Feasibility of Reduced Tritium Circulation in the Heliotron Reactor by Enhancing Fusion Reactivity Using ICRF*)

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A scheme for reducing the tritium fraction in DT fusion reactors is investigated by means of enhancing the fusion reactivity using high-power ICRF heating in heliotron reactors. We assume a situation that the density fraction of tritons is less than 10%, and the minority tritons are accelerated by ICRF waves. We then analyze the increase of fusion reactivity by assuming an effective temperature of high-energy tritons and examine the possibility of realizing a fusion reactor with this concept. The required ICRF power and the generated fusion power are also estimated.

Keywords: heliotron, FFHR, D-T reaction, ICRF, fusion reactivity enhancement, high-energy tail

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1. Inroduction

Handling of tritium is one of the most important technological issues for realizing fusion power plants. Since the burning ratio of the presently designed deuterium-tritium (D-T) fusion reactors remains in a couple of percentage level, a large amount of tritium should be recovered from the vacuum vessel and constantly circulated in the reactor system. Here, a big concern is the problem of permeation and retention of tritium within the vacuum vessel and circulation plumbing [1]. Moreover, unless the recovery rate is close to 100%, it would be very difficult to obtain the sufficient tritium breeding ratio (TBR).

In this respect, it would be very useful if the D-T reactivity could be enhanced by some means. For this purpose, one may think of applying neutral beams, however, it has been found that the efficiency remains rather low [2]. On the contrary, applying high-power Ion Cyclotron Range of Frequency (ICRF) waves has been found more effective for producing high-energy tails, accelerated by wave-particle energy transfers. And thus, many authors have been investigating such a scenario for fusion reactivity enhancement [3–5].

We here note that this kind of scheme for enhancing the fusion reactivity using ICRF may also provide the following benefits:

- As the circulation of tritium is reduced, the total inventory of tritium could also be reduced.
- By controlling ICRF power, the fusion output power could be controlled.
- D-T reactors could be more easily realized with lower temperature.
- Applying high-power ICRF heating for D-D plasmas could be used for producing the initial tritium loading for the startup of a D-T reactor.
- The final target of this kind of scenario is to realize the next generation fusion reactors using advanced fuels, such as D-^{3}He or D-D.

Regarding the application of ICRF to the present day experiments, here we should note that it has been quite successful in many devices, such as in the JET tokamak [6]. Owing to these results, it is now planned to inject ~ 40 MW of ICRF power in ITER [7]. Using ICRF, enhancement of fusion reactivity has actually been confirmed in the D-T experiments conducted in JET [8]. At the same time, ICRF has also been successfully applied to stellarator/heliotron devices, such as the Large Helical Device (LHD) [9]. In the ICRF experiments of LHD, it has been confirmed that a significant fraction of high-energy tail ions are formed, up to ~ 2 MeV range [10]. Furthermore, in LHD, the world's largest injected heating energy of 1.6 GJ was achieved in a 30 minute discharge with ICRF heating [11].

As has been demonstrated in the LHD experiments, the heliotron magnetic configuration is suitable for steady-state operation, and the conceptual design studies of the heliotron-type fusion energy reactor FFHR have been intensively carried out. Though the configuration optimization is still being pursued, the major radius could be ~ 17 m for a commercial reactor [12], whereas it could be a little smaller for a DEMO reactor. Since the heliotron magnetic configuration does not require the toroidal plasma current, there is no need to continuously inject neutral beams of

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~ 100 MW or higher for current drive. Therefore, we consider that this amount of power could be delivered to ICRF to enhance high-energy tritons.

In this paper, we propose an idea for enhancing the fusion reactivity by focusing on the possibility of reducing the tritium ratio from the standard case of 50-50% of D-T. We consider a situation that the density of tritons is considerably smaller than that of deuterons, and the minority tritons are accelerated by high-power ICRF waves. We examine the feasibility of this scenario by calculating the power balance and examining the condition for producing high-energy tritons.

