SciDAC Benchmarks

1. AORSA-1D Benchmark

The benchmark case for AORSA-1D is shown in Fig. 1 below and also in Fig. 6 of Jaeger *et. al*, Phys. Plasmas **7**, 3319 (2000). Figure 1 shows (a) the electric field, (b) the power absorbed, and (c) the poloidal flow velocity when 0.36 MW of fourth harmonic IBW power is launched directly into a D plasma with a 5% T minority. Parameters are modeled after TFTR with R = 2.71 m, a = 1.0 m, and B_0 = 3.44 T. Plasma profiles are assumed to be approximately parabolic with $n_0 = 2.2 \times 10^{19}$ m^{-3}, $T_{e,0}$ = 4.0 keV, and $T_{i,0}$ = 4.0 keV. The antenna is characterized by a frequency f = 76 MHz and a poloidal wave number, $k_y = 0$ m^{-1} indicating no net input of poloidal momentum by the waves. The toroidal wave number is $k_z = 5.0$ m^{-1}. In Fig. 1, we have modeled only a thin layer between R= 2.91 m and R = 3.31 m. The reduced spatial scale improves the resolution and requires fewer Fourier modes. For example, the calculation in Fig. 1 requires 1024 modes and one fifth of the computing time required to model the full cross-section. Only a 20 cm section of the plasma near the resonant layer is shown in Fig. 1. In this case, the IBW is absorbed primarily by ion cyclotron damping near the $\omega=5\Omega_{c,T}$ resonance. A redistribution of momentum within the resonance layer results in the bi-polar poloidal flow shown in Fig. 1(c). For the electrostatic waves in this example, the flow is dominated by the gradient of the kinetic pressure $-\nabla\cdot\mathbf{P}_2$, and there is little contribution from the electromagnetic force $\mathbf{F}_{EM}$. The peak differential flow velocity is 800 m/s, and the velocity shear corresponding to this flow is about 1×10^5 s^{-1} at R=3.15 m. This is marginally equal to the value required to stabilize microturbulence and thereby improve plasma confinement. Treating the reduced plasma cross section in Fig. 1 requires about 20 minutes of computing time for the wave solution and 644 mins. for the power deposition and flow drive on a single processor IBM RS/6000 workstation.

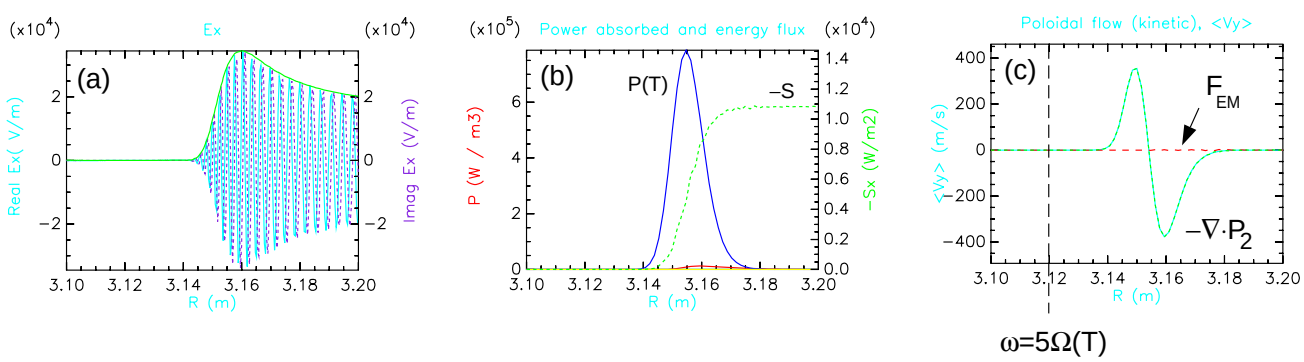

FIG. 1. (a) Wave electric field, (b) power absorption, and (c) poloidal flow velocity for 0.36 MW of fourth harmonic IBW power launched in a D plasma with a 5% T minority. Parameters are modeled after TFTR and results are calculated only over a thin section of plasma (2.91 m $\leq R \leq$ 3.31 m) near the $\omega=5\Omega_{c,T}$ resonance.

