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INSTITUTE FOR FUSION STUDIES
PROGRESS REPORT

for the period
1 September 1981 to 31 August 1982

USDOE Grant No. DE-FG05-80ET-53088

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Contents

I. INTRODUCTION AND SUMMARY

In its second year of operation, the Institute for Fusion Studies has maintained a broad and active program of theoretical activities, ranging from fundamental mechanics and stochastic processes to applied plasma stability and transport. Significant advances have been made in many areas, some involving extensive collaboration with other fusion programs, especially the National Laboratories.

The resident staff, visitors, and U. S.-Japan exchanges are listed in Section II. During the year, Philip Morrison joined the faculty as assistant professor, Jean-Noel Leboeuf joined the permanent staff as research associate, and Paul Terry and Jeffrey Tennyson began terms as post-doctoral research fellows. However, with the return of Kim Molvig to MIT, and the extended leave of absence of Frederick L. Hinton, the size of the permanent staff remained constant. An effort will be made to add one or two senior staff members later in the coming year. Long-term visits, as well as workshops within the U. S.-Japan Theory Exchange, have been highly successful (see Appendix A).

Technical progress is discussed in Section III. For convenience, the activities have been broken down into four categories: A. Mathematical physics and general theory; B. Tokamak theory; C. Theory of tandem mirrors and alternative concepts; and D. Computational physics. These topics overlap strongly and the division is somewhat arbitrary, especially between mathematical and computational physics and the applied categories. For example, the existence and properties of solitary waves are of fundamental significance, on the one hand (Section III, A.6 & A.7), and have been suggested as a model for tokamak turbulence, on the other (Section III, B.5). Other examples are the inclusion of implicit particle simulation code development in sub-section D , while numerical heliac equilibrium and stability studies are given in sub-section C .

II. PERSONNEL AND ACTIVITIES

A. Resident Faculty and Staff

1. Faculty and Permanent Research Staff

Marshall N. Rosenbluth, Director
David W. Ross,* Assistant Director
Daniel C. Barnes
Herbert L. Berk
John R. Cary
Patrick H. Diamond
William E. Drummond*
Richard D. Hazeltine*
Frederick L. Hinton (on leave of absence)
Werner Horsthemke
Wendell Horton, Jr.
Jean-Noel Leboeuf#
Swadesh M. Mahajan*
Philip J. Morrison
Toshiki Tajima#
James W. Van Dam
Alan A. Ware*
H. Vernon Wong

2. Post-doctoral Research Fellows

Ahmet Aydemir
Francois Brunel
Amitava Bhattacharjee
James D. Meiss
Philippe L. Similon
Kenneth Swartz
Jeffrey Tennyson**
Paul Terry

* Supported in part or fully by the Fusion Research Center

Supported in part by the National Science Foundation

** Supported in part by the Center for Statistical Mechanics, University of Texas

3. Fiscal 1983

James D. Meiss has been promoted to permanent staff, effective September 7, 1982. Michael Kotschenreuther and James Hanson have been appointed as Research Fellows.

B. Visitors to the IFS

1. U. S.-Japan Exchange

The U. S.-Japan exchange program has continued actively, with visits to the Institute for Fusion Studies by Dr. Hirotada Abe from Kyoto University and Dr. Tetsuo Kamimura from the Institute for Plasma Physics, Nagoya University. Dr. Kamimura's visit was especially stimulating, as noted in the section on technical progress.

2. Other Visitors

Other long-term visitors included C. Z. Cheng from Princeton Plasma Physics Laboratory, James Hammer from Lawrence Livermore National Laboratory, Barry Newberger and Thomas Cayton from Los Alamos National Laboratory, Dieter Biskamp and Dieter Pfirsh from Max Planck Institute, Garching, West Germany, and Leon Shohet from the University of Wisconsin.

Briefer visits, ranging from one day to three weeks, were made by:

D. Anderson	S. Ichimaru
T. M. Antonsen, Jr.	R. Kashuba
D. Baldwin	B. Lane
D. Biskamp	R. Littlejohn
B. Carreras	X. Llobet
K. Case	O. Manley
J. Clarke	H. Mynick
B. Coppi	J. Myra
R. Davidson	F. Pegoraro
D. D'Ippolito	A. Rechester

A. Rogister	R. Sudan
H. Rose	C. Surko
J. Sakai	J. Tataronis
D. Sigmar	R. Varma
A. Simon	S. Yoshikawa
G. Smith	S. Yoshikawa

3. Fiscal 1983

In September 1982, three visitors arrived under the U. S.-Japan exchange agreement. These are Dr. Sanae Inoue-Itoh and Dr. Kimitaka Itoh, who will stay for six months, and Dr. Toshio Tange, who spent two months at the University of California, Berkeley, and will be in Austin for four months. Other long-term visitors will include Keith Roberts of Culham Laboratory, England, and Ravi Sudan of Cornell University.

C. Workshops

This year, from January 11 to January 15, under the U. S.-Japan Exchange, one workshop was held in Austin on the theory of drift wave turbulence. The Japanese delegation consisted of H. Abe, R. Hatakayama, T. Hatori, S-I. Itoh, T. Sato, and T. Taniuti. K. Itoh also attended as an observer. Approximately 25 Americans participated in this Workshop, which reviewed both the theory and experimental observations of drift wave fluctuations and their association with anomalous transport.

Wendell Horton of the IFS, in addition to organizing the above Workshop, also helped to arrange the three others in the series, which took place in Oak Ridge, Tennessee, and in Japan at Kyoto and Nagoya, and coordinated the visits to Japan of Allen Boozer of Princeton (PPPL), H. Strauss of New York University, and Charles Karney of Princeton (PPPL). (See Appendix A.)

III. TECHNICAL PROGRESS

A. Mathematical Physics and General Theory

1. Two-dimensional Area-Preserving Maps
(J. D. Meiss, J. R. Cary)

The authors (with collaborators) have continued the study of two-dimensional area-preserving maps in the strongly stochastic limit. Statistical properties, such as correlation functions and diffusion coefficients, are calculated using a cumulant discard-like approximation scheme. Comparison with numerical experiments shows good agreement except when small islands are present. These can enhance the diffusion by an order of magnitude.

Reference: IFSR #57 (See Appendix B for list of IFS reports.)

2. Poisson Brackets (P. J. Morrison)

Formal transformations between the Poisson bracket descriptions in the Eulerian, Lagrangian, particulate and Clebsch descriptions have been obtained. The purpose of these transformations is to enable the comparison between approximations made in each description (e.g., differencing). A systematic Poisson bracket perturbation theory is sought.

Statistical descriptions in terms of the above representation are being investigated. This involves the comparison between the partition function and equilibrium quantities obtained in the various descriptions.

Reference: IFSR #54.

3. Non-integrable Periodic Solutions to the Poisson-Vlasov Equations (J. Tennyson, J. D. Meiss, P. J. Morrison)

We are investigating the existence and stability of time-periodic solutions to the Poisson-Vlasov equations. We are primarily interested in the asymptotic behavior of a saturated large-amplitude wave. For certain initial conditions, the distribution function relaxes to solutions which are at least nearly periodic in time. Unlike the BGK and Lewis-Symon modes, these solutions are non-integrable (certain components of the distribution behave stochastically). Our approach depends heavily on simulation and numerical analysis. So far, we have completed a study involving both simulation and analytic calculations which indicates that phase locking can occur in the post-saturation stage of wave evolution (this has been conjectured by previous authors but never adequately demonstrated).

4. The Stability of Single Particle Motion in Colliding-beam Machines [J. Tennyson, F. Izrailev (Novosibirsk)]

We have recently found a new, very simple analytic model for highly elliptical $e^+ - e^-$ beams. Simulations indicate the presence of an "effective wall" that sits well inside the actual beam aperture. This is actually a stochasticity border; particles with betatron amplitudes beyond a certain limit behave stochastically and are lost from the beam very quickly. Our main goal here is to calculate maximal tune shifts for both $p - \bar{p}$ and $e^+ - e^-$ machines. These tune shifts depend on the particle-transport rate in amplitude space. There are two primary mechanisms for transport: resonant enhancement of quantum fluctuations, and overlap of sychro-betatron resonances. Rough analytic estimates for the diffusion rate should be possible and can be verified by simulation. The simulations are straightforward; the isolation and identification of competing mechanisms is the primary obstacle.

