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Monte-Carlo Orbit/Full Wave Simulation of Fast Alfvén Wave (FW) Damping on Resonant Ions in Tokamaks

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Abstract. To simulate the resonant interaction of fast Alfvén wave (FW) heating and Coulomb collisions on energetic ions, including finite orbit effects, a Monte-Carlo code ORBIT-RF has been coupled with a 2D full wave code TORIC4. ORBIT-RF solves Hamiltonian guiding center drift equations to follow trajectories of test ions in 2D axisymmetric numerical magnetic equilibrium under Coulomb collisions and ion cyclotron radio frequency quasi-linear heating. Monte-Carlo operators for pitch-angle scattering and drag calculate the changes of test ions in velocity and pitch angle due to Coulomb collisions. A rf-induced random walk model describing fast ion stochastic interaction with FW reproduces quasi-linear diffusion in velocity space. FW fields and its wave numbers from TORIC are passed on to ORBIT-RF to calculate perpendicular rf kicks of resonant ions valid for arbitrary cyclotron harmonics. ORBIT-RF coupled with TORIC using a single dominant toroidal and poloidal wave number has demonstrated consistency of simulations with recent DIII-D FW experimental results for interaction between injected neutral-beam ions and FW, including measured neutron enhancement and enhanced high energy tail. Comparison with C-Mod fundamental heating discharges also yielded reasonable agreement.

INTRODUCTION

Conventionally, full wave [1] or ray-tracing codes [2] combined with Fokker-Planck code assuming zero banana width have been used to study the interaction between fast Alfven wave (FW) and the plasma. However, these approaches do not take into account both finite orbit drift width of non-Maxwellian ions produced from rf interaction and radial scattering of energetic particles across flux surfaces due to Coulomb collisions and perpendicular heating. Figure 1 shows the 2D full wave code TORIC4 simulation result on Alcator C-Mod hydrogen minority (5%) fundamental heating experiment at 78 MHz (C-Mod 1040415006). It is seen that predicted radial power deposition profile of FW on minority hydrogen ions is very sensitive to initially assumed Maxwellian temperature. For a thermal Maxwellian temperature of $T_H(0)$ = 3 keV (red curve), the FW could not penetrate a cut-off region inside the plasma (~2 cm on the low field side from magnetic axis) due to a weak Doppler shift effect. The radial profile is thus off-axis. But, with the assumption of an initial tail temperature of $T_H(0)$ = 20 keV (blue curve), a much broader Doppler shifted resonance produces more on-axis heating and stronger power absorption on minority ions.

A Monte-Carlo code, ORBIT-RF [3] provides a capability to investigate the interaction between FW and plasma resonant ions, self-consistently including rf heating and Coulomb collisions. The code solves the Hamiltonian guiding center drift equations [4] in magnetic coordinates ($\psi_p,\theta,\rho_{//},\zeta$) in a 2D axisymmetric numerical magnetic equilibrium where parallel and radial drift motions of each ion are directly solved in every time step. Monte-Carlo collision operators for pitch-angle scattering

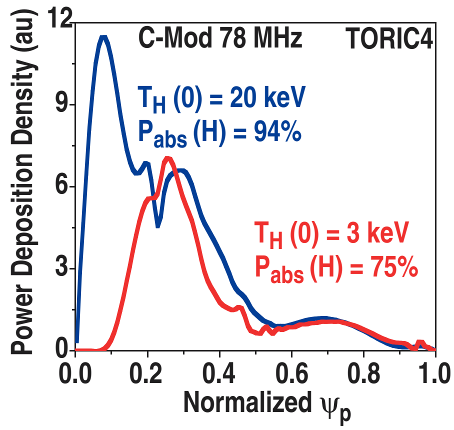

FIGURE 1. Sensitivity of radial power deposition profiles on initial temperatures of resonant ions.

