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A Global Simulation Study of ICRF Heating by TASK/WM and GNET in Helical Plasmas

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A global simulation code is developed to study the ICRF heating in helical plasmas combining two global simulation codes: a full wave field solver, TASK/WM, and a drift kinetic equation solver, GNET. The both codes can treat a 3-D magnetic configuration based on the MHD equilibrium by VMEC code. The developed code is applied to the ICRF minority heating in Large Helical Device (LHD). The ICRF wave propagation is solved by TASK/WM and the obtained RF electric field is used to solve the drift kinetic equation by GNET.

Keywords: ICRF heating, Simulation

1 Introduction

The ion cyclotron range of frequencies (ICRF) heating has long been considered a primary plasma heating method. The physics basis and the efficiency of ICRF heating have been confirmed by experimental, theoretical and simulation studies. However, there still remains several important issues in ICRF heating, e.g. finite orbit effect of energetic ions, current drive, toroidal flow generation, etc. In order to clarify these problems, a global simulation study which takes into account the wave-plasma interaction self-consistently is necessary.

In this paper, we study the ICRF heating in helical plasmas combining two global simulation codes: a full wave field solver TASK/WM [1] and a drift kinetic equation solver GNET [2], as a first step to develop a self-consistent simulation. The developed code is applied to the ICRF minority heating in the Large Helical Device (LHD). The realistic ICRF wave profile obtained by TASK/WM is used to solve a drift kinetic equation by GNET. The both codes can treat a 3-D magnetic configuration based on the MHD equilibrium by VMEC code.

In Sec. 2 the simulation models and codes are described and, then, simulation results are presented in Sec. 3. Finally, the obtained results are summarized in Sec. 4.

2 Simulation model

In this study we combine two simulation code to study the ICRF heating. The simulation model is illustrated in Fig. 1. First, Maxwell's equation for RF wave is solved by TASK/WM code, then the obtained RF wave electric field profile is used to solve a drift kinetic equation by GNET code. Finally, the steady state velocity distribution function of plasma is obtained.

TASK/WM code solves Maxwell's equation for RF

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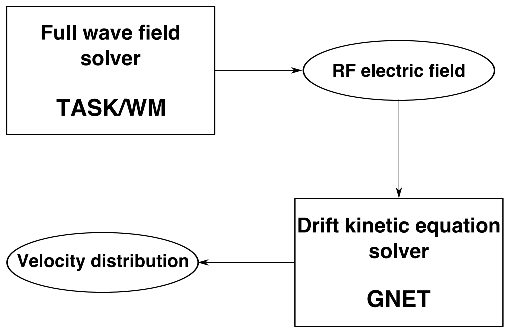

Fig. 1 The schematic diagram of simulation model

wave electric field, $\boldsymbol{E}$, with complex frequency, ω,

$$\nabla \times \nabla \times \boldsymbol{E} = \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \cdot \boldsymbol{E} + i\omega\mu_0 \boldsymbol{j}_{\mathrm{ext}}, \tag{1}$$

where the external current density, $\boldsymbol{j}_{\mathrm{ext}}$ denotes the antenna current in ICRF heating, as a boundary value problem in the 3-D magnetic configuration. In the present analysis, a simple collisional cold plasma model is applied [3]. Maxwell's equation Eq. (1) is formulated by expansion to Fourier mode in poloidal and toroidal direction and finite different method in radial direction. Then the electric field is formulated as

$$\boldsymbol{E}(\psi_l, \theta, \varphi) = \sum_{mn} \boldsymbol{E}_{mn}(\psi_l) e^{i(m\theta + n\varphi)}, \tag{2}$$

where l, m, n are the radial grid number, poloidal and toroidal mode numbers, respectively.

GNET code solves a linearized drift kinetic equation for energetic ions including complicated behavior of trapped particles in 5-D phase space as

$$\frac{\partial f}{\partial t} + (\boldsymbol{v}_{\parallel} + \boldsymbol{v}_{\mathrm{D}}) \cdot \nabla f + \boldsymbol{a} \cdot \nabla_{\boldsymbol{v}} f - C(f) - Q_{\mathrm{ICRF}}(f) - L = S, \tag{3}$$

where $C(f)$ and Q_{ICRF} are the linear Coulomb collision operator and the ICRF heating term, respectively. S and L

are the particle source term by ionization of neutral particles and sink (loss) term including orbit loss and charge exchange, respectively.