5. Multiple Slow-Resonance Crossing [J. Tennyson, B. Chirikov, D. Shepalyansky (both Novosibirsk)]

Chirikov and Shepalyanski have previously calculated analytically the jump in action of a system due to the crossing of the phase point by a slow-moving (in the phase space) nonlinear resonance. We have recently verified the validity of this expression with simulation and have analytically determined the diffusion rate of a system that experiences a periodic sequence of such crossings.

6. Regularized Long Wave (RLW) Equation (P. J. Morrison, J. R. Cary, J. D. Meiss)

The RLW equation has been shown to model certain aspects of drift-wave turbulence. Recently, Meiss and Horton have developed a statistical description based on the presence of RLW solitary waves (SW). Unlike the Korteweg-deVries equation, the RLW equation is not integrable by the method of inverse scattering--RLW solitary waves radiate upon collision. Little analytical work exists for this equation. We have utilized a Lagrangian density perturbation theory to calculate the phase shift resulting from the collision of two SWs. The techniques used may also enable the calculation of the amount of radiation per SW collision; hence, the time-scale over which SW gas models are valid could be obtained.

(See also Sections A.7, B.5, and D.4 of this report.)

7. Effect of Nonlinear Electron Motion on Ion-Acoustic Solitons (J. D. Meiss, P. J. Morrison)

It is shown that, by analogy with O'Neil's work on large-amplitude plasma waves, the trapped-particle effects phase-mix in several bounce periods and the damping of solitons stops. To develop this theory, a multiple time-scale perturbation theory is used to obtain coupled Vlasov-KdV equations. The conservation laws of this system describe the evolution of the soliton when self-similarity is assumed.

Reference: IFSR #65

(See also Sections B.5 and D.4 of this report.)

8. Analysis of Nonlinear Plasma Models

a) Hamiltonian Formulation of Reduced MHD
(P. J. Morrison, R. D. Hazeltine*)

Previous studies of the reduced MHD equations have been either numerical or, if analytical, based on turbulence theory. Since some important processes (e.g., coherent island formation) which the model is known to describe are not inherently turbulent, an analytical formulation which is not restricted to turbulent regimes is needed. To this end, a Hamiltonian formulation of reduced MHD has been developed. This has the form $\dot{\underset{\sim}{\xi}} = \{\underset{\sim}{\xi}, \underline{H}\}$, where $\underset{\sim}{\xi}$ represents the electrostatic and electromagnetic potentials, $\underline{H}$ is the field energy, and the Poisson bracket is an appropriate combination of functional derivatives. One immediate consequence, which could provide a check on the numerical work, is that reduced MHD conserves "areas" in $\underset{\sim}{\xi}$-space. Other applications, including predictions of the steady-state spectrum, are under investigation.

b) Reduced MHD (RMHD) and the (Charney-)Hasegawa-Mima Equation (CHM) (R. D. Hazeltine*)

These are tractable, physically relevant models for fluid non-linearities in plasmas. The two models are not trivially related. However, a simple, internally consistent model has been found which includes both RMHD and CHM as limiting cases. The inclusive model clarifies the relation between RMHD and CHM. It also provides generalizations of both models (electromagnetic CHM and finite-ρ_s RMHD), and appears to have intrinsic interest.

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* denotes author supported in part or fully by the Fusion Research Center

B. Tokamak Theory

1. Kinetic Modifications to the Ion Pressure-Gradient Driven Electromagnetic Modes [W. Anderson, W. Horton (in collaboration with D-I. Choi, KAIS, Seoul, Korea)]

Kinetic ion resonance and finite Larmor radius effects are included in the electromagnetic theory of the previously-analyzed ion pressure-gradient ballooning mode.[1] The full 3×3 electromagnetic problem is shown to reduce to the electrostatic limit for $\beta \lesssim \varepsilon^2$ and to the MHD ballooning problem for $\beta > \varepsilon$.** In the transitional region $\beta \lesssim \varepsilon$, we find that kinetic effects are important in determining the stability of the system. We are in the process of comparing the kinetic results with the fully-electromagnetic fluid results given earlier by Horton et al.[2]

References: 1. P. Terry, W. Anderson, W. Horton, Nucl. Fusion 22, 487 (1982). 2. W. Horton, D-I. Choi, B-G. Hong, IFSR #61 (1982), sub. to Phys. Fluids.

2. Tearing Modes and Tokamak Skin Current (S. M. Mahajan*, A. Bhattacharjee, R. D. Hazeltine*, J. C. Wiley*, and A. Aydemir)

Skin currents present in the initial phases of a tokamak discharge are characterized by (i) a local minimum in the safety factor, $q(r)$, profile; (ii) anomalously rapid relaxation (current penetration). The supposition that these two properties are related has been studied by both linear and nonlinear theory.

The analytic theory solves tearing eigenmode equations variationally, for a locally parabolic q-profile. Three classes of instabilities are found, one of which is entirely new. Numerical solution of the equation confirms these results.

** Here, $\beta = 8\pi p/B^2$ is the dimensionless plasma pressure and ε is the inverse aspect ratio of the torus.

Next the nonlinear effect of the instabilities on current penetration is studied, by a combination of quasi-linear analysis and numerical work. We rely on turbulence-enhanced resistivity, rather than island overlap, to relax the current. The theory yields a turbulent resistivity which exceeds classical resistivity by a factor of 2-4; surprisingly, this enhancement appears as sufficient to explain the observed penetration rates in the PRETEXT experiment.

3. The Tearing Mode at Finite Amplitude (K. Swartz, R. D. Hazeltine*, M. Kotschenreuther)

Magnetic islands of macroscopic size are observed in (pre-disruptive) tokamak discharges. The associated field perturbation is too large to be encompassed by linear theory, but the structure is visible because it is dominated by a single helicity component. A single-helicity nonlinear island theory for collision-dominated plasmas, due to Rutherford, has successively described certain features of the disruptive process. More recently, the collisionless limit has been studied. IFS investigations of the finite island problem are based on a kinetic equation written in terms of the flux coordinates of the island itself, for arbitrary collisionality. Previous results are obtained in appropriate limits. Moreover, in simplified but relevant cases, the nonlinear field equations can be solved analytically, to obtain a uniform description of island growth and saturation. Thus, the connection between collisional and collisionless behavior is clarified.

Understanding finite island effects in reactor or near-reactor conditions will require treatment of additional effects, including stochastic fields near the island separatrix which are now under investigation. Also being examined are kinetic effects due to temperature gradients in the Rutherford regime.

(Other work on magnetic reconnection is given in subsection D.4.)

4. Turbulent Transport (K. Swartz, S. M. Mahajan*, R. D. Hazeltine*)

Toroidal quasi-linear theory, using action-angle variables, shows that the Maxwellian part of the distribution function, alone, yields substantial radial transport in the presence of drift or tearing mode turbulence. However, the transport coefficients will be quantitatively affected by non-Maxwellian corrections which have not been computed. This program requires, first of all, an assessment of the effects of interference between fluctuations resulting from discreteness and those driven by micro-instabilities. The kinetic theory needed to calculate such interference effects has been formulated. It will be made tractable by means of suitable approximations, the consistency of which is now under investigation. (Other turbulence work is given in subsections B.5-B.8, and in D.1-D.4.)

5. Soliton Models for Drift-wave Turbulence (J. D. Meiss, W. Horton)

The authors have investigated simple one-dimensional fluid models for drift-wave turbulence. An assumption that the turbulence consists of solitons allows complete computation of the spectrum for a given fluctuation level. This spectrum is qualitatively different from linear mode spectra, which are concentrated about the linear dispersion relation.

They have also shown that two-dimensional drift-wave solitons (localized in the perpendicular plane) exist. In addition, the effect of shear is shown to be extremely weak on these objects as the nonlinearity acts as an effective well which localizes the soliton within the Pearlstein-Berk turning point.

References: 1. J. D. Meiss and W. Horton, Phys. Rev. Lett. 48, 1362 (1982) and IFSR #45. 2. IFSR #60.

(See also subsection D.2.)

