Final Report on DOE Grant # DE- FG02-04ER54737:A000.

The Theory of Fusion Plasmas. **P.I. Steven C. Cowley, UCLA.** .

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1 Scientific Progress

We have made considerable progress on the research outlined in the grant application. It is difficult to separate some of the research funded by this grant and that funded by the fusion science center and by my astrophysics grants – however most is clearly separated. I will briefly summarize the progress, details are given in our publications.

1.1 Explosive loss of Confinement.

Howard Wilson and I have further advanced our calculations of the nonlinear dynamics of the ballooning mode. We have shown (see papers 1, 5 and 8) that these modes have the explosive dynamics that is seen in disruptions (see 18) and in ELMs in MAST (see 6, 11 and 20). Andy Kirk's pictures of the nonlinear filament erupting from the edge of the plasma are being displayed in many ELM talks. Howard and I are using the edge stability code ELITE to evaluate the nonlinear coefficients in our theory to make quantitative comparisons with experiment. This is almost completed. Comparisons of our theory and JET disruptions was part of James Paley's PhD thesis. Fraser Lott another PhD student measured the heat load caused by the fingers on the divertor of MAST. Howard Wilson and I are (still) preparing a long paper on the theory of nonlinear ballooning. This theory will complement BOUT simulations by the YORK group.

1.2 Turbulence.

Using the GS2 code we have been analyzing the turbulence in MAST (see 9, 15, 19 and 28). Two students, Nathan Joiner and David Applegate, were running these simulations. We have found micro-tearing modes in both the ion regime $k_\perp \rho_i \sim 1$ and the electron regime $k_\perp \rho_e \sim 1$ – this suggests that another highly electromagnetic mechanism for transport is operating in Spherical tokamaks (see 28). We have also been concerned with the formation of streamers in ETG turbulence – see 24. I wrote an opinion piece for Nature on reducing turbulence in tokamaks – see 17.

1.3 Alfven Wave Cascades.

We have been developing the gyro-kinetic approach to calculate the cascade of Alfven waves in the collisionless regime and the heating caused by these waves. This is being done with Greg Hammett, Bill Dorland and Eliot Quataert (Berkeley). I am currently converting my lecture notes into a review article on gyro-kinetics and Alfven waves. Greg Howes (now at Berkeley) has published a paper on the linear comparison of GS2 with theory in astrophysical regimes – with betas ranging from 0.01 to 100 (see 22). This summer Alex Schekochihin and I completed a paper that shows how the gyro-kinetics passes over to reduced MHD for the Alfven wave part of the fluctuations in the small larmor radius limit. We also show that the slow part requires the solution of an kinetic equation where the nonlinearities are entirely from the interaction with the Alfven waves (see 30). This paper is now being refereed. Alexei Iskakov has written a parallel spectral MHD/fluid code to examine the fluid limits of the cascades.

1.4 High Beta Tokamaks

We have returned to the problem of high beta tokamaks – analysis of these devices is still hampered by the problems of numerical resolution. Jean Noel Leboeuf and Pierre Gourdain have written a code that efficiently solves the Grad-Shafranov equation at high betas (even unity beta). It is very hard to achieve such betas in standard equilibrium codes. The code reproduces the asymptotic states that we calculated analytically in 1990 (see Cowley et. al. Phys. Fluids B, **3** 2066(1991)). These states have interesting properties for transport and micro-stability (see Hsu et. al. Phys. Plasmas **3** 266(1996)). Russell Neches has compared the code to the analytic approximation showing that the asymptotic theory is a good approximation (see 31). Pierre Gourdain has prepared the output of his code to feed into Alan Glasser's DCON code and examined kink stability. Pierre has found some novel current hole configurations that attain very high beta that are stable to all MHD (internal and external) – see 23 and 26.

1.5 Magnetic Reconnection.

Nuno Loureiro completed a PhD on magnetic reconnection – he did high resolution (parallel) simulations of tearing mode growth in the high Δ' regime. He showed that the Rutherford growth gave way to x-point collapse and current sheet formation and that the current sheet broke up into secondary islands. This may describe the evolution during the sawtooth instability. This work has been published in Physical Review Letters (17). In 25 he produced a neat analytic solution of the current sheet breakup.