In order to solve the linearized drift kinetic equation (3) by Monte Carlo method, the Green function, $\mathcal{G}$, is introduced as

$$\frac{\partial \mathcal{G}}{\partial t} + (\boldsymbol{v}_{\parallel} + \boldsymbol{v}_{\mathrm{D}}) \cdot \nabla \mathcal{G} + \boldsymbol{a} \cdot \nabla_{\boldsymbol{v}} \mathcal{G} - C(\mathcal{G}) - Q_{\mathrm{ICRF}}(\mathcal{G}) - L = 0 \qquad (4)$$

with the initial condition $\mathcal{G}(\boldsymbol{x}, \boldsymbol{v}, t = 0|\boldsymbol{x}', \boldsymbol{v}') = \delta(\boldsymbol{x} - \boldsymbol{x}')\delta(\boldsymbol{v} - \boldsymbol{v}')$. The $\mathcal{G}$ is evaluated by solving the equation of motion for guiding center of test particles expressed by the Hamiltonian of charged particle

$$H = \frac{1}{2} m v_{\parallel}^2 + \mu B(\psi, \theta, \varphi) + q\Phi(\psi) \qquad (5)$$

in Boozer coordinate. In order to solve the equation of motion, 6th-order Runge-Kutta method is applied. The collisional effects are taken into account using the linear Monte Carlo collision operator [4].

The ICRF heating term is modelled by changing the perpendicular velocity of the test particle passing through the resonance layer, $\omega - k_{\parallel} v_{\parallel} = n\Omega$, by

$$\begin{aligned} \Delta v_{\perp} &\approx \left[\left(v_{\perp 0} + \frac{q}{2m} I |E_{+}| J_{n-1}(k_{\perp}\rho_{\mathrm{L}}) \cos\phi_{\mathrm{r}} \right)^2 + \frac{q^2}{4m^2} \{ I|E_{+}|J_{n-1}(k_{\perp}\rho_{\mathrm{L}}) \}^2 \sin^2\phi_{\mathrm{r}} \right]^{-\frac{1}{2}} - v_{\perp 0} \\ &\approx \frac{q}{2m} I|E_{+}|J_{n-1}(k_{\perp}\rho_{\mathrm{L}}) \cos\phi_{\mathrm{r}} + \frac{q^2}{8m^2 v_{\perp 0}} \{ I|E_{+}|J_{n-1}(k_{\perp}\rho_{\mathrm{L}}) \}^2 \sin^2\phi_{\mathrm{r}}, \end{aligned} \qquad (6)$$

where E_{+} and ϕ_{r} are the left-circularly polarized component of RF wave electric field and random phase, respectively. Also, q, m, ρ_{L}, J_n are the charge, mass, the Larmor radius of the particle and nth Bessel function, respectively. The time duration passing through the resonance layer, I, is given by the minimum value as, $I = \min(\sqrt{2\pi/n\dot{\Omega}}, 2\pi(n\ddot{\Omega})^{-1/3}\mathrm{Ai}(0))$, which corresponds to two cases; the simple passing of the resonance layer and the passing near the turning point of a trapped motion (banana tip).

In the simulation $|E_{+}|$ evaluated by TASK/WM is used in Eq. (6). We consider only fundamental ion cyclotron resonance. The finite larmor radius (FLR) effect, $J_{n-1}(k_{\perp}\rho_{\mathrm{L}})$ term in Eq. (6), is considered by evaluating the wave length, λ, from the electric field wave form directly as Fig. 2 and calculating the perpendicular wave vector, $k_{\perp} = 2\pi/\lambda_{\perp}$.

Assuming $B_{\varphi} \gg B_{\theta}$ for simplicity, $k_{\parallel}$ is evaluated as

$$k_{\parallel} \approx \frac{n}{R}, \qquad (7)$$

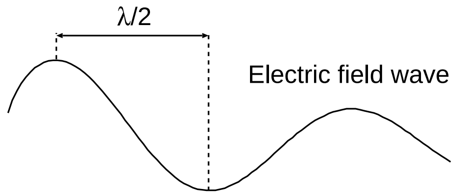

Fig. 2 Evaluation of wave length, λ, from electric field wave

where n is the toroidal mode number in Eq. (2) and R is the major radius.

