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### Title

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### Permalink

<https://escholarship.org/uc/item/9qk2g6kx>

### Journal

AIP Conference Proceedings, 1580(1)

### ISSN

0094-243X

### ISBN

9780735412101

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### Publication Date

2014-02-12

### DOI

10.1063/1.4864551

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Peer reviewed

# CQL3D-HYBRID-FOW Modeling of the Temporal Dynamics of NSTX NBI+HHFW Discharges

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**Abstract.** The CQL3D Fokker-Planck code[1] has been upgraded to include physics of finite-orbit-width (FOW) guiding-center orbits[2,3], as compared with the previous zero-orbit-width (ZOW) model, and a recent first-order orbit calculation[2]. The Fast Ion Diagnostic FIDA[4,5] signal resulting from neutral beam (NBI) and high harmonic fast wave (HHFW) RF power injected into the NSTX spherical tokamak can now be modeled quite accurately, using ion distributions from the CQL3D-Hybrid-FOW code, a rapidly executing variant that includes FOW+gyro-orbit losses to the plasma edge, FOW effects on NBI injection and HHFW diffusion, but does not include neoclassical radial diffusion. Accurate simulation of prompt fast ion (FI) losses is a key feature of the marked modeling improvement relative to previous ZOW results. By comparing NBI-only and NBI+HHFW shots, independent confirmation of the usual 35% edge loss of HHFW in NSTX is obtained. Further, HHFW prompt losses from the plasma core are shown to be 3X as large (>25%) as the NBI-only case. The modulated NBI and time-dependent background plasma variations and charge exchange losses of fast ions are accounted for, and the temporal neutron variation is in approximate agreement with NSTX observations.

**Keywords:** ICRF, QL, quasilinear, orbit integration

**PACS:** 52.25.Dg, 52.25.Xz, 52.35.Hr, 52.65.Cc, 52.65.Ff

## INTRODUCTION

Most of the CQL3D applications to date have been in the zero-orbit-width (ZOW) approximation[1], neglecting most effects of radial drift on the transiting and trapped tokamak orbits. Recent work has added finite-orbit-width (FOW) effects to the code[2,3]. Presently, the FOW effects are included in a “hybrid” mode[3], to be explained more fully below; the results have shown much more accurate simulation of radial orbit shift effects and prompt losses in NSTX FIDA experiments.

The development of the CQL3D guiding center FOW code is based on *two main steps*. At the *first step*, partial FOW capabilities have been implemented, which add FOW features into the particle source (NB) operator, RF quasilinear operator and diagnostics. Collisions remain ZOW, thus omitting banana regime neoclassical diffusion. Guiding center orbit losses with gyro-radius correction are included. The Fokker-Planck (FP) equation remains in its ZOW form, except the above mentioned modification of coefficients. To find the local distributions, transformations must be made going from the calculated bounce-averaged (BA) distributions versus particle BA position, to the local point. At the *second step*, the FP equation is being modified to include the radial transformation coefficients in the collision coefficients; and the boundary conditions are revised, introducing discontinuities in FOW orbit diffusion. This work, completed except for further work on the internal boundary conditions, will give full guiding center orbit-based neoclassical diffusion coefficients and transport, and can be compared with the NEO code[6] results. It differs from NEO in being a full guiding center (GC) code, rather than an expansion in GC orbit width. This will be an important difference for energetic particles, particularly in NSTX.

## RESULTS

The *first step*, referred to as **CQL3D-HYBRID-FOW**, has greatly improved agreement with FOW effects measured by the experimental NSTX FIDA diagnostic, yet the required execution time is only increased by 30% for the NBI-only case, and by 75% for NBI+HHFW compared to CQL3D-ZOW.

Figure 1 shows the applied powers versus time in a modulated NBI and HHFW in an NSTX experiment [5]. The HHFW power is reduced by the usual 35%, accounting for edge losses. Two shots are focused on, 129842 is with modulated beam only, and 128739 is with both the modulated beam and HHFW. CQL3D simulations utilizing input of time-dependent radial plasma profiles for electron and ion density and temperature, and neutral density, from the TRANSP analysis of this shot, were advanced in time.

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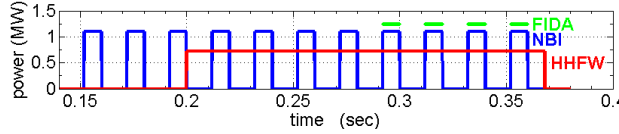


Figure 1. NBI and HHFW powers as a function of time for two NSTX shots, one with the modulated beam only, and a second comparison shot with added HHFW power [Liu, 2010]. CQL3D gives  $f(v, \theta, \rho, t)$ . The FIDA signal is obtained in experiment and simulation by averaging over the indicated time periods.

