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GENERATION OF PLASMA ROTATION BY ICRH IN TOKAMAKS[1]

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Abstract

A physical mechanism to generate plasma rotation by ICRH is presented in a tokamak geometry. By breaking the omnigenity of resonant ion orbits, ICRH can induce a non-ambipolar minor-radial flow of resonant ions. This induces a return current j_r^p in the plasma, which then drives plasma rotation through the $j_r^p \times B$ force. It is estimated that the fast-wave power in the present-day tokamak experiments can be strong enough to give a significant modification to plasma rotation.

1. INTRODUCTION

It is believed that a strong plasma rotation can improve confinement and stability of tokamak plasmas. It will greatly benefit the tokamak program if we can generate rotation by a controllable, external method other than the neutral beam injection. Recent experimental observations suggested a possibility that ICRF waves may become a controllable, external tool to generate plasma rotation [1-3]. We present a theoretical understanding how the Ion Cyclotron Resonance Heating (ICRH) by ICRF waves can generate radial electrical current and plasma rotation in tokamaks. We use the (r, θ, ϕ)-coordinate system. The minor radius r is often abbreviated simply to "radius."

In a tokamak, even though there is radial excursion due to vertical ∇B-drift, radial drift of a collisionless orbit averages to zero (omnigenity). ICRH can break the omnigenity and generate radial current j_r^{rf} by giving a localized kick in the ∇B-drift to the resonant ions. The main plasma then develops a return current j_r^p to keep the plasma quasineutral and stops an indefinite growth of E_r. The j_r^p imparts $j_r^p \times B$ torque and rotate the main plasma.

The mechanism considered here is different from the analytic, thin banana calculations of [4,5]. Reference [4] studied radial transport of ICRH-generated trapped ions from direct parallel momentum scattering by waves. Reference [5] considered radial transport of ICRH-generated trapped minority ions from the ambipolar Coulomb scattering process. The present finite-excursion mechanism does not require a parallel momentum scattering by waves or Coulomb collisions and can override the mechanism of [4,5]. For example, a closed steady-state orbit does not usually exist for a tail ion under a reasonably strong ICRH, as assumed to exist in [4,5].

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2. GUIDING CENTER MOTION AND RADIAL TRANSPORT BY ICRH

We use a Hamiltonian guiding center code[6] to follow the trajectory of resonant particles and evaluate j_r^{rf}. Average radial position is calculated by taking a time average over a complete poloidal circuit. The radial transport from the loss of omnigenity is studied from the single particle point of view only. Diffusive transport from a mild radial density gradient of the minority ions is neglected in the present report. Neglecting the usually-small parallel heating, the ICRH is simply modeled as a constant amount of perpendicular energy input per resonance. Due to the energetic nature of the resonant tail ions, the effect of the radial electric field on the guiding center motion has been neglected.

Dynamical properties of trapped and passing orbits are different. Let us first consider the trapped orbits. Figure 1 shows a trapped ion orbit under an on-axis resonance heating in a device similar to TFTR[1], simulating a minority tail ion whose perpendicular energy is increased along the resonance pitch angle where the banana tip location coincide with the resonance surface. The parameters used are $B_o = 3.1$ T, $R_o = 2.70\ m$, a=0.99 m, q = 1 + 5 $(r/a)^2$, $n_e = 2 \times 10^{19}$ m^{-3}, $Z_{\text{eff}} = 1.5$, $T_i = 1.8$ keV, and $T_e = 3.5$ keV. Every time the particle passes through resonance, it acquires perpendicular energy, its $V_{\nabla B}$ increases, and the banana width increases. The outer part of banana orbit expands faster than the inner part does, due to the toroidal effect on fat banana orbits. As a result, the time averaged radial position increases in time, giving a radially outward transport driven by ICRH. In Fig. 1, the perpendicular energy kick is exaggerated to 100 keV per pass to enhance the visual effect. The orbit shown is for 20 toroidal transits, starting at 50 keV and ending at 1 MeV. The slowing-down collision is also exaggerated at a proper rate.

One observation we can make here is that the sign of $k_{||}$ does not affect the outward direction of radial current. Regardless of the sign of $k_{||}$, the banana particles eventually turn ($v_{||} = 0$) near the resonance surface, and the outer part of banana orbit expands faster than the inner part does. A representative example for this case can be seen when the resonant minority ions are in the so called “rabbit-ear” distribution[5] in the trapped regime. Using the fact that the fast wave absorption is highly peaked toward the plasma center for an on-axis resonance, we can make another observation that the on-axis heating will yield j_r^{rf}-generation peaked in the core plasma. However, moving the resonance layer to the larger R side can yield more off-axis power-absorption and more efficient trapped particle generation at greater minor radius: Hence, a broader E_r profile can be expected.

