Final report for
DE-FC02-04ER54796

SciDAC Center for Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas, 12/28/2007

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During the first year of the SciDAC gyrokinetic particle simulation (GPS) project, the GPS team (Zhihong Lin, Liu Chen, Yasutaro Nishimura, and Igor Holod) at the University of California, Irvine (UCI) studied the tokamak electron transport driven by electron temperature gradient (ETG) turbulence, and by trapped electron mode (TEM) turbulence and ion temperature gradient (ITG) turbulence with kinetic electron effects, extended our studies of ITG turbulence spreading to core-edge coupling. We have developed and optimized an elliptic solver using finite element method (FEM), which enables the implementation of advanced kinetic electron models (split-weight scheme and hybrid model) in the SciDAC GPS production code GTC. The GTC code has been ported and optimized on both scalar and vector parallel computer architectures, and is being transformed into objected-oriented style to facilitate collaborative code development. During this period, the UCI team members presented 11 invited talks at major national and international conferences, published 22 papers in peer-reviewed journals and 10 papers in conference proceedings. The UCI hosted the annual SciDAC Workshop on Plasma Turbulence sponsored by the GPS Center, 2005-2007. The workshop was attended by about fifties US and foreign researchers and financially sponsored several gradual students from MIT, Princeton University, Germany, Switzerland, and Finland. A new SciDAC postdoc, Igor Holod, has arrived at UCI to initiate global particle simulation of magnetohydrodynamics turbulence driven by energetic particle modes. The PI, Z. Lin, has been promoted to the Associate Professor with tenure at UCI. Some highlights on the physics progress are listed below.

I. Nonlinear physics of ETG turbulence

Global gyrokinetic particle simulation and nonlinear gyrokinetic theory find that ETG instability saturates via nonlinear toroidal coupling, which is a nonlocal interaction, intrinsic to the toroidal geometries, in the wavevector space that transfers energy successively from unstable modes to damped modes preferentially with lower toroidal mode numbers. The electrostatic ETG turbulence is dominated by nonlinearly generated radial streamers. The length of the streamers scales with the device size, which is longer than the distance between mode rational surfaces and electron radial excursions. Both fluctuation intensity and transport level at saturation are independent of the streamer length, and are much smaller than mixing length estimates. These finds from global simulations are not consistent with previous flux-tube simulation results.

II. ITG turbulence spreading

Gyrokinetic particle simulations of toroidal ITG turbulence spreading[3,4] and its related dynamical model have been extended to the case with radially increasing ion temperature gradient, to study the inward spreading of edge turbulence toward the core[6]. Due to turbulence spreading from the edge, the turbulence intensity in the core region is significantly enhanced over the value obtained from simulations of the core region only. Even when the core gradient is so weak such that self-generated zonal flows reduce the transport to a negligible value, a significant level of turbulence and transport is observed in the core due to spreading from the edge. The scaling of the turbulent front propagation speed is closer to the prediction from a nonlinear diffusion model[5].

III. Global ITG/TEM turbulence simulation with kinetic electrons

Kinetic electrons have been implemented in GTC code using the fluid-kinetic hybrid electron model. The computational issues of electron-ion time scale separation and associated numerical noise have been resolved by using an expansion of the electron response based on the toroidal aspect-ratio and by using an electron sub-cycling method. The linear frequencies and grow rates of electrostatic ITG/TEM modes from GTC simulations are found to be in good agreement with a comprehensive linear eigenvalue code (FULL) of PPPL and a global gyrokinetic particle-in-cell code (GT3D) developed in Japan. Global nonlinear simulations of ITG/TEM turbulence have been carried out with contribution of kinetic electrons to zonal flows properly retained. The trapped electrons are found to make no responds to ITG modes, and thus to increase ITG linear growth rate and transport by decreasing the dielectric constant for ITG modes. The nonlinear electron dynamics of TEM dynamics is found to be constrained by the conservation of the second invariant, resulting in simultaneous diffusions of electron banana orbits in both energy and real space, which have not been studied in analytical theories or local simulations. Zonal flows with radial wavelength on the order of ion banana width are found to be generated in the TEM turbulence, and the electron contribution to the zonal flow generation is found to be larger than the ion contribution. The key difference between TEM and ITG is that the perpendicular wavelength of TEM is on the order of ion gyroradius, which is much shorter than that of the ITG. ExB nonlinearity and ion polarization nonlinearity are therefore on the same order of magnitude, which invalidates the nonlinear analysis of ITG turbulence assuming time scale separation between these two nonlinearities.

