Resonance at Hydrogen-Boron(11) Fusion Applied for High Density Laser Driven Volume Ignition

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Abstract: An anomalously strong increase of gains for laser driven compression and ignition of hydrogen-boron11 fusion has been determined from computations if the latest results by Newins and Swain (Nuclear Fusion 40 (2000) 865) about details of a resonance maximum of the fusion cross sections at 148 keV are used. For usual parameters, computations based on volume ignition show minor improvements of the fusion gains on usual level which were well of interest. However, for a very narrow range of parameters, the increase of the gain was found to be higher by more than a factor 6. This is very unusual in all similar computations. On top, this anomalous range is in the practically very interesting range for incorporation of laser pulse energies in the 2 to 4 MJ range, and the gains close to 10 may be of interest for power generation in further future by the high density fusion scheme.

1) Introduction

The main stream of controlled generation of nuclear fusion energy by inertial confinement is following the spherical laser compression of deuterium-tritium (DT) to more than thousand times the solid state density with subsequent thermal ignition. This is close to produce the very first controlled exothermal reaction using the largest laser on earth, the National Ignition Facility NIF [1]. After the laser has been commissioned, systematic measurements of plasma parameters for plasma compression is on the way [2]. The use of other fusion fuel than DT has been discussed before, especially the use of the reaction of light hydrogen H with the boron isotope ^{11}B (H-^{11}B) [3,4] where no neutrons are generated and the emitted radioactivity per gained energy is smaller than from burning coal [5], therefore negligible. The H-^{11}B fusion reaction is very much more difficult than for DT [4] if one uses the spherical compression and thermal ignition as in the case of NIF [1].

For completion of information an alternative way was opened recently in contrast to the compression and thermodynamic ignition – after some initial indications [6] - where instead of the thermodynamic processes the laser energy is converted directly into the motion of plasma blocks by nonlinear forces [7,8]. This interaction process without heating was confirmed from plasma accelerations of 10^{20} cm/s^2 by TW-ps laser pulses [9] based on very selective experimental conditions by Doppler measurements in full agreement further experiments and with preceding theory and computations of the nonlinear force [10]. The use of the generation of a fusion flame [11] for igniting modestly compressed or uncompressed solid fuel was concluded [12,13] on the basis of hydrodynamic theory and even could be generalized for igniting H-^{11}B [6-8]. The problem remains, whether the hydrodynamics for the fusion flame is a sufficient theory as has to be evaluated theoretically and experimentally.

In view of these open developments it is still interesting whether H-^{11}B fusion with spherical laser compression to very high densities can be simplified. Based on the accurate measurements of the resonance of the H-^{11}B cross sections at 148 keV by Nevins and Swain

[14] and based on new results of the stopping length of alpha particles [15] for the H-^{11}B reaction, positive changes were noticed. When, however, the range of the interesting laser pulse energies between 1 to 20 MJ were evaluated, a very strong increase of the fusion gain was observed in computations with volume ignition under special conditions.

2) Nevis & Swain results about the cross section resonance

A summary is given first about the new achievements for the following use of the reaction of light hydrogen with the boron isotope 11

$$^{1}\mathrm{H} + ^{11}\mathrm{B} \rightarrow 3\,(^{4}\mathrm{He}) + 8.664\ \mathrm{MeV}$$

Studies about the fusion cross section go a long time back with the first publication Miley [16]. Nevins and Swain [14] provided analytic approximations to the fusion rate coefficients for the H-^{11}B reaction with considering resonance in the astrophysical S-function. Then in this paper the fusion rate coefficient (averaged reactivity) uses the results [17] in the following used computer code for comparison with earlier results [3,4].

Fusion reactions between two nuclei can be divided into two independent steps (especially for heavy nuclei): the penetration of the Coulomb barrier and the fusion reaction. For light nuclei Xing Zhong Li et al. [17] proposed the selective resonant tunneling model for estimation of the fusion cross section. In this model the two steps of fusion reaction are not independent. And consequently, we do not observe any neutron emission in the H-^{11}B fusion reaction.

