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CompX Participation

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Abstract

Harnessing the energy that is released in fusion reactions would provide a safe and abundant source of power to meet the growing energy needs of the world population. The next step toward the development of fusion as a practical energy source is the construction of ITER, a device capable of producing and controlling the high performance plasma required for self-sustaining fusion reactions, or "burning" plasma. The input power required to drive the ITER plasma into the burning regime will be supplied primarily with a combination of external power from radio frequency waves in the ion cyclotron range of frequencies and energetic ions from neutral beam injection sources, in addition to internally generated Ohmic heating from the induced plasma current that also serves to create the magnetic equilibrium for the discharge. The ITER project is a large multi-billion dollar international project in which the US participates. The success of the ITER project depends critically on the ability to create and maintain burning plasma conditions, it is absolutely necessary to have physics-based models that can accurately simulate the RF processes that affect the dynamical evolution of the ITER discharge.

The Center for Simulation of WavePlasma Interactions (CSWPI), also known as RF-SciDAC, is a multi-institutional collaboration that has conducted ongoing research aimed at developing: (1) Coupled core-to-edge simulations that will lead to an increased understanding of parasitic losses of the applied RF power in the boundary plasma between the RF antenna and the core plasma; (2) Development of models for core interactions of RF waves with energetic electrons and ions (including fusion alpha particles and fast neutral beam ions) that include a more accurate representation of the particle dynamics in the combined equilibrium and wave fields; and (3) Development of improved algorithms that will take advantage of massively parallel computing platforms at the petascale level and beyond to achieve the needed physics, resolution, and/or statistics to address these issues.

CompX provides computer codes and analysis for the calculation of the electron and ion distributions in velocity-space and plasma radius which are necessary for reliable calculations of power deposition and toroidal current drive due to combined radiofrequency and neutral beam at high injected powers. It has also contributed to ray tracing modeling of injected radiofrequency powers, and to coupling between full-wave radiofrequency wave models and the distribution function calculations. In the course of this research, the Fokker-Planck distribution function calculation was made substantially more realistic by inclusion of finite-width drift-orbit effects (FOW). FOW effects were also implemented in a calculation of the phase-space diffusion resulting from radiofrequency full-wave models.

Average level of funding for CompX was approximately three man-months per year.

1. Introduction

In order to report on CompX contributions to the SciDAC Center for Simulation of Wave Particle Interactions (CSWPI), background will be presented here on the main CompX codes which have been provided, further developed, and supported within the context of the Cooperative Agreement. These are the CQL3D bounce-averaged Fokker-Planck code [Harvey & McCoy, 1993] for electron and ion distributions, the GENRAY radiofrequency (RF) ray tracing code [Smirnov & Harvey, 1995, 2001], and the DC finite-orbit width diffusion coefficient calculator[Harvey, 2009, 2017]. The CQL3D and GENRAY codes were brought to the collaboration and further developed, and the DC code was largely created as a component in the cooperation.

The CQL3D Fokker-Planck code had been coupled to GENRAY ray tracing prior to the present project. In the project, more comprehensive, accurate modeling was attained by coupling the CQL3D code to physically more accurate full-wave electromagnetic codes: AORSA[Jaeger, 2001, 2006a, 2006b, 2008], TORIC[Brambilla, 1999; Lee, 2017a, 2017b] and TORLH[Wright, 2009], in work with the other members of the team. This coupling will be outlined below. The CQL3D code, at the beginning of the project, was based on a zero-orbit-width (ZOW) approximation for the particle orbits in a tokamak. This approximation is often insufficiently accurate in simulations of energetic particles in present day experiments, and for energetic particles in ITER including fusion generated alpha particles. During the project, and partially supported by it, the CQL3D code was generalized to include finite-orbit-width (FOW) effects. This is a modification involving tens-of-thousands of lines of code. CompX also constructed a new code, DC, for the direct numerical calculation of RF diffusion coefficients from full-wave code electromagnetic fields based on the fundamental Lorentz force equation on the particles. The DC code verifies quasilinear diffusion calculations and facilitates coupling of the full-wave codes with the CQL3D-FOW simulation. These developments will be elaborated below.

2. Background on CompX Simulation Codes

Fokker-Planck codes are essential computational tools for the theoretical interpretation of existing plasma experiments and for projections to new experiments. Heating and current drive systems for fusion plasma applications usually involve the production of substantial nonthermal distributions of electrons and/or ions; understanding the resulting effects is often crucial to success of the experiments. This is particularly true for the current generation of existing and proposed toroidal experiments with high rf power density and/or strong radial transport. Also, the ITER experiment will involve the crucial alpha-particle slowing down distribution, its power deposition, diagnosis, interactions with MHD and RF waves and with the wall.

Moreover, nonthermal distributions hold particular information on the transport and driving forces, not obscured by the smoothing Maxwellization effects of Coulomb collisions. Particularly in cases of well modeled sources such as neutral beams, electron cyclotron power, single pass lower hybrid heating and current drive, or applied dc electric field, new information is obtainable on the velocity dependence of radial transport coefficients. This has been well-illustrated by C-Mod LH experiments[Bonoli, 2008; Schmidt, 2009, Wallace, 2009, 2010, 2011, 2012]. The CQL3D multi-species, bounce-averaged Fokker-Planck (FP) code [Harvey & McCoy, 1993] is a well-tested, general approach to addressing nonthermal distributions resulting from auxiliary heating and current drive in toroidally symmetric devices, built on the foundation of the 2D-in-velocity-space, 0D in radius, CQL code [Kerbel & McCoy 1985]. Radiofrequency wave data is obtained with the GENRAY all-frequencies ray tracing code [Smirnov & Harvey 1995, 2001] and more recently with the AORSA [Jaeger, 2006a, 2006b, 2008] and TORIC-LH[Wright, 2009] full wave codes. CQL3D has been broadly applied within the fusion community, and is proving to be increasingly useful. Twenty-six papers using this code suite were published or were in production during 2010-2012. The codes are used for modeling of NBI and EC, EBW, LH, and/or FW on DIII-D, CMod, NSTX, MST, TCV, HSX, and Pegasus devices, and also ITER. The code suite is a component in the RF-SciDAC and past SWIM-SciDAC projects.

GENRAY presently computes ray trajectories in axisymmetric equilibria, for several alternative dispersion relations; the ray tracing is performed fully in three dimensions, and some toroidally dependent effects and perturbations are accounted for.

