FINAL REPORT

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"Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas"

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Project Executive Summary

The three year project GPS-TTBP resulted in over 152 publications and 135 presentations. This executive summary focuses on the scientific progress made by the project team.

A major focus of the project was on the physics intrinsic rotation in tokamaks. Progress included the first ever flux driven study of net intrinsic spin-up, mediated by boundary effects (in collaboration with CPES), detailed studies of the microphysics origins of the Rice scaling, comparative studies of symmetry breaking mechanisms, a pioneering study of intrinsic torque driven by trapped electron modes, and studies of intrinsic rotation generation as a thermodynamic engine. Validation studies were performed with C-Mod, DIII-D and CSDX. This work resulted in very successful completion of the FY2010 Theory Milestone Activity for OFES, and several prominent papers of the 2008 and 2010 IAEA Conferences.

A second major focus was on the relation between zonal flow formation and transport non-locality. This culminated in the discovery of the $E\times B$ staircase - a conceptually new phenomenon. This also makes useful interdisciplinary contact with the physics of the PV staircase, well known in oceans and atmospheres.

A third topic where progress was made was in the simulation and theory of turbulence spreading. This work, now well cited, is important for understanding the dynamics of non-locality in turbulent transport.

Progress was made in studies of conjectured non-diffusive transport in trapped electron turbulence.

Pioneering studies of ITB formation, coupling to intrinsic rotation and hysteresis were completed. These results may be especially significant for future ITER operation.

All told, the physics per dollar performance of this project was quite good. The intense focus was beneficial and SciDAC resources were essential to its success.

Project Highlights

i.) Extensive progress in the understanding of intrinsic rotation. This includes theory, simulation, global simulation and phenomenology. Studies of heat flux driven rotation 'spin-up' were especially notable.

ii.) Discovery of the $E\times B$ staircase and is relation to non-locality in transport.

iii.) Extensive progress in the simulation study of turbulence spreading.

iv.) Progress in understanding the non-diffusive character of CTEM-induced turbulence transport.

v.) Pioneering studies of ITB formation, relaxation, hysteresis and coupling to intrinsic rotation.

Project Meetings/Workshops

1. *Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas and Gyrokinetic Simulation of Energetic Particle Turbulent and Transport Workshop Meetings*, UC Irvine, Irvine, CA 01/08
2. *Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas Meeting*, UC San Diego, La Jolla, CA 02-03/08
3. *Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas Meeting*, Boulder, CO 03/08
4. *Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas and Gyrokinetic Simulation of Energetic Particle Turbulent and Transport Workshop Meeting*, Dallas, TX 11/08
5. *Fusion SciDAC Winter School on Turbulence and Energetic Particles*, UC Irvine, Irvine, CA 02/09
6. *Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas Meeting*, San Diego, CA 04/09
7. *Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas Meeting*, Atlanta, GA 11/09
8. *Hierarchical Self-Organization of Turbulence and Flows in Plasmas, Oceans and Atmospheres JIFT Workshop*, UC San Diego, La Jolla, CA 03/10
9. *Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas Meeting*, Annapolis, MD 04/10
10. *Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas Meeting*, Chicago, IL 11/10

Teleconferences

Teleconferences to discuss aspects of the GPS-TTBP project were held on the following dates: 1/17/08, 2/10/08, 1/8/09.

Year III - Project Highlights

i.) Discovery of $E\times B$ staircase and its relation to non-locality (UCSD)

ii.) Demonstration of flux driven formation of *net* intrinsic rotation and its relation to boundary phenomena (UCSD and CIMS)

iii.) Studies of microphysics of Rice scaling (UCSD, PPPL and NFRI)

iv.) Studies of CTEM role in intrinsic rotation (PPPL)

v.) Role of intrinsic rotation in ITB dynamics (NFRI, UCSD)

vi.) Comprehensive theory of turbulence driven poloidal rotation (UCSD)

vii.) Studies of intrinsic rotation phenomenology (UCSD, PPPL, DIII-D, C-MOD)

viii.) Novel theory of intrinsic rotation efficiently (UCSD)

ix.) Studies of novel symmetry breaking mechanisms for intrinsic rotation (UCSD)

x.) Studies of CTEM (UCI)

xi.) Completion of the Momentum Transport DOE Theory Milestone (all but UCI)

INSTITUTIONAL REPORTS

University of California, San Diego (UCSD) Final Report for SciDAC GPS-TTBP
Grant No. DE-FC02-08ER54959
Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas
March 1, 2008 - February 28, 2011
Patrick H. Diamond, P.I.

UCSD Team Members

- Patrick H. Diamond (Principal Investigator)
- Fred L. Hinton (Senior Research Scientist)
- Mikhail Malkov (Research Scientist)
- Ozgur Gurcan (Postdoctoral Researcher)
- Christopher McDevitt (Postdoctoral Researcher)
- Kazuhiro Miki (Postdoctoral Researcher)
- Guilhem Dif-Pradalier (Postdoctoral Researcher)
- Shane Keating (Graduate Student Researcher)
- Yusuke Kosuga (Graduate Student Researcher)
- Lei Zhao (Graduate Student Researcher)
- Christopher Lee (Graduate Student Researcher)
- Pei-Chun Hsu (Graduate Student Researcher)
- Zhanhui Wang (Visiting Graduate Student Researcher)
- Zhibin Guo (Short Term Visiting Graduate Student Researcher)
- Andrew Ulvestad (Undergraduate Research Assistant)

UCSD Group External Recognition

- *European Physical Society-2010 Ph.D. Research Award*
  Awarded to Guilhem Dif-Pradalier for "a fundamental discussion of the formation needed to describe turbulence and transport in magnetized plasmas, including a collision operator in the Gysela gyrokinetic code that could modify the characteristics of the turbulence".
- *European Physical Society-2011 Hannes Alfven Prize*
  Awarded to Patrick H. Diamond, shared with A. Hasegawa and K. Mima, Osaka University, for outstanding contributions to plasma physics. The three were recognized "for laying the foundations of modern numerical transport simulations and key contributions on self-generated zonal flows and flow shear decorrelation mechanisms which form the basis of modern turbulence in plasmas".
- *Director, WCI Center for Fusion Theory, NFRI, Daejeon, Korea, 2011*
  Patrick H. Diamond
- *2010 National Science Foundation Graduate Research Fellowship*
  Awarded to Andrew Ulvestad
- *2010 Selma and Robert Silagi Award for Undergraduate Excellence*
  Awarded to Andrew Ulvestad

UCSD Technical Progress: Year III

i.) The major focus of year three was the successful completion of the Theory Milestone Activity on Momentum Transport. This exercise was highly productive, with many papers and meeting presentations resulting. A summary of results follows below. Detailed reports are available on the OFES website.

Summary

ii.) The E×B staircase was discovered and characterized. Its relation to non-locality in transport was identified.

iii.) In c ollaboration with WCI at NFRI, Korea, pioneering studies of ITB formation and its relation to intrinsic rotation were performd.

iv.) Detailed studies of the microphysics underlying the Rice scaling were performed. These, again, were in collaboration with NFRI.

v.) A comprehensive theory of poloidal rotation and its generation by turbulence was developed.

vi.) A novel theory of intrinsic torque efficiency was developed.

vii.) Several phenomenological studies of intrinsic rotation, in collaboration with C-Mod and DIII-D, were completed.

viii.) Work on the basic theory of coupled zonal flows and turbulence spreading progressed. Results were presented at several conferences.

All of i.) - viii.) are discussed in the Milestone Report.

Summary of Milestone Work

In this section, we present the conclusions of the four quarters of this Milestone study. The conclusions are presented and discussed in the form of an assessment -- i.e. issues are grouped according to:

a.) What we understand *well*,

b.) What we *think* we understand but could benefit from improvement in, and clarification of our comprehension,

c.) What we *don't* understand.

Q1, Q2, Q3, Q4 refer to the four quarterly reports.

What we understand

i.) Toroidal momentum transport is driven by parallel and perpendicular Reynolds stresses. (Q2)

ii.) Both of the above may be decomposed into a turbulent viscous piece, a (toroidal) pinch piece, and a residual stress piece, not proportional to velocity or velocity gradient. Thus, for $\Pi_{r,\phi}$:

$$\Pi_{r,\phi} = -\chi_\phi \frac{\partial \langle v_\phi \rangle}{\partial r} + V \langle v_\phi \rangle + \Pi_{r,\phi}^{resid}.$$

Here χ_ϕ is the viscosity, V is the pinch, and $\Pi_{r,\phi}^{resid}$ is the residual stress. (Q2; Q3; Q4)

iii.) χ_ϕ is similar to χ_i, with an intrinsic Prandtl number of roughly $0.5 < Pr < 0.7$, depending on deviation from threshold. The detailed physics underpinning of the dependence is the resonant particle velocity. (Q1)

iv.) The parallel flow pinch V is toroidal in origin, and consists of turbulent equipartition (TEP) and thermoelectric pieces. The thermoelectric pinch is driven by both ∇T_i and ∇n. These tend to oppose one another for a wide range of cases. (Q2); For the TEP pinch, produced by the compressibility of $v_{E\times B}$ in toroidal geometry, $V/\chi_\phi \sim O(1/R)$. TEP momentum and particle pinches are closely related. (Q2)

v.) The residual stress is driven by $\nabla T, \nabla p, \nabla n$, and produces a local intrinsic torque by its divergence. Residual stress can spin up the plasma from rest, acting in concert with boundary conditions. (Q2; Q3)

vi.) Residual parallel stress requires symmetry breaking, so as to convert radial inhomogeneity into parallel spectral asymmetry. Symmetry breaking mechanisms include electric field shear $\langle v_E \rangle'$ and intensity gradient $\partial r I$ -- both of which are self-reinforcing and linked to the driving heat flux -- as well as up-down asymmetry of current density. (Q2; Q3; Q4); Additional symmetry breaking sets the polarization stress ($\langle k_r k_\parallel \rangle \neq 0 \rightarrow$ essentially a quadrupole spatial moment of the spectrum is required) and the poloidal Reynolds stress, which drives flow through $\langle J_r \rangle B_\theta / c$ (again, $\langle v_E \rangle'$ and intensity gradient are the key elements). (Q2; Q4)

vii.) For ITG turbulence, Π_{resid}

- increases with $R/L_T - R/L_{Tc}$,

- is insensitive to collisional zonal flow damping, and
- couples to the zonal flow-turbulence self regulatory predator-prey interaction (Q2; Q4)

viii.) Residual stress is also robust in CTEM. Flow direction produced by CTEM turbulence can differ from that produced by ITG turbulence. (Q2; Q4)

ix.) Net intrinsic rotation (i.e. an increase in radially \textit{integrated} momentum) with a peak thermal Mach number $M_T \equiv \langle v_{\parallel} \rangle / v_{th}$ of $0.05 < M_T < 0.15$ can be produced in flux driven ITG simulations with no slip boundary conditions. (Q3; Q4)

x.) Strong intrinsic rotation can be generated by flux driven ITG turbulence in reverse shear ITBs with off-axis mimimum $q(r)$, with no slip boundary conditions. (Q4)

What we think we understand but would benefit from more work on

i.) The mechanism for generation of toroidal rotation by fluctuation driven radial currents -- i.e. via the toroidal projection of the perpendicular Reynolds stress. (Q2)

ii.) The basic structure of the Rice scaling $\left(\Delta v_T \sim \Delta W_p / I_p\right)$ originates from:

a.) strong localized temperature gradients, as in the pedestal and ITBs (i.e. the local origin of ΔW_p,

b.) $q(r)$ scaling (i.e. the origin of I_p). (Q4)

iii.) The apparent differences between macroscopic profile structures manifested for different boundary conditions (i.e. no slip vs. $\nabla \phi |_{boundary} = 0$. (Q4)

iv.) Saturation of Rice scaling in high power ITBs and the ultimate limit on intrinsic rotation. Of particular note here is dependence on collisional Prandtl number. (Q4)

v.) Relative hysteresis of ∇v_ϕ and ∇T in ITG intrinsic rotation. (Q4)

vi.) The theory of poloidal momentum transport by turbulence. (Q3; Q4)

vii.) The precise relation between turbulence propagation direction (i.e. v_{*e} vs. v_{*i}) and toroidal rotation direction. (Q2)

viii.) The theory of fluctuation entropy balance and how it relates to the notion of intrinsic rotation as the output of a plasma heat engine. (Q3; Q4)

ix.) The size scaling of intrinsic rotation. (Q3; Q4)

x.) How to realize the Solomon cancellation phenomenon. (Q4)

What we do not understand

i.) The interplay of turbulence and wave scattering with neoclassical effects and orbit loss in determining the boundary condition for intrinsic rotation.

ii.) The detailed interplay between core intrinsic torque and the edge boundary condition, and its role in determining net rotation direction.

iii.) The connection between SOL flows and core rotation.

iv.) The apparent absence of ρ_* scaling of intrinsic rotation.

v.) The effect of energetic particles on rotation.

vi.) The microphysics of formation of the PV staircase (Q3).

vii.) The detailed dynamics of how RF and current drive (i.e. LHCD, ECH) affect intrinsic rotation.

viii.) The detailed spatio-temporal dynamics of intrinsic rotation profile build-up.

ix.) The critical torque-to-power ratio that likely delimits pinch vs. residual stress dominated momentum transport regimes.

UCSD Publications

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97. Hinton, F.L., "Effect of Superbanana Diffusion on the Fusion Reactvity in QHS Stellarators", Phys. Plasma, Submitted for Publication
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UCSD Group Web Site

A web site, http://cass.ucsd.edu/groups/plasma/gps-ttbp/index.html, for the Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas (GPS-TTBP) project was created listing the goals of the research sponsored center, the people involved, publications related to the research and news and meetings information.

UCSD Presentations

1. *Physics and Modeling of Multi-Scale Interaction in Plasmas*, Invited Speaker, Kyoto University, Kyoto, Japan, 03/03-04/08 (Diamond - Unable to attend due to schedule conflicts)
2. *Geophysical Wave Interactions in Turbulent Magnetofluids*, Oral Presentation, Joint CAOS-MFD Seminar, Courant Institute, New York University, New York, NY, 03/08 (Keating)
3. *Mechanisms of Edge-Core Coupling: Some Speculations on How SOL Flows Influence Intrinsic Rotation and the L-H Transition*, Oral Presentation, 2008 U.S. Transport Task Force Meeting, Boulder, CO, 03/08 (Diamond)
4. *Poloidal Reynolds Stress, and its Influence on Intrinsic Rotation/Momentum Transport*, Oral Presentation, 2008 U.S. Transport Task Force Meeting, Boulder, CO, 03/08 (Gurcan)
5. *Transport of Parallel Momentum by Collisionless Electromagnetic Turbulence*, Oral Presentation, 2008 U.S. Transport Task Force Meeting, Boulder, CO, 03/08 (McDevitt)
6. *Non-Random Collision Method for Delta-f PIC Simulations*, Poster Presentation, 2008 U.S. Transport Task Force Meeting, Boulder, CO, 03/08 (Hinton)
7. *Formation and Propagation of Transport Barriers in a Coupled Heat and Particle Flux Model*, Poster Presentation, 2008 U.S. Transport Task Force Meeting, Boulder, CO, 03/08 (Malkov)
8. *Theoretical Approaches to Problem Reduction and Description of Multi-Scale Interaction in Tokamak Plasma Turbulence*, Oral Presentation, International Workshop on 'Multiscale Methods for Fluid and Plasma Turbulence: Applications to Magnetically Confined Plasmas in Fusion Devices', CIRM, Marseille, France, 04/08 (Diamond)
9. *'Thoughts on 'Thetergy', Is Magnetostrophic Turbulence As Simple As It Looks?*, Oral Presentation, Dynamo Theory Program, KITP Institute for Theoretical Physics, University of California at Santa Barbara, Santa Barbara, CA, 05/08 (Diamond)
10. *Mean Field MHD of (Magnetized Circumstellar) Accretion Disks*, Oral Presentation, Dynamo Theory Program, KITP Institute for Theoretical Physics, University of California at Santa Barbara, Santa Barbara, CA, 05/08 (Diamond)
11. *Quenching and Irreversibility in 2D Wavy MHD*, Oral Presentation, Dynamo Theory Program, KITP Institute for Theoretical Physics, University of California at Santa Barbara, Santa Barbara, CA, 05/08 (Keating)
12. *Momentum Theorems and the Structure of Atmospheric Jets and Zonal Flows in Plasmas*, Invited Speaker, The 35th European Physical Society Conference on Plasma Physics, Hersonissos, Crete, Greece, 06/08 (Diamond)
13. *Zonal Flow Generation Mechanisms - Wave Number and Configuration Space Perspectives*, Oral Presentation, Dynamo Theory Program, KITP Institute for Theoretical Physics, University of California at Santa Barbara, Santa Barbara, CA, 06/08 (Diamond)
14. *On the Fate of PV Homogenization with Magnetic Linkage and its Implication for Jet Formation in MHD,* Oral Presentation, Magnetic Field Generation in

Experiments, Geophysics and Astrophysics Conference, Dynamo Theory Program, KITP Institute for Theoretical Physics, University of California at Santa Barbara, Santa Barbara, CA, 07/08 (Diamond)