Following Bosch and Hale [18] we write the fusion cross section for H-^{11}B as a product of three factors:
a) Astrophysical S-function
b) Geometrical factor
c) Tunneling probability (Gamow factor)

$$\sigma(E) = S(E) \times \left(\frac{1}{E}\right) \times exp\left(-\sqrt{\frac{E_G}{E}}\right) \tag{1}$$

Where $E_G = 2\pi^2 \alpha (z_1 z_2)^2 \mu c^2$ is the Gamow energy, expressed in terms of the fine structure constant, $\alpha = \frac{e^2}{\hbar c} = \frac{1}{137.03604}$ and the reduced mass of the particles μ .For the H-^{11}B reaction the Gamow energy is $E_G = 22.589\,MeV$ [14].

The fusion rate coefficient (averaged reactivity) is related to the fusion cross section through the integral

$$\langle \sigma \mathrm{v} \rangle = \iint f(\mathrm{v}_i) f(\mathrm{v}_j) \sigma(|\mathrm{v}_i - \mathrm{v}_j|)\,|\mathrm{v}_i - \mathrm{v}_j|\, d\mathrm{v}_i d\mathrm{v}_j \tag{2}$$

When both ion species have thermal distributions this integral can be reduced to

$$\langle \sigma \mathrm{v} \rangle = \sqrt{\frac{8kT_{eff}}{\pi\mu}} \left(\frac{1}{kT_{eff}}\right)^2 \int_0^\infty dE\, E\, \sigma(E) \exp\left(-\frac{E}{kT_{eff}}\right) \tag{3}$$

where we have allowed possible differences in the temperature of the two ion species by defining

$$T_{eff} = \frac{m_1 T_2 + m_2 T_1}{m_1 + m_2} \quad (4)$$

By substituted equation (1) into equation (3) we obtain $\langle \sigma v \rangle$ as a function of astrophysical S-function.

$$\langle \sigma v \rangle = \sqrt{\frac{8kT_{eff}}{\pi\mu}} \left(\frac{1}{kT_{eff}}\right)^2 \int_0^\infty dE \; S(E) \exp\left[-\left(\frac{E_G}{E} + \frac{E}{KT_{eff}}\right)\right] \quad (5)$$

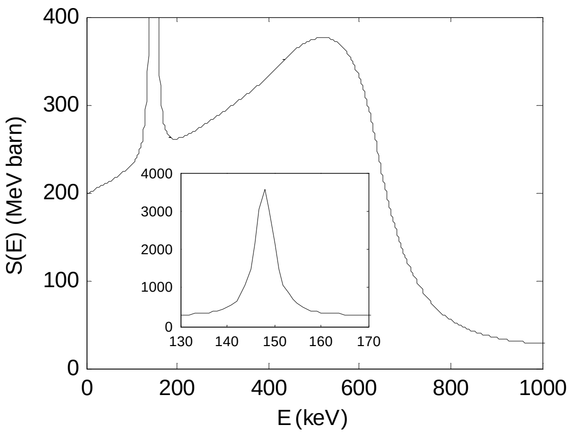

FIG. 1. Astrophysical S-function of H-^{11}B fusion reaction varies as a function of energy in keV. Ref. [14].

Nevins and Swain [14] obtained the analytical approximations to the astrophysical S- function for H-^{11}B fusion reaction. Figure 1 shows variations of $S(E)$ for E<1000 keV as a function of E white detailed in resonance at E=148 keV. One can see the second resonance at about 520 keV. The peak in the H-^{11}B fusion cross section is shifted upwards to ~ 590 keV due to the strong energy dependence of Gamow factor (see Fig.4 of Ref.14).

The fusion rate coefficient for the H-^{11}B fusion reaction according to [14] and Davidson [19] is shown in Figure 2. At higher temperatures the contribution from the 148 keV resonance can be neglected.