CQL3D is a finite-difference FP code which calculates time-dependent plasma particle distributions as a function of the three coordinates: momentum parallel and perpendicular to the ambient magnetic field, and non-circular plasma radius. The solution is time-step implicit in the 2D-velocity space. The main advantage of the finite-difference solution of the FP equations is that solutions are noise free, to machine accuracy, as compared to Monte Carlo calculations of particle distributions, and execution times are relatively low.

Most of the CQL3D applications to date have been in the zero-orbit-width (**ZOW**) approximation, neglecting most effects of radial drift on the transiting and trapped tokamak orbits. Recently finite-orbit-width (**FOW**) effects have been added to the code [Petrov & Harvey, 2016]. To achieve reduced CPU execution times, the FOW effects have also been included in a "hybrid" mode, to be explained more fully below; the results have shown much more accurate simulation of radial orbit shift effects in NSTX FIDA experiments.

Radial transport is included through a splitting algorithm, alternating between the velocity-solve and the radial diffusion equation-solve. Alternatively, during the present contract, a fully-implicit, simultaneous 3D solve using sparse matrix solution methods has been completed. FP solutions involving radial diffusion have become important, but most work has involved only the velocity-space solutions with radial transport neglected. Generally, the nonthermal plasma particles in toroidally symmetric magnetic fusion experiments are in a low-collisionality regime in which their bounce-time is shorter than the collision time, enabling bounce-averaging as a means of reducing the poloidal dimensionality of the problem, while still accounting for poloidal variation of particle, momentum, and heating sources. Also, for time periods of variation greater than the cyclotron period, the particle distributions are azimuthally symmetric about the direction of the ambient magnetic field. Toroidal symmetry further reduces the dimensionality. Thus, the three-dimensional solutions of CQL3D address the major dimensionalities of non-Maxwellian effects in toroidally symmetric machines on collisional and transport time scales. A 3D solution is sufficient.

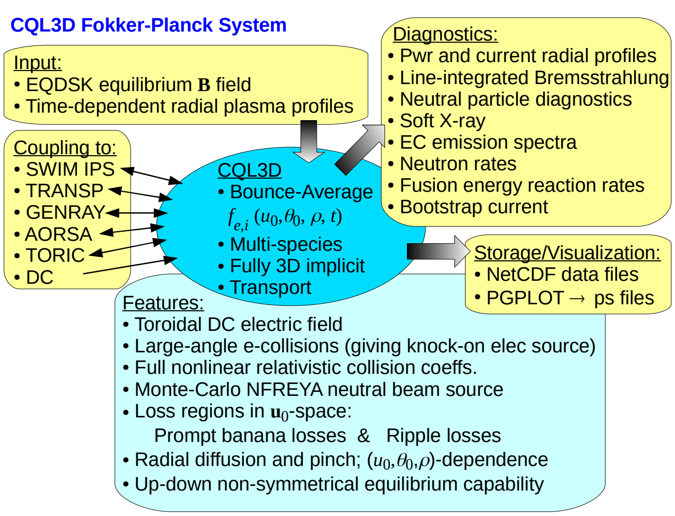


Fig. 1. Schematic of CQL3D code.

Additional features of this solution of the Fokker-Planck equations include that it: (1) is multi-species for both electrons and/or ions; (2) fully relativistic; (3) has fully nonlinear Coulomb collision operator; (4) has a general means for coupling in results from ray tracing codes for any wave mode; (5) calculates associated quasilinear rf diffusion coefficients and WKB ray damping self-consistent with nonthermal distortion of the distributions; (6) coupled to the FREYA neutral beam source of ions; (7) has large-angle knock-on source of electrons; and (8) has radial transport with velocity-dependent radial diffusion and pinch terms. Fig. 1 summarizes the major features of the code. Documentation is in [Harvey *et al* 1993a] and in more recent publications listed in the bibliography. Together with GENRAY (below), the quasilinear model has been well-verified against other EC current drive codes [Prater *et al* 2008].

The CQL3D code has been applied to the range of U.S. tokamak experiments, and also to the MST reversed field pinch(RFP). The rf QL portion of the code was first developed as a lower hybrid model; the 2D-in-momentum-space feature of the code enabled the first "no-free-parameter" 2D-in-velocity-space radial modeling of the Asdex LH experiment[Harvey, 1990]. The QL model was extended to electron (and ion) cyclotron harmonic

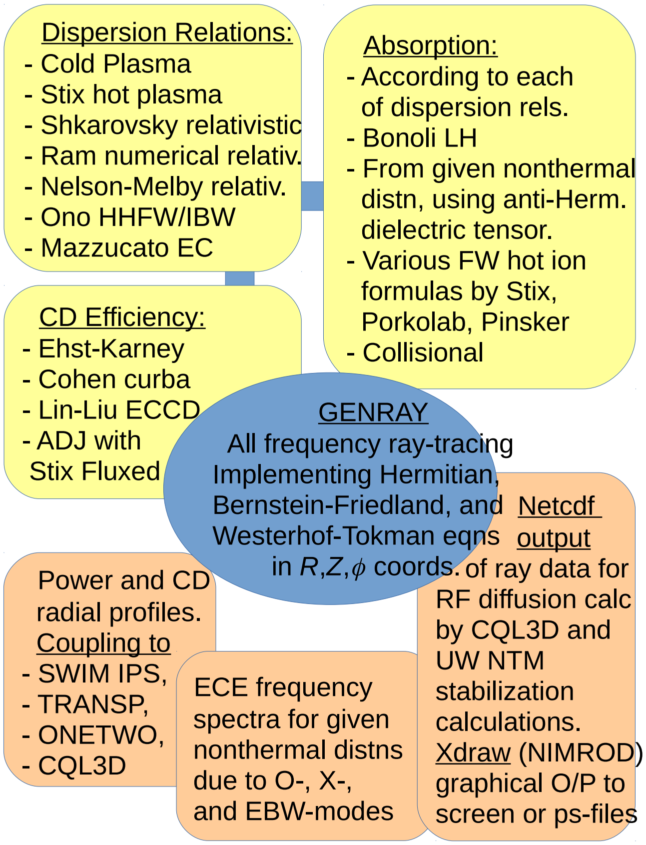


Fig. 2. Schematic of GENRAY calculation showing available dispersion relations, absorption calculation and current drive modules. Output gives easy visualization with xdraw, and couples to CQL3D and to transport codes. ECE and EBWE frequency spectra may be calculated from given nonthermal distributions imported from CQL3D.

interactions. The versatility of the code was illustrated by a study of synergies between LH, EC and fast wave (FW) current drive [Harvey, 1992]. CQL3D has been widely benchmarked against DIII-D ECH experiments.