2 Publications this Grant Period.

Some of these publications lie on the edge of the scope of this grant and the work was largely supported by other grants. However all these activities are part of our general activities in plasma science. This grant supported part of nine *Physical Review Letters* a *Science* perspective on fusion turbulence, a *Nature Physics* commentary on fast particles in fusion and many other publications.

1. *Explosive instabilities: from solar flares to edge localized modes in Tokamaks*, S. C. Cowley, H. Wilson, O. A. Hurricane and B.H. Fong. Plasma Physics and Controlled Fusion. **45**, 12.1, A31 - A38(2003).

2. *On the Existence of a Critical Prandtl Number for Small-scale Dynamo*, A.A. Scheckochihin, S.C. Cowley, J. Maron, and J. C. McWilliams, Phys. Rev. Lett., **92**, 054502(2004).

3. *The Self-Similar Turbulent Dynamo*, A.A. Scheckochihin, S.C. Cowley, J. Maron, and J. C. McWilliams, Phys. Rev. Lett., **92**, 064501(2004).

4. *Saturated State of the Nonlinear Small-Scale Dynamo*, A.A. Scheckochihin, S.C. Cowley, S.F. Taylor, G.W. Hammett, J. Maron, and J. C. McWilliams, Phys. Rev. Lett., **92**, 084504(2004).

5. *Theory for Explosive Ideal Magnetohydrodynamic Instabilities in Plasmas*, H.R. Wilson, S.C. Cowley, Phys. Rev. Lett., **92**, 175006(2004).

6. *Spatial and Temporal Structure of Edge-Localized Modes,* A. Kirk, H.R. Wilson, G.F. Counsell, R. Akers, E. Arends, S.C. Cowley, J. Dowling, B. Lloyd, M. Price, Phys. Rev. Lett., **92**, 245002(2004).

7. *Simulations of the Small-Scale Turbulent Dynamo,* Alexander A. Schekochihin, Steven C. Cowley, Samuel F. Taylor, Jason L. Maron, and James C. McWilliams, ApJ. **612**, 276-307(2004).

8. *Nonlinear Ballooning Theory and the consequences for ELMs in Tokamaks.* H.R. Wilson, S.C. Cowley, A. Kirk and P. Snyder. IAEA Nov. 2004.

9. *Microstability in a "MAST-like" high confinement mode spherical tokamak equilibrium* D. J. Applegate C. M. Roach, S. C. Cowley, W. D. Dorland, N. Joiner, R. J. Akers, N. J. Conway, A. R. Field, A. Patel, M. Valovic, and M. J. Walsh. Phys. Plasmas **11**, 5085 (2004)

10. *The Nonlinear Cascade,* J. Maron, S.C. Cowley, and J.C. McWilliams, ApJ. **603**, 569(2004).

11. *Structure of ELMs in MAST and the implications for energy deposition.* A. Kirk, H.R. Wilson, R. Akers, N.J. Conway, G.F. Counsell, S. C. Cowley, J. Dowling, B. Dudson, A. Field, F. Lott, B. Lloyd, R. Martin, H. Meyer, M .Price, D. Taylor, M. Walsh and the MAST team. Plasma Phys. Control. Fusion **47** No 2 (February 2005) 315-333.

12. *Diffusion of passive scalar in a finite-scale random flow,* A. A. Schekochihin, P. H. Haynes, and S. C. Cowley, Phys. Rev. E **70**, 046304 (2004) [e-print nlin.CD/0404016]

13. *Plasma instabilities in clusters of galaxies,* A. A. Schekochihin, S. C. Cowley, R. M. Kulsrud, G. W. Hammett, and P. Sharma, ApJ, **629**, 139(2005) [e-print astro-ph/0501362].

14. *Onset of small-scale dynamo,* A. A. Schekochihin, N. E. L. Haugen, A. Brandenburg, S. C. Cowley, J. L. Maron, and J. C. McWilliams, ApJL, 625, L115 (2005) [e-print astro-ph/0412594].