2. Power Balance for Ignition

As is well known, the power balance equation for fusion plasmas is given as follows [13]:

$$P_{\mathrm{L}} + P_{\mathrm{B}} = P_{\mathrm{H}}, \tag{1}$$

where P_{L} is the power loss by conduction and P_{B} is the power loss by Bremsstrahlung radiation, whereas P_{H} is the heating power provided both by the charged particles produced in fusion reactions and the externally applied heating power (e.g., ICRF in the present case).

For the plasma having the electron density and temperature n_{e} and T_{e}, associated with an energy confinement time τ_{E}, P_{L} and P_{B} are expressed as follows:

$$\begin{aligned} P_{\mathrm{L}} &= 3 n_{\mathrm{e}} T_{\mathrm{e}} / \tau_{\mathrm{E}}, \\ P_{\mathrm{B}} &= \gamma Z_{\mathrm{eff}} n_{\mathrm{e}}^2 T_{\mathrm{e}}^{1/2}, \end{aligned} \tag{2}$$

where $\gamma = 1.69 \times 10^{-38}$ and Z_{eff} is assumed to be unity for simplicity. Here, the ion density and temperature are assumed to be equal to those of electrons.

For the plasma consisting of deuterons and tritons, the plasma heating power P_{H} consists of the power produced by D-T reactions $P_{\mathrm{H,D\text{-}T}}$ and that by D-D reactions $P_{\mathrm{H,D\text{-}D}}$,

$$P_{\mathrm{H}} = P_{\mathrm{H,D\text{-}T}} + P_{\mathrm{H,D\text{-}D}}. \tag{3}$$

And each term is expressed as

$$\begin{aligned} P_{\mathrm{H,D\text{-}T}} &= n_{\mathrm{e}}^2 \left(\eta_{\alpha,\mathrm{D\text{-}T}} + \tfrac{1}{Q}\right)(1-f) f \langle \sigma v \rangle_{\mathrm{D\text{-}T}} U_{\mathrm{D\text{-}T}}, \\ P_{\mathrm{H,D\text{-}D}} &= n_{\mathrm{e}}^2 \left(\eta_{\alpha,\mathrm{D\text{-}D}} + \tfrac{1}{Q}\right) \frac{(1-f)^2}{2} \langle \sigma v \rangle_{\mathrm{D\text{-}D}} U_{\mathrm{D\text{-}D}}. \end{aligned} \tag{4}$$

In Eq. (4), for the D-T reaction, $\eta_{\alpha,\mathrm{D\text{-}T}}$ is the fraction of energy (= 0.2) given to the alpha particles (3.52 MeV) out of the total fusion power $U_{\mathrm{D\text{-}T}}$ of 17.58 MeV. The rest of the energy (14.06 MeV) is transported by neutrons. In the present analysis, we do not include the additional energy production (4.8 MeV) by the neutron-^{6}Li reaction in blankets. In Eq. (4), f is the density fraction of tritons and $\langle \sigma v \rangle_{\mathrm{D\text{-}T}}$ is the energy-averaged fusion reactivity of a D-T reaction at a specified temperature. Note that we also include the externally injected heating power in Eq. (4) through the Q-value; the ratio between the fusion output power and the external heating power.

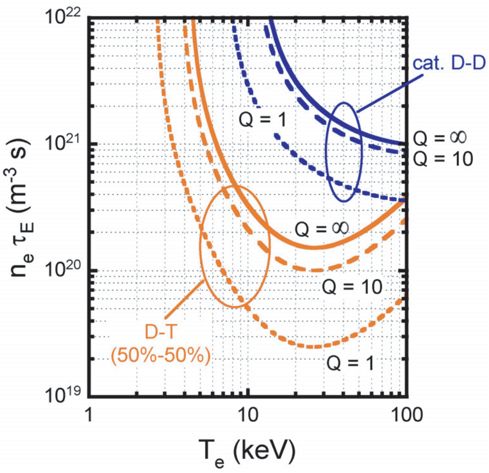

Fig. 1 Ignition condition for D-T and D-D fusion reactions. The externally injected power fraction is included as the Q-value.

