Center for Simulation of Wave-Plasma Interactions

Summary of Scientific Progress: June, 2006 – May, 2007

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A. Nonlinear Evolution of Nonthermal Ion Distributions

Recently we successfully simulated energetic ion tail production during minority ICRF heating by iterating the bounce-averaged Fokker Planck code CQL3D with the AORSA full-wave solver on a single platform at ORNL, where the iteration is controlled by a Python script [Jaeger, 2006a, 2006b]. The iteration process evolves the self-consistent nonthermal ion distribution function using the quasilinear diffusion coefficient evaluated from the ICRF wavefields, computed by AORSA. In turn, the plasma response in AORSA is evaluated using the exact nonthermal ion distribution. These simulations typically require ≈ 1000 processor hours on the CRAY XT3/XT4 JAGUAR, for a single toroidal mode of the antenna spectrum, using 256 processors for 4 hours. We have also worked with experimentalists at the Alcator C-Mod facility to employ the nonthermal minority ion distribution function computed by AORSA-CQL3D in a synthetic diagnostic for passive and active neutral particle analysis—CNPA [Tang, 2007]. This diagnostic is used on C-Mod to measure the energy distribution of the minority hydrogen tail. Comparisons between the measured and simulated charge exchange spectra are shown in Figure 1. The agreement between the measured and simulated spectra is remarkably good. It is thought that the failure of the simulated spectra to reproduce the negative sloping region in the passive data may be due to the omission of finite ion orbit effects in the AORSA-CQL3D simulation.

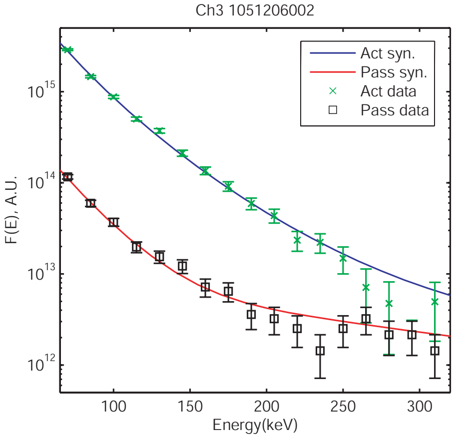

Figure 1: Comparison between the measured active and passive charge spectra and the spectra simulated using the AORSA-CQL3D synthetic diagnostic [Tang, 2007].

More recently we have begun to evolve multiple nonthermal ion species using the CQL3D-AORSA framework. This work is motivated by past simulations of ICRF waves on fast neutral beam ions at the 4th and 8th harmonic in DIII-D, where it was found that competition from cyclotron absorption due to background (H) (2nd and 4th harmonic) was significant [Jaeger, 2007]. We are currently in the process of simulating the DIII-D experiments again with the nonthermal background H effect included and have found that absorption of ICRF power on the nonthermal (H) can be comparable to the absorption on fast beam ions. We are also examining a number of other physics effects that maybe important for understanding the DIII-D fast wave – NBI interaction, including finite ion orbit width effects (not included in CQL3D). As part of this work we have implemented the Monte Carlo orbit code ORBIT RF on the CRAY XT3/XT4 and have found excellent scaling of the code up to 10^3 processors, where it is possible to follow up to 3×10^5 particles. The next step in this work will be to perform a closed loop computation between ORBIT RF and the full-wave solvers (AORSA and TORIC). We have also used our DC code to directly integrate particle orbits using the RF electric fields from the full-wave solvers. A quasilinear diffusion coefficient is formulated from the resulting orbit integrations, and compared with the diffusion coefficients from zero banana-width calculations. One final physics question that is being investigated with ORBIT RF is the validity of the quasilinear theory at the higher harmonic resonances present in the DIII-D experiments. Preliminary results indicate there is sufficient phase decorrelation at 4th harmonic to satisfy quasilinear theory. Analysis of the 8th harmonic interaction is now underway.

B. Antenna Coupling and Antenna – Edge Plasma Interactions

During 2006-2007 modifications were completed to the TORIC ICRF solver in order to couple the code to the 3D electromagnetic antenna code TOPICA. TORIC is now able to compute the matrix needed by TOPICA for a single electric field excitation $(E_\eta, E_\zeta)^{m,n}$ at the plasma surface. This interface underwent extensive testing that was only recently completed and the full impedance matrix is now ready to be passed to TOPICA, enabling linear ICRF coupling calculations using the full ICRF antenna spectrum, realistic antenna geometry and plasma response.

Also, during the past year we developed a model for the interaction of a fast wave (FW) encountering a wall that does not coincide with a flux surface [D'Ippolito, 2007]. In this situation, a slow wave (SW) is generated by the magnetic field-conducting wall mismatch and the SW drives a (far field) sheath. A formalism was derived to describe the coupling of the incident FW to a reflected FW and evanescent SW at the wall, and to obtain the self-consistent sheath potential for a given incident RF field. This model was used to post-process the local RF fields at the wall computed by the AORSA1D full-wave code for a DIII-D fast wave D(H) minority heating scenario with low single pass core absorption [D'Ippolito, 2007]. This work showed that far field sheaths can be quantitatively important when sheath-plasma-wave resonances are triggered. Finally, we have made significant progress in performing time domain simulations of RF sheath formation at the plasma edge using the 3D electromagnetic particle in cell (PIC) code VORPAL. Work was completed on a time domain module [Smithe, 2007] to provide the perturbed currents associated with the ICRF electric fields, the module was tested and implemented in VORPAL, and a proof of principle calculation was carried out in which a 3D ICRF antenna geometry of a model current strap was coupled with realistic edge plasma conditions. During the coming year we plan to employ the PIC algorithm in VORPAL for the ion response to perform fully nonlinear calculations of the antenna – edge plasma interaction.

