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Reduction in 14MeV Neutron Generation Rate by ICRF Injection in D-^{3}He Burning Plasmas

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Abstract

The triton distribution function during ion cyclotron range of frequency (ICRF) waves injection in D-^{3}He plasmas is examined by solving the 2-dimensional Fokker-Planck equation. Triton distribution function originally has a non-Maxwellian (tail) component around 1.01MeV birth energy range due to D(d,p)T fusion reaction. Owing to the extension of the original tail by ICRF injection, the high-energy resonance tritons further increase, and the velocity-averaged T(d,n)^{4}He fusion reaction rate coefficient, i.e. 14MeV neutron generation rate, decreases from the values when triton is assumed to be Maxwellian. It is shown that when tritons absorb ~1/200 of the fusion power from the waves in typical D-^{3}He plasma, i.e. T = 80keV, $n_D = 2\times10^{20}\mathrm{m}^{-3}$, τ_{E0} = 3sec and B = 6T, the 14MeV neutron generation rate is reduced by about ~20% from the values for Maxwellian plasmas.

Keywords:

ICRF heating, triton distribution function, D-^{3}He plasma, 14MeV neutron generation rate

1. Introduction

The use of D-^{3}He plasma in future fusion reactor is one of the most promising alternatives. In this plasma, the fraction of the fusion power carried by neutrons is small compared with the D-T plasma and highly efficient fusion is made possible by recovery of the fusion power carried by high-energy protons. The use of this plasma in Tokamak-based configuration, keeping radiation losses lower, is attractive and the studies for this purpose are important for improving the system efficiency and for increasing public acceptability in future fusion energy systems. So far many studies to investigate the characteristics of the D-^{3}He plasmas have been made [1]. We have especially examined the D-^{3}He burning characteristics considering the distortion of the fuel-ion velocity distribution functions [2-5]. When the fraction of the number of fuel ions increases in the velocity range where the fusion cross section is small, velocity-averaged fusion reactivity decreases [2]. We have previously evaluated the degree of the reduction in T(d,n)^{4}He reactivity (14MeV neutron generation rate) including the effects of the Nuclear Elastic Scattering [3,4] and magnetic field configuration [5].

In this paper, we attempt further reducing the 14MeV neutron generation rate by ICRF injection. So far various scenarios of plasma heating by ICRF waves using resonances at the fundamental cyclotron frequency [6] and its harmonics [7-9] for achieving the reactivity enhancement [10] have been made. In most of the previous studies the *enhancement* in the main fusion reactivity, e.g. ^{3}He(d,p)^{4}He (T(d,n)^{4}He) reactivity in D-^{3}He (D-T) plasma, has been considered. In this paper we focus our attention on the side reaction, i.e. T(d,n)^{4}He reaction in D-^{3}He burning plasmas, and try to *reduce* the T(d,n)^{4}He reactivity by considerably *small* radio-frequency (RF) heating power input. It is shown that owing to the RF power (1/100–1/200 of the fusion power) absorption in tritons, the 14-MeV neutron generation rate decreases by about 20% from the values for Maxwellian plasmas. An operation mode of the D-^{3}He fusion systems in which 14MeV neutron generation is suppressed, is proposed.

2. Analysis model

To facilitate the analysis we focus our attention only on the triton distribution function in burning D-^{3}He plasmas. Distribution functions of main fuel ions, i.e. D and ^{3}He, and electron are assumed to be Maxwellian at the same temperature. The distribution functions of α-particle and proton are ignored. Steady-state triton distribution function during ICRF heating in D-^{3}He plasmas is determined by solving the following 2D Fokker-Planck equation;

$$\left(\frac{\partial f_T}{\partial t}\right)^{Coulomb} + \left(\frac{\partial f_T}{\partial t}\right)^{RF} + \frac{1}{v^2}\frac{\partial}{\partial v}\left(\frac{v^3}{2\tau_E(v)}\right) f_T + S_T(v) - L_T(v) = 0\ , \qquad (1)$$

