GA–A27760

SciDAC CENTER FOR SIMULATION OF WAVE-PLASMA INTERACTIONS

ITERATED FINITE-ORBIT MONTE CARLO SIMULATIONS WITH FULL-WAVE FIELDS FOR MODELING TOKAMAK ICRF WAVE HEATING EXPERIMENTS

Final Report for the Period
April 1, 2008 through March 31, 2013

by
PROJECT STAFF

Prepared for
U.S. Department of Energy
under DE-FC02-08ER54952

FEBRUARY 2014

GENERAL ATOMICS

DISCLAIMER

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ABSTRACT

This final report describes the work performed under U.S. Department of Energy Cooperative Agreement DE-FC02-08ER54954 for the period April 1, 2011 through March 31, 2013. The goal of this project was to perform iterated finite-orbit Monte Carlo simulations with full-wall fields for modeling tokamak ICRF wave heating experiments. In year 1, the finite-orbit Monte-Carlo code ORBIT-RF and its iteration algorithms with the full-wave code AORSA were improved to enable systematical study of the factors responsible for the discrepancy in the simulated and the measured fast-ion FIDA signals in the DIII-D and NSTX ICRF fast-wave (FW) experiments. In year 2, ORBIT-RF was coupled to the TORIC full-wave code for a comparative study of ORBIT-RF/TORIC and ORBIT-RF/AORSA results in FW experiments.

1. DIII-D AND NSTX SIMULATIONS WITH IMPROVED ORBIT-RF/AORSA

The 5D finite-orbit Monte-Carlo code ORBIT-RF [1,2] has been coupled with the 2D full wave code AORSA [3,4]. The coupled ORBIT-RF/AORSA RF package has been applied extensively to investigate the finite-orbit effects of fast ions on their spatial and energy distributions, as well as the apparent significant absorption of wave power by fast ions in C-Mod, DIII-D and NSTX ion cyclotron radio frequency (ICRF) wave heating experiments at fundamental to high harmonics.

Previous ORBIT-RF/AORSA simulations reproduced the experimental trend in both the energy spectra and the outward spatial shifts of Fast-Ion D-Alpha (FIDA) signals from the magnetic axis. However, a discrepancy remained in that the simulations computed stronger outward shifts than the measured DIII-D and NSTX FIDA signals would indicate. This discrepancy could be due to a few reasons. Firstly, since the fast-ion data was recorded only once at the end of the simulation time interval, the statistics used to record the fast-ion data during the Monte-Carlo simulation may not be sufficiently adequate. In ORBIT-RF, the code tracks the energetic test particles through their excitation by ICRF waves and slowing-down via Coulomb collisions to thermal level, after which the test particles will no longer be tracked. Periodically, ORBIT-RF re-injects new test particles following the beam slowing-down distribution with new test particle weighting adjusted to commensurate with constant beam power. Since the test particles are being thermalized “continuously” while the re-injection occurs discretely, particle conservation is not exactly observed. Specifically, we found that test particles were poorly conserved at the time when the fast-ion data was recorded at the end of the simulation time. This may cause significant "under-counting" of the fast-ion population in space and energy. Secondly, the simulations were done over relatively short time intervals. For example, in the DIII-D discharge, the measured FIDA signals were averaged over a fairly long time window (~500 ms) to get reliable count statistics, while the simulations were done only for a fraction of that time. Thirdly, convergence might be insufficient. The iteration between ORBIT-RF and AORSA was done only once in the NSTX discharge and twice in the DIII-D discharge. Although the wave field patterns seemed to have converged in both cases, no rigorous criterion was used to determine the sufficiency of convergence.

During year 1, ORBIT-RF and its iteration algorithms with AORSA were improved to systematically study the role of these factors for the discrepancy in the simulations. First, ORBIT-RF is upgraded to record the fast-ion data more frequently. The numbers of recording of fast-ion data can now be specified in the input file. At each recording time the number of test particles is conserved. Then the fast-ion data is averaged over this entire ensemble, before it is passed on to the synthetic FIDA simulation (FIDASIM) code. Second, we have also extended the simulations over a much longer time window similar to that used in the experimental measurements. Third, the number of iterations between ORBIT-RF and AORSA has also been increased. The simulation results with these improvements are shown in Figs. 1 and 2. In these simulations, the fast-ion data is recorded more often (20 times) with 8 iterations between ORBIT-RF and AORSA for the DIII-D case and 3 iterations for the NSTX case.

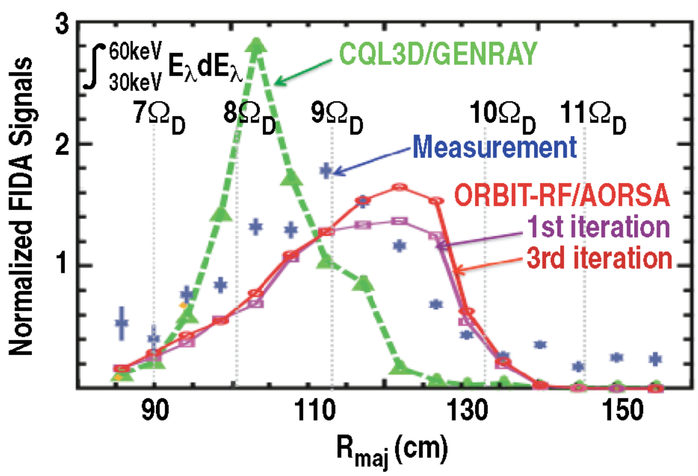

Figure 1. Comparison of enhanced synthetic FIDA signals from ORBIT-RF/AORSA computed distribution (solid lines with □ and ○) and the zero-orbit CQL3D/GENRAY results (dotted line with Δ) against experimental FIDA signals (error bars with X) for a NSTX high harmonic ICRF heating discharge combined with NB injection. The beam injection power is 1.0 MW at 65 keV energy. 1 MW RF power is launched into the plasma at 30 MHz frequency.