For the passing ion dynamics, alpha particles in the core of a fusion reactor can be a good example. Figure 2 shows poloidal projection of a counter-passing alpha orbit under a low-B side heating (dashed line). A circular plasma cross section is assumed with reactor-grade parameters: $R_0 = 8\ m$, $a = 3\ m$, $B_0 = 5.5\ T$, $q(0) = 1$, $q(a) = 4$, $Z_{\text{eff}} = 1.5$, $k_{||} = 7\ m^{-1}$, $T_i = 20\ keV$, and $n_e = 1 \times 10^{20} m^{-3}$. The counter-passing ion travels in the clock-wise direction poloidally. The particle obtains an extra radial drift after each pass through the resonance surface (∇B-drift is downward here). On the large-R side from the resonance, the added perpendicular kinetic energy gives extra inward shift in r, and outward shift in r on the small-R side. The direction and magnitude of time-averaged j_r^{rf} is then a function of the actual Doppler-shifted resonance location. In the case shown in Fig. 3, the outward excursion portion is greater, yielding a net outward transport. The orbit shown is for 9 toroidal transits, starting at 3.5 MeV and ending at 3 MeV. Heating per pass is exaggerated to 500 keV.

3. DEVELOPMENT OF TOROIDAL ROTATION

A non-ambipolar radial flow of resonant ions, denoted by the radial electric current j_r^{rf}, will generate radial electric field E_r in the plasma. The large radial dielectric constant of a tokamak plasma ($K_p \simeq c^2/V_{A\theta}^2$, where $V_{A\theta}$ is the Alfven speed in B_θ) allows plasma return current j_r^p grow immediately in response to E_r, and stops further growth of E_r when j_r^p reaches to be $-j_r^{rf}$. The main plasma will then be subject to the $j_r^p \times B_\theta$ toroidal force and the resonant species will be subject to $j_r^{rf} \times B_\theta$ toroidal force in the opposite direction. This makes the main plasma spin in one toroidal direction and the resonant species in the other direction. Ideally, the combined toroidal momentum will vanish. However, different (anomalous) toroidal momentum transport rates between the main and resonant ions may establish a non-vanishing combined toroidal momentum, locally or globally. In the present work, we study the rotation of the main species only.

Toroidal component of the main plasma force balance equation yields

$$m_i n_i \frac{\partial}{\partial t} < V_\phi R >= \frac{1}{c} < j_r^p \cdot \nabla\psi > - < R\hat{e}_\phi \cdot (\nabla \cdot \mathbf{\Pi}) > + < RF_\phi >, \tag{1}$$

where $< \cdots >$ represents the flux surface average. Since the neoclassical viscous force in the toroidal direction, $< R\hat{e}_\phi \cdot (\nabla \cdot \mathbf{\Pi}) >$, is small, the toroidal rotation develops until the $< j_r^p \cdot \nabla\psi >$-force is balanced by the friction force $< RF_\phi >$. We include any anomalous viscous force in $< RF_\phi >$. If we assume that the toroidal momentum and plasma energy losses are dominated by the same physical mechanism, we may write $< RF_\phi >$ in the form $< RF_\phi >= -m_i n_i < RV_\phi > /\tau_E$, where τ_E is the energy confinement time. The solution to Eq. (1) is, then, obtained as follows:

$$< RV_\phi >=< RV_\phi^0 > (1 - \exp^{-t/\tau_E}), \tag{2}$$

where $m_i n_i < RV_\phi^0 >$ is the terminal value of the toroidal angular momentum density, $< RV_\phi^0 >= \tau_E < j_r^p \cdot \nabla\psi > /c m_i n_i$. As V_ϕ develops, under a steady E_r driven and maintained by ICRH, the poloidal rotation speed V_θ will damp to a new equilibrium value according to the radial force balance relation, $E_r = \nabla_r P + V_\phi B_\theta - V_\theta B_\phi$. This simply means the shift of $\mathbf{E}\times\mathbf{B}$ speed from V_θ to V_ϕ. Obviously, in the present case, the generation of V_ϕ and the decay of V_θ have a common time scale τ_E.

