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FAST ION TRANSPORT AND
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Ion Cyclotron Heating Induced Fast Ion Transport and Plasma Rotation in Tokamaks

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Abstract. Minority ion cyclotron heating can produce energetic ions with banana orbits that are finite compared with the minor radius of a tokamak. The radial transport of the fast ions in the presence of Coulomb collisions results in a radial current and a corresponding $\mathbf{J} \times \mathbf{B}$ torque density on the bulk plasma. Collisions between the minority ions and majority ions provides an additional frictional torque that adds to or opposes the magnetic torque. Our study uses a code which follows the particle drift trajectories in a tokamak geometry under the influence of rf fields and collisions, modeled with an rf-quasilinear operator and a Monte-Carlo operator, respectively. It is shown that when the regions of negative and positive torque density are spatially separated, a finite central rotation velocity can result even when the volume integrated torque density is small. This is consistent with the results of Perkins [F.W. Perkins, et al., "Generation of Plasma Rotation in a Tokamak by Ion-Cyclotron Absorption of Fast Alfvén Waves," to appear in *Phys. Plasmas*, 2001], that uses a different approach. A physical picture emerges explaining the co- and counter-rotation with low- and high-field resonance respectively as a consequence of finite orbit width. The model also provides details of the rotation profile when ions are continuously being heated and slowed down in steady-state. Qualitative comparison with recent JET results will be discussed.

INTRODUCTION

Ion cyclotron resonance heating (ICRH) has been observed to change poloidal and toroidal rotation of the bulk plasma and induce a radial electric field in many experiments [1]. Understanding the physics of plasma rotation observed in ion cyclotron radio frequency (ICRF)-only discharges is very important for developing reliable rf techniques for plasma control. Recently, it was shown that a central co-rotation can be sustained in the system with zero net (volume-averaged) toroidal torque, provided there exist spatially separated regions of negative and positive torque [2]. The present work focuses on refining the theoretical approach to understanding the physics of the co-current central plasma rotation in the JET and Alcator C-Mod ICRF experiments in the absence of direct momentum input [3,4]. It clarifies several important questions including contributions from a realistic modeling for fast ion production, the mechanisms behind the co- and counter-rotation, the role of the stochastic rf heating on fast ion transport, and the general features of a driven system where a significant fast ion population is maintained in steady-state.

SIMULATION RESULTS AND DISCUSSION

There are two main sources of orbit stochasticity that can produce the radial current and the resultant $\mathbf{j} \times \mathbf{B}$ torque. The first mechanism of the radial redistribution of resonant ions is their pitch-angle scattering off the background ions. The $\mathbf{j}_r^p \times \mathbf{B}_\theta$ torque due to pitch-angle scattering must be carefully evaluated against the accompanying drag force exerted on the bulk ions due to angular momentum exchange with the resonant particles [5]. The absolute ratio of the collisional to the magnetic torque density is:

$$\frac{f_\zeta^{col}}{f_\zeta^m} = \frac{\langle \dot{\rho}_{||h}^{col} \rangle}{\langle v_{rh} \rangle} \left(\frac{B_\zeta}{B_\theta} \right) \simeq \frac{\langle v_\perp \rho_{||h}^{col} \rangle}{\langle \dot{\rho}_{||h} \rangle} q(r) \left(\frac{R}{r} \right) , \quad (1)$$

where $\langle \dots \rangle$ denotes magnetic surface averaging, v_\perp is the pitch-angle collision frequency, and $\rho_{||} = v_{||}/\Omega$. Using conservation of canonical momentum, the radial orbit displacement is related to the parallel precession velocity $\dot{\rho}_{||}$ by $\dot{\rho}_{||} = (r/Rq) \dot{\rho}_h$. If the only mechanism responsible for radial diffusion is pitch-angle scattering, and for finite orbit width, the volume-integrated ratio approaches unity, resulting in the zero net torque constraint.

The second stochasticity comes from wave-induced diffusion. Stochastic increases and decreases in perpendicular velocity correlate with significant converse changes in finite orbit widths as was pointed earlier [6]. Statistically, this results in radial particle transport. It is important to emphasize collisionless radial diffusion exists in steady-state (heating balanced by collisional drag) as will be demonstrated. Since the radial orbit displacement is not caused by pitch-angle scattering, the ratio in Eq. (1) does not approach unity in general, and a non-zero net torque can result which is balanced by radial momentum diffusion. In this work we account for both mechanisms of radial current drive.

In this study, to prevent the important aspects of particle-wave interaction from being masked by possible computational and conceptual intricacies, we construct the simplest prototype model that describes the key issues of minority ICRH in tokamak geometry. The standard Stix estimate [7] is used to relate the electric field magnitude to the absorbed rf power. The minority ions are treated as Monte-Carlo test particles coupled with a background plasma through the pitch-angle scattering and slowing-down collisions. The particle motion is resolved with an rf-enhanced version of the ORBIT code [8]. Details of the ORBIT-RF code are described in a more complete publication [V.S. Chan, et al., "RF-Driven Radial Current and Plasma Rotation in a Tokamak," General Atomics Report GA-A23660, to be submitted to Phys. Plasmas].

