Evaluation of Efficiency of Power Transferred from ICRF Fast Ions to Bulk Plasma Based on Orbit Following in Real Coordinates in LHD

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(Received 23 March 2015 / Accepted 26 June 2015)

In order to optimize the transferred power efficiency from ICRF fast ions to bulk plasma, we have developed a code in which models of behaviors of ICRF fast ion are minimally adopted in order to save calculation time. A tendency of the transferred power efficiencies evaluated by the developed code is almost the same as that evaluated from the full analyses. In the regime with low efficiency of transferred power, the effect of the position of the resonance layer is large. The efficiency of the resonance layer through the point near the magnetic axis is found to be smaller than that of the typical ICRF resonance layer.

Keywords: ICRF fast ion, evaluation of transferred power efficiency and transferred power profile

DOI: 10.1585/pfr.10.1402077

1. Introduction

In the Large Helical Device (LHD), a plasma discharge have been maintained for approximately one hour by minority ion heating of ICRF. To extend the operational density regime of the long-duration discharges, the operating scenario is under development [1].

In the ICRF minority ion heating, the minority ion is mainly accelerated near the resonance layer by the ICRF wave, and the fast minority ions are produced. Their energy is transferred to bulk plasma through collisions. Therefore, it is necessary to investigate the efficiency of the power transferred from the minority fast ions to bulk plasmas (Transferred power efficiency: ratio of the power received from ICRF wave to minority ions to the power transferred to bulk plasma.).

To find the optimized heating conditions, we must evaluate the transferred power efficiency for plasma in the wide regime of temperature and density. Moreover, in helical devices such as the LHD, the shape of the resonance layer is more complicated than that of a tokamak. The fast ions heated by the ICRF wave become a "banana orbit particle (helical trapped particle)" [2] which forms a closed drift surface or a "chaotic orbit particle" [2] which does not form the closed drift surface depending upon the shape of the resonance layer. The shape of the resonance layer may affect the transferred power efficiency from minority fast ions to bulk plasma. Therefore, it is very important to optimize a relationship between the shapes of the flux surface and the magnetic ripple and the position of the resonance layer.

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A conventional approach to evaluate the efficiency of the power transferred from the minority ions to bulk plasmas in the LHD uses the Monte-Carlo code. This code evaluates the distribution function and the heating power profile [3]. This approach thus requires large calculation resources. In finding the optimized heating conditions, this approach is not adequate because these analyses require larger calculation resources. In addition, since the ICRF wave propagation and absorption code are required when the actual heating power is evaluated, it is difficult to clarify its temperature and density dependence derived from the fast ion orbit.

We have developed a code in which models of behaviors of ICRF fast ions are minimally adopted from the point of view of saving calculation time and clarifying the orbit effect on transferred power efficiency. Using this code, the transferred power efficiency in the LHD minority ion heating is evaluated.

2. Transferred Power Efficiency and Profile Evaluation Code

2.1 Models in the developed code

In this section, models used in the developed code are explained. Figure 1 shows the overview of models used in developed code and the full analysis model of ICRF minority ion heating. The full analysis consists of two main parts, as follows:

a) evaluation of the ICRF electric field profile by solving the electromagnetic wave equations, and

b) evaluation of a velocity distribution function of minority ion and power transferred from minority ions to bulk

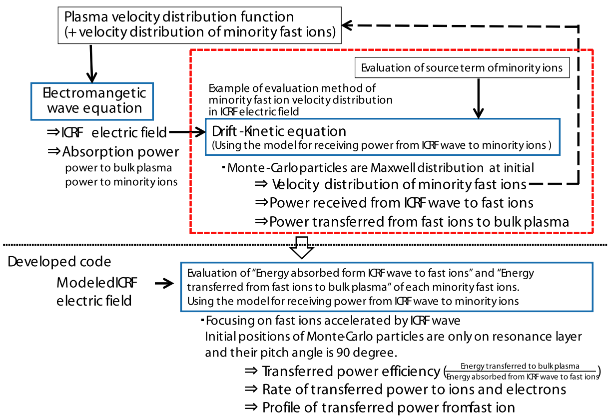

Fig. 1 Overview of models used in developed code and full analysis model of ICRF minority ion heating.

plasma.