15. *Microstability physics as illuminated in the spherical tokamak,* C. M. Roach, D. J. Applegate, J. W. Connor, S. C. Cowley, W. D. Dorland, R. J. Hastie, N. Joiner, S. Saarelma, A. A. Schekochihin, R. J. Akers, C. Brickley, A. R. Field, M. Valovic, and the MAST Team, Plasma Phys. Control. Fusion, Accepted, (2005).

16. *X-point collapse and saturation in the nonlinear tearing-mode reconnection,* N. F. Loureiro, S. C. Cowley, W. D. Dorland, M. G. Haines, and A. A. Schekochihin, Phys. Rev. Lett., 95, 235003(2005) [e-print physics/0507206].

17. *Reduced Turbulence and New Opportunities for Fusion.* Karl Krushelnick and Steve Cowley. Perspective in. Science, Vol 309, Issue 5740, 1502-1503 , 2 September 2005

18. *Energy flow during disruptions in JET,* J.I.Paley, P. Andrew, S.C. Cowley, W. Fundamenski, A. Huber and JET EFDA Contributors, Journal of Nuclear Materials 337-339 (2005) 702-706.

19. *Electron temperature gradient driven transport in a MAST H-mode plasma,* N. Joiner, D. Applegate, S.C. Cowley, W. Dorland and C.M. Roach Plasma Phys. Control. Fusion 48 No 5 (May 2006) 685-697 .

20. *Magneto-hydrodynamic stability of the H-mode transport barrier as a model for edge localized modes: an overview,* H R Wilson, S C Cowley, A Kirk and P B Snyder Plasma Phys. Control. Fusion 48 No 5A (May 2006) A71

21. *Thermonuclear Ringtones,* S C Cowley, News and Views, Nature Physics, May 2006.

22. *Astrophysical gyrokinetics: basic equations and linear theory,* G. G. Howes, S. C. Cowley, W. D. Dorland, G. W. Hammett, E. Quataert, and A. A. Schekochihin, Astrophys. J., 651, 590 (2006) [e-print astro-ph/0511812]

23. *Stability of highly shifted Equilibria in a Large Aspect Ratio Tokamak,* P.A. Gourdain, S. C. Cowley, J.N. Leboeuf, and R. Y. Neches Phys. Rev. Lett. 97, 055003 (2006)

24. *Characterizing electron temperature gradient turbulence via numerical simulation,* W.M. Nevins, J. Candy, S. Cowley, T. Dannert, A. Dimits, W. Dorland, C. Estrada-Mila, G.W. Hammett, F. Jenko, M.J. Pueschel and D.E. Shumaker, Phys. Plasmas 13, 122306 (2006)

25. *Instability of current sheets and formation of plasmoid chains,* N. F. Loureiro, A. A. Schekochihin, and S. C. Cowley Phys. Plasmas 14, 100703 (2007) [e-print astro-ph/0703631]

26. *Stability of highly shifted equilibria in a large aspect ratio low-field tokamak,* P.A. Gourdain, J.N. Leboeuf, and R.Y. Neches Phys. Plasmas 14, 112513 (2007)

27. *Numerical Demonstration of Fluctuation Dynamo at Low Magnetic Prandtl Numbers,* A.B. Iskakov, A. A. Schekochihin, S.C. Cowley, J. C. McWilliams and M.R.E. Proctor. Physical Review Letters 98, 208501(2007)

28. *Micro-tearing modes in the mega ampere spherical tokamak,* D.J. Applegate, C.M. Roach, J.W. Connor, S.C. Cowley, W. Dorland, R.J. Hastie and N. Joiner, Plasma Phys. Control. Fusion 49 No 8 (August 2007) 1113-1128.