and drag by electron and background ions calculate changes of test ion parallel velocity and pitch angle due to Coulomb collisions [3]. A rf-induced random walk model describing fast ion stochastic interaction with FW is implemented to reproduce quasilinear diffusion in velocity space, assuming that resonant ions lose their phase information with FW through successive collisions and wave stochasticity before they reenter the resonance region. A generalized arbitrary harmonic rf diffusion operator calculates perpendicular rf-kicks at resonances including Doppler shifts. Two-dimensional full wave code TORIC4 [1] is coupled to ORBIT-RF to determine the amplitudes of FW fields and their wave numbers in the plasma as a function of (R,Z). Steady-state slowing-down distribution of beam ion species is modeled using a reinjection method of thermalized beam ions [5]. In this work, only a single cyclotron resonance layer is modeled from each simulation. Self-consistent modeling of the interaction between FW heating and slowing-down of energetic ion species from ORBIT-RF offers a capability of identifying qualitatively the experimentally demonstrated strong interaction between FW and resonant ions in both C-Mod and DIII-D tokamaks.

This paper is organized as follows. First, quasilinear rf diffusion operator with arbitrary harmonic absorption is described in detail. In sequence, numerical results from ORBIT-RF are validated against experiments in both C-Mod minority fundamental heating and DIII-D fast wave current drive (FWCD) discharges. Lastly, summary and future plan are given.

QUASI-LINEAR ARBITRARY HARMONIC RF DIFFUSION OPERATOR

When ions pass through an ion cyclotron resonance layer satisfying the condition $\omega_{rf} - k_{//}v_{//} = n\Omega_i$ (n: harmonic number), they may either absorb energy from or lose energy to the wave depending on their phase with the wave polarization. This introduces a random walk motion in addition to a mean change in energy. We introduce a rf-induced random walk model to reproduce quasi-linear diffusion in velocity space through stochastic interaction of ions with the wave. The interaction of ions with FW at Doppler shifted resonances changes ions's velocities in both parallel and perpendicular directions. In this work, the change in $v_{//}$ due to parallel electric field component is ignored. Only perpendicular kicks of magnetic moment (μ) are considered. The increment of magnetic moment ($\Delta\mu_{rf}$) [Eq. (1)] is obtained by calculating a mean value [Eq. (2)] and random variance [Eq. (3)] from the quasi-linear equation governing rf-induced particle diffusion in velocity space.

$$\Delta\mu_{rf} = \overline{\Delta\mu_{rf}} + 2\sqrt{3}\left(R_s - \frac{1}{2}\right)\sqrt{\left\langle \overline{\overline{\Delta\mu_{rf}}}^{2} \right\rangle} \quad , \tag{1}$$

where

$$\overline{\Delta\mu_{rf}} = \frac{\pi q^2 l^2 \Omega^2}{m\omega^2 B}\left|E_+\right|^2 \times$$
$$\left[\left|J_{l-1} + e^{2i\vartheta_k}\frac{E_-}{E_+}J_{l+1}\right|^2 + \mu\left\{2\left(J_{l-1} + e^{2i\vartheta_k}\frac{E_-}{E_+}J_{l+1}\right)\left(\frac{\partial J_{l-1}}{\partial\mu} + e^{2i\vartheta_k}\frac{E_-}{E_+}\frac{\partial J_{l+1}}{\partial\mu}\right)\right\}\right]\frac{K}{\left|\dot{w}_l\right|} \tag{2}$$

$$\left\langle \overline{\overline{\Delta\mu_{rf}}}^{2} \right\rangle = 2\mu\left[\frac{\left|J_{l-1} + e^{2i\vartheta_k}\frac{E_-}{E_+}J_{l+1}\right|^2}{2\left(J_{l-1} + e^{2i\vartheta_k}\frac{E_-}{E_+}J_{l+1}\right)\left(\frac{\partial J_{l-1}}{\partial\mu} + e^{2i\vartheta_k}\frac{E_-}{E_+}\frac{\partial J_{l+1}}{\partial\mu}\right)}\right]\overline{\Delta\mu_{rf}} \tag{3}$$