2. AORSA-2D Benchmark

The benchmark case for AORSA-2D is shown in Fig. 2 below and also in Fig. 7 of Jaeger *et. al*, Phys. Plasmas **8**, 1573 (2001). This is a converged solution that resolves the IBW wavelength in two dimensions. While calculations with TORIC rely on the finite Larmor radius expansion, no such assumption is required with AORSA. Thus the IBW can be followed to wavelengths that are comparable to or less than an ion Larmor radius. In Fig. 2, the shortest wavelengths correspond to $k_\perp\rho \sim 1.2$.

This case is similar to a mode-conversion scenario for DIII-D which has been modeled previously by A. Jaun. Fast-wave power is launched into a deuterium plasma with 33% minority hydrogen. Parameters are R_0 = 1.68 m, a = 0.60 m, and B_0 = 2.14 T. A Solov'ev equilibrium is assumed with κ= 1.6 and a safety factor on axis, $q_0 \sim 1.5$. The antenna is located at R = 2.195 m, with f = 31 MHz and n_φ = 20. Plasma profiles are Gaussian, with $n_0 = 4.5 \times 10^{19}$ m^{-3}, $T_{e,0}$ = 2.0 keV, and $T_{i,0}$ = 1.5 keV on axis. In this case, adequate convergence requires about 240 modes in x and 138 modes in y.

This problem is at the limits of the ORNL Eagle computer. It requires 576 processors (or 230 GB of memory) and approximately 6.5 hours of clock time. At the present time, AORSA-2D is limited to analytic (Solov'ev) equilibria. Numerical equilibria as generated by EFIT cannot be used.

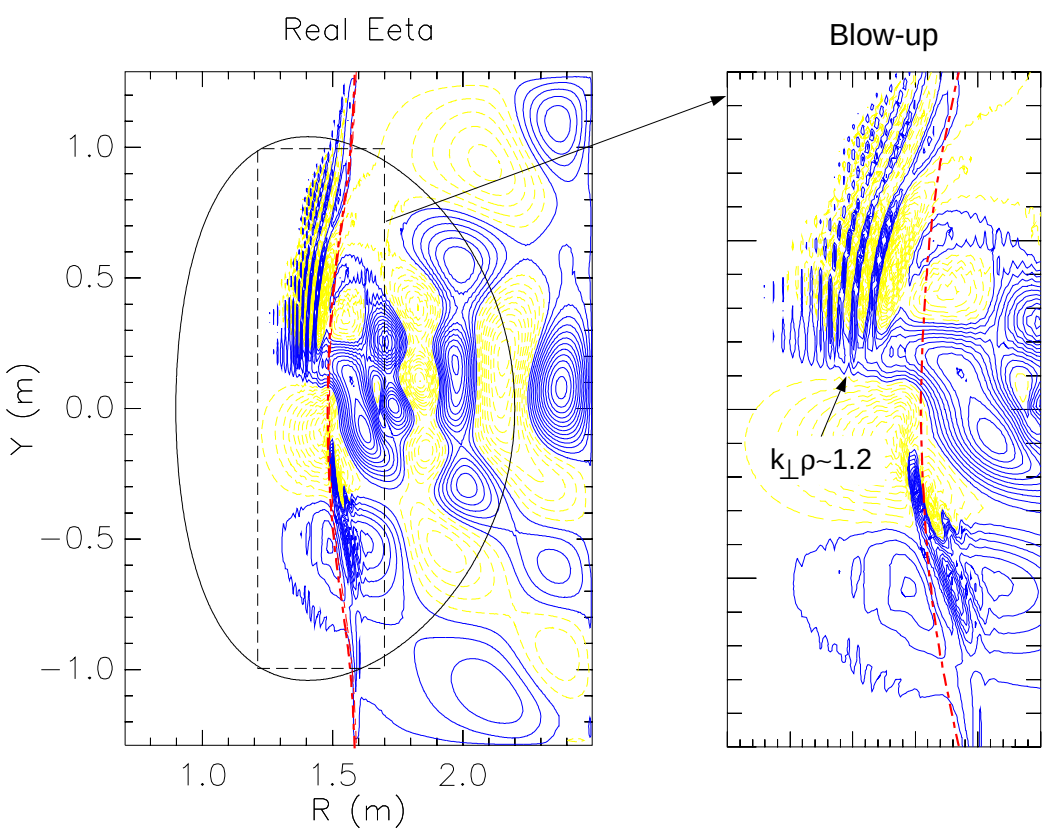

FIG. 2. All-orders spectral solution for mode conversion including the poloidal magnetic field. The dashed curve shows the mode conversion layer from 1D cold plasma theory.