IV. Global elliptic solver using finite element method and GTC code development

The existing gyrokinetic Poisson's solver in GTC code by a linear iterative method is inefficient in the presence of non-adiabatic electrons. This calls for the development of elliptic solver using finite element method for the gyrokinetic Poisson's equation and ampere's law. Our gyrokinetic simulation code GTC employs a global field aligned mesh and thus a logically non-rectangular grid. For application to this complicate geometry, a new finite element elliptic solver is developed[7] and successfully implemented into GTC. Optimistic CPU time scaling versus the matrix size is obtained, employing Portable Extensible Toolkit for Scientific Computation (PETSc) and High Performance Preconditioners (hypre) for the sparse matrix solve. The FEM elliptic solver has enable the implementation of advanced electron models including both the split-weight scheme and fluid-kinetic hybrid model, e.g., for solving Poisson type equation for the time derivative of electrostatic potential and the Ampere's law in the electromagnetic simulation. To transform GTC into an object-oriented code to facilitate collaborative development, objects are defined and implemented into the GTC code in collaboration with Viktor Decyk of UCLA. Higher level objects are used to encapsulate the original GTC variables. The original subroutines are also encapsulated by higher level methods. In collaboration with Stephane Ethier of Princeton Plasma Physics Laboratory (PPPL), the GTC code has also been ported and optimized on vector parallel computer[8].

V. Electromagnetic global simulation using fluid-kinetic hybrid electron model

Using the new FEM elliptic solver, we can now study the electromagnetic turbulence using the fluid-kinetic hybrid electron model. Two steps are taken in the code development phase in verifying the Alfven wave dynamics; (1) in the limit of massless electron fluid with the response of perturbed magnetic field lines, (2) in the case with kinetic electrons. After benchmarking the linear growth rate of the electromagnetic modes, we will study the nonlinear physics of the Alfvenic ion temperature gradient mode (AITG) and the kinetic ballooning mode (KBM).

Publications in refereed journals

1. *Turbulence Spreading and Transport Scaling in Global Gyrokinetic Particle Simulation,* Z. Lin and T. S. Hahm, *Phys. Plasmas* **11**, 1099-1108 (2004).
2. *Turbulence Spreading into Linearly Stable Zone and Transport Scaling*, T. S. Hahm, P. H. Diamond, Z. Lin, K. Itoh, and S.-I. Itoh, *Plasma Phys. Contr. Fusion* **46**, A323-A333 (2004).