Using the previously mentioned TFTR plasma condition with $\tau_E = 0.4s$, we find that the ICRH-driven toroidal speed at $r = 0.1$ m is $\simeq 2 \times 10^4$ m/s for an absorbed rf-power density of $0.16\ MW/m^3$ to the H-minority ions (corresponding to ~ 1 MW of absorption to H-minority in the core). This result agrees with the experimental observation reasonably well[1]. If we use a super shot parameter set, we can easily get rotation over 10^5 m/s from the same amount of rf power. In the reactor grade plasma case presented earlier, we find that about 50 MW of absorbed rf power to the core alpha particles (within $r = 0.75 = a/4$ m) with directional $k_{||} = -7m^{-1} > 0$ and cold resonance on the magnetic axis can generate toroidal rotation of $\simeq 4 \times 10^5 m/s$ at r $=$ 0.3 m in the direction opposite to the plasma current, if we use $\tau_E = 5\ s$. Considering that the alpha density gradient may be steep in the burning core, the random scattering nature of the ICRH may induce flattening of density gradient, resulting in radially outward transport. Thus, the counter-rotation in a fusion reactor may be greater than what is predicted here.

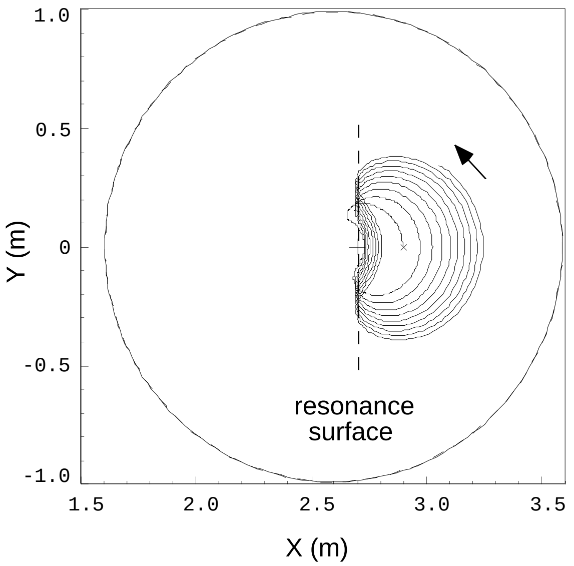

Fig. 1. Poloidal projection of a trapped ion orbit in TFTR under exaggerated on-axis ICRH

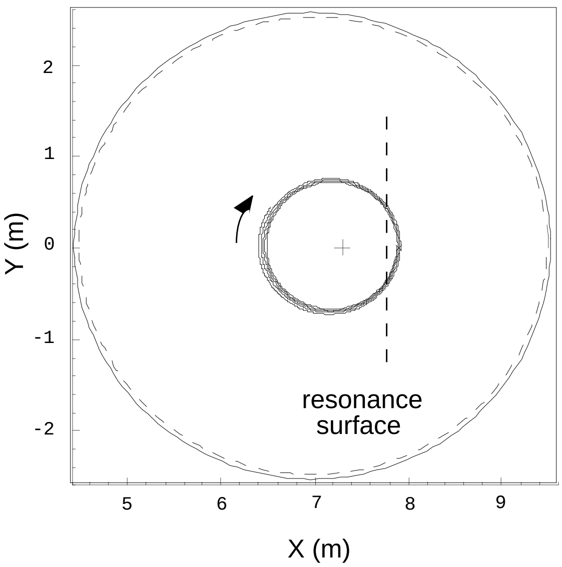

Fig. 2. Poloidal projection of a counter-passing alpha orbit in a reactor-size circular tokamak.

4. DISCUSSION

The present analysis shows that the counter-rotation generation in minority heating experiments in TFTR[1] can be explained from the ICRH-driven radially outward transport of trapped minority ions. It is predicted that the present mechanism may be used in a fusion reactor to generate central toroidal rotation $\simeq 1 \times 10^5 m/s$ per $25MW$ of absorbed power to the alpha particles. The co-rotation generation in Alcator C-Mod experiments can be due to the ICRH-driven inward transport of passing minority ions[2], and the counter rotation generation in DIII-D may be from the ICRH-driven radially outward transport of trapped beam ions[3]. The co-rotation generation reported in JET [7] may not have too much to do with the present mechanism. The centrally peaked rf-driven rotation should have decayed significantly at the radial observation point ($\overset{\sim}{<}$ 0.3 m). The observed rotation could be from the $\nabla_r P$ effect in H-mode as explained in [7].

In a reversed-shear profile, the radial excursion in the core plasma becomes more pronounced, hence, the generation of j_r^{rf} and V_ϕ by ICRH is expected to be enhanced.

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