First Order Finite-Orbit-Width Corrections in CQL3D Ion Fokker-Planck Modeling of the NSTX HHFW Experiment

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Experiments that combine high harmonic fast wave ion cyclotron range of frequency (ICRF) heating and neutral beam injection (NBI) on the National Spherical Tokamak Experiment exhibit significant radio-frequency acceleration of NBI-generated fast ions with energies up to 90 keV. At such high energies, the finite orbit width (FOW) of the fast ions has been found important for accurately modeling diagnostics[1,2,3] such as the FIDA (fast ion D-Alpha) diagnostic[4]. A synthetic diagnostic based on the zero-orbit-width (ZOW) CQL3D Fokker-Planck (FP) code[5] has calculated a FIDA signature of fast ions that is shifted inwards with respect to observations[1,2]. The work reported here discusses application of a first order FOW correction to CQL3D and to the FIDA synthetic diagnostic. A computationally efficient calculation is obtained of the shift of a fast ion, defined by its local velocity v, pitch angle w.r.t. B, θ, and R, Z location, from its bounce-averaged (BA) radius. For the ICRF quasilinear operator, there is strong dependence of BA radial position of resonant particles on their location in the plasma cross-section. Using the first order orbit

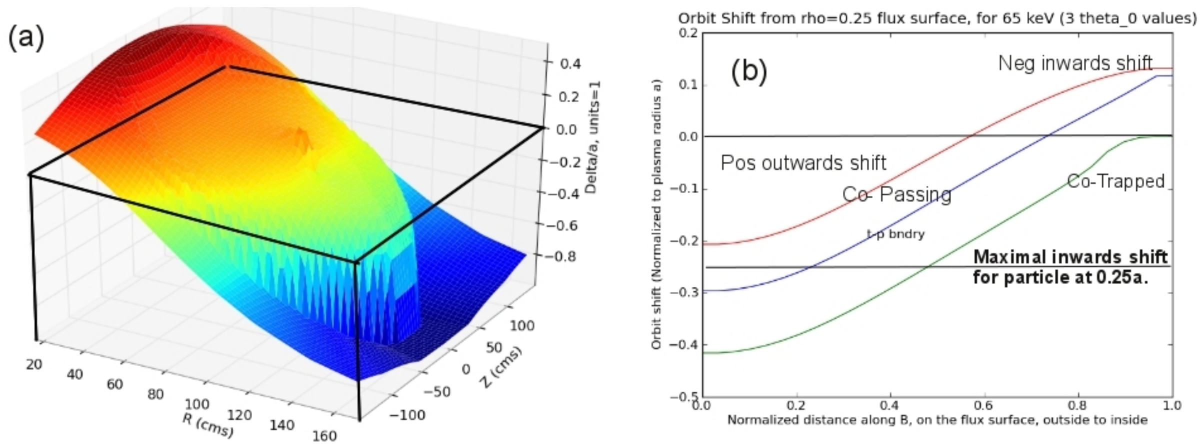

Fig. 1 Two views of calculated orbit shift for 65 keV ions: (a) is versus R,Z for zero pitch angle; and (b) is versus poloidal distance in the rho=0.25 flux surface measured from the outer midplane.

shift, each wave-particle resonance interaction or fast ion source particle is shifted to the BA location, and used to form the bounce-averaged Fokker-Planck equation. Effects of orbit losses are included. The resulting modified BA FP equation is solved to obtain the ion distribution at the midplane, as a function of velocity and BA ion radius. Similarly, the FIDA signal detects radiation from ions which are shifted from their BA location, and this shift is accounted for in calculation of the FIDA synthetic diagnostic signals. That is, the local distributions are obtained from the BA distributions, by consideration of the orbit shift. For an NBI discharge, comparison of the experimental FIDA signal radial distribution with synthetic diagnostic results based on FOW-corrected-CQL3D shows much better agreement than previously obtained with ZOW-CQL3D.

