Optimization study of ICRF heating in the LHD and HSX configurations

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Two global simulation codes, TASK/WM (a full wave solver) and GNET (a 5-D drift kinetic equation solver), are combined to simulate the ICRF heating in the 3D magnetic configuration. The combined code is applied to the ICRF minority heating in the LHD configuration. Also the optimization of the ICRF heating is considered in changing the magnetic configurations and the resonance surfaces in the LHD and HSX plasmas.

1. Introduction

ICRF heating experiments has been successfully done in helical systems and have demonstrated the effectiveness of this heating method in three-dimensional (3D) magnetic configurations. In LHD, significant performances of this method have also been demonstrated and up to 2.5MeV of energetic tail ions have been observed by fast neutral particle analysis (NPA). These measured results indicate a good property of energetic ion confinement in helical systems. However, the measured information by NPA is obtained as an integrated value along a line of sight and we need a reliable theoretical model for reproducing the energetic ion distribution to discuss the confinement of energetic ions accurately.

To solve this problem we study the ICRF heating in the LHD combining two simulation codes: a full wave solver TASK/WM[1] and a 5-D drift kinetic equation solver GNET[2]. Characteristics of energetic ion distributions in the phase space are investigated changing the resonance heating position; i.e. the on-axis and off-axis heating cases.

On the other hand, recent numerical studies of energetic ion confinements in the LHD configurations indicate that an optimized configuration of the energetic ion confinement is different from that of the neoclassical transport (R_{ax}=3.53m)[3] due to the finite orbit effect of the energetic ions. Additionally the previous simulation study of ICRF heating in LHD[2] shows that the stable trapped particles near the resonance surface play an important role in generating energetic tail ions. Thus there is a possibility to find a better configuration and heating scenario than the present ones, and it is interest to investigate an optimization of ICRF heating in point of views of the energetic tail ion generation and their confinements in a helical plasma.

In this paper optimizations of the configurations and the heating scenario of ICRF heating are investigated in the LHD and HSX plasmas. The difference between the ICRF heating optimization and the neoclassical transport one is discussed.

2. ICRF minority heating analysis by TASK/WM+GNET in LHD

First, we study the ICRF minority heating applying the TASK/WM+GNET code in the LHD configuration. We analyze the ICRF wave propagation and absorption in the plasma by TASK/WM. Figure 1 shows contour plots of the real part of left circularly polarized component of the RF electric field, Re(E^{+}), (left) and the power absorption (right) on the poloidal cross section in the case of the ICRF wave frequency f_{RF} =38.5MHz (off axis heating). The ICRF wave is exited by the antenna, which sets on the outer side of the torus (right side). The Re(E^{+}) component of the waves are absorbed and the wave amplitude is damped at the minority ion cyclotron resonance layer (green lines). Then the amplitude is damped further near the two-ion-hybrid cutoff and resonance layers.

We, then, analyzed the evolution of velocity distribution function of minority ions and the plasma heating efficiency by GNET. The RF electric field profile of $|E^{+}|$ and k_{perp} obtained by TASK/WM are used to accelerate the minority ions. The same plasma parameters are assumed as in the TASK/WM calculation. The test particle orbits are followed for about 0.6s to obtain the steady state of the distribution function.

The velocity distribution functions of minority ions are shown in Fig. 2. We plot contour plots of the velocity distribution averaged on the flux surface r/a~1/3 (left), r/a~1/2 (center), and r/a~2/3 (right) with f_{RF} =38.5MHz.

Figure 3 (left) shows the radial profile of the ICRF wave power absorbed by minority ions. The radial profile of the ICRF wave power absorbed by minority ions depends on f_{RF} and peaks at a specific radial position. The ICRF wave power absorbed by minority ions is transported to the background ions and electrons through collisions. The heating power profiles of background ions, Pdep (D), and electrons, Pdep (e), are shown in Fig. 3 (center and right). Although the both Pdep (D) and Pdep (e) slightly peak at the same radial point, the profile of them are broader compared to the profile of Pabs (H).

3. Optimization of ICRF heating in LHD configuration

Next, we consider the optimization of ICRF heating changing the magnetic configuration and resonance surface in LHD. We change the magnetic configuration by shifting the magnetic axis position in the major radius, R_{ax}, form 3.70m to 3.50m in the vacuum. The full time calculation obtaining the steady state needs a large CPU time. Thus, in order to reduce the calculation time we study the confinement of energetic tail ions without the background plasma interaction and only the kicks by the ICRF wave is considered.

