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Thermonuclear Reactivity of D-T Fusion Plasma with Spin-Polarized Fuel

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Abstract

The thermonuclear reactivity of deuterium(D) - tritium(T) fusion plasma with spin-polarized fuel has been studied. Two mechanisms of depolarization, collisions and waves, in the high temperature fusion plasma have been considered. The binary collisions have been found not to change the nuclear spin states. The waves with a frequency of a few GHz, however, changes the spin states appreciably, when $\delta B/B_0$ (the ratio of the amplitude of the fluctuating magnetic field to the external field) becomes larger than 10^{-5}.

keywords: spin-polarized fusion, thermonuclear reactivity, depolarization, spin-orbit interaction, waves

1 Introduction

In 1982, Kulsrud *et al.* have examined the possibility of spin-polarized fusion and found that the depolarization rate of polarized fusion fuels is very small compared to the reaction rates when we consider the mechanisms of depolarization such as the binary collisions, the fluctuation of magnetic field and the inhomogeneity of the field [1]. If it is possible to utilize the polarized fuels, there would be two merits of spin-polarized fusion.

One of the merits is the enhanced cross-section of fusion reaction up to 1.5 times large. If d_+, d_0 and d_- denote the fractions of D nuclei polarized parallel, transverse, and antiparallel to $\vec{B}$, respectively, and if t_+ and t_- represent the fractions of the T nuclei in the same manner as D, the total cross-section of spin-polarized D-T reaction have been found,

$$\sigma = (a + \frac{2}{3}b + \frac{1}{3}c)\sigma_{3/2} + (\frac{1}{3}b + \frac{2}{3}c)\sigma_{1/2}. \quad (1)$$

where $a = d_+t_+ + d_-t_-$, $b = d_0$, and $c = d_+t_- + d_-t_+$. The cross section $\sigma_{3/2}$ and $\sigma_{1/2}$ are the cross-section for $\frac{3}{2}^+$ state and $\frac{1}{2}^+$ state, respectively. Since the cross-section $\sigma_{3/2}$ is much larger than $\sigma_{1/2}$, we are able to estimate with only the first term alone in Eq.(1). Thus we found that the cross-section for the polarized fuels becomes 1.5 times as large as the one for unpolarized fuels, when both D and T are polarized paralell to $\vec{B}$ completely.

The other merit is related to the angular distribution of the fusion product. We will be able to control the angular distribution of 14MeV-neutrons, and to mitigate the damage of the first wall in the fusion reactor.

After the work of Kulsrud, the applications and the properties of spin-polarized fusion are investigated. Micklich and Jassby have investigated the ignition and energy breakeven conditions and also calculated the neutron wall loading and consequent tritium breeding ratio [2]. Ignition characteristics have been investigated for the polarized fusion plasma [3, 4]. The works in Ref. [2, 3, 4] assume no depolarization mechnisms in plasmas. The reviews for spin polarized fusion plasma are written in [5, 6]. There were several critical papers [7, 8]. A kinetic equation have described by Cowley *et al.*, including the new polarization space [9]. Therefore, it is complicated to solve the equation for polarizing plasma. To avoid the complicated task, we are able to classify the statistical quantity by the magnetic quantum number according to the neutron transport analysis [10]. Thus it is possible to describe the distribution function classified by the magnetic quantum numbers.

In the present paper, we have made the kinetic model for spin-polarized fusion plasmas and investigated the effect of depolarization of the polarized fuels on the thermonuclear reactivity for D-T fusion plasma.

2 Kinetic Model for Spin-Polarized Fusion Plasmas

We will study the kinetic model for the spin-polarized fusion plasmas in this section. The distribution functions for fusion fuels (D and T) are classified by the magnetic quantum number. If the transition rate of the spin states was dependent on the particle energy, the kinetic model should be employed to study the fusion reactivity. Without the dependence of the particle energy on the rates, the fluid model becomes convenient. It seems favorable, however, to employ the kinetic model for the future development of our study.

Here, we assume the availability of the perfectly polarized fusion fuels. And for simplicity, the isotropic distribution model is applied.

2.1 description of distribution function

Since the spin quantum number of deuteron D is unity, the magnetic quantum number of D, m_D, has the values of 1, 0 and -1. Deuteron D in the unpolarized plasmas equally exist in the three spin states. Thus the probabilities of the existence in each spin states become 1/3. The probabilities for polarized particles, however, should not be identical among three spin states. Therefore, the ordinary distribution function of D, i. e., $f_D(v)$, will be described by the expression:

$$f_D(v) = f_D^+(v) + f_D^0(v) + f_D^-(v), \tag{2}$$

where the superscript +, 0 and - represent the magnetic quantum number for $m = 1, 0$ and -1, respectively.

The method to classify the distribution function by the magnetic quantum number has reported in the neutron transport analysis. In Ref. [10], the neutron flux is classified by up and down of spin. And Boltzmann transport equation has described with the spin-dependent macroscopic cross section. According to their work, we are able to classify the statistical quantity by the magnetic quantum number.

Similary to D, the distribution function of T is also classable by the spin states. Since the spin quantum number of T is 1/2, the magnetic quantum numbers of T are 1/2 and -1/2. Thus the distribution function of T should be classified as

$$f_T(v) = f_T^+(v) + f_T^-(v), \tag{3}$$

where the superscript + and - represent $m = 1/2$ and $m = -1/2$.

If the plasma ions are polarized completely. such as

$$f_D^0(v) = f_D^-(v) = f_T^-(v) = 0,$$

the fusion reaction rate is enhanced 1.5 times. In the plasmas, however, some depolarization mechanisms exist and increase the above distribution function $f_D^0(v)$, $f_D^-(v)$, and $f_T^-(v)$. We will consider this process in the subsequent section.