15. *Mechanisms of Edge-Core Coupling: How SOL Flow Might Influence Intrinsic Rotation and the L-H Transition*, Invited Talk, European-U.S. Transport Task Force 2008 Workshop, Copenhagen, Denmark, 09/08 (Diamond - Unable to attend, T.S. Hahm presented talk)
16. *Toroidal Momentum Transport and Intrinsic Rotation: A Critical Transport Physics Issue for ITER and Beyond...*, Invited Speaker, 14th International Congress on Plasma Physics, Fukuoka, Japan, 09/08 (Diamond)
17. *Toroidal Momentum Transport and Intrinsic Rotation: A Critical Transport Physics Issue for ITER and Beyond...*, Invited Speaker, JAEA Seminar, Naka, Japan, 09/08 (Diamond)
18. *An Emerging Understanding of Momentum Transport and Intrinsic Rotation in Tokamaks*, Invited Speaker, Special Plasma Physics Seminar, University of California at Irvine, Irvine, CA, 10/08 (Diamond)
19. *Physics of Non-Diffusive Turbulent Transport of Momentum and the Origins of Spontaneous Rotation in Tokamaks*, Oral Presentation, 22nd IAEA Fusion Energy Conference, Geneva, Switzerland, 10/08 (Diamond - Unable to attend-talk presented by T.S. Hahm, PPPL)
20. *Interaction of Energetic Particles with Discontinuities Upstream*, Invited Talk, APS 50th Annual Meeting of the Division of Plasma Physics, Mini-Conference, Dallas, TX, 11/08 (Malkov)
21. *Impact of Collisions on Turbulence and Transport*, Oral Presentation, APS 50th Annual Meeting of the Division of Plasma Physics, Dallas, TX, 11/08 (Dif-Pradalier)
22. *Analysis of Feedback Loop Dynamics in Turbulence Spreading*, Poster Presentation, APS 50th Annual Meeting of the Division of Plasma Physics, Dallas, TX, 11/08 (Miki)
23. *Gyrokinetic Simulations Predict Anomalous Poloidal Rotation in Tokamak Plasmas*, Oral Presentation, APS 50th Annual Meeting of the Division of Plasma Physics, Dallas, TX, 11/08 (Dif-Pradalier)
24. *On the Fate of PV Homogenization with Magnetic Linkage and its Implication for Jet Formation in MHD*, Poster Presentation, APS 50th Annual Meeting of the Division of Plasma Physics, Dallas, TX, 11/08 (Keating)
25. *Improved δ-f Method*, Oral Presentation, CPES Meeting, Atlanta, GA, 12/08 (Hinton)
26. *Physics of Non-Diffusive Turbulent Transport of Momentum and Origins of Spontaneous Rotation in Tokamaks*, Oral Presentation, Fusion SciDAC Winter School on Turbulence and Energetic Particles, Irvine, CA, 02/09 (Diamond)
27. *Toroidal Momentum Transport and Intrinsic Rotation*, Oral Presentation, Fusion SciDAC Winter School on Turbulence and Energetic Particles, Irvine, CA, 02/09 (Diamond)
28. *Fermi Acceleration, Cosmic Rays and Fermi Mission*, Oral Presentation, Fermi Seminar, Berkeley, CA, 02/09 (Malkov)

29. *On Hysteresis of the H-L Back-Transition*, Oral Presentation, 2009 Joint US-EU Transport Task Force, San Diego, CA, 04-05/2009 (Malkov)
30. *Effect of Pedestal and SOL Physics on Core Rotation*, Oral Presentation, 2009 Joint US-EU Transport Task Force, San Diego, CA, 04-05/2009 (McDevitt)
31. *Analysis of GAM Shear Feedback Loop Dynamics in Transport Bifurcations and Turbulence Spreading*, Oral Presentation, 2009 Joint US-EU Transport Task Force Workshop, San Diego, CA, 04-05/2009 (Miki)
32. *A Second Look at Zonal Flow Dynamics*, Oral Presentation, 2009 Joint EU-US Transport Task Force Workshop, San Diego, CA, 04-05/2009 (Diamond)
33. *Re-visiting Poloidal Rotation and Transport Near Criticality*, Oral Presentation, 2009 Joint EU-US Transport Task Force, San Diego, CA, 04-05/2009 (Dif-Pradalier)
34. *Dynamics of Flux-Driven Turbulence Spreading with Self-Consistent Nonlinear Noise*, Poster Presentation, Joint U.S.-EU 2009 Transport Task Force Workshop, San Diego, CA, 04/09 (Wang)
35. *Self-Consistent Calculations of Zonal Flow Shears and Stability*, Poster Presentation, Joint U.S.-EU 2009 Transport Task Force Workshop, San Diego, CA, 04/09 (Kosuga)
36. *Momentum Transport*, Oral Presentation, CPES 2009 Spring Meeting, San Diego, 05/09 (Diamond)
37. *Direct Implicit Method for Drift-Kinetic Electrons in Collisionless PIC Simulations*, Oral Presentation, CPES 2009 Spring Meeting, San Diego, CA, 05/09 (Hinton)
38. 8th Annual International Astrophysics Conference, Invited Speaker, Kailua-Kona, HI, 05/01-05/07/09 (Diamond - Unable to attend due to schedule conflicts, M.A. Malkov presented talk)
39. *Wave Dynamics and Particle Acceleration in Shock Precursors*, Invited Speaker, 8th Annual International Astrophysics Conference, Kailua-Kona, HI, 05/09 (Malkov)
40. *Fluid and Gyrokinetic Momentum Theorems for Drift Wave - Zonal Flow Turbulence*, Invited Speaker, The 4th IAEA Technical Meeting on the Theory of Plasma Instabilities, Kyoto, Japan, 5/09 (Diamond - Unable to attend due to the influenza A (H1N1) outbreak in Japan)
41. *Self-Consistent Calculation of Turbulent Momentum Transport and Intrinsic Rotation: Viscosity, Pinch and Residual Stress*, Oral Presentation, The 4th IAEA Technical Meeting on the Theory of Plasma Instabilities, Kyoto, Japan, 05/09 (McDevitt)
42. *Analysis of GAM Shear Feedback Loop Dynamics in Transport Bifurcations and Turbulence Spreading,* Poster Presentation, The 4th IAEA Technical Meeting on the Theory of Plasma Instabilities, Kyoto, Japan, 05/09 (Miki)
43. Hasegawa-Mima Equation: 30 Year and Future, Invited Speaker, Kyoto University, Kyoto, Japan, 05/09 (Diamond - Unable to attend)
44. *Chaotic Dynamics and the Acceleration of High Energy Cosmic Rays by Nonlinear Shocks*, Invited Speaker, Minisymposium Conference on Applications of Dynamical Systems, Society for Industrial and Applied Mathematics (SIAM), Snowbird, UT, 05/09 (Diamond - Unable to attend due to schedule conflict)

45. *Dynamics of Granulations in GFD and Vlasov Plasmas*, Lecturer, 4th Festival de Theorie, Aix-en-Provence, France, 07/09 (Diamond)
46. *Turbulence, Profile Dynamics and Collisions: Investigating Their Interplay*, Short Talk, 4th Festival de Theorie, Aix-en-Provence, France, 07/09 (Dif-Pradalier)
47. *Wave Phenomena and Cosmic Ray Acceleration Ahead of Strong Shocks*, Oral Presentation, TeV Particle Astrophysics, SLAC National Accelerator Laboratory, Menlo Park, CA, 07/09 (Malkov)
48. *Introduction to Quasilinear Theory*, Invited Speaker, Korean Fusion Plasma Summer School 2009, Korea Advanced Institute of Science and Technology, Daejeon, Korea, 07/09 (Diamond)
49. International Conference "Turbulent Mixing and Beyond", Invited Key-Note Lecturer, Trieste, Italy, 07-08/09 (Diamond - Unable to attend due to conference schedule conflict)
50. *Acoustic Turbulence and Particle Acceleration in CR-Modified Shocks*, Oral Presentation, Particle Acceleration in Astrophysical Plasmas, KITP, Santa Barbara, CA, 09/09 (Malkov)
51. *Stabilization of the CR-Driven Non-Resonant Instabilities*, Invited Speaker, Nonlinear Processes in Astrophysical Plasmas: Particle Acceleration, Magnetic Field, Amplification and Radiation Signatures, Santa Barbara, CA, 09-10/09 (Malkov)
52. *Radial Current, Residual Stress and Intrinsic Rotation*, Poster Presentation, 12th International Workshop on H-mode Physics and Transport Barriers, Princeton Plasma Physics Laboratory, Princeton, NJ, 09-10/09 (Diamond)
53. *Rotation Dynamics With & Without Internal Transport Barriers*, Oral/Poster Presentation, 12th International Workshop on H-mode Physics and Transport Barriers, Princeton Plasma Physics Laboratory, Princeton, NJ, 09-10/09 (Dif-Pradalier)
54. *A Simple Dynamical Model of Flux-Driven Turbulence and Profile Evolution*, Oral/Poster Presentation, 12th International Workshop on H-mode Physics and Transport Barriers, Princeton Plasma Physics Laboratory, Princeton, NJ, 09-10/09 (Wang)
55. *A Simple Non-Perturbative Model of Turbulence Spreading in the Presence of Dissipation and Zonal Flows*, Poster Presentation, 12th International Workshop on H-mode Physics and Transport Barriers, Princeton Plasma Physics Laboratory, Princeton, NJ, 09-10/09 (Diamond)
56. *GAM Shearing Feedback Loop in Transport Bifurcation and Turbulence Spreading*, Poster Presentation, 12th International Workshop on H-mode Physics and Transport Barriers, Princeton Plasma Physics Laboratory, Princeton, NJ, 09-10/09 (Miki)
57. *Toroidal and Poloidal Flow Evolution*, Poster Presentation, 12th International Workshop on H-mode Physics and Transport Barriers, Princeton Plasma Physics Laboratory, Princeton, NJ, 09-10/09 (McDevitt)
58. *Potential Vorticity Dynamics in Drift Wave & MHD Turbulence*, Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas, University of Wisconsin-Madison, Madison, WI, 10/09 (Diamond - Unable to attend due to illness)

59. *A Second Look at Zonal Flows*, Invited Talk, APS 51st Annual Meeting of the Division of Plasma Physics, Atlanta, GA 11/09 (Diamond)
60. *GAM Shear Feedback Loop Dynamics in Transport Bifurcations and Turbulence Spreading*, Oral Presentation, 51st Annual Meeting of the Division of Plasma Physics, Atlanta, GA, 11/09 (Miki)
61. *On the Validity of the Local Diffusive Paradigm in Turbulent Plasma Transport*, Poster and Oral Presentations, APS 51st Annual Meeting of the Division of Plasma Physics, Atlanta, GA, 11/09 (Dif-Pradalier)
62. *On Modeling Multi-Scale Interaction in DSA*, Invited Talk, 5th Korean Astrophysics Workshop Shock Waves, Turbulence, and Particle Acceleration, APCTP, Pohang, Korea, 11/09 (Diamond)
63. *Analytic Studies of the Diffusive Shock Acceleration*, Invited Talk, 5th Korean Astrophysics Workshop Shock Waves, Turbulence, and Particle Acceleration, APCTP, Pohang, Korea, 11/09 (Malkov)
64. Japan Society of Plasma and Fusion, Invited Speaker, Kyoto, Japan, 12/09 (Diamond - Unable to attend due to schedule conflict)
65. *Wave Momentum, Potential Vorticity Mixing, Symmetry Breaking and the Physics Self-Accelerating Plasma Flows*, Invited Plenary Speaker, The 19th International Toki Conference on Advanced Physics in Plasma and Fusion Research, Toki-City, Gifu, Japan, 12/09 (Diamond)
66. *Issues in the Theory of Intrinsic Rotation*, Oral Presentation, Center for Momentum Transport and Flow Self-Organization in Plasmas Workshop, La Jolla, CA, 1/10 (Diamond)
67. *Dynamics of Pedestal Formation*, Oral Presentation, DIII-D Pedestal Transport Workshop, San Diego, CA, 02/10 (Diamond)
68. *Spreading and Overshoot in Drift Wave Turbulence*, Oral Presentation, Nonlinear Wave Workshop 8, La Jolla, CA, 03/10 (Diamond)
69. *Instabilities in Astrophysical Shock Precursors and Their Saturation*, Oral Presentation, Nonlinear Wave Workshop 8, La Jolla, CA, 03/10 (Malkov)
70. *Momentum Theorems for Zonal and Toroidal Flows in Drift Wave Turbulence*, Oral Presentation, JIFT Workshop, La Jolla, CA, 03/10 (Diamond)
71. *Spreading and Entrainment in 2D and Drift Wave Turbulence*, Oral Presentation, JIFT Workshop, La Jolla, CA, 03/10 (Ulvestad, Diamond)
72. *Turbulent Transport and Acceleration of Cosmic Rays in Supernova Remnant Shocks*, Oral Presentation, JIFT Workshop, La Jolla, CA, 03/10 (Malkov)
73. *Non-Locality in Transport*, Oral Presentation, JIFT Workshop, La Jolla, CA, 03/10 (Dif-Pradalier)
74. *An Edge Turbulence Model with Multi-Frequency Shearing Effects*, Oral Presentation, JIFT Workshop, La Jolla, CA, 03/10 (Miki)
75. *Enstrophy, Entropy and Efficiency in Flow Generation*, Oral Presentation, JIFT Workshop, La Jolla, CA, 03/10 (Kosuga)
76. *Turbulent Transport of Poloidal and Toroidal Momentum*, Oral Presentation, 4th ITPA Transport & Confinement Meeting, Culham, Oxford, UK, 03/10 (McDevitt)
77. *Progress in the Theory of Pedestal Evolution*, Oral Presentation, 2010 U.S. Transport Task Force Workshop, Annapolis, MD, 04/10 (Diamond)

78. *Poloidal Rotation and Its Relation to the Mixing of Potential Vorticity*, Oral Presentation, 2010 U.S. Transport Task Force Workshop, Annapolis, MD, 04/10 (McDevitt)
79. *On the Validity of the Local Diffusive Paradigm in Turbulent Plasma Transport*, Oral Presentation, 2010 U.S. Transport Task Force Workshop, Annapolis, MD, 04/10 (Dif-Pradalier)
80. *Quantifying the Efficiency of the Spontaneous Flow Generation "Engine" in Confined Plasmas*, Oral Presentation, 2010 U.S. Transport Task Force Workshop, Annapolis, MD, 04/10 (Kosuga)
81. *Methods for Simulating Collisions in Particle Codes*, Poster Presentation, 2010 U.S. Transport Task Force Workshop, Annapolis, MD, 04/10 (Hinton)
82. *An Edge Turbulence Model with Multi-Frequency Shearing Effects*, Oral Presentation, 2010 U.S. Transport Task Force Meeting, Annapolis, MD, 04/10 (Miki)
83. *Current Driven Drift-ITG Turbulence*, Poster Presentation, 2010 U.S. Transport Task Force Workshop, Annapolis, MD 04/10 (Lee)
84. *Inter-species Energy Transfer and Turbulent Heating in Drift Wave Turbulence*, Poster Presentation, 2010 U.S. Transport Task Force Workshop, Annapolis, MD 04/10 (Zhao)
85. *Penetrative Overshoot and the Spatial Distribution of Drift Wave Turbulence*, Poster Presentation, 2010 U.S. Transport Task Force Workshop, Annapolis, MD 04/10 (Ulvestad)
86. *Problems and Opportunities in L-H Transition and Intrinsic Rotation Physics*, Oral Presentation, Fifth US-PRC Magnetic Fusion Collaboration Workshop, Huazhong University of Science and Technology (HUST), Wuhan, China, 05/10 (Diamond)
87. *Analytic Studies of Astrophysical Shock Precursors*, Invited Speaker, 37th European Physical Society Conference on Plasma Physics, Dublin, Rep. of Ireland, 06/10 (Malkov)
88. *From the Interplay Between Flows, Collisions and Turbulence to the Question of the Non-Local, Non-Diffusive Character of Tokamak Transport*, Oral Presentation, 37th European Physical Society Conference on Plasma Physics, Dublin, Rep. of Ireland, 06/10 (Dif-Pradalier)
89. *Instabilities and CR Confinement in Shocks: Impact on CR Spectra and Shock Morphology*, Invited Talk, Dublin Institute for Advanced Study, Dublin, Rep. of Ireland, 06/10 (Malkov)
90. *On the Validity of the Local Diffusive Paradigm in Turbulent Plasma Transport*, Oral Presentation, Workshop on Electric Fields, Turbulence and Self-Organization in Magnetized Plasmas-a satellite meeting of the 37th European Physical Society Conference on Plasma Physics, Dublin, Rep. of Ireland, 06/10 (Dif-Pradalier)
91. *From Kinetic Theory to Microscopic Transport*, Oral Presentation, ISIMA Conference: Transport Processes in Astrophysics, Santa Cruz, CA, 07/10 (Diamond)
92. *The Edge Temperature Gradient as the Intrinsic Rotation Drive in Alcator C-Mod Tokamak Plasmas*, Oral Presentation, 3rd EFDA Transport Topical Group

Meeting combined with the 15th EU-US Transport Task Force Meeting, Cordoba, Spain, 09/10 (Diamond)

