5-D Simulation Study of Energetic Tail Ion Transport during ICRF Heating in LHD

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1. Introduction

The behaviors of trapped particles are complicated and have relatively large orbit size in the radial direction in heliotrons. These radial motions of trapped particle would enhance the radial transport of energetic ions. Also, because of fast drift motion of energetic ions, the direct convective transport by grad-B drift of ripple trapped particle would be important in the energetic ions confinement in addition to the diffusive (neoclassical) transport, which plays dominant role in the thermal plasma. Thus, the ripple induced transport of energetic ions is an important issue for the energetic ion confinement.

ICRF heating experiments[1-3] have been successfully done and have shown significant performance of this heating method in LHD. Up to 400keV of energetic tail ions have been observed by fast neutral analysis. However, the measured information is obtained as an integrated value along a line of sight and we need the theoretical model for the energetic tail ion distribution to discuss the role of ripple induced transport.

In this paper we study the transport of energetic tail ions during ICRF heating in LHD using a global transport simulation code in 5-D phase space (GNET)[4,5]. We make clear the characteristics of minority ion distribution in the phase space and show the role of ripple-induced transport in the energetic tail ion confinement in LHD.

2. Simulation Model

Many efforts have been made to analyze the energetic particle distribution and the transport during ICRF heating, analytically and numerically (Fokker-Planck model and etc.), but most of the analyses using local approximation. A simple Orbit following Monte Carlo simulation has been used to take into account the non-local effect due to finite orbit size of energetic ions. However, the energetic particle distribution changes in time and we can not obtain a correct steady state by this type of Monte Carlo simulation. To obtain a steady state we should consider the balanced state between particle source and sink correctly in a global simulation.

We solve the drift kinetic equation of minority ion during ICRF heating in 5D phase-space

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

where $C(f)$ and Q_{ICRF} are the linear Clulomb Collision operator and the ICRF heating term by the wave-particle interaction. $S_{particle}$ is the particle source term by ionization of neutral particle [Fig. 1; n_0=1x10^{19}m^{-3} (dashed line) and 2x10^{19}m^{-3} (solid line)] and the radial profile of the source is evaluated using AURORA code. $L_{particle}$ is the particle sink (loss) term consists of two parts; one is the loss by the charge exchange loss assuming the same neutral particle profile as the source term calculation and the other is the loss by the orbit loss escaping outside of outermost flux surface. In GNET code the minority ion distribution f is evaluated through a convolution of $S_{particle}$ with a characteristic time dependent Green function evaluated using test particle Monte Carlo method.

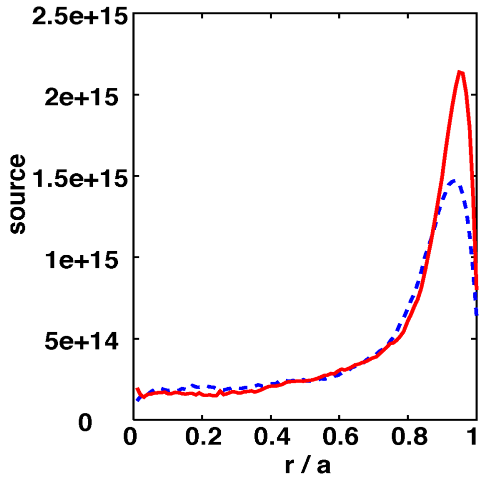

Fig.1 : Source profile of minority ions

3. Simulation Results

We, here, consider two LHD configurations with different values of the magnetic axis shift in the major radius direction; one is the "standard" configuration (R_{ax} = 3.75m) satisfying the requirements for highly balanced plasma performance (i.e. a high plasma beta, relatively good particle confinement, and creating a divertor configuration) and the other is the "inward shifted" configuration (R_{ax} = 3.6m) where the confinement of ripple trapped particle is improved drastically and the good confinement of energetic ions would be expected.