2.2 model equation for spin-polarized plasmas

When we discuss the kinetic equation for spin-polarized plasmas, we will employ the distribution function indexed by the magnetic quantum numbers m. Here, we consider the transition of the spin states of polarized particles in fusion plasmas. Particles supplied into the plasma are assumed to be perfectly polarized in states $m_D = 1$ and $m_T = 1/2$. We are able to consider the fuel particle loss due to the D-T fusion reaction. The particle and the energy loss are expressed by using the confinement time dependent on the velocity of particles. The model equation is given by:

$$\begin{aligned}(\frac{\partial f_a^m}{\partial t}) &= (\frac{\partial f_a^m}{\partial t})_{cou} + \frac{1}{v^2}\frac{\partial}{\partial v}[\frac{v^3 f_a^m}{2\tau_E(v)}] \\ &+ S_a^m(v) - L_a^m(v) \\ &- \sum_{m'}(\frac{\partial f_a^m}{\partial t})_{m\to m'} + \sum_{m'}(\frac{\partial f_a^{m'}}{\partial t})_{m'\to m} \\ &= 0. \end{aligned} \tag{4}$$

The equation (4) is based upon the model used by Matsuura *et al.* to study the high energy tail effect in fusion plasmas [11]. The first term $(\frac{\partial f_a^m}{\partial t})_{cou}$ represents the Coulomb collision term. The second term describes the particle loss from unit volume in velocity space due to the heat conduction. The third and fourth term, i. e. , $S_a^m(v)$ and $L_a^m(v)$, indicate the source and the loss of a species particles in real space due to the particle injection, the nuclear reaction and the convection of particles, respectively. Here we will consider the following case:

$$S_a(v) = L_a(v) = \sum S_a^m(v) = \sum L_a^m(v). \tag{5}$$

Let us remind that throughly polarized particles are supplied into the plasma. Thus

$$S_a(v) = \sum S_a^m(v) = S_a^+(v). \tag{6}$$

The explicit form of loss term $L_a^m(v)$ are discussed in Appendix A. The term $(\frac{\partial f_a^m}{\partial t})_{m\to m'}$ represents the number of particles in unit volume of real and velocity space changing its magnetic quantum number m to m'. Prohibited transitions are omitted here. The transition terms for some depolarization mechanisms are discussed after this section.

2.3 thermonuclear reactivity

In general, the thermonuclear reactivity of D-T reaction is discribed in the following form:

$$\langle\sigma v\rangle_{DT} = \frac{1}{n_D n_T}\iint f_D(\overrightarrow{v_D}) f_T(\overrightarrow{v_T}) \sigma v_r d\overrightarrow{v_D} d\overrightarrow{v_T}. \tag{7}$$

When the particles are isotropically distributed in the velocity space, the reactivity will be written as

$$\begin{aligned}
&\langle\sigma v\rangle_{DT} \\
&= \frac{8\pi^2}{n_D n_T}\int_0^\infty v_D f_D(v_D)\int_0^\infty v_T f_T(v_T) \\
&\times \left(\int_u^w v_r^2\sigma(v_r)dv_r\right)dv_D dv_T, \\
&u = |v_D - v_T|, \quad w = v_D + v_T \qquad (8)
\end{aligned}$$

Since the fusion reaction cross-sections vary depending on the spin states of D and T, it is neccesary to modify the description of the fusion reactivity. When deuterons with magnetic quantum number m_D react with tritons which have m_T, the thermonuclear reactivity $\overline{\langle\sigma v\rangle}_{DT}^{m_D m_T}$ is expressed by

$$\begin{aligned}
&\overline{\langle\sigma v\rangle}_{DT}^{m_D m_T} \\
&= \frac{8\pi^2}{n_D n_T}\int_0^\infty v_D f_D^{m_D}(v_D)\int_0^\infty v_T f_T^{m_T}(v_T) \\
&\times \left(\int_u^w \epsilon_{m_D m_T} v_r^2\sigma(v_r)dv_r\right)dv_D dv_T \qquad (9)
\end{aligned}$$

Thus thermonuclear reactivity of spin-polarized D-T fusion plasmas becomes,

$$\overrightarrow{\langle\sigma v\rangle}_{DT} = \sum_{m_D}\sum_{m_T}\overline{\langle\sigma v\rangle}_{DT}^{m_D m_T}. \qquad (10)$$

Suppose the perfectly polarized fuels are supplied into the plasma without no depolarization mechanisms, the reactivity $\overrightarrow{\langle\sigma v\rangle}_{DT}$ increases 1.5 times as large as the one for unpolarized plasmas. The polarization mechanisms in the plasmas, however, decrease $\overrightarrow{\langle\sigma v\rangle}_{DT}$.

3 Effects of Depolarization

Mechanisms of depolarization exist in high temperature plasma and they are discussed in this section. We consider two mechanisms of depolarization such as binary collision and the magnetic fluctuation due to the RF current drive. The transition terms in Eq.(4) due to two deplarization mechanisms will be formulated.

