Fusion Plasma Theory Project Summaries

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INTRODUCTION

This Project Summary book is a published compilation consisting of short descriptions of each project supported by the Fusion Plasma Theory and Computing Group of the Advanced Physics and Technology Division of the Department of Energy, Office of Fusion Energy. The summaries contained in this volume were written by the individual contractors with minimal editing by the Office of Fusion Energy. Previous summaries were published in February of 1982 and December of 1987.

The Plasma Theory program is responsible for the development of concepts and models that describe and predict the behavior of a magnetically confined plasma. Emphasis is given to the modelling and understanding of the processes controlling transport of energy and particles in a toroidal plasma and supporting the design of the International Thermonuclear Experimental Reactor (ITER). A tokamak transport initiative was begun in 1989 to improve understanding of how energy and particles are lost from the plasma by mechanisms that transport them across field lines. The Plasma Theory program has actively participated in this initiative. Recently, increased attention has been given to issues of importance to the proposed Tokamak Physics Experiment (TPX).

Particular attention has been paid to containment and thermalization of fast alpha particles produced in a burning fusion plasma as well as control of sawteeth, current drive, impurity control, and design of improved auxiliary heating. In addition, general models of plasma behavior are developed from physics features common to different confinement geometries.

This work uses both analytical and numerical techniques. The Fusion Theory program supports research projects at U.S. government laboratories, universities and industrial contractors. Its support of theoretical work at universities contributes to the Office of Fusion Energy mission of training scientific manpower for the U.S. fusion energy program.

Fusion Plasma Theory and Computer Group

Personnel

<i>Staff Members</i>	<i>Area of Responsibility</i>
Walter Sadowski	Group Chief
Michael Crisp	Project Manager
Mary Anne Scott	Project Manager
Sheila Frizzell	Group Secretary

Budget Authority (in Thousands of Dollars)

<i>Operating Budget (by area)</i>	<i>FY90</i>	<i>FY91</i>	<i>FY92</i>
Alternate Concept Theory	\$ 2,250	\$ 1,500	\$ 685
Atomic Physics Theory	550	500	510
Generic Theory	2,260	2,500	2,335
Toroidal Theory	14,200	14,900	15,607

Fusion Plasma Theory Project Summaries

TABLE OF CONTENTS

Institution & Project	Page
AUBURN UNIVERSITY <i>Theoretical Studies of Radiofrequency Radiation and Magnetic Topology of Toroidal Plasmas</i>	1
COLLEGE OF WILLIAM AND MARY <i>Theory of Fusion Plasmas</i>	3
COLUMBIA UNIVERSITY <i>High Beta Plasma Theory</i>	5
DARTMOUTH COLLEGE <i>Nonlinear Magnetohydrodynamics</i>	7
GENERAL ATOMICS <i>Applied Plasma Physics Fusion Theory</i>	9
HAMPTON UNIVERSITY <i>Anomalous Transport in Toroidal Plasmas</i> <i>Electron Transport in the Stochastic Fields of Reversed Field Pinch ZT40M</i>	11 13
INSTITUTE FOR FUSION STUDIES <i>Establishment of an Institute for Fusion Studies</i>	15
INSTITUTE OF NON-LINEAR SCIENCE APPLICATIONS <i>Chaotic Dynamics in Plasmas: Method of Symbolic Kinetic Equation</i>	17
KRALL ASSOCIATES <i>A Program of FRC Theory Research</i>	19
LEHIGH UNIVERSITY DEPARTMENT OF PHYSICS <i>Electron Cyclotron Heating and Current Drive in Toroidal Geometry</i>	21

LODESTAR RESEARCH CORPORATION	
<i>Fundamental Studies of Fusion Plasmas</i>	23
LOS ALAMOS NATIONAL LABORATORY	
<i>Alternate Concept Theory</i>	26
<i>Moving Finite Elements</i>	29
<i>Simulation of Transport in Magnetized Plasma</i>	31
<i>Toroidal Transport Theory</i>	33
MASSACHUSETTS INSTITUTE OF TECHNOLOGY	
<i>Fusion Theory and Computations</i>	36
<i>Physics of Thermonuclear Plasmas</i>	39
NEW YORK UNIVERSITY	
<i>Advanced Toroidal Theory</i>	43
<i>Plasma Properties</i>	45
<i>Superdiffusion</i>	47
OAK RIDGE NATIONAL LABORATORY	
<i>Fusion Theory and Computing</i>	48
OLD DOMINION UNIVERSITY	
<i>Wave Propagation in Tokamaks</i>	53
PRINCETON PLASMA PHYSICS LABORATORY	
<i>Theoretical Plasma Physics for Fusion</i>	55
SCIENCE APPLICATIONS INTERNATIONAL CORPORATION	
<i>3-D ICRF Antenna Modeling and Simulation</i>	60
<i>Transport and Dynamics in Toroidal Fusion Systems</i>	62
STI OPTRONICS	
<i>Theory of Field-Reversed Configurations</i>	64
UNIVERSITY OF CALIFORNIA—BERKELEY	
<i>Research in Theory and Simulation of Bounded Plasmas</i>	66
UNIVERSITY OF CALIFORNIA—LOS ANGELES	
<i>Applications of Computer Modeling to Fusion Research</i>	69
<i>Heating, Transport and Wave Diagnostics of Fusion Plasmas</i>	72

UNIVERSITY OF CALIFORNIA—SAN DIEGO	
<i>Investigations in Anomalous Transport and Ignition Physics</i>	74
UNIVERSITY OF COLORADO	
DEPARTMENT OF ASTROPHYSICAL, PLANETARY, AND ATMOSPHERIC SCIENCES	
<i>Collisional and Chaotic Transport in Toroidal Plasma</i>	76
UNIVERSITY OF ILLINOIS AT URBANA—CHAMPAIGN	
<i>Methods for Testing Transport Models</i>	78
UNIVERSITY OF MARYLAND	
<i>Maryland Controlled Fusion Research Program</i>	80
THE UNIVERSITY OF TEXAS AT AUSTIN	
FUSION RESEARCH CENTER	
<i>Plasma Confinement Theory and Transport Simulation</i>	82
UNIVERSITY OF WASHINGTON	
<i>Helicity Injected Tokamak (HIT)—</i>	
<i>Supporting Theoretical Research</i>	85
UNIVERSITY OF WISCONSIN—MADISON	
<i>Auxiliary Radiofrequency Heating in Tokamaks</i>	87
<i>Low Frequency RF Current Drive</i>	89
<i>Low Frequency RF Current Drive Theory:</i>	
<i>Task 1 of the Phaedrus Grant</i>	91
<i>Magnetic Confinement Fusion Plasma Theory</i>	93
<i>Stellarator Theory</i>	96
<i>Theoretical Reversed Field Pinch and Tokamak Studies</i>	97
<i>Theoretical Studies of Turbulence and</i>	
<i>Anomalous Transport in Toroidal Confinement Devices</i>	99
YALE UNIVERSITY	
<i>Theoretical and Numerical Studies in Magnetic Fusion</i>	102

Auburn University

Project

Theoretical Studies of Radiofrequency Radiation and Magnetic Topology of Toroidal Plasmas

D.G. Swanson and J.D. Hanson

Funding

FY 1990	FY 1991	FY 1992
\$95.0k	\$85.0k	\$81.2k

Purpose

1. The purpose of the mode conversion studies is to complete the analysis of the types of mode conversion problems, emphasizing the coupling of the X-mode and the O-mode at various harmonics of the ion cyclotron frequency, and to evaluate the effects of mode conversion on electron synchrotron radiation, which include the effects of radiation transport within the plasma.

2. The purpose of the magnetic topology portion of this project is to understand and control the magnetic field structure within toroidal plasmas. One part of the project is the computational support of the experimental program of the Compact Auburn Torsatron (CAT) involving the comparison of observed and computed magnetic field structures. A second part is the investigation of fixing small asymmetries in tokamak magnetic fields.

Approach

1. In analyzing the X-mode/O-mode coupling at electron cyclotron harmonics, we have used a combination of analytic and numerical techniques developed previously, which include the Green function method which converts the tunneling equation into an integral equation. Having already established the Generalized Kirchhoff's Law (GKL), the investigation of synchrotron radiation has been directed at determining the nature of the source distribution function through a variational principle. For estimating the total reduction in synchrotron radiation from a fusion, plasma, simplified numerical methods are being developed to accelerate the survey over the broad range of parameters encountered.

2. Our approach to magnetic topology issues is firmly grounded in the recognition that magnetic fields are a Hamiltonian system. The structures which are observed in magnetic fields, such as islands, x and o points, flux surfaces, and separatrices are well understood (although sometimes with different terminology) from a nonlinear dynamics perspective. The insight gained from the nonlinear dynamics guides the computations which are performed.

1. It has been determined that all mode conversion problems in plasmas are either three branch or five branch problems, and we have solutions for both cases. There is only one range of parameters for a five branch problem yet to be completed, and then every possible case will have been completed formally.

The most important cases have already been studied, but the range of parameters is still limited. We have already determined the source distribution function for all three branch problems for a representative range of parameters [5]. Analytic expressions for the source distribution function for the five branch case have recently been completed. An exact analysis of some of the scattering coefficients for the three branch cases (which can be extended to the five branch cases) has clarified the difference between transmission coefficients and absorption, and led to a redefinition of opacity and the probable demise of the concept of optical depth for all cyclotron or synchrotron radiation cases [6].

2. Earlier work on stellarator design led to the development of a code, named IFT, which was used to design the Compact Auburn Torsatron. The code is now being used to compute the magnetic field from the torsatron coils, and to design correction coils. A recent paper on controlling magnetic islands with a horizontal-field trim coil has been accepted for publication [1]. A second paper on the local rotational transform within islands is in preparation. The toroidal location of locked modes in tokamaks is often correlated with a known magnetic field asymmetry, such as a horizontally shifted poloidal field coil. These locked modes can cause decreased confinement and disruptions. Since it is extremely difficult to control all sources of asymmetry during the construction of a tokamak, I have investigated the possibility of using a set of small trim coils to eliminate the magnetic islands at outer rational magnetic surfaces. The main computational problem, which has been solved, is to compute the currents in the correction coils which are needed to correct a given set of magnetic field asymmetry.

Plans

1. Both analytic and numerical work on the last five branch problem will be completed, along the corresponding source distribution function. Simplified numerical methods will be developed to facilitate the survey of synchrotron radiation to determine the net reduction of synchrotron radiation due to mode conversion effects. The importance of radiative transport with the plasma will be further evaluated. There is some indication that the effects of nonthermal distribution functions on synchrotron radiation might also be treated with the methods discovered for thermal plasmas, and this suggestion will be pursued with an attempt to determine the magnitude of any approximations involved. A book on mode conversion theory is in progress, and should be finished in the first half of 1993.

2. In the next year, the computational support of CAT will continue, with a substantial part of the running of the code being done by a graduate student. As the experimental program on CAT changes direction, there will be additional work needed to keep the computational capabilities applicable to the experiment. The tokamak asymmetry work will soon be extended to the design of trim coils for proposed tokamaks such as SSAT-TPX and ITER. On a longer time scale, the work will be extended to look at the magnetic topology and asymmetry effects in divertors and ergodic magnetic limiters, and to look at design issues for future torsatrons.

Other Professional Staff

Dr. Vadim F. Shvets, Senior Research Fellow

Collaborations

The experimental work on CAT is of course done in collaboration with the experimentalists at Auburn.

Students

Mr. Jianlong Hu has finished writing his dissertation and should graduate in March, 1993. Mr. S.C. Ng is still working on the project, and has about another year to finish.

Major Recent Publications

1. R.F. Gandy, M.A. Henderson, J.D. Hanson, S.F. Knowlton, T.A. Schneider, D.G. Swanson, J.R. Cary, "Design of the Compact Auburn Torsatron," *Fusion Technology* **18**, 281 (1990).
2. John R. Cary and James D. Hanson, "Simple Method for Calculating Island Widths," *Physics of Fluids* **B 3**, 1006 (1991).
3. Suwon Cho and D.G. Swanson, "Absorption and Emission of Plasma Waves in Mode Conversion Layers at General Harmonics of the Ion Cyclotron Frequency," *Physics of Fluids* **B2**, 2693 (1990).
4. Suwon Cho and D.G. Swanson, "Reciprocity Relations and the Mode Conversion-Absorption Equation with an Inhomogeneous Source Term," *Physics of Fluids* **B2**, 2704 (1990).
5. D.G. Swanson and V.F. Shvets, "Cyclotron Emission from Nonuniformly Magnetized Plasmas," *Physical Review Letters* **68**, 3036 (1992).
6. D.G. Swanson and V.F. Shvets, "The Independence of Transmission and Absorption in Mode Conversion," *J. Math. Phys.*, January, 1993.
7. D.G. Swanson and V.F. Shvets, "Cyclotron and Synchrotron Radiation from a Mode Conversion Layer," *Radio-Frequency Power in Plasmas*, (Ninth Topical Conference, AIP Conference Proceedings 244, American Institute of Physics, New York, 1991), 385.

College of William and Mary

Project

Theory of Fusion Plasmas

Allen H. Boozer, George M. Vahala and Eugene Tracy

Funding

FY 90	FY 91	FY 92
\$85.0k	\$75.0k	\$97.5k

Purpose

The goal of our research is the development of theoretical plasma physics in areas that are of critical importance to the achievement of economical fusion energy. In particular we have worked on the physics of steady state fusion plasmas (tokamak plasmas with a strong bootstrap effect and stellarators), transport (confinement of alpha particles and turbulence), and diagnostic techniques using microwave scattering.

Approach

We have used a range of techniques from mathematics and theoretical plasma physics to investigate problems of fusion interest. Areas of strength include coordinate transformation techniques, Hamiltonian methods, and renormalization group techniques.

Progress

We have derived a general expression for the strength of the magnetic field in general plasma equilibria. Using this expression we have shown that it is possible to have fully three dimensional stellarator equilibria that have similar confinement properties for high energy particles as tokamaks. More precisely we have shown that the terms that lead to the loss of high energy particles are proportional to ϵ^2 where ϵ is the inverse aspect ratio of the plasma.

The drift approximation is the standard used to study the confinement of high energy particles such as alphas in plasmas of fusion interest. The adequacy of this approximation for alpha particles in a reactor has previously received only very limited attention. The standard expression for particle drift motion depends only on the magnetic field strength. We have derived the next order in ratio of gyroradius to system size correction to the drift motion and shown that this term depends on the shape of the magnetic surfaces as does the exact particle motion.

We have studied the properties of tokamaks in which the current is maintained by a combination of the bootstrap current plus tearing modes with no external power input. Our studies indicate that tokamaks can be self-maintaining. The current driven by the bootstrap effect, I_b , is somewhat larger than the actual current, I , due to the effects of tearing modes in the outer parts of the plasma.

The effects of magnetic and density fluctuations on electromagnetic wave propagation have been studied. In particular, we are proposing a mode conversion diagnostic that should be able to detect magnetic fluctuations in tokamaks. Renormalization group techniques are being pursued to model the effects of small unresolvable scales on broad turbulence.

Plans

The work on the confinement of high energy particles will be extended to study the effect of the jitter of the turning point of tokamak bananas due to a non-zero gyroradius on the confinement of alpha particles in a tokamak with toroidal ripple. The stochastic loss of alphas may persist to lower values of ripple than previously believed. This effect would be of primary importance for reactors that have a very long alpha slowing down time due to operating at a high electron temperature.

We are also working on a Monte Carlo code that calculates the deviation of the distribution function from a Maxwellian. Such a code would be useful for the study of plasma currents, such as the bootstrap current or RF driven currents, and the heat transport when the electron mean free path is comparable to the scale for the temperature gradient, an issue of importance for tokamak divertors.

Renormalization group methods are being employed to study the energy transfer dynamics for dissipative trapped ion convective cell turbulence.

Other Professional Staff

None

Collaborations

Allen Boozer is an external scientific member of the Max Planck Institute for Plasma Physics at Garching, Germany and spends two months a year at that institute. He also interacts with a large number of American fusion groups. George Vahala has an ongoing collaboration with Norton Bretz of the Princeton Plasma Physics Laboratory.

Students

Three doctoral students are associated with the project: Qun Yao, Xian-Zhu Tang, and Maciek Sasinowski. Two students received doctorates in 1992 for associated work: David Garren on the topic "Magnetic Fields Strength in Toroidal Plasma Equilibria," and Richard Weening on the topic "Completely Bootstrapped Tokamak."

Publications

1. A.H. Boozer, "The Evolution of Magnetic Fields and Plasmas in Open Field Line Configurations," *Phys. Fluids B* **2**, 2300-2305 (1990).
2. A.H. Boozer and H.J. Gardner, "The Bootstrap Current in Stellarators," *Phys. Fluids B* **2**, 2408-2421 (1990).
3. A.H. Boozer, D.E. Baldwin, R.R. Dominguez, A.H. Glasser, C.W. Horton, J.A. Krommes, G.H. Neilson, W.L. Sadowski, K.-C. Shaing, and H. Weitzner, "Alternate Transport," *Phys. Fluids B* **2**, 2871-2878 (1990).
4. A. Punjabi, A.H. Boozer, M. Lam, M.H. Kim, and K. Burke, "Monte Carlo Calculations for Transport Due to MHD Modes," *J. Plasma Phys.* **44**, 405-430 (1990).
5. Allen H. Boozer, "The Drift Hamiltonian in a Magnetic Field with a Separatrix," *Phys. Fluids B* **3**, 875-879 (1991).
6. D.A. Garren and A.H. Boozer, "Magnetic Field Strength of Toroidal Plasma Equilibria," *Phys. Fluids B* **3**, 2805-2821 (1991).
7. D.A. Garren and A.H. Boozer, "Existence of Quasihelically Symmetric Stellarators," *Phys. Fluids B* **3**, 2822-2834 (1991).
8. R.H. Weening and A.H. Boozer, "Completely Bootstrapped Tokamak," *Phys. Fluids B* **4**, 159-170 (1992).
9. A.H. Boozer, "Dissipation of Magnetic Energy in the Solar Corona," *Astrophys. J.* **394**, 357-362.
10. Q. Yao and A.H. Boozer, "The Exact and Drift Hamiltonian," *Phys. Fluids B* **4**, 2429-2440 (1992).
11. A.H. Boozer, "Onsager Symmetry of Transport in Toroidal Plasmas," *Phys. Fluids B* **4**, 2845-2853 (1992).
12. Y. Zhou and G. Vahala, "Hydrodynamic Turbulence and Subgrid Scale Closure", *Phys. Lett. A* **147**, 43 (1990).
13. L. Vahala, G. Vahala and N. Bretz, "Measurement of Magnetic Fluctuations by O—X Mode Scattering," *Rev. Sci. Instrum.*, **61**, 3022 (1990).
14. L. Vahala and G. Vahala, "Filamentation in High-Plasmas and Flux Penetration in Type II Superconductors," *Phys. Essays* **4**, 223 (1991).
15. Y. Zhou and G. Vahala, "Aspects of Subgrid Modeling and Large Eddy Simulation of MHD Turbulence," *J. Plasma Physics* **45**, 239 (1991).
16. L. Vahala, G. Vahala and N. Bretz, "Detection of Internal Magnetic Fluctuations by Electromagnetic Scattering in Tokamaks," *Proc. 9th Topical Conf. on Radio Frequency Power in Plasmas* (AIP Conference Proceeding, Charleston S.C. August 1991).
17. L. Vahala, G. Vahala and N. Bretz, "Electromagnetic Wave Scattering from Magnetic Fluctuations in Tokamaks," *Phys. Fluids B* **4**, 619 (1992).
18. L. Vahala and P.T. Bonoli, "Effect of Fluctuations on Lower Hybrid Power Deposition and Hard X-Ray Detection," *Rev. Sci. Instrum.* **63**, 4682 (1992).
19. Y. Zhou and G. Vahala, "Local Interactions in Renormalization Methods for Navier-Stokes Turbulence", *Phys. Rev. A* **46**, 1136 (1992).
20. G. Vahala, L. Vahala, and P.T. Bonoli, "Effect of Magnetic and Density Fluctuations on the Propagation of Lower Hybrid Waves in Tokamaks," *Phys. Fluids B* **4** (Dec. 1992).

Columbia University

Project

High Beta Plasma Theory

A. Bhattacharjee

Funding

FY 90	FY 91	FY 92
\$80k	\$80k	\$100k

Purpose

The present goal of this research program is the theoretical investigation of nonlinear magnetic island dynamics in high-temperature toroidal plasmas. Magnetic island dynamics play a key role in triggering both major and minor disruptions ("sawtooth") in a tokamak, and determine operational beta limits in a stellarator. The understanding and control of magnetic island growth is, therefore, a task of high priority in present day tokamaks and stellarators as well as the proposed International Tokamak Experimental Reactor (ITER). The goal of the present program is to develop theoretical models for island growth in high-temperature plasmas typical of present day devices, and to test methods of island control by coordinating theory with experimental studies. In particular, the program includes specific collaborative tasks with the experimental tokamak research programs at Columbia University and the University of Texas at Austin.

Approach

There are several interesting aspects of nonlinear magnetic island dynamics which call for the consideration of new physical models and techniques. For instance, it has become quite clear that resistive magnetohydrodynamics (MHD), which has been historically a very successful model, is no longer adequate for describing the nonlinear evolution of the sawtooth instability in tokamaks. Our approach has been to go beyond resistive MHD and consider the generalized Ohm's law including the Hall effect. For the problem of disruption control in tokamaks, we have undertaken the theoretical study of a new technique involving the use of energetic ions to control the size of magnetic islands. As far as further work in other traditional methods of disruption control is concerned, our plan is to carry these methods forward by developing theoretical models for actual experiments in tokamaks like TEXT (at Texas) or HBT-EP (at Columbia). Our recent collaboration with TEXT experimentalists on suppression of magnetic islands using Electron Cyclotron Heating (ECH) is an example of this type of work.

Progress

Our accomplishments in studies of magnetic island dynamics are:

1. Suppression of magnetic islands by energetic ions:

We have shown that a beamlet of energetic ions, introduced just outside the $q=2$ rational surface via parallel neutral beam injection, can reduce the size of an $m=2$, $n=1$ island drastically. A detailed kinetic theory, including bootstrap currents and resistive interchange effects, has been developed. Estimates show that the energy of the beamlet required for this scheme is rather modest, and only a fraction of that used for Ohmic, or beam-heating, of the background plasma.

2. Equilibrium beta limits in stellarators due to magnetic island overlap:

It has been shown that a fundamental equilibrium beta limit in stellarators is caused by the overlap of magnetic island induced by finite pressure. The theory gives an analytical formula for the island width at a rational surface in terms of the well-known resistive interchange parameter D_R . These island widths have been computed for the Heliotron-E configuration using a modified version of the three-dimensional code STEP. For Heliotron-E, the theory predicts an equilibrium beta limit of approximately 2%. It now appears that earlier experimental observations on internal disruptions in Heliotron-E can be interpreted as evidence of this equilibrium beta limit.

3. Optimum theory of a turbulent plasma:

The main strength of the "optimum theory," which was first developed for problems of heat transport in hydrodynamics, is that it provides rigorous bounds for transport. In order to obtain useful bounds, it is necessary to know what are some of the important global constraints on the system. We have applied the theory to a reversed field pinch turbulent with resistive MHD modes, imposing the constraints of global energy and helicity balance. Our calculation predicts bounds on the fluctuational power absorption in good agreement with observations from the

ZT-40 device (at Los Alamos). Since the fluctuational power absorption is experimentally found to be strongly correlated with ion heating in a reversed field pinch, the theoretically calculated bounds have significant implications for ion heating in these experiments.

4. Nonlinear dynamics of the $m=1$ instability and fast sawtooth collapse in high-beta plasmas:

One of the interesting unresolved issues of tokamak physics is the "fast trigger" problem of sawtooth collapse. The "fast trigger" problem is concerned with the sudden onset of the sawtooth collapse. Stimulated by recent numerical results due to Aydemir, we have developed a new theoretical model for the nonlinear growth of the $m=1$ instability governed by a generalized Ohm's law that includes the Hall term. It is shown that the Hall term qualitatively changes our current understanding of this nonlinear instability. Under the influence of this term, the $m=1$ island grows almost explosively, and then decays rapidly once the island grows to a large size. The predictions of the theory are in good agreement with the JET data on the "fast trigger."

5. Suppression of $m=2$ islands by ECH in TEXT: experiment and theory:

It has been known for some time that ECH can be an effective method for suppressing $m=2$ islands and can thus help eliminate major disruptions that result from the nonlinear growth of these islands. However, the earlier experimental implementations of this idea on the T-10 or the TFR device were not conclusive. Recent experiments on TEXT using a moving focussable antenna demonstrate conclusively the suppression of $m=2$ islands that do not return even after the ECH is turned off. The experiment is modeled using a three dimensional resistive MHD code, and the observations are attributed to current profile modification. The theoretical interpretation of the observed suppression calls for some subtle considerations pertaining to the nonlinear stability of magnetic islands.

Plans

During the next year, we hope to build on the accomplishments described in items (1), (2), (4) and (5) of the last section. To be concise, we propose to undertake theoretical studies that will lead to the understanding and possible control of major and minor ("sawtooth") disruptions in high-beta tokamaks and stellarators. Through collaborative research with experimentalists involved with the TEXT and HBT-EP devices, we hope to help consolidate a corpus of possible methods that can be implemented in larger devices.

Students

The following students have finished their Ph.D. dissertations, supported by this grant: C.C. Hegna: "Formation and Dynamics of Magnetic Islands in Toroidal Plasmas," (1989), X.H. Wang: "Effects of Energetic Particles and Plasma Rotation on Ballooning Modes," (1989), C.Y. Wang: "Optimum Theory of a Turbulent Plasma," (1992). The grant presently supports one graduate student (Y. Yuan) fully and provides partial support for a post-doctoral fellow (Dr. X.H. Wang).

Collaborations

We are presently involved in a significant collaborative effort on disruption control studies with the TEXT group (University of Texas at Austin), and Dr. D. Schnack (SAIC, San Diego).

Publications

1. C.C. Hegna and A. Bhattacharjee, "Suppression of Magnetic Islands by Energetic Ions in Toroidal Plasmas," *Physics of Fluids B* 2, 1804 (1990).
2. X.H. Wang and A. Bhattacharjee, "Ballooning Stability of Anisotropic, Rotating Plasmas," *Physics of Fluids B* 2, 2396 (1990).
3. Y. Nakamura, M. Wakatani, C.C. Hegna and A. Bhattacharjee, "Equilibrium Beta Limits in Heliotron-E Due to Magnetic Island Overlap," *Physics of Fluids B* 2, 2528 (1990).
4. C.Y. Wang, A. Bhattacharjee and E. Hameiri, "Upper Bounds on Power Dissipated by Fluctuations in a Turbulent Reversed-Field Pinch," *Physics of Fluids B* 3, 715 (1991).
5. C.C. Hegna, A. Bhattacharjee, Y. Nakamura and M. Wakatani, "Suppression and Control of Magnetic Islands in Toroidal Plasmas," (Invited Paper at the 32nd APS meeting), *Physics of Fluids B* 3, 2285 (1991).
6. C.Y. Wang and A. Bhattacharjee, "Optimum Theory for the Energy Dissipation in a Turbulent Pinch," *Physics of Fluids B* 3, 3462 (1991).
7. R. Iacono and A. Bhattacharjee, "Poloidal Beta Scaling for a Bootstrapped Tokamak," *Physics of Fluids B (Letter)* 4, 1685 (1992).
8. X. Wang and A. Bhattacharjee, "Forced Reconnection and Current Sheet Formation in Taylor's Model," *Physics of Fluids B* 4, 1795 (1992).
9. A. Bhattacharjee, G.M. Schreiber and J.B. Taylor, "Geometric Phase, Rotational Transforms and Adiabatic Invariants in Toroidal Magnetic Fields," *Physics of Fluids B* 4, 2737 (1992).

Dartmouth College

Project

Nonlinear Magnetohydrodynamics

David C. Montgomery

Funding

FY 90	FY 91	FY 92
\$67.5k	\$70.0k	\$75.0k

Purpose

The purpose of our project is to investigate the nonlinear behavior of resistive, viscous magnetofluids in regions above the stability thresholds for *resistive* equilibria without flow. The investigations are carried out in periodic cylinder geometry, with realistic boundary conditions, by a combination of analytical and computational methods. It is intended to re-examine the basic dynamics of the nonlinear magnetohydrodynamics of processes that are thought to limit tokamak operation, particularly those involving the appearance of flows, or velocity fields. This re-examination is thought to be necessary because of the limitations of the ideal equilibrium paradigm, and the fact that many if not most experimental developments of the last two decades have not been anticipated by that paradigm. As yet unmeasured departures from axisymmetry are also a primary concern. The roles of the Hartmann number and zero-flow pinch ratio (or safety factor evaluated at the wall) are being increasingly shown to be important. Accurate evaluation of the Hartmann number involves a necessarily better grasp of the plasma viscous stress tensor than has been available heretofore.

Approach

Our approach has been to go as far as we can analytically, in calculating the stability thresholds, and the non-axisymmetric states above them, for resistive, voltage-driven, current-carrying magnetofluids in periodic cylinder geometry (these calculations are described in detail in the references in the list of publications at the end of this). Only the uniform-resistivity profile is entirely tractable by analytical means. For non-uniform resistivity profiles, a fully 3-D spectral method numerical code has been developed, utilizing an expansion in the (complete) set of Chandrasekhar-Kendall orthonormal eigenfunctions of the curl. The code has been extensively tested and several results from it have been published and are in press. A supplementary program of basic nonlinear research on the guiding-center plasma (one which $\mathbf{E} \times \mathbf{B}$ drifts in the electrostatic field which it self-consistently generates) has also been pursued for several years, since we introduced vortex coalescence as a central effect in low-beta plasma physics twenty years ago. Many effects seen first in this simplified model have turned out to have nonlinear MHD analogues.

Progress

We have extensively diagnosed the bifurcations of zero-flow, axisymmetric, resistive equilibria into non-axisymmetric states with flow about their stability thresholds. The resulting paired helical vortices have variable (poloidal, toroidal) mode numbers (m, n) that depend upon Hartmann number, aspect ratio, zero-flow pinch ratio, and driving voltage in a way that is not simple. It is thought that these vortices, connecting as they do the hot geometrical center of the plasma column with the perimeter, are an effective mechanism at transporting heat. Recent measurements of large flow velocities in JET by Schram, Hawkes, and others seems to emphasize the need to include steady-state d.c. convection in our picture of the working tokamak. The general absence of the incorporation of flows into the design of future tokamak reactors is perhaps some cause for alarm.

In a recent computation with the Shan 3-D MHD spectral code, we have considered the time development of three identical zero-flow axisymmetric equilibria that differ only in the numerical values of the plasma viscosities. The viscosity affects the Hartmann number, which ranges in the three runs from about 700 to about 14,000. These are three situations for which a conventional resistive "tearing mode" analysis would predict identical results, but the three different situations behave in very different ways. The $H = 700$ case is stable; an $H = 2800$ case is unstable, and saturates with a single-helicity $(m, n) = (2, 1)$ non-axisymmetry; and the $H = 14,000$ case is more strongly unstable, and saturates at a more strongly deformed "mixed" helical state that contains more than one ratio of m/n in the deformed state.

Plans

A simple application [Plasma Phys. & Contr. Fusion *34*, 1157 (1992)] of the simple-minded uniform-resistivity stability theory to the onset of MHD activity in the JET tritium shot points up the need for a hard look at the MHD viscous stress tensor. The Braginskii-Balescu expressions are the principal theoretical models for viscosities that are rugged enough to use in a dynamical evolution in which magnetic surfaces may cease to exist. There are three of them: the ion parallel viscosity, the gyroviscosity, and the shear viscosity (most commonly used). They differ, for JET parameters, by two factors of 10. We found rather close prediction of the current at which MHD activity appeared in the tritium shot if the ion parallel viscosity were used, and were miles off if the shear viscosity were used instead. An important activity for the coming year is a reassessment of plasma viscosity and an attempt to find experimental estimates of it for relevant flows (unfortunately, none of those may come from neutral beam injection experiments, the geometry of which is vastly different from the case in which we are interested).

It turns out that the ion parallel viscous term is what should be used in the MHD equation of motion, its rather different functional form will involve some rewriting of the code, and a new set of boundary conditions on the velocity also needs to be implemented (no slip velocity field boundary conditions are what we have in mind next). The long term goal is to include locally temperature-dependent transport coefficients and an energy equation. This has long been done for "reduced" MHD, but not for full 3-D MHD.

Other Professional Staff

Two post doctorals (Xiaowen Shan and Hudong Chen) are partially supported by this grant.

Collaborations

Collaborations with Gary Doolen and Richard Nebel of Los Alamos National Laboratory are presently in progress.

Students

One graduate student, Wesley Jones, is peripherally connected to this project but presently devotes most of his time to the electrostatic guiding centers plasma.

Major Recent Publications

1. D. Montgomery, "Magnetohydrodynamic Stability Thresholds as a Function of Hartmann Number and Pinch Ratio," Plasma Phys. & Contr. Fusion *34*, 1157 (1992).
2. D. Montgomery, "Reduced Magnetohydrodynamics and Minimum Dissipation Rates," Phys. Fluids *B4*, 292 (1992).
3. X. Shan, D. Montgomery, and H. Chen, "Nonlinear Magnetohydrodynamics by Galerkin-Method Computations," Phys. Rev. A *44*, 6800 (1991).
4. J. P. Agim and D. Montgomery, "Nonideal, Helical, Vortical, Magnetohydrodynamic Steady States," Plasma Phys. & Contr. Fusion *33*, 881 (1991).
5. X. Shan, H. Chen, and D. Montgomery, "Ideal and Resistive MHD Equilibria and States of Minimum Dissipation," in *Nonlinear and Relativistic Electrodynamics*, ed. by V. Stefan, American Institute of Physics, New York, 1992; pp. 168-197.
6. H. Chen, X. Shan, and D. Montgomery, "Galerkin Approximations for Magnetohydrodynamics," Phys. Rev. A *42*, 6158 (1990).
7. D. Montgomery, W. H. Matthaeus, W. T. Strubling, D. Martinez, and S. Oughton, "Relaxation in Two Dimensions and the Sinh-Poisson Equation," Phys. Fluids *A7*, 3 (1992).
8. X. Shan and D. Montgomery, "On the Role of the Hartmann Number in Magnetohydrodynamic Activity," accepted for publication by Plasma Phys. & Contr. Fusion (in press, 1993).

General Atomics

Project

Applied Plasma Physics Fusion Theory

V.S. Chan and R.E. Waltz

Funding

FY 90	FY 91	FY 92
\$1,565k	\$1,600k	\$1,700k

Purpose

The long range purpose of the theoretical plasma physics research at General Atomics (GA) is to support the DIII-D and other tokamak experiments and to significantly advance our ability to design a commercially attractive fusion reactor. We categorize our efforts into three broad areas: (1) development of magnetohydrodynamic (MHD) stable equilibria optimized for high beta and non-inductive current; (2) understanding plasma transport and scaling to next generation devices with emphasis on enhanced confinement regimes compatible with divertor and boundary physics requirements; (3) and radio frequency (RF) tokamak heating and current drive.

