Simulation Study of Energetic Ion Distribution during Combined NBI and ICRF Heating in LHD

S. Murakami[1], A. Fukuyama[1], V. Kasilov[2], T. Mutoh[3], R. Kumazawa[3], T. Seki[3], K. Saito[3], T. Watari[3], M. Isobe[3], M. Nishiura[3], T. Ozaki[3], M. Osakabe[3], M. Sasao[4], and LHD Experimental Group

[1]Department of Nuclear Engineering, Kyoto University, Kyoto 606-8501, Japan
[2]Institute of Plasma Physics, National Science Center, KIPT, Kharkov, Ukraine
[3]National Institute for Fusion Science, Oroshi, Toki, Gifu 509-5292, Japan
[4]Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan

e-mail contact of main author: murakami@nucleng.kyoto-u.ac.jp

1. Introduction

In the LHD, significant performances of ICRF heating (fundamental, minority heating regime) have been demonstrated[1-4] and up to 500keV of energetic tail ions have been observed by fast neutral particle analysis (NPA)[5-7]. These measured results indicate a good property of energetic ion confinement in helical systems. From the 9th campaign of LHD experiment (FY2005) a new perpendicular NBI heating system (P<3MW) has been installed and an effective heating of perpendicularly injected beam ions by the higher harmonics ICRF heating is expected.

ICRF heating generates highly energetic tail ions, which drift around the torus for a long time (typically on a collisional time scale). Thus, the behavior of these energetic ions is strongly affected by the characteristics of the drift motions, which depend on the magnetic field configuration. In particular, in a three-dimensional (3D) magnetic configuration, complicated drift motions of trapped particles would play an important role in the confinement of the energetic ions and the ICRF heating process. Therefore a global simulation of ICRF heating is necessary for the accurate modeling of the plasma heating process in a 3D magnetic configuration.

In this paper we study the energetic ion distribution during combined NBI and 2nd harmonics ICRF heating in LHD using two global simulation codes: a full wave field solver TASK/WM[8] and a drift kinetic equation solver GNET[9-11]. GNET solves a linearized drift kinetic equation for energetic ions including complicated behavior of trapped particles in 5-D phase space. TASK/WM solves Maxwell's equation for RF wave electric field with complex frequency as a boundary value problem in the 3D magnetic configuration.

2. Simulation Model

In order to study the ICRF heating in a 3D magnetic field configuration we have been developing two global simulation codes; GNET and TASK/WM. GNET solves a linearized drift kinetic equation for energetic ions including complicated behavior of trapped particles in 5-D phase space

$$\frac{\partial f_{beam}}{\partial t} + (\mathbf{v}_{//} + \mathbf{v}_D)\cdot\nabla f_{beam} + \mathbf{a}\cdot\nabla_{\mathbf{v}} f_{beam} - C(f_{beam}) - Q_{ICRF}(f_{beam}) - L_{particle} = S_{beam}\ , (1)$$

where $C(f)$ and Q_{ICRF} are the linear Coulomb Collision operator and the ICRF heating term. S_{beam} is the particle source term by NBI heating. The $S_{particle}$ is evaluated by NBI heating analysis code, HFREYA.

The particle sink (loss) term, $L_{particle}$, consists of two parts. One is the loss by the charge exchange loss. In the simulation we assume the same neutral particle profile as the source term calculation. The other is the loss by the orbit loss escaping to outside of the simulation region. In this simulation we assume the outermost flux surface as the boundary of simulation region.

The Q_{ICRF} term is modeled by the Monte Carlo method. When the test particle pass through the resonance layer where $\omega - k_{//}v_{//} = n\omega_c$, the perpendicular velocity of this particle, $\mathrm{v}_{\perp 0}$, is changed by the following amount

$$\begin{aligned}\Delta \mathrm{v}_{\perp} &= \sqrt{\left(\mathrm{v}_{\perp 0} + \frac{q}{2m} I|E_+|J_{n-1}(k_\perp \rho)\cos\phi_r\right)^2 + \frac{q^2}{4m^2}\left\{I|E_+|J_{n-1}(k_\perp\rho)\right\}^2 \sin^2\phi_r} - \mathrm{v}_{\perp 0} \\ &\approx \frac{q}{2m} I|E_+|J_{n-1}(k_\perp\rho)\cos\phi_r + \frac{q^2}{8m^2\mathrm{v}_{\perp 0}}\left\{I|E_+|J_{n-1}(k_\perp\rho)\right\}^2 \sin^2\phi_r\end{aligned} \qquad (5)$$

where E_+ and ϕ_r are the RF wave electric fields and random phase, respectively. Also, q, m, ρ, J_n are the charge, mass and the Larmor radius of the particle, and n-th Bessel function, respectively. The time duration passing through the resonance layer, I, is given by the minimum value as, $I = \min(\sqrt{2\pi / n\dot{\omega}}\ , 2\pi(n\ddot{\omega}/2)^{-1/3}Ai(0)\ )$, which corresponds to two cases; the simply passing of the resonance layer and the passing near the turning point of a trapped motion (banana tip).