93. *Poloidal Rotation in Strongly Magnetized Plasmas*, Oral Presentation, 3rd EFDA Transport Topical Group Meeting combined with the 15th EU-US Transport Task Force Meeting, Cordoba, Spain, 09/10 (McDevitt)
94. *Role of Neoclassical and Turbulence Mechanisms on Rotation and Flow Structure Formation*, Oral Presentation, 3rd EFDA Transport Topical Group Meeting combined with the 15th EU-US Transport Task Force Meeting, Cordoba, Spain, 09/10 (Dif-Pradalier)
95. *Nonlocal Dynamics of Turbulence, Transport and Zonal Flows in Tokamak Plasmas*, Poster Presentation, 23rd IAEA Fusion Energy Conference, Daejeon, Rep. of S. Korea, 10/10 (Dif-Pradalier)
96. *Developments in the Theory of Tokamks Flow Self-Organization*, Poster Presentation, 23rd IAEA Fusion Energy Conference, Daejeon, Rep. of S. Korea, 10/10 (McDevitt)
97. *Boundary Layer and Streamer Flows in Interchange-Unstable Plasma*, Poster Presentation, 52nd Annual Meeting of the APS Division of Plasma Physics, Chicago, IL, 11/10 (Malkov)
98. *Interaction of Charged Particles with Collisionless Shock Ensembles*, Poster Presentation, 52nd Annual Meeting of the APS Division of Plasma Physics, Chicago, IL, 11/10 (Malkov)
99. *Poloidal Rotation in Strongly Magnetized Plasmas*, Poster Presentation, 52nd Annual Meeting of the APS Division of Plasma Physics, Chicago, IL, 11/10 (McDevitt)
100. *Momentum Studies with Sources and Sinks in Fusion*, Oral Presentation, Mini-Conference on Momentum Transport in Magnetic Fusion and Astrophysical Systems I, 52nd Annual Meeting of the APS Division of Plasma Physics, Chicago, IL, 11/10 (Dif-Pradalier)
101. *On Flow Structures and the Hierarchy of Shears*, Poster Presentation, 52nd Annual Meeting of the APS Division of Plasma Physics, Chicago, IL, 11/10 (Dif-Pradalier)
102. *On the Efficiency of Intrinsic Rotation Generation in Tokamaks*, Poster Presentation, 52nd Annual Meeting of the APS Division of Plasma Physics, Chicago, IL, 11/10 (Kosuga)
103. *Inter-species Energy Transfer and Turbulent Heating in CTEM*, Poster Presentation, 52nd Annual Meeting of the APS Division of Plasma Physics, Chicago, IL, 11/10 (Zhao)
104. *Current Driven Drift Wave Turbulence*, Poster Presentation, 52nd Annual Meeting of the APS Division of Plasma Physics, Chicago, IL, 11/10 (Lee)
105. *Hyper-resistivity in 2D-MHD Turbulence*, Poster Presentation, 52nd Annual Meeting of the APS Division of Plasma Physics, Chicago, IL, 11/10 (Guo)
106. *Multi-Scale Interaction in Diffusive Shock Acceleration*, Invited Colloquium Speaker, Joint Plasma Kavli Institute for Astronomy and Astrophysics, Peking University, People's Republic of China, 01/11 (Diamond)

107. *Intrinsic Rotation and Toroidal Momentum Transport: Status and Prospects*, Oral Presentation, Center for Momentum Transport and Flow Organization Annual Meeting, New Orleans, LA, 01/11 (Diamond)
108. *Zonal Flow Physics-A Momentum Transport Perspective*, Oral Presentation, Center for Momentum Transport and Flow Organization Annual Meeting, New Orleans, LA, 01/11 (Diamond)
109. *Some Ideas on Flow Structure, Nonlocality & Staircases*, Oral Presentation, Center for Momentum Transport and Flow Organization Annual Meeting, New Orleans, LA, 01/11 (Dif-Pradalier)
110. *Transport in Stochastic Fields and MHD Turbulence*, Oral Presentation, WCI-CNU Astro-Fusion Plasma Joint Meeting, Daejeon, Korea, 02/11 (Diamond)
111. *Intrinsic Rotation and Toroidal Momentum Transport: Status and Prospects (A Largely Theoretical Perspective*, Invited Talk, 2011 KSTAR Conference and KO-US Workshop, Muju, Korea, 02/11 (Diamond)
112. *Drift Waves Turbulence and Flows*, Oral Presentation, Dynamics and Turbulent Transport in Plasmas and Conducting Fluids, Ecole de Physique des Houches, France, 02-03/11 (Diamond)
113. *Zonal Flows: From Wave Momentum and Potential Vorticity Mixing to Shearing Feedback Loops and Enhanced Confinement*, Oral Presentation, Dynamics and Turbulent Transport in Plasmas and Conducting Fluids, Ecole de Physique des Houches, France, 02-03/11 (Diamond)
114. *A Theory of the Efficiency of the Plasma Flow Generation*, Oral Presentation, Dynamics and Turbulent Transport in Plasmas and Conducting Fluids, Ecole de Physique des Houches, France, 02-03/11 (Kosuga)
115. *Intrinsic Rotation and Toroidal Momentum Transport: Status and Prospects*, Oral Presentation, Dynamics and Turbulent Transport in Plasmas and Conducting Fluids, Ecole de Physique des Houches, France, 02-03/11 (Diamond)

Visitors to UCSD for the Purpose of Research and Collaboration

1. T.S. Hahm (*PPPL*), Y. Xiao (*UCI*), W. Zhang (*UCI*), L. Chen (*UCI*), I. Holod (*UCI*), G. Rewoldt (*PPPL*), W. Horton (*UT Austin*), Z. Lin (*UCI*), A. White (*UCLA*), S. Kaye (*PPPL*) - *GPS-TTBP Research and Collaboration Meeting*, UC San Diego, La Jolla, CA, 02-03/08
2. Yansong Wang (*PPPL*) 04/08
3. Guilhem Dif-Pradalier (*CEA Cadarache, France*) 04/08
4. Taik-Soo Hahm (*Princeton Plasma Physics Laboratory*) 06/08
5. Junjun Liu (*California Institute of Technology*) 10/08
6. Michael Van Zeeland (*General Atomics*) 10/08
7. Andrey Beresnyak (*University of Wisconsin*) 10/08
8. Naohiro Kasuya (*National Institute for Fusion Science*) 11/08
9. Stanley Kaye (*Princeton Plasma Physics Laboratory*) 02/09
10. Nic Brummell (*University of California, Santa Cruz*) 02/09
11. Tamara Rogers (*University of Arizona*) 03/09
12. Yong Xiao (*University of California, Irvine*) 03/09
13. Edriss Titi (*University of California, Irvine*) 04/09

14. Mark Miesch (*University of Colorado, Boulder*), 04/09
15. C.S. Chang (*CIMS, New York University*) 05/09
16. Xavier Garbet (*CEA*) 05/09
17. Ozgur Gurcan (*CEA*) 05/09
18. Carlos Hidalgo (*CIEMAT*) 05/09
19. Kenichi Nagaoka (*NIFS*) 05/09
20. Katsumi Ida (*NIFS*) 05/09
21. Takeshi Ido (*NIFS*) 05/09
22. Naohiro Kasuya (*NIFS*) 05/09
23. Mark Miesch (*University of Colorado, Boulder*) 05/09
24. Annick Pouquet (*NCAR*) 05/09
25. Luke Drury (*Dublin Institute for Advanced Studies*) 09/09
26. Lu Wang (*PPPL*) 11/09
27. Taik-Soo Hahm (*PPPL*) 01/10
28. Janghoon Seo (*KAIST, Daejeon, ROK*) 02/10-03/10
29. Wayne Solomon (*PPPL/General Atomics*) 03/10
30. Eric King (*UCLA*) 3/10
31. Roald Sagdeev (*University of Maryland, College Park*) 05/10
32. Wolf Mueller (*Max Planck Institute for Plasma Physics*) 06/10

UCSD Group Travel/Research and Collaboration

1. *Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas and Gyrokinetic Simulation of Energetic Particle Turbulent and Transport Workshop Meetings and Research and Collaboration*, UC Irvine, Irvine, CA (Diamond, Gurcan) 01/08
2. *Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas Research and Collaboration Meeting*, UC San Diego, La Jolla, CA (Diamond, Malkov, Hinton, Gurcan, McDevitt, Keating, Wang) 02-03/08
3. *21st U.S. Transport Task Force Workshop Meeting*, Boulder, CO (Diamond, Malkov, Hinton, Gurcan, McDevitt, Wang) 03/08
4. *Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas Meeting and Research and Collaboration*, Boulder, CO (Diamond, Malkov, Hinton, Gurcan, McDevitt, Wang) 03/08
5. *Dynamo Theory Workshop*, Kavli Institute for Theoretical Physics, UC Santa Barbara, Santa Barbara, CA (Diamond, Keating) 05-07/08
6. *Magnetic Field Generation in Experiments, Geophysics and Astrophysics Conference*, Kavli Institute for Theoretical Physics, UC Santa Barbara, Santa Barbara, CA (Diamond, Keating) 07/08
7. *Research and Collaboration*, UC Irvine, Irvine, CA (Miki) 10/08
8. *Research and Collaboration*, UC Irvine, Irvine, CA (Diamond, Miki) 10/08
9. *22nd IAEA Fusion Energy Conference and Research and Collaboration*, Geneva, Switzerland (McDevitt) 10/08
10. *50th Annual Meeting of the APS/DPP, Research and Collaboration*, Dallas, TX (Diamond, Malkov, Hinton, McDevitt, Wang, Miki, Dif-Pradalier) 11/08

11. *Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas and Gyrokinetic Simulation of Energetic Particle Turbulent and Transport Workshop Meeting and Research and Collaboration*, Dallas, TX (Diamond, Malkov, Hinton, Miki, Dif-Pradalier, Wang) 11/08
12. *CPES Fall Meeting and Research and Collaboration*, Atlanta, GA (Hinton, Dif-Pradalier) 12/08
13. *Lectures and Research and Collaboration*, Peking University, Beijing, China (Diamond) 12/08
14. *XGC1 Meeting and Research and Collaboration*, Courant Institute of Mathematical Sciences at NYU, New York, NY (Diamond, Dif-Pradalier) 01/09
15. *Fermi Workshop and Research and Collaboration*, UC Berkeley, Berkeley, CA (Malkov) 02/09
16. *Fusion SciDAC Winter School on Turbulence and Energetic Particles and Research and Collaboration*, UC Irvine, Irvine, CA (Diamond, McDevitt, Miki, Dif-Pradalier, Hsu, Kosuga, Wang, Lee, Hsu) 02/09
17. *MIT Plasma Science and Fusion Center Seminar Speaker and Research and Collaboration*, MIT, Cambridge, MA (Diamond) 03/09
18. *Research and Collaboration*, PPPL, Princeton, NJ (Diamond) 03/09
19. *Research and Collaboration*, Washington DC (Diamond) 04/09
20. *U.S.-EU 2009 Transport Task Force Workshop Meeting and Research and Collaboration*, San Diego, CA (Diamond, Malkov, Hinton, McDevitt, Miki, Dif-Pradalier, Wang, Kusuka, Zhao, Lee, Hsu) 04/09
21. *SciDAC Prototype FSP Center for Plasma Edge Simulation Meeting and Research and Collaboration*, UC San Diego, La Jolla, CA (Diamond, Dif-Pradalier) 04/09
22. *CPES Meeting*, San Diego, CA (Hinton) 05/09
23. *8th Annual International Astrophysics Conference and Research and Collaboration*, Kona, Hawaii (Malkov) 05/09
24. *The 4th IAEA Technical Meeting on the Theory of Plasma Instabilities*, Kyoto University, Kyoto, Japan (McDevitt, Miki) 05/09
25. *Lecture Meeting of the Hasegawa-Mima Equation and Research and Collaboration*, Kyoto University, Kyoto, Japan (Miki) 05/09
26. *Lectures and Research and Collaboration*, Korea Advanced Institute of Science and Technology, Daejeon, Republic of South Korea (Diamond) 06/09
27. *Rotation and Momentum Transport in Magnetized Plasmas at the Festival de Theorie 2009*, Aix-en-Provence, France (Diamond, McDevitt, Miki, Dif-Pradalier) 07/09
28. *TeV Particle Astrophysics 2009*, SLAC National Accelerator Laboratory, Menlo Park, CA (Malkov) 07/09
29. *Lectures and Research and Collaboration*, Korea Advanced Institute of Science and Technology, Daejeon, Republic of South Korea (Diamond, Dif-Pradlier) 07-08/09
30. *Lectures and Research and Collaboration*, Peking University, Beijing, China (Diamond) 08/09

31. *Nonlinear Processes in Astrophysical Plasmas: Particle Acceleration, Magnetic Field Amplification and Radiation Signatures*, Kavli Institute for Theoretical Physics, UC Santa Barbara, Santa Barbara, CA (Malkov) 08/09/10-09
32. *Research and Collaboration*, Oak Ridge National Laboratory, Oak Ridge, TN (Dif-Pradalier) 09/09
33. *12th International Workshop on 'H-Mode Physics and Transport Barriers'*, Princeton University, Plasma Physics Laboratory, (Diamond, McDevitt, Hinton, Miki, Dif-Pradalier, Wang) 09-10/09
34. *ITPA Joint Transport & Confinement/Pedestal Meetings and Research and Collaboration*, PPPL, Princeton, NJ (Diamond, McDevitt) 10/09
35. *Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas General Meeting*, University of Wisconsin, Madison, WI (Diamond - Unable to attend due to illness) 10/09
36. *51st Annual Meeting of the APS/DPP, Research and Collaboration*, Atlanta, GA (Diamond, Hinton, McDevitt, Miki, Dif-Pradalier, Kosuga, Lee; Malkov - Unable to attend due to schedule conflict) 11/09
37. *Fermi Meeting*, Washington, DC (Malkov) 11/09
38. *5th Korean Astrophysics Workshop-Shock Waves, Turbulence and Particle Acceleration*, Asia Pacific Center for Theoretical Physics, Pohang, Korea (Diamond, Malkov) 11/09
39. *The 19th International Toki Conference (ITC19) on Advanced Physics in Plasma and Fusion Research*, Ceratopia Toki, Toki, Japan (Diamond, Kosuga) 12/09
40. *Research and Collaboration at NFRI*, Daejeon, Korea (Diamond) 01/10
41. *DIII-D Pedestal Transport Workshop*, San Diego, CA (Diamond) 02/10
42. *CMTFO Annual Meeting*, Santa Cruz, CA (Diamond, Hsu) 03/10
43. *Nonlinear Wave Workshop 8*, La Jolla, CA (Diamond, Malkov) 03/10
44. *Hierarchical Self-Organization of Turbulence and Flows in Plasmas, Oceans and Atmospheres JIFT Workshop*, La Jolla, CA (Diamond, Hinton, Malkov, Miki, Dif-Pradalier, Kosuga, Zhao, Lee, Ulvestad) 03/10
45. *4th Meeting of Transport and Confinement ITPA Topical Group*, Culham, UK (McDevitt) 03/10
46. *CPES Meeting*, Annapolis, MD (Diamond, Hinton, Dif-Pradalier) 04/10
47. *2010 U.S. Transport Task Force Workshop*, Annapolis, MD (Diamond, Hinton, McDevitt, Miki, Dif-Pradalier, Kosuga, Lee, Zhao, Seo, Ulvestad) 04/10
48. *European Physical Society 37th Conference on Plasma Physics*, Dublin, Ireland (Malkov, Dif-Pradalier) 06/10
49. *Workshop on Electric Fields, Turbulence and Self-Organization in Magnetized Plasmas*, Dublin, Ireland (Dif-Pradalier) 06/10
50. *Research and Collaboration - HL-2A Center for Fusion Science*, Chengdu, China (Diamond) 06/10
51. *Research and Collaboration at CEA Cadarache*, St Paul lez Durance, France (Dif Pradalier) 07/10
52. *International Summer Institute for Modeling in Astrophysics Transport Processes in Astrophysics*, Santa Cruz, CA (Diamond) 07/10
53. *Research and Collaboration at University of Maryland*, College Park, MD (Malkov) 08/10

54. *Research and Collaboration at WCI NFRI*, Daejeon, ROK (Diamond, Hsu, Zhao, Kosuga) 08/10-11
55. *3rd EFDA Transport Topical Group Meeting combined with 15th EU-US Transport Task Force Meeting*, Cordoba, Spain (McDevitt, Dif-Pradalier) 09/10
56. *Research and Collaboration at Ecole Polytechnique*, Saclay, France (Diamond, Dif Pradalier) 09/10
57. *23rd IAEA Fusion Energy Conference*, Daejeon, Republic Of Korea (Diamond, McDevitt, Dif-Pradalier, Guo, Hsu) 10/10
58. *Research and Collaboration at WCI NFRI*, Daejeon, Republic Of Korea (Dif-Pradalier) 10/10
59. *52nd Annual Meeting of the APS Division of Plasma Physics*, Chicago, IL (Diamond, Malkov, Hinton, Dif-Pradalier, Kosuga, Lee, Zhao) 11/10
60. *Research and Collaboration at WCI NFRI*, Daejeon, Republic Of Korea (Diamond, Hsu, Zhao, Kosuga) 08/10-11
61. *20th International Toki Conference (ITC-20) on the Next Twenty Years in Plasma and Fusion Science*, Toki, Japan (Kosuga) 12/10
62. *Joint Plasma Kavli Institute for Astronomy and Astrophysics*, Peking University, People's Republic of China, 01/11 (Diamond)
63. *Center for Momentum Transport and Flow Organization Annual Meeting*, New Orleans, LA (Diamond, Dif-Pradalier) 01/11
64. *2011 KSTAR Conference and KO-US Workshop*, Muju, Korea, 02/11 (Diamond)
65. *Dynamics and Turbulent Transport in Plasmas and Conducting Fluids*, des Houches, France (Diamond, Kosuga, Hsu) 02/11

UCI Final Report for SciDAC GPS-TTBP (3/1/2008-2/28/2011)
3/25/2011

Institution:	University of California, Irvine
City, State:	Irvine, CA
Award No.:	DE-FC02-08ER54957
Award Title:	Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas
PI:	Lin, Zhihong

Team members:
Zhihong Lin, Liu Chen, Y. Nishimura, I. Holod, W. L. Zhang, Y. Xiao, W. J. Deng, H. S. Zhang
Department of Physics and Astronomy, University of California, Irvine

3.) Executive Summary, to include:
a.) how the research adds to the understanding of the area investigated
b.) the technical effectiveness and economic feasibility of the methods or techniques investigated or demonstrated
c.) how the project is otherwise of benefit to the public

This grant ($190,000 per year at UCI) partially supports PI and co-PI (Lin and Chen), four postdoctoral researchers (Nishimura, Holod, Zhang, and Xiao), and two Ph. D graduate students (Deng and Zhang) on several research topics related to the gyrokinetic particle simulation of electrostatic and electromagnetic instabilities and turbulence in fusion plasmas. The UCI GPS-TTBP research heavily leveraged outside collaborators and other UCI resources including SciDAC GSEP and CPES centers, Plasma Science Center, and OFES base theory program.

