Avalanche effect: The necessary condition for self-sustained fusion process in Hydrogen-Boron fuel

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Abstract

The main goal of the present work is the investigation of the "chain reactions" effect occurring during the $p^{11}B$ (Hydrogen-Boron) nuclear fusion process, in two different schemes (a non-thermal and a thermal one). The main advantage of the Hydrogen-Boron ($p^{11}B$) fusion is the production of three alphas with total energy of 8.7 MeV, which could enhance the alpha heating effect of the species (protons, Boron) and allow the development of "clean" devices for power generation, avoiding neutron radiation. The "chain reactions" effect described also as the avalanche effect is the necessary condition for "fast ignition enhancement" of fusion process in the medium by continuous elastic central collisions, where proton and ^{11}B particles gains energy from the produced alpha particles. This alpha heating effect increases the medium species energy in a self-sustained operation, as well as the gain of the output fusion power. The "chain reactions" effect in the non-thermal scheme, is ignited by energetic protons (~10^{9} cm/sec) interacting with a low temperature Hydrogen-Boron medium. The produced alpha particles from the nuclear fusion reaction, transfer energy to the low energy particle of the medium and generate relatively high energy protons with energies corresponding to the maximum $p^{11}B$ fusion cross section (~ 600 keV). This process improves the fusion reaction probability and produces a new cascade of energetic alphas. The protons energy losses due to frictions with the medium electrons (stopping power) is sustained up to 600 keV, applying a periodical pulsed external electric field. Evaluation on the stooping power enables the optimization of the fusion power as a function of the medium electron density. The result of the aforementioned operation is an important enhancement of the alpha particle production and consequently of the energy transfer to protons which in turn improves the fusion energy output. In the thermal scheme the "chain reactions" effect is investigated numerically, calculating the temporal evolution of the $p^{11}B$ plasma parameters (density, temperature and reaction rate) with initial density ~ 10^{19} $m^{-3,}$ and relatively low initial temperature of the order of 30 keV, using a multi-fluid, global particle and energy balance code, including collisions between all species (p, B, e, alpha). The code allow to study the temporal production of alphas in the $p^{11}B$ plasma, as well as the temporal energy transfer from the alphas to the plasma ions. The latter increases the ions (p, ^{11}B) initial temperatures to values corresponding to the optimum value of the cross section (600keV) and maximizes the reaction rate (RR). The temporal evolution of the RR enables the definition of the necessary time interval for the appearance of strong alpha heating effect, which generates a "fast ignition enhancement" of fusion process, until the fuel depletion. An important numerical result is that the effect of the "fast ignition enhancement" of the RR, is initiated, when the density of the produced alphas in the plasma is approximately one order of magnitude lower than the initial plasma ion density.
The analysis of the two above mentioned schemes shows important physical process similarities with emphasis on the "chain reactions" effect [or avalanche effect] which is proved to be the necessary condition to ignite a self-sustained fusion process in the $p^{11}B$ fuel. The important increases of the alpha density enables to overcome the energy losses of the species in the fusion medium through the increase their temperature up to the optimum cross section values for fusion

Introduction

The study of the p-^{11}B nuclear fusion reaction was very attractive from the beginning [1], because firstly, it produces three (3) stable helium nuclei, with total energy of 8.9 MeV and secondly, as an aneutronic reaction, it is a good candidate for clean energy production [2]. The relatively small alpha number produced by the early experiments on laser induced proton-boron fusion, as well as the small p-^{11}B fusion cross section values for energies lower than 250 keV, limited the interest for further fusion oriented, experimental investigation of p-^{11}B fusion. However, nowadays, the proton-^{11}Boron fusion activity has been re-examined and it is beginning to gain worldwide interest, compared to DT fusion [3], mainly due to recent important experimental measurements [5, 6, 7, 8, 9], and also theoretical [10, 11, 12, 13] and numerical results [14, 15, 16, 17, 18], which have effectively contributed to the strengthening of the aspect that, the proton-boron fusion may be the new, near future solution for clean energy production [2, 19]. In this context, the present work emphasizes on this effort, through the exploration of two (2) cases, that are referred respectively as "the non-thermal fusion medium" and "the high temperature, non-neutral fusion medium". These cases present interest because, although they start from two distinct, initial approaches for potential future experiments, they end up to the same result, which is the proof of the "chain reactions alpha heating effect" (avalanche effect), as the necessary condition for the fast enhanced fusion ignition of the p -^{11}B fuel.