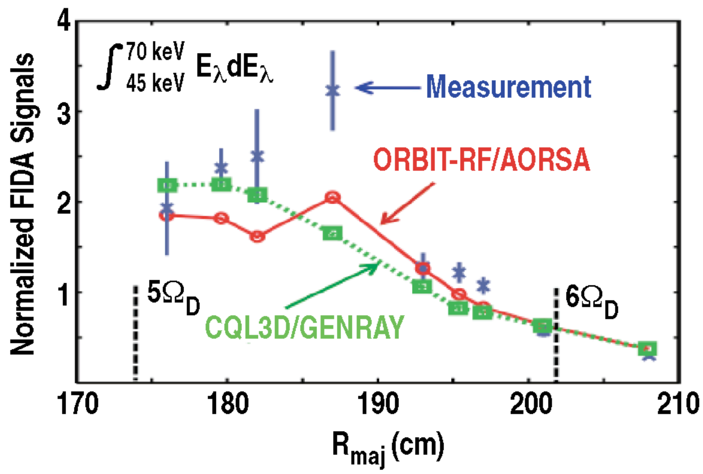

Figure 2. Comparison of enhanced synthetic FIDA signals from ORBIT-RF/AORSA computed distribution (solid line with ○) and CQL3D/GENRAY computed distribution (dotted line with □) against those from FIDA measurements (error bars with X) in a DIII-D moderate harmonic ICRF heating discharge combined with NB injection. 1 MW RF power is launched into the plasma at 60 MHz frequency

With these improvements, ORBIT-RF/AORSA simulation results generally agree better with DIII-D and NSTX experimental FIDA data. To illustrate the importance of the finite-orbit effects, also shown in Figs. 1 and 2 are results from the zero-orbit CQL3D/GENRAY [5] simulations that indicate an on-axis fast-ion spatial distribution.

2. ORBIT-RF AND TORIC COUPLING

In ORBIT-RF [1], a random walk model is implemented to reproduce stochastic diffusive nature in the magnetic moment (μ) space during resonant interaction of plasma ions with fast wave (FW) [2].

As discussed above, ORBIT-RF was successfully coupled with AORSA in an iterative way. ORBIT-RF computes a particle distribution function of an ensemble of fast-ion species in velocity and physical space by solving a set of Hamiltonian guiding center equations under Monte-Carlo Coulomb collisions and quasi-linear diffusive heating. AORSA computes ICRF wave fields by solving Maxwell's equations with oscillating current related to wave fields by a constitutive relation (conductivity tensor). Particle distribution computed from ORBIT-RF due to Monte-Carlo technique is reconstructed to a continuous distribution using an interface code. Wave field amplitude and its spatial pattern computed from AORSA are passed to ORBIT-RF to evolve fast-ion distribution. Evolved fast-ion distribution is then fed back to AORSA to update the dielectric tensor and ICRF wave fields. In this coupling work, certain simplifications were made in the wave parameters. In particular, the perpendicular wave number was approximated using a cold plasmas dispersion relation.

In year 2, ORBIT-RF was coupled with TORIC [6] in a similar way. One benefit of coupling ORBIT-RF with TORIC is that the perpendicular wave number is computed using a more comprehensive hot plasmas dispersion relation. For a test comparison, a typical DIII-D 5th harmonic 90 MHz FW heating discharge with neutral beam injection is selected. Using same plasma and FW heating parameters, TORIC and AORSA are simulated. Benchmarking of FW solutions indicates that TORIC and AORSA produce similar solutions. These values are passed to ORBIT-RF to compute "kicks" in μ.

Local power absorption profiles computed by ORBIT-RF/TORIC (blue line) and ORBIT-RF/AORSA (red line) are compared in Fig. 3. Computed local power absorption profile from ORBIT-RF/TORIC is within 10 % of that computed from ORBIT-RF/AORSA.

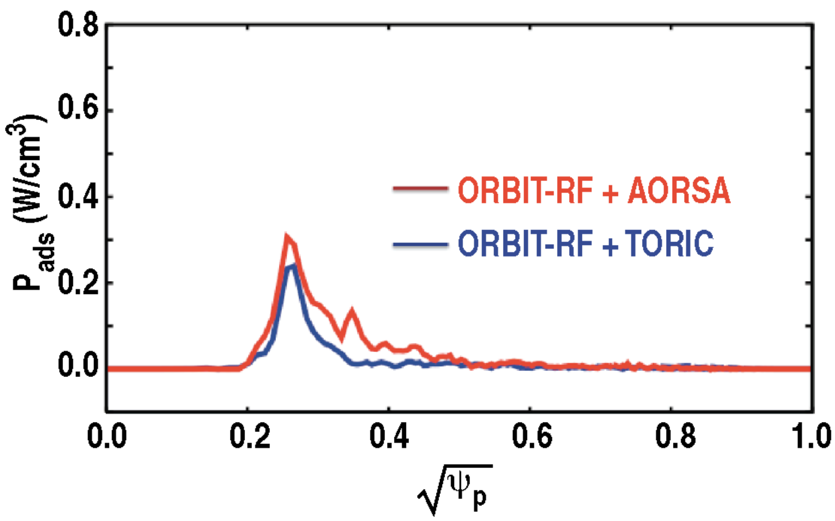

Figure 3. Comparison of local power absorption profiles computed by the two suites ORBIT-RF/TORIC (blue line) and ORBIT-RF/AORSA (red line).

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