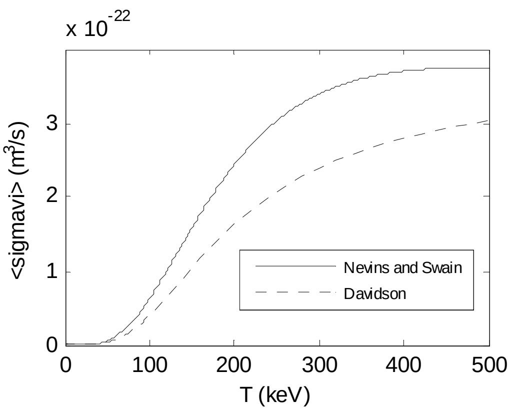

FIG. 2. Temperature dependence of the fusion rate coefficient $\langle \sigma v \rangle$, for H-^{11}B fusion reaction [14,19].

3) Computation of volume ignition of hydrogen-boron 11 reactions

In this paper we employ the just explained rate coefficients to calculate the energy gain in the H-^{11}B fusion reaction with volume ignition model. In the direct drive approach to inertial confinement fusion, the driver beams or laser light are incident directly at the very small spherical pellets. The laser energy is absorbed by electrons in the target's outer corona. The hydrodynamic transfer of laser energy into the ideal compression profile (i.e. volume ignition) is prevented by the fact that the laser initially deposits its energy into a shallow volume of plasma at the pellet surface. Then this hot corona plasma ablate and momentum of it cause compressed recoil to the interior aiming to get a uniform or Gaussian density profile [3].

The simplified fusion reactions gain (core gain) is defined by the ratio of nuclear fusion reaction energy, E_f , to the input energy, $E_\circ$,.

$$G = \frac{E_f}{E_\circ} = \frac{\varepsilon_{HB}}{E_\circ} \int_0^{\infty} dt \int_{-\infty}^{+\infty} d^3 r \, \frac{n_i^2}{A} \langle \sigma \mathrm{v} \rangle \tag{6}$$

where ε_{HB} = 8.664 MeV is the energy per fusion reaction ,H-^{11}B, n_i is ion density and $A = 4$ in contrast to binary reactions where $A = 2$ for cases like DD. Following Stening et al. [3], the here considered algorithm includes the direct temperature changing elements, the adiabatic cooling, the alpha particles reheat, and the temperature change due to Bremsstrahlung losses and partial re-absorption. To include the re-absorption of the Bremsstrahlung, the classical collision frequency was used.

The problem of reheat is involved with the very complex question, what penetration depth for the MeV alphas in the high density plasma is to be taken. It should be mentioned that the Gabor Theory [21] of the stopping power of alpha particles for collisions with the whole collective of the electrons in the Debye sphere (collective effect) has to be used in contrast to the binary collisions with electrons following from the Bethe-Bloch theory [15]. We introduce the probability for the absorption of an alpha particle by the plasma itself

$$P_\alpha = \frac{R}{R + R_\alpha} \tag{7}$$

where R_α denotes the range of alpha particle according to the collective effect [15,21], and R is the radius of the spherical plasma. With including of this probability we calculate deposition energy of alpha particles.

We base the computation of gain on the model of spherical plasma with initial temperature $T_\circ$, radius $R_\circ$ and ion density $n_{i\circ}$ expanding symmetrically in vacuum. This self-similarity model has also been used by Hora and Ray [22] as continued later [3,4]. We use these calculations and improved the with respect to the accuracy of the cross sections. We assume that a laser supplies the energy $E_\circ$ transferred into the plasma sphere of initial radius $R_\circ$ so that

$$E_\circ = 2\pi(1 + \overline{Z})\, n_{i\circ} R_\circ^3\, T_\circ \tag{8}$$

Where $n_{i\circ}$ is the initial ion density, $\overline{Z}$ is the average ionic charge, and $T_\circ$ is the initial energy of ions after the laser heating. The numerical results were obtained with considering conservation of energy and momentum.

4) Results of the computations

For a generation of energy in a reactor with the H-^{11}B fusion reaction, 10^5 times the solid state density and 20% efficiency of the drivers should be reached at least [3,4] though these values may look rather beyond realistic aiming. Hence, we calculate fusion gains from eq. (6) for H-^{11}B at initial compressed density 10^5 times the solid state density and various volumes as shown in figure 3. As can be seen from this figure, fusion gain increased and driver energy decreased due to resonance at fusion cross section.

