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Report on Fusion Plasma Theory Grant

Theoretical Studies of Turbulence and Anomalous Transport in Toroidal
Confinement Devices

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Theoretical Studies of Turbulence and Anomalous Transport in Toroidal Confinement Devices

Abstract

The research performed under this grant has focused on key issues with respect to turbulence and transport in toroidal confinement devices. Progress and publications in these areas are summarized in this report. This work includes analytical and numerical studies of spectral energy transfer and the saturation dynamics and transport of dissipative and collisionless trapped electron turbulence, the role of flow curvature in L-H mode transition physics, fully nonlinear calculations of the anomalous particle transport from the ion mixing mode, and the development of a theory for the drift wave frequency spectrum. Novel aspects of this work include an elucidation of the role of nonlinear frequency shifts in producing nonstationary saturated states, an identification of reverse and non-conserved flows in Hasegawa-Mima turbulence, and a description of the way incoherent emission affects the frequency of turbulent fluctuations.

I. Introduction

This report describes work completed during the period Sept. 15, 1992 through Sept. 14, 1993 as part of the research funded under the Fusion Plasma Theory DOE Grant number DE-FG02-89ER53291 at the University of Wisconsin. The period covered by this report represents the second of a three year grant period.

The research summarized in this report is devoted to the theoretical understanding of turbulence and anomalous transport in toroidal magnetic fusion devices. It covers a range of topics from basic properties of drift wave turbulence to transport predictions for specific fluctuation models. The underlying objective of this work is an understanding of the turbulence of small scale fluctuations in tokamaks, with an eye toward controlling the anomalous losses of heat and particles.

In subsequent sections, work performed on the following topics will be briefly described: II. The properties of trapped electron mode turbulence; III. The role of flow curvature and flow shear in self-regulated turbulence; IV. Nonlinear transport fluxes for ion mixing mode particle transport in the dissipative trapped electron regime; and V. Incoherent emission and shifted frequencies in drift wave turbulence.

II. Trapped Electron Mode Turbulence [A.4, A.7, A.8, A.9, A.11, A.12, A.14, A.15, A.16, A.19, A.21]

Previous results from numerical solutions of long wavelength dissipative trapped electron turbulence uncovered a large, finite amplitude-induced shift of the fluctuation frequency¹. Analysis of the renormalized model equations^{1,2} showed the shift to result from the cross coupling of the ExB and polarization drift nonlinearities, which figure in the long to moderate wavelength parts of the spectrum. The shift was sufficiently large to stabilize unstable modes, though the dynamics of the stabilization process (through the inertia of adiabatic electrons) was not included in the one-field model. This model has been extended to introduce a second field, the electron density, and therefore the feedback on the instability of the nonlinear frequency shift. Numerical solutions of the two-field model yield a nonstationary saturated state characterized by long timescale oscillations of virtually all observables, from the energy and wavenumber spectra to the transport fluxes. The oscillations can be as large as 30% - 50%, with periods of many (order 10) eddy turnover times. These oscillations represent a cycle in which 1) the finite amplitude-induced frequency shift quenches the

instability at peak fluctuation levels, 2) the low wavenumber part of the spectrum then collapses without the instability to replenish the loss of energy from nonlinear transfer to high wavenumber, 3) the resulting decrease in amplitude at low wavenumber reduces the frequency shift, allowing the instability to re-emerge and the cycle to repeat. The process is cyclical because the varying growth rate can not be matched instantaneously by the nonlinear transfer: adjustments in the shape of the wavenumber spectrum are required to balance the instability, thereby providing an inertia that drives overshoot. A multiple time scale analysis of the renormalized model equations has been developed to describe the cycling oscillations. Quantitative comparisons will be made in future work.

The collisionless regime of trapped electron turbulence has also been explored numerically. In the collisionless regime, the electron nonlinearity becomes important. Because the electron nonlinearity (ExB advection of fluctuating electron density) drives an efficient transfer of energy to high wavenumber, the fluctuation level and transport fluxes are markedly reduced relative to values obtained without the electron nonlinearity. Reductions of an order of magnitude indicate that the practice of ignoring the electron nonlinearity in analytical theory leads to gross overestimates of the transport.