with $w_l = \omega_{rf} - n\Omega_i - k_{//}\rho_{//}\Omega_i$. R_s is a random number between 0 and 1 where the factor $2\sqrt{3}$ is such that

$$\int_0^1\left[2\sqrt{3}\left(R_s - \frac{1}{2}\right)\right]^2 dR_s = 1 \quad ,$$

assuming uniform probability. J_n is the *n*th order Bessel function of the first kind, and *m* is a test ion mass. An operator K is expressed by [6]

$$K = \begin{cases} 1 & \sqrt{2}\tau_{uc} \le \tau_c \\ \dfrac{2\pi Ai^2(\zeta)\left|\dot{Z}_n\right|}{\left|\ddot{Z}_n/2\right|^{2/3}} & \sqrt{2}\tau_{uc} > \tau_c \end{cases} . \quad , \tag{4}$$

$$\zeta = -\frac{\left|\dot{Z}_n\right|^2}{\left|2\ddot{Z}_n^2\right|^{2/3}}, \quad \tau_{uc} = \sqrt{\frac{2\pi}{\left|\dot{Z}_n\right|}}, \quad \tau_c = \frac{2\pi Ai(\zeta)}{\left|\ddot{Z}_n/2\right|^{1/3}}. \quad , \tag{5}$$

where *Ai* is the Airy function in order to include the case when the successive interactions between a particle orbit and the cyclotron resonances are close to each other. In Eq. (2), E_+ and E_- are left-hand and right-hand polarized components of wave electric field. The $e^{2i\vartheta_k}$ is the phase difference between E_+ and E_-. Radial profiles of $|E_+|^2$, $e^{2i\vartheta_k}$, $k_\perp$ and $k_{//}$ required in Eqs. (2) and (3) are computed from TORIC4. Since TORIC4 calculates unit current wave fields, we rescale the wave fields using actual experimental input power to pass on to ORBIT-RF [7]. Presently, the wave fields from TORIC4 are approximated using a single dominant toroidal and poloidal Fourier components.

VALIDATION OF ORBIT-RF AGAINST EXPERIMENTS

In this section, numerical results from ORBIT-RF are validated against experimental results from both C-Mod minority fundamental heating at 78 MHz and DIII-D FWCD discharges at 60 MHz and 116 MHz. We follow trajectories of ion species by solving the Harmiltonian guiding center drift equation at each time step (Δt is usually ~10^{-5} s) using a Runge-Kutta fourth order integration scheme subject to the FW heating and slowing-down collisions/pitch angle scattering with background ions and electrons. Simulation time is typically several slowing-down times of test ion species, which usually requires several ten thousand transit times of test ions. The grid size used is (ψ, θ) = (100,50). In ORBIT-RF, electrons are only considered as neutralizing background. Their role in altering the radial electric field is not considered. For simulations presented in this paper, we used mostly 5000 particles to present Monte-Carlo test ions.

C-Mod Minority Fundamental Heating Discharge at 78 MHz

Recent ICRH minority distribution measurements from the 2004 Alcator C-Mod compact neutral particle analyzer (CNPA) [7] can be directly compared with ORBIT-RF results. In the following discharge, Shot 1040415006, $T_e(0) = T_D(0) =$ ~3 keV, $n_e(0) < 1.0\times10^{14}$/cm^{-3}, B_0 = 5.5 T, I_p = 0.8 MA, and 1 MW of 78 MHz FW is applied to the ~4% D(H) plasma. The symmetric antenna power spectrum with (0,π,π,0) phasing has a peak at toroidal mode number $N_\varphi = \pm7$. Figure 2 shows increases of raw voltage from the CPNA [7] and electron temperatures during ICRH. Simulation results for this discharge from TORIC4 (blue curve) and ORBIT-RF (red one) are compared in Fig. 3. The ORBIT-RF result shows much broader radial deposition profile than that from TORIC4 with initial minority ion temperature of 20 keV. The broader profile from ORBIT-RF may be explained by radial diffusion of resonant ions due to successive pitch angle scattering and perpendicular rf heating, as shown in Fig. 4. In Fig. 5, the CNPA experimentally measured on-axis hydrogen-minority perpendicular