6. Kinetic Theory of Low-frequency Microturbulence in Tokamaks (P. H. Diamond, P. L. Similon, P. W. Terry)

Research in the area of kinetic theory of low-frequency microturbulence in tokamaks is focused on developing a unified dynamical theory for the fluctuation spectra and anomalous transport in tokamaks. The basic agents considered are microscale turbulence driven by density and temperature gradients. Throughout these investigations, toroidal geometry is treated as accurately as feasible. The basic nonlinear equations are cast in the ballooning representation, which is used throughout the calculations. In addition, an attempt is made to examine the consequences of a basic agent (i.e., drift waves) in a unified manner, so as to correlate (theoretically) properties of fluctuation spectra with transport. Specific investigations are:

a) Theory of Ion Compton Scattering for Toroidal Drift Waves (Similon, Diamond)

Starting from the nonlinear toroidal gyro-kinetic equation, the theory of ion Compton scattering for toroidal drift waves is developed. Ion Compton scattering is considered, as it appears to be the simplest possible nonlinear saturation mechanism. A spectrum equation is derived and solved for various destabilizing mechanisms. Quasi-linear electron diffusion coefficients and scaling laws (using Conner-Taylor constraints) are calculated. While considering dissipative drift, dissipative trapped electron, and trapped-electron growth mechanisms, it was found that confinement time-density dependence changes from being similar to n to $n^{3/8}$, while scaling as approximately a^3 ($a \equiv$ minor radius). This trend is in rough accord with experimental tendencies as hotter, higher density regimes are explored.

b) Theory of Two-point Correlation for Trapped Electrons and the Frequency Spectrum of Drift-wave Turbulence in Tokamaks (Diamond, Terry)

Experimental studies of density fluctuation spectra (commonly associated with drift waves) have the universally-observable characteristic of broad-frequency line-width $(\Delta\omega_k)$ at fixed wavenumber k. Hence, the turbulence contains a significant non-mode-like constituent, generated by incoherent emission (mode coupling) processes. In this calculation, incoherent mode coupling in a system governed by wave-particle resonance effects was considered. Such a mode-coupling process distorts the distribution function (at resonance) and generates incoherent fluctuations (noise) which broaden the line-width. In addition, the condition of balance in the saturated state requires that the collective resonances (modes) of the system be over-saturated, so as to balance growth and noise emission. Thus, the issues of frequency width and nonlinear stability are intimately related. This investigation addreses these issues for the case of trapped-electron turbulence. The principal results are: (1) the construction of a renormalized two-point theory in the ballooning representation; (2) the identification of a novel mechanism for extraction of expansion free energy [this mechanism has no analogue in the one-point (mode) theory]; (3) the determination of an analytic expression for $\Delta\omega_k$, the line-width (for typical parameters, $\Delta\omega_k \sim \omega_k$ can result); (4) the determination of the effect of frequency-broadening on nonlinear wave-particle (ion) scattering proccesses [for certain cases, nonlinear ion-Landau damping is significantly enhanced (in comparison to weak turbulence theory)]; (5) the determination of the energy flux in the saturated state, in particular, the phase shift between density and potential is proportional to the enhanced growth rate.

Work is continuing on the two species and ion problems.

c) Universal-Mode Growth Rate from a Theory of Two-point Correlation (Terry, Diamond)

In linear theory, the universal mode in a sheared slab is quasi-marginally stable. The effect of enhanced accessibility of expansion-free energy (see subsection B.6.b.2 above) is considered in a theory of universal mode turbulence incorporating two-point effects (incoherent mode-coupling). For certain regimes, the growth enhancement is sufficient to effectively destabilize the universal mode resonance.

References: 1. presented at the Annual Controlled Fusion Theory Conference, Santa Fe (1982). Manuscript in preparation.
2. presented at IAEA Controlled Fusion Conference, Baltimore, 1982, paper D-1-2. 3. Invited paper, APS Division of Plasma Physics, New Orleans, November 1982.

(Other work on drift-wave turbulence is given in subsections D.1 and D.2.)

7. Theory of Edge Turbulence in Tokamaks [B. A. Carreras et al. (ORNL), J. D. Callen (University of Wisconsin, Madison), P. H. Diamond]

The experimental data on the high level of turbulence in the edge of tokamaks was considered in terms of theoretical models. The "rippling" resistive MHD instability was advanced as a candidate for this turbulence. The linear, quasi-linear, and turbulent regimes of the rippling instability were investigated with a combination of computational models and analytic treatments. Parallel electron heat conduction effects are included and found to ultimately limit the modes spatial extent and induced transport. A number of features of rippling-mode turbulence (poloidal and radial correlation lengths of the potential and magnetic fluctuations, dominance of low-frequency components, etc.) were found to be in reasonable agreement with experimental observations of edge turbulence. In addition to its possible relevance to tokamak edge turbulence, the model developed illustrates the interplay and ultimate effects of a number of nonlinear processes in resistive MHD turbulence.

Reference: presented at IAEA Controlled Fusion Conference, Baltimore, 1982, paper D-2-2.

8. Theory of Resistive and Kinetic Ballooning-Mode Turbulence and Anomalous Transport in High β Tokamaks
[P. H. Diamond, P. L. Similon; B. A. Carreras et al. (ORNL)]

It is obviously crucial to understand the degradation of confinement (beyond inter-scaling losses) and saturation of β in neutral beam-heated tokamaks. One candidate for the cause of such phenomena is ballooning-mode induced transport. Hence, the linear and nonlinear theory of resistive (and kinetically-modified resistive) ballooning-mode turbulence has been extensively studied. Specific results include:

a) For the resistive MHD model, the linear dispersion relation $\gamma^3 + \omega_s^2\gamma = \gamma_0^3$ was derived. Here, $\omega_s = c_s/Rq$, $\gamma_0^3 = (\eta k_\theta^2)\omega_A^2\alpha^2$, $\omega_A = v_A/Rq$, $\alpha = \epsilon\beta_p$. For $\omega_s \lesssim \gamma$, which can be relevant for ISX beam-driven equilibria, a mode with growth rate scaling as γ_0 is predicted. Modifications to this dispersion relation by ion viscosity, diamagnetic effects, and parallel conductivity have been considered.

b) A theory of nonlinear saturation for incompressible resistive ballooning turbulence has been developed and compared successfully with numerical solution of the nonlinear equations. A kinetic theory (which reduces smoothly to the MHD limit) has been developed for the diamagnetic regime.

c) The electrostatic energy at saturation has been used (via Ohm's law) to compute the stochastic field diffusion coefficient in the strong turbulence regime. This result can be used to constrict the thermal conductivity χ_E .

$$\chi_E = \left(\frac{3}{2} v_{Te} a\right) \frac{q}{S}\left(\frac{\beta_0}{\epsilon_T} \frac{q^2}{\hat{S}} \frac{1}{L_p}\right)^{3/2}$$

$[S = (\tau_{Hp}/\tau_R)^{-1}]$. This conductivity has compared to ISX-B

Figure for Sec. III.B.8, "Theory of Resistive and Kinetic Ballooning-Mode Turbulence and Anomalous Transport in High β Tokamaks", from Ref. 2.

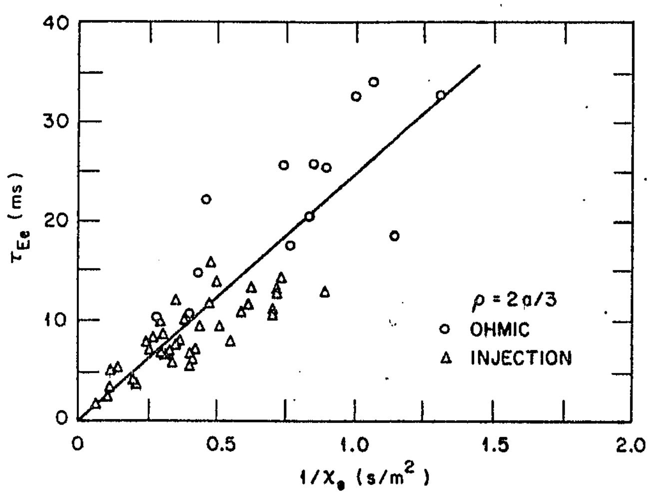

FIG. 6. Correlation between the inverse of electron thermal diffusivity (χ_e) and $\rho = 2a/3$.