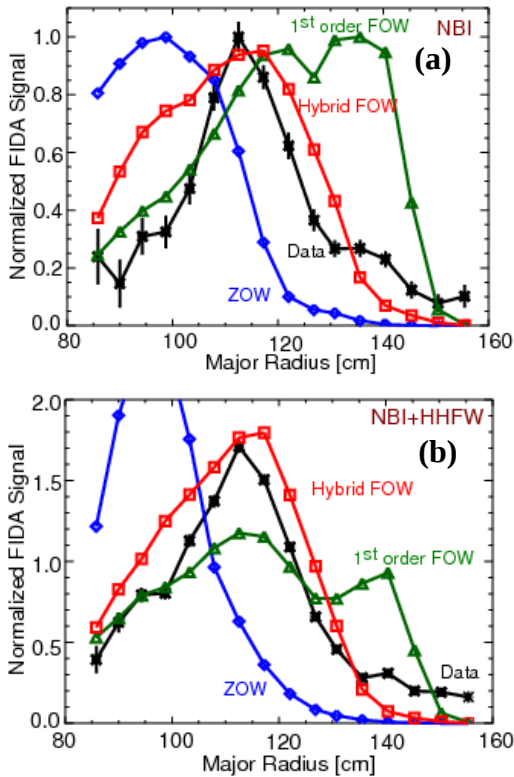
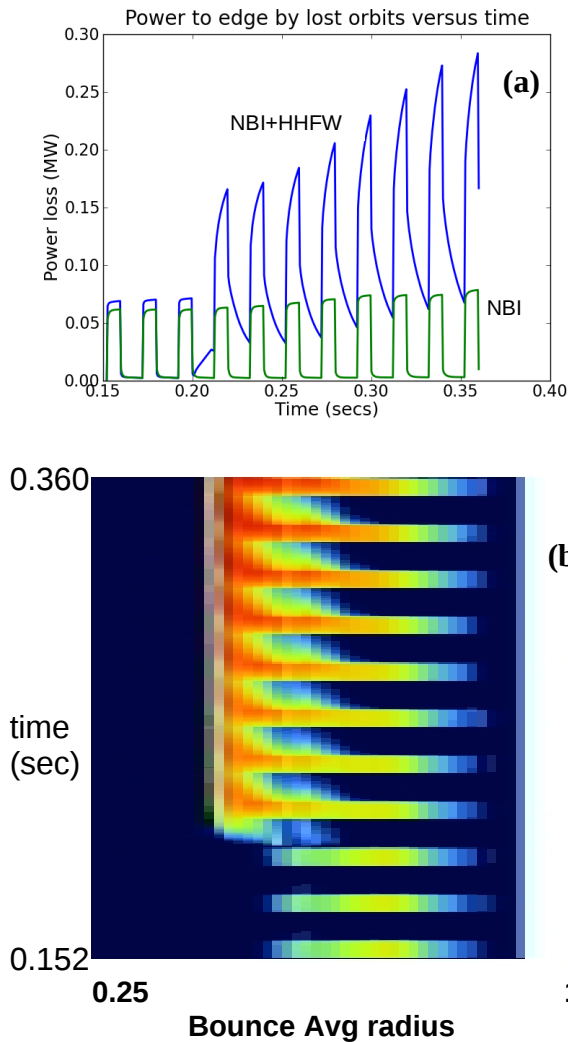


Figure 2. Experimental FIDA signal indicative of fast ion radial distribution (a) for modulated NBI, and (b) for modulated NBI+HHFW. The black curves are experimental results, blue is ZOW, green is a 1<sup>st</sup> order approximation, and red is the hybrid-FOW result.

The FIDA signal, a measure of the major radius profile of the fast ions, is given in Fig. 2(a), NBI-only, and (b), NBI+HHFW, as derived from the CQL3D distributions and the FIDASIM code[7], in comparison with the the experimental curve in black[5]. NBI FIDA signals are normalized to the same peak value, and this normalization is also used with the NBI+HHFW.

Results of three different CQL3D models are shown for comparison: (1) the original ZOW analysis (blue) which is shifted inwards from the experimental profile (black), indicated the need to include finite orbit width effects[5]; (2) A first order correction for orbit width (green), which turned out to overestimate the radial shift, not too surprising in view of the very large NSTX orbits[2]; and (3) the Hybrid-FOW treatment including the GC orbit effects (red). Evidently inclusion of the GC FOW effects is crucial for reasonably accurate simulation of the experiment.

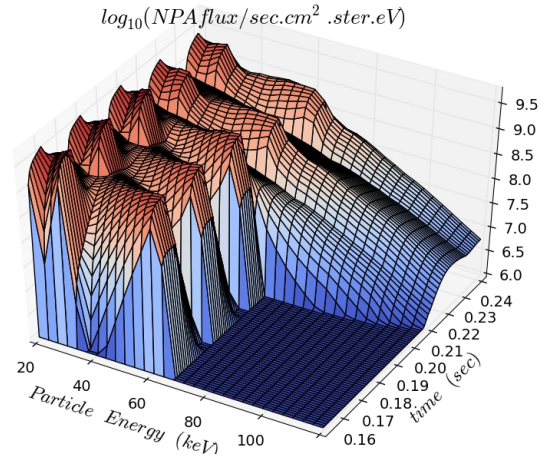
In Figure 2(a), the NBI-only case, attempts were made to further refine the code so as to account for the somewhat elevated calculated FIDA signal (the red curve) versus the experimental data (black) at the smaller major radii. NUBEAM[8] calculated hot ion birth-points were read into the CQL3D in place of those from the older-cross-section-based NFREYA code. It was found that neutral beam stopping, i.e., ionization was reduced, and this somewhat broadened the calculated FIDA signal. Adding charge exchange losses of the fast ions, based on time-dependent radial profiles from the flux-surface FRANTIC neutral code[9], as read in from the TRANSP code, compensated for the