In the part a) part of the developed code, electromagnetic wave equations are not solved for saving time and clarifying the temperature and density dependence of transferred power efficiency derived from fast ions. And ICRF electric field is uniformly distributed in one-tenth of the torus (half pitch of helical symmetry) based on the model that the ICRF electric field exists only in the region in the front of an ICRF antenna.

In part b), in order to evaluate only the transfer rate from minority fast ions to bulk plasma, "an energy received from the ICRF wave to minority fast ions" and "an energy transferred from the minority fast ions to bulk plasma" are calculated. Particularly in the developed code, only minority fast ions accelerated by ICRF wave are focused upon. As the model of their fast ions, their initial points are set on the resonance layer on the vertically elongated poloidal plane, and the pitch angle is 90 degrees. This assumption leads to saving time because the number of Monte-Carlo particles decreases.

In the developed code, using the above modes, minority fast ions are traced until they are lost with a collision and acceleration due to the ICRF electric field. Thus, the evaluated efficiency becomes the value of the steady state. The orbit of each fast ion is traced with the guiding center equations. In the acceleration term, a model [3] in which the fast ions are accelerated in a direction perpendicular to field line on the resonance layer is used for clarifying effects of position and shape of a resonance layer on the fast ion's behavior. In a collision with bulk plasma, the collision operator [4] which includes a pitch angle scatter and energy relaxation is adopted.

In addition, the particle loss boundary is set on vacuum vessel in the developed code. Transferred power efficiency with including the re-entering fast ions can be evaluated and the lost points of ICRF fast ions can be analyzed.

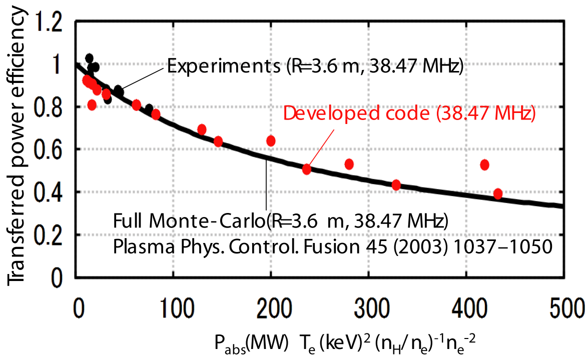

Fig. 2 Efficiencies of developed code and full analyses of part b).

2.2 Comparision of results of the developed code with full analyses

We have verified that the results of the developed code explained in Sec. 2.1 are the same as the full analyses [3] where models of full analyses are used only in part b) explained in Sec. 2.1. Here, the transferred power efficiency in the case of the typical LHD ICRF condition (R_{ax} = 3.6 m, 38.47 MHz, B_t = 2.75 T) is evaluated by changing the temperature, density, and strength of the wave electric field. Figure 2 shows the efficiencies of developed code (red points) and full analyses of part b (black line: full Monte-Carlo code). In the developed code, the absolute value of the absorption power cannot be directly evaluated because the only ICRF fast ions are traced. In Fig. 2, the dependence of absorption power is evaluated from the average of an energy received from the ICRF wave to minority fast ions. In Fig. 2, a tendency of the efficiencies evaluated by the developed code is almost the same as that evaluated from the full analyses.

3. Heating Efficiency and Power Profile of ICRF Fast Ions

We investigate the transferred power efficiency and its profile in the case (R_{ax} = 3.6 m, 38.47 MHz, B_t = 2.75 T) of typically ICRF minority ion heating in the plasma consisting of helium ion (major ion), hydrogen ion (minority ion), and electron. Here, the strength of the wave electric field is set at 1 kV/m by reference to the advice of the LHD ICRF group and to the wave calculation [5].