Finally the velocity distribution function is calculated by integrating the particle in the phase space over initial position $(\boldsymbol{x}', \boldsymbol{v}')$ and initial time t' as

$$f(\boldsymbol{x}, \boldsymbol{v}, t) = \int_0^t dt' \int d\boldsymbol{x}' \int d\boldsymbol{v}' S\, \mathcal{G}(\boldsymbol{x}, \boldsymbol{v}, t - t'|\boldsymbol{x}', \boldsymbol{v}'). \qquad (8)$$

3 Simulation results

We study the ICRF minority heating using the developed code in the helical plasma (LHD). The poloidal cross sections of the MHD equilibrium by VMEC code are shown in Fig. 3. The assumed plasma parameters are listed in Table 1. We assume deuterium (D) as a majority ion and hydrogen (H) as a minority ion.

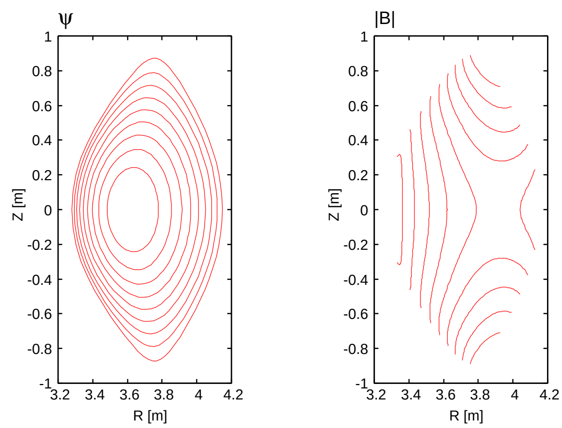

Fig. 3 Equilibrium data by VMEC and NEWBOZ, Contour plots of magnetic flux ψ (left) and absolute value of magnetic field (right) on a poloidal cross section

Table 1 Parameters of helical plasma (LHD)

Plasma major radius	R_0	3.6 m
Plasma minor radius	a	0.58 m
Magnetic field at magnetic axis	B_0	2.75 T
Temperature at magnetic axis	T_0	3.0 keV
Temperature on plasma boundary	T_s	0.3 keV
Density at magnetic axis	n_0	$0.7 \times 10^{20}/\mathrm{m}^3$
Density on plasma boundary	n_s	$0.07 \times 10^{20}/\mathrm{m}^3$
Antenna current density	$j_{\rm ext}$	1.0 A/m
Wave frequency	$f_{\rm RF}$	38.5, 40.0 MHz
Minority ion ratio	H/D+H	5 %
Collisionality	ν_s	0.003

We first analyze the ICRF wave propagation and absorption in the plasma by TASK/WM. Fig. 4 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 $f_{\rm RF}$ = 40.0 MHz (on axis heating). Fig. 5 are the same manner in the case of $f_{\rm RF}$ = 38.5 MHz (off axis heating). The ICRF waves are exited in the plasma from the antenna set on the outer side of the torus (right side). In the both cases, the Re E_+ component of the wave is absorbed by the plasma and the wave amplitude is damped near the minority ion cyclotron resonance layer (the minority ion cyclotron resonance layers are drawn as green lines in the left figure of Fig. 4 and 5). Then the amplitude is damped further near the two-ion-hybrid cutoff and resonance layers.

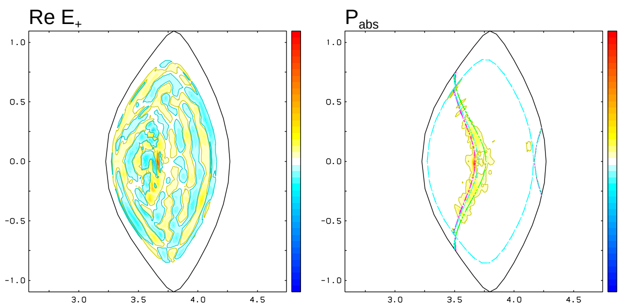

Fig. 4 Contour plots of Re E+ (left) and $P_{\rm abs}$ (right) on the poloidal cross section in the case of $f_{\rm RF}$ = 40.0 MHz.