Approach

Our general approach to problems in MHD, transport, and RF physics emphasizes a close interaction between theory and experiment. This requires the continuous development and application of several large scale codes to analyze experiments and suggest new ones. These include codes for MHD equilibrium and ideal and resistive stability, time dependent as well as steady state transport for the bulk and boundary plasma, turbulence simulations in two and three dimensions, geometric optics and full wave propagation codes, and Fokker-Planck evolution of plasma distribution functions.

Progress

Our recent accomplishments in the area of MHD have included: (1) Development of techniques for achieving high beta and high current discharges. This involves mapping the ideal stability envelope of DIII-D discharges over a wide range of current and elongation, and optimizing current profile to obtain high internal inductance and large regions in second stability, regimes which offer possibility of enhanced tokamak performance. (2) Development of codes to test stability of Toroidal Alfvén Eigenmodes (TAE) in experimental equilibria of arbitrary shape. TAE modes are thought to cause large fast alpha particle losses in ignited devices. The code has found generally good agreement with neutral beam driven fast particle experiments in high beta DIII-D plasmas. Finally (3) development of new energy principle methods allowing standard ideal MHD codes for general geometry to treat resistive MHD instabilities. The methods have already been successfully applied to simple circular plasma.

In the area of plasma transport we have developed: (1) A novel first principles basis for scaling confinement time from present tokamaks to ignition devices by a "wind tunnel like" method which varies only the relative gyroradius. This has stimulated new experiments to determine the scaling with relative gyroradius and the underlying characteristics of the turbulence. (2) Edge transport bifurcation models for the L-H mode transition based on stabilization of turbulence by shear in the plasma rotation. Recent applications of the models in a divertor boundary layer transport code have led to a theory for the power threshold of the VH-mode in terms of the plasma flow and edge recycling. Finally, (3) a novel nonlinear ballooning mode representation code for simulating turbulent transport in toroidal geometry. This has been applied to gyro-Landau fluid (GLF) models encompassing the effects of Landau resonances and gyro-motion at the smallest scale.

In the area of RF heating and current drive we have: (1) Continued to develop and upgrade codes for validating the physics of electron cyclotron heating (ECH) and fast wave ion cyclotron resonance heating (ICRH) in tokamaks. These are important elements of the DIII-D experimental program and our codes routinely provide analysis of absorption profiles, energetic electron distributions and current drive. (2) Developed a general theoretical understanding of wave helicity injection in relation to classical dynamo action, as part of a study to discover novel current drive concepts and current profile control techniques.

Plans

During the coming year we plan to extend this work by improving the driving and damping physics in the TAE mode analysis and extending the resistive energy principle to general geometry. The toroidal GLF model turbulence simulation code will be extended from ions to electron and electrostatic to electromagnetic. There will be further efforts to verify the rotational shear models for H- and VH-modes. The Fokker-Planck code studies will be emphasizing the physics of radial transport of fast electron tails and bootstrap current.

Students

At present there is one UCSD graduate student, T.O. Kingsbury, working on numerical simulation of turbulence and in particular the interaction of long wave trapped on modes with shortwave trapped electron drift modes. Also Dr. Olivier Sauter is working on Fokker-Planck codes for RF heating and current drive. He is at GA on a postdoctoral fellowship from the Swiss National Science Foundation.

Other Professional Staff

S.C. Chiu, M.S. Chu, R.R. Dominguez, J.M. Greene, R.W. Harvey, F. Hinton, Y. B. Kim, Y-R. Lin-Liu, G. Staebler, and A. Turnbull.

Collaborations

There is a continuing collaboration with the UCSD Physics Department. Professors. M.N. Rosenbluth and P.H. Diamond are consultants and J.M. Greene and R.E. Waltz are Adjunct Professors. Presently other key collaborators include G.D. Kerbel and M. McCoy (NERSC), G. Hammett (PPPL), H. Berk, R. Mett and S. Mahajan (IFS), and A. Hassam (Maryland, sabbatical 92-93). There have been many personnel exchange visits with the Max-Planck-Institute fur Plasmaphysik (IPP, Garching), Culham theory group, IPP Nagoya University, JAERI, Tore-Supra, and the Kurchatov Institute.

Publications

1. W. Howl, A.D. Turnbull, J.R. Ferron, E.J. Strait, "Sensitivity of the Kink Instability to the Pressure Profile," *Phys. Fluids B4*, 1724 (1992).
2. M.S. Chu, M.S. Chance, J.M. Greene, T.H. Jensen, "A Tearing Mode Energy Principle for Axisymmetric Finite Beta Plasma," *Phys. Fluids B2*, 97 (1990) [see also *Phys. Fluids B1* (1989) 62].
3. F.L. Hinton, "Thermal Confinement Bifurcation and the L- and H-Mode Transition in Tokamaks," *Phys. Fluids B3*, 696 (1991).
4. G.M. Staebler, R.R. Dominguez, "Electric Field Effects on Ion Temperature Gradient Modes in a Sheared Slab," *Nuclear Fusion 31*, 1891 (1991).
5. R.E. Waltz, R.R. Dominguez, G.W. Hammett, "Gyro-Landau Fluid Models for Toroidal Geometry," *Phys. Fluids B4*, 3138 (1992).
6. R.W. Harvey and R.O. Dendy, "A Trapped-Passing Fluid Model for Tokamak Neoclassical Transport," *Phys. Fluids B4*, 902 (1992).
7. S.C. Chiu, M.J. Mayberry, and W.D. Bard, "Theoretical Comparison of Coupling of a Recessed Cavity Antenna and a Conventional Loop Antenna for Fast Waves and Ion-Bernstein Waves," *Nuclear Fusion 30*, 255 (1990).
8. V.S. Chan, R.L. Miller and T. Ohkawa, "Current Drive by Wave Helicity Injection," *Phys. Fluids B 2*, 1441 (1990).

Hampton University

Project

Anomalous Transport in Toroidal Plasmas

A. Punjabi

Funding

FY 91

\$40k

FY 92

\$40k

Purpose

To study the effects of magnetic asymmetries on the heat deposition onto divertor plates of tokamak, and to attempt to determine if the heat deposition can be broadened.

Approach

Motion of magnetic field lines in a tokamak is described by a Hamiltonian with one degree of freedom. The structure and properties of such Hamiltonian systems near a separatrix are generic. We use area-preserving discrete maps called tokamak divertor maps, and their continuous analogs to study the motion of plasma particles in the stochastic scrape-off layer of divertor tokamaks. The continuous analog is a solution of the Hamiltonian equations of motion. The effects of special diffusion are included by applying the radial expansion operator after each iteration. The safety factor profile of a tokamak can be reproduced by considering a fixed number of iterations of the map to be equivalent to one toroidal circuit. Stochastic broadening is determined by the stripe formed by the particle trajectories as they cross the plane of divertor plate.

Progress

Based on the above approach, we have developed a map called the simple tokamak divertor map. This map faithfully represents the magnetic topology of a single null divertor tokamak. By varying the map parameter, we can adjust the width of the stochastic scrape off layer. The width of this layer varies as square root of the asymmetric magnetic perturbations. In this map, we also include the effects of spatial diffusion of plasma particles. We start with a large number of particles on a good magnetic surface well inside the stochastic region around ideal separatrix. We find that the width of the footprint of trajectories of these particles on the divertor plate varies as fourth root of diffusion coefficient. For very small values of diffusion coefficient, the width of footprint becomes independent of the diffusion coefficient. In the limit of vanishing diffusion coefficient, the footprint splits up into discrete stripes. The open field lines of stochastic layer enter the region from one divertor plate and leave striking another divertor plate after an integral number of complete poloidal circuits. The discrete stripes on the plates correspond to the number of poloidal circuits made by open field lines. The area of stripe scales as the inverse square of poloidal circuits. The open field lines that approach the last confining surface make many poloidal circuits before striking the divertor plate in a stripe that is much narrower than the stochastic layer, but nevertheless is of nonzero width. An open field line that makes many poloidal circuits in going from one plate to another in essence densely fills the stochastic layer except for the regions that are occupied by magnetic islands. The complicated filling of the stochastic layer by open field lines gives an associated complexity to the ambipolar electric potential that exists along any open field line embedded in plasma. We expect the resulting drift motion to smear the stripes.

Plans

We plan to extensively use such maps to study the problem of heat deposition pattern on divertor plates. We plan to extend the simple map described above. These extensions will include maps with double-null divertor tokamak magnetic topology, high, adjustable shear, perturbations with low toroidal and poloidal numbers, diffuser coils, effects of velocity scattering, energy scattering, and drifts due to ambipolar fields in the stochastic layer. Our aim is to predict and preferably to control the heat deposition pattern on the divertor plates of a tokamak.

Other Professional Staff

None

Collaboration

This research is done in collaboration with Dr. Allen Boozer of the College of William and Mary. Computational resources of NERSC are used for this work.

Students

One MS level graduate student is supported by this project.

Major Recent Publication

1. A. Punjabi, A. Verma and A. Boozer, "Stochastic Broadening in the Stochastic Scrape-Off Layer for a Single-Null Divertor Tokamak," Proc. 1992 Int. Con. Plasma Phys., Innsbruck, Austria, 29 June-3 July 1992, eds. W. Freysinger, K. Lackner, R. Schrittwieser and W. Lindinger, vol. 16C, p. 863-866 (1992).

Hampton University

Project

Electron Transport in the Stochastic Fields of Reversed Field Pinch ZT40M

A. Punjabi

Funding

FY 91

\$60k

FY 92

\$70k

Purpose

The purpose is to identify the mechanisms driving the electron transport in the Reversed Field Pinch ZT40M device.

Approach

The approach is to use the Monte Carlo method to estimate the transport of various groups of particles in the Reversed Field Pinch to determine the important transport mechanisms by a comparison of the numerical with the experimental data. The important groups of particles are: runaway electrons, thermal electrons, and both passing and trapped diagnostic beam ions. The three basic transport mechanisms are: spatial variation of magnetic field strength in the magnetic surface, spatial variation of electric potential in the magnetic surface, and loss of magnetic surfaces. Equations of motion are obtained from the drift Hamiltonian. The effects of collisions are represented by appropriate stochastic changes in the constants of motion at each time step. Comparison of transport coefficients for the various groups of particles with the experimental data can give far more information on the transport mechanisms than can be obtained by the standard confinement time measurements.

Progress

We have developed a Monte Carlo code based on the above approach. The code is capable of implementing one or more transport mechanisms. This code also includes the effects of collisions in velocity space, as well as the effects of flux generation at the magnetic axis. The code uses Boozer coordinates as well as the non-canonical practical coordinates, and switches to the non-canonical rectangular co-ordinates for particles crossing the magnetic axis. The code is used to calculate electron trajectories and diffusion coefficient due to ideal and resistive MHD modes in the Reversed Field Pinch ZT40M. For calculation of magnetic fields and currents in the Reversed Field Pinch, a Bessel function model is used. The code has been used extensively to estimate the diffusion coefficient for electrons in the stochastic magnetic fields of Reversed Field Pinch ZT40M caused by tearing modes. Electron diffusion coefficients have been calculated for various combinations of toroidal modes with and without collisions and loop voltage.

Plans

Our future plans call for detailed study of electron transport in the stochastic fields in the Reversed Field Pinch ZT40M when various combinations of tearing modes are present in the quasilinear regime with the effects of collisions and loop voltage. We would also like to include the effects of energy scattering, and to calculate energy and momentum transport. We have developed a framework to investigate the correlation between the particle diffusion and field diffusion when the magnetic surfaces are broken using the concept of magnetic quasi-surfaces. We plan to implement this in our code for the Reversed Field Pinch, and study this problem with ZT40M parameters.

Other Professional Staff

None

Collaboration

This research is done in collaboration with Dr. Allen Boozer of the College of William and Mary. The research has also greatly benefited from cooperation and comments of RFP theory group at LANL, especially Dr. Richard Gerwin, Dr. Ronald Moses, Dr. Rich Nebel and Dr. David Barnes. This work could not have been carried out without the computational resources of NERSC.

Students

One graduate student at MS level worked on this project. Thesis title: "Electron Transport in the Stochastic Fields of RFP ZT40," Myung-Hee Kim, (March 1991).

Major Recent Publications

1. A. Punjabi, A. Boozer, M. Lam, M. Kim, and K. Burke, "Monte Carlo Calculations for Transport Due to MHD Modes," J. Plasma Phys., **44**, p.405-430 (1990).
2. P. W. Terry, et al., "Advances in Reversed Field Pinch Theory and Computation," Proc. 13th Int. Conf. Plasma Phys. Cont. Nuc. Fus. Res., Washington DC, 1-6 Oct. 1990, pub. IAEA, Vienna, vol. 2, p. 169-180 (1991).
3. A. Punjabi, A. Verma, M. Kim and A. Boozer, "Electron Transport in the Stochastic Fields of RFP ZT40M," Proc. XXth Int. Conf. on Phenomena in Ionized Gases, eds. V. Palleschi and M. Vaselli, pub. Institute of Atomic and Molecular Phys.-CNR, Pisa, Italy, p.424-425 (1991).

Institute for Fusion Studies

Project

Establishment of an Institute for Fusion Studies

Richard D. Hazeltine

Funding

FY 90	FY 91	FY 92
\$2,610k	\$2,644k	\$2,685k

Purpose

To conduct research in the theoretical physics of plasma confinement and controlled fusion energy, with special emphasis on fundamental problems of long-range significance; to serve as a center for controlled-fusion information exchange, nationally and internationally, by hosting exchange visits, conferences and workshops; and to train students and postdoctoral research personnel in plasma physics research for the fusion energy program.

Approach

The Institute for Fusion Studies (IFS) focuses its primary attention on fusion and plasma physics. However, it maintains substantial involvement with research in related fields, such as nonlinear dynamics, plasma astrophysics, accelerator physics and computational science. To facilitate scientific exchange and dissemination of information within the plasma community, the Institute hosts scientific visitors and conducts collaborative research programs with laboratories and universities throughout the United States and the world. It is the principal site in the United States for the exchange activities of the U.S.-Japan Joint Institute for Fusion Theory. Research and scientific collaboration form the foundation for the training of postdoctoral scientists and the education of graduate students studying controlled fusion energy or plasma physics.

Progress

Recent progress has involved several different areas:

1. IFS scientists continued to receive national and international recognition for their research. They have presented numerous invited papers at workshops, conferences and scientific meetings held in the United States and abroad. During the last three years, IFS scientists published 228 scientific articles in refereed journals and two books.
2. The Institute sponsors collaborative research programs with laboratories and universities throughout the U.S. and the world, and is the principal site of the U.S.-Japan Joint Institute for Fusion Theory. In the last three years, the IFS hosted 165 visitors for periods covering anywhere from a few days to a year.
3. The IFS normally has 15-25 graduate students working on fusion and plasma physics thesis-degree projects under the supervision of senior IFS scientists, who also teach courses in the Physics Department. Last year, 17 graduate students studied at the Institute and three received the Ph.D. in plasma physics.
4. As part of its educational role, the IFS maintains a postdoctoral training program, employing nine postdoctoral students last year.
5. Research advances were made in many areas, including advanced computational algorithms for plasma simulation, confined plasma stability in the presence of fusion reaction products, plasma turbulence and its effects on confinement, fundamental theory of negative energy-wave stability, and the electromagnetics of the plasma boundary.

Plans

The Institute for Fusion Studies was organized in 1980 with funding provided jointly by the Department of Energy and the University of Texas. The initial term of the Institute was for five years. This term has been renewed twice after favorable reviews by the Department of Energy. The IFS will continue to follow its mandate to conduct research on theoretical questions concerning the achievement of controlled fusion energy, to serve as a center for information exchange, and to train students and postdoctoral fellows for research in the physics of controlled fusion power. Scientific research will continue on many fronts, such as plasma simulation, ignited plasma physics, plasma edge physics and the nonlinear dynamics of confined plasma evolution. Efforts will be made to further

strengthen ties with the fields of fluid dynamics, computational mathematics, statistical mechanics, accelerator physics and space physics.

Students

Postdoctoral scientists who are currently working on this project are: Kuan-Ren Chen, Jiaqi Dong, Michael Isichenko, Jin-Yong Kim, James Koga, Richard Mett, and Huanchun Ye. The graduate students are: Paul Acevedo, David Barnett, Mark Calvin, Bo Chen, John Cobb, Diego Del Castillo, David Fisher, Geoffrey Furnish, Jose Hernandez, Rodney Kinney, Chris Kueny, David Nystrom, Nikolai Petviashvili, Martin Prahovic, Brad Shadwick, Xiang Ning Su, Jinlong Wu, Hong Xiao, and Xiao-Dong Zhang. Undergraduate students are: Yi Liu and Kind Kresimir Josic. The following is a list of graduate students who received Ph.D. degrees during the past three years (no Master's Degrees were given): Xueqiao Xu, "The Effect of Trapped Ions and Lower Hybrid Current Drive on Tokamak Instabilities: Theory and Simulations," (July 24, 1990), Fongyan Gang, "Kinetic Theory of Trapped Electron Turbulence in Sheared Magnetic Field and Statistical Theory of Two-Field Drift Wave Turbulence," (July 5, 1990), Jung Hoon Han, "Particle Simulation of Finite Beta Interchange Modes in a Sheared Magnetic Field," (July 26, 1990), Sam Cable, "Low Frequency Fluctuations in Plasma Magnetic Fields," (April 28, 1992), Leon Ofman, "Resistive MHD Studies of Tearing Mode Instability with Equilibrium Shear Flow and Magnetic Reconnection," (April 29, 1992), and James Koga, "Beam-Beam Interaction Effects on Particle Dynamics," (August 15, 1992).

Other Professional Staff

Ahmet Aydemir, Herbert Berk, Boris Breizman, Wendell Horton, Michael Kotschenreuther, Maurice Lebrun, Wadesh Mahajan, William Miner, Philip Morrison, Barry Newberger, Toshiki Tajima, James Van Dam, Alan Ware, Vernon Wong, and Petr Yushmanov.

Collaborations

The Institute actively sponsors collaborative research programs with laboratories and universities throughout the United States and the world. In particular, on behalf of the Department of Energy, the IFS is the principal site in the United States for the exchange activities of the U.S.-Japan Joint Institute for Fusion Theory. During a typical year this program normally includes two workshops in each country, six exchange scientist visits, and several joint computational projects on the U.S.-Japanese international computer data link.

Selected Publications

- R.D. Hazeltine, "Self-Consistent Radial Sheath," *Phys. Fluids B* **1**, 2031 (1989).
- A.Y. Aydemir, "Linear Studies of $m=1$ Modes in High-Temperature Plasmas with a Four-Field Model," *Phys. Fluids B* **3**, 3025 (1991).
- H.L. Berk, B.N. Breizman and H. Ye, "Finite Orbit Energetic Particle Linear Response to Toroidal Alfvén Eigenmodes," *Phys. Lett. A* **162**, 475 (1992).
- S. Hamaguchi and W. Horton, "Modelling of Drift Wave Turbulence with a Finite Ion Temperature Gradient," *Plasma Phys. and Contr. Fusion* **34**, 203 (1992).
- M. Kotschenreuther, H.L. Berk, R. Denton, S. Hamaguchi, W. Horton, C-B. Kim, M. Lebrun, P. Lyster, S. Mahajan, W.H. Miner, P.J. Morrison, D.W. Ross, R.D. Sydora, T. Tajima, J.B. Taylor, P.M. Valanju, H.V. Wong, S.Y. Xiao, Y.Z. Zhang, "Novel Computational Techniques to Predict Transport in Confinement Devices, and Applications to Ion Temperature Gradient Driven Turbulence," in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991), Vol. 2, p. 361.
- M.N. Rosenbluth, H.L. Berk, J.W. Van Dam, and D.M. Lindberg, "Continuum Damping of High-Mode-Number Toroidal Alfvén Waves," *Phys. Rev. Lett.* **68**, 596 (1992).
- R. Mett and J.B. Taylor, "Steady-State Dynamo and Current Drive in a Nonuniform Bounded Plasma," *Phys. Fluids B* **4**, 73 (1992).

Institute of Non-Linear Science Applications

Project

Chaotic Dynamics in Plasmas: Method of Symbolic Kinetic Equation

A.B. Rechester and R.B. White

Funding

FY 90	FY 91	FY 92
\$0	\$0	\$45k

Purpose

The purpose of our project is the development and application of methods of symbolic analysis of complex dynamical processes in plasma physics. Specific applications include: 1) development of a new method for solution of the Louiville-Vlasov equation and 2) development of a new method for symbolic signal processing of experimental data.

Approach

Symbolic dynamics provides a means of partitioning the phase space so that information concerning the time evolution is embedded in the partitioning. This allows us to significantly simplify the Markov matrix in comparison with the traditional partitioning used when we are solving Louiville-Vlasov equation. The symbolic analyses of the outputs of dynamical system could also be used as a powerful tool for pattern recognition and forecasting. We can construct the correct symbolic language capable of reading all complicated patterns exhibited by complex dynamical processes by maximizing topological and metric entropies using only output data, without prior knowledge of the equations of motion.

Progress

1. We have used symbolic dynamics for partitioning the phase space (coarse graining) into "states" of some of the simplest models of chaotic dynamics: quadratic mapping, Henon map and area preserving Chirikov-Taylor (CT) model. The time evolution equation for a distribution function has been made discrete and a closed system of coupled linear equations with constant coefficients has been obtained. The Markov matrix for this equation is much simpler than for a usual coarse graining with equal size domains. The evolution equation is called a symbolic kinetic equation. It describes a relaxation process toward a steady state defined by invariant distribution functions on a chaotic attractor (in the case of the CT model there is no attractor but still this relaxation process is well defined). The interconnected structure of these equations can be presented graphically as a dynamical network diagram. The topology of this network identifies different co-existing chaotic attractors and also tells which of the states are transient and which support the structure of an attractor. We calculated the invariant distribution function, correlation functions, etc. using this method and found good agreement with direct time averaged computations. Our method appears to be quite general and can be applied for multi-dimensional problems.

2. We have developed the algorithm for computer optimization of symbolic languages. This algorithm presents the output data in symbolic form and then constructs topological and metric entropies. By maximizing these quantities we are able to find the correct symbolic language. We have tested our algorithm using variety of dynamical models from nonlinear science.

Plans

We are planning to apply symbolic signal processing method for the analysis of experimental data. Specifically we are interested in analysis of Mirnov oscillations. Everybody in the fusion community knows what an important role they play as a precursor of disruptions. Usually by doing Fourier analysis they can be associated with resistive MHD modes. On the other hand in nonlinear theory the plasma state is just one helically distorted dissipative MHD structure. We are planning to apply our symbolic signal processing method for analysis of actual experimental data for Mirnov oscillations. We have held preliminary discussions of this project with Dr. Robert Kaita who is experimental physicist from Princeton Plasma Physics Lab. He agreed to provide us with experimental data for different regimes of tokamak operation.

Other Professional Staff

None

Collaborations

This work is done in close collaboration with Princeton Plasma Physics Laboratory.

Students

None

Publications

1. A.B. Rechester and R.B. White, "Symbolic Kinetic Equation for a Chaotic Attractor," Physics Letters **A156**, 419 (1991).
2. A.B. Rechester and R.B. White, "Symbolic Kinetic Analysis of Two-Dimensional Maps," Physics Letters **A158**, 51 (1991).
3. A.B. Rechester and R.B. White, "Symbolic Signal Processing and Pattern Recognition," paper 3C13 1992 International Sherwood Fusion Theory Conference Santa Fe, New Mexico.
4. A.B. Rechester and R.B. White, "Signal Processing Using Symbolic Dynamics," paper 7R13 Bull. Amer. Phys. Soc. 1992.

Krall Associates

Project

A Program of FRC Theory Research

Nicholas A. Krall, Principal Investigator

Funding

FY 90

\$85k

FY 91

\$85k

FY 92

\$55k

Purpose

To explore the theory of the parameter ranges characteristic of the Field Reversed Configuration (FRC). The purpose is two-fold. One aim is to advance our understanding of the FRC fusion concept. An equally important aim is to advance our understanding of plasma under the conditions of high β and strong spatial variations which characterize the FRC, but will also arise in other attempts to manipulate plasma into the economic production of fusion energy.

Approach

Our general approach is to find descriptions of the plasma state which are sufficiently simplified to allow analytic calculations of stability, confinement and transport, while retaining enough characteristics (β , drift speeds) to make the calculations applicable to realistic situations. Guided by these calculations, we are often able to develop more detailed numerical solutions to the same problems.

Progress

One evolving product of this research has been a general increase in our understanding of high β ($\equiv 8\pi nT/B^2$) stability and transport. In the area of stability, high β has proven to be a stabilizing influence. We have been able to calculate the stability of a FRC to low frequency universal instabilities and drift dissipative waves for arbitrary β , and have found the parameters (combinations of β , field line length, and ion gyroradius) which mark the onset of high beta stabilization. The transport due to these instabilities is in general agreement with experiment, although regimes exist (particularly some of the last results obtained at Los Alamos) for which the transport model, which we have developed, does not appear relevant. Furthermore, theory predicts that at higher temperatures, where the collision frequency is markedly reduced, confinement should improve. No experiments have operated in a regime adequate to test this important prediction. Lastly, a new parameter range for drift waves at high β has been discovered, in which the relative size of the various perturbed drifts changes from that in all previous studies. The consequences of this new high β regime have yet to be explored.

A second aspect of high- β physics in which we have made progress is the confinement of plasma by cusped fields. This is relevant to the end loss problem in the FRC (a magnetic x-point exists which is cusp-like), as well as to other geometries which include cusp regimes. We have found, in a computer simulation, that confinement in a cusp improves markedly as the plasma pressure increases. This fact has for some time been an implicit part of the cusp literature, but until now there has never been a rigorous theoretical or experimental demonstration that it is correct. Magnetic x-points are common to many magnetic geometries, including some tokamak divertor schemes as well as the FRC as mentioned above; our progress in this area potentially has widespread value.

Plans

During the present year, we intend to prepare the generalized high β stability study for publication, to begin an exploration of the new high- β drift parameter range alluded to above, and to complete the cusp confinement work in sufficient detail to justify publication of the results in a refereed journal.

Students and Other Professional Staff

None

Collaborations

We intend to continue our collaboration with Dr. Loren Steinhauer of STI Optronics/University of Washington, which has been fruitful for many years, as well as with experiments at STI Optronics/University of Washington, if

and when they develop. We also plan a collaboration at some level with Japan, where FRC experiments still exist. This is important for the U.S. fusion program, particularly since the U.S. has drastically downsized its own experimental involvement in fusion schemes which attempt to improve on the success of the tokamak program.

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Lehigh University

Department of Physics

Project

Electron Cyclotron Heating and Current Drive in Toroidal Geometry

Arnold H. Kritz

Funding

FY 90	FY 91	FY 92
\$60k	\$40k	\$50k

Purpose

Deposition of wave energy in a tokamak may contribute to achieving plasma parameters that result in ignition. Our focus is the deposition of electron cyclotron (EC) energy and the associated driven current. This current may contribute to steady state (or long pulse) operation of a fusion reactor and may be important in achieving stabilization of magnetohydrodynamic (MHD) instabilities. We also consider the diagnostic information carried by emitted electron cyclotron power that results from purposeful perturbation of the tokamak plasma. The goal of our research is to carry out simulations of electron cyclotron heating and emission that aids in the planning and interpretation of experiments involving EC waves.

Approach

Develop and use numerical tools for studying electron cyclotron phenomena in plasmas. Support on going and planned ECH experiments. In order to accomplish this it is necessary to compute the deposition of the electron cyclotron power in MHD equilibria that accurately describe the plasma density, temperature and magnetic field profiles, and it is necessary to use wave and launch descriptions that accurately reflect the injection of the power in actual experiments. We have sought to make our numerical tools consistent with an accurate description of plasma parameters. This has required that we use plasma equilibria generated by MHD codes and that we link our codes with transport codes.

Progress

We have investigated scenarios in which electron cyclotron heating leads to improved stability and contributes to ignition in tokamaks. Numerous studies have been carried out (with collaborators listed below) that relate to issues associated with deposition and emission of electron cyclotron power in toroidal plasmas. In particular, the energy requirements for bringing a compact tokamak to ignition have been examined. We have demonstrated the diagnostic potential of incremental synchrotron radiation and have shown that this technique can yield information about the electric field profile in a tokamak, an important plasma parameter not easily measured.

Plans

Controlling the deposition, and in particular its location, is important in many of the applications that are envisioned for this form of supplementary power. We are studying the effects of density and magnetic fluctuations on current driven by EC waves. In particular, we are concerned with how these fluctuations modify the current perturbation needed for improved stability. Also, we are examining the various approximations and assumptions that have been made in computing the ECH deposition. Since the computational time and accuracy are of the utmost importance, we are examining the range of validity of the nonrelativistic, weakly relativistic and fully relativistic calculations of power deposition. We are working on the development of a scheme to efficiently calculate the absorption for numerical velocity distribution functions, and we plan to explore the use of a distributed computational environment for improving the efficiency of EC heating and current drive calculations using a number of work stations to provide a parallel processing environment.

Students

Su Yue

Other Professional Staff

Christopher Sheldon Radin

Collaborations

The principal investigator has collaborated, and continues to collaborate, with scientists at Livermore, Princeton, MIT, O-X, University of Texas and William and Mary as well as with scientists at a number of Laboratories in Europe, Canada, Australia and Japan. The computational tools that have been developed, and the associated analysis of ECH ray tracing, current drive, and mode stabilization have been strengthened as a result of these collaborative efforts. Of particular note is the collaboration with Gary Smith of the Lawrence Livermore National Laboratory. This collaboration has been ongoing for the past six years and the pace of interaction remains strong. The work on the theory regarding the use of incremental synchrotron radiation as a diagnostic and continued work on the application of this diagnostic has been done in collaboration with Nat Fisch of Princeton. Work on the linking of ray tracing with Transport Codes and the study of transport in ECH plasmas has been carried out in collaboration with Paul Benoli, Ron Englade and Miklos Porkolab of MIT and Gary Smith. Work on ECH for stabilization of MHD instabilities has involved collaborative efforts with Masaaki Yamada, Manny Manickam, Martha Redi and Glenn Bateman of Princeton as well as with scientists at MIT and Livermore listed above. Currently work is being done in collaboration with Antoine Pochelon and others who work on the ECH experiments in TCV in Lausanne. A collaborative effort has been started with George Vahala and Linda Vahala (Old Dominion University) on scattering of electron cyclotron waves from magnetic fluctuations. In addition to the scientists named above, there have been many others with whom there have been collaborative efforts and who are co-authors of papers of the work that relates to electron cyclotron wave studies.

Publications

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Lodestar Research Corporation

Project

Fundamental Studies of Fusion Plasmas

Richard E. Aamodt, Principal Investigator

Funding

FY 90	FY 91	FY 92
\$515k	\$600k	\$535k

Plan

This program will investigate fundamental physics phenomena involved in confining and heating high density tokamak fusion plasmas, and will apply that understanding to predictive and comparative performance studies of relevant tokamak systems. This endeavor combines fundamental plasma theory, computer and analytic modeling, numerical simulation and an interaction with experimental teams to achieve this goal.

Approach

ICRF Edge Physics:

Theoretical analyses and computer simulation have been employed to understand the interaction of high-power ion cyclotron radio frequency (ICRF) antennas with the edge plasma, including the issues of impurity generation, rf-induced transport, and anomalous power dissipation.

ICRF core heating studies:

Analytical and numerical techniques have been employed to investigate fast wave minority heating. The techniques enable treatment of all geometrical effects known to be crucial to modeling minority heated tokamak plasmas. Anisotropic minority driven instabilities have also been studied in the uniformly magnetized warm plasma using a bi-Maxwellian (two temperature) minority distribution function to model the effects of ICRF heating.

Electron transport studies:

Runaway electrons are being used as a diagnostic of the intrinsic magnetic fluctuations in the TEXT tokamak. A combination of experimental and theoretical techniques have led to a new understanding of the energetic particle behavior and have provided insights into thermal electron transport.

Progress

ICRF Edge Physics:

A model based on the theory of rf sheaths has been successfully used to gain an understanding of the metal impurity generation from the Faraday screens during ICRF heating in JET. The model explains the important parametric dependencies of the impurity influx and provides a practical prescription for reducing these impurities to negligible levels. Rf-sheath models also predict substantial power dissipation in the sheaths when the induced voltage across the sheath and the local plasma density are sufficiently large. These models have been applied to explain observations of reduced fast wave heating efficiency under extreme conditions on JET and ion Bernstein wave heating on the DIII-D. The formation of rf sheaths near the antenna produces a spatially-varying DC potential which can drive $\mathbf{E} \times \mathbf{B}$ convection in the scrape-off-layer (SOL). A fluid simulation shows that these convective cells significantly enhance the edge transport, flattening the SOL density and temperature profiles and possibly inhibiting the formation of the H-mode transport barrier. This work agrees qualitatively with the JET data on H-mode formation by ICRF heating alone.

ICRF core heating studies:

A quasilinear description of fast wave minority heating has been developed which properly treats off magnetic axis heating effects in a tokamak. Off axis effects occur when the minority resonance is nearly tangent to a flux surface. Work in progress has shown that off axis effects can be used to enhance the local power deposition and control the trapped/passing power split, permitting optimization of off axis heating and stabilization scenarios. In a separate study, an improved analytical description of the minority dielectric response has been developed which retains the parallel variation of the tokamak magnetic field, thereby including trapped as well as passing particle effects. In a separate study of anisotropic minority driven instabilities, a code was developed to solve the dispersion relation for complex frequencies. Instability was discovered in bands near each of the first seventy harmonics of the minority cyclotron frequency for a minority temperature ratio ($T_{\text{per}}/T_{\text{par}}$) of 400, chosen to be consistent with experiments performed on JET.

Electron transport studies:

Analysis of transient transport experiments in the TEXT edge plasma has yielded measurements of the runaway electron diffusion coefficient and shown it to be consistent with intrinsic stochastic magnetic field transport. Simultaneous hard and soft x-ray measurements confirm that the intrinsic stochasticity does not account for the anomalous thermal electron losses. In related theoretical studies, it has been shown that drift-orbit corrections to runaway electron diffusion are negligible in TEXT.

ICRF Edge Physics:

We will extend the computer simulation of rf convection to include more realistic models of the interaction with the H-mode, and study whether this effect can be used to spread the heat load in the divertor for ITER. Work is in progress to extend our analyses of impurity generation and edge convection to include the action of far field sheaths, which arise in regimes of poor single pass absorption (e.g., in fast wave current drive experiments).