3.1 Density dependence

Figure 3 shows a plasma density dependence on the transferred power efficiency to bulk plasma and maximum energy of fast ions with an electric temperature T_e = 1 keV. In Fig. 3, the maximum energy of ICRF fast ions decrease with increase in the density. In the regime where maximum energy is approximately 10 keV, the transferred power efficiency becomes larger and its value is ~ 0.9. On the other hand, the maximum energy becomes large in the

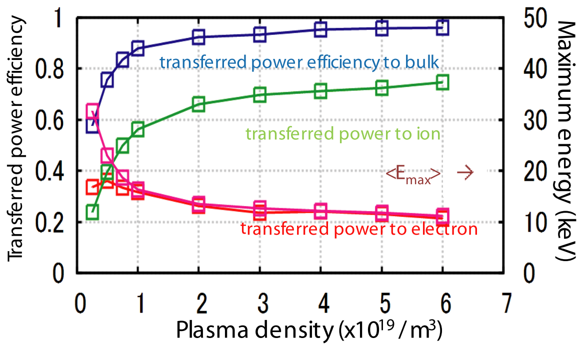

Fig. 3 Density dependence of transferred power efficiency with T_e = 1 keV. In this figure, the blue line shows transferred power efficiency to bulk plasma (ions and electrons). The green and red lines are the efficiency to ion and to electron, respectively. In addition, the purple line shows the maximum energy of ICRF fast ions. The maximum energy shown in the figure is the average value of the maximum energy of each fast ion.

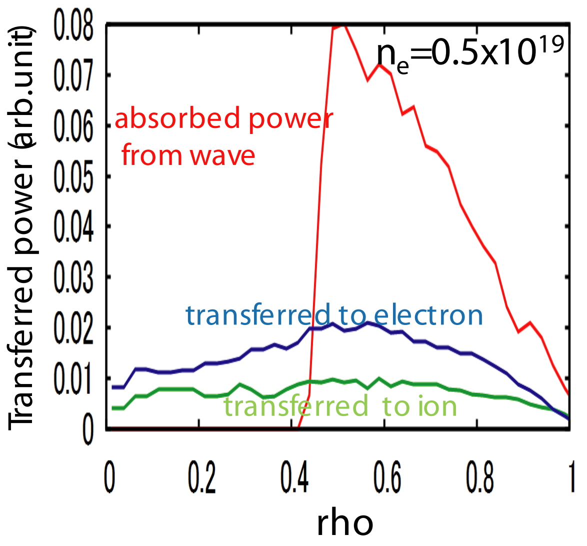

Fig. 4 Typical profiles of the transferred power and absorbed power from wave in the case of T_e = 1 keV and n_e = 0.5×10^{19} m^{-3}.

