

CONFERENCE PRE-PRINT

HIGH GAIN FUSION BURNING IN INERTIAL CONFINEMENT FUSION PLASMA,

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Abstract

The National Ignition Facility (NIF) in the United States has, after half a century of research, achieved a historic milestone by surpassing the generalized Lawson criterion, demonstrating nuclear fusion ignition with an energy gain of 1.5 and a burn fraction of 4.5%. To advance toward the realization of Inertial Fusion Energy (IFE) with a target energy gain of 100, it is essential to achieve efficient fuel burning up to 100 % with reduced input laser energy. This requires control of the fusion burn process. In the paper, a novel concept of chain nuclear fusion reactions is proposed; fundamentally distinct from conventional generalized Lawson-based ignition, in which α -particles directly collide with deuterium-tritium (DT) ions to initiate avalanche fusion. The reaction is triggered once the α -particle density exceeds 0.1 of the DT ion density and the fuel density exceeds 400 g/cm³. Once the avalanche fusion is initiated, the reaction proceeds in a chain process within small spatial ($\sim\mu\text{m}$) and temporal ($\sim\text{ps}$) scales. Ideally, the avalanche fusion can achieve burn fractions approaching 100%, thereby realizing higher fuel utilization at lower input energies than required by the Lawson condition. Theoretical calculations are presented to discuss the relevant parameters, offering a new perspective for advancing the physics of fusion-burn plasmas.

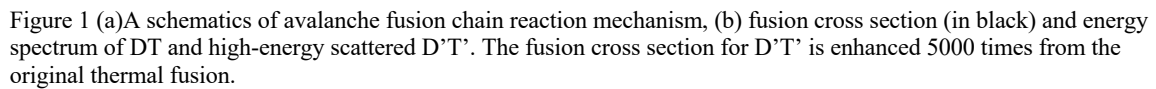
1. INTRODUCTION

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 $T_i=13\text{KeV}$, and $\rho R=0.44\text{g/cm}^2$, 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/cm² 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.

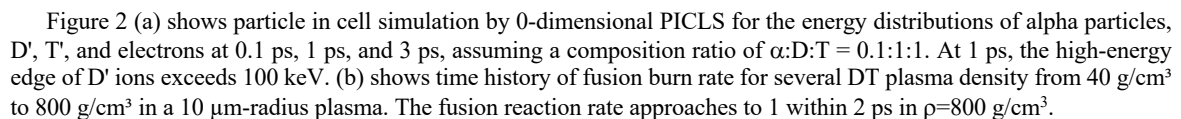
2. AVALANCHE FUSION MECHANISM

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 $\rho>400\text{ g/cm}^3$, and (2) high density ratio of α particle-to-DT ion density ratio, $\alpha/\text{DT}>0.1$. 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 $\sim$ 1 MeV) within 1ps. These D'T' ions typically relax to the average ion energy ($\sim$ 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 $\rho=800\text{ g/cm}^3$ as shown in Fig2 (b) despite a modest of $\rho R=0.8\text{ g/cm}^2$.

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 produces the first generation α , then α produce multiple of D'T'. Subsequent D'+T



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 $\text{ps}/\mu\text{m}$ 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.



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