**Fig.3.** Fast ion orbit power loss versus time. (a) Comparison of the loss power for NBI only (green) and the NIB+HHFW simulation (blue). (b) Fast ion loss versus bounce-average position and time. Both plots exhibit a marked increase of loss when the the HHFW is turned on at  $t=0.200$  secs.

of phase space, and the particles mainly slow down at constant pitch, whereas the HHFW causes QL perpendicular velocity diffusion into the FOW loss regions in velocity space which extend into the magnetic axis.

Synthetic diagnostic signals are available, based on the time- and spatial-varying electron and ion distributions. An example, for the NSTX shot we are discussing is shown in Fig. 4. Several basic plasma time scales are evident, which can be tested against experiment. Neutrons in CQL3D match the time-history of the experimental data quite well (Fig. 5), except for a 20%(NBI-only)-40%(NBI+HHFW) underestimate of the calculations compared to the experimental values. Results with a more complete 3D neutral code will be investigated to determine if the 1D model is the origin of the neutron simulation underestimate.

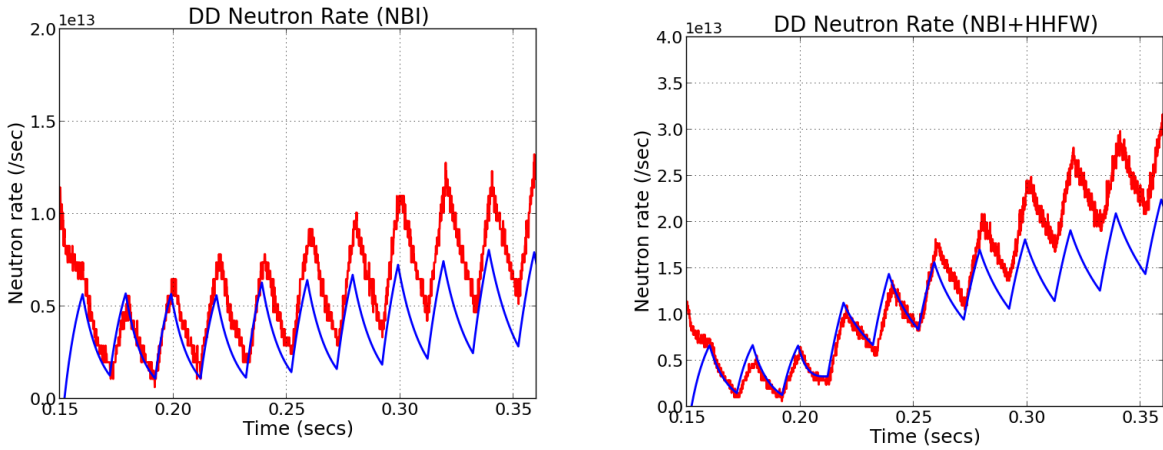


**Fig. 4.** Time-dependent energy-spectra of NPA calculated from simulated ion distributions in a modulated NBI+HHFW NSTX experiment. The HHFW is turned on a 0.2 secs. Heating, collisional, QL diffusion time scales, and neutrals, all play testable roles in the results.

NUBEAM deposition broadening, with the profile shown in Fig. 2 remaining almost unchanged.

A key feature of FOW is accurate calculation of the orbit loss region, which at the higher energies in the NBI+HHFW experiment in NSTX and extends inwards to particles (at certain pitch angles) near the magnetic axis. Figure 3 shows the power lost to the plasma edge. Fig. 3(a) compares total power loss in the NBI and NBI+HHFW shots. The prompt FI loss is 7% of the NBI power, but rises to 28% of the HHFW power, the latter being due to quasilinear (QL) velocity space diffusion into the orbit loss region. Fig. 3(b) shows the radial origin of the orbit-loss particles versus time, showing substantial near-central loss of HHFW generated fast ions. The explanation of enhanced HHFW losses, compared to NBI, is that the NBI is injected into a low loss region

It also anticipated that, pending the completion of the fully neoclassical CQL3D-FOW, the additional radial transport will fill in the calculated FIDA signal near the plasma periphery.



*Fig. 5. Comparison of experimental neutrons (red) with simulation results (blue). Fast ion charge exchange losses are included from a 1D neutral code*

## CONCLUSIONS

It is possible, even with HHFW such as in the NSTX case, to calculate accurate ion distribution functions with desktop computer resources, and to test the resulting synthetic diagnostic signals against many available tail ion diagnostics, such as FIDA, NPA and neutron rates. This detailed comparison will validate that calculated sources are accurate. A detailed, physics-verifiable representation of tokamak plasma physics will need to focus on plasma phase-space distributions.

*Research supported by USDOE Grants SC0006614, ER54744, and ER54649.*

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