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FINITE ORBIT WIDTH MONTE-CARLO SIMULATION OF ION CYCLOTRON RESONANCE FREQUENCY HEATING SCENARIOS IN DIII-D, NSTX, KSTAR AND ITER

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Simulations of ion cyclotron resonance frequency (ICRF) heating experiments on DIII-D and NSTX fusion devices, using the 5-D finite-orbit Monte-Carlo code ORBIT-RF [1] coupled self-consistently with the 2-D full wave code AORSA [2], have validated the importance of fast-ion drift orbit effect and iteration between the fast-ion distribution and ICRF wave fields in the modeling and understanding of ICRF heating experiments.

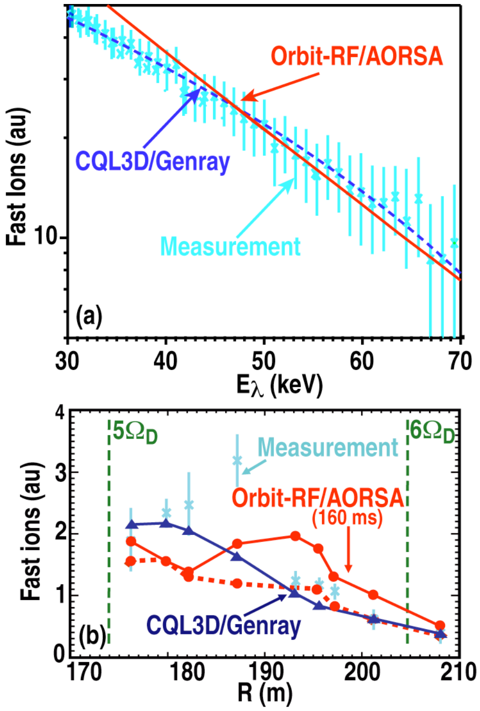

Fig. 1. DIII-D discharge #122993 (5th harmonic ICRF heating): (a) FIDA spectra for a single spatial location where E_λ is the component of fast-ion velocity along vertical collection lens. The CQL3D/GENRAY (dashed) and ORBIT-RF/AORSA (solid) synthetic results are overlaid. (b) Fast-ion spatial profiles from FIDA, CQL3D/GENRAY (solid, triangles), ORBIT-RF/AORSA (dashed at 80 ms and solid at 160 ms, circles). Vertical dashed lines are 5th and 6th harmonic resonance layers of injected deuterium beam ions at the midplane.

The drift of fast ion orbits from magnetic flux surfaces can produce significant radial diffusion and losses to the wall in the fast ion population. These finite-width effects can modify wave propagation and power absorption. Therefore, a self-consistent iterative calculation that includes these modifications to the plasma distribution is required. ORBIT-RF/AORSA does this. Fig. 1 [3] compares the fast ion D-alpha (FIDA) [4] spectroscopic measurement with synthetic diagnostic results from both the ORBIT-RF/AORSA (including finite-width orbits) and CQL3D/GENRAY [5] (ignoring finite-width orbits) simulations for a 5th harmonic ICRF heating discharge on DIII-D. Both simulation results produce qualitative agreement of fast-ion spectra with the FIDA spectroscopic data as shown in Fig. 1(a). However, Fig. 1(b) shows that the ORBIT-RF/AORSA simulation predicts a spatial profile that is somewhat more consistent with the FIDA spectroscopic data than the CQL3D/GENRAY result. Computed enhanced neutron rate from ORBIT-RF/AORSA is also in good agreement with neutron emission measurement and indicates significant absorption of ICRF power by fast ions. It should be noted that work is underway to include finite orbit effects in the CQL3D framework.

The outward radial shift cannot be reproduced by conventional zero-width-orbit theory. This shift is due to radial diffusion of ICRF heated fast-ions across magnetic surfaces. Twice-iterated results between fast-ion distribution and ICRF wave fields produce more consistent results with FIDA measurements than the once-iterated result. A noted discrepancy is that ORBIT-RF/AORSA predicts a larger outward shift from the magnetic axis than is observed with FIDA. This discrepancy has a few possible explanations: (1) Parallel acceleration that is not included in ORBIT-RF may affect the pitch-angle and energy distribution [6], and hence enhance the radial collisional transport of fast ions. As a result, the fast ion radial excursion may be overestimated; (2) The $k_\perp$ required in computing the Bessel function that accounts for the FLR effects and phase difference between E+ and E- is computed using the cold plasma dispersion relation in

ORBIT-RF. Also, the up-shift in $k_{\parallel}$ due to the poloidal magnetic field is not included due to the assumption $k_{\parallel} = n_{\varphi} / R$; (3) Data measured by FIDA is averaged over approximately a 500 ms time window to achieve reliable statistics, whereas simulations are done for approximately one slowing down time (160 ms). This suggests longer simulations should be performed to allow a more quantitative comparison with the FIDA measurements. Similar results are also obtained in NSTX 3rd to 11th harmonic ICRF heating experiments.

Proposed scenarios in KSTAR [7] include heating of minority thermal hydrogen (H) ion species in majority deuterium (D) plasma at fundamental (at full B field) or second harmonic (at half B field). Highly energetic H tails are expected due to the proposed 3 to 6 MW of ICRF power. In ITER [8], approximately 20 MW of ICRF power is planned to heat minority helium-3 (He^3). In addition, a large population of fast-ions exists in the form of injected neutral beam ion and fusion-born 3.5 MeV alpha particles. In Fig. 2, orbit trajectories are shown for a 3.5 MeV alpha particle born at the core and a 1 MeV deuterium beam ion in an ITER equilibrium, indicating non-negligible finite-width drift orbit motions of fast-ions across magnetic flux surfaces. The dashed line in Fig. 2 indicates the resonance surface of resonant ion species.

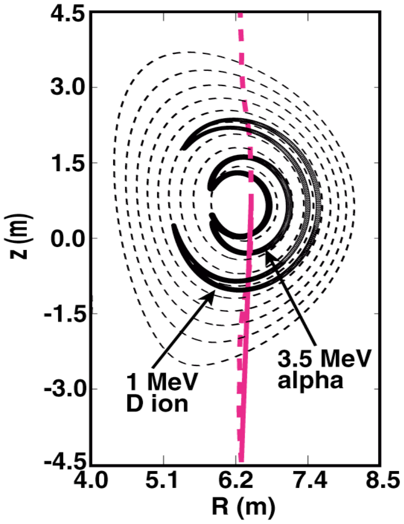

Fig. 2. Orbit trajectories of a 3.5 MeV alpha and a 1 MeV D ion in an ITER equilibrium.

Preliminary simulation using ORBIT-RF coupled with AORSA for an ITER ICRF heating scenario with an initially Maxwellian distribution indicates a slight radial outward shift of absorption peak compared to linear absorption directly evaluated using the AORSA dielectric tensor. This radial shift may be indicative of finite-width orbit effects [9], which may produce more significant outward shift as energetic tails increase. Details of the finite-width orbit effects of fast ions on KSTAR and ITER ICRF heating scenarios using self-consistent ORBIT-RF/AORSA will be presented.

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