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where f_T is total (i.e. bulk plus tail) distribution function of triton, and is normalized so that the triton density is given by

$$n_T = \int f_T(v,\theta) d\vec{v} \, . \qquad (2)$$

The first term in Eq. (1) represents the influence of the Coulomb collisions with background particles, i.e. D, ^{3}He and electron. The second term accounts for the quasi-linear diffusion due to the ion cyclotron range of frequency (ICRF) waves. Following Stix treatment [6], we write the distortion of the triton distribution function by ICRF injection as

$$\left(\frac{\partial f_T}{\partial t}\right)^{RF} = \frac{\partial}{\partial v_\perp}\left(D_{RF}\frac{\partial f}{\partial v_\perp}\right), \qquad (3)$$

where $v_\perp$ is the velocity perpendicular to the magnetic field, i.e. $v_\perp = v \sin\theta$. The RF- induced diffusion in the velocity parallel to the magnetic field is neglected since it only gives a small contribution [11]. The perpendicular diffusion coefficient [6-9] due to nth harmonic ICRF waves, D_{RF} is given as

$$D_{RF} = C_{RF} J_{n-1}^2\left(\frac{k_\perp v_\perp}{\Omega_T}\right), \qquad (4)$$

where Ω_T is the cyclotron frequency of the triton, and J_{n-1} represents the Bessel function of the first kind of order n–1. The perpendicular wavenumber of the ICRF wave, $\kappa_\perp$, is obtained from the cold plasma dispersion relation. Throughout the calculation the injected wave frequency is chosen as $\omega = 5\Omega_T$. The coefficient C_{RF} is determined so that the absorbed RF power by tritons is equal to P_{fusion}/Q_{RF}. Here P_{fusion} represents the total fusion power. The parameter Q_{RF}, which implies the ratio of fusion power to the absorbed RF power by tritons, is externally given in the calculations.

The third term of the left hand side of Eq. (1) represents sink of energy due to thermal conduction. The velocity-dependent energy confinement time may be written as $\tau_E(v) = c_E\tau_{E0}\mathrm{Max}[1,v/v_0]^\gamma$. Here τ_{E0} is the energy confinement time, i.e. τ_{E0} = 3sec. The dimensionless coefficient C_E is adjusted so as to keep the velocity-integrated energy loss as $(3/2)n_T T/\tau_{E0}$. We can simulate various loss mechanism by adjusting the parameters v_0 and γ.

The triton source (S_T) and loss (L_T) can be written

$$S_T(v) = \frac{1}{2} n_D^2 \langle\sigma v\rangle_{D(d,p)T} \frac{\delta(v - v_T)}{4\pi v^2} S_{D(d,p)T} \, , \qquad (5)$$

$$L_T(v) = -\frac{f_T}{\tau_P(v)} - \varsigma(v) f_T \, , \qquad (6)$$

where $\tau_P(v) = c_P\tau_{P0}\mathrm{Max}[1,v/v_0]^\gamma$. Here τ_{P0} is the particle confinement time, i.e. $\tau_{P0} = 2\tau_{E0}$, and v_T represents the velocity corresponding to 1.01MeV birth-triton energy. The second term in Eq. (6) represents a triton loss by T(d,n)^{4}He fusion reactions, here

$$\zeta(v) = \frac{n_D}{\sqrt{2\pi}}\left(\frac{m_D}{T}\right)^{3/2}\frac{1}{v}\int dv_D v_D \exp\left(-\frac{m_D}{2T}v_D^2\right)\left[\int_{|v-v_D|}^{v+v_D} dv_r v_r^2 \sigma_{DT}(v_r)\right]. \qquad (7)$$

For given background temperature ($T \equiv T_D = T_{^3He} = T_e$), fuel-ion densities ($n_D = 2n_{^3He}$) and Q_{RF}, we numerically solve Eq. (1). From the derived triton distribution function, we can evaluate the T(d,n)^{4}He fusion reactivity;

$$\langle\sigma v\rangle_{T(d,n)^4He} = \frac{4\pi^2}{n_T}\left(\frac{m_T}{2\pi T}\right)^{3/2}\int dv_D v_D \exp\left(-\frac{m_D}{2T}v_D^2\right)\int dv_T \int d\mu v_T f\left[\int_{|v_D - v_T|}^{v_D + v_T} dv_r v_r^2 \sigma(v_r)\right]. \qquad (8)$$

