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Time-Dependent Distribution Functions and Resulting Synthetic NPA Spectra in C-Mod Calculated with the CQL3D-Hybrid-FOW, AORSA Full-Wave, and DC Lorentz Codes

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Abstract. A time-dependent simulation of C-Mod pulsed ICRF power is made obtaining minority hydrogen ion distributions with the CQL3D-Hybrid-FOW finite-orbit-width Fokker-Planck code. Cyclotron-resonant ICRF fields are calculated with the AORSA full wave code. The RF diffusion coefficients used in CQL3D are obtained with the DC Lorentz gyro-orbit code for perturbed particle trajectories in the combined equilibrium and ICRF electromagnetic fields. Prior results with a zero-banana-width simulation using the CQL3D/AORSA/DC time-cycles showed a pronounced enhancement of the H distribution in the perpendicular velocity direction compared to results obtained from Stix's quasilinear theory, and this substantially increased the rampup rate of the observed vertically-viewed neutral particle analyzer (NPA) flux, in general agreement with experiment. However, ramp down of the NPA flux after the pulse, remained long compared to the experiment. The present study compares the new FOW results, including relevant gyro-radius effects, to determine the importance of these new effects on the the NPA time-dependence.

INTRODUCTION

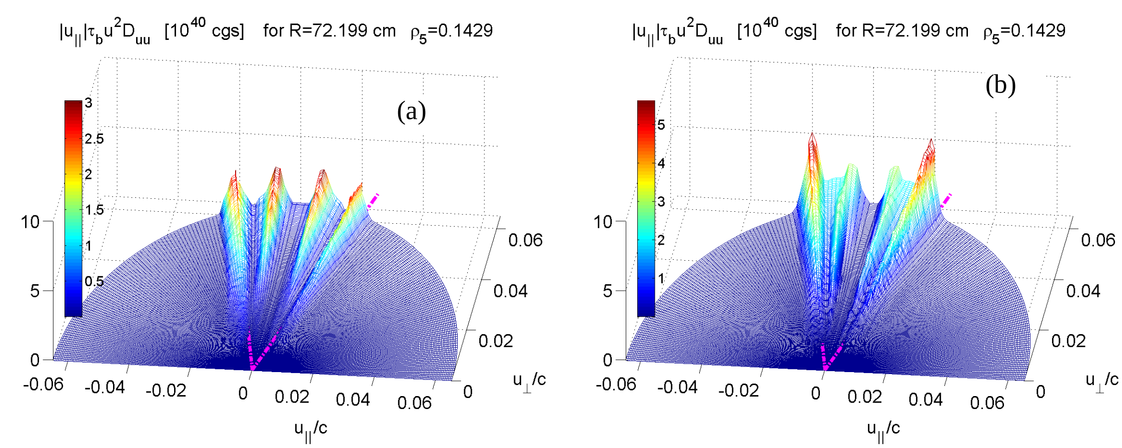
This work is a continuation of Ref. [1] which compared exact orbit calculation of ICRF particle diffusion with that from quasilinear (QL) theory. The previous work was implemented with zero-guiding-center-orbit-width (ZOW), in order to compare with the ZOW AORSA code[2] results. The present work obtains ICRF diffusion coefficient including finite-guiding-center-orbit-width (FOW) effects, and uses them in the new CQL3D-HYBRID-FOW code [3] to obtain time-dependent velocity-space effects on the distribution of minority H-ions in a C-Mod ICRF heated discharge [4]. These distributions are used to calculate a synthetic neutral particle analyzer (NPA) signal.