Figure 2 shows the steady state distribution of the minority ions during ICRF heating obtained by GNET code for the two configurations of LHD (R_{ax} = 3.6m and 3.75m). We plot the flux surface averaged tail ion distribution in the three dimensional space (r/a, $v_{//}$, v_{perp}), where a/r, $v_{//}$ and v_{perp} are the normalized averaged minor radius, the parallel and perpendicular velocities normalized by the thermal velocity at the plasma center, respectively. We assume the same heating and plasma parameters as the experimental ones, where the RF heating power of about 2.5MW, the magnetic field strength at R=3.6m is

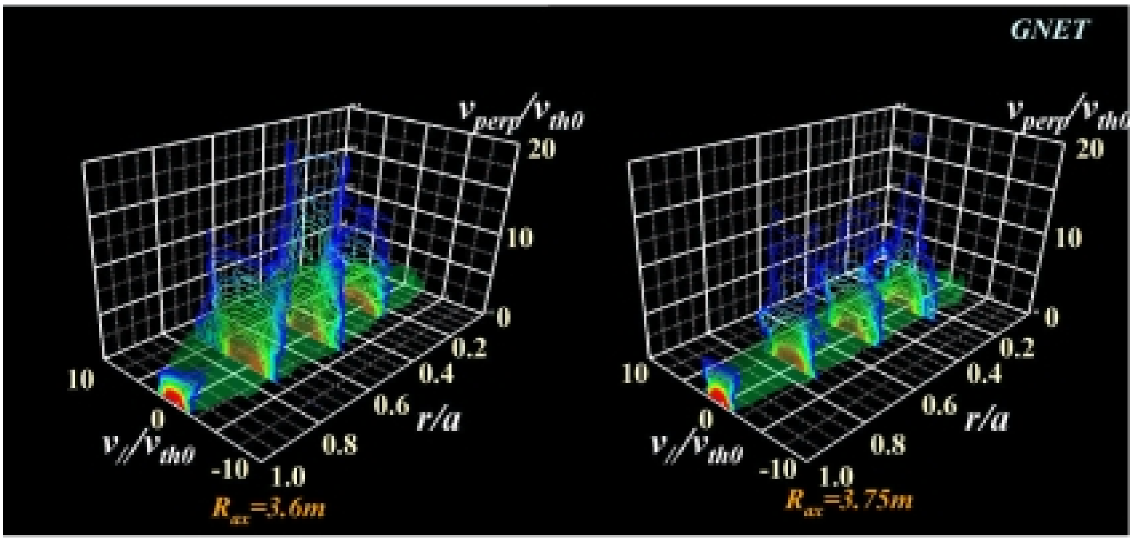

Fig. 2: Energetic tail ion distribution in the (r/a, $v_{//}$, v_{perp}) coordinates in the LHD plasma for two different configurations; R_{ax} = 3.6m (left) and R_{ax} = 3.75m (right).