3. *Porting the 3D Gyrokinetic Particle-in-Cell Code GTC to the NEC SX-6 Vector Architecture: Perspectives and Challenges*, S. Ethier and Z. Lin, *Computer Physics Communications* **164**, 456-458 (2004).
4. *Particle-in-Cell Simulations of Electron Transport from Plasma Turbulence: Recent Progress in Gyrokinetic Particle Simulations of Turbulent Plasmas*, Z. Lin, G. Rewoldt, S. Ethier, T. S. Hahm, W. W. Lee, J. L. V. Lewandowski, Y. Nishimura, and W. X. Wang, *Journal of Physics: Conference Series* **16**, 16 (2005).
5. *Gyrokinetic particle-in-cell simulations of plasma microturbulence on advanced computing platforms*, S. Ethier, W. M. Tang, and Z. Lin, *Journal of Physics: Conference Series* **16**, 1 (2005).
6. *Global Gyrokinetic Particle Simulation of Turbulence and Transport in Realistic Tokamak Geometry*, W. X. Wang, Z. Lin, W. M. Tang, W. W. Lee, S. Ethier, J. L. V. Lewandowski, G. Rewoldt, T. S. Hahm, and J. Manickam, *Journal of Physics: Conference Series* **16**, 59 (2005).
7. *Dynamics of Turbulence Spreading in Magnetically Confined Plasmas*, O. D. Gurcan, P. H. Diamond, T. S. Hahm, and Z. Lin, *Phys. Plasmas* **12**, 032303 (2005).
8. *A Gyrokinetic Electron and Fully Kinetic Ion Plasma Simulation Model*, Yu Lin, Xueyi Wang, Zhihong Lin, and Liu Chen, *Plasma Phys. Contr. Fusion* **47**, 657-669 (2005).
9. *Role of Nonlinear Toroidal Coupling in Electron Temperature Gradient Turbulence*, Z. Lin, L. Chen, and F. Zonca, *Phys. Plasmas* **12**, 056125 (2005).
10. *On the Dynamics of Edge-Core Coupling*, T. S. Hahm, P. H. Diamond, Z. Lin, G. Rewoldt, O. Gurcan, and S. Ethier, *Phys. Plasmas* **12**, 090903 (2005).
11. *Nonlinear Toroidal Mode coupling: A New Paradigm for Drift Wave Turbulence in Toroidal Plasmas*, L. Chen, F. Zonca, and Z. Lin, *Plasma Phys. Contr. Fusion* **47**, B71-B81 (2005).
12. *A Finite Element Poisson Solver for Global Gyrokinetic Particle Simulations*, Y. Nishimura, Z. Lin, J. L. V. Lewandowski, and S. Ethier, *J. Comput. Phys.* **214**, 657-671 (2006).
13. *Global particle-in-cell simulations of microturbulence with kinetic electrons*, J. L. V. Lewandowski, G. Rewoldt, S. Ethier, and W. W. Lee, and Z. Lin, *Phys. Plasmas* **13**, 072306 (2006).
14. *A Finite Element Mesh in a Tokamak Edge Geometry*, Y. Nishimura and Z. Lin, *Contributions Plasma Phys.* **7-9**, 551-556 (2006).
15. *Gyro-kinetic simulation of global turbulent transport properties in tokamak Experiments*, W. X. Wang, Z. Lin, W. M. Tang, W. W. Lee, S. Ethier, J. L. V. Lewandowski, G. Rewoldt, T. S. Hahm, and J. Manickam, *Phys. Plasmas* **13**, 092505 (2006).
16. *Statistical analysis of fluctuations and noise-driven in particle-in-cell simulations of plasma turbulence*, I. Holod and Z. Lin, *Phys. Plasmas* **14**, 032306 (2007).
17. *Electromagnetic global gyrokinetic simulation of shear Alfven wave dynamics in tokamak plasmas*, Y. Nishimura, Z. Lin, and W. X. Wang, *Phys. Plasmas* **14**, 042503 (2007).
18. *Gyrokinetic theory and simulation of mirror instability*, H. Qu, Z. Lin, and L. Chen, *Phys. Plasmas* **14**, 042108 (2007).
19. *Simulation of Fusion Plasmas: Current Status and Future Direction*, D. A. Batchelor, M. Beck, A. Becoulet, R. V. Budny, C. S. Chang, P. H. Diamond, J. Q. Dong, G. Y. Fu, A. Fukuyama, T. S. Hahm, D. E. Keyes, Y. Kishimoto, S. Klasky, L. L. Lao, K. Li, Z. Lin, B. Ludaescher, J. Manickam, N. Nakajima, T. Ozeki, N. Podhorszki, W. M. Tang, M. A. Vouk, R. E. Waltz, S. J. Wang, H. R. Wilson, X. Q. Xu, M. Yagi, and F. Zonca, *Plasma Sci. Technol.* **9**, 312-387 (2007).
20. *Linear comparison of gyrokinetic codes with trapped electrons*, G. Rewoldt, Z. Lin, and Y. Idomura, *Comp. Phys. Commun.* **177**, 775 (2007).
21. *Global gyrokinetic particle simulations with kinetic electrons*, Z. Lin, Y. Nishimura, Y. Xiao, I. Holod, W. L. Zhang, and L. Chen, *Plasma Phys. Contr. Fusion* **49**, B163 (2007).
22. *Wave-particle decorrelation and transport of anisotropic turbulence in collisionless plasmas*, Z. Lin, I. Holod, L. Chen, P. H. Diamond, T. S. Hahm, and S. Ethier, *Phys. Rev. Lett.* **99**, 265003 (2007).