3.1 transition of spin states

Let $r_{m\to m'}$ denote the rate of change from m to m' then the transition term $\sum_{m'}(\frac{\partial f_a^m}{\partial t})_{m\to m'}$ becomes

$$\sum_{m'}(\frac{\partial f_a^m}{\partial t})_{m\to m'} = \sum_{m'} r_{m\to m'}(v)f_a^m(v). \qquad (11)$$

We will devote to find the explicit form of $r_{m\to m'}$ hereafter

(1) spin-orbit interaction

Several transition cross-sections $\sigma_{m\to m'}$ due to spin-orbit interaction among fusion fuels are obtained and presented in Appendix B. Since the cross-sections are found to be independent of the particles energy, the transition rate is written as

$$\begin{aligned}
&r_{m\to m'}(v) \\
&= \sum_b \frac{4\pi}{3v}\sigma_{m\to m'}\left\{\int_0^v (v_b^4 + 3v^2 v_b^2)f_b(v_b)dv_b\right. \\
&+ \left.\int_v^\infty (v_b v^3 + 3v_b^3 v)f_b(v_b)dv_b\right\}. \qquad (12)
\end{aligned}$$

Here the subscript b stands for the background particles. Since the electron distribution is considered Maxwellian, the rate $r_{m\to m'}$ by the effect of electrons becomes

$$\begin{aligned}
&r_{m\to m'}(v) \\
&= n_e\sigma_{m\to m'}v\left\{\left(1+\frac{1}{2\alpha v^2}\right)\mathrm{erf}(\sqrt{\alpha}v)\right. \\
&+ \left.\frac{1}{v\sqrt{\pi\alpha}}\exp(-\alpha v^2)\right\}, \qquad (13)
\end{aligned}$$

where $\alpha = m_e/(2T_e)$.

(2) resonance with waves

Since oscilating magnetic field whose frequency range in the resonant region with spin precession frequency depolarizes the particles, this is the key issue for the spin polarized fusion. Waves in the plasma are kinds of fluctuating field and therefore are worthy to study. Some waves are caused by the plasma instabilities, which have a relatively low frequency according to the experimental observation in tokamaks. Fusion fuels are resonant with the waves which have a frequency of a few GHz. Therefore, the nuclear spin seems not to be resonant with the waves due to instabilities. However, in the other configurations waves may have the higher frequency than tokamaks. On the other hand, for plasma heating or current drive we utilize also the magnetic waves. These frequencies vary in the wide range. Thus the waves externally applied may be resonant with the spin precession frequency.

In this paper, we will study the properties in the parameters of the oscilating magnetic field and the external magnetic field. And we will have no restriction to discuss both the waves applied externally and the waves due to instabilities.

When the waves in the polarized plasma have a frequency of a few GHz, plasma ions will depolarize. In this case, according to Appendix C, the rate $r_{m\to m'}(v)$ becomes:

$$r_{m\to m'}(v) = \lambda_a\left(\frac{\delta B}{B_0}\right)^2\Omega_a, \quad (14)$$

where δB and B_0 denote the amplitude of fluctuating magnetic field and the non-fluctuating external magnetic field. The constant quantity λ_a and the frequency Ω_a depend on the particle species. In our calculation, we use $\lambda_D = 1/8$ and $\Omega_D = 0.206$ GHz for deuterons, and $\lambda_T = 1/4$ and $\Omega_T = 1.42$ GHz for tritons.

3.2 prameters for discussion

For the quantitative discussion of depolarization, we will define the polarization P and the alignment A for the plasma. These physical quantities are obtained by calculating the number density of D and T in certain spin state. The number density for a species with the magnetic quantum number m is given

$$n_a^m = \int_0^\infty 4\pi v^2 f_a^m(v)dv. \quad (15)$$

The polarization of D and T are written by the above n_a^m in the following form:

$$P_D = \frac{n_D^+ - n_D^-}{n_D^+ + n_D^0 + n_D^-}, \quad P_T = \frac{n_T^+ - n_T^-}{n_T^+ + n_T^-}. \quad (16)$$

If D and T are polarized completely in the states $m_D = 1$ and $m_T = 1$ respectively, polarizations P_D and P_T become unity. For the complete description of polarization condition, we should caluculate the alignment A for the particles with spin quantum number $s \geq 1$. Since deuteron's spin quantum number s=1, its alignment A is expressed:

$$A = \frac{n_D^+ - 2n_D^0 + n_D^-}{n_D^+ + n_D^0 + n_D^-}. \quad (17)$$

The alignment A ranges in $-2 \leq A \leq 1$, and it is unity in a case $P_D = 1$. The thermonuclear reactivity for a polarized plasma with no depolarization is 1.5 times as large as the one for non polarized plasma. Due to the depolarization mechanisms in the plasma the reactivity decreases to some extent. We will calculate the decrement of the reactivity η defined as

$$\eta = \frac{\overrightarrow{\langle\sigma v\rangle}_{DT} - \overrightarrow{\langle\sigma v\rangle}_0}{\overrightarrow{\langle\sigma v\rangle}_0} \times 100 \quad [\%], \quad (18)$$

where $\overrightarrow{\langle\sigma v\rangle}_0$ denotes the reactivity for complete polarization. The decrement η becomes -33.3 [%] as the fuels depolarize completely.

4 Results and Discussions

We have solved Eq. (4) numerically at steady state under the condition given in Table 1. After calculating the distribution functions, we have estimated the polarization (P_D and P_T), the alignment of deuteron A, and the decrement of the reactivity η.

Table 1: Input parameters

deuteron density n_D	5.0×10^{20}[m^{-3}]
triton density n_T	5.0×10^{20}[m^{-3}]
electron temperature T_e	10[keV]
deuteron temperature T_D	9.819[keV]
triton temperature T_T	9.812[keV]

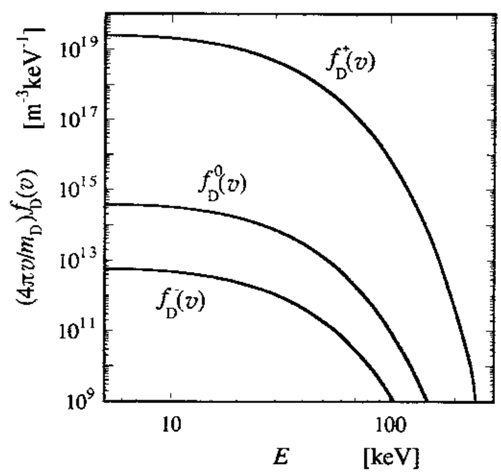

Fig. 1: Distribution function for deuterons.

