INSTITUTE FOR FUSION STUDIES PROGRESS REPORT

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Contents

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Chapter I

AN OVERVIEW OF IFS

A. Introduction

In 1979 the Department of Energy proposed the establishment of a theoretical Institute for Fusion Studies. It should be noted that the National Science Foundation in this same time frame also saw the need for new theoretical institutes in other disciplines. In June, 1980, IFS began operations at UT Austin on a basis of matched funding by DOE and The University of Texas.

With respect to fusion needs, IFS was envisaged as filling a perceived gap between national laboratory theory groups, which would inevitably become increasingly committed to local experiments, and the already existing university groups, which were in many cases too small to be effective outside of limited scientific areas. We have seen our role in the national program to be located in this middle ground: to work in areas which involve genuinely excellent theoretical physics but which, at the same time, are clearly of fusion relevance. Thus, while it would not be appropriate for us to study intermittency in Navier-Stokes turbulence, it clearly has been appropriate to look at the nonlinear behavior of, and turbulence induced by, tearing modes. At the other end of the spectrum, it would not be appropriate for us to undertake specific coil design, but it has been appropriate for us to study general properties of stellarator-type magnetic fields.

In order to follow this Middle Way, we have tried to operate in the traditional mode of a community of autonomous scholars. A formal program with assigned tasks has not been attempted. Obviously this places a heavy responsibility on the young scholars, who must be the core of any effort to bring new thoughts and techniques to bear on fusion physics. The mechanism for instilling the necessary feeling for fusion needs and opportunities has been primarily that of providing an atmosphere in which discussion is welcomed and of facilitating contacts with those experienced in the field, both inside IFS and outside it in the larger fusion world. Frequent seminars and visitors have characterized our program. Another role we have undertaken is that of U.S. coordinator of the Joint Institute for Fusion Theory with Japan. We have had long and short-term visitors from many countries.

It would be traditional to present an organization chart at this point, but in fact organization has been loose and our scientific accomplishments are due primarily to the skills and motivation of dedicated individuals and to their self-organization into informal research and study groups for evolving purposes.

It should be noted that in view of the fact that for the past decade or so world fusion efforts have been largely based on U.S. theory, it represented a notable commitment by the Department of Energy to attempt to strengthen still further the U.S. theory base by establishment of IFS. We wish to stress also that, faithful to its original philosophy, DOE has not attempted to control the IFS or to specify its tasks or objectives, although of course many of us have individually been involved in DOE reviews and similar activities.

Similarly, The University of Texas has been more than generous in fulfilling its commitments and doing everything reasonable to facilitate our progress. In particular the University has informally signified its desire to continue to provide matching funds for another five-year period of IFS operation. The University, of course, has a broad commitment to fusion research, as exemplified by its operation of the TEXT Tokamak and its intention to set up a center to study fusion engineering questions. The massive new commitment of the University to computer sciences and computation should prove of great benefit to IFS in the coming years.

The rest of the fusion community has been supportive and, in particular, has provided us with advice and encouragement through the IFS Advisory Committee. As evidence of our good relations with the fusion community, it will be noted that a great many of our publications represent joint efforts with outside individuals or groups. In short, we have been treated generously by our sponsors and by our colleagues.

Of course, we have been fortunate indeed in our cooperative and very skillful support staff who perform so many essential functions. Research staff have also participated willingly in the committee work necessary for such things as recruitment, space and computer allotment, newsletter publication, library acquisitions, etc. It is further worth noting that most of the traditional administrative burden of running IFS has been borne by its Assistant Directors, at first David Ross and now Richard Hazeltine, and that the very complex and demanding diplomatic chores of organizing and running the U.S.-Japan theory exchanges have fallen on the shoulders of Wendell Horton.

B. A Road Map to IFS Research

In Chapter II, we will try to summarize our accomplishments of the past 3-1/2 years in various areas of research. These undertakings probably also provide the best indicators of the directions which we expect future research to take. While as pointed out above, we have had little formal organization, the scientific tasks undertaken have for the most part tended to fall into a few natural groupings with, of course, considerable overlap. Here we attempt to present a very brief roadmap for what follows, with some indications of "fusion relevance".

1. Mathematical Physics. Fusion research played a key role in the birth, about twenty years ago, of two now flourishing areas of theoretical physics: soliton solutions of nonlinear equations, and transition to chaotic behavior, as exemplified by stochastic magnetic fields. These areas have been active at IFS. The stable existence of two-dimensional drift wave solitons even in the presence of magnetic shear has been demonstrated and a quantitative discussion given of the mechanism of the final breakdown of KAM surfaces in the Taylor-Chirikov map. Another fundamental problem solved is the calculation of the change of adiabatic invariants due to trapping in time varying potentials. The nature of strange attractors arising from three-wave drift interactions has been explored.

Such phenomena undoubtedly play some role in microturbulence and anomalous transport, but we remain far from able to apply them quantitatively except in simplified cases. A development which may

yield practical results sooner is a new noncanonical Hamiltonian formulation of MHD and Vlasov stability which appears suitable for studying such issues as nonlinear MHD ballooning limits, crucial to tokamak β limits.

2. Energetic Particles and Alternate Concepts. An important line of research at IFS and elsewhere in the past few years has been to study the role of energetic particles whose magnetic drift frequency is comparable to MHD frequencies. Such particles may partly decouple from MHD motions inducing novel MHD behavior. IFS understanding of this topic has had a number of implications: a) the possibility of utilizing MeV particles to stabilize tokamaks and perhaps attain the second stability regime; b) the elucidation of EBT stability properties, with a plausible explanation of the T-M transition; c) the proposal of a stable axisymmetric tandem geometry; and d) the explanation of "fishbones" as a consequence of intermediate-energy beam-injected particles which can resonate with the internal kink mode.

In related work, we have illuminated the relationship between trapped particle modes and MHD modes and shown that in some tandem mirror geometries, where coupling is weak between central-cell and plugs, the trapped particle mode becomes equivalent to an MHD central-cell mode. The importance and impact of rotation on mirror stability has also been examined.

Some directions we are thinking about for the future include extension of the study of hot particle effects to compact torii, a more complete treatment of FLR effects of hot particles, and development of a nonlinear theory of trapped particle modes.

3. Tearing Modes and Stellarators. Tokamak and RFP behavior is often dominated by tearing mode effects, which determine the accessible parameter ranges. We report some work on the turbulent behavior of tearing modes under Section F below. However, understanding even of single helicity modes is incomplete. At the linear level, it has long been known that toroidal compressibility effects can stabilize tearing modes and much recent work has indicated that at high temperatures kinetic effects play a similar role. Clearly, as regimes of higher β and temperature are attained, such stabilization can become very important. We have looked at the nonlinear (Rutherford) regime of tearing modes and find that many of these stabilizing effects are confined to the island surface and hence become less important in the nonlinear regime. A related topic is the problem of understanding 3D stellerator equilibria, which can be viewed as equilibria attained as a limit of finite resistive island growth. Much other stellarator work has been part of the IFS program, including the systematic optimization of multiple helicity vacuum fields, and an evaluation of ballooning stability limits on β.

We see the subject of kinetic nonlinear tearing modes as increasingly important in high temperature tokamaks. One particular topic of interest for the future is the behavior of tearing modes in tokamaks where the current is primarily carried by high-energy, relatively collisionless, r.f. induced electrons as is planned for TFCX. Our point of view on stellarator equilibria may also lead us to undertake improved equilibrium codes.

4. Tokamaks and TEXT Support. Most of our tokamak research has been subsumed in this report under other generic categories. However it is worth mentioning that we continue to look at neoclassical effects, finding, for example, some explanation for observed ion spectra anomalies, plasma asymmetries and plasma convection. An objective, not yet attained, is to understand the observed high damping rate of toroidal rotation.

It will have been noted by the astute reader that one large area of importance in which there has not been much IFS activity is r.f. heating. However, we have had some participation with FRC in the development of the theory of Alfvén wave heating. In this connection, the discovery of undamped global Alfvén modes may be of considerable importance. As a corollary to this work, we have observed that these global modes can be excited strongly by alpha particles, and we are continuing to explore the ramifications of this for burning plasmas.

The TEXT experiment is now reaching the stage of producing quantitative results on such issues as fluctuations, scaling laws, and plasma potentials. In some areas such as the nature of edge fluctuations there is clear overlap with IFS theory and consequent strong interaction. While we are organizationally completely divorced from TEXT, the propinquity of interesting data should lead to increased interaction in coming years.

5. Computational Physics. It has been our objective to develop new computational techniques which could serve as quantitative checks and guides to the analytic work. Since we often study 3D nonlinear problems, in many cases dominated by kinetic effects, this is a

difficult objective and progress has been slow. Emphasis must be on finding parameters which are both calculable and representative of the phenomena of interest, and on developing computational methods, such as implicit codes and gyrokinetic formulations, which allow faster computation. If this program is to bear fruit it must receive greater attention in the future. Computational progress should be helped by the new UT commitment to this area.

A 3D resistive MHD code, which eliminates the fast compressional wave implicitly, has been successfully implemented, demonstrating the dynamo effect in RFP's. A computational study of the current-driven ion cyclotron instability has shown indications of nonlinear threshold lowering, due to incoherent fluctuations (clumps). 2D studies of drift waves have shown the importance of ion damping and a variety of 3D codes is in preparation to look at toroidally induced modes and possibly clump effects. In the latter codes, electrons are treated in the drift approximation, some implicit treatment of parallel plasma oscillations is included, and work is proceeding on gyrokinetic ions. In addition, more conventional MHD codes have studied island coalescence and explosive merging. Some related work on space plasmas and plasma accelerators (funded by other agencies) is also being pursued part time by IFS personnel.

6. Turbulent Phenomena. We are all painfully aware that turbulence is often a dominant feature of fusion plasmas: MHD turbulence in RFP's and disrupting tokamaks, microturbulence in "stable" tokamaks and mirrors. The former topic has reached a high level of understanding, often to the point of quantitative

predictability, while in the area of microturbulence, we are still trying to perfect qualitative understanding of observed fluctuations and a sense of scalings to be expected in various parameter regimes.

In the case of MHD turbulence, we have developed a theory of interacting tearing modes, noting that mode coupling phenomena are dominated by behavior near the singular tearing layers of driven modes. Many characteristics of Tokamak disruptions can be so explained, while in RFP's the level of excited m=1 modes, the observed dynamo effect, and the scaling of temperature with current, as determined from transport along stochastic fields, all seem consistent with this picture. A key study for the future is to extend this picture into the regime where tearing modes become more kinetic in character in order to predict high temperature RFP scaling. Still, at the MHD level, the nonlinear theory of resistive ballooning modes has produced the Carreras-Diamond scaling law which seems consistent with ISX data and may also play a role in RFP's.

Passing now to microturbulence, a fundamental advance in understanding has been achieved by noting that incoherent fluctuations (clumps) can play a significant role. For example, drift waves in a sheared slab become linearly unstable, and considerable broadening of the saturated spectrum is also predicted. In another study, DIA spectral broadening of interacting wave triplets has been shown to be significant. While these problems are very complex, a qualitative understanding of the dominant mechanisms producing the observed broad frequency spectra can be said to exist.

While our studies indicate that collisional drift waves and rippling modes may be dominant near the plasma edge in producing transport, the important microinstabilities in the bulk of the plasma are probably those induced by toroidal effects. Using a nonlinear ballooning formalism, we have shown that the behavior of trapped-electron modes and toroidicity-induced drift modes produces scaling like that observed in ohmic plasmas, and that the adverse electron temperature dependence produces a degradation of confinement like that seen in auxiliary heated plasmas.