CQL3D uses ZOW orbits. To account for FOW effects on the bounce-averaged (BA) Fokker-Planck coefficients, an estimate of the radial shift from each point on the FOW orbit to the BA radial position is required. That is, we need the radial coordinate orbit shift Δ(R,Z,v,θ) for each position along an orbit to the corresponding BA midplane radial position ρ_0 of the particle. The quantity Δ(R,Z,v,θ) will be used to shift: (1) each local QL diffusion coefficient contribution from a short ray tracing element (a spatially local, 2D-in-velocity-space region) to the corresponding BA surfaces; and (2)each NBI particle birth point to its corresponding BA surface The bounce averaged collisional coefficients are unchanged since particles spend approximately equal times at higher density/temperature on one side of the BA surface and lower density/temp on the other side. After solving the BA CQL3D equations with the FOW modified coefficients, the local distributions necessary for diagnostics such as NPA and FIDA, are obtained from the BA distributions, again using Δ(R,Z,v,θ). The ZOW version of CQL3D has particularly simple particle orbits which ignore radial drifts: $v_0=v(z), \quad \sin^2\theta_0=(B_0/B)\sin^2\theta(z),$ where v_0,θ_0 are corresponding velocity and pitch angle at the midplane.

To calculate the orbit shift, a simplified vertical orbit drift equation is used, expanding around the ZOW (i.e., on a flux surface) in CQL3D (the COM could have been used, but this would introduce the zoo of new orbit types, which we ignore here):

$$\frac{dZ}{dt}=v_{Dz}=\frac{v^2-v_\perp^2/2}{R\Omega_c}, \quad \textit{taking } B\approx 1/R\textit{, then}$$

$$\frac{d\psi}{dt}=\frac{\partial\psi}{\partial Z}\frac{dZ(z)}{dt}\textit{, giving}$$

$$\Delta\psi(R,Z,v,\theta)=v\int_1^2\frac{dz}{|(\cos\theta)|}\frac{\partial\psi}{\partial Z}\frac{(1-1/2\cos^2(\theta(z)))}{R\Omega_c}$$

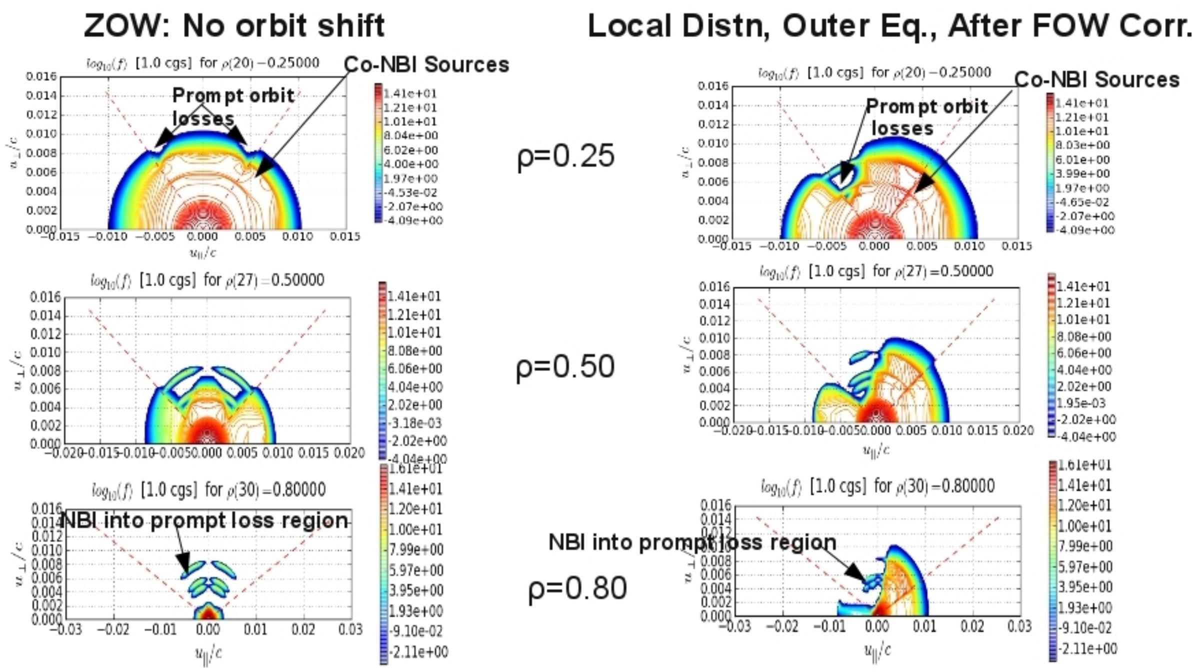

Fig. 2 Calculated deuterium distribution functions at several radii. Left column is the standard zero-orbit-width result, and the right column shows local midplane distributions at the same radii. This is a steady state with 400 kW neutral beam into NSTX.

