HIGH GAIN FUSION BURNING IN INERTIAL CONFINEMENT FUSION PLASMA

[1]Y. ARIKAWA, [1]H. SHIRAGA, [1]R. YAMADA, [1]A. MORACE, [1]A. YOGO, [1]S. FUJIOKA, [2]T. JOHZAKI, [1]N. IWATA, [1]Y. SENTOKU, [1]R. KODAMA,

[1]Institute of Laser Engineering, Osaka University, 2-6, Suita, Osaka, Japan,
[2]Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima City Hiroshima, Japan

Email: arikawa.yasunobu.ile@osaka-u.ac.jp

In inertial fusion research, ignition and burning have been demonstrated at the U.S. National Ignition Facility (NIF), achieving an ignition by exceeding generalized Lawson's criterion with T_i=13KeV, and ρR=0.44g/cm^2, an energy gain of 1.5, and a burn ratio of 4.3% [1,2]. The energy gain is the ratio of fusion output energy which is fusion yield multiplied by 17.6 MeV and input laser energy. The burn ratio is the fusion yield to the initial number of deuterium-tritium (DT) in the confinement plasma. According to conventional theory, the fusion reaction rate is proportional to the fuel $\rho R/(\rho R+B)$ where B is temperature-dependent parameter with nearly constant values with 8 g/cm^2 given by $B = 8m_{DT}C_s/\langle\sigma v\rangle$ [3]. For NIF-class fuel the 4.3% burn ratio achieved is so far represents the theoretical limit. To enhance the energy gain further, a novel mechanism capable of inducing chain fusion reactions within a timescale much shorter than plasma confinement time is required.

Here we propose a new scheme to increase the burn ratio. In DT plasmas the α (3.5 MeV) are generated by fusion reaction are stopped by Coulomb collisions with the surrounding DT plasma. In the figure 1(a) concept of the new scheme is illustrated, (b) a fusion cross section (black) and energy spectrum of DT (in red) is shown. A particle in cell simulation by using PICLS [4] with 0-dimension in space 1-dimension in velocity space are performed to simulate α-DT collisions with a very high density plasma. The 3D PIC calculation that includes such ultra-high density, large volume, extended time, and degeneracy effects is desirable, though practically impossible. However, no significant difference is expected, as collisions in such a high-density DT plasma occur with nearly homogeneous angular distributions, making the system comparable to the 0D assumption. Two parameters are assumed: (a) a hot spot of high density with ρ> 400 g/cm³, and (2) high density ratio of α particle-to-DT ion density ratio, α/DT >0.1. In this regime, electrons in the DT plasma are rapidly heated by α collisions, causing the alpha-particle stopping power reduction. This enables direct α particles scattering with DT ions. A large angle scattering Coulomb collisions α-DT generate high-energy D'T' ions (here D' or T' infer high energy ions having energy of 100 keV~1 MeV) within 1ps. These D'T' ions typically relax to the average ion energy (~10 keV) within 3ps therefore their contribution is usually ignored. However, in very high-density DT, D'+T reaction occurs within ps, because D' +T beam-fusion has cross-sections of up to 5 barns, which is 1000 times of higher than thermal fusion. The time dependent fusion burn ratio within 10 μm radius are estimated for several densities. The burn rate is approaching to 1 within 2 ps when ρ= 800 g/cm^3 as shown in Fig2 (b) despite a modest of ρ R=0.8 g/cm².

This high burn rate suggests the possibility of explosive fusion burning. The probability of generating D'T' ions is proportional both to α/DT ratio and ρ. D+T reaction produce the first generation α, then α produce multiple of D'T'. Subsequent D'+T reactions produce second generation alpha particle (α'), which then generate multiple of D''T'' ions, initiating a chain fusion reaction. They react in much shorter time than inertial confinement time, leading to an explosive burning. The number of fusion reactions is proportional to high order of density (~ρ^6), therefore it causes instability growth of fusion reaction by density inhomogeneous. We define this process as avalanche fusion reaction.