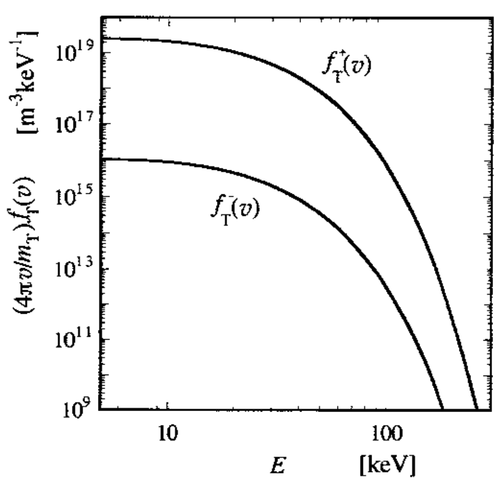

Fig. 2: Distribution function for tritons.

At first, we consider the spin-orbit interaction alone as the depolarization mechanisms. The distri-

Table 2 Effects of spin-orbit interaction

polarization of deuterons P_D	0.9999(8)
polarization of tritons P_T	0 9991(4)
alignment of deuterons A	0.9999(5)
decrement of the reactivity η	-0.5033(6)[%]

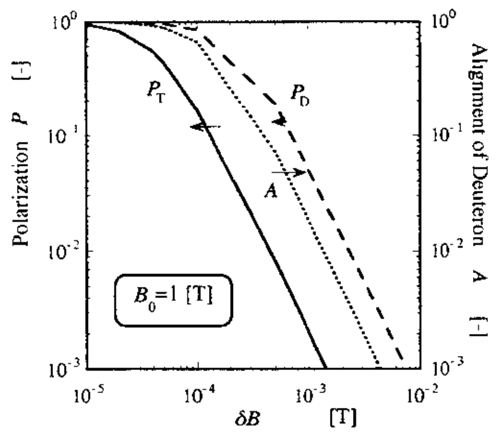

Fig 3: Polarization for deuteron and triton and alignment for deuteron in a case of the external field $B_0 = 1$ [T].

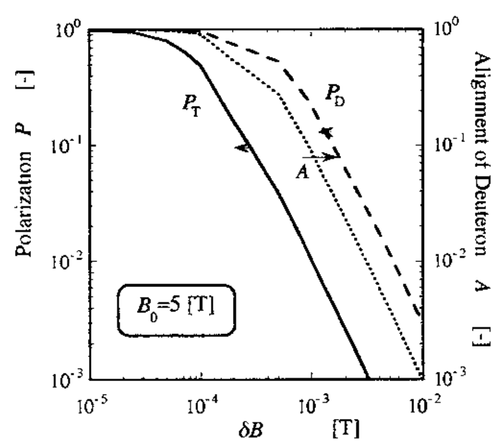

Fig. 4: Polarization for deuteron and triton and alignment for deuteron in a case of the external field $B_0 = 5$ [T]

bution function classified by the magnetic quantum number of deuterons and tritons are shown in Fig 1 and Fig. 2 For deuterons, the distribution $f_D^0(v)$ is about five orders of magnitude smaller than $f_D^+(v)$ Since particles with $m_D = -1$ are generated by the transition process from $m_D = 0$, therefore the density of those is the smallest among three spin states. For tritons, the distribution $f_T^-(v)$ is about three orders of magnitude smaller than $f_T^+(v)$. The consequent polarization and alignment of deuterons are presented in Table 2. If the perfectly polarized fuels in $m_D = 1$ and $m_T = 1/2$ are supplied, the polarization and alignment are kept to be almost unity. The decrement of the reactivity η is found -0.5 %. We are able to conclude that the effect of spin-orbit interaction on the thermonuclear reactivity is neglegible.

Varying the external magnetic field B_0 and the amplitude of magnetic fluctuation δB in Eq (14), the effects of waves have been considered The polarization and the alignment are shown in Fig. 3, Fig. 4 and Fig. 5 in the external field $B_0 = 1$ T, $B_0 = 5$ T and $B_0 = 10$ T, respectively. In all cases, when δB is smaller than 10^{-5} T, the polarization and the alignment are kept unity. Thus the decrement of reactivity η has a vanishing value as you can see in Fig 6 The amplitude δB become greater than 10^{-5} T, however, the polarization become ineffective. We show the amplitude of the oscilating magnetic field with the resonance frequency to reduce the reactivity by 10, 20, and 30 % in the external magnetic field B_0 in Fig. 7. The strong external field is found preferable in order to gain the sufficient polarization effect.

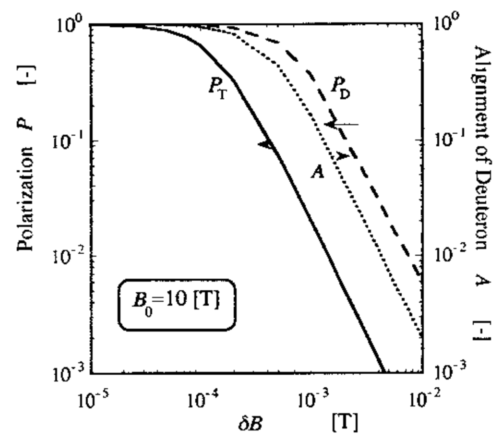

Fig. 5: Polarization for deuteron and triton and alignment for deuteron in a case of the external field $B_0 = 10$ [T].