Obviously, these are topics requiring a great deal of further effort, particularly inclusion of the effects of finite β and stochastic magnetic fields. Even a small additional level of understanding reached in these matters can be very important for optimizing large tokamaks such as TFCX. A self-consistent treatment of stochastic magnetic fields, including the plasma response, will require a good understanding of turbulence theory and nonlinear tearing modes, with perhaps some applications of the general theory of transition to chaos. It is also clear that achieving more computational power and finesse would be very helpful to further advances in studying turbulent approximation schemes.

A somewhat fuller discussion of our research achievements and aspirations will be found in Chapter II, but of course any reasonable comprehension of the calculations or appreciation of the individuals involved can only be obtained by reference to the IFS reports listed in Appendix D. We note with pride the large number of invited talks given by IFS personnel. For example, out of a total of about 15 theory papers accepted by the U.S. selection committee for presentation at the

upcoming IAEA meeting, nine were authored in whole or in part by IFS scientists.

Chapter II

TECHNICAL SUMMARIES

A. Mathematical Physics

Based on the fraction of reports published, approximately one fifth of the research at the IFS is in the area of mathematical physics. This research applies new mathematical methods to the most difficult problems of the fusion program, such as turbulent transport, providing a format for practical advances. The effort can be divided into four areas: 1. Stochasticity and Turbulence, 2. Poisson Brackets and Hamiltonian Structures, 3. Solitons and Coherent Structures, and 4. Variational Techniques.

Research in stochasticity has tended either to be directed toward particle motion in perturbed magnetic fields, and thus applied to the problem of anomalous transport, or toward the motion of particles in electrostatic waves with applications to wave heating and the saturation of instabilities such as the beam-plasma instability. This research has led to a precise definition of the concept of transport in a deterministic system and techniques for computing transport rates have been applied to model systems. The foundations of turbulence theory are addressed by the study of the randomness associated with the interaction of a small number of waves. It was shown that broad (hence turbulent) frequency spectra can be obtained in dynamical systems with few degrees of freedom.

The second category, which traces its origins to the 19th century traditions of mathematical physics, has been revived by the discovery that many equations of plasma physics and fluid dynamics have formulations as Hamiltonian systems. To utilize the physical fields as dynamical variables it is usually necessary to adopt a noncanonical formulation where the Poisson bracket becomes the fundamental object. The advantage of the Hamiltonian formulation is that the full apparatus of the theory of dynamical systems, including many ideas from group theory and differential geometry, can now be applied. It leads to a new classification of equations—by Poisson structure—and to a codification of a method for determining the nonlinear stability of plasma and fluid equilibria.

The theory of solitons has many applications in plasmas: ion acoustic waves, Langmuir waves, etc. At the IFS, it was shown that results obtained in oceanography for Rossby waves could be applied to drift waves in a slab, yielding a structure localized in two-dimensions. A significant result in this area is that these solitary waves were shown to persist in the presence of magnetic shear; this result was a surprise since linear drift waves radiate in this situation. A study of the effect of solitary drift waves in turbulent situations brings to plasma physics the concept of coherent structures in turbulence; a topic of current interest in fluid dynamics. Finally, nonlinear soliton-particle interactions and inelastic soliton collisions have been studied.

Variational techniques for determining linear stability have a long and distinguished history in plasma physics, particularly in MHD. At Texas, variational techniques were also developed for the study of

modes localized to rational surfaces, but for which kinetic effects are included. At the IFS, this study was extended to obtain a self-adjoint variational principle for the linearized Vlasov-Maxwell system.

The results obtained in these four areas are summarized below:

1. Stochasticity and Turbulence. The nonlinear equations for three-wave interactions can be obtained from a Hamiltonian which is integrable (for real frequencies). As more triads are added to the system, the motion typically becomes stochastic, and computations should be expected to compare with weak, or resonance-broadened turbulence theory [IFSR #7]. However, a special case, with an arbitrary number of interacting triads, remains integrable [IFSR #46]; for this case the integrals were constructed explicitly.

When dissipation is added to the three-wave system, integrability is destroyed and chaos ensues. The chaos is such as to create broad frequency spectra, similar to those observed in tokamaks, and the phases of the waves evolve in an effectively random way, making the random phase approximation appropriate even in the case of three-waves [IFSR #20, #56].

As the number of interacting triplets is increased the saturation amplitude of the modes decreases, while the frequency spectrum remains broad [IFSR #58]. It is also seen that the saturation amplitude depends sensitively on the the total amount of dissipation in the system, γ_t, defined as the sum over the mode linear growth rates. The condition $\gamma_t < 0$ appears to be necessary and sufficient for saturation of the instability, and as γ_t decreases from zero the saturation amplitude decreases.

The study of particle motion in a turbulent spectrum of electrostatic modes can be carried out by use of the time dependent, one degree of freedom Hamiltonian. As the frequency spectrum becomes broad this system can be reduced to a map: the standard or Chirikov-Taylor map. Furthermore, this map exhibits most features of Hamiltonian flow, and applies directly to magnetic field lines. Transport due to stochastic field lines appears to predominate in RFP's and may also be important in tokamaks.

When a large axial magnetic field is present, it is more appropriate to consider the motion of guiding-centers for which the coordinates (x,y) are canonical conjugates. The motion of guiding-centers in a spectrum of electrostatic drift waves yields a qualitatively new map for which the linear motion has no shear [Escande and Horton, Sherwood Theory Meeting 1984].

Transport in area-preserving maps can be studied by a technique called the method of characteristic functions [IFSR #6], where the Fourier transform of the orbit probability distribution is formally constructed by a recursion relation. The recursion relation can be solved exactly in a special case, the sawtooth map, to obtain statistical properties such as the correlation functions and diffusion coefficients [IFSR #25], showing rigorously that a determincan betic (mixing) map can be diffusive. For more general maps (e.g. the standard map) it is not known whether the series for the diffusion coefficient actually converges. It was shown [IFSR #57] that the correlation function develops a long, slowly decaying tail due to orbits remaining in the neighborhood of "sticky" regular regions. which generally persist even for large perturbations. These tails are

difficult to obtain analytically since they are due to very high-order terms in the series.

The general theory of transport in dynamical systems, including effects such as the tenacity of regular regions, can be assessed by considering the flux of orbits through surfaces in phase space [IFSR #106]. The best estimate of transport is obtained by determining those surfaces through which the flux is smallest. For the case of maps these curves are called cantori [IFSR #109], and are the remnants of destroyed invariant circles. A universal form for the flux through a cantorus can be obtained just above the critical value of the perturbation parameter, k, for which the invariant circle is destroyed: Flux $\propto (k-k_c)^{3.01}$. This formula holds for any two degree of freedom Hamiltonian, and can be seen to agree with Monte Carlo transport calculations in realistic fields which show a three order of magnitude increase in transport in the universal regime above the stochastic threshold.

Universal properties of dynamical systems are studied by use of the renormalization group. Another universal property is that invariant circles of "noble" winding number are more robust than any in their neighborhood [IFSR #118]. This result is obtained using an approximate version of the renormalization group.

When the system is far above the stochastic transition, quasilinear transport theory is usually applicable. However, if the amplitude becomes so large that the bounce time is shorter than the field correlation time, quasilinear theory breaks down. In this case an adiabatic invariant can be defined which undergoes occasional jumps due to crossings of an approximate separatrix. The jumps in the action

can be calculated for a generic separatrix upon showing that only the motion near the unstable fixed points is important [Tennyson, Cary, and Escande, Sherwood Theory Meeting 1984]. The calculation yields a new scaling for the diffusion coefficient in the strongly turbulent regime, which is relevant in plasmas for which trapping is important.

Area-preserving maps can also be used to study the effects of quantum mechanics on a classically chaotic system. The initial value problem for the quantum standard map can be solved by use of a discrete time version of the Schrödinger equation. The effects of tunneling out of classically regular regions reduces the long-time correlations seen in the classical problem [IFSR #101]. While a quantum system generally has a discrete spectrum and therefore no diffusive motion, it can be shown that a small amount of noise can restore diffusive behavior [Hanson, Ott, and Antonsen, Sherwood Theory Meeting 1984].

The motion of particles in a magnetic field with a null, such as occurs in field reversed configurations, was shown to depend on the ellipticity of the flux surfaces and a normalized particle energy [IFSR #78]. The magnetic moment is adiabatically preserved only if the energy is small enough relative to the ellipticity. Moderate energies lead to stochastic motion.

2. <u>Poisson Brackets and Hamiltonian Structures</u>. Hamiltonian perturbation theory has recently been reformulated using the theory of Lie transforms [IFSR #14]. The main advantage of this technique, which becomes clearly visible when high-order calculations are done, is that the mixed variable representation is avoided.

Hamiltonian formulation of the field theories in plasma physics has led to a synthesis of ideas in mathematics, fluid dynamics, and plasma physics [IFSR #54]. The basic idea is that systems which are not Hamiltonian in the canonical sense can be made so by generalizing the Poisson bracket. Generalized Poisson brackets have been constructed for ideal MHD, the Vlasov-Maxwell equations, multi-fluid theories, the BBGKY hierarchy [IFSR #122], and reduced MHD models [IFSR #97]. Systems with a common Poisson structure belong to the same family of field theories. To each bracket there are functions that commute with all other functions, called Casimir invariants. The Casimirs are used in constructing analytic equilibria and a Lyapunov functional which is used to test linear and nonlinear stability. This method is being applied to reduced MHD to determine the nonlinear stability of nonlinear Alfvén waves and Grad-Shafranov equilibria with flows [Morrison and Hazeltine, Sherwood Theory Meeting 1984]. An obvious future application is to the nonlinear behavior of ballooning modes.

Present lines of research in this area include the construction of higher-order nondegenerate brackets for systems with Casimir invariants, and the construction of symmetric brackets to represent dissipation. In the latter case, the positive definiteness of the symmetric part of the bracket guarantees an H-theorem.

Generalized reduced fluid models in the spirit of reduced MHD, can be obtained including effects neglected by simpler reductions. One such model, compressible reduced MHD, includes effects fundamental to finite β tearing modes; another model includes electron inertia [IFSR #88]. A more general reduced model including gyroviscous and long

mean-free path effects is called the four-field model [Kotschenreuther, Hazeltine, and Morrison,1984]. Reduction simplifies the geometrical manipulations inherent in toroidal geometry and allows the determination of the important nonlinear effects.

3. Solitons and Coherent Structures. Fluctuation measurements in tokamaks demonstrate that nonlinearity is of importance at lowest order. Therefore, non-perturbative effects of nonlinearity such as solitary waves should be considered. A simple one-dimensional model of drift waves can be shown to reduce to an equation known as the regularized long wave (RLW) equation. Turbulent behavior in the RLW equation can be modelled to zeroth order as a superposition of an almost ideal gas of solitary waves with a background of nearly linear modes. The ideal gas model yields a fluctuation spectrum which has support in the regions of Fourier space where the linear modes do not contribute [IFSR #45].

One correction to the ideal gas model arises from the inelasticity of collisions of the RLW solitary waves. They are not exact solitons. A trial function approximation of this interaction, using the RLW Lagrangian, yields information about the phase shifts due to the collisons [IFSR #80]. Numerical studies of the radiation produced during the collision show a pronounced resonance effect for solitary waves with opposite velocities.

When a linear instability is present, numerical studies show that a gas of coherent solitary waves can arise from a random phase initial condition [IFSR #82]. The treatment of nonlinear wave-particle interactions in the presence of a large amplitude solitary wave can be

carried out following O'Neil's analysis of nonlinear Landau damping [IFSR #65]. It was shown that the final state of the interaction is a finite amplitude solitary wave.