Publications in conference proceedings

1. Nonlinear Toroidal Coupling: a New Paradigm for Plasma Turbulence, Z. Lin, L. Chen, and F. Zonca, *In Proceedings of Joint Varenna-Lausanne International Workshop on Theory of Fusion Plasmas*, Varenna, Italy, 2004.
2. Electron Thermal Transport in Tokamak: ETG or TEM Turbulences? Z. Lin, Y. Nishimura, H. Qu, and Y. Li, *in Proceedings of the 20th International Conference on Plasma Physics and Controlled Nuclear Fusion Research* (Vilamoura, Portugal, 2004) (International Atomic Energy Agency, Vienna, Austria, 2004). *Paper IAEA-CN-116/TH/8-4.*
3. Gyrokinetic Studies of Turbulence in Steep Gradient Region: Role of Turbulence Spreading and E X B Shear, T. S. Hahm, Z. Lin, P. H. Diamond, G. Rewoldt, W. X. Wang, S. Ethier, O. Gurcan, J. A. Kromme, R. A. Kolesnikov, W. W. Lee, J. Lewandowski, and W. M. Tang, *ibid, Paper IAEA-CN-116/TH/1-4.*
4. Comparative studies of nonlinear ITG and ETG dynamics, F. Zonca, L. Chen, Z. Lin and R.B. White, *in Proceedings of the Second IAEA Technical Meeting on the Theory of Plasma Instabilities: Transport, Stability and their Interaction* (Trieste, Italy, 2005).
5. Fine-Scale Zonal Flow Suppression of Electron Temperature Gradient Turbulence, S. E. Parker, J. J. Kohut, Y. Chen, Z. Lin, F. L. Hinton, and W. W. Lee, *In Proceedings of Joint Varenna-Lausanne International Workshop on Theory of Fusion Plasmas*, Varenna, Italy, 2006.
6. Gyrokinetic particle simulation of neoclassical transport in the pedestal/scrape-off region of a tokamak plasma, S. Ku, C.-S. Chang, M. Adams, J. Cummings, F. Hinton, D. Keyes, S. Klasky, W. Lee, Z. Lin, S. Parker, and the CPES team, in SciDAC2006, *Journal of Physics: Conference Series* 46, 87-91 (2006).
7. Electron Transport Driven by Short Wavelength Trapped Electron Mode Turbulence, Z. Lin, L. Chen, I. Holod, Y. Nishimura, H. Qu, S. Ethier, G. Rewoldt, W. X. Wang, Y. Chen, J. Kohut, S. Parker, and S. Klasky, *in Proceedings of the 21th International Conference on Plasma Physics and Controlled Nuclear Fusion Research* (Chengdu, China, 2006) (International Atomic Energy Agency, Vienna, Austria, 2006). *Paper IAEA-CN-138/TH/P2-8.*
8. Simulations on the Nonlinear Mode Coupling in Multiple-scale Drift-type Turbulence with Coherent Flow Structures, Jiquan Li, K. Uzawa, Z. Lin, Y. Kishimoto, N. Miyato, T. Matsumoto, J.Q. Dong, *ibid, Paper IAEA-CN-138/TH/2-3.*
9. Long Time Simulations of Microturbulence in Fusion Plasmas, W. W. Lee, S. Ethier, T. G. Jenkins, W. X. Wang, J. L. V. Lewandowski, G. Rewoldt, W. M. Tang, S. E. Parker, Y. Chen, and Z. Lin, *ibid, Paper IAEA-CN-138/TH/2-6Rb.*
10. Integrated particle simulation of neoclassical and turbulence physics in the tokamak pedestal/edge region using XGC, Chang, C.S., Ku, S., Adams M., D$\hat{\text{A}}$zevedo, G., Chen, Y., Cummings, J., Ethier, S., Greengard, L., Hahm, T.S., Hinton, F., Keyes, D., Klasky, S., Lee, W.W., Lin, Z., Nishimura, Y., Parker, S., Samtaney, R., Stotler, D., Weitzner, H., Worley, P., Zorin, D., and the CPES Team, *ibid, Paper IAEA-CN-138/TH/P6-14.*

Invited talks

1. Z. Lin, oral presentation, 20th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, International Atomic Energy Agency, Vilamoura, Portugal, 2004.
2. Z. Lin, invited talk, 46th American Physical Society Annual Meeting, Division of Plasma Physics, Savannah, GA, USA, 2004.
3. Z. Lin, invited talk, Joint Varenna - Lausanne International Workshop on Theory of Fusion Plasmas, Varenna, Italy, 2004.
4. L. Chen, invited talk, 32nd European Physical Society Conference on Plasma Physics, Tarragona, Spain, 2005.

5. Z. Lin, invited talk, 19th International Conference on Numerical Simulation of Plasmas and Asia Pacific Plasma Theory Conference, Nara, Japan, 2005.
6. L. Chen, invited talk, 19th International Conference on Numerical Simulation of Plasmas and Asia Pacific Plasma Theory Conference, Nara, Japan, 2005.
7. Z. Lin, invited talk, SciDAC 2005, San Francisco, USA, 2005.
8. Z. Lin, invited talk, *Workshop on ITER Simulation, Beijing, China. 2006.*
9. Z. Lin, invited talk, 2nd International School on Plasma Turbulence and Transport, Daejeon, South Korea, 2007.
10. Z. Lin, invited talk, *34th European Physical Society Conference on Plasma Physics, Warsaw, Poland, 2007.*
11. Z. Lin, invited talk, *49th Annual Meeting of American Physical Society, Division of Plasma Physics, Orlando, USA, 2007.*

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E-mail Address(es):
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Name	Signature	Title	Date
Zhihong Lin		Professor	11/13/13

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