On the other hand, for D-D reactions, $\eta_{\alpha,\mathrm{D\text{-}D}}$ corresponds to the heating power by charged particles which are tritons, ^{3}He and alpha particles. We here consider that these tritons and ^{3}He immediately fuse with deuterons and produce alpha particles and neutrons, which is the so-called "catalyzed D-D" process.

By combining Eqs. (1)-(4), we obtain a zero-dimensional "$n\tau$-T" curve for satisfying the power balance and the result is expressed as follows:

$$n_{\mathrm{e}} \tau_{\mathrm{E}} = \frac{\frac{3}{2}(T_{\mathrm{e}} + T_{\mathrm{i}})}{p_{\mathrm{H,D\text{-}D}} + p_{\mathrm{H,D\text{-}T}} - \gamma Z_{\mathrm{eff}} T_{\mathrm{e}}^{1/2}}, \tag{5}$$

with $p_{\mathrm{H,D\text{-}T}} = P_{\mathrm{H,D\text{-}T}}/n_{\mathrm{e}}^2$ and $p_{\mathrm{H,D\text{-}D}} = P_{\mathrm{H,D\text{-}D}}/n_{\mathrm{e}}^2$. In Eq. (5), the ion temperature is assumed to be the same for both deuterons and tritons: $T_{\mathrm{D}} = T_{\mathrm{T}} = T_{\mathrm{i}}$.

Using Eq. (5), the $n\tau$-T curves are calculated for D-T reactions with 50%-50% of D-T ratio as well as for catalyzed D-D reactions, and the results are plotted in Fig. 1. In both reactions, the Q-value is included as a parameter.

3. Enhancement of Fusion Reactivity

We here consider an enhancement of fusion reactivity in the power balance equation by including high-energy components of tritons. For simplicity, we assume that the high-energy component can still be expressed by a Maxwellian distribution function, having an effective temperature which is q times the temperature of the bulk deuterons: $T_{\mathrm{T}} = qT_{\mathrm{D}}$. In the case of $q = 10$, the fusion reactivity is plotted in Fig. 2 as a function of the bulk deuteron temperature.

In Fig. 2, we observe that the fusion reactivity is increased also by ten times or more compared to the case without having a high-energy component in the energy

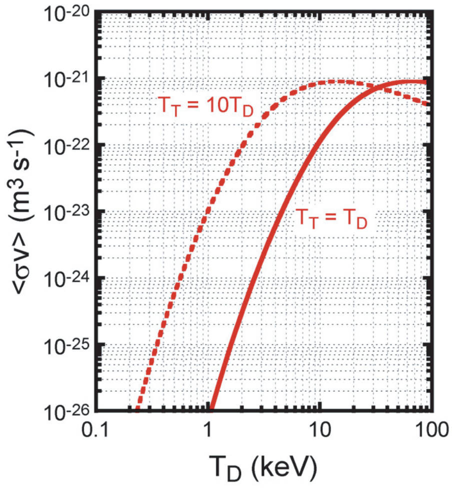

Fig. 2 Enhancement of fusion reactivity by having high-energy tritons with ten times the temperature of bulk deuterons. The horizontal axis is taken as the bulk deuteron temperature T_D.