The first simulation is for Alcator C-Mod-like parameters with the cyclotron resonance at $(R - R_0)/a = -0.15$ on the high field side. We use this to illustrate the characteristics of the test particle radial diffusion due to stochastic rf heating and Coulomb scattering. We note the rf-induced diffusion has a positive mean value and a "random walk" about that mean. The Coulomb collision consists of ion-electron slowing down and ion-ion pitch-angle scattering. The net integrated torque as a function of radius is depicted for four cases with: [Fig. 1(a)] the rf "random-walk" turned off and the pitch-angle scattering turned off; [Fig. 1(b)] the rf "random-walk" off and pitch-angle on, [Fig. 1(c)] the rf "random walk" on and pitch-angle scattering off; and [Fig. 1(d)] the rf "random walk" on and pitch-angle scattering on. The net torque at ψ_{pedge} is zero for the first two cases, but non-zero for the last two cases with the rf "random walk" turned on. This is consistent with the explanation following Eq. (1), and suggests that while the zero net torque assumption may be valid for the model in Ref. [2], it does not necessarily hold

for the more complex rf model discussed here. The net torque is sensitive to the plasma parameters and a larger value is expected for low density, high temperature plasmas.

The next set of simulations is aimed at clarifying the correlation between the directionality of the rf-induced rotation and the location of the cyclotron resonance. One of the main findings in Ref. [2] is the plasma rotates in the co-current direction on-axis when the cyclotron resonance is on the low-field side (LFS), and in the counter-direction on-axis when the resonance is on the high-field side (HFS). In our simulations, parameters are chosen to minimize the net torque to reproduce the same situations. With the resonance at $(R - R_0)/a = -0.15$ on the HFS, we show the integrated magnetic torque [Fig. 2(a)] and frictional torque [Fig. 2(b)]. The integrated magnetic torque is positive on the inside and negative on the outside, consistent with fast ions scattered inward and outward, compensated by equal and opposite return currents in the bulk plasma. The frictional torque is negative on the inside and positive on the outside. Two mechanisms are responsible. When a banana fast ion is scattered inward, the corresponding rate of change of the precessional velocity is negative, hence a negative frictional force is imparted by the fast ions on the bulk plasma. The opposite is true for a banana orbit scattered outward. Secondly, HFS resonance tends to energize barely-trapped particles that are readily de-trapped by collisions. This process creates more counter-passing fast ions on the inside and co-passing fast ions on the outside that also contributes to the shape of the frictional torque. The net torque obtained by combining the magnetic and frictional torque [Fig. 2(c)] is negative and does not approach zero for $r/a = 1$ because of the stochastic rf-diffusion. The integral of the net torque is the normalized toroidal angular velocity I_N [Fig. 2(d)] indicating a counter-rotation on-axis in agreement with Ref. [2]. The dimensional rotational speed is given by

$$V_\zeta(0) = \frac{1}{(2\pi)^2} \left(\frac{\Omega_0^2}{\langle n \chi_M \rangle} \right) (I_N \times 10^{10}) \quad . \quad (2)$$

When the cyclotron resonance is moved to the LFS ($(R - R_0)/a = 0.15$), the magnetic torque [Fig. 3(a)] is analogous to Fig. 2(a) indicating test particles are being scattered

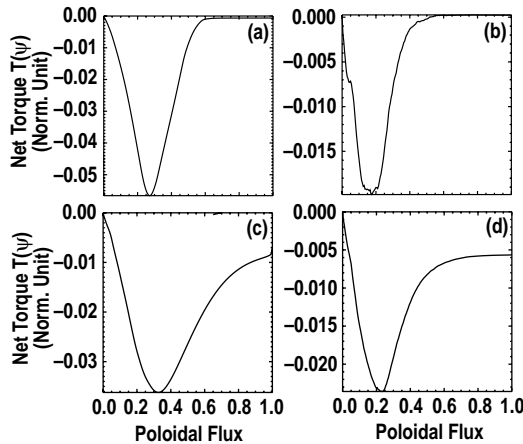


Figure 1. The net torque $T(\psi)$ as a function of poloidal flux (radial) for (a) rf “random-walk” off and pitch-angle scattering off, (b) rf “random-walk” off and pitch-angle scattering on, (c) rf “random-walk” on and pitch-angle scattering off, (d) rf “random-walk” on and pitch-angle on.

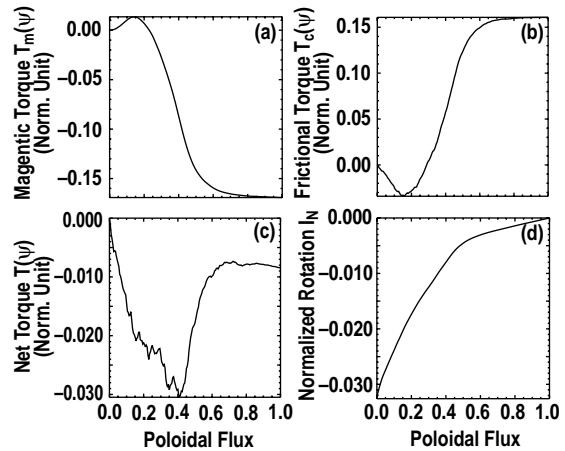


Figure 2. Spatial profile of (a) the magnetic torque, (b) the frictional torque, (c) the net torque and (d) the normalized rotation of HFS resonance at $r/a = -0.15$.