The frequencies of fluctuating magnetic field due to the instability in tokamaks have been observed in a lower range from the resonating GHz frequency. Thus we conclude no effective depolarization in tokamak plasmas due to instabilities. For the current drive and the heating, lower hybrid waves are applied, whose frequency exist in GHz. If lower hybrid current drive (LHCD) and heating (LHH) are applied, the plasmas will be depolarized consequently.

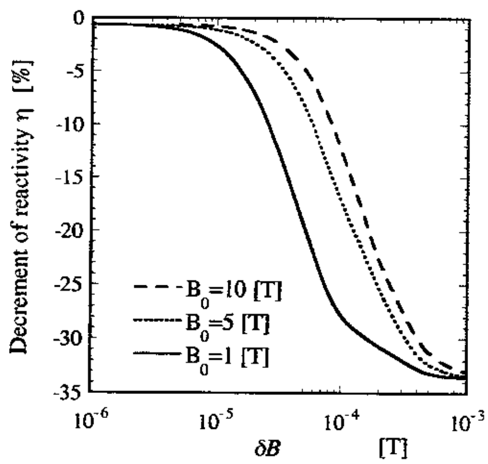

Fig. 6: Decrement parameter η versus the fluctuating magnetic field.

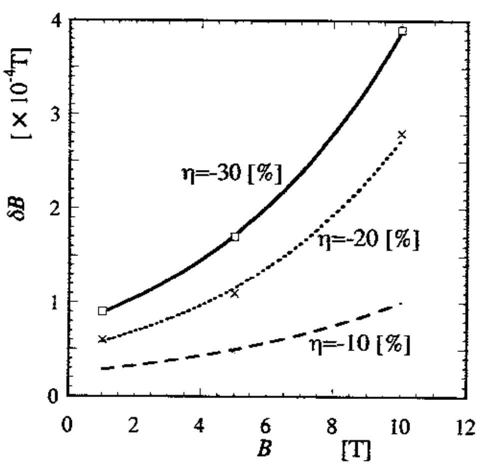

Fig. 7: The amplitude of the fluctuating magnetic field with the resonance frequency to reduce the reactivity by 10, 20, and 30 % in the external magnetic field B_0.

5 Concluding Remarks

We have studied the kinetic model for spin-polarized fusion plasmas. We have investigated the depolarization in the plasma supplied with the perfectly polarized deuterons D and tritons T having the magnetic quantum number $m_D = 1$ and $m_T = 1/2$, respectively. Especially, we consider the depolarization mechanisms such as 1) spin-orbit interaction, and 2) manetic waves. The following results are obtained in the present research.

1. spin-orbit interaction
   (a) The decreases of polarization are less than 0.1 [%] both for the deuterons and tritons.
   (b) The decrease of thermonuclear reactivity $\langle \sigma v \rangle$ from the perfectly polarized plasma is 0.5 [%].
2. magnetic waves
   (a) When the ratio of the amplitude of fluctuating magnetic field δB to the external magnetic field B_0, i. e., $\delta B / B_0$, is smaller than 10^{-5}, then the polarization effect is maintained safely.
   (b) The resonance frequency with spin-polarized fuel is estimated to be about GHz. The frequency range of lower hybrid current drive and heating (LHCD and LHH) is in this range. Thus LHCD and LHH are incompatible with the spin-polarized fusion.

In this paper, though the effect of the binary collisions by spin-orbit interaction on the polarization is found neglegible, the magnetic wave for current drive and heating seem to damage considerably on the polarization advantages. Depolarization rates due to inhomogenious field and precise calculation of the spin-wave resonance have been remaind for our future study.

Acknowledements

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Appendix

A Loss Term

We have considered the particle diffusion and the fusion reaction as the loss mechanisms of ions from the polarized plasmas. For diffusion process, particles are assumed to be trapped during the confinement time τ_p, which is made dependent on the particle velocity. The loss term due to the diffusion is expressed in the form

$$\left(\frac{\partial f_a^{m_a}}{\partial t}\right)_{diff} = \frac{\partial f_a^{m_a}}{\tau_p(v)}, \qquad (A.1)$$

where the confinement time is described by

$$\tau_p(v) = \tau_p \max\left[1, \frac{v}{v_{th}}\right]^{\gamma}. \qquad (A.2)$$

In our case, $\tau_p = 4$ [sec] and $\gamma = 4$ are used in all calculations.

The number of particles lost due to the fusion reaction in the unit phase space and the unit time is written

$$\left(\frac{\partial f_a^{m_a}}{\partial t}\right)_{DT} = \sum_{m_b} \int f_a^{m_a}(\overrightarrow{v_a}) f_b^{m_b}(\overrightarrow{v_b}) \times \epsilon_{m_a m_b} \sigma(v_r) v_r d\overrightarrow{v_b}, \qquad (A.3)$$

where $v_r = |\overrightarrow{v_a} - \overrightarrow{v_b}|$. For the isotropic distribution, we can rewrite the above equation:

$$\left(\frac{\partial f_a^{m_a}}{\partial t}\right)_{DT} = r_a^{m_a}(v_a) f_a^{m_a}(v_a), \qquad (A.4)$$

where,

$$r_a^{m_a}(v_a) = \sum_{m_b} \frac{2\pi}{v_a} \int_o^{\infty} v_b f_b^{m_b}(v_b) \times \left(\int_u^w \epsilon_{m_a m_b} \sigma(v_r) v_r^2 dv_r\right) dv_b. \qquad (A.5)$$

Therefore, the loss term for a species particles with m_a is expressed by

$$\begin{aligned} L_a^{m_a}(v) &= \left(\frac{\partial f_a^{m_a}}{\partial t}\right)_{diff} + \left(\frac{\partial f_a^{m_a}}{\partial t}\right)_{DT} \\ &= \frac{\partial f_a^{m_a}}{\tau_p(v)} + r_a^{m_a}(v) f_a^{m_a}(v). \qquad (A.6) \end{aligned}$$