29. *Kinetic Simulations of Magnetized Turbulence in Astrophysical Plasmas,* G.G. Howes, W. D. Dorland, S. C. Cowley, G. W. Hammett, E. Quataert, and A. A. Schekochihin, Physical Review Letters 100, 065004(2008)

30. *Astrophysical gyrokinetics: kinetic and fluid turbulent cascades in magnetized weakly collisional plasmas,* A. A. Schekochihin, S. C. Cowley, W. Dorland, G. W. Hammett, G. G. Howes, E. Quataert, and T. Tatsuno, Astrophys. J. Suppl., submitted (2007) [e-print arXiv:0704.0044]

31. *The Convergence of Analytic High β Equilibrium in a Finite Aspect Ratio Tokamak.* R.Y. Neches, S.C. Cowley, P.A. Gourdain and J.N. Leboeuf. Submitted to Physics of Plasmas.

3 Talks

The PI has given invited talks in a number of places, they include:

1. Invited talk: *Explosive Instabilities,* TOKI conference, Toki, Japan October 2003.

2. BBC Radio "Material World," discussion of Magnetic Fields in the Universe, October, 2003.

3. BBC Radio "Material World," discussion of Nuclear Fusion, March, 2004.

4. BBC Radio "World Service," discussion of ITER, May 26, 2004.

5. Invited talk: *Plasmas in Astrophysics and Laboratory Physics,* Spitafields day Dec. 2004 Newton Institute, Cambridge University, UK.

6. *An Experiment to Save the World,* BBC Horizon documentary on fusion 02/17/05. Small part.

7. KITP seminar: *Magnetic Fields in Clusters,* May 2005.

8. Stanford Linear Accelerator colloquium: *Fusion and the ITER Era,* October 10th 2005.

9. UCLA physics colloquium: *Fusion and the Burning Plasma Era,* November 16th 2005.

10. UCLA, Institute for Geophysics and Planetary Physics colloquium: *Magneto-genesis in Clusters,* November 22nd. 2005.

11. Cal State Los Angeles Physics Colloquium. *Fusion and the Burning Plasma Era,* April 27th 2006.

12. *Magneto-genesis in Clusters,* Physics Department Colloquium, University of New Hampshire, November 27th 2006.

13. BBC Radio 4 morning news interview about ITER signing. 12/11/2006

14. *Turbulence in Fusion Experiments,* Invited talk Wolfgang Pauli Institute, University of Vienna, February 7th 2007.

15. *Making Magnetic Fields on Cosmic Scales,* Invited talk 03/07/2007 March APS meeting Denver.

16. *Magnetogenesis,* Physics Colloquium, University of Calgary, march 23rd 2007.

17. *The Origin of Magnetic Fields in the Universe? and the Turbulent Dynamo,* Invited Talk in the conference Turbulent Mixing and Beyond, The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy. August 20th 2007.

18. *The Physics Challenges of ITER,* Physics Department Colloquium at the University of California Santa Barbara, Oct. 16th 2007.

19. *Fusion Turbulence,* A series of lectures at Wolfgang Pauli Institute, University of Vienna, Oct, 6th-10th 2007.

20. *Explosive Instabilities in Plasmas,* Engineering Colloquium, UCSB, 24th October 2007,

4 Personnel.

A clear focus of our work is training and therefore we concentrate here on the young people who have moved on to bigger and better things. Post-doc, Alexi Isakov, has now moved to Imperial College. Researcher Pierre Gourdain has moved to Cornell to take up an Asssistant Professor position. Greg Howes graduated and moved to Berkeley and now will become a Assistant Professor at Iowa is continuing to work on the Alfven wave problems. Russell Neches who joined our effort to work on the high beta problems. I kept contact with JET and MAST through British students Gianpaolo Turri (graduated and received a Marie Curie fellowship to go to Lausanne), Nathan Joiner (graduated and gone to Saskachewan), Nuno Louiero (Graduated and joined the Center for Multi-scale Plasma Dynamics), David Applegate (Graduated and joined the York group), Fraser Lott (Graduated and joined Cadarache) and James Paley (Graduated and joined Lausanne) and colleagues at Culham. Howard Wilson has moved to a professorship at the University of York and where he is pursuing ELM studies. A trip to the UK funded by this grant supported this activity.