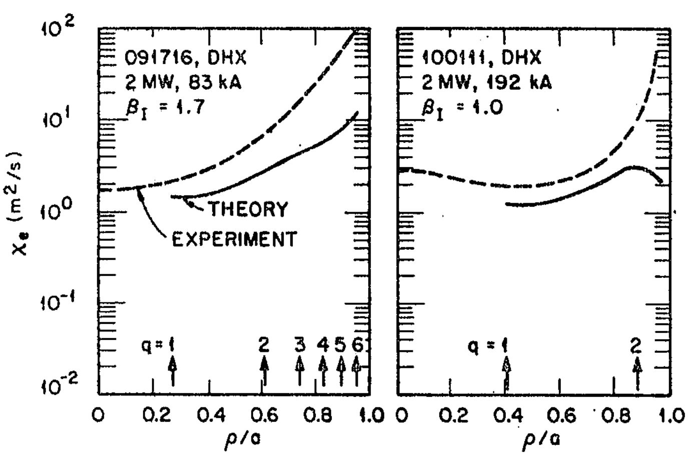

FIG. 7. Comparison between radius-dependent electron thermal diffusivities from the experiment and the Carreras and Diamond model.

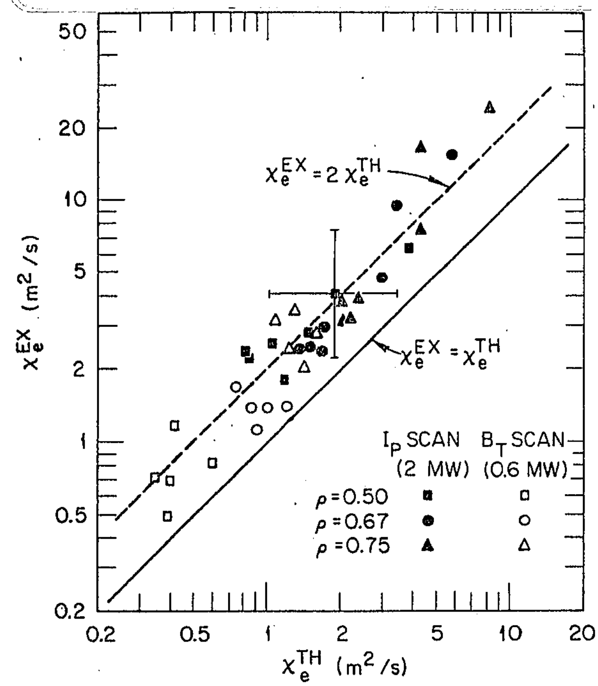

FIG. 8. Comparison between electron thermal diffusivities (in the confinement region) from the experiment and the Carreras-Diamond model.

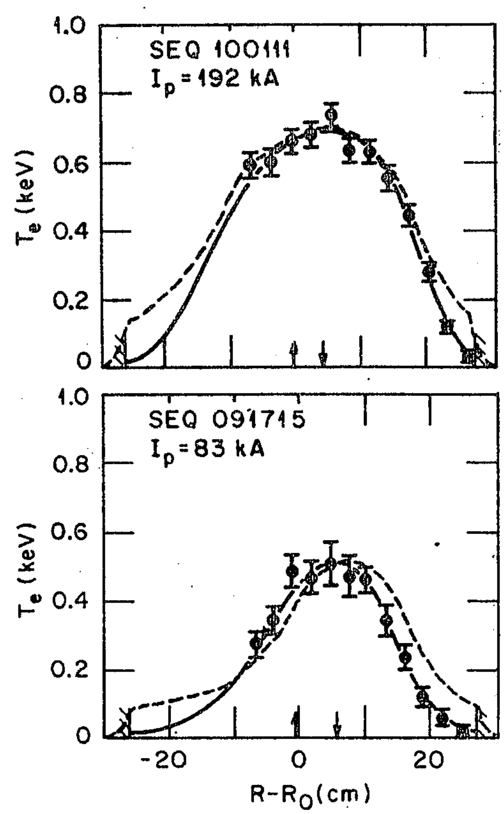

FIG. 9. Results (dashed curves) of the transport simulation, using the Carreras-Diamond model, compared with the experimental measurement (data points and continuous curves).

experimental results with excellent agreement. See accompanying figure.

Work is continuing on linear and nonlinear theory of fluid and kinetic ballooning modes and on trapped-particle (ion) driven instabilities.

References 1. presented at the Annual Controlled Fusion Theory Conference, Santa Fe, 1982. 2. presented at the IAEA Controlled Fusion Conference, Baltimore, 1982, paper A-4. 3. Invited paper, APS Division of Plasma Physics, New Orleans, November 1982.

9. Ion Heat Conduction in Tokamaks with High Ion Temperature

(A. A. Ware*)

A study is being made of large poloidal gyro-radius effects on the ion transport in tokamaks with hot ion plasmas. The reason for this study is that recent experimental results[1] on PDX have confirmed the earlier ATC results[2] that in hot ion plasmas where $A_i T_i(ev)/[I(kA)]^2 \gtrsim .04$, the ion distribution function (f_i) is highly non-Maxwellian with an enhanced tail for minor radii away from the central region. (A_i = hydrogen ion atomic number.) From the Fokker-Planck equation, the enhanced tail can be explained by finite poloidal Larmor radius effects for the outward diffusing tail of f_i. The effective "temperature" of the tail $(T_H = 1/\partial \ln f_i/\partial\varepsilon)$ is enhanced by two factors relative to the inward diffusing low-energy part of f_i. One factor has the form $[1 + (Z_{eff,i}/2\pi)(2r/R)^{1/2}(\rho_\theta/\alpha)^2]$ where $\rho_\theta^2 = 2m_i T_H/e^2 B_\theta^2$ and $\alpha^{-2} = (B_\theta^2/n_i r^{3/2} f_i)\, \partial/\partial r(r^{3/2} n_i B_\theta^{-2}\, \partial f_i/\partial r)$ and the other factor results from the modified Rosenbluth potentials. The enhanced tail to f_i has important implications for both ion heat conduction and ion charge exchange energy losses.

References: 1. C. J. Keane et al., Bull. Amer. Phys. Soc. 26, 863 (1981). 2. R. J. Goldston, Nucl. Fusion 18, 1611 (1978).

10. Theory of Alfvén Wave Heating [D. W. Ross*, S. M. Mahajan*, G. L. Chen* (now at ORNL), T. Cayton (IFS visitor from LANL), Y-M. Li*, W-Q. Li*]

This (mostly Fusion Research Center) work is concerned with the kinetic theory of Alfvén wave absorption, heating, and current drive. In our previous work, a numerical code was set up to compute wave structures, energy deposition, and total impedance of individual poloidal and toroidal harmonics in cylindrical geometry. Work in the past year has focused upon three related topics. These are:

a) Antenna Fourier Decomposition and Comparison with Experimental Observations of Loading Impedance

Each physical antenna can be approximated by a sum of individual poloidal harmonics, only a few of which generate modes with Alfvén resonances in the plasma interior. Summing over these modes with the appropriate weighting factors, we obtain excellent measurements taken on the TCA tokamak in Lausanne, Switzerland. This agreement persists over a range of densities encompassing the "global Alfvén mode" or discrete "kink mode", previously discovered in our numerical work.

b) Analytic and Numerical Studies of Alfvén Eigenmodes

We have derived dispersion relations for the global Alfvén or kink modes, which have frequencies below the Alfvén continuum threshold. The frequencies found from the MHD equations with finite ω/ω_{ci} corrections by means of WKB and variational techniques. This is the first time that the spectrum of such modes has been given. These same techniques may be used to solve a variety of related problems including fast-wave eigenmodes, and, possibly, singular-continuum modes. Kinetic effects can then be treated by perturbation theory and the results compared with numerical and experimental work.