B Cross-Section for Spin-Orbit Interaction

We will calculate the magnetic field generated by the motion of charged particle and the interaction between the magnetic field and the nuclear spin. Here, we assume the non-relativistic and linear motion with constant velocity. The vector potential associated with the motion of the charged particle is

$$\overrightarrow{A} = \frac{q}{4\pi\varepsilon_0 c^2} \overrightarrow{v}. \qquad (B.7)$$

The corresponding magnetic field is easily obtained in the form

$$\begin{aligned} \overrightarrow{B} &= \nabla \times \overrightarrow{A}, \\ &= \frac{qvb}{4\pi\varepsilon_0 c^2 r^3} \overrightarrow{n}, \qquad (B.8) \end{aligned}$$

where, $\overrightarrow{n}$ is the vector with the unit length in the same direction as $\overrightarrow{r} \times \overrightarrow{v}$. Since the angular momentum $\overrightarrow{l}$ is

$$\begin{aligned} \overrightarrow{l} &= m(\overrightarrow{r} \times \overrightarrow{v}) \\ &= -mvb\overrightarrow{n}, \qquad (B.9) \end{aligned}$$

thus the magnetic field due to the motion of charged particle is witten as

$$\overrightarrow{B} = -\frac{q}{4\pi\varepsilon_0 c^2 r^3 m} \overrightarrow{l}. \qquad (B.10)$$

The interaction between the magnetic field and the magnetic moment of the nucleus is in the form

$$U = -\overrightarrow{\mu_i} \cdot \overrightarrow{B}, \qquad (B.11)$$

where μ_i denotes the magnetic moment of the nucleus, which is written as

$$\overrightarrow{\mu_i} = \frac{g_i e}{2m_p} \overrightarrow{s}. \qquad (B.12)$$

The g factors of respective particles g_i are 0.86 for D and 5.94 for T. The spin vector operaters $\overrightarrow{s}$ for D and T are

$$\overrightarrow{s} = \begin{cases} \frac{\hbar}{2}(\sigma_x \overrightarrow{x} + \sigma_y \overrightarrow{y} + \sigma_z \overrightarrow{z}) & \text{for T} \\ \hbar(s_x \overrightarrow{x} + s_y \overrightarrow{y} + s_z \overrightarrow{z}) & \text{for D.} \end{cases}$$

The vectors $\overrightarrow{x}$, $\overrightarrow{y}$, and $\overrightarrow{z}$ indicate the unit vecors for x, y, and z direction, respectively. The matrices σ disignate Pauli's spin matrices. The matrices s are given as follows.

$$s_x = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

$$s_y = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & i & 0 \\ i & 0 & i \\ 0 & i & 0 \end{pmatrix},$$

$$s_z = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}.$$

Thus the interaction is given

$$U = \frac{g_i e q}{8\pi\varepsilon_0 c^2 m m_p r^3} \overrightarrow{s} \cdot \overrightarrow{l}. \quad \text{(B.13)}$$

Next, we calculate the cross-section of the spin-orbit interaction by a use of Born approximation. The differential cross-section of the transition from the state m' to m due to the interaction U is given

$$\frac{d\sigma}{d\Omega} = \frac{m^2}{4\pi^2\hbar^2}\left| \int \left\langle m'; \exp(-i\overrightarrow{k'} \cdot \overrightarrow{r})\right| U \left| m; \exp(-i\overrightarrow{k} \cdot \overrightarrow{r})\right\rangle d\overrightarrow{r}\right|^2. \quad \text{(B.14)}$$

Inserting Eq.(B.13) into the above, we obtain

$$\frac{d\sigma}{d\Omega} = \frac{g_i^2 e^2 q^2}{256\pi^4\hbar^2\varepsilon_0^2 c^4 m_p^2}\left| \int \left\langle m'; \exp(-i\overrightarrow{k'} \cdot \overrightarrow{r})\right| \frac{\overrightarrow{s} \cdot \overrightarrow{l}}{r^3} \left| m, \exp(-i\overrightarrow{k} \cdot \overrightarrow{r})\right\rangle d\overrightarrow{r}\right|^2. \quad \text{(B.15)}$$

The spin vector $|m\rangle$ acts only on the vector operater $\overrightarrow{s}$. One has to know $\langle m'|\overrightarrow{s}|m\rangle$ for the possible transition m' to m, which is given below.

$$\begin{aligned}
\langle -\tfrac{1}{2}|\overrightarrow{s}|\tfrac{1}{2}\rangle &= \frac{\hbar}{2}(\overrightarrow{x} + i\overrightarrow{y}) \\
\langle \tfrac{1}{2}|\overrightarrow{s}| - \tfrac{1}{2}\rangle &= \frac{\hbar}{2}(\overrightarrow{x} - i\overrightarrow{y}) \\
\langle -1|\overrightarrow{s}|1\rangle &= 0 \\
\langle 0|\overrightarrow{s}|1\rangle &= \frac{\hbar}{\sqrt{2}}(\overrightarrow{x} + i\overrightarrow{y}) \\
\langle 1|\overrightarrow{s}|0\rangle &= \frac{\hbar}{\sqrt{2}}(\overrightarrow{x} - i\overrightarrow{y}) \\
\langle -1|\overrightarrow{s}|0\rangle &= \frac{\hbar}{\sqrt{2}}(\overrightarrow{x} + i\overrightarrow{y}) \\
\langle -1|\overrightarrow{s}|1\rangle &= 0 \\
\langle 0|\overrightarrow{s}| - 1\rangle &= \frac{\hbar}{\sqrt{2}}(\overrightarrow{x} - i\overrightarrow{y})
\end{aligned}$$