Case 1 : Non-thermal fusion medium

The "chain reactions" effect in the non-thermal scheme [11, 20, 21], is ignited by energetic protons (~10^9 cm/sec), interacting with a low temperature Hydrogen-Boron medium. The produced alpha particles from the nuclear fusion reaction, transfer energy to the low energy particle of the medium and generate relatively high energy protons with energies corresponding to the maximum p^{11}B fusion cross section (at center of mass energy ~ 600 keV). This process improves the fusion reaction probability and produces a new cascade of energetic alphas. The protons and alphas lose kinetic energy, mainly due to friction with the medium electrons (stopping power). In the relevant proton energies of 1-50 MeV, the stopping power can be reduced, by either increasing the temperature, or by reducing the electron density (non-neutral plasma), or by both factors. In particular, lowering the stopping power, through the reduction of the electron density, there are several consequences, that significantly increase the reaction rate; The Bremsstrahlung losses are reduced and thus, keeping the plasma temperature high, the reaction probability increases for the initial proton pulse and the secondary high energy protons and also, the probability of a non-thermal (elastic) energy transfer from the high energy produced alphas to the fuel ions is increased, thus, maintaining the avalanche process [11]. A possible scenario for the increase of the alpha production rate is the application of a periodical pulsed external electric field [21]. Evaluation on the stopping power enables the optimization of the fusion power, as a function of the medium electron density. The result of the aforementioned operation is an important enhancement of the alpha particle production and consequently, of the energy transfer to protons, which in turn improves the fusion energy output.

Case 2 : High temperature, non-neutral fusion medium

Numerical simulations using a multi-fluid, global particle and energy balance code [22] enable the study of the temporal evolution of the physical parameters of the p-^{11}B fusion medium, as a function of the plasma fluids (species) initial conditions of density and temperature. The code includes collisions between all species (p, B, e, alpha) and allows the investigation of the temporal evolution of the production of alpha density, as well as of the temporal rise of the temperature of the fusion species (p, B), due to the energy transfer from alphas. In the present work, the numerical simulations correspond to an initial p, ^{11}B medium ion density, of the order of $n_p = n_B = 4\ 10^{19}$ m^{-3}, which is relevant to the study of the fusion process in compact magnetic fusion devices, operating with plasma densities 10^{13} cm^{-3} -10^{15} cm^{-3}. In USA, there is an increased interest on the development of such devices for high power generation [23, 24, 25]. In our simulations, the electron density, n_e, is seven (7) orders of magnitude lower than the initial p, ^{11}B fusion species density, for the optimization of Bremsstrahlung losses. This non-neutral plasma could be formed, by the injection of high-density ion beams (p, B) in a magnetic configuration, allowing a relatively long trapping time, until the appearance of the fast enhanced fusion ignition of the p-^{11}B fusion RR and the significant temperature rise of the fusion species (p, B, a). In Subcase 2a, the initial temperature of the fusion medium species (p, B) is selected at a relatively low temperature, T_{in} = 30 keV. This low initial medium temperature aims to the better understanding of the contribution of the avalanche effect, to the enhancement of the RR and the ignition of a self-sustained fusion process in the p-^{11}B fuel. In Subcase 2b, the initial temperature of the fusion species (p, B), is increased by a factor of 3, at T_{in} = 90 keV. The most important result of all simulations is that, the enhanced fusion ignition of the p-^{11}B RR appears, when the density of the produced alphas is 1-2 orders of magnitude lower, than the initial fusion species (p, B) density.

Subcase 2a : T_{in} = 30 keV p, ^{11}B medium temperature

The main comment about this case concerns the fast alpha fluid thermalization (~ 2.5 sec), with the initial medium temperature, which for later times than 2.5 sec, is followed by a slight increase of the slope of the fusion species temperature (p, B and alpha (Figure 1.b)), until the appearance of the fast enhanced fusion ignition of the p - ^{11}B fusion RR and the ignition of a self-sustained fusion process. This slight species temperature rise has a time duration of ~85 sec and is continued until the increase of the alpha density to a characteristic value, which is 1-2 orders of magnitude lower than the initial medium ion density of p and ^{11}B. The fast enhanced fusion ignition leads to the maximization of the RR after ~105 sec. At this time, the relative p and ^{11}B center-of-mass energy (~ 345 keV) corresponds approximately to an optimum cross section value, σ (~ 5.0 10^{-25} cm^2), of the p - ^{11}B nuclear fusion reaction. For times longer than ~110 sec, the RR curve declines, due the depletion of the fusion fuel (Figure 1.a), while the fusion species temperatures (p, B, a) continue to increase slightly, reaching a thermalization temperature of ~1150 keV, after ~220 sec.