A two-dimensional solitary drift wave can be obtained for the equation of Hasegawa and Mima [IFSR #60]. Using techniques derived from oceanography, the solitary drift wave is shown to have a size of order ρ_s and to fall off exponentially at large distances. Addition of magnetic shear couples the drift mode to the ion acoustic mode. Using a generalization of boundary layer theory it is possible to show that the solitary drift wave is self-trapped in a nonlinearly generated well, which effectively inhibits the radiation due to this coupling [IFSR #60].

4. Variational Techniques. With a variational principle, trial function techniques can be used to obtain bounds on eigenvalues and thus stability of various equilibria. The variational formulation of the linearized Vlasov-Maxwell equations can be easily obtained by forming a quadratic form using the adjoint equation. This form is only useful if it is self-adjoint, for then only one trial function is necessary. Self-adjointness was explicitly demonstrated for equilibria with two ignorable coordinates using symmetry properties of the particle orbits [IFSR #13]. This result can be generalized to systems with a single ignorable coordinate providing there is no magnetic field in the ignorable direction [Dominguez and Berk, General Atomic Report A10735].

Several of the lines of research described above could be expected to yield "fusion-relevant" results over the next few years. The stochastic transport theory provides a natural framework for a self-consistent theory which couples particle dynamics to the evolution of the fields. In the determination of three-dimensional equilibria with finite pressure, the cantori provide approximate flux surfaces and the radial thermal flux is determined by the local stochastic flux. The competition between stochastic transport and collisional transport should also be addressed.

The Lyapunov stability principle using noncanonical Poisson brackets will be applied to determine nonlinear MHD ballooning stability limits, and may lead to an assessment of the saturation levels of ballooning instabilities. The development of reduced models including ω_* effects, compressibility effects, etc. will give a computationally useful set of models to replace reduced MHD as tokamaks enter new parameter regimes. A ballooning-reduced MHD (in general geometry) may allow nonlinear treatment of large n modes.

Coherent structures provide possibly observable phenomena in driftwave turbulence. Wave interactions with solitons, as well as particle resonance effects, should be studied to determine whether such solitons tend to grow or decay. Possible statistical correlation techniques for detection of soliton if they exist in edge turbulence need to be developed.

B. Energetic Particles and Alternate Concepts

1. Introduction. A major area of research at the IFS since its inception has been the investigation of fundamental stability properties for tandem mirrors and bumpy tori and for the superhot particle species that may be contained in these devices or in tokamaks. Such superhot ($\omega_d > \omega$) species have been found to yield fundamental changes in the magnetohydrodynamic equations.

In the past, low-frequency instabilities driven by magnetic curvature were typically analyzed by means of the ideal MHD fluid and guiding-center descriptions. These theories are predicated on the "frozen-in" assumptions of the frequency response of the unstable wave being faster than the particle curvature drift rate across the magnetic field and also fast enough to prevent a parallel electric field perturbation. The breakdown of the latter assumption is known to allow trapped particle and resistive instabilities with slow growth rates. Recently, however, it was found that trapped particle modes in tandem mirrors, especially those with thermal barriers, can have near-MHD growth rates and thus pose a significant threat to confinement.

The former assumption fails for a high-energy plasma component, such as the relativistic ring electrons in the Elmo Bumpy Torus (EBT). This failure has been found to allow stable operation in configurations that would be deemed unstable in MHD theory, although new modes of instability with no MHD counterpart also become possible.

Moreover, if the superhot particle stabilization method is effective in EBT, it could also be applied to tokamaks and tandem mirrors. Our studies in tokamaks have shown how hot particles can be

used during a build-up phase into the second stability regime. Also, recent work predicts that energetic particles can eliminate all MHD-type instabilities in a symmetric tandem mirror plug.

The following sections briefly highlight these studies and related mirror research.

2. Trapped Particle Modes in Tandem Mirrors. The tandem mirror is designed to be stable against MHD interchange and ballooning perturbations by means of minimum-B anchor cells at the ends of a maximum-B central-cell. The confinement time and power efficiency are optimized by thermal barriers that inhibit the central-cell plasma from flowing into the end cells. MHD theory does not indicate any penalty for such isolation.

However, this confinement scheme could be threatened by trapped particle modes[1], which localize in the unfavorable-curvature central-cell region without adding field line bending energy. Unlike in tokamaks, the trapped particle mode growth rates in tandem mirrors can be large, comparable to those for MHD instabilities. This was demonstrated by generalizing the energy principle to include parallel electric field terms[2], which gave the first unified description of trapped particle and MHD modes.[3] The growth rate is large when few central-cell confined particles sample the stabilizing end plug. As the particle fraction sampling both regions increases, the growth rate becomes smaller than the MHD rate, as in tokamaks.

Stabilization is provided by charge separation effects due to finite ion gyroradius and to non-similar ion and electron-bounce orbits, the latter also being effective for the m=1 mode.[4] Trapped

particle stability, in the absence of dissipation, can thus be achieved for a minimum density ratio of transit particles to central-cell particles approximately given by $n_t/n_o \gtrsim 4(r_p/R_c)(L_c/L_t)$, where n_t is the density of transit particles in the end plug whose length is L_t, n_o is the central-cell density, r_p is the pressure gradient scale length, and L_c and R_c are the length and radius of the bad curvature region. Fulfillment of this criterion is now a guiding principle in tandem mirror design.

Even when the stability condition is satisfied, remnant drift wave instabilities can arise from Landau damping and collisional dissipation.[5]

Also, the same formalism indicates that large axial variation of the radial electric fields existing in tandem mirrors can lead to a new instability.

3. Energetic Particle Stabilization in EBT, Mirrors, and Tokamaks. The special stability properties of plasmas that contain a highly energetic component have also received considerable theoretical attention. Examples of such systems are an axisymmetric version of the tandem mirror, as well as EBT (and its recent offshoot, the bumpy square). Usually the energetic particles are microwave-heated electrons, although the use of hot ions has been considered.[6]

A new type of semi-kinetic theory was developed to explain how the large curvature drift of the hot particles decouples their response from the fluid motion to provide a diamagnetic well for MHD stability.[7] However, it also predicts instability when the core plasma pressure exceeds a relatively low threshold, approximately given by

$\beta_c \lesssim 2(\Delta_h/R_c)(1+P_{\parallel h}/P_{\perp h})$ where β_c is the plasma beta value, Δ_h is the hot electron ring half-width, R_c is the radius of curvature, and $P_{\parallel,\perp h}$ are the anisotropic hot pressure components. There are experimental efforts to verify this critical beta limit.

Another theoretically predicted oscillation, in which a plasma mode resonates with the negative energy precessional mode of the hot particles, is thought to be associated with recently measured fluctuations that grow rapidly near the disruptive T-M boundary of EBT operation where strongly unstable plasma-ring interaction is observed.[8] Gas puffing to increase the plasma density can suppress this mode, in agreement with theory.

A similar unstable coalescence of the precessional mode in the end cell of an axisymmetric hot electron-stabilized tandem mirror device, with shear Alfvén standing waves in the central-cell, has been predicted to severely restrict the maximum length of the central-cell.[9,10]

Detailed analyses of both the ballooning[11] and radial mode structure[8] of hot electron instabilities have been carried out. The various core plasma and hot particle density and beta stability boundaries, shown in Fig. 1 for EBT-S, define a substantial window for stable operation except for intermediate mode numbers where precessional mode resonance occurs.

On the positive side, finite Larmor radius (FLR) effects can convert all short-wavelength curvature-driven modes to positive energy wave, thereby eliminating their beta limits, negative energy instabilities, and resonant destabilization.[12,13] Thus, long wavelength layer modes, which are less sensitive to FLR effects, pose the most

stringent conditions on stability.[14-16] Figure 2 shows that the transition to MHD instability occurs at beta values appreciably lower than the Lee-Van Dam critical limit ($\tilde{\beta}_c$=1) unless the hot particle temperature is sufficiently high and that, even without FLR considerations, the layer modes are more unstable than the short wavelength WKB modes.

Recent work[17] has shown that the m=1 precessional mode for a disk of hot particles in a symmetric tandem mirror can be stabilized by image currents in conducting walls, in analogy with the rigid precessional mode known in Aston. The conditions for MHD stability and elimination of negative energy modes are nearly identical, and the higher azimuthal mode number modes would be prevented by FLR effects. This scheme could be tested with hot electrons, although hot ions would be required at reactor-relevant parameters.

The application of hot particle stability theory has not been limited to mirror-based fusion devices. An analysis of ballooning modes in tokamaks has found that the introduction of a very energetic, trapped particle population during start-up may provide direct access to the high-beta second stability regime.[18] Figure 3 shows that hot particles localized poloidally between $\vartheta_o=\pm\pi/4$ can stabilize ballooning modes for all plasma pressures α_c and for shear values up to S=0.9. This concept would require approximately MeV ions for a D-T tokamak reactor.

Another application of this theory to toroidal devices involves the excitation of the internal kink mode, at beta values below its MHD threshold, due to the resonance at the curvature drift frequency of

injected hot ions. This mechanism has been successfully used to explain the fishbone oscillations observed in beam-heated tokamaks.[19]

4. Related Mirror Research. Plasmas in mirror devices can also be stabilized against MHD interchange by means of sloshing ion distributions, a technique currently being employed in thermal barrier tandem mirror end plugs. Stability for this method has been calculated, along with the required injection energy and the power drain.[20]

An electromagnetic description of drift waves in the tandem mirror has yielded their mode structure and indicated that the associated radial transport loss rate is faster than that given by neoclassical theory.[21] The influence of a conducting wall on the m=1 drift mode has also been investigated, with the effect of rotation.[22] Figure 4 shows the growth rates for modes m=1-3 as a function of the ratio of wall radius b to plasma radius a.

Finally, two extensions of the gyrokinetic formalism, a nonlinear Hamiltonian formulation[23] and a relativistic high-frequency linear version[24], have been derived, which are particularly suitable for studying the stability of energetic particle plasmas, (e.g., in conjunction with particle simulation studies[25]).

5. Summary. Considerable progress has been made at the IFS in understanding and applying novel generalizations of MHD theory to basic stability issues for tandem mirrrors, bumpy tori, and toroidal devices. The theoretically predicted stability criteria have been very useful for interpreting fluctuation phenomena in current experiments, determining operating regimes for planned experiments, and assessing reactor feasibility.

This area of research has involved six IFS scientists, approximately twenty outside collaborators, and three graduate students and has resulted in thirteen invited talks at major fusion conferences.

Further studies already underway or expected in the near future concern:

1. Coupled effects of rotation and trapped particles in mirrors;
2. FLR theory with applicability to large-orbit compact tori;
3. Feasibility of symmetric tandem mirrors;
4. Numerical computation of hot particle stabilization for finite aspect ratio, high-beta tokamaks;
5. Approximate formulae for drift wave spectra and transport in tandem mirrors;
6. Ballooning stability in the Elmo bumpy square;
7. Degradation of tokamak confinement by beam ions; etc.

The past four years have been quite fruitful both in extending the fundamental theoretical description of stability processes and in obtaining applied stability considerations of relevance to the national fusion program. Our future investigations are intended to maintain these directions.