By comparing the obtained reactivity with the one when triton distribution is Maxwellian, i.e. $\langle\sigma v\rangle^{Maxwell}_{T(d,n)^4He}$, the degree of decrement in T(d,n)^{4}He fusion reactivity by ICRF injection is estimated. For this purpose, we introduce the following decrement parameter;

$$\eta = \left(\frac{\langle\sigma v\rangle_{T(d,n)^4He}}{\langle\sigma v\rangle^{Maxwell}_{T(d,n)^4He}} - 1\right) \times 100 \ [\%] \, . \qquad (9)$$

3. Results and discussion

In Fig. 1 we first show the steady-state triton distribution function as a function of parallel and perpendicular velocity components to the magnetic field. The distribution function and velocities are normalized to the thermal velocity, i.e. v_{th}, and to the velocity v_T respectively. In this calculation, plasma temperature T = 80keV, fuel-ion and electron densities $n_D = 2n_{^3He} = (1/2)n_e = 2\times10^{20}\mathrm{m}^{-3}$, external magnetic field B = 6T and Q_{RF} = 160 are assumed. It has previously shown that in

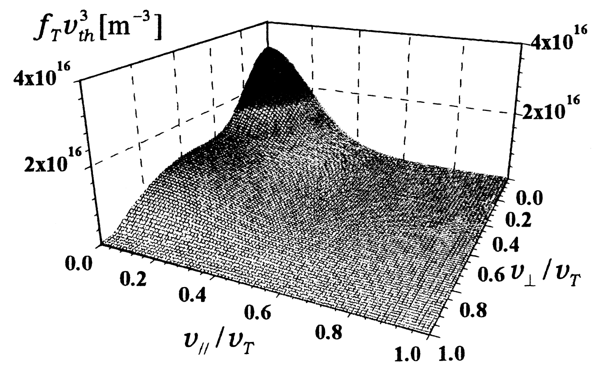

Fig. 1 Triton distribution function during ICRF injection in D-^{3}He plasmas, i.e. T = 80keV, $n_D = 2\times10^{20}\mathrm{m}^{-3}$, B = 6T and Q_{RF} = 160.

typical D-^{3}He plasmas, high-energy tail is formed in triton distribution due to continuous triton generation by D(d,p)T reaction around 1.01-MeV triton birth energy range. It is found that the triton tail is extended by ICRF injection in high-energy (high perpendicular velocity) range. This is owing to the wave energy is transferred to the tritons, who have resonant velocity, through the cyclotron motion. The number of the high-energy resonant tritons hence increases compared with Maxwellian.

In Fig. 2 the T(d,n)^{4}He fusion cross sections [12] are presented as a function of triton energy (and also as a function of normalized triton velocity) in the laboratory systems. As is well known, the T(d,n)^{4}He cross section has a peak around ~100keV triton energy, and high-energy tritons more than several hundreds-keV energy hardly make the T(d,n)^{4}He fusion reaction. As a result of increment in the fraction of the high-energy component to the total (bulk plus tail) tritons, the velocity-averaged T(d,n)^{4}He fusion reaction rate coefficient decreases from the values for Maxwellian. By using the Eq. (8), we can evaluate the T(d,n)^{4}He fusion reaction rate coefficient for the triton distribution function shown in Fig. 1 as 6.8×10^{-22}m^{3}sec^{-1}. (If we assume both deuteron and triton distribution functions are Maxwellian, the T(d,n)^{4}He fusion reaction rate coefficient is 8.9×10^{-22}m^3 sec^{-1}). In this case, the decrement in the T(d,n)^{4}He fusion reaction rate coefficient by ICRF injection is estimated as $\eta = -23.5\%$.