ICRF core heating studies:

This work is nearing completion and manuscripts are in the final stages of preparation or have been submitted for publication. A working Fokker-Planck code exists which will allow Lodestar to investigate geometrical effects on ICRF heating scenarios in future tokamak experiments. Anisotropic minority driven instabilities will be studied using more realistic minority distribution functions to model magnetic field inhomogeneity in subsequent work.

Electron transport studies:

A calculation which is in progress evaluates the electron distribution function in the presence of stochastic diffusion as well as the induced electric field. The model determines the source distribution of runaways required for more sophisticated analyses of energetic electron transport experiments in TEXT.

Students

None

Other Professional Staff

P.J. Catto, D.A. D'Ippolito, J.R. Myra and D.A. Russell

Collaborations

ICRF Edge Physics:

The work on impurity generation and convective cells has been carried out in close collaboration with J. Jacquinot and M. Bures of the JET RF Division. The theory and computer simulation of rf sheaths was carried out in collaboration with M. Gerver of MIT and with D.W. Forslund and J.U. Brackbill of the Los Alamos Scientific Laboratory.

ICRF core heating studies:

The dielectric response study has been performed in collaboration with C.N. Lashmore-Davies and T.J. Martin of Culham Laboratory. The numerical implementation of the quasilinear description was performed under a Phase I, SBIR grant. Collaboration with C.N. Lashmore-Davies is commencing on anisotropic minority driven instabilities and related problems.

Electron transport studies:

The electron transport measurements have been performed by A.J. Wootton, R.D. Bengtson, and P.W. Wang at the Fusion Research Center, University of Texas. Theoretical collaborators include J.B. Taylor (IFS/UT Austin), H.E. Mynick (PPPL), and R.E. Duvall (Weizmann Institute). The sawtooth investigations were performed using a Phase I SBIR grant.

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Los Alamos National Laboratory

Project

Alternate Concept Theory

R. A. Nebel

Funding

FY 90	FY 91	FY 92
\$0	\$1,150k	\$300k

Purpose

The purpose of this theory activity is to develop analytic and computational models in support of the alternate concepts program, principally the Reversed Field Pinch (RFP) program at the University of Wisconsin and International Tri-Partite RFP agreement. The goal is to extend our understanding of the physics of confinement and transport in these devices. This effort benefits both the RFP and the tokamak in that we are developing tools that will be used to analyze and compare both devices. Application of these tools will provide guidance for building and operating improved devices of both types.

Approach

Our principal approach is to develop and provide advanced computational tools for the alternates theory program. We have extensive expertise in numerical methods and large-scale computation. We rely heavily on outside collaborations in order to best bring these tools to bear on problems of interest to the experimental programs.

Technical Progress

During the past year alternate concept theory concentrated on two areas: finishing up projects relating to the former LANL alternate concepts experimental program and developing new tools applicable to both alternate concepts and tokamaks.

1. Three Reversed-Field Pinch projects were finished and submitted for publication. The first project was a collaboration with the University of Maryland to study the possibility of inducing single helicity states in RFPs. The purpose of this work was to restrict the RFP dynamo to a single helicity in order to eliminate the stochastic field structure typically associated with RFPs. Results indicated that not only do single helicity states exist, but they are also attractors. The basin of attraction for these states depends on the amount of dissipation in the system. The second project was a collaboration with The Pennsylvania State University to study impurity transport in RFPs. The goal of this work was to develop a model to aid with the data analysis of ZTH. Studies were made of the ZT-40M data to try to better understand the behavior of discharges with vastly varying radiation fractions in order to benchmark the ZTH model. The third project was a collaboration with the Lebedev Institute on kinetic electron effects in RFPs. A new model for kinetic effects was derived and tested numerically. Results indicated behavior similar to that observed experimentally.

2. Work was started on a 3-D Implicit delta-f PIC code. Although this code is primarily for tokamak applications, it is being written with primitive variables so it is equally applicable to alternate concepts. This effort is discussed in detail in the tokamak theory section.

Plans

Our primary goal in alternate concepts theory is to provide computational tools for the existing programs. These include both existing tools and tools presently under development. We have two goals along these lines for the next year.

1. To make our hybrid MHD/minority species PIC code available to the University of Wisconsin in order to continue the self-consistent studies of the behavior of the long mean free path electron current produced by kinetic electrons wandering along stochastic fields. Wisconsin has expressed a desire to pick up this project and we have agreed to help them with it.

2. To continue the development of the Implicit PIC code alluded to in the above section. We plan to have an operational code for RFP geometries by October 1993, at which time we will institute new RFP physics studies.

Students

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2. R. Veerasingham, "A One-Dimensional Plasma and Impurity Transport Model for Reversed Field Pinches," (Ph.D., 1991).
3. J.L. Staudenmeier, "A Fluid and Kinetic Study of the Gross Stability of Field Reversed Configurations," (Ph.D., 1991).
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5. P.L. Matheson, "Modeling of a Toroidal Field Divertor in a Reversed Field Pinch," (Ph.D., 1989).
6. J.W. Cobb
7. P. Papanikolaou

Other Professional Staff

D.C. Barnes, L. Turner, K.M. Ling, and A.H. Glasser

Collaborations

A major collaboration is being carried out with A. Gurevich of Lebedev Institute in Moscow. This involves turbulent transport effects in RFPs. Recent collaborations have occurred with J. Finn at U. of Maryland; R. Veerasingham, E. Klevans, J.L. Staudenmeier, and M. Hsiao at Penn State; K. Sidikman, J. Callen, J. Beckstead, and R. Dexter at U. of Wisconsin; P.L. Matheson and G. Mason at Brigham Young University; D.D. Schnack, Y-L. Ho, and R.C. Bishop at Science Applications International Corporation; R.D. Milroy at Spectra-Technology Corporation; J.W. Cobb at U. of Texas; P. Rosenau at Technion University; H.R. Lewis at Dartmouth; P. Papanikolaou and C.K. Choi at Purdue University.

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Los Alamos National Laboratory

Project

Moving Finite Elements

A. H. Glasser

Funding

FY 90	FY 91	FY92
\$0k	\$0k	\$100k

Purpose

The purpose of this work is to develop applications of the method of Moving Finite Elements (MFE) to magnetic fusion energy research. MFE is a powerful new fluid simulation technique which continuously adapts the grid to the evolving solution. It is especially useful for solving problems with narrow regions of sharp gradients, multiple length scales, and strong anisotropy, all of which are characteristic of problems in magnetic fusion energy. One problem of immediate interest is low- n singular modes, such as tearing and interchange modes in tokamaks, and associated nonlinear behavior, such as disruptions. Another is the Numerical Tokamak, a Grand Challenge Problem, which could benefit greatly from this approach by reducing the required grid size and number of particles by a factor of order 100.

Approach

Modeling a fluid on a digital computer requires approximating the smooth variation of fluid quantities, such as density, velocity, temperature, and electromagnetic fields, by a large number of discrete values. The most common approach is to represent these quantities by their values on a regular mesh or grid covering the spatial domain of interest. The behavior of the fluid at successive moments of time is calculated by converting the known fluid equations to a large system of algebraic equations which can be solved on the computer. The finer the mesh and the shorter the time steps, the more accurate the solution becomes, at the expense of greater demands on computer time and storage capacity. In fact, the fastest and largest supercomputers have been developed mainly to allow accurate solution of such complex fluid problems. Moving Finite Elements is a moving node adaptive grid method which has a tendency to pack the grid finely in regions where it is most needed at each time and to leave it coarse elsewhere. It does so in a manner which is simple and automatic, and does not require a large amount of human ingenuity to apply it to each particular problem. At the same time, it often allows the time step to be large enough to advance a moving shock by many shock thicknesses in a single time step, moving the grid smoothly with the solution and minimizing the number of time steps required for the whole problem. For 2-D problems (two spatial variables), the grid is composed of irregularly shaped and irregularly connected triangles which are very flexible in their ability to adapt to the evolving solution. While other adaptive grid methods have been developed which share some of these desirable properties, this is the only method which combines them all. In many cases, the method can save orders of magnitude of computing time, equivalent to several generations of advancing computer hardware. Visualization of the complex results of our computations is treated with the help of the state of the art graphics hardware and software provided by the Silicon Graphics Iris Workstations. Computer-generated movies, with hidden surfaces, real time animation, nearly continuous variation of color, and flexible user interaction have been developed to provide maximum comprehension.

Progress

A general-purpose code has been developed for treating a large class of difficult, nonlinear, time dependent fluid problems in two dimensions, expressed by equations (1) and (2). Boundary conditions can be any of a large range, including Dirichlet, Neumann, mixed, or periodic. Recent developments include a new form, an iterative matrix solution procedures, which is completely local and parallelizable, and a capability to add and delete grid nodes in order to allow it greater topological flexibility. In addition, a conceptual framework has been developed to apply the method to kinetic plasma problems in the less collisional banana regime characteristic tokamak plasmas.

Plans

The existing code will be applied to the study of singular modes in toroidal plasmas. Work will begin on further generalizing the fluid code to 3-D, and to developing a kinetic simulation code using Moving Finite Elements.

Students

Andrew Kuprat, "Creation and Annihilation of Nodes for the Moving Finite Element Method," (Ph.D., 1992). Andrew is now a post-doc with us in T-15.

Collaborations

Professor Keith Miller of the University of California at Berkeley along with his students Neil Carlson and Andrew Kuprat have been collaborators for some time.

Publications

1. Alan H. Glasser, "A Moving Finite Element Model of the High Density Z-Pinch," Los Alamos Report LA-UR-88-746, *Journal of Computational Physics*, 159 (1989).
2. A.H. Glasser, "Moving Finite Elements for Fluid Simulation in 1D and 2D," presented at the Fluid Dynamics Workshop of the Mexican Physical Society, Instituto de Ciencias Nucleares, Universidad Nacional Autonoma de Mexico, September 10-12, 1990.
3. Alan H. Glasser, Keith Miller, and Neil Carlson, "MFE2: A General-Purpose 2D Moving Finite Element Code for Nonlinear, Time-Dependent Fluid Problems," presented at the 1991 Sherwood Theory Meeting, Seattle, Washington, April 22-24, 1991.
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6. Alan H. Glasser, Keith Miller, and Neil Carlson, "MFE2: A General-Purpose 2D Moving Finite Element Code for Nonlinear, Time-Dependent Fluid Problems," invited talk presented at the Physics Computing '91 Conference, San Jose, CA, June 10-14, 1991.
7. Alan H. Glasser, Keith Miller, and Neil Carlson, "Moving Finite Elements for Fluid Simulation," course presented at the Instituto Tecnológico de Estudios Superiores de Monterrey, Mexico City, Mexico, July 8-14, 1992.
8. A.H. Glasser, "A New Variational Formulation of Kinetic Plasma Theory and the Application of Moving Finite Elements," invited talk presented at the 14th International Conference on the Numerical Simulation of Plasma, Annapolis, MD, September 3-6, 1991.
9. A.H. Glasser, "A New Variational Formulation of Kinetic Plasma Theory and the Application of Moving Finite Elements," seminar present at Lawrence Livermore National Laboratory, September 12, 1991.
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11. Andrew Kuprat, Keith Miller, and Alan H. Glasser, "Graph Massage: An Improved Technique in Moving Finite Elements," to be presented at the 1992 International Sherwood Fusion Theory Conference, Santa Fe, NM, April 6-8, 1992.

Los Alamos National Laboratory

Project

Simulation of Transport in Magnetized Plasma

Jeremiah U. Brackbill

Funding

FY 90

\$0k

FY 91

\$80k

FY 92

\$100k

Purpose

We seek to develop numerical models for plasma simulation to study transport processes in tokamak plasmas in realistic geometries. Our models include kinetic effects but are still suitable for computing on magnetohydrodynamic time scales. Kinetic effects, which are driven by deviations from thermodynamic equilibrium, are believed to cause a confined plasma to behave in a fundamentally different manner from a fluid, even on time scales long compared with typical plasma phenomena. Inclusion of kinetic effects may bring theory and experiment into better agreement. In this project, we seek an understanding of the persistence of kinetic effects on fluid time scales through numerical plasma simulation.

Approach

Our approach incorporates new techniques for grid generation, for implicit dynamical equations, and for particle-in-cell algorithms into a general purpose plasma simulation code, CELEST3D, in three dimensions. The code will be used to model transport in magnetically confined plasmas in a toroidal geometry. The code is written in modular form, so that individual capabilities, such as grid generation, can be extracted and used in other fusion codes, or even for other applications. As each module is developed and tested, it will be ported to highly concurrent computers.

The implicit numerical approximations allow us to solve the full kinetic equations with large time steps. The grid generator allows us to control the distribution of grid points adaptively so as to use available computing resources effectively. The new developments in particle-in-cell techniques allow us to change the number of particles dynamically in order to maintain accuracy and a uniform distribution of computational effort over the grid. The use of these combinations of techniques makes this effort unique in the fusion community.

Progress

Recent progress in developing CELEST3D is summarized as follows:

1. A method for solving particle equations of motion on a non-rectilinear grid that combines solutions in natural grid coordinates and physical coordinates has been developed. The particle mover accurately models the orbits of both trapped and passing particles in a tokamak-like magnetic field.
2. A linked-list data structure that allows vectorization of both gather and scatter operations in mesh-length vectors without memory conflict has been implemented.
3. An adaptive grid algorithm that controls both grid spacing and alignment of the grid with the magnetic field has been developed. In a recent application to magnetic reconnection, the ability to control the orientation of the grid reduced the cost of the calculation by an order of magnitude.
4. Electromagnetic field equations that can accommodate both non-rectilinear grids and significant $\mathbf{E} \times \mathbf{B}$ drifts have been developed. The efficient solution of the field equations is a critical issue, not only for the development of CELEST3D but also for the extension of the gyrokinetic model to realistic geometry. An extensive investigation of conjugate-gradient type algorithms, including bi-conjugate gradient and conjugate gradient squared methods, indicates that only a conjugate gradient algorithm for solving the equations in normal form can supply the necessary reliability.
5. Simple test problems exercising the full code have provided limited verification of the reliability and accuracy of CELEST3D.
6. A geometry module, including a multi-block data structure, grid generator, and generalized difference equation package has been written in CM-Fortran and executed on a CM2. The module is a paradigm for future code development that uses netCDF for communication and AVS for visualization.
7. A new technique has been developed to detect when there are too few or too many particles in a cell and automatically to change the number as required. It allows one to use an adaptive grid to provide increased resolution of selected parts of the domain while maintaining a uniform distribution of computational effort over the grid.

Plans

We plan to apply CELEST3D to plasma transport problems in a three-dimensional toroidal geometry in the coming year. These problems include single particle studies, such as a study of bootstrap current effects, requiring only the solution of single particle equations of motion in prescribed fields, and more complex problems such as the suppression of edge turbulence by $\mathbf{E} \times \mathbf{B}$ drifts, the ion-temperature-gradient instability, and trapped particle instabilities, which require the solution of the fully self-consistent model.

Other Professional Staff

None

Collaborations

Dr. John Reynders of the Advanced Computing Laboratory at Los Alamos and Dr. Steven Roy at Caltech are responsible for the development of the parallel implementation of CELEST3D, and its extension to incorporate the gyrokinetic model. The project is assisted by advice from Prof. Deborah Sulsky of UNM on particle methods and iterative equation solvers. Dr. Hoanh Vu of Los Alamos has contributed to the development of implicit plasma simulation methods for very large time steps, and to their application to the modeling of collisionless shocks in the earth's magnetosphere. Dr. David Forslund of the Advanced Computing Laboratory provides advice on plasma physics, parallel computing, and graphics.

Students

Giovanni Lapenta, a doctoral candidate at the University of Torino, has developed new techniques for the dynamical control of the number of particles during an extended visit to Los Alamos.

Major Recent Publications

1. J.U. Brackbill, "Plasma Simulation on Magnetohydrodynamic Time Scales," *International Conference on Supercomputing in Nuclear Applications (SNA'90)*, T. Asaoka, Japan Atomic Energy Research Institute, Mito City, Ibaraki, Japan, 192-197, 1990.
2. J.R. Myra, D.A. D'Ippolito, D.W. Forslund and J.U. Brackbill, "Sheath-Plasma Waves and Anomalous Loading in Ion-Bernstein Wave Experiments," *Physical Review Letters*, **66**, 1173-1176, 1991.
3. J.U. Brackbill, "FLIP MHD: A Particle-In-Cell Method for Magnetohydrodynamics," *J. Comput. Phys.*, **96**, 163-192, 1991.
4. H.X. Vu and J.U. Brackbill, "CELEST1D: An Implicit, Fully-Kinetic Model for Low-Frequency, Electromagnetic Plasma Simulation," *Computer Physics Communications*, **69**, 253-276, 1992.
5. H.X. Vu, J.U. Brackbill and D. Winske, "Multiple Switch-Off Shock Solutions," *Journal of Geophysical Research*, **97**, 13839-13852, 1992.
6. D. Burgess, J.U. Brackbill and D. Sulsky, "Mass Matrix Formulation of the FLIP Particle-In-Cell Method," *Journal of Computational Physics*, **70**, 1-15, 1992.
7. J.U. Brackbill, "An Adaptive Grid with Directional Control," *Journal of Computational Physics*, 1992-submitted.

Los Alamos National Laboratory

Project

Toroidal Transport Theory

D. C. Barnes

Funding

FY 90

\$0k

FY 91

\$0k

FY 92

\$650k

Purpose

The purpose of the Los Alamos magnetic fusion theory program is to provide basic understanding and detailed interaction with the national and international MFE experimental program. The theory program provides an alternative view of the national tokamak confinement program and supports the Los Alamos experimental activities directed toward the fusion product diagnosis of the TFTR device at the Princeton Plasma Physics Laboratory. In pursuing these programmatic goals, the theory program also carries out basic plasma physics research which is necessary to support the required applied research.

Approach

The approach to carrying out the program relies on analytical and computational expertise in macroscopic and microscopic plasma physics theory, and in related subjects such as atomic physics and plasma-material interactions. Because of the many specialties involved, external collaborations are sometimes invoked.

Progress

A. Singular Modes

Major progress has been made on the study of singular modes in axisymmetric toroidal plasmas. A subset of the complete fluid equations governing the inner region of singular modes in toroidal geometry has been solved exactly and analytically. The subset includes toroidal curvature as well as ion and electron diamagnetic and $\mathbf{E} \times \mathbf{B}$ drifts, but not viscosity or thermal conductivity. The Fourier-transformed equations are expressed as a second-order ordinary differential equation with singular points at 0 and infinity. Exact solutions have been found in terms of confluent hypergeometric functions. A dispersion relation $\Delta' = \Delta(Q)$ has been derived from the matching condition between inner and outer solutions in configuration space, with Δ' the jump in the ratio of small to large asymptotic coefficients in the ideal outer region and $\Delta(Q)$ a complicated function of the scaled growth rate Q obtained from the inner region analysis.

The most interesting result is a new instability for $Q > 1$ which exists even in the absence of curvature and drift effects. Unlike most previous treatments, the validity of this one is not restricted by the constant- y approximation or its relatives to the regime $Q \ll 1$. Such previous treatments have found that systems with $\Delta' > 0$ are unstable, while systems with $\Delta' < 0$ are stable, although some works have replaced 0 by a threshold value Δ_c . With the restriction $Q \ll 1$ removed, $\Delta(Q)$ is found to have a pole at or near $Q = 1$, which has profound and surprising significance for stability theory. This pole was found in previous analytical and numerical treatments, but its significance was not appreciated. In the presence of the pole, there are strong instabilities for $\Delta' < 0$, with $Q > 1$ and approaching ideal MHD growth rates as Δ' goes to zero from below. Thus, while $\Delta' > 0$ remains unstable, $\Delta' < 0$ is *more* unstable. The new instabilities are essentially ideal modes extending over more than one singular interval. The key role of the singular layer is to form a connecting bridge between adjacent ideal intervals, allowing a larger class of nearly ideal unstable modes to fit into the enlarged box. Beyond this main effect, the influence of resistivity on the growth rate gets weak as Δ' goes to zero from below.

The full dispersion relation, including curvature and drift effects, is complicated and difficult to analyze, containing ratios of Γ functions of complex arguments. A complete analysis has been performed by studying the locations of its rich variety of poles and zeroes and by means of Nyquist plots constructed with the help of Mathematica. This analysis permits a deeper understanding of the number of unstable roots and of the relationship among various drift and resistive roots in different regimes of approximation than in previous treatments of drift tearing modes.

Besides these analytical solutions, a computer code has been written to solve the more general class of equations including viscosity and thermal conductivity. The solutions obtained numerically agree to arbitrarily high accuracy with the analytical solutions when they are available, the accuracy depending only on the tolerance specified to the ordinary differential equation solver. In addition, this code allows the determination of behavior which is not accessible to the analytical solutions.

B. Quiet Implicit PIC

During the past year, we have pioneered the application of δf methods to long time step, electromagnetic plasma simulation. This development has led to a new approach, **Quiet Implicit PIC (QIP)**. This is a new technique for carrying out particle simulations for the solution of the nearly collisionless Boltzmann equation. In this approach, the unknown distribution function f is separated into a *bulk* portion f_b and an *intrinsically* kinetic portion δf . Single simulation particle shot noise is greatly reduced by treating only the intrinsically kinetic portion using PIC methods. The bulk portion, on the other hand, is determined by the solution of moment equations coupled to Maxwell's equations and differenced time-implicitly. The QIP method is fully kinetic, nonlinear, electromagnetic, and appropriate for domains of arbitrary dimensionality with general boundary conditions. The QIP method is a generalization of previous " δf " developments. Generalizations include local variation of the bulk distribution in both space and time, a fully electromagnetic formulation, and implicit time differencing.

The separation of f_b from δf leads to an enormous noise reduction, in the case when δf is small compared to f . For example, an intrinsic noise level of less than 10^{-4} has been observed using 10 particles per cell. Such quiet, long time step simulations allow the investigation of previously inaccessible kinetic phenomena, such as fluctuation driven particle and energy transport in magnetically confined plasmas, where observed fluctuation levels are a few 10^{-3} , and fluctuation time scales are 10^5 times longer than particle orbit time scales.

We have confirmed several rather dramatic advantages associated with employing the moment equations in our formulation. First, it is straight forward to arrange the conservation of charge, momentum, and energy, since these properties depend only on the consistent centering of quantities on the mesh. This permits us to drop Gauss's law and $\text{div}(\mathbf{B}) = 0$ from Maxwell's equations and avoid the need to perform divergence cleaning or other charge correcting machinations. Second, linear stability depends only on the combined moment and Maxwell's equations. Thus, there is great flexibility in evaluating the particle quantities. For example, we have confirmed that substepping the particles and averaging over these substeps in a first-order accurate manner does not adversely affect stability. Finally, use of the moment equations somewhat simplifies the treatment of complex geometries and boundary conditions.

We have implemented QIP in one and three-dimensions. In the one-dimensional case, a nonlinear instability associated with errors in evaluation of the heat flux has been observed. This instability is associated with the loss of synchronization between the representation of low-order moments by the particle list and by the moment list. Thus, for example, truncation errors in the time advance may lead to a case in which no particles are present in one portion of the mesh, while the moment list indicates a significant density there. These instabilities may be avoided by enforcing synchronization between the two representations. We have found that an effective strategy is to modify the particle list to conform to the moment list. This produces a smooth solution and avoids the nonlinear instability mentioned previously. The optimum method of synchronization is still being investigated.

The three-dimensional code is presently able to time advance the two-fluid (electrons + ions) moment equations with large time steps. We are applying this method to the study of MHD instabilities, including the internal kink (sawtooth) instability in a straight tokamak geometry. Particle movers for the three dimensional code have also been implemented and tested. During the remainder of FY 92, we will couple these components to obtain initial kinetic results for MHD modes.

Plans

During the next several years, the Los Alamos theory program will continue a mission which consists of two parts. First we will focus on one or two areas of plasma science, the advancement of which will provide fundamentally new insights of general importance to magnetic confinement. Secondly, we will address narrower, focussed topics essential for the advancement of the tokamak toward a practical fusion reactor. The areas of general plasma science we have chosen to emphasize are:

1. Development and refinement of more complete fluid models of confined plasmas.
2. Development of new, MHD based hybrid models which include the low-frequency effects of fully kinetic, nearly collisionless species on fluid phenomena.
3. In these areas, a range of applications to tokamak physics will be pursued and external collaborations sought.
4. The areas of specific topics we will pursue are the following.

Singular Modes

Future work on singular modes will follow several lines. First, the Analytical solutions obtained so far omit the important effects of viscosity and thermal conductivity. There is some possibility that some of these terms can be incorporated into exact analytical solutions of the form already obtained. Beyond that, a numerical procedure will be used to complete the study, using a method described in the recent publication by Glasser. The analytical solutions obtained thus far can be used to verify and understand the results of the numerical procedure. Beyond this, work will begin on a derivation of equations governing singular modes in the less collisional, kinetic regime. In addition, the method of Moving Finite Elements will be used to solve an initial value problem for singular modes in toroidal geometry.

Quiet Implicit PIC

During FY 93, the straight torus three dimensional code developed and applied during the remainder of this fiscal year will be extended to true toroidal geometry. We will initially confirm the predicted toroidal affects on the sawtooth using the fluid component of this code. Next, kinetic affects will be added to the algorithm. By the end of FY 93, we expect to be able to deliver a UNIX/CFT77 compatible version of this code to the Numerical Tokamak Project.

Other

We will continue to investigate the possibility of efficient toroidal current drive by low frequency MHD waves using existing and emerging analytic and numerical methods.

Students

W. D. Nystrom

Other Professional Staff

A. H. Glasser, K. M. Ling, R. A. Nebel, L. Turner

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Massachusetts Institute of Technology

Project

Fusion Theory and Computations

D. J. Sigmar, J. Freidberg, A. Bers, J. Kesner, J. Ramos and T. Dupree

Funding

FY90	FY91	FY93
\$753k	\$925k	\$1,000k

Purpose

Motivated by the upcoming D-T experiments in TFTR, collisional transport theory is being extended to account for poloidal density variations and poloidal flows in tokamaks. New physics issues are associated with the fusion produced alpha-particles including their neoclassical losses, their interaction with background plasma collective modes such as Alfvén waves and their contribution to the bootstrap currents. Studies are being carried out of plasma heating and current drive with radiofrequency (RF) waves in reactor grade plasmas. Investigations are being made of spatial-temporal chaos induced by instabilities that arise in the presence of intense coherent fields. Investigations of the magnetohydrodynamic (MHD) problems relevant to present or next generation tokamak plasmas including resistive wall instabilities, Alfvén gap eigenmodes. Reconstruction of plasma equilibrium from magnetic diagnostic data are also underway. Studies are of the operation of low current, high temperature tokamaks, especially equilibrium stability and confinement at high poloidal beta are being carried out. This work is closely linked to ongoing experimental collaborations with the Princeton Plasma Physics Laboratory at the TFTR and PBX-M tokamaks. Theoretical investigations of tokamak beta limit issues including an explanation of the empirical Troyon limit and its dependence on the safety factor, access to the second stability region, and feasibility of stable equilibria with nearly 100% bootstrap generated current are carried out.

Approach

This project covers theoretical work on fusion plasmas in toroidal magnetic confinement (tokamak), and is divided into five subtasks:

1. Impurity and alpha transport—Dieter J. Sigmar, Principal Investigator.
2. Radiofrequency heating and current drive: Transport and chaotic dynamics—Abraham Bers, Principal Investigator, Abhay K. Ram, Co-principal investigator.
3. Magnetohydrodynamic equilibrium and stability, and plasma engineering—Jeffrey P. Freidberg, Principal Investigator.
4. Stability and transport in high poloidal beta plasmas—Jay Kesner, Co-principal Investigator.
5. Theory of the tokamak beta limit—Jesus J. Ramos, Co-principal Investigator.

Using analytical (but nonlinear) neoclassical theory, we studied nonlinear coupling between poloidal flow and poloidal density variations resulting in a bifurcation of poloidal equilibrium. This, along with the ensuing radial electric field, alters the transport of the bulk plasma as well as of the impurities. Pitch angle scattering and slowing-down drag were incorporated in the calculation of neoclassical losses of fusion born alphas and their contribution to the bootstrap current. Resonant destabilization of toroidal Alfvén eigenmodes (TAE) by alpha particles has been studied with a guiding center following code based on Hamiltonian drift orbit formalism. Two dimensional relativistic Fokker-Plank simulations were used to investigate lower hybrid (LHW) and fast Alfvén (FAW) wave current drive. The quasilinear Fokker-Plank formulation was generalized by using Hamiltonian gyrokinetic theory in order to include wave induced radial transport of fast electrons. Radiofrequency fields were determined by toroidal ray tracing. Spatial-temporal chaos was studied in the nonlinear interaction of three coherent wavepackets with an extension of soliton theory to nonconservative systems. Resistive wall instabilities were analyzed with a variational principle and a Green's function formulation of the vacuum field energy. Analytic methods were employed to find Alfvén gap eigenmodes induced by noncircular geometrical effects in tokamaks, and to derive stability theorems. Experimental data from TFTR and PBX-M discharges were analyzed with the time dependent reconstruction code TRANSP. This provides enough information to determine local diffusivities and to perform MHD stability analyses. Comparison with prevailing theories is then carried out. Proposed experiments on current profile control were studied with a newly developed code that couples the transport package BALDUR with the lower hybrid code of P. Bonoli's that contains a realistic ray tracing and Fokker-Plank current drive calculation. Analytic methods were

developed based on asymptotic scaling properties of the MHD equations. These were applied to derive general properties of the tokamak beta limits. Extensive numerical calculations were carried out with the two-dimensional MHD equilibrium and the Princeton PEST stability code package, in order to establish operation limits in plasma parameter space. Special attention was paid to making the equilibrium current profile compatible with the bootstrap profile as calculated from neoclassical theory.

Progress

The possibility that the transition between low (L) and high (H) confinement modes in tokamaks is due to a bifurcation of the poloidal equilibrium flows and associated radial electric fields was investigated. Two such stable bifurcated solutions were found by retaining density nonlinearities induced by the parallel friction between bulk ions and impurities which is sufficiently strong in the outer edge of the plasma. The Hamiltonian guiding center code, ORBIT, was used to analyze the alpha-particle dynamics as they interact with and destabilize the Alfvén waves, and their anomalous diffusion due to stochastic orbit losses was established. A self-consistent nonlinear evaluation of the destabilized TAE amplitude shows no saturation before global stochasticity sets in. After that, large diffusion losses occur. The alpha-particle induced bootstrap current has been calculated, including both collisional drag and pitch angle scattering. Its magnitude is less than or equal to 10% of the total plasma current.

A detailed analysis of current drive by combined LHW and FAW has been carried out. It was found that the effect of the FAW is to increase the perpendicular temperature in the tail of the electron distribution function induced by the LHW. This enhancement of the current drive efficiency is in good apparent agreement with experimental observations at JET. Spatial-temporal chaos in the nonlinear interaction of an unstable wave coupled to two damped waves at lower frequencies was completed. The ensuing saturated chaotic state was obtained and analyzed first by numerical methods. An analytic approach has been developed by treating the nonconservative aspects as a perturbation of the conservative three wave interaction which is exactly integrable by inverse scattering techniques. The analytic results described all characteristic scales in the spatial-temporal chaos and are corroborated by the numerical simulations.

A general stability theorem was derived for the resonant interaction of energetic particles and Alfvén waves, and the stabilizing effect of ion Landau damping was demonstrated. The ellipticity induced Alfvén eigenmode has been discovered. A procedure has been derived to evaluate the growth rates of external MHD modes in the presence of arbitrarily shaped resistive walls. This can be easily coupled to standard ideal MHD codes. A fast, time dependent code that evaluates tokamak equilibrium solutions and the required poloidal field coil currents, including the effect of eddy currents in the vacuum vessel, was completed. Contributions were made to the problem of inferring the plasma shape and internal parameters from external magnetic measurements.

Results from the collaborative experiments at high poloidal beta in TFTR have been analyzed. Poloidal betas up to 1.3 times the aspect ratio and energy confinement times up to 3.5 times the L-mode were achieved. Thermal diffusivity measurements appear to agree with resistive ballooning mode scaling at high poloidal beta, but the resistive ballooning turbulence is observed to become subdominant at lower poloidal beta values. The effect of the equilibrium distortion at high poloidal beta on temperature gradient driven modes was studied, and stabilizing trends were found. A second stability access experiment via current profile control that can be performed in the PBX-M facility has been realistically simulated. To this effect a new code was developed which incorporates the Bonoli lower hybrid current drive code into the BALDUR equilibrium and transport code.

A theoretical explanation of the Troyon-Sykes beta limit for ballooning modes and its dependence on the safety factor was found. Stable paths to the ballooning second stability region were established and this scenario was adopted as the basis for the ARIES II/IV reactor design and the MIT-PBX-M collaborative experiment. Low- n external modes in low-current, high poloidal beta regimes have been systematically studied for the first time, and a characteristic current driven, edge localized instability with low beta threshold has been identified. This may explain recent beta collapse results in the DIII-D and JET tokamaks. Systematic studies of numerical convergence showed shortcomings in the PEST-II stability code. The possibility of tokamak equilibria in the ballooning second stability region with almost completely bootstrap generated current was demonstrated.

Collaborations

Collaboration have taken place with Oak Ridge National Laboratory personnel (K-C. Shaing, S. Hirshman) on transport theory, with General Atomic personnel (A. Turnbull and DIII-D experimentalists) on TAE modes, with B. Braams at New York University on improving the B2 code, with M. McCoy at Livermore and R. Harvey at GA on LHW and FAW current drive, with R. Betti at University of Rochester on Alfvén gap instabilities, with G. Berge (Norway) on resistive wall growth rates, with S. Haney at Livermore on the SuperCode, with J. Wesson at JET on sawteeth problems, with the TFTR and Columbia University teams as part of the ongoing Princeton-Columbia-MIT experiment at TFTR, with the PBX-M team as part of the ongoing Princeton-MIT experiment at PBX-M. With the

MHD theory groups at Princeton and GA (S. Jardin et al. and A. Turnbull et al.) on advanced tokamak MHD, and with the ARIES and TPX design teams as active participants.

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Massachusetts Institute of Technology

Project

Physics of Thermonuclear Plasmas

B. Coppi

Funding

FY 90

\$400k

FY 91

\$450k

FY 92

\$450k

Purpose

This project addresses the study of magnetically confined plasmas in regimes of thermonuclear interest: high temperatures and densities, with special attention paid to the case of compact, high magnetic field experiments. These regimes are becoming of timely interest, as present-day toroidal experiments [e.g., Toroidal Fusion Test Reactor (TFTR) and Joint European Torus (JET)] have reached the stage where Deuterium-Tritium fuels are being used (or soon will be) for the first time, and fusion reactions are producing non-negligible fluxes of fusion reaction products. The research involves the important role of plasma collective modes in producing plasma transport processes and changes of magnetic field topology (so-called reconnection) with the intent of elucidating the mechanisms responsible for the anomalous (i.e., larger than predicted by "classical" theories) losses of particles and energy from the plasma that are observed describing the onset of macroscopic internal modes (e.g., leading to the so called sawtooth and fishbone oscillations) that can prevent the attainment of ignition conditions.