C. Full-wave / Fokker Planck Studies of Lower Hybrid Current Drive

This past year we made significant progress on two crucial aspects of a coupled Fokker Planck and full-wave LHCD simulation model. First, we implemented and tested modules for non-Maxwellian electrons (and ions) in the full-wave field solver (TORIC). Second, we modified the TORIC solver to use a completely in-core matrix inversion algorithm and demonstrated excellent scaling of the modified code to ≈ 6000 processors on the CRAY XT3/XT4 JAGUAR computer. During the coming year we expect to complete a module for evaluation of the RF diffusion coefficient from the full-wave fields. It should then be possible to perform closed loop iterations between the Fokker Planck and LH field solvers in 7-10 wall clock hours utilizing 4000-5000 processors.

D. Simulations of ICRF Mode Conversion, Flow Drive, and 3D Wave Field Reconstructions

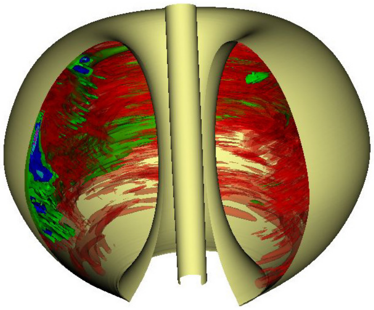

Figure 2: AORSA reconstruction of the 3D ICRF wave fields in NSTX.

During the past year we continued to improve the resolution of ion cyclotron wave (ICW) mode conversion calculations in ITER that were reported last year, where we increased the mode resolution in AORSA from 350 (k_x) × 350 (k_z) to 450 (k_x) × 450 (k_z). These simulations achieved 73 TF on the CRAY XT4 at ORNL using 22,500 processor cores and establish that we can use AORSA with the mode resolution needed to investigate ICW mode conversion and flow drive [Berry, 2006] at ITER or DEMO relevant plasma densities. In anticipation of the need to understand how ICRF wave fields will interact with 3D structures in the tokamak edge, we have also started to perform 3D reconstructions of the wave fields from antenna launching structures, including the entire toroidal mode spectrum of the antenna. An example of this type of calculation for NSTX is shown in Figure 2, where 81 toroidal modes of the antenna were used. Itcan be seen that the fast wave fields have a significant toroidal extent, raising the question of whether or not surface waves are excited in this situation that could be responsible for parasitic edge losses. We have also reproduced the 3D wave fields and RF current profiles for fast wave current drive (FWCD) in ITER using 169 toroidal modes. This calculation utilized 2048 processor cores for 8 hours on the CRAY XT3/XT4.

Publication List for Center for Simulation of Wave-Plasma Interactions (2006 – 2007)

Berry L A, Batchelor D B, Bonoli P T *et al* 2006 "Analysis of Ion Cyclotron Heating Issues for ITER," *IAEA Fusion Energy Conference* (Chengdu, China)

Bonoli P T, Harvey R W, Kessel C *et al* 2006 "Benchmarking of Lower Hybrid Current Drive Codes with Application to ITER-Relevant Regimes", *IAEA Fusion Energy Conference* (Chengdu, China)

Choi M, Chan V S, Pinsker R I, *et al.* 2006 "Simulation of Fast Alfven Wave Interaction with Beam Ions over a Range of Cyclotron Harmonics in DIII-D Tokamak," *Nucl. Fusion* **46** 409.

D'Ippolito D A and Myra J R 2006 "A radio-frequency sheath boundary condition and its effect on slow wave propagation," *Phys. Plasmas* **13** 102508

D'Ippolito D A, Myra J R, Jaeger E F and Berry L A 2007 "Far-field sheaths due to fast waves incident on material boundaries," Lodestar report LRC-07-113

Jaeger E F, Berry L A, Ahern S D *et al* 2006a "Self-consistent full-wave and Fokker-Planck calculations for ion cyclotron heating in non-Maxwellian plasmas," *Phys. Plasmas* **13** 056101

Jaeger E F, Harvey R W, Berry L A *et al* 2006b "Global-wave solutions with self-consistent velocity distributions in ion cyclotron heated plasmas," *Nucl. Fusion* **46** S397

Jaeger E F, Berry L A, Harvey R W *et al*, 2007 "Evolution of Multiple Ion Tails in ICRF Heating", *17th Topical Conference on Radio Frequency Power in Plasmas*, (May 7-9, 2007) Paper B13.

Qin H, Phillips C K, and Davidson R C 2007 "A New Derivation of the Plasma Susceptibility Tensor for a Hot Magnetized Plasma Without Infinite Sums of Products of Bessel Functions," submitted to *Phys. Plasmas*

Smith S P, Phillips C K, Valeo E J, PPPL; Smithe D N, Tech-X Corp.; The RF SciDAC Team 2006, "The Wavelet Approach to Solving the Mode Conversion Wave Equation," VP1 51, BAPS **51** (2006) 306]

Smithe D 2007 "Finite-difference time-domain simulation of fusion plasma at radiofrequency time scales," *Phys. Plasmas* **14** 056104

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