Final Report: Computational Center for Studies of Microturbulence

The Department of Energy funded the Maryland Computational Center for microoturbulence (CCSM) from 2002-2006. The Center was one component of a larger, multi-institutional Plasma Microturbulence Project, which was funded through what eventually became DOE's Scientific Discovery through Advanced Computing program. Three post-doctoral fellows (Priyanka Goswami, Angus Macnab, and Klaus Hallatschek) were funded all or in part through the Center, together with a fraction of the salary for Dr. William Dorland, the Principal Investigator.

The primary focus of research in the Center was to develop, deploy, maintain, and utilize kinetic simulation techniques, especially the gyrokinetic code called `GS2`. "Gyrokinetics" refers to a particular model of plasma dynamics, appropriate for the description of turbulence in hot, magnetized plasma. Over the lifetime of the CCSM, gyrokinetic analysis moved from a single-author, single-user prototype activity to a widely used, highly influential mainstay of plasma physics research programs around the world. The `GS2` code, developed at the CCSM, is now used by more than thirty scientists, at every major fusion laboratory in the world.

Source code and documentation for `GS2` is available on the web, at
`http://gs2.sourceforge.net`.
These materials were produced and maintained by CCSM scientists, and constitute a major component of the research product of the Center.

CCSM scientists and scientists trained to use gyrokinetic tools by Dorland produced twenty-four refereed articles (including two articles in Physical Review Letters) documenting the scientific progress and activities of the center. These articles may be grouped into three main categories:

1. Gyrokinetic analyses of experimental data (12)
2. Theoretical explication of kinetic physics (7)
3. Algorithm development for kinetic physics (5)

The highlights from these papers may be summarized as follows.

Analyses of experimental data Tokamak experiments rely on gyrokinetics to understand the energy and particle confinement quality attained in a given experiment, and to plan new experiments. CCSM supported detailed analyses of data from the National Spherical Torus Experiment (NSTX) at the Princeton Plasma Physics Laboratory,[1, 2] from the Joint European Torus (JET) in the United Kingdom,[3, 4] from the Doublet III-D (DIII-D) tokamak at General Atomics (San Diego, CA),[5, 6, 7] from the Frascati Tokamak Upgrade (FTU) in Italy,[8] from the Mega-Ampere Spherical Tokamak (MAST) in the United Kingdom,[9, 10] and from the Alcator C-Modified (Alcator C-Mod) tokamak at the Massachusetts Institute of Technology.[11, 12] Clear identification of key confinement trends and correlation with fluctuation measurements was made in this work, which focused on confinement in the "core" plasma as well as in "internal transport barriers" (ITB's).

Theoretical explication of kinetic physics More generally, CCSM scientists worked to understand the physical processes which underlie the observed fluctuation spectra and inferred transport properties. Key advances in this area included the identification of the potential importance of electron-temperature-gradient-driven (ETG) turbulence (and an explanation of how this happens),[13] the potential importance of turbulence in electron-positron plasmas in the small anti-matter stellarator confinement experiment at Columbia University,[14] the demonstration that the transport properties associated with ion-temperature-gradient-driven turbulence are radially local,[15] the role of beta gradients in the stabilization of microturbulence,[16] the prediction of confinement properties of a spherical tokamak fusion power plant,[17] first-principles' calculations of particle transport induced by turbulence, including particle "pinch" effects,[18] and the identification of important instabilities that arise as a result of the strong velocity shear that is characteristic of transport barriers in tokamak experiments.[19]

Algorithm development for kinetic physics CCSM sponsored research into algorithms that can be used to study nonlinear, weakly collisional (kinetic) plasma dynamics. Progress was made in the understanding of the limitations of certain particle-in-cell algorithms,[20] in the development of high-performance, parallel algorithms for simulations of magnetic reconnection,[21] in the development of Lattice-Boltzmann techniques,[22] and in the application of collisionless closure models of Landau damping for the study of weakly collisional magnetohydrodynamic instabilities which are thought to arise in astrophysical accretion disks.[23]

References

[1] E. J. Synakowski, M. G. Bell, R. E. Bell, C. E. Bush, C. Bourdelle, D. Darrow, W. Dorland, A. Ejiri, E. D. Fredrickson, D. A. Gates, S. M. Kaye, S. Kubota, H. W. Kugel, B. P. LeBlanc, R. Maingi, R. J. Maqueda, J. E. Menard, D. Mueller, A. Rosenberg, S. A. Sabbagh, D. Stutman, G. Taylor, D. W. Johnson, R. Kaita, M. Ono, F. Paoletti, W. Peebles, Y.-K. M. Peng, A. L. Roquemore, C. H. Skinner, and V. A. Soukhanovskii, Plasma Phys. Control. Fusion **44**, A165 (2002).