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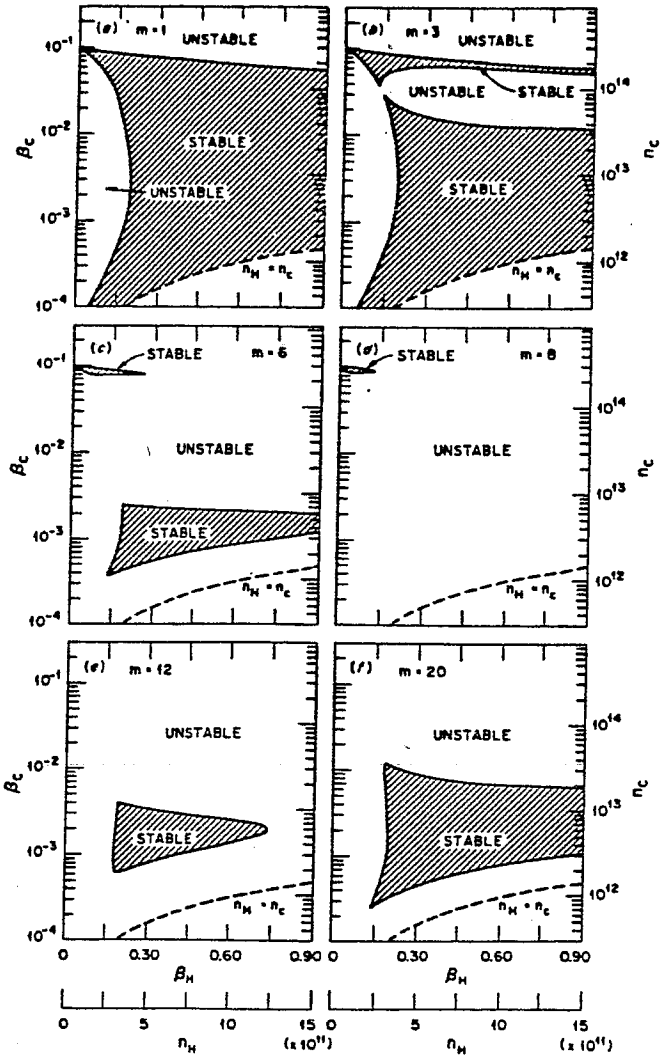

FIG. 1. EBT-S stability for short-wavelength modes [Ref. 8].

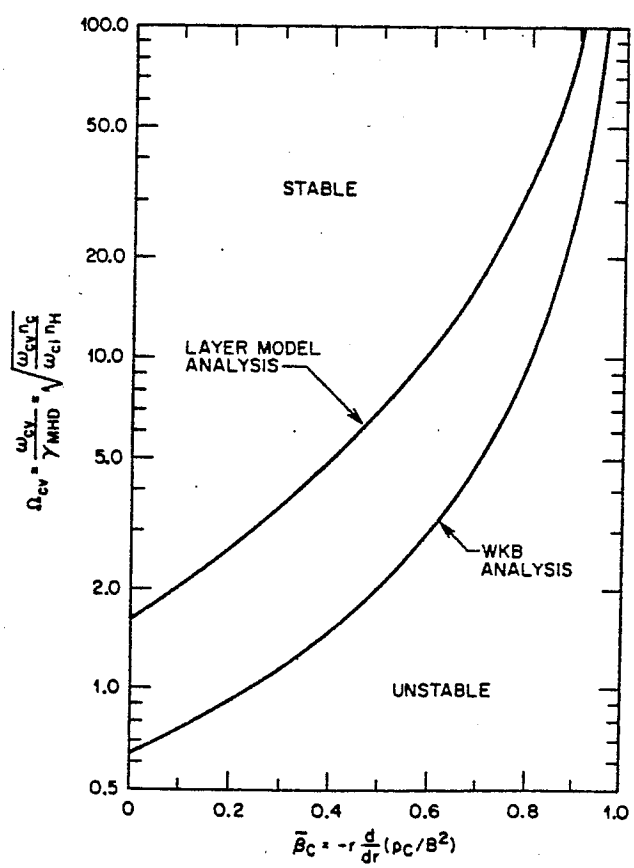

FIG. 2. Layer mode stability [Ref. 16].

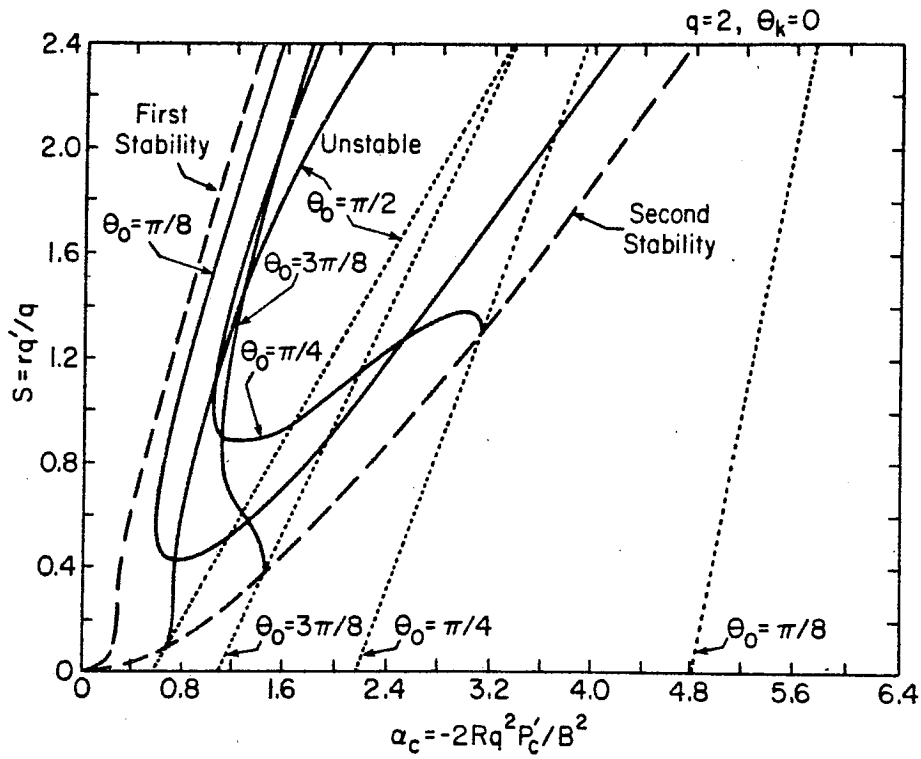

FIG. 3. Tokamak stability boundaries with hot particles [Ref. 17].

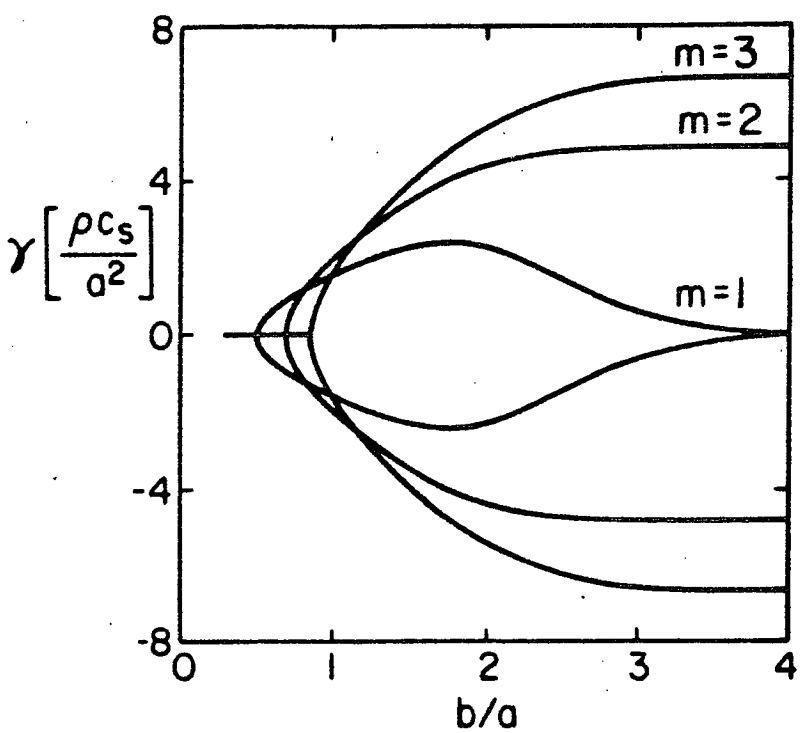

FIG. 4. Tandem mirror drift wave growth rates [Ref. 21].

C. Tearing Modes and Stellarators

As they are closely related, stellarator research and tearing mode research have progressed synergistically at the Institute for Fusion Studies. As tearing modes grow to finite size, they deform an initially symmetric plasma to a fully three-dimensional system. Thus, knowing how tearing modes saturate nonlinearly bears on the problem of three-dimensional equilibrium and vice versa.

Stellarator research at the Institute for Fusion Studies has encompassed both equilibrium and stability theory. The equilibrium theory includes the development of a method for finding three-dimensional equilibria having nested flux surfaces, the development of a technique for finding coil-winding laws that yield highly integrable vacuum magnetic fields, and a calculation of the extent of flux surface degradation by three-dimensional effects. The stability analyses concern drift waves in helically symmetric (so-called straight) stellarators, ballooning modes in low-pressure toroidal stellarators, and free boundary modes of high-pressure straight stellarators.

Bhattacharjee, Wiley, and Dewar have developed a new variational method for determining three-dimensional equilibria (c.f. IFSR #48-R and IFSR #85). The method uses a variational principle to determine the transformation from flux coordinates to physical coordinates. Flux coordinates are coordinates with the property that field lines are confined to contours of one of the coordinates, and they progress linearly in the other two coordinates. The transformation between cylindrical coordinates (r,ϕ,z) and the flux coordinates (v,η,ζ) determines the metric tensor, which enters the variational principle

through quantities such as $|B|^2$. Thus, the variation yields a set of nonlinear differential equations for the transformation functions. These equations are solved numerically by Fourier expansion and truncation which leads to a more efficient coputational procedure.

Hanson and Cary have developed a technique for finding coil-winding laws that produce vacuum magnetic fields with dense nested flux surfaces (c.f. IFSR #55, IFSR #95, and IFSR #107). The technique identifies the stochasticity inducing islands by their remnants, the closed magnetic lines. Motion of nearby lines gives a measure of the degree of stochasticity produced by this island. The parameters describing the coil winding law are varied to minimize this measure. The resulting systems are highly integrable; no visible stochasticity is present. This procedure increases rotational transform and inverse aspect ratio, both of which are desirable for producing high-pressure plasma equilibria.

To understand how these highly integrable systems are affected by the presence of plasma, Cary and Kotschenreuther (c.f. IFSR #134) have analyzed island formation in integrable magnetic fields by plasma pressure. This low-pressure analysis relies on linearization far from the low-order rational surfaces and a single-helicity approximation near these surfaces. The analyses of the two regions are combined by asymptotic methods similar to those of tearing-mode theory. The results indicate that in typical stellarators the importance of islands is determined not so much by the three-dimensional effects as it is by the presence or absence of a magnetic well. Generally, the presence of a magnetic well insures that island effects will remain small, while its absence guarantees overlap at arbitrarily low pressure.

As drift waves are believed to be of fundamental importance in the understanding of anomalous transport in tokamaks, it is natural to determine their behavior in stellarators. A first cut at this problem was undertaken by Bhattacharjee et al. (c.f. IFSR #73). In this theory ions are treated as a cold magnetized fluid, while the electron response is given by the Boltzmann law. This analysis shows the presence of two classes of solutions. The destabilization of these two solutions is under investigation.

Berk, Rosenbluth, and Shohet have used the ballooning mode formalism to study MHD stability of three-dimensional stellarator configurations (c.f. IFSR #87). The short perpendicular wavelength approximation is used to derive a one-dimensional equation describing ballooning modes. The differential equation is integrated along vacuum magnetic field lines. The effects of pressure are included perturbatively. A survey of configurations shows that in most cases ballooning-mode stability is no more stringent than Mercier stability. However, an exception to this rule has been found in the heliac configuration.

Recently, the heliac configuration generated much interest because internal-mode calculations at Princeton indicated that heliacs should be stable at quite large values of plasma pressure. This led Barnes and Cary (c.f. IFSR #128) to calculate the stability of this configuration to external, free-boundary modes. This calculation is based on the sharp boundary model, which reduces the two-dimensional partial differential equation to a one-dimensional, integral equation. This calculation indicates that the heliac is stable also to free-boundary modes. In fact, the pressure limit is determined by lack

of equilibrium rather than onset of instability. As a side result, it is found that stellarators without a magnetic well can be stabilized by adding a net current.