A coordinated campaign has delivered a single GTC version capable of nonperturbative (full-f) and perturbative (δf) simulations, multiple ion species, global general geometry (EFIT) and profile (TRANSP), neoclassical effects with Fokker-Planck collision operators conserving particle, momentum and energy, equilibrium radial electric field with toroidal and poloidal rotations, sources/sinks and external antenna, kinetic electrons and electromagnetic fluctuations, and perfectly scalable on the petascale computer with more than 10^5 cores. GTC is the unique gyrokinetic code in the world fusion program that possesses simultaneously all these advanced physics capabilities and computational power.

The UCI team continued to productively apply GTC for physics studies leading to high-impact publications (including 3 PRL papers) and invited talks at major national and international conferences (including APS-DPP, EPS, Sherwood, IAEA-TCM, and SciDAC). These physics applications include the discovery of nondiffusive transport in CTEM turbulence, kinetic electron effects on momentum transport, spreading and propagation of ITG and CTEM turbulence in reversed shear plasmas, and the cancellation between the perpendicular convective nonlinearity and the parallel nonlinearity in GAM self-interaction.

The GTC team at UCI worked with outside collaborators on GTC simulation of ETG turbulence in CLM experiment at Columbia University (Horton), GTC optimization (Klasky of ORNL, Wichmann of Cray, Decyk of UCLA, Chame of USC), object-oriented programming (Decyk), visualization (Ma of UC Davis and Shen of Ohio State U), workflow and advance I/O (Klasky and Lofstead of George Tech), identification of structures and statistical analysis of event sizes (Kamath of LLNL), and critical study of applications and architectures designated by DOE ASCR.

2.) Provide a comparison of the actual accomplishments with the goals and objectives of the project.

UCI Project summary in the proposal submitted in 2007 states:

"We propose to further develop the global, particle-in-cell, gyrokinetic toroidal code (GTC) for simulations of plasma turbulence and transport, and to advance understanding and our ability to control radial transport of heat, momentum, and particles in magnetically confined plasmas with temperatures up to those required for nuclear fusion power production regimes called burning plasmas. Building on the excellent physics capabilities and high performance computing, GTC will be extensively applied to simulate experimentally relevant parameter regimes including electromagnetic fluctuations, kinetic electrons, multiple ion species, realistic collision operators, and shaped plasmas. Collaborative code development will be pursued to accelerate implementations of new physics capabilities including long time steady state simulation with profile evolution, and core-edge coupling. The new simulation capabilities and access to tera- and petascale computers will allow us to address new physics and parameter regimes important for burning plasma experiments such as International Thermonuclear Experimental Reactor (ITER)."

Among the three key goals and objectives (code development, comprehensive physics simulation, and core-edge coupling), we have achieved fully the first two goals, namely,

1. "to further develop the global, particle-in-cell, gyrokinetic toroidal code (GTC) for simulations of plasma turbulence and transport, and to advance understanding and our ability to control radial transport of heat, momentum, and particles in magnetically confined plasmas with temperatures up to those required for nuclear fusion power production regimes called burning plasmas."
2. "GTC will be extensively applied to simulate experimentally relevant parameter regimes including electromagnetic fluctuations, kinetic electrons, multiple ion species, realistic collision operators, and shaped plasmas."

Regarding the third objective,

3. "Collaborative code development will be pursued to accelerate implementations of new physics capabilities including long time steady state simulation with profile evolution, and core-edge coupling."

While we have productively engaged in collaborative code development and made satisfactory progress on implementing new physics including long time steady state simulation with profile evolution, we have not achieved the goal of core-edge coupling.

3.) Summarize project activities for the entire period of funding including:

a.) original hypotheses
b.) approaches used
c.) problems encountered and departure from planned methodology and an assessment of their impact on the project results

Include, if applicable, facts, figures, analyses and assumptions used during the left of the project to support the conclusions.

Summary of physics highlights:

(1) Evidence of non-diffusive transport of trapped electron mode turbulence--

GTC simulations of collisionless trapped electron mode (CTEM) turbulence find the electron heat transport exhibiting a gradual transition from Bohm to gyro-Bohm in device size scaling. Turbulence eddies are predominantly microscopic but with a significant mesoscale component. The radial profile of the electron heat conductivity only follows the profile of fluctuation intensity on a global scale, whereas the ion transport is more sensitive to the local fluctuation intensity. This suggests the existence of a non-diffusive component in the electron heat flux, which is characterized by a probability density function that deviates from a lognormal distribution. The non-diffusive transport arises from the ballistic radial *ExB* drift of trapped electrons due to a combination of the presence of mesoscale eddies and the weak detuning of the toroidal precessional resonance that drives the CTEM instability. In contrast, the ion radial excursion is not affected by mesoscale eddies due to the parallel decorrelation. This effect is not operational for trapped electrons because of the bounce averaging process associated with the fast electron parallel motion and was confirmed by a comprehensive analysis of kinetic and fluid time scales.

(2) Turbulence spreading and non-local transport in reversed shear plasmas--

GTC simulations of reversed magnetic shear plasmas find that the linear eigenmode of the ITG instability exhibits a mode gap around the minimum safety factor ($q_{\min}$) region when $q_{\min}$ is an integer, and that the CTEM instability is suppressed in the negative-shear region. However, after nonlinear saturation, the ITG gap is filled up by turbulence spreading. The CTEM fluctuations propagate into the stable negative-shear region. Our finding indicates that the electrostatic drift wave turbulence itself does not support either a linear or a nonlinear mechanism for the formation of internal transport barriers in reversed magnetic shear plasmas, when the $q_{\min}$ crossing is an integer. In a related analytic study, the stationary solution of the coupled partial differential equations governing the self-consistent spatiotemporal evolution of a drift-wave (DW) radial envelope and a zonal-flow (ZF) amplitude yields the formation of DW-ZF soliton structures, which propagate radially with speed depending on the envelope peak amplitude. The propagation of solitons causes significant radial spreading of DW turbulence and therefore can affect transport scaling with the system size by broadening of the turbulent region.

(3) Energetic particle transport by microturbulence--

GTC simulations of the energetic particle diffusion by the ITG turbulence find that the diffusivity decreases drastically for high-energy particles due to the averaging effect of the large gyroradius and banana width, and also the fast wave-particle decorrelation. By performing the integration in phase space, we can calculate the diffusivity for any distribution function. The NBI ion diffusivity driven by the ITG turbulence is found to decrease rapidly for born energies up to an order of magnitude of the background plasma thermal energy and is a very low level at even higher born energies. Results from GTC simulations have been used to explain many features of the measured fast-ion transport in the DIII-D tokamak.

(4) Momentum turbulent transport--

On the turbulence simulation time scale (many correlation times or milliseconds), a significant redistribution of toroidal momentum is observed in GTC simulations of ITG turbulence, resulting in a peaked momentum profile in the central region of the radial domain. Diffusive and off-diagonal (pinch and residual) fluxes are identified and delineated. Both simulation and quasilinear theory find that the ratio of momentum to heat conductivity is smaller than unity even after subtracting the pinch contribution when wave-particle resonance energy is larger than the thermal energy. The magnitude and structure of the momentum flux follows gyroBohm scaling for large device size. The symmetry breaking due to the shear of the radial electric field is found to be a mechanism for generating the residual momentum flux. However, it is small compared to the momentum pinch term in the case of a finite background rotation. The trapped electrons in the ITG turbulence increase the intensity and modify the spectral properties, leading to the increase of the toroidal momentum pinch.

Highlights of GTC developments

Parallelization and optimization—

GTC employs three levels of parallelism. The original parallel scheme implemented in GTC is a 1D domain decomposition using MPI. Each MPI process is in charge of a spatial domain with both particles and fields. Particles can move from one domain to another, but all communications are one-directional to avoid traffic congestion. A second level of parallelism was later implemented to increase the concurrency. Within each spatial domain, we divide the particles between several MPI processes, but each process keeps a copy of all the fields in the domain. To take advantage of the shared memory capability of multi-core nodes, a third level of parallelism was implemented at the loop level using OpenMP compiler directives. These three levels of parallelism enable GTC to scale up to a very large number of processors. The weak scaling of the GTC computing power is almost a linear function of the number of cores for more than 100,000 of cores on the Cray XT5. GTC is portable and optimized for various scalar and vector supercomputers including Blue Gene/L, Earth Simulator, and Cray XT5.

Monitoring and controlling particle noise in PIC simulation—

PIC simulation suffers from discrete particle noise. To quantify the effects of the particle noise, statistical properties and noise-driven transport were studied in GTC simulations of stable plasmas. The noise spectrum was directly measured in the simulation. A quasilinear theory was employed to calculate the transport driven by this spectrum. This analytic result agrees with the measured noise transport. It is established both analytically and computationally that the noise contribution to the overall transport in turbulence simulations can be estimated using the numerical entropy. Such estimation of noise transport is computationally easy and has become a routine diagnostic in all GTC simulations to monitor the effects of particle noise.

4.) Identify products developed under the award and technology transfer activities, such as:

a.) Publications (include journal name, volume, issue), conference papers, or other public releases of results

1. *Guiding center orbit studies in a tokamak edge geometry employing Boozer and Cartesian coordinates*, Y. Nishimura, Y. Xiao, and Z. Lin, *Contributions Plasma Phys.* 48, 224-228 (2008).
2. *Transport of Energetic Particles by Microturbulence in Magnetized Plasmas*, Wenlu Zhang, Zhihong Lin, and Liu Chen, *Phys. Rev. Lett.* 101, 095001 (2008).
3. *Gyrokinetic particle simulations of toroidal momentum transport*, I. Holod and Z. Lin, *Phys. Plasmas* 15, 092302 (2008).
4. *Full Torus Electromagnetic Gyrokinetic Particle Simulations with Kinetic Electrons*, Y. Nishimura, Z. Lin and L. Chen, *Commun. Comput. Phys.* 5, 183-194 (2009).
5. *Turbulent transport of trapped electron modes in collisionless plasmas*, Yong Xiao and Zhihong Lin, *Phys. Rev. Lett.* 103, 085004 (2009).
6. *Radial Spreading of Drift-Wave-Zonal-Flow Turbulence via Soliton Formation*, Z. H. Guo, L. Chen, F. Zonca, *Phys. Rev. Lett.* 103, 055002 (2009).
7. *Properties of microturbulence in toroidal plasmas with reversed magnetic shear*, Wenjun Deng and Zhihong Lin, *Phys. Plasmas* 16, 102503 (2009).
8. *The Importance of parallel nonlinearity in the self-interaction of geodesic acoustic mode*, H. S. Zhang, Z. Qiu, L. Chen, and Z. Lin, *Nuclear Fusion* 49, 125009 (2009).
9. *Collisionless damping of short wavelength geodesic acoustic modes*, Z. Y. Qiu, L. Chen, and F. Zonca, *Plasma Phys. Control. Fusion* 51, 012001 (2009).
10. *Advanced simulation of electron heat transport in fusion plasmas*, Z Lin, Y Xiao, I Holod, W Zhang, W Deng, S Klasky, J Lofstead, C Kamath, and N Wichmann, *Journal of Physics: Conference Series* 180, 012059 (2009).
11. *Electromagnetic formulation of global gyrokinetic particle simulation in toroidal geometry*, I. Holod, W. L. Zhang, Y. Xiao, and Z. Lin, *Phys. Plasmas* 16, 122307 (2009).
12. *Effects of electron dynamics in toroidal momentum transport driven by ion temperature gradient turbulence*, I. Holod and Z. Lin, *Plasma Phys. Contr. Fusion* 52, 035002 (2010).
13. *Fluctuation characteristics and transport properties of collisionless trapped electron mode turbulence*, Yong Xiao, Ihor Holod, Wenlu Zhang, Scott Klasky, and Zhihong Lin, *Phys. Plasmas* 17, 022302 (2010).
14. *Scalings of energetic particle transport by ion temperature gradient Microturbulence*, Wenlu Zhang, Viktor Decyk, Ihor Holod, Yong Xiao, Zhihong Lin, and Liu Chen, *Phys. Plasmas* 17, 055902 (2010).
15. *Trapped Electron Damping of Geodesic Acoustic Mode*, Huasen Zhang and Zhihong Lin, *Phys. Plasmas* 17, 072502 (2010).
16. *Gyrokinetic Simulation of Turbulence Driven Geodesic Acoustic Modes in Edge Plasmas of HL-2A Tokamak*, Feng Liu, Z. Lin, J. Q. Dong, K. J. Zhao, *Phys. Plasmas* 17, 112318 (2010).
17. *Gyrokinetic particle simulations of reversed shear Alfven eigenmode excited by antenna and fast ions*, Wenjun Deng, Zhihong Lin, Ihor Holod, Xin Wang, Yong Xiao, and Wenlu Zhang, *Phys. Plasmas* 17, 112504 (2010).
18. *Gyrokinetic particle simulation of beta-induced Alfven eigenmode*, H. S. Zhang, Z. Lin, I. Holod, X. Wang, Y. Xiao, W. L. Zhang, *Phys. Plasmas* 17, 112505 (2010).

Invited Talk:

1. L. Chen, Alfven Prize address, *35th European Physical Society Conference on Plasma Physics; 2008, Crete, Greece.*
2. Y. Xiao, *International Sherwood Fusion Theory Conference*, May 3-5, 2009, Denver.
3. W. Zhang, *51st Annual Meeting of the APS Division of Plasma Physics*, November 2-6, 2009, Atlanta, GA.
4. Z. Lin, *SciDAC Conference*, June 14-18, 2009, San Diego.
5. Z. Lin, *Transport Task Force workshop*, 2009, San Diego, USA.
6. Z. Lin, *4th IAEA-Technical Meeting on the Theory of Plasma Instabilities*, May 18-20 2009, Kyoto, Japan.
7. L. Chen, *4th IAEA-Technical Meeting on the Theory of Plasma Instabilities*, May 18-20 2009, Kyoto, Japan.
8. W. J. Deng, *International Sherwood Fusion Theory Conference*, April 19-21, 2010, Seattle, USA.
9. W. L. Zhang, *International Sherwood Fusion Theory Conference*, April 19-21, 2010, Seattle, USA.
10. Z. Lin, *7th International Conference on Computational Physics*, May 17-20, 2010, Beijing, China.

Media highlights:

1. 07/26/2010 USBPO Topical Group Highlights: Gyrokinetic Simulations and Experimental Evidence of Energetic Particle Transport by Microturbulence
2. *SciDAC Review*, special issue 2009, "*Breakthrough Fusion Simulation Sheds Light on Plasma Confinement*",
3. *HPCwire*, 07/29/2009, "*Fusion Gets Faster*".
4. SciDAC Review, Spring 2008, "*Supercomputing Boosts Fusion Research*".
5. *Reuters*, 07/29/2008, "*Researchers Run World's Largest-Scale Fusion Energy Simulation on Cray Supercomputer*".

b.) Web sites that reflect the results of this project
http://phoenix.ps.uci.edu/GTC/

c.) Networks or collaborations fostered
d.) Technologies/Techniques
e.) Inventions/Patent Applications, licensing agreement
f.) Other products, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment

The key production code GTC of the project has been released on:
http://phoenix.ps.uci.edu/GTC/

A parallel 1D PIC code for education has been released on:
http://phoenix.ps.uci.edu/zlin/pic1d/

5.) Projects involving computer modeling, provide the following:

a.) model description, key assumptions, version, source and intended use
b.) performance criteria for the model related to the intended use
c.) test results to demonstrate the model performance criteria were met (e.g. code verification/validation, sensitivity analyses, history matching with lab or field data, as appropriate)
d.) theory behind the model, expressed in non-mathematical terms
e.) mathematics to be used, including formulas and calculation methods
f.) whether or not the theory and mathematical algorithms were peer reviewed, and, if so, include a summary of theoretical strengths and weaknesses
g.) hardware requirements
h.) documentation (e.g. users guide, model code)

GTC is a gyrokinetic particle code for simulation of microturbulence and energetic particle turbulence and transport in general toroidal geometry. A single GTC version (GTC3) has the following capabilities:

- both nonperturbative (full-f) and perturbative (δf) simulations
- kinetic electrons and electromagnetic fluctuations
- global general geometry (e.g., up-down asymmetry & non-axisymmetric) and profiles
- multiple ion species
- Fokker-Planck collision operators conserving particle, momentum and energy
- equilibrium radial electric field with toroidal and poloidal rotations
- sources/sinks and external antenna
- perfectly scalable on the petascale computer with more than 10^5 cores
- global field-aligned mesh without any approximation in geometry
- parallel solver PETSc
- advanced I/O ADIOS

GTC solves nonlinear gyrokinetic Maxwell equations and uses finite difference in time and space and PETSc linear solver. A multi-level parallelism leads to perfect scalability for 100,000+ cores and is portable on most of parallel supercomputers (jaguar & jaguarpf at ORNL, franklin & hopper II at NERSC), Tianhe-1A in Tianjin (currently the fastest computer) and linux clusters.

GTC has been verified for simulation of the following physical modes: ITG, CTEM, ETG, TAE, RSAE, EPM, BAE, KBM, ideal ballooning mode, and neoclassical transport. GTC has performed simulation for the following tokamak discharges: DIII-D (shots #101391, 126442, 138392), NSTX (shot # 120967), and HL-2A (shot # 6835).

GTC has been benchmarked with FULL, GT3D, XGC1, GYSELA, HMGC, TAEFL, and BOUT++. Verification of GTC includes zonal flow R-H residue and collisional damping of zonal flows, cyclone benchmark, kinetic electron and electromagnetic fluctuations, and neoclassical transport. GTC global simulation of device size scaling of ITG transport (PRL2002) has now been verified by both PIC and continuum codes after eight years (PRL2010).