Since 1969, our group has been involved in the design of a continuing series of compact, high magnetic field experiments (starting with the successful Alcator line of machines), which has made the most substantial advance in the value of the confinement parameter $n\tau_e$ with pure plasmas and still holds the record for this kind of plasma. This effort, which involves a substantial part of our resources, is presently focussed on the Ignitor device, which is the first experiment to be proposed and designed for the purpose of studying fusion burning and ignition in a D-T plasma. Continuing participation in the activities surrounding the Alcator C-MOD, currently starting operation at M.I.T., the latest experiment in the Alcator line that, like Ignitor, combines the favorable characteristics of high magnetic fields and optimized plasma shaping in order to produce plasmas with high densities and currents. A considerable fraction of our effort is also devoted to the issue of "neutronless" reactors burning advanced fuels that produce relatively low levels of fast neutrons (e.g., D-³He). With the discovery of the so-called second stability region (a high- β regime of operation where ideal MHD ballooning modes are stable) and the understanding of techniques to prevent the so-called "sawtooth crashes" of the central plasma pressure, both achievements that originated in our group, we have shown that the burning of advanced fuels can be attained by experiments that are feasible with present-day technologies.

Approach

Our research group combines efforts along several avenues: theory, conception and proposal of new experiments, and numerical modelling. The first concerns itself with transport processes and coherent collective modes: microturbulence, "sawtooth" and fishbone oscillations, excitation of modes leading to ion cyclotron emission, impurity-driven fluctuations, ballooning modes driven by fusion reaction products populations. Each of the considered collective modes has its own cause (e.g., pressure gradients or an anisotropic distribution of high energy particle populations ions), region of activity (e.g., the inner portion of the plasma where $q(r) \leq 1$, for the case of "sawteeth"), and experimental signature (e.g., radiation at harmonics of the helium cyclotron frequency). Linear and nonlinear aspects of the theory governing each of these phenomena form the substance of the theoretical effort. Whenever possible, the relevant particle and energy transport coefficients are then incorporated into existing transport codes in order to study present day experiments and to predict levels of losses in future devices (e.g., Ignitor and ITER). Transport modelling is a continuing investigation in its own right. Codes are continually being improved. Transport coefficients have also been formulated on the basis of global constraints and considerations, when theory is unable to derive them from first principle analysis. Important aspects of the modelling include the investigation of nonsteady state processes, such as the initial current rise, of D-T ignition, and of the ignition of advanced fuel scenarios (i.e., D-³He), which lead to fusion burning with minimal neutron production and therefore minimal radioactive activation of the containment vessel. We are also involved in the Numerical Tokamak Project, in the development, parallelization, and use of a 3-D toroidal, hybrid code (either a two fluid main plasma with a gyrokinetic hot particle population or a plasma consisting of fluid electrons and gyrokinetic ions) in collaboration with W. Park and others at PPPL and members of M. McCoy's computational group at LLNL (NERSC).

Progress

Following our earlier success in explaining the cessation of "sawtooth" oscillations in experiments with auxiliary heating (this stabilization was due to the presence of a population of high energy ions), our work on $m=1$ modes (which are considered to be the cause of these "sawteeth") has concentrated on explaining the fast growth rate, corresponding to the early nonlinear stage of the crash phase of the plasma pressure, observed in high temperature, collisionless regimes. We have ascribed it to the characteristics of the $m=1$ mode that can produce magnetic reconnection in these regimes. The distances $\rho_s = (T_e + T_i)^{1/2} / m_i \Omega_i$ and $d_e = c / \omega_{pe}$ are the dominant scale lengths for the process of reconnection that takes place at the $q(r_i) = r_i B / R B_0 = 1$ surface. The linear growth rate of the instability is about proportional to ρ_s / τ_i and is found to be numerically consistent with the crash time for the so called "monster sawteeth" that occur after sawteeth are suppressed and the electron temperature is allowed to rise and enter the mode collisionless regime. Stability conditions have been formulated, whereby finite drift wave frequency effects are shown to be important and compared to experimental situations realized in the TFTR and JET machines. The early nonlinear stage of the $m=1$ sawtooth crash has been examined, providing a unique solution for the configuration of the island (so called "Waelbroeck" solution) when the relevant drift frequency effects are negligible. A crash evolution equation has been formulated from the nonlinear equations and, subject to the postulate that the speed of the radial displacement of the hot plasma core is independent of the reconnecting layer width, continued exponential growth has been shown to occur. Linear and nonlinear evolution are also being investigated numerically, using a full 3-D, toroidal code that includes the effects of fluid electrons and either fluid or gyrokinetic ions.

Cyclotron emission at harmonics of the Helium gyro-frequency evaluated at the outer edge of the plasma column have been observed in JET, and correlated with the neutron emission from Deuterium-Tritium plasmas. We have explained this emission as the result of the excitation of modes that we had predicted to occur on the basis of a well developed theory of ours that had been motivated by the search for modes excited in spin polarized fusing plasmas. The excitation of these modes is in fact connected with the presence of an anisotropic population of fusion α -particles and in particular with the gradient in velocity space, $\partial f / \partial v$, of their distribution function. We have proposed to make use of this emission to study the effect of the plasma current on single particle confinement and the effect of peaking the particle density on the α -particle population at the edge of the plasma column. Conversely, we have also proposed to stimulate, by external means, the excitation of the same modes in order to scatter the interacting α -particles and change their population at the edge of the plasma column. The role played by impurities in energy transport is under continued study. Impurities can provide a stabilizing influence for one of the leading agents of ion energy loss: the Ion Temperature Gradient (ITG) mode. Impurities dilute the concentration of fusing ions and their stabilizing effect is helped by the constraints imposed on the mode topology by the shaping of the plasma cross section. To balance this beneficial effect on transport there are drawbacks, however, one of which is the appearance of a class of instabilities driven by the combined presence of an ion temperature gradient and the impurity ions. These modes occur with parallel phase velocities intermediate between the thermal speeds of the ion species and, thus, are mass sensitive. This sensitivity has been proposed by us to explain the experimental observation of an "isotopic effect": the energy confinement time scales roughly with the square root of the primary ion mass (i.e., Hydrogen or Deuterium). These instabilities survive in the collisional regime (hence are active at the edge of the plasma, as well as in the interior) and are relatively insensitive to magnetic shear.

The achievement of ignition in a toroidal, magnetically confined plasma depends, in a significant way, on the temporal and spatial evolution of the plasma quantities. An important example is its dependence on the evolution of the toroidal plasma current. Significant advantage can be gained by maintaining a substantial ohmic heating up to (D-T) ignition, thereby avoiding the inefficiencies of externally injected heating and also the associated degradation of the plasma energy confinement. Using a numerical Tokamak Simulation Code (TSC) we have shown that such ohmic heating can be maintained in a compact, high field configuration (e.g., $R=1.3$ m, $a=0.48$ m, $b/a = 1.8$, $B_t \leq 13$ T, $I_p = 12$ MA), by properly programming the initial, current rise phase of the discharge. In this phase, the plasma current, toroidal magnetic field, plasma density, and plasma shape and position are simultaneously increased. The current rise can produce a strongly inhomogeneous toroidal electric field that produces strong ohmic heating away from the magnetic axis. At the same time, the current density profile can be maintained stable to tearing-type instabilities and the central value of the magnetic parameter q maintained above unity, or the $q < 1$ region small, until the central temperature rises enough to begin to stabilize $m=1$ modes. A small amount of injected heating during the current ramp is found to easily keep q_{min} above unity until well beyond ignition. These results were found using a modified version of the TSC, which solves the MHD evolution of the free boundary plasma and the flux surface transport within the plasma. We have also checked these results using a standard fixed boundary 1 1/2-D transport code, BALDUR. In addition, we have used the TSC code to study the vertical stability of the plasma and to evaluate the volt-second consumption of the ignition scenario.

We have been one of the major users of the TSC code over the past several years and, in a close collaboration with its authors (S. Jardin and N. Pomphrey at PPPL), have pioneered its use to study the current ramp phase and

D-T ignition. It is now used extensively for the ITER project and groups in Europe are now improving their transport codes to carry out similar studies. A drawback of the commonly used model for the effective electrical resistivity that contains the effects of trapped particles (the so-called neoclassical expression) is that, when the electron temperature profile is well behaved (e.g., Gaussian), the toroidal current density acquires a profile with features that we do not consider realistic. This is one of the motivations that have led us to extend the electron thermal energy balance equation and Ohm's law with the introduction of new terms that bring about asymmetry in the diffusion terms due to the temperature and current density gradient in the two equations. These new terms introduce a new effective thermal conductivity and a thermal viscous coupling. Their form is deduced from the symmetry properties of the matrix equation and the requirement that the resulting current and temperature profiles be spatially well-behaved. This description provides a natural framework for thermal energy inflow, the so-called "heat pinch." These equations are proposed as a natural set of transport equations for ohmic regimes, where current and temperature are strongly coupled. When auxiliary heating is applied, decoupling of the current and temperature leads naturally to a degradation in the energy confinement (e.g., the so-called L mode regime). These equations are presently being implemented in a transport code.

Plans

In the near term, we shall continue our broad based effort and give special attention to the nonlinear theory of $m=1$ modes using both analytical and numerical approaches, to varying aspects of pressure gradient driven microturbulence (plasma shaping, velocity shear, and impurities), and to cyclotron emission from fast fusion particles. These topics, which were introduced in the preceding paragraphs, remain of considerable interest as experiments continue in high temperature regimes and begin to address situations where significant concentrations of fusion reaction products occur. Both the $m=1$ and microturbulence studies have the eventual goal of producing "cures" (where available), whereby the disruptive effects of these phenomena can be minimized. Cyclotron emission at harmonics of the α -particle gyrofrequency, when successfully explained, can be used as a diagnostic tool to examine the properties of the fusion α -particle population (e.g., density, velocity, and space characteristics). Conversely, injection of radio waves at those frequencies could be used to "shape" the dynamics of this population. In the next year we hope to have a parallel processor version of the MHD gyrokinetic toroidal code running on the CM 5 machine at LANL and also on the parallel machine that is to be acquired by M.I.T., in close collaboration with groups at PPPL and NERSC.

Continued modelling of transport in present and advanced toroidal configurations is necessary in order to help identify the optimal path toward fully ignited experiments. The use of the free boundary code TSC enables our group to produce simulations with realistic physics. This effort is also being undertaken to provide theoretical support to existing experiments (i.e., JET, TFTR, Alcator C-MOD) at the same time as we test ignition scenarios.

Students

Doctoral students

N. Asherie, R. Betti, W. Daughton, M. Erba (Visiting), D. Ernst, R. Gatto, D. Gloss, G. Lapenta (Visiting), G. Penn, C. Riconda, T. Rider, G. Svolos.

Undergraduate students

E. Carpignano, D. Hijirida, H. Ohkawa, V. Portnoy.

Ph.D. Theses

R. Betti, "Kinetic Effects on Global Alfvén Waves," M.I.T., Department of Nuclear Engineering.

Y.K. Pu, "Trapped Electron Modes and Anomalous Electron Thermal Energy Transport," M.I.T., Department of Physics.

Other professional staff

P. Detragiache, S. Migliuolo, M. Nassi, B. Rogers (post-doctoral fellow), L. Sugiyama, L. Zakharov

Collaborations

This research group maintains fruitful collaborations with scientists at numerous institutions, both in the U.S. and abroad. Of note are recent and ongoing joint activities with B. Basu (Phillips Laboratory), J. Cottrell (JET), R. Wilson (PPL), E. Mazzucato (PPL), R. Aamodt and collaborators (Lodestar), J. Jacquinet (JET), W. Horton (University of Texas), S. Jardin, W. Park, and N. Pomphrey (Princeton University), F. Pegoraro (University of Turin), F. Porcelli (JET), A. K. Sen (Columbia University), R. Sydora (UCLA), M. McCoy, G. Kerbel, and others at LLNL.

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New York University

Courant Institute of Mathematical Sciences

Project

Advanced Toroidal Theory

Paul R. Garabedian

Funding

FY 90

\$75k

FY 91

\$75k

FY 92

\$75k

Purpose

A unified theory of tokamaks and stellarators is being developed within the framework of computational physics. The emphasis is on complications in the toroidal geometry of the configuration when three-dimensional effects are significant. The design of an optimal stellarator configuration is being undertaken in collaboration with laboratories in Germany, Japan and Australia.

Approach

Methods of high performance computing are applied to problems of equilibrium, stability and transport in plasma physics. A novel approach to transport is under investigation that stresses the role of quasineutrality. Improved analysis of equilibrium and stability is being made available through the application of a new spectral technique based on weak solutions of magnetostatic equations.

Progress

High performance computer codes have been developed to study equilibrium, stability and transport in tokamaks and stellarators with an emphasis on three-dimensional asymmetry. Bifurcated equilibria without axial symmetry are advanced as a mathematical model appropriate for the prediction of transport in tokamaks. Anomalous transport of electrons is explained as the effect of trapping in the wells and hills of the relatively small parallel component of an electrostatic field determined by quasineutrality. Conservation of momentum should not, in general, be expected to produce quasineutrality. Calculations have been performed to assess the merits of a standard configuration for ITER. The results are compared with the optimized design of a stellarator obtained by adding an $m=2$, $n=1$ sideband to a Heliac of large aspect ratio to reduce three-dimensional effects.

Quasineutrality plays a significant role in calculating transport. When the displacement current is significant, oscillations of the electric field account for transport. If the displacement current is negligible because of small Debye length, the equations $\text{div}(\mathbf{B})=0$, $\text{curl}(\mathbf{B})=\mathbf{J}$ for the magnetic field cannot be solved unless the compatibility requirement $\text{div}(\mathbf{J})=0$ of quasineutrality is imposed. In this context the argument that conservation of angular momentum implies ambipolarity in two dimensions is circular. Conservation of momentum in collisions is not the mechanism enforcing quasineutrality, and Ohm's law is an inadequate equation for the electric field. If quasineutrality is used to determine the electrostatic potential from a simplified form of Poisson's equation, then the electron confinement time comes into line with that of the ions and both agree with experimental data. This theory is substantiated by numerical evidence from high performance computations.

Plans

Further studies will be undertaken of confinement in tokamaks to validate our result that three-dimensional asymmetry and quasineutrality drive what is commonly viewed as anomalous transport. The two dimensional theory that purports to correlate conservation of angular momentum with ambipolarity will be examined. Perhaps it can be shown that the reasoning here is circular because quasineutrality is assumed in the construction of the magnetic field when the displacement current is to be neglected. To substantiate the mathematical analysis in this area we will undertake to develop new particle codes in collaboration with other efforts in high performance computing.

We are developing a unified theory of tokamaks and stellarators. This seems appropriate at a stage where there is interest in building a steady state advanced tokamak experiment. Comparisons will be made between tokamaks

and stellarators for such an undertaking. It may be possible to design a stellarator that could be constructed in a quite simple way to look much like a tokamak except that one important helical coil would be added to achieve steady operation. This study will involve both new code development and new theoretical concepts, and the Plasma Physics Laboratory at Kyoto University will participate in the project.

Students

Mark Taylor, Mathematics Thesis: "A High Performance Spectral Code for Nonlinear MHD Stability," (Ph.D., September 1992).

Other Professional Staff

Frances Bauer

Collaborations

Dr. H. Gardner, The Australian National University, Canberra, Australia.

Professor M. Wakatani, Plasma Physics Laboratory, Kyoto University, Kyoto, Japan.

Dr. Franz Herrnegger, Max-Planck Institute for Plasma Physics, Garching, Germany.

Publications

1. P. Garabedian, "Computational Models in Fusion Research," *SIAM Rev.* 31, 542-559, 1989.
2. F. Bauer and P. Garabedian, "Methods of Magnetohydrodynamics for the Design of Stellarators," *Mathematical Approaches in Hydrodynamics*, ed. T. Miloh, *SIAM*, 439-449, 1991.
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4. P. Garabedian and M. Taylor, "Tokamak Transport Driven by Quasi-Neutrality and Helical Asymmetry," *Nuclear Fusion* 32, 265-270, 1992.
5. M. Taylor, "A High Performance Spectral Code for Nonlinear MHD Stability," September 1992, DOE/ER/53223-193.

New York University

Courant Institute of Mathematical Sciences

Project

Plasma Properties
Harold Weitzner

Funding

FY 90	FY 91	FY 92
\$939k	\$880k	\$925k

Purpose

The group attempts to develop new theoretical models and employ existing theory in order to understand, interpret and predict the behavior of plasmas in fusion experiments. Since the group is presently composed of seven senior researchers with diverse interests and areas of activity, there is not a single purpose or approach. The group is unified by its commitment to the development of fusion plasma theory.

Approach and Progress

Edge plasma and divertor modelling.

A code has been developed and is one of the standards of comparison between plasma edge behavior and theoretical prediction.

Statistical data analysis advances.

The state-of-the-art statistical methods have been applied and in many cases extended in order to interpret and understand energy confinement scalings, time series of tokamak data, and profile determination of tokamak variables.

MHD numerical simulations.

Three-dimensional codes based on the dissipative magnetohydrodynamics model have been applied to explain the transition between confinement regimes in a tokamak. Correlations with experiments have been developed.

Ballooning mode instabilities.

The analysis of a particular class of instabilities in a plasma without flow has been extended to the case with flow. Flow can either act to stabilize or destabilize a system.

Effects of electrostatic potentials.

A theory has been developed and applied to an experiment at University of California, Los Angeles, where electrostatic effects have been claimed to occur. This work continues.

Transport in slightly non-equilibrium plasmas.

The effect of very high energy particles on energy and particle loss in a plasma has been studied and theories have been developed. It may be possible to induce the loss of burnt fuel in a reactor and to improve tokamak performance.

Alternate transport theories.

In view of the difficulties of predicting tokamak transport, alternate theories are being developed to compare with experiments. The theories include moment approximations, tests of moment approximations, and variant neo-classical theories. The first two are done and the third is in progress.

Lower hybrid wave propagation.

Waves at lower hybrid resonance are of some interest to drive currents in plasmas. A code has been prepared to calculate wave propagation in a plasma. Difficulties in the code, originating from the lower hybrid resonance, lead to study of a simpler model problem. The simpler case clarified the difficulties. The simpler case made apparent the difficulties and indicated what to expect in numerical calculations of the original problem.

Reconnection studies.

An outstanding problem continues on the nonlinear effects of certain plasma instabilities. Through analysis it has been shown that the instabilities do not necessarily destroy the confinement of a confined plasma.

Studies in chaos.

Determinate mechanical systems may exhibit what appears to be random behavior and large losses of energy or material. Theories of such effects are being tested, which may finally be applied to fusion plasmas.

Plans

All of the above projects have natural continuations. The following few are specifically noted. Edge plasma work will also start to develop kinetic models. The statistical modelling of time series and profiles is being applied to specific experiments. The transport predictions of loss of spent fuel will be tested by modelling in experiments. A variant neoclassical transport calculation for a tokamak will be carried out. Further magnetohydrodynamic plasma simulations will be performed. Chaotic dynamics and the effect on transport will be considered in model situations.

Professional Staff

B. Braams, C.S. Chang, E. Hameiri, K.S. Riedel, D.C. Stevens, H.R. Strauss and G.M. Zaslavsky

Post-Doctoral

D. Rayevski and A. Sidorenko

Students

M. Tippet (now gone) and J. Rennekamp

Collaborations

Extensive collaborations exist. In Europe, with JET, England; and Jülich and Max-Planck Institute for Plasma Physics, Germany. In the U.S. with the Massachusetts Institute of Technology, Princeton Plasma Physics Laboratory, Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, General Atomics, and the University of California at Los Angeles.

A Sample of Papers

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3. S.T. Chun and E. Hameiri, "Local Stability of Fluid Plasmas in the Presence of Flows," *Phys. Fluids B* **2**, 1745 (August 1990).
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New York University

Project

Superdiffusion

George M. Zaslavsky

Funding

FY 93

\$50k

Purpose

A new mechanism for anomalous transport caused by the chaotic destruction of magnetic surfaces will be studied for the toroidal geometry related to tokamaks. The mechanism is based on the possibility of occurrence of stochastic webs inside the separatrix loop when the conditions of the KAM theory are not valid. The project is to find the conditions for perturbation when the described phenomena does exist and to study the transport in such a situation.

Approach

Our approach to the development of the toroidal geometry magnetic surfaces destruction due to perturbations of the magnetic field is based on our previous results which were obtained for particle dynamics and for passive scalar dynamics in fluids. Particularly the conditions to get the stochastic web inside the separatrix loop were found for a fairly simple model. The similar approach will be used for the magnetic surfaces problem. The particle transport through the stochastic web is anomalous in general. Some special tools were developed in our previous publications to study such transport. They will be applied to the project too. The main feature of the transport examination is to observe flights and trappings due to symmetry properties of the phase space.

Progress

The work only has been started.

Plan

We expect to derive equations for the toroidal magnetic field with perturbation, to write the program for computer simulation, to study stability, chaos and web formation, and to proceed in investigation of transport.

Other Professional Staff

None

Collaborations

None

Students

Quing Lie, a doctoral student from the Department of Physics, takes part in the project.

Oak Ridge National Laboratory

Project

Fusion Theory and Computing

User Service Center:

D.B. Batchelor, B.A. Carreras, R.A. Dory, J-N. Leboeuf

Funding

Theory:

FY 90	FY 91	FY 92
\$2,332k	\$2,315k	\$2,469k

User Service Center:

FY 90	FY 91	FY 92
\$265k	\$250k	\$300k

Purpose

To develop theoretical and computational models of plasma behavior in fusion plasma confinement systems. The User Service Center provides access to the National Energy Research Supercomputing Center (NERSC) and local network support (workstation, personal computer).

Approach

Primary emphasis is on understanding confinement and its limitations in both tokamaks and alternative stellarator/torsatron confinement devices. Simplified physical models are developed and their implications are determined and compared with experimental data or with the results of computer simulation. On the basis of the comparisons, the models are refined as needed and used eventually to design new experiments and devices and to predict their behavior. Close collaboration is maintained with experimental groups at ORNL and throughout the world.

Progress

ORNL theorists have developed plasma dynamics computational models, including linear and nonlinear plasma instability simulation models. These have been used to test and validate turbulence models and methods for estimation of anomalous energy flow in the central and edge regions of confinement devices.

We have defined relations between plasma flows, rotation and collisional processes modified by the primary magnetic and electric fields. These are critically influenced by effects from turbulence phenomena. Since the instabilities and turbulence are influenced in turn by the flows and rotation, self-consistent theories are essential to unravel inter-connections of the physics. An ORNL theory, relating the transition in tokamaks from a low-confinement to a high confinement regime, is widely believed to contain the essential ingredients for an eventual full understanding of this important phenomenon.

We have developed plasma computational models to analyze the launching of rf waves and subsequent propagation into plasma systems and the resulting heating and drive of non-Ohmic currents, an essential ingredient of any future steady state or ultra-long-pulse tokamak reactor system. Antennas designed with collaboration from the group are in use or planned at several fusion laboratories throughout the world program.

We have developed new methods to provide closure of the moment hierarchy after a small number of moments, so that kinetic effects can be treated in fluid-like simulation models, both linearly and non-linearly.

We have established feasibility of conversion of fusion turbulence simulation codes to massively parallel computer systems and determined performance on several generations of supercomputers.

In the field of stellarator design, we have analyzed means by which externally imposed magnetic and electric fields can be used to tailor particle drift behavior. This yields reduced orbit losses for experiments and improves the underlying collisional transport. An essential ingredient for this purpose is analysis of means to generate beneficial electric fields and experiments to validate the theories.

We have defined and developed theories of fueling and heating techniques to adjust profiles and control energy and particle sources and modify loss factors. Energy and particle sources permit tailoring profiles of plasma density, pressure and current, which are controlling factors in overall confinement performance and define stable/unstable behavior.

The theoretical effort is directed toward studies which enhance the U.S. world programs in the stellarator field. It is also directed toward applications which improve U.S. tokamak initiatives (the new initiative TPX effort, and the Advanced Reactor Innovation and Evaluation Study) and the international ITER effort.

Plans

In the stellarator area, at a rate depending on funding, we hope to carry out joint research with CIEMAT, Madrid and Kharkov, USSR to develop and apply configuration optimization for stellarator systems. We hope to extend analysis of ATF confinement scaling by joint efforts with Garching and Kyoto/Nagoya groups, including efforts to obtain enough data to begin local analysis. We also hope to reawaken earlier work on optimizing ATF performance.

In stability and turbulence, we plan to extend analysis of ATF stability and will analyze fluctuation data obtained from ATF, TFTR and PBX-M tokamaks at Princeton and TEXT tokamak at Texas. We plan further development and application for ITER of nonlinear simulation codes capable of treating instability physics in the presence of fusion produced alpha particle populations. We will extend capabilities of hybrid fluid-particle models by further development of the Landau closure schemes and test reliability in non-linear regimes.

We expect to continue efforts to define and validate modules needed in using massively parallel computers as vehicles for carrying out the national Numerical Tokamak collaboration.

In kinetic areas, we will refine and extend the studies of the linkage between particle flows, rotations, radial electric fields, turbulence and anomalous transport of energy. We will refine analysis and detail results of theories of poloidal rotation, poloidal density variation and standing shock wave formation, and extend to finite aspect ratio the time-dependent models of tokamak plasma viscosity. We will also refine calculations of bootstrap currents to account properly for non-thermal particle populations.

The last elements have vital implications for improving methods to analyze the physics of the plasma edge region and the divertor/scrape-off layer.

We will extend and develop models of the effects of radio-frequency heating processes on direct particle losses in stellarator systems, including self-consistent electric field generation. We plan to add lower hybrid current drive models to the RAYS ray tracing model for electron cyclotron heating systems, and incorporate self-consistent plasma equilibria into the PICES full-wave model for rf heating. We will develop and apply improved antenna models to rf heating and current drive systems in TFTR, JET, DIII-D, Tore-Supra, etc., and complete a design for a folded wave-guide rf launcher. We will apply rf models to the US national project to develop a steady state tokamak and to the international ITER project. We expect to extend analysis of the effects of edge plasmas on rf heating and vice versa, and continue joint efforts with Princeton in integrating rf models and general plasma modeling codes.

We plan to propose replacement of the present User Service Center system with a Unix-based workstation network and eliminate the obsolescent Versatec printer based graphic output system.

Professional Staff

S.A. Attenberger, M.D. Carter, L.A. Charlton, N. Dominguez, R.C. Goldfinger, C.L. Hedrick, S.P. Hirshman, J.T. Hogan, W.A. Houlberg, E.F. Jaeger, D.K. Lee, V.E. Lynch, J.A. Rome, K-C. Shaing, D.A. Spong, D.C. Stallings and N.A. Uckan.

Collaborations

These include joint research with ITER, General Atomic, Princeton, Los Alamos and Sandia Laboratories, MIT, U. Wisconsin, UCLA, UCSD, JET, Caderache, Garching, Jflich, Madrid, Kharkov, Kyoto/Nagoya, NIFS.

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Old Dominion University

Project

Wave Propagation in Tokamaks

Linda Vahala

Funding

FY 90	FY 91	FY 92
\$20.0k	\$20.0k	\$23.5k

Purpose

The long range goal of our project is to understand the effects of density and magnetic fluctuations on wave propagation in tokamaks. With this information, one may then be able to design appropriate diagnostics to detect internal magnetic fluctuation. This is of significance in understanding tokamak transport—especially in the DT phase of tokamak operation when internal magnetic fluctuation levels may lead to anomalous transport losses of energetic particles. We also determine the effects of fluctuations on using lower hybrid waves for heating, toroidal current sustainment, and current profile shaping.

Approach

We have been studying the effects of density and magnetic fluctuations on the propagation of lower hybrid (LH) waves in toroidal geometry. The ray trajectory is followed under the geometric optics approximation (with appropriate absorption mechanisms) while the effects of the fluctuations are determined from the solution of a wave kinetic equation. This wave equations is then solved by Monte Carlo techniques. The electron power density deposition profiles determined from the solution of the wave kinetic equation are then compared to experimental hard X-ray data measurements.

Progress

We have proposed a mode-conversion electromagnetic scattering diagnostic that should be able to distinguish between magnetic and density fluctuations, even when the level of magnetic fluctuations are orders of magnitude below that of the density fluctuations. In particular, we have considered the mode conversion process of ordinary (O) $\rightarrow$ extraordinary (X) mode for microwave propagation perpendicular to the magnetic field. For perpendicular propagation, the O-mode is linearly polarized along B, while the X-mode is elliptically polarized perpendicular to B. Since density fluctuations are scalar in form, they cannot participate in this O $\rightarrow$ X mode conversion. Hence, any scattered X-mode detected by the receiver antenna can only come from tensorial magnetic fluctuations localized within the scattering volume. We have considered nonideal effects such as finite angular microwave beam width, wave launch polarization mismatch at the plasma edge, antenna polarization resolution limitations and conclude that these effects will not mask the magnetic fluctuations signal.

Recent studies of lower hybrid (LH) heating and current drive have used a one-dimensional radial transport code, coupled to a Fokker-Planck toroidal ray tracing code. These computer models examine the containment of the suprathermal electrons produced by the LH current drive as well as the transport properties of the bulk electrons. Unfortunately, it is computationally prohibitive to incorporate into these codes the effects of scattering from fluctuations—even though it is well known that fluctuations can play a major role in LH wave propagation, accessibility and absorption. We have been considering the effects, on LH wave propagation, of both density and magnetic fluctuations. The resulting wave kinetic equation is solved by Monte Carlo procedures and we have found that even for magnetic/density fluctuations levels on the order of 10^{-4} there can be significant magnetic fluctuations effects on the wave power deposition into the plasma electrons. Moreover, this effect can be quite pronounced if the magnetic fluctuation spectrum is peaked within the plasma. We have been able to interpret the hard X-ray profile data from the JT-60 tokamak as giving direct information on the fluctuations in the plasma. For Alcator C-Mod parameters, we find that similar hard X-ray data could give some information on the magnetic fluctuation spectrum.

Plans

Further studies of the Monte Carlo solutions for LH wave propagation will be performed that take into account the LH wave beam width and its spectrum in launch parallel refractive index. We will also develop a multidimen-

sional WKB approach for wave propagation in tokamaks that will incorporate both ray information and wave diffraction effects perpendicular to the ray trajectory. This will be applied to LH wave propagation as well as O and X mode propagation. Effects of density and magnetic fluctuations will also be included.

Other Professional Staff

None

Collaborations

The work on O-X mode conversion was performed with Dr. Norton Bretz (PPPL) who is in the process of putting this diagnostic onto TFTR. The LH wave propagation problem is being done in collaboration with Dr. Paul Bonoli (MIT).

Students

None

Major Recent Publications

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2. "Electromagnetic Scattering from Magnetic Fluctuations in Tokamaks," L. Vahala, G. Vahala, and N. Bretz, *Phys. Fluids* **B4**, 619 (1992).
3. "Detection of Internal Magnetic Fluctuations by Electromagnetic Scattering in Tokamaks," L. Vahala, G. Vahala, and N. Bretz, in *Radio Frequency Power in Plasmas*, AIP Conf., Proc. vol. 244, ed D. Batchelor, New York, NY (1992), p. 389.
4. "Effect of Fluctuations on Lower Hybrid Power Deposition and Hard X-ray Detection," G. Vahala, L. Vahala, and P.T. Bonoli, *Rev. Sci. Instruments* (to appear, 1992).
5. "Effect of Magnetic and Density Fluctuations on the Propagation of Lower Hybrid Waves in Tokamaks," G. Vahala, L. Vahala, and P.T. Bonoli, *Phys. Fluids B* (to appear, 1992).

Princeton Plasma Physics Laboratory

Project

Theoretical Plasma Physics for Fusion

R.B. White, Head, Theory Division

Liu Chen, Deputy Head, Theory Division

Funding

FY 91

\$2.60M

FY 92

\$2.65M

FY 93

\$2.75M

Purpose

The purpose of the fusion program is to insure the expedient and economical development of the physics knowledge that is required to achieve economic fusion reactors. The theoretical program contributes to the development of the required body of knowledge by determining the implications for fusion of the laws of physics and by involvement in the suggestion, design, and interpretation of experiments. The fundamental laws that determine the behavior of fusion-relevant plasmas, such as Maxwell's equations and the equations of classical mechanics, are known. Since even these simple nonlinear equations produce very complex and unexpected behavior, much fundamental theoretical research is necessary to understand the basic mechanisms involved in toroidal confinement. Much of the advance of the fusion program has been in the appreciation of the implications of these laws and not just in the development of empirical rules for scaling. Recent improvements in tokamak operational reproducibility and in diagnostic techniques has made possible realistic fitting of experimental results to theoretical models, providing increased understanding and the development of better confinement techniques. The theory group maintains a broad spectrum of effort, ranging from long range work to understand basic nonlinear processes responsible for both anomalous losses and more rapid large scale behavior to phenomenological studies undertaken to deduce, from the experimental data, the nature of the relevant mechanisms producing anomalous transport. At the same time it has embarked on the implementation of advanced computational techniques, including gyro-kinetic modelling and 3-D MHD programs, to maintain its position of leadership in the program. Alpha particle physics and high- β optimization are also important elements.

Approach

Detailed theoretical calculations are required to interpret and extrapolate experimental observations. Their implementation is permitting less conservative experimental design and providing guidance to the experimental program. The theoretical program has been the origin of a large fraction of the innovations and developments in the fusion effort. Innovations are impossible to predict, but they can be expected only if the theoretical program continues to provide an appropriate environment for creativity. The work in the Princeton Plasma Physics Laboratory (PPPL) theory group is conducted through a collection of Working Groups, made up of staff members from both the theoretical department and the experimental programs. The activities are coordinated by a Theory Steering Committee, a member of which is active in each working group. The membership of these groups is not static, with individuals moving from one to another as the needs of the groups and the interests of the individuals change. Major emphasis of all of the groups is centered on improving our ability to interpret the results of present experiments and providing input to the ITER and TPX design teams. At present, there are groups centered on Transport, Gyrokinetics, kinetic 3D-MHD, α -Particle Physics, Lower Hybrid Current Drive (for PBX), Ideal MHD (with a group identified with PBX, one with Post-TFTR Studies, and one with ARIES), Resistive MHD, 3-D MHD Equilibrium, and Edge Plasmas.

Progress

During the past year, fusion research advanced in all areas of theoretical activity including transport studies, α -particle physics, optimization of plasma shape and current and pressure profiles to obtain reliable tokamak operation at high- β and low q , 3-dimensional behavior of tokamaks associated with the imposition of error fields and magnetic islands associated with tearing modes, and TAE modes. Much work was done for design and optimization of future tokamaks. Highlights include:

1. Development of the capability to better understand the long mean-free-path physics responsible for the primary transport trends observed in major tokamaks has been motivated by the observation that these kinetic prop-

erties are more relevant to the actual experiments than the short mean free path properties emphasized in the fluid models that are being employed elsewhere. For example, results from new fluctuation measurements (BES etc.) and the empirical observations of Bohm-like transport scaling, have highlighted the importance of long wavelength behavior. Calculations with the most comprehensive existent kinetic toroidal eigenmode codes have been carried out and have indeed yielded long wavelength trapped ion mode structures extending over many rational surfaces.