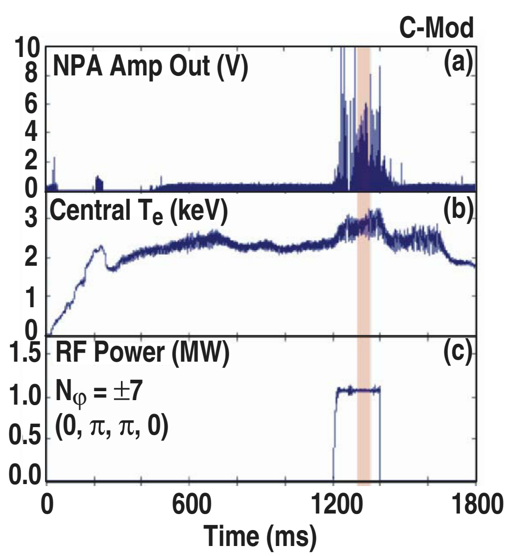

FIGURE 2. (a) Raw voltage from CNPA, (b) central electron temperature, and (c) rf power. The highlighted time band indicates a 50 ms DNB pulse for active neutral particle analysis.

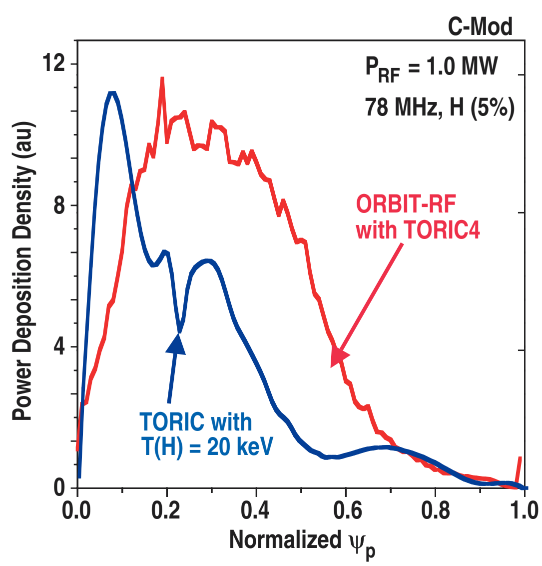

FIGURE 3. Power deposition density from TORIC4 and ORBIT-RF for Alcator C-Mod 78 MHz.

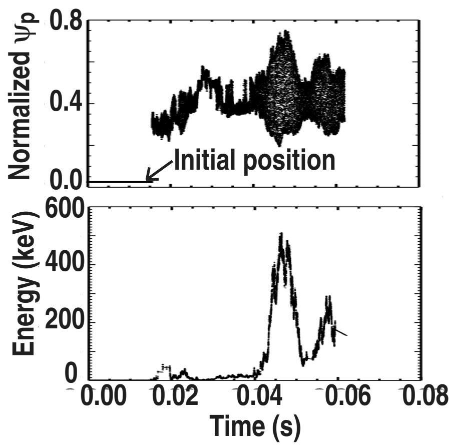

FIGURE 4. Time trajectories of a single resonant ion showing radial scattering due to Coulomb collision and perpendicular rf heating.

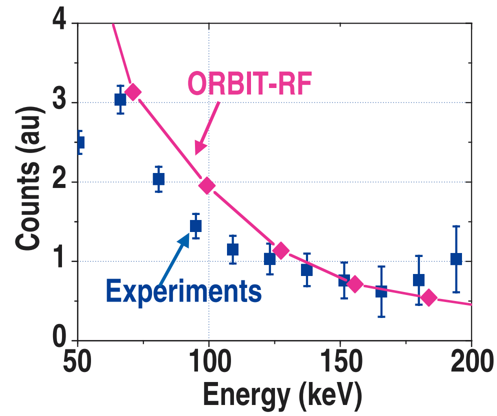

FIGURE 5. Comparison of ORBIT-RF and experiments on C-Mod 78 MHz.