The orbit shift at position 2, relative to 1, is obtained by simple numerical integration with respect to z = distance along the magnetic field. The flux function ψ(R,Z) is known everywhere in the plasma cross-section, through bi-cubic spline of the equilibrium data. *Fortunately*, velocity v is outside the integral; therefore, only a 3D object needs to be calculated and stored. (A similar decomposition occurs in the standard simplified banana width formula $\delta_{banana} = v_{\|0}/\Omega_{c\,pol}$). Fig. 1 shows two views of the resulting orbit shifts. We note that the shift is a quite regular function. However, due to the expansion around zero-orbit-width, inwards shifts are obtained which take the particle to less than zero radial coordinate; in this case, the shift is cutoff at the smallest radial grid point.

We have used the orbit shifts to locate both the local quasilinear resonant contributions and the NBI source particles at the corrected bounce averaged radii forming the corrected bounce-averaged equation. For the NSTX shot under consideration [1], half the 400 kW neutral beam power is deposited within radius rho=0.4a. We show CQL3D ion distributions in Fig. 2 for the ZOW case on the left, and the FOW corrected case on the right, for the steady state neutral beam phase of the discharge. We notice several new features in the **local** distributions on the right: The prompt losses and (neutral beam) sources are no longer symmetric within the

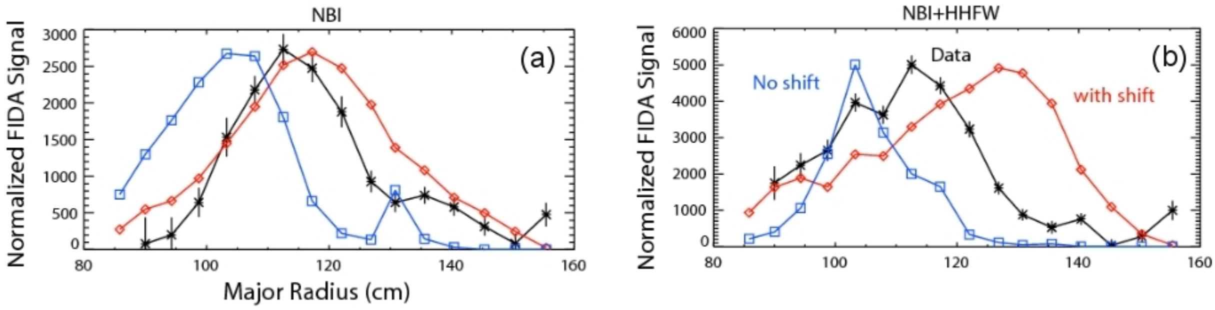

Fig. 3 Comparison of FIDA signals for (a) steady state neutral beam phase of the discharge, and (b) at 217 msec after the beginning of the HHFW_NBI phase. The experimental and ZOW (No shift) CQL3d results have been previously reported by Liu et al, PPCF (2010). We see good agreement between FOW corrected CQL3D and experiment for NBI in (a), and an over-correction in the HHFW+NBI in (b).

trapped region, contrary to the ZOW cases on the left. In the FOW case, fast ions exist out to near the plasma edge, whereas our prompt loss model in the ZOW case removed all particles whose banana width exceeded the distance to the plasma edge. These changes in the distribution will have large effects on synthetic diagnostics such as for NPA and FIDA which are sensitive to the angular distribution of ions, and their radial distribution. Similar results are obtained for the HHFW+NBI phase of the shot, but with much larger ion tail distributions.

Figure 3 compares the FIDA synthetic diagnostic with and without the FOW correction, with the experimental results[1]. The main result of this work is that much better agreement is obtained between computational model and experiment when the FOW effect is included. In comparison with the HHFW+NBI phase of the discharge, the FOW effect is too strong, that is, the radial shift of the FOW based signal is too great. We postulate that this results from the first order character of our orbit-shift calculation, which over-estimates shifts when they become comparable to the plasma radius.

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