For the ITER tokamak design, ECCD was shown to readily penetrate to the plasma center, and to give current drive efficiency comparable to other auxiliary sources [Harvey 1997]. For ECCD applications, [Westerhof 1995] has compared available 3D FP codes, showing CQL3D to be a leading application. In general, the 3D Fokker-Planck codes provide a framework within which to incorporate nonthermal rf, NBI, fusion, and transport effects, similar to the function of moment equation transport codes for near-Maxwellian plasmas. The 3D FP codes enable realistic, systematic comparison of nonthermal plasma theory with experiment. They also provide theoretical predictions of nonthermal distributions to be further studied for microstability and excitation of energetic particle modes.

The all-frequencies GENRAY ray tracing code, supported by this contract, maintains generality within the CQL3D framework, providing data for calculation of RF quasilinear diffusion coefficients. Fig. 2 gives a schematic of GENRAY. In general, ray tracing in conjunction with 3D Fokker-Planck modeling provides an accurate model for nonthermal rf power absorption and current drive, at least thus far in the EC and LH regimes.

CQL3D Fokker-Planck-transport modeling and comparison with the ECCD experiment on the Lausanne TCV tokamak [Harvey, 2002] revealed that the ECH power completely dominated the tail of the electron distribution, giving, in the absence of radial diffusion, 5.5 times the experimentally observed current. This result was obtained with the CQL3D code which has shown remarkably good agreement with DIII-D observations, typically with less than 10 percent disagreement. For TCV, introducing diffusive radial transport of the electron distribution with coefficient closely consistent with the observed energy transport gave a huge 5-fold reduction in calculated ECCD, in good agreement with the experiment. Radial diffusion at the level of thermal transport brought the large, irregular, calculated radial current profile down to a smooth, Guassian-looking current profile with the observed total magnitude.

3. Coupling CQL3D to AORSA

AORSA is a leading full-wave solution for plasma waves in tokamaks [Jaeger, 2001], including all-orders in $k_{\perp}\rho_L$ in the ion cyclotron interaction. Prior to the CSWPI project, calculation of the propagation and damping of ion cyclotron radiofrequency waves (ICRF) was based on Maxwellian ion distributions, which is only expected to be a sufficiently accurate approximation for low injected RF power. The CQL3D code provided a means to calculate the non-Maxwellian ion distributions modified through RF quasilinear diffusion coefficients. But, prior to the project, the coefficients were not available from US full-wave codes. On the other hand, particularly in the ICRF case, full-wave codes are necessary for accurate calculation of the wave fields in the common situation of wave-lengths not much less than the local plasma scale lengths, and mode conversion being an important part of the physics.

For the AORSA full-wave code, these coefficients were derived by [Jaeger, 2006a, 2006b] and passed by file to the ZOW version of the CQL3D code. By iterating back and forth between AORSA and CQL3D, a self-consistent propagation and damping including the important non-Maxwellian energetic "tail" distribution. Figure 3 illustrates the iterative evolution for the deuterium distribution in the General Atomics DIII-D tokamak experiment, when 1.1 MW of 60 MHz fast wave ion cyclotron heating is turned on in a neutral beam heating plasma. The left column gives distributions near the center of the plasma versus iteration number, and the right column shows the corresponding radial power absorption profile. Distribution function contour levels are chosen to be equi-spaced for a Maxwellian. At the 0^{th} iteration, the distribution function feature to the upper right is the effect of an initial condition for an 81 keV neutral beam

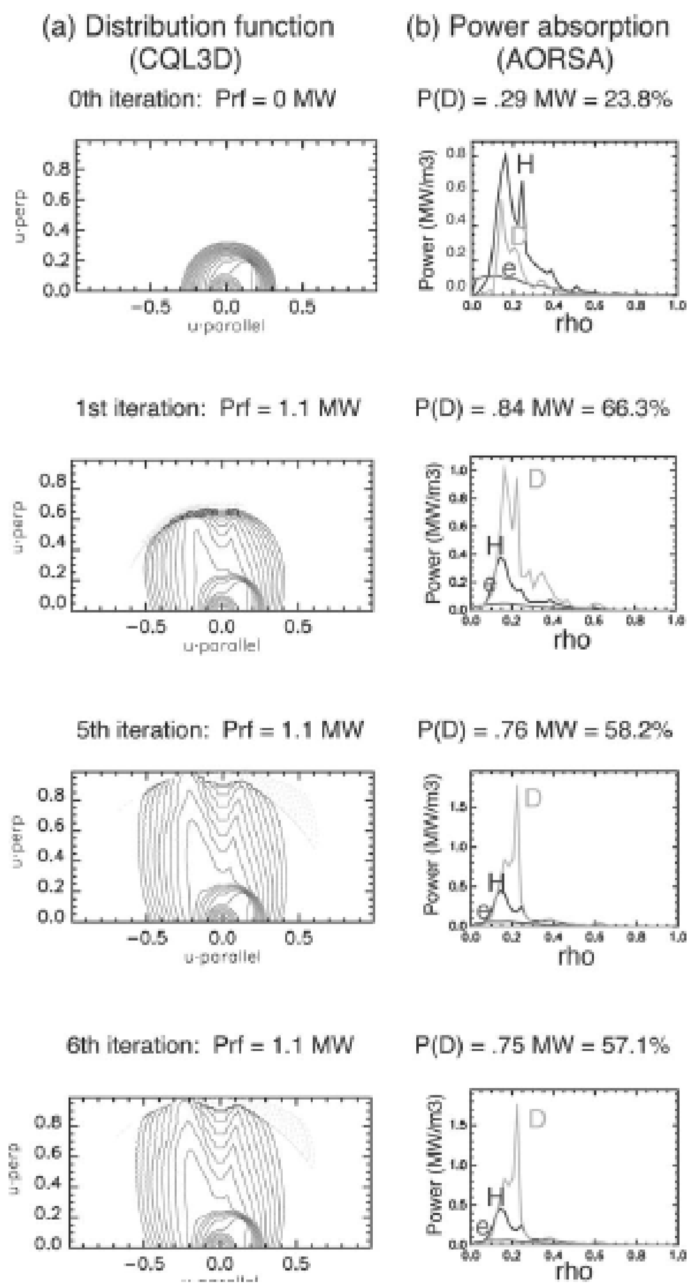


Fig. 3. Iterative solution for (a) the deuterium distribution function and (b) the rf power absorption in DIII-D Ref. 8 shot No. 122080 with 1.1 MW of fast wave heating at 60 MHz [Jaeger, 2006a].