Figure 4 (left) shows the ratio of the confined minority ions after a few msec as a function of the resonance magnetic field strength in the five different R_{ax} configurations. We can see the optimum point near B_{res}~2.2T in the strongly inward shifted (R_{ax}=3.53m and 3.55m) configurations and near B_{res}~2.4T in the R_{ax}=3.6m configuration. The confinement ratio tends to decrease as the B_{res} increases in the outward shifted (R_{ax}=3.65m and 3.70m) configurations.

Although the strongly inward shifted configuration shows higher confinement ratio the radial profile of the energetic ion population shows a large peak near the periphery r/a~0.9. This means the heating profile would also show the peaks near the periphery and this is unfavorable for heating the plasma. Thus the effect of the heating profile should be taking into account in the optimization process.

Figure 4 (right) shows confinement ratio of the energetic minority ions assuming the effective confinement region in the minor radius; 0.66 and 0.8 in the R_{ax}=3.53m and 3.6m cases. We can see the optimum magnetic field near Bres~2.4 (r/a<0.8) and 2.53 (r/a<0.66) in the R_{ax}=3.6m configuration and the ratio is monotonically increases as the B_{res} increases in the R_{ax}=3.53m configuration.

As a result the optimum heating is obtained at B_{res} ~2.4T in the R_{ax}=3.6m configuration in LHD if we assume the effective confinement region as $r/a<0.8$.

5. Conclusions

We have studied the ICRF heating in the 3D magnetic configurations. The two global simulation codes, TASK/WM (a full wave solver) and GNET (a 5-D drift kinetic equation solver), have been combined to simulate the ICRF heating. The combined code has been applied to the ICRF minority heating in the LHD configuration. Also the optimization of the ICRF heating has been considered in changing the magnetic configurations and the resonance surfaces in the LHD plasmas.

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[2] S. Murakami, *et al.*, Nucl. Fusion **46** (2006) S425.
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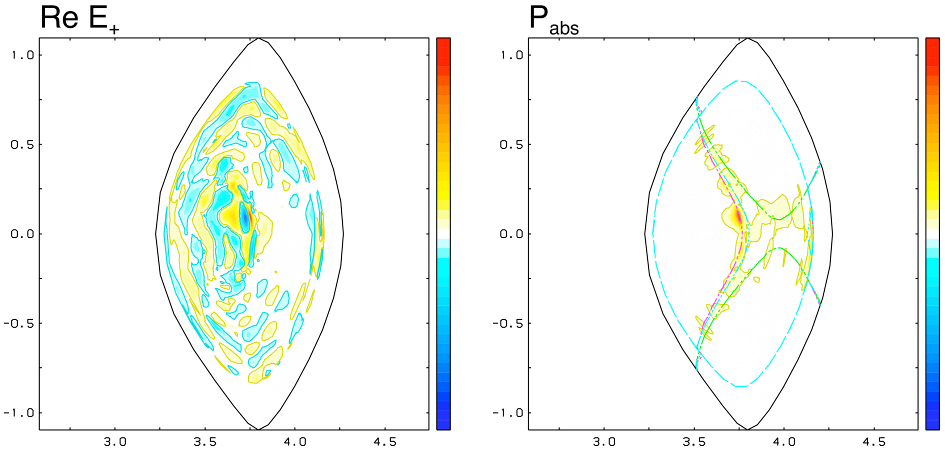

Fig. 1: Contour plots of the real part of left circularly polarized component of the RF electric field, Re(E^+), (left) and the power absorption (right) on the poloidal cross section in the case of the ICRF wave frequency f_{RF} *=38.5MHz (off axis heating).*