2. A 3-dimensional toroidal electrostatic gyrokinetic code has been developed and applied. It predicts much lower transport levels than those obtained from analytic fluid turbulence estimates and in reasonable agreement with experimental observation. This code has been implemented on a Connection Machine with a significant improvement in speed over that obtained on the Cray II.

3. Continued progress has been made in the understanding of α -particle physics. It has been shown that α particles can stabilize or destabilize global modes, possibly leading to resonant α loss, and also modifying transport. These particles could provide a sawtooth-free tokamak. We have made significant progress in our understanding of TAE modes, which were originally discovered at PPPL, and have developed the NOVA-K code for study of the linear properties of these modes. This code has been used in ITER and BPX design studies. Work is in progress to develop a fully 3-dimensional hybrid kinetic-fluid code to investigate the saturation of these modes. Rapid estimation of alpha particle loss induced by toroidal field ripple is provided by the code RIPLoS.

4. The LSC current drive code has been coupled to the TSC equilibrium and transport code. It will be benchmarked on the PBX tokamak and be used to evaluate current drive experiments to enhance stability of PBX-M and the TPX device.

5. PPPL has continued its MHD studies aimed at obtaining high- β by optimizing the configuration shaping and current and pressure profiles. It has contributed extensively to device design and data interpretation for many tokamaks including PBX-M, TFTR, CMOD, ASDEX-U, TCV, ITER, and BPX, and has led advanced reactor studies (ARIES) in its investigations.

6. Two 3-dimensional MHD codes, PIES and MH3D, have contributed to our ability to obtain disruption avoidance and control. The PIES code has provided guidance to the BPX design team on the effects of field errors and error compensation coils. The MH3D code has followed the nonlinear evolution of field perturbations which can contribute to active feedback control.

7. An effort has been started to develop an understanding of plasmas outside the last flux surface. This is part of an effort to contribute to the problem of power and particle handling. We are developing a new Fokker-Planck code for modeling behavior in the divertor region with particular attention to the sheath near the divertor plate.

Plans

1. Transport.

Application of the computational tools to experimental measurements in order to understand anomalous transport in tokamaks will continue. This should provide further guidance concerning the need for incorporating global properties of the unstable modes in the formulation of analytical models for transport. A 2-dimensional low- n kinetic stability code will be improved to complement the present high- n code that utilizes the ballooning formalism.

2. Gyrokinetics and Kinetic 3D-MHD Groups.

Application of the 3-dimensional electrostatic gyrokinetic code to the simulation of toroidal ion temperature gradient (η_i) modes and other instabilities will continue, as will work on the implementation of a similar electromagnetic code. Coupling of the gyrokinetic model into the 3-dimensional MHD initial value code will provide key kinetic physics effects necessary for realistic studies of the nonlinear saturation of TAE as well as kinetic ballooning modes.

3. α -Particle Physics

Calculations of the localization of lost α -particles will be made. Further work will be done on sawtooth modification in conjunction with TFTR experiments. Analytical and computational work on TAE and kinetic ballooning mode damping and threshold will be carried out to provide detailed comparison with experiment. With the completion of the MHD-gyrokinetic code, the full nonlinear evolution of coupled hot particle—fluid system will be investigated.

4. Lower Hybrid Current Drive.

The integration of the LSC current drive code into the TSC transport code will provide the necessary tools for interpretation and guidance of PBX-M profile shaping experiments. This code will also be used for studies for ITER, ARIES, and other tokamaks.

5. MHD.

The TSC code will continue to be used to define plasma control strategies and the PEST and CAMINO codes will provide information about ideal instabilities in PBX-M and TFTR as well as ITER, ARIES, and TPX. The MH3D and NOVA-W codes will continue to be used for studies of resistive modes in tokamaks. Application of the PIES code to

the behavior of plasmas with error fields will continue as part of an effort to provide disruption control. This code will be applied to study ATF, TJ-II, W7X, and LHQ stellarator equilibria, with emphasis on comparisons with other codes and the nature of magnetic islands in nonsymmetric configurations. The STEP stability code will be used to provide a calibration of the 3-dimensional MHD stability code TERPSICHOE.

6. Edge Plasmas.

The development of tools for studying plasmas in the divertor region will continue. Research in edge plasmas is concentrated on the study of divertors. One major project is a comprehensive rewriting of the neutrals code, DEGAS. This solves for the transport of neutral atoms and molecules and includes the major atomic processes relevant to the divertor region. The new code will be easier to extend and will be more efficient to couple to the fluids codes which describe the behavior of the plasma. With DEGAS coupled to a suitable fluid code, we will get a complete picture of the behavior of a divertor and be able to assess divertor designs reliably. The other important effort we are undertaking is kinetic modeling of the sheath region, where fluid theory breaks down.

7. Code Development Projects.

Many major codes are being developed at PPPL or are currently being improved and extended. Improvements are planned for FULL, GEM1, NOVA-K, TSC, MH3D-K, and many others. A description of these codes can be found in the Survey of Physics Computer Codes published by PPPL, December 1991.

Collaborations

Not only does plasma theory provide much of the physics basis for each of the experimental programs of the Laboratory, but individual theorists have close collaborations with each of the programs. There is close cooperation between the individual theorists and physicists in other institutions both in the United States and throughout the world.

1. TFTR:

Theorists are closely involved in the experimental program on TFTR, helping formulate some of the actual experiments and providing analysis and interpretation of the data. Close cooperation is maintained in the areas of transport where microinstability-based transport models are being tested, in MHD where studies of profile effects are being made to provide interpretation of sawtooth and fluctuation observations, in the areas of high energy particle loss due to field ripple and MHD fluctuations, the excitation of MHD modes by high energy particles, and in sawtooth stabilization by high energy particles.

2. PBX-M:

The PBX-M device is a good example of close interaction between theory and experiment. The device design was based on theoretical ideas and the purpose was to test novel confinement techniques. Although the machine did not operate for two years because of budgetary constraints, theoretical studies associated with it have continued. These include work with the TSC code to optimize control strategies, application of the CAMINO and PEST codes to determine optimum plasma profiles to get into second stability, and application of the LSC code to guide current drive efforts. With the start up of renewed experiments, the collaboration between theory and experiment will be more exciting than ever.

3. ITER:

The theory group has contributed to all physics phases of the ITER design study, both in providing tools such as TSC, PEST, RIPLOS, NOVA-K, and support to workers in other areas and in carrying out specific studies for the program. With the importance of this device, the group will continue this work and increase these activities.

4. ARIES:

The physics part of the ARIES reactor studies program are being led by PPPL. This effort is taken seriously in the planning of the group's program. Many of the advanced tokamak ideas that originated in our group in conjunction with the ARIES studies are now being proposed for the post-TFTR device.

5. TPX:

We have made major contributions to the design and analysis of the BPX and SSAT devices. The techniques and tools that were developed for this work are being applied to the determination of what we should be doing in the post-TFTR era.

6. TTF:

We are providing leadership and support to the Transport Task Force. We have provided a member of the Steering Committee and the leader of the High Energy Particle Studies working group, and are contributing to the various parts of the work, including studies of the kinetic analysis of long wavelength structures and sheared flow effects on microturbulence, transport scaling relationships, and active control.

7. Numerical Tokamak.

The gyrokinetic basis for the numerical tokamak project was developed at PPPL. We have worked closely with the community this past year to help organize the community-wide numerical tokamak project, which we are proposing to be funded jointly by HPCC (computers) and OFE (physics).

8. Collaboration

The theory program is maintaining its close collaborations with theorists in major fusion programs in other parts of the United States, Europe, Japan, and Russia. The theory group is universally recognized for its outside contributions and not just for its support of the Princeton experiments. This international collaboration must be supported both to provide help to the world program and to enrich and stimulate ourselves.

9. Code Support

A large number of codes that have been developed in the Theory Division, including PEST, TSC, STEP, ORBIT, WKB, EQUIL, CAMINO, LSD, MH3D, and PIES, are being used extensively outside of PPPL. The Division plays an important, but time consuming role, in the development and maintenance of these codes, and in training and assisting users outside the laboratory.

10. Education

The Theory Division contributes strongly to the training of physicists in plasma physics through teaching graduate courses, providing guidance to second year students in theory projects, and advising thesis students.

Recent Publications

10/91-12/91

- M. Artun and W.M. Tang, "Gyrokinetic Analysis of Ion Temperature Gradient Modes in the Presence of Sheared Flows," PPPL Report 2810, Phys. Fluids
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- H. Biglari, E. Zonca, L. Chen, "On Resonant Destabilization of Toroidal Alfvén Eigenmodes by Circulating and Trapped Energetic Ions/Alpha Particles in Tokamaks," PPPL Report 2789
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- A.H. Reiman and D.A. Monticello, "Three Dimensional Tokamak Equilibria in the Presence of Resonant Field Errors," PPPL Report 2818, Nucl. Fusion
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Science Applications International Corporation

Project

3-D ICRF Antenna Modeling and Simulation

W. Grossmann, Y. L. Ho and S. Riyopoulos

Funding

FY90	FY91	FY92
\$25k	\$90k	\$150k

Purpose

The purpose of this project is to support the development of advanced ICRF heating for fusion plasmas. The Science Applications International Corporation (SAIC) is developing advanced simulation tools for modeling Ion Cyclotron Radio Frequency (ICRF) heating in tokamak fusion plasmas. The emphasis is placed on modeling the launching antenna structure and the rf coupling to the nearby plasma. A realistic, 3-D representation of the antenna environment, including the supporting enclosure, is essential for our goal. In addition, we are developing detailed physical models of rf driven sheath formation to understand the complex nature of the plasma in the vicinity of ICRF antenna Faraday bars. The sheath studies are leading to an appropriate set of boundary conditions for the full 3-D simulation code that will allow the micro-scale sheath physics to be included in the global scale antenna simulation.

Approach

Theoretical modeling and simulation of ICRF heating and current drive has traditionally been decomposed in two parts: one that deals primarily with the wave launching and antenna coupling to the plasma, and one that concentrates on the wave absorption and the related effects taking place in the plasma core. Power coupling to the plasma depends on the antenna launched spectrum which in turn is affected by the plasma response. Our three dimensional fully electromagnetic simulation code, ARGUS, is used to address the issue of the antenna-plasma coupling, without preliminary assumptions about the current density distribution on the antenna strap. The poloidal and toroidal rf spectrum is self-consistently determined, including the effects of the plasma feedback. The plasma-vacuum interface is currently represented by a surface impedance deduced from 2-D code results. The ARGUS code allows a fairly detailed representation of the 3-D antenna enclosure including current straps, Faraday shields, and protection tiles. In addition to addressing the antenna plasma coupling on the macroscopic level, we also investigate the microscopic scale physics. Time dependent simulations of rf driven sheath formation around 2-D surface plasma interfaces have been carried out using SAIC's two-dimensional MASK code in the electrostatic regime. The scaling of the sheath parameters is crucial for the estimate of the energetic ion production and the consequential impurity release from sputtering on the metal surfaces of such structures as Faraday shields. Significant deviations from 1-D scaling, particularly in the lower edge density limits, are observed numerically and addressed analytically.

Progress

The earliest benchmarking of ARGUS, applied to a model antenna geometrically similar to the TFTR design, yielded excellent agreement with the experimentally determined vacuum characteristics obtained in model experiments at the University of Wisconsin. Our antenna performance studies were continued last year where ARGUS was used to analyze the current strap phase velocity and the self and mutual inductances of the ORNL TFTR Bay 1 antenna. The results indicated a phase velocity between 0.57c and 0.60c, depending on the width of the test pulse, versus the experimentally determined 0.66 centimeters. The numerically deduced self inductance $L = 2.4 \times 10^{-7}$ Henrys and mutual inductance $M = 4.9 \times 10^{-7}$ Henrys are also in reasonable agreement with their experimental values. More recently we have developed a new frequency domain solver for ARGUS, including a self-consistent plasma response, by modeling the vacuum plasma boundary in terms of the plasma surface impedance. This development allows for the first time a realistic 3-D modeling of the self-consistent strap current and wall image current distribution in the presence of plasma. Benchmarking simulations are currently under way and the preliminary comparisons are positive.

Our last year's work on rf driven sheath physics concentrated on 2-D particle simulations around a Faraday bar cross-section, using MASK. The emerging picture of 2-D Faraday shield sheath structure is quite distinct from

the 1-D picture. Two dimensional time-averaged plasma potential cells and circulation vortices have been observed. Analytic estimates have also demonstrated that the sheath thickness Λ is determined by the bar cross-section d and the inclination q of the magnetic field. A critical angle q_c was found, signifying a transition from a magnetic field aligned to a cross-field parapotential ion flow. The 1-D limit applies when $\Lambda/d \ll 1$ and $q > q_c$. Increased ion influx relative to the 1-D predictions has been observed. This effect is attributed to the $\mathbf{E} \times \mathbf{B}$ ion drift from the pre-sheath into the sheath at speed exceeding the ion sound speed.

Plans

During the upcoming year we expect to continue the ARGUS antenna simulations. Our immediate goals are to improve the code speed by using a conjugate gradient solver, and to continue code benchmarking with curved vacuum-plasma interfaces by adopting a radiative boundary condition developed by D. Batchelor of ORNL. Finally we will work with ORNL to integrate ARGUS in the ORNL antenna design, analysis and evaluation system. In the sheath structure effort, we expect that extended time simulations using MASK will resolve the issue of steady-state sheath behavior, including possible relaxation to macro-structures. Also, starting from the microscopic sheath properties we hope to be able to: (i) evaluate the macroscopic sheath effects on the fast wave in terms of power absorption, reflection and harmonic generation; and (ii) obtain boundary conditions to be used for the metal plasma interfaces in the ARGUS simulations.

Publications

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Science Applications International Corporation

Project

Transport and Dynamics in Toroidal Fusion Systems

Dalton D. Schnack

Funding

FY90	FY91	FY92
\$250k	\$250k	\$200k

Purpose

The purpose of this project is threefold: (1) to study the long-wavelength, low-frequency, nonlinear dynamics inherent in fusion plasmas, and determine the effect of these motions on thermal and mass transport; (2) to develop and support numerical algorithms appropriate for such studies; and, (3) to develop new, advanced numerical algorithms for the spatial representation of the geometric details of fusion experiments in toroidal geometry.

Approach

Our approach has been to apply advanced methods of numerical simulation to mathematical models of fusion plasmas. A particularly appropriate model for the description of low frequency, long wavelength dynamics is resistive magnetohydrodynamics (MHD). This model consists of eight simultaneous partial differential equations in three space coordinates and time for the three components of the magnetic field, the three components of the velocity, the pressure, and the mass density. The temperature is related to the pressure and mass density by an equation of state. These equations are solved numerically as an initial/boundary-value problem to determine the long time-scale, nonlinear dynamics of driven fusion plasmas. The most powerful available supercomputers are required for this task.

Progress

The approach described above has required that we derive new algorithms for the numerical integration of partial differential equations, and implement them in efficient computer codes. The integration of the MHD equations is difficult because of the wide variety of space- and time-scales that can occur in their solutions. We have employed pseudo-spectral methods with the fast Fourier transform (FFT) for certain spatial representations, and have developed an efficient semi-implicit algorithm for time integration. Both cylindrical and toroidal geometries have been used. Computer codes based on these techniques have become mature, and are in production use at several US laboratories and universities.

Over the past ten years, we have applied these codes to detailed studies of the dynamo effect and its consequences in a cylindrical model of the Reversed-Field Pinch (RFP), a type of toroidal fusion device. The dynamo in the RFP causes the magnetic field profiles in this device to be sustained much longer than would be expected from the effects of plasma resistance. As a result of this research, the principle plasma dynamics that is responsible for the RFP dynamo have been elucidated, and the effect of these motions on confinement have been estimated. A fairly complete understanding of the operation of RFP devices has been obtained.

Because of our long involvement in RFP research, we have become a leader in the international RFP program. We have provided theoretical and computational support to the RFX experiment at Padua, Italy, to the Royal Institute of Technology in Stockholm, Sweden, and to Culham Laboratory on the UK.

A present requirement for tokamaks is to develop numerical models with which to make quantitatively accurate estimates of the performance of real devices. This requires that the details of the geometry, such as limiters, divertors, and coils, be represented accurately. An efficient representation also requires that the resolution of the finite spatial mesh fit not only to the static geometry, but also adjust in response to plasma dynamics. We have begun to apply the method of unstructured, adaptive meshes to these problems. These techniques have been extremely successful in applied fluid dynamics. One obstacle in their direct application to fusion devices is the proper mathematical representation of the electromagnetic field on these meshes. This has become one of our primary research topics.

Plans

We will continue our studies of the effect of the RFP dynamo on thermal confinement. We will determine the effect of aspect ratio and relative plasma current on the relevant dynamics. We will continue to maintain and refine the computer codes that have been developed under this program. We will continue to provide the community with first class computational support. We will continue our active involvement in the international RFP community. Our major effort will be to adapt algorithms for unstructured, adaptive meshes to the description of real toroidal fusion devices.

Students

No students are directly supported under this grant. However, E.J. Zita and C. Sovenic of the University of Wisconsin, and X-H. Wang of Columbia University, are using our computational tools and collaborating with our staff during their doctoral research.

Other Professional Staff

Dr. Dalton D. Schnack, Dr. Yung-Lung Ho, and Dr. Zoran Mikić

Collaborations

(1) University of Wisconsin: "Feedback Control of Dynamo Fluctuations; Current Drive by DC-Helicity Injection." (2) Columbia University: "Effect of a Resistive Shell on Tokamak Disruptions." (3) Los Alamos National Laboratory: "Advanced Computational Methods for Toroidal Fusion Devices." (4) Royal Institute of Technology, Stockholm, Sweden: "Effect of Aspect Ratio on Resistive Wall Modes in the RFP." (5) CNR, Padua, Italy: "General Computational and Theoretical Collaborations."

Recent Publications

D.D. Schnack, "Computational Methods for Long Time-Scale, Dissipative Magnetohydrodynamics," in *Theory of Fusion Plasmas*, (Proc. Int. School of Plasma Physics, Varenna, 1992) (to be published) (1992).

G.G. Craddock, Phys. Fluids B 3, 316 (1991).

Y-L. Ho, Nucl. Fusion 31, 341 (1991).

Y-L. Ho and G.G. Craddock, Phys. Fluids B 3, 721 (1991).

Y-L. Ho and S.C. Prager, Phys. Fluids B 3, 3099 (1991).

D.D. Schnack, "Magnetohydrodynamic Theory of the Reversed-Field Pinch Dynamo," in *Physics of Alternative Magnetic Confinement Schemes* (Proc. Int. School of Plasma Physics, Varenna, 1991) p. 631 (1991).

D.D. Schnack and S. Ortolani, Nucl. Fusion 30, 277 (1990).

STI Optronics

Project

Theory of Field-Reversed Configurations

L.C. Steinhauer

Funding

FY 90

\$150k

FY 91

\$125k

FY 92

\$60k

Purpose

The purpose is to explore all aspects of the physics of field reversed configurations (FRC). This includes the topics of FRC formation in a theta pinch, FRC equilibria, macrostability (especially the tilting instability), transport mechanism, and global confinement properties. The research has been in support of the ongoing FRC experimental program at STI Optronics on the TRX-1, TRX-2, and LSX facilities. The long-range goal is to develop the FRC as a viable fusion energy concept.

Approach

FRC theory research is complicated by the fact that FRCs have very high β (plasma pressure/magnetic pressure) with a nearly magnetic field free region in the heart of the plasma. Consequently many methods useful for other magnetic confinement schemes do not apply to FRCs. The approach then has been to develop new analytical and quasi-analytical models or to modify old methods to apply to FRCs. A second approach is the development of global models of FRC behavior (e.g., formation or confinement) to serve as interpretive tools to infer the behavior observed in experiments for which diagnostic information is limited. Finally, an important practical "approach" used to leverage the limited resources available for the program has been to establish collaborations with overseas scientists on topics of FRC research.

Progress

"Profile consistency" in FRC experiments has been found using interpretive modelling, in which the toroidal current profile is hollow (i.e., has a minimum in the neighborhood of the magnetic axis). The cause of the profile consistency has been proposed to be small-scale ballooning-like modes which regulate the profile. This is the subject of continued research.

A gyroviscous stability theory, a modification on the standard ideal MHD treatment, has successfully explained the appearance of stable tilt behavior in nearly all experimental FRCs to date. The theory determines a marginal stability condition within which ion kinetic effects are strong enough to suppress the tilting mode.

Electron thermal loss along magnetic field lines in the edge layers of experimental FRCs was examined using interpretive modelling. The thermal loss was found to be convective (similar to that in magnetic mirror plasmas) rather than conductive. Conductive behavior was expected because of the relatively high collisionality of FRCs. The dominance of the convective mechanism means that electron thermal loss rates will always be comparable to the convective loss of ions.

The flow of plasma in the edge layer is being examined using anisotropic fluid models that distinguish between the "parallel" and "perpendicular" (relative to the magnetic field lines) temperatures, as well as additional dimensions of anisotropy. Preliminary results indicate that the low magnetic fields and sharp magnetic field gradients near the x-points (one at each end of the FRC) introduce inertial and electrostatic effects which significantly throttle the loss of plasma along the edge layer.

Plans

In view of changes in emphasis that have resulted from budgetary constraints on the Fusion Energy program, the future direction of this project will have two objectives. The first is to study FRC physics for the application of tokamak refueling by FRC injection. The second is a low-level of basic FRC research to facilitate monitoring active FRC experimental and theoretical programs overseas in Japan and Russia.

Other Professional Staff

R.D. Milroy

Collaborations

This project includes collaborations on three topics. A collaboration has been in progress for five years with A. Ishida (Niigata University) on the stability of FRCs. This year, new collaborations were started with R.A. Clemente (Campinas University, Brazil) on FRC edge flow physics, and with A. Ishida and N.A. Krall (Krall Associates) on microstability and transport in FRCs.

Students

None.

Major Recent Publications

1. L.C. Steinhauer and A. Ishida, "Gyroviscous Stability Theory with Application to the Internal Tilt Mode of a Field-Reversed Configuration," *Phys. Fluids B* 2, 2422 (1990).
2. L.C. Steinhauer, "A Nearly One-and-One-Half-Dimensional Confinement Model Field-Reversed Configurations," *Phys. Fluids B* 2, 2679 (1990).
3. L.C. Steinhauer, "Improved Analytic Equilibrium for a Field Reversed Configuration," *Phys. Fluids B* 2, 3081 (1990).
4. A. Ishida, L.C. Steinhauer, and H.L. Berk, *Phys. Fluids B* 3, 1552 (1991).
5. D.C. Barnes and R.D. Milroy, "Stabilization of the Field-Reversed Configuration (FRC) Tilt Instability with Energetic Ion Beams," *Phys. Fluids B* 3, 2609 (1991).
6. L.C. Steinhauer and A. Ishida, "Profile Consistency in Equilibria of Field-Reversed Configurations," *Phys. Fluids B* 4, 645 (1992).
7. A. Ishida, R. Kanno, and L.C. Steinhauer, "Tilt Stability of a Gyroviscous Field-Reversed Configuration with Realistic Equilibria," *Phys. Fluids B* 4, 1280 (1992).
8. H. Momota, A. Ishida, Y. Kihzaki, G.H. Miley, S. Ohi, M. Ohnishi, K. Sato, L.C. Steinhauer, Y. Tomita, and M. Tuszewski, "Conceptual Design of the D-³He Reactor Artemis," *Fusion Technol.* 21, 2307 (1992).
9. L.C. Steinhauer, "Electron Thermal Confinement in the Edge Plasma of a Field-Reversed Configuration," *Phys. Fluids B* 4, December issue, in press (1992).

University of California–Berkeley

Project

Research in Theory and Simulation of Bounded Plasmas

Charles K. Birdsall and Edward Morse

Funding

FY91	FY92	FY93
\$120k	\$120k	\$120k

Purpose

Our objective is to create kinetic theory, followed by particle and fluid simulations, applied to bounded plasmas, and plasma boundaries. We are a small group, so we work on models that complement the programmatic efforts leading to a numerical tokamak at the national laboratories. Our strong point is developing new ideas for plasma-edge models, trying them out, and applying them to pressing problems, such as the large E_r in the DIII-D tokamak edge.

Approach

One result has been our development of bounded plasma particle codes (plasma device series, PD) including collisions with neutrals, real electrodes, arbitrary magnetization, with connections to external circuits and sources. These codes (1d3v, PIC-MCC) have been presented at many meetings and many short courses and are now being used worldwide. The newer versions (2d, 3v in x, y and r, z, some implicit, some with orbit averaging) are in use by us and nearing release. Our PD series may be setting word standards for desk-top computer interactive real-time plasma simulations.

Progress

Currently we are deeply into two models:

1. three region, core-separatrix-scape-off layer, applied to the ∇T_e end loss instability and turbulence;
2. merging core and edge codes [e.g., gyrokinetic core (or core edge) with fully kinetic bounded edge].

Core-Separatrix-Scapeoff Layer (Dr. X. Xu)

This is a remarkable model as it incorporates three plasma regions: the edge of the tokamak core, the separatrix, the scape-off layer and two divertor plates. The initial simulation is being done with fluids, with particles to follow (actually, a hybrid). The model theory was presented at the June IAEA Technical Committee Meeting in Montreal, and the initial simulations plus divertor bias results were presented at the September IAEA Technical Committee Meeting, also in Montreal.

The plasma straddles the separatrix. $\mathbf{B}$ is along z , winding around the toroid. The theory for the ∇T_e end loss instability has dispersion relation (12), which for DIII-D parameters produces a growth rate of $\omega_i < 10^6/\text{sec}$ for collisional electrons (but, the instability is essentially insensitive to the electron collision frequency). The initial results show saturated turbulence which is clear evidence of the expected mode penetration into the core edge, indicating an inverse cascade of wave energy (toward long wavelengths). The saturated amplitudes are somewhat above and the flux levels are well below those of the simple mixing-length estimates. Lastly it is shown that DC biasing of the divertor plates tends to stabilize the ∇T_e mode at long wavelengths. The present conclusions are that large fluctuations do not correspond to large transports, as has been found experimentally in boundary plasmas.

From the initial fluid simulation results, we have gained some understanding of the fluctuations and related transport in the regions of core edge separatrix SOL. But more questions should be answered for realistic tokamak plasma conditions and geometries, as follows.

Merging of Core Codes with Edge Codes (Dr. A. Tarditi)

Core codes run at low frequencies ($\omega < \omega_{ci}$) and long wavelengths ($\lambda > \rho_i$); kinetic edge codes work at higher frequencies and shorter wavelengths and may be bounded by recombining, absorbing, emitting, reflecting, etc. walls. Hence, there is an incompatibility in time and space scales, as well as in boundary conditions.

For example, Dr. Scott Parker, with a 3-d toroidal gyrokinetic model, simply reflects his GK particles at a prescribed edge. No SOL, no divertors, no walls. Hence, we have devised and tried out a method of merging two or

more codes at a common edge, within the plasma. The merged codes may be particle or fluid, and have disparate Δx and Δt . The methods used and the (good) results obtained were presented at the June IAEA meeting (Montreal).

Plans

The next steps include:

3. parallel processing on the department CM-5, first, with Dr. Scott Parker's gyrokinetic 3d tokamak code (he visited here the week of October 1), then perhaps with LLNL GK codes (Bruce Cohen and co-workers), finally moving toward a core-edge merged model (possibly Parker's core and our edge);
4. expanding our studies of stochastic transport across potential structures (to a wide range of T_e , B) and seeking (anomalous) mobility due to large edge (radial) electric fields;
5. a gas collisional divertor, using our PDP2 (2d, 3v, PIC-MCC) codes;
6. exploring core profiles [$n(r)$, $T(r)$, etc.] as affected by various edge boundary conditions, seeking those bc's with high leverage on altering the profiles;
7. understanding the magnetized pre-sheath space and time behavior, including various source regions. Future efforts will be in the same vein, exploratory, imaginative, seeking both essence and lab values, as is the most effective mode for a small university group.

Students

Current post-docs are Dr. Xuequiao Xu and Dr. Alfonso Tarditi (a NATO Fellow). Current graduate students are Hyso-Sung Cho and Bigel Modi. Current undergraduate students are Eric Lopez and Payam Mirrashidi. The Ph.D. on this project was awarded (since March 1990) to Scott Parker, "Particle Simulation of Bounded Plasmas with a Wide Range of Space and Time Scales," (March 19, 1990) and Richard Procassini, "Kinetic Particle-in-Cell Simulations of Transport in a Tokamak Scrape-Off Layer," (March 1990).

Other Professional Staff

None.

Collaborations

We have had regular meetings with LLNL professionals on both the collisional modeling (useful for (e) above) and on the theoretical and numerical modeling of (a). We welcomed Dr. Parker's visit from PPPL on (c) above. We interact well with Prof. T.K. Fowler's nuclear engineering students and seminars on his collaboration with GA (especially Gary Porter) on transport analysis of DIII-D tokamaks; his students are involved in our projects, as has been true for many years.

Publications

See attached list of DOE related publications (note that other support led to more publications, which are not listed).

Journal Articles-1991

- T.L. Crystal, P.C. Gray, W.S. Lawson, C.K. Birdsall, and S. Kuhn, "Trapped Electron Effects on Time-Independent Negative-Bias States of a Collisionless Single-Emitter Plasma Device: Theory and Simulation," *Physics of Fluids B* 3 (1), January 1991, pp.244.
- C.K. Birdsall, "Particle-in-Cell Charged-Particle Simulations, Plus Monte Carlo Collisions with Neutral Atoms, PIC-MCC," *IEEE Trans. Plasma Science* 19 (2), April 1991, pp. 65-85 (invited paper).
- R.J. Procassini, and C.K. Birdsall, "Particle Simulation Model of Transport in a Bounded, Coulomb Collisional Plasma," *Phys. Fluids B* 3 (8), August 1991, pp. 1876-1891.
- A. Friedman, S.E. Parker, S.L. Ray, and C.K. Birdsall, "Multi-Scale Particle-In-Cell Plasma Simulation," *J. Comp. Physics* 96, September 1991, pp. 54-70.
- S.E. Parker, and C.K. Birdsall, "Numerical Error in Electron Orbits with Large ω_{ce} ," *J. Comp. Physics* 97 (1) pp. 91-102, November 1991.
- S.E. Parker, X.Q. Xu, A.J. Lichtenberg, and C.K. Birdsall, "Evidence of Stochastic Diffusion across a Cross-Field Sheath," accepted for publication, *Phys. Rev. A*.
- S.E. Parker, A. Friedman, S.L. Ray, and C.K. Birdsall, "Bounded Multi-Scale Plasma Simulation: Application to Sheath Problems," accepted by *J. Comp. Physics*.
- N.F. Otani, J-S. Kim, C.K. Birdsall, B.I. Cohen, W. Nevins, and N. Maron, "Elimination of Velocity Space Rings-and-Spokes Instabilities in Magnetized Electrostatic Particle Simulations of Plasmas," accepted by *J. Comp. Physics* (approx. June 1992).
- S.E. Parker, R.J. Procassini, C.K. Birdsall, and B.I. Cohen, "A Suitable Boundary Condition for Bounded Plasma Simulation without Sheath Resolution," accepted by *J. Comp. Physics*.

- J.P. Verboncoeur, M.V. Alves, and V. Vahedi, "Simultaneous Potential and Circuit Solution for Bounded Plasma Particle Simulation Codes," accepted by *J. Comp. Physics*.
- H.L. Berk, D.D. Ryutov, Y.A. Tsidulko, R.H. Cohen, and X.Q. Xu, "Electron Temperature-Gradient and Endloss Driven Transport in SOL of Tokamak Plasmas," submitted to *Comments on Plasma Physics and Controlled Nuclear Fusion*.
- D. Hua, X. Xu, and T.K. Fowler, "Ion-Temperature-Gradient Modes in Non-Circular Tokamak Geometry," to be submitted by the end of year.
- X.Q. Xu, G. DiPeso, V. Vahedi, and C.K. Birdsall, "Theory and Simulation of Plasma Sheath Waves," to be submitted by end of year.
- C.K. Birdsall and A.B. Langdon, *Plasma Physics via Computer Simulation*, Adam-Hilger edition (with ES1 disk) 1991.
- C.K. Birdsall and A.B. Langdon, "Particle Simulation Techniques," in *Computer Applications in Plasma Science and Engineering*, ed. A.T. Drobot, (Springer-Verlag: New York), pp. 7-41, 1991.

Journal Articles-1992

- S.E. Parker, X.Q. Xu, A.J. Lichtenberg, and C.K. Birdsall, "Evidence of Stochastic Diffusion Across a Cross-Field Sheath Due to Kelvin-Helmholtz Vortices," *Physical Review A*, 45 (4) pp. 3949-3961, 15 February 1992.

Talks, Poster Papers

Sherwood Fusion Theory Conference, April 6-8, 1992, Santa Fe, NM.

- X.Q. Xu, P.H. Diamond, and M.N. Rosenbluth, "Turbulent Transport Across a Separatrix Due to ETG Driven Instability in Tokamak SOL."
- C.K. Birdsall and X.Q. Xu, "A Hybrid Particle-Fluid Simulation for Model Tokamak Plasma Edge Turbulence."
- A. Tarditi, "1D and 2D Code-Merging with Applications to a Self-Consistent Core-Edge Plasma Simulation."
- R.H. Cohen, H.L. Berk, D.D. Ryutov, T. Tsidulko, and X.Q. Xu, "Electron-Temperature-Gradient Turbulence in Tokamak Scrape-Off Layers," *IAEA Technical Committee Meeting, Advances in Simulation and Modeling Thermonuclear Plasmas*, June 15-17, 1992, Montreal, Canada.
- C.K. Birdsall, X.Q. Xu, and A. Tarditi, "Magnetized Plasma Kinetic Edge: Theory, Models and Simulations," *4th Symposium on Double Layers and Other Nonlinear Potential Structures in Plasmas*, July 6-8, 1992, Innsbruck, Austria.
- C.K. Birdsall and V. Vahedi, "Strongly Driven Sheaths," invited paper, *IAEA Technical Committee Meeting on Tokamak Plasma Biasing*, September 8-10, 1992, Montreal.
- X. Xu and C.K. Birdsall, "Electron Temperature Gradient Driven Turbulence in Boundary Plasmas," *American Vacuum Society*, November 9-13, 1992, Chicago, IL.
- V. Vahedi, R.A. Stewart, M.A. Lieberman, "An Analytic Model of the Ion Angular Distribution Function in a Collisional Sheath," *APS Division of Plasma Physics*, November 16-20, 1992, Seattle, WA.
- X.Q. Xu, M.N. Rosenbluth, P.H. Diamond, and C.K. Birdsall, "Electron Temperature Gradient Driven Turbulence in Boundary Plasmas."
- A. Tarditi, "Code-Merging for Slab and Fully Bounded Two-Dimensional Geometries."
- R.H. Cohen, X.Q. Xu, and B. Modi, "Parallel-Current Effects and Mode Structure of Endloss-Driven Scrape-off Layer Instability."
- D.D. Hua, X.Q. Xu, and T.K. Fowler, "Ion-Temperature-Gradient Modes in Non-Circular Tokamak Geometry."