3. AORSA-3D Benchmark

The benchmark case for AORSA-3D is shown in Fig. 3 below, and also in Figs. 6–8 of Jaeger *et. al*, in the Special Issue of Phys. Plasmas devoted to DPP invited papers (May, 2002). The 3-D magnetic field geometry for LHD is calculated from the VMEC code with fixed boundaries. Figure 3 shows a 3-D rf solution for this geometry assuming identical antennas in each helical field period and using 50 modes in both the *x* and *y* directions and 16 coupled modes in the toroidal direction. Flux surfaces and magnetic field strength are shown at four equally spaced toroidal angles within a single helical field period. The red dashed lines show the location of the fundamental ion cyclotron resonance for hydrogen. A helium plasma is assumed with a 5% hydrogen minority. The antenna is centered in the $\varphi = 0$ plane, and assumed to have monopole phasing with frequency $f = 44$ MHz. Figure 3(a) shows contours of the wave electric field at four equally spaced toroidal angles within a single helical field period, and Fig. 3(b) shows contours of the minority ion heating at the four toroidal angles in the field period. The dashed lines show the location of the fundamental ion cyclotron resonance for hydrogen. The ion heating is peaked near the two-ion-hybrid resonance which is close to the ion cyclotron resonance for hydrogen in this case.

This problem is also at the limits of the ORNL Eagle computer. It requires 576 processors (or 230 GB of memory) and approximately 6.5 hours of clock time.

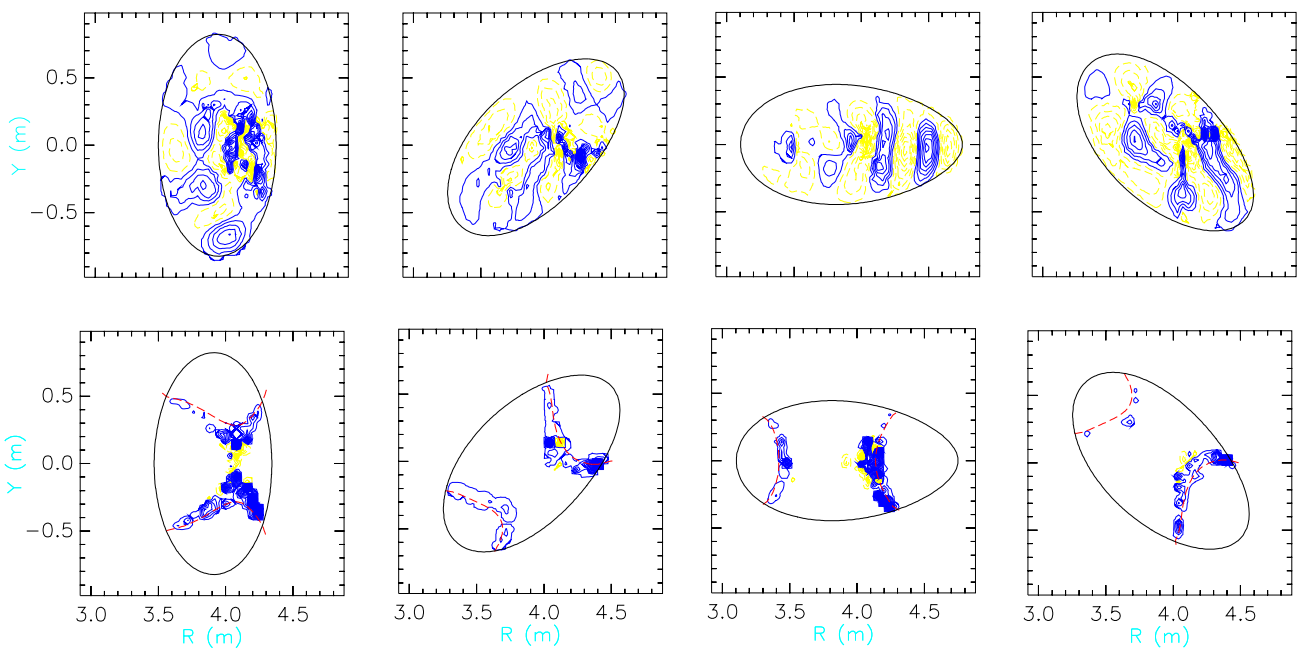

FIG. 3. All orders spectral calculation of minority ion cyclotron heating for a single helical field period of LHD: (a) contours of the wave electric field, and (b) contours of minority ion heating