PPPL INSTITUTIONAL FINAL REPORT – The SciDAC Project of Gyrokinetic Particle Simulation of Turbulence and Transport in Burning Plasmas (GPS-TTBP)

T. S. Hahm (PPPL's co-PI), S. Ethier, W. W. Lee, G. Rewoldt, W. X. Wang

Executive Summary

At PPPL during the funding period of the SciDAC project, extensive research using high performance global gyrokinetic simulations with the GTS and GTC-NEO codes has been carried out in close coupling with experimental and theoretical studies to address key physics issues identified by the GPS-TTBP project. The emphasis of our studies was placed on non-diffusive momentum transport, intrinsic rotation generation and electron thermal transport that are critical to burning plasma confinement physics.

Momentum transport and plasma flow generation are complex transport phenomena of great importance in magnetic confinement fusion research. It is generally believed that the prospects for achieving high quality plasma performance in magnetically-confined plasmas will be significantly enhanced by optimizing plasma flow characteristics. This can play a critical role in both controlling large-scale (macroscopic) plasma instability and in reducing energy loss due to plasma micro-turbulence. The intrinsic or spontaneous rotation phenomena widely observed in current fusion devices are expected to have a major influence on controlling the plasma rotation in ITER burning plasma experiments. Developing the needed understanding for realistically simulating/modeling the associated dynamics is clearly a high priority area of current research. Computational studies of turbulence-driven non-diffusive momentum transport and intrinsic rotation using nonlinear global gyrokinetic simulations have produced original results which have contributed to elucidating the underlying mechanisms for intrinsic rotation generation and the physics lying behind the associated empirical scalings deduced from the large experimental database (e.g., the well-known Rice scaling [J. E. Rice *et al.*, Nucl. Fusion, **47**, 1618 (2007).]) obtained in multiple devices. These are important contributions for building the fundamental understanding required to make reliable predictions of plasma rotation in ITER. Systematic gyrokinetic simulations were extended to address the role of the residual turbulence found in the presence of strong $\mathbf{E} \times \mathbf{B}$ flow shear, which provides a viable explanation of the puzzling experimental result of highly anomalous momentum transport coexisting with near neoclassical ion heat transport. These simulation studies mainly focused on electron turbulence regimes due to trapped electron modes, and have made essential contributions to the success of the FY 2010 DOE FES Theory Performance Target on momentum transport (led Dr. P. H. Diamond of UCSD).

Plasmas in various magnetic fusion experiments universally exhibit anomalous electron energy transport whose origin, however, remains unknown under most circumstances. As a candidate for driving the electron transport, short scale fluctuations driven by the electron temperature gradient (ETG) modes have been a subject of high interest to experiment, sim-

ulation and theory. The role of ETG turbulence is also an important issue for ITER, for which energy losses are expected to be dominated by electron transport. Using the GTS code, global, nonlinear simulations of ETG turbulence for experimental discharges have been carried out with emphasis on direct validation against high-k scattering measurements of electron gyroradius scale fluctuations in NSTX, and quantitatively testing the role of ETG for driving anomalous electron energy transport in experiments. This unique simulation study offers interesting new insight into the characteristics of ETG turbulence in experimental conditions and the underlying nonlinear spectral dynamics. The key results of our simulations also include the prediction of significant ETG-induced contributions to anomalous electron heat transport in NSTX, and predicted frequency and wavenumber spectra that are in general agreement with experimental observations.

In summary, computational and theoretical studies have been actively pursued at PPPL under the scientific and financial support of the GPS-TTBP project, which have closely and effectively addressed the important physical issues targeted by the project. Particularly, state-of-the-art, first-principles-based global gyrokinetic simulations, which exploit leadership-class computational resources and cooperate with experimental and theoretical studies, were shown to lead to real advances in understanding key physics issues in fusion science, meeting the proposed goal of the GPS-TTBP project.

Summary of project activities and accomplishments

– **Nonlinear gyrokinetic simulation studies of non-diffusive toroidal momentum transport and intrinsic rotation generation** Systematic studies of turbulence-driven non-diffusive momentum transport and intrinsic rotation using nonlinear global gyrokinetic simulations have produced original results which have contributed to elucidating the underlying mechanisms for intrinsic rotation generation and the physics lying behind the associated empirical scalings deduced from the large experimental database (e.g., the well-known Rice scaling) obtained in multiple devices. These contribute to building the fundamental understanding required to make reliable predictions of plasma rotation in ITER. The simulation studies have carried out in close collaboration with theoretical and experimental studies. Key results include the discovery of an important nonlinear flow generation process due to a non-diffusive component of turbulent stress (called residual stress). This is produced by the fluctuation intensity and the intensity gradient of the turbulence associated with the well-known ion temperature gradient (ITG) mode and the trapped electron mode (TEM) – all in the presence of asymmetry in the parallel wave-number spectrum induced by the turbulence self-generated low-frequency zonal flow shear. This provides an effective, universal mechanism to drive intrinsic rotation via wave-particle resonant interactions. Such turbulence-driven intrinsic rotation has a strong relevance to experimental observations because it scales close to linearly with plasma gradients and the inverse of the plasma current in various turbulence regimes. As such, it can qualitatively recover the empirical scalings of intrinsic rotation observed in various experiments. The origin of the current scaling is

found to be the enhanced $k_{\|}$-symmetry breaking induced by increased magnetic shear as the current decreases. The physics origin for the linear dependence of intrinsic rotation on the pressure gradient comes from the fact that both turbulence intensity and the zonal flow shear, which are two key ingredients for driving the stress, increase with the strength of the turbulence drive. The special impact of this research is that it focuses on electron transport dominated regimes that are especially significant for ITER, but which are difficult to access in current experiments.

– **Nonlinear gyrokinetic theory of turbulence and transport** Significant, fruitful progress in theoretical studies of turbulence driven non-diffusive momentum transport has been achieved with the support of this SciDAC project, which has contributed a great deal to the research goals of the GPS-TTBP project. The theoretical studies using modern nonlinear gyrokinetics mainly focused on elucidating the physics mechanisms for turbulence driven non-diffusive transport, particularly, the momentum pinch and residual stress.

– **The effect of meso-scale transport in trapped electron mode turbulence** Global GTS simulations have found that meso-scale phenomena and associated nonlocal transport are largely enhanced in the trapped electron mode (TEM) turbulence regime due to strong coherent wave-particle interaction at the trapped electron precession frequency. Robust radial pinches in toroidal flow, heat and particles, which emerge "in phase" in collisionless TEM turbulence, are found to play important roles in determining plasma profiles. Particularly, toroidal flow perturbations, which are generated locally by the turbulence, are found to propagate radially. This "flow pinch" result amazingly reproduces the experimental phenomenon of radially inward penetration of perturbed flows created by modulated beams in peripheral regions, and thus is highly illuminating.

– **How particles contribute to plasma transport due to turbulence** Our nonlinear gyrokinetic simulations have revealed highly distinct phase space structures between ITG and TEM turbulence for momentum, energy and particle fluxes, with a lot of interesting details with regard to which and how particles contribute to ion and electron transport in different channels. This study can ultimately help elucidate the roles of resonant and non-resonant particles in plasma transport in different turbulence regimes, which is a highly non-trivial issue under turbulence circumstances with many modes nonlinearly coupled together.

– **Investigation of the effect of residual fluctuations in strong $\mathbf{E}\times\mathbf{B}$ shear** The co-existence of neoclassical-level ion heat and anomalous momentum transport has been widely observed in various machines, but with little theoretical understanding. Motivated by this, we investigated residual low-k turbulence in the regime of strong $\mathbf{E}\times\mathbf{B}$ shear and its effect on momentum and energy transport. In the presence of a strong mean (equilibrium) $\mathbf{E}\times\mathbf{B}$ flow shear, where ITG instability is linearly stabilized in the conventional sense, residual turbulence is found to survive and drive experimentally relevant toroidal momentum and ion energy transport. This observation is closely related to the observation that the dissipation effect of the $\mathbf{E}\times\mathbf{B}$ flow shear is fluctuation-mode-dependent. The $\mathbf{E}\times\mathbf{B}$ flow shear appears to act more efficiently in suppressing the growth of radially elongated linear eigenmodes,

which have lower radial wavenumbers k_r, than in damping saturated fluctuations with higher k_r. We have demonstrated for a DIII-D experiment that the residual-fluctuation-driven transport may offer one explanation for widely observed puzzling experimental results that toroidal momentum transport remains highly anomalous, even when ion heat transport is reduced to close to the neoclassical level.

– **Global Gyrokinetic Simulation of Electron Temperature Gradient Turbulence and Transport in NSTX Plasmas** Global, nonlinear gyrokinetic simulations of electron temperature gradient (ETG) driven turbulence were carried out with the GTS code using actual experimental parameters of NSTX discharges. Our simulations reveal remarkable new features with regard to nonlinear spectral dynamics in 2D perpendicular wavenumber space. Specifically, there exists direct, strong energy coupling between high-k ETG modes and electron geodesic acoustic modes (e-GAMs with high frequency and poloidal mode number m = 1). At the same time, zonal flows are generated and continuously grow with a fine radial scale. This direct energy coupling may represent a new insight into the underlying mechanism for nonlinear ETG saturation. It also implies that the collisional damping of zonal flows and e-GAMs may have considerable impact on the formation of the steady state spectrum and saturation level. Further, the ETG fluctuation spectra are characterized by strong anisotropy with $k_r \ll k_\theta$. The $k_\perp$ spectrum of density fluctuations is in general agreement with the experimental measurements using coherent scattering of electromagnetic waves. Sensitivity studies of simulated ETG-driven electron thermal transport with respect to the local profiles of electron temperature, safety factor and effective charge number have been carried out, given that plasma profiles and parameters are subject to significant experimental errors. Within experimental uncertainties in plasma profiles, we conclude that ETG turbulence may drive experimentally relevant transport for electron heat in NSTX. ETG turbulence spreading and its effects are also identified in our global simulations. Finally, a newly developed synthetic diagnostic, which reproduces the experimental conditions of high-k scattering, is shown to yield frequency spectra for simulated fluctuations, which are in reasonable agreement with experimental observations.

– **Validation applications – effects of trapped electrons on turbulent transport in experiments** GTS with fully kinetic electron physics has been applied to DIII-D experiments in the electrostatic turbulence regime, in particular for comparison with experimental results of toroidal momentum and heat transport. i) In the ITG marginality regime, trapped electron physics is shown to play a critical role in determining plasma transport, not only producing the proper ion heat flux in experiments but also largely enhancing the residual stress generation. ii) In the ITG dominant transport regime, both momentum flux and ion heat flux obtained from GTS simulation agree reasonably well with experimental measurements. iii) Large fluctuation structure (eddy) formation due to dramatic nonlinear toroidal energy cascades is observed in GTS simulations of electron temperature gradient driven TEM turbulence. This nonlinear phenomenon may have possible connection with edge blob generation in experiments.

– **Neoclassical simulation of impurity poloidal flow with nonlocal effects** A multiple ion-species simulation capability has been developed in the global particle-in-cell neoclassical code GTC-NEO. The new simulation capability of GTC-NEO has been applied to NSTX and DIII-D, calculating the poloidal flow velocity of impurities, for which experimental results in comparison with neoclassical theory predictions are not well converged, showing strong machine (or geometry) dependence. We focus our study on comparison of impurity poloidal flow between GTC-NEO predictions and NSTX measurements, and clarification of finite ion orbit effects. The key results include that GTC-NEO-predicted nonlocal poloidal flow in the collisionless regime is extended to impurities. The newly discovered poloidal flow is identified to be due to toroidal rotation shear together with the pressure gradient, which modifies the parallel flow through the finite orbit effect. Another nonlocal effect is also observed to relate to E_r shear. Simulation results are compared with theoretical estimates based on a new model using profiles relevant for NSTX. The carbon poloidal velocity observed in the simulation is in good agreement with the neoclassical theory modified by the newly identified nonlocal effects. This work has led to four theoretical papers and contributed to one experimental paper.

– **Neoclassical simulation of toroidal momentum transport with finite orbit effect** A significant off-diagonal element of neoclassical momentum flux associated with the ion temperature gradient has been identified. However, the overall neoclassical contribution to the toroidal momentum transport was shown to be negligibly small compared to experimental levels for NSTX and DIII-D plasmas.

Description of computational model and method

The proposal simulation research of GPS-TTBP project at PPPL was mainly carried out by the Gyrokinetic Tokamak Simulation (GTS) code [W. X. Wang *et al.*, Phys. Plasmas **13**, 092505 (2006); Phys. Plasmas 17, 072511 (2010)] and the GTC-NEO code [W. X. Wang *et al.*, Phys. Plasmas **13**, 082501 (2006)]. The GTS code is a full geometry, particle-in-cell code, targeting at studying core plasma micro-turbulence and transport of tokamak experiments. At present, GTS is a δf code, based on a generalized gyrokinetic simulation model and the use of realistic magnetic configurations. GTC-NEO is a global particle-in-cell neoclassical code. The major physical and computational features of GTS are described as follows.

– In the first place, the GTS code is targeted at simulating plasma turbulence and transport in practical fusion experiments. It is highly robust at treating globally consistent, shaped cross-section tokamaks by directly importing plasma profiles of temperature, density and rotation, from the TRANSP experimental database, along with the related numerical MHD equilibria reconstructed by MHD codes.

– GTS employs straight-field-line magnetic coordinates and a field-line-following mesh. The particle guiding center motion is calculated by Lagrangian equations in the flux coordinates, which allows for very accurate particle orbit integration, even with a relatively low order method due to the separation between fast parallel motion and slow perpendicular

drifts. The field-line-following mesh can best represent the nature of the quasi-2D mode structures of drift wave turbulence in toroidal systems, and hence offers the most efficient spatial resolution for highly anisotropic fluctuations. The associated grid is built according to the plasma profiles. Specifically, the grid spacing in the perpendicular direction follows the variation in the particle gyroradius according to the temperature profile. This ensures a uniform coverage of the phase space in terms of resolution.

– The GTS code solves the gyrokinetic Poisson equation in configuration space for the turbulence potential at the particle coordinates, using the field line following mesh. Unlike in flux-tube or wedge simulations, the real space, global Poisson solver, in principle, retains all toroidal modes from ($m/n = 0/0$) all the way up to a limit which is set by the grid resolution, and therefore retains full-channel nonlinear energy couplings. A proper treatment of the nonlinear toroidal mode couplings is essential, which, as generic, fundamental processes, are believed to play an important role in determining the turbulence saturation and associated transport. With the combination of inner and outer iterations, a generalized field solver is developed to approach the gyrokinetic Poisson equation in integral form, which contains different spatio-temporal scales for turbulence fluctuations and zonal flows. The generalized Poisson solver is more robust, particularly for treating kinetic electrons in general geometry, without using various approximations often adopted in other gyrokinetic simulations. This is particularly crucial for turbulence simulations under experimental conditions. The global Poisson solvers end up with a large size sparse matrix which is solved by the use of the parallel PETSc package developed at the Argonne National Laboratory.

– Fully-kinetic electron physics is included in GTS in order to simulate electron turbulence and ion turbulence with non-adiabatic electron physics. For ITG and TEM turbulence with $k_\perp \rho_e \ll 1$, we use a drift kinetic description for electrons, neglecting the finite gyroradius effects. However, for electron gyroradius scale turbulence, such as ETG driven turbulence, electrons are treated as fully gyrokinetic. Kinetic electrons are treated via two different approaches which use minimum approximations while achieving reduced noise: a) a δf method which solves for the total perturbed electron distribution function corresponding to turbulence fluctuations, and thus treats both adiabatic and non-adiabatic electrons kinetically; b) a split weight method which simulates only non-adiabatic electrons kinetically. One highlighted feature distinct from many other gyrokinetic simulations is that both trapped and untrapped electrons are included in the non-adiabatic response.

– Coulomb collisions between like particles are implemented via a linearized Fokker-Plank operator with particle, momentum and energy conservation. Electron-ion collisions are simulated by the Lorentz operator.

– GTS is coupled with neoclassical physics via interfacing with the GTC-NEO code which calculates the neoclassical equilibrium, transport and electric field with finite orbit effects.

– GTS has three levels of parallelism: a one-dimensional domain decomposition in the toroidal direction, dividing both the grid and the particles, a particle distribution within each domain, which further divides the particles between processors, and a loop-level multi-

threading method. The domain decomposition and the particle distribution are implemented with MPI, while the loop-level multi-threading is implemented with OpenMP directives. The three levels make GTS a massively parallel, highly scalable code that can run ITER scale simulations on petaflop machines with hundreds of thousands of processor cores. Simulations associated the GPS-TTBP project were performed on Franklin at the National Energy Research Scientific Computing Center (NERSC) and on Jaguar/pf at the National Center for Computational Sciences (NCCS).

Verification and validation of simulation models

The GTS code has been well benchmarked in various turbulence regimes in simple geometry cases with other gyrokinetic codes including FULL, GEM and GTC. As part of the verification studies, extensive convergence studies have been also carried out in nonlinear ITG and TEM turbulence regimes. Ideally, the dynamics of gyrokinetic turbulence should be robust to numerical techniques. These convergence studies have assured that simulation results are robust to different approaches for solving the gyrokinetic Poisson equation, the size of the simulation grids and the number of simulation particles. Discrete particle noise and its effect on simulation results have been also examined in GTS simulations. It was shown that the growth of particle weight is driven by physics associated with plasma profile evolution induced by turbulence transport, and is independent of the number of particles used in the GTS production simulations. Over a time scale which is much longer than the turbulence correlation time, but shorter than the profile evolution time, the particle weight remains at a low level, showing little impact on the results of simulated transport (Fig. 1).

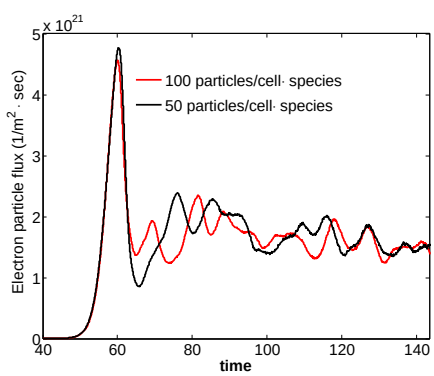

FIG. 1: Time history of electron particle fluxes driven by CTEM turbulence from two simulations using different numbers of simulation particles.