The DC **d**iffusion **c**oefficient calculator numerically integrates the trajectories of ions launched from tokamak midplane points in the combined equilibrium and AORSA full-wave RF fields. Particles are launched equispaced in initial gyro-phase about a given gyro-center and also equispaced in toroidal length. The diffusion coefficients are obtained by averaging the resulting square of the velocity changes after one (or more) ion poloidal circuits, to obtain the ICRF bounce-averaged diffusion tensor. This is carried out for a 3D array ($u_\parallel$, $u_\perp$, R) of initial conditions, giving the six independent RF diffusion coefficients in 3D constant-of-motion space. The method follows the formalism of Refs. [5,6]. For comparison, we have the zero-banana-width RF diffusion coefficients calculated in the AORSA code[2]. In the previous work, comparison is more directly achieved by subtracting off the perpendicular guiding center drifts using a fictitious force in the Lorentz equation, $\mathbf{F}_\perp = \mathbf{u}_{gc} \times \mathbf{B}$. This removes the finite banana width effects, but leaves correlation, finite gyro-radius, and other effects. The DC code is similar to the MOKA code[7], but has been coupled to the CQL3D Fokker-Planck code[6] and AORSA to obtain a time-dependent, noise-free solution to the ICRF heating problem across the whole plasma width.

The integration of (32 radii) × (128 $u_\perp$) × (256 $u_\|$) × (8 gyro-phase) × (1 toroidal angle) starting positions (8M Lorentz orbits) is well-parallelized and takes 5 minutes on 1152 cores; these calculations are implemented on the Cray XC30 supercomputer[8]. For the time-dependent calculation, each aorsa-dc-cql3d cycle takes 22 minutes using 1192 core. The DC portion is 6 minutes; the 10 subcycle steps of CQL3D-HYBRID-FOW require 4 minutes. Forty cycles are used.

AORSA-DC-CQL3D RESULTS

Figure 1(a-c) compares the velocity space D_{uu} diffusion coefficient calculated with (a) AORSA QL theory, (b) DC with the ZOW implementation, and (c) DC with full FOW orbits. Two toroidal modes, +/- 10, approximate the C-Mod antenna. The AORSA-QL coefficients are calculated directly from the full-wave fields using quasilinear



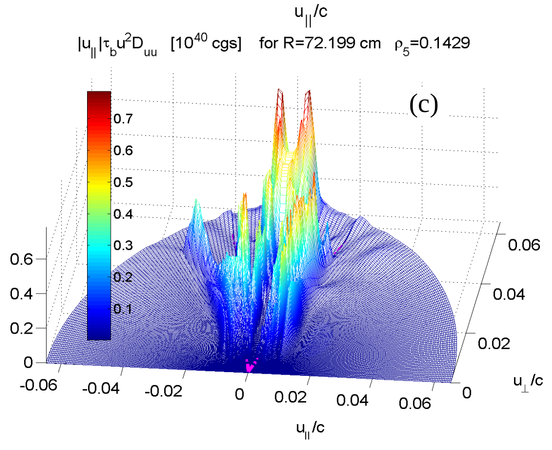


FIGURE 1. RF velocity diffusion coefficients D_{uu} from (a) the AORSA code using quasilinear theory; (b) the DC gyro-orbit calculation with added term in the Lorentz equation to remove radial drift, for more direct comparison with (a); and (c) diffusion from DC using full ion gyro-orbit calculation.

theory which incorporates spatial delta function wave-particle interactions at resonances, and assumes the random phase approximation for each wave-particle interaction[2]. The one-bounce-time DC-ZOW orbits used for 1(b) contain some correlation effects, but these do not substantially change the radial power absorption profile or distributions compared to higher number of bounce-times [1]. The FOW diffusion coefficents in Fig. 1(c) are for ions whose bounce averaged position is at the same flux surface radius as in 1(a) and 1(b). FOW evidently introduces much new velocity-space structure. There also is a high velocity cutoff due to particles exiting the last closed flux-surface. The three DC coefficient radial sets show reasonable agreement in radial power absorption.