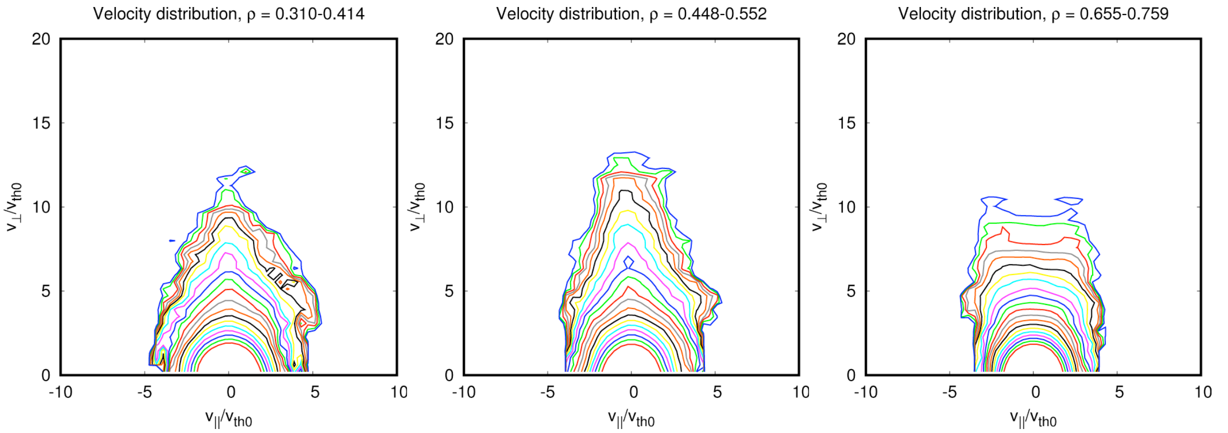

Fig. 2: Contour plots of the velocity distribution averaged on the flux surface r/a~1/3 (left), r/a~1/2 (center), and r/a~2/3 (right) with f_{RF} =38.5MHz.

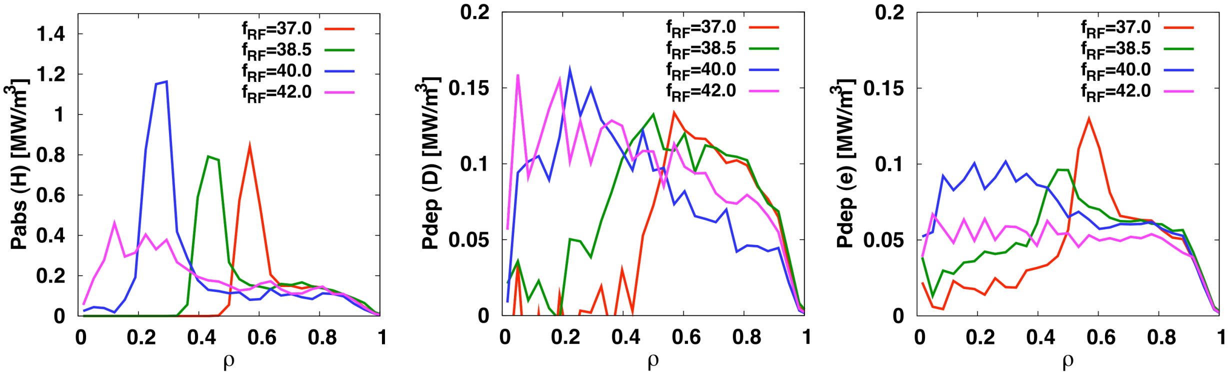

Fig. 3: Radial profile of the ICRF wave power absorbed by minority ions (left), the power deposition of the background ions (center) and electrons (right).

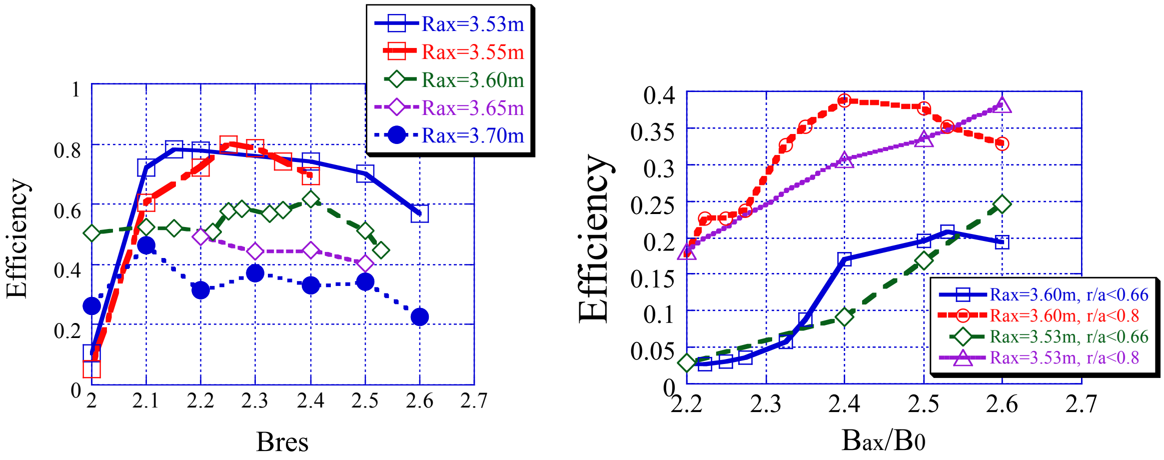

Fig. 4: Confinement ratio of the energetic minority ions during the ICRF heating as a function of the resonance magnetic field strength in the five different magnetic configurations (left) and the ratio assuming the effective confinement minor radius; 0.66 and 0.8 (right).