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ANNUAL PROGRESS REPORT ON FUSION PLASMA THEORY GRANT

Task I: Magnetic Confinement Fusion Plasma Theory

Principal Investigator: J. D. Callen

Period: November 16, 1992 through November 15, 1993

The research performed under this grant during the current year has concentrated on a few tokamak plasma confinement issues: applications of our new Chapman-Enskog-like approach for developing hybrid fluid/kinetic descriptions of tokamak plasmas; multi-faceted studies as part of our development of a new interacting island paradigm for the tokamak "equilibrium" and transport; investigations of the resolution power of BES and ECE diagnostics for measuring core plasma fluctuations; and studies of net transport in the presence of fluctuating surfaces. Recent progress and publications in these areas, and in the management of the NERSC node and the fusion theory workstations are summarized briefly in this report.

I. Introduction

This "annual" progress report on Task I of the Fusion Plasma Theory DOE grant number DE-FG02-86ER53218 at the University of Wisconsin-Madison covers research performed during the second year (November 16, 1992 through November 15, 1993) of the current three-year grant period. This is the third three-year grant under the same DOE grant. These grants evolved from DOE Contract Number DE-AC02-80ER53104 that supported research in this area at the University of Wisconsin-Madison from July 15, 1980 through December 31, 1985.

The Task I research summarized in this report involves magnetic confinement fusion plasma theory, primarily in areas that are either: unique developments; relevant to plasma experiments and/or fusion reactor design studies at the UW-Madison; or areas in which we are closely coupled to some critical issues in the present generation of large tokamaks (e.g., via our TFTR Experimental Data Analysis collaboration which primarily supports Dr. Z. Chang on essentially permanent assignment at PPPL). As originally proposed for this three-year grant period, and in concert with the dominant themes of the magnetic fusion program at this time, the research during the current period has concentrated almost entirely on tokamak-related fusion plasma theory, and in particular on tokamak plasma transport issues.

Research progress on this grant during the past year is briefly summarized in Sections II - V. The summaries are quite brief because so much of the work has been already (or is in the process of being) published in public forums -- 9 journal publications, 4 reports, 13 meeting abstracts, 8 other talks (see Appendix A). Also, recent developments in the management of the UW-Madison NERSC node and fusion theory workstations are touched on in Section VI. The last regular section (VII)

provides a brief overall summary and is followed by a list of regular references (e.g., [1]). Appendix A lists publications and fusion program activities supported by this grant during the current period, and provides a list of project references (e.g., [A.1]). Appendix B summarizes the current personnel (including a number of short-term visitors this year) and their degree of involvement this past year. Finally, Appendix C indicates the professional history of previous graduate students, postdocs, and scientists supported by this grant and its antecedent contract.

II. Applications Of Hybrid Fluid/Kinetic Approach [A.1, A.8, A.12, A.14, A.16, A.32, A.34]

Our development of the rigorous Chapman-Enskog-like approach for deriving hybrid fluid/kinetic descriptions of plasmas has now been published [1,2]. This past year applications of this work to nonlinear calculation of the gyroviscous force and its effects [A.1], and to fluid-like modeling of the plasma presheath region [A.8] have also been published. In addition, our determination of the poloidal variation of the neoclassical parallel viscous force, which was made possible by this new approach, has now been published [A.12]. Also, we have been using the same general fluid moment formalism to explore fast ion effects on the collisional friction and parallel viscous forces [A.14]. Further, review-type talks on this new general procedure and some of its applications have been presented [A.32, A.34]. Finally, this new approach underpins our suggestion [A.16] that a numerical model of tokamak plasmas should be based on a fluid-like description (with appropriate kinetic closures), intrinsically include collisional effects (e.g., to obtain an appropriate parallel Ohm's law), and allow for magnetic reconnection.

III. Effects And Interactions of Magnetic Islands [A.2, A.5, A.6, A.7, A.11, A.17, A.18, A.20-A.23, A.26-33]

Recently we have been advancing a new paradigm for the "equilibrium," stability and transport properties of tokamak plasmas based upon a neoclassical MHD [3] model of pressure-gradient-driven, interacting mini-magnetic islands [A.2]. In exploring various aspects of this new paradigm over the past year we have: explored the structure of the pressure profile in the vicinity of a magnetic island [A.6, A.28] and the free energy available to an island [A.17]; determined the resultant structure of plasma parameter fluctuations near an isolated magnetic island [A.30, A.32, A.33]; investigated the ideal MHD stability of ballooning modes near a magnetic island [A.5, A.29] -- they are slightly destabilized; performed numerical simulations [A.18, A.23] of the model equations [A.2] for the interacting magnetic islands; studied the possible effects of trapped-ion (or poloidal ion gyroradius) effects [A.21, A.22]; and explored possible neoclassical MHD [3] effects on the $m/n=1/1$ modes in tokamaks [A.26]. Also, we have given a number of presentations [A.7, A.20, A.27, A.28, A.30-A.33] on various aspects of this work in various forums. Overall, the model has been rather well received and seems like it may naturally explain a number of experimental conundrums which are themselves still somewhat controversial -- "flat spots" on the temperature

profile near low order rational q values (due to the interacting islands), enhanced perturbative transport (due to the mix of good, bad transport regions), effective diffusion coefficients that tend to increase with minor radius (because of the density of rational surfaces).