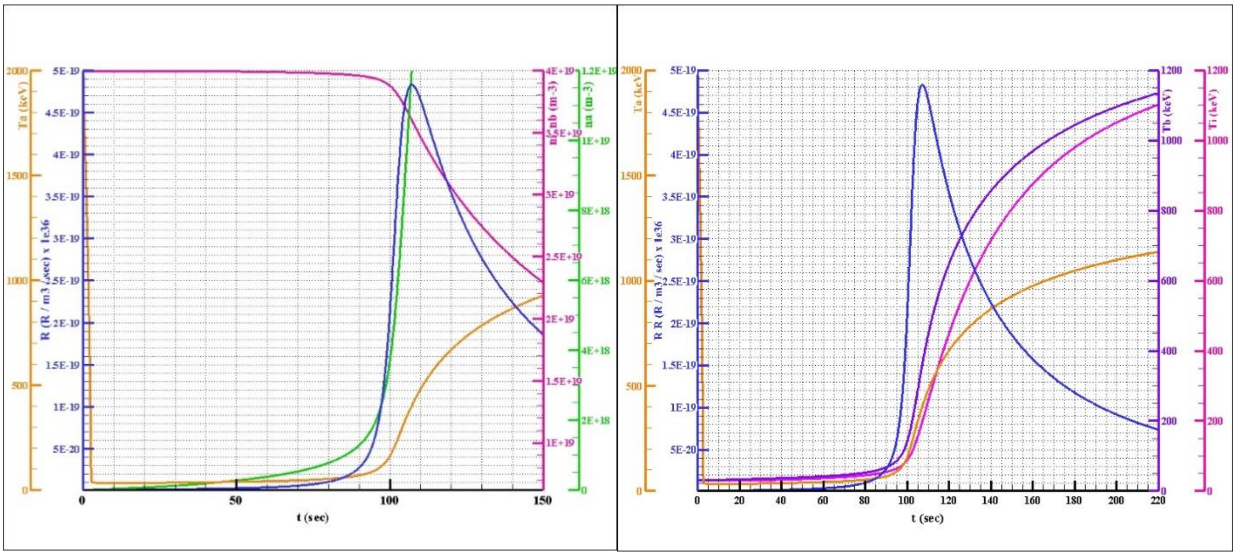

Figure 1. (a) : Temporal evolution of the p - ^{11}B fusion RR (blue curve) and of the fusion fuel species densities : protons (pink curve), ^{11}B ions (pink curve) and alphas (green curve), and alphas temperature (orange curve) at T_{in}= 30 keV. 1. (b) : Temporal evolution of the p - ^{11}B fusion RR (blue curve) and of the fusion fuel species temperatures : protons (pink curve), ^{11}B ions (purple curve) and alphas (orange curve) at T_{in}= 30 keV. [*]

Subcase 2b : T_{in}=90 keV p, ^{11}B medium temperature

In this subcase, we increase the initial medium species (p, B) temperature up to 90 keV, sustaining all the other parameters, as in the first subcase (T_{in} = 30 keV). This increase, by a factor of 3, of the initial input energy, enables the evaluation and the comparison with the results of Subcase 2a, concerning mainly, the temporal rise of the medium species temperature (p, B, a) and the times t, at which, the fast enhanced fusion ignition of the p -^{11}B RR appears and the RR is maximized.