The transition from $m' = 1/2$ to $m = -1/2$ is given for instance

$$\frac{d\sigma}{d\Omega} = \frac{g_i^2 e^2 q^2}{1024\pi^4\varepsilon_0^2 c^4 m_p^2} \cdot \left| \overrightarrow{k} \times (\overrightarrow{x} + i\overrightarrow{y}) \int \frac{\overrightarrow{r}\exp(-i\overrightarrow{q}\cdot\overrightarrow{r})}{r^3} d\overrightarrow{r}\right|^2. \quad \text{(B.16)}$$

Since the integration in terms of $\overrightarrow{r}$

$$\int \frac{\overrightarrow{r}\exp(-i\overrightarrow{q}\cdot\overrightarrow{r})}{r^3} d\overrightarrow{r} = -\frac{4\pi i\overrightarrow{q}}{q^2}, \quad \text{(B.17)}$$

thus we obtain

$$\sigma = \frac{g_i^2 e^2 q^2}{768\pi^2\varepsilon_0^2 c^4 m_p^2}\int_o^\pi \frac{\sin^3\theta}{\sin^4\frac{\theta}{2}} d\theta = \frac{g_i^2 e^2 q^2 \ln\Lambda}{48\pi^2\varepsilon_0^2 c^4 m_p^2}, \quad \text{(B.18)}$$

where, $\ln\Lambda$ is the Coulomb logarithm. Here we use the relation

$$\left|\frac{\overrightarrow{k} \times (\overrightarrow{x} + i\overrightarrow{y}) \quad \overrightarrow{q}}{q^2}\right|^2 = \frac{2}{3}\left|\frac{\overrightarrow{k} \times \overrightarrow{q}}{q^2}\right|^2 = \frac{2}{3}\left(\frac{\sin\theta}{4\sin^2\frac{\theta}{2}}\right)^2. \quad \text{(B.19)}$$

Giving $\ln\Lambda = 20$, the cross-sections of spin-orbit interaction are presented in Table A Note that the deuterons' cross-section from $m_D = 1$ to $m_D = -1$ and *vice versa* are zero, that is not indicated in the Table. The length r_p denotes the classical proton radius expressed as

$$r_p \equiv \frac{e^2}{4\pi\varepsilon_0 c^2 m_p}. \quad \text{(B.20)}$$

The spin-orbit cross-sections are small compared with the fusion reaction cross-section.

Table A: Spin-orbit cross-sections

tritons	$235\pi r_p^2$	by ions
	$235\pi r_p^2$	by electrons
deuterons	$9.86\pi r_p^2$	by ions
	$9.86\pi r_p^2$	by electrons

C Transition Probability due to Magnetic Waves

The spin state of nucleus changes temporaly by suffering the fluctuating magnetic field. This changes follow Schrödinger equation:

$$i\hbar\frac{\partial c_i}{\partial t} = H_{ij} c_j. \quad \text{(C.21)}$$

Here, H_{ij} and C_j denote Hamiltonian matrix and the complex vector of probability amplitude. Subscript i and j stand for respective spin states. We assume the uniform magnetic field $\overrightarrow{B}_0$ in the z-axis and the fluctuating part $\overrightarrow{\delta B}$. Thus

$$\overrightarrow{B}(t) = \overrightarrow{B}_0(t) + \overrightarrow{\delta B}(t). \quad \text{(C.22)}$$

Since z component of the external field is not associated with the change of the nuclear spin state thus oscilating field is assumed to have x and y components in this calculation Under this situation. Hamiltonian matrix for tritons is given

$$H_{ij} = -\frac{g_i e \hbar}{2m_p}\begin{pmatrix} B_0 & \delta B_x - i\delta B_y \\ \delta B_x + i\delta B_y & -B_0 \end{pmatrix}.$$

and for deuterons

$$H_{ij} = -\frac{g_i e \hbar}{2m_p}\begin{pmatrix} B_0 & \frac{1}{\sqrt{2}}(\delta B_x - i\delta B_y) & 0 \\ \frac{1}{\sqrt{2}}(\delta B_x + i\delta B_y) & 0 & \frac{1}{\sqrt{2}}(\delta B_x - i\delta B_y) \\ 0 & \frac{1}{\sqrt{2}}(\delta B_x + i\delta B_y) & -B_0 \end{pmatrix},$$

To solve Eq (C.21), the fluctuating field should be given in explicit form In this paper we suppose the following oscilating field:

$$\delta B_x(t) = \delta B \cos \omega t. \qquad \delta B_y(t) = 0. \qquad \text{(C 23)}$$

We are able to rearrange Schrödinger equation by substituting the explicit form of Hamiltonian matrices into. then

$$\begin{aligned}
i\hbar\frac{d\gamma_{1/2}}{dt} &= -\frac{\hbar}{2}\frac{\delta B}{B_0}\Omega_p\Big[e^{i(\omega-2\Omega_p)t} + e^{-i(\omega+2\Omega_p)t}\Big]\gamma_{-1/2} \\
i\hbar\frac{d\gamma_{-1/2}}{dt} &= -\frac{\hbar}{2}\frac{\delta B}{B_0}\Omega_p\Big[e^{i(\omega+2\Omega_p)t} + e^{-i(\omega-2\Omega_p)t}\Big]\gamma_{1/2} \\
i\hbar\frac{d\gamma_1}{dt} &= -\frac{\hbar}{2\sqrt{2}}\frac{\delta B}{B_0}\Omega_p\Big[e^{i(\omega-\Omega_p)t} + e^{-i(\omega+\Omega_p)t}\Big]\gamma_0 \\
i\hbar\frac{d\gamma_0}{dt} &= -\frac{\hbar}{2\sqrt{2}}\frac{\delta B}{B_0}\Omega_p\Big\{\Big[e^{i(\omega+\Omega_p)t} + e^{-i(\omega-\Omega_p)t}\Big]\gamma_1 \\
&+ \Big[e^{i(\omega-\Omega_p)t} + e^{-i(\omega+\Omega_p)t}\Big]\gamma_{-1}\Big\} \\
i\hbar\frac{d\gamma_{-1}}{dt} &= -\frac{\hbar}{2\sqrt{2}}\frac{\delta B}{B_0}\Omega_p\Big[e^{i(\omega-\Omega_p)t} + e^{-i(\omega+\Omega_p)t}\Big]\gamma_0 .
\end{aligned} \qquad \text{(C.24)}$$