During the GPS-TTBP project period, extensive validation studies have been carried out by applying the GTS code to NSTX and DIII-D plasmas in the electrostatic regime. Mentioned below are just a couple of typical examples. Global, nonlinear GTS simulations of ETG turbulence for experimental discharges have been carried out with emphasis on direct validation against high-k scattering measurements of electron gyroradius scale fluctuations in NSTX, and quantitatively testing the role of ETG for driving anomalous electron energy

transport in experiments. The key results of this unique study include the prediction of significant ETG-induced contributions to anomalous electron heat transport in NSTX, and predicted frequency and wavenumber spectra that are in general agreement with experimental observations (see Fig. 2 below). This simulation study also offers interesting new insight into the characteristics of ETG turbulence in experimental conditions and the underlying nonlinear spectral dynamics. GTS simulations for a DIII-D discharge with large toroidal flow driven by neutral beam injection have found that residual fluctuations can survive strong mean $\mathbf{E} \times \mathbf{B}$ flow shear, and drive experimentally relevant transport. This finding provide a plausible explanation for the puzzling experimental observation of the co-existence of anomalous momentum transport and a neoclassical level of ion heat transport.

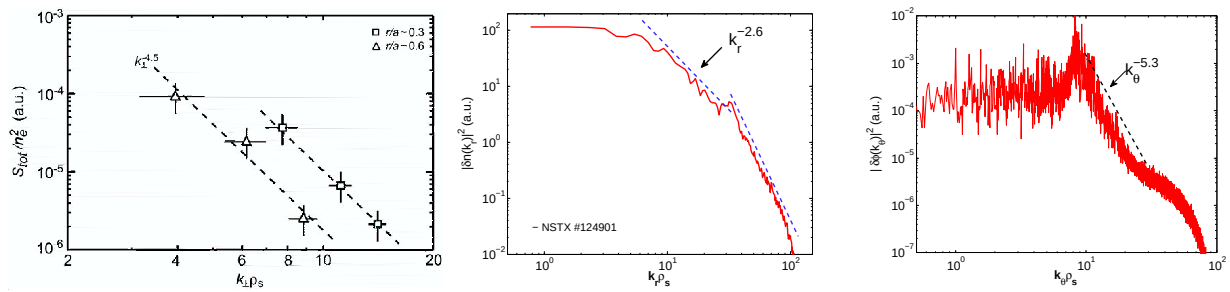

FIG. 2: Turbulence fluctuation spectral comparison between experiment (left) and simulation (right). The power index value measured from the NSTX experiment (-4.5) is a combination of the radial and poloidal directions of the wave vector, which is in general agreement with the simulated spectra for which the power index in k_r and k_θ are -2.6 and -5.3, respectively.

Publications and conference papers of GPS-TTBP project produced during the funding period

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University of Texas at Austin Final Report for SciDAC
GPS-TTBP (3/1/2008-2/28/2011)
3/30/2011

Institution:	University of Texas at Austin
City, State:	Austin, TX
Award No.:	DE-FC02—08ER54961
Award Title:	Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas
PI:	Horton, Wendell

Team members:
Wendell Horton, Sean (Xiangrong) Fu, Lee Leonard, Cynthia Correa,
Institute for Fusion Studies and Department of Physics, University of Texas at Austin

1) Executive Summary

This grant ($90,000 per year at the University of Texas at Austin) partially supports the PI, two Ph.D graduate students (X. Fu and C. Correa), and collaborating scientists (E. Asp, B. Hu, S. Futatani and Y. Xiao) on several research topics related to the use of gyrokinetic particle simulation and gyrofluid simulations for the interpretation and predictions of turbulent transport in tokamaks. Electrostatic and electromagnetic turbulent transport in fusion plasmas, including NSTX, Alcator C-Mod, Tore Supra, and TCV, were developed and published. The research was leveraged by outside collaborators from Japan, France and other US institutions and resources from the base IFS-DoE Grant.

a) The research adds to the understanding of how the simulation codes compare with the data from several of the important tokamaks and key university basic plasma physics experiments. The group at IFS UT Austin used the support to carry out large scale simulations for the NSTX, CMOD and the Columbia Linear Machine in the US and for the TCV machine in Europe. The results reported extensively at the national and international meetings. The work follows the outline presented in the original proposal of using the massively parallel machines at NERSC and the NSF-Teragrid to increase understanding of the ability of the turbulent transport codes in interpret and predict the plasma magnetic confinement data.

b) The technical effectiveness was achieved by showing the interpretations with plasma data from various tokamaks on a variety of key issues that must be solved or better understood in order to achive make fusion power. Issues associated with the loss of thermal energy through turbulent transport on multi-scale problems and the transport of impurities was the focus of the simulations performed. The methods are directly applicable to the US fusion experiments and the large international tokamak called ITER.

c) The University of Texas at Austin group worked to show the benefit of advanced computer simulations on predicting the performance of plasma discharges in the transient plasmas and that of the steady state plasma in the RF-driven steady high confinement mode fusion grade plasma in a the Tokamak Configuration Variable called TCV in Lausanne and published the results with young scientists E. Asp from Tore Supra Group in France and John (J-Y) Kim at the University as first authors with the PI experimentalists from the École Polytechnique Laboratory in Lausanne. The publication Asp, et al., Physics of Plasmas, 15, 082117 (2008) is of wide interest. Four plasma states relevant to the ITER machine were analyzed in detail with simulations. The code development simulations in 2009 and 2010 have concentrated on the Alcator C-Mod and the Columbia linear machine, while continuing comparisons with NSTX and TCV data.

The simulations will benefit the public by showing how the tokamak can be an effective new method of generating power without uranium or plutonium.

2) Comparison of the actual accomplishments with the goals and objectives of the project

The University of Texas Project proposal states:

"The IFS pseudospectral codes will be run on large parallel machines including Bassi, X10 Cray in the DoE and the Lonestar Dell cluster at the Texas Advanced Computer Center [TACC], University of Texas at Austin. The Lonestar Dell cluster has 5200PEs on 1300 Dell blades with four Intel processors per blade. This machine is being used by IFS graduate students in a Teragrid DAC project."

These projects were carried out and the Teragrid DAC project used 100,000 SUs by the end of March 2011. Much of the run time was used in the current project using the gyrokinetic code GTC in collaboration with the UC Irvine group to interpret the electron temperature gradient (ETG) driven turbulence in the basic physics experiment at the University of Columbia on a high-tech machine called the CLM. The GTC code was modified by Sean Fu (UT Austin) and the UCI developers for use on the CLM machine.

Other parts of the proposal promised simulations for comparisons with tokamaks and this was carried out and published in a large body of work on the TCV tokamak with four types of high confinement regimes. Recently, the comparisons have concentrated on the transport of boron in the Alcator C-Mod experiments with both gyrofluid and gyrokinetic simulations.

In view of the fact that the walls of ITER will be coated with Beryllium (Z=4), the validation of the simulations for Boron (Z=5) transport, which is the wall coating in C-Mode, fulfills that part of the proposal that stated:

"The new simulation capabilities and access to tera- and petascale computers will allow us to address new physics and parameter regimes important for burning plasma experiments such as International Thermonuclear Experimental Reactor (ITER)."

3) Summary of project activities for the entire period of funding:

a) Original hypothesis

The hypothesis was that the drift wave turbulence provides the means to understand and predict the observations in tokamaks and university basic plasma experiments. Through advanced simulations on massively scaled computers, this hypothesized was validated by the group's research findings.

b) Approaches used

The approach used was to continue development of the gyrofluid and gyorkinetic drift wave codes and run them for the parameters of the experiments. It often requires more than ten parameters to define the state of the plasma being measured and simulated. The nonlinear dynamics of plasmas is akin to a type of weather system, so there is sensitivity to small changes in these input parameters, especially those key drivers of input power. This is illustrated well in simulations published for the TCV discharge by the UT Austin group in collaboration with Cadarache and École Polytecnique of Lausanne.

c) Problems encountered and departure from planned methodology and an assessment of their impact on the project results: NA

Summary of physics highlights

Highlights of the Verification and Validation developments

1) Electron Turbulent Transport in NSTX device at PPPL

The simulations are used to interpret the experimental data. There are numerous examples in the publication list for this report where the simulations are essential to understand the fluctuation and transport measurements. We give one important example here in Fig. 1 for the microwave reflectometer data taken in NSTX by Mazzucato 2010. The fluctuation spectrum from the ETG turbulence simulation for NSTX is shown in the figure with the maximum linear growth rate marked by the circle on the vertical k_y axis. The data from the reflectometer is shown on the horizontal k_x axis by the four crosses. The net thermal transport is given by the sum over the entire k_x-k_y plane of the spectrum with a phase shift. Thus, without the simulation, there would not be a way to infer the thermal diffusivity from the four measurements of the electron density fluctuations.

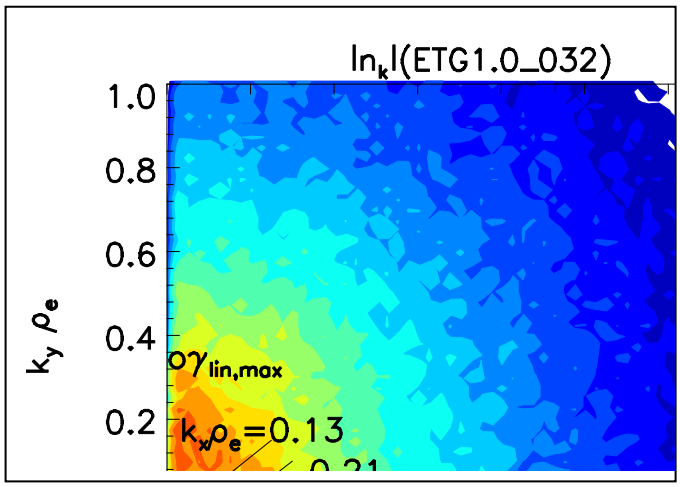

Fig. 1 The simulated spectrum of turbulence of the NSTX machine in a regime of the electron temperature gradient driven turbulence. [source Horton et al (Kaye et al. IAEA Chengdu, China 2008 and Asp, Kim , Horton et al. Physics of Plasmas, 15. 0821317 (2008). Here we show the recent results of 2010 with improvements in the simulations resolution for the NSTX experiment. The k-space in the simulation extends to twice the value shown to resolve the smallest scales of the turbulence.

There are numerous examples in the work published under this UT Austin SciDAC Grant that make the understanding of the diagnostics meaningful for the turbulent transport.

2) ETG Turbulence in the Columbia Linear Machine for Basic Validation of the ETG Mechanisms

The basic plasma experiment carried out on the Columbia Linear Machine (CLM) for the mechanisms of the ETG turbulent transport was a key topic of research during the last year of the Sci-DAC grant. We have given numerous presentations on these studies listed in Sec. 4 of the report and are preparing a journal article in collaboration with the UCI and Columbia groups.

The comparisons with both the gyrokinetic simulations and the gyrofluid codes are possible since the ETG turbulence is well described by the two-component finite electron gyroradius fluid equations. This is not true for the trapped electron mode. Therefore, the ETG mode is a more suitable problem for comparison of different simulations codes. Here we give a few key results obtained in 2010 for the ETG turbulence in the CLM machine.

In Fig. 2 we show the results of simulation obtained in March 2011 on the grant with our highest resolutions runs on the TACC Ranger computer on the Teragrid. The contours are of electric potential fluctuation in the nonlinear stage of the ETG simulation using the GTC code. Red and yellow colors represent positive values while blue and green represent negative values. Counting the number of vortex structures around the circle shows that the turbulent energy is concentrated in dominant modes with m ~ 30. This is an improvement over earlier lower resolution simulations that showed the energy concentrated at higher mode numbers near the maximum linear growth rate. The mode numbers that dominate the turbulence in Fig.2 range from m=15 to 30 and are much below the mode number for the fastest growing linear mode. In the initial stage with small amplitude waves the fastest growing with m ~ 100 grows up and dominates the spectrum. This simulation for temperature gradient instability proves that there is strong nonlinear coupling in the dynamics giving a transformation of the turbulent energy to long wavelengths.

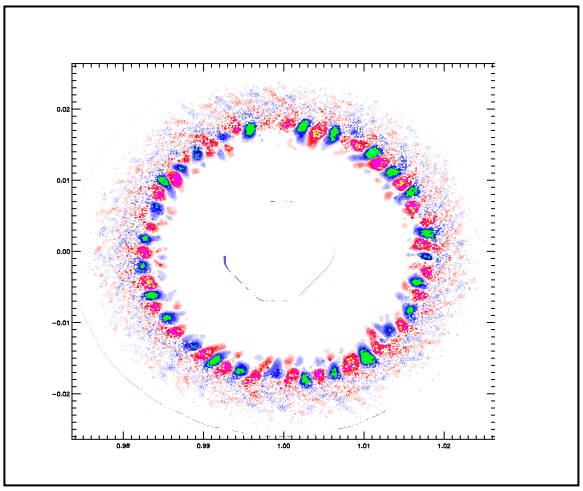

Fig. 2 Contours of constant electrostatic potentials in the nonlinear saturated state from the GTC code in a high-resolution simulation of the temperature gradient instability in the Columbia Linear Machine.

Parallelization and optimization

The simulation codes used in the project employ different levels of parallelism. The first parallel scheme implementation is over the radial direction, with radial zones communicating through MPI code.

Each radial zone has its own MPI processor with its own FFTW that computes the local wave-wave interactions. A second level of parallelism is formed by using OpenMP compiler directives. These directives tell each processor about the overall input power and slopes of the profiles across the range of local radial processors. The codes are run on both the NERSC machines and through the NSF TerraGrid authorization on the TACC machine, in particular the Ranger.

In a collaboration with T.-H. Watnabe and Todo at the National Institute for Fusion Science in Japan, we compared the scaling efficiency of several codes on the Ranger at TACC with the Earth Simulator and the Cray XT5 in Watanabe, Todo , Horton (2008).

The GTC simulations were compared with those on other machines including the University of Texas at Austin on the Sun-AMD massively parallel computer Ranger.

With a proposal, we secured a TeraGrid Project TG-PHY090081 for using GTC on the Ranger in 2009-2010. We used 100,000 SUs in the last year in running comparisons between the GTC simulations and with gyrofluid simulations. We carried out electron temperature gradient driven turbulence simulations in various types of tokamaks and in the basic plasma physics experiments at Columbia University for the properties of the ETG turbulence in steady-state hydrogen plasmas.

We ran both the gyrokinetic code GTC developed at UC Irvine and the gyrofluid Dtrans code at UT Austin for full toroidal geometry of tokamaks. The gyrokinetic code uses both openMP and MPI parallel computing technologies to derive nearly 100% efficient scaling with increasing number of processors. The gyrofluid code is mpi code with good scaling for a fluid code. Fluid codes due to the global message passing required intrinsically have lower scaling efficiency than particle-in-cell based codes.

For a typical run simulating ETG in CLM, we used 4096 cores running for 10 hours. The grid size of the simulation domain is roughly 400(radial) times 2000(poloidal) times 32(axial) simulation cells in the GTC simulations. The gyrofluid simulations use the parallelized fast fourier transform code FFTW with psuedospectral techniques, as documented in Horton and Ichikawa, Chaos and Structures in Nonlinear Plasma, for simple drift wave problems. The large grids are 512^3 and 256 $X1024^2$ which give physical k-spaces of 2/3 the size of the FFTW spectrum used in the simulation. The number of macrogyro-particles used in the simulations is 10^9.

The full 100,000 SUs of time on the on the Teragrid Project award were used by March 2011. A large, comparable number of SUs were on the NERSC computing facilities.

4) Products developed under the award and technology transfer activities, such as:

The products of this research are the computer codes developed and given on the public websites the publications and the presentations at national and international meetings.

a) Publications and presentations

Publicadtions in peer-reviewed journals published in 2009-2010

- S. Futatani, W. Horton, S. Benkadda, I. O. Bespamyantov, and W. L. Rowan, "Fluid Models of Impurity Transport via Drift Wave Turbulence," Physics of Plasmas, vol. 17, p. 072512 (2010).
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- W. Horton, C. Correa, G. D. Chagelishvili, V. S. Avsarkisov, J. G. Lominadze, J. C. Perez, J.-H. Perez, and T. A. Carter, "On generation of Alfvenic-like fluctuations by drift wave-zonal flow system in large plasma device experiments," Physics of Plasmas, vol. 16, p. 092102 (2009). doi/10.1063/1.3211197.
- T.-H. Watanabe, Y. Todo, and W. Horotn, Plasma Fusion Res. **3**, (2008) 061.

Invited Talks and Poster Presentations:

- W. Horton, X. R. Fu, W. Rowan, I. Bespamyatnov, S. Futatani, and S. Benkadda, "Turbulent Impurity Transport in ITER based on theory and C-Mod data," Session NO4: International Tokamak Research and ITER, American Physical Society –Division of Plasma Physics Annual Meeting, Atlanta, November 4, 2009.
- W. Rowan, I. Bespamyatnov, K. Gentle, K. Liao, W. Horton, X. Fu, C. Fiore, S. Benkadda, S.

Futatani, and X. Garbet, "Simulation of Turbulent Impurity Transport in Alcator C-Mod," Session PP8: C-Mod; NSTX and General Spherical Tori; Simulation and Modeling of Basic Plasma Phenomena, American Physical Society –Division of Plasma Physics Annual Meeting, Atlanta, November 4, 2009.