The AORSA-DC-CQL3D code suite has been stepped forward in time, and ion distributions compared with results from time-stepping only the AORSA-CQL3D (Fig. 2(a)), *i.e.* only quasilinear coefficients. Results are

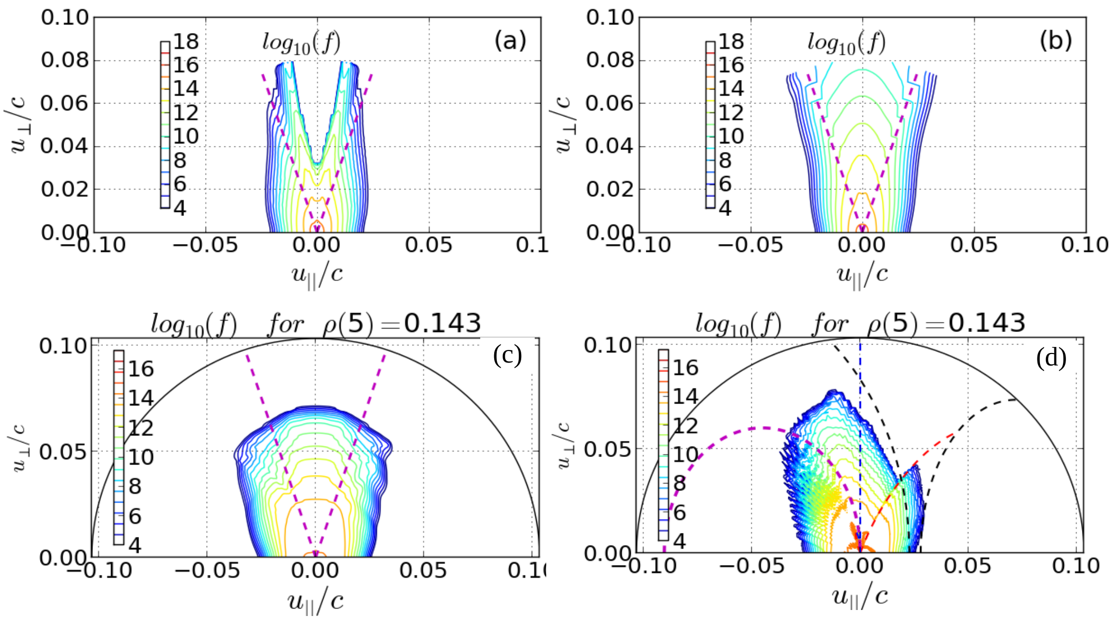


FIGURE 2. H$^+$ distributions at radius ρ=0.143 near the peak of power absorption after 4.0 msec of time evolution: (a)The classical 'rabbit' ears distribution resulting from one dimensional quasilinear diffusion; (b) Filled in trapped-particle distribution resulting from the physically comprehensive DC code model, but in ZOW mode; (c) The solution distribution for ions with given bounce-averaged postion using DC FOW diffusion coefficents; and (d) Local ion distribution on the outer midplane with the given radius obtained from the bounce-average-position disributions such as (c). The distribution inflation in the perpendicular direction seen in (a-c) may be due to higher order terms beyond point support QL coefficients, due to near tangent resonance condition[7]. Maximum energy is 5 MeV.

shown at simulation time *t*=4.0 msec; Fig. 2(b) shows the previous results[1] using ZOW-DC along with AORSA and CQL3D, and Fig. 2(c) gives the new results with FOW-DC along with AORSA and CQL3D-HYBRID-FOW. The large difference for the near perpendicular velocity particles in both 2(b) and 2(c) appears to be due to the more physically accurate DC model which includes a full treatment of tangent resonances, breaking the usual one-dimension ql diffusion[9] and/or other aspects of the Lorentz integration diffusion calculation, as considered in Ref. [1]. Fig. 2(c) is the solved-for distribution of H+ at the given bounce-averaged position. The actual local midplane distribution reconstructed from the solution distributions is shown in Fig. 2(d), and such distributions are used for the NPA synthetic diagnostic. The boundaries of the distribution in 2(d) result from particle loss. The vertical viewing NPA is sensitive to near perpendicular velocity H+, and the distribution remains inflated in the perpendicular direction compared to 2(b), but losses slightly reduce the effect at higher energies on the NPA, *cf.* Ref. [1].

