Simulation of Fast Alfvén Wave Interactions
with Neutral-Beam and Minority Ions in Tokamaks

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ORBIT-RF has been applied to simulate and validate fast Alfvén wave (FW) heating over a range of cyclotron harmonics. ORBIT-RF with TORIC4 qualitatively reproduces the strong FW-beam interaction at 60 MHz ($4\Omega_D$) and lack of interaction at 116 MHz ($8\Omega_D$) in DIII-D, consistent with observed neutron reaction rate. The result at $8\Omega_D$ differs from linear theory suggesting the importance of finite orbit and Coulomb collisions for resonant fast ions. Fast ion energy spectrum calculated from ORBIT-RF is also in agreement with measurement from fundamental ion cyclotron radio frequency (ICRF) heating experiment on Alcator C-Mod.

I. Introduction

A Monte Carlo code ORBIT-RF [1] is coupled with a 2D full wave code TORIC4 [2] to study the resonant interaction of FW with fast ions at arbitrary ion cyclotron harmonics. ORBIT-RF [1] provides a comprehensive physics package to investigate the interaction between fast ions with finite orbits and FW. It solves the Hamiltonian guiding center drift equations in magnetic coordinates in a 2D axisymmetric numerical magnetic equilibrium. Monte-Carlo operators for pitch-angle scattering of fast ions and drag by electron and background ions calculate changes of test ions in velocity and pitch angle due to Coulomb collisions. An rf-induced random walk model describing fast ion stochastic interactions with FW is used to reproduce quasi-linear (QL) diffusion in velocity space. A generalized arbitrary harmonic rf diffusion coefficient is related to the perpendicular rf-kicks at resonances including Doppler shifts. Steady-state slowing-down distribution of beam ion species is modeled using a re-injection method of thermalized beam ions. TORIC4 [2] provides FW electric fields for the QL diffusion operator in ORBIT-RF. This work did not attempt to self-consistently iterate the wave fields from TORIC4 with the ion distribution from ORBIT-RF, which will be left for future study.

II. Stochastic Interaction of Resonant Ion with FW

Assuming that resonant ions lose their phase information with FW through successive collisions and wave stochasticity before they re-enter the resonance region, ion stochastic interaction with FW is expressed by Eqs. (1–3), as sum of mean change $(\overline{\Delta\mu_{rf}})$ and fluctuating change $(\overline{\overline{\Delta\mu_{rf}}})$ in magnetic moment (μ)[1]

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

$$\overline{\Delta \mu_{rf}} = \frac{\pi q^2 n^2 \Omega^2}{m_i \omega^2 B} |E_+|^2 \times \left[\left| J_{n-1}(k_\perp \rho_i) + e^{2i\vartheta_k} \frac{E_-}{E_+} J_{n+1}(k_\perp \rho_i) \right|^2 + \right.$$

$$\left. \mu \left\{ 2 \left(J_{n-1} + e^{2i\vartheta_k} \frac{E_-}{E_+} J_{n+1} \right) \left(\frac{\partial J_{n-1}}{\partial \mu} + e^{2i\vartheta_k} \frac{E_-}{E_+} \frac{\partial J_{n+1}}{\partial \mu} \right) \right\} \right] \frac{K}{|\dot{w}_n|} \quad , \tag{2}$$

$$\left\langle \overline{\overline{\Delta \mu_{rf}}}^2 \right\rangle = 2\mu \left\{ \left| J_{n-1} + e^{2i\vartheta} k \frac{E_-}{E_+} J_{n+1} \right| \right/$$

$$\left[2 \left(J_{n-1} + e^{2i\vartheta} k \frac{E_-}{E_+} J_{n+1} \right) \left(\frac{\partial J_{n-1}}{\partial \mu} + e^{2i\vartheta} k \frac{E_-}{E_+} \frac{\partial J_{n+1}}{\partial \mu} \right) \right] \right\} \overline{\Delta \mu_{rf}} \quad , \tag{3}$$