Energy carried into the shorter wavelength part of the spectrum by the ExB nonlinearity, or originating there if a short wavelength instability mechanism is present, is transferred by the polarization drift nonlinearity. This nonlinearity has a well known inverse cascade³, capable of carrying energy to long wavelengths, and has provided some of the rationale for claims⁴ that energy injected at a scale $k = \rho_e^{-1}$ by the η_e instability reaches longer scales typified by $k = c/\omega_{pe}$. An analytical and numerical study of energy transfer by the polarization drift nonlinearity *in a finite spectrum* has been carried out. Unlike the spectrum of infinite extent in which a self-similar inverse cascade has been proved to occur⁵, transfer in a finite spectrum proceeds in both directions in wavenumber space. Though the net transfer of energy, as determined by summing over the entire spectrum, is conservative, significant components of the energy are transferred *nonconservatively* in subranges above and below the scale of energy injection. These facts provide a significant modification of the conventional view of spectral transfer in drift wave turbulence.

III. Role of Flow Curvature and Flow Shear in Self-Regulated Turbulence [A.1, A.2, A.3, A.5]

In previous work⁶, a model for dissipative trapped electron turbulence was used to study H-mode fluctuation dynamics under shear suppression and stabilization⁷ from a turbulently generated, self-regulated flow. This work has been extended to include the curvature, or second radial derivative, of the flow. It has been found that for trapped electron modes, positive curvature is stabilizing. Moreover, single helicity effects responsible for reducing the efficacy of the flow shear suppression levels⁶, do not produce reductions of the curvature effect. On the other hand, it is found that the curvature operates by inducing a shift of the fluctuation frequency to higher values, thereby decreasing the instability drive.

The self-consistent treatment of saturated turbulence in the presence of turbulently generated flow shear and curvature yields solutions with a bifurcation-like transition. At low edge temperature, strong magnetic pumping is unfavorable for flow generation and the only solution is one with no flow and a large fluctuation level. At high edge temperature, this solution becomes unstable and curvature and shear are spontaneously generated. The system undergoes a transition to a new stable state having either flow shear or flow curvature and a decreased fluctuation level. The set of equations that yield this behavior suggest the possibility of a L-H transition process that occurs in a single step and that does not require external (non-turbulent) mechanisms such as orbit loss.

IV. Nonlinear Particle Transport in the Dissipative Trapped Electron Regime [A.17]

Previous calculations of the particle flux arising from the convection of nonadiabatic electron density by ion temperature gradient driven turbulence have been restricted to a quasilinear treatment.^{9,10} In the quasilinear treatment, an inward particle pinch is predicted in the highly collisional regime ($v_{\text{eff}} = v_e / e > \omega_b$, i.e. no trapped particles) and in the collisionless trapped electron regime ($v_{\text{eff}} < \omega < \omega_b$) above a critical temperature threshold.¹ In the dissipative trapped electron regime ($\omega < v_{\text{eff}} < \omega_b$), the quasilinear particle flux is wholly outward.

Our efforts have been focused on the analytic calculation of the fully turbulent particle flux in the dissipative trapped electron regime. The nonlinear effects incorporated in this analysis are derived primarily from a renormalized trapped

electron phase space density response, and is therefore consistent with a strong turbulence approach. The $\mathbf{E} \times \mathbf{B}$ nonlinearity in the electron equation gives rise to wave-electron resonance broadening, a shift in the wave-electron resonance frequency, and renormalized source terms or β terms. In addition to the electron nonlinearities, we also consider a turbulently broadened frequency spectrum. The spectrum includes a finite linewidth produced by the turbulent eddy damping which balances incoherent ion emission in the steady state¹¹ and a nonlinear shift of the peak away from the linear frequency, ω_k . The shift is an observed feature of mode-coupling simulations.¹

While the nonlinear flux calculated is a highly complicated function due to the amplitude dependence and recursive definitions of the nonlinearities in the strong turbulence limit, qualitative statements can be made about the flux. The analysis indicates that nonlinear effects in the fluctuating particle distribution do give rise to inward components of the particle flux in the dissipative trapped electron regime. The inward components are due primarily to the shift (in the electron direction) of the peak of the frequency spectrum. The renormalized source terms can also produce inward components, but the effect of these terms is less clear. In the strongly dissipative limit, an analytic expression for the flux is derived by expanding in the parameter $(\epsilon\omega/n_e)(v/v_e)^3 < 1$. Lowest order terms indicate a reduction of the overall flux due to finite linewidth and an inward component due to the shift. However, a numerical analysis using TEXT data¹² indicates that higher order terms have a strong effect, actually doubling the outward particle flux above the quasilinear prediction. While the inward component due to the frequency shift remains, the magnitude of this term is unclear as the shift is not calculated self-consistently. Further analysis is indicated.