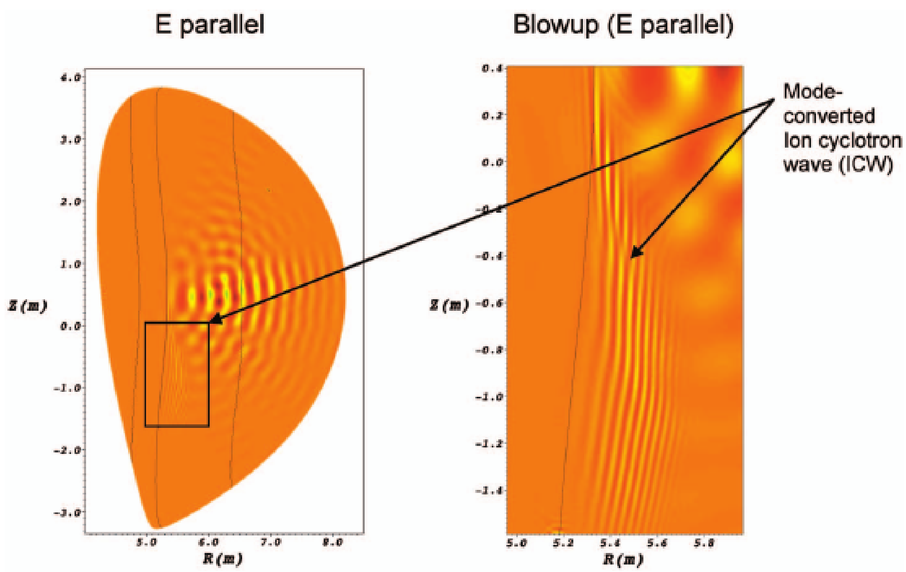


Fig. 4. Mode conversion from the fast wave to the ion cyclotron wave ICW in ITER Scenario 4 for n = −27 [Jaeger, 2008].

injection. Successive iterations show the excitation of a large tail on the deuterium and the self-consistent large modification of the RF absorption profile in the right hand column. It is important to account for the modifications of the power deposition in the quantitative simulation of the plasma transport. Also, synthetic diagnostics based on the calculated distributions are compared with experimental diagnostic observations, to validate the AORSA-CQL3D simulations.

Non-Maxwellian ion tail features also play an important role [Jaeger, 2008] in modeling of ICRF in the ITER international burning plasma tokamak under construction in France [https://www.iter.org]. Fig. 4

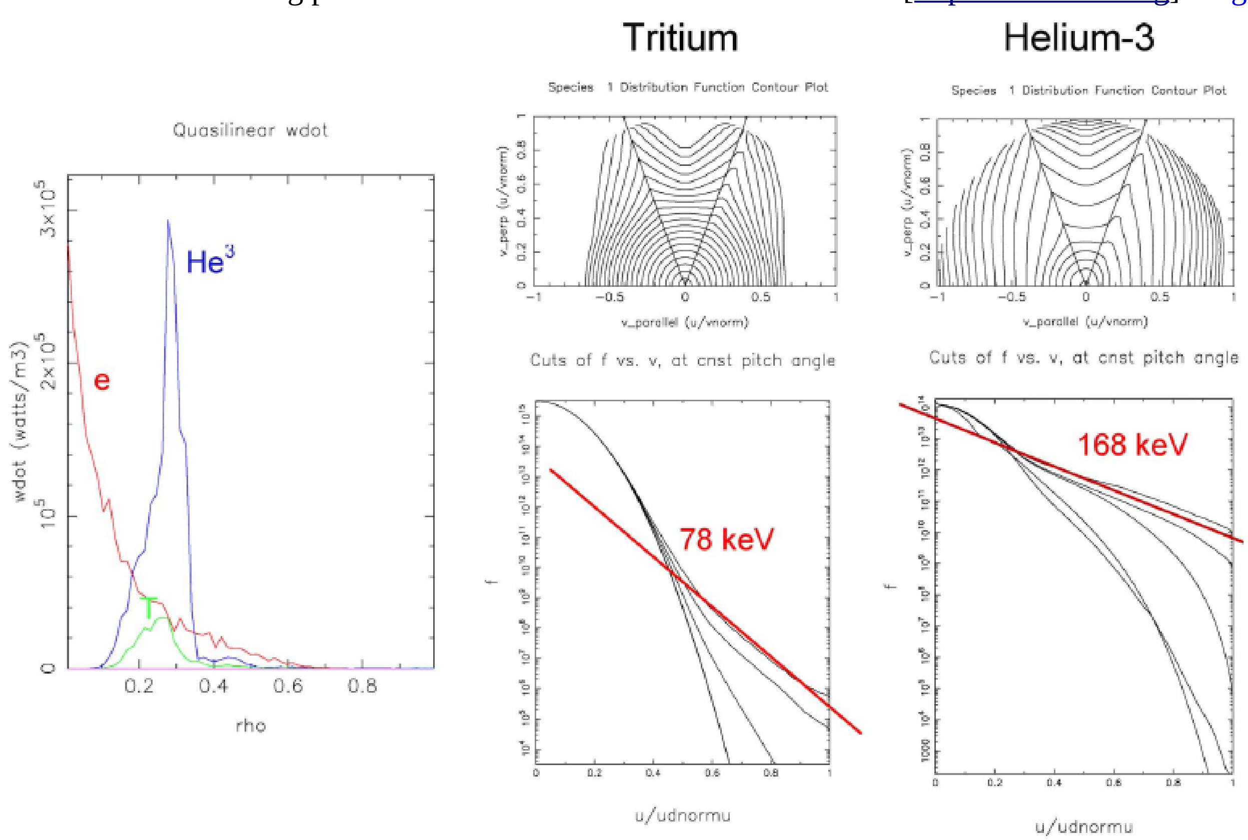


Fig. 5. Self-consistent heating profiles and minority ion distribution function for a minority He3 heating scheme in ITER, r / a = 0.270 and n = −27 [Jaeger, 2008].

illustrates wave fields obtained for an ITER ICRF scenario, including the mode-converted ICW wave, not obtained by simple ray tracing as in GENRAY. The quasilinear diffusion from AORSA is iterated with CQL3D for a minority He3 heating scenario to obtain Fig. 5, again demonstrating the formation of substantial nonthermal distributions, which must be accounted for in accurate modeling of ICRF in ITER.

