eV}$ (10^5K), and using the neutron physics data of the Brookhaven National Laboratory [5], one finds that $\tau \cong 6 \times 10^2\ \text{cm}^2$. This implies a slowing down length of the order $\sqrt{\tau} \cong 20$ cm. For water, one has, by comparison for the E_0=2MeV fission energy, neutrons slowed down to the thermal energy $E = 2 \times 10^{-2}$eV, $\tau = 33\text{cm}^2$, and $\sqrt{\tau} = 5.7$cm. However, for the production of a 10^5K fire ball, water is unsuitable because at these temperatures most of the energy goes into blackbody radiation. For this reason alone, hydrogen is to be preferred.

The expression for τ given by (2) ignores neutron absorption during the slowing down process. If taken into account, one has to multiply $\tau(E)$ with the resonance escape probability p(E) given by

$$p(E) = \exp\left(-\frac{1}{\xi} \int_E^{E_o} \frac{\Sigma_a}{\Sigma_a + \Sigma_s} . \frac{dE}{E} \right) \tag{6}$$

where $\Sigma_a = n_a \sigma_a$ is the macroscopic absorption cross-section, with n_a as the particle number density of the neutron absorbing substance, and σ_a is the microscopic absorption cross-section. For graphite-moderated reactors $p \approx 0.5$. For large σ_a and even if $n_a << n$, p(E) can substantially reduce τ and hence the stopping length.

Another important number is the slowing down time for the neutrons, given by

$$t_0 = \frac{\sqrt{2M}}{\xi \Sigma_s} \left(\frac{1}{\sqrt{E_{th}}} - \frac{1}{\sqrt{E_0}} \right) \tag{7}$$

where M is the neutron mass.

For liquid hydrogen $t_0 \approx 10^{-5}$ sec. This time is much longer than the time of the DT micro-explosion, but it must be about equal to the inertial expansion time of the fire ball with an initial radius R. For an expanding plasma fire ball of initial radius R and expansion velocity v,

$$t_0 \cong \frac{R}{V} \tag{8}$$

At a temperature of 10^5K, the expansion velocity is $V \approx 30$ km/s and setting $R \cong \sqrt{\tau} = 20\,\text{cm}$, one has $t_o \cong 10^{-5}$ sec. For liquid hydrogen where $n = 5 \times 10^{22}\ \text{cm}^{-3}$, the total number of hydrogen atoms in a spherical volume with a radius of 20 cm, is of the order $N = 2 \times 10^{27}$. Heated to a temperature of $T = 10^5$ K, the thermal energy of the fire ball is of the order $E \cong NkT \approx 3 \times 10^{16}$

erg = 1 ton of TNT. For a DT target requiring an ignition energy of 1-10MJ, this is a gain of the order 300, impossible with the LIFE concept.

A fireball that large and containing an energy of that magnitude can drive a pulsed MHD generator by pushing aside a magnetic field of the order $B \approx 10^4$G. This field strength is attainable with iron magnets, with the field filling a cavity having a radius of the order of 20m [6].

Another interesting possibility is the conversion into chemical energy, by letting the expanding fireball hit a mixture of coal dust and liquid hydrogen or liquefied methane There, under the high pressure of the resulting shockwave, the coal and hydrogen are transformed into hydrocarbons, needed for internal combustion engines.

3. Spatial Distribution of the Decelerated Neutrons

Making the point-source approximation for the neutrons released from the DT fusion micro-explosion, their spatial distribution by the Fermi age equation is

$$q(r,t) = \frac{e^{-r^2/4\tau}}{(4\pi\tau)^{\frac{3}{2}}} \tag{9}$$

The slowing down of the neutrons is followed by their diffusion which is ruled by the diffusion equation in spherical coordinates

$$D\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\phi}{\partial r}\right) - \Sigma_a\,\phi + S = \frac{\partial n}{\partial t} \tag{10}$$

where ϕ is the neutron flux, $\Sigma_a = n\sigma_a$, with σ_a the neutron absorption cross-section. S is the neutron source given by pq.

Surrounding the hydrogen by boron, the diffusion equation must be solved with the boundary condition for the neutron flux in the hydrogen A, and boron B

$$\left.\begin{aligned} \phi_A &= \phi_B \\ D_A\frac{d\phi_A}{dr} &= D_B\frac{d\phi_B}{dr} \end{aligned}\right\} \tag{11}$$

Because of the very large neutron absorption cross section for thermal (or epithermal) neutrons, only a comparatively thin layer of boron is needed. The 3MeV of energy released in charged particles by the neutron absorption of neutrons in boron, can be simply added to the 14MeV of the neutron energy of the DT reaction.

