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Simulation of the DIII-D Beam Ion Heating Experiment Using A Monte-Carlo Particle Code Combined With a Full Wave Code

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Abstract. To fully account for finite drift orbit effect of fast ions on wave-particle interaction in ion-cyclotron radio frequency (ICRF) heating experiments in tokamaks, the 5-D finite orbit Monte-Carlo plasma distribution solver ORBIT-RF is coupled with the 2-D full wave code AORSA in a self-consistent way. Comparison results of ORBIT-RF/AORSA simulation against fast-ion D_α (FIDA) measurement of fast-ion distribution as well as CQL3D/ray-tracing simulation with zero-orbit approximation in the DIII-D ICRF wave beam-ion acceleration experiment are presented. Preliminary ORBIT-RF/AORSA results suggest that finite orbit width effects may explain the outward radial shift of the spatial profile measured by FIDA.

Keywords: Ion cyclotron heating, high harmonics.

PACS: 52.50.Gj, 52.50.Qt, 52.65.Pp.

INTRODUCTION

The ICRF wave absorption is one of the main auxiliary heating methods used in tokamak experiments and ITER [1]. Finite-drift motion of fast ions generated by this heating process can significantly modify the ICRF wave propagation and absorption in the plasma. To more accurately model the DIII-D and C-Mod ICRF heating experiments including finite orbit effects, substantial computational work has been done through collaborations in RF SciDAC community [2]. As a result, the ORBIT-RF code [3] has been successfully coupled with the full-wave code AORSA [4] in a self-consistent way. The distribution function computed from the transport code TRANSP [5] is coupled to ORBIT-RF as an initial condition. Simulations with CQL3D [6] combined with ray-tracing using zero orbit-width assumption show discrepancies in the radial profile of FIDA enhancement in the DIII-D ICRF beam ion acceleration experiment [7]. To assess finite-orbit effects on this difference, the non-Maxwellian plasma distribution evolution calculated by ORBIT-RF is iterated with wave fields computed from AORSA including quasilinear and collisional orbit diffusion for a slowing down time. Simulation results on the DIII-D experiments will be of great interest to provide more quantitative understanding of ICRF heating experiments on NSTX and ITER.

INITIAL CONDITIONS FOR EXPERIMENT AND SIMULATION

A. Experimental conditions

During the DIII-D beam-ion acceleration discharge #122993 [7], the 1.0 MW beam injects 75-81 keV deuterium (D) ions in the plasma to the direction of plasma current $I_p \sim 1.0$ MA. Tangency radius is 1.15 m (left source). The ICRF wave power 1.0 MW with the 60 MHz frequency is launched into the plasma with counter-current drive phasing. At the toroidal field $B_0 = 1.58$ T, the 60 MHz ICRF wave interacts with the D beam ions at three cyclotron resonance locations along the major radius R , the fourth harmonic at $R = 136$ cm, the fifth at $R = 174$ cm, and the sixth at $R = 206$ cm. Spectroscopic measurement of cold H_α and D_α lines indicates that the hydrogen concentration is usually below 1% during the discharge. Therefore, the resonant interaction between the ICRF wave and minority hydrogen is ignored in this work.

B. Modeling of beam ion slowing-down distribution

The TRANSP [5] calculates classical beam slowing-down distribution function using experimental profiles when the ICRF wave does not exist. Fig. 1(a) shows beam-ion distribution in phase space computed from TRANSP for the DIII-D discharge #122993. Using TRANSP distribution function to predict FIDA signal before the ICRF turns on, a good agreement is obtained in measured spectral intensity and shape [7]. To compare ORBIT-RF/AORSA prediction with FIDA measurement during the ICRF heating period, bin-averaged beam-ion distribution (Fig. 1(a)) is coupled to ORBIT-RF as an initial distribution. For this coupling, ORBIT-RF reconstructs it as a Monte Carlo particle distribution, the result of which is shown in Fig. 1(b). Radial beam-ion pressure profile calculated from ORBIT-RF using the distribution shown in Fig. 1(b) qualitatively agrees with the reconstructed one from TRANSP before the ICRF turns on.

FIGURE 1. (a) Bin-averaged beam-ion distribution computed from TRANSP, (b) Reconstructed Monte-Carlo beam-ion distribution from ORBIT-RF.

C. Modeling of the 60MHZ ICRF wave fields

The ICRF wave fields and their spatial pattern, used in quasi-linear heating operator [3] implemented in ORBIT-RF for calculation of wave power absorption by beam-ions, are computed from AORSA. Starting with a Monte Carlo particle distribution [Fig. 1(b)] as an initial condition in AORSA, AORSA reconstructs this particle distribution as a differentiable bounce-averaged distribution [8]. Fig. 2 shows E_+ (left-hand polarized) and E_- (right-hand polarized) components of wave fields computed

from AORSA for the DIII-D discharge #122993 using the distribution shown in Fig. 1(b). Toroidal mode number $N_\phi=13$ is used. Wave amplitudes are normalized with the ICRF power 1.0 MW, assuming that it is all absorbed by the plasma.

FIGURE 2. The 60MHz ICRF wave field structures computed from AORSA for DIII-D #122993.

SIMULATION RESULTS

ORBIT-RF is iterated with AORSA including quasilinear and collisional orbit diffusion for approximately 140 msec (approximately one slowing down time). Non-Maxwellian beam-ion distribution computed by ORBIT-RF using AORSA wave fields shown in Fig. 2 is fed back to AORSA to update the dielectric tensor. ORBIT-RF is re-run to update beam distribution with updated wave fields from AORSA. This process should be in principle repeated until the result converges. Fig. 3(a) shows radial profiles of the ICRF wave power absorption density computed from ORBIT-RF and AORSA in early linear regime using the ICRF wave fields shown in Fig. 2. Resonant interaction of injected beam-ions with the 60MHz ICRF wave occurs largely at the 5th harmonic resonance layer near the magnetic axis. ORBIT-RF qualitatively reproduces AORSA linear wave absorption. However, slightly near-axis and broad profile is computed from ORBIT-RF. This is understood as due to the finite orbit effect of energetic ions [3]. Energetic trapped particles pass through four resonant points due to its large banana orbit width at a single resonance layer, which results in more near-axis power absorption, while AORSA assumes always only two resonance points with zero orbit approximation. In Fig. 3 (b), updated beam-ion distribution at the end of simulation is plotted, indicating formulation of tails above beam injection energy (80 keV). Fig. 4 shows preliminary comparison result of ORBIT-RF/AORSA simulations using the distribution function shown in Fig. 3 against the measurement of fast-ion distribution as well as CQL3D/ray-tracing prediction. The ORBIT-RF/AORSA results qualitatively explain finite orbit effect of fast ions on off-axis peaked radial profile of FIDA against the zero orbit prediction.

A noted discrepancy is that FIDA enhancement computed from ORBIT-RF/AORSA at larger radius of R (>200cm) is much smaller than the measurement.

The FIDA data is averaged over a fairly long time window to get better statistics for the steady-state discharge. Similar improvement on simulation statistics, a better equilibrium model and convergence study of ORBIT-RF/AORSA iteration are in progress to resolve the difference.

FIGURE 3. (a) Power absorptions computed from ORBIT-RF and AORSA and (b) Beam ion distribution computed from ORBIT-RF at $t=140$ msec.

FIGURE 4. Radial neutron enhancement profiles among the FIDA, ORBIT-RF/AORSA and CQL3D/Ray-tracing for DIII-D discharge #122993.

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