The spatial profile of RF wave electric field is necessary for the accurate calculation of the ICRF heating. The profile of RF wave field is an important factor on the ICRF heating and this profile affects the particle orbit. We evaluate the RF wave field by the TASK/WM code. TASK/WM solves Maxwell's equation for RF wave electric field, $\mathbf{E}_{RF}$, with complex frequency, ω, as a boundary value problem in the 3D magnetic configuration.

$$\nabla\times\nabla\times\mathbf{E}_{RF} = \frac{\omega^2}{c^2}\vec{\varepsilon}\cdot\mathbf{E}_{RF} + i\omega\mu_0\mathbf{j}_{ext}, \qquad (8)$$

Here, the external current, $\mathbf{j}_{\mathrm{ext}}$, denotes the antenna current in ICRF heating. The response of the plasma is described by a dielectric tensor including kinetic effects in a local normalized orthogonal coordinates.

3. Simulation Results

We consider a LHD configuration (R_{ax} = 3.6m; the in-ward shifted configuration) to investigate the energetic ion distribution during combined heating of perpendicular NBI and ICRF heating. The LHD configuration of R_{ax} = 3.6m conforms the σ-optimized configuration and shows relatively good trapped particle orbit. Most of ICRF heating experiments have been performed in this configuration because of the relatively good performances of this configuration.

We, first, solve the drift kinetic equation for the beam ions without ICRF heating using GNET. Figure 1 shows the iso-surface plot of the steady state distribution of beam ions without ICRF heating. We plot the flux surface averaged tail ion distribution in the three dimensional space (r/a, E, θ_p), where a/r, E and θ_p are the normalized averaged minor radius, the total energy and the pitch angle, respectively. The plasma temperature and density are assumed as $T_s=(T_{s0}-T_{sw})(1-(r/a)^2)+T_{sw}$ with $T_{e0}=T_{i0}$=1.6keV and $n_e=(n_{e0}-n_{ew})(1-(r/a)^8)+n_{sw}$ with $n_{e0}=1.0\times10^{19}$m^{-3}. The injection perpendicular beam ion energy, E_b, is 40keV.

The high distribution regions can be seen near the beam sources: the pitch angle is about π/2 (almost perpendicular) and the three energy components (E_b, $E_b/2$, $E_b/3$). The beam ion distribution shows slowing down and pitch angle diffusion in velocity space.

Next we study the energetic ion distribution during combining heating of perpendicular NBI and 2nd harmonics ICRF. Based on the wave field profile by TASK/WM code, a simple RF wave electric fields profile; $E_+= E_{+0}\tanh((1-r/a)/l)\cos\theta$ with l=0.2 is assumed as a first step in the GNET simulation. The other wave field parameters are set as k_{perp}=62.8m^{-1} and $k_{//}$=0. The amplitude of the wave field, E_{+0}, is changed in the range 0.5kV/m through 1.5kV/m to obtain the dependency on the heating power.

Figure 2 shows the iso-surface plot of the steady state distribution of the beam ions with 2nd harmonics ICRF heating obtained by GNET. The RF wave accelerates beam ions perpendicularly in the velocity space and we can see perpendicularly elongated beam ion distributions by 2nd-harmonics ICRF heating. We find a peaked energetic tail ion distribution near r/a~0.5. The elongation of the distribution is larger than that of the fundamental heating case[11].

We next evaluate the beam ion pressure (a energy weighted population of energetic ions) in the real space. We plot the one of ten helical pitches and the right (left) side is the outside (inside) of torus. We can see the clear difference between two heating cases. The high-pressure regions are localized along the helical ripples where the magnetic field is weak in the case without the ICRF heating. On the other hand the high-pressure region is strongly localized near the resonance surface along the helical ripples in the case with the ICRF heating.

We have simulated the NDD-NPA[7] using the GNET simulation results. It is found that the tail ion energy is enhanced to MeV order and a larger tail formation can be seen than that of the fundamental harmonic heating case.

5. Conclusions

We have been developing an ICRF heating simulation code in toroidal plasmas using two global simulation codes; GNET and TASK/WM. The GNET code solves a linearized drift kinetic equation for energetic ions including complicated behavior of trapped particles in 5-D phase space and the TASK/WM code solves Maxwell's equation for RF wave electric field with complex frequency as a boundary value problem in the 3D magnetic configuration. The complete combining of these two codes is being developed and we perform a simulation using the tentative version.

The developed code has been applied to investigate energetic ion distribution during combining heating of the perpendicular NBI and 2nd harmonics ICRF heating in the LHD. A steady state distribution of energetic tail ion has been obtained and the characteristics of distribution in the phase space are clarified. The GNET simulation results have shown an effective energetic particle generation in the 2nd harmonics ICRF heating in LHD.