Work is proceeding to convert the kinetic Alfvén wave code to find global eigenmodes, whose frequencies and damping (or growth) rates may be compared with resonances found numerically in the driven problems and with the analytic theory. Applications to the kinetic theory of tearing and "twisting" instabilities are also being investigated.

c) Toroidal Effects

In collaboration with T. Cayton of LANL, a numerical code is being developed to treat the coupling of poloidal harmonics *via* the R^{-1} dependence of B_0. The single harmonic version is currently being compared with our previous code. Related analytic work involves the study of the distortion of resonant surfaces by finite ω/ω_{ci} terms of both hydrogen ions and impurities, which are strongly affected by the R^{-1} dependence.

References: 1. D. W. Ross, G-L. Chen and S. M. Mahajan, Phys. Fluids 25, 652 (1982). 2. S. M. Mahajan, D. W. Ross and G-L. Chen, Fusion Research Center Report #249 (1982).

C. Theory of Tandem Mirrors and Alternative Concepts

1. Tandem Mirror Stability [M. N. Rosenbluth, H. L. Berk, H. V. Wong, with T. M. Antonsen, Jr. (U. of Maryland) and D. E. Baldwin (LLNL)]

Tandem mirrors consist of a central cell with essentially straight field lines, connected by a transition region of average unfavorable curvature in which most particles are reflected by magnetic or electrostatic barriers, to a quadruple anchor, in which there are sufficient trapped particles to give pressure-weighted $\int d\ell/B$ stability. However, the designs are characterized by having very few particles which thread the whole system. In fact, to achieve good thermal insulation, this is highly desirable. Thus, one may wonder how many particles are required to provide good electrical connection.

Proceeding from the drift kinetic equation, we may write down a variational principle to find the worst perturbation. $\tilde{B}_\parallel$, as usual, simply may be chosen to eliminate the diamagnetic well. One then finds that for $\beta \ll \beta_{MHDcr.}$, the worst modes are essentially electrostatic, thus eliminating line-bending energy, and nearly flute-like in the interior with a sharp cut-off in the low density region.

An approximate dispersion relation is:

$$\omega^2(\varepsilon + k_\perp^2\rho_c^2) - \omega\omega_{*i}\left(k_\perp^2\rho_c^2 + \varepsilon\,\frac{\omega_{*t}}{\omega_i}\right) + \omega_*\omega_c = 0 .$$

Note that for $\varepsilon = n_t/n_0$, the ratio of connecting particle to central cell density less than $k^2\rho_c^2$, growth rates are equal to their MHD values. The origin of the term proportional to $\varepsilon\omega_{*t}\omega$ is that usually the transiting particles will be of predominantly one sign of charge so that charge separation arises. Looking at $m = 1$, a rough stability criterion is $\varepsilon > 4(r/R_c)$. Modified MFTF-B designs are barely compatible with this criterion. One finds, not surprisingly, that such negative energy modes are destabilized by collisions, bounce resonances, etc. A principal subject of research now is to quantitatively evaluate these growth rates, make a better treatment of global modes, and eventually look at nonlinear phenomena. The possible (and unknown) axial variation of the ambipolar potential gradient is also a complication we are studying.

References: 1. IFSR #56 2. IFSR #62 .

2. Curvature-driven Modes in EBT (H. L. Berk, M. N. Rosenbluth J. W. Van Dam)

The effects of finite ion and hot electron Larmor radii on the stability of curvature-driven modes in the Elmo Bumpy Torus device were investigated, using general geometry eigenmode equations derived in the eikonal limit from a new form of the gyro-kinetic equation valid for arbitrary frequency. It was found that small FLR for the hot electrons can prevent the previously-predicted deterioration of stability at mode numbers for which high-frequency positive and negative energy waves match. Moreover, although small FLR reduces the beta limit for core plasma interchange stability, stronger FLR effects are found to stabilize all modes with radial wavelength less than the hot electron layer thickness. This theory predicts a minimum ring-width consistent with recent experimental observation of the high-frequency hot-electron interchange mode in EBT-S.

A procedure for numerically obtaining the equilibrium magnetic field and self-consistent electrostatic potential appropriate to a periodic bumpy cylinder plasma with energetic electron rings was developed by Van Dam in collaboration with scientists at the Institute for Fusion Theory (Hiroshima, Japan). Each plasma species is described by a kinetic distribution function that includes temperature anisotropy, mirror trapping, and small gyro-radius effects.

3. Stellarator Design (J. R. Cary, D. C. Barnes)

Stellarators have long suffered from the lack of a dense set of flux surfaces. The concomitant stochasticity and island structure increases stellarator transport. This year a technique was developed for eliminating the stochasticity of the vacuum magnetic fields. The resultant fields have larger rotational transform and smaller aspect ratio, both of which are likely to improve achievable plasma pressure. Examples of applications have been given. Extensions to the case of finite plasma pressure are under investigation.

References: 1. John R. Cary, Phys. Rev. Lett. 49, 276 (1982).
2. John R. Cary and Robert G. Littlejohn, Noncanonical Hamiltonian Mechanics and Its Application to Magnetic Field Line Flow, UCLA Report (1982). A more complete discussion of this work is in preparation.

4. Ion Orbits of Field-reversed Theta Pinches (J. R. Cary with Jin-Soo Kim of the Lawrence Berkeley Laboratory)

FRΘP's are observed to be stable, yet MHD calculation predicts instability. Presumably, finite orbit effects will resolve this paradox. Unfortunately, standard gyro-orbit theory does not apply because of the magnetic null present in this system. For this reason we have undertaken a study of these orbits. We have found that most orbits are integrable in the long, thin systems characteristic of the Los Alamos experiments. Depending upon the particle's energy and angular momentum, either magnetic moment or radial action provides a third invariant.

Reference: J-S. Kim and J. R. Cary, Character of Ion Orbits in an Elliptical Z-pinch, (Annual Controlled Fusion Theory Conf., Santa Fe, 1982)

5. Heliac Stability (D. C. Barnes, J. R. Cary)

The free-boundary stability of a straight, high-β heliac has been investigated. This work was motivated by previous studies of high-β helical systems, which found long-wavelength instabilities. This work employs the sharp-boundary model, which can be used to study a system of arbitrary helical symmetry, cross section, and β. The growth rates of unstable $\ell = 1$ systems have been previously determined to scale with helical aspect ratio, becoming very small for long-wavelength systems. Accordingly, the present analysis has been carried out for arbitrary helical aspect ratio.

The low-β limit of this high-β theory gives a new stability criterion for free-boundary modes. As with the well known local stability criteria for diffuse systems, sharp-boundary stability at low-β depends on the vacuum magnetic well and the shear at the plasma boundary. Many $\ell = 1,2$, and 3 systems have been investigated for low-β stability. Heliac type $\ell = 1$ systems are remarkably stable, but no stable $\ell = 2$, or 3 systems have been found.

A numerical minimization of δW is used to extend these low-β results to arbitrary β. For the heliac, stability to all free-boundary modes persists up to the equilibrium β limit (where the separatrix reaches plasma boundary), which is about 20%. These results, taken together with equally favorable results for fixed boundary modes, indicate remarkable overall stability for the heliac configuration.

An effort to establish collaboration with the Princeton Plasma Physics Laboratory is underway.

6. Stellarator Equilibrium (A. Bhattacharjee, J. C. Wiley*)

A variational method has been developed for computing three-dimensional MHD equilibrium in toroids. In this method, the so-called inverse solutions, $R(v,\theta,\zeta)$, $\phi(v,\theta,\zeta)$, and $z(v,\theta,\zeta)$ [where (R,ϕ,z) are cylindrical coordinates and (v,θ,ζ) are "straight field-line" coordinates], are determined by Fourier expanding in θ and ζ , and deriving from the variational principle a set of ordinary differential equations for the amplitudes in v . The boundary conditions are obtained from the shape of the outermost flux surface and expansions near the magnetic axis and are consistent with natural boundary conditions from the variational principle. A fully three-dimensional, toroidal code has been developed and is at the present time being tested against analytical and quasi-analytical models.

Reference: IFSR #48.