4. Coupling CQL3D to TORIC

The TORIC full-wave code solves the electromagnetic plasma wave equation in toroidal geometry by using different techniques than the AORSA code: There is a Fourier decomposition in only two dimensions as compared with in three dimensions in AORSA, and the warm plasma finite $k_{\perp}\rho_L$ effects are modeled only through first order as compared to all-order in AORSA. As a result of these differences, TORIC models the ICRF mode conversion physics but cannot accurately follow the mode converted wave far from the mode-conversion region; in many cases of interest, the damping of the mode converted wave is sufficiently strong that the physics effects of the truncated $k_{\perp}\rho_L$ expansion have no effect of the solution, and the TORIC and AORSA codes agree well. The major advantage of the TORIC code has been than it requires much less computer CPU time than AORSA.

The calculation of the quasilinear diffusion coefficient from the TORIC full-wave solution was considerably more difficult, analytically, than in the AORSA formulation. This has now been accomplished by [Lee et al, 2017a and 2017b], and then TORIC coupled to CQL3D through passing of the coefficients by file. Figure 6 shows calculated tritium distributions with the coupled codes, for a case of 50:50 DT ITER plasma heating predominantly the tritium at the second cylotron harmonic [Lee 2017b]. The results are very close to what is obtained with AORSA-CQL3D, with minor differences explained as resulting from the first order $k_{\perp}\rho_L$ expansion used in TORIC.

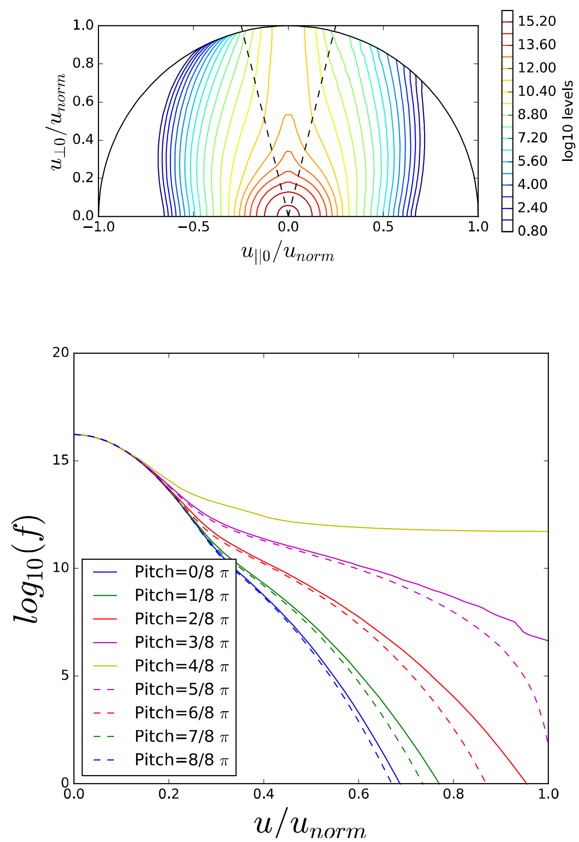


Fig. 6. *Reduced model results by TORIC-CQL3D : (a) 2-D contour plots of the distribution function in velocity space at r/a=0.1 (b) 1-D distribution functions in terms of speed for several pitch-angles. Here, u_{norm} is the momentum corresponding to the energy of Tritium 4 MeV. [Lee, 2017b]*

CQL3D has also been coupled to a modified version of TORIC (TORLH) for lower hybrid wave heating and current drive simulations [Wright, 2009]. The electron parallel (to the magnetic field) velocity space diffusion coefficient is calculated from the TORLH full wave field, and passed to CQL3D. Self-consistency between the LH damping and QL distortion of the distribution function is obtained by iteration. Figure 7 shows TORLH lower hybrid waves, and Fig. 8 gives the characteristic non-Maxwellian raised tail distribution also obtained by iteration between ray tracing and CQL3D (see, for example , [Harvey, 1991]).

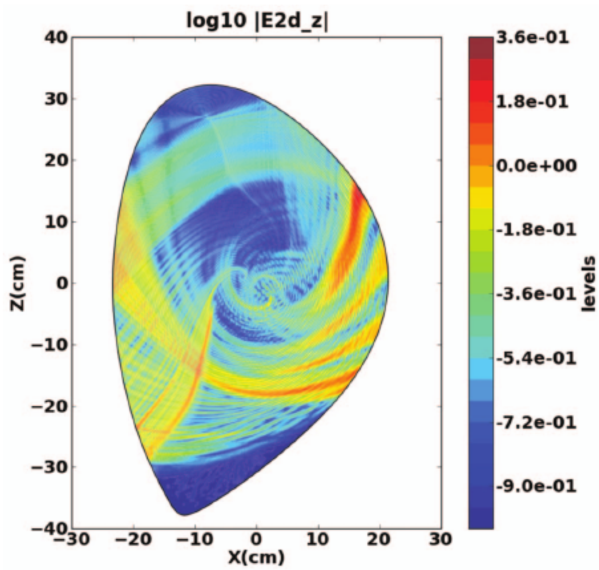


Fig. 7. Full wave calculation of LH waves in Alcator C-Mod at electron density of 7 x 1019 m−3 using a self-consistent non-Maxwellian di-electric response achieved after four iterations. The electric field component parallel to the equilibrium magnetic field is shown [Wright, 2009].

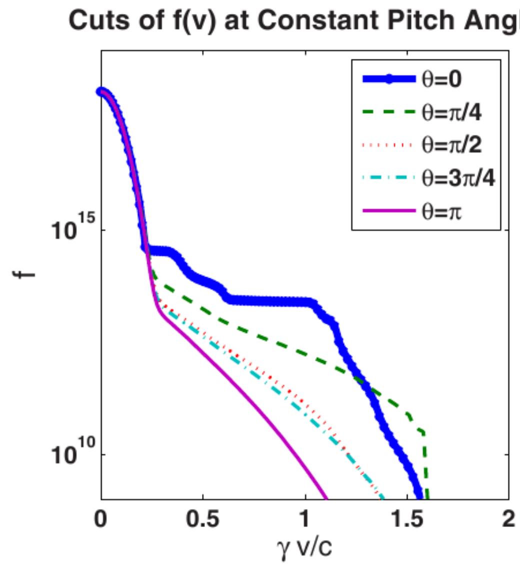


Fig. 8. Electron distribution response to the LH waves in Fig. XX5. Plots of the distribution function vs relativistic velocity measure for several different pitch angles, at a flux surface of r/a~0.50 in the multipass case. γ is the relativistic Lorentz factor [Wright, 2009].