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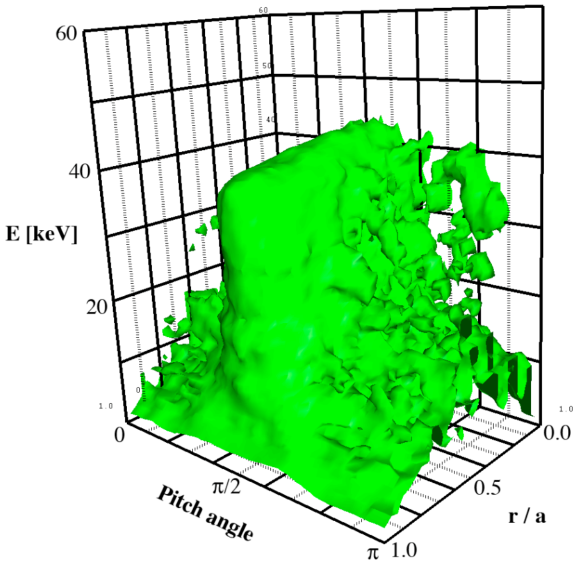

FIG. 1 *Steady state distribution of beam ions in the (r/a, E, pitch angle) space without ICRF heating.*

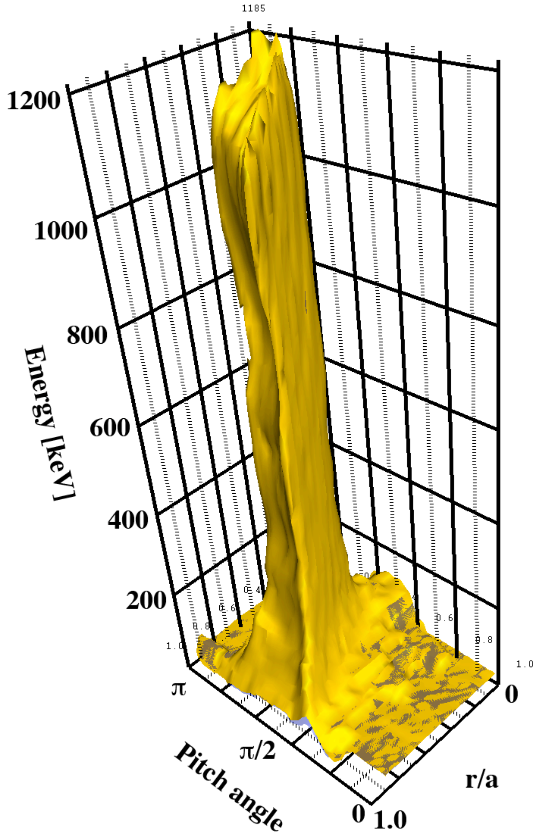

FIG. 2 *Steady state distribution of beam ions in the (r/a, E, pitch angle) space with 2nd harmonics ICRF heating.*

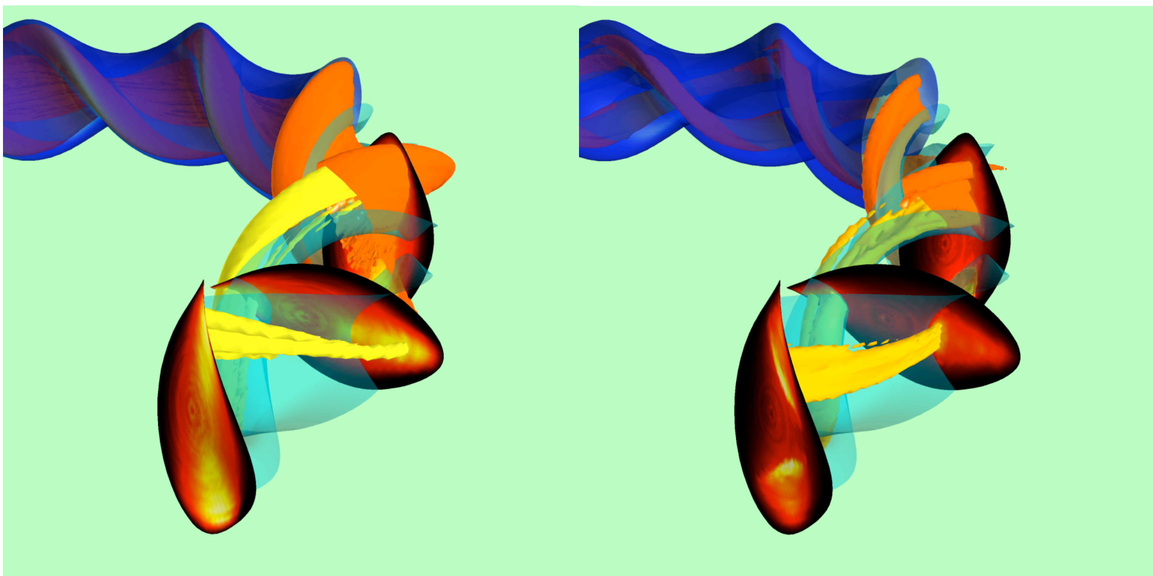

FIG. 3: *3D plots of the beam ion pressure without ICRF heating (left) and with the 2nd harmonics ICRF heating (right).*