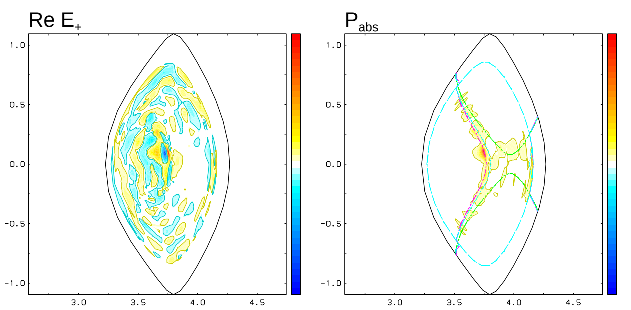

Fig. 5 Contour plots of Re E+ (left) and $P_{\rm abs}$ (right) on the poloidal cross section in the case of $f_{\rm RF}$ = 38.5 MHz

Next, we analyze the evolution of velocity distribution function of minority ions and the plasma heating efficiency by GNET. The RF electric field profile obtained by TASK/WM is used to accelerate the minority ions following Eq. (6). The $k_\perp$ is directly calculated from electric field waves by the method illustrated in Fig. 2. The $k_\perp$ and the $|E_+|$ are shown in Fig. 6. The same plasma parameters are

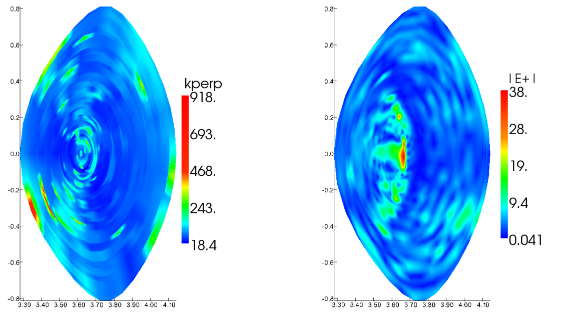

Fig. 6 $k_\perp$ (left) and $|E_+|$ (right) in the case of $f_{\rm RF}$ = 40.0 MHz

assumed as in the TASK/WM calculation. The test particle orbits are followed for about 0.6 s to obtain the steady state of the distribution function.

The velocity distribution functions of minority ions are shown in Fig. 7 ($f_{\rm RF}$ = 40.0 MHz) and 8 ($f_{\rm RF}$ = 38.5 MHz). Fig. 7 are contour plots of the velocity distribution averaged on the flux surface between ρ (= $\sqrt{\psi/\psi_a}$) = 0.0 and 0.10 (left upper), ρ = 0.31 and 0.41 (right upper), and ρ = 0.45 and 0.55 (left lower), ρ = 0.66 and 0.76 (right lower) with $f_{\rm RF}$ = 40.0 MHz. Fig. 8 shows in the same manner of Fig. 7 in the case of $f_{\rm RF}$ = 38.5 MHz.

Figure 9 shows the radial profile of the ICRF wave

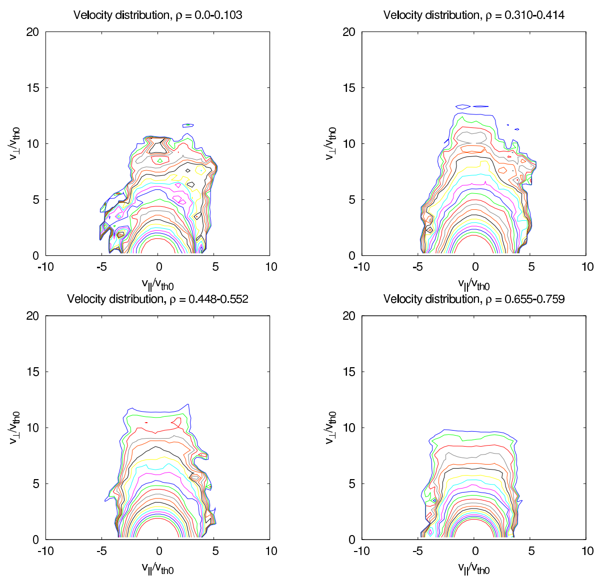

Fig. 7 Velocity distribution averaged in each radial ρ interval ($f_{\rm RF}$ = 40.0 MHz)

power absorbed by minority ions in the case of $f_{\rm RF}$ = 40.0 MHz (red line) and $f_{\rm RF}$ = 38.5 MHz (green line). We can see that the radial profile of the absorbed ICRF