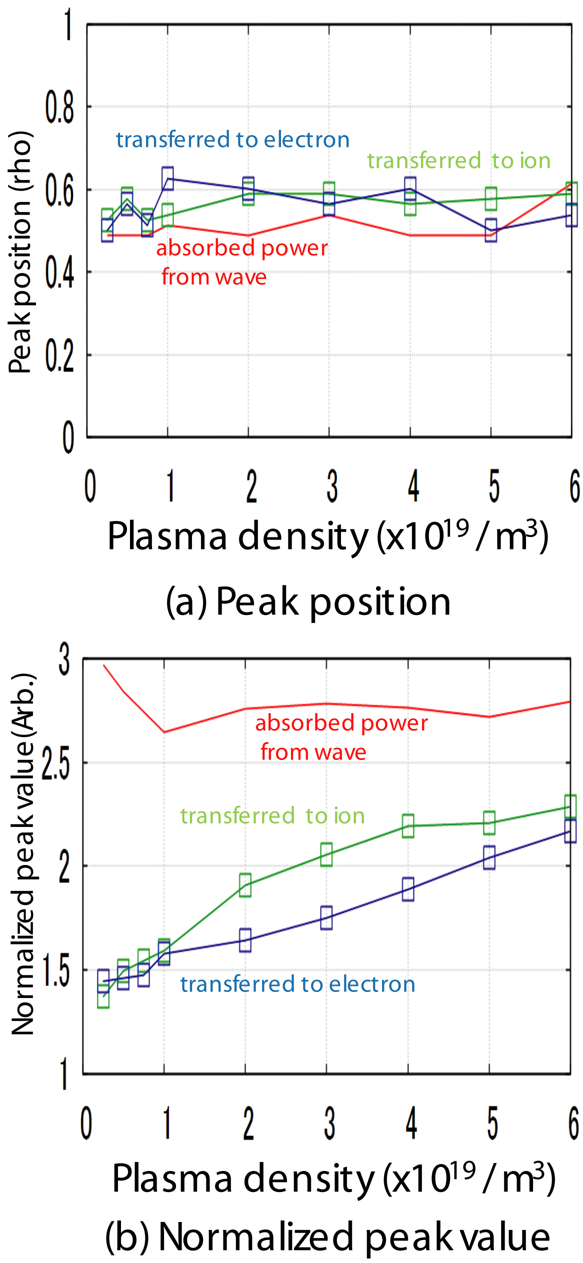

Fig. 5 Density dependence of peak positions and normalized peak value of transferred power profiles in the case of T_e = 1 keV. In this figure, the red line shows absorbed power profile from wave. The green and blue lines are the transferred power profile to ion and to electron, respectively.

low density regime. In this regime, transferred power efficiency is small. In Fig. 3, when the density is more than $\sim 1 \times 10^{19}$ m^{-3}, the efficiency to ions is larger than that to electrons.

Next, the character of the transferred power profile is investigated in terms of the density. First, the typical profiles of the transferred power and absorbed power from the wave are shown in Fig. 4. It is found from Fig. 4 that the absorbed power form wave peaks at normalized minor radius $\rho \sim 0.5$. On the other hand, the shape of the transferred power profile is broad. However, its peak is near the peak position of the absorbed power profile.

As an index of the peakedness of profiles shown in Fig. 4, the normalized peak value is defined as

$$\hat{P} = p_{\text{peak}} / \int p \mathrm{d}\rho. \tag{1}$$

When this normalized peak value = 1, the profile is flat. The shape of the profile becomes more a peaked profile with an increase in the normalized peak value. Figure 5 shows the density dependence of peak positions and normalized peak value of transferred power profiles. In Fig. 5 (a), the peak position of transferred power profiles

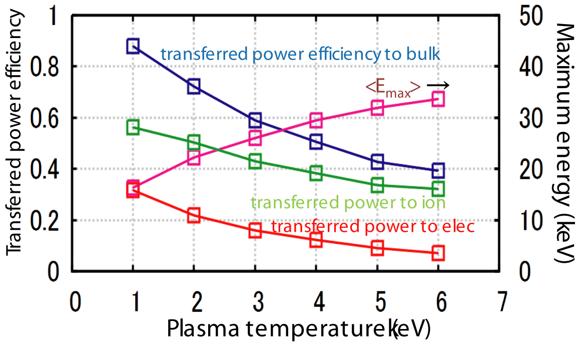

Fig. 6 Temperature dependence of transferred power efficiency with $n_e = 1.0 \times 10^{19}$ m^{-3}.

is at the same position regardless of density. On the other hand, the normalized peak value of the transferred power profile increases with an increase in density (see Fig. 5 (b)). In the case of high density, the shape of the transferred power profile is close to the absorbed power profile. This is because the fast ion energy absorbed from the wave is quickly transferred to the bulk plasma in the case of high density. In the low density case, the normalized peak value of the transferred power profile is much smaller than that of the absorbed power profile and the shape of transferred power profile is found to be flat.

3.2 Temperature dependence

Figure 6 shows the temperature dependence of the transferred power efficiency and maximum energy of ICRF fast ions. In Fig. 6, when the temperature becomes large, the maximum energy of ICRF fast ions increases and the transferred power efficiency is found to be small. This relation between the efficiency and the maximum energy is the same as that of density dependence (see Fig. 3). On the other hand, the efficiency to ion is larger than that to electron even when the maximum energy is large. This is because the critical energy increases with an increase in the plasma temperature.

