Scientific Application Project – *"Tera-scale computation of wave-plasma interactions in multidimensional fusion plasmas"*

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Summary

This Scientific Application Project (SAP) assists the fusion scientists in exploring and implementing efficient algorithms for modeling the response of fusion plasma to radio frequency (rf) waves in two-dimensional tokamak and fully three-dimensional stellarator geometries on high performance computers. The project has optimized advanced algorithms to speedup full-wave spectral codes, in some cases by several orders of magnitude. This enabled the study of new regimes of wave physics that previously could only be treated in one dimension or with approximate techniques, and to carry out multiple code runs at high resolution for scientific case studies where it was previously not feasible.

There is great potential for electromagnetic wave techniques to exert control of fusion plasma by means of localized heating, current drive, flow drive and energetic particle production. Fundamental understanding of these interactions of radio frequency (rf) waves on high temperature fusion plasma is of major importance. This Scientific Application Project (SAP) collaborates with fusion scientists on the project "Tera-scale computationa of wave-plasma interactions in multidimensional fusion plasmas" as part of the Scientific Discovery Through Advanced Computing (SciDAC) program.

A suite of full-wave codes has been developed to model the wave-plasma interactions. Full-wave models are needed because traditional ray tracing model cannot fully capture certain characteristics in the plasma such treatment of realistic antenna spectra, plasma cutoffs, or mode conversion layers, nor does ray tracing include large scale coherent effects such as diffraction, interference, and wave focusing. Recent full-wave codes use a superposition of Fourier modes for representing the electric fields and currents. This formulation requires the solution very large dense complex linear systems. The project has optimized advanced algorithms to speedup full-wave spectral codes, in some cases by several orders of magnitude. This enabled the study of new regimes of wave physics that previously could only be treated in one dimension or with approximate techniques, and to carry out multiple code runs at high resolution for scientific case studies where it was previously not feasible.

The All-ORders, Spectral Analysis code (AORSA) uses a fully spectral

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representation for wave field in a Cartesian coordinate system. AORSA-2D is used in two-dimensional tokamak geometry and AORSA-3D in fully three-dimensional stellarators geometry. All modes in the spectral representation are coupled and so computing the solution requires calculating and inverting a very large dense matrix. For example, with 272x272 Fourier modes in two-dimensions or 34x34x64 modes in three-dimensions, the system about 220,000 coupled complex equations that require about 788 GBytes of memory. AORSA-3D took about 358 minutes on 1,936 Power 3 processors at NERSC. The efficient computation achieved over 60% of available peak performance (over 1.9 Teraflops or 1,900 billion operations per second) and has been cited in highlights at NERSC and IBM.

A new formulation of AORSA-3D transforms the linear system from Fourier basis to a representation in the real configuration space. This alternate representation exposes new opportunities in reducing the overall number of equations used. In one example of 34x34x64 modes, the number of equations was reduced by over a factor of 5 from 220,000 to about 40,000. The new reduced system required only 26 GBytes of memory and completed in about 13.4 minutes, with a 100 fold speedup in the linear solver and 27 fold speedup in overall runtime. The efficiency gained from the real space formulation of AORSA-3D allows higher resolution and more design analysis for the Quasi-Poloidal Stellarator (QPS) to be considered.

The reduced linear system in the real space is considered a dense matrix even though many matrix entries are small with rapid decay from the main diagonal. Further enhancements will exploit a sparse approximation to the original system and consider preconditioned iterative methods to potentially extract another order of magnitude speedup and increase in problem size.

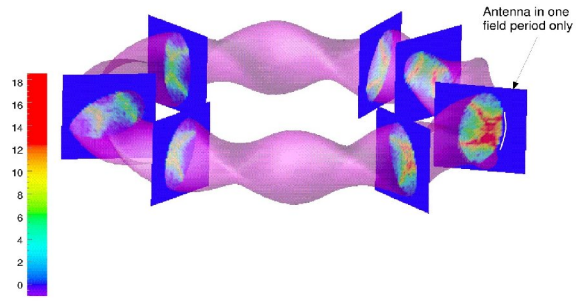

Figure 1. AORSA-3D calculation of minority ion cyclotron heating. Individual cross sections show the logarithm of the minority ion power absorption at various toroidal angles.

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