Figure 3 shows calculated and experimental time-traces of flux to the NPA in the energy range 300-800 keV, proportional to the minority hydrogen distributions in this energy range and also to the boron B+5 density along the sightline. The three vertical NPA sightlines have major radius R=65, 67.5, and 70 cms. The ICRF cyclotron resonance, un-Doppler shifted, is at R=70cms Only the relative experimental flux is known. A primary question has been in the earlier AORSA-CQL3D calculation that the experimental fluxes increased and decreased about twice as rapidly as the calculated fluxes.

This discrepancy was partially resolved by ZOW AORSA-DC-CQL3D calculations. The vertical NPA is sensitive to ions at near perpendicular velocity, and this part of the distribution was not greatly inflated using the AORSA QL coefficients in CQL3d (see Fig. 2(a)). However using DC coefficients (even in the ZOW mode), gave rapid RF diffusion in the perpendicular direction (Fig. 2(b)) due to a new gyro-orbit effect, and the resulting NPA flux consequently grows faster as shown in Fig. 3(a), in better accord with the experiment. However, this effect could not explain the rapid experimental drop in NPA flux when the RF is turned off, at t=60 msec in Fig. 3.

With the inclusion of the full gyro-orbit effects in DC and in the RF calculation of CQL3D-HYBRID, the calculated turnoff the NPA flux is much more rapid, as shown in Fig. 3(b), in closer accord with experiment. This improvement may be due to the newly included FOW shifted and gyro-width offsets in the NPA viewing, or small changes in the absorption profile. An additional effect yet to be considered is time-variation of background plasma profiles. It is also to be expected that the boron neutral density profile (thus far held constant in the modeling) could

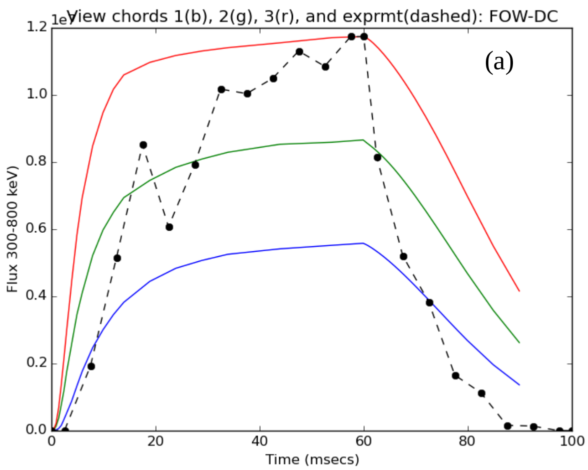


FIGURE 3. Time traces of calculated vertical viewed NPA flux at three major radii settings: (1) R=65, blue (2) 67.5, green, and (3) 70 cms, red; and a normalized experimental trace [4] in the vicinity. Fig. 3(a) is from calculated distributions using the AORSA-DC-CQL3D in the ZOW mode, and Fig. 3(b) with the codes operating in FOW mode. The ICRF is turned off at time t=60 msec after turnon.

rise and fall with the RF power, bringing the calculated and experimental traces into even better agreement. These effects may be considered in future work. Future work can also include modeling with the full CQL3D-FOW code, including the guiding-center effects on the collision operator which produce collisional radial diffusion[3,10]. RF radial diffusion is also obtained with DC, and is yet to be introduced into the full-FOW modeling. This radial diffusion will likely dominate the collisional radial diffusion.

In conclusion, time-stepping of AORSA-DC-CQL3D gives NPA time-traces which show substantial agreement with experimental time-traces. There are several additional effects which are expected to further improve agreement.

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