Next, Fig. 7 shows the peak position and the normalized peak value of the transferred power profile in terms of the temperature. In Fig. 7 (a), there is no significant difference of peak position between transferred power profiles and the absorbed power profile regardless of the temperature and its tendency is the same as the density dependence. In addition, the normalized peak value rarely changes with temperature (Fig. 7 (b)). Since the normalized peak value is 1, its profile is nearly flat. This is because the frequency of collision with ions is greater than that with electrons regardless of temperature (see Fig. 6). In this regime, since the pitch angle scatter is large, the transferred power profile becomes flat.

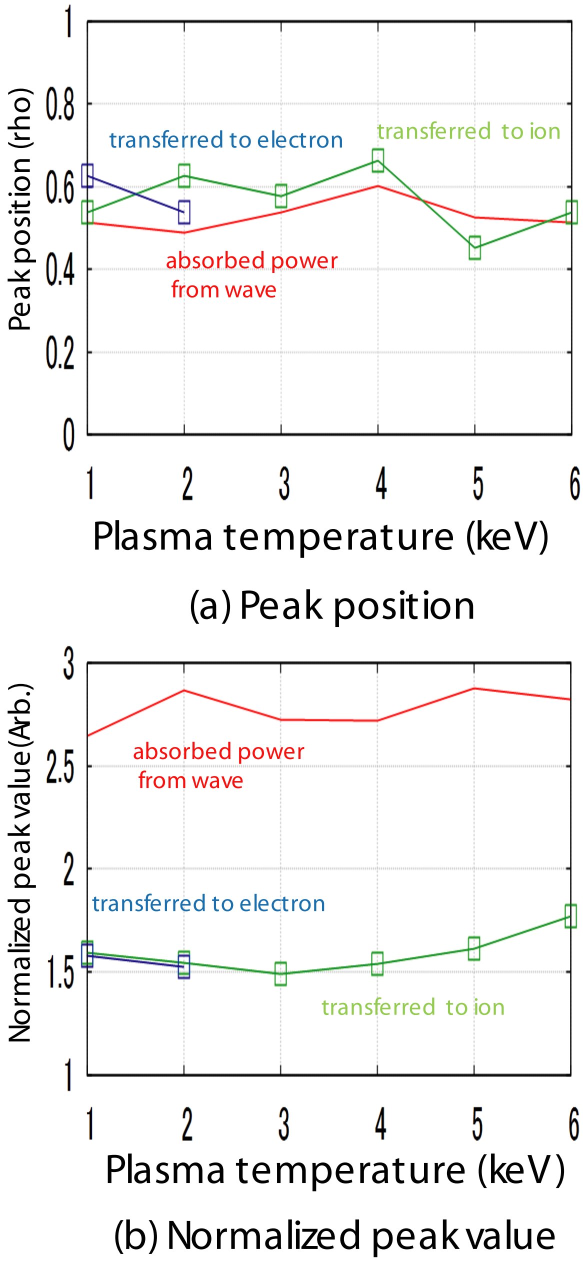

Fig. 7 Typical profiles of the transferred power and absorbed power from wave in the case of $n_e = 1.0 \times 10^{19}$ m^{-3}. In this figure, the red line shows absorbed power profile from wave. The green and blue lines are the transferred power profile to ion and to electron, respectively.

