Simulation study of toroidal flow generation by the ICRF minority heating in the Alcator C-Mod plasma

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Introduction

Important role of the plasma flow and its shear in the transport improvement is suggested by many experimental observations, e.g. H-mode transition, ITB formation, RWM suppression. In a future reactor the driving of the plasma flow by NBI heating is not efficient and other driving method is required. The spontaneous toroidal flow has been observed during ICRF heating with no direct momentum input in JIPP-TIIU[1], JET[2], Alcator C-Mod[3, 4] and etc. Especially, in the Alcator C-Mod plasma, the spontaneous toroidal flow and ITB formation have been investigated intensively in the ICRF heating plasma. They found that the ITB plasma (ITB foot point is located near $r/a \sim 0.5$.) was obtained when the ICRF resonance location was placed at well off the magnetic axis, near $r/a \sim 0.5$.

We have studied the toroidal flow generation by the ICRF heating using GNET code[5] which can solve a linearized drift kinetic equation for energetic ions including complicated behavior of trapped particles. In our previous study[6, 7] we have found that a co-directional toroidal flow is generated outside of the RF wave power absorption region and that the dominant part of toroidal flow does not depend on the sign of $k_{\parallel}$. When we change the sign of the toroidal current we obtain a reversal of the toroidal flow velocity, which is consistent with the experimental observations. We have also shown that the toroidal precession motion of trapped energetic tail ions is enhanced because of the large banana size and the large poloidal drift, and this enhanced toroidal motion plays an important role in generating the averaged toroidal flow.

In this paper we study the toroidal flow generation by the ICRF minority heating to make clear the relation between the ICRF resonance location and the ITB formation in the Alcator C-Mod plasma. We investigate the velocity space distribution function of the energetic tail ions and toroidal flow profile changing the resonance location.

Simulation Model

In order to study the ICRF minority heating including finite orbit effect we have developed a global simulation code, GNET[4, 5], which can solve a linearized drift kinetic equation for energetic minority ions, $f_{\rm min}$, including complicated behavior of trapped particles in 5-D phase space

$$\frac{\partial f_{\rm min}}{\partial t} + (v_{\parallel} + v_D) \cdot \nabla f_{\rm min} + a \cdot \nabla v f_{\rm min} - C(f_{\rm min}) - Q_{\rm ICRF}(f_{\rm min}) - L_{\rm particle} = S_{\rm particle} \quad (1)$$

where $C(f_{\rm min})$ and $Q_{\rm ICRF}(f_{\rm min})$ are the linear Coulomb Collision operator and the ICRF heating term. $S_{\rm particle}$ is the particle source term by ionization of neutral particle and the radial profile of the source is evaluated using AURORA code. The particle sink (loss) term, $L_{\rm particle}$, 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.

Simulation results

We perform the simulation using GNET code until we obtain a steady state distribution of energetic minority ions in the Alcator C-Mod plasma ($R = 0.67$m, $r \sim 0.21$m) with following plasma parameters; $n_{e0} \sim 8 \times 10^{19}$m^{-3}, $T_0 \sim 3.2$keV and B_0=5.4T. We use the same plasma parameters and change the resonance location, r_{res}/a, in the major radius direction from $r_{res}/a = -0.6$ to $+0.6$ on the equatorial plane. The RF wave electric field is assumed as, $E^+(r) = E_0^+ \tanh 20(1 - r/a)$ and $E_0^+ = 4.0$kV/m. The parallel and perpendicular wave numbers are $k_{\parallel} = 5$m^{-1} and $k_{\perp}$ =50m^{-1}, respectively.

Radial profiles of the RF power absorption by the minority ion show a clear shift of the absorption region according to the resonance location. Also the minority ion pressure profiles show the shift of the energetic minority ion population.

Figure 1 shows the flux averaged distributions of minority ions in the velocity space $(v_{\parallel}, v_{\perp})$ at the different minor radius; $r/a = 0.5$ (left) and 0.75 (right) in the case of r_{res}/a =-0.55. The minority ions are accelerated perpendicular direction by wave-particle interactions and we can see a energetic ion tail formation by the ICRF heating. Interestingly strong asymmetries can be seen in the parallel direction and, also, the asymmetry direction changes between two radial positions. These indicate the toroidal shear flow is driven by the ICRF heating near $r/a \sim 0.5$.

The radial profiles of the averaged toroidal velocity of minority ions driven by the ICRF heating are shown in Fig. 2-(left). The velocity is normalized by the central ion thermal velocity. We can see large co direction toroidal flows in the outside region of the resonance location, $r/a > |r_{res}/a|$, in all cases. In the inside region of the resonance location, $r/a < |r_{res}/a|$, almost