- C. Correa, W. Horton, G. Chagelishvili, V. Avsarkisov, J. Lominadze, J. Kim, J.C. Perez, and T. Carter, "On Generation of Alfvenic-like Fluctuations by Drift Wave-Zonal Flow System in Large Plasma Device Experiments," Session GP8: ITER, General Tokamak, Simulation and Modeling; MHD, Linear and Nonlinear Phenomena; Waves and Instabilities in Basic Plasmas, American Physical Society –Division of Plasma Physics Annual Meeting, Atlanta, November 4, 2009.
- X. Fu, P. J. Morrison, W. Horton, and I. Caldar, "Transport with Reversed Er in Gamma-10, LAPD, and the Sao Paulo Tokamak," Session UP8: Alternates; Turbulence, Transport, and Stability; Space and Astrophysical Plasmas, American Physical Society –Division of Plasma Physics Annual Meeting, Atlanta, November 5, 2009.
- G. Bateman, A. Pankin, A. Kritz, T. Rafiq, G. Park, S. Ku, C. S. Chang, W. Horton, and J. Pratt, "Extension of XGC Kinetic Simulation Codes to Magnetic Mirror Configurations," Session CM9: Mini-Conference on Innovative Magnetic Mirror Concepts and Applications II, American Physical Society –Division of Plasma Physics Annual Meeting, Atlanta, November 2, 2009.
- W. Horton, "Drift-Wave Turbulence", invited seminar, Institute for Plasma Physics and Fusion, Peking University, October 15, 2009. (invitation from Prof. X. G. Wang of Physics Department of Peking University)
- W. Horton, S. Fu, A. Beklemishev, and A. Ivanov, "Parameter Optimization Studies for a Tandem Mirror Neutron Source," Innovative Concept Conference, Princeton, New Jersey, February 16-19, 2010 (organized by Prof. Rob Goldston, Princeton University).
- W. Horton, "Electron Thermal Transport and Inpurity Transport," review talk for Department of Energy IFS Site Visit, August 27, 2009.
- W. Horton, O. Yamagishi, and A. K. Sen, "Electron Temperature Gradient Drift Mode in the Columbia Linear Machine", invited talk at the International Sherwood Fusion Theory Conference, April 23, 2010, Seattle, Washington.

b) Web sites that reflect the results of this project:
http://pecos.ph.utexas.edu/~vortex
http://orion.ph.utexas.edu/~starpower

c) Networks or collaborations fostered
- Graduate Student Sean Fu visited UCI during Mar 15-19, 2010, and Aug 16- Aug 20, 2010.
- W. Horton visited UCI during February 2010 and gave the Plasma Physics Seminar on verification and validation of the simulations with data from NSTX and TCV tokamaks.
- X. Fu, G. Hagstrom, and W. Horton visited Texas A&M University to meet fission scientists and French –US Meeting of Nuclear Energy Engineers and Scientist January 2011.
- Poster presentation and invited talks at the Young Engineer and Scientists Symposium *Turbulent Transport of Electrons in Nuclear Fusion Devices*, by Xiangrong Fu , Wendell Horton , Amiya Sen (Columbia University)

d) Technologies/Techniques
Work with National Instruments based in Austin Texas has been started with the use of the fast parallelized gyrofluid codes to design real-time control systems using their products.

This collaboration permitted the submission of two proposals to DoE and NSF-DoE for development of real-time control systems based on super fast simulations of transport and the NI PXI Express system for plasma control. The proposals were to integrate these simulation techniques and take the product to Plasma Research Center at Tsukba University to verify the data reported for the GAMMA-10 facility.

e) Inventions/Patent Applications, licensing agreement - NA

f) Other products, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment:
   - Numerous movies created from advanced simulations giving visualizations of the complex nonlinear dynamics in turbulent transport for tokamaks. http://pecos.ph.utexas.edu/~vortex

5) Projects involving computer modeling

GTC is a gyrokinetic particle code for simulation of microturbulence and energetic particle turbulence, and transport in general toroidal geometry. A single GTC version (GTC3) has the following capabilities:

- both nonperturbative (full-f) and perturbative (df) simulations
- kinetic electrons and electromagnetic fluctuations
- global general geometry (e.g., up-down asymmetry & non-axisymmetric), and profiles
- multiple ion species
- Fokker-Planck collision operators conserving particle, momentum, and energy
- equilibrium radial electric field with toroidal and poloidal rotations
- sources/sinks and external antenna
- perfectly scalable on the petascale computer with more than 10^5 cores
- global field-aligned mesh without any approximation in geometry
- parallel solver PETSc
- advanced I/O ADIOS

GTC solves nonlinear gyrokinetic Maxwell equations, and uses finite difference in time and space, and PETSc linear solver. A multi-level parallelism leads to perfect scalability for 100,000+ cores and is portable on most parallel supercomputers (jaguar & jaguarpf at ORNL, franklin & hopper II at NERSC), Tianhe-1A in Tianjin (currently the fastest computer) and linux clusters.

GTC has been verified for simulation of the following physical modes: ITG, CTEM, ETG, TAE, RSAE, EPM, BAE, KBM, ideal ballooning mode, and neoclassical transport. GTC has performed simulation for the following tokamak discharges: DIII-D (shots #101391, 126442, 138392), NSTX (shot # 120967), and HL-2A (shot # 6835).

GTC has been benchmarked with FULL, GT3D, XGC1, GYSELA, HMGC, TAEFL, and BOUT++. Verification of GTC includes zonal flow R-H residue and collisional damping of zonal flows, cyclone benchmark, kinetic electron and electromagnetic fluctuations, and neoclassical transport. GTC global simulation of device size scaling of ITG transport (PRL2002) has now been verified by both PIC and continuum codes after eight years (PRL2010).

Oak Ridge National Laboratory Final Report for SciDAC GPS-TTBP

PI: Scott Klasky

The Gyrokinetic Particle Simulation Center is a program that brings together leading experts in plasma simulation, theory, and computational sciences toaddress the grand-scientific challenge of achieving a better understanding of turbulent transport in fusion plasmas for: (1) the parameter regimes relevant to magnetic fusion experiments such as the International Tokamak Experimental Reactor (ITER), and (2) the groundwork for an integrated fusion simulation project in the future. At Oak Ridge National Laboratory (ORNL), we developed real-time monitoring routines for the Gyrokinetic Toroidal Code utilities for I/O and post-processing environments.

The research that went into this project help drive the development of the ADIOS project, http://www.olcf.ornl.gov/center-projects/adios/. This research and development centered around I/O componentization, and how to reduce the impact of I/O on simulations. This work has lead many other high-profile DOE projects to adopt theADIOS system. This work also helped to contribute to 3 publications in the computer science field. ADIOS 1.2 has now been released as an open source package, and continues to gain support within DOE, NSF, and NASA.

Our work has also been on dashboards, leveraging the OLCF funding to place the esimon dashboard, http://www.olcf.ornl.gov/center-projects/esimmon/, into the GTC workflows.

In this project, we have worked with GTC + ADIOS + esimon, and integrated these technologies into this code.

Publications:

1. Lofstead, Zheng, Klasky, Schwan, “Adaptable Metadata Rich IO Methods for Portable High Performance IO”, IPDPS 2009, IEEE Computer Society Press 2009.

2. Abbasi, H., Wolf, M., Eisenhauer, G., Klasky, S., Schwan, K., and Zheng, F. 2009. DataStager: scalable data staging services for petascale applications. In Proceedings of the 18th ACM international Symposium on High Performance Distributed Computing (Garching, Germany, June 11 - 13, 2009). HPDC '09. ACM, New York, NY, 39-48.

3. H. Abbasi, J. Lofstead, F. Zheng, S. Klasky, K. Schwan and M. Wolf,

“Extending I/O through High Performance Data Services”, Cluster Computing 2009, New Orleans, LA, August 2009.

4. R. Barreto, S. Klasky, N. Podhorszki, P. Mouallem, M. Vouk: “Collaboration Portal for Petascale Simulations”, International Symposium on Collaborative Technologies and Systems, pp. 384-393, Baltimore, Maryland, May 2009.

5. M. Polte, et al., "...And Eat it Too: High Read Performance in Write-Optimized HPC I/O Middleware File Formats," in In Proceedings of Petascale Data StorageWorkshop 2009 at Supercomputing 2009, ed, 2009.

Final Report for grant ER54797, "Center for Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas"

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The UCLA contribution to this collaborative proposal is in two general areas. One area is to enhance the performance of GTC to perform optimally on the DOE leadership class computers, the other part is to contribute to the overall object-based design for GTC as it evolves. Most of the effort during this grant period has been in the former area. High performance computing is undergoing a revolution of greatly increasing parallelism, which is expected to lead to an exaflop computer by the end of the decade. However, the path there is uncertain. A number of hardware architectures have been proposed as well as new parallel languages. It is a disruptive time. In addition to this grant, this work is also funded by a gift from Northrop Grumman and UCLA's Institute for Digital Research and Education.

In spite of the variety of proposed hardware, we feel that there is a hardware abstraction that describes the most likely features of the next generation high performance computers. This abstraction consists of a hierarchy of computational layers. At the lowest layer, we have a SIMD (vector) processor whose computational elements work together in lockstep and have fast synchronization and shared memory. At the next higher layer, we have a collection of such processors which communicate through a slower shared memory. At the highest layer, we have a cluster of such collections, which communicate via message-passing. The bottom two layers of this abstraction has been implemented in a language called OpenCL. Although different hardware implements different features of this abstraction, such as the SIMD or vector length, such an abstraction allows one to design parameterizable algorithms that can adapt to different hardware.

We believe the hardware which most closely resembles a future exaflop computer is a collection of Graphical Processing Units (GPUs), and we have focused our attention on developing Particle-in-Cell (PIC) algorithms for this hardware initially. PIC codes are widely used in plasma modeling in DOE, not only in areas in fusion energy as exemplified by GTC, but in high energy physics, plasma accelerators, ICF, and other areas. In 2010, about 12% of the INCITE grants in DOE were devoted to PIC codes.

We began by developing a simple 2D electrostatic PIC code for the NVIDIA Tesla C1060 GPU based on one of the codes from the UPIC Framework [1]. The major new feature of this code was the implementation of a streaming algorithm, where the two major data elements (particles and fields) are read only once each time step with an optimal memory access pattern (unit stride). To achieve this, particles need to be ordered by cell and we developed a particle re-ordering scheme that worked effectively on this hardware. The first results used global memory only and achieved a speedup of 13 compared to a 2.67 GHz Intel Nehalem processor, and were published in the ICAP conference proceedings [2] in 2009.

In the next version, we parameterized the code to make it adaptable to different architectures. The reordering algorithm was generalized to allow more than one grid per sorting cell and more than one sorting cell per thread. We also added support for shared memory. The four tunable parameters were defined as follows: lth, the number of tightly coupled threads, ngpx and ngpy, the number of grids in a sorting cell, and ngpt, the number of sorting cells assigned to a thread. Increasing the number of grids per sorting cell reduced the cost of particle reordering, but it could increase the particle processing time because more shared memory was required. For the NVIDIA C1060, the optimal parameters were lth=32, ngpx=2, ngpy=3, ngpt = 1. Speedups of 15-25 were obtained compared to the Intel Nehalem, depending on plasma temperature. Details about the algorithm and performance results were published in 2011 [3].

The electrostatic PIC code was very simple, with low computational intensity (few floating point operations per memory access). Codes with higher computational complexity, such as electromagnetic or gyrokinetic codes should perform better. We therefore implemented an 2-1/2D electromagnetic, relativistic code, which used the same algorithms and data structures as the electrostatic code. Typical speedup achieved on the Tesla C1060 was about 40. The Fermi C2050, a newer GPU, achieved a speedup of 55, with a particle processing time of 2.2 nsec/particle/time step. These results were reported at the APS Division of Plasma Physics Meeting [4] and the US-Japan Workshop on Development of Simulation Science in Plasma Physics [5].

Finally, the 2D electrostatic code was translated into Cuda Fortran and OpenCL. The Cuda Fortran code gave results very similar to Cuda C (within 10%), but was easier to use, since GPU memory arrays are defined as normal arrays with a new attribute, and copying data between host and GPU is implicit and automatic. OpenCL is intended as a portable language, and allows one to run on devices other than NVIDIA GPUs. The translation of the kernel functions from Cuda to OpenCL was straightforward, but initiating and controlling kernels is very low level, complex, and painful. Nevertheless, the OpenCL code was able to run on NVIDIA, AMD, and Apple hardware, but did not run on the Sony Playstation.

The new PIC algorithms were largely a hybrid combination of previous techniques, including vector techniques from the early Cray machines, blocking (tiling) techniques from cached-based architectures, and message-passing techniques from distributed memory architectures. The current work is directly applicable to electrons in GTC. Applying them to ions would require additional research because the ions are not local in a gyrokinetic code. This research is particularly timely now, since the number one computer in the world is a GPU-based machine in China, and many more GPU clusters are being built, including a 288 GPU cluster at UCLA funded by NSF. There is widespread interest in GPUs just now, and I have given many invited talks on this topic [2,5-9], as well as presentations at the Culham Scientific Center in the UK and at the Instituto Superior Technico in Portugal.

The object-oriented version of GTC, which I helped develop, is being used to model energetic particles. A description of the object-oriented features was included in a paper, with Wenlu Zhang from UC Irvine as first author, which was published in 2010 [10].

At the International Conference on Numerical Simulation of Plasmas, I received the 2009 John Dawson Award for “pioneering advances to plasma physics obtained through simulations.”

The award citation read: “for his seminal contributions to the development of parallel algorithms for particle-in-cell simulations, for his subtraction technique, and for the body of work which has benefited from his PIC codes and software.”

Finally, I have continued work on developing software engineering techniques for scientific computing, including one publication [11] in this grant period. This paper indicated how to pass data between Fortran90 and C in a portable way, without hacking into vendor-specific hidden Fortran90 structures.

References

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[2] V. K. Decyk, T. V. Singh, and S. A. Friedman, "GPU-based PIC Simulations," 10th Intl. Computational Accelerator Physics (ICAP 2009) Conference, San Francisco, CA, September 2, 2009. (http://www.jacow.org/)

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[4] "Adaptable Particle-in-Cell Algorithms for Graphical Processing Units," Bull. Am. Phys. Soc. 55, p.271, (2010), paper PP9.93.

[5] "Adaptable Particle-in-Cell Algorithms for Graphical Processing Units" US-Japan Workshop on Development of Simulation Science in Plasma Physics, Chicago, IL, Nov. 12, 2010. (http://w3fusion.ph.utexas.edu/~jift2010/)

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Final Report

GPS-TTBP: Advanced Visualization Techniques for Gyrokinetic Particle Simulations

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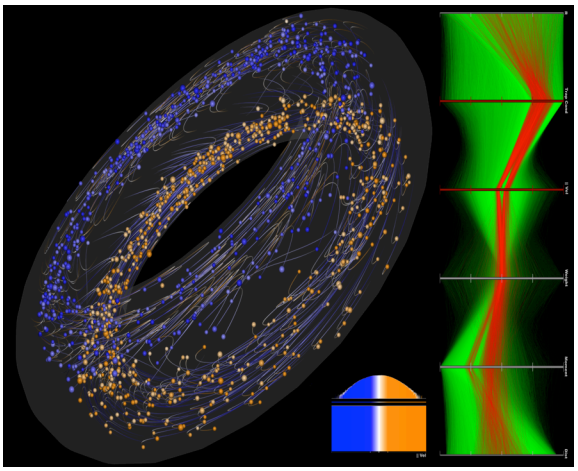
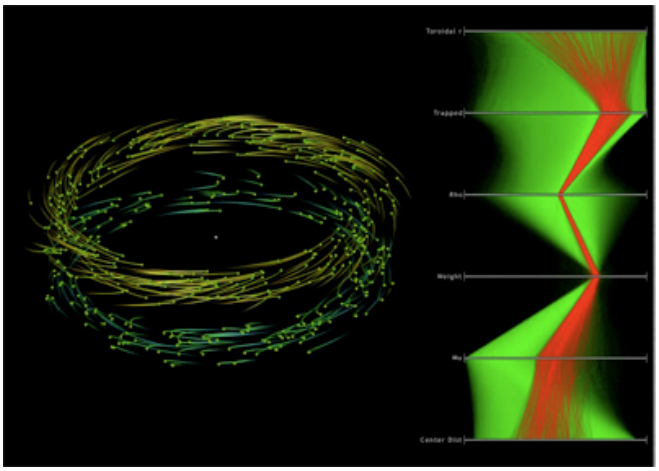
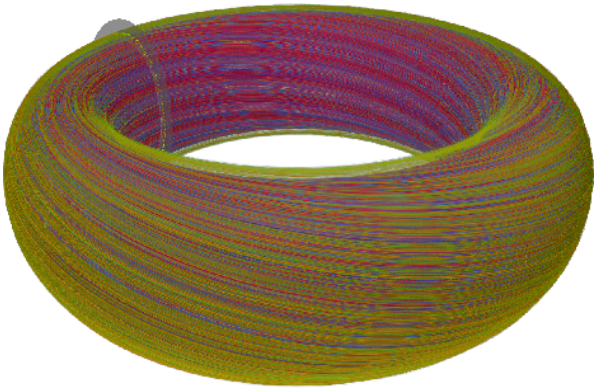
Accomplishments

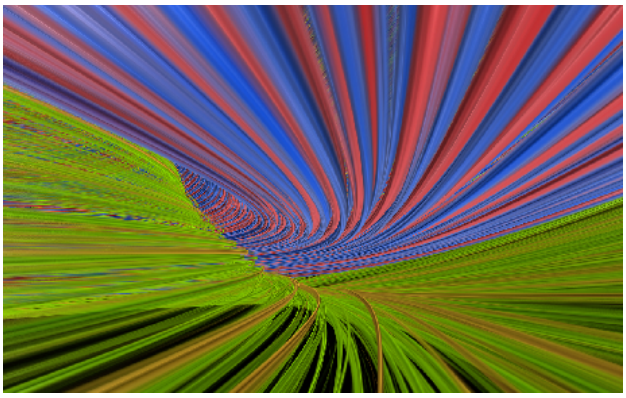
In this project, we have developed techniques for visualizing large-scale time-varying multivariate particle and field data produced by the GPS_TTBP team. Our basic approach to particle data visualization is to provide the user with an intuitive interactive interface for exploring the data. We have designed a multivariate filtering interface for scientists to effortlessly isolate those particles of interest for revealing structures in densely packed particles as well as the temporal behaviors of selected particles. With such a visualization system, scientists on the GPS-TTBP project can validate known relationships and temporal trends, and possibly gain new insights in their simulations. The two images below created using this new interface effectively highlight particles of interest. The dataset was provided by the Princeton Plasma Physics Laboratory (PPPL). We have tested the system using over several millions of particles on a single PC. We will also need to address the scalability of the system to handle billions of particles using a cluster of PCs.