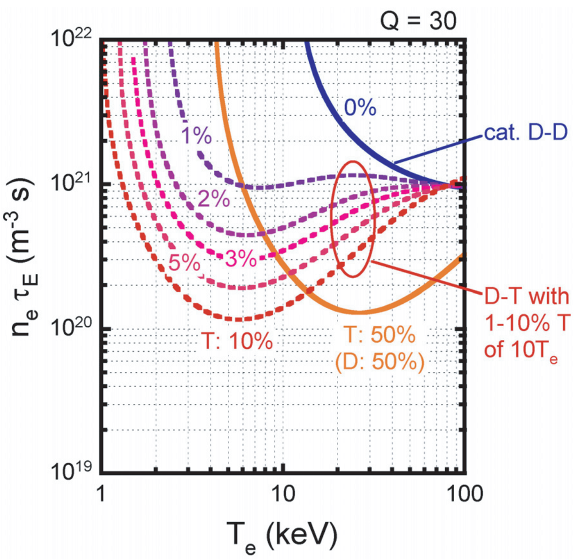

Fig. 3 Ignition conditions with high-energy components of tritons having ten times the temperature of bulk deuterons and electrons. The Q-value is 30.

range lower than ~ 10 keV. Using this enhanced fusion reactivity, we then modify the term $p_{\mathrm{H,D-T}}$ in the power balance Eq. (5), and it is written as

$$n\tau = \frac{\frac{3}{2}(2 - f + fq)T_e}{p_{\mathrm{H,D-T(high-energy)}} + p_{\mathrm{H,D-D}} - \gamma Z_{\mathrm{eff}} T_e^{1/2}}. \quad (6)$$

Here we replaced the ion temperature T_i in the numerator by

$$T_i \to (1 - f)T_D + f\,T_T = (1 - f + fq)T_D$$
$$= (1 - f + fq)T_e.$$

The calculated results are plotted in Fig. 3 for the tritium fractions of 1, 2, 3, 5 and 10%. Here the Q-value is assumed to be 30. As a reference, the 50%-50% of D-T ratio is also plotted. The 0% tritium fraction corresponds to the catalyzed D-D reaction. As is shown in Fig. 3, when the T ratio is 5%, the minimum value of $n_e\tau_E$ for the power balance is found at ~ 2×10^{20} m^{-3} s and T_e ~ 6 keV, which is significantly lower than the standard condition of 50%-50% D-T with ~ 1.5×10^{20} m^{-3} s at T_e ~ 20 keV for self-ignition.

4. Discussion

In order to examine the feasibility of assuming the generation of significant fraction of high-energy components with minority ICRF heating of tritons, we here examine the ξ-parameter derived by T.H. Stix, which is expressed as follows [14]:

$$\xi = 1.68 \times 10^6 \frac{m\langle P\rangle}{n_e n Z^2 \ln\Lambda}\left(\frac{2T_e}{m_e}\right)^{1/2}, \quad (7)$$

where n_e is the electron density (given in the unit of 10^{20} m^{-3}), m_e is the electron mass and T_e is the electron temperature (given in the unit of keV). For the minority ions accelerated by ICRF, n is the density (in 10^{20} m^{-3}), Z is the charge number and m is the mass. For the present case of tritons, $Z = 1$ and $m = 5.01 \times 10^{-27}$ kg. The volume averaged power density of ICRF waves is given as $\langle P\rangle$ and $\ln\Lambda$ is the Coulomb logarithm.

Using the ξ-parameter, the effective temperature of the high-energy minority heated ions can be approximately given as [15]

$$T_{\mathrm{eff}} \sim T(1 + \xi).$$

In the present analysis, this means that we are assuming $q = 1 + \xi$. In order to achieve $q = 10$, which is assumed in Fig. 3, the ξ-parameter should exceed 9.

Then, we here roughly examine the ξ-parameter expected at the operation point of $n_e\ \tau_E \sim 1.9 \times 10^{20}$ m^{-3} s and T_e ~ 6 keV on the $n\tau$-T curve obtained for the tritium ratio of 5% in Fig. 3. More specifically, we employ $n_e = 0.8 \times 10^{20}$ m^{-3} and $\tau_E = 2.4$ s at $T_e = 6$ keV, which are supposed to be achievable within the FFHR conceptual design [16] For estimating the power density, we assume to inject ~100 MW of ICRF to the burning core plasma of 500 m^3, and this gives $\langle P\rangle$ ~ 0.2 MW/m^3.