In Fig. 3 the decrement parameter η is presented as a function of temperature for several Q_{RF} values. The background deuteron density is fixed as $n_D = 2\times10^{20}$m^{-3}. The degree of the decrement parameter has a maximum value around ~90keV plasma temperature. This is because the non-Maxwellian component, i.e. high-energy tail, is trapped into the bulk component in high temperature range, whereas the fraction of the tail becomes small in low-temperature range. It should also be noted that the degree of the decrement becomes small with increasing Q_{RF} values. This is because the extension of the high-energy tail in triton distribution function by ICRF waves is weakened for small RF power absorption.

We next show the decrement parameters as a function of deuteron density in Fig. 4. The plasma temperature is fixed as 80keV. The degree of the decrement has a peak around $n_D = 1.5\times10^{20}$m^{-3}. This is explained, in high-density range, the collisional slowing-down via Coulomb collisions with background ion is enhanced, and the number of tritons who belong in the tail-component decreases. In low density range the fusion power output decreases, and the RF power absorption is relatively small.

Throughout the calculation it has been shown that in a typical reactor-grade D-^{3}He plasma, the 14-MeV neutron generation rate can be decreased more than 20% by extending the original triton tail using the ICRF injection. We have shown an idea of the operation mode in which 14MeV neutron generation rate is suppressed by small ICRF injection, through a simple 2D Fokker-Planck simulation. In this paper

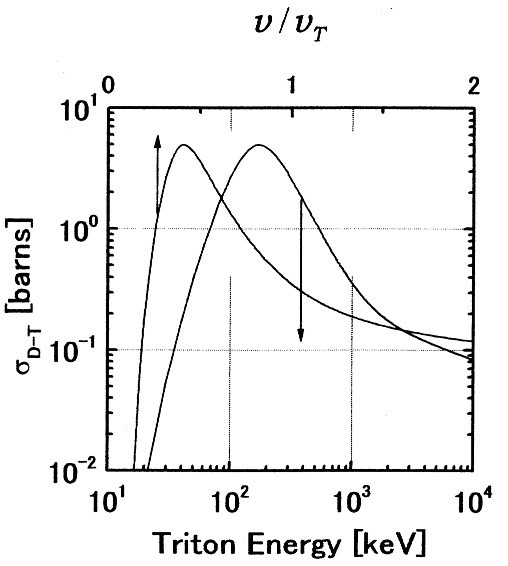

Fig. 2 T(d,n)^{4}He fusion cross sections as a function of triton energy (velocity) in the laboratory systems.

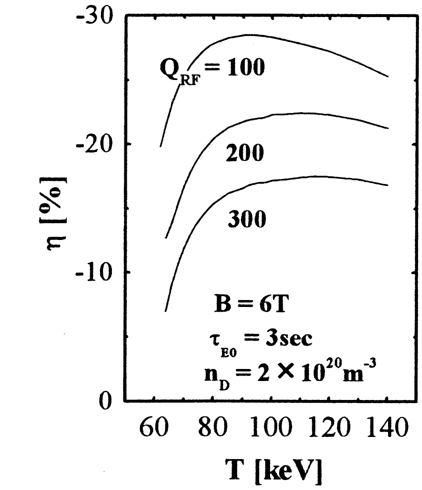

Fig. 3 The decrement parameters η as a function of plasma temperature.

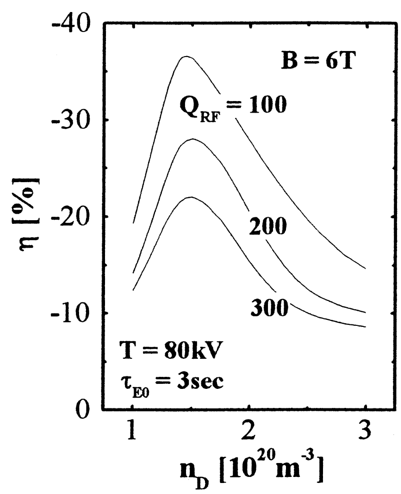

Fig. 4 The decrement parameters η as a function of deuteron density.

we have not examined how much fractions of the injected RF power is actually absorbed by tritons. To make this point clear, more detailed analysis including the space profiles of plasma temperature and density would be necessary.

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