To achieve the avalanche fusion, these two conditions need to be satisfied. The high α/DT ratio serves two functions: (1) rapid electron heating and (2) efficient generation of D'. Additionally, the high ρ ensures sufficiently fast reactions compared to the confinement time of the DT core plasma. Such conditions could potentially be achieved by NIF. In recent study, a high energy neutron spectrum has been observed in ignited fusion shots, however it remains unknown as it cannot be explained [5]. We hypothesize that it is due to our new model. By analysing experimental data based on our model, we expect to validate the feasibility of our approach. Furthermore, future work should focus on developing neutron diagnostics with ps/μm resolution [6] to study the avalanche fusion in the NIF experiment. Achieving avalanche fusion would maximize fusion energy utilization, reaching a burn rate of 1 and enabling the highest possible energy gain.

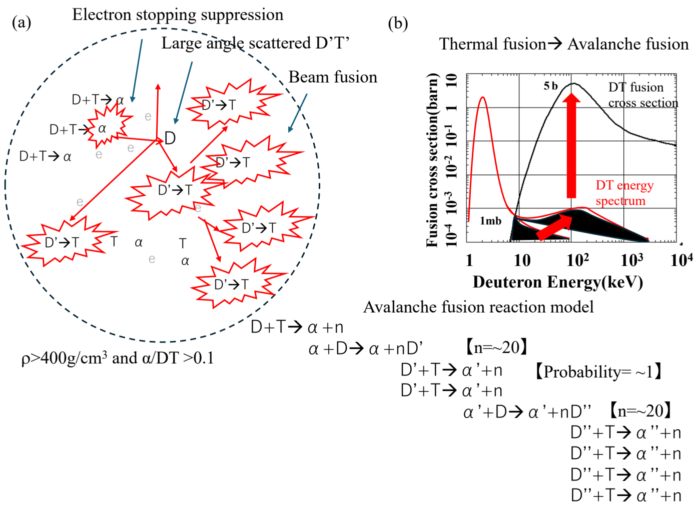

Figure 1 (a)A schematics of avalanche fusion chain reaction mechanism, (b) fusion cross section (in black) and energy spectrum of DT and high-energy scattered D'T'. The fusion cross section for D'T' is enhanced 5000 times from the original thermal fusion.

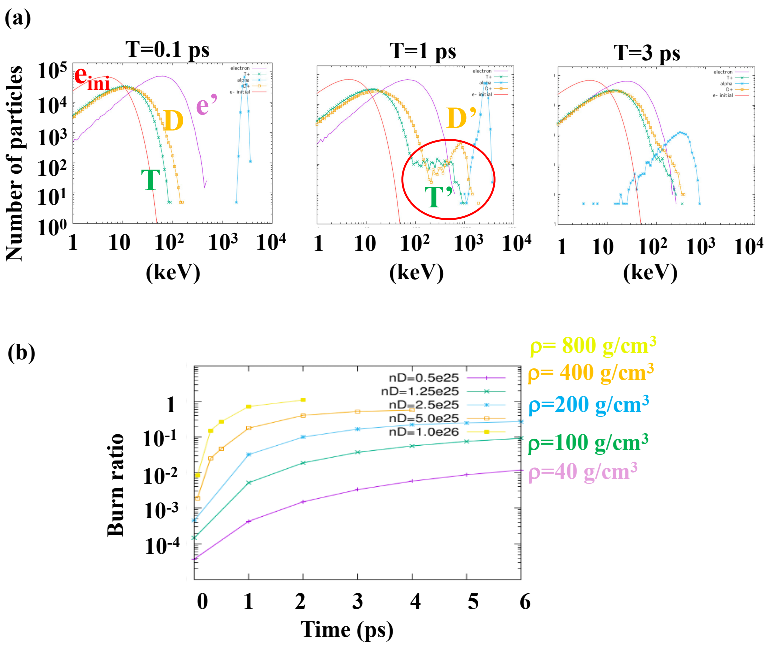

Figure 2 (a) shows particle in cell simulation by 0-dimensional PICLS for the energy distributions of alpha particles, D', T', and electrons at 0.1 ps, 1 ps, and 3 ps, assuming a composition ratio of α:D:T = 0.1:1:1. At 1 ps, the high-energy edge of D' ions exceeds 100 keV. (b) shows time history of fusion burn rate for several DT plasma density from 40 g/cm³ to 800 g/cm³ in a 10 μm-radius plasma. The fusion reaction rate approaches to 1 within 2 ps in ρ=800 g/cm³.

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