5. The DC Code Developed Within the RF-SciDAC Collaboration

The quasilinear theory of plasma velocity-space diffusion due to wave-particle resonance (Kennel & Engelmann, 1996; Stix, 1992) has been a backbone of radiofrequency wave theory of formation of non-Maxwellian distributions. It therefore is of interest to examine validity and limits of the theory, by comparison with results of direct calculation of the effects of RF wave interactions with charged particles.

We have directly calculated “exact” ion cyclotron rf diffusion by integrating the Lorentz force equation gyro-orbits in combined tokamak equilibria and the full-wave rf fields from the AORSA full-wave code[Jaeger, 2001]; this gives “kicks” in velocity-space which are used in the zero-orbit-width approximation to obtain the three independent coefficients describing bounce-averaged diffusion in ion velocity and pitch angle, after one or more poloidal bounces/transits in the equilibrium field. The rf fields are assumed small enough so that the particle evolution can be described as diffusive [Kaufman, 1972; Eriksson & Helander, 1994]. A parallelized code designated as DC (diffusion calculator), has been constructed; the calculations are carried out at a large computational facility [NERSC]. The primary challenges in this work are: (1) developing algorithms for stopping particles after one or more poloidal turns to obtain the wave-particle “kicks” in phase space, and yet not add unphysical contributions due to, for example, stopping at a gyrophase different from the launched gyrophase; (2) effective parallelization algorithms which pipeline particles to the available computer core, accounting

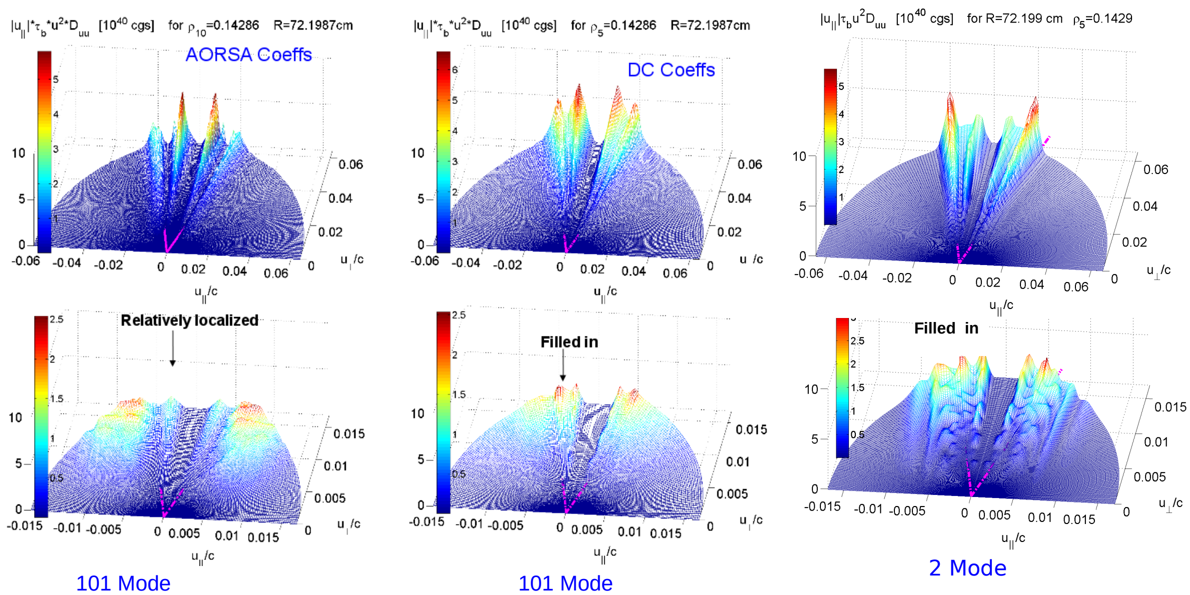


Fig. 9. Velocity-space plots of D_{uu} Diffusion coefficients at radius near the peak of the ICRF power deposition profiles from (a) 101 mode spectrum for C-Mod minority heating from AORSA using quasilinear theory, (b) 101 mode spectrum from DC, and (c) the dominant N_ϕ =+/-10 two modes also from DC. The top row shows results to 2000 keV, whereas the bottom row plots are zoomed in to maximum energy 125 keV. The DC diffusion coefficients, even the 2 mode case, are more filled in, in pitch angle, near the trapped-passing boundary than the AORSA coefficients in (a). The t-p boundary is indicated by the magenta lines.

for different time durations of each orbit; and (3) working with highly loaded massively parallel computers while requiring substantial CPU resources.

The velocity-space diffusion is compared with an rf quasilinear (QL) theory-based calculation in the AORSA code[Jaeger, 2006a, 2006b]. The AORSA calculation assumes that the ions remain on magnetic flux surfaces, that is, radial drift effects on the ion orbits are neglected, an approximation referred to as zero-orbit-width (ZOW). To compare the Lorentz force equation calculation results directly with AORSA, the guiding-center perpendicular radial drifts are subtracted in the Lorentz equation gyro-orbit calculation, thus providing a ZOW gyro-orbit diffusion. Direct comparison of the diffusion coefficients then shows substantial agreement between the velocity diffusion coefficients, with some important differences in the pitch angle diffusion as will be shown.

Coupling the DC and, in separate simulations, the AORSA-derived QL diffusion coefficients, into the CQL3D Fokker-Planck code [Harvey, 2012, 2017], enables a comparison of the radial power profiles. Close agreement is found between the power deposition from ZOW DC and AORSA QL coefficients, in an ITER relevant time-dependent simulation of minority-H heating experiment in the high magnetic field C-Mod experiment [Bader, 2012]. The physical configuration in the C-Mod NPA experiment includes a range of vertical viewing sightlines. ICRF wave heating is applied at 80 MHz, with balanced toroidal modes peaked at N_ϕ =+/-10. The H^+ cyclotron resonance passes 2 cms outside the magnetic axis.

[Bader, 2012] performed time-dependent simulations of the neutral particle analyzer (NPA) signals for a pulsed ICRF power experiment in C-Mod, with a coupled AORSA-CQL3D model; the ZOW version of CQL3D used. We use this experiment as a target for the comparisons presented here between Lorentz equation rf diffusion results and quasilinear theory results. Future work will examine the additional effects of a finite-orbit-width (FOW), that is, including the guiding center perpendicular drifts.