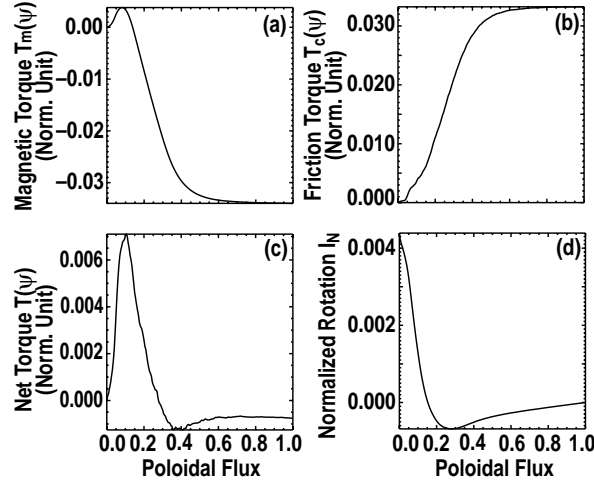


Figure 3. Spatial profile of (a) the magnetic torque, (b) the frictional torque, (c) the net torque and (d) the normalized rotation of LFS resonance at $r/a = 0.15$.

inward and outward about the resonance. The frictional torque [Fig. 3(b)] however is quite different. Specifically the frictional torque is positive inside the resonance. This suggests that some other mechanism other than the precisional force (negative or counter-direction) is dominant inside the resonant layer. An examination of the energetic particle orbits provides the explanation. For LFS resonance, the rf heats deeply trapped particles that are not easily detrapped by collisions. From finite drift orbit analysis [9], particles scattered inward can either remain trapped or become co-passing (so called “potato” orbits). At high enough energy, the co-passing orbits are favored resulting in a co-current frictional torque on the bulk. The net torque [Fig. 3(c)] is positive near the center with a slight negative value at $r/a = 1$ again due to the stochastic rf-diffusion. The normalized angular rotation is in the co-direction on axis [Fig. 3(d)] as suggested in Ref. [2], although it becomes slightly counter-rotating off-axis. Finally, we report some preliminary results with finite $N_{//}$. The parameters chosen are typical of the JET experiment [J.-M. Noterdaeme, this conference]. Figure 4(a) shows a case with a

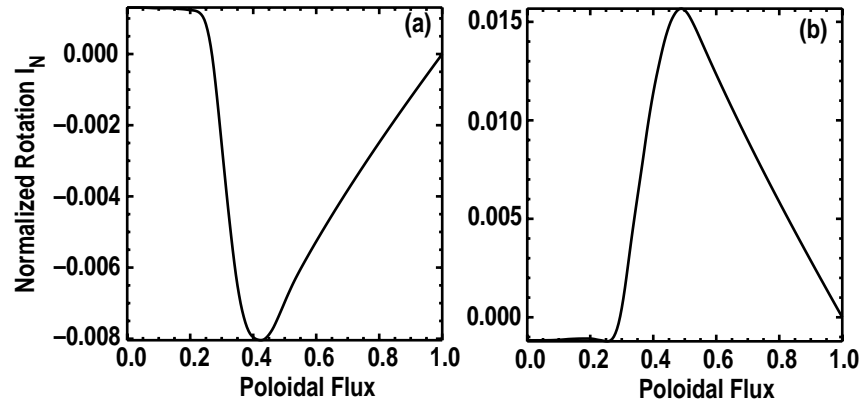


Figure 4. Normalized rotation profile for LFS resonance with (a) symmetric $N_{//}$ and (b) positive $N_{//}$ in a JET-like plasma ($k_{//}R = +10$).

symmetric $N_{//}$ spectrum. The result is similar to the LFS resonance discussed earlier. Figure 4(b) shows an asymmetric spectrum with $N_{//}$ in the co-direction only. The result is drastically different with a co-rotation peaked off-axis. This may be explained by the excitation of co-moving energetic ions on the outside of the resonance due to the Doppler effect. More detailed study is in progress.

SUMMARY

Our study is motivated by a previous study² that uses a different method to model the rf heating and predicts co-current rotation when the resonance is on the LFS and counter-current rotation with the resonance on the HFS. Our more detailed rf model allows us to follow the heating dynamics to steady-state. We find that the stochastic rf-diffusion can produce a net integrated torque in general. In comparing our findings with that of Ref. [2] when the net torque is relatively small, we find similarly, a co-rotation on-axis for LFS resonance and counter-rotation on-axis for HFS resonance. The directionality of the rotation can be attributed to finite drift-orbit effect that prevents the complete cancellation of the magnetic and frictional torque. Close to the magnetic axis, the “potato” orbit effect becomes important and can lead to a change of sign for the frictional torque. Finally, with a finite positive $N_{//}$, a co-rotation peaked off-axis is demonstrated for JET parameters for LFS resonance heating.

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