Tearing modes have a strong effect on the performance of tokamaks. For this reason, their study has been a strong component of research at the Institute for Fusion Studies. This research includes the study of the effects of diffusion and curvature on the collisionless tearing mode, the nonlinear evolution of single helicity solutions in both the collisionless and fluid regimes, the development of a general formalism for studying electromagnetic perturbations, and the island coalescence instability.

The effects of turbulent diffusion on collisionless tearing modes was studied by Meiss et al. (c.f. IFSR #26). This study indicates that the primary effects of diffusion are anomalous viscosity and broadening of the current channel. While for conventional tearing modes these effects are insignificant, they produced significant stabilization of the m=1 mode.

The effects of curvature on tearing modes was studied by Cary and Newberger [c.f. Bull. Am. Phys. Soc.27,912(1982)]. To correctly account for curvature, the standard set of equations is generalized to include all finite-pressure effects: parallel magnetic field perturbations, curvature drifts, and gradient drifts. Algebraic elimination reduces the problem to a fourth-order system of ordinary differential equations. A rigorous proof shows that bad curvature does not drive tearing modes or drift modes unstable unless the Suydam criterion is violated. Numerical analysis shows that curvature does

significantly affect the amount of external driving energy needed to destabilize the tearing mode.

The nonlinear kinetic theory of a single helicity kinetic tearing instability was studied by Swartz and Hazeltine (c.f. IFSR #103). In this work, the modification of the orbits by the islands is included. The resulting equations show that collisionless tearing modes saturate at very small island widths. As collisionality is increased, the slow Rutherford type of growth is seen.

Kotschenreuther et al. studied the nonlinear dynamics of the single-helicity tearing mode in the fluid limit including the effects of curvature (c.f.IFSR #135). The analysis shows that while good curvature leads to linear stability, it becomes progressively less important as the island width increases. Thus, the curvature stabilization of Glasser, Greene, and Johnson is ineffective if the initial mode amplitude is large enough. The analysis also shows that resistive pressure-driven modes saturate if there is no external driving energy ($\Delta'<0$).

Mahajan further developed the general theory of electromagnetic mode equations in slab geometry (c.f. IFSR #47). His work shows that the coupled set of differential equations describing electromagnetic perturbations can be reduced to a single integral equation with a symmetric kernel. This formulation has both analytical and computational advantages.

An additional tearing phenomenon studied at the Institute for Fusion Studies is the coalescence instability (c.f. IFSR #93 by Bhattacharjee et al.). The coalescence instability has been invoked to explain the disappearance of all but the lowest order modes on a given

rational surface. The present work studies the effects of longitudinal magnetic field and compressibility. It is shown that these effects cause a qualitative difference by introducing a new nonlinear phase during which the destruction of flux proceeds at a much faster rate.

A quasi-thermodynamic model for relaxation of tokamak discharges has been developed by Bhattacharjee et. al (c.f. IFSR #19, #51, #52). In this model, which is inspired by Taylor's theory of self-reversal in pinches, the potential energy of a plasma is minimized subject to a set of global "invariants", which are exactly preserved by all ideal instabilities and approximately preserved by a class of resistive instabilities. It is argued that relaxation in tokamaks is dominated y modes of a single helicity of the type described by the Kadomtsev-Monticello model. Minimum-energy equilibria, with zero and finite pressure-gradients, are constructed and shown to be ideally and resistivity stable to a large class of modes.

D. Tokamaks and TEXT Support

1. Tokamak Theory. The work done on tokamak theory will be considered under the headings of the main tokamak problems, namely, the anomalous electron energy loss, anomalous ion transport, disruptions and impurity transport. Some of these issues are discussed elsewhere, especially in Section 6.

a. The Anomalous Electron Energy Loss

A major problem which is universal to all tokamaks is an anomalous electron energy loss. This is generally assumed to be due to an anomalously large electron thermal conductivity although this has not been proved experimentally; an anomalous transfer of energy to the ions could equally explain the observations or a combination of the two processes. The most likely cause of enhanced electron thermal conductivity is drift wave turbulence and the IFS contributions on this subject have been reviewed in Section II. Approximate expressions for the electron thermal conductivity have been obtained by Mahajan[1] and by Similon and Diamond.[2] For ohmically heated discharges, both results lead to scaling laws for the energy containment time (τ_{Ee}) close to the experimentally observed Pfeiffer and Waltz scaling which is now generally accepted for ohmic discharges before density saturation sets in. Other drift wave theory to explain the broad spectra of fluctuations observed in tokamaks is reported in the papers of Terry and Horton.[3]

Work on the alternative explanation – transfer of energy to the ions – has been done by Ware who has found several mechanisms which cause such transfer, including neoclassical effects, direct ohmic heating of the ions and even the drift wave.[4] He has also shown that if

a dominant fraction of the ohmic power is conducted out by the ions, this assumption plus the critical electron temperature (T_e) for loss of poloidal equilibrium in the central sawtooth region[5] leads to the Pfeiffer and Waltz scaling for both T_e and τ_{Ee}.[6]

In high-β discharges MHD-turbulence can be expected; Diamond and co-workers have obtained expressions for the enhanced electron thermal conductivity in the presence of such turbulence (see Section 6). The predictions show good agreement with the experimental observations on ISX-B.[7]

b. Anomalous Ion Transport

There is growing experimental evidence that the ion heat conduction in tokamaks exceeds the predictions of neoclassical theory. This is found even when only the collisional transfer of energy from electrons to ions is accounted for; allowing for the extra transfer processes increases the anomaly. The transport of toroidal momentum (ion viscosity) is also found to be anomalously large.

A variety of neoclassical effects has been discovered which help to explain this anomaly. The enhancement of ion thermal conductivity (χ_i) due to energy scattering collisions was first discovered by Bolton and Ware.[8] The two component ion distributions observed in PDX have been shown to be consistent with neoclassical ion heat conduction[9] and the presence of the anomalous distribution tail increases χ_i by a factor of 4. In the case of tokamaks where T_i is significantly greater than T_e, it has been found that electron collisions will substantially increase both χ_i and the ion viscosity.[10]

Enhancement of ion transport can also be caused by drift waves and a considerable amount of work has been done on this subject by Horton and co-workers.[1]

c. Disruptions

Work on tearing-mode theory and disruptions will be covered in Section 6.

d. Impurity Transport

The observed rates of diffusion of impurity ions in tokamaks are found to be substantially larger than the predictions of simple neoclassical theory which allows for only magnetic trapping and particle drifts. However, more extensive neoclassical theory allowing for electrostatic trapping, non-uniformity of the impurity ions on a magnetic surface and poloidal rotation leads to new terms in the impurity diffusion which could easily be dominant.[12] Until these three effects are measured, no decision can be made as to whether impurity transport is anomalous.

2. Theory Support for the TEXT Tokamak. In March 1981, an IFS committee was set up to give theoretical support to the TEXT tokamak. This committee held frequent joint meetings with the experimentalists to review results from TEXT and other tokamaks and also recent advances in tokamak theory. The emphasis in the TEXT program is the study of the anomalous electron energy loss, impurity transport and MHD activity, including disruptions. As well as giving theoretical support

to the TEXT program the committee meetings aid communication between experimenters and theoreticians.

Among the highlights of these meetings were several talks by Ross reviewing drift-wave theory and its predictions. Although the theory has produced scaling laws for the energy containment time in qualitative agreement with experiment, there are still major problems. In particular the observed poloidal variations of the amplitude and spectra of the high-frequency fluctuations are not explained in detail by the theory.

Another highlight involved the reported observation of giant sawteeth in the x-ray signals from TEXT. Such sawteeth occur among normal sawteeth and exhibit twice the normal sawtooth period with the signal amplitude climbing to approximately twice the normal amplitude. The observations cannot be explained by either the tearing-mode theory of sawtooth disruptions or by the loss of poloidal equilibrium theory.[5] As TEXT enters its high productivity phase, we may expect more such challenges to the IFS theorists.

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E. Computational Physics

TABLE OF CONTENTS

1. MHD Simulations

a) Nonlinear 3D MHD Studies of RFP's and Tokamaks

The presence of the fast compressible Alfvén time scale in the primitive equations makes it impractical to apply them directly to the study of relevant resistive instabilities, which have much longer time-scales. Consequently, two techniques have been developed for the elimination of these fast waves.

In a first approximation, the fast Alfvén waves were removed from the system by assuming an incompressible equation of state[1], and the resulting algorithm was applied to the self-reversal problem in reversed field pinch (RFP) studies. Low-β resistive kink mode activity was shown to reverse an initially non-reversed paramagnetic toroidal field profile and maintain the reversal on a resistive time scale[2], thus indicating the presence of a dynamo mechanism.

Later, the need for the incompressibility assumption was removed by developing an efficient method for treating the fast Alfvén waves implicitly.[3] This code that solves the compressible resistive MHD equations in three dimensions has been used to verify our earlier incompressible results, with some quantitative, but not qualitative differences.

Studies of zero-β tearing modes, and their contribution to the dynamo mechanism in RFP's are presently being performed. Numerical studies of finite-β effects of these modes will be initiated in the near future in collaboration with other members of the Institute.

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b) Evidence of Discrete Alfvén Waves in a Plasma Column

Discrete or global Alfvén eigenmodes (GAE)[1] have been observed in a plasma column modeled as a straight cylinder with square cross-section, using a 3D particle MHD code.[2] The code was first run with a thermal level of fluctuations (linear case) to pinpoint the spatial structure and frequency of the modes.

A number of GAE's with different m (poloidal) and n (toroidal) mode numbers and radial locations were detected. They all have the following predicted properties: helical structure with helicity opposite to the kink modes, broad spatial structure, frequency $\omega_{mn}<(k_{\parallel}c_A)_{mn}^{min}$, narrow symmetric spectral width $\Delta\omega/\omega\lesssim 2\%$. Next, selected modes were externally driven one at a time (nonlinear case) by antennas. Saturation of the modes occurs after 10-20 wave periods with some mode coupling and considerable asymmetric broadening of the resonance (for the modes considered) up to $\Delta\omega/\omega\lesssim 15\%$ for perturbation levels of $\tilde{b}/B_o\approx 10\%$. We plan to add fast particles to the code, modelling α-particle distributions, to study their effect on these global Alfvén eigenmodes. Such a method is being implemented in the particle MHD code.[3] More importantly, the effects of toroidicity on the GAE's will be studied using toroidal versions of our various MHD codes.

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c) Other MHD Simulations

The particle MHD code in 2-1/2 D has been successfully used to elucidate the process of fast magnetic field reconnection. It was found that compressibility can greatly enhance the reconnection rate.[1] The effect of compressibility and magnitude of the toroidal field on the coalescence instability was also studied. Compressibility enhances the reconnection rate while increasing the toroidal field decreases it.[2]

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2. Particle Simulations

a) Particle Simulations of Resistive g-modes in Sheared Slab Geometry

A 2-1/2 D guiding-center electron, full dynamics ion, electrostatic particle code is used with curvature modeled as an effective gravity. Collisions have been added to the model according to a standard Lorentz gas model. Both fast and slow interchange orderings have been considered. Simulation results agree well with linear theory and/or shooting code predictions for the unstable modes and their growth rates. Fast interchange growth is almost independent of resistivity and obeys the classical result. Slow interchange growth rate scalings of $\gamma=\nu_{ei}^{1/3}$ have been obtained. Convective mixing of the pressure profile has been found to be the saturation mechanism of the resistive g-mode. The theoretical level $e\varphi/T_e$ scales with $(\nu_{ei}/\omega_*)^{2/3}$. 3D extensions of the present work are being initiated.

b) Particle Simulations of Drift Waves in Tokamak-like and Stellarator-like Geometries

For a sheared slab with a single rational surface and strong shear ($L_s/L_n \lesssim 28$), the damped drift eigenmodes predicted by linear theory are found to persist. This is so as long as the ion resonance layer is well within the simulation domain. For a sheared slab and weak shear ($L_s/L_n > 28$), where the possibility of convective amplification exist, weak initial growth of local transients, but not significant enough to modify the background profile, does not prevent the formation of the linearly predicted stable global eigenmodes. In 3D, with strong shear

and multiple rational surfaces, the simulations are so far inclusive as to whether nonlinear instability takes place and absolute growth results.