7. Stellarator Stability (A. Bhattacharjee, J. E. Sedlak, P. L. Similon, M .N. Rosenbluth, D. W. Ross*)

Stimulated by experimental results on density fluctuations in the recent Wendelstein VII A experiment, we are investigating the stability of drift waves in stellarators using the ballooning mode formalism. In the low-beta approximation, the equilibrium $\vec{B}$ ($= \vec{\nabla}\Psi\times\vec{\nabla}\beta$, in Clebsch form) may be determined analytically from the vacuum solutions $\vec{\nabla}\times\vec{B} = 0$, for which the helical flux function Ψ is known and $\vec{\nabla}\beta$ is determined by integrating a magnetic differential equation. A simple model, in which the electron response is adiabatic and the ions constitute a cold fluid, has been studied. The equation governing the perturbed electrostatic potential is reduced to a one-dimensional equation (along a field line) which is numerically integrated. The "effective potential" for this eigenmode problem in a straight stellarator is strikingly different from that in the analogus tokamak problem, with rapid helical modulations in $\vec{B}$ providing a chain of localized wells on an overall "anti-well" envelope.*

D. Computational Physics

1. Implicit Particle Simulation of Magnetized Plasmas
   [D. C. Barnes, J. N. Leboeuf, T. Tajima, T. Kamimura (IPP, Nagoya, Japan)]

A second-order, accurate, direct method for the simulation of magnetized, multi-dimensional plasmas is developed. A time-decentered particle push is combined with the direct method for implicit plasma simulation to include finite-sized particle effects in an absolutely stable algorithm. A simple iteration (renormalized Poisson equation) is used to solve the field corrector equation. Details of the two-dimensional, electrostatic, constant magnetic field, periodic case are given. Numerical results for ion-acoustic fluctuations and for an unstable gravitational interchange confirm the accuracy and efficacy of the method applied to low-frequency plasma phenomena.

The second-order accurate simulation method described here is appropriate for the study of low-frequency phenomena in a 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

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* We have found two classes of solutions: those which are localized in a helical well, and those which have a more global structure spanning several helical wells. The localized solutions are destabilized by nonadiabatic effects in the electron response.

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 are obtained in two stringent test cases. 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 phemomena at extremely low frequencies (growth rate $\gamma \simeq 10^{-5}\omega_e$).

The method described here may be easily extended in three directions. First, gyro-averaged forces may be added to Lorenz force and gyro-averaged sources to the field equations to represent finite ion gyro-radius effects. Second, the simulation may be made fully electromagnetic by the addition of a nearly-explicit time advance of the vector potential. Third, the simulation geometry may be readily changed to represent more realistic configurations with more realistic boundary conditions. Many of these extensions have been outlined in the references and details will be presented in future publications.

Reference: IFSR #70.

2. Drift-wave Turbulence Simulation [J. N. Leboeuf, R. Sydora (Tajima's student), T. Tajima]

We are developing 2.5-D and three-dimension explicit electrostatic codes. The 2.5-D version shows that the strong-shear case has a very weak drift-wave excitation.

3. Drift-wave Turbulence in Truncated $\underset{\sim}{k}$ Space (P. W. Terry, W. Horton)

Continuing previous work on the dynamics of fluctuations, we have extended our computer simulations from a 20-mode system[1] to a $\underset{\sim}{k}$ space of variable size. The largest simulations run so far have used a 15×15 $\underset{\sim}{k}$ space following 224 interacting modes. The system exhibits strong stochasticity in the dynamics with appreciable power in fluctuations many times greater than the linear frequencies. We have shown that the saturation level is essentially independent of the frequency ω_k^ℓ and increases with the maximum growth rate γ_m^ℓ until the line width $\nu_k(W) \gtrsim \omega_k^\ell$, at which point the turbulence level saturates, and is given approximately by the mixing length formula. For $\gamma_m^\ell = 0$, the steady state is an equipartition of modal energy. Relaxation to this steady state shows that the nonlinear transfer of energy is predominantly through the dissipative terms in the nonlinear mode-coupling.

We have derived the random-phase approximation for the system and shown that it predicts well the spectral distribution in $\underset{\sim}{k}$ space for the fluctuations. Recent studies have been concerned with using the full DIA approximation to solve numerically for the mean response function and determine the frequency spectra for comparison with the spectra measured in the fluctuation-dynamics code. We have made a parametric study of the functional dependence of the frequency spectrum in the fluctuation dynamics.

Reference: 1. P. W. Terry and W. Horton, IFSR #58 (1982) to be published in The Physics of Fluids.

4. Interaction of the Drift-wave Solitons and the Unstable Drift-wave Spectrum [J. D. Meiss, W. Horton, J. Sedlak (in collaboration with T. Kamimura, IPP, Nagoya, Japan)]

New work was started during the visit of T. Kamimura, using numerical simulations and theory to study the interactions of drift waves and drift-wave solitons. The simulations indicate that a solitary wave component to the electric potential evolves from low-amplitude noise. By varying the strength of the linear instability, we can vary the degree to which the fluctuation energy is divided between the wave and the soliton components. Computer experiments show that soliton-soliton collisions produce wave components and that a single large-amplitude soliton decays on a long time-scale controlled by the dissipative processes. A number of theoretical calculations, including the amplitude saturation of the solitons, the modulational stability of the system, and the evolution of the wave component of the spectrum from the DIA equations are being carried out.

5. Fast Magnetic Reconnection Driven by the Coalescence Instability in Compressible Plasmas (A. Bhattacharjee, F. Brunel, T. Tajima)

We have studied the effect of compressibility and the magnitude of the toroidal field on the coalescence instability, using a 2.5-D Particle Code which advances in time the full set of resistive MHD equations. A family of exact, two-dimensional hydromagnetic equilibria in rectangular geometry, with a periodic chain of islands, for which

$$\vec{B} = \vec{\nabla}\Psi(x,y)\times\vec{\nabla}z + B_z(x,y)\vec{\nabla}z$$

with

$$\Psi = -\frac{B_0}{k}\,\ln(\cosh kx + \cos ky) \quad .$$

In the limit $B_z \to \infty$, the plasma is almost incompressible, and the rate of reconnection in the nonlinear phase is approximately linearly proportional to time t . However, for moderate and low toroidal fields, cases have been found for which compressibility makes a qualitative difference by introducing a new nonlinear phase during which the destruction of flux proceeds at a much faster rate. In particular when $\varepsilon = 0.7$, for which the force of attraction between two neighboring current channels is strong, the rate of reconnection in the vicinity of the x-point is approximately proportional to t^2 for $s \simeq 10^3$.

References: 1. F. Brunel, T. Tajima, and J. Dawson, Phys. Rev. Lett. 49, 323 (1982). 2. IFSR #38 .

6. Radio Frequency Induced Transport and Current Drive

[T. Tajima, T. Hatori (LBL and IPP, Nagoya, Japan),
D. Pfirsch (Max Planck Inst., West Germany),
J. N. Leboeuf, S. M. Mahajan*]

We have studied the collisionless limit of transport due to ion cyclotron resonance heating in tokamaks and straight stellarators. The "neoclassical-type" of contribution due to wave-interaction does not exist and transport is mainly of the "classical-type". Work on current drive simulation has exhibited a scaling $j_{\parallel} \propto E^{3/2}$.

APPENDIX A

JOINT INSTITUTE FOR FUSION THEORY

NEWSLETTER

April 1982

The Institute for Fusion Theory in Austin works with the International Center for Fusion Theory in Nagoya to form JIFT - the Joint Institute for Fusion Theory. The primary purpose of JIFT is to implement the exchange of theoretical plasma physics and fusion research as supported through the Applied Plasma Physics Division of MFE in the Department of Energy and the research supported by the Ministry of Education in Japan. The protocol for the exchange was worked out by D. B. Nelson, J. M. Dawson, M. N. Rosenbluth and T. Ohkado, H. Kakihana and K. Nishikawa during 1980-81.

JIFT WORKSHOPS

The Joint Institute organizes special topic Workshops for the purpose of exchanging current research results not available in the literature. Recent Workshops and their organizers, along with those planned for 1982-83, are given in this Newsletter:

1. "The Theory of Non-Axisymmetric Confinement Systems"
   December 8-12, 1980, Austin, Texas
   T. Kamimura and M. N. Rosenbluth

2. "Long-Time Prediction for Conservative Dynamical Systems"
   March 16-19, 1981, Lakeway, Texas
   W. Horton, L. Reichl and Y. Ichikawa

3. "3-D MHD Studies of Toroidal Devices"
   October 19-21, 1981, Oak Ridge, Tennessee
   B. Carreras and I. Kawakami

Institute for Fusion Theory, University of Texas at Austin, Austin, Texas. Tele (512) 471-3396, FTS 734-5340. For suggestions write to W. Horton.

