Final Report on Project "Center for Gyrokinetic/MHD Hybrid Simulation of Energetic Particle Physics in Toroidal Plasmas"

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This SciDAC project is a collaboration between Princeton Plasma Physics Lab, the Institute for Fusion Study of University of Texas, Austin, University of Colorado at Boulder and Oak Ridge National Lab. Guo-Yong Fu of PPPL is the PI of this project and Yang Chen is the co-PI at CU-Boulder. CU's budget from this project is primarily used to cover part of Yang Chen's salary and his travels to meetings.

At CU-Boulder the primary task is to extend our gyrokinetic Particle-in-Cell simulation of tokamak micro-turbulence and transport to the area of energetic particle physics. We have implemented a gyrokinetic ion/massless fluid electron hybrid model in the global δf-PIC code GEM, and benchmarked the code with analytic results on the thermal ion radiative damping rate of Toroidal Alfvén Eigenmodes (TAE) and with mode frequency and spatial structure from eigenmode analysis [1]. We also performed nonlinear simulations of both a single-n mode (n is the toroidal mode number) and multiple-n modes, and in the case of single-n, benchmarked the code on the saturation amplitude vs. particle collision rate with analytical theory. Most simulations use the δf method for both ions species, but we have explored the full-f method for energetic particles in cases where the burst amplitude of the excited instabilities is large as to cause significant re-distribution or loss of the energetic particles.

We used the hybrid model to study the stability of high-n TAEs in ITER [2]. Our simulations show that the most unstable modes in ITER lie in the rage of $10 < n < 20$. Thermal ion pressure effect and alpha particles non-perturbative effect are important in determining the mode radial location and stability threshold. The thermal ion Landau damping rate and radiative damping rate from the simulations are compared with analytical estimates. The thermal ion Landau damping is the dominant damping mechanism. Plasma elongation has a strong stabilizing effect on the alpha driven TAEs. The central alpha particle pressure threshold for the most unstable n=15 mode is about $\beta_\alpha(0) = 0.7\%$ for the fully shaped ITER equilibrium. We also carried nonlinear simulations of the most unstable $n = 15$ mode and found that the saturation amplitude for the nominal ITER discharge is too low to cause large redistribution or loss of alpha particles [3].

To include kinetic electron effects in the hybrid model we have studied a kinetic electron closure scheme for the fluid electron model. [3] The most important element of the closure scheme is a complete Ohm's law for the parallel electric field $E_\parallel$, derived by combining the quasi-neutrality condition, the Ampere's equation and the $v_\parallel$ moment of the gyrokinetic equations. A discretization method for the closure scheme is studied in detail for a three-dimensional shear-less slab plasma. It is found that for long-wavelength shear Alfvén waves the kinetic closure scheme is both more accurate and robust than the previous GEM algorithm using the split-scheme, whereas for the ion-gradient-driven instability the previous algorithm is more efficient. This kinetic electron closure scheme will be implemented in GEM in the future.

We have studied the beam driven Reverse Shear Alfven Eigenmodes (RSAE) observed in DIII-D discharge 142111. For this purpose a new scheme for obtaining the electric potential is implemented, i.e., by solving the gyrokinetic moment (GKM) equation, which is essentially the equation for $\partial\phi/\partial t$ used in GEM's split-weight scheme, and then integrating in time. Due to charge-neutrality the ExB motions of the equilibrium densities of all species cancel each other and do not cause charge separation if there is no finite Larmor radius effect. The advantage of solving the GKM equation is that this lowest-order cancellation can be made explicit. The GKM approach is found to be more accurate and robust. GEM simulations have reproduced many features of RSAE seen in the experiment, such as frequency chirping and the chirping range. It has been reported by other simulation codes that the shearing direction of the mode structure in the poloidal plane disagrees with observation. We found that the mode structure, including the shearing in the poloidal plane, is in general sensitive to the beam distribution. Using the same beam density profile as in other codes but with a slowing-down distribution in velocity, GEM simulations reproduce the mode shearing direction seen in the experiment. We have carried out extensive nonlinear simulations of RSAE and are in the process of writing a paper for publication.

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[1] J. Lang, Y. Chen, S. E. Parker, and G.-Y. Fu, Phys. Plasmas **16**, 102101 (2009).

[2] Y. Chen, S. E. Parker, J. Lang, and G.-Y. Fu, Phys. Plasmas **17**, 102504 (2010).

[3] Y. Chen and S. E. Parker, Phys. Plasmas **18**, 055703 (2011).