V. Frequency Spectrum [A.10, A.20]

The work discussed in Secs. II - IV indicates the importance of the fluctuation frequency in microturbulence. In dissipative trapped electron turbulence, the nonlinear shift of the frequency dramatically alters the saturation dynamics, whereas, in the ion mixing mode, shifts of the frequency (assuming any exist) represent the most robust mechanism for obtaining an anomalous particle pinch in the dissipative trapped electron regime. Clearly, a theory of the drift wave frequency spectrum, including the physics of nonlinear shifts of the fluctuation frequency, is highly desirable. In previous work, an exploratory study into frequency spectrum physics was undertaken¹³. This work indicated the importance of incoherent emission on frequency shifts, in addition

to its previously described role on frequency spectrum linewidths¹¹. In the past year, this work has been extended to provide a theoretical framework describing physically how the incoherent emission process can induce frequency shifts in the collective resonance spectrum. Specifically, the frequency of granular fluctuations is calculated from a two-time, two-point equation and related to collective resonances through the reactive (real) part of the spectrum balance equation describing the saturated state. The frequency of the collective mode is ultimately governed by the linear frequency, nonlinear shifts of the coherent response function (such as the shift described in Sec. II), and a shift induced by the frequency of granular fluctuations. This preliminary work indicates that the test-clump description of incoherent emission from granular fluctuations into collective resonances captures the physics of both the mean frequency (shift) and mean square frequency (linewidth). Future work will produce quantitative predictions and undertake comparison with simulations¹⁴⁻¹⁵ and previous theory¹³.

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Appendix A
Grant-Related Publications and Fusion Program Activities

Journal Articles or Equivalent (published or submitted, since September 15, 1992):

- [A.1] B.A. Carreras, K. Sidikman, P.H. Diamond, P.W. Terry, and L. Garcia, "Theory of Flow Shear Effects on Long Wavelength Drift Wave Turbulence", *Phys. Fluids* **B4**, 3115 (1992).
- [A.2] N. Matter, "Peeling of Convection Cells and the Generation of Sheared Flow as Relaxation to Minimum Enstrophy", *Phys. Fluids* **B4**, 3448 (1992).
- [A.3] P. Terry, P.H. Diamond, B. A. Carreras, and K. Sidikman, "Tokamak Turbulence in Self-Regulated Differentially Rotating Flow and L-H Transition Dynamics," in New Ideas in Tokamak Confinement, edited by V. Stefan, published by the American Institute of Physics, New York.
- [A.4] P.W. Terry, et al., "Non-Local Transport Phenomena and Long Wavelength Turbulence in Tokamaks", Plasma Physics and Controlled Nuclear Fusion Research 1992, IAEA, Vienna, 1993) in press.
- [A.5] P.H. Diamond, et al., "Self-Regulation of Fluctuation Levels and Transport by Generation of Sheared Electric Fields", Plasma Physics and Controlled Nuclear Fusion Research 1992, (IAEA, Vienna, 1993) in press.
- [A.6] D.D. Schnack, Y.L. Ho, B.A. Carreras, K. Sidikman, G.G. Craddock, N. Matter, R.A. Nebel, S.C. Prager, P.W. Terry, and E.J. Zita, "Advances in Reversed-Field pinch Theory and Computation", Plasma Physics and Controlled Nuclear Fusion Research 1992, (IAEA, Vienna, 1993) in press.
- [A.7] D.E. Newman, P.W. Terry, P.H. Diamond, and Y.-M. Liang, "The Dynamics of Spectral Transfer in a Model of Drift Wave Turbulence with Two Nonlinearities", *Phys. Fluids* **B5**, 1140 (1993).
- [A.8] Y.-M. Liang, P.H. Diamond, X.-H. Wang, D.E. Newman, and P.W. Terry, "A Two-Nonlinearity Model of Dissipative Drift Wave Turbulence", *Phys. Fluids* **B5**, 1128 (1993).
- [A.9] P.W. Terry and D.E. Newman, "Nonconservative and Reverse Spectral Transfer in Hasegawa-Mima Turbulence", *Phys. Fluids B*, in press.
- [A.10] P.W. Terry, "Granular Fluctuations in Plasma Turbulence and Their Role in Transport", in Interdisciplinary Workshop on Statistical Description of Transport in Plasma, Astro-, and Nuclear Physics, in press.