University of California-Los Angeles

Project

Applications of Computer Modeling to Fusion Research

John M. Dawson

Funding

FY 90

\$400k

FY 91

\$350k

FY 92

\$300k

Purpose

1. To develop computer models that accurately simulate plasma behavior in fusion devices. Most of our effort is devoted to particle models (full electron and ion dynamics, gyrokinetic models in two and three dimensions); a small amount of our effort is devoted to fluid models.

2. The application of the models and associated computer codes to problems of importance to controlled fusion. Most of our effort is presently devoted to the so-called "Numerical Tokamak." This is an attempt to model modest existing experimental Tokamaks using our three dimensional gyrokinetic codes. We also have a project on the generation of Bootstrap current using a full dynamics code and we have a small amount of work on RF heating of plasmas by intense waves.

3. To explore advanced computing techniques and their applications to solving plasma problems related to CTR; in particular we are investigating the use of parallel computers; we are investigating the use of graphic displays and animation for data analysis of simulation results.

4. To train graduate students and postdoctoral fellows for work in fusion physics.

Approach Taken, Techniques Used, and Resources Applied

We have concentrated our modeling efforts on particle codes since we feel they contain most fully the subtle physics of real plasmas. At present, we are concentrating on gyrokinetic models as these allow us to handle the low frequency large time and space scale processes that seem to be related to plasma and heat transport in tokamaks. There is a firm theoretical basis for these models and the computational techniques for handling them are fairly well developed.

The resources we use are: the NERSC CRAYs, the UCLA IBM-30-9000, graphic work stations at UCLA (not supplied by DOE), the UCLA Visualization Center; we make related simulations (supported by other contracts) on the San Diego Supercomputer and at the Cornell Supercomputer Center.

Progress

Tokamak Physics Problems Run

1. Turbulence and transport associated with the hi mode. The calculation was done for both two and three dimensional models. Steady transport was found only in the three dimensional case. For the three dimensional case the turbulent spectrum was compared with observations made by Peebles on the Texas tokamak and there was semi-quantitative agreement (we could not exactly duplicate the conditions of the measurement or make exact comparisons of the computed spectra and the microwave scattering spectra). The observed heat transport was also about right.

2. Turbulence and transport associated with the collisionless trapped electron drift instability has been investigated. Again the turbulence spectra was compared with observations made by Peebles on the Texas tokamak and there was semi quantitative agreement. The observed particle and heat transport were also about right. The electron heat transport was about five times the particle transport.

3. Using the magnetostatic model we started investigating the development of the internal kink mode. We compared the results with predictions of MHD. For a zero temperature plasma there was good agreement. For finite temperature (finite Larmor radii) there were significant differences in the critical i on axis and the conditions at which the instability set in and the instability growth rates were modified. During the instability many of the magnetic surfaces broke up and became ergodic; later some healing of the surfaces was observed.

Boot Strap Current

We have carried out calculations on a fully dynamic electromagnetic 2 and 1/2 dimensional particle code of bootstrap and dynamo driven currents. Recently Lorentz collisions have been added to the model. This work grew

out of some observations of Bob Taylor; these showed that in CCT with a vertical $\mathbf{B}$ field, a steady state current could be maintained if the source of plasma was in the central region of the tube. By using a quasi toroidal magnetic field plus a vertical field, $\mathbf{B}_z$, and starting with the plasma in the center, the plasma generated a $\mathbf{J}_z$ as it moved out in x and ultimately produced closed magnetic surfaces. The results are in agreement with a simple physical model we have developed.

We have explored the case of a current-carrying plasma which is initially in equilibrium in the quasi toroidal and vertical $\mathbf{B}$ fields. We removed particles at a circular limiter and reinjected them at the center of the tube (to simulate loss and source terms). We have found that with collisions turned off the plasma current is not only maintained but actually rises with time; increases of up to 20% were observed with out any indication of saturation. The plasma transport for this case is due to convective cells. At the limiter, particles with the wrong sign of their momentum (opposite to that required for the current) are lost. This leaves extra current at the edge; we believe the convective cells transport this current to the axis where it provides the seed current for the Boot Strap effect. We have developed a simple analytic model that also gives this effect. While the transport in our model is different from that which exists in real tokamaks, we believe it has many similarities and that self-sustained current is a definite possibility for tokamaks. If this proves to be true it has tremendous implications for fusion reactors.

Investigations of Parallel Computing

Our gyrokinetic codes are very large and require long runs to simulate experimental tokamaks (100 hour runs have been made). It is clear that to have an effective Numerical Tokamak Program, machines with considerably more power will be required. The parallel computers that are coming into being promise increases in power of perhaps two orders of magnitude or more (in both speed and memory). In order to assess the potential here we have been collaborating with the California Institute of Technology on the use of their Hyper Cube for plasma simulation. We have put one and two dimensional electrostatic and electromagnetic PIC models on these machines. We have achieved very good parallelism (roughly 95%) on the MARK III (64 processors). Recently on the INTEL GAMMA machine (32 processors), the particle push was found to be twice as fast as a 4 processor CRAY 2 (all processors working in parallel). For the field solver the performance was somewhat less than the 4 processor CRAY 2. The DELTA machine will have 512 processors and should be roughly 16 times faster. Since the structure of the gyrokinetic code is essentially the same as that of these PIC codes we expect to get similar performance gains there.

Code Development

We developed a gyrokinetic code that includes collisions. The technique conserves both energy and momentum; electron-ion, electron-electron, and ion-ion collisions are included. Extensive tests of the code have been made by testing against situations where analytic results exist. The tests include plasma transport across a magnetic field, heat transport across a magnetic field, the slowing down and thermalization of test charges and ion electron energy exchange. The technique used is fast enough to use in practical codes.

Schedule of Major Research Activities

For the next year we have four major research efforts underway. Our program for following years will depend on our successes during 1993 and on our budget. We will continue to work towards Numerical Tokamak Models with predictive capability for experiments.

1. Studies of kinetic effects on the internal kink mode and its relation to saw teeth using our three dimensional gyrokinetic EM model. We will explore its effects on plasma and heat transport.

2. Get our collisional version of the three dimensional gyrokinetic code in full operation. Start to explore the effects of collisions on the hi and trapped particle instabilities and the resulting turbulence and transport. Attempt to compare results with experimental ones.

3. Continue to explore the generation of bootstrap current using our two and one half dimensional full particle code and start to explore the effects we have found there for longer times and more realistic geometry using our three dimensional gyrokinetic code.

4. Continue our efforts to put particle codes on parallel computers and start to put a gyrokinetic model on one or more parallel machines.

Students

Present students, Bill Nunan and Pete Sheehy

Recent Ph.D. recipient, K.R. Chen (Ph.D., Sept. 91)

Other Professional Staff

Scientific

Richard Sydora: Associate Research Physicist (75% time), Viktor Decyk: Research Physicist (50% time), Sifeng Ma: Assistant Research Physicist (100% time).

Technical Personnel

Pieter Kokelaar: Computer and Communications Maintenance (25% time), C.C. Lin: Principal Programmer (10% time).

Collaborations

Collaborate with UCLA experimentalists Bob Taylor and Tony Peebles, Paulett Liewer (Cal Tech/JPL), and the Numerical Tokamak Consortium.

Publications

The following papers with DOE sponsorship appeared in the period FY90-FY92:

L.L. LoDestro, B.I. Cohen, R.H. Cohen, A.M. Dimits, Y. Matsuda, W.M. Nevins, W.A. Newcomb, T.J. Williams, A.E. Koniges, W.P. Dannevik, J.A. Crotinger, P.A.K. Amala, R.D. Sydora, J.M. Dawson, S. Ma, V.K. Decyk, W.W. Lee, T.S. Hahn, N. Naitou, and T. Kamimura, "A Comparison of Simulations and Theory of Low-Frequency Plasma Turbulence μ ," Proc. of IAEA, Washington, DC, October 1990.

J.M. Dawson, R.D. Sydora, V.K. Decyk, P.C. Liewer, and R.D. Ferraro, "Physics Modeling of Tokamak Transport: A Grand Challenge for Controlled Fusion," Int'l. J. Supercomputing Applications, 5, 13 (1991).

S. Ma, R.D. Sydora, and J.M. Dawson, "Binary Collision Model in Gyrokinetic Simulation Plasmas," submitted to Phys. Rev. Lett., (1992).

J.M. Dawson, "Nonenergy Applications for Fusion," accepted for publication, Nuclear Fusion (1991).

J.M. Dawson, W. Nunan, and S. Ma, "On the Possibility of a Steady State Tokamak Maintained by Bootstrap Current Drive Alone," Proceedings of European Topical Conference on RF Heating and Current Drive of Fusion Devices, Brussels, Belgium, July 7-10, 1992.

A.C.J. Paes, R.D. Sydora, and J.M. Dawson, "Particle Simulation of the Magnetized RF Plasma Sheath," In press, Phys. Fluid B, (1992).

F. Kazeminezhad, J.M. Dawson, J.-N. Leboeuf, R. Sydora, and D. Holland, "A Vlasov Particle Ion Zero Mass Electron Model for Plasma Simulations," J. Comput. Phys., 102, 1 (1992).

F. Kazeminezhad, J.-N. Leboeuf, F. Brunel, and J.M. Dawson, "A Discrete Model for MHD Incorporating the Hall Term," sub. to J. Comput. Phys., (1992).

University of California–Los Angeles

Project

Heating, Transport and Wave Diagnostics of Fusion Plasmas

George J. Morales, P.I. and Burton D. Fried, Co-P.I.

Funding

FY 90	FY 91	FY 92
\$211k	\$200k	\$200k

Purpose

Our group is engaged in analytical and computational studies of applied plasma physics issues related to the operation of tokamak devices and the planning of major fusion experiments. The topics being investigated span the areas of heating and current drive, transport and wave diagnostics. In the area of heating and current-drive we are investigating issues related to the anomalous ion heating experienced by large Larmor radius particles, as is the case when alpha particles are present. In the transport studies we are pursuing a novel approach based on energy transport arising from radiating current filaments having transverse dimensions on the order of the electron skin-depth. Another transport topic being pursued pertains to the modelling of H-mode behavior induced by controlled radial currents.

Progress

During the period November 1, 1991 through September 30, 1992, we have achieved significant progress in the study of the following topics: analytic solution of mode conversion in parabolic density profiles; role of Alfvén-wave filaments in tokamak transport; perpendicular ion acceleration by edge RF electric fields; relaxation and energy transport in narrow channels by electrostatic waves. We have also completed an extensive modelling activity aimed at a quantitative explanation of the L-H mode transition observed in the CCT (Continuous Current Tokamak) device at UCLA. In addition, we have brought to fruition our collaborative study with Dr. R.J. Taylor, on the topic of perpendicular ion acceleration in toroidal plasmas. This study resulted in a Ph.D. dissertation by J. Evans, and clearly illustrates that a universal (and very efficient) mechanism exists that results in energetic ions perpendicular to the toroidal field. The theoretical explanation of such a mechanism is being pursued as part of our more general study of Large Larmor radius interactions.

During this research cycle, four papers have appeared in print. The manuscript on L-H transition has been submitted to the Physics of Fluids. These research activities have been reported at the Annual Meeting of the Plasma Physics Division of the American Physical Society, at the Sherwood Theory Meeting, at the Boulder ICRF Workshop and at the 1992 International Conference on Plasma Physics in Innsbruck, Austria.

A list of major technical results includes:

Mode Conversion

We have undertaken the analytic study of the fundamental mode conversion process between a Langmuir Wave and an Electromagnetic wave at an arbitrary point in a parabolic density profile, which is a problem that has not been previously solved. We have been very pleased to demonstrate that our scale separation technique which was developed for the linear density profile [Hinkel-Lipsker, Fried, Morales, Phys. Rev. Lett. 62, 2680 (1989)] allows a systematic solution of this problem in closed analytic form. Moreover, we have demonstrated how this solution reduces to the linear profile, in the appropriate limits, and on peak results, which we had solved for previously. This comprehensive study shows that we have developed a robust and powerful methodology to attack mode conversion problems. The specific results are extremely useful in interpreting spontaneous emissions from a given point in the density profile as well as for a detailed understanding of features associated with reflectometry.

Modelling of L-H Transition in CCT

A simple, but realistic model has been developed that isolates the essential features of a magnetically confined plasma undergoing anomalous transport and whose properties are manipulated by externally injected currents. The model exhibits the following intrinsic properties (not built-in a priori): Ohmic confinement improves with density; L-mode scaling depends on heating power as $P^{-0.6}$; a transition to H-mode behavior is induced by radial currents on the order of 10 Amps. The model has been benchmarked against the experiments performed in the CCT device [R.J. Taylor, et al., Phys. Rev. Lett. 63, 2365 (1989)] and excellent quantitative and qualitative agreement has been obtained. The new effects explored include: H-modes induced by multiple electrodes, auxiliary heating in the presence of radial currents, and concept of H-mode as a "phase-transition."

Alfven-Wave Filaments

This analytical study has investigated the properties of kinetic Alfven waves driven by filamentary electron current fluctuations. The radiation and absorption of the filamented waves suggests a picture of energy transport that does not require particle transport. The energy transport can be viewed as self-consistent RF heating, with the current fluctuations on a magnetic surface playing the role of an in-situ antenna. The radiation properties of such antennas have been calculated and form the basis of an energy-balance formalism presently being explored.

Plans

We plan to pursue, in greater depth, the description of large Larmor-radius particles interacting with RF electric fields and to apply the results to ICRF experiments, current-drive scenarios, and explanation of the universal mechanism of perpendicular ion acceleration. We are considering the improvement of our modelling of the L-H transition to incorporate wave-mediated transport and nonlocal interactions, as seems necessary to explain experimental observations. Particle simulations of the relaxation of nonequilibrium narrow "hot channels" will be pursued and a wave-mediated mechanism for current spreading will be sought. The conceptual advancement of the novel concept of energy transport mediated by Alfven-wave filaments will be pursued and compared to experimental observations.

Students

Dr. H. Ramachandran is a postdoctoral scientist whose research is sponsored by this project. The following graduate students are partially supported with DOE funds: K. Reitzel, A. Reynolds, R. Loritsch, J. Penano. The following students completed Ph.D. dissertations related to this project: D.E. Hinkel-Lipsker: "Resonant Absorption in an Inhomogeneous Plasma," (June 1990), D.L. Holland: "The Magnetized Plasma Sheath," (September 1990), and J.D. Evans: "Perpendicular Fast Ion Generation in Toroidal Plasmas," (June 1990).

Collaborations

A significant fraction of our effort is devoted to assisting in the interpretation and planning of experiments being conducted at the UCLA Tokamak Laboratory by Dr. R.J. Taylor. We also maintain contacts with RF experiments being performed in JET through informal collaborations with Dr. Marco Brusati, who spent 2 weeks visiting our group during August of 1992.

Publications

The following papers with DOE sponsorship appeared in the period FY90-FY92:

- E.A. Berro and G.J. Morales, "Excitation of the Lower Hybrid Resonance at the Plasma Edge by ICRF Couplers," *IEEE Transac. on Plasma Sci.* 18, 142 (1990).
- R.J. Taylor, B.D. Fried and G.J. Morales, "Burn Threshold for Fusion Plasmas with Helium Accumulation," *Comm. Plasma Phys. and Cont. Fus.* 13, 227 (1990).
- H. Romero and G.J. Morales, "Effects of Coherent Density Fluctuations on the Ion-Ion Hybrid Resonance," *Phys. Fluids B* 2, 2007 (1990).
- H. Romero and G.J. Morales, "Inverse Mode Conversion of Ion Bernstein Waves in Tokamak Plasmas," *Phys. Fluids B* 2, 3054 (1990).
- D.E. Hinkel-Lipsker, B.D. Fried and G.J. Morales, "Conversion of Electrostatic and Electromagnetic Waves in a Plasma at the Peak of a Parabolic Density Profile," *Phys. Rev. Lett.* 66, 1862 (1991).
- H. Romero and G.J. Morales, "Absorption at the Ion-Ion Hybrid Resonance in the Presence of Incoherent Density Fluctuations," *Phys. Fluids B* 3, 2960 (1991).
- D.E. Hinkel-Lipsker, B.D. Fried and G.J. Morales, "Analytic Expressions for Mode Conversion in a Plasma with a Linear Density Profile," *Phys. Fluids B* 4, 559 (1992).
- G.J. Morales and H. Ramachandran, "Role of Alfven-Wave Filaments in Tokamak Transport," *Europhysics Conf. Abst.*, Vol. 16C, III-135 (1992).
- D.E. Hinkel-Lipsker, B.D. Fried and G.J. Morales, "Analytic Expressions for Mode Conversion in a Plasma at the Peak of a Parabolic Density Profile," *Phys. Fluids B* 4, 1772 (1992).
- J.D. Evans, G.J. Morales and R.J. Taylor, "Observation of Perpendicular Ion Acceleration in Toroidal Plasmas," *Phys. Rev. Lett.* 69, 1528 (1992).

University of California-San Diego

Project

Investigations in Anomalous Transport and Ignition Physics

P. Diamond and M. Rosenbluth

Funding

FY 90

\$250k

FY 91

\$300k

FY 92

\$350k

Purpose

This research deals with core transport physics, edge transport, L to H transition, concept optimization and basic plasma theory. More specifically, in the area of transport, the topics considered are: convective cell turbulence and the interaction of long wavelength cells with short wavelength drift wave turbulence to check whether such modulational interactions are responsible for non-locality phenomena in tokamak; interaction of convective cells with sheared toroidal flows; trapped electron modes, including $\mathbf{E} \times \mathbf{B}$ and polarization drift nonlinearities for dissipative mode turbulence. The phenomenon of core ion temperature gradient driven turbulence is being studied with emphasis on nonlinear interaction between finite- n radial eigenmodes and the related problems of the effect of flow shear on these modes. In the area of L to H transition, work continues on the nonlinear dynamics of drift waves in sheared flows, saturation of self-consistently driven flows, development of a general theory of flow generation and study of neoclassical impurity flows. In the area of edge turbulence, the work will include impurity gradient driven drift wave turbulence and toroidal collisional ITG turbulence. In the area of ignition physics, shear Alfvén instabilities driven by super-Alfvénic alpha particles is being studied.

Approach

In addition to the use of analytical and numerical approaches to the development of models and theories, collaboration with experiments is being undertaken on TFTR, TEXT and DIII-D. The topics involve fluctuations, edge-center heating, edge turbulence, analysis of impurity rotation data and the effect of shear on fluctuations.

Progress

In the area of Drift Wave Turbulence Theory, significant progress has been made in understanding disparate scale interactions. In particular, a two-paper series on a two nonlinearity model was produced. These uncovered a blocking of the oft-invoked *inverse cascade* and demonstrated the importance of nonlocal transfer in k space due to $\mathbf{E} \times \mathbf{B}$ nonlinearity. Work on coherent structures helped elucidate their relevance to anomalous transport. In particular, studies of a simple 2-D Hasegawa-Wakatani model revealed that in the adiabatic regime structures form, but have little or no impact on transport predictions. However in the hydrodynamic regime, transport is significantly lower than either the prediction of quasilinear theory or standard resonance broadened quasilinear theory. This reduction in transport may be due to trapping in structures.

Recent work has focused on the nonlinear dynamics of convective cells (trapped ion modes). In particular it has been demonstrated that decay instability, driven by short wavelength drift wave turbulence, may energize trapped ion modes more rapidly than linear growth processes. Also, a type of two-dimensional structure which is formed naturally by the Reynold's stresses of the drift waves acting on the long wavelength cells has been identified. This tends to trap the long wavelength cells between bipolar structures of the drift wave envelope.

Major progress has been made on the theory of flow generation and the L- $\rightarrow$ -H transition. A General theory which encompasses both dynamo-like instabilities and direct generation of shear and curvature was developed. This theory was demonstrated to include previous results by us and the Maryland group. It was also well established that flow *curvature* (not shear!) is the dominant stabilizing mechanism, in agreement with recent experimental observations from DIII-D and JET. A self-consistent model of the flow turbulence evolution in a simplified context was developed and shown to demonstrate bifurcation-like phenomenon. Furthermore, the ongoing research on flow generation has uncovered an important relation between vorticity transport and particle transport.

Another topic of research is the area of active control. In particular, the theory of active control of plasma rotation by ion Bernstein wave injection was developed. The competing roles of Reynold's stress flow redistribution and direct momentum input due to acceleration of ions by high frequency waves was elucidated. Ongoing work is focused on extending this quasilinear calculation to the highly nonlinear edge. Also, an extensive study of helicity

injection by Alfvén waves in a high temperature plasma was carried out. In particular, it was demonstrated that the efficiency of kinetic Alfvén wave helicity injection is significantly lower than that predicted by MHD calculations.

Another topic of research concerns magnetic fluctuation dynamics and dynamo theory. In the realm of dynamo theory, a simple analytical physical interpretation of the interesting result of Vainshtein and collaborators that magnetic diffusion is suppressed in 2-D MHD was developed. Extensions to 3-D reduced MHD and 3-D MHD are in progress. Also, a more complete and inclusive kinetic theory of the effects of high frequency microturbulence on low frequency dissipative instabilities was developed.

Significant progress on the theory of toroidal Alfvén eigen modes has occurred. In particular, a precise calculation of the linear damping of toroidal Alfvén eigen modes by coupling to the continuum occurred and was published in Physical Review Letters. Extensions which include FLR effects are in progress.

Plans

This group expects to focus on the development and dynamics of the L-H bifurcation, both with and without ion orbit loss, the theory of Flow Generation and Flow Profile Modification in Toroidal Geometry, the *nonlinear* theory of Flow Generation by Ion Bernstein Waves, the development of a more accurate resonance broadened quasilinear theory (which reflects potential vorticity conservation constraints in transport predictions), comparisons of structure dynamics with closure code predictions, and further work on toroidal Alfvén wave eigen-modes, including kinetic corrections.

Other Professional Staff

Stefanie Conover

University of Colorado

Department of Astrophysical, Planetary, and Atmospheric Sciences

Project

Collisional and Chaotic Transport in Toroidal Plasma

John R. Cary and S. G. Shasharina

Funding

FY 90	FY 91	FY 92
\$60k	\$110k	\$90k

Purpose

To investigate the transport of thermal and supra-thermal particles in toroidal magnetic devices in the regimes where the effects of both collisions and collisionless chaotic transport are taken into account. The primary focus is on the influence of the toroidal and up-down asymmetry of the magnetic field on transport processes: stochastic losses of alpha-particles, the transition probability, and a new kind of transport due to the different amplitude of the ripple in the upper and lower mid-planes of the tori.

Approach

Our approach to the investigation of the classical transport (i.e., not turbulent effects) proceeds along two lines. First of all, we investigate the collisionless motion of the particles in a magnetic configuration typical for modern asymmetric toroidal devices (e.g., tokamaks with ripple and stellarators). The main tools of investigation here are the guiding center equations of motion and the adiabatic theory which we employ both numerically and analytically. To analyze the problems related to the transition probability, we introduce a new approximation for the toroidal magnetic field with ripple or helical perturbation.

The second line of our approach is dealing with the solutions of the kinetic (Fokker-Planck) equation, which allows us to investigate the transport in the collisional regimes. To solve it, we use the traditional perturbation analysis in the low and high collisional regimes as well as numerical approach to solve the occurring eigenvalue problems. To model the stochastic diffusion, we introduce the loss cone corresponding to the stochastic region in the velocity space.

Progress

1. We have defined the trapping probability in asymmetric tori (i.e., the fraction of a toroidally trapped particles that make a transition to the locally trapped state at the end of the bounce motion), in terms of relative changes of the phase volume corresponding to these states along the trajectory. By introducing a new model for the magnetic field, we have evaluated the adiabatic invariants of the locally and toroidally trapped particles with finite rotational transform per period, τ/N , taken into account. The trapping probability evaluated with the new model agrees with numerical results much better than the previous calculations.

2. We have also evaluated the adiabatic invariants for the locally and toroidally trapped particles in asymmetric tori near the separatrix, for the finite but small rotational transform, with the help of perturbation analysis of the longitudinal equation of motion, and without using any model approximation for the magnetic field. The results agree with the model approach through lowest order in τ/N .

3. We have evaluated the loss of alpha-particles in a tokamak due to ripple including both collisional (pitch angle scattering and slowing down) and collisionless (chaotic) mechanisms. Chaotic diffusion was accounted for by assuming that chaotic particles immediately leave the device.

4. We have also started the investigation of the effect of up-down ripple asymmetry on transport. Here, we have discovered a new type of the transition orbits which are unclosed and, thus, might give rise to a rapid convective loss at low collisionality. It turns out that due to the conservation of the collisionless flux of the transitioning particles and the averaging procedure of the kinetic equation, the additional fluxes of the particles in the different states cancel each other at high collisionality. Nevertheless, we have proven a theorem that gives insight into the interaction between particle trajectories and transport mechanisms.

Plans

1. During the coming year, we plan to continue the investigation of ripple transport in the toroidal devices. Specifically we expect to include the field line to field line variation of the distribution function of the toroidally trapped particles into our investigation of the transport associated with the up-down asymmetry in a tokamak.

2. We shall study the formation of the poloidal electric field due to ECRF and ICRF in a tokamak, which might increase or decrease the radial flux of the particles and might account for the enhanced losses of ECRF experiments.

3. We shall also start studies of the influence of neoclassical phenomena on anomalous transport. We expect that the inhomogeneity of the magnetic field and related to that time scales if the particle's motion is connected with the anomalous transport and its time scale.

Students

None

Other Professional Staff

None

Collaborations

The studies concerning the transport processes in the up-down asymmetric tokamak are performed in collaboration with P.N. Yushmanov at Institute of Fusion Studies and Fusion Research Center, the University of Texas at Austin.

Recent Publications

1. S.G. Shasharina and J.R. Cary, "Stochastic Losses of Alphas in Tokamak," Bull. Am. Phys. Soc. **36**, 2393 (1991).
2. S.G. Shasharina and J.R. Cary, "Transition Probabilities in Asymmetric Tori," Bull. Am. Phys. Soc. **35** (9), 2033 (1990).
3. S.V. Bulanov and S.G. Shasharina, "Near Separatrix Behavior of Adiabatic Invariant in Stellarator," to be published in Nuclear Fusion.
4. John R. Cary and S.G. Shasharina, "Probability of Orbit Transition in Asymmetric Toroidal Plasma," submitted to Physics of Fluids.

University of Illinois at Urbana-Champaign

Project

Methods for Testing Transport Models

Clifford E. Singer and Dennis D. Cox

Funding

FY 90	FY 91	FY 92
\$85k	\$80k	\$75k

Purpose

The purpose of our project is to develop and begin to apply adequate statistical methods for using large multi-institutional experimental data bases for calibrating and testing sophisticated models of energy and mass transport. The goal is to test existing transport theories and to develop models which can predict the properties of fusion-relevant plasmas in magnetic confinement devices with significantly more accuracy. Particular attention is paid to use of dimensionally correct and theoretically based transport models. The methods developed will be useful for predicting performance in future confinement systems which have different sizes and magnetic fields but with physically relevant dimensionless parameters similar to those in the existing data base.

Approach

Our approach concentrates on using real multi-institutional databases and the most sophisticated available computational models and theories. This allows realistic sources of variance between experiment and code predictions to drive the development of appropriate statistical models of the source of such variance. Use of multi-institutional data bases forces the project to deal with sources of variance due to different operations and diagnostic calibration procedures in different experiments, as well as with more familiar random measurement errors due to limitations such as the finite number of photons collected for a particular temperature or density measurement. The use of complex computational models forces dealing with random fluctuations in outputs of codes which include Monte Carlo algorithms as well as development of efficient interpolation methods to minimize the number of code runs needed to develop and test transport models.

Progress

We have made major progress in four different areas of this research. These include the following:

1. Realistic theory-based comprehensive transport models have been developed and shown to reproduce a broad spectrum of experimental results using a fixed value of a single a priori unknown parameter. A number of more recent theoretical models have also been explored by modelling a wide variety of different discharges from a data base collected during interviews with experimentalists working on eight different toroidal magnetic confinement devices.
2. "Code emulators" have been developed for interpolating the transport code input-output relation (or its expected value, for our not untypical case where code algorithms use random number generators). These emulators have been used to estimate confidence contours for a priori uncertain parameters using a data base far too large to process otherwise.
3. Confidence levels for multi-parameter models have been computed, accounting for both random measurement errors on a given experiment and additional random errors resulting from different experimental techniques and modelling inaccuracies between different experiments.
4. Earlier statistical methods for dealing with these problems for a scalar output from each experiment (the "global energy confinement time") have been extended to vector outputs (temperature and density data at various distances from the center of the magnetic surfaces which confine the hot plasma). An automated procedure for processing code inputs and outputs to estimate transport coefficient multipliers (corresponding physically to empirically estimate turbulence saturation amplitudes) has also been developed.

Plans

As a result of the work discussed above, we are now in a position to start shifting from the development of computational and statistical methods to their application to large scale data bases. We are presently in the process

of applying these methods to a multi-parameter calibration of G. Bateman's modification of our earlier transport models. This calibration will initially use temperature and then density profiles from twenty very well documented experiments on eight different toroidal magnetic ("tokamak") devices. Using these results to guide the choice of boundary conditions, code emulators will then be constructed to allow the inclusion of data from over one thousand experiments. A previously developed theoretically motivated and empirically adjusted boundary conditions model will allow the inclusion of both "low" confinement mode results (with rather low boundary temperatures) and "high" confinement mode results (with higher, so-called "pedestal" boundary temperatures). As this work proceeds on various minor adjustments of Bateman's model, we will also be running smaller scale calibrations of more recent theoretical models (such as ones including effects described by the "neo-classical magnetohydrodynamic" theory developed by J. Callen and colleagues).

Students

Jon Kinsey and Nanxiang Ge are respectively continuing Ph.D. thesis work on transport and statistics, based on the groundwork laid in the following theses from the University of Illinois at Urbana-Champaign (UIUC): Jonathan E. Kinsey, "H-Mode Transport of Tokamak Plasmas," UIUC Department of Nuclear Engineering Master's thesis (1991); Jeong Soo Park, "Tuning Complex Computer Codes to Data and Optimal Designs," UIUC Department of Statistics Ph.D. thesis (1991); Elsayed M. Ghanem, "Theoretical Transport Model for Tokamaks," UIUC Department of Nuclear Engineering Ph.D. thesis (1991); Toufik Djemil, "Methods for Testing Transport Models," UIUC Department of Nuclear Engineering Ph.D. thesis (1992).

Professional Staff

The project receives a small amount of computer maintenance support from Eric Iwamoto.

Collaborations

This project proceeds in very close collaboration with Glenn Bateman and his colleagues at the Princeton Plasma Physics Laboratory. Coordinated code and transport model development has been greatly facilitated by development by Singer and Bateman of methods to embed coding in Latex text documentation and automatically extract it for compilation on the NERSC computers. This allows instant access to current and high quality documentation through TELNET for all workers on the project. Bateman has been the most recent avenue for collaborated with W. Houlberg and colleagues, which has allowed us access to improved computational techniques as well. Development and documentation of theoretical transport models has also benefited from collaboration with R. Dominguez and colleagues at General Atomics. Experimentalists working on JET, JT-60, ASDEX, DIII-D, and other tokamaks have been extraordinarily helpful in providing complete and detailed background information on published and some as yet unpublished experiments. W. Miner and colleagues at the University of Texas, in Austin, have also facilitated access to their somewhat less detailed but far more comprehensive profile database. These collaborations have insured that our advanced statistical methods can be developed and applied with the best available transport models to the most practicably complete multi-institutional database.

Publications

- E.S. Ghanem, C.E. Singer, G. Bateman, and D. Stotler, "Multiple Mode Model of Tokamak Transport," Nucl. Fusion 30 (1990) 1595.
- C.E. Singer, W. Choe, D. Cox, T. Djemil, E. Ghanem, et al., "Predictive Modelling of Tokamak Plasmas," Proc. Thirteenth Intern. Conf. on Plasma Physics and Controlled Fusion Research, IAEA, Vol. 2 (Vienna, 1991) 265.
- D. Cox, J.S. Park, J. Sacks, and C. Singer, "Tuning Complex Computer Code to Data," Proc. Interactions Meeting (Seattle, 1991).
- G. Bateman, C.E. Singer, and J. Kinsey, "Transport Simulation Using Theory-Based Models," Proc. 18th European Conf. on Controlled Fusion and Plasma Physics (Berlin, 1991).
- E.S. Ghanem, J. Kinsey, and C. Singer, "Theory-Based Transport Simulation of Density Scaling," Proc. 19th European Conf. on Controlled Fusion and Plasma Physics (Innsbruck, 1992).
- T. Djemil, C.E. Singer, and D. Cox, "A Bayesian Analysis of Multisite Tokamak Confinement Data," submitted to Technometrics.
- D. Sigmar, R. Batchelor, G. Bateman, M.G. Bell, B.J. Braams, et al., "Physics Objectives and Design of CIT," Proc. Thirteenth Intern. Conf. on Plasma Physics and Controlled Fusion Research, IAEA, (Vienna, 1991).
- R.J. Goldston, R.E. Waltz, G. Bateman, D. Stotler, C.E. Singer, and J. Kinsey, "Confinement," Chap. III, pp. 1076-1112 of "Burning Plasma Experiment Physics Design Description," by R.J. Goldston, et al., Fusion Technology 21 (1992) 1047.

University of Maryland

Project

Maryland Controlled Fusion Research Program

T.M. Antonsen, J.F. Drake, J.M. Finn, P. Guzdar, A. Hassam, C.S. Liu, and E. Ott

Funding

FY 90	FY 91	FY 92
\$380k	\$430k	\$440k

Purpose

The general goal of Maryland Research Program is to address critical issues of tokamak physics and to suggest techniques for improving stability and confinement. Over the past three years we have focused on two key problems: a) the L/H transition and the dynamics of the edge plasma, and b) large scale disruptive events. The transition from low (L) to high (H) operation in tokamaks leads to a factor of 2-3 increase in the confinement time of energy. Because of the sensitivity of ignition to the energy confinement time, the design of future tokamaks such as ITER require H-mode operation. A sound understanding of the essential physical processes underlying the transition is therefore required if we are to have confidence that the H operation is possible in such future tokamaks.