4. "Nonequilibrium Statistical Physics"
   November 9-13, 1981, Kyoto, Japan
   Allan N. Kaufman, John M. Greene and Kyoji Nishikawa

5. "Stellarator Equilibrium and Stability"
   December 14-18, 1981, Nagoya, Japan
   Shoichi Yoshikawa and M. Wakatani

6. "Drift Wave Turbulence"
   Janaury 11-15, 1982, Austin, Texas
   T. Sato and M. N. Rosenbluth

JIFT Exchange Scientists

1. Atsushi Fukuyama, Okayama U., September 1980-March 1981

2. Daniel Barnes, IFS, March-May, 1981

3. Nat Fisch, PPPL, February-May, 1981

4. James W. Van Dam, IFS, May-October, 1981

5. Hirotada Abe, Kyoto U., September 1981-January 1982

6. Hank Strauss, NYU, July-September, 1981

7. Charles F. Karney, PPPL, November 1981-February, 1982

8. Allen Boozer, PPPL, February-May, 1982

9. Tetsuo Kamimura, IPP, Nagoya, March-July, 1982

The research and personal opportunities made possible by the U.S.-Japan cooperation are very exciting. Here are brief reports from recent visitors who have participated in this program.

Dr. Hank Strauss, N.Y.U. to Kyoto

I visited the Plasma Physics Laboratory, directed by Prof. K. Uo, at Kyoto University and worked with the theorists, Drs. M. Wakatani and K. Hanatani, on computational MHD. During my visit, they were working on a 3-D resistive MHD code, similar to those at Oak Ridge and Princeton, which they plan to extend to study stellarators. They gave me assistance with a new mirror machine MHD code which I wrote during my visit.

The major experiment at Kyoto is the Heliotron E, one of the world's largest stellarators, which was then beginning current free operation with neutral beam injection. During my stay I visited several other laboratories, where large experiments are planned or under construction: JT-60 at Tokai, which is comparable to TFTR, and Gamma-10 at Tsukuba, which is comparable to TMX Upgrade. Nagoya University is planning the R-project, a large tokamak, and the A-project, perhaps an EBT. I was impressed to see that the Japanese will soon be operating large scale experiments comparable to those in the U.S., Europe, and Russia. It is surprising that this is being done by only a few plasma physicists. There are less than 30 plasma theoreticians in Japan. The experimenters work closely with the large technology companies, building the experiments. The Japanese effort to acquire fusion technology is similar to previous efforts in electronics and other fields. The Japanese will provide competitive impetus to fusion research.

Dr. Charles Karney, PPPL to Nagoya

I was involved in four major research activities while in Japan. In collaboration with Fukuyama of Okayama University, I worked on the nonlinear stages of ion cyclotron heating. As an ion cyclotron wave damps, a non-Maxwellian distribution develops. This either can cause the wave to be regenerated or can excite other waves. At Nagoya I worked with Ichikawa and Kamimura on particle diffusion in tandem mirrors. By deriving a reduced map to describe the particle motion it was possible to obtain an analytical expression for the diffusion coefficient. Also at Nagoya, I began some work, which is still in progress, on the long-time correlations in the stochastic regime of nonlinear systems. Such correlations are caused by small regular regions which appear even well above the stochasticity threshold. Lastly, I worked in Tokyo with Ida on getting a code to model ion cyclotron heating on the Tokyo University computer. This code was written to provide input for the Princeton transport code BALDUR. At Tokyo, it will be used to help understand the ion cyclotron heating experiments on the Tokyo Non-circular Tokamak under the direction of Miyamoto.

Dr. Allen Boozer, PPPL to Nagoya

My stay as a Visiting Professor at Nagoya University is made more pleasant by the determination of people at the Institute of Plasma Physics and on the street to make me feel like a welcomed guest in Japan. Daily living is remarkably simple. Food stores are laid out much as they are at home; so they do not test one's knowledge of Japanese. Except for beef being prohibitively expensive, there is no problem cooking in American style. However, I have developed a taste for the raw tuna, green tea, and seaweed. My son David is enrolled in the Nagoya International School. The school is academically American. It even uses the American rather than the Japanese academic calendar. However, more than half the children are local Japanese and the school lunches offer such delicacies as squid.

The facilities of the Institute of Plasma Physics are excellent. The library is unusually complete. I have primarily been working on transport in three dimensional plasmas. One paper has been completed. It gives a simple, but canonical Hamiltonian, description of a particle drift motion in magnetic coordinates for arbitrary time dependent fields.

Future JIFT Workshops and Working Groups Planned for 1982-83

(1) Statistical Physics and Chaos for Fusion Plasmas

Organizers: Wendell Horton, Linda Reichl and Yoshi Ichikawa
Location: IFS, Austin, Texas

(2) 3D MHD Configurations

Key Persons: Tetsuya Sato and Ben Carreras
Location: ICFT, Nagoya, Japan

(3) Anomalous Transport and Critical Beta Values

Key Persons: Yoshinosuke Tereshima and Bruno Coppi
Location: ICFT, Nagoya, Japan

(4) Hot Electron Physics

Key Persons: James Van Dam and Tsuguhiro Watanabe
Location: IFS, Austin, Texas

APPENDIX B

INSTITUTE FOR FUSION STUDIES REPORTS

IFSR	Author(s)	Title	Date
1	Horton, W.	"ANOMALOUS ION CONDUCTION FROM TOROIDAL DRIFT MODES" (sub. to Plasma Physics)	10/80
2	Leboeuf, J. N., Tajima, T., & Dawson, J. M.	MAGNETIC X-POINTS, ISLANDS COALESCENCE AND INTENSE PLASMA HEATING appears in Physics of Auroral Arc Formation, S. I. Akasofu and J. R. Kan (eds.), (American Geophys. Union, Washington, DC., 1981) p. 337.	10/80
3	Ware, A.	NEOCLASSICAL ENERGY TRANSFER BETWEEN ELECTRONS AND IONS IN A TOKAMAK [Nucl. Fusion 21, 631 (1981)]	10/80
4	Hitchcock, D., Hazeltine, R., & Mahajan, S. M.	UNIFIED KINETIC THEORY IN TOROIDAL SYSTEMS	12/80
5	Horton, W. (ed.)	SUMMARY OF U.S.-JAPAN WORKSHOP ON THE THEORY OF NON-AXISYMMETRIC CONFINEMENT SYSTEMS	1/81
6	Cary, J. R., Meiss, J. D., & Bhattacharjee, A.	STATISTICAL CHARACTERIZATION OF PERIODIC MEASURE-PRESERVING MAPPINGS [Phys. Rev. A23, 2744 (1981)]	1/81
7	Meiss, J. D.	NUMERICAL COMPUTATION OF RELAXATION RATES FOR THE TEST WAVE MODEL [appears in Nonlinear Properties of Internal Waves (A.I.P., New York, 1981), p. 129]	2/81
8	Ware, A.	ELECTRON TEMPERATURE LIMIT FOR POLOIDAL EQUILIBRIUM AND TOKAMAK CONTAINMENT SCALING (accepted by Comments on Plasma Physics and Controlled Fusion)	2/81
9	Horton, W.	DRIFT MODES IN AXISYMMETRIC TANDEM MIRRORS [Phys. Fluids 24, 1270 (1981)]	2/81
10	Cary, J. R.	NECESSARY STABILITY CONDITION FOR FIELD-REVERSED THETA PINCHES [Phys. Fluids 24, 2239 (1981)]	3/81