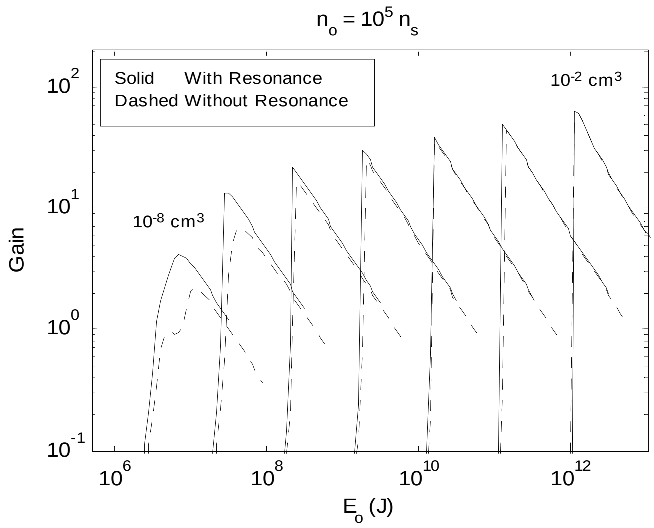

FIG. 3. Dependence of the fusion gain on the input energy of the H-^{11}B reactions for 10^5 times the solid state density and initial pellet volumes in the range $10^{-8} – 10^{-2}$ cm^3.

Decreasing driver energy for maximum gain and increasing gain causes irregular variations for different initial volumes. The strongest effect of resonance due at the cross section can be seen occur at lower volumes of energies. For example for an initial density of 10^5 times the solid state and initial volume 10^{-7} cm^3 resonance at fusion cross section leads to a 94.60% increasing of the gain and a 36.92% decreasing on the driver energy. We suggest that the reason of this effect can be negligible contribution from the 148 keV resonance in H-^{11}B fusion cross section at higher temperatures as seen from Figure 4.

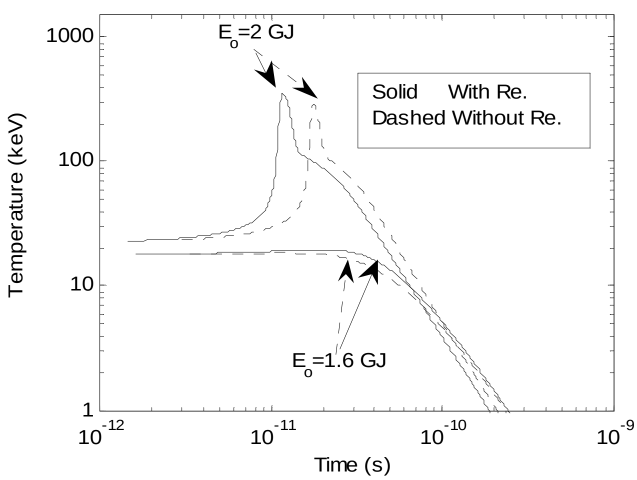

FIG. 4. Dependence of the temperature in keV of a H-^{11}B pellet on time for an initial compression of 10^5 times of the solid state density and initial volume 10^{-5} cm^{3}at various initial energy.

To demonstrate the effect due to the resonance of the fusion cross sections we calculated the time dependence of the plasma temperature as shown in figure 4. In this figure we see these cases for an initial volume 10^{-5} cm^3 and an initial density 10^5 times solid state density and a set of initial energies of 1.6 and 2 GJ for both with (solid line curves) and without (dashed line curves) resonance cases. At 1.6 GJ energy for both cases shows that the reheat is nearly keeping a constant plasma temperature despite the adiabatic cooling of expansion. However in the case of initial 2 GJ energy, the ignition and self-burning is shown, raising the plasma temperature above 354 keV (with resonance) and 291 keV (without resonance) after some picoseconds.