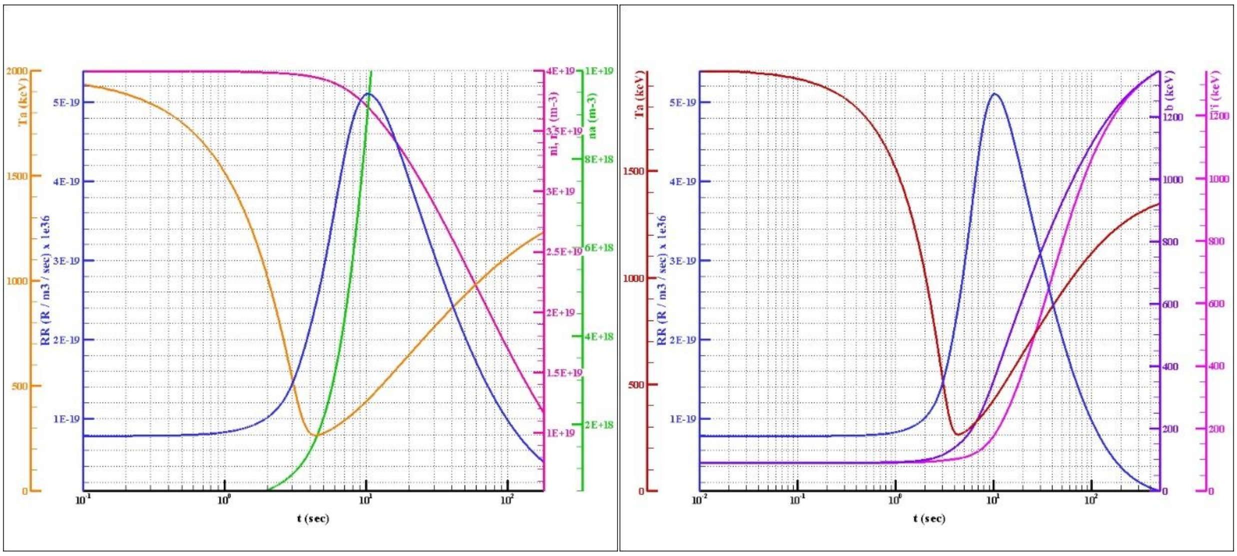

Figure 2. (a) : Temporal evolution of the p - ^{11}B fusion RR (blue curve) and of the fusion fuel species densities : protons (pink curve), ^{11}B ions (pink curve) and alphas (green curve), and alphas temperature (orange curve) at T_{in}= 30 keV. 2. (b) : Temporal evolution of the p - ^{11}B fusion RR (blue curve) and of the fusion fuel species temperatures : protons (pink curve), ^{11}B ions (purple curve) and alphas (orange curve) at T_{in}= 90 keV. [*]

As it is shown in Figures 2a,2b, for T_{in} = 90 keV, the latter times are decreased, by about a factor of 10, compared to Subcase 2a. Also, for T_{in} = 90 keV, Figures 2a and 2b show a fast temporal decline of the alpha temperature (~2.5 sec) at a minimum value, T_a ~ 300 keV, which is higher than the corresponding temperatures of the fusion species (p, B) and thus, there isn't thermalization. This minimum temperature of alphas remains constant for a relatively shorter period of time (few sec), compared to the subcase of T_{in} = 30 keV (Figures 1a, 1b). However, in both subcases, the species temperatures of p, B, a and the produced alpha density, at the RR maximization (t ~110 sec and t ~ 10 sec respectively), have almost the same values. This is justified by the fact that, at the RR maximization, there are approximately the same center-of-mass energies of fusion species (p, B), which correspond to the optimum of their nuclear reaction cross section. In subcase 2b, the faster appearance in time of the maximum RR signifies that the output power is much higher than this of Subcase 2a. Moreover, as in both subcases, the range of temperature variations of the species are very close, the corresponding fluid pressures are similar. Consequently, in potential, future experiments using magnetic confinement devices, for a $\beta < 1$, a magnetic field ~ 10 Tesla could be used for medium trapping [26]. However, for both subcases, the criticism is that, in the subcase of T_{in}= 30keV, it is necessary to trap the plasma for a longer time interval [~x10] compared to T_{in} = 90 keV, in order to avoid plasma losses, while for T_{in} = 90 keV, a higher initial input energy for the formation of the non-neutral plasma is necessary. Also, as in the previous case, thermalization of all species is achieved after ~120 sec.

Conclusions

The analysis of the non-thermal and the high temperature fusion medium shows physical process similarities, emphasizing on the proof of the avalanche effect (chain reactions alpha heating effect), which is the necessary condition, for temperature rise of fusion species (p, B), in order to ignite a self-sustained fusion process in the $p^{11}B$ fuel. The increase in the energy (temperature) of the fusion species (p, B) is in direct correlation with the decrease in the energy (temperature) of the alpha (figure 1 and figure 2), which indicates the transfer of energy, until the time of appearance of the fast enhanced fusion ignition of the RR. For later times the temperature of all species (p, B and a) increases, due to the significant rise in the alpha production, the transfer of energy from alpha to p and B species and the depletion of the fuel density. The simulation results establish the fact that the fast enhanced fusion ignition of the RR appears at a characteristic time, at which the produced alpha density is approximately 1-2 orders of magnitude lower, than the initial medium ion (p, B) density. For both cases, there is net power output gain, due to the selected conditions for the optimization of Bremsstrahlung losses.

[*] In all figures, we use different time scales, in order to emphasize on the alpha density and temperature rise.