Meeting Abstracts or Summaries:

DPP-APS Annual Meeting, Seattle, WA, November 16-20, 1992.

- [A.11] P.W. Terry and D.E. Newman, "Reverse Spectral Transfer in Turbulence with Dual Cascade".
- [A.12] G.G. Craddock, A.E. Koniges, J.A. Crotinger, P.H. Diamond, D.E. Newman, and P.W. Terry, "Turbulent Dynamics of Fluid Collisionless and Dissipative Two-Field Trapped Electron Models".
- [A.13] G.A. Riggs, K. Sidikman, B.A. Carreras and P.W. Terry, "Radial Structure of Drift Wave Turbulence".
- [A.14] D.E. Newman, P.W. Terry, P.H. Diamond, and G.G. Craddock, "Dynamical Effects of Two Nonlinearities: Frequency Shift Induced Mode Instability and Structure Evolution".
- [A.15] A.E. Koniges, G.G. Craddock, J.A. Crotinger, C.L. Anderson, P.H. Diamond, A.V. Pillipas, D.E. Newman, and P.W. Terry, "Computational Diagnostic Techniques Applied to Tokamak Turbulence".

IAEA Meeting, Wüzburg, Germany, September 30-October 7, 1992.

Three papers were presented. These are listed as papers [A.4] [A.5], and [A.6] under journal articles or equivalent.

Sixth Transport Task Force Meeting, Newport, RI, February 22-25, 1993.

- [A.16] P.W. Terry and P.H. Diamond, "Analytical Studies of 2-Field Trapped Electron Mode Turbulence".
- [A.17] A.S. Ware and P.W. Terry, "Nonlinear Particle Transport in the Dissipative Trapped Electron Regime".
- [A.18] D.E. Newman and P.W. Terry, "Saturation Level Fluctuations and k-space Perturbative Energy Propagation Studies in a 2-D DTEM Model".
- [A.19] G.G. Craddock, A.E. Koniges, J.A. Crotinger, P.H. Diamond, D.E. Newman, and P.W. Terry, "Turbulent Dynamics of Fluid Collisionless and Dissipative Trapped Electron Models".

Sherwood Theory Conference, Newport, RI, March 29-31, 1993

[A.20] A.S. Ware and P.W. Terry, "The Effect of Clumps on the Frequency Spectrum of Dissipative Trapped Electron Driven Drift Wave Turbulence".

[A.21] G.G. Craddock, A.E. Koniges, J.A. Crotinger, P.H. Diamond, D.E. Newman, and P.W. Terry, "Turbulent Dynamics of Fluid Collisionless and Dissipative Trapped Electron Models".

Additional Meetings/Workshops Attended/Talks (given by P.W. Terry, A.S. Ware of D.E. Newman.

P.W. Terry, "Granular Fluctuations in Plasma Turbulence and Their Role in Transport, at Les Houches Workshop on Statistical Descriptions of Transport in Plasma, Astro-, and Nuclear Physics, Les Houches, France, February 2-11, 1993.

A.S. Ware, "The Frequency Spectrum of Drift Wave Turbulence", Plasma Theory Seminar, University of Wisconsin-Madison, May 3, 1993.

D.E. Newman, "Nonlinear Transfer and Saturation of Long Wavelength Drift Wave Turbulence", Seminar, Oak Ridge National Laboratory, April 28, 1993.

OFE/DOE Programmatic Activities

Member, Joint Institute for Fusion Theory (JIFT) Management Committee.

Member, Sherwood Theory Executive Committee, 1991-1993.

Lecturer, Third Transport Task Force Summer School, Madison, WI, August 16-20, 1993.

Member, Institute for Fusion Studies Advisory Committee, 1993.

Member, Sherwood Theory Meeting Program Committee, 1993.

Interim Working Group Leader, Core Fluctuations Working Group, Transport Task Force.

Member, L-H Transition Working Group, Transport Task Force.

Appendix B

Grant Modalities

During the second year of the grant period (September 15, 1992 to September 14, 1993) the participating personnel and their approximate degree of involvement are follows:

Faculty: P.W. Terry (Principal Investigator: summer salary of 2-1/2 months, 1993).

Postdocs: A. Ware (6 months)

Graduate Students: D.E. Newman (50% research assistant for 12 months)
E. Fernandez (hourly summer salary, 1993)

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