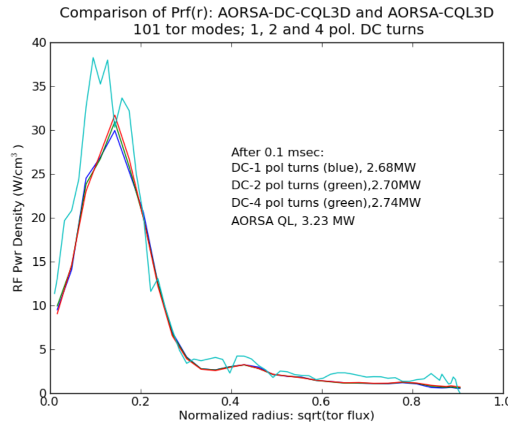


Fig. 10. Radial profile of ICRF power deposition derived from DC with 1,2, and 4 poloidal orbit turns, and from AORSA QL coefficients.

The DC derived rf diffusion coefficients were verified reasonably well against those resulting from quasilinear theory with AORSA. Figure 9 compares the AORSA and DC Duu diffusion coefficients in (a) and (b) due to 101 toroidal modes. The velocity variable is designated as "u". At high velocity the shape and magnitude of the diffusion coefficients are close, however the DC coefficients are more filled in in pitch angle near the trapped-passing boundary. The absorption profiles quite close to that obtained with AORSA, independent of the number of poloidal turns used in determining the coefficients (Fig. 10).

We have performed two types of ZOW simulations of the time-dependence of the distributions obtained with pulsed-on and -off RF power as in the experiment: (1) AORSA RF diffusion coefficients are coupled directly with CQL3D to time-step forward the simulation (Aorsa-ZOW-cql3d); and (2) AORSA fields are then used by DC to obtain the diffusion coefficients, which are then passed to CQL3D, at each time-step of the simulation (Aorsa-ZOW-dc-ZOW-cql3d). Figure 11a and 11b shows comparison between the resulting time-traces of the neutral particle analyzer (NPA) fluxes and experimental trances. Both simulations are quite close to experiment, with the simple Aorsa-ZOW-cql3d case slightly better as regards the fall-off of the NPA signal after the RF pulse is turned off.

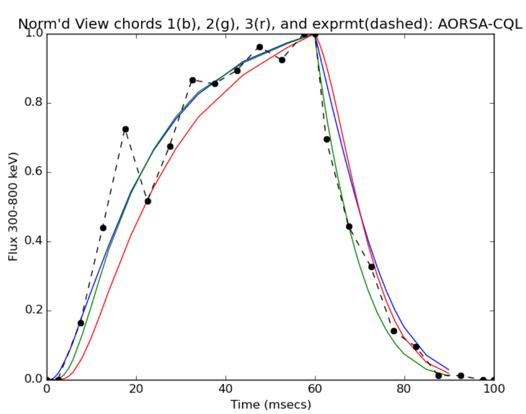


Fig. 11a. Simulation traces normalized to maximum experimental value. Aorsa-ZOW-cql3d case.

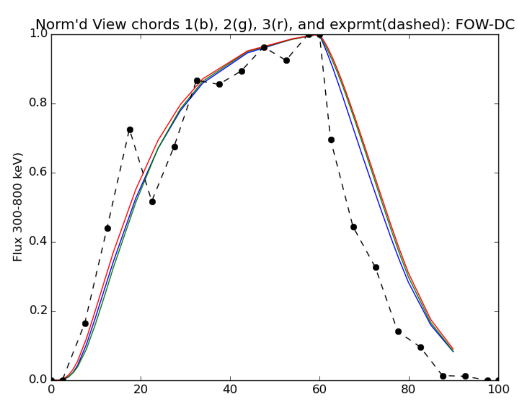
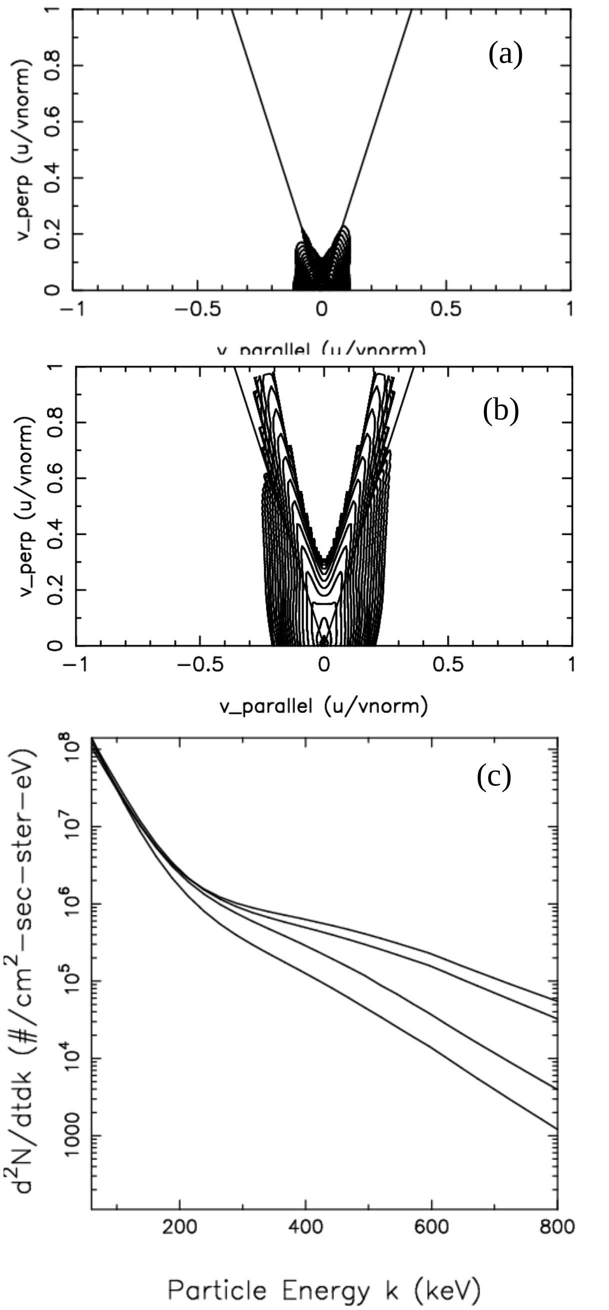


Fig. 11b. Simulation traces normalized to maximum experimental value. Aorsa-ZOW-dc-ZOW-cql3d case.