References

[1] M.L.E. Oliphant, and Lord Rutherford "Experiments on the transmutation of elements by protons," *Proceedings of Royal Society London* A, vol. 142, p. 259, 1932
[2] H. Hora, G.H. Miley, M. Ghorannviss, H. Malekynia, N. Azizi, and X-T. He, "Fusion energy without radioactivity: laser ignition of solid proton-boron(11) fuel", *Energy and Environment Science*, vol. 3, p. 479-486, 2010.
[3] H. Hora, G. Korn, L.Giuffrida, D.Margarone, A. Picciotto, J. Krasa, K. Jungwirth, J. Ullschmied, P. Lalousis, S. Eliezer, G.H. Miley, S. Moustaizis, and G. Mourou, "Fusion energy using avalanche increased boron reactions for bock-ignition by ultrahigh power picoseconds laser pulses", *Laser and Particle Beams*, vol. 33, p. 607, 2015.
[4] M.L.E. Oliphant, and Lord Rutherford "Experiments on the transmutation of elements by protons," *Proceedings of Royal Society London* A, vol. 142, p. 259, 1932
[5] V.S. Belyaev, et al., "Observation of neutronless fusion reactions in picosecond laser plasma", *Phys. Rev.*, vol. E 72, p. 026406, 2005.
[6] C. Labaune, et al., , *Nature Communications*, vol. 4, Article ID 2506, https://doi.org/10.1038/ncomms3506, 2013.
[7] G. Korn, et al., *Lecture at the IZEST conference*, Paris, Romanian Embassy, 19 September 2014.
[8] A. Picciotto, et al., *, Phys. Rev.*, vol. X 4, p. 031030, 2014.
[9] D. Margarone, et al., Plasma Phys. Controlled Fusion, vol. 57, p. 014030, 2015.
[10] S. Eliezer, et al., P*hysics of Plasmas*, vol. 23, p. 050704, 2016.
[11] S. Eliezer, et al., "Avalanche proton-boron fusion based on elastic nuclear collisions", *Physics of Plasmas*, vol. 23, p. 050704, 2016.
[12] F. Belloni, "On a fusion chain reaction via super thermal ions in high-density H–11B plasma", *Plasma Phys. Control. Fusion*, vol. 63, no. 5, p. 055020, 2021.
[13] J. Gruenwald, *Journal of Technological and Space Plasmas*, vol. 2, Issue 1, p. 104-108, 2021.
[14] P. Lalousis, H. Hora, S. Eliezer, Josè Maria Martinez-Val, S. D. Moustaizis, G.H. Miley, and G. Mourou, *Physics Letters*, vol. A377, p. 885-888, 2013.
[15] P. Lalousis, H. Hora, and S. Moustaizis, *Laser and Particle Beams*, vol. 32, p. 409-411, 2014.
[16] H. Hora, G. Miley, P. Lalousis, S. Moustaizis, K. Clayton, and D. Jonas, *IEEE Transaction of Plasma Science*, vol. 42, p. 640-644, 2014.
[18] P. Lalousis, S. Moustaizis, H. Hora and G.H. Miley, "Kilotesla Magnetic Assisted Fast Laser Ignited Boron-11 Proton Fusion with Nonlinear Force Driven Ultrahigh Accelerated Plasma Blocks", *Journal of Fusion Energy*, vol. 34, p. 62-67, 2015.
[19] H. Hora, S. Eliezer, G. J. Kirchhoff, N. Nissim, J. X. Wang, Y. X. Xu, G. H. Miley, J. M. Martinez-Val, W. McKenzie, and J. Kirchhoff, "Road map to clean energy using laser beam ignition of boron-proton fusion," *Laser and Particle Beams*, vol. 35, no. 4, p. 730–740, 2017.
[20] 2) S. Eliezer, J. M. Martinez-Val. A novel fusion reactor with chain reactions for proton–boron11. Laser and Particle Beams. Vol. 38, p. 39–44, 2020.
[21] S. Eliezer, Y. Schweitzer, N. Nissim, and J. M. Martinez Val, "Mitigation of the Stopping Power Effect on Proton-Boron11 Nuclear Fusion Chain Reactions", Front. Phys., vol. 8, 573694, 2020.
[22] P. Lalousis, "Alpha heating in magnetic and inertial confinement fusion", *EPS Conference*, 2016.
[23] T. J. Mcguire, "Active cooling of structures immersed in plasma", US Patent 2014/0301517, 2014.
[24] T. J. Mcguire, "Heating plasma for fusion power using magnetic field oscillation", US Patent 2014/0301519, 2014.
[25] N. Rostoker, M. W. Binderbauer, H. J. Monkhorst, "Colliding Beam Fusion Reactor", SCIENCE, VOL. 278, p. 1119, 1997, https://tae.com/research-library
[26] M. Greenwald et al., "The High-Field Path to Practical Fusion Energy", https://sites.nationalacademies.org/cs/groups/bpasite/documents/webpage/bpa_185099.pdf