Tera-scale computation of wave-plasma interactions in multidimensional fusion plasmas

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There is great potential for electromagnetic wave techniques to exert control of fusion plasmas by means of localized heating, current drive, flow drive and energetic particle production. With support from the Scientific Discovery Through Advanced Compuatation (SciDAC) program, we have established a multi-institutional partnership between plasma physicists and computational scientists, the overarching goal being to obtain quantitatively accurate predictive understanding of electromagnetic wave processes important for heating, current drive, stability and transport applications in fusion-relevant plasmas.

Activities during the first year of the project have focussed on massive parallelization and acceleration of computer-intensive full-wave RF field solver codes, extension of all-orders methods to two- and three-dimensional plasmas, benchmarking and code comparison, and application to wave propagation problems in Alcator C-Mod, NSTX and LHD.

Full-wave models are needed because ray tracing does not optimally treat realistic antenna spectra, plasma cutoffs, or mode conversion layers, nor does it include large-scale coherent effects such as diffraction, interference, and wave focussing. Recent full-wave models such as PICES [1] and TORIC [2], use a superposition of Fourier modes in the poloidal direction to represent the wave field, thus reducing the parallel gradient to an algebraic operator. These codes can accurately calculate electron and ion damping, but still rely on FLR expansions in the radial direction to express the plasma current as a differential operator. The TORIC code has been modified to use an out-of-core linear solver thereby reducing memory requirements by a factor of 25 and processing time by a factor of 3. Calculation of D(^{3}He) mode conversion in Alcator C-Mod have been carried out with up to 256 poloidal modes, whereas it was previously infeasible to use as many as 100 modes. The IBW wave fields appear to be converged with this number of modes and now exhibit the proper localization to the high field side. Also the partitioning of power deposition between electrons and minority ions is in much better experimental agreement than previous calculations with fewer poloidal modes [3].

In practice, FLR codes are limited to relatively long wavelengths and cyclotron harmonics of two or less (because each cyclotron harmonic raises the radial order of the differential equation by 2). In addition, the magnetic flux coordinates required for the poloidal mode expansion are singular at the origin, and often lead to numerical problems near the magnetic axis. Recently, alternate full-wave models have been developed that eliminate these difficulties by using a fully spectral representation for the wave field, a Cartesian coordinate system, and a collocation method of discretization. These all-orders, spectral algorithms (AORSA) [4-6] solve the integral form of the wave equation with no assumption regarding the smallness of $k\rho$ and no limit on the number of cyclotron harmonics retained. The earliest example of such a model is the one-dimensional (1D) METS95 code [4]. This technique has now been extended to two dimensions in the AORSA-2D code [5]. This code has been applied

to obtain fully resolved solutions for high-harmonic fast-wave experiments on NSTX at cyclotron harmonics up to 20. It has also been applied to study fast-wave to IBW mode conversion problems in 2D. The fully converged, high-resolution solutions show complex spatial structures not revealed in 1D calculations, such as a marked up/down asymmetry. More recently, the All-Orders Spectral Algorithm has been extended to give fully three-dimensional solutions of the integral wave equation for minority ion cyclotron heating in stellarator geometry. By combining multiple periodic solutions for individual helical field periods, we have obtained complete wave solutions valid over the entire volume of the stellarator for arbitrary antenna geometry [6].

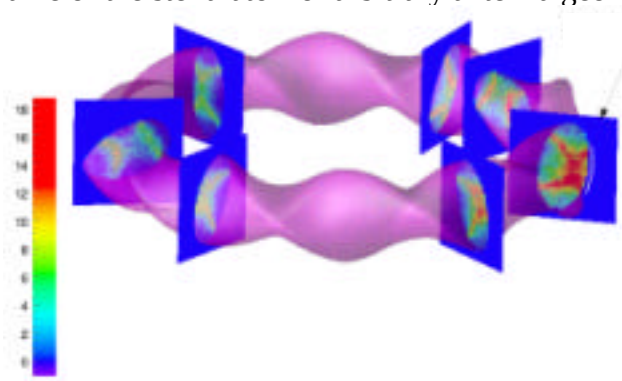

Fig. 1*. All-orders spectral calculation of minority ion cyclotron heating for all ten field periods of LHD with a single antenna located at the extreme right-hand side. Individual cross sections show the logarithm of the minority ion power absorption at various toroidal angles. Antenna is in one field period only.*

All modes in the spectral representation are coupled, so solution requires calculating and inverting a very large, dense matrix. For example, with 200 x 200 Fourier modes in 2D, or equivalently, 50 x 50 x 16 modes in 3D, it is necessary to solve 120,000 coupled complex equations, requiring storage for the resulting matrix ~ 230 Gbytes. The required memory is distributed over many processors and the matrix is inverted using a library of high-performance linear algebra routines for distributed-memory, parallel computers. Using 576 processors on the Oak Ridge National Laboratory IBM RS/6000 SP computer, up to 200,000 coupled complex equations have been solved, while achieving 0.66 teraflops (660 billion operations per second) during matrix factorization. Computing speed scales linearly with the number of processors and there is no indication of saturation caused by communication between processors.

We will report on progress in understanding the effects of realistic 2D and 3D equilibrium variations and non-Maxwellian distributions to modify mode conversion as well as local wave energy and momentum deposition. Also, we will describe exploratory research toward completely reformulating wave-plasma problems to alternate fields representations such as spectral elements or wavelets.

References

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