5) High increase of H-^{11}B fusion gains in the 1- 15 MJ range

The anomalous behavior of the fusion gains for initial volume V_o of 10^{-9} cm^3 can be seen in Figure 5. The maximum gain has the respectable value of G = 9.3 with the resonance in the cross sections at input energy of only E_o = 1 MJ and a density of $n_o = 2.7\times10^5$ n_s. The maximum gain is 6.2 times higher than without resonance. The anomaly of this result for the discovered values of the parameters can be seen from the fact that for higher as well as for lower initial volume, the curves in the relevant diagrams are rather “normal” and very similar to the usual cases.

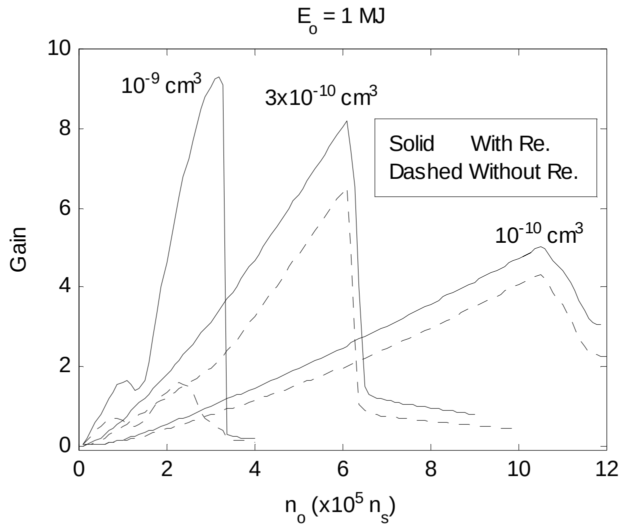

FIG. 5. Fusion gains for energies E_o in the interesting range strongly changing due to the resonance maximum for initial H-^{11}B volume of 10^{-9} cm^3 with an increase of the gain by a factor 6.2 at input laser energies of only one MJ at densities from only 2.3 to $2.7\times10^5 n_s$. The maximum gain is 9.3.

A very high gain of 20.5 has been reached (Figure 6) for an input energy E_o = 15 MJ for a volume $V_o = 2.8\times10^{-8}$ cm^3. It is most interesting that this anomaly just happens at parameters of gains near 10 to 20 and input laser energy in the range of one to several MJ. These are numbers which are interesting of the operation in power stations. There is still the density about 100 times higher than for the spherical laser compression for thermal ignition than for deuterium-tritium fuel. Nevertheless the result of this anomaly provides a significant progress for consideration of H-^{11}B for using the classical laser compression and ignition for power generation.

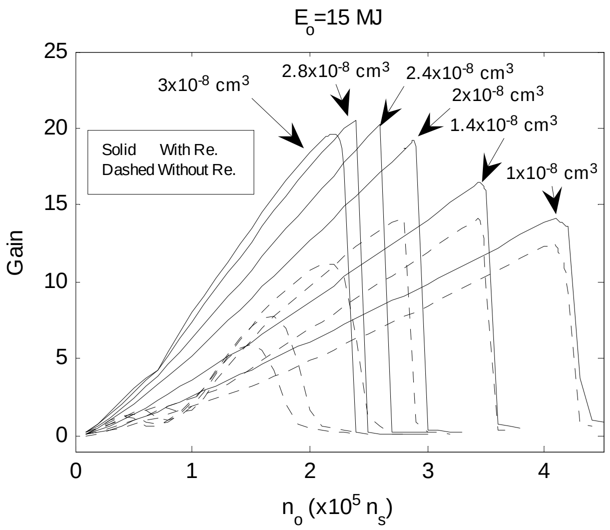

FIG. 6. A optimum gain of 20.5 is reached for a Volume $V_o = 2.8\times10^{-8}$ cm^3 at a density 2.4×10^5 n_s

To the question of compression it should be mentioned that there is experimental evidence, that clusters of fusion fuel are possible in solid state targets which have been measured to be at least at 100 times higher density than the solid state [23] or even at the ultrahigh density [24] of 10^6 times the solid state density.

It is important to note that the very interesting and optimized values for the parameters for a power station are highly sensibly limited to narrow ranges. These were discovered now as a surprise compared with the usually much less interesting lower gains for exorbitant laser pulse energies.

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