11	Rosenbluth, M. N.	MAGNETIC TRAPPED PARTICLE MODES [Phys. Rev. Lett. 46, 1525 (1981)]	3/81
12	Van Dam, J. W., Rosenbluth, M. N., & Lee, Y. C.	A GENERALIZED KINETIC ENERGY PRINCIPLE [Phys. Fluids 25, 1349 (1982)]	3/81
13	Berk, H. L., Dominguez, R. R., & Maschke, E. K.	VARIATIONAL STRUCTURE OF THE VLASOV EQUATION [Phys. Fluids 24, 2245 (1981)]	3/81
14	Cary, J. R.	LIE TRANSFORM PERTURBATION THEORY FOR HAMILTONIAN SYSTEMS (sub. to Physics Reports)	4/81
15	Leboeuf, J. N., Tajima, T., & Dawson, J. M.	DYNAMIC MAGNETIC X-POINTS [Phys. Fluids 25, 784 (1982)]	3/81
16	Yoshikawa, S.	INTERCHANGE INSTABILITIES CAUSED BY IMPURITY IONS IN ROTATING PLASMAS	3/81
17	Mahajan, S. M., Hazeltine, R., & Hitchcock, D.	QUASI-LINEAR MOMENTUM TRANSPORT [Phys. Fluids 24, 1164 (1981)]	3/81
18	Hazeltine, R.	RENORMALIZATION OF PLASMA TURBULENCE IN TOROIDAL GEOMETRY	4/81
19	Bhattacharjee, A., & Dewar, R. L.	ENERGY PRINCIPLE WITH GLOBAL INVARIANTS [Phys. Fluids 25, 884 (1982)]	4/81
20	Terry, P., & Horton, W.	STOCHASTICITY AND THE RANDOM PHASE APPROXIMATION FOR THREE ELECTRON DRIFT WAVES [Phys. Fluids 25, 491 (1982)]	5/81
21	Diamond, P., & Rosenbluth, M. N.	THEORY OF THE RENORMALIZED DIELECTRIC FOR ELECTROSTATIC DRIFT WAVE TURBULENCE IN TOKAMAKS [Phys. Fluids 24, 1641 (1981)]	5/81
22	Yoshikawa, S.	BALLOONING STABILITY IN TOROIDAL DEVICES (also Princeton Plasma Physics Laboratory report PPPL-1812)	5/81
23	Tajima, T., Joshi, C., Dawson, J. M., Baldis, H., & Ebrahim, N.	FORWARD RAMAN INSTABILITY AND ELECTRON ACCELERATION [Phys. Rev. Lett. 47, 1285 (1981)]	5/81

24	Diamond, P., & Rosenbluth, M. N.	THEORY OF ION COMPTON SCATTERING FOR DRIFT WAVE TURBULENCE IN A SHEARED MAGNETIC FIELD	5/81
25	Cary, J. R., & Meiss, J. D.	RIGOROUSLY DIFFUSIVE DETERMINISTIC MAP [Phys. Rev. A24, 2664 (1981)]	6/81
26	Meiss, J., Hazeltine, R., Diamond, P., & Mahajan, S. M.	EFFECT OF TURBULENT DIFFUSION ON COLLISIONLESS TEARING INSTABILITIES [Phys. Fluids 25, 815 (1982)]	6/81
27	Wang, L. T., Dawson, J. M., Lin, A. T., Menyuk, C. R., & Tajima, T.	COMPUTER SIMULATION OF SYNCHROTRON RADIATION IN TWO DIMENSIONS [J. Plasma Phys. 28, 133 (1982)]	6/81
28	Thayer, E., & Molvig, K.	ENERGY CONSERVATION AND RELATED CONSTRAINTS IN DRIFT WAVE TURBULENCE	7/81
29	Tajima, T.	ION CYCLOTRON RESONANCE HEATING appears in Fusion Energy--1981 (IAEA, Trieste, 1982) p. 85.	7/81
30	Molvig, K., Freidberg, J., Potok, R., Hirshman, S., Whitson, J., & Tajima, T.	TURBULENT RESPONSE IN A STOCHASTIC REGIME [to appear in Long-time Prediction in Stochastic Systems, C. W. Horton, L. Reichl, & Szebehely, (eds.), (Wiley and Sons, New York, 1982)]	6/81
31	Mahajan, S. M.	ANOMALOUS TRANSPORT FROM DRIFT MODES DRIVEN BY TEMPERATURE GRADIENTS AND TRAPPED ELECTRONS (accepted by Phys. Fluids)	7/81
32	Horton, W., & Brock, D.	EVOLUTION OF TOROIDAL DRIFT-WAVE FLUCTUATIONS DRIVEN BY ION PRESSURE GRADIENTS	7/81
33	Hirshman, S., & Diamond, P.	SELF-CONSISTENT SPECTRUM OF ELECTRO-STATIC DRIFT WAVE FLUCTUATIONS DUE TO ELECTRON PHASE SPACE CORRELATIONS IN A SHEARED MAGNETIC FIELD	7/81
34	Van Dam, J. W., Berk, H. L., Rosenbluth, M. N., & Spong, D. A.	EIGENMODE STABILITY ANALYSIS FOR A BUMPY TORUS [Proc. EBT Stability Theory Workshop (ORNL, Oak Ridge, 1981) Conf.-810512, p. 97]	7/81
35	Horton, W.	DRIFT WAVE TURBULENCE AND ANOMALOUS TRANSPORT	9/81

36	Terry, P., Anderson, W., & Horton, W.	KINETIC EFFECTS ON THE TOROIDAL ION PRESSURE GRADIENT DRIFT MODE	10/81
37	Molvig, K., Lidsky, L. M., Hizanidis, K., & Bernstein, I. B.	BREAKDOWN OF ONSAGER SYMMETRY IN NEOCLASSICAL TRANSPORT THEORY	6/81
38	Tajima, T.	NONLINEAR COLLISIONLESS TEARING AND RECONNECTION (sub. to Physics Review Letter)	9/81
39	Brunel, F., & Tajima, T.	CONFINEMENT OF A HIGH-BETA PLASMA COLUMN (sub. to The Physics of Fluids)	9/81
40	Saltzman, B.	THE FEASIBILITY OF A RING STABILIZED PLASMA REACTOR IN THE LEE-VAN DAM LIMIT	10/81
41	Cary, J. R.	RELATION OF LINEAR RESPONSE TO NONLINEAR MOTION	10/81
42	Hinton, F., & Rosenbluth, M. N.	STABILIZATION OF AXISYMMETRIC MIRROR PLASMAS BY ENERGETIC ION INJECTION	10/81
43	Hinton, F.	IMPURITY FLOW REVERSAL IN TOKAMAKS WITHOUT MOMENTUM INPUT	10/81
44	Cary, J. R.	ANALYSIS OF CHAOTIC, AREA-PRESERVING MAPS	11/81
45	Meiss, J. D., & Horton, W.	FLUCTUATION SPECTRA OF A DRIFT WAVE SOLITON GAS [Phys. Fluids , (1981)] (appeared under title "Drift Wave Turbulence from a Soliton Gas" [Phys. Rev. Lett. 48, 1362 (1982)]	12/81
46	Meiss, J. D.	INTEGRALS OF THE TEST WAVE HAMILTONIAN: A SPECIAL CASE appears in Mathematical Methods in Hydrodynamics and Integrability in Dynamical Systems, (A.I.P., New York, 1982) p. 293.	12/81
47	Mahajan, S.	INTEGRAL EQUATION FORMULATION OF ELECTROMAGNETIC MODE EQUATIONS (accepted by Phys. Fluids)	11/81
48	Bhattacharjee, A., Wiley, J., & Dewar, R. L.	VARIATIONAL METHOD FOR THE THREE-DIMENSIONAL INVERSE EQUILIBRIUM PROBLEM IN TOROIDS (accepted by Phys. Fluids)	12/81

49	Brunel, F., Tajima, T., & Dawson, J.	FAST MAGNETIC RECONNECTION PROCESSES [Phys. Rev. Lett. 49, 323 (1982)]	2/82
50	Berk, H. L., Van Dam, J. W., Rosenbluth, M. N., & Spong, D. A.	CURVATURE-DRIVEN INSTABILITIES IN A HOT ELECTRON PLASMA: RADIAL ANALYSIS (accepted by Phys. Fluids)	12/81
51	Bhattacharjee, A., Dewar, R. L., Glasser, A. H., Chance, M. S., & Wiley, J. C.	ENERGY PRINCIPLE WITH GLOBAL INVARIANTS: APPLICATIONS [Phys. Fluids 25, 887 (1982)]	1/82
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