Using a 2-1/2 D electrostatic code, we have studied the stability of drift waves in a stellerator-like environment. Our simulations show that the drift waves are stabilized when the electron ∇B drift (note ∇B here is a function of x) cancels out the electron diamagnetic drift, too stringent a condition to be relevant to Wendelstein. The stabilization condition corresponds roughly to R/a~2-4, too stringent to explain stability in Wendelstein VII where R/a~10. Realizing that drift surfaces and magnetic surfaces can differ by as much as a/2, we have started a study of the effect of perpendicular diffusion or harmonic bounce motion of the electrons on drift wave stability with mode localization through weak shear.

c) Other Particle Simulations

2-1/2 D electrostatic and electromagnetic explicit codes have been used to study plasma injection across transverse and curved magnetic fields and have verified many of the features of theory.[1] 2-1/2 D electromagnetic simulations of collisionless tearing, reconnection and coalescence of magnetic fields for a sheet-pinch-like configuration have shown that the coalescence instability can occur in an explosive fashion in compressible plasmas but is suppressed for a toroidal field of the order of the poloidal one.[2] Beat-wave current drive in a magnetized plasma has been investigated using two-fluid theory and 1-2/2 D electromagnetic particle simulations. It is found that large

currents can effectively be driven in magnetically confined plasmas by the ponderomotive force created by the beating of two electromagnetic waves. These beating waves can be cyclotron waves propagating parallel to the magnetic field or light waves propagating obliquely to it.[3] 2-1/2 D electromagnetic simulations of the Toroidal Cusp Experiment have also been continued. While the recent TCX configuration, with cusp magnets arranged poloidally, only exhibits ion current and ion heating, adding a toroidal field or winding the cusp magnets helically around the chamber allows electrons to carry a current and electron heating.[4] Finally, particle simulations of current-driven ion cyclotron waves using a 1-2/2 D guiding-center electrons, full dynamic ions, electrostatic code have been initiated in collaboration with R. H. Berman of MIT. These simulations have had partial success in verifying the scaling of anomalous resistivity predicted by the theoretical studies of Chiueh and Diamond[5].

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3. Model Equations Simulations

a) Mode Coupling Simulations of Drift Wave Turbulence

Drift wave instabilities can be represented by the two-component fluid equations for wavelength components comparable to or greater than the ion gyroradius. Representing the fluctuating density and potential fields in a truncated $\underset{\sim}{k}$ space with N Fourier modes, the dynamics are given by a volume contracting flow in a 2N dimensional phase space with coordinates $\varphi_{\underset{\sim}{k}_\ell}=y_{2\ell-1}(t)+iy_{2\ell}(t)$. The lowest order system with a single triplet was shown by Terry and Horton[1] to contain a chaotic attractor giving rise to temporal chaos. A further study[2] for the lowest dimensional isotropic $\underset{\sim}{k}$ space distribution with N=10 demonstrated the usefulness of these low-order representations of drift wave turbulence. Recent studies[3] with N=200-400 use the full memory of the CRAY and about 20 minutes of CPU time. The recent studies give details of the frequency and wave number spectrum, the statistics of the $\varphi_{\underset{\sim}{k}}$ field components, and direct values of the anomalous transport coefficient in the turbulent state. Further studies will attempt to compare the numerical experiments with turbulence theory and find the best set of reduced field variables for describing the dynamics on the chaotic attractor.

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4. Code Development

a) Implicit Particle Simulation of Magnetized Plasmas

The second-order accurate simulation method described here is appropriate for the study of low-frequency phenomena in a multi-dimensional, magnetized plasma. A field corrector derived by the direct-method (with differencing simplified) correctly treats finite-sized particles. The guiding-center motion of both ions and electrons is accurately followed for $\Omega_\alpha >> 1$ by a simple decentered differencing of the Lorentz force particle-pushing equations. A straightforward iteration of the field corrector is developed based on the renormalized plasma simulation method.

Numerical results confirm reduced electron cooling for the second-order accurate method. The numerical experiments also show that finite particle size may only be incorporated in an implicit calculation as indicated by the direct-method derivation. The efficiency of the iterative method for solving the field corrector is demonstrated for both nearly uniform and strongly inhomogeneous plasmas.

Accurate numerical results were obtained in two stringent test cases.[1] First, the ion-acoustic fluctuations of a thermal plasma demonstrate the accuracy with which kinetic electron effects on low-frequency oscillations are represented. Second, the simulation of an unstable gravitational interchange in a sharp density gradient plasma, demonstrates the applicability of the method to nonlinear phenomena at extremely low-frequencies (growth rate $\gamma \approx 10^{-5}\omega_e$).

A formulation appropriate for simulation of low-frequency electrostatic drift wave fluctuations is obtained by replacing the point ions with gyroaveraged clouds of charge. It has recently been shown[2] that such an explicit calculation of the ion response may be combined with an implicit guiding-center calculation of the electron response. The resulting algorithm is linearly stable for any time step satisfying the electron streaming and describes ion nonlinearity to all orders in $e\Phi/T$. Implementation of a three-dimensional slab version of this method will be an important area for future code development.

A 2-1/2 D, electromagnetic direct implicit algorithm has recently been implemented. This code was developed during a recent segment of the JIFT program with T. Kamimura of JIPP, Nagoya. In contrast to previous implicit electromagnetic simulation techniques, this algorithm describes the electrons by small gyroradius, guiding-center equations. The ions are treated as finite sized particles with full particle dynamics. An explicit ion, implicit electron treatment is used. This code is curently being used to study collisionless tearing mode evolution in a single helicity calculation.

1. D. Barnes, T. Kamimura, J. N. Leboeuf and T. Tajima, JCP 52, 480 (1983).

2. D. Barnes and A. B. Langdon, "Direct Implicit Plasma Simulations", a chapter to appear in Computational Techniques, (1984).

b) Other Codes

A variety of explicit particle codes is under development and testing to study low-frequency plasma dynamics. They involve attempts to tackle longer time scales, larger space scales and more realistic geometries. In particular, a guiding-center electron, full dynamic ions, Darwin or magnetostatic code is being applied to a study of Alfvén wave heating.[1] Also, with applications to collisionless tearing in mind, a multiple grid, fully electromagnetic code in 2-1/2 D is being developed: the code accommodates large spatial dimensions while resolving small scale structure.[2] Finally, a full dynamics electrostatic code in 3D and toroidal geometry has also been built and will be used in a study of toroidal drift waves.[3]

1. J. L. Geary, J. N. Leboeuf and T. Tajima, BAPS 28, 1125 (1983).
2. E. Zaidman, D. Barnes and T. Tajima, BAPS 28, 1125 (1983).
3. M. Lebrun, F. Brunel and T. Tajima, BAPS 28, 1125 (1983).

5. Computational Needs. Our yearly computer-time allocation on both CRAYS at MFECC is 580 hours for FY 84. This represents a negligible increase of 30 hours over FY 83. We have managed to consistently use up our allocation at a reasonable priority since the beginning of the IFS. Our present allocation is clearly inadequate to handle the very diverse problems outlined in the overview: it is about half of what we have requested for the past two years. In particular,

3D simulations (kinetic or MHD) can only be carried out at the expense of a very long turnaround time (one month or more). Clearly, more computer-time is needed for faster progress and more interesting results. An improved link with MFECC with higher baud rate and larger bandwidth would also be desirable for better data throughout. We have tried to make full use of the local computers but they are already overloaded by the TEXT and PRETEXT experiments. Even with the new commitment of the University to computing resources, the local situation will not improve rapidly in the near future. Moreover, we are severely limited in system sizes by the memory of the existing machines. We hope that the next machine acquired by MFECC will not only be faster but also will make more memory available to the users, as the Japanese supercomputers already do.

F. Turbulent Phenomena

Research Topics

1. Drift Wave Turbulence

-Nonlinear evolution, transport scaling

-Spectrum

-Nonlinear stability

a. Slab Nonlinear Electron Response	IFSR 21
b. Nonlinear Trapped Electron Response	IFSR 117
c. General Toroidal Response	IFSR 18
d. T_e' Driven Trapped Electron	IFSR 31
e. Ion Compton Scattering-Slab	IFSR 24
f. Ion Compton Scattering-Torus	IFSR 105
g. Drift Wave Soliton Gas	IFSR 45
h. Drift Wave Soliton with Shear	IFSR 60
i. RPA for Drift Wave Turbulence	IFSR 20
j. Low Order k Space-Drift Wave Turbulence	IFSR 58
k. Statistical Description Drift Wave Turbulence	IFSR 92
l. Interaction Clumps and Drift Waves	IAEA 1982
m. Clumps and Nonlinear Stability	IFSR 91
n. Dissipative Density-Gradient Driven Turbulence	IFSR 114

2. MHD Turbulence

-Nonlinear Tearing: Disruptions, RFP, Dynamo

-Hign β Confinement: Tokamak, RFP

-Edge Turbulence

a. Tearing Mode Turbulence and Major Disruption	IFSR 116
b. Tearing Mode Interaction and Dynamo in RFP: Theory	IFSR 136
c. Tearing Mode Interaction in RFP and Tokamak: Comparison	IFSR 129
d. Quasilinear Evolution Tearing Mode Turbulence	IFSR 115

e. Resistive Ballooning Mode Turbulence and Confinement in ISX-B	IAEA 1982
f. Effect Compressibility on Resistive Ballooning Mode	IFSR 108
g. Kinetic Theory of Resistive Ballooning Modes	IFSR 113
h. Mixing Length Theory and Resistive Pressure Driven Modes in RFP:	
Electrostatic and Electromagnetic	Cmpt. Torus Workshop 1984 IFSR 121
i. Rippling Mode Turbulence	IAEA 1982 APS 1983
j. Collisional Drift Wave Turbulence	see A.n.
k. Microtearing Mode Turbulence	Sherwood 1984
3. Miscellaneous	
a. Drift Waves in Tandem Mirror	IFSR 9
b. Drift Waves in Rotating Plasma	IFSR 117
c. Non-Intrinsic Ambipolarity	IFSR 83
d. Breakdown Onsager Symmetry	IFSR 37
e. Coalescence of Islands	IFSR 93
f. Nonlinear Ion Cyclotron Instabilities	APS 1983

Extended Summary

Research in turbulence and anomalous transport in fusion plasma has been a popular pursuit at IFS - over thirty research projects involving eleven staff members, six postdoctoral fellows, and nine graduate students can be identified. The excellence of the work in this particular area is indicated by the nearly twenty invited papers and talks presented by IFS scientists in the past four years. This report summarizes progress in research in turbulence and anomalous transport at IFS and indicates proposed topics for furthur investigation. For convenience, the various research topics are classified under the headings of drift wave turbulence, MHD turbulence, and miscellaneous topics. Specific investigations listed earlier are referred to in parentheses. Thus, for example (B.b) refers to Tearing Mode Interaction and Dynamo in RFP: Theory, discussed in IFSR #136.