Substituting these values in Eq. (7), the ξ-parameter is calculated to be 9.5, and thus, the assumed condition of having an effective temperature of minority tritons ten times that of bulk deuterons is verified. However, we find in this case that the generated fusion power is ~ 500 MW, and thus, the Q-value is only 5. This means that the assumption of $Q = 30$ in Fig. 3 is not satisfied. In order to increase the fusion power, one may increase the density (for example by two times), however, the ξ-parameter is reduced (by four times) and we cannot expect sufficient generation of high-energy tritons.

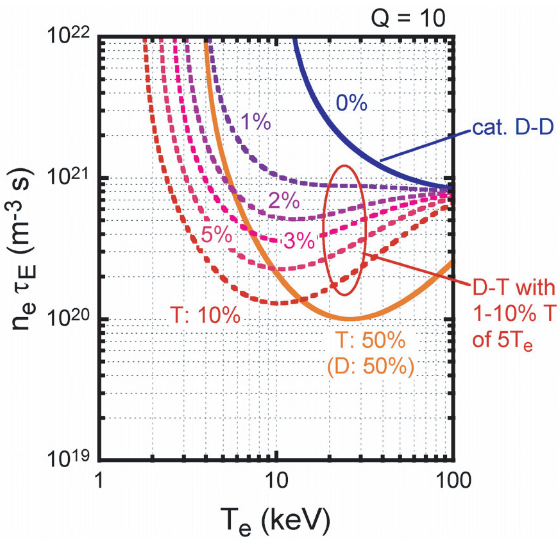

Fig. 4 Ignition condition with high-energy component of tritons having five times the temperature of bulk deuterons and electrons. The Q-value is 10.

Therefore, we examine another case of having 10% density fraction of tritons with five times the temperature of bulk deuterons. The $n\tau$-T diagram corresponding to this case with $Q = 10$ is shown in Fig. 4. At the operation point of $n_e = 0.8 \times 10^{20}\,\mathrm{m}^{-3}$ and $\tau_E = 1.8\,\mathrm{s}$ at $T_e \sim 10\,\mathrm{keV}$ with the tritium fraction of 10%, the ξ-parameter is found to be 3.9. Thus the assumption of $q = 5$ is verified in this case. At the same time, we find that $\sim 1\,\mathrm{GW}$ of fusion power is produced, which gives $Q \sim 10$.

These results suggest that we need to consider some more improvement to make this scenario more attractive and practical. At the same time, we need to incorporate more precise analysis such as the test particle calculation [17]. Moreover, we note that the operation of ICRF antennas at the intense neutron environment in D-T fusion reactors should be an important technological issue. On the other hand, we also consider that the application of ICRF heating could also be used for producing tritium in D-D operations [18] in order to start up a D-T fusion reactor without external supply of initial tritium loading.

5. Summary

Feasibility of reduction of tritium circulation is investigated through enhancing the fusion reactivity with high-power ICRF heating. It is observed that the fusion reactivity is enhanced by almost ten times if the minority tritons are assumed to have an effective temperature ten times the temperature of bulk deuterons. In this case, a density fraction of 5% tritons gives a power balance for fusion reactions at $n\tau \sim 2 \times 10^{20}\,\mathrm{m}^{-3}\mathrm{s}$ and $T_e \sim 6\,\mathrm{keV}$, which seems easier to realize. However, the fusion power output is as low as $Q \sim 5$ in this case. Though a 10% fraction of tritium with five times the bulk temperature is a little superior and one may achieve $Q \sim 10$ we need to consider some more improvement to make this scenario more attractive and practical. We should also try to incorporate more precise analysis using the test particle calculation. The startup scenario with D-D operations assisted by ICRF heating will also be examined in our future studies.

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