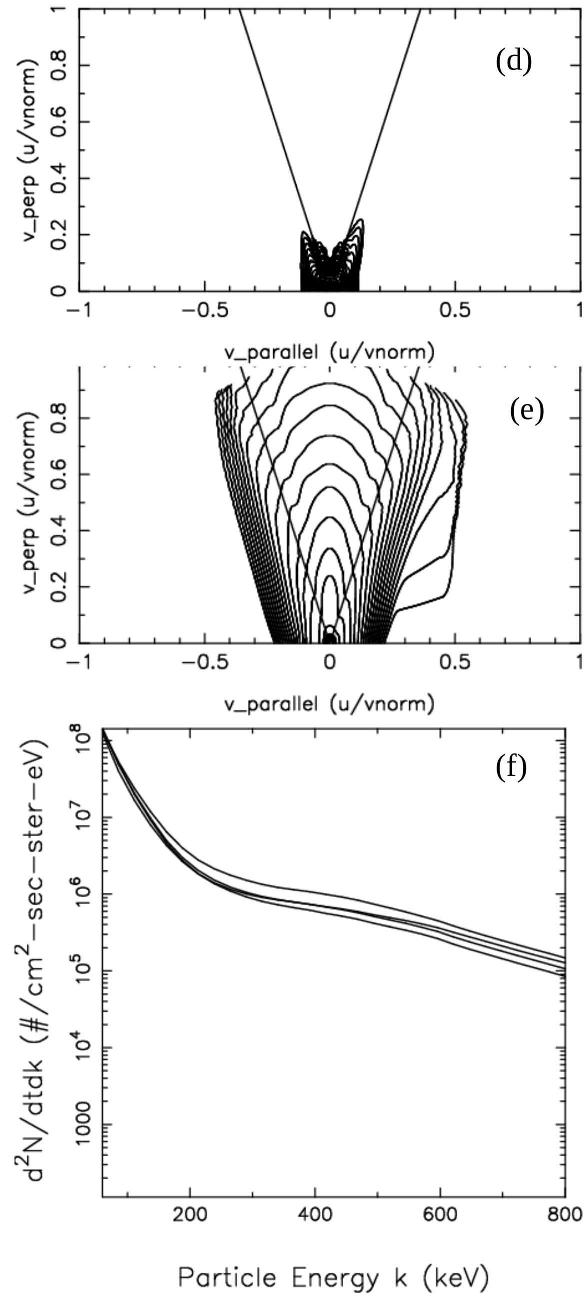


Fig. 12a-c. AORSA-ZOW-CQL3D case, distribution at rho/a=0.175, (a) after 0.1 msec, and (b) at the end of the RF-on pulse at 60 msec. Maximum energy is 5 MeV. (c) shows NPA spectra at 60 msec.

Fig 12d-f. AORSA-ZOW-DC-ZOW-CQL3D case, (d) after 0.1 msec, and (d) at the end of the RF-on pulse at 60 msec. (f) shows NPA spectra at 60 msec

However, the fast ion distributions from the Aorsa-ZOW-cql3d and Aorsa-ZOW-dc-ZOW-cql3d simulations are quite different, as show in Figs. 12a-c and 12d-f. The DC ICRF diffusion coeffcients give much more filled in distributions in the perpendicular velocity direction. The is the portion of the distribution which the vertically viewing NPA is sensitive to. As a result, the NPA energy spectra are significantly more flat for Aorsa-ZOW-dc-ZOW-cql3d simulations. It turns out that this agrees better with experiment, Fig. 13, than the simpler Aorsa-ZOW-cql3d simulation.

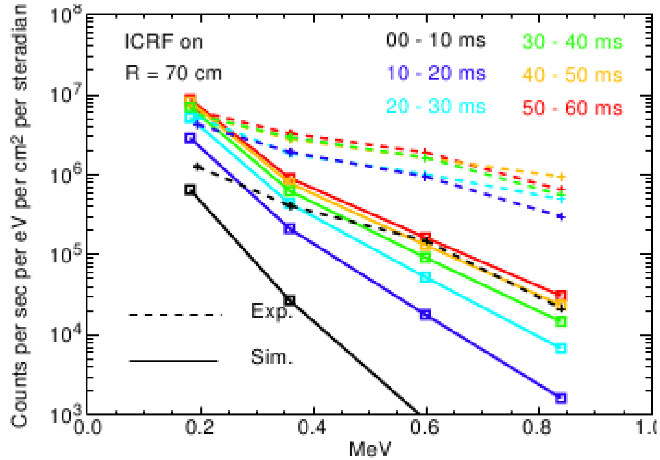


Fig. 13. NPA energy spectra comparing experiment (dashed) and AORSA-CQL3D calculation (solid), at times within the RF-on pulse, indication that the fast ions rise to a near steady state in ~30 msec[Bader, 2012].

In summary, for the DC code development, the calculated diffusion coefficients give reasonable agreement between bounce-averaged quasilinear theory and the results of numerical integration for the exact particle trajectories in combined equilibrium and full-wave electromagnetic fields. For the case examined in C-Mod experiment, the effect of correlations between one or more particle poloidal circuits in the tokamak fields is not large. These calculations substantially verify quasilinear theory in the random-phase approximation, such as is obtained with AORSA. The diffusion of fast ions in the perpendicular direction is substantially enhanced using the DC diffusion coefficients compared to quasilinear theory, but this does not strongly affect the power aborption. On the other hand, DC constitutes an additional, direct method for coupling full-wave codes to the CQL3D Fokker-Planck code, it is physically more comprehensive than quasilinear theory, and in some cases is faster than the semi-analytic quasilinear approaches. Further work with DC will focus on the additional effects of inclusion of finite orbit width effects in both DC and CQL3D-FOW.

6. Summary

During the fifteen years of radiofrequency plasma physics research with the SciDAC Center for Wave Particle Interactions, CompX has further developed its GENRAY all-frequencies ray tracing code and its multi-species CQL3D tokamak Fokker-Planck code to mesh with needs of the Center. The CQL3D/GENRAY codes have been substantially validated agains the C-Mod lower hybrid experiment. CQL3D have been coupled to the AORSA, TORIC, and TORLH full-wave codes enabling the modeling of important non-Maxwellian effects on ion and electron distribution functions obtained with combined codes. GENRAY ray tracing has been used in verification of the more physically comprehensive and accurate AORSA and TORLH codes. A new code, DC, for the direct calculation of wave-particle diffusion was constructed, and used to verification of AORSA diffusion coefficients and has been substantially validated against C-Mod tokamak experiment at Plasma Science and Fusion Center, Massachusetts Institute of Technology.

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