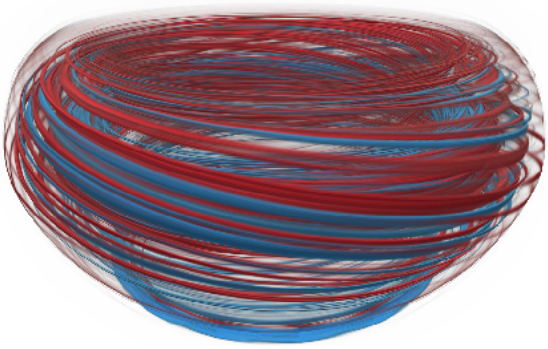


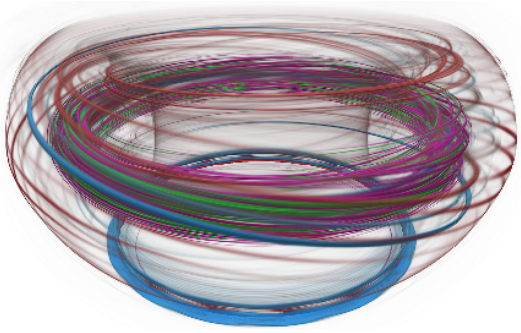
To visualize the field data, we choose to use direct volume rendering. Because the data provided by PPPL is on a curvilinear mesh, several processing steps have to be taken. The mesh is curvilinear in nature, following the shape of a deformed torus. Additionally, in order to properly interpolate between the given slices we cannot use simple linear interpolation in Cartesian space but instead have to interpolate along the magnetic field lines given to us by the scientists. With these limitations, building a system that can provide an accurate visualization of the dataset is quite a challenge to overcome. In the end we use a combination of deformation methods such as deformation textures in order to fit a normal torus into their deformed torus, allowing us to store the data in toroidal coordinates in order to take advantage of modern GPUs to perform the interpolation along the field lines for us. The resulting new rendering capability produces visualizations at a quality and detail level previously not available to the scientists at the PPPL, as demonstrated by the two images shown below.





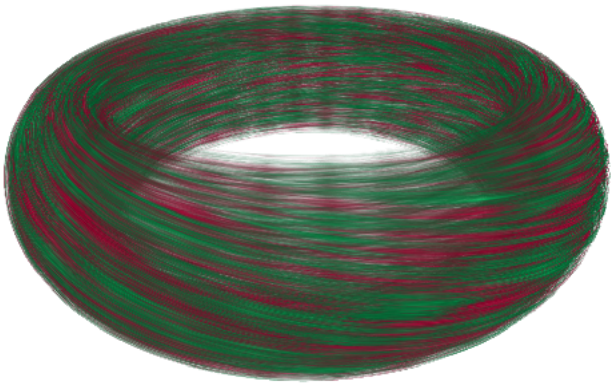
The second dataset we have worked on was provided by Professor C.S. Chang at the New York University. This plasma dataset is similar to the PPPL dataset, but still different enough to be challenging to visualize. Instead of a curvilinear volume (albeit a deformed and twisted one) this dataset is a set of point mesh slices. This data however also requires that interpolation be done along magnetic field lines instead of along simple Cartesian space. Because of this, we can not store them in toroidal space for the GPU. Instead, each slice is stored in cylindrical space using a triangulated mesh, and interpolation is forced at the shader level by sampling two slices at a time. Similar deformation methods were used, but rendering is not the only goal. Instead, Professor Chang also wants to decompose/segment the volume based on frequency analysis, rendering the high frequency and low frequency bands using different colors. However, we are able to efficiently pack this into video memory for rendering, producing the two images shown below. The left one is the unfiltered image, and the right one with the data segmented.





Even though this project came to an end, we plan to continue our collaboration with PPPL. The latest dataset provided by PPPL is more of a combination of the NYU and previous PPPL datasets. Whereas the old PPPL dataset can be stored in a twisted toroidal space, the new one cannot be stored so easily. Instead, they have to be untwisted as the NYU data is, but still stored with the efficiency of toroidal space. Additionally, unlike the NYU and the first PPPL datasets, this new dataset also come with additional variables such as velocity. We plan to visualize that velocity data by constructing stream surfaces within the torus in order to highlight the features of the flow field. However, as the flow field stores values in cylindrical rather than

Cartesian space, and as the data is stored in toroidal space, integrating the stream surface becomes rather difficult. Included is an image of a timestep from the dataset. As work on this dataset is ongoing, the image shown below does not represent what we hope to achieve in the final visualization but instead allows us to verify our current understanding of the nature of the data.



In summary, in this project we have successfully created new capabilities for the scientists to visualize their 3D data at higher accuracy and quality, enhancing their ability to evaluate the simulations and understand the modeled phenomena.

Publications

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GPS-TTBP Report

USC-ISI

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During 2010 we have continued our research and development of compiler technology for automatic performance tuning of high-performance applications. The main activities of this past year were continuing the development of our automatic performance tuning framework and compiler tools and the autotuning of PETSc library functions using specialization.

Autotuning framework and compiler tools.

CHiLL, a framework for composing high-level loop transformations designed to generate efficient code for complex loop nests, developed at ISI and University of Utah, was publicly released in 2010. CHiLL supports an extensive collection of loop transformations for perfect and imperfect loop nests, including tiling, permutation and unroll-and-jam, thus lifting the burden of generating multiple intermediate steps from compilers or optimization tools. CHiLL uses the Omega test to manipulate integer arithmetic and relies on polyhedral scanning provided by Omega's code generator. Recently we have integrated new features into CHiLL, including support for user input to the tool. Users can now relay information about the code and input data that could not be derived by static analysis alone, and this information often results in more efficient code generation. We have also updated the Omega Library, released as Omega library Plus, which is a main component of CHiLL. Both CHiLL and Omega Library Plus have been released and can be found, respectively, at http://www.cs.utah.edu/~chunchen/chill and http://www.cs.utah.edu/~chunchen/omega.

Over the past year, we have worked extensively to increase the capability of CHiLL. A major focus of this work is on providing the appropriate interface to application and library developers to increase their productivity. In working with application and library developers, we have discovered that many optimizations that are well-known and available in most compilers are performed manually by the application developers. The reason behind this is the application developers do not have sufficient control over how the optimizations are performed or the parameters that are used by the compiler, and they cannot see the results of the optimization. Our goal in building the interface to CHiLL was to expose the transformation capability to the programmer, and then rely on the compiler and auto-tuning framework to automate code generation and parameter selection. Over the past year, we have broadened the capabilities of the interface in CHiLL We now support OpenMP and CUDA code generation through high-level directives provided by the programmer, and work is underway for OpenCL code generation. We have also raised the level of abstraction for this interface so that programmers have a higher level of abstraction when interacting with the system.

Autotuning of PETSc library functions.

We have developed techniques for combining automatic performance tuning (autotuning) with specialization (in collaboration with Argonne and University of Utah), as reported in 2009. Specialization information allows autotuning tools to derive highly optimized specialized versions of a computation for known input sizes or parameters. CHiLL, a loop transformation framework based on the polyhedral model, can automatically generate specialized versions according to user-specified optimization

strategies. CHiLL provides a high-level script interface that allows a user or compiler to specify an optimization strategy as a sequence of code transformations and parameters.

In the past year we have applied autotuning and specialization to optimize PETSc functions used in many scientific applications (including GTC) such as solvers (MatSolve_SeqBAIJ_N), matrix factorization (MatLUFactorNumeric_SeqBAIJ_N) and matrix multiplication (MatMul_SeqBAIJ_N). These functions use a block sparse matrix representation, where the input matrix is a collection of dense blocks of a fixed size. The N at the end of the function names denotes that the fixed block size is a parameter to the function.

In addition to the size-independent functions, PETSc also provides size-dependent specialized implementations for a range of small sizes, which are hand-optimized. Writing specialized code is a technique often used by library developers to optimize applications. However, manually-written code has several disadvantages when compared to our framework.

- The library developer will not possess the values of parameters along with their frequencies at design time. Hence, he would be able to write specialized functions only for specific values.
- It gets a little difficult for the developer to reason about the best implementation when the number of variables/parameters along with each of their possible values is more than a few.
- It is not feasible to expect the application programmer to write specialized code.
- Performance of implementations varies according to the architecture.

To automate the optimization of the PETSc functions, we start with a clean implementation of the key loop nests, with no pointer arithmetic and eliminating the copies at the beginning of the functions. In this way, we focus on just the computation in the functions. Figure 1 summarizes the autotuning process for triangular solve using our CHiLL transformation and code generation system and the Active Harmony framework from University of Maryland for navigating the optimization search space.

(a) Triangular solver

```
#define SIZE 15
void forward_solve_kernel(…)
{
  …
  for (cntr=SIZE-1; cntr>=0; cntr--) {
    x[cntr] = t+bs*(*vi++);
    for (j=0; j<bs; j++)
      for (k=0; k<bs; k++)
        s[k]-=v[cntr][bs*j+k]*x[cntr[j]];
  }
}
```

(b) CHiLL transformation script

```
original()
known(bs>14)
known(bs<16)
unroll(stmt1,loop2,u1)
unroll(stmt1,loop3,u2)
```

(c) Constraints on search parameters

```
0 ≤ u1 ≤ 16
0 ≤ u2 ≤ 16
compilers ∈ {gnu, pathscale, cray, pgi}
```

(d) Search space

```
17*17*4 = 1156 points
```

Figure 1. Autotuning process for forward solve.

Figure 1(a) shows the forward solve portion of the triangular solve code. Figure 1(b) shows a transformation recipe provided to CHiLL to specialize the function for a given block size (15 in the example). The optimization strategy used for this loop nest is to unroll the two innermost loops to expose both instruction-level parallelism and data reuse that can be exploited in registers. The unroll factors are constrained so that they are less than the block size. Figure 1(c) shows the constraints on the possible values for the optimization parameter (unroll factors). In addition, the constraints on the search space of possible code variants specify the set of compilers that will generate the final code.

Active Harmony searches the space of possible unroll factors for this loop nest to identify the one that leads to the best performance. The search space consists of over 1000 points, but Active Harmony employs a parallel rank order search to limit the number of points that must be considered.

These autotuning experiments were performed on Jaguar, a Cray XT5 at Oak Ridge National Laboratory, and a summary of performance results is shown in Table 1.

Compiler	Original code	Active Harmony search			Exhaustive search		
	Time	Time	(u1,u2)	Speedup	Time	(u1,u2)	Speedup
pathscale	0.58	0.32	(3,11)	1.81	0.30	(3,15)	1.93
gnu	0.71	0.47	(5,13)	1.51	0.46	(5,7)	1.54
pgi	0.90	0.53	(5,3)	1.70	0.53	(5,3)	1.70
cray	1.13	0.70	(15,5)	1.61	0.69	(15,15)	1.63

Table 1. **Autotuning performance summary for PETSc triangular solve.**

The experiment involved trying all combinations of unroll factors for the two innermost loops, and the four compilers available on Jaguar (the four rows) to achieve speedup over the original execution time (the second column). The search space was small enough that it was possible to exhaustively search these options. The exhaustive search results are shown in the rightmost three columns: the execution time, two unroll factors and speedup over the original execution time. By comparison, columns three through five show the comparable results with Active Harmony, showing slightly different unroll factors, and performance. Active Harmony results are obtained by evaluating, on average, less than 50 points, which amounts to less than 5% of the total points in the search space. Another perhaps surprising result is how such a simple piece of code achieves very different performance on the same architecture using different compilers. The optimization strategy and results are similar for the matrix vector multiply. We specialized for different column sizes (105, 90, 75, 60) and row size 15. Since the search space is fairly small, we did an exhaustive parameter sweep (two unroll factors) for the most dominant column sizes 105 and 90 using the PGI compiler. On average, the best CHiLL-generated code variant performs 1.5X faster than the original implementation.

PETSc alone has 29 functions which have been specialized, amounting to a total of 242 manually-written functions. We have been investigating how to combine CHiLL with PETSc such that applications can use the CHiLL framework to generate these specialized versions to reduce the amount of code that is provided by the library and, using auto-tuning and specialization, derive more highly optimized versions of the library functions. This code generation could be deferred until the build of the application so that the code can be specialized for the application and execution context. Such an integration would allow users to study the hotspots in the PETSC library and extract frequent values if possible. The best performing code would then be automatically generated and included in the PETSC library. Applications, such as GTC, that use PETSc library, could take advantage of libraries specialized for the application's context, features and problem sizes.

Autotuning and CO-Design.

In 2010, we collaborated with the GTC team on the proposal "Co-Design Center for Exascale Simulations of Fusion Plasmas" submitted to the Department of Energy.

We believe that auto-tuning technology can play an important role in the co-design of exascale systems and applications. New hardware features and new technology will bring new challenges and opportunities for code generation and optimization. With auto-tuning technology code developers could quickly implement new code variants that take advantage of new designs and technologies and evaluate their impact on the application. As the co-design process converges, new performance critical computations become candidates for optimization. At this point, auto-tuning technology can be used to create domain-specific code generators and libraries of optimized code variants for the exascale version of the application.

Publications (2011 and 2010)

Jacqueline Chame, Chun Chen, Mary Hall, Jeffrey K. Hollingsworth, Kumar Mahinthakumar, Gabriel Marin, Shreyas Ramalingam, Sarat Sreepathi, Vamsi Sripathi and Ananta Tiwari, **PERI Autotuning of PFLOTRAN**, in *SCIDAC 2011*, July 2011.

J. Shin, M. W. Hall, J. Chame, C. Chen, P. F. Fischer, and P. D. Hovland, **Speeding up Nek5000 with Autotuning and Specialization**, in *Proceedings of the 24nd International Conference on Supercomputing*, 2010.

G. Rudy, C. Chen, M. W. Hall, M. M. Khan, and J. Chame, **Using a programming language interface to describe GPGPU optimization and code generation**, in *Proceedings of the 23nd International Workshop on Languages and Compilers for Parallel Computing*, 2010.

Columbia University Final Report for SciDAC GPS-TTP
3/1/2008-02/28/2011

Institution: Columbia University
City, State: New York, NY
Award No.: DE-FC02-08ER54962
Award Title: Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas
PI: Mark Adams

Team Members: Mark Adams

Executive Summary

Columbia's contribution, with 10% of staff scientist effort, was to provide support for equation solvers and related operators in the shaped cross section gyrokinetic particle in cell (PIC) code GTS from Princeton Plasma Physics Laboratory (PPPL). Note, the original proposal included this code in the "GTC framework" and did not distinguish it by name. We also provided expertise in data model design for gyrokinetic PIC codes.

This work included: 1) maintaining the PETSc interface and library, and the finite element solver, 2) extending this existing solver technology to new operators and 3) consulting on the design of new scalable data modes for GTS. This works adds to the goals of the project by enabling the physicists to compute the operators that their mathematical models require effectively on the extreme-scale compute platforms used in this project.

Actual accomplishments vs. the goals and objectives of the proposal

The support of the equation solvers and extension to the use of algebraic multigrid (AMG) solvers (eg, HYPRE) through the PETSc interface was accomplished much as described in the original proposal. The extension of the solver technology to flux surface averaging solvers and isotropic smoothers was a response to a demand that was not anticipated in the original proposal. The development of new data model (called "2D domain decomposition" in the original proposal) did not attract the necessary additional development resources to accomplish this task as stated in the original proposal but we have made progress on identifying several data potential data models and we are considering tasking a current postdoc to implement one of these models in the final year and a half of his appointment.

Project activities for the entire period

The solver activities included simply porting the solver codes and the PETSc libraries to new compute platforms. We worked with PPPL staff scientists to develop a flux surface averaging Poisson solver. We used the basic solver infrastructure to develop an isotropic matrix-smoothing operator in GTS that is based on a linear finite element discretization of the Laplacian and implemented as a PETSc matrix. This provides isotropic smoothing in Cartesian geometry and parallelizes the smoothing operator. We also continue to work with PPPL staff scientist on the design of a new data model for GTS.

These activities are in support of the implementation of the physicist's mathematical models and enabled them to perform their simulations.

Publications and invited talks

Columbia participated in the following talks and papers:

Invited talk at workshop "Simulating the Future; Using one million cores and beyond", Sponsored by EDF R&D and Univ. of Tennessee, September 22-24 2008, Chateau de Tremblay France.

Relationship between Toroidal Momentum and Heat Transport in Tokamaks, W. X. Wang, T. S. Hahm, M. Adams, S. Ethier, S. Kaye, W. W. Lee, G. Rewoldt and W. M. Tang, Proceedings of 35th European Physical Society Conference on Plasma Physics (Hersonissos, Grete, Creece, 2008).

Petascale Parallelization of the Gyrokinetic Toroidal Code, S. Ethier, M. Adams, J. Carter and L. Oliker, VECPAR: High Performance Computing for Computational Science (June 2010).

Non-Diffusive Momentum Transport and Intrinsic Rotation in Tokamaks,W. X.Wang, S. Ethier, S. Klasky, M. Adams, T. S. Hahm, G. Rewoldt, W. W. Lee, W. M. Tang and P. H. Diamond, Proceedings of SciDAC 2010 Conference (2010).