where $w_n = \omega_{rf} - n\Omega_i - k_{//}v_{//}$, $\rho_i = v_\perp / \Omega_i = \sqrt{2\mu B} / \Omega_i$ and R_s is a random number satisfying Gaussian probability and J_n the nth order Bessel function of the first kind. K is introduced to include the case when successive interactions between a particle orbit and cyclotron resonances are close to each other and the phase information needs to be retained. In Eqs. (2) and (3), E_+ and E_- are the left-hand and right-hand polarized components of FW fields and ϑ_k is defined as the direction of wave in x-y plane. TORIC4 provides radial profiles of $|E_+|$, $e^{2i\vartheta_k}(E_-|/E_+|)$, $k_\perp$ and $k_{//}$ in Eqs. (2) and (3) as a function of (R,Z) for each Fourier poloidal mode number. Presently, we represent the FW fields by a single dominant toroidal and poloidal Fourier component. Since TORIC4 calculates unit current wave fields, we rescale the antenna current using actual experimental input power (P_{EXP}) and loading resistance (R) predicted from TORIC4 to obtain FW amplitudes corresponding to complete power absorption according to linear theory as $I(A) = \sqrt{P_{Exp}(MW)/R(MW/kA^2)}$. Rescaled FW fields are passed to ORBIT-RF to calculate changes in magnetic moment when ions pass through ion cyclotron resonance layer. Magnitudes of FW fields are fixed during simulation time.

III. Simulation Results on DIII–D and Alcator C-Mod Experiments

In deuterium beam injected plasma in DIII–D tokamak, beam ion absorption of FW has been observed during fast wave current drive experiments in frequency range of 60 MHz to 117 MHz [3]. Strong damping of 60 MHz FW on beam species at $4\Omega_D$ has been observed in L-mode experiments. However, beam ion absorption of 116 MHz FW at $8\Omega_D$ appears to be relatively weak in similar L-mode discharges. Figure 1 shows experimental results for discharge 122087 (dotted line for NB heating only) and 122080 (solid for NB+ICRF heating) where P_{NB} = 3.7 MW, E_b = 80 keV with P_{rf} = 1.6 MW at 116 MHz, P_{rf} = 0.8 MW at

60 MHz. Figure 1(b) indicates much stronger beam ion acceleration at 60 MHz ($4\Omega_D$) than 116 MHz ($8\Omega_D$) as inferred by the increased neutron reaction rate during ICRF heating.

Fig. 1. DIII-D experimental results for 122080 and 122087 (dotted).

Experimental results for 122080 and 122087 are simulated using ORBIT-RF and TORIC4. For all simulations in this paper, we used 200 radial meshes and 63 poloidal mode numbers. With experimental plasma kinetic profiles $[n_e(0) \sim 7.0{\times}10^{13}/cm^{-3}$, $T_e(0) \sim$ 1.5 keV, $T_i(0) \sim 2.0$ keV], TORIC4 predicts $R \sim 1.2{\times}10^{-2}$ (MW/kA^2) and $I \sim 7$ (kA) for 116 MHz with $P_{rf} = 1.6$ MW while $R \sim 2.6{\times}10^{-1}$ (MW/kA^2) and $I \sim 1$ (kA) for 60 MHz with $P_{rf} = 0.8$ MW in a wide range of beam ion densities (n_b/n_e=0.05~0.12). ORBIT-RF coupled with wave fields rescaled by I reproduces qualitatively experimental observations for both 60 MHz and 116 MHz. In Fig. 2, radial profile of beam ion pressure calculated from ORBIT-RF is compared between 122080 (60 MHz and 116 MHz ICRF heating) and 122087 (without ICRF). For 60 MHz case, ORBIT-RF calculates energetic tails extending up to a few hundreds keV above beam injection energy (80 keV) during FW heating. These tails are prominent in $0<\psi_p<0.2$ encompassing the Doppler shifted 4th harmonic resonance, which results in a significant increase of fast ion pressure near the magnetic-axis. However, ORBIT-RF shows no significant increase in fast ion pressure during 116 MHz FW heating, which is consistent with minimal increase of neutron rate at 116 MHz in experiment, as shown in Fig. 1(b) but at variant with linear theory. The prediction of observable absorption at 116 MHz from linear theory is based on large $k_\perp\rho_i$ near the cyclotron resonance. Due to finite orbits and Coulomb collisions that scatter particles away from resonances, the range of $k_\perp\rho_i$ experience by resonant test ions in ORBIT-RF has maximum values of ~5 for 116 MHz and ~3 for 60 MHz. Corresponding values of Bessel functions are $J_7(5) \sim 0.054$, $J_9(5) \sim 0.00552$ for 116 MHz and $J_3(3) \sim 0.31$, $J_5(3) \sim 0.04$ for 60 MHz which, when substituted into Eqs. (2) and (3), explain the much stronger absorption at $4\Omega_D$ over that at $8\Omega_D$.