Appendix

The most interesting aspect of the proposed inertial confinement fusion concept, where the 14MeV neutrons are used to generate a dense high temperature hydrogen plasma, is for the production of liquid hydrocarbons. In the Bergius high pressure coal liquefaction technique, hydrocarbons are produced (with an iron catalyst) by bringing together coal dust with hydrogen at a temperature of 500°C and a pressure of 200-300 atmospheres. The generation of the high temperature and pressure are there obtained by an exothermic reaction of burning coal, which is also used for the generation of hydrogen from water, while in the proposed DT fusion concept the high temperature and pressure can be provided by the energy released in the DT fusion reaction. To test the feasibility of this idea does not require the ignition of a DT micro-explosion, because it can be simulated by heating a small amount of liquid hydrogen to a temperature of 10^5K. This can be done by a variety of ways like by a pulsed laser or an intense relativistic electron beam, or by electric pulse power driven thin wire explosions. The generation of hydrocarbons can then be studied by placing some coal dust mixed with liquid hydrogen side by side to the rapidly expanding hydrogen plasma fire ball.

Fig. 2 shows two ways how this could be done. In Fig. 2a, a small sphere of liquid hydrogen is placed into one focus of an ellipsoidal cavity, with a larger sphere of coal dust mixed with liquid hydrogen placed in the other focus. Bombarding the liquid hydrogen with a pulsed laser or particle beam a small 10^5K fire ball is created in the one focus, which is rapidly expanding inside the cavity with the energy of the fire ball focused onto the coal dust mixed with liquid hydrogen placed in the other focus, where it shock-heats and compresses the hydrogen with the carbon. In Fig. 2b, an exploding wire is simply surrounded by a mixture of coal dust and liquid hydrogen. This second arrangement should be quite inexpensive to demonstrate the feasibility of the concept.

These proposed experiments could also be used to determine how to maximize the yield for the production of liquid hydrocarbons.

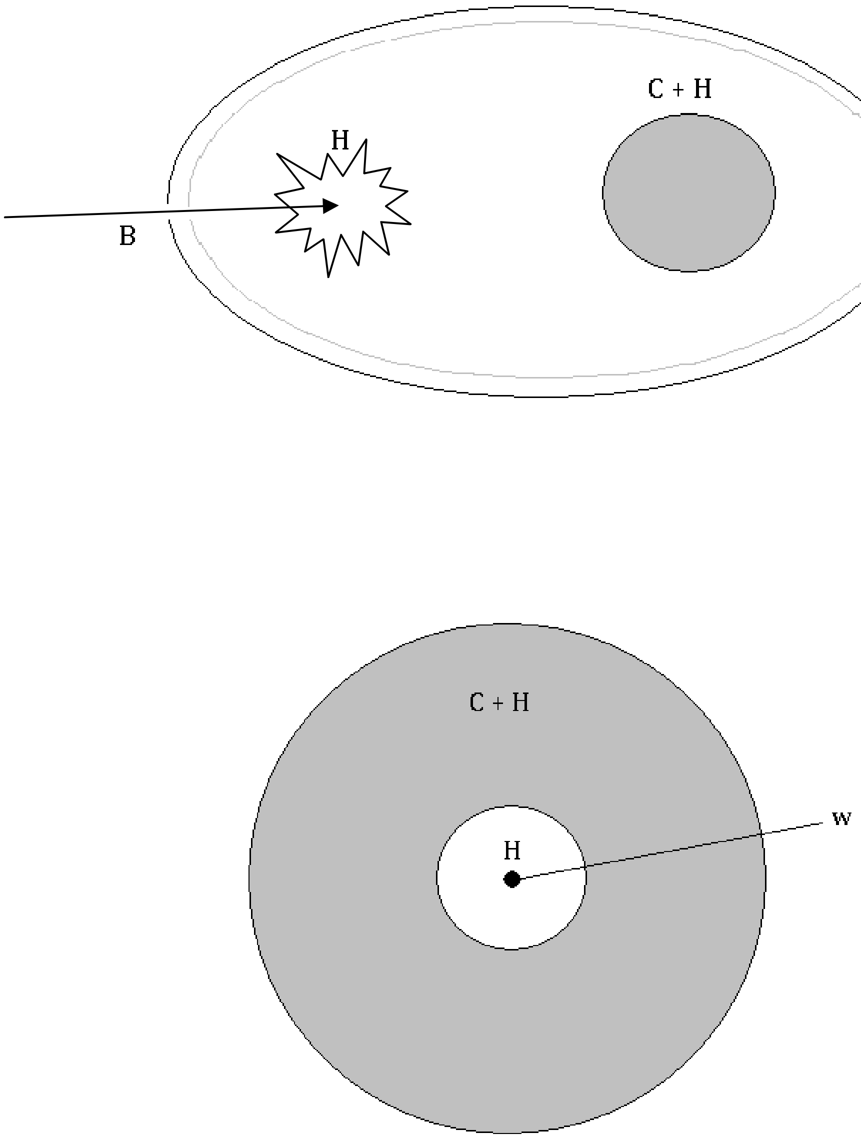

Figure 2a and 2b

The generation of hydrocarbons from a hot 10^5K hydrogen plasma made by rapidly heating liquid hydrogen, impinging a mixture of coal dust and liquid hydrogen. H hydrogen, C + H coal dust with hydrogen, B laser or particle beam, w thin wire.

References

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