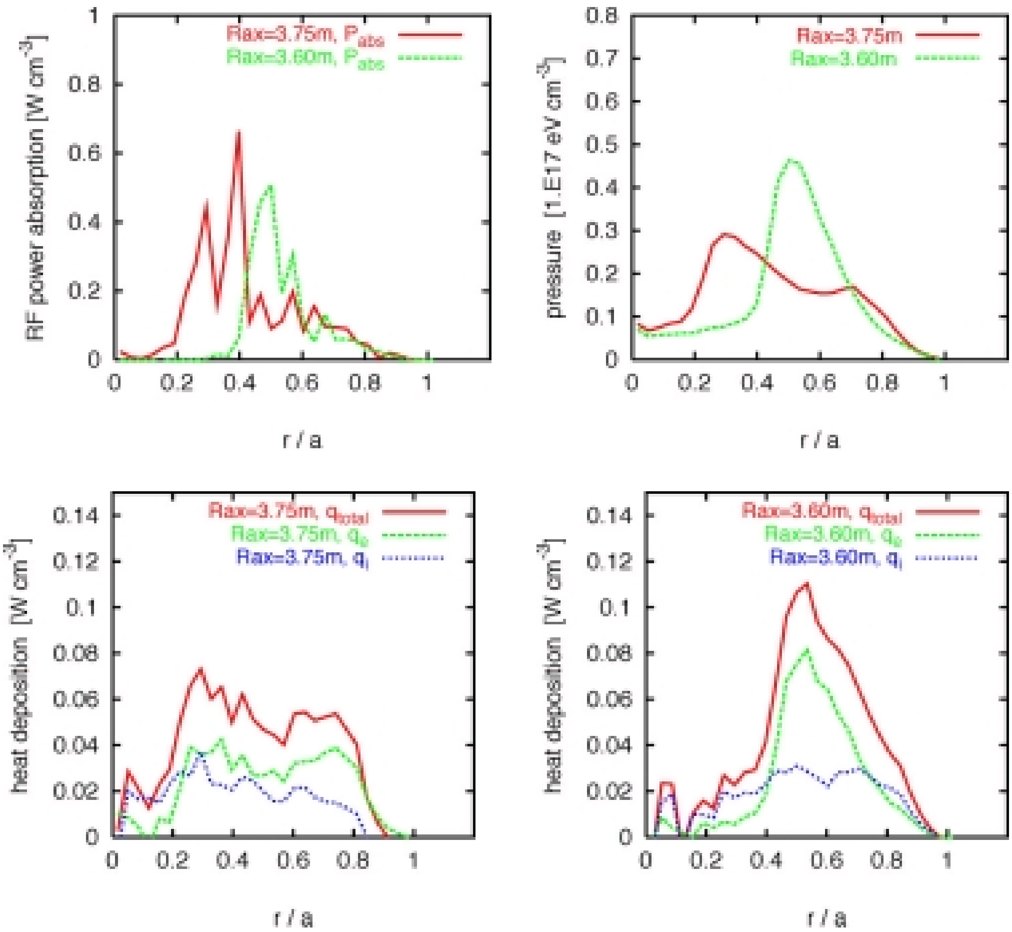

Fig. 3: Radial profiles of RF power absorption (left top), energetic ion pressure (right top), heat deposition (left bottom; R_{ax} = 3.6m and right bottom of R_{ax} = 3.75m).

2.75T and the resonance region only exists r/a>0.5 in the R_{ax} = 3.6m configuration. The density, n, and temperature, T, are assumed to be $n=n_0(1-(r/a)^8)$ and $T=T_0(1-(r/a)^2)$ where $n_0=1\text{x}10^{19}\text{m}^{-3}$ and T_0=1.6keV.

The RF wave accelerates minority ions perpendicularly in the velocity space and we can see perpendicularly elongated minority ion distributions in both cases. Also we find a peaked energetic tail ion distribution near r/a~0.5 in the R_{ax} = 3.6m case, while a broader distribution of energetic tail ions can be seen in the R_{ax} = 3.75m case. This is due to the larger trapped particle orbit size. The energetic particle would be localized more in the R_{ax} = 3.6m case.

Figure 3 (left top and right top) shows the radial profiles of RF power absorbed by minority ions and pressure profile of minority ions. The peak of RF power absorption appears at r/a ~0.5 in the R_{ax} = 3.6m case and is at r/a ~0.4 in the R_{ax} = 3.75m case. Then, we can see the peak of pressure profile also at r/a ~0.5 in the R_{ax} = 3.6m case. On the other hand we can see a broader pressure profile in the R_{ax} = 3.75m case. This shows that the larger ripple induced transport occurs in the R_{ax} = 3.75m case. The heat deposition profile (Fig.3: bottom) also shows the broader profile in the R_{ax} = 3.75m case than that in the R_{ax} = 3.6m case and the obtained heating efficiency is 40% higher in the R_{ax} = 3.6m case.

4. Conclusions

We have developed a 5D (3D+2D) phase space simulation code, GNET, for studying the global collisional transport in non-axisymmetric configurations. The GNET code has been applied to the analysis of energetic tail ion transport during ICRF heating in the LHD plasma. A steady state distribution of energetic tail ion has been obtained and the characteristics of distribution in the phase space are clarified. The configuration dependency on the distribution have been shown and higher heating efficiency have been obtained in the R_{ax}=3.6m.

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