4. Effect of Shape of Resonance Layer

In this section, we discuss the effect of the position of the resonance layer on the transferred power efficiency. The resonance layers of 38.47 MHz and 41.5 MHz are shown in Fig. 8. 38.47 MHz is the typical frequency of LHD ICRF minority heating and the good result from experiments with 38.47 MHz is obtained (it is used in Sec. 2 and 3). In the 41.5 MHz, the resonance layer is through the point near the magnetic axis. Here, the strength of the wave electric field is set at 1 kV/m by reference to the advice of

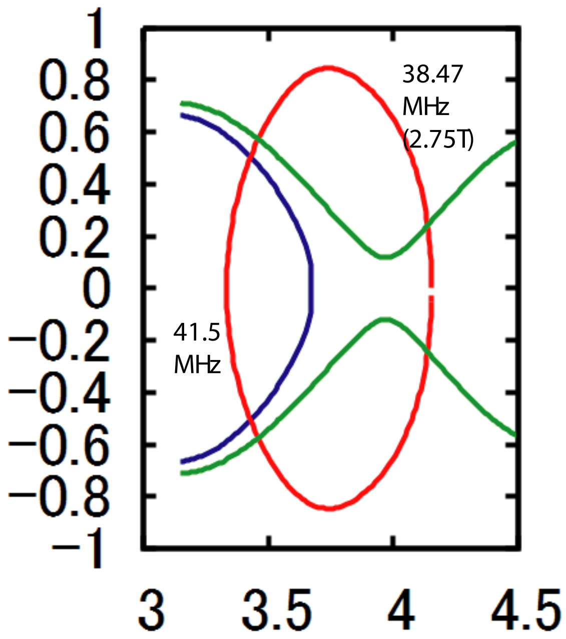

Fig. 8 Resonance layers of 38.47 MHz (green) and 41.5 MHz (blue) on the vertical elongated poloidal plane.

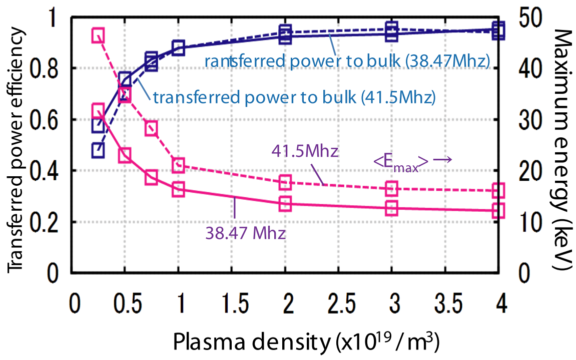

Fig. 9 Difference of transferred power efficiency and maximum energy due to position of resonance layer with T_e = 1 keV.

LHD ICRF group and to the wave calculation [5].

Figure 9 shows the difference of transferred power efficiency and maximum energy between 41.5 MHz and 38.47 MHz. When transferred power efficiency is over 0.8, there is no significant difference between two frequencies. In the regime with the efficiency < 0.8, the efficiency of 41.5 MHz is smaller than that of 38.47 MHz. In addition, the maximum energy of 41.5 MHz is larger than that of 38.47 MHz. This is because the distance between resonance layers is smaller near the magnetic axis and the energy of fast ions near the magnetic axis becomes large.

5. Summary

In order to optimize the transferred power efficiency from ICRF fast ions to bulk plasma, we have developed a code in which models of behaviors of ICRF fast ion are minimally adopted from the view point of saving calculation time.

Using the developed code, the transferred power efficiency in the LHD minority ion heating is evaluated. The efficiency evaluated by the developed code is verified with that evaluated by full analyses. As a result, the tendencyies of the efficiencies evaluated by the developed code are almost the same as that evaluated from the full analyses.

The temperature and the density dependences of the transferred power efficiency are evaluated. When the maximum energy of ICRF fast ions is large, such as low density and high temperature cases, the transferred power efficiency becomes small.

In addition, in order to investigate the effect of the position of the resonance layer on the transferred power efficiency, the efficiency of the typical ICRF resonance layer is compared with that of the resonance layer through the point near magnetic axis. In the regime with low efficiency of transferred power, the effect of the position of the resonance layer is large. The efficiency of the resonance layer through the point near magnetic axis is smaller than that of the typical ICRF resonance layer.

Acknowledgments

This work is supported by General Collaboration Research of NIFS (NIFS13KNSR002).

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