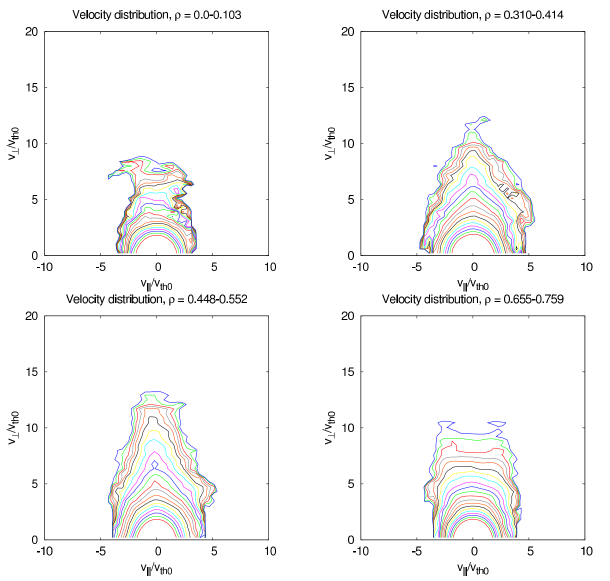

Fig. 8 Velocity distribution averaged in each radial ρ interval (f_{RF} = 38.5 MHz)

wave power depends on f_{RF} and peaks at a specific radial position. The ICRF wave power absorbed by minor-

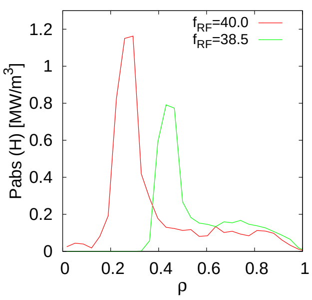

Fig. 9 Power profile absorbed by minority ions (H) in the case of f_{RF} = 40.0 MHz (red line) and f_{RF} = 38.5 MHz (green line)

ity ions is transferred to the background ions and electrons through particle collisions. The heating power profiles of background ions, P_{dep} (D), and electrons, P_{dep} (e), are shown in Fig. 10. Although the both P_{dep} (D) and P_{dep} (e) slightly peak at the same radial point, the profile of them are broader compared to that of P_{abs} (H). The heating efficiencies (Total heating power/Total power absorption) are 0.697 (f_{RF} = 40.0 MHz) and 0.396 (f_{RF} = 38.5 MHz), respectively.

4 Conclusion

We have carried out a global simulation of ICRF heating in the helical plasma (LHD) combining the full wave field solver (TASK/WM) and the drift kinetic equation solver (GNET). The realistic ICRF wave profile have been obtained by TASK/WM and been used to solve a drift kinetic

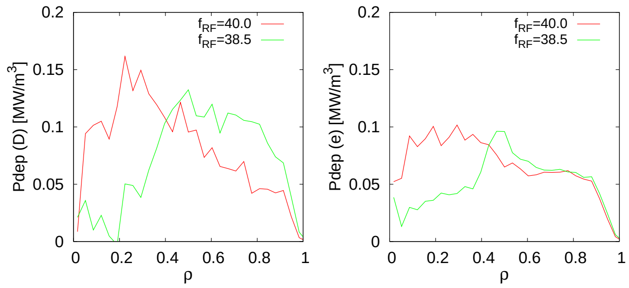

Fig. 10 Heating power profile of background ion (left) and electron (right) in the case of f_{RF} = 40.0 MHz (red line) and f_{RF} = 38.5 MHz (green line)

equation in the GNET. The wave number $k_\perp$ profile has been directly evaluated from the wave form.

The characteristics of the ICRF minority heating in the LHD have been shown.

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