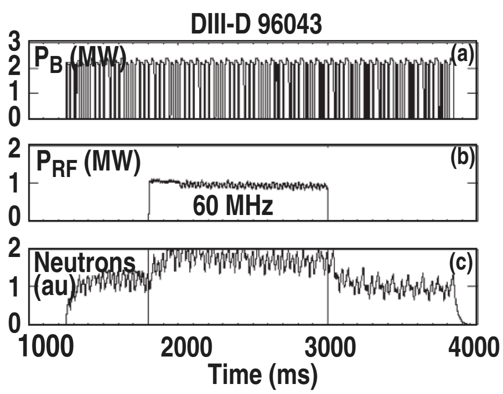

FIGURE 6. (a) Injected beam power (b) rf power [$n_e(0) = 5.0\times10^{13}$ cm^{-3}, $T_e(0) = 2.7$ keV, $T_i(0) = 3.5$ keV], (c) neutron flux for DIII-D 60 MHz.

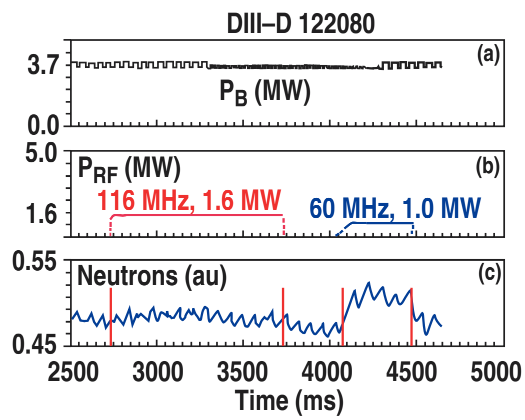

FIGURE 7. (a) Injected beam and (b) rf powers [$n_e(0) = 7.0\times10^{13}$ cm^{-3}, $T_e(0) = 1.5$ keV, $T_i(0) = 2.0$ keV], (c) neutron flux and ORBIT-RF for DIII-D 116 MHz.

energy spectrum (blue curve) and ORBIT-RF simulated one (red curve) are compared, showing reasonable agreement.

DIII-D FWCD at 60 MHz and 116 MHz

Figures 6 and 7 show previous (96043.01920) and recent (122080.2700) DIII-D FWCD experimental results. Plasma parameters for these discharges are summarized in Table 1. The results at 60 MHz indicate beam ions acceleration at 4th harmonic resonance [8] while very little interaction of beam ion with 116 MHz is shown at 8th harmonic resonance. This is clearly evident experimentally from neutron reaction rates and electron temperatures that show an increase during rf heating at 60 MHz, while no increase is observed at 116 MHz.

In the simulations, initial distribution of beam ions in velocity space is assumed to be mono-energetic with a full energy component of 80 keV. In real space, they are distributed with a probability $n_f(\psi) \propto (1-\psi^2)^2$. To model a steady-state regime, thermalized beam ions are re-injected at their birth energy (80 keV) into the plasma periodically during a given simulation time. To model actual NB+ICRF experimental situation realistically, NB only heating is first turned on for several slowing-down times

TABLE 1. Plasma parameters at DIII-D FWCD discharges

	96043.01920	122080.2700
$N_e(0)(cm^{-3})$	5.0×10^{13}	7.0×10^{13}
$T_e(0)$ (keV)	2.7	1.5
$T_i(0)$ (keV)	3.5	2.0

of 80 keV deuterium beam ions. Almost all beam ions have gone through at least one thermalization within this duration to reach a steady-state distribution. Then the FW heating is turned on for a few additional slowing-down times to explore the interaction of beam ions with FW. In Fig. 8, spatial distributions of deuterium beam ions are displayed at t=0, 60000, 90000 transit times. The 60 MHz FW is turned on from t=60000 transit time to 90000 transit time. It is seen that the energetic tails extend up to a few hundreds keV above beam injection energy (80 keV) after the ICRF heating is turned on. These tails are built up in relatively broad layers ($0 < \psi < 0.4$) encompassing Doppler shifted 4th harmonic resonances, as shown in Fig. 8(c).

