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Effect of non-thermal nuclear reactions on tritium balance in burning plasmas

非熱的核反応が核燃焼プラズマのトリチウムバランスに及ぼす影響

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Effect of non-thermal nuclear reactions on tritium balance in burning DD, D^3He and DT plasmas is examined on the basis of the Boltzmann-Fokker-Planck (BFP) analysis model. The non-thermal fusion reaction is induced by energetic ions in non-Maxwell fuel-ion velocity distribution functions, and the reaction rate coefficients for fusion reactions that produce or consume tritium are increased or decreased from the values for Maxwellian plasmas. The degree of the change in the rate coefficients strongly depends on the plasma condition. The resulting modification of tritium density in burning plasma is discussed and the degree of the modification is evaluated for various plasma conditions.

1. Introduction

It is well known that energetic ions are produced in a burning plasma and play important role for plasma sustainment and operation. The energetic ions are continuously produced by fusion reactions, by external heating and by nuclear plus interference (NI) scattering [1] etc. As a result of the existence of the energetic-ion source, non-Maxwellian components always appear in fuel-ion velocity distribution functions and fusion reaction rate coefficients are changed from the values for Maxwellian plasmas [2]. The tritium is continuously produced by the D(d,p)T reaction and is consumed by the $T(d,n)^4He$ reaction in a burning plasma. According to the plasma condition, the effect of the reactions on tritium balance becomes influential. In recent progress of fusion reactor studies, concern for amount of tritium in the fusion system becomes gradually increases, from the viewpoint of environmental protection and also fusion-reactor operation. It is important to grasp the effect of non-thermal reactions caused by non-Maxwellian components in fuel-ion velocity distribution functions on the tritium balance in burning plasmas.

In deuterium-tritium (DT) plasmas tritium is externally supplied, and the most part of fueled tritium is considered to be lost from the plasma. In such a case the equilibrium tritium density is determined mainly by the tritium loss rate from the plasma. On the other hand, in deuterium and deuterium-helium3 (D^3He) plasmas, the tritium is not externally provided, and the tritium source by the D(d,p)T reaction plays important role to determine the equilibrium tritium density. In addition, the tritium consumption rate by $T(d,n)^4He$ reaction can also become another important factor as well as the loss rate depending on the plasma parameters.

In this paper we consider deuterium and D^3He plasma, and on the basis of the Boltzmann-Fokker-Planck (BFP) analysis model [3], distortion of the fuel-ion velocity distribution functions in burning plasma and their effects on tritium balance (fusion reaction rate coefficients) are examined. As a driving force to induce distortion of the distribution functions, we consider the 1.01-MeV triton source by D(d,p)T reactions and NI scattering between tritons and energetic ions. The degree of the modification in the triton equilibrium density due to the reactivity (fusion reaction rate coefficient) enhancement or reduction is evaluated.

2. Analysis Model

The Boltzmann–Fokker–Planck (BFP) equation [3] for fast ions, i.e., protons produced by the $^3He(d,p)^4He$ reactions, alpha-particles produced by the $T(d,n)^4He$ reactions, triton produced by the D(d,p)T reaction, ^3He produced by the $D(d,n)^3He$ reaction, and deuteron are simultaneously solved considering both Coulomb and NI scattering effects. As background-particle species, all the above ions

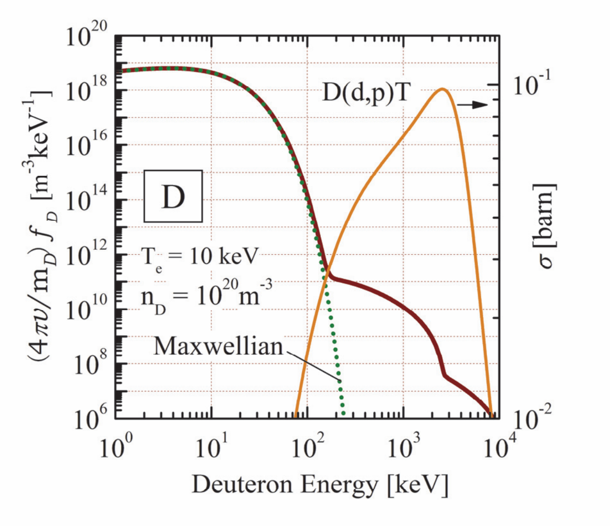

Fig.1 Deuteron distribution function in deuterium plasma and D(d,p)T cross section as a function of deuteron energy in the laboratory system.