Research in drift wave turbulence (DWT) is aimed at a theoretical understanding of the spectrum of microscopic low-frequency fluctuations observed in tokamaks and the anomalous transport caused by such fluctuations. The major theoretical questions to be addressed are:

A. How do realistic effects such as magnetic shear, toroidicity and inhomogeneity (trapped particles) affect the nonlinear low frequency plasma response? How do drift waves saturate? What are the consequences of DWT for confinement?

B. What determines the structure of the density and potential fluctuation spectrum? In particular, what causes the large frequency broadening at fixed wavenumber $\Delta\omega_k \sim \omega$? What underlies the (presumed) randomness of mode phases?

C. How does DWT affect the expansion-free energy release mechanism? Are there nonlinear instabilities?

Concerning A., renormalized perturbation theory has been used to calculate the nonlinear response of electrons in a sheared magnetic field (A.,a.), of trapped-electrons in toroidal geometry (A.b.,A.c.), and of ions in a slab (A.e.) and torus (A.f.). the principal results are:

1. In (A.e.), ion Compton scattering, which causes ion heating and energy scattering to long wavelength, was identified as a strong stabilizing effect in the sheared slab. Combining the results of (A.e.) with (A.a.), it appears that drift waves are <u>nonlinearly stable</u> in slab geometry, thus rendering that model inadequate for studies of DWT in tokamaks.

2. In (A.b.)-(A.d.), it was demonstrated that the response of trapped electrons in a torus is essentially linear, and not modified by turbulence for realistic fluctuation levels. Hence, in (A.f.) the nonlinear ion response in toroidal geometry, computed using a renormalized perturbation theory in ballooning representation, was combined with linear trapped-electron destabilization to obtain fluctuation levels and spectra. The resulting confinement time scalings were calculated. Results indicate that in the dissipative trapped-electron regime ($\nu_{eff} > \omega_{*e}$), τ_E scales (when balanced with ohmic heating) as $\tau_E \sim n^{9/8} R^2 a^{7/8} \hat{s}^{7/8} B^{-1/2} q^{5/4}$, as observed in many experiments. For the collisionless regime ($\omega_* > \gamma_{eff}$), $\tau_E \sim n^{3/8} a^{21/8} \varepsilon^{-7/16} q^{3/4} s^{-5/8} B^{1/2}$ (OH) or $\tau_E \sim T_e^{-3/2}$ (not balanced with OH). The unfavorable T_e scaling and weak density dependence are consistent with the results of several beam-heating experiments.

Concerning B., the physics of triad mode interaction in (DWT) was elucidated in (A.i.), (A.j.) and (A.l.). A novel, strong coupling approach based on a soliton gas model was pursued in (A.g.) and (A.h.). In (A.l.), (A.m.) and (A.n.) renormalized perturbation theory was used to analytically calculate the frequency width $\Delta\omega$. Research on the first two topics is discussed in the Mathematical Physics section.

In (A.l.) renormalized perturbation theory was used to calculate the (collisionless) trapped-electron phase space density correlation function and the resulting wave number and frequency spectrum, including the frequency width $\Delta\omega_k$. The physical processes underlying the frequency broadening mechanism were elucidated. In particular, it was demonstrated that frequency broadening is a result of overdamping of collective resonances which is necessary to balance nonlinear noise (incoherent emission) at steady state. The size of the incoherent emission was directly related to the expansion-free energy relaxation process, thus establishing a link between frequency broadening and the dynamics of relaxation. It was demonstrated that incoherent fluctuations (clumps) can tap expansion-free energy in a fundamentally different way than waves do. This new mechanism is a consequence of inter-species interaction necessitated by maintenance of ambipolarity during density gradient relaxation. In the course of this work, aspects of the physics of clump-wave interaction were elucidated. Hence, this effort is complementary to that of Dupree and co-workers.

In (A.n.), the theory was applied to dissipative DWT, relevant to tokamak edge phenomena. Wavenumber and frequency spectra, fluctuation levels, and particle transport coefficients were determined and found to be in good (in some cases excellent) agreement with experimental results. The mechanisms of nonlinear frequency broadening and growth enhancement were elucidated for a fluid-plasma system, thus extending

ideas and methods first developed for Vlasov turbulence. The effects of electric fields were included. Comparisons between predictions of electric field modified DWT models and Kelvin-Helmholtz turbulence were made. This investigation was stimulated by close interaction with experimentalists involved with probe studies of edge turbulence on TEXT and PRETEXT.

In (A.m.) the clump instability (as opposed to mode instability) growth rate was calculated for DWT in a sheared slab. In collaboration with the computational effort, a particle simulation study of this instability is now in progress.

Research in MHD turbulence (MHDT) is concerned with the development of theoretical understanding of macroscopic turbulent phenomena observed in fusion devices and the associated consequences of such phenomena for stability and confinement. The principal theoretical issues are:

A. What are the physical processes which govern the nonlinear interaction of tearing modes in tokamaks and Reversed Field Pinches (RFP)? What are the mechanisms for the disruption in tokamaks and the dynamo in RFP? Can a theory of MHDT, which self-consistently treats the dynamics of current and temperature, be developed?

B. What are the physical processes which govern the nonlinear saturation of resistive pressure-driven modes in high-β tokamaks and RFP? What are the consequences of such turbulence for confinement? What scaling laws can be derived? How can transport caused by magnetic fluctuations and instability dynamics be treated self-consistently?

C. What is the cause of the relatively large-edge turbulence observed in tokamaks? Can we explain the (comparatively)

excellent experimental data obtained from edge studies and use them to calibrate our general approach to microturbulence? What are the implications of existing results for higher temperature regimes?

A unique feature of nonlinear MHD studies conducted under the auspices of the fusion program, both at IFS and elsewhere, is the successful, strong interaction between theory and computational efforts. Virtually all of the investigations undertaken to answer the questions posed in (A)-(C) have involved collaboration of analytic theorists with computational physicists, both at IFS and other institutions. In this regard, the IFS collaboration with the resistive MHD group at ORNL is worthy of special mention.

Regarding (A), (B.a.)-(B.d.) are concerned with nonlinear tearing mode interaction and its consequences for disruptions in tokamaks and the dynamo effect in RFP. The principal results are:

1. A reasonably complete theory of MHDT in a current-carrying plasma has been developed and successfully applied to several problems. The theory is constructed by using renormalized perturbation expansion methods to derive a set of coupled equations for the energy spectra and turbulent response functions. The crucial, novel features are the faithful treatment of the relative spatial orientation of interacting, resonant kink-tearing modes and the taking into account of essentially nonlocal mode structure ($\underline{k}\cdot\underline{B}_0$ resonances, layers, exterior regions, etc.). As a consequence, considerations of MHD stability affect the direction and rate of energy cascade, and the nature of the interaction of long wave-length tearing modes with short wave-length turbulence. In addition to the specific applications discussed below, this theory may be relevant to reconnection in solar flares, magnetic viscosity in accretion disks, and coronal heating.

2. The final phase of the major disruption in tokamaks is characterized by rapid growth of low m tearing modes (at a rate which is independent of the collisional resistivity) and the nonlinear generation of short wavelength turbulence. Application of the theory described above (B.a.,B.d.) indicates the major effect of small scale turbulence on low m tearing is to act as an anomalous magnetic diffusivity, thus nonlinearly destabilizing the long wavelength tearing modes at the rate $\gamma_{\underline{k}} \simeq (k_y/L_s)^{1/8} (\Delta'_{\underline{k}})^{1/2} (\sum_{\underline{k}'} < \hat{V}_r^{\,2} >_{\underline{k}'})^{3/8}$, where $< \hat{V}_r >_{\underline{k}'}$ is the velocity spectrum of short wavelength turbulence. This result is in excellent agreement with the numerically determined growth rate. The voltage spike, caused by expulsion of flux by fluid turbulence, occurs at a similar rate, consistent with the theory. Finally, it appears that the disruption can be viewed as a type of positive feed-back instability where interaction of long wavelength tearing modes nonlinearly generates short wavelength turbulence, which in turn acts as a dissipation mechanism for the long wavelength modes, furthur destabilizing them. Thus, growth is explosive, and occurs in a few inverse Alfvèn times.

3. The nonlinear interaction of tearing modes and their relation to the dynamo effect (B_z configuration maintenance) in RFP are discussed in (B.b.) and (B.c.). In RFP, magnetic islands produced by m=1 tearing modes (destabilized by resistive diffusion away from the force free state) overlap at low fluctuation levels. Hence, strong resonant nonlinear interaction occurs. Since m=2 modes are linearly stable and because current gradient flattening by global m=1 modes prevents (nonlinear) destabilization, nonlinear coupling to $m \geq 2$ is a good candidate for an m=1 saturation mechanism. A theory of m=1 saturation by a coupling to $m \geq 2$ has been developed. Balancing the m=1 mode driving (as approximated by the linear growth rate) with coupling to

stable m=2 modes predicts a saturated m=1 fluctuation level $\delta B/B \sim S^{-1/3}/|\Delta_2' a|$, where Δ' ($\Delta_2' < 0$) is the usual tearing mode stability parameter. Computational studies have verified this basic model of the nonlinear interaction and have shown that nonlinearly coupled modes of differing helicity saturate considerably faster than single helicity modes do. m=1 energy coupled to m=2 ultimately cascades to smaller scales and is dissipated by resistivity or expended driving large m, stable modes. An interesting point is that in a current carrying plasma, the energy cascade to small scales can be viewed as a progressive current filamentation process, where nonlinear interaction drives progressively more stable, small scale current sheets. Computational studies have verified that spectrum broadening occurs.

The effect of m=1 tearing mode turbulence on the RFP magnetic configuration was determined by <u>calculating</u> the quasilinear electric field $< \hat{\underline{V}} \times \hat{\underline{B}} >$ <u>using</u> the m=1 saturation level discussed above. It has been demonstrated that the fluctuation levels scale properly to ensure maintenance of the reversed B_z field. It is interesting to note that unlike solar dynamo theory (where symmetry breaking appears in the form of finite helicity fluid turbulence) in the RFP, radial eigenmode structure and boundary conditions provide the information which specifies the direction of the induced poloidal currents. Finally, it has been shown that the thermal energy losses caused by stochastic magnetic fields resulting from overlapping islands are consistent with experimentally observed confinement properties. In particular, for plasma density proportional to current (I_p), the scaling $T_e \sim I_p^{.7}$ has been derived.

Regarding (B), (B.e.)-(B.h.) are concerned with the degradation of confinement in high-β resistive tokamaks, such as ISX-B, and in the RFP. In (B.e.)-(B.g.) a theory of resistive ballooning mode turbulence in high-β, beam heated tokamaks was presented. For high-β_p, low temperature discharges, it was shown that resistive ballooning modes with $n > 10-15$ are unstable throughout the cross-section. Detailed numerical study indicated that the effects of compressibility (ion sound) are irrelevant for ISX-B parameters and hence modes grow at the rate $\gamma \sim (\varepsilon\beta_p)^{2/3}\ S^{-1/3}$. Resistive ballooning modes saturate by turbulent pressure mixing when the fluid turbulence level is large enough to convect a pressure element through the resistive layer in a growth time. Magnetic fluctuations ($\delta B_r/B_o \sim S^{-2/3}$) occur. Since at saturation, the quasi-mode length is comparable to the parallel magnetic field line correlation length, a state of <u>strong magnetic turbulence</u> exists and the magnetic diffusion coefficient D_M scales as $D_M \sim \delta B_r/B_o$ (as opposed to $(\delta B_r/B_o^2)$). The predicted thermal conductivity was $\chi_E \sim \beta_p^{3/2}/T_e$, which was shown to be in excellent agreement with experimental results from ISX-B. For higher T_e discharges with steeper density gradients, a similar analysis based on modes with $\omega_{*e} > \gamma_{MHD}$ (where $\gamma \sim \gamma_{MHD}^3/\omega_*^2$) predicts that $\chi_E \sim \beta_p^2/T_e^{5/2}$. Recent results have indicated that this predicted thermal conductivity is in good agreement with results from Z-mode ISX-B discharges, which are characterized by, among other things, higher temperatures, steep density gradients, and better confinement!