IV. Fluctuation Diagnostic Resolution Issues [A.4, A.10, A.30, A.32, A.33]

Many diagnostics have difficulty resolving smallish (few cm or smaller) magnetic island and other fluctuations in the core of hot tokamak plasmas. In order to clarify how fine a scale the fluctuations can be resolved, and other fluctuations diagnostic issues, we have become involved in modeling some key aspects of Beam-Emission-Spectroscopy (BES) and Electron-Cyclotron-Emission (ECE) diagnostics. For the BES studies we wrote a code [A.10] that facilitated calculation [A.4] of the edge fluctuation effects on the plasma core multi-step excitation states of the beam neutrals that are measured by BES. An outgrowth of this work is that this code has now been interfaced (by a combination of T.A. Gianakon of this grant and D.C. McCune of PPPL) into TRANSP to facilitate calculation of these important multi-step excitation effects for neutral beam penetration and deposition in TFTR. These effects are expected to be quite important in the upcoming TFTR D-T experiments. In another area, we have begun [A.30, A.32, A.33] calculations of the temperature fluctuations (level, temporal variation, etc.) that should be expected in the vicinity of a magnetic island, including the finite resolution characteristics of the ECE diagnostics.

V. Net Transport In The Presence of Fluctuations [A.9, A.13, A.15, A.24, A.25]

When fluctuations, particularly magnetic ones, are present, the flux (or flux plus vorticity [4]) surfaces across which "radial" transport is to be measured may themselves be fluctuating. We have been investigating the net "radial" transport in the presence of various types of fluctuations to determine precisely what should be calculated and measured to determine net transport. In particular, we have been: investigating [A.15] the net transport relative to nested invariant magnetic flux plus vorticity [4] surfaces; exploring possible sources for anomalous energy or heat pinches [A.25]; and clarifying the scaling of plasma transport processes in topologies consisting of mixtures of magnetic islands, stochastic regions and "good" flux surfaces [A.9, A.13, A.24]

VI. Local Fusion Computer Systems Management

While the Principal Investigator on this grant is responsible for the local computer host (UWMFE) for the NERSC network, it is actually simply run on a VAXstation 3100 as part of the Phaedrus VAX cluster. The UWMFE and NERSC user accounts are administered by our secretary and the net cost of at out \$7 k per year is apportioned among approximately 115 registered NERSC users at UW-Madison. Previously we have had only a DECstation 5000 workstation. In May of this year using a combination of a special APT/OFE/DOE computer equipment grant of \$20 k plus \$22.1 k of UW matching funds, we were able to obtain 3 additional new workstations --

2 DEC-alphas and a SUN SPARC 10-41. These workstations are all administered by fusion theory personnel (primarily advanced graduate students). They are utilized by a large fraction of fusion theory researchers at UW-Madison and their costs are apportioned to the local fusion theory grants.

VII. Summary

As discussed in the preceding text, notable progress has been achieved in most of the areas originally proposed for the current three-year grant: a) we have applied our Chapman-Enskog-like approach to some new areas; b) we have made considerable progress developing our new interacting island model for the tokamak "equilibrium" and transport; c) we have been involved in determining just what fluctuations BES and ECE diagnostics are capable of measuring; and d) we have been exploring how to determine net transport due to fluctuations in plasmas whose "flux" surfaces are themselves fluctuating.

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REFERENCES

- [1] J. P. Wang and J.D. Callen, Phys. Fluids B 4, 1139 (1992).
- [2] Z. Chang and J.D. Callen, Phys. Fluids B 4, 1167 (1992); 1182 (1992).
- [3] J.D. Callen, W.X. Qu, K.D. Siebert, B.A. Carreras and D.A. Spong, "Neoclassical MHD Equations, Instabilities and Transport in Tokamaks," in Plasma Physics and Controlled Nuclear Fusion Research 1986 (IAEA, Vienna, 1987), Vol. II, p. 157.
- [4] J.D. Callen and J.B. Hollenberg, "Net Transport Equations for a Tokamak Plasma," EPS Meeting on Plasma Physics and Controlled Fusion, Berlin, GERMANY, 3-7 June 1991.