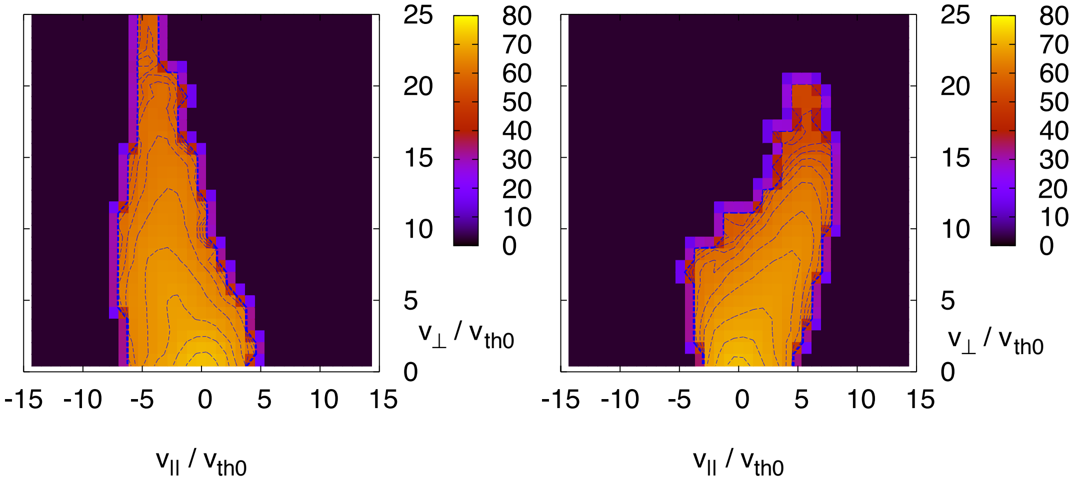

Figure 1: *Contour of the flux surface averaged velocity space distribution,* $\ln f_{min}$*, at the radial regions;* r/a *= 0.5 (left) and 0.75 (right) in the case the resonance location* r_{res}/a *=0.55.*

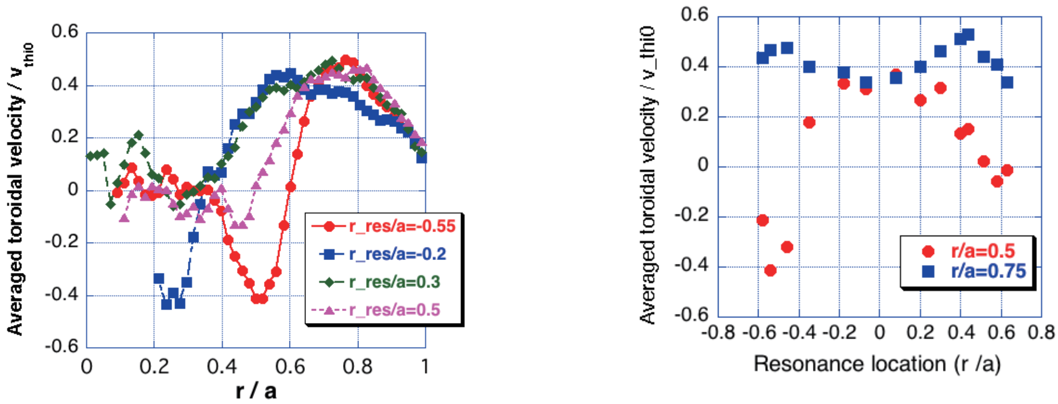

Figure 2: *Radial profiles of the averaged toroidal velocity (left) and the resonance location dependences of the averaged toroidal velocity at* r/a *= 0.5 and 0.75 (right).*

no toroidal flow is obtained in the cases $r_{res}/a = 0.3$ and 0.5, because of small energetic tail ion population. Additionally, in the cases $r_{res}/a = -0.2$ and -0.55, large opposite direction toroidal flows are observed near the resonance location region, $r/a \sim |r_{res}/a|$. This is because the accelerated particles in this region are located at the trapped-passing boundary in the velocity space and, as the particle reaches to this boundary the toroidal precession motions reduce to 0 or change to opposite direction. The maximum averaged velocity of the minority ion reaches about 300km/s, which is more than five times bigger than the experimentally observed bulk velocity[3], and we think that the energetic minority ion can drive the toroidal flow of the bulk plasma to the observed velocity level.

Figure 2-(right) shows the resonance location dependences of the toroidal velocity at $r/a =$

0.5 and 0.75. We can see that the toroidal flow shear near $r/a = 0.5$ is enhanced when the resonance location shifted to $|r_{res}/a| > 0.5$. The obtained shear is also more than five times bigger than that of the experimental observation of bulk plasma, where they have shown that the $E \times B$ shearing rate is comparable with the ITG growth rate[8]. This suggests a role of the ICRF driven toroidal flow on the experimentally observed ITB formation during ICRF heating in the Alcator C-Mod plasma, where the ITB plasma (ITB foot is located near $r/a \sim 0.5$.) is observed when the resonance location shift to out side of $|r_{res}/a| \sim 0.5$.

Summary

We have studied the toroidal flow generation by the ICRF minority heating in the Alcator C-Mod plasma applying GNET code, in which the drift kinetic equation is solved including complicated orbits of accelerated energetic particles. We have found that a co-directional toroidal flow of the minority ion is generated in the outside region of the resonance location and that the toroidal velocity reaches more than 40% of central ion thermal velocity ($V_{tor} \sim 300km/s$ with $P_{ICRF} \sim 2$MW). When we shift the resonance location to the out side of $|r/a| \sim 0.5$ the toroidal flow just inside of the resonance location reduces to 0 or changes to opposite direction, and the toroidal velocity shear is enhanced. This suggests a role of the ICRF driven flow on the experimentally observed ITB formation during ICRF heating in the Alcator C-Mod plasma.

In this simulation study we have not used the magnetic configuration and plasma parameter from the experimental data. In order to compare the simulation and experimental results quantitatively we will include precise experimental plasma data and the RF wave electric field by the TORIC ICRF solver.

References

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