In (B.h.), a similar methodology was applied to the question of determining the thermal energy losses caused by resistive interchange modes in an RFP. An electron thermal conductivity scaling as $\chi_E \sim (\varepsilon/q)^3\ \beta^{3/2}\ V_{Te}\ a/S$ was derived. When balanced with ohmic heating, this χ_E indicates that $T_e \sim I_p^2/N \sim I_p$, for $N \sim I_p$, and

$\beta \sim 10\%$. This scaling is consistent with that observed in many experiments. It was also found that tearing-parity resistive interchange modes cause similar confinement degradation.

Regarding (C), models of edge turbulence in tokamaks based on rippling modes (B.i.), collisional drift waves (B.j.), discussed above, and microtearing modes (B.k.) have been developed. The investigation of rippling mode turbulence has focused on the mechanism of saturation of many interacting multiple helicity modes in the presence of large parallel thermal conductivity. Computational studies indicate that in the course of nonlinear evolution, temperature diffusion results in a decoupling of the current and resistivity, leaving a predominantly electrostatic fluctuation in the final state. Theoretical and computational results indicate that the principal nonlinear effect is temperature convection. In the renormalized theory, radial temperature diffusion couples strongly to parallel thermal conductivity, thus reducing the resistivity perturbation and stabilizing the mode. Results indicate that diffusion at saturation scales as $D \sim \chi_{\parallel}^{-1/3}$. Numerical studies support this conclusion. The significance of this result is that rippling mode <u>turbulence</u> persists into parallel thermal conductivity regimes where the <u>linear</u> growth rate is exceedingly feeble. Hence, rippling modes may be important in regimes where they were not previously thought to be. Furthur studies of the fluctuation spectrum are in progress, as are studies of microtearing mode turbulence.

Various other investigations which do not fall into one of our two main categories have been pursued. These include drift waves in rotating plasmas and tandem mirrors, nonlinear ion cyclotron instabilities, and coupling of turbulent and collisional transport

effects. The reader is referred to the individual IFS reports for details.

Several topics suggest themselves as areas for future work. These include:

1. An understanding of the interaction of stochastic magnetic fields with dissipative, pressure-driven modes is crucial for developing a predictive theory of high-β energy confinement. While this is clearly a question for the ages, an investigation of a simple model, such as a reduced Braginskii system with separate evolution of density and temperature, is planned. Continued interaction of theory and computation is expected.

2. It is crucial to understand the differences between the ways in which stochastic magnetic fields interact with current (anomalous electron viscosity) and temperature. This issue can be studied simultaneously (in the context of the same model) with that proposed in number one, above.

3. The role of nonlinear instability in plasma turbulence remains poorly understood. Possible investigations to elucidate this issue are:

   a. A study of the mechanism of extraction of current gradient free energy in fully developed MHD turbulence.

   b. Furthur study of dissipative density gradient-driven turbulence.

Both investigations would build on experience in nonlinear instability gained in the course of work described above.

Projects of a more short range character are concerned with understanding:

4. Nonlinear trapped-ion-mode saturation.

5. Evolution of single helicity, nonlinear m=1 tearing modes.

6. Rippling mode turbulence at higher temperature-relation to edge properties of H-mode discharges.

7. Interaction of clumps with nonlinear wave-scattering processes.

8. High temperature dynamo processes in RFP-effect of ω_{*e}, etc. on m=1 tearing mode interaction, generalized MHD quasilinear theory for magnetic fields, etc.

9. Effect of stochastic magnetic field losses estimated for trapped-electron-mode driven turbulence and its implications for confinement in TFCX.

10. Effect of microtearing mode type processes on energy confinement in tokamaks and high temperature RFP.

11. Spectra of temperature and density perturbations at the tokamak edge, effects of electric fields.

APPENDIX A

Scientific Staff (April, 1984)

SCIENTIFIC STAFF (April, 1984)

Faculty

Herbert L. Berk, Professor

*William E. Drummond, Professor (Director, FRC)

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Michael Kotschenreuther

Elena Montalvo, Research Fellow

Spilios Riyopoulos, Research Fellow

Jeffrey L. Tennyson, Research Fellow

David Thayer, Research Fellow

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APPENDIX B

Institute for Fusion Studies Reports, FY 1984

Institute For Fusion Studies Reports

IFSR #	Author(s)	Title
98	Rosenbluth, M. Tsai, S. Van Dam, J. Engquist, M.	ENERGETIC PARTICLE STABILITY OF BALLOONING MODES IN TOKAMAKS [Phys. Rev. Lett. 51, 1967 (1983)]
99	Mako, F. Tajima, T.	COLLECTIVE ION ACCELERATION BY A REFLEXING ELECTRON BEAM: MODEL & SCALING (sub. to Phys. Fluids)
100	Hazeltine, R.	INSTITUTE FOR FUSION STUDIES PROGRESS REPORT
101	Hanson, J. Ott, E. Antonsen, T.	INFLUENCE OF FINITE WAVELENGTHS ON THE QUANTUM KICKED ROTATOR IN THE SEMI-CLASSICAL REGIME [Phys. Rev. A 29, 819 (1984)].
102	Aydemir, A. Barnes, D.	SUSTAINED SELF-REVERSAL IN THE REVERSED FIELD PINCH [Phys. Rev. Lett. 52, 930 (1984)]
103	Swartz, K. Hazeltine, R.	NONLINEAR KINETIC THEORY OF A SINGLE HELICITY TEARING INSTABILITY (sub. to Phys. Fluids)
104	Tsai, S. Van Dam, J. Chen, L.	LINEAR RELATIVISTIC GRYOKINETIC EQUATION IN GENERAL MAGNETICALLY CONFINED PLASMAS (accepted by Plasma Physics)
105	Similon, P. Diamond, P.	NONLINEAR INTERACTION OF TOROIDICITY INDUCED DRIFT MODES (sub. to Phys. Fluids)
106	MacKay, R. Meiss, J.	STOCHASTICITY AND TRANSPORT IN HAMILTONIAN SYSTEMS [Phys. Rev. Lett. 52, 697 (1984)]

107	Hanson, J. Cary, J.	ELIMINATION OF STOCHASTICITY IN STELLERATORS (accepted by Phys. Fluids)
108	Hender, T. Carreras, B. Cooper, W. Holmes, J. Diamond, P.	THE EFFECT OF COMPRESSIBILITY ON THE RESISTIVE BALLOONING MODE (sub. to Phys. Fluids)
109	MacKay, R. Meiss, J. Percival, I.	TRANSPORT IN HAMILTONIAN SYSTEMS (accepted by Physica D)
110	Galvao, R. Tajima, T.	BETA-WAVE CURRENT DRIVE IN A MAGNETIZED PLASMA (sub. to Phys. Fluids)
111	Liu, J. Horton, W.	DRIFT WAVES IN ROTATING PLASMAS (accepted by Phys. Fluids)
112	Leboeuf, J.N. Tajima, T. Brunel, F. Sakai, J. Wu, C. Dawson, J.	COMPUTER MODELING OF FAST COLLISIONLESS RECONNECTION (to be published in Geophysical Monograph Series)
113	Diamond, P. Similon, P. Hender, T. Carreras, B.	KINETIC THEORY OF RESISTIVE BALLOONING MODES
114	Diamond, P. Terry, P.	THEORY OF DISSIPATIVE DENSITY GRADIENT DRIVEN TURBULENCE IN THE TOKAMAK EDGE (in preparation)
115	Horton, W. Tajima, T. Galvao, R.	QUASILINEAR EVOLUTION OF TEARING MODES DURING MAGNETIC RECONNECTION (to be published in Geophysical Monograph Series)
116	Diamond, P. Hazeltine, R. An, Z.G. Carreras, B. Hicks, H.	THEORY OF ANOMALOUS TEARING MODE GROWTH AND THE MAJOR TOKAMAK DESCRIPTION
117	Swartz, K. Diamond, P. Mahajan, S. Hazeltine, R.	NONLINEAR TRAPPED ELECTRON RESPONSE FOR DRIFT WAVE TURBULENCE (sub. to Phys. Fluids)
118	Escande, D. Mohamed-Benkada, M.	THRESHOLD OF GLOBAL STOCHASTICITY AND UNIVERSALITY IN HAMILTONIAN SYSTEMS (sub. to Phys. Rev. Lett.)

119	Sydora, R. Leboeuf, J.N. Tajima, T.	PARTICLE SIMULATION OF DRIFT WAVES IN A SHEARED MAGNETIC FIELD (sub. to Phys. Fluids)
120	Leboeuf, J.N. Ratliff, S. Dawson, J.	STUDY OF GENERALIZED TOROIDAL CUSP CONFIGURATIONS (sub. to Nucl. Fusion)
121	Horton, W. Tajima, T. Galvao, R.	QUASILINEAR EVOLUTION OF COLLISIONAL TEARING MODES (sub. to Phys. Fluids)
122	Marsden, J. Morrison, P. Weinstein, A.	HAMILTONIAN STRUCTURE OF THE BBGKY HIERARCHY
123	Aydemir, A. Barnes, D.	IMPLICIT ALGORITHM FOR COMPRESSIBLE THREE DIMENSIONAL MAGNETOHYDRODYNAMIC CALCULATIONS (sub. to Jour. Comp. Phys.)
124	Yang-Zhong, Z.	RENORMALIZATION THEORY OF STATIONARY HOMOGENEOUS STRONG TURBULENCE IN A COLLISIONLESS PLASMA (sub. to Phys. Fluids)
125	Sydora, R. Leboeuf, J.N. Diamond, P. An, Z.G. Tajima, T.	PARTICLE SIMULATION OF THE RESISTIVE G-MODE IN A SHEARED MAGNETIC FIELD (sub. to Phys. Fluids)
126	Escande, D. Souillard, B.	LOCALIZATION OF WAVES IN A FLUCTUATING PLASMA (sub. to Phys. Rev. Lett.)
127	Marsden, J. Morrison, P.	NONCANONICAL HAMILTONIAN FIELD THEORY AND REDUCED MHD
128	Barnes, D. Cary, J.	FREE-BOUNDARY STABILITY OF STRAIGHT STELLARATORS (sub. to Phys. Fluids)
129	Holmes, J. Carreras, B. Hender, R. Hicks, H. Lynch, V. An, Z.G. Diamond, P.	NONLINEAR INTERACTION OF TEARING MODES - A COMPARISON BETWEEN THE TOKAMAK AND THE REVERSED FIELD PINCH CONFIGURATIONS (sub. to Phys. Fluids)
130	Berk, H. Rosenbluth, M. Wong, H.V. Antonsen, T.	STABILIZATION OF AN AXISYMMETRIC TANDEM MIRROR CELL BY A HOT PLASMA COMPONENT (sub. to Phys. Fluids)
131	Berk, H. Wong, H.V.	In preparation

132	Berk, H. Kaiser, T.	In preparation
133	Cary, J.	RELATION OF FLUID DRIFT TO OSCILLATION CENTER DRIFT (sub. to Phys. Fluids)
134	Cary, J. Kotschenreuther, M.	PRESSURE INDUCED ISLANDS IN THREE-DIMENSIONAL TOROIDAL PLASMA (sub. to Phys. Fluids)
135	Kotschenreuther, M. Hazeltine, R. Morrison, P.	NONLINEAR DYNAMICS OF MAGNETIC ISLANDS WITH CURVATURE AND PRESSURE (sub. to Phys. Fluids)
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