APPENDIX A

GRANT-RELATED PUBLICATIONS AND FUSION PROGRAM ACTIVITIES

Journal Articles or Equivalent:

- [A.1] Z. Chang and J.D. Callen, "Generalized Gyroviscous Force And Its Effect On The Momentum Balance Equation," Phys. Fluids B **4**, 1766 (1992).
- [A.2] C.C. Hegna and J.D. Callen, "Interaction of Bootstrap-Current-Driven Magnetic Islands," Phys. Fluids B **4**, 1855 (1992).
- [A.3] J.D. Callen, "Transport Processes in Magnetically Confined Plasmas," Phys. Fluids B **4**, 2142 (1992).
- [A.4] T.A. Gianakon, R.J. Fonck, J.D. Callen, J.S. Kim, R.D. Durst and S.F. Paul, "Effects of Edge Plasma Turbulence On Radial Correlation Length Measurements With BES," Rev. Sci. Instrum. **63**, 4931 (1992).
- [A.5] C.C. Hegna and J.D. Callen, "Ideal Ballooning Stability Near An Equilibrium Magnetic Island," Phys. Fluids B **4**, 3031 (1992).
- [A.6] C.C. Hegna and J.D. Callen, "Pressure Profiles, Resonant Pfirsch-Schlüter Currents, Thermal Instabilities, and Magnetic Island Formation," Phys. Fluids B **4**, 4072 (1992).
- [A.7] C.C. Hegna and J.D. Callen, "Magnetic Bubbling Due To Interacting Bootstrap-Current-Driven Magnetic Islands," Proc. of Int. Conf. on New Ideas in Tokamak Confinement, V. Stefan, Ed. (La Jolla, 1992).
- [A.8] B.J. Lee and J.D. Callen, "Fluidlike Modeling Of The Plasma-Material Interaction," Phys. Fluids B **5**, 1647 (1993).
- [A.9] C.C. Hegna and J.D. Callen, "Plasma Transport in Mixed Magnetic Topologies," Phys. Fluids B **5**, 1804 (1993).

Reports:

- [A.10] T.A. Gianakon, "Calculation of Neutral Beam Deposition Accounting for Excited States," UW-CPTC 92-4, September 1992.
- [A.11] C.C. Hegna and J.D. Callen, "Long Wavelength Magnetic Fluctuations in Toroidal Plasmas," UW-CPTC 92-5, October 1992 (to be published in the Proceedings of the International Workshop on Magnetic Turbulence and Transport, Cargèse, FRANCE, 6-12 July).

- [A.12] J.P. Wang and J.D. Callen, "Poloidal Variation of Viscous Forces in the Banana Collisionality Regime," UW-CPTC 92-6, December 1992 (to be published in Phys. Fluids B).
- [A.13] C.C. Hegna and J.D. Callen, "Plasma Transport in Mixed Magnetic Topologies," UW-CPTC 92-7, December 1992 (published in Phys. Fluids B -- see [A.9] above).

Meetings Abstracts, Summaries or Papers:

DPP-APS Annual Meeting in Seattle, WA, 16-20 November

- [A.14] J.P. Wang, M. Azumi, K. Tani and J.D. Callen, "Fast Ion Neoclassical Transport, Frictional and Viscous Forces," Bull. Am Phys. Soc. **37**, 1366 (1992).
- [A.15] J.B Hollenberg and J.D. Callen, "Turbulent Transport Across Invariant Flux Surfaces," Bull. Am. Phys. Soc. **37**, 1543 (1992).
- [A.16] J.D. Callen, "On Developing A Numerical Model Of Tokamak Plasmas," Bull. Am. Phys. Soc. **37**, 1544 (1992).
- [A.17] C.C. Hegna and J.D. Callen, "Energy Involved in Magnetic Island Formation," Bull. Am. Phys. Soc. **37**, 1595 (1992).
- [A.18] T.A. Gianakon, C.C. Hegna and J.D. Callen, "Simulations of Interacting Bootstrap-Current-Driven Magnetic Islands," Bull. Am. Phys. Soc. **37**, 1595 (1992).
- [A.19] C. Litwin and C.C. Hegna, "Non-MHD and Anomalous Effects on the Alfvén Wave Induced Dynamo Current Drive," Bull. Am. Phys. Soc. **37**, 1604 (1992).