Disruptions in tokamaks cause a rapid loss of the stored energy and toroidal current, and the associated development of large unbalanced forces can potentially damage the mechanical structure of the machine. Understanding these phenomena can lead to techniques for mitigating their impact by either early detection or feedback stabilization.

Approach

Experimentalists have demonstrated that the L/H transition is triggered in the edge of the tokamak, close to the divertor or limiter. Coincident with the transition is a sudden increase in the poloidal rotation and abrupt drop in the electric and magnetic fluctuations in the edge plasma. The working hypothesis is that the field fluctuations drive the transport and that the enhanced poloidal rotation at the H-mode onset shears apart the fluctuations, thereby improving confinement. Our approach is, therefore, to explore the source of fluctuations and particle and energy transport in the edge and to understand the bi-directional coupling between this turbulence and poloidal and toroidal flows in the edge so that a fully self-consistent theoretical model of the L/H transition can be constructed.

Tokomaks operate free of large scale instabilities or disruptions in a well-defined operating space defined by limits on the line-averaged density n and toroidal current I . As the boundary to this operational space is approached, (e.g., n approaches the density limit) the discharge undergoes an abrupt transition to a violently unstable state with strong magnetohydrodynamic (MHD) activity which causes a loss of stored energy on a time of the order of 100-200 μ s. The nature of this transition has been a mystery although observations indicate that near the density limit cooling of the plasma edge from line radiation leads to a contraction of the current profile. Our approach is to study the nonlinear behavior of large scale MHD modes in such contracting current profiles by including line radiation in a 3-D MHD code in an attempt to mimic the processes leading to disruptions in the actual experiments.

Progress

The resistive ballooning instability has been identified as the dominant source of transport in the plasma edge¹. The instability is driven by unfavorable curvature on the outside of the torus and therefore is intrinsic to toroidal plasmas. Toroidal fluid simulations have been completed² which demonstrate that transport rates are consistent with observations on the TEXT and DIII-D tokamaks and that the transport is peaked on the outside of the torus as inferred from experiments. Based on this instability we have developed a conceptual model of the tokamak edge in both L- and H-mode. We identify three important ingredients of the dynamics of the edge plasma: poloidally asymmetric transport driven by the resistive ballooning mode; parallel flows of the order of the sound velocity (c_s) produced by the asymmetric transport; and poloidal rotation produced by these parallel flows. The nonlinear interaction between these three components determines whether the plasma remains in L-mode or makes a transition to the H-mode. When the effective viscosity is large, the poloidal rotation remains small. Poloidally asymmet-

ric transport produces a significant variation of the density along flux surfaces in the edge and results in parallel flows of order c_s . This is the L-mode. Experimentalists on CCT and TEXT have recently confirmed the presence of the parallel flows in L-mode and measurements on DIII-D are planned. When the effective viscosity is small, the Stringer mechanism causes the edge plasma to spin.³ Poloidal rotation increases until poloidal rotation competes with the parallel flow in smoothing the edge poloidal asymmetries.² In this H phase the poloidal asymmetries and consequently parallel flows are greatly reduced. Transport is suppressed by sheared rotation, allowing steepened edge density gradients.³

Global 3-D MHD simulations of tokamak discharges with a model for line radiation have led to a new understanding of density limit disruptions.⁴ The key ingredient of this new model has been confirmed in experiments on TFTR in a collaboration between Maryland and Princeton.⁵ Cooling of the edge plasma leads to a contraction of profile of the toroidal current and eventually to a top hat current distribution (flat on top with steep sides) which is violently MHD unstable. The resulting kinking of plasma leads to the injection of the cold bubble into the interior of the discharge and to the subsequent breakup of the confining magnetic field and loss of stored energy. The injection of the cold bubble has been seen clearly in soft x-ray and ECE emission measurements on TFTR. Based on this theory, catastrophic disruptions can be prevented by maintaining a sufficiently high edge temperature (> 100 - 200 eV).

Plans

A fully self-consistent toroidal fluid simulation of the L/H transition is being undertaken which includes turbulent transport from resistive ballooning and poloidal and toroidal rotation. Key factors such as viscosity which control the onset of the L/H transition will be identified. A 3-D fully compressible MHD code has recently been developed which will be used to study disruptions in tokamaks with arbitrarily shaped cross-section. Density limit as well as β (plasma to magnetic pressure ratio) limit disruptions will be investigated with the goal of ultimately providing techniques for mitigating disruptions in large tokamaks.

Students

D.R. McCarthy, Ph.D. Dissertation: "Transport, Equilibrium and Stability of Toroidal Edge Plasma," (12/92).

Other Professional Staff

R.G. Kleva, R. Sagdeev and F.W. Waelbroeck

Collaborations

The Maryland theory group maintains an active interaction with experimentalists at Princeton University, University of Texas at Austin, General Atomics and U.C.L.A. and is active in various working groups in the Transport Task Force. The collaboration with Drs. Eric Frederickson, Kevin McGuire and the TFTR MHD group has led to a new understanding of disruptions.

Publications

1. D.R. McCarthy, P.N. Guzdar, J.F. Drake, T.M. Antonsen Jr., and A.B. Hassam, "Stability of Resistive and Ideal Ballooning Modes in TEXT and DIII-D," *Phys. Fluids B4*, 1846 (1991)
2. J.F. Drake, T.M. Antonsen Jr., J.M. Finn, P.N. Guzdar, A.B. Hassam, C.S. Liu, D. McCarthy and F.W. Waelbroeck, "Tokamak Edge Transport, the L-H Transition and Generation of Velocity Shear Layers," in *Plasma Physics and Controlled Nuclear Fusion Research* (IAEA, Vienna, 1991).
3. A.B. Hassam, T.M. Antonsen Jr., J.F. Drake, and C.S. Liu, "Spontaneous Poloidal Spin-Up of Tokamaks and the Transition to H Mode," *Phys. Rev. Lett.* **66**, 309 (1991).
4. R.G. Kleva and J.F. Drake, "Density Limit Disruptions in Tokamaks," *Phys. Fluids B3*, 372 (1991).
5. A. Janos, E. Frederickson, K. McGuire and the TFTR group and J.F. Drake and R.G. Kleva, "Phenomenology of Disruptions in the TFTR Tokamak," in *Plasma Physics and Controlled Nuclear Fusion Research* (IAEA, Vienna, 1991).

The University of Texas at Austin

Fusion Research Center

Project

Plasma Confinement Theory and Transport Simulation

David W. Ross

Funding

FY 90

\$870k

FY 91

\$775k

FY 92

\$800k

Purpose

The principal objectives of the Fusion Research Center (FRC) Theory Program are: (1) to advance tokamak studies generally by providing the Magnetic Fusion Energy Database (MFEDB) and other computational support, and (2) to provide theoretical interpretation and computer modelling for the Experimental Program on the TEXT and TEXT-Upgrade tokamaks.

Approach

The MFE database activity provides services for storing, retrieving, and manipulating profile data from tokamaks and stellarators in a form readily accessible for analysis and comparison with theory. We strive to maintain strong ties with laboratories supplying data to insure the diversity, quality, and correct interpretation of the data sets.

The FRC Theory Program contributes to the understanding of tokamak plasmas by providing computational aids, interpreting observations of turbulent fluctuations, incorporating theoretically based models into simulation codes, studying edge physics, and advancing the calculation of toroidal Alfvén waves. The emphasis is on the microscopic level, identifying features predicted by theoretical models and their effects on transport and heating.

Progress

1. Magnetic Fusion Energy Database

The Magnetic Fusion Energy Database (MFEDB) now contains profiles from more than 1000 discharges from nine different tokamaks. Recently, we have emphasized tools to access and manipulate the data and have moved the database to an IBM RS6000 which allows access via an X-window application. There is a batch-like procedure using *Netlib*-based software, which allows a user to mail an SQL query across the *Internet* and have the results mailed back. Our most powerful solution to the access problem, however, is a new interface called MDI, which uses a *Mathematica*® package that defines a basic set of MFEDB access functions and will also accept standard SQL queries. MDI also provides utility functions for plotting and analyzing the data, essentially making the MFE database an extension of *Mathematica*. MDI is an example of distributed computing. It relies on the network communication capabilities of *Mathematica* to connect the user to a workstation running the *Mathematica* kernel. The *Mathematica* kernel is then connected to the MFEDB host workstation by a client/server pair of RPC processes. The user may use any of the many *Mathematica* front-ends including Telnet, X-Windows, or a Macintosh interface. MDI has also been installed on a workstation at NERSC.

General queries about the database may be made to miner@hagar.ph.utexas.edu. The MDI.m package may be obtained by anonymous FTP from the MFE-database site or by use of netmfe, an E-mail interface. Send the message "help" to netmfedb@hagar.ph.utexas.edu.

2. Support for TEXT-Upgrade and Diagnostics

We have performed extensive calculations of TEXT-Upgrade divertor equilibria. Most recently, we adapted an iron-core version of the code EFIT (L.L. Lao et al., Nucl. Fusion **25**, 1611 (1985)) to run on the IBM RS6000. A typical case runs in 20 seconds, allowing the use of EFIT for magnetic analysis between shots.

We have designed, and assisted in assembling and testing, an apparatus to measure the magnetic-field profile on TEXT-U, using successive charge exchange collisions. Additional work has led to a design for a multi-chord apparatus to measure a q-profile in a single shot. We have studied TEXT fluctuation and transport diagnostics, with particular attention on calculating sample volume and attenuation effects in heavy ion beam probe fluctuation measurements, and on drift-wave interpretation of particle and energy fluxes.

3. *Instabilities and Transport*

We have developed and now maintain the CHAPO transport simulation code. Using CHAPO, we simulated oscillating gas-puff experiments on TEXT using models based on turbulence theory, with various dependencies on plasma parameters. In analogy with diffusion convection models, we investigated the importance of off-diagonal transport coefficients.

We are pursuing a broad range of edge physics and H-mode studies. We have calculated impurity flows in the presence of collisions and charge exchange. Impurity Rotation has been measured in TEXT and compared with the theory. We also collaborated in a study of particle, thermal, and impurity transport in He for comparison with H and D discharges. In some cases fluctuation measurements allowed an examination of proposed turbulence drive mechanisms. One of these, the effect of ionization on the drift wave instability is complicated by the non-existence of equilibrium assumed in the slab model, owing to the ionization. We have considered several equilibrium models to try to overcome this difficulty.

Neoclassical transport traditionally assumes a poloidally constant poloidal magnetic field. We are studying, both analytically and numerically, the effect of a magnetic X-point on particle orbits and the consequences for transport.

Working with General Atomics, we have considered, as an H-mode paradigm, a transport model that exhibits confinement bifurcation in time-dependent calculations. It assumes that turbulence is suppressed by shear in the equilibrium $\mathbf{E} \times \mathbf{B}$ flow.

We now benefit from work carried out in the former Soviet Union and continued at FRC. This includes, first, a new transport mechanism appearing specifically under cyclotron wave heating in toroidal devices, and second, a new approach to plasma transport where the toroidal drift is considered as a perturbation to the motion of particles in electromagnetic oscillations.

4. *Alfven Waves*

We have written an antenna-driven kinetic Alfven code to study toroidal eigenmodes. We have identified these modes as resonances in the impedance $Z(\omega)$, and plot the radial wave fields and energy deposition. Collaborating with the Institute for Fusion Studies (IFS), we compare with analytic theories.

Plans

We will focus our MFEDB efforts on strengthening contacts with experimentalists and ITER, obtaining additional data, and developing statistical analysis tools for use with MDI. We are preparing to include information, such as fluctuation amplitudes, that goes beyond the requirements of transport analysis. We have begun a statistical investigation to determine the parametric dependence of energy fluxes in auxiliary heated regimes, which we propose to develop into a collaboration among the laboratories.

TEXT-Upgrade and diagnostics support will include integrating the EFIT code with magnetic-probe data for plasma shape reconstruction, completion of the q-profile measurement, and investigating wave-number measurements with the new 2-MeV heavy-ion beam probe.

Theoretical studies will continue to emphasize edge physics and H-mode models, core fluctuations and transport, and perturbation experiments such as modulated gas puffing and electron cyclotron heating.

Other Professional Staff

William E. Drummond, W-Q. Li, Alan B. Macmahon, Robert T. McCann, William H. Miner, Emilia R. Solano, Prashant M. Valanju, James C. Wiley, Peter N. Yushmanov and Y-Z. Zhang.

Collaborations

Principal collaborations are with the TEXT program, including joint work with the Rensselaer heavy-ion beam-probe and the UCLA laser-scattering groups to interpret fluctuation measurements. Equilibrium studies have been pursued jointly with General Atomics. A publication on transport modelling arose from participation in the Transport Task Force. There is close contact with the Institute for Fusion Studies (IFS), including one joint appointment for theoretical-experimental liaison. The database project is also allied with the ITER CDA.

Selected Publications

E.R. Solano, L.L. Lao, and G.H. Nielson, "Equilibrium and Stability Studies for an Iron Core Tokamak with a Poloidal Divertor," Nucl. Fusion **30**, 1107 (1990).

W.A. Houlberg, D.W. Ross, G. Bateman, et al., "Modeling Transport in Toroidal Plasmas: Status and Issues," Phys. Fluids B **2**, 2913 (1990).

P.M. Valanju, R.D. Bengtson, and A. Ouroua, "Development of a New q-Diagnostic for TEXT," Rev. Sci. Instrum. **61**, 2935 (1990).

D.W. Ross, R.V. Bravenec, C.P. Ritz, et al., "Comparison of Drift Wave Models with Fluctuation Data from the Interior of the TEXT Tokamak," Phys. Fluids B **3**, 2251 (1991).

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- D.W. Ross, "On Standard Forms for Transport Equations and Quasilinear Fluxes," *Plasma Phys. and Contr. Fusion* **34**, 137 (1992).
- Y.Z. Zhang and S.M. Mahajan, "Impurity and Neutral Effects on the Dissipative Drift Wave in Tokamak Edge Plasmas," *Phys. Fluids* **4**, 207 (1992).
- B. Richards, M.E. Austin, R.V. Bravenec, et al., "Tests of Plasma Transport Models via Perturbation Techniques," *Nucl. Fusion* **32**, 567 (1992).
- P.M. Valanju, M.D. Calvin, R.D. Hazeltine, and E.R. Solano, "The Effect of Charge Exchange on Plasma Flows," *Phys. Fluids B* **4**, 2675 (1992).

University of Washington

Project

Helicity Injected Tokamak (HIT)—Supporting Theoretical Research

T.R. Jarboe

Funding

FY 92

\$35k

Purpose

The purpose of this portion of the Helicity Injected Tokamak (HIT) project is to provide theoretical analysis to complement the HIT experimental results. Since helicity injection current drive is not yet fully understood, calculations of the state of the plasma as it evolves in time will aid in interpreting the experiment data and enable us to develop a more complete model of helicity injection current drive. The resulting physical model will aid in applying the results of HIT to other fusion devices.

Approach

Our approach is to modify existing computer codes or develop new ones as needed to analyze the behavior of the HIT plasma. In particular, we plan to fit our experimental data to plasma equilibria using EFIT, an equilibrium and fitting code developed at General Atomics. This effort will require significant modifications of the basic EFIT code to enable it to accurately model the HIT experiment. In addition to doing equilibrium and fitting calculations with EFIT, we will analyze the time-dependent behavior of the plasma using 2-D and 3-D magnetohydrodynamic (MHD) codes. Initially we will use the MACH2 code developed at Los Alamos National Laboratories to do 2-D calculations. More detailed calculations will require a 3-D code. Although several such codes exist, we plan on developing a new code that solves the resistive MHD equations in conservative form, which has not been done before. The advantage of solving the equations in this form is that accuracy is retained even in regions of large gradients, due to the conservative nature of the equations.

Progress

We obtained the EFIT code from General Atomics and modified it to run on our computer system. The changes included replacing IMSL math subroutine calls with public domain LINPACK subroutines (suggested by E. Solano, University of Texas) and modifying output subroutines to work with the Interactive Data Language (IDL) plotting program. We first used EFIT in equilibrium mode to calculate the equilibrium flux surfaces for the HIT experiment. Then we used it to create best fit equilibrium surfaces using internal magnetic probe and partial Rogowski data. We are the first to successfully use the new "portable" (machine independent) version of EFIT in fitting mode. These initial calculations were presented at the 1992 APS meeting.

We also made progress in the area of MHD analysis. George Marklin of Phillips Laboratory helped us install MACH2 on the National Energy Research Supercomputer Center Cray 2 and trained us in using the code. We then modified several subroutines to allow us to accurately model the HIT magnetic fields due to the bias coil and toroidal field coils. Initial MACH2 simulations of HIT were presented at the 1992 APS meeting.

Plans

The first step in our equilibrium analysis will be to do further equilibrium fitting calculations using EFIT. A key challenge will be to determine the current on the open field lines on HIT. We also plan to verify the accuracy of our EFIT solutions by running baseline cases with only the vacuum field. After we are confident that we are accurately predicting the equilibrium flux surfaces, we will use the equilibrium surfaces as inputs to a stability code such as General Atomic's GATO code to determine stable and unstable modes.

Our plans in the MHD area are to do further calculations with MACH2 and to proceed with developing a new 3-D MHD solver. The first step in developing the new code will be to write a simple 2-D code to solve the ideal MHD equations in conservation law form. This code will enable us to quickly experiment with applying various solution methods that have been developed for the Euler and Navier-Stokes equations in fluid dynamics, which are similar in form to the MHD equations. When we have successfully adapted these techniques, we will extend them to 3-D and use the code for detailed analysis of the time evolution of the HIT plasma.

Other Professional Staff

S. Eberhardt, B.A. Nelson, and C. Zhang (Visiting Scientist, Institute of Plasma Physics, Academia Sinica, China)

Collaborations

General Atomics provided us with a copy of their EFIT computer code. We have also helped start an "EFIT Users Group" with General Atomics, the University of Texas at Austin, UCLA, MIT, and the Centre Canadien de Fusion Magnetique in Quebec. We plan to collaborate with the University of Manchester Institute of Science and Technology in the area of helicity injection current drive and low aspect ratio tokamaks. Ricardo Farengo of the Comision Nacional de Energia Atomica, Argentina will be providing assistance to us in the area of Taylor relaxation states.

Students

O.S. Jones

Recent Publications

A. Martin, T.R. Jarboe, O.S. Jones, B.A. Nelson, D. Orvis, C. Painter, J.P. Xie, C. Zhang, and L. Zhou, "Equilibrium and Plasma Source Studies on the Helicity Injected Tokamak," *Bulletin of the American Physical Society* **37**, 1492 (1992).

University of Wisconsin

Project

Auxiliary Radiofrequency Heating in Tokamaks

John E. Scharer

Funding

FY 90

\$80k

FY 91

\$70k

FY 92

\$50k

Purpose

This analytical and computational research is focussed on radio frequency heating, confinement enhancement and current drive for tokamak fusion plasmas. The current emphasis is on ion cyclotron frequency range (ICRF) antenna coupling, heating, confinement and current drive issues. We are examining methods for efficient new coil and waveguide antenna coupling of radiofrequency power (10-50 MW) to tokamak fusion plasmas. We are addressing absorption processes including ion and electron cyclotron harmonic heating and mode conversion processes in inhomogeneous tokamak plasmas. We are also examining the interaction of fusion produced alpha particles ($^4\text{He}^{++}$) with ion cyclotron frequency range heating. We are examining ion cyclotron frequency range heating to optimize break even and ignition conditions.

Approach

We have concentrated on efficient antenna coupling to fusion plasmas by means of an electromagnetic model with appropriate boundary conditions for Maxwell's equations to describe two dimensional antenna and waveguide arrays. The spectrum of the launched antenna array is coupled to the plasma surface impedance at the plasma-antenna edge region. The propagation of wave modes launched in the edge region is analyzed and reflections from the plasma steep edge density gradient region are incorporated in the analysis. The radiation resistance for coupling to the plasma and the spectrum of launched waves are evaluated. These quantities can be used to determine the wave absorption and heating of different plasma species at different locations in the plasma interior. We also examine the effect of antenna spacing and phasing to control the launched wave spectrum incident on the plasma interior. This has an important influence on the species heating and can be tailored, for example, to heat fast electrons to maintain toroidal current in the plasma which provides plasma confinement for long periods.

The second major area we are examining is that of heating different plasma species in the plasma interior. We have developed methods for analyzing what happens to ion cyclotron frequency range waves as they pass through the tokamak plasma interior. A formulation of nonlocal power absorption and a set of coupled differential equations is used to describe the wave fields in the plasma interior. A power conservation relation which examines incident, absorbed, mode converted, reflected and transmitted power is sought to describe the wave propagation and heating. We are currently extending this analysis to include fast ions and alpha particles which interact with the ion cyclotron frequency waves.

The above theoretical and computational work is applied to current and future planned tokamak experiments, such as the Tokamak Fusion Test Reactor (TFTR), the Joint European Tokamak (JET), the Tokamak Plasma Experiment/Steady State Advanced Tokamak (TPX/SSAT) and the International Tokamak Experimental Reactor (ITER). The comparison with current experimental results provides confidence to predict future performance and physics results for planned experiments.

Progress

We have made progress in the area of ion cyclotron frequency range antenna and edge plasma modelling for efficient coupling and heating of radio frequency power to tokamak plasmas. We developed a new computer code called ANTIMP which was used to examine coupling efficiencies and launched wave spectra for the Burning Plasma Experiment (BPX) which utilized substantial ICRF power. The code incorporates finite toroidal and poloidal cavities, a current distribution on the antennas enclosed and multiple feeders to optimize power handling capabilities for coupling to high confinement H-mode edge density profiles. We compared our predictions to those measured on JET to benchmark our results and found moderate agreement. We found that the poloidal cavity extent reduced the radiation resistance and modified the antenna spectrum for applications including current drive. We published these results in the Nuclear Fusion and Fusion Science and Technology journals.

We have also made progress in the area of ion cyclotron frequency range heating and mode conversion in inhomogeneous plasmas. We have developed fundamental expressions for nonlocal power absorption, kinetic flux and wave propagation in a hot, inhomogeneous plasma with transverse magnetic field gradients. The analysis that we developed incorporates nonlocal reflections, wave absorption for fundamental and second harmonic ion cyclotron frequencies and electron Landau and transit time absorption. It also examines mode conversion between fast magnetosonic and ion Bernstein waves in the plasma. A power conservation relation is also developed which is accurate as long as the transverse wavelength is larger than the ion gyroradii. We have examined fundamental $^3\text{He}^{++}$ heating in the JET tokamak as an application and published the work in the *Physics of Fluids*. The primary results show strong fundamental $^3\text{He}^{++}$ absorption for fast wave incidence and strong, almost complete, $^3\text{He}^{++}$ absorption for ion Bernstein wave incidence from the high field side of the tokamak. This heating scenario is a necessary objective for heating deuterium-tritium fusion plasmas.

Plans

We are currently extending our antenna analysis by writing an object oriented computer code to incorporate three dimensional effects including the antenna feeders and an adjustable alignment between the Faraday shield and the tokamak magnetic field. We are focussing on the wave behavior in the high density gradient edge region and the possible launching of some ion Bernstein wave power in addition to the dominant fast magnetosonic wave power coupled to the plasma. Once the analysis and computer program are completed, we will address current and planned heating and current drive experiments in TFTR, JET and TPX/SSAT.

Our current research is also focussed on the evaluation of alpha particle and neutral beam particles heated by ion cyclotron frequency range waves. This can have an important influence on such topics as fusion reactivity, plasma stability, current drive and fusion product ash removal. We are utilizing equivalent Maxwellian distributions to represent the slowing down distributions of fast fusion produced alpha particles and neutral beams which interact with the waves in planned experiments for TFTR, JET and ITER. We are focussing on fundamental deuterium heating and second harmonic tritium heating because of their promise and on plans for near term and future tokamak high fusion reactivity experiments. We are examining integral equation methods which will accurately describe large gyroradius wave nonlocal interactions and include the effect of trapped particles and the parallel magnetic field gradient in the formalism.

Other Professional Staff

We have had Dr. Nguyen Lam, an assistant scientist and Dr. Brian McVey, a visiting senior scientist from Los Alamos National Laboratory who have collaborated with us during the past three years.

Collaborations

This research has and continues to benefit from collaborations with Drs. Jean Jacquinet and V. Bhatnagar at JET, Drs. Pat Colestock, Cynthia Phillips, Dick Majeski and Randy Wilson at Princeton Plasma Physics Laboratory and Dr. Don Batchelor at Oak Ridge National Laboratory.

Students

Brad Jost, Michael Bettenhausen and Richard Sund are currently Ph.D. dissertation students and have contributed substantially to the research program. We have also benefited from graduate students Yiannikis Mouzourkis and Jeffrey Rufinus.

Major Recent Publications

1. N.T. Lam and J.E. Scharer, "Analysis of an ICRF Waveguide Launcher for CTF," *Fusion Engineering and Design* 7, 1-6 (1990).
2. B.M. Jost and J.E. Scharer, "An Analysis of the Folded Waveguide: A Compact Waveguide Launcher for ICRF Heating," *IEEE Journal of Plasma Sciences*, 78, 802-813 (1990).
3. R. Sund and J. Scharer, "Full Wave Field Solutions and Power Conservation for the Ion Cyclotron Range of Frequencies (ICRF) in Nonuniform Plasmas," *Physics of Fluids B* 3, 1326-1337 (1991).
4. N.T. Lam, J.E. Scharer and M.H. Bettenhausen, "Effects of the L- to H- Mode Transition in BPX on a Recessed Coil Antenna," *Nuclear Fusion*, 31, 2141-2146 (1991).
5. D.B. Batchelor, ..., J.E. Scharer, et al., "The Burning Plasma Experiment, Part VI, ICRF Heating," *Fusion Technology* 27, 1214-1242 (1992).
6. N.T. Lam, J.E. Scharer and R. Sund, "Influence of Alpha Particle Absorption on ICRF Heating in a Fusion Plasma," submitted to *Nuclear Fusion*, (1992).
7. J.E. Scharer, N.T. Lam and R.S. Sund, "Analysis of ICRF Coupling and Heating in CTF and JET," 17th Conference on Controlled Fusion and Plasma Heating, *IAEA*, Part III, 1023-1026 (1990) Amsterdam.
8. J.E. Scharer, N.T. Lam and M. Bettenhausen, "ICRF H- Mode Coupling and Heating in BPX and JET," 18th European Conference on Controlled Fusion and Plasma Physics, *IAEA*, Part III, pp. 381-384 (1991) Berlin.

University of Wisconsin-Madison

Phaedrus Laboratory for Plasma Science

Project

Low Frequency RF Current Drive

N. Hershkowitz, C. Litwin and P. Moroz

Funding

FY 90	FY 91	FY 92
\$95k	\$95k	\$96k

Purpose

The goal is to develop theoretical and numerical support of the Phaedrus-T experimental program on low frequency current drive in the Phaedrus-T tokamak, as well as scaling the effects found to reactor parameters. Of specific interest are nonresonant Alfvén wave current drive effects.

Approach

The theoretical program includes analytical and numerical investigations and consists of seven interrelated components: (1) ICRF and Alfvén wave physics studies in a tokamak; (2) Resonant and nonresonant low frequency current drive studies including effects of possible non-Maxwellian electron distribution in a tokamak; (3) Helicity current drive studies. Analysis of helicity content associated with the waves and with the plasma currents, and the helicity balance during wave absorption in a tokamak plasma; (4) Investigation of local Alfvén resonance and mode conversion to the kinetic Alfvén wave and local ion-ion hybrid resonance and mode conversion to the ion Bernstein wave from the point of view of their effects on RF current drive; (5) Global Alfvén waves (GAW) and Toroidicity Induced Alfvén Wave Eigenmodes (TAE) in a tokamak and their effects on low frequency RF current drive; (6) Low frequency RF current drive efficiency studies including effects of electron trapping due to magnetic field inhomogeneity and electron detrapping under the influence of waves and collisions; (7) Current drive by Alfvén wave induced dynamo enhanced by various anomalous processes. Alpha particle effects on the current drive in a reactor. Effects of particle trapping and sawtooth oscillations in the presence of Alfvén wave-induced dynamo.

Progress

Theoretical efforts have yielded a locally developed RF modeling capability (the full wave codes, FASTWA and FASTWAC, and the 1-D code, FAST1D) which can deal with such important features of the Phaedrus program as wave coupling, propagation, absorption and RF current drive in a tokamak at arbitrary antenna phasings and frequencies from slightly below to above the ion cyclotron frequency, including the fast wave frequency range. The $E_{\parallel}$ effects and electron power deposition through Landau damping, TTMP, and the cross-term effect have been considered in detail because they are the main source for RF current drive. Analytical investigation of resonant current drive, which is due to resonant Cherenkov wave-electron interactions, nonresonant electron current drive, which is due to wave-ion interactions or collisions, and helicity current drive, related to the wave helicity flux, are being pursued. Ohmic and bootstrap currents (for given density and temperature profiles) have also been included in the analysis.

We have shown that the ponderomotive force of applied waves can stabilize the internal kink and might be responsible for sawtooth stabilization observed in several experiments. Generalizing this approach to resistive instabilities we have more recently shown that the electron magnetization induced by electromagnetic oscillations can decrease the growth rate of the kink-tearing mode. This might affect the reconnection process after the sawtooth crash and help to explain the apparent freezing of the safety factor on the axis throughout the sawtooth period.

We have addressed the question of the dynamo effect enhancement by the stochastic magnetic field. Field line stochasticity has two effects on Alfvén waves: it causes current filamentation and current diffusion. The collisionless dissipation due to the current diffusion is found to increase the dynamo field compared to the collisional case but this effect is not dramatic for realistic parameters. However, current filamentation and subsequent enhanced resistive dissipation appears to lead to a much larger effect.

Plans

Our studies of current drive have been motivated by trying to understand the role of wave helicity as an efficient current drive method working in a hot and dense tokamak plasma. These studies have led us to the study of Alfvén waves.

During the coming year we plan to continue our study of various RF current drive components: resonant, nonresonant and helicity. Also, we plan an investigation of a current produced directly by Alfvén waves and indirectly by waves that are excited by mode conversion within the plasma. We plan to devote time to the study of Alfvén wave physics, wave penetration, mode conversion and excitation of global Alfvén waves, as well as electron absorption of the waves.

Numerical codes will be extended to include effects of the magnetic field produced by plasma currents in a tokamak, coupling of various eigenmodes due to toroidicity, inhomogeneity or plasma shape effects. Current drive by an Alfvén wave induced dynamo enhanced by various anomalous processes will be studied.

We are presently continuing to investigate the effect of magnetic field line stochasticity on nonresonant Alfvén wave current drive, in particular the effect of current filamentation. We are considering field line stochasticity generated by magnetic islands (e.g., due to bootstrap-current driven tearing modes or by externally generated islands).

In the coming year we shall continue the investigations of the nonresonant current drive taking into account the Landau damping which will be modelled via gyroviscosity. Finally we shall investigate possible effects of alpha particles on Alfvén wave current drive.

Major Recent Publications

1. P.E. Moroz, P.L. Colestock, "Electron Absorption of Fast Waves in Global Wave Calculations," *Plasma Phys. and Contr. Fusion* **33**, p.417 (1991).
2. P.E. Moroz, N. Hershkowitz, "Mode Conversion in Global Wave Calculations," *Sherwood International Fusion Theory Conf.*, Seattle, WA, April 1991, Paper 1C13.
3. N. Hershkowitz, P.E. Moroz, R. Majeski, J.A. Tataronis, "Numerical Modeling of ICRF Heating and Current Drive," *Sherwood International Fusion Theory Conf.*, Seattle, WA, April 1991, Paper 1D9.
4. J.A. Tataronis, P.E. Moroz, N. Hershkowitz, "Fast Wave Helicity Current Drive in Tokamaks," *Proc. 18th Eur. Conf. on Contr. Fusion and Plasma Physics*, Berlin, 1991, Vol. 15C, Part III, p.289.
5. P.E. Moroz, N. Hershkowitz, "Mode Conversion Analysis Based on the Fast Wave Consideration," University of Wisconsin-Madison Report PLR-91-8 (1991), and in *Radio-Frequency Power in Plasmas: 9th Top. Conf.*, Charleston, SC, 1991, American Institute of Physics, New York, 1991, Ed. D. B. Batchelor, p. 201.
6. J.A. Tataronis and P.E. Moroz, "Helicity Injection and Fast Wave Current Drive in Tokamaks," *Invited Paper, Proc. IAEA Technical Committee Meeting on Fast Wave Current Drive in Reactor Scale Tokamaks*, Arles, France, Sept. 1991, p. 166.
7. P.E. Moroz, N. Hershkowitz, R.P. Majeski, J.A. Tataronis, "Fast Wave Damping on Non-Maxwellian Electrons," *Physics of Fluids B* **4**, 2915 (1992).
8. P.E. Moroz, N. Hershkowitz, J.A. Tataronis, "Theoretical Studies of Low Frequency Plasma Heating and Current Drive in Tokamaks," *Sherwood International Fusion Theory Conf.*, Santa Fe, New Mexico, April 1992, 1C48.
9. P.E. Moroz, N. Hershkowitz, J.A. Tataronis, "Theoretical Studies of Fast Wave Plasma Heating and Current Drive in Tokamaks," *Proc. Int. Conf. on Plasma Physics*, Innsbruck, Austria, July 1992, Vol. 16c, Part II, 909 (1992).
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11. M. Porkolab, D.B. Batchelor, S. Bernabei, P.T. Bonoli, D. Ehst, R. Englade, M.E. Fenstermacher, R. J. Goldston, L.R. Grisham, N. T. Lam, T. K. Mau, D. Mikkelsen, P. Moroz, W.M. Nevins, G.H. Neilson, J. Scharer, G. Smith, D. Swain, J. Yugo, "Non-Inductive Current Drive Scenarios and Bootstrap currents in the Steady-State Advanced Tokamak," *Proc. Eur. Top. Conf. on RF Heating and Current Drive of Fusion Devices*, Brussels, Belgium, 1992, Vol. 16E, p. 119.
12. R. Majeski, N. Hershkowitz, P. Probert, P. Moroz, D. Diebold, T. Tanaka, R. Breun, D. Bouchous, R. Fonck, T. Intrator, M. Kishinevsky, G. McKee, P. Nonn, J. Sorensen, M. Vukovic, "Recent RF Results from the Phaedrus-T Program," *Proc. 14th IAEA Int. Conf. on Plasma Phys. and Contr. Fusion Research*, Wurzburg, Germany, 1992, Paper IAEA-CN-56/E-3-7.
13. P.E. Moroz, "Global Analysis of Radio-Frequency Current Drive," University of Wisconsin-Madison, Report PLR-92-18 (1992); submitted to *Plasma Phys. and Contr. Fusion*.
14. R. Majeski, P. Probert, P. Moroz, T. Intrator, R. Breun, D. Bouchous, H.Y. Che, J.R. DeKock, D. Diebold, M. Doczy, R. Fonck, N. Hershkowitz, R. D. Johnson, M. Kishinevsky, G. McKee, J. Mayer, P. Nonn, S. P. Oliva, J. Pew, J. Sorensen, T. Tanaka, M. Vukovic, G. Winz, "Alfvén Wave Experiments in the Phaedrus-T Tokamak," to be published in *Phys. of Fluids*.
15. C. Litwin, "Alfvén-Ion-Cyclotron Instability and Absence of Sawteeth in Tokamaks," *Phys. Fluids B* **2**, 463 (1990).
16. C. Litwin, S.C. Prager, "Effect of Drift-Alfvén Wave Fluctuations on Internal Resistive Kink," *Sherwood International Fusion Theory Conf.*, Seattle, WA, April 1991, Paper 3C5.
17. C. Litwin, "Fluctuations and Low-Frequency Stability," *Phys. Fluids B* **3**, 2170 (1991).
18. C. Litwin, N. Hershkowitz, "Ponderomotive Current Drive by Alfvén-Ion-Cyclotron Waves", *Sherwood International Fusion Theory Conf.*, Santa Fe, New Mexico, April 1992, 2C29.