and electrons are considered, hence the equations include nonlinear collisions. The electrons are assumed to be Maxwellian and its temperature is given as an initial condition. We consider the NI scattering between 1) alpha-particle and D, 2) alpha and T, 3) alpha and ^{3}He, 4) proton and D, 5) proton and T and 6) proton and ^{3}He. The cross-sections for NI scattering are taken from the work of Perkins and Cullen. [4] The cross sections for the D(d,p)T, D(d,n)^{3}He, T(d,n)^{4}He and ^{3}He(d,p)^{4}He reactions are taken from the work of Bosch. [5]

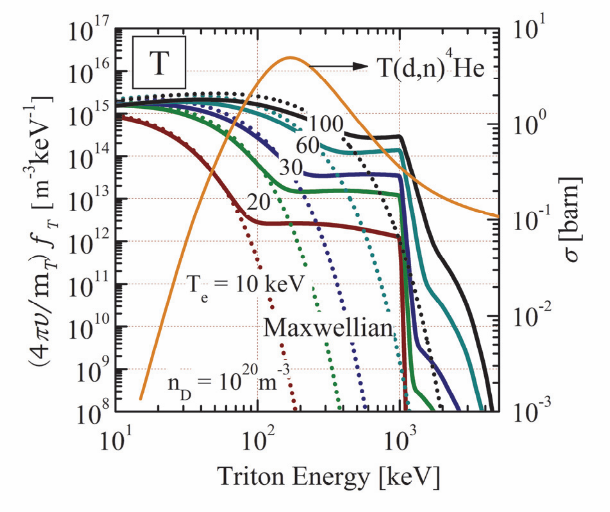

Fig.2 Triton distribution functions in deuterium plasma for several electron temperatures and T(d,n)^{4}He cross section as a function of triton energy in the laboratory system.

3. Results and Discussion

In Fig.1 the deuteron distribution function in deuterium plasma is shown with D(d,p)T fusion cross section as a function of deuteron energy in the laboratory system. In this case the electrons are assumed to be Maxwellian with 10 keV temperature, and deuteron density is taken as 10^{20} m^{-3}. The dotted line shows the Maxwellian. We can see that the knock-on tail is created due to the NI scattering of bulk deuterons by energetic protons. Since the knock-on tail appears in the energy range where the D(d,p)T cross section has large value, the triton production rate by the D(d,p)T reaction increases compared with Maxwellian plasma. In this case the degree of the enhancement of the triton production rate (thus the triton density) becomes almost 10 %. In Fig.2 we next show the triton distribution functions for several background electron temperatures. The large non-Maxwellian components appear owing to the energetic triton production (with 1.01-MeV birth energy) by the D(d,p)T reactions. We can also find that the knock-on tails created by NI scattering of energetic fusion-produced protons in the energy rage beyond 1.0 MeV. The reaction rate coefficient is also changed compared with the values for Maxwellian plasmas. The degree of the change in the reaction rate coefficient is determined depending on the relation between non-Maxwellian tail and the T(d,n)^{4}He fusion cross section. The enhancements are evaluated as 48, 10, −1.3, −12.4 and −14.1 % for 10, 20, 30, 60, 100 keV temperature respectively. In low temperature range the fraction of reactive component, i.e., tritons with almost 180 keV energy, increases as a result of non-Maxwellian tail formation. However, in high-temperature range, the reactive component reduces as a result of the non-Maxwellian tail formation. The change in the T(d,n)^{4}He reaction rate coefficient is directly related to the triton density.

At the presentation, the degree of the change in the triton density is discussed for various plasma conditions in deuterium and D^{3}He plasmas.

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