[2] D. Mueller, M. Ono, M. G. Bell, R. E. Bell, M. Bitter, C. Bourdelle, D. S. Darrow, P. C. Efthimion, D. A. G. E. D. Fredrickson, R. J. Goldston, L. R. Grisham, R. J. Hawryluk, K. W. Hill, J. C. Hosea, S. C. Jardin, H. Ji, S. M. Kaye, R. Kaita, H. W. Kugel, D. W. Johnson, B. P. LeBlanc, R. Majeski, E. Mazzucato, S. S. Medley, J. E. Menard, H. K. Park, S. F. Paul, C. K. Phillips, M. H. Redi, A. L. Rosenberg, C. H. Skinner, V. A. Soukhanovskii, B. Stratton, E. J. Synakowski, G. Taylor, J. R. Wilson, S. J. Zweben, W. Dorland, Y. K. M. Peng, R. Barry, T. Bigelow, C. E. Bush, and M. Carter, IEEE Transaction on Plasma Science **31**, 60 (2003).

[3] J. Pamela, Nuclear Fusion **43**, 1540 (2003).

[4] R. V. Budny, R. Andre, A. Bécoulet, C. D. Challis, G. D. Conway, W. Dorland, D. R. Ernst, T. S. Hahm, T. C. Hender, D. McCune, G. Rewoldt, and S. E. Sharapov, Plasma Phys. Control. Fusion **44**, 1215 (2002).

[5] D. W. Ross, R. V. Bravenec, W. Dorland, M. A. Beer, G. W. Hammett, G. R. McKee, R. J. Fonck, M. Murakami, K. H. Burrell, G. L. Jackson, and G. M. Staebler, Phys of Plasmas **9**, 177 (2002).

[6] D. W. Ross and W. Dorland, Phys of Plasmas **9**, 5031 (2002).

[7] K. H. Burrell, Nuclear Fusion **43**, 1555 (2003).

[8] M. Romanelli, C. Bourdelle, and W. Dorland, Physics of Plasmas **11**, 3845 (2004).

[9] D. J. Applegate, C. M. Roach, S. C. Cowley, W. Dorland, N. Joiner, R. J. Akers, N. J. Conway, A. R. Field, A. Patel, M. Valovic, and M. J. Walsh, Physics of Plasmas **11**, 5085 (2004).

[10] C. M. Roach, D. J. Applegate, J. W. Connor, S. C. Cowley, W. Dorland, R. J. Hastie, N. Joiner, S. Saarelma, A. A. Schekochihin, R. J. Akers, C. Brickley, A. R. Field, and M. Valovic, Plasma Physics. Control. Fusion **47**, B323 (2005).

[11] M. H. Redi, W. Dorland, C. L. Fiore, J. A. Baumgaertel, E. M. Belli, T. S. Hahm, G. W. Hammett, and G. Rewoldt, Physics of Plasmas **12**, 072519 (2005).

[12] D. R. Ernst, P. T. Bonoli, P. J. Catto, W. Dorland, C. L. Fiore, R. S. Grantez, M. Greenwald, A. E. Hubbard, I. H. Hutchinson, J. Irby, E. S. Marmar, D. Mossessian, M. H. Redi, M. Porkolab, J. E. Rice, S. M. Wolfe, S. J. Wukitch, and K. Zhurovich, Phys. of Plasmas **11**, 2637 (2004).

[13] F. Jenko and W. Dorland, Phys. Rev. Lett. **89**, 225001 (2002).

[14] T. S. Pedersen, A. H. Boozer, W. Dorland, J. P. Kremer, and R. Schmitt, J. Phys. B: At. Mol. Opt. Phys. **36**, 1029 (2003).

[15] J. Candy, R. E. Waltz, and W. Dorland, Phys. Plasmas **11**, L25 (2004).

[16] C. Bourdelle, W. Dorland, X. Garbet, G. W. Hammett, M. Kotschenreuther, G. Rewoldt, and E. J. Synakowski, Phys of Plasmas **10**, 2881 (2003).

[17] H. Wilson, J.-W. Ahn, R. J. Akers, D. Applegate, R. A. Cairns, J. P. Christiansen, J. W. Connor, G. Counsell, A. Dnestrovskij, W. Dorland, M. J. Hole, N. Joiner, A. Kirk, P. J. Knight, C. N. Lashmore-Davies, K. G. McClements, D. E. McGregor, M. R. O'Brien, C. M. Roach, S. Tsaun, and G. M. Voss, Nuclear Fusion **44**, 917 (2004).

[18] K. Hallatschek and W. Dorland, Phys. Rev. Letters **95**, 055002 (2005).

[19] B. N. Rogers and W. Dorland, Physics of Plasmas **12**, 062511 (2005).

[20] W. M. Nevins, G. W. Hammett, A. M. Dimits, W. Dorland, and D. E. Shumaker, Physics of Plasmas **12**, 122305 (2005).

[21] M. A. Shay, J. F. Drake, M. Swisdak, W. Dorland, and B. N. Rogers, Geophys. Res. Lett. **30**, (2003).

[22] A. Macnab, G. Vahala, L. Vahala, J. Carter, M. Soe, and W.Dorland, Physica A **326**, 48 (2006).

[23] E. Quataert, W. Dorland, and G. W. Hammett, Astrophys. J. **577**, 524 (2002).