International Sherwood Fusion Theory Conference, Newport, RI, 29-31 March

- [A.20] C.C. Hegna, J.D. Callen, T. A. Gianakon, W.X. Qu, A.I. Smolyakov and J.P. Wang, "Magnetic Islands and Their Effects in Tokamaks," paper 1B4 (selected for oral presentation, paper to be published in Plasma Physics and Controlled Fusion).
- [A.21] J.D. Callen, A.I. Smolyakov and C.C. Hegna, "Trapped-Particle Effects In The Nonlinear Evolution of Magnetic Islands," paper 1D30.
- [A.22] J.P. Wang, C.C. Hegna and J.D. Callen, "Finite Banana Orbit Effects In The Presence of Mini-Magnetic Islands," paper 1D31.
- [A.23] T.A. Gianakon, C.C. Hegna and J.D. Callen, "Simulations of Interacting Bootstrap-Current-Driven Magnetic Islands," paper 1D32.

- [A.24] C.C. Hegna and J.D. Callen, "Plasma Transport in Mixed Magnetic Topologies," paper 1D49.
- [A.25] A.I. Smolyakov, "Anomalous Energy Pinch In Turbulent Transport," paper 2C32.
- [A.26] W.X. Qu and J.D. Callen, "Neoclassical MHD Modified Eigenmode Equations For Internal Kink Modes In Tokamak Plasmas," paper 3C49.

Additional Meetings and Workshops Attend. Talks Given:

- [A.27] C.C. Hegna, "Interaction of Bootstrap-Current-Driven Magnetic Islands," International Workshop on Magnetic Turbulence and Transport, Cargèse, FRANCE, 6-12 July 1992.
- [A.28] C.C. Hegna, "Effects of Magnetic Islands on Pressure Profiles and Ideal MHD Instabilities," Theory Seminar, Culham Laboratory, Abingdon, ENGLAND, 14 July.
- [A.29] C.C. Hegna, "Ideal Ballooning Stability Near An Equilibrium Magnetic Island," US/Japan Workshop on Theory of High Beta Plasmas, San Diego, CA, 11-13 November.
- [A.30] J.D. Callen, "Possible Structures and Their Measurement in Tokamaks," and "Transient Transport Working Group Activities," at Transport Task Force Meeting, Newport, RI, 22-25 February.
- [A.31] C.C. Hegna, "Magnetic Islands in Toroidally Confined Plasmas," Physics Colloquium, University of Texas, Austin, TX, 4 March.
- [A.32] J.D. Callen, "Effects and Interactions of Magnetic Islands in Tokamaks," and "Hybrid Fluid/Kinetic Descriptions of Plasmas And Some Applications of Them," Third International Summer School on Plasma Physics and Controlled Fusion, St. Petersburg, RUSSIA, 15-22 June.
- [A.33] J.D. Callen, "Magnetic Islands and Their Effects in Tokamaks," JET Symposium, Abingdon, ENGLAND, 24 June.
- [A.34] J.D. Callen, "Hybrid Fluid/Kinetic Descriptions of Plasmas," Theory Seminar, Culham Laboratory, Abingdon, ENGLAND, 25 June.

Other OFE or Programmatic Activities and Meetings Attended (J.D. Callen)

Leader of Transient Transport Working Group of TTF -- hosted Transient Transport workshops at DPP-APS Seattle (16 November 1992), TTF Newport, RI (22-23 February); attended TTF Working Group Leaders and Steering Committee meetings in Seattle (15 November), Newport, RI (22, 24 February).

TFTR Advisory Committee -- met 24 September at Princeton Plasma Physics Laboratory

Coordinated tests of superworkstations (DEC-alpha, HP 735, SUN SPARC 10, SGI R4000) for UW College of Engineering faculty and for deciding which to buy with our OFE/DOE \$20k special equipment grant (plus \$22.1k UW matching support), February/March

Chair, -TPX conceptual Design Review, PPPL, 29 March - 1 April

Host for D.H. Crandall of OFE/DOE visit to UW-Madison, 20 May

System Manager for the University of Wisconsin UWMFE computer system for accessing NERSC computers at Livermore.

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APPENDIX B

GRANT MODALITIES

During the current grant period (11/16/92 - 11/15/93 -- \$250k) the participating personnel and their approximate degree of grant-related involvement has been as follows:

Faculty:	J.D. Callen (Principal Investigator: average of 20% during the academic year plus 2 summer months)
Visiting Scientists:	A.I. Smolyakov (Kurchatov Institute, Moscow, RUSSIA, 100% time for 8.5 months)
	W.X. Qu (Leshan Institute, Sichuan, CHINA, 50% time for 6 months)
	M. Yagi (JAERI, Naka, JAPAN, 3 months at no cost to grant)
Postdocs:	C.C. Hegna (50% time for 12 months) J.P. Wang (65% time for 9.5 months)
Graduate Students:	R.L. Coffey (50% Research Assistant for 9.5 months) T.A. Gianakon (50% Research Assistant for 12 months) J.B. Hollenberg (50% Research Assistant for 12 months)

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