To derive Eq. (C 24) we used these relations are used·

$$\begin{aligned}
c_{1/2} &= \gamma_{1/2}\exp(-\frac{i}{\hbar}E_0 t) \\
c_{-1/2} &= \gamma_{-1/2}\exp(-\frac{i}{\hbar}E_0 t) \\
c_1 &= \gamma_1\exp(-\frac{i}{\hbar}E_0 t) \\
c_0 &= \gamma_0 \\
c_{-1} &= \gamma_{-1}\exp(-\frac{i}{\hbar}E_0 t) \\
E_0 &= -\frac{g_i e\hbar}{2m_p}B_0.
\end{aligned} \qquad \text{(C.25)}$$

The oscilation of the exponential with $\omega + \Omega_p$ and $\omega + 2\Omega_p$ are much faster than those with $\omega - \Omega_p$ and $\omega - 2\Omega_p$, the time average of $\exp(\omega + \Omega_p)t$ and $\exp(\omega + 2\Omega_p)t$ reduces to zero Therefore, approximated equations become.

$$\begin{aligned}
i\hbar\frac{d\gamma_{1/2}}{dt} &= -\frac{\hbar}{2}\frac{\delta B}{B_0}\Omega_p e^{i(\omega-2\Omega_p)t}\gamma_{-1/2} \\
i\hbar\frac{d\gamma_{-1/2}}{dt} &= -\frac{\hbar}{2}\frac{\delta B}{B_0}\Omega_p e^{-i(\omega-2\Omega_p)t}\gamma_{1/2} \\
i\hbar\frac{d\gamma_1}{dt} &= -\frac{\hbar}{2\sqrt{2}}\frac{\delta B}{B_0}\Omega_p e^{i(\omega-\Omega_p)t}\gamma_0 \\
i\hbar\frac{d\gamma_0}{dt} &= -\frac{\hbar}{2\sqrt{2}}\frac{\delta B}{B_0}\Omega_p\{e^{-i(\omega-\Omega_p)t}\gamma_1 \\
&+ e^{i(\omega-\Omega_p)t}\gamma_{-1}\} \\
i\hbar\frac{d\gamma_{-1}}{dt} &= -\frac{\hbar}{2\sqrt{2}}\frac{\delta B}{B_0}\Omega_p e^{i(\omega-\Omega_p)t}\gamma_0 .
\end{aligned} \qquad \text{(C.26)}$$

We calculate the transition probability for spin 1/2 for example. Waves interact the nuclear spin for the small duration t_{int}. In addition, when $\delta B/B_0$ is small enough to keep unchanging in γ's. the γ's in the R. H. S of the equation are safely assumed to be constant. The solution to the above equation is

$$\begin{aligned}
\gamma_{-1/2} &= \frac{i}{2}\frac{\delta B}{B_0}\gamma_{1/2}\int_0^{t_{int}} e^{-i(\omega-2\Omega_P)t}dt \\
&= \frac{\gamma_{1/2}}{2}\frac{\delta B}{B_0}\Omega_p\frac{1-e^{-i(\omega-2\Omega_p)t_{int}}}{\omega-2\Omega_p}.
\end{aligned} \qquad \text{(C.27)}$$

Calculating the probability $|\gamma_{-1/2}|^2$. and we obtain.

$$|\gamma_{-1/2}|^2 = (\frac{\gamma_{1/2}}{2})^2(\frac{\delta B}{B_0})^2(\Omega_p t_{int})^2\left\{\frac{\sin\frac{(\omega-2\Omega_p)t_{int}}{2}}{\frac{(\omega-2\Omega_p)t_{int}}{2}}\right\}^2. \qquad \text{(C.28)}$$

Because of the sharp peak at $\omega = 2\Omega_p$ in this probability, the transition process is considered as the resonance at $\omega = 2\Omega_p$. Taking the limits using

$$\lim_{\omega \to 2\Omega_p} \left\{ \frac{\sin \frac{(\omega - 2\Omega_p) t_{int}}{2}}{\frac{(\omega - 2\Omega_p) t_{int}}{2}} \right\}^2 \longrightarrow 1 \qquad \text{(C.29)}$$

we obtain

$$|\gamma_{-1/2}|^2 = (\frac{\gamma_{1/2}}{2})^2 (\frac{\delta B}{B_0})^2 (\Omega_p t_{int})^2. \qquad \text{(C.30)}$$

In addition, since $t_{int} \approx 1/\Omega_p$ and $\gamma_{1/2}$ then the transition probability per unit time becomes

$$\frac{|\gamma_{-1/2}|^2}{t_{int}} \approx \frac{1}{4} (\frac{\delta B}{B_0})^2 \Omega_p. \qquad \text{(C.31)}$$

We are able to calculate the transition rate for spin 1 (deuterons). From the state $m_D = 0$ to the other transtion, we have the following rate:

$$\frac{|\gamma_0|^2}{t_{int}} \approx \frac{1}{8} (\frac{\delta B}{B_0})^2 \Omega_p. \qquad \text{(C.32)}$$

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