The University of Wisconsin

Project

Low Frequency RF Current Drive Theory: Task 1 of the Phaedrus Grant

J. A. Tataronis

Funding

FY 92

\$44k

FY 93

\$60K

Purpose

To explore and evaluate nonresonant radio frequency (RF) current drive processes in toroidal plasma configurations. Radio frequency current drive is normally viewed as a resonant wave-particle process that acts asymmetrically on a select group of electrons. However, current can also be produced by nonresonant processes associated with macroscopic wave forces that affect the bulk plasma dynamics rather than a select group of charged particles. For example, at low frequencies, the wave-induced dynamo electric field results in a nonresonant force that can produce a steady current. The research focuses on current drive by plasma waves in the ion cyclotron range of frequencies and below.

Approach

Our research emphasizes nonresonant current drive resulting from magnetohydrodynamic (MHD) waves. The analysis is self-consistent, meaning that the modeling of the wave propagation is coupled directly to the changes of the equilibrium by the induced current. RF fields are represented, in quasi-plane wave form, with slowly varying envelopes that result from plasma dissipation, spatial inhomogeneities of the plasma and nonlinear mode interactions. The goal of our analysis is to associate the changes of the wave envelopes with current evolution in the background plasma. We are now expanding our research to include neoclassical effects. The analysis will be based on a kinetic treatment of the plasma dynamics.

Progress

We have succeeded in connecting, in a self-consistent manner, circularly polarized MHD waves to the evolution of current in the plasma equilibrium. We have derived analytical solutions of the nonlinear MHD equations that relate the induced average current to the RF wave amplitude. The induced current can be connected to a transfer of wave helicity to the helicity of the background magnetic field. Our results demonstrate that the current is strongly influenced by plasma dissipation and spatial inhomogeneities of the plasma profiles.

Plans

During the new grant period (FY 93), we plan to include neoclassical effects in our analysis of nonresonant current drive. Past work suggests that trapped particles can limit the current produced by resonant forces. We will determine if an analogous limitation is associated with nonresonant forces. A second issue that we will treat is the influence of nonresonant wave forces on the bootstrap current. Our analysis will be based on the macroscopic moment equations of each particle species, corrected to account for neoclassical effects.

Students

Richard Mett wrote his Ph.D. thesis on the subject of nonresonant current drive. A new doctoral student, Shahid Raufwill, will join the project in January 1993.

Other Professional Staff

None

Collaborations

We are currently establishing a collaboration with Dr. A.G. Elfimov, who is a plasma theorist at the I.N. Vekua Institute of Physics and Technology, Sukhumi, Georgia, and Dr. V. Petrzilka, a theorist at Institute of Plasma Physics, Czechoslovakia Academy of Sciences, Prague. Doctors Elfimov and Petrzilka have extensive experience in RF processes in toroidal plasma. Contact with them should enhance this program.

Publications

- R.R. Mett, and J.A. Tataronis, "Plasma Current Drive via Magnetohydrodynamic Helicity Waves," *Phys. Rev. Letts.* **63**, 1380 (1989).
- R.R. Mett, and J.A. Tataronis, "Current Drive via Magnetohydrodynamic Helicity Waves in a Nonuniform Plasma," *Phys. Fluids B* **2**, 2334 (1990).
- R.R. Mett, and J.A. Tataronis, "Current Drive via Injection of Wave Helicity," Joint Varenna-Lausanne International Workshop on the Theory of Fusion Plasmas, Villa Monastero, Varenna, Italy, 27-31 August 1990 [paper published in workshop proceedings, p. 453].
- J.A. Tataronis, "Current Drive via Magnetohydrodynamic Helicity Waves," Annual Meeting of the Plasma Physics Division of the American Physical Society, Cincinnati, OH, November 12-16, 1990, **Invited Talk**.
- J.A. Tataronis, P.E. Moroz, and N. Hershkowitz, "Fast Wave Helicity Current Drive in Tokamaks," 18th European Conference on Controlled Fusion and Plasma Physics, Berlin, Germany, 3-7 June 1991 [paper published in conference proceedings, Volume III, page 289].
- J.A. Tataronis and P.E. Moroz, "Helicity Injection and Fast Wave Current Drive," IAEA Technical Committee Meeting on Fast Wave Current Drive in Reactor Scale Tokamaks (Synergy and Complementarity with LHCD and ECRH), Arles, France, 23-25 September 1991, **Invited Talk** [paper published in conference proceedings, page 166].

University of Wisconsin–Madison

Project

Magnetic Confinement Fusion Plasma Theory

J.D. Callen

Funding

FY 90	FY 91	FY 92
\$336k	\$275k	\$265k

Purpose

This project is concerned with developing magnetic confinement theory for controlled thermonuclear fusion plasmas. The major emphasis is on unique development areas that bear upon experimental and fusion reactor design studies at University of Wisconsin at Madison, and on experiments in the largest tokamaks in the world. In particular, the research has recently concentrated on the following important anomalous transport areas: 1) development and application of a new Chapman-Enskog-like approach for deriving fluid/kinetic descriptions of plasmas; 2) development of a new paradigm for tokamak plasma behavior and transport based upon constantly interacting magnetic islands; 3) collaboration with Beam-Emission-Spectroscopy (BES) diagnosticians on understanding core plasma fluctuation data; and 4) developing net transport equations for a tokamak plasma. In addition, during FY 90 and 91, the Principal Investigator led the U.S. fusion program Transport Task Force activity.

Approach

Although aimed toward explaining various experimental results, this research is entirely theoretical. Approximately half of the research is analytical and half computational. The computational studies are carried out partially on local computer workstations, with the larger, more time-consuming calculations being done on the NERSC CRAYs at LLNL.

Progress

Major areas in which significant progress was accomplished over the past three fiscal years on this project were:

1. Neoclassical MHD.

This theory of fluid-like phenomena in a resistive-MHD-like tokamak description, which adds the effects of the parallel viscous force that damps poloidal flows in the torus, has been significantly expanded beyond its pioneering development on this grant in the mid 1980's. The neoclassical MHD theory, which is more relevant for the present generation of low collisionality tokamaks than resistive MHD, has been applied to studies of pressure-gradient-driven and tearing type instabilities in tokamaks [1, 4], ion-temperature-gradient type instabilities [5, 6] and other tokamak plasma instabilities and turbulence studies. Also, a new paradigm for the tokamak plasma "equilibrium" based upon a constantly interacting set of neoclassical MHD mini magnetic islands has been proposed [15].

2. Transport Task Force (TTF).

This OFE/DOE-sponsored U.S. program-wide activity was initiated and led by the Principal Investigator on this grant during the 1988-91 period. The early TTF reports on the status of transport studies were published in late 1990 [3]. A major *Physics Today* article that emphasized the importance of the scientific research on plasma turbulence and transport was published in early 1992 [8]. A summary of TTF progress during its first 3 years of existence was presented as a major review paper at the American Physical Society's Division of Plasma Physics meeting in late 1991 and published in the *Physics of Fluids* in mid 1992 [16].

3. Effects of Macroscopic Phenomena On Energy Confinement.

A theory quantifying the effects of macroscopic phenomena (sawteeth, Mirnov oscillations, ELMs) and heating profiles on energy confinement in tokamaks was developed [2]. This theory was used to explore the significance of sawtooth effects on energy confinement in DIII-D plasmas at low q and high density [9], and to quantify their potential impact in ITER [7].

4. New Chapman-Enskog-like Approach.

A new approach for developing rigorously valid, hybrid fluid/kinetic generalization of the Chapman-Enskog approach in the kinetic theory of gases has been developed over the past few years [10–12]. In particular, collisional [10] and collisional [11, 12] formalisms and concomitant closure relations for the fluid moment equations have been developed. Also, the nonlinear form of the gyroviscous forces has been clarified [14], and the fluid-like

moment equations are being used to develop net transport equations relative to fluctuating magnetic plus vorticity flux surfaces in a tokamak plasma.

Plans

The primary emphasis at present is on exploring mini magnetic island effects in tokamaks, and particularly in further developing our new "magnetic bubbling" paradigm for tokamak "equilibrium" and transport. In addition, we plan to: a) use our new Chapman-Enskog-like approach to continue calculations of the needed viscosity coefficients for calculating an appropriate neoclassical Ohm's law in fusing D-T plasmas and to extend the neoclassical MHD description to include dynamical and Landau-damping effects; b) continue our development of a new formalism for determining net transport in tokamaks with fluctuating electric and magnetic fields; and c) finish interfacing with the TRANSP code at PPPL the impurity state code that we have developed [13] for calculating absorption of an energetic neutral beam injected into tokamak plasmas containing a mixture of hydrogenic and impurity species.

Students and Postdocs

Undergraduate student:

S.P. Schulz ('90, 3 mos.)

Graduate students:

Z. Chang ('87-'91), R.L. Coffey ('92-), T.A. Gianakon ('88-), J.B. Hollenberg ('88-), M.W. Kissick ('87-), B.J. Lee ('86-'91), T. Thorson ('91-'92), J.P. Wang ('87-'91).

Postdocs:

Z. Chang ('91, 6 mos.), C.C. Hegna ('91-), B.J. Lee ('91, 3 mos.), K.L. Sidikman ('90, 3 mos.), J.P. Wang ('91, 6 mos, '92-).

Ph.D. theses:

J.P. Wang, "Fluid/Kinetic Hybrid Moment Description of Plasmas via a Chapman-Enskog-like Approach," (Jan. 1991), Z. Chang, "Unified Plasma Fluid/Kinetic Equations for Tokamak Microinstability and Turbulence Studies," (March 1991), B.J. Lee, "Fluidlike Studies of the Sheath and Presheath Regions of a Plasma," (May 1991).

Other Professional Staff

Visitors: A.K. Sundaram, Institute for Plasma Research, INDIA ('90-'91, 3 mos.); G. Rowlands, University of Warwick, ENGLAND ('90, '92, 1-1/2 mos.)

Collaborations

During the 1990-'91 period, we collaborated extensively with A.G. Kellman, D.P. Schissel, and R.D. Stambaugh of the DIII-D experiment at General Atomics on the subject of sawtooth-induced energy confinement degradation effects at low edge safety factor [9]. Over the last couple of years we have been collaborating with TFTR experimentalists at PPPL, particularly K. McGuire, M.C. Zarnstorff, P.C. Efthimion and E.D. Fredrickson, primarily on subjects related to anomalous transport processes in D-T relevant plasmas. The Principal Investigator on this grant spent the 1991-'92 academic year and the summer of 1992 in the Princeton, New Jersey area and was a visiting scientist at PPPL during that period.

Recent Publications

- [1] J.D. Callen, Y.B. Kim, A.K. Sundaram, B.A. Carreras, L. Garcia, K.C. Shaing, D.A. Spong, H. Biglari, P.H. Diamond, O.J. Kwon, "Neoclassical MHD Descriptions of Tokamak Plasmas," in *Plasma Physics and Controlled Nuclear Fusion Research 1988* (IAEA, Vienna, 1989), Vol. II, p. 55.
- [2] Z. Chang and J.D. Callen, "Global Energy Confinement Degradation Due to Macroscopic Phenomena in Tokamaks," *Nuclear Fusion* 30, 219 (1990).
- [3] J.D. Callen, "Anomalous Transport in Tokamaks, Transport Task Force Reviews," *Phys. Fluids B* 2, 2869 (1990).
- [4] A.K. Sundaram and J.D. Callen, "The Evolution of Resistive Ballooning Modes in the Banana-Plateau Collisionality Regime," *Phys. Fluids B* 5, 336 (1993).
- [5] Y.B. Kim, P.H. Diamond, H. Biglari and J.D. Callen, "Theory of Neoclassical Ion Temperature Gradient Driven Turbulence", *Phys. Fluids B* 3, 3584 (1991).
- [6] Y.B. Kim, H. Biglari, B.A. Carreras, P.H. Diamond, R.J. Groebner, O.J. Kwon, D.A. Spong, J.D. Callen, Z. Chang, J.B. Hollenberg, A.K. Sundaram, F.W. Terry, J.P. Wang, "Tokamak Fluidlike Equations With Applications to Turbulence in H-Mode Discharges," in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991), Vol. II, p. 527.

- [7] N.A. Uckan, P.N. Yushmanov, T. Takizuka, K. Borass, J.D. Callen, J.G. Cordey, S. Cohen, F. Engelmann, O. Kardaun, S.M. Kaye, K. Lackner, V.S. Mukhovatov, A. Noncentini, V.V. Parail, D.E. Post, S. Putvinskii, K. Reidel, T. Tsunematsu, R. Yoshino and the participants in the ITER Conceptual Design Activities, "Energy and Particle Confinement in ITER", in *Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna, 1991), Vol. III, p. 307.
- [8] James D. Callen, Benjamin A. Carreras and Ronald D. Stambaugh, "Stability and Transport Processes in Tokamak Plasmas," *Physics Today* **45** (January), 34 (1992).
- [9] D.P. Schissel, A.G. Kellman, R.T. Snider, R.D. Stambaugh, K.H. Burrell, J.C. DeBoo, T.H. Osborne, J.D. Callen, Z. Chang, "Examination of Energy Confinement in DIII-D at Small Values of the Plasma Safety Factor," *Nuclear Fusion* **32**, 107 (1992).
- [10] J.P. Wang and J.D. Callen, "Fluid/Kinetic Hybrid Moment Description of Plasmas via a Chapman-Enskog-like Approach," *Phys. Fluids B* **4**, 1139 (1992).
- [11] Z. Chang and J.D. Callen, "Unified Fluid/Kinetic Description of Magnetized Plasmas. Part I: Basic Equations in a Sheared Slab Geometry," *Phys. Fluids B* **4**, 1167 (1992).
- [12] Z. Chang and J.D. Callen, "Unified Fluid/Kinetic Description of Magnetized Plasmas. Part II: Applications," *Phys. Fluids B* **4**, 1182 (1992).
- [13] T.A. Gianakon, R.J. Fonck, J.D. Callen, R.D. Durst, J.S. Kim, S.E. Paul, "Effects of Edge Plasma Turbulence on Radial Correlation Length Measurements with BES," *Rev. Sci. Instrum.* **63**, 4931 (1992).
- [14] Z. Chang and J.D. Callen, "Generalized Gyroviscous Force and its Effect on the Momentum Balance Equation," *Phys. Fluids B* **4**, 1776 (1992).
- [15] C.C. Hegna and J.D. Callen, "Interaction of Bootstrap-Current-Driven Magnetic Islands," *Phys. Fluids B* **4**, 1855 (1992).
- [16] J.D. Callen, "Transport Processes in Magnetically Confined Plasmas," *Phys. Fluids B* **4**, 2142 (1992).

University of Wisconsin–Madison

Project

Stellarator Theory

W.N.G. Hitchon

Funding

FY 90	FY 91	FY 92
\$40.0k	\$40.0k	\$49.9k

Purpose

We are providing theoretical and numerical tools to aid in understanding plasma behavior in stellarators and other fusion devices. In particular, we are promoting development of the stellarator configuration by modeling the Wisconsin stellarators, and by studying proposed new devices.

Approach

The key issues that we have focused on have been primarily transport related, and have been addressed by means of self-consistent kinetic calculations. These have included analytic and numerical treatments of ripple transport, and numerical studies of edge plasma behavior. To these ends we have developed new numerical methods for solving kinetic equations and performed detailed comparisons with experiments. We have also developed extremely flexible tools for describing 2-D plasmas and their self-consistent electric fields, which can readily be used and modified by non-experts.

Progress

In the last 3 years, we have developed two numerical schemes, which have been used in several codes and in the solution of a variety of problems. The first of which is a procedure for solution of kinetic equations, in one or more of both velocity and space coordinates. This consists of finding a Green's function, in order to advance the distribution function in time. The particular Green's function we have developed is easy to implement, allows large time steps, conserves particles and energy exactly and provides low levels of numerical diffusion. This has been used in self-consistent kinetic studies of stellarator (and other) edge-plasmas.

We have also written a powerful general-purpose numerical tool, which is in some regards a high-level computer language, the Simulation Generation Language And Translator (or SGLAT). This allows a set of finite difference or other sets of equations to be the input in their 'usual' form, and 'SGLAT' writes a code to solve these equations, using a Newton's method. SGLAT constructs a Jacobian matrix by symbolic differentiation, and inverts the matrix equations, using sparse matrix techniques as appropriate. SGLAT is distinct from other packages of which we are aware, in its ability to handle massive sets of equations. This allows it, for instance, to easily solve the continuity and Poisson equations consistently and implicitly, in a 2-D plasma. This permits non-expert users to set up and solve problems which have previously been out of reach of most plasma physicists. This has obvious applications to experiments involving biasing of divertor plates and probe measurements, in stellarator plasmas.

Plans

We are in the process of extending our self-consistent kinetic codes to 2-D, so as to be able to study divertor behavior in stellarators in a highly realistic fashion. We are also using SGLAT in 2-D self-consistent fluid calculations, to model electrostatic phenomena in the Interchangeable Module Stellarator.

Students

T.S. Chen, K. Kramer, K.A. Buckle (Ph.D. 1984), C.D. Beidler (Ph.D. 1987) and W.D. D'Haeseleer (Ph.D. 1988).

Publications

W.D. D'Haeseleer, W.N.G. Hitchon, and J.L. Shohet, "Self-Consistent Numerical 'Bounce-Averaged' Transport Computations in Stellarators Employing a Multi-Mesh Approach," *J. Comp. Physics*, Vol. 95, (1991) 117-166.

C.D. Beidler, W.N.G. Hitchon, D.L. Grekov, and A.A. Shishkin, "Monte Carlo Evaluation of Neoclassical Transport in Torsatrons with Different Helical Winding Laws," *Nucl. Fus.*, 30, (1990) 405-411.

M.A. Hussein, and W.N.G. Hitchon, "Effect of Ion-Neutral Collisions on Plasma Flow in the Edge Region of Stellarators," *Nucl. Fus.*, 31, (1991) 2107-2116.

University of Wisconsin–Madison

Project

Theoretical Reversed Field Pinch and Tokamak Studies

S.C. Prager, P.W. Terry and J.D. Callen

Funding

FY 90	FY 91	FY 92
\$60k	\$75k	\$75k

Purpose

To investigate the cause and transport consequences of fluctuations in the reversed field pinch (RFP) fusion concept. Transport of particles, energy, and current is studied. Based upon the developing understanding, techniques are devised to reduce the fluctuations and transport. Topics are investigated which also have application beyond the RFP, particularly to the tokamak.

Approach

Analytic and computational techniques are employed to study turbulence and transport. Nonlinear three-dimensional resistive magnetohydrodynamic computation investigates tearing instabilities, magnetic reconnection, and fluctuation suppression techniques. Analytic turbulence theories, based upon closure techniques or simple energy flow models, investigate microturbulence and transport.

Progress

1. Anomalous ion heating:

A well-known experimental anomaly is that ions are heated by a mechanism other than collisional transfer from electrons. Analytical work suggests that the heating may result from ion cyclotron damping of short scale fluctuations generated by an energy cascade from large scale tearing instabilities.

2. Feedback of resistive wall instabilities:

Resistive wall instabilities are a potential major obstacle to an RFP reactor. Feedback stabilization has been demonstrated to be feasible, from a physics viewpoint, through nonlinear MHD computation.

3. Rippling and g-mode turbulence:

The amplitude of steady-state electrostatic turbulence, from rippling and g-mode turbulence, has been calculated from analytic turbulence theory. The amplitudes are small compared to experimental values.

4. Bi-spectral analysis of tearing fluctuations:

Bi-spectral analysis has been applied to both MHD computational and experimental data to measure three-wave nonlinear wave coupling. Good semi-quantitative agreement is indicated.

5. Analytical study of radial transport of field-aligned current by collisionless transport:

This study has demonstrated that magnetic fluctuation induced transport is small. The self-consistent interaction between waves and particles is included in this analysis.

6. Feedback stabilization of RFP tearing fluctuations to a value lower than that obtained with a conducting shell:

This has been investigated.

Plans

1. Evaluate feasibility and physics properties of electrostatic helicity injection as a technique to suppress fluctuations and transport in the RFP. Employ the results of nonlinear, resistive 3-D MHD computation to guide and compare with experiments in the MST device.

2. Use 3-D MHD computation to study current density transport in the presence of MHD relaxation. Compare the results with experimental measurements of current diffusion in the outer portion of MST.

3. Evaluate the direct energy cascade from large scale tearing mode using analytic turbulence theory. The resulting spectrum of magnetic fluctuations will be compared with experiment and employed to evaluate the contribution of damping at the small scale to anomalous ion heating.

4. Investigate the radial transport of field-aligned current from collisional drift-Alfven turbulence or resistive tearing modes, taking into account the self-consistent relationship between the fluctuations and transport.

5. Investigate rf current-drive techniques appropriate to the low field RFP, with a goal of current profile control for fluctuation suppression.

6. Investigate, through MHD computation, the effect of various current density profiles on fluctuations and transport.

7. Combine the helicity injection MHD code with a finite pressure MHD code to examine the effect of electrostatic helicity injection on energy transport.

8. Operate MHD code with the additional feature of self-consistent evolution of single particles to examine the contribution of electron motion, parallel to the magnetic field, to the dynamo effect.

Students and Postdoctoral Research Associates

E.J. Zita, Ph.D., "MHD Computational Study of Feedback of Resistive Wall Instabilities," (1992), C. Sovinec (present graduate student), P. Figliozzi (undergraduate).

Other Professional Staff

None.

Collaboration

Science Applications International Corp., La Jolla, extensive collaboration in 3-D MHD computation. University of California-San Diego, collaboration in analytic turbulence theory. University of Montana, collaboration on investigation of rf current drive techniques.

Publications

1. P.W. Terry and P.H. Diamond, "A Self-Consistent Theory of Radial Transport of Field-Aligned Current by Microturbulence," *Phys. Fluids* **B2**, 1128 (1990).
2. Y.Z. Agim and S.C. Prager, "Magnetic Fluctuations Due to Thermally Excited Alfvén Waves," *Phys. Fluids* **B2**, 1138 (1990).
3. S.C. Prager, "Transport and Fluctuations in Reversed Field Pinches," *Plasma Physics and Controlled Fusion* **32**, 903 (1990).
4. P.W. Terry, et al., "Advances in RFP Theory and Computation," *Plasma Physics and Controlled Nuclear Fusion Research*, IAEA, Vienna, p. 169 (1991).
5. Y.L. Ho and S.C. Prager, "Nonlinear Reversed Field Pinch Dynamics and Nonideal Boundaries," *Phys. Fluids* **B3**, 3099 (1991).
6. S. Assadi, K. Sidikman, and S.C. Prager, "Measurement of Nonlinear Mode Coupling of Tearing Fluctuations," *Phys. Rev. Lett.* **69**, 28 (1992).
7. N. Mattor, P. Terry, and S.C. Prager, "Anomalous Heating from the Dynamo in a Reversed Field Pinch," *Comments on Plasma Physics and Controlled Fusion* **5**, 65 (1992).
8. S.C. Prager, "Reversed Field Pinch: Recent Results," *Plasma Physics and Controlled Fusion* **34**, 1895 (1992).
9. A.J. Wooton, H. Tsui and S.C. Prager, "Edge Turbulence in Tokamaks, Stellerators and Reversed Field Pinches," *Plasma Physics and Controlled Fusion* **34**, 2023 (1992).
10. D.D. Schnack, et al., "Advances in RFP Theory and Computation," in *Plasma Physics and Controlled Nuclear Fusion Research*, IAEA, Vienna (1993), in press.
11. S.C. Prager, et al., "Current Density Fluctuations, Nonlinear Coupling, and Transport in MST," in *Plasma Physics and Controlled Nuclear Fusion Research*, IAEA, Vienna (1993), in press.
12. E.J. Zita, S.C. Prager, Y.L. Ho, and D.D. Schnack, "Magnetohydrodynamic Computation of Feedback of Resistive Shell Instabilities in the Reversed Field Pinch," *Nuclear Fusion*, in press.
13. H. Tsui, et al., "Comparison of Edge Turbulence in Tokamaks, Stellerators, and Reversed Field Pinches," *Physics Fluids* **B**, in press.

University of Wisconsin-Madison

Project

Theoretical Studies of Turbulence and Anomalous Transport in Toroidal Confinement Devices

P.W. Terry

Funding

FY 90	FY 91	FY 92
\$100k	\$100k	\$100k

Purpose

This project is concerned with theoretical and computational research in the area of turbulence and anomalous transport in toroidal plasma confinement devices. This work pursues development of analytical turbulence models describing general dynamical behavior and observed phenomena, calculation of relevant turbulence characteristics and transport fluxes for such models, and numerical simulation of plasma turbulence. Topics being investigated are: the physics of enhanced confinement regimes in tokamaks (specifically the H-mode), the transition to the H-mode, and the characteristics of transport in the H-mode; the characteristics and turbulent properties (including heat and particle transport) of fluctuations in tokamak core plasmas; theory and phenomenology of the frequency spectrum of drift wave turbulence and its relation to tokamak fluctuation measurements; and magnetic fluctuations and magnetic fluctuation induced transport.

Approach

This work is generally based on the application of statistical closure (renormalized) theories of plasma turbulence and direct spectral simulation of model equations to the problem of understanding fluctuations and fluctuation induced transport in tokamaks. Specifically, enhanced confinement regimes are studied analytically by modeling turbulently generated flow self-consistently, along with saturation of turbulence by the differentially rotating flow. Core fluctuations and transport are studied in the context of long wavelength turbulence, including dissipative trapped ion convective cell turbulence and collisionless trapped electron mode turbulence. Both analytic theory and simulation are utilized. The frequency spectrum of drift wave turbulence is investigated using two-point closure theory and comparing with the results of numerical calculations. Magnetic fluctuations and magnetic fluctuation induced transport is examined in the context of ion heating from tearing modes in the reversed field pinch, and microtearing fluctuations in tokamaks.

Progress

1. The simple scaling theory prediction for suppression of turbulence by flow shear that has become the working paradigm for understanding H-mode transport was derived. Extensions to this work include a demonstration that the curvature of the flow is also capable of suppressing turbulence, an analysis of finite amplitude induced effects which weaken shear suppression, and a model for the L—H transition based on the self-consistent coupling of fluctuation driven shear flow and flow suppressed turbulence.

2. Numerical solution of a model equation for dissipative trapped ion convective cell turbulence produced a demonstration that energy transfer in the long wavelength part of wavenumber space is toward small scales, contrary to conventional wisdom. This work also demonstrated that the spectral transfer is predominately nonlocal in wavenumber space. Extending this work to higher wavenumber, it was shown that two transfer regimes exist, with a dual cascade process that is local in wavenumber space in the shorter wavelength regime. From the numerical solutions a large shift in the frequency spectrum was discovered and subsequently derived analytically. The shift was shown to have an important effect on the dynamics and basic instability driving the turbulence.

3. Magnetic fluctuations in a collisionless plasma were found to be incapable of transporting the field aligned current required to sustain the reversed toroidal field in a reversed field pinch (RFP), indicating the tearing mode fluctuation driven dynamo is the only viable candidate for sustaining reversal. It was shown that the observed ion heating in the RFP can be produced by the tearing mode fluctuations through the turbulent cascade they drive. Transport coefficients for high beta microtearing turbulence were also derived.

4. The quasilinear heat and particle fluxes for trapped electron mode turbulence were calculated and their magnitude evaluated for the measured spectrum of core fluctuations in the Texas Experimental Tokamak Experiment (TEXT). These were compared with the estimated heat and particle fluxes from power and particle balance.

Reasonable agreement was found if the mean wavenumber of the fluctuations is given by the value found from far infrared scattering, as opposed to the smaller value inferred from measurements made with the heavy ion beam probe.

5. The structure and dynamics for self-trapping fluctuations in three dimensional magnetized plasmas were derived. Coherent structures and self-organization were also observed and described in simulations of compressible magnetoturbulence and collisional drift waves.

6. The general phenomenology of frequency shifts in drift wave turbulence was examined and predictions were made for the direction in frequency space of shifts of the spectrum peak.

7. The principal investigator served as interim co-chairman of the Core Fluctuation Working Group of the Transport Task Force, as a member of the Fluctuation Subpanel of the Transport Task Force (phase I), organized a US-Japan theory workshop on edge physics and the L-H transition in August of 1991, served on the U.S. DOE Joint Institute for Fusion Theory Management Committee, and served on the Sherwood Theory Executive Committee.

Plans

Plans for the future include the derivation of the wavenumber spectrum for drift wave turbulence in the presence of flow shear. This derivation will also determine the effect of nonlocal spectral transfer on the spectrum. A theory for the frequency spectrum and spectrum shift based on incoherent emission into collective trapped electron drift wave fluctuations will be worked out and predictions for the frequency shift will be obtained. Fluid theories for dissipative and collisionless trapped electron mode turbulence will be developed in order to predict the fluctuation level and particle transport. These theories will specifically examine the role of the frequency shift on fluctuation dynamics and transport. Steady state magnetic turbulence will be studied numerically using magneto-hydrodynamic and compressible magnetoturbulence models.

Students

David E. Newman, Doctoral candidate (estimated graduation date, 1993), Gene Riggs, third year graduate student (DOE Fellow), Eduardo Fernandez, second year graduate student. Other Professional Staff: Nathan Mattor, Postdoctoral associate, 1990-1991

Collaborations

University of California at San Diego: Physics of enhanced tokamak confinement regimes, and core fluctuations and transport. University of Texas at Austin: Theory/experiment comparison for particle and heat transport in TEXT. Oak Ridge National Laboratory: Physics of enhanced tokamak confinement regimes. Lawrence Livermore National Laboratory: Core fluctuations and transport. Science Applications International Corporation, San Diego: Magnetic fluctuation induced transport.

Publications

1. H. Biglari, P.H. Diamond, and P.W. Terry, "Influence of Sheared Poloidal Rotation on Edge Turbulence," *Phys. Fluids B2*, 1 (1990).
2. P.W. Terry and P.H. Diamond, "A Self-Consistent Theory of Radial Transport of Field-Aligned Current by Microturbulence," *Phys. Fluids B2*, 1128 (1990).
3. P.W. Terry, P.H. Diamond, and T.S. Hahm, "The Structure and Dynamics of Electrostatic and Magnetostatic Drift Holes," *Phys. Fluids B 2*, 2048 (1990).
4. Y.B. Kim, P.H. Diamond, H. Biglari, and P.W. Terry, "Theory of Resistivity-Gradient-Driven Turbulence in a Differentially Rotating Plasma," *Phys. Fluids B 2*, 2143 (1990).
5. A.J. Wootton, B.A. Carreras, H. Matsumoto, K. McGuire, W.A. Peebles, C.P. Ritz, P.W. Terry, and S.J. Zweben, "Fluctuations and Anomalous Transport in Tokamaks," *Phys. Fluids B 2*, 2879 (1990).
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7. Bruce D. Scott, H. Biglari, P.W. Terry, and P.H. Diamond, "Self-Organization in Sheared Drift-Wave Turbulence," *Phys. Fluids B 3*, 51 (1991).
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27. 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," submitted for publication.
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Yale University

Project

Theoretical and Numerical Studies in Magnetic Fusion

Ira. B. Bernstein

Funding

FY 90

\$25k

FY 91

\$80k

FY 92

\$80k

Purpose

The object of this program is to analytically develop simple and numerically implementable descriptions of transport in toroidal fusion devices for the ready interpretation of experiment and eventual efficient reliable engineering design.

Approach

The research involves the systematic and critical survey of the relevant theory in an attempt to identify those features and results which are robust and essential to the purposes of the program. These essential elements will then be incorporated into analytically simpler models whose numerical implementation is more readily accomplished than attempting to deal with the complete description. For example, this study will be adapted to develop a relaxation model for collisions which provides neoclassical transport coefficients which agree well with the restricted body of known results but allow rapid accurate determination, in general, of such transport coefficients.

Progress

Gyrokinetic theory has been streamlined and has been employed to derive the collisional transport theory for any topologically toroidal device possessing well defined magnetic surfaces $\psi(r,t)=\text{const.}$, without a detour via moment equations. Thus it includes the theory appropriate for a Tokamak with rotation, as well as that for the Stellarator. It allows for finite mean flows.

An analysis is underway to determine the correct boundary conditions to apply to the transport equations. In the case where there is no edge turbulence and there is no reflux from the boundaries it is clear that kinetically one must view as unpopulated all drift orbits that touch an absorber. This indicates that there is a boundary layer, of thickness roughly equal to an effective drift orbit, in which the distribution function passes from almost Maxwellian to far from Maxwellian.

A start has been made on the rough characterization and parametric dependence of the neoclassical transport coefficients. This consists of classifying the parts of energy magnetic moment space that contribute and bounding the associated effective collision time that enters the model expressions.

The general equations governing the ensemble average field quantities in the presence of both collisions and turbulence have been derived and are being analyzed. We will attempt to use experimental information to determine which terms are dominant and see if one can asymptotically match the associated fluxes in the turbulent outer layer to the neoclassical results which dominate the center. The theory proceeds from the governing equations in conservation form.

Plans

In the next year, the work on gyrokinetics and transport will be summarized in a solicited article in the *Reviews of Modern Physics*. The boundary layer analysis near a wall will be extended to incorporate edge turbulence. The numerical determination of effective collision times required for the reduced collision operator will be undertaken. The numerical implementation of the simplified theory will begin. Initial modeling of edge turbulence and methods for matching the associated transport to neoclassical theory will be initiated.

Other Staff

Qun Chen, Post Doctoral Research Associate

Marian Rose, Visiting Fellow

Collaborations

This work will be done in collaboration with Dr. Francesco Romanelli and colleagues of the fusion laboratory at Frascati, Italy.

Students

No students are currently involved in this work.

Major Recent Publications

Ira B. Bernstein, Leigh Brookshaw, Peter A. Fox, "A Numerical Procedure for the Solution of Systems of Linear Ordinary Differential Equations Exhibiting Very Fine Structure," *J. Comp. Phys.* **98** 269 (1992).

END

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