ORBIT-RF has also been validated against a recent C-Mod experiment for hydrogen minority fundamental harmonic heating. In
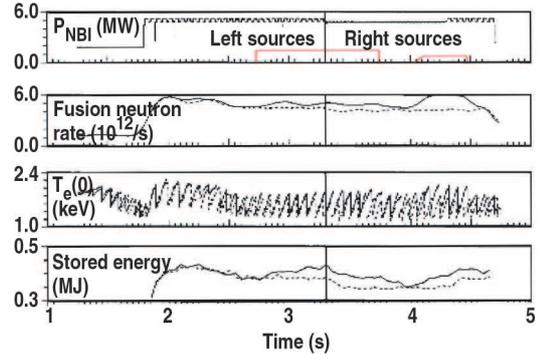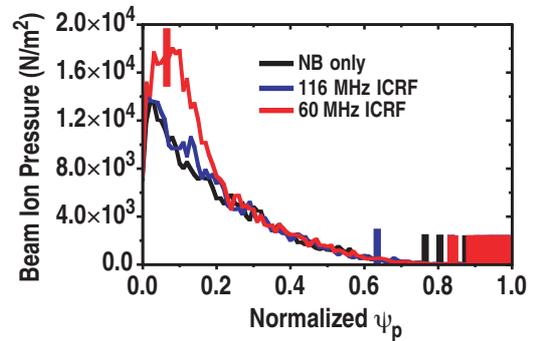

Fig. 2. ORBIT-RF results for radial (solid) profile of beam ion pressure for 122080 and 122087.

discharge 1040415006, 78 MHz FW with P_{rf} = 1 MW is launched into D(95%)-H(5%) plasma where $T_e(0) = T_D(0) = 3$ keV, $n_e(0) = 8 \times 10^{13}/cm^{-3}$, $B_0 = 5.5$ T and $I_p =$ 0.8 MA. During ICRF heating, significant increase of raw voltage from a new C-Mod compact neutral particle analyzer (CNPA) [4] has been measured with increase of $T_e(0)$. In Fig. 3, measured fast ion energy spectrum from CNPA is compared with

Fig. 3. Fast ion distribution from ORBIT-RF and experiment on C-Mod./

ORBIT-RF, showing good agreement. In summary, ORBIT-RF has been applied to simulate and validate FW heating over a range of cyclotron harmonics. ORBIT-RF with TORIC4 qualitatively reproduces the strong FW-beam interaction at 60 MHz ($4\Omega_D$) and lack of inter-action at 116 MHz ($8\Omega_D$) in the DIII–D, consistent with observed neutron reaction rate. The result at $8\Omega_D$ differs from linear theory suggesting the importance of finite orbit and Coulomb collisions for resonant fast ions. Fast ion energy spectrum calculated from ORBIT-RF is also in agreement with that measured from fundamental ICRF heating experiment on C-Mod.
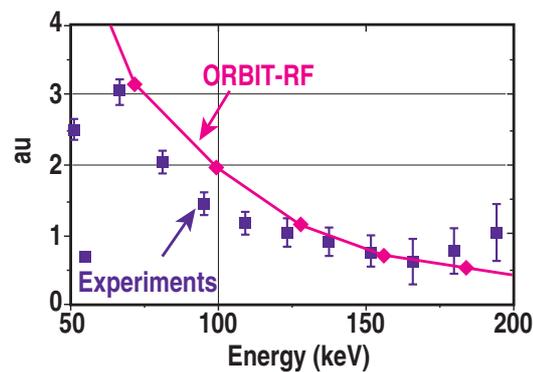
References

[1] M. Choi, *et al*., to be published in Phys. Plasmas (2005).

[2] M. Brambilla, Plasma Phys. Control. Fusion **41**, 1 (1999).

[3] R.I. Pinsker, *et al*., Proc. 15th Top. Conf. on Radio Frequency Power in Plasma, Park City, Utah (2005).

[4] V. Tang, *et al*., Bull. Am. Phys. Soc. **49**, 75 (2004).