In Fig 9, radial profiles of beam ion pressure from ORBIT-RF are compared between NB only and NB+ICRF at 60 MHz and 116 MHz cases. Increased peakedness in the beam ion pressure profile observed in the central region of plasma at 60 MHz is reproduced qualitatively from ORBIT-RF. Very little increase of neutron rate at 116 MHz in experimental measurements (Fig. 7) is qualitatively explained in ORBIT-RF results showing no significant difference in the beam ion pressure profile after the rf is turned on.

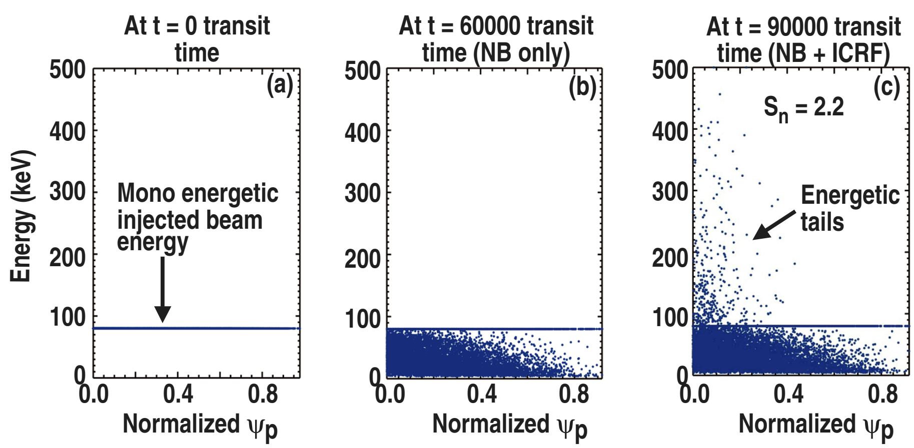

FIGURE 8. Spatial distributions of deuterium beam ions at (a) t=0, (b) t=60000, (c) t=90000 transit time where the 60 MHz ICRF wave is turned on from t=60000 to 90000 transit time.

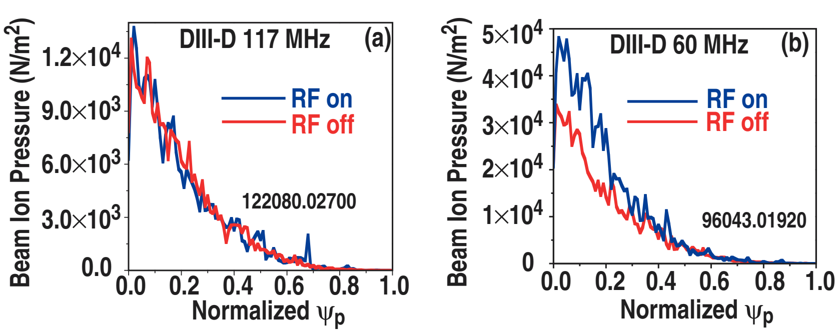

FIGURE 9. Radial profiles of pressure of beam ions as a function of normalized poloidal flux from ORBIT-RF at (a) DIII-D 116 MHz and (b) DIII-D 60 MHz.

SUMMARY AND FUTURE PLANS

ORBIT-RF provides a comprehensive physics package to self-consistently simulate interaction between ICRF and non-Maxwellian fast ions with finite orbit effects.ORBIT-RF with TORIC4 qualitatively reproduces various C-Mod and DIII-D experimental results in fast ion spectrum and neutron enhancement. Specifically, ORBIT-RF reproduces qualitatively the strong wave-beam particle interaction at 60 MHz and lack of wave-particle interaction at 116 MHz in DIII-D. The energetic particle energy spectrum with fundamental heating on C-Mod is also in agreement.

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